Experimental Proposal for Phase-I of the COMET Experiment at J-PARC

July 9, 2012

Executive Summary

We hereby submit an experimental proposal for Phase-I of the staged construction of the COherent Muon to Electron Transition (COMET) experiment that, when fully deployed, will search for neutrinoless $\mu^- - e^-$ conversions with a single-event sensitivity of 3×10^{-17} . This sensitivity is a factor of 10,000 better than achieved by the SINDRUM-II experiment which set the current world's best limit for $\mu^- - e^-$ conversions. The COMET experiment was given Stage-1 approval, of two stages, by the J-PARC Program Advisory Committee in 2009 and given the experiment number J-PARC E21.

The proposed J-PARC mid-term plan includes the construction of the COMET beamline. This will provide the proton beamline for COMET and part of the muon beamline in the south area of the J-PARC Nuclear and Particle Physics Experimental Hall (NP Hall). We consider a staged approach for COMET as described below. To realize this approach we would like to construct the muon beamline up to the end of the first 90° bend in the muon beamline so that a muon beam can be extracted to the experimental area. We refer to this as "COMET Phase-I". In COMET Phase-I, we will:

- 1. make a direct measurement of the proton beam extinction and other potential background sources for the full COMET experiment, using the actual COMET beamline, and
- 2. carry out a search for $\mu^- e^-$ conversion with a singe-event sensitivity of 3×10^{-15} , which is better than achieved by SINDRUM-II.

The direct measurement of potential background sources will be vital for the full COMET experiment. The current background estimates are made by extrapolating existing measurements over four orders of magnitude, and uncertainties are therefore difficult to quantify and are potentially large. However, once the partial muon beamline is completed, it will become possible to make realistic background estimations from direct measurements. Based on these, the final design of the COMET beamline and detectors will be optimised and uncertainties on the background estimations minimized. This will significantly enhance the ultimate sensitivity of the COMET experiment.

A search for $\mu^- - e^-$ conversion with a sensitivity beyond that achieved to date will be performed. The pion contamination in the muon beam at COMET Phase-I will be high because of the shorter muon beamline. However, since the muon intensity will be the highest in the world by several orders of magnitude, as for the full COMET experiment, we will be able to probe beyond the current limit and set the world's best limit should no signal be observed. The addition of the full muon beamline in Phase-II will give the ultimate sensitivity for the COMET experiment. The proposed staged approach will produce valuable scientific outcomes at each phase and the physics impact of our CLFV search in COMET Phase-I will be significant.

In summary, we have identified a strong physics case to stage the construction of the COMET experiment that is aligned with the proposed J-PARC mid-term plan for the

construction of the COMET beamline. We are hoping to start the construction of COMET Phase-I in JFY2013 and to carry out our measurements in 2016.

KEK/J-PARC-PAC 2012-10

The COMET Collaboration

R. Akhmetshin, A. Bondar, L. Epshteyn, G. Fedotovich, D. Grigoriev, V. Kazanin, A. Ryzhenenkov, D. Shemyakin, Yu. Yudin Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia

R. Palmer

Department of Physics, Brookhaven National Laboratory, USA

Y. Arimoto, K. Hasegawa, Y. Igarashi, M. Ikeno, S. Ishimoto, Y. Makida, T. Mibe,

S. Mihara, T. Nakamoto, H. Nishiguchi, T. Ogitsu, C. Omori, N. Saito, K. Sasaki,
 M. Sugano, Y. Takubo, M. Tanaka, M. Tomizawa, T. Uchida, A. Yamamoto,
 M. Yamanaka, M. Yoshida, Y. Yoshii, K. Yoshimura
 High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

Yu. Bagaturia Ilia State University (ISU), Tbilisi, Georgia

P. Dauncey, P. Dornan, B. Krikler, A. Kurup, J. Nash, J. Pasternak, Y. Uchida Imperial College London, UK

> P. Sarin, S. Umasankar Indian Institute of Technology Bonbay, India

Y. Iwashita Institute for Chemical Research, Kyoto University, Kyoto, Japan

V.V. Thuan Institute for Nuclear Science and Technology, Vietnam

H.-B. Li, C. Wu, Y. Yuan Institute of High Energy Physics (IHEP), China

A. Liparteliani, N. Mosulishvili, Yu. Tevzadze, I. Trekov, N. Tsverava Institute of High Energy Physics of I.Javakhishvili State University (HEPI TSU), Tbilisi, Georgia

S. Dymov, P. Evtoukhovich, V. Kalinnikov, A. Khvedelidze, A. Kulikov, G. Macharashvili, A. Moiseenko, B. Sabirov, V. Shmakova, Z. Tsmalaidze, E. Velicheva Joint Institute for Nuclear Research (JINR), Dubna, Russia

> M. Danilov, A. Drutskoy, V. Rusinov, E. Tarkovsky Institute for Theoretical and Experimental Physics (ITEP), Russia

> > T. Ota

Max-Planck-Institute for Physics (Werner-Heisenberg-Institute), Munchen, Germany

Y. Mori, Y. Kuriyama, J.B. Lagrange

KEK/J-PARC-PAC 2012-10

4

Kyoto University Research Reactor Institute, Kyoto, Japan

C.V. Tao

College of Natural Science, National Vietnam University, Vietnam

M. Aoki, I.H. Hasim T. Hayashi, Y. Hino, T. Iwami, T. Itahashi, S. Ito, Y. Kuno^{*}, Y. Matsumoto, T.H. Nam, H. Sakamoto, A. Sato, N.D. Thong, N.M. Truong, K. Yai Osaka University, Osaka, Japan

> M. Koike, J. Sato Saitama University, Japan

D. Bryman University of British Columbia, Vancouver, Canada

S. Cook, R. D'Arcy, A. Edmonds, M. Lancaster, M. Wing University College London, UK

> J.F. Solehan, W.A. Tajuddin University of Malaya, Malaysia

R.B. Appleby, W. Bertsche, M. Gersabeck, H. Owen, C. Parkes, G. Xia University of Manchester, UK

> F. Azfar, M. John University of Oxford, UK

Md. I. Hossain University Technology Malaysia

> T. Numao TRIUMF, Canada

* Contact Person

Contents

1	Ove	Dverview					
	1.1 Introduction \ldots						
	1.2	COMET Staged Approach and the J-PARC Mid-term Plan	12				
		1.2.1 Direct background measurements	12				
		1.2.2 Search for $\mu^ e^-$ conversion and other CLFV muon processes	13				
		1.2.3 Towards the Full COMET Experiment (COMET Phase-II)	13				
2	Phy	sics Motivation	14				
	2.1	Introduction	14				
		2.1.1 History I — the establishment of the concept of lepton flavor	14				
		2.1.2 History II — the discovery of lepton flavor violation in neutrinos	15				
	2.2	New Physics and CLFV	17				
		2.2.1 Supersymmetric models	18				
		$2.2.1.1 \text{General features} \dots \dots \dots \dots \dots \dots \dots \dots \dots $	18				
		2.2.1.2 Models with the seesaw mechanism $\ldots \ldots \ldots \ldots$	19				
		2.2.2 Little Higgs models	20				
		2.2.3 Extra dimensional models	21				
		2.2.3.1 Anarchic Randall-Sundrum model	22				
		$2.2.3.2 \text{UED models} \dots \dots \dots \dots \dots \dots \dots \dots \dots $	23				
	2.3	CLFV at the LHC Era	23				
	2.4	$\mu^ e^-$ Conversion	25				
		2.4.1 What is a $\mu^ e^-$ conversion process ?	25				
		2.4.2 Signal and background events	25				
		2.4.3 $\mu^ e^-$ conversion vs. $\mu^+ \to e^+ \gamma$	26				
		2.4.4 Why is $\mu^ e^-$ conversion the next step ?	27				
		2.4.5 Present experimental status of $\mu^ e^-$ conversion	27				
		2.4.5.1 SINDRUM-II	29				
		2.4.5.2 MECO	29				
		$2.4.5.3$ Mu2e \ldots	30				
	2.5	Other Muon CLFV Physics Processes	31				
		2.5.1 $\mu^ e^+$ conversion process	31				
		2.5.1.1 Event signature and backgrounds	32				
		2.5.1.2 Experimental status of $\mu^ e^+$ conversion	32				

C(ONTI	ENTS
		2.5.2 $\mu^- + e^- \rightarrow e^- + e^-$ conversion process
3	Pro	ton Beam 34
-	3.1	Requirements for the proton beam
	0.1	3.1.1 Proton energy
		3.1.2 Proton beam power
		313 Proton beam time structure
	3.2	Proton Acceleration 36
	0	3.2.1 LINAC operation 37
		3.2.2 BCS operation 37
		3.2.3 Main ring operation 38
		3 2 3 1 Injection from the BCS to the MB
		3232 Beam emittance at 8 GeV 41
		3233 Extraction 41
	33	Proton Beam Transport 43
	0.0	3.3.1 Transport heam line hardware
		3311 Magnet system 44
		3312 Power supply system $4/$
		3.31.3 Vacuum system 44
4	Mu	on Beam 45
	4.1	Introduction
	4.2	Pion production
		4.2.1 Pion production yields
		4.2.2 Comparison of different hadron production codes
		4.2.3 Pion production target
		$4.2.3.1$ Target material $\ldots \ldots 48$
		$4.2.3.2$ Target length and radius $\ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 48$
		4.2.3.3 Target tilt angle
		$4.2.3.4$ Target heating $\ldots \ldots \ldots$
	4.3	Pion capture
		4.3.1 Pion capture in a solenoidal magnetic field
		4.3.2 Superconducting solenoid design
		4.3.2.1 Radiation heating and radiation dose
		4.3.3 Adiabatic transition from high to low magnetic fields
	4.4	Muon Beam
		4.4.1 Beam optics of curved solenoids
	4.5	Muon Beam Simulation Study
	4.6	Beam at the End of the First 90° Bend $\ldots \ldots 58$
	-	4.6.1 Dispersion distribution
		4.6.2 Momentum distribution
		4.6.3 Time distribution
	4.7	Beam at the Muon Stopping Target

	4.8	Muon	Stopping	Target		•	•					61
5 Detector												64
0	5.1	Introd	uction .									64
	5.2	Detect	or for Ba	ckground Measurements								64
	5.3	Detect	fors to Se	arch for $\mu^ e^-$ Conversion								66
		5.3.1	Cvlindri	cal Drift Chamber								66
		0.0.2	5.3.1.1	CDC structure								67
			5.3.1.2	CDC wire configuration								68
			5.3.1.3	CDC mechanical design								69
			5.3.1.4	CDC gas system								70
			5.3.1.5	CDC hit rates								71
			5.3.1.6	CDC trigger counters and trigger rates		•						72
			5.3.1.7	CDC momentum resolution								73
	5.4	Transv	verse Trac	ker Detector for $\mu^ e^-$ Conversion Search								74
		5.4.1	Straw T	ube Tracker		•						77
			5.4.1.1	Overview								77
			5.4.1.2	Design								77
			5.4.1.3	Performance								78
			5.4.1.4	Architecture of Tracker System								79
		5.4.2	Electron	Calorimeter		•						79
			5.4.2.1	Overview		•					•	79
			5.4.2.2	Crystal selection		•						81
			5.4.2.3	Photon Sensors		•					•	81
			5.4.2.4	Electronics		•					•	82
			5.4.2.5	Performance		•	•		•	•	•	83
6	\cos	mic Ra	ay Shield	ling								85
	6.1	Introd	uction .			•					•	85
	6.2	Passiv	e Shieldir	lg		•			•		•	85
	6.3	Active	Shielding	r_{5}		•	·		•	•	•	86
7	Dat	a Acqu	uisition S	System								94
	7.1	Trigge	r concept			•			•		•	94
	7.2	Data 1	ates			•			•		•	95
	7.3	Data a	acquisition	n system		•	•			•	•	95
8	Sig	nal Sen	sitivity	and Backgrounds								97
	8.1	Introd	uction .			•	•			•	•	97
	8.2	Signal	Sensitivi	ty for $\mu^ e^-$ Conversion		•	•			•	•	97
		8.2.1	Signal a	cceptance for the COMET Phase-I CDC		•				•	•	97
		8.2.2	Signal A	cceptance for COMET Phase-I Transverse T	lra	cke	er i	De	te	cto	or	100
	8.3	Backg	round Est	timation for $\mu^ e^-$ Conversion		•	•			•	•	100

	8.4	Backg	round Estimation for COMET Phase-I CDC
		8.4.1	Intrinsic physics backgrounds
			8.4.1.1 Muon decays in orbit $\ldots \ldots \ldots$
			8.4.1.2 Beam-related prompt backgrounds
			8.4.1.3 Radiative pion capture
			8.4.1.4 Beam electrons, electrons from muon and pion decays in
			flight \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 105
			8.4.1.5 Background induced by beam neutrons 106
		8.4.2	Cosmic ray induced backgrounds
	8.5	Summ	ary of background estimations
9	Sup	ercond	lucting Solenoid Magnets 108
	9.1	Overv	iew
		9.1.1	Layout
		9.1.2	Design Requirements
		9.1.3	Conductor Choice
		9.1.4	Pion Capture Solenoid
		9.1.5	Muon Transport Solenoids
	9.2	etic Field Distribution With Iron Yokes	
		9.2.1	3-dimensional field calculation
		9.2.2	Magnetic fields on the solenoid axis
		9.2.3	Magnetic Fields in Iron Yoke and Coil Surface
	9.3	Electro	omagnetic Forces With the Iron Yoke
		9.3.1	Compressive electromagnetic force
		9.3.2	Hoop stress from electromagnetic forces
	9.4	Crvoge	enic System $\ldots \ldots 120$
		9.4.1	Overview
	9.5	Influer	nce of Irradiation (COMET Phase-II)
	9.6	Crvost	$at Design \ldots 123$
		9.6.1	Overview
		9.6.2	Cryostat-1
		9.6.3	Cryostat-2
		9.6.4	Cryostat-3
	9.7	Mecha	nical Analysis of Cryostats and Coil Supports
		9.7.1	Mechanical Analyses $\dots \dots \dots$
			9.7.1.1 Distortion of the vacuum vessels
			9.7.1.2 Von Mises stress of the vacuum vessels
			9.7.1.3 Distortion of coil support structure 129

CONTENTS

9.7.2 Results of Mechanical Strength 129 9.8

CONTENTS

10	Infrastructure10.1 Primary Proton Beam line10.2 Experimental Area10.3 Electricity and Cooling Water	135 135 135 137
11	Cost and Schedule 11.1 Cost	140 140 140
12	Summary	143
A	χ^2 Function for Straw Tube Tracker Analysis	153
в	Neutron Irradiation Tests at KUR	154

Chapter 1

Overview

1.1 Introduction

Charged lepton flavor violation (CLFV) has yet to be observed and is known to be sensitive to new physics beyond the Standard Model (SM), as discussed in Chapter 2. The J-PARC E21 experiment is an experiment to search for a CLFV process of neutrinoless muon-toelectron conversion (μ^--e^- conversion) in a muonic atom,

$$\mu^{-} + N(A, Z) \to e^{-} + N(A, Z),$$
 (1.1)

at a single-event sensitivity of 3×10^{-17} at the Japanese Proton Accelerator Research Complex (J-PARC). This experiment is called COherent Muon to Electron Transition (COMET). This anticipated sensitivity goal of the COMET experiment is a factor of 10,000 better than that of the current experimental limit¹.

The COMET experiment is designed to be carried out in the Nuclear and Particle Experimental Hall (NP Hall) using a bunched proton beam that is slow-extracted from the J-PARC main ring (MR). The experimental set-up consists of the dedicated proton beam line, the muon beam section and the detector section. The muon beam section is composed of the pion capture solenoids with high magnetic field, and the muon transport with curved and straight solenoids. The detector section is composed of the muon stopping target, the electron transport for $\mu^- - e^-$ conversion signals, followed by the detector systems. A schematic drawing of the experimental set-up is shown in Fig. 1.1.

In order to improve the sensitivity by a factor of 10,000 over the current limit, several important features have been considered, such as

- a highly intense muon source,
- a pulsed proton beam with high proton extinction factor, and
- curved solenoids for charge and momentum selection.

The COMET experimental design has several advantages. These are mainly due to the C-shaped design of the muon transport and the electron transport:

¹The present published limit is $B(\mu^{-} + Au \rightarrow e^{-} + Au) = 7 \times 10^{-13}$ from SINDRUM-II at PSI [1].

CHAPTER 1. OVERVIEW



Figure 1.1: Schematic layout of COMET and COMET Phase-I

• C-shape muon transport in the muon beam

Instead of the S-shape that was adopted by a previously proposed experiment at BNL (MECO) [2], the C-shape muon transport in the muon beam line (from the pion production to the muon-stopping target) is chosen in COMET. This requires an additional compensating dipole field, which can be produced using separate dipole coils or by tilting the solenoid coils. Since the muon momentum dispersion is proportional to a total bending angle, the C-shape beamline will produce a larger separation of the muon tracks as a function of momentum, resulting in improved momentum selection, which can also be varied independently of the solenoidal field if separate dipole coils are employed.

• C-shape electron transport in the detector

Instead of a straight solenoid, a C-shaped electron transport (from the muon-stopping target to the detector) is adopted in the COMET spectrometer. The principle of momentum selection is the same as that used in the muon transport system, but, in the spectrometer, electrons of low momenta which mostly come from muon decay in

orbit (DIO) are removed. As a result, the detector rate will be reduced significantly and the probability of false-tracking is highly suppressed. The tracking detector rate, including the direct hit of DIO electrons and secondary electrons from scattering and photon conversion, is expected to be less than 1 MHz. This is almost two orders of magnitudes less than the expected detector rate for the MECO experiment. Another advantage of using a curved solenoid for the electron transport is that it will eliminate the need for a proton absorber to remove low-energy protons emitted after muon captures by nuclei. This suppresses possible deterioration of the detector performance. Also because of the suppression of low-energy particles, the detector geometry can be made simple—as is the case with the present configuration with straw tube tracker planes transverse to the field axis and an electron calorimeter whose front face is perpendicular to the field axis.

1.2 COMET Staged Approach and the J-PARC Midterm Plan

The proposed J-PARC mid-term plan includes the construction of the COMET beam line. This will provide the proton beam line for COMET and part of the muon beam line in the south area of the J-PARC NP Hall. We consider a staged approach for COMET. To realize this staged approach, we would like to construct the COMET muon beam line up to the end of the first 90° bend so that a muon beam can be extracted to the experimental area. This stage is called "COMET Phase-I". Figure 1.1 shows the part of the muon beamline that will be constructed in COMET Phase-I.

COMET Phase-I has two major goals:

- direct measurement of the proton beam extinction factors and other potential background sources for the full COMET experiment by using the actual COMET beamline constructed at Phase-I, and
- a search for $\mu^- e^-$ conversion with a single-event sensitivity of better than 3.1×10^{-15} which is a factor of 200 times better than the SINDRUM-II limit.

1.2.1 Direct background measurements

The direct measurement of potential background sources will be vital for the full COMET experiment. The current background estimates are made by extrapolating existing measurements over four orders of magnitude, and uncertainties are therefore difficult to quantify and are potentially large. However, once the partial muon beamline is completed, it will become possible to make realistic background estimations from direct measurements. Potential backgrounds that can be measured are pions, neutrons, antiprotons, gammas and electrons in the beam, and the electron spectrum of muon decays in orbit (DIO), and so on. To carry out these direct measurements, a dedicated detector with charged particle tracking and an electromagnetic calorimeter will be prepared. Based on these, the final design of the COMET beamline and detectors will be optimised and uncertainties on the

CHAPTER 1. OVERVIEW

background estimations minimised. This will significantly enhance the ultimate sensitivity of the COMET experiment.

1.2.2 Search for $\mu^- - e^-$ conversion and other CLFV muon processes

A search for $\mu^- - e^-$ conversion with a single-event sensitivity beyond that achieved to date will be performed. This anticipated single-event sensitivity is about a factor of 200 better than the current limit by SINDRUM-II. To carry out a search for $\mu^- - e^-$ conversion, two types of detector options are being considered. One is a detector dedicated for COMET Phase-I, and the other is a re-use of the detector used for the background measurements.

The former is based on a cylindrical drift chamber which surrounds a muon stopping target. The detector is placed inside a large superconducting solenoid magnet producing a 1 Tesla magnetic field, similarly to the SINDRUM-II detector. From our studies, COMET Phase-I would carry out a search for $\mu^- - e^-$ conversion in aluminum with a single-event sensitivity of 3.1×10^{-15} . The measurement can be done with a 8 GeV proton beam of 3.2 kW power over a running time of 1.5×10^6 seconds (18 days). The background of about 0.03 events is expected at this sensitivity with a proton extinction factor of 10^{-9} . The details are described in Chapter 8.

In addition to the $\mu^- - e^-$ conversion search, the special features of the COMET Phase-I detector allows for further possibilities:

- This detector can detect both positive and negative particles, whereas the full COMET detector can detect only negatively charged particles owing to the electron transport system which uses curved solenoids. This allows for a search for the lepton-number-violating process $\mu^- + N \rightarrow e^+ + N'$ ($\mu^- e^+$ conversion) concurrently with the $\mu^- e^-$ conversion search. The anticipated experimental sensitivity for $\mu^- e^+$ conversion could be similar to $\mu^- e^-$ conversion, although a detailed estimation has not been performed.
- This detector can have a large geometrical coverage, and thereby a coincidence measurement with a large solid angle is achievable. And also the J-PARC MR can provide a DC proton beam with a duty factor of about 0.3. These facts indicate that a search for μ⁻ + e⁻ → e⁻ + e⁻ conversion in a muonic atom is possible. This is a previously-unmeasured process. With a beam of less than 10⁷ muons/sec in intensity, a measurement of μ⁻ + e⁻ → e⁻ + e⁻ can be carried out by this detector.

1.2.3 Towards the Full COMET Experiment (COMET Phase-II)

The addition of the full muon beamline in Phase-II will give the ultimate single-event sensitivity for the COMET experiment of 3×10^{-17} . The proposed staged approach will produce valuable scientific outcomes at each phase and the physics impact of our CLFV search in COMET Phase-I will be significant.

Chapter 2

Physics Motivation

2.1 Introduction

The origin of the flavors of elementary particles is a puzzling enigma. Their properties and structure should reflect the nature of the physics beyond the SM. Flavor physics is thereby believed to provide a path to new physics. The flavor-changing neutral current (FCNC) processes are of particular interest since they are expected to include the effect of new physics that are observable in high-precision experiments. Among the FCNC processes, the CLFV processes have recently attracted much attention from both theoretical and experimental points of views. The search for CLFV processes has notable advantages, including the following. (1) CLFV can have **sizable contributions from new physics** and thus can manifest themselves in future experiments. (2) CLFV gives **no sizable contribution in the Standard Model** unlike the FCNC process of the quarks; such contributions give serious background events and limit the sensitivity to new physics.

2.1.1 History I — the establishment of the concept of lepton flavor

"Can a muon convert into an electron ?" This has been a big question since 1937, when the muon was first discovered [3]. Its mass was about 200 times heavier than the electron's, and hence at first it was conjectured to be Yukawa's meson[4]. Soon afterwards, however, it was found that its lifetime was too long and its interaction cross section too weak for it to be the Yukawa meson[5, 6]. This led to the idea of two mesons, which was the first theoretical notion of the muon[7, 8]. The leptonic nature of the muon was soon confirmed experimentally [9]. Furthermore, masses aside, the nature of the muon and the electron were found to be quite similar[10].

"Who ordered that?", the famous comment by Rabi, suggests how puzzling the existence of the new lepton was at that time. It was considered that the muon could be an excited state of the electron. If this were correct, a consequence of this would be that the muon should decay into an electron and a photon. In 1947 Hincks and Pontecorvo[11]

experimentally searched for the process $\mu^+ \to e^+ + \gamma$. This was the first search for lepton flavor violation of charged leptons (CLFV). They found a negative result and set an upper bound for the branching ratio of this process of less than 10%. Almost at the same time, it was suggested that the muon could decay into three particles[12]. One of them would be the electron and the others two neutral particles, namely neutrinos. Note that the neutrinos were assumed to be identical — thus far, the concept of lepton flavor had not arisen.

Since then, successive searches for muon CLFV have been carried out, for example for the neutrinoless $\mu^- - e^-$ conversion process ($\mu + N \rightarrow e + N$, with N a nuclei), and $\mu \rightarrow e + \gamma [13, 14, 15]$. All the results were negative and set strong limits on these branching ratios.

Such a stringent limit on muon decay led to the idea that there are two kinds of neutrino[16, 17]. This was the first notion of lepton flavor — muon flavor (L_{μ}) and electron flavor (L_e) . This was verified experimentally at Brookhaven National Laboratory (BNL) by observing that only muons were produced by neutrinos which come directly from pion decay[18].

Then the concept of generations of particles was developed[19]. It was extended to three generations [20] and hence the concept of lepton flavor was also extended to include a third flavor, the tau L_{τ} . All ideas are finally integrated into the SM, in which lepton flavor conservation is guaranteed by an exact symmetry, owing to massless neutrinos.

2.1.2 History II — the discovery of lepton flavor violation in neutrinos

Following the initial quest for CLFV, searches with various elementary particles, such as muons, taus, kaons, and others have been carried out. The upper limits have been improved at a rate of two orders of magnitude per decade, as can be seen in Figure 2.1. The present upper limits of various CLFV decays are listed in Table 2.1, where it can also be seen how high the sensitivity of the muon system is to CLFV. This is mostly because of the large number of muons available for present experimental searches (about $10^{14} - 10^{15}$ muons/year). Moreover, an even greater number of muons (about $10^{19} - 10^{20}$ muons/year) will be available in the future, if new highly intense muon sources are realized.

While all of these earlier searches gave negative results for CLFV, lepton flavor violation among neutrino species has been experimentally confirmed with the discovery of neutrino oscillations[34, 35], and lepton flavor conservation is now known to be violated. The phenomenon of oscillation means that neutrinos are massive and hence the SM must be modified so that neutrinos are massive and CLFV can occur. Furthermore, there are other reasons which compel us to modify the SM, including the existence of dark matter, and stability of the weak scale against quantum corrections. These indicate that new physics beyond the SM will reveal itself at TeV scale. This scale is within the scope of the Large Hadron Collider and expected CLFV experiments including COMET.



Figure 2.1: History of searches for CLFV in muon and kaon decays

Reaction	Present limit	Reference
$\mu^+ \to e^+ \gamma$	$< 2.4 \times 10^{-12}$	[21]
$\mu^+ \to e^+ e^+ e^-$	$<1.0\times10^{-12}$	[22]
$\mu^- Ti \to e^- Ti$	$< 6.1 \times 10^{-13}$	[23]
$\mu^-Au \to e^-Au$	$< 7 \times 10^{-13}$	[1]
$\mu^+e^- ightarrow \mu^-e^+$	$< 8.3 \times 10^{-11}$	[24]
$\tau \to e\gamma$	$< 3.9 \times 10^{-7}$	[25]
$ au o \mu \gamma$	$< 3.1 imes 10^{-7}$	[26]
$ au o \mu \mu \mu$	$< 1.9 \times 10^{-7}$	[27]
$\tau \rightarrow eee$	$< 2.0 imes 10^{-7}$	[27]
$\pi^0 \to \mu e$	$< 8.6 \times 10^{-9}$	[28]
$K_L^0 \to \mu e$	$<4.7\times10^{-12}$	[29]
$\tilde{K^+} \to \pi^+ \mu^+ e^-$	$< 2.1 \times 10^{-10}$	[30]
$K_L^0 \to \pi^0 \mu^+ e^-$	$< 3.1 \times 10^{-9}$	[31]
$Z^{0} \rightarrow \mu e^{1}$	$< 1.7 \times 10^{-6}$	[32]
$Z^0 \rightarrow \tau e$	$<9.8\times10^{-6}$	[32]
$Z^0 \to \tau \mu$	$< 1.2 \times 10^{-5}$	33

Table 2.1: Present limits of CLFV of the muon, tau, pion, kaon and Z boson.

2.2 New Physics and CLFV

Although CLFV has never been observed, lepton flavor violation among neutrino species has been experimentally confirmed with the discovery of neutrino oscillations [34, 35], and hence lepton flavor conservation is now known to be violated. The phenomenon of oscillation means that neutrinos are massive and hence the SM must be modified so that CLFV can occur. Furthermore, there are other reasons which compel us to modify the SM, including the existence of dark matter, and stability of the weak scale against quantum corrections. These indicate that new physics beyond the SM will reveal itself at the TeV scale. This scale is within the scope of the Large Hadron Collider and expected CLFV experiments including COMET and COMET Phase-I.

It is well known that in the minimally extended SM, which includes vanishingly small neutrino masses to account for neutrino oscillations, the predicted rate for CLFV is too small to be observed. For example, the prediction for $Br(\mu \to e\gamma)$ is given by the graph in Figure 2.2 [36, 37, 38, 39],

$$\operatorname{Br}(\mu \to e\gamma) = \frac{\alpha}{2\pi} \left| \sum_{k} U_{ek} U_{\mu k}^{*} \left| \frac{m_{\nu_{k}}^{2}}{m_{W}^{2}} \right|^{2} \simeq \frac{\alpha}{2\pi} \left| U_{e3} U_{\mu 3}^{*} \frac{\Delta m_{\operatorname{atm}}^{2}}{m_{W}^{2}} \right|^{2} < 10^{-54}.$$
(2.1)

Here $U_{\beta i}$ is the Maki-Nakagawa-Sakata Matrix [19] with β denoting a charged lepton flavor eigenstate and *i* a neutrino mass eigenstate with mass m_i , and m_W is the *W* boson mass, and α is the fine structure constant. Note that the GIM mechanism [40] leads to a prediction dependent on differences in the masses of the neutrinos. For the $\mu \to e\gamma$ process, a similar suppression arises due to gauge symmetry.



Figure 2.2: One of the diagrams of massive neutrino contributions to a μ to e transition $(\mu \rightarrow e \ "\gamma")$.

Therefore, the discovery of CLFV would imply new physics beyond not only the SM but also beyond "neutrino oscillations". In fact, all new physics or interactions beyond the Standard Model predict CLFV at some level. Examples of such new physics models include supersymmetric (SUSY) models, extra dimension models, little Higgs models, models with new gauge Z' bosons, models with new heavy leptons, lepto-quark models, etc.. Each gives a prediction for FCNC, including CLFV.

In the following three subsections, we discuss relations between $Br(\mu \to e\gamma)$ and $Br(\mu + N \to e + N)$ for several new physics models.

