# Report from the 15th Meeting of the Accelerator Technical Advisory Committee for the Japan Proton Accelerator Research Complex (J-PARC)

February 25 - 27, 2016
J-PARC Research Building
Tokai, Japan

## Introduction

The Accelerator Technical Advisory Committee (ATAC) for the J-PARC Project held its fifteenth meeting February 25 to 27, 2016, at the J-PARC Research Building in Tokai, Japan.

The ATAC members are: Alberto Facco (INFN), Roland Garoby (ESS), Simone Gilardoni (CERN), Alan Letchford (STFC), Subrata Nath (LANL), Akira Noda (NIRS), Michael Plum (ORNL), Thomas Roser (BNL, Chair), Jie Wei (MSU), Robert Zwaska (FNAL). All ATAC members attended to meeting.

The ATAC thanks the J-PARC management and staff for their hospitality during this meeting, and all the presenters for their excellent and comprehensive talks. The Committee also greatly appreciates that the J-PARC team has addressed all recommendations from the previous report.

The Committee is very impressed with the progress of the performance that the J-PARC accelerator complex has achieved over the last year. Unfortunately, difficulties with the MLF target prevented the new high intensity capabilities of the RCS of up to 1 MW of beam power to be used for the science program. New record performance of 394 kW beam power from the MR for the T2K neutrino experiment and 42 kW of slow extracted beam for hadron science was also achieved. The difficulty with the MLF target highlights the importance of optimizing the operation of the whole facility in order to maximize the science output. The committee commends J-PARC management for establishing international collaborations to address high intensity targetry issues.

The J-PARC facility is now on track to soon achieve the original performance goals of the J-PARC project. (MLF: 1MW, FX: .75MW, SX: 50 kW). The facility now needs to shift the main emphasis to reliable and stable facility operation. Based on a comprehensive reliability analysis the necessary strategies, procedures and hardware improvements and upgrades should be implemented to maximize the facility availability.

### R1: Develop a strategy to maximize facility availability and science output.

The committee was presented with various ways of exceeding megawatt and even multi-megawatt beam power. Before extensive studies are undertaken J-PARC should develop, together with the facility users, future performance goals.

**R2: Establish, in discussions with the user communities, their future needs for the J-PARC accelerators.**

**<u>J-PARC accelerator overview and projections:</u>**

The J-PARC accelerators have now approached their design intensities. The RCS has demonstrated 1 MW equivalent beam to the MLF and operated above 500 kW. The MR has delivered 394 kW to T2K, which is equivalent to more than 750 kW with the power supply upgrade. The MR has also delivered 42 kW to slow extraction and has started to explore higher powers. Now the facility has the opportunity to give more priority to reliability and stability to users in addition to achieving high intensity.

*RCS for MLF:*

- The RCS has provided up to 513 kW, and is ready for 1 MW, but the limitations of the MLF target has limited operations to 500 kW, and recently only 200 kW.
  - Recent operation has included two periods of continuous operation with beam power exceeding 500 kW. Each of these run periods was prematurely terminated by MLF target failures.
  - 753 hours of beam delivery were achieved out of 2,776 scheduled. The downtime was predominantly due to target issues.
  - 1 MW has been essentially demonstrated, but awaits a MLF target that can handle this beam power.
  - For the near term, operation may be limited to 200 kW until confidence is gained with the MLF targets. Further limits are possible in the near-term. The next target design is estimated to be valid to more than 800 kW. The MLF team is focused on providing stable and reliable beam to users before aggressively pursuing higher beam power.
  - Operations to the MLF are further impacted by a contamination problem in the helium refrigeration system. Downtime of ~ 25% (6 days out of 28) may be required to allow regeneration of the refrigerator system. The status of this system is not yet clear and is under continued investigation by the MLF team.
- 1 MW equivalent beam operation was demonstrated multiple times. An upgrade of the RF anode supply led to a significant reduction in losses caused by beam loading.
  - The most recent study produced a beam of $8.45\times10^{13}$ protons, an intensity equivalent to 1.014 MW operation.
  - The equivalent beam loss was less than 133 W (reduced from 300 W). This loss is far less than the collimator limit of 4 kW, and is dominated by foil losses.
- Further plans to approach 1.5 MW from the RCS in the mid-term were presented. 1.5 MW is to be achieved by extending the linac pulse length 20% and increasing its current 20%.
  - Preliminary simulation and experimental studies suggest the higher beam intensity in the RCS should be achievable within loss limits. Simulations have been provided to support linac projections.