Although expected at the LHC, discrimination of these new physics models will be very difficult[41]. The search for $\mu^- - e^-$ will be crucial in discriminating between these models, and it is especially synergistic with the $\mu \to e\gamma$ search. Thus the argument for studying the physics of CLFV throughout the next decade is very robust[42].

2.2.1 Supersymmetric models

2.2.1.1 General features

Supersymmetric extensions to the SM are the leading candidates for physics beyond the SM. In this class of model, a form of parity, called R-parity, is often imposed to suppress FCNC, rapid proton decays and other phenomena. In this case the source for CLFV is the soft mass matrix $(m_{\tilde{l}}^2)$ for sleptons, the scalar partners of the leptons. In principle, this can be arbitrary and a large FCNC can be introduced. However strong constraints are imposed on these parameters. For example, the branching ratio of $\mu \to e + \gamma$ is given similarly with Eq. (2.1) by

$$\operatorname{Br}(\mu \to e\gamma) = \frac{\alpha}{2\pi} \left| \sum_{k} \tilde{U}_{ek} \tilde{U}_{\mu k}^{*} \frac{\Delta m_{k}^{2}}{m_{S}^{2}} \right|^{2} \left(\frac{m_{W}}{m_{S}} \right)^{4}, \qquad (2.2)$$

where m_S is the typical scale of scalar masses, \tilde{U} denotes the mixing matrix between sleptons and leptons, and Δm_k^2 is the mass squared difference between the k^{th} and the 1st sleptons. To suppress this, the conditions that, by some mechanism, \tilde{U} is almost diagonal and/or Δm_k^2 is small enough compared with m_S^2 have to be assumed. To implement these conditions at the weak scale, it is often assumed that at a certain scale M_G ,

$$\tilde{U} = 1 \text{ and } \Delta m_k^2 = 0, \tag{2.3}$$

and an observable effect arises as a radiative correction. As a result, $\tilde{U} \simeq 1$ and $\Delta m_k^2 \simeq 0$ are maintained at the weak scale.

Under this condition, the SUSY contribution to a muon-to-electron transition ($\mu \to e$ " γ ") is given by Figure 2.3, where the mixing between a smuon ($\tilde{\mu}$) and a selectron (\tilde{e}) is denoted by $\Delta m_{\tilde{\mu}\tilde{e}}^2$, and plays a key role.

This slepton mixing parameter, $\Delta m_{\tilde{\mu}\tilde{e}}^2$ (or similarly $\Delta m_{\tilde{e}\tilde{\mu}}^2$) is given by the off-diagonal element of the slepton mass matrix $(m_{\tilde{l}}^2)$ that is given in Eq. (2.4)¹.

$$m_{\tilde{l}}^2 = \begin{pmatrix} m_{\tilde{e}\tilde{e}}^2, \Delta m_{\tilde{e}\tilde{\mu}}^2, \Delta m_{\tilde{e}\tilde{\tau}}^2 \\ \Delta m_{\tilde{\mu}\tilde{e}}^2, m_{\tilde{\mu}\tilde{\mu}}^2, \Delta m_{\tilde{\mu}\tilde{\tau}}^2 \\ \Delta m_{\tilde{\tau}\tilde{e}}^2, \Delta m_{\tilde{\tau}\tilde{\mu}}^2, m_{\tilde{\tau}\tilde{\tau}}^2 \end{pmatrix}$$
(2.4)

¹It is noteworthy that the SUSY contributions to the muon g-2 and the muon electric dipole moments are the real and an imaginary parts of the diagonal element $m^2_{\tilde{\mu}\tilde{\mu}}$, respectively.

Therefore, the determination of these SUSY contributions would enable us to study the structure of the slepton mass matrix, and then more importantly the "SUSY soft breaking" that is the origin of SUSY particle masses. It should be noted that the slepton mixing is difficult to study, as precisely as in CLFV studies, at high energy collider experiments such as the LHC. Hence, studies of CLFV would provide a **unique opportunity to study slepton mixing**. In the following, the SUSY contributions to CLFV are presented in more detail.



Figure 2.3: One of the diagrams of SUSY contributions to a μ to e transition ($\mu \to e \ "\gamma"$). $\Delta m_{\tilde{u}\tilde{e}}^2$ indicates the magnitude of the slepton mixing.

2.2.1.2 Models with the seesaw mechanism

There are several mechanisms which give the conditions in Eq. (2.3). Among these, gravitymediated soft breaking is the most often employed. It gives the conditions in Eq. (2.3) at the gravity scale (=Planck, ~ 10^{19} GeV) or grand unified scale (~ 10^{16} GeV). Non-zero off-diagonal matrix elements can then be induced by radiative corrections from M_G to the weak scale (~ 10^2 GeV).

To reproduce lepton mixing and the neutrino masses, the seesaw mechanism[43, 44] has been studied most extensively. In this mechanism, three right-handed neutrinos N_i are introduced. Mass terms for the neutrinos are given by the Yukawa coupling between the lepton doublets (L_{α}) and the right-handed neutrinos and the Majorana mass term for the right-handed neutrinos:

$$W = \bar{N}_{i} f_{\nu}^{i\alpha} L_{\alpha} H_{u} + \frac{1}{2} \bar{N}_{i} M_{R_{i}} \bar{N}_{j}.$$
 (2.5)

It induces Eq. (2.4)[45]

$$(\Delta m_{\tilde{L}}^2)_{\alpha\beta} \simeq -\frac{(6+a_0^2)m_0^2}{16\pi^2} (f_{\nu}^{\dagger}f_{\nu})_{\alpha\beta} \log \frac{M_G}{M_B}.$$
 (2.6)

Here m_0 denotes the SUSY breaking scale and a_0 , a parameter for A term breaking, is an O(1) parameter.

Thus in a SUSY model with the seesaw mechanism, slepton mixing can be induced from neutrino mixing. CLFV processes in muon decays are then also expected to occur[46, 47, 48]. An example of the branching ratio is shown in Figure 2.4.



Figure 2.4: Predictions of $\mu^+ \rightarrow e^+ \gamma$ branching ratio in SUSYseesaw models. The three lines correspond to the cases of $\tan \beta = 30, 10, 3$ from top to bottom, respectively. Taken from[47].

The most important result here is the robust relation between the branching ratio of $\mu \to e + \gamma$ and that of μ to e conversion. In this model, $\mu^- - e^-$ conversion is dominated by a dipole operator similar to Figure 2.3, with a quark line attached at the other end of the photon line. Therefore the important relation[49]

$$\frac{\operatorname{Br}(\mu + N \to e + N)}{\operatorname{Br}(\mu \to e + \gamma)} \sim \alpha \tag{2.7}$$

is achieved. The details of this depend on the nucleus, as can be seen in Figure 2.5.

2.2.2 Little Higgs models

In Little Higgs models[50, 51], Higgs bosons appear as a quasi-Nambu-Goldstone boson to ensure its stability against quantum corrections. There are several implementations of this idea. Among them the model with T-parity[52] is the most extensively studied. In this model, to prevent the little hierarchy problem, mirror fields of the ordinary fields are introduced. These have odd T-parity, while ordinary fields are even under T-parity. This parity works similarly to R-parity in SUSY models.



Figure 2.5: Prediction of the branching ratio of $\mu^- - e^-$ conversion in various nuclei in SUSY-seesaw models normalized to the branching ratio of $\mu \to e\gamma$. Taken from[49].

The source of CLFV arises from the misalignment between mirror fields and the ordinary fields[53]. There is no principle to forbid large FCNC and current limits on CLFV strongly constrain models. In Figure 2.6, the predictions for $\mu^- - e^-$ conversion and $\mu \to e\gamma$ are shown with an appropriate assumption taken for the misalignment.

The contribution to $\mu \to e\gamma$ is depicted in Figure 2.7. In addition to the GIM suppression, there is another accidental cancellation among these diagrams. Therefore, unlike the SUSY case these diagrams do not give a leading contribution to $\mu^- - e^-$ conversion, and box and Z penguin diagrams dominate the amplitude for $\mu^- - e^-$ conversion[55, 54, 56]. Incidentally, due to T-parity conservation, there is no tree-level contribution to $\mu^- - e^-$ conversion and hence both branching ratios are loop-suppressed.

Thus the branching ratios in this model are almost equal as shown in Figure 2.6

$$\frac{\operatorname{Br}(\mu + N \to e + N)}{\operatorname{Br}(\mu \to e + \gamma)} \sim 1.$$
(2.8)

2.2.3 Extra dimensional models

There are many kinds of models involving extra dimensional space. Here we discuss two models. The first is the Randall-Sundrum model[57] and the second is a universal extra dimensional model (UED)[58]



Figure 2.6: Prediction of the branching ratio of $\mu^- - e^-$ conversion and of $\mu \to e\gamma$ in Little Higgs Models. Taken from [54].



Figure 2.7: Diagrams for $\mu \to e\gamma$ in Little Higgs Models. Taken from [54].

2.2.3.1 Anarchic Randall-Sundrum model

To explain the hierarchy among Yukawa couplings, the SM fields are permitted to propagate in the full 5D space [59, 60]. In this scenario, the SM fields are localized at a different

point of 5th dimension. Yukawa couplings are quite sensitive to the position and this fact explains the hierarchy among the Yukawa couplings in effective 4D theory with O(1) group 5D couplings. These O(1) couplings indicate a large mixing among generation in a full 5D theory. It manifests itself in the self-couplings of the 1st Kaluza-Klein (KK) gauge bosons and the ordinary fermions as follows.

First we note that in the interaction basis (e_F, μ_F, τ_F) , the gauge coupling "universality" among fermions are modified:

$$g^{SM}(\bar{e}_F,\bar{\mu}_F,\bar{\tau}_F)A^{(n)}\begin{pmatrix}\alpha_e & 0 & 0\\ 0 & \alpha_\mu & 0\\ 0 & 0 & \alpha_\tau\end{pmatrix}\begin{pmatrix}e_F\\\mu_F\\\tau_F\end{pmatrix}.$$
(2.9)

Here g^{SM} stands for the gauge coupling in the SM corresponding to the gauge field A. Since it is the self-coupling of the 1st KK gauge bosons, $\alpha_{e,\mu,\tau}$ are not necessarily equal to 1. In the mass eigenstate, (e, μ, τ) , therefore, there arise CLFV couplings

$$g^{SM}(\bar{e},\bar{\mu},\bar{\tau}) A^{(n)} U_{L(R)} \begin{pmatrix} \alpha_e & 0 & 0\\ 0 & \alpha_\mu & 0\\ 0 & 0 & \alpha_\tau \end{pmatrix} U^{\dagger}_{L(R)} \begin{pmatrix} e\\ \mu\\ \tau \end{pmatrix}$$
(2.10)

Here $U_{L(R)}$ are the mixing matrices to diagonalize the mass matrix given in the basis of the interaction state. Note that since $\alpha_{e,\mu,\tau}$ are not equal, the effect of the mixing matrices remains. In principle, it causes a large CLFV effect. With the appropriate assumption, the prediction for CLFV is given in Figure 2.8. There is not a strong correlation between $\mu \to e\gamma$ and $\mu^- - e^-$. The branching ratios are predicted to be rather large and give a similar magnitude:

$$\frac{\operatorname{Br}(\mu + N \to e + N)}{\operatorname{Br}(\mu \to e + \gamma)} \sim 1.$$
(2.11)

2.2.3.2 UED models

In this class of model, in general, there is no misalignment between ordinary matter and the KK particles. Therefore even if neutrino masses are introduced[62], no CLFV effect beyond the SM and neutrino contribution in Eq. 2.1 arises. Hence

$$\operatorname{Br}(\mu + N \to e + N) \sim \operatorname{Br}(\mu \to e\gamma) < 10^{-54}.$$
(2.12)

Note that with information from LHC even if we do not see any CLFV signal, it will serve a very important information, since in many case new physics must predict no CLFV.

2.3 CLFV at the LHC Era

At the time of writing this proposal, no new physics phenomena has been found at the LHC. Therefore, the search for CLFV is crucial to find any clues of new physics beyond



Figure 2.8: Prediction of the branching ratio of $\mu^- - e^-$ conversion and for $\mu \to e\gamma$ in anarchic Randall-Sundrum models. Taken from[61].

the SM. There are many other models to account for neutrino CLFV (lepton mixing and neutrino masses), the existence of dark matter, the stability of the electroweak scale and so on. All of them predict a new particle at the TeV scale which will be found LHC. Each model has its prediction for $Br(\mu \to e\gamma)$ and $Br(\mu^- + N \to e^- + N)$. These are parametrized in the effective operator as

$$\mathcal{L} = \frac{a_{\mu e}^2 m_{\mu}}{\Lambda^2} \bar{e} \sigma^{\mu\nu} F_{\mu\nu} \mu + \frac{b_{\mu e}^2}{\Lambda^2} \bar{e} \mu \bar{q} q \qquad (2.13)$$

Here Λ indicates a typical new physics scale and $a_{\mu e}^2$ and $b_{\mu e}^2$ stand for couplings and/or loop factors. The current limits of CLFV [63, 22, 23] give a stringent limit on these effective scales as $\Lambda/a_{\mu e}, \Lambda/b_{\mu e} > 10^3$ TeV. It means, for example, if these operators are loop suppressed, the scale explored by new CLFV experiments is the TeV range.

In general, the relation between $a_{\mu e}$ and $b_{\mu e}$ is model dependent. For example in a SUSY model they are both loop suppressed and are related with each other tightly while in a Little Higgs model, they are both loop suppressed but are not related so much. Therefore the relation between $\mu \to e\gamma$ and $\mu^- - e^-$ conversion shows a characteristic feature for each model. It is expected that the LHC will find evidence for new physics. It is, however very difficult to discriminate a true model from other candidates. It is, therefore, essential to determine the relation between $a_{\mu e}$ and $b_{\mu e}$.

This demonstrates that the $\mu^- - e^-$ conversion search has outstanding physics motivation, even in the LHC era and after the MEG experiment.

2.4 $\mu^- - e^-$ Conversion

2.4.1 What is a $\mu^- - e^-$ conversion process ?

One of the most prominent muon CLFV processes is coherent neutrinoless conversion of muons to electrons ($\mu^- - e^-$ conversion). When a negative muon is stopped by some material, it is trapped by an atom, and a muonic atom is formed. After it cascades down energy levels in the muonic atom, the muon is bound in its 1s ground state. The fate of the muon is then to either decay in orbit ($\mu^- \to e^- \nu_\mu \overline{\nu}_e$) or be captured by a nucleus of mass number A and atomic number Z, namely, $\mu^- + N(A, Z) \to \nu_\mu + N(A, Z - 1)$. However, in the context of physics beyond the Standard Model, the exotic process of neutrinoless muon capture, such as

$$\mu^{-} + N(A, Z) \to e^{-} + N(A, Z),$$
 (2.14)

is also expected. This process is called $\mu^- - e^-$ conversion in a muonic atom. This process violates the conservation of lepton flavor numbers, L_e and L_{μ} , by one unit, but the total lepton number, L, is conserved. The final state of the nucleus (A, Z) could be either the ground state or one of the excited states. In general, the transition to the ground state, which is called coherent capture, is dominant. The rate of the coherent capture over noncoherent capture is enhanced by a factor approximately equal to the number of nucleons in the nucleus, since all of the nucleons participate in the process.

2.4.2 Signal and background events

The event signature of coherent $\mu^- - e^-$ conversion in a muonic atom is a mono-energetic single electron emitted from the conversion with an energy of $E_{\mu e} \sim m_{\mu} - B_{\mu}$, where m_{μ} is the muon mass and B_{μ} is the binding energy of the 1s muonic atom.

From an experimental point of view, $\mu^- - e^-$ conversion is a very attractive process. Firstly, the e^- energy of about 105 MeV is far above the end-point energy of the muon decay spectrum (~ 52.8 MeV). Secondly, since the event signature is a mono-energetic electron, no coincidence measurement is required. The search for this process has the potential to improve sensitivity by using a high muon rate without suffering from accidental background events, which would be serious for other processes, such as $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^+e^-$ decays.

The electron is emitted with an energy $E_e \approx m_{\mu}$, which coincides with the endpoint of muon decay in orbit (DIO), which is the only relevant intrinsic physics background event. Since the energy distribution of DIO falls steeply above $m_{\mu}/2$, the experimental setup can have a large signal acceptance and the detectors can still be protected against the vast majority of decay and capture background events. Energy distributions for DIO electrons have been calculated for a number of muonic atoms [64, 65, 66] and energy resolutions of the order of 0.1% are sufficient to keep this background below 10^{-18} .

There are several other potential sources of electron background events in the energy region around 100 MeV, involving either beam particles or cosmic rays. Beam-related background events may originate from muons, pions or electrons in the beam. Apart from

DIO, muons may produce background events by muon decay in flight or radiative muon capture (RMC). Pions may produce background events by radiative pion capture (RPC). Gamma rays from RMC and RPC produce electrons mostly through e^+e^- pair production inside the target.

There are three methods to suppress the beam-related background events:

• Beam pulsing

Since muonic atoms have lifetimes of the order of 1 μ s, a pulsed beam with buckets that are short compared with this lifetime would allow the removal of prompt background events by performing measurements in a delayed time window. As will be discussed below there are stringent requirements on beam extinction during the measuring interval.

• Beam purity

The lifetime of the pion (26 ns) is much shorter than the lifetime of muon (2.2×10^3 ns). Thus, if the beam momentum is low enough, most of beam pions will decay away as they transport through a muon beamline. If the beam momentum is less than 70 MeV/*c*, the level of pion contamination will be decreased by an order of magnitude for each 10 m.

• Beam momentum

The in-flight decay of beam muons produces 100 MeV/c electrons if the beam momentum is larger than 70 MeV/c. Beam electrons would be also a source of 100 MeV/celectron background. Thus, if the beam momentum is restricted to be lower than 70 MeV/c, these backgrounds can be suppressed.

2.4.3 $\mu^- - e^-$ conversion vs. $\mu^+ \rightarrow e^+ \gamma$

There are considered to be two possible contributions in the μ^--e^- transition diagrams. One is a photonic contribution of dipole interaction, and the other is a non-photonic contribution of contact interaction. For the photonic contribution, there is a definite relation between the μ^--e^- conversion process and the $\mu^+ \to e^+\gamma$ decay. Suppose the photonic contribution is dominant, the branching ratio of the μ^--e^- conversion process is expected be smaller than that of $\mu^+ \to e^+\gamma$ decay by a factor of a few hundred due to electromagnetic interaction of a virtual photon. This implies that the search for μ^--e^- conversion at the level of 10^{-16} is comparable to that for $\mu^+ \to e^+\gamma$ at the level of 10^{-14} .

If the non-photonic contribution dominates, the $\mu^+ \to e^+\gamma$ decay would be small whereas the μ^--e^- conversion could be sufficiently large to be observed. It is worth noting the following. If a $\mu^+ \to e^+\gamma$ signal is found, the μ^--e^- conversion signal should also be found. A ratio of the branching ratios between $\mu^+ \to e^+\gamma$ and μ^--e^- carries vital information on the intrinsic physics process. If no $\mu^+ \to e^+\gamma$ signal is found, there will still be an opportunity to find a μ^--e^- conversion signal because of the potential existence of non-photonic contributions.

The effective Lagrangian that includes both the photonic and non-photonic contribu-

tions is given by

$$\mathcal{L} = \frac{1}{1+\kappa} \frac{m_{\mu}}{\Lambda^2} \bar{\mu}_{\mathrm{R}} \sigma^{\mu\nu} e_{\mathrm{L}} F_{\mu\nu} + \frac{\kappa}{1+\kappa} \frac{1}{\Lambda^2} (\bar{\mu}_{\mathrm{L}} \gamma^{\mu} e_{\mathrm{L}}) (\bar{q}_{\mathrm{L}} \gamma_{\mu} q_{\mathrm{L}})$$
(2.15)

Figures 2.9 and 2.10 show the relation at a tree level between the branching ratios of $\mu^+ \rightarrow e^+ \gamma$ and $\mu^- - e^-$ conversion in terms of as a function of a ratio of the photonic and non-photonic contributions for the tree levels and the loop level with loop suppression respectively. The 90 % C.L. upper limits expected from COMET Phase-I, COMET and PRISM (as a future prospect) are also shown.

2.4.4 Why is $\mu^- - e^-$ conversion the next step ?

Considering its marked importance to physics, it is highly desirable to consider a nextgeneration experiment to search for CLFV. There are three processes to be considered; namely, $\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^+e^-$, and μ^--e^- conversion.

The three processes have different experimental issues that need to be solved to realize improved experimental sensitivities. They are summarized in Table 2.2. The processes of $\mu^+ \rightarrow e^+\gamma$ and $\mu^+ \rightarrow e^+e^+e^-$ are detector-limited. To consider and go beyond the present sensitivities, the resolutions of detection have to be improved, which requires innovative improvement of the detector technology. In particular, improving the photon energy resolution is difficult. On the other hand, for $\mu^- - e^-$ conversion, there are no accidental background events, and an experiment with higher rates can be performed. If a new muon source with a higher beam intensity and better beam quality for suppressing beam-associated background events can be constructed, measurements of higher sensitivity can be performed.

Table 2.2: LFV processes and issues

Process	Major backgrounds	Beam	Sensitivity Issues
$\mu^+ \to e^+ \gamma$	accidental	DC beam	detector resolution
$\mu^+ \to e^+ e^+ e^-$	accidental	DC beam	detector resolution
$\mu^ e^-$ conversion	beam-associated	pulsed beam	beam qualities

Furthermore, it is known that in comparison with $\mu^+ \to e^+\gamma$, there are more physical processes that μ^--e^- conversion and $\mu^+ \to e^+e^+e^-$ could contribute to. Namely, in SUSY models, photon-mediated diagrams can contribute to all the three processes, but the Higgs-mediated diagrams can contribute to only μ^--e^- conversion and $\mu^+ \to e^+e^+e^-$. In summary, with all of the above considerations, a μ^--e^- conversion experiment would be the natural next step in the search for lepton flavour violation.

2.4.5 Present experimental status of μ^--e^- conversion

Table 2.3 summarizes the history of searches for $\mu^- - e^-$ conversion. From Table 2.3, it is seen that over about 30 years the experimental upper limits has been improved by 5 orders



Figure 2.9: Relation between $\mu^+ \rightarrow e^+\gamma$ and $\mu^- - e^-$ conversion estimated from Eq.(2.15). The parameter κ interpolates between the photonic and the non-photonic contributions. The current searches are sensitive to $O(10^3)$ TeV energy scale. The anticipated COMET Phase-I limits are shown.

Figure 2.10: Relation between $\mu^+ \to e^+\gamma$ and $\mu^- - e^-$ conversion from Eq.(2.15) with loop suppressions. A parameter of κ interpolates between the photonics and the non-photonic contributions. The current searches are sensitive to O(1) TeV energy scale. The anticipated COMET Phase-I limits are shown.

of magnitude. In the following, the past and future experiments of searching for $\mu^- - e^-$ conversion will be described.

Process	upper limit	place	year	reference
$\mu^- + Cu \to e^- + Cu$	$<1.6\times10^{-8}$	SREL	1972	[67]
$\mu^- + {}^{32}S \rightarrow e^- + {}^{32}S$	$< 7 \times 10^{-11}$	SIN	1982	[68]
$\mu^- + Ti \to e^- + Ti$	$< 1.6 \times 10^{-11}$	TRIUMF	1985	[69]
$\mu^- + Ti \rightarrow e^- + Ti$	$< 4.6 \times 10^{-12}$	TRIUMF	1988	[70]
$\mu^- + Pb \rightarrow e^- + Pb$	$< 4.9 \times 10^{-10}$	TRIUMF	1988	[70]
$\mu^- + Ti \rightarrow e^- + Ti$	$<4.3\times10^{-12}$	\mathbf{PSI}	1993	[71]
$\mu^- + Pb \rightarrow e^- + Pb$	$< 4.6 \times 10^{-11}$	\mathbf{PSI}	1996	[72]
$\mu^- + Ti \rightarrow e^- + Ti$	$< 6.1 \times 10^{-13}$	\mathbf{PSI}	1998^{*}	[23]
$\mu^- + Au \to e^- + Au$	$< 7 \times 10^{-13}$	\mathbf{PSI}	2006	[1]

Table 2.3: Past experiments on $\mu^- - e^-$ conversion. (* reported only in conference proceedings.)

2.4.5.1 SINDRUM-II

The latest search for $\mu^- - e^-$ conversion was performed by the SINDRUM-II collaboration at PSI. Figure 2.11 shows their results. The main spectrum, taken at 53 MeV/*c*, shows the steeply falling distribution expected from muon DIO. Two events were found at higher momenta, but just outside the region of interest. The agreement between measured and simulated positron distributions from μ^+ decay means that confidence can be high in the accuracy of the momentum calibration. At present there are no hints concerning the nature of the two high-momentum events: they might have been induced by cosmic rays or RPC, for example. They set the current upper limit on $B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$ [1].

2.4.5.2 MECO

There was an experimental proposal at BNL, the MECO experiment [2], aiming to search with a sensitivity of 10^{-16} . This project was planned to combat beam-related background events with the help of a pulsed 8 GeV/*c* proton beam. Figure 2.12 shows the proposed layout. Pions are produced by 8 GeV/*c* protons crossing a 16 cm long tungsten target, and muons from the decays of the pions are collected efficiently with the help of a graded magnetic field. Negatively charged particles with 60–120 MeV/*c* momenta are transported by a curved solenoid to the experimental target. In the spectrometer magnet, a graded field is also applied. A major challenge is the requirement for proton extinction in between the proton bursts. In order to maintain the pion stop rate in the 'silent' interval, a beam extinction factor better than 10^{-8} – 10^{-9} is required. Unfortunately, the MECO experiment was canceled in 2005, owing to the NSF funding problems.

events per 0.25 MeV/c



Figure 2.12: Setup of the MECO experiment.

2.4.5.3Mu₂e

However, the revival of the MECO experiment has been actively made at the Fermi National Laboratory (Fermilab), the "Mu2e experiment" (see Fig. 2.13). The muon beam line and detector for the Mu2e experiment are almost the same as those of the MECO experiment. The aimed experimental sensitivity is also the same. The experimental proposal was stage-one approved at Fermilab fall, 2008 [73]. The Mu2e experiment would strongly

Recent results by



Figure 2.13: A schematic layout of the Mu2e experiment.

compete with the COMET experiment. The Mu2e experiment will use the Fermilab proton source, and the desired proton beam structure from their 8 GeV Booster can be made by reusing the 8 GeV Debuncher and Accumulator storage rings, which are both housed in the anti-proton beam enclosure.

2.5 Other Muon CLFV Physics Processes

The other muon CLFV processes that can be potentially searched for at COMET Phase-I are presented. They are $\mu^- - e^+$ conversion and $\mu^- + e^- \rightarrow e^- + e^-$ in a muonic atom.

2.5.1 $\mu^- - e^+$ conversion process

The other neutrinoless muon-conversion process is a charge-changing reaction, such as

$$\mu^{-} + N(A, Z) \to e^{+} + N(A, Z - 2)^{*},$$
 (2.16)

which violates the conservation of total lepton number (LFV) as well as the lepton flavor numbers, L_e and L_{μ} . This process is closely related to neutrinoless double β -decay ($\beta\beta_{0\nu}$), since both processes require a mechanism involving two nucleons. The final state of the nucleus $N(A, Z - 2)^*$ could be either the ground state (gs) or an excited state (ex). Since the final nucleus is not the same as the initial nucleus, no coherent enhancement is expected, even for the transition to the ground state. The branching ratio of μ^--e^+ conversion is defined by

$$B(\mu^{-}N(A,Z) \to e^{+}N(A,Z-2)^{*}) \equiv \frac{\Gamma(\mu^{-}N(A,Z) \to e^{+}N(A,Z-2)^{*})}{\Gamma(\mu^{-}N(A,Z) \to \text{capture})}.$$
 (2.17)

Various theoretical models predict experimentally accessible rates. One is the minimum supersymmetric model (MSSM) with R-parity violation, which allows a branching ratio for μ^--e^+ conversion of about 10^{-12} , since the relevant λ and λ' parameters are not constrained [74]. Left-right symmetric models with a low-mass W_R also predict a μ^--e^+ conversion branching ratio of 10^{-14} .

2.5.1.1 Event signature and backgrounds

The energy of the positron from $\mu^- - e^+$ conversion is given by

where Δ_{Z-2} is the difference in the nuclear binding energy between the (A, Z) and (A, Z-2) nuclei, with the excitation energy in the final nucleus taken into account. Usually, it is assumed that a large fraction of the final nucleus could be in the giant dipole resonance state, which has a mean energy of 20 MeV and a width of 20 MeV. Therefore, the e^+ from $\mu^- - e^+$ conversion would have a broad momentum distribution corresponding to the width of giant dipole resonance excitation.

The principal background is radiative muon capture (RMC) or radiative pion capture (RPC), followed by asymmetric e^+e^- conversion of the photon. For some nuclei, the endpoint of the RMC background can be selected to be well separated from the signal. The background from RPC must be reduced by the rejection of pions in the beam.

2.5.1.2 Experimental status of $\mu^- - e^+$ conversion

Table 2.4: Historical progress and summary of $\mu^- - e^+$ conversion in various nuclei. gs and ex respectively denote the transitions to the ground state and excited states (mostly giant dipole-resonance states), respectively.

Process	90% C.L. upper limit	place	year	reference
$\mu^- + Cu \to e^+ + Co$	2.6×10^{-8}	SREL	1972	[67]
$\mu^- + S \rightarrow e^+ + Si$	9×10^{-10}	SIN	1982	[68]
$\mu^- + Ti \to e^+ + Ca(gs)$	9×10^{-12}	TRIUMF	1988	[70]
$\mu^- + Ti \to e^+ + Ca(ex)$	1.7×10^{-10}	TRIUMF	1988	[70]
$\mu^- + Ti \to e^+ + Ca(gs)$	4.3×10^{-12}	\mathbf{PSI}	1993	[71]
$\mu^- + Ti \rightarrow e^+ + Ca(ex)$	8.9×10^{-11}	\mathbf{PSI}	1993	[71]
$\mu^- + Ti \to e^+ + Ca(gs)$	1.7×10^{-12}	\mathbf{PSI}	1998	[75]
$\mu^- + Ti \to e^+ + Ca(ex)$	3.6×10^{-11}	PSI	1998	[75]

The SINDRUM-II Collaboration at PSI has reported a search for the charge-changing process $\mu^- + Ti \rightarrow e^+ + Ca$ in muonic atoms [75]. It was carried out simultaneously with a measurement of $\mu^- + Ti \rightarrow e^- + Ti$. The results are given separately for the transition to the ground state and that to the giant dipole resonance. They are summarized in Table 2.4, together with the previous results.

2.5.2 $\mu^- + e^- \rightarrow e^- + e^-$ conversion process

The other CLFV process in a muonic atom is

$$\mu^- + e^- \to e^- + e^-,$$
 (2.19)

where e^- in the initial state is an atomic electron in a muonic atom. This process violates the conservation of the lepton flavor numbers, L_e and L_{μ} . This process is closely related to $\mu^+ \to e^+e^+e^-$ decay [76]. The advantage of $\mu^- + e^- \to e^- + e^-$ over $\mu^+ \to e^+e^+e^-$ is that the final state has clear kinematics of two body decays. The disadvantage is small overlap of the wave functions of μ^- and e^- in the initial state. Since the wave function of the 1s atomic electrons in a muonic atom are determined by the atomic number of the nucleus Z, when a heavy target material is used, the rate will be increased by Z^3 . There have been no experimental limits on this process and so any measurement would have significant impact.

Chapter 3 Proton Beam

This chapter describes the proton beam used to produce the COMET muon beam. The J-PARC main ring (MR) is used to supply a pulsed 8 GeV proton beam, which is slow extracted, maintaining its bunch structure, into the J-PARC Nuclear and Particle Experimental Hall (NP Hall). The pulsed proton beam then hits the pion production target located inside the pion capture solenoid magnet. The produced pions decay to muons as they are transported from the pion production target to the muon stopping target. These muons are momentum selected by the curved solenoid transport channel as described in Chapter 4. Phase-I of the COMET experiment requires the same beam structure as proposed in the COMET experiment.

3.1 Requirements for the proton beam

The J-PARC MR will deliver a proton beam, as the design goal, with an intensity of 3.3×10^{14} protons per cycle and a cycle time of about 0.3 Hz. Protons from the J-PARC MR are extracted either to the NP Hall by slow extraction, or to the neutrino experimental hall (T2K) by fast extraction. When operated in slow extraction mode, the average beam current and duty factor are 15 μ A and 0.2 respectively.

Since COMET Phase-I requires the intensity of muons on the stopping target to be as high as tolerable for the detector system, the intensity of the proton beam needs to be high enough in order to provide an intense flux of pions.

3.1.1 Proton energy

The number of pions (and therefore their daughter muons) produced by a proton beam is proportional to the proton beam power, which is given by the product of the beam energy and beam current. This is due to the fact that the pion cross-section increases linearly with proton beam energy.

The required beam power in Phase-I is approximately 1 to 2 orders of magnitude lower than that for the full COMET experiment. The reasons for the relatively low proton beam



Figure 3.1: Average multiplicity of anti-proton production as a function of the incident proton energy [77].

energy, i.e. 8 GeV, are twofold. One is to suppress production of anti-protons, and the other is to ease the requirements of the beam extinction system if needed, where a lower beam energy is easier to deflect. The cross section of anti-proton production, $p+p \rightarrow p+p+p+\bar{p}$ whose threshold is at 5.6 GeV, rapidly increases above a proton beam energy of 10 GeV as shown in Figure 3.1. Thus a proton beam energy of 8 GeV is used in the current design. At this energy, even if anti-protons are produced, most of them can be eliminated by inserting a stopping foil in the muon transport line. The foil separating the vacuum between the COMET experimental area and the primary beam line can be used for this purpose.

3.1.2 Proton beam power

The required proton beam power is 8 GeV × (0.00001–0.4) μ A ((0.000063–2.5) × 10¹² protons/s), which will provide enough muons at COMET Phase-I to allow the beam properties to be studied and the physics goals to be achieved. We start at lower intensities, which are also suitable for performing the accelerator studies that are needed to realize 8 GeV beam extraction from the MR. If the beam power could be upgraded by increasing the repetition cycle of the accelerator, that is ideal for COMET Phase-I, whose sensitivity reach will be limited by the detector hit rate. For example, reducing the acceleration and extraction cycle time by a factor of two will provide twice the beam power without modifying the proton time structure and detector.
3.1.3 Proton beam time structure

There are two main purposes to COMET Phase-I; to study the properties of the beam and to conduct a $\mu^- - e^-$ conversion search. For the former purpose, a normal slow-extraction beam is best for reducing the instantaneous detector hit rate. For the latter, as in the case of $\mu^- - e^-$ conversion search using the full COMET experiment, the proton beam needs to be pulsed with a time separation of about 1 μ s, which corresponds to the lifetime of a muon in a muonic atom. The signal electrons are emitted from the stopping target and enter the detector during the interval between proton pulses. The beam-related background come within a few hundred ns after the proton pulse since these are mostly prompt processes. This timing information is very important for distinguishing signal events from background events. It is also very important to reduce the number of residual protons between pulses as these produce beam-related background in the signal timing window. For COMET Phase-I to achieve its expected sensitivity, the relative number of residual protons between pulses needs to be as small as the requirement for the full COMET experiment, namely 10^9 times smaller than the number of protons in the main pulse, because of the shorter length of the muon transport line, which leads to a larger survival rate for the pions.

Table 3.1 summarizes the required parameters of the pulsed proton beam for COMET Phase-I μ^--e^- conversion search. They are almost same as the COMET final configuration except the beam power. Figure 3.2 shows a typical time structure for the pulsed proton beam suitable for the COMET experiment.

Beam Power	3.2 kW
Energy	$8 { m GeV}$
Average Current	$0.4 \ \mu A$
Beam Emittance	$10\pi\mathrm{mm}\cdot\mathrm{mrad}$
Protons per Bunch	$< 10^{10}$
Extinction	10^{-9}
Bunch Separation	$1 \sim 2 \ \mu s$
Bunch Length	100 ns

Table 3.1: Pulsed proton beam for the COMET experiment.

3.2 Proton Acceleration

Proton beam acceleration for COMET Phase-I is, in principle, identical to that for the final COMET configuration in all aspects but the beam power. As described in the COMET proposal and CDR [78], COMET requires a special operation mode of the J-PARC MR in order to obtain the required beam structure. The time between two consecutive bunches should be as long as the muon life time when bound by a nucleus, i.e. $1-2 \mu$ s, and the bunch

CHAPTER 3. PROTON BEAM



Figure 3.2: Bunched proton beam in a slow extraction mode.

width should be small (~100 ns) compared to this. In addition to this the proton beam has to be transported to the pion production target whilst keeping its pulse structure. This can be realized using the bunched slow extraction technique. The requirements on the time structure are satisfied by operating the MR by filling only three (four) out of nine buckets in the case when the ring is operated at a harmonic number of nine. The three (four) filled buckets are distributed along the ring in such a way that two (one) empty buckets exist between two filled buckets. Since the time difference between two consecutive buckets is 585 ns, as determined by the acceleration RF frequency, the bunch-bunch spacing will then be 1.751 (1.17) μ s. This satisfies the COMET proton pulse separation requirement.

We now discuss in further detail the J-PARC accelerator chain, which consists of the Linac, a Rapid-Cycling Synchrotron (RCS) and the Main Ring (MR).

3.2.1 LINAC operation

Operation of the proton Linac will be almost the same as that in normal operation mode [79]. The proton beam bunch structure needed to fill the RCS is formed by a high-frequency chopper cavity and scraper installed in the Linac system. The chopper has a very fast rise time of 10 ns in order to form a gap in the bunch structure to allow the RCS to be filled without producing huge losses.

3.2.2 RCS operation

The RCS accepts the beam from the Linac, accelerates it to 3 GeV, and then passes it to the MR for further acceleration. The injection energy of the RCS is currently set to be 181 MeV and will be upgraded to 400 MeV in the future. Four sets of accelerations with two bunches (with a harmonic number of 2) are performed in the RCS for each MR acceleration cycle. Those four pairs of bunches are passed to the MR successively after acceleration at the RCS. For the COMET experiment and COMET Phase-I physics, the

CHAPTER 3. PROTON BEAM



Figure 3.3: An example of COMET beam acceleration bunch configuration. This is the case for 3 buckets filled out of 9 acceleration buckets.

MR is operated with empty buckets interspersed between the buckets containing protons (filled buckets) to enable the necessary proton beam time structure as described in the following. This MR beam bunch configuration is realized by configuring the order of filled and empty buckets in the four RCS acceleration cycles. This RCS bunch configuration is possible by changing the chopping time structure in the Linac. One drawback of this scheme is acceleration of particles that intrude in empty buckets, resulting in deterioration of the beam extinction factor. This is caused by the Linac chopper inefficiency while forming the pulse structure. A systematic study of this leakage effect on the proton beam extinction is being carried out. Innovative methods that has been proposed to remove this leakage at the stage of beam injection to the MR will be studied extensively as part of the accelerator development programme for COMET.

3.2.3 Main ring operation

The operation scheme of the MR for COMET and COMET Phase-I physics is different from the normal scheme, especially the pulse structure. As already mentioned above, the COMET beam needs to be pulsed with a pulse separation of $1-2 \ \mu$ s and pulse width ~100 ns. This will be realized by filling every third (second) bucket, which gives a total of three (four) out of nine buckets filled in the MR. The schemes are illustrated in Figures 3.3 and 3.4 for the case of three and four buckets filled respectively.

3.2.3.1 Injection from the RCS to the MR

Once the proton beam is accelerated to 3 GeV, it is injected to the MR, as is the case for normal operations. A single injection transfers two beam buckets from the RCS to the MR totally, and this is repeated four times in one MR cycle. The bunch configuration of



Figure 3.4: An example of COMET beam acceleration bunch configuration. This is the case for 4 buckets filled out of 9 acceleration buckets.

the RCS needs to be arranged as shown in Table 3.2 to realize the necessary MR bunch configurations.

	Three buc	kets filling	Four buckets filling		
Injection	Bucket A	Bucket B	Bucket A	Bucket B	
1st	filled	empty	filled	empty	
2nd	empty	filled	filled	empty	
3rd	empty	empty	filled	empty	
4th	filled	empty	filled	empty	

Table 3.2: RCS bunch configuration for the COMET acceleration

A series of injection kicker magnets kicks the beam bunches to bring the beam on to the MR accelerator orbit. For the COMET beam these kicker magnets are excited in different ways from that for the normal operation in order to remove remaining protons in empty buckets. There are two kinds of injection methods considered at the moment. One is called "Double Injection Kicking" and the other "Single Bunch Kicking".

The double injection kicking is conducted as follows. The kickers are excited only once when the beam reaches the end of the transfer line in normal operation mode, while for the double injection kicking they are excited again with its phase delayed by half a cycle after the two bunches that have been injected have made one turn in the MR (Figure 3.5).



Figure 3.5: Kicker magnets excitation timing after the injected beam bunches make a single turn in the MR (double injection kicking).



Figure 3.6: Kicker magnets excitation timing for the single bunch kicking (A) as compared to the normal injection kicking shown in (B).

This enables us to sweep away efficiently the particles that remain in the empty buckets because of the inefficiency of the LINAC chopper. A preliminary test of this new injection scheme was conducted in 2010 and has proved to improve the extinction significantly.

The single bunch kicking is simpler method for COMET to improve the beam extinction. This is realized by shifting the injection kicker excitation timing by 600 nsec as illustrated in Figure 3.6. In this method particles remaining in empty buckets can never injected nor accelerated. A preliminary test of this method was performed in 2012 and has proved also to improve the extinction significantly. Moreover, it was found that the extinction does not deteriorate while the beam is circulating along the ring after acceleration until it is extracted if we keep the RF voltage for acceleration above certain level. We need further investigation to optimize the operating condition of the acceleration RF taking into account heat load of the RF modules and possible particle leakage during beam circulation.



Figure 3.7: Layout of the dynamic collimator system.

3.2.3.2 Beam emittance at 8 GeV

The initial emittance of the proton beam before injection is limited by optimizing the collimator in the injection line from the RCS to the MR. The collimator consists of a series of slits and capture jaws which prevent the scraped beam from being transferred into the MR. In normal operation mode the collimator is set to limit the beam emittance to be less than $54 \pi \text{ mm} \cdot \text{mrad}$. There are also collimators in the MR itself. These are mainly used to remove the beam halo, which would possibly produce beam loss during further acceleration and extraction, rather than to control the emittance.

The acceptance of the MR slow extraction line and hadron transport line is limited to 25π mm·mrad. The beam emittance is smaller than this in normal operating conditions because of adiabatic damping. However, in accelerator operations for COMET and COMET Phase-I the proton beam is only accelerated up to 8 GeV and therefore the damping effect is smaller than for a 30 GeV beam. This results in the 8 GeV beam having a larger emittance than the acceptance of the slow extraction and hadron transport lines.

We intend to suppress this large beam emittance for the COMET and COMET Phase-I experiments. The J-PARC MR accelerator group is planning to operate a new "dynamic collimator" system [80]. This was originally designed to further reduce beam loss due to emittance growth during early stages of beam acceleration. The system is designed to be applied while the beam is accelerated up to 9 GeV, which is suitable for the COMET beam of 8 GeV. The system is composed of three components configured in the MR as shown in Figure 3.7; a thin target, and a first and second "catcher" made of thick blocks. During acceleration, horizontal and vertical bump orbits are made to optimize the collimation at the catchers as well as scraping at the target. The injection bump magnets and the steering magnets are utilized for COD correction. The thickness of the target and the catchers is optimized by considering the effective collimation from 3 to 9 GeV during acceleration. The anticipated emittance of the beam is 20.9 π mm·mrad at 9 GeV and slightly larger at 8 GeV according to simulation studies, which is sufficiently small compared to the acceptance of the MR slow extraction line and hadron transport line.

3.2.3.3 Extraction

The beam in the MR needs to be extracted and delivered to the pion production target whilst maintaining the pulse structure of the beam. The hardware components used to perform this task for COMET are the same as those used in normal extraction of the 30 GeV beam from the MR.



Figure 3.8: Measured extinction levels at the MR abort line with single bucket filling with 10^{11} protons as a function of applied RF voltage during beam circulation after acceleration.

What is different in the COMET case is that all extraction parameters have to be adjusted and optimized for 8 GeV operation. In addition to this, the RF voltage needs to be kept at a certain value in order to maintain the pulse structure during extraction. In normal slow extraction of the protons from the MR, the RF cavity voltage is usually switched off in order to yield a flat time structure of the proton beam. However, for the COMET experiments, the RF cavity voltage is not switched off in order that the proton pulse structure is maintained when pions are produced at the target. This is referred to as the bunched slow extraction method. Figure 3.8 shows a preliminary result of extinction measurement at the MR abort line as a function of applied voltage on the RF cavities before extraction. We have observed that accelerated particles started to be scattered along the ring when the RF voltage was reduced. However it will probably be necessary to reduce the voltage in order to minimize the heat load in the cavities. This needs to be optimized.

It is also necessary to modify the feed-back time constant for slow extraction. The COMET beam has a time structure with a frequency of about 1 MHz and this needs to be taken into account in spill control. COMET beam extraction is simulated by using a simple particle tracking method. In Figure 3.9, particle phase space distributions are shown after extraction at the electro-static septum (ESS) magnet. The sharp edges in the x - x' and x - y distributions are due to separation at the ESS. It can be seen in the right-bottom figure that the longitudinal distribution of the particles is less than 20 m. This corresponds to a bunch width of less than 70 ns, which satisfies the COMET beam requirement.

CHAPTER 3. PROTON BEAM



Figure 3.9: Simulations of the phase space distributions of the beam extracted from the MR.

3.3 Proton Beam Transport

The proton beam transport line is used to take the 8 GeV beam extracted from the MR and deliver it to the pion production target. In spite of the different extraction method to be employed in COMET, the beam transport scheme is the same for COMET and the other experiments at the NP Hall which use the normal slow extracted beam. A conceptual design for the beam transport line is shown in the COMET CDR [78]. Further optimization is necessary before construction, taking into account the availability of hardware, beam separation from the A-line, and the beam switching scheme between the high-momentum primary line which shares the upstream beam line and the COMET beam line.

3.3.1 Transport beam line hardware

In this section, the proton beam line hardware is described. Most of the hardware elements introduced in the proton beam transport line are of a conventional design, thus we do not

CHAPTER 3. PROTON BEAM

need any special development except for the AC dipole magnet ¹. Auxiliary components such as power supply and vacuum systems are also standard.

3.3.1.1 Magnet system

Most of the beam transport line magnets will be shared with the high-momentum beam line and they are therefore required to be able to transport a proton beam of 30 GeV. The beam is bent in the NP hall to be transported onto the COMET target. For this bending we need a series of bending magnets probably with a C-shape to allow beam branching. An interlock system is necessary for radiation safety and needs to be designed to allow for different magnet excitation configurations such that the experimental area can be accessed both in the high momentum proton beam line and COMET beam line without shutting down the accelerator.

3.3.1.2 Power supply system

The power supply system can be the same as those used in the A-line beam transport line. The necessary electricity and cooling water is estimated based on the specifications the A-line magnets.

3.3.1.3 Vacuum system

Since we need to reduce beam loss and unexpected radiation doses, it is necessary to evacuate the transport line beam pipe. The required level of 0.1–1 Pa can be realized without any difficulty by installing scroll vacuum pumps at about every 20 m of the beam line. Oil-free scroll pumps will be used to prevent radiation-contaminated oil mist from being distributed in the environment.

 $^{^{1}}$ The AC dipole magnet is not necessary in case we confirm that the beam extinction factor is maintained during bunched slow extraction

Chapter 4 Muon Beam

4.1 Introduction

This chapter describes the muon beam proposed for the COMET Phase-I experiment. An 8 GeV proton beam from the J-PARC Main Ring (MR) is collided with a target to produce pions. The pions thus produced are captured with high efficiency using a 5 T superconducting solenoid magnet surrounding the pion-production target. The muons, which are produced by pion decays, are captured and transported through subsequent solenoids and are brought to a muon-stopping target in the detector solenoid. The muon beam line is composed of a combination of straight and curved superconducting solenoids. The curved solenoids are used to select the charge and momentum of muons in the beam line and have a compensating dipole magnetic field overlaid. The expected muon beam intensity is enormous, about $10^9 \ \mu^-$ /sec for a 3 kW proton beam power, which would be the highest in the world. In the following sections describe the pion production, pion capture and muon transport in detail.

4.2 Pion production

4.2.1 Pion production yields

The COMET experiment uses negatively-charged low-energy muons, which can be easily stopped in a muon-stopping target. The low-energy muons are mostly produced by in-flight decay of pions of low energy. Therefore, the production of low energy pions is of major interest. At the same time, high-energy pions, which could potentially cause background events, should be eliminated as much as possible.

The π^- production yields by protons incident on gold are presented in Figs. 4.1 for different momentum regions. They were produced by a hadron production code, MARS15 (2004)[81]. It can be seen that there is a maximum at a transverse momentum (p_T) around 100 MeV/*c* for a longitudinal momentum (p_L) of $0 < p_L < 200$ MeV/*c* for both the forward and backward scattered pions. The maximum total momentum for backward



46



Figure 4.1: Pion production in a gold target. (top) Correlation between p_L and p_T . (middle) Total momentum distributions for forward and backward π^- s. (bottom-left) p_T distributions for $-0.2 < p_L < 0$ GeV/c, $-0.4 < p_L < -0.2$ GeV/c, and $-0.6 < p_L < -0.4$ GeV/c. (bottom-right) p_T distributions for $0 < p_L < 0.2$ GeV/c, $0.2 < p_L < 0.4$ GeV/c, and $0.4 < p_L < 0.6$ GeV/c.

scattered pions is about 120 MeV/c, whereas that for forward scattered pions is about 200-400 MeV/c. It can also be seen that high-energy pions are suppressed in the backward direction. The yields of low energy pions are not so different, lying within a factor of two between the forward and backward directions. Thus backward pions are less contaminated by high energy pions while retaining those having low energy. For these reasons, it has been decided to collect pions emitted backward with respect to the proton beam direction.

Figure 4.2 shows yields of pions and muons as a function of proton energy. As seen in Figure 4.2, the pion yield increases almost linearly with proton energy, therefore with proton beam power. Also it is seen that at a very high proton energy (> 30 GeV), pion production yield starts to be saturated.

The choice of proton energy can be determined by considering the pion production yield and backgrounds. In particular backgrounds from proton beam between beam pulses (extinction) and antiproton production. At this moment, our choice of proton energy is 8 GeV, as described in Section 3.



Figure 4.2: Yields per proton of backward pions and muons (in left) and forward pions and muons (in right) from a graphite target in a magnetic field of 5 Tesla as a function of proton energy.

4.2.2 Comparison of different hadron production codes

In order to study the pion production yields, Monte Carlo simulations have been performed using three different types of hadron codes, namely QGSP, QGSP_BIC in the Geant4 [82] physics lists and MARS [81]. It is noted that the MARS code is a hadron production code developed at Fermilab. Figure 4.3 shows momentum spectra of π^- forward and backward production from a tungsten target for different hadron codes. As seen in Figs. 4.3, a difference of a factor of about two exists. The π^- yields at low-energy are summarized in Table 4.1.

Hadron	π^{-}/p backward	π^{-}/p forward
codes	(p < 500 MeV/c)	(p < 500 MeV/c)
MARS	0.11	0.15
QGSP	0.10	0.75
QGSP_BIC	0.22	0.41

Table 4.1: Ratios of π^-/p for different hadron codes.



Figure 4.3: Negative pion production of forward (left) and backward (right) directions from a tungsten target as a function of their momenta for different hadron production codes. QGSP_BIC gives twice higher pion yields than MARS.

4.2.3 Pion production target

4.2.3.1 Target material

Pion production cross section is higher for heavier materials, as shown in Figure 4.4. The production cross section is almost 2 times larger for tungsten than graphite. Although our original target material was graphite, the present candidate for the target material is either platinum, gold or tungsten. However, if it is a metal target, it would melt when exposed to an incident high power proton beam. Therefore target cooling is necessary. The current target design for this experiment is based on a water-cooled rod of heavy material.

4.2.3.2 Target length and radius

Figure 4.5 shows pion yields as a function of a graphite target length. The pion yield at low energy is almost proportional to the target length up to about 1.5 interaction lengths (60 cm). Although the longer target provides more pion yields, it must be optimized considering radiation heat loads to the pion capture solenoid in which the target is embedded. In the current design with a tungsten target, the length (which corresponds to 1.5 interaction lengths) is about 16 cm.



Figure 4.4: Pion yields for various target materials.



Figure 4.5: Yields of backward pions from a graphite target in 5 Tesla magnetic field as a function of target length (left figure) and target tilt angle (right figure).

Figure 4.6 shows muon yields for various cases of target radius and proton beam size.

49

Low-momentum muons ($p_{\mu} < 80 \text{ MeV/c}$) are counted after transfer in a 15 m straight solenoid. The yield of pions at low energy decreases as the radius of the target increases. This result can be explained by absorption of pions at low energy. It has been found that the optimum radius is about 0.6 cm for a gold target.



Figure 4.6: Muon yields for various cases of target size and proton beam size. Lowmomentum muons ($p_{\mu} < 80 \text{ MeV/c}$) are counted after transfer in a 15 m straight solenoid.

4.2.3.3 Target tilt angle

The pion production target is embedded in a solenoid magnet to capture and transport the generated pions. Since the proton beam is injected into the solenoid magnet through a gap in the coils, the proton beam axis and the target should be tilted with respect to the solenoid axis. Figure 4.5 shows the pion yields as a function of tilt angle of a graphite target. As seen in Fig. 4.5, the pion yield is almost saturated around a tilt angle of 10 degree.

4.2.3.4 Target heating

Target design needs to be considered in envisaging the use in COMET phase-II where proton current is as high as 7μ A, 18 times larger than that of Phase-I. Foru this purpose target heating by proton bombardment was simulated by MARS15(2004). Densities of energy deposition in a tungsten target are shown in Figure 4.7. Here, the length and diameter of the tungsten target are 16 cm and 0.8 cm, respectively. From the simulation, a total heat of 3.4 kW for a proton beam of 8 GeV and 7 μ A (Phase-II case) was obtained. And the maximum heat density is found to be about 170 joule/g/10¹⁴ protons.



Figure 4.7: Energy deposit density in a tungsten target for a proton beam of 8 GeV and 7 μ A.

Cooling of a tungsten target by water has been considered. The estimation by the ANSYS CFD analysis was made with the assumption of steady state conditions. The result is shown in Figure 4.8, where the size of the tungsten target is 0.8 cm in diameter and 16 cm in length. The inlet temperature of the cooling water is about 300 K.

Table 4.2 summarizes the ANSYS analysis results, where pressure drops and target temperature are shown for different thickness of the coolant layer surrounding the target, and the flow rate of water. From these, it can be concluded that target cooling by water can be made.

Table 4.2: Parameters in cooling of tungsten target by water obtained by ANSYS analysis. The length and diameter of the target is 16 cm and 0.8 cm, respectively. Inlet water temperature is fixed to be 300 K. Proton beam power is assumed to be 8 GeV \times 7 μ A.

Thickness of coolant layer (mm)	0.3	0.3	1.0
Flow rate (ℓ/\min)	2	5	17
Speed (m/s)	3	10	10
Pressure drop (MPa)	0.099	0.476	0.080
Maximum fluid temperature (K)	343	322	322
Target temperature (K)	356	343	343



Figure 4.8: Tungsten target cooling by water. Color indicates temperature from 300 K (Blue) to 356 K (Red). Water with initial temperature of 300 K flows in a thin layer surrounding the target rod from the left to the right.

4.3 Pion capture

4.3.1 Pion capture in a solenoidal magnetic field

To collect as many pions (and cloud muons) of low energy as possible, the pions are captured using a high solenoidal magnetic field with a large solid angle. Figure 4.9 shows a layout of the pion capture system, which consists of the pion production target, high-field solenoid magnets for pion capture, and a radiation shield. In this case, pions emitted into a half hemisphere can be captured within the transverse momentum threshold (p_T^{\max}) . This p_T^{\max} is given by the magnetic field strength (B) and the radius of the inner bore of solenoid magnet (R) as

$$p_T^{\max}(\text{GeV}/c) = 0.3 \times B(\text{T}) \times \frac{R(\text{m})}{2}.$$
(4.1)

The optimization of the magnetic field of the capture solenoid was performed by looking at the muon yields 10 m downstream from the target; the exit of the transport solenoid located downstream of the capture solenoid magnet. Note that most pions decay into muons in the transport solenoid magnet. As shown in Figure 4.10, it was observed that the higher the pion capture magnetic field, the better the muon yield at the exit of the pion decay system. Therefore, a higher magnetic field is preferable. According to Section 4.2, placing



Figure 4.9: Layout of the pion capture system, which consists of the pion production target (proton target), the pion capture solenoid magnets, and its radiation shield.

 p_T^{max} at around 100 MeV/c would be sufficient. Furthermore, since we are interested in the muon momentum being less than 75 MeV/c, a solenoid magnet with the bore radius of 15 cm can accept most of the parent pions of such low-energy muons. Detailed optimization of the bore radius strongly depends on the available technology of the superconducting solenoid magnet. In the current design, we employ conservative design values, namely of B = 5 T, R = 15 cm.

4.3.2 Superconducting solenoid design

The details of the design of the pion capture solenoids can be found in Chapter 9. As in the case of the pion production target design, the pion capture solenoid also has to be designed in envisaging the use in COMET Phase-II where proton proton beam power is 56 kW. Figure 4.9 shows a schematic view of the system of pion production and capture. It consists of a proton target, a surrounding radiation shield, a superconducting solenoid coil for pion-capture with a 5 Tesla magnetic field. The radiation shield is inserted between the pion production target and the coil which generates 5-Tesla magnetic field.

Backward-scattered pions are captured in the 5-Tesla magnetic field and focused forward in the degrading magnetic field. There is a matching section needed to connect to the transport solenoid system with a 3 Tesla field. The matching section has a large bore due to the increasing diameter of the pion orbits in the tapered magnetic field, and also to inject a proton beam into the magnets through the coil gap in between the matching section and the transport section.

An aluminum-stabilized superconducting cable is used for the pion capture and the matching section in terms of reducing the heat load on the cold mass. The coils are irradiated by the particles from the pion production target embedded in the pion capture solenoid magnet. Reducing the cold mass using aluminum is necessary to reduce a nuclear



Figure 4.10: Muon yields at 10 m from the entrance of the pion decay system as a function of magnitudes of a pion capture field.

heating caused by interactions with the radiation particles. If copper is used as a stabilizer, a total thickness of the coil might be about 20 cm or more, and a total impact on the 4.5 K refrigeration load will be over 1 kW in case of COMET Phase-II. In order to overcome this difficulty, we have designed the magnets using an aluminum-stabilized superconducting cable.

To achieve a low heat load enough below 100 W, a 45 cm-thick tungsten shield is necessary for COMET Phase-II operation. An inner radius of the 5-Tesla coil is 65 cm. The inner bore of the shield is tapered to keep it away from beam protons and high-energy pions, which are scattered forward. To collect backward-scattered pions, the proton beam should be injected through the barrel of the solenoid, and should be tilted with respect to the solenoid axis by 10 degrees. The solenoid coils near the proton beam duct should have a larger radius to escape the beam halo. In the current design, the coil edge is designed to be placed greater than 10-cm from the beam axis.

4.3.2.1 Radiation heating and radiation dose

Radiation dose from proton bombardment on the pion production target was estimated by and MARS15(2007) with MCNP mode for the case of COMET Phase-II. For the case of COMET Phase-I the dose can be evaluated by scaling the result by a factor 17. The radiation heat comes mostly from neutrons. One of the purpose of this study is to estimate heat loads by radiation in the pion capture solenoid that surrounds the pion production target, as well as a total radiation dose in it. To reduce radiation at the pion capture solenoid, radiation shielding made of tungsten is inserted between the pion production target and the pion capture solenoid magnet. The maximum thickness of the radiation shielding is about 45 cm.

The energy deposited for each component is presented in Figure 4.11. It was found that an average energy deposited at the pion capture solenoid coils including matching section to the transport solenoid is about 60 W for a proton beam of 8 GeV and 7 μ A. A peak radiation dose in aluminum is about 0.5 MGy. And a neutron fluence is more than 10²¹ neutrons/m². The capture solenoid gets peak deposit of 16 μ W/g and about 30 Watts of total radiation heating.