- Several improvements will be required in the linac and RCS to accommodate the beam and reduce losses as possible. Plans to achieve these improvements are being formulated.

MR with fast extraction for neutrinos:

- Beam intensity increased to 394 kW in JFY15, exceeding the projections at the previous ATAC. Intensity improvements will be marginal until the major upgrade of the magnet power supplies. Running time to T2K has been limited due to turn-on of the slow extraction and maintenance issues in the target hall.
  - Beam power to T2K increased from 300 kW to 394 kW by the end of the year, with $2 \times 10^{14}$ protons per pulse. This beam intensity is equivalent to 751 kW if the cycle time were 1.3 s, instead of 2.48 s.
  - 677 hours of beam were delivered out of 812 hours. Scheduled hours were limited by the choice to provide beam preferentially to slow extraction.
  - Losses were approximately 1 kW for this level of operation, being distributed in several locations and well below the 2 kW collimator limit.
  - Studies with higher intensity beam ($3.48 \times 10^{13}$ per bunch) show promise for > 500 kW beam, previous to the power supply upgrade. These projections are extrapolated from two-bunch operation and require some loss reduction. The mid-term plan cites 400 kW in JFY16 and 450 kW in JFY17.
- J-PARC has begun implementation of a plan to reduce the cycle time to 1.3 sec as its primary path to achieving 750 kW in the MR.
  - MR RF cavities are nearly fully upgraded to provide more voltage
  - Funding has started for the major upgrade of the MR magnet power supplies. This investment will take about three years to realize, such that the cycle may be shortened to 1.3 sec. by the end of JFY 18.
  - Along with further improvements to beam intensity in the RCS and MR, beam powers beyond 1 MW may be possible. The mid-term plan has been updated to expect 800 kW in JFY18 and 900 kW in JFY19.

MR with slow extraction to the Hadron Facility:

- Beam of up to 42 kW was delivered to the Hadron Facility in JFY15.
  - Slow extracted beam was restarted for the first time since the target was damaged. 1517 hours of beam were delivered out of 1752 scheduled.
  - Improvements in the cycle time allowed the facility to deliver up to 42 kW with excellent efficiency (99.5%) and good beam quality (duty factor 42%).
  - Slow extraction at 24-25 GeV was investigated to reduce power consumption during slow extraction. However, the magnet power supplies were found to be insufficiently stable at that energy to allow efficient slow extraction. Furthermore, beam of this energy is known to be less useful for users.
- Slow extraction studies have restarted with operations, but the push to higher intensities will continue to be challenging.

- The present target is limited to 50 kW. An upgraded target capable of 70-75 kW is expected be installed in 2017. Designs are under consideration for higher power.
- The mid-term plan quotes a goal of 50-70 kW in JFY17/18, and 100 kW in JFY19.

J-PARC operating hours continue to be limited due to the high operating cost associated with the electrical consumption of the J-PARC accelerators. J-PARC has investigated strategies to reduce consumption in its systems. Presently, the accelerator systems consume about 50 MW of electricity. Several reductions of < 1 MW were identified, but come at the cost of reliability or complexity in operation.

**Comment**
The operating temperatures of the klystrons and Finemet cavities could be increased, which would make it potentially worth recovering the waste heat. In addition, the number of chillers and cooling towers would be decreased, further reducing power consumption.

## Linac status and beam studies

The linac was operated successfully with high availability during FY2015 and many of the past problems have been resolved. User operation was regularly held at 30 and 40 mA with reasonable number of trips. All specifications have been achieved.

*Ion Source and RFQ*

The new $H^-$ source has demonstrated up to 60 mA beam current. Continuous operation of 1,100 hours at 33mA and 1,004 hours at 45mA were achieved without any significant issues. The old pre-conditioning procedure, developed to reduce the start up time, was modified with a pulsed plasma conditioning stage, which reduced the original failure rate of antennas from 75% to 25%.

The RFQ has still 10 trips per day at 30 mA and 16 at 40 mA. This rate did not change significantly from last year's review. Trips are recovered within about a minute. This rate causes only 1% beam downtime, which is to be considered acceptable. No vacuum degradation or cavity Q degradation is observed after trips. The recovery time is mostly dictated by the system check before restart.

**Comment**s
It is not clear if the "spark events" that cause the trips actually can damage the cavity or whether the system could survive them without any problems or adverse effect to the system. If no damages could be ascertained, a different logic setting of the machine protection parameters might further reduce trips and downtime. It would be advisable to better understand the nature of these trips and adjust the control-logic accordingly.

*DTL/SDTL*

After summer maintenance, DTL/SDTL operation was characterized by two problems:

1) An increase of the trip rate was observed in two cavities. This was attributed to lack of conditioning after exposure of RF surfaces to air. However, continued operation caused cavity conditioning and trip rate went back to well tolerable levels.
2) A reduction of the cooling water flow rate in the DTL, reducing the cooling power during operation, was causing several stops lasting about 5 hours each. The problem was fixed by adding individual regulating valves in each cavity, obtaining a satisfactory and constant flow rate. However, the cause of the original decrease is not understood.

**Comment**
A better understanding of the cooling-water problem is needed to rule out the possibility that the water pipes in the cavity are progressively clogging up, leading to the possibility of future critical shutdowns. An alternative cooling design was presented. The origin of the problem should be understood first before embarking on an alternative cooling circuit. Additional modifications might be required.

**R3: Investigate and clarify the reasons for the cooling issues with the DTL.**

**<u>SDTL05 Status</u>**

**Findings**
After the earthquake it became difficult to operate SDTL cavities 05 and 06. RF signals showed strange behaviors at power levels of 250 – 450 kW indicative of multipacting. Having applied the usual countermeasures, rather than alleviating the problem, the upper limit of multipacting simply increased. Three possible strategies were identified: cleaning, acid pickling and building a new cavity.

In the summer of 2015 cavity S05B was removed from the linac and opened. The internal surfaces of the cavity were very dirty, possibly due to cracked hydrocarbons from an oil filled vacuum pump. There were also many foreign objects and other debris inside the cavity. After removing the debris and cleaning with acetone the multipacting was cured with a constant VSWR at all power levels and no strange field shape signals. In addition to this remedy, acid pickling tests were conducted on the prototype cavity and steel for a new cavity was procured.

**Comments**
Having opened the cavity the cause of the multipacting was fairly obvious and the fix straightforward. Following the success of a simple cleaning of the surfaces, acid pickling or manufacturing a new cavity might not be necessary. It is likely that cleaning the cavities S05A and S06A will solve the issue.

*ACS*
ACS was running stably and according to specifications and cavity conditioning is improving with time. The initial trip rate, after two years of operation, has reduced by two thirds.

*Beam Chopper System*

The beam chopper system, which in FY2014 showed difficulties in operating at the design current of 50 mA, was modified according to the plans and to a recommendation of this committee. A new high-speed pyrometer was installed to measure scraper temperature in operation up to 3500 C, and the scraper angle was increased from 45 to 67 degrees to reduce the beam power deposition density.

The scraper temperature in the new configuration was measured and its decrease was observed with short pulses. However:

1) There was not enough testing time to measure with long pulses and full current
2) A steady increase of temperature with operation time was observed. The cause was attributed to the change of heat transmission coefficient in Carbon after irradiation.