Figure 4.11: Energy deposit at the pion capture solenoid and radiation shielding, calculated by MARS15(2007) with MCNP mode

4.3.3 Adiabatic transition from high to low magnetic fields

Since the pions captured at the pion capture system have a broad directional distribution, it is intended to make them more parallel to the beam axis by changing a magnetic field adiabatically. From the Liouville theorem, a volume in the phase space occupied by the beam particles does not change. Under a solenoidal magnetic field, the relation between the radius of curvature (R) and the transverse momentum (p_T) leads to the relation given by

$$p_T \times R \propto \frac{p_T^2}{B} = \text{constant},$$
 (4.2)

where B is a magnitude of the magnetic field. Suppose the magnetic field decreases gradually, p_T also decrease, yielding a more parallel beam. This is the principle of the adiabatic transition. Namely, when a magnetic field is reduced by a factor of two, p_T decreases by $1/\sqrt{2}$. On the other hand, since

$$p_T \times R \propto B \times R^2 = \text{constant}'.$$
 (4.3)



Figure 4.12: Adiabatic transition from a high magnetic field to a low magnetic field. This adiabatic transition reduces the magnitude of transverse magnetic field.

the radius of curvature increase by a factor of $\sqrt{2}$. Therefore, the inner radius of a magnet in the pion decay section has to be $\sqrt{2}$ times that of the pion capture solenoid. With the cost of a beam blow up, a pion beam becomes more parallel. Furthermore, it is not effective in reality to have a long magnet with a high magnetic field, connected to a magnetic field that has to be lowered at some point. Figure 4.12 illustrates the principle of adiabatic transition.

The muon beam line of COMET Phase-I will include the pion capture section and the muon transport section up to the end of first 90° bend of the COMET experiment. The design of the muon beam line of COMET Phase-I is identical to that of the full COMET experiment, and therefore the technical details of the pion capture section and muon transport section are not described in this document. We focus instead on features that are specific to COMET Phase-I, such as the beam configuration at the end of COMET Phase-I muon beam line. Figure 4.13 shows a schematic layout of the muon beam line and detector for COMET Phase-I.

4.4 Muon Beam

COMET Phase-I uses negatively-charged low-energy muons, which can be easily stopped in a muon-stopping target. The low-energy muons are mostly produced by the decay in flight of low-energy pions. Therefore, the production of low-energy pions is of major interest. At the same time, high-energy pions, which could potentially cause background events, should be eliminated as well as possible.

Muons and pions are transported to the muon stopping target through the muon beam



Figure 4.13: Schematic layout of the muon beam line for COMET Phase-I.

line, which consists of curved and straight superconducting solenoid magnets. The requirements for the muon beam line section are:

- the muon beam line should be long enough for low-energy pions to decay to muons,
- the muon beam line should have high transport efficiency for muons with a momentum of 40 MeV/c,
- the muon beam line should select low momentum negative muons and eliminate high momentum $(p_{\mu} > 75 \text{ MeV}/c)$ muon to avoid backgrounds from muon decays in flight.

At COMET Phase-I, we intend to construct the muon beam line at least up to the end of the first 90° bending section so that the muon beam can be extended beyond the concrete radiation shielding. It would be desirable to extend the muon beam line further if additional funds are available.

4.4.1 Beam optics of curved solenoids

Charge and momentum selection of beam particles can be performed using curved (toroidal) solenoids, which introduce dispersion into the beam. It is known that in a curved solenoid, the center of the helical trajectory of a charged particle drifts in a direction that is perpendicular to plane containing the curved solenoid. The magnitude of drift (D[m]) is given by

$$D = \frac{1}{qB} \left(\frac{s}{R}\right) \frac{p_L^2 + \frac{1}{2}p_T^2}{p_L}, \qquad (4.4)$$

$$= \frac{1}{qB} \left(\frac{s}{R}\right) \frac{p}{2} \left(\cos\theta + \frac{1}{\cos\theta}\right) , \qquad (4.5)$$

where q is the electric charge of the particle (including its sign), B [T] is the magnetic field at the axis, and s [m] and R [m] are the path length and the radius of curvature of

the curved solenoid, respectively. Here, $s/R(=\theta_{\text{bend}})$ is the bending angle θ_{bend} and D is proportional to θ_{bend} , and p_L and p_T [GeV/c] are the longitudinal and transverse momenta, respectively. The pitch angle of the helical trajectory is represented by θ . Charged particles with opposite signs drift in opposite directions. This can be used for charge and momentum selection if a suitable collimator is placed after the curved solenoid.

An additional vertical dipole field can be applied in order to maintain along the solenoidal axis the centers of the helical trajectories of the muons that have a specific momentum p_0 . The magnitude of this compensating dipole field is given by

$$B_{\rm comp} = \frac{1}{qR} \frac{p_0}{2} \left(\cos \theta_0 + \frac{1}{\cos \theta_0} \right) , \qquad (4.6)$$

where the trajectories of negatively charged particles with momentum p_0 and pitch angle θ_0 are corrected to be on-axis.

4.5 Muon Beam Simulation Study

A full Geant4 based Monte Carlo simulation suite for COMET, called "COMET_G4", has been developed for studies of the muon beam and other components including the detector systems. COMET_G4 has been used to perform full-scale simulations of the muon beam.

The hadron production code, MARS, is used to provide input data for COMET_G4. Three-dimensional magnetic field distributions were calculated using TOSCA, taking account the geometry of each coil and the iron yokes.

4.6 Beam at the End of the First 90° Bend

The beam properties at the end of the first 90° bend are obtained using COMET_G4. At this location, a beam collimator is placed to eliminate particles that represent backgrounds to the μ^--e^- conversion search.

4.6.1 Dispersion distribution

By the end of first 90° solenoid bend, the beam becomes dispersive. This momentum dispersion is very important and useful for eliminating high energy muons above 75 MeV/c, which would otherwise contribute to background events through their decay in flight. At the same time, it is useful to eliminate positively charged particles. Figure 4.14 shows histograms of momentum (namely, dispersion) vs. vertical position (Y) before the beam collimator for different correction dipole fields. It is noted that there are two numbers that represent the magnetic fields, corresponding to the different dipole fields which are superimposed on the fields of the first 90° bend and the second 90° bend respectively. For COMET Phase-I, only the first number is relevant.



Figure 4.14: Dispersion of negative muons (momentum vs. vertical (Y) position) at the end of the first 90° bend for different correction dipole fields.

4.6.2 Momentum distribution

Figure 4.15 shows the momentum distribution of the different types of particles at the end of the first 90° bend for a correction dipole field of 0.018T.

4.6.3 Time distribution

Figure 4.16 shows the time distributions of different charged particles in the muon beam, such as μ -s, π -s, and e-s before the collimator at the first 90° bend. The width is determined by different helical pitches of the muon trajectories. The time distribution of electrons is very sharp earlier in the pulse, however, followed by a small tail.

4.7 Beam at the Muon Stopping Target

Since the magnetic field at the detector (of 1 Tesla) is smaller than that at the muon beamline, the beam would spread when it enters the detector. The beam collimator is placed just after the end of the first 90° bend to determine a beam size so that muons that are not stopped in the muon stopping target are eliminated before entering the detector. And at the same time, it would eliminate high momentum muons of $P_{\mu} > 75 \text{ MeV}/c$. The diameter of the collimator is 200 mm.

59



Figure 4.15: Momentum distribution of the different types of particles at the end of the first 90° bend for a correction dipole field of 0.018T.



Figure 4.16: Arrival time distributions of various beam particles for the case of a correction dipole field of 0.018 T.

To do simulation studies, several virtual beam monitors were placed to examine beam profiles. Figure 4.17 shows those virtual beam monitors used in the present beam simulation studies.



Figure 4.17: schematic layout of the muon beamline for COMET Phase-I and locations of virtual beam monitors.

The beam profiles of negative muons and negative pions before and after the beam collimator are presented in Figs. 4.18 and 4.19 respectively. In these figures, momentum distribution (left), dispersion of vertical position vs. momentum (middle), and timing distribution (right) are shown. It can be seen that the beam collimator is effective for the selection of a beam.

Figure 4.20 shows momentum distribution of negative muons coming to the muon stopping target and a faction of muons stopped in the muon stopping target. A fraction of the muon stopped is about 0.5. The numbers of particles coming to the muon stopping target (after the beam collimator) are summarized in Table 4.3.

Table 4.3 :	Numbers	of	different	beam	particles	per	proton	at	the	muon	stopping	target.
					P 012 0 2 0 2 0 0	r ~-	P				~~rr0	

	π^{-}		
all	stopped	$P_{\mu} > 75 \text{ MeV}/c$	all
0.0066	0.0023	5.7×10^{-4}	6.9×10^{-5}

4.8 Muon Stopping Target

The muon-stopping target is composed of 17 aluminum disks of 200 μ m thickness with a distance between disks of 50 mm. This configuration is the same as for COMET. The



Figure 4.18: Profile of negative muons before and after the beam collimator.



Figure 4.19: Profile of negative pions before and after the beam collimator.

target parameters are summarized in Table 4.4.



Figure 4.20: Momentum distribution of muons coming to the muon stopping target. The spectrum in red is a fraction of muons stopped in the muon stopping target.

parameter	value
target disk diameter	200 mm
target disk thickness	$200 \ \mu \mathrm{m}$
number of target disks	17
spacing between disks	50 mm
total length of target system	800 mm

Table 4.4: Parameters of muon stopping target.

Chapter 5

Detector

5.1 Introduction

In COMET Phase-I, we would like to

- 1. make a direct measurement of the proton beam extinction and other potential background sources for the full COMET experiment, using the actual COMET beamline; and
- 2. carry out a search for $\mu^- e^-$ conversion with a sensitivity better than achieved by SINDRUM-II.

The detector configurations for the two goals mentioned above could be different, once they are optimized for their best performance. In the following, detector configurations for the two goals are described.

5.2 Detector for Background Measurements

The direct measurement of potential background sources will be vital for the COMET experiment. The current background estimates are made by extrapolating existing measurements over four orders of magnitude and uncertainties are therefore difficult to quantify and are potentially large. However, once the partial muon beamline is completed, realistic background estimations can be made from direct measurements. Based on these, the final design of the COMET beamline and detectors will be optimised and uncertainties on the background estimations minimized. This will significantly enhance the ultimate sensitivity of the COMET experiment.

Figure 5.1 shows a schematic view of the setup for background measurement. Measurement of the proton beam extinction ratio will be done by using segmented hodoscope counters as used in previous studies. The setup composed of a solenoid magnet with 0.85–1 T magnetic field strength, 5 layers of tracker, and crystal calorimeter. Detectors are located in a vacuum vessel functioning as a cryostat of the spectrometer magnet. The same detector technology as the COMET detector will be employed. The tracker will be



Figure 5.1: Setup for the background measurement in COMET Phase-I.

constructed using straw chambers being developed for the COMET tracker. The crystal calorimeter will be composed of GSO or LYSO crystals; R&D is in progress and production will be ready in time for COMET Phase-I. We will make a decision which crystal to use according to the result of R&D. Performance of these detectors will be investigated in this measurement and upgraded for the COMET experiment if necessary. It is also possible to test readout electronics and the data acquisition scheme. In this sense this setup will be a real prototype of the COMET detector.

The detector is required to provide sufficient information to identify particles in the beam and measure their momenta. When charge selection is not performed in the Phase-I beam transport setup, all kind of particles are contained in the beam; p, \overline{p} , e^{\pm} , μ^{\pm} , and π^{\pm} (K[±]). These particles are identified mainly using dE/dx information in the tracker and the ratio of energy and momentum (E/p). The momentum measurement is carried out by reconstructing the track using the tracker hits. The Kalman filter technique will be used for evaluating track momenta as is planned for the COMET experiment. Shower shape information in the calorimeter will be utilized for \overline{p} identification. The possibility to measure the direction of photons contained in the beam is under consideration. We expect that this can be carried out by inserting a converter between tracker layers. The configuration will be optimized with Monte Carlo simulation.

We need to reduce the primary proton intensity much below 1 kW to ensure safe detector operation. In addition proton beam extraction from the MR should be done in the normal slow extraction mode. This will help to reduce the detector occupancy rate,

realizing reliable and stable measurements. The primary proton beam energy is supposed to be 8 GeV but measurement at higher energy will also be made. The reason for a beam energy of 8 GeV is that the antiproton production cross section is known to rapidly increase above 8 GeV. We plan to investigate how the number of antiprotons is reduced by inserting a stopper in the beam line and what kind of possible background particles are emitted from it. Currently estimation of the number of antiprotons contained in the secondary beam for the final COMET configuration is done only with Monte Carlo simulation. Thus, a real measurement will certainly provide invaluable information. If the antiproton rate above 8 GeV stays in an acceptable range, we can use higher energy proton beam, which can provide a higher pion production rate and smaller beam emittance when the beam is extracted from the MR.

Details of the straw tube tracker and crystal calorimeters will be described in later sections.

5.3 Detectors to Search for $\mu^- - e^-$ Conversion

The search for $\mu^- - e^-$ conversion with a sensitivity beyond that achieved to date can be made. The pion contamination in the muon beam at COMET Phase-I will be high due to the shorter muon beamline. However, since the muon intensity will be the highest in the world by several orders of magnitude, as for the full COMET experiment, we will be able to probe beyond the current limit and set the world's best limit should no signal be observed.

Two types of detector configuration are considered for the μ^--e^- conversion search in COMET Phase-I. One is a cylindrical detector option, and the other is a transverse tracker detector option, in which the detector for background measurements mentioned before is reused. The former is a detector dedicated for COMET Phase-I to maximize an experimental sensitivity for μ^--e^- conversion search, and the latter is a prototype detector for the full COMET experiment.

5.3.1 Cylindrical Drift Chamber

The baseline detector to search for $\mu^- - e^-$ conversion is a cylindrical drift chamber (CDC). Figure 5.2 shows a schematic view of the detector setup, where the CDC surrounds the muon-stopping target located at its center. Segmented trigger hodoscope counters are placed at both the upstream and downstream ends of the CDC. Using Cherenkov detectors for these trigger counters will allow positive electron identification. The CDC is placed inside a superconducting solenoid magnet which produces a magnetic field of 1~1.5 T. The solenoid magnet has an iron yoke which acts as passive shielding for cosmic rays. In addition, an active cosmic-ray shield is installed outside the detector. To monitor the number of muons stopped in the muon stopping target, a detector to measure muonic X-rays is employed. One of the main differences to the CDC design from the LOI is the removal of the proton absorber (made of plastic scintillator) that were placed cylindrically

at the entrance to the CDC to reduce the contribution to the material budget for the passage of electrons, and to improve the momentum resolution. One of the drawbacks from this design is an increase in the single hit rates per wire from protons in the CDC.

The cylindrical detector has several features as follows:

- To reduce background events, in particular electrons from muon decays in orbit and protons emitted from nuclear muon capture, tracks with a transverse momentum (P_T) below a certain value should be rejected. In a cylindrical detector, this requirement can be easily implemented using the radial position of the first layer of tracking chambers and a solenoidal magnetic field.
- Most beam particles that do not stop in the muon-stopping target will continue downstream and escape the detector. The background rate is therefore reduced as well as the rate in the detector that is to be read out.



Figure 5.2: Schematic view of the CDC for $\mu^- - e^-$ conversion search.

5.3.1.1 CDC structure

The role of the CDC is to reconstruct charged particle tracks and measure their momenta precisely. The baseline option for the tracking chamber is a gaseous drift chamber. The main parameters for the CDC are listed in Table 5.1. The drift chamber covers the region from 545 mm to 805 mm in the radial direction. The length of the drift chamber is 1500

mm. It has 5 super-layers, and each super-layer has 5 sense wires. The 1st, 3rd and 5th super-layers are in the axial direction, and the 2nd and 4th super-layers are stereo layers with a stereo angle of about 60 mrad (or 3.5°). A sense wire is surrounded by field wires, forming a drift cell of 1 cm². The drift chamber gas is He : C₂H₆ = 50 : 50. The inner wall of the drift chamber is CFRP of 400 μ m in thickness.

Parameter	Value
Radius of inner cylinder	540 mm
Radius of outer cylinder	840 mm
Radius of innermost sense wire	550 mm
Radius of outermost sense wire	830 mm
# of layers	25
Gas	$He:C_2H_6 = (50:50)$
Length	1500 mm

Table 5.1: Parameters for COMET Phase-I Central Drift Chamber

5.3.1.2 CDC wire configuration

We have semi-square cells and a super-layer wire configuration. Having five layers in each super-layer allows track segments to be formed reliably. An additional two layers are located in the innermost and outermost super-layers. These have active guard wires, since high hit rates are expected because of proton backgrounds and the wall effect. Even if the first two layers cannot provide good performance, the other five layers will provide sufficient performance to allow track segments to be formed as in the other super-layers. Super-layers alternate between axial and stereo configurations. The total number of layers is thus 29.

The radial cell size is 10 mm. The number of the cells in each layer is chosen considering the following: multiples of 32 simplify the mapping of electronics channels and trigger segments. Better azimuthal granularity would guard against large rates from background hits, but the size of the cells is constrained by the physical dimensions of the feedthroughs. The wire configuration and the numbers of cells in each layer are shown in Table 5.2

A Garfield field simulation has been performed for this case. It is shown in Fig. 5.3.

The stereo angles are chosen as shown in Table 5.2. A larger stereo angle provides for better resolution in z, but larger variations of the radial cell size along the z-direction occur at the boundary region between the axial and stereo super-layers. and therefore stereo angles of about 60 mrad are chosen.

The numbers of sense and field wires are 9,684 and 28,352 respectively. These numbers are not too large compared to large cylindrical drift chambers that have been constructed recently (e.g. 14,336 sense wires for the BELL-II CDC).



Figure 5.3: Garfield simulation of the CDC cell.

Table 5.2. ODC whe comignation	Table	5.2:	CDC	wire	configuration
--------------------------------	-------	------	-----	------	---------------

Super	# of layers	# of	radius	azimutha	l cell size	Stereo angle
Layer	per layer	cells	(mm)	inner (mm)	outer (mm)	(mrad)
Axial 1	7	352	550 - 610	9.82	10.89	0
Stereo 2	5	384	620 - 660	10.14	10.80	54.0 - 57.5
Axial 3	5	288	670 - 710	14.6	15.5	0
Stereo 4	5	320	720 - 760	14.1	14.9	56.5 - 59.6
Axial 5	7	320	770 - 830	15.1	15.1	0

5.3.1.3 CDC mechanical design

There are three main parts to the CDC, a thin carbon fiber reinforced plastic (CFRP) inner cylinder, two aluminum endplates and a CFRP outer cylinder.

The outer cylinder of 5 mm thickness supports a total wire tension of about 3.42 tons. The inner cylinder should be thin, at about 400 μ m thickness, to minimize materials as well as the absorption of protons from muon nuclear capture. But it should support the wire tension for the innermost super-layer. The endplates are flat and their thickness is about 10 mm. The endplates are machined and drilled separately and they are connected

	sense wire	field wire
material	tungsten	aluminum
plating	gold	no
diameter (μ m)	30	126
tension (g)	50	80
number of wires	12,064	35,232

Table 5.3: Material and thickness of CDC wires

to the outer cylinder with careful alignment.

The mass of the tension and sense wires is 50 grams, and that of field wires is 80 grams. In this case, gravitational sags for both types of wire are different by 80 μ m. We estimate the magnitude of the distortion of the *x*-*t* relation function by using the Garfield simulation framework.

The total size of the CDC is thin in the radial direction and the total tension is supported by the outer cylinder. And therefore wire-stringing can be performed without the inner cylinder attached. In this case, it could be easier to string wires in a horizontal setting from the outside to inside, where the wires can be seen directly throughout the procedure. There are no special jigs required to do this.

The feedthrough is used to fix the sense wires and to ensure insulation between high voltage and the endplate ground. We are considering using the feedthrough that has been developed by the BELLE CDC group. The insulator material is Noryl because of its more reliable insulation performance against high voltage. For the field wires, aluminum pins are used to hold the wire tension and are attached directly to the aluminum endplates.

The CDC is covered by aluminum covers. Since there is enough space for the electronics in both the upstream and downstream sides, the readout electronics can be located on both sides. This reduces the constraints on the size of readout electronics. Similarly, the connection of high voltage cables can be located on both sides.

The CDC should be supported by the superconducting solenoid magnet. Cables for signals and HV are placed through the holes in the iron yoke of the magnet, on both the upstream and downstream sides.

5.3.1.4 CDC gas system

A gas mixture with a fast drift velocity is needed in order to reduce the maximum drift time. Several gas mixture candidates have been studied, and a mixture of 50% helium and 50% ethane is considered as the primary candidate at this time. Its performance has been established in the BELLE CDC. It adds little to the material budget, gives good position resolution and energy loss resolution, presents a low cross section to photons and is tolerant to radiation. The present gas system, based on the current BELLE CDC gas system, is as follows. Separate pure gas bottles are located in a gas stock room and gas mixing is

performed using two mass flow controllers in a gas mixing room located near the detector. The mixtures gas is fed into the detector though a gas pipe. The gas system consists of a circulation pump, flow controller, pressure controller and oxygen filter as shown in Fig. 5.4. Some flow (e.g., 2 litres/min) is required to remove oxygen from the CDC gas volume. Fresh gas will be fed in at only 1/10 of the circulation flow rate to reduce gas consumption. To maintain circulation, an oil-free metal bellow bump is used. A small amount of Hydrogen gas is mixed into the Oxygen filter for a Platinum catalyst.



Figure 5.4: Gas system for the CDC.

5.3.1.5 CDC hit rates

The maximum usable muon beam intensity will be limited by the detector occupancy. As described before, charged particles with transverse momentum (P_T) greater than 70 MeV/c are expected to reach the tracking chamber. There are several sources of such charged particles; (1) electrons from muon decays in orbit (DIO), (2) electrons and positrons from high energy photon conversion, and (3) protons emitted after nuclear muon capture, namely $\mu^- + N \rightarrow N' + p + \nu_{\mu}$.

The hit rate due to proton emission dominates. Although there is no experimental data available for the rate of protons emitted after muon capture in aluminum, we can estimate using the measured energy spectrum of charged particles emitted from muon capture in 28 Si [83]. In our estimation it is assumed that the proton emission probability per muon capture in aluminum is 0.15, as for the measurement for 28 Si. It should be noted that the theoretical estimation is 0.04 proton emissions per muon capture in aluminum; thus our assumption is conservative. Figure 5.5 shows an energy spectrum of protons emitted after nuclear muon capture on 28 Si. ¹

To estimate detector hit rates by proton emission, the energy spectrum of protons

¹The COMET collaboration is planning to measure the proton emission rate from muon capture in aluminum either at TRIUMF or at PSI using their DC muon beam, together with the Mu2e group.


Figure 5.5: Energy spectrum of protons emitted after nuclear muon capture on Si.

emitted after muon capture is fit to an empirical function as follows [84]:

$$P(T) = A \left(1 - \frac{T_{th}}{T}\right)^{\alpha} \exp^{-\frac{T}{T_0}},$$
(5.1)

where T is the kinetic energy with fitted parameters $T_{th} = 1.4$ MeV, $\alpha = 1.328$ and $T_0 = 3.1$ MeV, and A is a normalization factor. In our Monte Carlo simulation, protons are generated isotropically based on Eq. (5.1).

If we assume the number of muons stopped in the muon-stopping target is 5.8×10^9 /s, the number of muon captures on aluminum is about 3.5×10^9 /s, since the fraction of muon captures in aluminum is $f_{cap} = 0.61$. Therefore the total number of hits in all the cells in the first layer is estimated to be 1.4×10^6 /s (= $(3.9 \times 10^{-3}) \times (3.5 \times 10^9)$) for the case of no proton absorber. The total number of cells in the first layer of the drift chamber is 332. Therefore, the hit rate per drift chamber wire will be about 40 kHz. This rate is well below the limit of the region of stable operation of a gaseous detector. And since the rate of proton emission follows the muon lifetime in a muonic atom, this single rate becomes lower in the time window of the measurement. In addition, the inner supporting frame also helps to reduce the hit rate by proton emissions after muon capture. Thus the detector operating condition will be safe enough for physics measurement at COMET Phase-I.

5.3.1.6 CDC trigger counters and trigger rates

Segmented trigger counters are placed both at the upstream and downstream ends of the CDC. For this purpose, we employ a layer of concentric segmented Cherenkov counters.

These also provides trigger timing and are not sensitive to protons. The trigger rate is dominated by the DIO electrons that impinge on the trigger counter. Figure 5.6 shows the energy spectrum of Decay-In-Orbit (DIO) electrons from muonic aluminum with the fraction of DIO events hitting the trigger counters shown in green. The rate is about 1.2×10^{-7} per muon decay. Since the number of muons stopped in the stopping target is estimated to be 5.8×10^9 , the trigger rate is estimated to be $270 \text{ Hz} (= 5.8 \times 10^9 \times 0.39 \times (1.2 \times 10^{-7}).$



Figure 5.6: Energy spectrum of DIO electrons hitting the trigger counters (shown in green) for aluminum.

5.3.1.7 CDC momentum resolution

The momentum resolution of the CDC is critical to allow the discrimination of $\mu^- - e^-$ conversion signal electrons from electrons originating from DIO. The end point of the DIO spectrum approaches the energy of the $\mu^- - e^-$ conversion signal, although it falls off quickly, being proportional to $(\Delta E)^5$ where $\Delta E = E_{\mu-e} - E_{\text{DIO}}$, $E_{\mu-e}$ is the energy of $\mu^- - e^-$ conversion electron, and E_{DIO} is the energy of the DIO electron. For aluminum, $E_{\mu-e}$ is 104.9 MeV. The DIO electron energy spectrum has been calculated for muonic aluminum [66]. Figure 5.7 shows the DIO electron spectrum for muonic aluminum. The energy difference of $\Delta E = 1.5$ MeV is seen at a DIO branching ratio of 10^{-15} .

The tracking performance was studied by using a Geant4 Monte Carlo simulation[82]. In this simulation, electrons of 105 MeV/c leaving the stopping target were generated isotropically from 17 disks of aluminum of 200 μ m thickness. The drift chamber wall is modelled correctly and a gas mixture of He:C₂H₆=50:50 is simulated in the chamber volume.

Hit information generated in the simulation is smeared by the expected position resolutions of the drift chamber, $\Delta x = \Delta y = 100 \ \mu \text{m}$ and $\Delta z = 2 \ \text{mm}$. The hit positions thus obtained with smearing are used for track reconstruction.



Figure 5.7: Energy spectrum of electrons from muon DIO from muonic aluminum

Track reconstruction is performed by "Genfit" [85] with "GeaneTrackRep2" as the track follower, which uses a Kalman filter to take account of multiple scattering in tracking materials. In Genfit, to find a good track it is required for the number of reconstructed hits to be more than 8 and for the normalized χ^2 to be less than five. Figure 5.8 shows an example display of reconstructed events, where it can be seen that a track loses energy after passing the inner wall. The intrinsic momentum resolution is evaluated from the residual distribution of true momentum and reconstructed momentum. The fitted momentum can be lower than the true momentum of 105 MeV/c, since electrons can lose energy in the muon stopping target and the inner supporting frame. This energy loss reduces the peak of the momentum distribution and also produces a low-energy tail and broadens the core peak width owing to energy straggling. Figure 8.2 shows the reconstructed momentum distribution.

5.4 Transverse Tracker Detector for μ^--e^- Conversion Search

This option re-utilizes the setup for background measurement shown in Figure 5.1. A cylindrical muon-stopping target composed of 11 aluminum disks with 5 cm spacing is located near the exit of the muon transport solenoid. Muons that are not stopped in the target and high momentum electrons emitted from muon decay in flight are prevented from entering the detector by a beam blocker located behind the target. Two wedges to stop the high momentum protons emitted after muon capture are located between the target and detector. Those are fixed on the inner surface of the spectrometer magnet. The tracker is composed of 5 layers of straw tube tracker modules followed by a crystal calorimeter to



Figure 5.8: Event displays of the cylindrical detector. Views from 45 degrees (top) and the side (bottom) are shown of a typical track. The green section is the drift chamber layers. The brown section indicates the superconducting magnet coil, and the blue line is the reconstructed track for a 105 MeV/c electron.



Figure 5.9: Intrinsic momentum resolution. The RMS resolution is about 600 keV.

measure the electron energy. The calorimeter is expected also to provide a timing signal to reject prompt background and to measure drift length in the tracker. A schematic view of the setup together with signal momentum tracks are shown in Figure 5.10. Acceptance to the signal event is estimated to be $22.5 \pm 1.5\%$ by generating 105 MeV/c electrons at the center of 1st and last target disks and taking a mean of transmission probabilities.

High momentum protons emitted after muon capture are blocked by the blocker when emitted in forward direction, and stopped by the wedges when emitted with large transverse



Figure 5.10: Schematic view of the transverse tracker detector with 5 layers of straw tube trackers (blue) and calorimeter (red). Superimposed are 105 MeV/c electron tracks generated in the last target disk. The beam blocker and two wedges to stop protons with high transverse momenta are shown in green.

momentum. On the other hand low momentum protons, dominating the charged particle spectrum emitted after muon captures, cannot be reduced efficiently by either of these. To remove these protons we locate a degrader of 500 μ m thickness 150 mm downstream of the target. The degrader works to eliminate low-momentum protons producing enormous amount of hits in the 1st layer of the tracker. These protons carry kinetic energy as small as 4 MeV and thus can be easily removed by a thin foil without deteriorating the momentum resolution of signal electrons. The momentum spread of signal electrons caused by the degrader is estimated to be 200 MeV/c in FWHM.

Detector hit rate is estimated in a similar way as done for the cylindrical detector. If we use 100 straw tubes in the front-most layer, the hit rate will be less than 100 kHz for 5×10^9 muon stops per second. This is sufficiently small for stable detector operation.

The momentum resolution of the spectrometer is expected to be as good as that of the COMET detector (1.0% in sigma) since almost the same detector configuration is employed. This will be studied in future with a full Monte Carlo simulation in future.

5.4.1 Straw Tube Tracker

5.4.1.1 Overview

In COMET Phase-I, a set of 5 straw tube tracker modules will be constructed and used for measurements of beam backgrounds and possibly for a search for μ^--e^- conversion. In COMET Phase-II the straw tube tracking system is selected as the tracking detector because of its superior performance operational in vacuum. The requirements to the straw tube tracker for COMET Phase-I are as follows:

- 1. It should withstand for a total rate of charged particle up to 800 kHz, and
- 2. It should withstand for a total flux of gamma rays up to 8 MHz.