Thus although improvement were observed, the 50 mA efficacy of a single scraper is yet to be demonstrated. Such a test could be performed on the test stand with increased chopping duty factor. An important mitigation of this risk was presented whereby the power deposition density can be halved by using two scrapers in a "tandem" configuration, as was demonstrated in 2014.

**Recommendations:**

**R4: Perform a 50 mA equivalent long-term test in the single scraper configuration in the machine or on the test stand to understand the limits of the system.**

*Bunch Shape Monitor*

The work on development of a Bunch Shape Monitor (BSM) working without the need of a dedicated turbo molecular pump (TMP), to be installed in the ACS between cavities, has progressed successfully. A new BSM with modified design and materials is under testing off-line and reached $2\text{x}10^{-7}$ Pa without TMP, which is comparable to the present BSM with TMP. The new BSM units will be installed in ACS during year 2016.

*RF system*

RF system operated regularly during 2015 except for two replacements of failing 972 MHz units, which caused a total beam downtime of 24 hours. The procurement of spare klystrons continued with 4 new 324 MHz and 3 new 972 MHz units, and will continue in 2016 with 3 more units of each type.

The possibility of refurbishing used klystrons was explored and a first klystron made with refurbished parts is planned for 2016.

**Comment**

15 of the 324 MHz klystrons have reached 45,000 hours of operation. Although still working reliably, a significant increase in the failure rate and necessary replacement has to be expected in the near future.

*Alignment*

The alignment of the linac components was verified this year, showing that horizontal alignment was preserved during the last two years, while the vertical alignment slightly changed at a few locations. The magnet re-alignment task is scheduled for 2017.

## Beam studies

Linac beam studies have been continued to clarify problems pointed out at ATAC 2015, namely:

- Important discrepancies between calculated and measured values were found in the MEBT1
- Longitudinal emittance growth on MEBT2
- Beam halo and beam losses at 50 mA
- Beam losses and activation in ACS

Inconsistencies in MEBT1 were removed by an improved simulation made with a more powerful code (LINACSrfqSIM) and by a systematic Q scan measurement along MEBT1. This led to an agreement between simulations and measurements, as well as to an improved beam matching to the DTL at 40 mA and a 15% reduction of the emittance at the linac end.

The longitudinal matching in MEBT2 was improved by BSM measurements. Discrepancies between measurements and calculations are still present but an empirical correction method was able to reduce them. The measurements allowed for an improved longitudinal matching.

Finally, the beam losses observed along ACS could be largely attributed to Intra Beam Stripping (IBSt). The measured dose was consistent with the IBSt loss calculations. An attempt to mitigate IBSt by relaxing the quadrupole strength and moving away from equipartitioning in the ACS has shown promising simulation results for T=0.7, reducing beam losses by 40% and increasing the emittance by 14% compared to the T=1 case. Lower T (T=0.5) caused larger beam losses at the end of ACS.

Beam losses could also be reduced by increasing components aperture and by changing materials along the line.

### Comment and recommendation

Linac beam studies have significantly improved the understanding of the system. Removal of the MEBT1 inconsistency and discovery of the IBSt dominant effect in beam losses is paving the way to reduced emittance growth and reduced activation with 50 mA beams.

**R5: Continue experiments with relaxing magnet strengths to find the best compromise between IBSt reduction and emittance growth.**

## Status of RCS and beam study results

**Main achievements**

Stable operation has been achieved at 500 kW for MLF and 600 kW equivalent for MR. Three additional wire scanners have been installed in the L3BT line to allow improved matching at injection. New ceramic chambers have been installed to increase the vertical bump aperture by 50%.

At 1 MW operation insufficient margin in the ring RF anode power supplies was leading to beam loss in the high dispersion regions due to beam loading causing large momentum spread. This was partially overcome by increasing the anode current limit to 125A and re-tuning the cavity resonant frequency to 2.1 MHz. A permanent solution has been to add additional modules to the anode power supplies, increasing the current limit to 148A allowing operation at 1.7 MHz resonant frequency with zero loss in the high dispersion area at full beam loading.

The remaining beam loss was mainly at injection due to foil scattering in the zero dispersion collimator straight section. Reducing foil hits by increasing the transverse painting area from 100 to 150 π mm mrad led to an increase in beam loss due to beta beating but this was successfully mitigated with the use of the quadrupole correctors. Further increases in painting were restricted by emittance growth through the combined effect of the $\nu_x+2\nu_y=19$ and $\nu_x-\nu_y=2\nu_x-2\nu_y=0$ resonances with the correlated painting scheme. Changing to anti-correlated injection painting with no chromatic correction and the use of correction quadrupoles allowed for an increase of the painting area to 200 π mm mrad with 0.2% beam loss. Reducing the foil width and withdrawing the foil by 4mm achieved further reductions in foil hits. Under these new conditions 1MW operation is possible with the same residual activation of the foil chamber as previously at 300 kW.

Beam instability due to the kicker magnet impedance can be suppressed even for the 1 MW beam by suitable choice of tune variation and less chromaticity correction.

Minimizing the emittance for MR injection can be achieved by correlated painting to 50 π mm mrad and selecting a suitable tune variation. However the optimal tune variation leads to beam instability above 800 kW operations. One possible solution is to introduce negative chromaticity in the middle and late stages of acceleration.

**Comments and recommendations**

The team is systematically studying several relevant and interconnected mechanisms including enlarging the transverse and longitudinal phase space admittances with refined painting and bunching factor reduction, correction of resonance strength using correctors, suppression of instability with chromaticity enhancements, and the alternative design reducing the coupling impedance of the extraction kickers together with its pulse forming network. The alternative design of the reduced impedance RCS extraction kicker/PFN assembly should be brought to conclusion with bench and eventually beam test comparison.

On one hand systematic operational optimization is a necessary step towards raising the performance of a state-of-the-art accelerator. On the other hand, focused efforts are important to mitigate bottlenecks in design and hardware like the extraction kicker assembly.

Advanced beam diagnostics is key to a deeper understanding of complicated beam dynamics and delicate mechanisms. We urge the team to continue deployment of such systems including the ionization profile monitor.

**<u>Status of MR and beam studies</u>**

MR operation at 30 GeV has been resumed

- 390kW has been supplied for practical operation with FX, 42 kW for SX (duty: 37~40 %, Extraction Efficiency ~99.5 %). The improved SX beam power has been achieved by reducing the rise time of the magnetic field from 1.9 s to 1.4 s.

- Both FX and SX have realized availabilities of 83.4% and 86.6%, respectively, and attained a reliability higher than 80%, which is expected to be increased even further during JFY2016 operation.

The reflected pulse of the new injection kicker has been corrected by a separate compensation kicker, which reduced the beam loss during injection from 101 W to 66 W.

Chromaticity correction in the MR has been carefully studied. Too small chromaticity will lead to instability while too large one will probably cause beam loss due to chromatic beam spread. Instability has also been suppressed with the use of bunch-by-bunch and intra-bunch feedback. Horizontal instability has been suppressed by adjusting the delay and gain of the feedback just before the ATAC.

Longitudinal beam profile has been enlarged increasing bunching factor from about 0.2 to about 0.3 by additional a second harmonic RF field. Bunch length has also been increased from 200 ns to 400 ns for 500 kW equivalent high power beam operations.

Two new injection beam collimators with 4-axes and Titanium ducts have been installed. Beam losses of up to 2 kW can be collimated.

With an RF phase offset at injection beam losses due to a beam instability was suppressed for the beam power of 38 kW while the instability was observed without the offset.

Linear coupling resonance correction has been applied using skew quadrupole magnets both at the injection and during acceleration from 3 to 30 GeV resulting almost no loss throughout the whole process. Third order resonance correction with trim coils of the skew quadrupole magnets has also been applied at 3 GeV.

Residual radioactivity on contact was found to be larger than 10 mSv/h at a location in between ESS1 and ESS2 four hours after the end of SX operation.