Note that the signal rate coming from the gamma rays will be much less than 8 MHz as long as the tracker is thin enough to be transparent to gamma rays. The average energy of the gammas is about 0.2 MeV, and their mean free path is about 5.5 g/cm^2 . If the thickness of the tracker is thinner than, 0.2 g/cm^2 for examples, the rate from gamma will be only less than 400 kHz. The average number of hits per 100 nsec is only 0.2. Therefore, the track reconstruction error due to gamma rays should be negligibly small.

5.4.1.2 Design

In the current design, the tracker consists of 5 of tracker modules. Each straw tube tracker module consists of four straw tube planes to measure the X coordinate and four straw tube planes to measure the Y coordinate. The total thickness of the tracker is less than $0.2 \ g/\text{cm}^2$ since the straw-wall thickness is less than 40 μ m. This helps minimize the hit rate coming from gamma conversions.

The tracker resolution is limited by the following three factors:

- 1. spatial resolution of the tracker,
- 2. multiple scattering by the tracker plane material,
- 3. miss-reconstruction of the track.

The transverse momentum of the detected tracks should be larger than 50 MeV/c in order to suppress backgrounds from beam electron scattering. The minimum radius of the particle trajectory in a 1 T magnetic field is then 16.7 cm. On the other hand, the momentum resolution is required to be better than 1 MeV/c (FWHM) to achieve good signal acceptance. This corresponds to 0.4%(RMS) momentum resolution, and 700 μ m spatial resolution.

The multiple scattering could change the direction of the track. The track displacement by the multiple scattering becomes maximum after $\pi/4$ turns of helix, and minimum (zero at the 1st order) after $\pi/2$ turns. Therefore, the 2nd module should be placed at the position where the phase of helix turns $\pi/2$ from the 1st module. However, if it is exactly

at $\pi/2$, charge information for the helix is lost. Taking this into account, the phase advance of the helix between the modules should be large, but not exceed $\pi/2$. In the current design, the distance between the modules is chosen to be 480 mm, which corresponds to $\pi/3$ turns on average. The minimum phase advance of the track is about 1.3 rad, so 5 modules will cover 1 turns of helix by all trackers.

As for track reconstruction errors from accidental background hits, this can be minimized by requiring the number of hits per layer to be one. The reduction of the analysis efficiency by doing this is only 15% since the tracker rate is only less than 1 MHz.

5.4.1.3 Performance

In order to estimate the tracker performance, a Monte Carlo simulation for the $\mu^- - e^-$ conversion signal electrons was carried out with a slightly simplified tracker geometry. Each tracker module was approximated by a single film of Polyimide with 160 μ m thickness.

It is concluded by analysing the simulation data that even if we strictly select the events with the number of hits being equal to 5, the loss of the efficiency is only 12%. In this study, we accept the events with $5 \le N_{\text{hits}} \le 8$, and the acceptance loss is 5%. The track fitting algorithm we employ takes care of the multiple scattering effect.

The track fitting algorithm we employ takes care of the multiple scattering effect. The track helix was a chain of 4 partial helixes. The adjacent helixes are connected at the tracker module position with angles, where the angle imitates the deflection by the multiple scattering. In the track fitting procedure, the χ^2 function as described in detail in Appendix A is formulated.

The function minimization for the above χ^2 is performed by using non-linear function minimization package, MINUIT. The detector resolution is conservatively assumed to be 250 μ m. The RMS from multiple scattering is found to be $\sigma^{\text{scat}_{\theta}} = 0.0025$ rad so that the obtained χ^2 distribution is consistent with the one for 5 d.o.f. It is consistent with the expected value of $\sigma^{\text{scat}_{\theta}}$ from the module thickness. Figure 5.11 shows the probability distribution of the track fitting. The peak at P < 0.05 may be caused by the large angle tail from multiple scattering, which is not considered in the current fitting function. The fitting algorithm could be improved to save those events, but for the moment, the track with P < 0.05 is selected as a good track.

Figure 5.12 shows the momentum resolution obtained by the track fitting after applying the further event selection cut: $P_{\perp} > 50 \text{ MeV}/c$. The RMS of the main distribution is 0.17 MeV/c. The low momentum tail may be from energy loss of the electron from Moller scattering. On the other hand the high momentum tail extends only up to 1 MeV/cabove. Figure 5.13 shows the true momentum spectrum and the reconstructed momentum spectrum at the tracker entrance. Figure 5.14 shows net momentum resolutions as a function of the spatial resolution of detector. There is no significant difference in the momentum resolution even if the detector resolution is as worse as 100 μ m. This is because of the current momentum resolution is limited by the multiple scattering.

It is also note worth that the gross momentum resolution is a convolution of the net momentum resolution by the tracker and the energy loss uncertainly in the muon-stopping target. The contribution from the later factor is almost 200 keV/c-rms. In order to balance



Figure 5.11: Probability distribution of the track fitting with the detector resolution $\sigma_x = \sigma_y = 0.250$ mm, and the uncertainty of the multiple scattering angle $\sigma_{\theta}^{\text{scat}} = 0.0030$ radian.

the tracker performance with this natural width, the detector resolution could be as poor as 1 mm(RMS), and the detector thickness could be as thick as twice the current design².

5.4.1.4 Architecture of Tracker System

Each tracker module consists of 8 planes of straw tubes, 4 planes to measure the X coordinate and 4 planes to measure the Y coordinate. Straws are stretched along vertical direction for X (Y) planes, and the horizontal (vertical) position of anode wires are staggered between them to solve left-right uncertainty. Each anode signal will be digitized by wave-form digitizer electronics developed for the COMET experiment.

5.4.2 Electron Calorimeter

5.4.2.1 Overview

The electron calorimeter is positioned downstream of the straw chamber detector and serves three purposes in COMET Phase-I:

- 1. to measure the energy of electrons and photons in beam study. It is also important to achive good energy resolution for using the detector to search for $\mu^- e^-$ conversion in order to produce an efficient trigger and add redundancy to the energy measurement.
- 2. to provide a timing signal, i.e. a trigger, with respect to which the beam events (for beam study) and electron events (for $\mu^- e^-$ search) are referenced.

79

 $^{^{2}}$ However, in this case, the gamma induced tracker rate will also double to about 400 kHz



Figure 5.12: A difference between fit momentum and true momentum. Left plot is in linear scale and the right plot is in log scale. The detector resolution is $\sigma_x = \sigma_y = 0.250$ mm, and the uncertainty of the multiple scattering angle is $\sigma_{\theta}^{\text{scat}} = 0.0030$ radian.



Figure 5.13: Left plot shows true total energy, E^{true} , at the tracker entrance. Right plot shows fit momentum. The detector resolution is $\sigma_x = \sigma_y = 0.250 \text{ mm}$, and the uncertainty of the multiple scattering angle is $\sigma_{\theta}^{\text{scat}} = 0.0030 \text{ radian}$.

3. to provide additional position information on the charged track trajectory correlating the measured energy with the track.

For $\mu^- - e^-$ conversion search independent and redundant measurements of the energy and momentum of electrons are of critical importance to separate true muon-to-electron conversion from reconstructed tracks that conspire to mimic a signal. Although the likelihood of a combination of lower energy electrons being mistaken for a 105 MeV electron track is small, it must be remembered that the number of low energy electrons between 85 to 95 MeV is a factor of more than a thousand larger than for electrons above 95 MeV. A calorimeter constructed of segmented scintillating crystals can have an energy resolution of better than 5% and an energy-correlated position coordinate accuracy of about 1 cm (rms). Finally, the event topology, given good crystal granularity, helps discriminates between electrons, neutrons and low energy gammas. The crystals need good light yields,



Figure 5.14: Track-fit momentum resolution as a function of spatial resolution of detector plane.

fast time response, and fast decay time to reduce pile-up.

5.4.2.2 Crystal selection

Table 5.4 compares various scintillating crystals, which have a large light yield and a small decay constant. GSO(Ce) and LYSO are attractive crystals in view of their performance. Newly developed inorganic crystals, such as LaBr(Ce) and LGSO, would also result in good performance. We need further studies on their fundamental characteristics which would affect the performance of the calorimeter. The choice of crystal type depends on not only its performance, but also cost of the crystal. Here, we describe our plan to construct the electron calorimeter with cerium doped Gd₂SiO₅ (GSO) crystals with dimensions of $2 \times 2 \times 15$ cm³ as a base design. We also describe performance evaluation for the case of using LYSO. The length of the crystals corresponds to 11 radiation lengths for GSO and 13 radiation lengths for LYSO.

5.4.2.3 Photon Sensors

Operation of the calorimeter readout in a 1 T field essentially precludes the use of highgain, low-noise phototubes. In order to circumvent this problem, we plan to use Avalance Photodiodes (APD) for the readout.

APDs, with typical gains of 500-1000, are now generally available [86]. The MECO experiment was able to achieve an energy spectrum with a full width at half maximum of 4 MeV with a low energy tail from energy leakage in their R&D. Generally, resolution can be represented by the following form.

$$\sigma_E(E) = A \oplus B\sqrt{E} \oplus CE \tag{5.2}$$

81

	GSO(Ce)	LYSO	PWO	CsI(pure)
Density (g/cm^3)	6.71	7.40	8.3	4.51
Radiation length (cm)	1.38	1.14	0.89	1.86
Moliere radius (cm)	2.23	2.07	2.00	3.57
Decay constant (ns)	$600^{s}, 56^{f}$	40	$30^{s}, 10^{f}$	$35^{s},\!6^{f}$
Wave length (nm)	430	420	$425^s, 420^f$	$420^{s}, 310^{f}$
Refraction index	1.85	1.82	2.20	1.95
Light yield $(NaI(Tl)=100)$	$3^{s},\!30^{f}$	83	$0.083^s, 0.29^f$	$3.6^{s}, 1.1^{f}$

Table 5.4: The characteristics of inorganic scintillator crystals.

The first term is the contribution from electronic noise. The second is due to photon statistics, and the third term which is proportional to the energy, includes errors in calibration, non-uniform light collection, energy leakage, and temperature and gain drifts. Additional terms, dependent on other powers of E are sometimes included as well. The equivalent noise energy is the ratio of the equivalent charge noise (expressed in units of e) to the collected light (in photoelectrons per MeV).

R&D for the MECO calorimeter found that the series noise contribution can be reduced using two APDs. In the MECO CDR it was found that using 2 PIN diodes, the resolution for a BGO crystal and an RC time constant of 300 nsec was 1.3 MeV/crystal, 0.42 MeV, and 1.7 MeV for electronic noise, photostatistics, and shower fluctuations, respectively. Combining these in the above equation and summing in quadrature over the noise from nine crystals (expected shower size) the expected resolution, exclusive of pileup, would be 4.3 MeV. The signal reaches its maximum at 900 nsec. It is anticipated that both the resolution and shaping time can be significantly reduced when using APD's.

Light collection is also an important parameter and must be carefully studied. A smaller area diode has less capacitance and thus less noise, and if the crystal-diode configuration is carefully constructed (*e.g. wrapped or coated crystal*) light that misses the diode can be reflected and collected later. Currently we plan to use $5 \times 5 \text{ mm}^2$ APD for readout according to our studies using GSO and LYSO crystals irradiated by cosmic rays. This also simplifies the design of the supporting structure of crystals thanks to smaller coverage on the crystal end.

5.4.2.4 Electronics

Because of APD noise, the signal from the crystals must be integrated over 100-300 ns. The front-end preamp takes the output current, shaping the signal and sends it to a waveform digitizer. We plan to use a modern waveform ASIC, the DRS4 used to readout the MEG photon calorimeter [87]. Analysis of the waveform permits the removal of pile-up, improving the energy resolution and trigger efficiency.

Full analysis of the waveform is expected to be undertaken offline. To develop a trigger,

calorimeter signals will be processed locally by an FPGA that will cut on energy deposited in shower clusters within the calorimeter. At trigger decision must be made within 500 ns in order to extract valid information from the tracker.

5.4.2.5 Performance

Energy resolutions of the calorimeter is studied using Geant4 with Optical Photon Processes. The resolution depends on crystal, light guide, photon detector, and their geometrical configuration. In this section, we discuss dependence of the resolution on the crystals under a possible configuration of the calorimeter.



Figure 5.15: A typical event display of the simulation study of the calorimeter. An electron injected to the calorimeter, then optical photons from scintillation processes are ray-traced to the photon detectors.

Figure 5.15 shows a typical event display of this simulation. The calorimeter is a cylinder 0.8 m in diameter, and consists of 1224 rectangular segments. The crystal has size of $20 \times 20 \times 150$ mm³ as already mentioned. In this simulation readout by photomultipliers with a quantum efficiency dependence on the wavelength is supposed for simplifying light transmission model from the crystal end to the photo sensor surface.

Figure 5.16 shows photoelectron distributions for 105 MeV election injections to the calorimeter. Energy resolutions of 5.0% in FWHM for GSO(Ce) and 3.6% in FWHM for LYSO are expected. Note that these does not include the effect of electron energy loss in the muon stropping target material which is estimated to be less than 1MeV in FWHM.



Figure 5.16: Distributions of the number of photoelectrons observed in photon detectors for GSO(Ce) (left) and LYSO (right).

Chapter 6 Cosmic Ray Shielding

6.1 Introduction

Cosmic rays can produce significant backgrounds to the signal being searched for. Although cosmic rays include small amounts of almost all types of particle, muons are the most numerous charged particles at sea level and hence are the main source of backgrounds. Cosmic muons can decay in flight or interact with the solenoid walls producing signal-like electrons in regions of the solenoid where they can have an impact on the measurement. This region covers the end of the muon transport solenoid and whole spectrometer solenoid including the muon-stopping target and detectors.

It should be mentioned that the backgrounds induced from cosmic rays can be estimated and measured when the beam is off, during proton acceleration cycle, since they are not related to the beam.

6.2 Passive Shielding

Passive and active shielding will be used to protect this region against cosmic rays. The passive shielding consists of an inner shielding and an outer shielding. The passive outer shielding will be used to reduce low energy cosmic rays as well as sky-shine neutrons. It includes a combination of steel and concrete walls. The 3.5 m concrete wall on the top side will suppress a rate of the cosmic ray background by a factor of about 3–4, as shown in Figure 6.1. Concrete walls will reduce the rates of cosmic rays coming with a large polar angle. Because the overall polar angle distribution for cosmic muons at the ground level is approximately $\cos 2\theta$, the background contribution from large polar angle muons is small.

The inner shielding consists of, from the outside to the inside, an iron layer, a polyethylene layer and a lead layer. The iron layer will reduce fluxes of high energy neutrons, mostly with $E_n > 2$ MeV, by 3–4 orders of magnitude. The flux of low energy neutrons ("fast neutrons") will be increased since the high-energy neutrons slow down. As a result, the total neutron flux after the iron shield is only one order of magnitude less than the original flux. The polyethylene layer absorbs fast neutrons. The total neutron flux, including the



Figure 6.1: Momentum distributions of cosmic muons with and without 3.5 m of concrete. Cosmic rays of momentum less than 1 GeV are the majority (¿90 %) of those that produce backgrounds and these are reduced down by a factor of 3–4.

low energy region, after the polyethylene layer (20 cm) is reduced by almost three orders of magnitude from the original flux. On the other hand, the gamma ray flux increases due to gamma-ray emission through fast neutron absorption. These gamma-rays are absorbed by the lead layer.

6.3 Active Shielding

The active shielding is provided by a scintillator-based veto system placed on top of the spectrometer magnet. The veto system consists of 3 super-modules with 3 modules in each super-module¹. The modules contain four layers of scintillator strips in vertical direction. All strips in the system are placed in parallel. The strips are equipped with wavelength-shifting (WLS) fibers in the center groove. To readout signals Silicon Photomultipliers (SiPMs) are connected to one end of the fibers while the other end is mirrored. Some details of proposed design for the veto system is discussed below.

 $^{^{1}}$ In COMET Phase-II 15 super-modules will be used to cover the area including the muon-stopping target, curved solenoid and the spectrometer solenoid.

Experience from previous experiments and preliminary Monte Carlo estimates show that the veto system must provide a rejection power of about 10^4 for cosmic muons. The proposed design is expected to satisfy this requirement, however, a detailed Monte Carlo simulation should be performed to obtain a more accurate estimate of the suppression efficiency for the chosen setup and for its optimization. The veto system is located on the top of the solenoid and covers an area of 3×5.4 m². To avoid dead zones between the super-modules along their length, we plan to place the even-numbered super-modules on top of the odd-numbered ones with an overlap (Figure 6.2. In the other direction, super-modules will be connected with a 3 cm shift between pairs of layers at their ends (Figure 6.3). A space of 1 cm between the super-modules is required to read out signals from the middle super-module.



Figure 6.2: The positions of the 15 modules $(1.8 \times 3 \text{ m}^2 \text{ each})$ on the top of solenoid. The muon target and trackers are shown schematically.



Figure 6.3: The connection of short sides of super-modules (left). An illustration of the layers' placement with shifts in two directions (right).

Modules are fixed inside the super-modules with u-beam channel bars as shown in Figure 6.4(left). The positioning of four layers of scintillator strip modules inside each

super-module is shown in Figure 6.4 (right). Supporting plates used to align the modules inside a super-module are indicated with hatched areas. A shift of about 2 mm between odd and even layers allows us to avoid efficiency losses near the edges of modules.



Figure 6.4: The supports used to fix four layers of modules inside a super-module. The 3D view (left) and xy projection with sizes in x scaled down by a factor of 10 (right) are shown.

Modules consist of 15 strips in each layer. All strips have the same size $(0.8 \times 4 \times 300 \text{ cm}^3)$, and are made of polystyrene-based scintillator with a matted surface (that provides a diffuse reflection of light), produced by Uniplast (Russia)[88]. Each is equipped with a 1.2 mm diameter WLS fiber in a central groove (Figure 6.5). The fiber is glued inside the groove with a special gel. This assures a good optical contact between the scintillator and the fiber and hence increases the light collection efficiency.



Figure 6.5: Sketch (left) and photo (right) of the proposed strip for the veto system.

The fibers are mirrored at the rear end and read out at the other end with the 1.3×1.3 mm² active area SiPM. We consider two possible types of SiPM: MPPCs from Hamamatsu

Photonics [86] and Russian-made MRS APD [89] (see Figure 6.6). A SiPM is mounted on the strip by a special plastic connector that fixes its position and guarantees a small air gap to the fiber as is shown in Figure 6.7



Figure 6.6: View of 796 pixel MRS APD fiber (CPTA, Russia).

The proposed strip design has the following advantages over a wider strip with several WLS fibers:

- Light from a MIP is not shared between different SiPMs. This allows for a very high efficiency even with a high signal threshold. Our measurements demonstrate that the efficiency for a MIP for the worst case of a particle crossing at the far end of the strip is larger than 99% for a 7-pixel threshold (Figure 6.8). As will be shown below, at such a threshold the MPPC noise rate is less than 10 Hz, i.e. below the cosmic ray rate. The dependence of the strip light yield for a MIP versus the distance to the photo-detector is shown in Figure 6.9. Figure 6.10 shows the SiPM noise rate distribution for a 7-pixel threshold for more than 200 Hamamatsu MPPCs.
- It is easier to estimate the efficiency of each strip with cosmic muons using coincidences with other strip signals.
- In case of problems with one channel only a small part of the detector is affected.
- Time resolution of about 1 ns can be achieved.

For each module, the SiPMs are read out with 15 differential preamplifier channels (see Figure 6.11), that allows the signals to be transferred along large distances. This preamplifier has been tested and a compact 15 channel layout will be developed soon.



Figure 6.7: View of connector for the WLS to photo-detector coupling.



Figure 6.8: Response of a scintillator strip to cosmic particles (left) and LED flashes (right). The distributions are obtained using cosmic particles crossing the far end of the strip

To form a $60 \times 300 \text{ cm}^2$ module, both sides of a set of 15 strips are glued to a 1.5 mm-thick plastic support. The insensitive area between strips is about 300 μ m for tracks with normal incidence. It corresponds to less than 1 % of the total area. A module with four layers of scintillator strips should provide perfect geometrical efficiency, because the single-layer efficiency is larger than 99 %. However this efficiency can go down to ~95 %

90



Figure 6.9: The light yield of 2 scintillator strips for MIP crossings, corrected by the angle distribution, photo-detector cross talk and after-pulsing. Horizontal bars show the size of trigger counters.

after long-term irradiation.

A second layer is put on the first one without any additional support. As described above, the layers are shifted by 2 mm in x in order to avoid gaps (see Figure 6.2). The installation procedure is repeated for the next 2 layers, which are shifted by about 3 cm in z to avoid dead zones between super-modules. All four layers will be covered by black plastic to protect strips from outer light.

One of the most important issues for the effective operation of the veto system is SiPM efficiency decrease due to neutron flux exposure althoug this would not be the case for COMET Phase-I because of its shorter operation period. Nevertheless we have estimated an acceptable level for the neutron flux using SiPM irradiation by protons, assuming about the same damage produced to SiPMs by protons and neutrons. These tests of radiation hardness of SiPMs [90] show the variation of noise and strip efficiency versus accumulated proton fluence (Figure 6.12).

When the proton fluence reaches $7.4 \times 10^{10} \text{ p/cm}^2$, the typical noise rate at the 7pixel threshold is about several kHz and the efficiency is still as high as 98 %. For COMET Phase-II the total duration of the experiment is expected to be about 4×10^7 sec. Therefore a fluence of $7.4 \times 10^{10} \text{ n/cm}^2$ corresponds to a flux of $7.4 \times 10^{10} \text{ n/cm}^2/4 \times 10^7$ sec = 1850



Figure 6.10: Distribution of the noise rates with a 7-pixel threshold for more than 200 tested MPPCs.



Figure 6.11: Amplifier for SiPM readout

92



Figure 6.12: The noise rate (left) and the strip efficiency (right) as a function of the pixel threshold number for different accumulated proton fluences.

 $n/cm^2/sec$. This neutron flux is critical to the operation of SiPMs. It has to be mentioned that this flux counts only neutrons with energies of about 1 MeV or larger because low energy neutrons practically do not affect SiPMs. This noise rate will result in ~ 25 % dead time by the end of the experiment. For this estimate we assumed that a signal from any strip of the veto system rejects events in a gate of 30 ns width. The noise rate grows very slowly with the accumulated neutron flux and the mean dead time will be less than 10 %.

If one chooses the admissible neutron fluence to be $3.9 \times 10^{10} \text{ n/cm}^2$ (that is equivalent to ~ 1000 n/cm²/s), then the expected dead time by the end of the experiment (Phase-II) is only ~3 % and the mean dead time is less than 1 %. It is potentially possible to reduce the noise rate of SiPMs by increasing the pixel threshold, but this will lead to a drop in efficiency. We conclude that an acceptable level for the neutron flux is about ~ (1000-1800) n/cm²/s or less and a higher flux will result in a very large dead times. Therefore the neutron flux in the experimental hall should be evaluated before the final choice of SiPMs. This will be perfomed in the beam backgroud study period. If the neutron flux will be unacceptably high, we can require signal coincidences between layers in modules, which will drastically reduce the noise rate. It has to be noted that the placement of the strips and readout electronics in the proposed design allows for the possibility of replacing noisy SiPMs without moving the system.

The R&D for the proposed option can be finalized in 2013 and we are able to produce all the modules (520 strips in total for Phase-I and 2700 strips for Phase-II) in 2014. We are currently constructing the Belle II end cap KLM detector with \sim 16K such strips. The existing infrastructure for production and tests can be later used for COMET veto system construction.

Chapter 7 Data Acquisition System

The potentially high rates which the trigger and data acquisition (DAQ) system need to handle arise from irreducible physics backgrounds such as muons decaying in orbit and backgrounds due to particles in or produced by interactions of the beam faking an electron signature. The DIO spectrum can be measured for the whole electron energy spectrum in special runs or using triggers with a pre-scale. During normal data-taking, a minimum energy cut on the electron candidate can be applied to reduce the DIO background to a manageable value; this will ensure a precise and constant measure of the primary background as well as keeping all potential signal events. Such an energy requirement along with timing and coincidence requirements will also reduce beam-related background.

7.1 Trigger concept

The event trigger is obtained by measuring the total energy an electron deposits in the calorimeter. The DIO spectrum falls as a function of the 5th power of the difference between this energy and the kinematic end-point and so any reduction in the minimum energy will reduce in many more events triggered. The kinematic end-point where conversion electrons are expected is 105 MeV and a minimum value for the trigger cut would be about 80 MeV to ensure the value is far enough was so as to remove no signal and allow the background spectrum to be measured as well as not having a rate too high for the planned system. The exact value of this minimum energy trigger cut can be tuned depending on the conditions of the experiment. Although no DIO events are expected to be higher than the end-point, beam backgrounds may lead to signatures at higher energies and so an upper cut of about 100 MeV may also be needed.

The trigger is based on an analogue summation of energy deposited in the calorimeter crystals within a time window. This is information is processed by a trigger FPGA module which uses the total deposited energy and the number of contiguous crystals that have a signal above a minimum energy threshold. It can be made as cascade structure, as shown in the schematic of the trigger system Fig. 7.1.

CHAPTER 7. DATA ACQUISITION SYSTEM



Figure 7.1: Trigger concept using analogue summation.

7.2 Data rates

The data rate will be dominated by the tracker. For the straw tracker a total data size of 600×16 kbit = 9.6 Mb is expected which given a trigger rate of 1 kHz leads to a data size of 6.72 Gb over a 0.7 s cycle. Given a detector with 20–40 layers, this leads to a data transfer per spill of 336 Mb/s, comfortably below Gigabit ethernet. Having 20–40 optical fibres to read out each layer is a manageable number for a network system. A crystal calorimeter with 1 000 channels will give a significantly lower rate and so will require fewer connections.

7.3 Data acquisition system

The DAQ system is network based in which switches or concentration cards take the data from electronics on the individual sub-detectors, combine the data and send them over a Gigabit network to a PC farm which will the send the data to long-term storage. Trigger, timing and control information will be sent to the detectors along a separate data line or along the same network used to readout the data. Network-based DAQ systems have been used in many systems (e.g. [91]) and offer the following advantages : high-speed devices are commercially available at reasonable cost; networks are flexible and easily modified; and a network offers direct control and monitoring of the DAQ FPGAs and DAQ operations.

Each front-end will be locally controlled by an FPGA, programmed to readout its detector and process an event structure, storing this information in local memory from which it is read via a command from the DAQ system. Because each detector has a local buffer from which events are transferred to a system processor, an event builder must sort the data stream by event number, before event processing and storage. A PC farm, also controlled by a system computer, processes the data committing appropriate events to

CHAPTER 7. DATA ACQUISITION SYSTEM

permanent storage, and transferring a sample for online monitoring.

A schematic view of a network configuration is shown in Fig. 7.2. Such a network DAQ system can accept about 100 MB/s (i.e. Gigabit network) data flow. Networks which support 10 Gbit/s are becoming increasingly used and could also be an option to reduce the number of links.

Finally, there will be a second acquisition system for slow control and environmental monitoring. Environmental variables will be read every fixed number of beam-spills and will be correlated with the data triggers.



Figure 7.2: DAQ network-based system.

Chapter 8

Signal Sensitivity and Backgrounds

8.1 Introduction

In this chapter, the signal sensitivity, and the expected background events in the COMET Phase-I search for $\mu^- - e^-$ conversion are evaluated. To estimate the experimental sensitivity, a 0.4 μ A proton beam at 8 GeV, yielding a total beam power of 3.2 kW, is assumed. It corresponds to about 2.5×10^{12} protons per second. A nominal running time of 1.5×10^6 s (about 18 days), gives a total of 3.8×10^{18} protons on target.

8.2 Signal Sensitivity for $\mu^- - e^-$ Conversion

As described in Chapter 5, we could have two detector systems to search for $\mu^- - e^-$ conversion at COMET Phase-I. One is a cylindrical drift chamber (CDC) as the baseline design, and the other is a transverse tracker detector. In the following, the estimations of signal sensitivity for each system are described.

8.2.1 Signal acceptance for the COMET Phase-I CDC

The major differences of the geometrical design of CDC from that in the COMET Phase-I LOI are to eliminate plastic scintillator counters (proton absorbers) placed in front of the CDC, and instead to place the trigger counters at the forward and backward ends of the CDC. From these modifications, the net momentum resolution of the CDC has been improved, although the geometrical acceptance became smaller by installing the trigger counters at the ends of the CDC.

The acceptance for $\mu^- - e^-$ conversion signals is determined by several factors. They are

- geometrical acceptance including a solid angle of the CDC,
- requirement of hits at the CDC trigger counters,
- efficiency of track reconstruction with track quality cuts,
- efficiency of momentum selection (a momentum window cut),

- efficiency of timing selection (a timing window cut), and
- efficiency of event trigger and a DAQ live time.

The geometrical acceptance depends on the detector configuration such as the size and radial positions of the CDC and of the trigger counters, and a magnetic field. In the present design, charged particles with momenta less than 70 MeV/c do not reach the CDC. Figure 8.1 shows the distributions of transverse momenta (P_T) and longitudinal momenta (P_L) for the generated events (in black) and reconstructed events (in blue) and those reconstructed events hitting the trigger counters (in magenta) of 105 MeV/c electrons, in forward and backward directions separately. From this, it is found that electron tracks with P_T of more than 80 MeV/c can be reconstructed. The geometrical acceptance of tracks of about 24%, with the requirements of the trigger counter hits is obtained. It can be seen that the tracks with a large pitch (with large P_L) angle would miss the trigger counters.



Figure 8.1: Distributions of transverse momenta (P_T) and longitudinal momenta (P_L) for the generated events (in black) and reconstructed events (in blue) and those reconstructed events hitting the trigger counters (in magenta) of 105 MeV/c electrons, in forward and backward directions separately.

A momentum cut can be used to reduce contamination from DIO electrons. Figure 8.2 shows the reconstructed momentum spectrum of $\mu^- - e^-$ conversion signal events that were generated using Monte Carlo simulations and the DIO electron spectrum. In Figure 8.2,

Event selection	Value	Comments
Geometrical acceptance	0.24	tracking efficiency included
Momentum selection	0.74	$104.1 \text{ MeV}/c < P_e < 106 \text{ MeV}/c$
Timing selection	0.39	same as COMET
Trigger and DAQ	0.9	same as COMET
Total	0.062	

Table 8.1: Breakdown of the $\mu^- - e^-$ conversion signal acceptance per stopped muon

the vertical scale is normalized so that the integrated area of the signal event curve is one event, assuming a branching ratio of $B(\mu N \rightarrow eN) = 3 \times 10^{-15}$. A detailed description of the estimation of contamination from DIO electrons is presented in Section 8.4.1.1. In this study, the momentum cut of 104.1 MeV/ $c < P_e < 106 \text{ MeV}/c$, where P_e is an electron momentum, is determined in such a way that a contamination from DIO electrons of 0.01 events is expected for a single event sensitivity of $\mu^- - e^-$ conversion of 3×10^{-15} .