SX-abort system has been introduced in order to avoid the delivery of the extraction beam in an abnormal way.

A flat top energy of 25 GeV for slow extraction has been studied, but due to the higher current ripple at 24 GeV, this mode is found to be not useful.

A beam power of 50 kW for SX mode, the goal of the 1$^{st}$ phase, has essentially been realized, but demonstration is prevented by the required safety margin below the radiation safety permission of 50 kW. The need and schedule for beam power beyond 50 kW of the SX mode should be clarified with the users.

## Impedance and Instabilities

**Findings and comments**

Residual activation measured during beam studies and beam loss distribution calculations have been used to guide the analysis and to validate the design optimizations. Such practices are appropriate as performance limitation of high power accelerators is determined by hands-on maintainability and residual activations. We encourage the team to adopt standardized maintenance criteria, e.g. using residual activation level measured 30 cm from the surface, 4 hours after the machine shutdown and at specific locations. Local and global power loss limits can then be established to maintain activation below the acceptable limits. The Committee agrees with the conservative guidelines used by J-PARC, as low as 0.1 W/m.

**R6: Calibrate the beam loss monitors with the measured residual activation for both the RCS and MR.**

Encouraged by the successful demonstration of 1 MW equivalent beam tests in the RCS, studies are being conducted to pursue beam power upgrade to 1.5 MW in the RCS based on raising the linac output peak current from 50 mA to 60 mA, and pulse length from 500 μs to 600 μs. Such studies are highly useful in facilitating the understanding of machine performance bottlenecks and in maximizing the potential of machine performance.

**Findings and comments**

Hardware systems implemented in improving MR performances include the compensation injection kicker and the second harmonic RF system and resonance correction with correction coils. Systematic studies are performed in evaluating the coupling impedance of most susceptible devices like the kickers and cavities. Attempts are made to measure the transverse coupling impedance with beam. We encourage the team to seek collaboration with other accelerator facilities in pursuing targeted beam dynamics studies. Compare the measured ring impedances with the impedance model obtained by bench measurements or simulations for new and old elements.

**R7: Continue the efforts to measure with beam the transverse and longitudinal ring impedances in the RCS and MR.**

The development of an improved wide-band pick-up for the transverse damper should be continued in the view of operating the machine at higher beam intensities where new phenomena might occur.

## MR upgrade plan

### Findings and comments

The basic upgrade plan of the MR is to increase the delivered power by the FX cycle up to 750 kW, by increasing the repetition rate (2.48 s cycle → 1.3 s cycle) using new power supplies while keeping beam losses under control. The SX cycle should provide a 100 kW beam after 2019.

Studies were performed also according to the recommendation of the ATAC-2015

The control of the longitudinal emittance by using either the 2nd RF harmonics or a new RF system based on 100 MHz cavities was presented. The increase of the longitudinal emittance contributes to reduction of the maximum direct space-charge tune spread, with the net effect of minimizing losses due to resonance crossing at low energy. The increased momentum spread reduces also transverse instabilities.

The beam tests with the FX cycle with the 2nd harmonic cavity were successful in reducing beam losses especially at low energy. During acceleration losses related the large chromatic tune spread (uncorrected chromaticity and large dp/p) could be minimized by dynamically adjusting the working point to avoid dangerous resonances. A 394 kW beam was successfully accelerated with losses concentrated at low energy and at the collimators. The controlled longitudinal emittance blow up will also be tested for the SX cycle.

Simulations of the longitudinal emittance control at injection and extraction energies were also done using a 100 MHz RF system, which is now being designed.

Once again, the committee would like to congratulate the team for reaching 394 kW beam delivered on the FX cycle. This is an important milestone before the MR repetition rate increase.