Figure 8.2: Distributions of reconstructed $\mu^- - e^-$ conversion signals and reconstructed DIO events The vertical scale is normalized so that the integrated area of the signal is equal to one event with its branching ratio of $B(\mu N \rightarrow eN) = 3 \times 10^{-15}$. The momentum cut of 104.1 MeV/ $c < P_e < 106$ MeV/c, where P_e is an electron momentum, is applied.

The efficiencies of the timing selection and the trigger and DAQ are assumed to be the same as those in the COMET CDR [78]. From these, the net acceptance for the $\mu^- - e^-$ conversion signal, $A_{\mu-e} = 0.062$, is obtained. The breakdown of the acceptance is shown in Table 8.1.

The single event sensitivity is given by

$$B(\mu^{-} + \mathrm{Al} \to e^{-} + \mathrm{Al}) = \frac{1}{N_{\mu}^{\mathrm{stop}} \cdot f_{\mathrm{cap}} \cdot A_{\mu-e}}, \qquad (8.1)$$

where N_{μ}^{stop} is the number of muons stopping in the muon target, f_{cap} is the fraction of muon capture and $A_{\mu-e} = 0.062$ is the signal acceptance. The fraction of muon capture for aluminum is $f_{\text{cap}} = 0.61$.

By assuming a proton beam of 8 GeV with 0.4 μ A, a total beam power is about 3.2 kW. A proton current of 0.4 μ A corresponds to 2.5×10^{12} protons/s. With a running period of 1.5×10^6 s, a total number of protons on target is about 3.8×10^{18} .

A number of muons stopped at the muon stopping target is estimated to be 0.0023 per proton from the COMET_G4 simulation program, as mentioned in Chapter 4. From these, a total number of muon stopped of $N_{\mu}^{stop} = 8.7 \times 10^{15} \ (= 0.0023 \times 3.8 \times 10^{18})$ is obtained. It corresponds to 5.8×10^9 muons stopped/s.

By using these numbers thus obtained, from Eq.(8.1), the single event sensitivity is given by

$$B(\mu^{-} + \text{Al} \to e^{-} + \text{Al}) = 3.1 \times 10^{-15}.$$
 (8.2)

The 90 % confidence upper limit with zero background events is given by

$$B(\mu^{-} + \text{Al} \to e^{-} + \text{Al}) < 7.2 \times 10^{-15}.$$
 (8.3)

8.2.2 Signal Acceptance for COMET Phase-I Transverse Tracker Detector

The transverse tracker detector may have less geometrical coverage since the detector can detect only events coming into the downstream hemisphere. Detailed simulation studies to estimate geometrical acceptance will be made soon, together with tracking efficiencies.

The transverse tracker detector has a 20% coverage. This is less than the CDC design because of the use of only downstream hemisphere seen from the muon-stopping target. Trigger and analysis efficiencies have not been estimated in a reliable manner with these setup, thus we suppose conservatively 10% in total in either case. The single event sensitivity can be calculated from these assumption;

•
$$1/(8.7 \times 10^{15} \times 0.61 \times 0.32 \times 0.1) = 5.9 \times 10^{-15}$$

for the transverse tracker detector option. These correspond to 90% C.L. upper limits of 1.4×10^{-14} in case of no candidate observation.

8.3 Background Estimation for $\mu^- - e^-$ Conversion

As in the Conceptual Design Report (CDR) of COMET [78], potential backgrounds sources for the search for $\mu^- - e^-$ conversion are grouped into four categories.

100

Intrinsic physics backgrounds		
Muon decay in orbit	Bound muons decay in a muonic atom	
Radiative muon capture (external)	$\mu^- + A \to \nu_\mu + A', A' \to \gamma + A,$	
	followed by $\gamma \to e^- + e^+$	
Radiative muon capture (internal)	$\mu^- + A \rightarrow \nu_\mu + A', A' \rightarrow e^+ + e^- + A$	
Neutron emission	$\mu^- + A \to \nu_\mu + A', A' \to n + A,$	
after μ^- capture	and neutrons produce e^-	
Charged particle emission	$\mu^- + A \to \nu_\mu + A',$	
after μ^- capture	$A' \to p \text{ (or } d \text{ or } \alpha) + A$	
	followed by p (or d or α) produce e^-	
Beam related prompt backgrounds		
Radiative pion capture (external)	$\pi^- + A \to \gamma + A'$	
	followed by $\gamma \to e^- + e^+$	
Radiative pion capture (internal)	$\pi^- + A \to e^+ + e^- + A'$	
Beam electrons	e^- scattering off a muon stopping target	
Muon decay in flight	μ^- decays in flight to produce e^-	
Pion decay in flight	π^- decays in flight to produce e^-	
Neutron induced backgrounds	neutrons hit material to produce e^-	
Beam related delayed backgrounds		
Delayed-pion radiative capture	$\pi^- + A \rightarrow \gamma + A', \ \gamma \rightarrow e^- + e^+$	
\overline{p} induced backgrounds	\overline{p} hits material to produce e^-	
Other backgrounds		
Cosmic-ray induced backgrounds		
False tracking		

Table 8.2: A list of potential backgrounds for a search for $\mu^- - e^-$ conversion.

- intrinsic physics backgrounds,
- beam-related prompt backgrounds,
- beam-related decayed backgrounds, and
- other backgrounds including cosmic ray backgrounds.

The intrinsic physics backgrounds come from muons stopped in the muon stopping target. The beam-related prompt backgrounds are background events originated from protons coming and hitting the proton target between beam pulses. The beam-related delayed backgrounds are backgrounds originating from the main proton beam pulse and coming at a later time within the measurement time window. A list of background events are summarized in Table 8.2.

8.4 Background Estimation for COMET Phase-I CDC

The background events for the COMET Phase-I CDC design are evaluated as follows.

8.4.1 Intrinsic physics backgrounds

Negative muons stopped in material are immediately trapped by the Coulomb potential of the nucleus of the material, and fall down to the 1S orbit of a muonic atom. There are two major allowed processes in which a bound μ^- could proceed. They are

- muon decays in orbit (DIO), and
- nuclear muon capture (NMC).

8.4.1.1 Muon decays in orbit

Muon DIO is a Michel decay, $\mu^- \rightarrow e^- \nu_{\mu} \overline{\nu}_e$, of the muons that are bound in a muonic atom under a Coulomb potential of the nucleus. Because of the recoil of the nucleus, an electron from the Michel decay can be boosted. The maximum energy of the e^- exceeds the end point energy of the ordinary Michel decay of 52.8 MeV and extends to the momentum range of the μ^--e^- conversion signal. This is one of the dominant background sources.

The momentum spectrum of electrons from muon decay in orbit for aluminum can be calculated based on the model described in [66]. Figure 5.7 shows the momentum spectrum of DIO electrons from aluminum. Based on the calculated spectrum, DIO electrons are generated in a Monte Carlo simulation and their tracks are reconstructed with Genfit (see Section 5.3.1.7 in details). Figure 8.2 shows the reconstructed momentum spectrum of DIO electrons with $\mu^- - e^-$ conversion signals. This momentum spectrum is then integrated above the momentum threshold of the $\mu^- - e^-$ conversion signal region. Figure 8.3 shows the integrated fraction of DIO events as a function of momentum threshold, and the fraction of $\mu^- - e^-$ conversion signal events. The momentum range of the $\mu^- - e^-$ conversion signal region is determined so that the fraction of DIO electrons in the signal region is 0.01 events. From this, as described before, the momentum cut of 104.1 MeV/c < P_e < 106 MeV/c is determined. Note that the current estimate is a preliminary one and the number could change in future with more detailed Monte Carlo simulation being developed at the moment, especially in case we need hardware design modification to make background rejection more reliable.

8.4.1.2 Beam-related prompt backgrounds

The beam-related prompt backgrounds arise from protons between the beam pulses. These backgrounds are suppressed by the proton beam extinction factor. The proton beam extinction factor, $R_{\text{extinction}}$ of 3×10^{-11} is used, since this was obtained from our recent



Figure 8.3: Event fractions for DIO electron events and $\mu^- - e^-$ conversion events as a function of lower momentum threshold of the signal region.

experimental measurements in the fast extraction mode at the J-PARC MR with an improved injection scheme as described in Section3.2.3.3. 1

8.4.1.3 Radiative pion capture

The radiative pion capture (RPC) background is caused by pions contaminated in the muon beam. Those pions are stopped in the muon stopping target, and are captured by an aluminum nucleus immediately to form an excited state of the daughter nucleus.

There are two processes, one of which produces directly a γ of high energy (direct process) and the other produces γ s as an evaporate process of the excited daughter nucleus to their ground state. During these processes, a probability of γ emission is as high as 2%. Some of such emitted γ s convert into e^- and e^+ in the target or in material outside the target. When the e^+e^- pair creation occurs in an asymmetric energy distribution and the e^- has a high energy, it would mimic $\mu^- - e^-$ conversion signals. This is external conversion of a photon from RPC. And also there is an internal conversion of RPC, which contributes to almost same rate.

The probability of γ emission and the energy spectrum of γ s were extensively studied experimentally and theoretically more than 20 years ago. According to [92], the probability of γ emission has very small Z dependence. It is almost 2% for C, O, and Ca as shown in Table 8.3. The energy of γ from RPC ranges from 50 MeV to 140 MeV as shown in Figure 8.4 The overall shapes of the spectra are very similar between C, O, and Ca. Therefore, we implement the experimentally obtained spectrum for Ca to our Monte Carlo code for this study.

¹It is necessary to confirm this number with the slow-extraction beam from J-PARC MR.

Table 8.3: Experimentally measured branching ratios of radiative pion capture. This table was taken from the Table 4 in [92].

$1^{12}C$	$1.84 \pm 0.08, 1.92 \pm 0.91, 1.6 \pm 0.1$
^{16}O	$2.27 \pm 0.24, 2.24 \pm 0.48$
⁴⁰ Ca	1.82 ± 0.05



Figure 8.4: Momentum distribution of γ s from RPC. This figure is reprinted from [92]. The histogram is experimental data, and the lines are from some theoretical models.

The number of RPC backgrounds is expressed as

$$N_{\rm RPC} = N_{\rm proton} \times R_{\rm extinction} \times R_{\pi-{\rm stop}/p} \times P_{\rm RPC} \times P_{\gamma-e^-} \times A_{\rm geometry} \times A_{\rm tracking}, \qquad (8.4)$$

where N_{proton} is a total number of protons on the pion production target, $R_{\text{extinction}}$ is a proton beam extinction factor, $R_{\pi-\text{stop}/p}$ is a number of $\pi^-\text{s}$ coming to a muon stopping target per proton, P_{RPC} is a branching ratio of radiative pion capture, $P_{\gamma-e^-}$ is a probability of conversion of the RPC photon to an electron of 105 MeV/c, A_{geometry} is a detector acceptance of the RPC-originated electrons of 105 MeV/c, A_{tracking} is an efficiency of tracking. Parameters that have to be evaluated specifically for the COMET Phase-I are $R_{\pi-\text{stop}/p}$, $P_{\gamma-e^-}$, A_{geometry} , and A_{tracking} . In order to estimate those numbers, a Monte Carlo simulation was performed.

From the muon beam simulation in the COMET Phase-I, $R_{\pi-\text{stop}/p} = 6.9 \times 10^{-5}$ at the target position, as shown in Section 4. It could be compared with that in the COMET Phase-II, of $R_{\pi-\text{stop}/p} = 3.5 \times 10^{-7}$. RPC photon conversion was simulated for the COMET Phase-I CDC design, based on the photon spectrum in Figure 8.4. The simulation was started from the RPC photons generated uniformly inside the muon stopping target (of 17 aluminum disks) and isotropically emitted. A total number of 10^7 photon events were generated. Electrons and positions were created by pair production, and also electrons were generated by Compton scattering, The photon conversion could occur at the muon stopping target (TG), at the CDC inner wall (IW) and outer wall (OW), in the CDC gas (GS), and the CDC trigger counter (TR) and so on. For the electron events with their momenta above 90 MeV/c, tracking was performed. In the COMET Phase-I CDC geometry, relative ratios of electrons between 102 MeV/c to 106 MeV/c occurring at different locations were found to be TG:IW:OW:GS:TR=19:2:22:1:4. Among them, the electrons from TG and IW cannot be discriminated from the signals, whereas the others can be discriminated. In the signal region of 104.4 MeV/c to 106 MeV/c in momentum, 336 events that occurs at the muon stopping target and CDC inner wall remains. It should be noted that photon conversion mostly occurs inside the muon stopping target. In the end, these would give $P_{\gamma-e^-} \times A_{\text{geometry}} \times A_{\text{tracking}} = 3.4 \times 10^{-5}$. With $N_{\text{proton}} = 3.8 \times 10^{18}$ protons on target, a total of 0.0048 background events from the external conversion of radiative pion capture is obtained. The contribution of internal conversion is about the same as that of external conversion. Therefore, $N_{\rm RPC} = 0.0096$ events is estimated with a proton beam extinction factor of 3×10^{-11} .

8.4.1.4 Beam electrons, electrons from muon and pion decays in flight

Beam electron background is caused by electrons contaminating in the muon beam. The electrons in the muon beam mostly originate decays of π^0 s produced by proton bombardment. Electrons will scatter off the muon-stopping target and fake the signal electrons if the electron momentum is in the signal region.

Similarly, decays of muons in flight during the muon transport system can produce energetic electrons that have sufficient total momentum. For the decay electrons to have $p_{\text{total}} > 102 \text{ MeV}/c$, the muon momentum must exceed 77 MeV/c ($p_{\mu} > 77 \text{ MeV}/c$). Furthermore, $\pi \to e + \nu$ decay of pions in flight are also a potential source of background. The π momentum must exceed 60 MeV/c to make this background process. It is noted that the branching ratio of $\pi \to e + \nu$ is about 1.2×10^{-4} .

$$N_{\text{e-scat}} = N_{\text{proton}} \times R_{\text{extinction}} \times R_{\text{e-beam}/p} \times R_{\text{e-det}} \times P_{\text{e-signal}}$$
 (8.5)

Monte Carlo beam simulations based on Geant4 were made to estimate energetic elections in the muon beam. which includes the beam electrons, electrons from muon and pion decays in flight. After the beam collimator, a number of all the electrons with their momentum greater than 80 MeV/c is $R_{e-\text{beam}/p} = 1.7 \times 10^{-5}$ per proton. It should be noted that an electron should have transverse momentum, P_T , greater than 70 MeV/c to reach the CDC.

The electrons thus obtained from the Monte Carlo beam simulations are injected into the COMET Phase-I CDC to examine what is a probability for them to reach the CDC. Out of 4.0×10^6 electrons, none of them reach the CDC, and thereby the upper limit of the product of the probabilities of $R_{e-det} \times P_{e-signal} < 2.5 \times 10^{-5}$ is obtained. Therefore, from Eq.(8.5), the estimated background is less than 0.00048.

8.4.1.5 Background induced by beam neutrons

Background induced by neutrons in a beam with high kinetic energy coming through the muon beam line is estimated a Monte Carlo simulation. Those neutrons could pass through the muon beam line by continuously reflecting from its inner sides of the beam duct. In principle the neutrons which can produce electrons of 100 MeV must exceed its kinetic energy of 100 MeV. According to a GEANT3 Monte Carlo simulation, an average transit time of those neutrons arriving at the muon stopping target is estimated to be about 300 nsec. This is much less than the time of 700 nsec before the measurement time window opens. Therefore, it is regarded as a prompt background and only late arrival protons can be the source.

Investigating almost all possible processes using simulations, we have concluded that most probable process to produce a 100 MeV electron is π^0 production from energetic neutrons, followed by π^0 decays with photon conversion. Thus neutrons with their kinetic energy of more than 180 MeV (about 600 MeV/*c* in momentum) were produced and transported through the COMET Phase-I beam line to examine their rate and energy distributions. The rate of $R_{n/p}$ of 10^{-5} neutrons per proton is obtained at the end of the first 90° bend. Then out of a total number of neutrons of 8×10^8 , 57 π^0 s are produced with interaction of neutrons to the muon stopping target made of aluminum, yielding a rate of $R_{\pi^0/n}$ of 7×10^{-8} . Then, by producing $10^6 \pi^0$ s following the above kinetic distributions, about 16 electrons fall into the signal region. From this, the rate of R_{e/π^0} of 1.6×10^{-6} is obtained. The prompt background rate $N_{neutron}$ can be estimated by

$$N_{\text{neutron}} = N_{\text{proton}} \times R_{\text{extinction}} \times R_{n/p} \times R_{\pi^0/n} \times R_{e/\pi^0}$$
(8.6)

This gives about 1.3×10^{-10} , resulting in the negligible contribution.

8.4.2 Cosmic ray induced backgrounds

The background events induced by cosmic rays are proportional to the total running time. The running time of COMET Phase-I is short, at 1.5×10^6 sec, in comparison to that of the full COMET of 2×10^7 sec. Therefore, the estimated background events are about a factor of 13 less than that of the full COMET experiment.

Table 8.4: Summary of estimated background events for a single-event sensitivity of 3.1×10^{-15} with a proton extinction factor of 3×10^{-11} . The numbers with * is directly proportional to the proton extinction factor.

Background	estimated events
Muon decay in orbit	0.01
Radiative muon capture	< 0.001
Neutron emission after muon capture	< 0.001
Charged particle emission after muon capture	< 0.001
Radiative pion capture	0.0096*
Beam electrons	
Muon decay in flight	$< 0.00048^{*}$
Pion decay in flight	
Neutron induced background	$\sim 0^*$
Delayed radiative pion capture	0.002
Anti-proton induced backgrounds	0.007
Electrons from cosmic ray muons	< 0.0002
Total	0.03

8.5 Summary of background estimations

Table 8.4 shows a summary of the estimated backgrounds. The total estimated background is about 0.03 events for a single event sensitivity of 3.1×10^{-15} with a proton extinction factor of 3×10^{-11} . If the proton extinction factor is improved, the expected background events are further reduced.
Chapter 9 Superconducting Solenoid Magnets

Superconducting solenoid magnets are used to transport muons from the pion capture section to the muon stopping target (Phase-I & Phase-II), as well as to transport electrons from the muon stopping target to the detector section, with high transport efficiencies (Phase-II). Therefore, the superconducting solenoid magnet system is one of the most important elements in the COMET experiment, and it is also one of the largest cost drivers. Since the COMET CDR [78], R&D studies on the superconducting solenoid magnet system have been significantly improved, in cooperation with the magnet vendors. In COMET Phase-I, only the pion capture section and muon transport up to the end of the first 90° bend are relevant. However, in envisioning the future extension to COMET Phase-II, the whole superconducting system must be designed at this time. For that reason, magnetic field optimization is described for the whole system while details of the magnet structure are described only about components necessary for Phase-I.

9.1 Overview

9.1.1 Layout

Figure 9.1 presents a schematic view of the magnet system. The superconducting solenoid magnet system can be grouped into several sections and their conventional names are shown in Figure 9.1, will be referred to in this chapter. They consist of the pion Capture Solenoid (CS), the Matching Solenoids (MS1 and MS2), the Transport Solenoids (TS1, TS2, TS3, TS4 and TS5), the Stopping Target solenoids (ST1, ST2, ST3), the Spectrometer Solenoid (SS), and the Detector Solenoid (DS). In the curved solenoid sections of TS and SS, dipole coils are installed on the solenoid coils to compensate vertical drifts of the center of trajectories for charged particles whose momenta is of interest. The COMET Phase-I needs CS, MS and TS1, TS2, TS3 to produce a muon beam and extract it to the experimental hall.



Figure 9.1: A schematic view of the superconducting solenoid magnet system and the coil names. The COMET Phase-I needs CS, MS and TS1, TS2, TS3 as indicated.

9.1.2 Design Requirements

The most important requirements for the magnetic field are summarized below:

- The magnetic field at the center (on the axis) at CS should be more than 5 T. The magnetic field at the TS is 3 T, and that at the SS and the DS is 1 T.
- To achieve an enhancement in pion collection from mirroring, the location for the maximum of the magnetic field should be about 100 mm upstream from the center of the pion production target. This displacement of the position of maximum magnetic field can be achieved though designing the coil layout of the pion capture solenoid and the iron yoke appropriately.
- The magnetic field from CS to SS should be graded monotonically to send charged particles towards the downstream direction. This grading is designed into the solenoid sections except for TS2, TS4 and SS, where dipole correction fields are applied. This

grading requirement covers the region within a radius of 150 mm from the central axis.

- Radiation shielding should be installed inside the CS magnet. Some optimization on the structure of the CS and MS should be considered to accommodate the radiation shielding.
- The coil structure should be compact to reduce its cost and radiation shielding. The region for the beam should be large enough. For the CS, provision for the proton beam must be made. The size of the proton beam duct is about 100 mm in diameter.

9.1.3 Conductor Choice

Aluminum-stabilized superconductors can be used for CS, MS and TS1 for which a highradiation environment is to be expected. It is desirable to have a series connection of electric currents for all the magnets, but for MS and TS1, some additional trimming current supplies can be used.

For the other magnets, copper-stabilized superconductors can be used. The operating electric current is less than 300 A and an electric current density of less than 100 A/mm^2 should be considered.

9.1.4 Pion Capture Solenoid

The design parameters for the aluminum stabilized conductor being considered are summarized in Table 9.1. A cross sectional image of the conductor is shown in Figure 9.2. A Rutherford-type cable with 14 copper stabilized strands is encased in an aluminum stabilizer using conforming technology.

Item	Value
Cable Dimension (without insulation)	$15 \times 4.7 \text{ mm}^2$
Cable Dimension (with insulation)	$15.3 \times 5.0 \text{ mm}^2$
Strand Diameter	1.15 mm
Number of Strands	14
Al/Cu/NbTi	7.3/0.9/1.0
Aluminum RRR	500
Copper RRR	50
NbTi Jc at 5 T 4.22 K	$2700 \mathrm{A/mm^2}$
Al yield strength	55 MPa
Overall yield strength	$150 \mathrm{MPa}$

Table 9.1: Design parameters for the aluminum stabilized conductor.

The capture solenoid magnet consists of 4 coils, CS0, CS1, MS1, and MS2. CS0 and CS1 are located closest to the target. They are edgewise winding coils with a 9-layer structure.

110



Figure 9.2: Cross section image of the aluminum stabilized superconductor.

MS1 and MS2 are necessary for creating a matching field to the transport solenoid. Both are also edgewise winding coils using the same superconducting cable, but with a 5-layer (8-layer) structure for MS1 (MS2). The design parameters of the CS and MS coils are listed in Table 9.2.

Coil	Len [mm]	IR [mm]	OR [mm]	$J [A/mm^2]$	AT [MAt]	B_{max} [T]
CS0	175	662	806	35	0.882	5.74
CS1	1350	662	806	35	6.804	
MS1	1800	662	742	35	5.040	3.97
MS2	380	662	790	35	1.702	3.88

Table 9.2: Design parameters of the CS, MS coils

The coils are structurally connected to each other making a single ridged cold mass. The cold mass is encased in the cryostat that provides the thermal insulation vacuum. The cryostat is then covered by an iron return yoke. A maximum magnetic field on the CS coils is about 5.8 T with an operation current of 2500 A. The load line curve of CS is shown in Figure 9.3. The critical temperature at the operating point is about 6.2 K.

9.1.5 Muon Transport Solenoids

The muon transport solenoid system consists of two bent solenoids (TS2 and TS4) and a straight solenoid (TS3) to connect TS2 and TS4. Only TS2 and TS3 are constructed in COMET Phase-I and TS4 will be constructed in COMET Phase-II. These solenoids bend the muon beam by 90 degrees each and transport the muon beam to the muon stopping section. The solenoids have an inner coil diameter of 460 mm to provide the space for the beam tube with an inner diameter of 360 mm. The bent sections are composed of a total of 32 (16 per section) short solenoids each of which is 200 mm long. A thin aluminum foil will be put at the end of TS3 as a radiation shield.



Figure 9.3: Critical current of aluminum stabilized superconductor as a function of temperature. The load line curve of CS1 is shown.

The transport section is designed in this way for the purpose of installation, calibration and to provide additional space for a muon beam monitor. A straight solenoid (TS5) about 1 m long follows the curved section connecting to the subsequent solenoid magnets in COMET Phase-II. The solenoids of TS1–TS3 (Phase-I) and TS1–TS5 (Phase-II) are connected in series and produce a field of about 3 T. In the bend solenoids, small $\cos \theta$ dipole coils are also wound in each solenoid bobbin to produce vertical field of about 0.03 T in TS2 and about 0.05 T in TS4, respectively. The main parameters of the TS coils are summarized in Table 9.3. The current density in TS1, which is made from Al-stabilized cable, should be same as the one in the Pion Capture Solenoid to avoid additional current leads, although the current density is not adjusted in this study.

A NbTi based copper stabilized conductor is suitable for use in the muon transport solenoids. This type of conductor is commercially available for the purpose of magnetic resonance imaging, and hence is cost-effective. The proposed conductor has a strand diameter of 1.5 mm and a copper-to-superconductor ratio of 6. The operation current of 200 A is chosen to give a critical temperature of about 6.8 K. The loadline of the operation point is shown in Figure 9.4.

Coil	Len	IR	OR	J	AT	B_{max}	
	[mm]	[mm]	[mm]	$[A/mm^2]$	[MAt]	[T]	
TS1a	210	250	266	62	0.208	3.46	Phase-I
TS1b	390	250	282	62	0.774		Phase-I
TS1c	310	250	298	62	0.923		Phase-I
TS1d	180	250	282	62	0.357		Phase-I
TS2-1	200	230	275	75	0.675	3.89	Phase-I
TS2-2 - TS2-15	200	230	279	75	0.735		Phase-I
TS2-16	200	230	259	75	0.435	3.65	Phase-I
TS3	600	400	447	75	2.115		Phase-I
TS4-1	200	230	259	75	0.435		Phase-II
TS4-2 - TS4-16	200	230	279	75	0.735		Phase-II
TS5a	200	230	272	75	0.630	3.40	Phase-II
TS5b	450	230	260	75	0.450		Phase-II
TS5c	460	230	255	75	0.375		Phase-II

Table 9.3: Design parameters of the TS coils



Figure 9.4: Critical current of copper stabilized superconductor as a function of temperature. The load line curve of TS is shown.

9.2 Magnetic Field Distribution With Iron Yokes

9.2.1 3-dimensional field calculation

A 3-dimensional field calculation is performed for the whole superconducting system in view of the future extension to COMET Phase-II. The structure and dimensions of the



Figure 9.5: Dimensions of the iron yokes for the COMET superconducting solenoid magnets.

magnetic iron yoke are shown in Figure 9.5. The total mass of about 510 tons of iron yoke is needed. The magnetic field distributions are calculated using a finite element analysis (FEM) package (Vector Field OPERA 14.0) with an iron yoke covering the whole magnet system.

The curved section of the TS is divided at the middle for installation, maintenance and calibration. To produce a smooth magnetic field across the solenoid magnets, a larger solenoid coil, TS3 is placed at the connection of TS2 between TS4. The layout of TS5 is tuned to extend the smooth magnetic field to the stopping target region which follows it.

The muon stopping target, made of aluminum foils, is installed inside the ST (Phase-II). Coils with gradually increasing radii generate a field gradient to send the signal electrons downstream. The field strength at the target is around 2 T. The field connection from the TS to the ST is optimized by tuning the coils of TS5. The Spectrometer Solenoid consists of a series of short solenoid coils arranged along the arc with a curvature of 3 m, generating 1 T field on axis. The length of the Detector Solenoid is determined to be 4.4 m in this design, although a longer coil can generate a more uniform field at the detector region in the magnet bore. The non-uniformity of the field is estimated to be approximately $\pm 12\%$

114



Figure 9.6: FEM modelling for the cross section of the solenoid magnet system.

in a cylindrical region 3 m in length and 1 m in diameter where the electron tracker is installed.

The field distribution in the CS and MS is optimized to peak at over 5 T at the pion production target and to connect smoothly to a 3 T magnetic field in TS. The coil geometry and electric current through the individual coils are tuned to avoid magnetic field bumps at the connections between neighboring coils, and to suppress field fluctuations to within 8% on the solenoid axis.

In particular, the following features need to be taken into consideration:

- smooth transitions of the magnetic field on the solenoid axis from the CS to TS,
- smooth transitions of the magnetic field on the solenoid axis from the TS to the ST, and
- a steep gradient to the magnetic field at ST2.

The modelling of the solenoid magnets in the FEM analysis are shown in Figs. 9.6. Coordinates are defined as follows: the origin is the location of the pion production target, and the horizontal plane is the x - y plane, and the z axis is determined to be along the vertical direction. The total stored energy is about 73.8 MJ.

9.2.2 Magnetic fields on the solenoid axis

Figure 9.7 shows the magnetic field distribution along the solenoid axes from CS to DS. Requirements described above are satisfied substantially.



Figure 9.7: Field distribution along the solenoid axis.

9.2.3 Magnetic Fields in Iron Yoke and Coil Surface



Figure 9.8: Magnetic field distribution along the solenoid axis.

The magnetic field distributions in the iron yoke have been estimated. These are shown in Figs. 9.8. They are mostly below the iron saturation level, except at two locations. One saturation location is at the middle of the TS, where the magnetic field is about 1.8 T,



Figure 9.9: Magnetic fields at the surface of the CS. Fields strengths are given in Tesla.

exceeding the iron saturation level. It would be difficult to thicken the iron yoke from the point of view of fabrication, but the leakage magnetic field from there is not large, so it can be concluded that it is not serious. The other location is at the end of the CS, where the maximum field is about 2.5 T. Again, the leakage magnetic field from that position is small. This can be further optimized by reducing the magnet diameter at that location, where the radiation shielding wall for the primary beam line is installed.