Alternative transverse working points were investigated to search for an area in the tune diagram as far as possible from harmful structure resonances. A possible area was found just above (21,21), but more studies should be done in particular considering that the optics in the straight sections seems to indicate larger beam envelopes compared to the nominal case. In preparation of this new optics, 3rd order resonance correction was successfully done by empirically determining the settings of the Trim-Sextupoles, significantly reducing beam losses. A tune scans in both planes finally led to the definition of the new working point corresponding to minimum achievable losses. Two bunches of ~530kW-equivalent beam power (2 bunches correspond to ~132 kW beam power) could be accelerated with a transmission of 97% (99.5%

transmission efficiency was reached during the injection period). Studies should continue to identify the sources of the betatron resonances found during the tune scan.

The extrapolation of machine performances for 2 to 8 bunches is based on the hypothesis that there are no sources of coupled bunch impedances present in the machine. Although a transverse coupled-bunch instability could be cured by the transverse damper, a longitudinal coupled bunch instability would require a completely new longitudinal damper.

The new proposed working point was not yet applied to the FX nominal beam because 8-bunch operations would require the upgrade of transverse feedback and a new collimator system. All of these activities are planned, which makes it plausible that more than 1 MW beam could be reached with the new MR power supplies. The committee would like to encourage beam studies that support higher beam power.

Particular attention should be given to the field quality of the 6 new large aperture QDTs needed to keep the activation in the 155 sections below 2 mSv/h during high intensity operations. Although they reduce losses due to their larger aperture, they could also introduce new systematic resonances. The field quality of the large aperture quadrupoles should be measured once the coils will be available and the influence on the machine lattice was established.

## Power supplies upgrade

### Findings and comments

The MR maximum power of 750 kW can be realized by increasing the repetition rate, i.e., by reducing the magnetic cycle length for FX from 2.48 s to 1.3 s. This implies the renovation of the power converters of the 21 different magnet families. With the technology used for the existing power converters, this faster cycle would require a maximum power variation induced on the electrical grid of 140 MW, exceeding the maximum variation tolerated by the electrical power company. For this reason, the new power converters are designed with full energy recovery based on local storage via capacitor banks.

The R&D conducted for the concept used for new power converters, conducted during the period 2011-2014, can be considered concluded.

The development of capacitor banks with different electrode materials was done to choose the most appropriate for this application. The chosen solution has a very promising estimated lifetime with an extrapolated 5% capacitance drop over 10 years verified during a realistic hardware tests. Eventually more tests could be envisaged since the different magnetic circuits provide different functions during the magnetic cycle, forcing the different power converters to operate in different conditions of voltage and current. This could follow the tests of the first capacitor bank foreseen during the summer.

The power converter design and its control system are well advanced. In particular, stable output current can be realized due to low noise measurements and digital control. With the FPGA-based architecture a current tracking error of less than $10^{-5}$ is achievable.

The production of some of the new power converters started already in 2015. The reduction of the project cost by separating the controller part from the power circuit part seems to be sound. The KEK staff has been dedicated to following up the final production at the companies.

The standardization of the IGBTs units for all the circuits is a good choice to maintain a reasonable price and to limit the number of spares of different components. 10 IGBTs are already being produced and should be ready for installation in the QFR circuit by this summer.

With the very large number of components, in particular for the IGBTs and the capacitor banks, quality control of the production is of primary importance, as is the procurement of an adequate number of spares.

Reliability and system maintainability should also be considered. In particular, it is not clear if the current power converter design includes any redundancy that might help in case of a failure of one of the modules within a give power converter.

The budget for the power converter buildings and the 18 containers needed for the power converters was approved and the presented schedule is reasonable.

Some data concerning the noise generated by a specific power convert circuit was presented.

It is of primary importance, in particular for the main magnet circuits, that the noise is measured in amplitude and frequency to verify that there is no overlap between the betatron resonance lines during the slow extraction and a perturbation introduced by noise from the power converters.

**R8: Validate that the power converters stability/reproducibility and noise spectrum during the long SX flat top are compatible with high spill duty factor slow extraction.**

## New injection and fast extraction system of MR

### Findings and comments

Several upgrades and improvements to the injection and extraction septa and kickers are required for the shorter 1.3 second cycle period.

The kicker upgrades are mostly limited to changing to higher capacity and/or more cooling for the terminating resistors. The fast extraction kicker system will also use a new charging supply.