Coil	CS	MS1	MS2	TS1	TS2	TS3	TS4	TS5	ST1	ST2	ST3	\mathbf{SS}	DS
$B_{\rm max}$ [T]	5.74	3.97	3.88	3.46	3.89	3.65	3.89	3.40	3.15	2.13	1.48	2.03	1.66

The magnetic fields at the surface of the solenoid coils have also been estimated. They are shown in Figure 9.9. And the maximum magnetic fields in the coils are shown in Table 9.4. The maximum field in the CS coil is about 5.8 T for aluminum-stabilized super-conductors, whereas that in the TS4 is about 3.89 T for copper-stabilized superconductors.



Figure 9.10: Compressive stress distributions in CS0, CS1, MS1 and MS2 with support ribs in between coils.

9.3 Electromagnetic Forces With the Iron Yoke

9.3.1 Compressive electromagnetic force

Compressive electromagnetic forces in the axial direction are calculated. With the assumption that the coils that can be connected mechanically are grouped into one cluster, and the net electromagnetic force is calculated for each cluster

It is found that CS, MS1 and MS2 are subjected to a large electromagnetic force. In particular, the net force on the CS coil will be about 1000 tons. And those at MS1 and MS2 will be about 500 tons each to balance the CS. Besides these, the forces on the ST1, ST2 and DS coils will be about 100 tons. However, once CS, MS1 and MS2 are linked together mechanically to form one structure, the net electromagnetic force will be reduced to about 30 tons.

Regarding the electromagnetic forces that are perpendicular to the beam axis, the forces on each coil are not so large. However, at the curved sections, such as TS2, TS4 and SS, the forces add up and the radial component of the force will be non-zero, and could become significant, in particular for the case that the coils are connected together mechanically. In this case, a strong support structure for these coils may be required.

9.3.2 Hoop stress from electromagnetic forces

The average hoop stress (σ_h) is calculated by using the maximum magnetic field (B_{max}) on each coil. They are summarized in Table 9.5. The strength of the aluminum-stabilized superconductors, and the stress in the aluminum stabilizer is calculated based on the

Coil	IR [mm]	thickness [mm]	$B_{\rm max}$ [T]	σ_h [MPa]	$\sigma_{\rm Al}$ [MPa]
CS	650	144	5.74	59.2	56.1
MS1	650	80	3.97	51.0	48.3
MS2	650	128	3.88	30.4	28.9
TS1a	230	16	3.46	68.5	64.9
TS1b	230	32	3.46	34.2	32.5
TS1c	230	48	3.46	22.8	21.6
TS1d	230	32	3.46	34.2	32.5
TS2-1	230	45	3.89		30.8
TS2-2 to 2-15	230	49	3.89		28.2
TS2-16	230	29	3.89		47.7
TS3	230	47	3.65		25.9
TS4-1	230	29	3.89		47.7
TS4-2 to 4-16	230	49	3.80		28.3
TS5a	230	42	3.40		25.1
TS5b	230	30	3.40		35.2
TS5c	230	25	3.40		42.2
ST1-1	400	38	3.15		41.6
ST1-2	400	31	3.15		50.9
ST2-1	470	38	2.13		22.3
ST2-2	470	23	2.13		36.9
ST3	610	15	1.48		35.3
SS	750	33	2.03		37.2
DS	750	11	1.66		74.8

Table 9.5: Hoop stress in each coil.

assumption that the matrix ratio of Al : Cu : NbTi = 9.3 : 0.75 : 1, and the Young's modulus of $E_{\rm Al} = 70$ GPa and $E_{\rm Cu} = 110$ GPa and $E_{\rm NbTi} = 82$ GPa, and the equivalent stiffness of the superconductor would be $E_{\rm SC} = 73.8$ GPa.

The maximum stress allowed in the aluminum stabilizer can be calculated with the relationship:

$$\sigma_{\rm Al} = \sigma_{\rm h} \times \frac{E_{\rm Al}}{E_{\rm SC}}.\tag{9.1}$$

If we assume that the allowable stress of aluminum stabilizer is 33.3 MPa, which is 2/3 of the proof strength of aluminum stabilizer (50 MPa), the CS, MS1 and TS1a coils would have hoop stress larger than the allowed ones. Therefore it can be concluded that they might need additional support shell structure (of stainless steel).

120

9.4 Cryogenic System

9.4.1 Overview

The solenoids for the upstream section from the CS to TS3 are cooled using two-phase liquid helium provided by a high cooling power helium refrigerator. The liquid helium is circulated in pipes attached to the cold mass to remove a heat by conduction. Helium can be supplied to these solenoid magnets using a thermo-siphon system. The estimated heat loads are listed in Table 9.6 for COMET Phase-I, in which overall heat loads are 34 W, including dynamic heating by AC loss and nuclear heating assuming a few kW proton beam injection. The cooling power of a refrigeration of at least 70 W at 4.4 K is necessary in COMET Phase-I to preserve sufficient margin.

Heat loads in COMET Phase-II are estimated in Table 9.7. Nuclear heating by 50 kW proton beam injection is estimated to be 60 W by MARS simulation. Thus overall heat load in CS–TS3 is 88 W including dynamic heating by AC loss and nuclear heating. The refrigerator system for COMET Phase-II should be designed such that a thermal cycle to 10 K can be achieved in 6 hours for rapid monitoring of the RRR of the aluminum stabilizer. A thermal cycle to room temperature can be achieved in one week for an efficient start of the COMET experiment.

In COMET Phase-II, the coils for the downstream section from TS4 to the DS can be cooled using a number of GM cryocoolers. The estimated heat loads are listed in Table 9.7. A total heat load to the TS4 and TS5 coils that are contained in Cryostat-2 is estimated to be 4.6 W at 4 K, and 125 W on the radiation shield. A two-stage GM cryocooler of 1.5 W cooling power at 4 K will be sufficient to provide cooling for the coils. The six cryocoolers for Cryostat-2 will have a cooling power of 9 W at 4K and 210 W at 50K. Cryostat-3 needs 12 cryocoolers for a total cooling power of 18 W at 4K and 420 W at 50K.

Heat Load Item	4K	Shield
Static heat (CS,MS)	$14.4 \mathrm{W}$	$372 \mathrm{W}$
Static heat (TS1-TS3)	$4.3 \mathrm{W}$	$146 \mathrm{W}$
Static to transfer tube etc. (tentative)	$4 \mathrm{W}$	$80 \mathrm{W}$
AC loss at ramp up (tentative)	$4 \mathrm{W}$	$1 \mathrm{W}$
Nuclear heating	$< 10 \mathrm{W}$	$10 \mathrm{W}$ (tentative)

Table 9.6: Estimated heat loads in COMET Phase-I.

9.5 Influence of Irradiation (COMET Phase-II)

In COMET Phase-II with a proton beam power of 50 kW, the coil is subjected to a large amount of radiation, although thick tungsten absorber is inserted between the proton target

Heat Load Item	4K	Shield
Static heat (CS,MS)	14.4 W	$372 \mathrm{W}$
Static heat (TS1-TS3)	$4.3 \mathrm{W}$	$146 \mathrm{W}$
Static heat (TS4,TS5)	$3.6 \mathrm{W}$	$125 \mathrm{W}$
Static heat (ST-DS)	$11.0 \mathrm{W}$	$335 \mathrm{W}$
Static to transfer tube etc. (tentative)	$4 \mathrm{W}$	$80 \mathrm{W}$
AC loss at ramp up (tentative)	$7 \mathrm{W}$	$1 \mathrm{W}$
Nuclear heating	$60 \mathrm{W}$	$60 \mathrm{W}$ (tentative)

Table 9.7: Estimated heat loads in full COMET.

and the coils. The heat loads to the coil caused by radiation are estimated to be 45 W in CS coils, and exceed 60 W overall.

The neutrons can produce tritium in the coolant helium as well as heat deposits inside the coil. To reduce the amount of tritium produced by irradiation, a conduction cooling scheme is adopted to cool down the coils instead of liquid helium bath cooling. As shown in Figure 9.11, the induced heat is removed by aluminum strips installed in between coil layers. The strips carry heat to cooling pipes attached either to the coil ends or outer support cylinder. Since neutron irradiation can degrade the thermal conduction in aluminum strips, the cooling scheme must be examined carefully.

The temperature gradient in the CS coil is estimated through analytical calculations assuming uniform heat distribution of 60 W in the CS coil. The heat is transferred along the solenoid axis to both coil ends, where the aluminum strip is anchored to the liquid helium piping. In case 0.5 mm thick aluminum strips has good thermal conduction, $\lambda = 4000$ W/m-K, the estimated temperature gradient from the center to the end is 0.36 K. If the thermal conduction is degraded by neutron irradiation by one order (i.e. $\lambda = 400$ W/m-K), the temperature gradient could deteriorate to a level that can affect magnet stability. Therefore the current design employs aluminum strips of 2 mm thickness, resulting in temperature gradients in the coil that are adequately small, to about $\Delta T = 0.9$ K in the worse case.

Radiation damage to the coil material is also a critical issue. The maximum lifetime of the coil under a fast neutron flux environment is estimated to be about 6×10^{20} neutrons/m². This is because fast neutrons can degrade the RRR of aluminum stabilizer.

The irradiation effects in the electrical properties of aluminum stabilizer has been studied by the reactor neutrons at KUR as described in Appendix B. It is reported that degradation starts to be observed at 10^{20} neutron/m² and it reaches 1/10 at 2×10^{22} neutron/m² according to an estimation. Figure 9.21 indicates that RRR degradation of about 1/10 (RRR of 50) gives a maximum temperature rise to 150 K which is still acceptable, while degradation of 1/100 (RRR of 5) gives a maximum temperature rise above 300 K which is not acceptable anymore. This estimation indicates that the neutron flux of 2×10^{21} neutron/m² is the critical value for solenoid quench protection.



Figure 9.11: Coil structure with aluminum strips for heat removal in the CS.

Nevertheless it is reported and actually we confirmed in our own tests that the RRR degradation can be recovered through thermal cycling to room temperature. This means that in addition to careful protection of neutron radiation on the coil, the solenoid should be thermally cycled to the room temperature for safe operation, before significant degradation is observed. Although we need careful investigations of the behavior of materials under the operating condition of the superconducting magnet, the degradation may be detected by warming up the solenoid to about 10 K and measuring the conductivity of the cable. This can minimize and optimize the thermal cycle period without heating the system to the room temperature.

9.6 Cryostat Design

9.6.1 Overview

The cryostat for the solenoid magnet system can be separated into 3 parts. The first part is from the CS to TS3, which will be built for COMET Phase-I. The second part is from the middle of the TS to the ST. The third part is the ST to the DS, which will be included in the full COMET. Overview of the cryostat is shown in Figure 9.12.



Figure 9.12: A schematic view of the superconducting solenoid magnet system.

The upstream part of the magnet system from the CS to TS3 will be installed inside the radiation shielding wall for the primary proton beamline. The first cryostat contains the CS, MS and the first half of the TS. Those coils are cooled with liquid helium to remove the higher heat load caused by radiation from the pion production target. The remainder is designed to be refrigerated by GM cryocoolers for easy operation and maintenance. Here, since the curved section of the TS is split at the middle, it is easier to install the later half of the TS coil for installation, maintenance and calibration purposes. The main parameters of the cryostat are summarized in Table 9.8.

The design of the whole cryostat system is described here in view of the future extension. As described before, the overall system is divided into three cryostats. They are presented in Table 9.9. In the following, the design for each cryostat and its cooling are presented.

123

Item		Value	comments
Cryostat-1			
Weight	Total mass	264 tons	
	Yoke mass	234 tons	
	Magnet	30 tons (16.6 tons in 4K)	
Heat Load	4K	27.7 W +nuclear heating 60 W	for 50 kW beam
	Shield	768 W	
Refrigeration	4K	LHe conduction cooling	
	Shield	GHe conduction cooling	
Current		2500 A (CS-MS)	
		4400 A (TS1)	
		200 A (TS2-TS3)	
Cryostat-2			
Weight	Total	46 tons	
	Yoke	35 tons	
	Magnet	10.2 tons (5.8 tons in 4K)	
Heat Load	4K	4.6 W	
	Shield	125 W	
Refrigeration		GM Cryocooler conduction cooling	
Current		200 A (solenoid)	
		200 A (dipole)	
Cryostat-3			
Weight	Total	204 tons	
	Yoke	170 tons	
	Magnet	33.3 tons (18.8 tons in 4K)	
Heat Load	4K	12.0 W	
	Shield	335 W	
Refrigeration		GM Cryocooler conduction cooling	
Current		400 A (solenoid)	
		400 A (dipole)	

Table 9.8: Main parameters for the SC magnet cryostats.

The coils of aluminum-stabilized superconductors in Cryostat-1 are cooled by a high power refrigerator since they might have large heat loads, including radiation heating. Cryostat-2 and Cryostat-3 can be cooled by a small refrigerator such as a GM-cryocooler, and an indirect thermal contact cooling will be adopted.

crvostat coils cooling comments $\overline{\mathrm{CS}}$ Cryostat-1 LHe refrigerator inside the concrete shielding MS LHe indirect cooling (4K)(in the radiation control area) $TS1 \sim TS3$ GHe indirect cooing (shield) space for beam monitors $TS4 \sim TS5$ Cryostat-2 indirect cooling outside the concrete shielding GM cryocooler movable for maintenance space for beam monitors Cryostat-3 STindirect cooling outside the concrete shielding SSGM cryocooler movable for maintenance DS

Table 9.9: COMET Cryostats

9.6.2 Cryostat-1

The conceptual layout of Cryostat-1 is shown in Figure 9.13. It includes the coils from CS to TS3 in one cryostat. The cryostat vacuum for superconducting coils and the vacuum for the proton beam line will be separate and independent. The proton beam line penetrates Cryostat-1 from the upstream end to the downstream end. Cryostat-1 is cooled by a liquid helium refrigerator, and a chimney for the electric current lead and cooling pipes is placed on Cryostat-1 and is connected to the control dewar that is located near Cryostat-1. The proton target and the radiation shielding for the superconducting coils will be placed inside the warm bore of the CS. However, for TS1, TS2 and TS3, an inside bore for a beam is cold (namely using a cold bore).

The proton target and the radiation shielding are located in the same vacuum region, which is a separate vacuum region as described before. The radiation shielding will be installed from the downstream end (towards the proton beam dump). The outer wall of the radiation shielding will also serve the inner wall of the CS coil bore, and therefore a pillow seal will be used to make Cryostat-1 vacuum tight. A detailed design study will be needed since the structure design depends on the total mass of the radiation shielding and its support structure, etc.

The coils for CS0, CS1, MS1 and MS2 are linked together with aluminum supports as a single body. This entire structure can be supported from the vacuum vessel. The coils are indirectly cooled by helium supplied by the pipes from the chimney. The radiation shield is also indirectly cooled by helium gas from a refrigerator. Aluminum can be used to make thermal contact with the cooling pipe for this indirect cooling.

The specifications Cryostat-1 cooling are summarized in Table 9.10.



Figure 9.13: Conceptual layout of Cryostat-1.

9.6.3 Cryostat-2

The conceptual layout of Cryostat-2 is shown in Figure 9.14. It has a separate vacuum structure from those of Cryostat-1 and Cryostat-3. The muon beam vacuum is common with those of Cryostat-1 and Cryostat-3. However, the option to have a separate vacuum from Cryostat-1 and Cryostat-3 could be preserved so that a beam monitor can be installed at a later point. Feedthroughs for signal and power cables for the beam monitor system should be prepared at the entrance and exit ends of Cryostat-2. Similarly, vacuum manifolds can be located at the same locations. Cryostat-2 is indirectly cooled by GM-cryocoolers. A port for cooling and electric current leads is attached at the middle of the 90° bending section of Cryostat-2. The beam bore of Cryostat-2 is a cold bore.

9.6.4 Cryostat-3

The conceptual layout of Cryostat-3 is shown in Figure 9.15. Two ports for cooling and electric current leads are attached at the middle of the 90° bending section of Cryostat-3. The beam bore of Cryostat-3 is a cold bore. Inside the cold bore of Cryostat-3, a beam blocker, a DIO blocker and detectors will be installed, and special consideration might be needed.

Quantity	Parameters	Value	Comments
Total length		11.8 m	
Cooling method	4K shield	LHe indirect cooling	refrigerator
	radiation shielding	GHe indirect cooling	
Conductor	CS, MS and TS1	Al-stabilized NbTi/Cu	
	TS2 and TS3	Cu-stabilized NbTi/Cu	
Electric current	CS and MS	2500 A	
	TS1	4400 A	
	TS2,TS3 solenoid	200 A	
	TS2,TS3 dipole	200 A	
Mass	total	264 tons	
	yoke	234 tons	
	coils	30 tons	
	4 K	16.6 tons	
Heat load	$4\mathrm{K}$	27.7 W + 60 W	for 50 kW beam
		(nuclear heating)	
	shield	768 W	

Table 9.10: Cooling specifications for Cryostat-1

9.7 Mechanical Analysis of Cryostats and Coil Supports

9.7.1 Mechanical Analyses

The mechanical strengths of the support structure for Cryostat-1 are estimated by employing Finite Element Methods (FEM), taking into account atmospheric pressure and electromagnetic forces. Analysis for Cryostat-3 is also performed as reported in a report [93]. The structure for Cryostat-1, including the vacuum vessel and the coil winding structure, and their supports, is shown in Figure 9.16. The mandrels of CS and MS are to be made of aluminum to reduce nuclear heating and to match the Al-stabilized conductor. All support rods between the cryostats and the coil mandrels are assumed to be GFRP.

The analysis modelling for Cryostat-1 is shown in Figure 9.17. The parameters for the material properties used in the mechanical analysis are shown in Table 9.11. To evaluate the mechanical strength of the cryostats, electromagnetic forces and forces from atmospheric pressure are considered. The electromagnetic forces that have been calculated in three dimensions with the iron yokes are used for each coil support and mandrels. A uniform pressure from atmospheric forces of 0.1 MPa is applied to all outside surfaces of the vacuum vessels. The cryostat is fixed to the floor.



Figure 9.14: Conceptual layout of Cryostat-2.

Table 9.11.	Materials	properties	for N	Mechanical	Analysis
14010 9.11.	Materials	properties	101 1	victuanitai	Analysis

	Materials	Young	Poisson
		ratio	ratio
vacuum vessels	stainless steel	200	0.3
coil winding mandrel (Cryostat-1)	aluminum	61	0.3
support between vacuum vessel and mandrel	glass epoxy	71	0.3
support between mandrels	stainless steel	200	0.3

9.7.1.1 Distortion of the vacuum vessels

Figures 9.18 shows the distortions to the vacuum vessels for Cryostat-1. The maximum distortion is about 0.65 mm, which is within an allowable range.

9.7.1.2 Von Mises stress of the vacuum vessels

The von Mises stresses on the cryostats of Cryostat-1 is estimated as shown in Figure 9.19. The maximum magnitudes of von Mises stress are 39 MPa. Both of them are well below the yield strength of stainless steel.



Figure 9.15: Conceptual layout of Cryostat-3.

9.7.1.3 Distortion of coil support structure

Distortions of the coil winding structures of the CS and MS in Cryostat-1 are calculated based on the model described above, as shown in Figure 9.20. The maximum distortion is 2.7 mm, which is observed in MS2. The axial force on the support rod is estimated to be less than 49 kN, and the maximum stress is 69 MPa assuming the cross section of 706.5 mm².

9.7.2 Results of Mechanical Strength

From the mechanical analysis shown above, the following conclusions can be made. The vacuum vessel for Cryostat-1 is sufficiently strong against distortions from electromagnetic forces and forces from atmospheric pressure. Von Mises stresses are found to be within the tolerance for the construction materials. Therefore, it can be concluded that the present design of Cryostat-1 is adequately strong. The coil mandrel undergoes a displacement of about 2.7 mm, which is quite large. Some optimization of the support arrangement and the number of coil supports will be needed. The axial stress on the coil support is within the materials' tolerance.



Figure 9.16: Cryostat structure of Cryostat-1.



Figure 9.17: FEM mechanical analysis model of Cryostat-1 (left) and its cross section (right)

9.8 Quench protection

Quench protection for the solenoid is provided mainly by an external dump resister system. The dump resistor will be set to 0.1 Ohm that gives maximum terminal voltage of 400 V during discharge. The inductance of the solenoid is about 2 H, which results in a discharge time constant of 20 sec.

The temperature increase in the conductor is estimated using the integral of current squared $(MIITs)^1$ as is shown in Figure 9.21 with the various residual resistances of aluminum stabilizer (RRR). The cable considered in this calculation is assumed to have alu-

¹MIIT is a time-integral of current squared and given by Mega I (current) \times I (current) \times T (time).



Figure 9.18: Mechanical distortions of the vacuum vessel for Cryostat-1, showing the outer surface (top) and cross section (bottom)

minum RRR of about 500. The time constant defined by the protection dump circuit of 20 sec will give MIITs of 160. The resultant maximum temperature in the coil is about 100 K. There will also be normal zone resistance in the coil that will enhance the current dumping. The maximum temperature is thus further reduced.

The quench protection for the solenoid system is engaged by protection heaters attached to the solenoid coil. As shown in Figure 9.22, the heaters are connected in series with a protection dump circuit. The system is designed to achieve a dumping time constant of 20 sec.



Figure 9.19: Von Mises stress of the vacuum vessel of Cryostat-1 (CS-MS).



Figure 9.20: Distortions of the coil structure for CS and MS in Cryostat-1.



Figure 9.21: Temperature increase in the aluminum stabilized superconductor. The curves are, from top to bottom, for aluminum with RRR=500, RRR=50, and RRR=5.

134

CHAPTER 9. SUPERCONDUCTING SOLENOID MAGNETS



Figure 9.22: The quench protection scheme for the transport solenoids.

Chapter 10 Infrastructure

This chapter describes the necessary infrastructure for COMET Phase-I. To start up the experiment promptly and derive valuable results, we propose the construction of the proton beamline, pion production and collection system, muon transport solenoid up to first 90 degree bend, proton beam dump, and the experimental area as a J-PARC facility. Construction will be a in cooperative effort between the facility and the experimental collaboration. It is important to deal with necessary utilities such as electricity and cooling water to cover future upgrades of the experiment.

10.1 Primary Proton Beam line

Figure 10.1 shows a schematic of the proposed beam line configuration. The primary proton beam for COMET Phase-I is extracted from the MR and transported through the beam switch yard area. In the switch yard area a new primary line (B line, shown in orange in Figure 10.1) will be branched from the existing primary line (A line). The B line is used to transport the primary beam both to the high-momentum beam line (shown in yellow in Figure 10.1) and the COMET beamline (shown in orange in Figure 10.1). A switching magnet will be installed to control the beam destination between the high-momentum beam line and COMET beam line. The COMET beam line will transport and focus the 8 GeV pulsed proton beam onto the pion production target located in the COMET Experimental hall. The high-momentum beam line, COMET beam line, and the upstream primary line that is shared by these two lines will be newly constructed in the medium term together with their beam dumps.

10.2 Experimental Area

The existing beam line is located 3.7 m below ground level, and the COMET beam line will be constructed at the same height. This means that the experimental area needs to accommodate this configuration for the set-up to be installed at the same height. It is also necessary to prepare a cooling water service dedicated for the use in high-radiation



Figure 10.1: Schematic view of the primary beam line in the nuclear and particle physics experimental hall. A new primary beam line, B line shown in orange, will be branched from the existing A line. High-momentum beamline shown in yellow and COMET beam line shown in orange will share the upstream primary line.

environment. For this purpose a service room will be constructed at the same level of the experiment floor.

The ground floor space of the experimental area will be used for utility installations such as a refrigerator, cooling tower, and magnet power supplies. A helium compressor will be installed in a separate cabin constructed 12.8 m away to the west of the COMET experimental hall. Access areas will be prepared to install equipment on the beam line floor.

Necessary equipment for controlling and monitoring apparatus should be located in the vicinity of this. We plan to construct an upper floor for this purpose. Figure 10.2 shows a conceptual view of the beam line floor and COMET experimental hall. Figure 10.3 shows a conceptual view of the cross section of the COMET experimental hall. A crane with a lifting height of 6 m will be install on the ground floor.

Figure 10.4 shows a layout of the COMET experimental hall. Taking into account all necessities for operation and maintenance, we need a floor space of $18.5 \times 30 \text{ m}^2$. A layout in the compressor cabin is schematically shown in Figure 10.5. Compressed helium is supplied through pipes both to the COMET experimental hall and equipments installed in the NP hall.



Figure 10.2: Conceptual view of the COMET beam line floor (left) and experimental hall building (right). The building will be constructed as an annex of the existing hall building.



Figure 10.3: Conceptual view of the cross section of the COMET experimental hall.

10.3 Electricity and Cooling Water

We estimate here the necessary electricity for the proton beam transport magnets, the pion capture solenoid and its refrigerator, the muon transport solenoid, the detector solenoid,



Figure 10.4: Layout in the COMET experimental hall.



Figure 10.5: Layout in the compressor cabin and compressed helium supplying lines to the COMET hall and NP hall.

CHAPTER 10. INFRASTRUCTURE

Table 10.1: Power requirements. External extinction devices and GM-type refrigerators will not be installed in COMET Phase-I but are included here considering the possibility of upgrades in the future.

Equipment	Power (MW)
Beam transport magnets	0.2
External extinction devices	0.2
Solenoid magnets	0.12
He refrigerator	0.12
GM-type refrigerators	0.2
Vacuum pumps	0.1
Detectors Electronics	< 0.02
DAQ system	< 0.02
Front-end computers	< 0.02
Total	1.0

Table 10.2: Cooling water requirements. The requirements for GM-type refrigerators are included for as they will be needed in any future upgrades.

Equipment	Cooling water (ℓ/\min)
Magnets and extinction devices	400
Helium refrigerator compressor	180
GM-type refrigerator compressors	100

and the detector components. In Phase-I, only a part of muon transport solenoid is constructed and no spectrometer curved solenoid; however considering future upgrades we provide estimates for all possible configuration options. In addition to this, as described in COMET CDR [78], the COMET experiment may need to install an external-extinction device for improving the beam extinction factor. In these estimates, the necessary electricity for external beam extinction is also included. Table 10.1 summarizes the estimated required electric power. In total 1.0 MW is needed to power the full configuration.

Cooling water is needed for the beam line magnets and related equipment and the helium refrigerator compressor for supplying liquid helium to the solenoid magnet. As in the case of electricity, cooling water for GM-type refrigerators is included as this will be needed in a future upgrade. Table 10.2 summarizes the necessary amount of cooling water. Here we assume a cooling water temperature of 25-30 °C and pressure of 7kg/cm²-G.

Chapter 11 Cost and Schedule

11.1 Cost

Table 11.1 summarizes the cost estimate required to initiate COMET Phase-I. We expect that the budget request for the J-PARC mid-term plan will cover the building for the COMET experimental hall, the primary proton beam and its beam dump, the pion capture solenoid and muon transport solenoid magnets, radiation shielding for 3 kW operation, and beam line installation. We are also expecting the J-PARC project budget further to complete installations. We will likely be able to reuse existing equipment such as power supplies for the superconducting magnets and a refrigerator system to maximise cost reductions. The proton beam line magnets that were used at the KEK 12-GeV synchrotron will be also reused, but it may be that new magnets will be necessary for higher-power operation. The detector will be constructed with funding external to KEK. The experimental group will secure the financial resources needed for the detector.

11.2 Schedule

The technically-driven schedule for COMET Phase-I is shown in Table 11.1. Currently we are expecting to start construction in 2013, first by starting superconducting wire production, which is estimated to take one year. Technical design work of superconducting magnets will proceed to allow the timely start of construction after wire production. Magnet construction is estimated to take two years including all necessary testing, followed by installation and engineering runs on-site. The construction of the experimental area be started early in Japanese fiscal year (JFY) 2013 and be completed in JFY 2015. The beam line construction schedule is expected not to conflict with the operation of other beam lines. The construction schedule for the high-momentum beam line is an important consideration. Currently this is scheduled for JFY 2015–2016. As explained in the previous section, detector constructions is dependent on external funding outside KEK and is not guaranteed yet. However we plan to construct all components to be ready in time for the start of the experimental engineering run scheduled in JFY 2016.

CHAPTER 11. COST AND SCHEDULE

Table 11.1: Cost estimate for COMET Phase-I in Oku (= 10^8) Japanese yen.	Additional
funding is required to upgrade to the final COMET Phase-II configuration.	

		Budget	KEK	External	Optional	Future	Comments
		request	internal	funding		funding	
Building		8.0					
Beam		1.0	0.5				
dump							
SC		8.0					to first 90° bend
magnet						20.0	remaining beam line
	W shield					2.0	for higher power
Power					2.0		if purchased
supply			0.5				installation
						2.5	for upgrade
refrig-					2.0		if constructed
erator			0.5				installation
Beam	magnet		0.5				installation
line						5.0	for higher power
	piping	0.3	0.3				
	cabling	0.6	0.6				
	vacuum	0.6	0.6				
Radiation	NP-hall	1.5					for 3 kW operation
shielding						6.5	for high power
Safety			0.5				
π target				0.8			experimental group
Detector	magnet		0.5	0.5			for Phase-I
	μ target			0.1			experimental group
	μ monitor			1.5			experimental group
	tracker			1.1			experimental group
	ECAL			1.6			experimental group
	CR veto			5.7			experimental group
	DAQ			0.5			experimental group
Total		20.0	4.5	11.8	4.0	36.0	72.3+4.0



Figure 11.1: Technically-driven schedule for COMET Phase-I.

142

Chapter 12 Summary

This experimental proposal for COMET Phase-I presents the first part of the staged construction of the COherent Muon to Electron Transition (COMET) experiment which will search for coherent neutrinoless conversion of muons to electrons (μ^--e^- conversion).

To realize this staged approach, we would like to construct the COMET proton beamline and the COMET muon beamline up to the end of the first 90° bend so that a muon beam can be extracted to the experimental area of the J-PARC NP experimental hall.

Firstly, with COMET Phase-I we would like to make a direct measurement of the proton beam extinction and other potential background sources for the full COMET experiment, using the actual COMET beamline. The direct measurement of potential background sources will be vital for the COMET experiment. The current background estimates are made by extrapolating existing measurements over four orders of magnitude and uncertainties are therefore difficult to quantify and are potentially large. However, once the partial muon beamline is completed, it will be possible to make realistic background estimations using direct measurements. Based on these, the final design of the COMET beamline and detectors will be optimized and uncertainties on the background estimations minimized. This will significantly enhance the ultimate sensitivity of the COMET experiment.

Secondly, we would like to carry out a search for $\mu^- - e^-$ conversion with a singe-event sensitivity of better than 3.1×10^{-15} which is a factor of 200 better than achieved by SINDRUM-II.

Ultimately, with the completion of the rest of COMET beamline and detector, we intend to carry out the full COMET experiment (COMET Phase-II) to achieve a singleevent sensitivity of 3×10^{-17} . Additionally, there is physics potential at COMET Phase-I to carry out other important CLFV searches, such as $\mu^- + Al \rightarrow e^+ + Na$ and $\mu^- + e^- \rightarrow e^- + e^-$ in a muonic atom. The proposed staged approach will produce valuable scientific outcomes *at each phase* and the physics impact of our CLFV search in COMET Phase-I will be significant.

In summary, we believe that the physics case made by the COMET Phase that is presented here for the staged approach of the COMET experiment is extremely strong, and that it is aligned with the proposed J-PARC mid-term plan for the construction of the
CHAPTER 12. SUMMARY

COMET beamline. We are hoping to start construction in 2013 and carry out measurements in 2016.

Bibliography

- W. Bertl et al., "A search for μ-e conversion in muonic gold," The European Physical Journal C - Particles and Fields 47 (2006) 337-346.
 http://dx.doi.org/10.1140/epjc/s2006-02582-x. 10.1140/epjc/s2006-02582-x.
- [2] **MECO Collaboration**, Bachman M, "A Search for $\mu^- N \to e^- N$ with Sensitivity Below 10⁻¹⁶, **M**uon **E**lectron **CO**nversion," *a research proposal to Brookhaven* National Laboratory AGS.
- [3] S. Neddermeyer and C. Anderson, "NOTE ON THE NATURE OF COSMIC RAY PARTICLES," *Phys. Rev.* 51 (1937) 884–886.
- [4] H. Yukawa, "On the interaction of elementary particles," *Proc. Phys. Math. Soc. Jap.* 17 (1935) 48–57.
- [5] W. Heitler, "On the Stopping of fast particles and on the creation of positive electrons," *Proc.Roy.Soc.Lond.* A166 (1938) 529.
- [6] L. W. Nordheim, "Lifetime of the Yukawa Particle," *Phys. Rev.* 55 (Mar, 1939) 506-506. http://link.aps.org/doi/10.1103/PhysRev.55.506.
- S. Sakata and T. Inoue, "On the Correlations between Mesons and Yukawa Particles," *Progress of Theoretical Physics* 1 no. 4, (1946) 143–150. http://ptp.ipap.jp/link?PTP/1/143/.
- [8] Y. Tanikawa Prog. Theor. Phys. 2 (1947) 220.
- [9] M. Conversi, E. Pancini, and O. Piccioni, "ON THE DISINTEGRATION OF NEGATIVE MESONS," *Phys. Rev.* 71 (1947) 209–210.
- [10] B. Pontecorvo Phys. Rev. 72 (1947) 246.
- [11] E. P. Hincks and B. Pontecorvo Phys. Rev. 73 (1947).
- [12] J. Steinberger Phys. Rev. **74** (1948).
- [13] A. Lagarrigue and C. Peyrou Acad. Sci. Paris, C. R. 234 (1952).
- [14] S. Lokonathan and J. Steinberger Phys. Rev. 98 (1955).

- [15] J. Steinberger and H. B. Wolfe *Phys. Rev.* **100** (1955).
- [16] K. Nishijima *Phys. Rev.* **108** (1957) .
- [17] J. Schwinger Ann. Phys. 2 (1957).
- [18] G. Danby et al. Phys. Rev. Lett. 9.
- [19] Z. Maki, M. Nakagawa, and S. Sakata, "Remarks on the unified model of elementary particles," *Prog. Theor. Phys.* 28 (1962) 870–880.
- [20] M. Kobayashi and T. Maskawa, "CP Violation in the Renormalizable Theory of Weak Interaction," Prog. Theor. Phys. 49 (1973) 652–657.
- [21] MEG Collaboration, J. Adam *et al.*, "New Limit on the Lepton-Flavor-Violating Decay $\mu^+ \rightarrow e^+\gamma$," *Phys. Rev. Lett.* **107** (Oct, 2011) 171801. http://link.aps.org/doi/10.1103/PhysRevLett.107.171801.
- [22] U. Bellgardt *et al.*, "Search for the decay $\mu^+ \rightarrow e^+e^+e^???$," *Nuclear Physics B* **299** no. 1, (1988) 1 6. http://www.sciencedirect.com/science/article/pii/0550321388904622.
- [23] P. Wintz in Proceedings of the First International Symposium on Lepton and Baryon Number Violation, H. K. Kleingrothaus and I. Krivosherina, eds. 1998.
- [24] L. Willmann *et al.*, "New Bounds from a Search for Muonium to Antimuonium Conversion," *Phys. Rev. Lett.* 82 (Jan, 1999) 49-52. http://link.aps.org/doi/10.1103/PhysRevLett.82.49.
- [25] Belle Collaboration, K. Hayasaka *et al.*, "New search for $\tau \to \mu \gamma$ and $\tau \to e \gamma$ decays at Belle," *Physics Letters B* **666** no. 1, (2008) 16 22. http://www.sciencedirect.com/science/article/pii/S0370269308007673.
- [26] Belle Collaboration, K. Abe *et al.*, "Upper Bound on the Decay $\tau \to \mu \gamma$ from the Belle Detector," *Phys. Rev. Lett.* **92** (Apr, 2004) 171802. http://link.aps.org/doi/10.1103/PhysRevLett.92.171802.
- [27] BABAR Collaboration, B. Aubert et al., "Search for Lepton-Flavor Violation in the Decay τ⁻ → ℓ⁻ℓ⁺ℓ⁻," Phys. Rev. Lett. 92 (Mar, 2004) 121801. http://link.aps.org/doi/10.1103/PhysRevLett.92.121801.
- [28] P. Krolak *et al.*, "A Limit on the lepton family number violating process $\pi^0 \to \mu^{\pm} e^{\mp}$. FNAL-799 experiment," *Phys. Lett.* **B320** (1994) 407–410.
- [29] D. Ambrose *et al.*, "New Limit on Muon and Electron Lepton Number Violation from $K_L^0 \to \mu^{\pm} e^{\mp}$ Decay," *Phys. Rev. Lett.* **81** (1998) 5734–5737, arXiv:hep-ex/9811038.

- [30] A. M. Lee *et al.*, "Improved limit on the branching ratio of $K^+ \rightarrow \pi^+ \mu^+ e^-$," *Phys. Rev. Lett.* **64** (Jan, 1990) 165–168. http://link.aps.org/doi/10.1103/PhysRevLett.64.165.
- [31] K. Arisaka *et al.*, "Search for the lepton-family number violating decays $K_L \to \pi^0 \mu^{\pm} e^{\mp}$," *Phys. Lett.* **B432** (1998) 230–234.
- [32] R. Akers *et al.*, "Measurement of the $\tau^- \rightarrow h^- h^+ h^- \nu_{\tau}$ and $\tau^- \rightarrow h^- h^+ h^- \ge 1\pi^0 \nu_{\tau}$ branching ratios," *Zeitschrift für Physik C Particles and Fields* **68** (1995) 555–567. http://dx.doi.org/10.1007/BF01565256. 10.1007/BF01565256.
- [33] P. Abreu et al., "Search for lepton flavour number violating Z⁰-decays," Zeitschrift für Physik C Particles and Fields 73 (1997) 243-251. http://dx.doi.org/10.1007/s002880050313. 10.1007/s002880050313.
- [34] Super-Kamiokande Collaboration, Y. Fukuda *et al.*, "Evidence for Oscillation of Atmospheric Neutrinos," *Phys. Rev. Lett.* 81 (Aug, 1998) 1562–1567. http://link.aps.org/doi/10.1103/PhysRevLett.81.1562.
- [35] Super-Kamiokande Collaboration, S. Fukuda *et al.*, "Constraints on Neutrino Oscillations Using 1258 Days of Super-Kamiokande Solar Neutrino Data," *Phys. Rev. Lett.* 86 (Jun, 2001) 5656-5660. http://link.aps.org/doi/10.1103/PhysRevLett.86.5656.
- [36] T.-P. Cheng and L.-F. Li, "Muon-number-nonconservation effects in a gauge theory with V + A currents and heavy neutral leptons," *Phys. Rev. D* 16 (Sep, 1977) 1425–1443. http://link.aps.org/doi/10.1103/PhysRevD.16.1425.
- [37] B. W. Lee and R. E. Shrock, "Natural suppression of symmetry violation in gauge theories: Muon- and electron-lepton-number nonconservation," *Phys. Rev. D* 16 (Sep, 1977) 1444–1473. http://link.aps.org/doi/10.1103/PhysRevD.16.1444.
- [38] S. Petcov, "The Processes $\mu \to e\gamma, \mu \to e + e + \bar{e}, \nu' \to \nu + \gamma$ in the Weinberg-Salam Model with Neutrino Mixing," Sov. J. Nucl. Phys. **25** (1977) 340.
- [39] W. Marciano and A. Sanda, "Exotic decays of the muon and heavy leptons in gauge theories," *Physics Letters B* 67 no. 3, (1977) 303 305.
 http://www.sciencedirect.com/science/article/pii/037026937790377X.
- [40] S. Glashow, J. Iliopoulos, and L. Maiani, "Weak Interactions with Lepton-Hadron Symmetry," *Phys. Rev.* D2 (1970) 1285–1292.
- [41] A. Datta, K. Kong, and K. T. Matchev, "Discrimination of supersymmetry and universal extra dimensions at hadron colliders," *Phys. Rev. D* 72 (Nov, 2005) 096006. http://link.aps.org/doi/10.1103/PhysRevD.72.096006.

- [42] Y. Kuno and Y. Okada, "Muon decay and physics beyond the standard model," Rev. Mod. Phys. 73 (2001) 151–202, arXiv:hep-ph/9909265.
- [43] T. Yanagida in *Proceedings of the Workshop on Unified Theory and Baryon Number of the Universe*, Sawada and Sugimoto, eds. 1979.
- [44] M. Gell-Mann, P. Ramond, and R. Slansky, *Supergravity*. North-Holland, Amsterdam, 1979.
- [45] F. Borzumati and A. Masiero, "Large Muon- and Electron-Number Nonconservation in Supergravity Theories," *Phys. Rev. Lett.* 57 (Aug, 1986) 961–964. http://link.aps.org/doi/10.1103/PhysRevLett.57.961.
- [46] J. Hisano, T. Moroi, K. Tobe, M. Yamaguchi, and T. Yanagida, "Lepton-flavor violation in the supersymmetric standard model with seesaw-induced neutrino masses," *Physics Letters B* 357 no. 4, (1995) 579 - 587. http://www.sciencedirect.com/science/article/pii/037026939500954J.
- [47] J. Hisano and D. Nomura, "Solar and atmospheric neutrino oscillations and lepton flavor violation in supersymmetric models with right-handed neutrinos," *Phys. Rev.* D 59 (Apr, 1999) 116005. http://link.aps.org/doi/10.1103/PhysRevD.59.116005.
- [48] N. Haba, J. Sato, M. Tanimoto, and K. Yoshioka, "Possible flavor mixing structures of lepton mass matrices," *Phys. Rev. D* 64 (Nov, 2001) 113016. http://link.aps.org/doi/10.1103/PhysRevD.64.113016.
- [49] V. Cirigliano, R. Kitano, Y. Okada, and P. Tuzon, "On the model discriminating power of $\mu \rightarrow e$ conversion in nuclei," *Phys. Rev.* **D80** (2009) 013002, arXiv:0904.0957 [hep-ph].
- [50] N. Arkani-Hamed, A. G. Cohen, and H. Georgi, "(De)Constructing Dimensions," *Phys. Rev. Lett.* 86 (May, 2001) 4757–4761. http://link.aps.org/doi/10.1103/PhysRevLett.86.4757.
- [51] N. Arkani-Hamed, A. Cohen, E. Katz, and A. Nelson, "The Littlest Higgs," JHEP 0207 (2002) 034, arXiv:hep-ph/0206021 [hep-ph].
- [52] H.-C. Cheng and I. Low, "TeV symmetry and the little hierarchy problem," JHEP 0309 (2003) 051, arXiv:hep-ph/0308199 [hep-ph].
- [53] J. Hubisz, S. J. Lee, and G. Paz, "The Flavor of a little Higgs with T-parity," JHEP 0606 (2006) 041, arXiv:hep-ph/0512169 [hep-ph]. 29 pages, 7 figures.
- [54] M. Blanke *et al.*, "Charged Lepton Flavour Violation and (g-2)(mu) in the Littlest Higgs Model with T-Parity: A Clear Distinction from Supersymmetry," *JHEP* 0705 (2007) 013, arXiv:hep-ph/0702136 [hep-ph].

- [55] S. R. Choudhury *et al.*, "Lepton flavor violation in the little Higgs model with T parity," *Phys. Rev. D* 75 (Mar, 2007) 055011. http://link.aps.org/doi/10.1103/PhysRevD.75.055011.
- [56] F. del Águila, J. Illana, and M. Jenkins, "Precise limits from lepton flavour violating processes on the littlest Higgs model with T-parity," *Journal of High Energy Physics* 2009 no. 01, (2009) 080. http://stacks.iop.org/1126-6708/2009/i=01/a=080.
- [57] L. Randall and R. Sundrum, "Large Mass Hierarchy from a Small Extra Dimension," *Phys. Rev. Lett.* 83 (Oct, 1999) 3370-3373. http://link.aps.org/doi/10.1103/PhysRevLett.83.3370.
- [58] T. Appelquist, H.-C. Cheng, and B. A. Dobrescu, "Bounds on universal extra dimensions," *Phys. Rev. D* 64 (Jun, 2001) 035002. http://link.aps.org/doi/10.1103/PhysRevD.64.035002.
- [59] Y. Grossman and M. Neubert, "Neutrino masses and mixings in non-factorizable geometry," *Physics Letters B* 474 no. 34, (2000) 361 371. http://www.sciencedirect.com/science/article/pii/S037026930000054X.
- [60] T. Gherghetta and A. Pomarol, "Bulk fields and supersymmetry in a slice of AdS," *Nuclear Physics B* 586 no. 12, (2000) 141 - 162.
 http://www.sciencedirect.com/science/article/pii/S0550321300003928.
- [61] K. Agashe, A. E. Blechman, and F. Petriello, "Probing the Randall-Sundrum geometric origin of flavor with lepton flavor violation," *Phys. Rev. D* 74 (Sep, 2006) 053011. http://link.aps.org/doi/10.1103/PhysRevD.74.053011.
- [62] S. Matsumoto, J. Sato, M. Senami, and M. Yamanaka, "Solving cosmological problem in universal extra dimension models by introducing Dirac neutrino," *Physics Letters B* 647 no. 56, (2007) 466 - 471. http://www.sciencedirect.com/science/article/pii/S0370269307002389.
- [63] MEGA Collaboration, M. L. Brooks *et al.*, "New Limit for the Lepton-Family-Number Nonconserving Decay μ⁺ → e⁺γ," *Phys. Rev. Lett.* 83 (Aug, 1999) 1521–1524. http://link.aps.org/doi/10.1103/PhysRevLett.83.1521.
- [64] O. U. Shanker, "High-energy electrons from bound muon decay," Phys. Rev. D25 (1982) 1847.
- [65] R. Watanabe, M. Fukui, H. Ohtsubo, and M. Morita, "Angular distribution of electrons in bound muon decay," *Prog. Theor. Phys.* 78 (1987) 114–122.
- [66] A. Czarnecki, X. Garcia i Tormo, and W. J. Marciano, "Muon decay in orbit: Spectrum of high-energy electrons," *Phys. Rev. D* 84 (Jul, 2011) 013006. http://link.aps.org/doi/10.1103/PhysRevD.84.013006.

- [67] D. Bryman, M. Blecher, K. Gotow, and R. Powers, "Search for the reaction $\mu^- + Cu \rightarrow e^+ + Co$," *Phys.Rev.Lett.* **28** (1972) 1469–1471.
- [68] A. Badertscher, K. Borer, G. Czapek, A. Fluckiger, H. Hanni, et al., "A SEARCH FOR MUON - ELECTRON AND MUON - POSITRON CONVERSION IN SULFUR," Nucl. Phys. A377 (1982) 406.
- [69] D. Bryman, E. Clifford, M. Leitch, I. Navon, T. Numao, et al., "SEARCH FOR mu e CONVERSION IN Ti," Phys. Rev. Lett. 55 (1985) 465.
- [70] S. Ahmad, G. Azuelos, M. Blecher, D. Bryman, R. Burnham, et al., "SEARCH FOR MUON - ELECTRON AND MUON - POSITRON CONVERSION," *Phys. Rev.* D38 (1988) 2102.
- [71] **SINDRUM II Collaboration.**, C. Dohmen *et al.*, "Test of lepton flavor conservation in $\mu \rightarrow e$ conversion on titanium," *Phys.Lett.* **B317** (1993) 631–636.
- [72] SINDRUM II Collaboration, W. Honecker *et al.*, "Improved limit on the branching ratio of $\mu \rightarrow e$ conversion on lead," *Phys. Rev. Lett.* **76** (1996) 200–203.
- [73] **Mu2e collaboration**, "Proposal to Search for $\mu^- + N \rightarrow e^- N$ with a Single Event Sensitivity Below 10⁻¹⁶ (Mu2e Experiment)," a research proposal to Fermilab (2008)
- [74] K. Babu and R. Mohapatra, "New vector scalar contributions to neutrinoless double beta decay and constraints on R-parity violation," *Phys. Rev. Lett.* **75** (1995) 2276–2279, arXiv:hep-ph/9506354 [hep-ph].
- [75] **SINDRUM II Collaboration**, J. Kaulard *et al.*, "Improved limit on the branching ratio of $\mu^- \rightarrow e^+$ conversion on titanium," *Phys.Lett.* **B422** (1998) 334–338.
- [76] M. Koike, Y. Kuno, J. Sato, and M. Yamanaka, "A new idea to search for charged lepton flavor violation using a muonic atom," *Phys.Rev.Lett.* **105** (2010) 121601, arXiv:1003.1578 [hep-ph].
- [77] T. Shibata and Y. Futo, "Production cross-section of antiprotons for the study of cosmic-ray propagation in the galaxy," Astropart. Phys. 29 (2008) 30–41.
- [78] **COMET Collaboration**, Y. G. Cui *et al.*, "Conceptual design report for experimental search for lepton flavor violating $\mu^- \rightarrow e^-$ conversion at sensitivity of 10^{-16} with a slow-extracted bunched proton beam (COMET),". KEK-2009-10.
- [79] M. Ikegami, "181 MeV acceleration at J-PARC LINAC," High Energy Physics News, JAHEP 25-4 (2007) 177–189.
- [80] M. Tomizawa et al., "Design of dynamic collimator for J-PARC Main Ring," in PAC07, Albuquerque, New Mexico, USA. 2007.

- [81] N. V. Mokhov and S. I. Striganov, "MARS15 overview," vol. 896, pp. 50-60. 2007. http://www.scopus.com/inward/record.url?eid=2-s2. 0-34248227478&partnerID=40&md5=45ccb7d322b71bbf1ac8a738eead3db2.
- [82] S. Agostinelli et al., "Geant4-a simulation toolkit," Nucl. Instrum. Meth. A623 no. 3, (2003) 250 303.
 http://www.sciencedirect.com/science/article/pii/S0168900203013688.
- [83] S. E. Sobottka and E. L. Wills, "Energy Spectrum of Charged Particles Emitted Following Muon Capture in Si²⁸," *Phys. Rev. Lett.* **20** (Mar, 1968) 596-598. http://link.aps.org/doi/10.1103/PhysRevLett.20.596.
- [84] E. V. Hungerford, "Comment on proton emission after muon capture," MECO Technical Note 034.
- [85] C. Höppner, S. Neubert, B. Ketzer, and S. Paul, "A novel generic framework for track fitting in complex detector systems," *Nucl. Instrum. and Meth* 620 no. 2-3, (2010) 518 525.
 http://www.sciencedirect.com/science/article/pii/S0168900210007473.
- [86] "Hamamatsu Photonics K.K.,". http://www.hamamatsu.com.
- [87] S. Ritt, R. Dinapoli, and U. Hartmann, "Application of the DRS chip for fast waveform digitizing," Nucl. Instrum. Meth. A623 no. 1, (2010) 486 – 488. http://www.sciencedirect.com/science/article/pii/S0168900210006091. jce:title¿1st International Conference on Technology and Instrumentation in Particle Physicsj/ce:title¿.
- [88] http://www.uniplast-vladimir.com.
- [89] "CPTA,". http://www.cpta-apd.ru.
- [90] E.Tarkovsky, "Performance of a scintillating strip detector with G-APD readout," Presented at 12th Vienna Conference on Instrumentation, VCI 2010, Vienna, February 15, 2010 (2010).
- [91] M. Goodrick, L. Hommels, R. Shaw, D. Ward, D. Bailey, et al., "Development of a modular and scalable data acquisition system for calorimeters at a linear collider," *JINST* 6 (2011) P10011, arXiv:1106.5863 [physics.ins-det].
- [92] J. E. Amaro, A. Lallena, and J. Nieves, "Radiative pion capture in nuclei: A Continuum shell model approach," *Nucl. Phys.* A623 (1997) 529–547, arXiv:nucl-th/9704022 [nucl-th].
- [93] **COMET Collaboration**, "COMET Progress Report, submitted to 13th J-PARC PAC,".

[94] M. Okada *et al.*, "Improvement of low-temperature irradiation facility at Kyoto University Reactor (KUR)," *Nucl. Instrum. and Meth.* A463 no. 12, (2001) 213 – 219. http://www.sciencedirect.com/science/article/pii/S0168900201005204.

Appendix A

χ^2 Function for Straw Tube Tracker Analysis

In the track fitting procedure for the straw tube tracker a χ^2 function described below is employed for minimization;

$$\begin{split} &\chi^2(p,\theta_x,\theta_y,x,y,\theta_{x,1}^{\mathrm{scat}},\theta_{x,2}^{\mathrm{scat}},\cdots,\theta_{x,n_{\mathrm{scat}}}^{\mathrm{scat}},\theta_{y,1}^{\mathrm{scat}},\theta_{y,2}^{\mathrm{scat}},\cdots,\theta_{y,n_{\mathrm{scat}}}^{\mathrm{scat}}) \\ &= \sum_{i=1}^{n_{\mathrm{det}}} \left(\frac{x_i - X(z_i;p,\theta_x,\theta_y,x,y,\theta_{x,1}^{\mathrm{scat}},\theta_{x,2}^{\mathrm{scat}},\cdots,\theta_{x,n_{\mathrm{scat}}}^{\mathrm{scat}},\theta_{y,1}^{\mathrm{scat}},\theta_{y,2}^{\mathrm{scat}},\cdots,\theta_{y,n_{\mathrm{scat}}}^{\mathrm{scat}})}{\sigma_x} \right)^2 \\ &= \sum_{i=1}^{n_{\mathrm{det}}} \left(\frac{y_i - Y(z_i;p,\theta_x,\theta_y,x,y,\theta_{x,1}^{\mathrm{scat}},\theta_{x,2}^{\mathrm{scat}},\cdots,\theta_{x,n_{\mathrm{scat}}}^{\mathrm{scat}},\theta_{y,1}^{\mathrm{scat}},\theta_{y,2}^{\mathrm{scat}},\cdots,\theta_{y,n_{\mathrm{scat}}}^{\mathrm{scat}})}{\sigma_y} \right)^2 \\ &+ \sum_{j=1}^{n_{\mathrm{scat}}} \left(\frac{\theta_{x,j}^{\mathrm{scat}}}{\sigma_{\theta}^{\mathrm{scat}}} \right)^2 + \sum_{j=1}^{n_{\mathrm{scat}}} \left(\frac{\theta_{y,j}^{\mathrm{scat}}}{\sigma_{\theta}^{\mathrm{scat}}} \right)^2 \end{split}$$

where X and Y are the expected x- and y-position of hit, σ_x and σ_y are the spatial resolution of detector, σ_x^{scat} and σ_y^{scat} are the root-mean square of the multiple scattering angle distribution. X and Y are the function of parameters defining the chain of partial helix: momentum (p), angles (θ_x, θ_y) , position (x, y) of the 1st helix and deflection angles θ_x^{scat} , θ_y^{scat} on successive super layers. The number of parameters to be fitted is $n_{\text{param}} = 5 + 2n_{\text{scat}}$, and the degrees of freedom (d.o.f) is $n_d = 5$.

Appendix B Neutron Irradiation Tests at KUR

All the components of the COMET experiment, such as the pion production target, the muon stopping target and the tracker are embedded in superconducting solenoids. The pions are captured in a 5 T solenoid magnet with a diameter of 1.3 m. The pion capture solenoid is designed to be as small as possible; however, thick shielding is necessary within the solenoid to avoid severe radiation from the target. Aluminum-stabilized NbTi superconducting wires are employed to reduce the cold mass and the energy deposited in it. A large neutron fluence of 10^{21} neutrons/m² is expected and so the damage to the aluminum stabilizer needs to be estimated carefully. A test experiment at the Kyoto University Research Reactor Institute (KURRI) has begun to estimate the irradiation effect on the resistivity of the aluminum stabilizer at low temperature.

The Kyoto University Reactor (KUR) at KURRI has a maximum thermal power of 5MW. A low-temperature irradiation facility (LTL) [94] is co-located with the reactor. Samples inserted in the sample-chamber located close to the reactor core are cryogenically cooled down to 10K-20K by a helium-gas loop. At 1MW operation, the maximum fast-neutron flux at the top of the sample chamber is approximately 9.5×10^{14} neutrons/m²/s corresponding to an integrated flux of 1.6×10^{20} neutrons/m² in a one week cycle (~46 hours). The fast-neutron flux estimate is confirmed by measuring the radioactivity induced in a Ni sample irradiated together with the aluminum sample.

The experiment was performed at KUR-LTL for two days commencing on 16 November 2010 with the thermal power of the reactor at 1 MW. The aluminum stabilizer of the superconductor manufactured by Hitachi Cable in JFY2009 was cut at KEK into a short pieces with dimensions of 1 mm \times 1 mm \times 70 mm as shown in Figure B.1. The aluminum stabilizer is made from pure aluminum with Cu and Mg additives. A four-wire method was used to measure the resistance employing a Keithley 6221 current source and a Keithley 2182A voltmeter. Polyimide-coated wires were attached at both ends of the sample as current feeds and voltage sensing wires were attached with an spacing of 45 mm on the sample by clamping with copper sleeves. Wires of length 9 m were used to reach the instrumentation placed beyond the surrounding radiation shielding. A current of 100 mA was fed into the sample. The polarity was changed at a frequency of 5 kHz and the measurements were averaged over 100 cycles. The temperature was measured using a CX-

APPENDIX B. NEUTRON IRRADIATION TESTS AT KUR

1050-SD CERNOX sensor, calibrated in the range of 4K to 325K. The sensor was covered with polyimide film and placed just behind the aluminum sample. The sensor measures the temperature of the helium gas environment and thus the sample temperature. The in-situ measurements were performed throughout the cool-down period, the irradiation period and the warm-up period.



Figure B.1: The aluminum sample cut from the aluminum stabilized superconductor.

Figure B.2 shows the temperature dependence of the sample's resistance measured during cool-down in the sample chamber without reactor operation. The resistance was measured to be 1.35 m Ω at room temperature and 3.0 $\mu\Omega$ at 10 K. The residual resistance ratio (RRR) of the sample agreed well with the specification from the superconductor manufacturer. After cooling down to 10 K, the reactor was turned on to a power of 1 MW. The resistance and the temperature changes during the irradiation are shown in Fig. B.3. The temperature jumped from 10 K to 12 K at the beginning due to radiation from the reactor core. During irradiation, the temperature gradually increased at a rate of 0.07 K/hr, probably due to heating of the environment surrounding the sample chamber, such as the cryostat wall. The sample resistance increased to 5.7 $\mu\Omega$ at 15.3 K after 46 hours of exposure. The resistance change due to the temperature rise is expected to be only 0.2 $\mu\Omega$ which is calculated using the temperature dependence measured during cool-down without irradiation, shown in Fig. B.2. From the resistance measurement at low temperature with a fast-neutron flux of about 1020 neutrons/ m^2 the neutron induced resistance is determined to be 2.5 $\mu\Omega$, which is comparable with the original residual resistance of the aluminum stabilizer.

After the irradiation, the cryogenics was turned off and the sample was warmed up in the chamber for half a day. The cryogenics was restarted to check the resistance after the thermal cycle to room temperature. Figure B.4 shows the history of the sample resistance and temperature during the warm-up and cool-down periods. The resistance reached 3.0

155

APPENDIX B. NEUTRON IRRADIATION TESTS AT KUR



Figure B.2: Resistance of the aluminum sample before irradiation as a function of temperature.

 $\mu\Omega$ after cool down thus showing that the sample recovers from the effect of irradiation after the thermal cycle.

First of all, we have to consider some guidelines on what level of deterioration for aluminum resistance at low temperature should be allowed. When RRR = 500, it is anticipated that the coil temperature will rise up to about 100 K after quenching. From the estimation shown in Figure 12.5 in the COMET Conceptual Design Report (CDR), when RRR becomes about 10 times worse at low temperature owing to neutron irradiation, the coil temperature will rise to 150 K after quenching. Discussions with experts on superconducting technology indicate that this temperature rise (of up to 150 K) is close to the maximum temperature acceptable.

Given the fact that degradation of resistance by a factor of 10 at low temperature is acceptable at best, we can estimate how much neutron irradiation this would correspond to, from the present measurements. It has been found that the resistance increases by about 83 % with neutron irradiation of 1.6×10^{20} neutron/m². Based on some extrapolations, neutron irradiation of 20×10^{20} neutrons/m² would cause RRR to be about 10 times worse. In our simulations using MARS, the pion capture solenoid coils would receive about 6×10^{20} neutrons/m² for the whole running period of COMET. This suggests that it might not be necessary to carry out the thermal cycle to warm the coil up to room temperature. Even when uncertainties are taken into account, one or two thermal cycles may be sufficient. In summary, for COMET experimental running, neutron damage to aluminum at low

APPENDIX B. NEUTRON IRRADIATION TESTS AT KUR



Figure B.3: Resistance and temperature of the aluminum sample during irradiation.

temperatures should not pose a problem, and frequent thermal cycles of the pion capture solenoid should not be required,



Figure B.4: Resistance and temperature of the aluminum sample during the thermal cycle to room temperature after irradiation.