A new injection septum magnet and power supply have been built and pre-installation tests look good. Installation is planned for summer 2016. Displacements up to 225 μm have been measured on the septum plate for the new injection septum. The committee is concerned about possible material fatigue issues. If a fatigue analysis predicts poor performance, it may be possible to change materials or further constrain the moving parts.

Extensive replacements are planned for the fast extraction system. New magnets and new power supplies are being built and tested. Installation is planned for 2017 and 2018.

The committee agrees that all of these upgrades are important and necessary to operate the MR at the 1.3 sec. cycle period.

The committee suggests looking into DC operation for the injection septum magnet. The duty factor is about 50% (0.6 s every 1.3 s). There may have been good reason to pulse this magnet for the original design with a 2.5 s cycle time, but now with the shorter cycle time it may be worth re-evaluating the reasons for pulsing this magnet.

The committee remains committed to the concept of measuring the impedances and multi-pole field components of all new equipment to be installed in the rings, especially the new septum magnet prior to installation, if this has not already been done.

**Recommendation:**

**R9: Perform a fatigue analysis for the new injection septum magnet with displacements up to 225 μm.**

## <u>Linac upgrade plan</u>

### Findings and comments

The J-PARC linac is performing remarkably well and has demonstrated the capability to supply beam at the nominal level of performance (400 MeV, 50 mA, 500 μs at 25 Hz) and is hence ready to contribute to running the synchrotrons at their nominal power (1 MW for the RCS and 750 kW for the MR). Up to 1.3 MW is feasible for the 1.3 s MR FX cycle.

Staying at this level will require adequate maintenance and replacement of ageing components like klystrons. 15 of the 324 MHz klystrons may have to be changed in the near future, after operating for more than 45,000 hours. The Committee took note that 7 new and conditioned devices are in stock and 3 more will be acquired in 2016.

Progressing beyond this level will be necessary for bringing the RCS beam power up to 1.5 MW and supplying beam to a potential ADS program. It would also allow delivering beam of high power simultaneously to all user communities (MLF, SX and FX).

To reach 1.5 MW beam power from the RCS, the plan is to increase by 20% both beam current and pulse length. This implies optimization of the LLRF for operating with some klystrons at 0.85 of saturated power. Otherwise only some minor cooling upgrade will be sufficient.

Feeding the ADS with beam at 25 Hz requires pulsing the linac at 50 Hz, which is significantly more demanding. Beyond the LLRF optimization, additional developments are necessary for the ion source to reduce emittances and for the MEBT-1 scrapers to make them more resistant.

Significant investments should also be made in the HVDC power supplies and in the cooling systems to double its capacity.

Preliminary investigations were conducted, using beam simulations based on 10% larger emittance at exit of the RFQ with 60 mA compared to 50 mA. Beam losses are identified at multiple locations (DTL entrance, ACS and arc) but their minimization to a tolerable level seems within reach. However, the relevance of these results remains unclear since the initial conditions are not satisfyingly justified and errors have not been considered.

The Committee encourages the pursuit of further ion source developments and LLRF optimizations.

**Recommendations**

**R10: Perform end-to-end beam simulations starting with a known and preferably measured beam distribution at the entrance of the RFQ and with errors included.**

## RCS upgrade

**Findings**

The RCS beam power could reach 1.5 MW by injecting 60mA for 600 μs. This is high enough to present challenges on several fronts, yet still achievable.

The primary issues have been identified to be:

1) The anode current in the RF systems.
2) The 100 μs longer pulse length of the shift bump and painting bump injection magnets.
3) The extraction kicker impedance.
4) Increased activation in the vicinity of the injection stripper foil.

Conceptual ideas were presented to address each of these issues. This work is in the initial stages, and the level of development is appropriate for this time.

**Comment**

The committee commends looking ahead to future power upgrades, but cautions, for the RCS as well as the whole facility, that this work should not detract from the focus on high availability and reliability of facility operations.