Shielding Calculation
for the Target Station Design

- Contents
  - Calculation Code & Nuclear Data Libraries

  - Biological Shield
    - 1-Dimensional
    - 3-Dimensional

  - Neutron Beam Line (NBL)
    - Methodology
    - Junction of Bulk Shield and NBL
    - Shielding Calculation for NBL
    - Beam Stop
    - Neutron Beam Shutter
    - To-Chopper, Activation & Blade Size

Topics in RED
will be presented.

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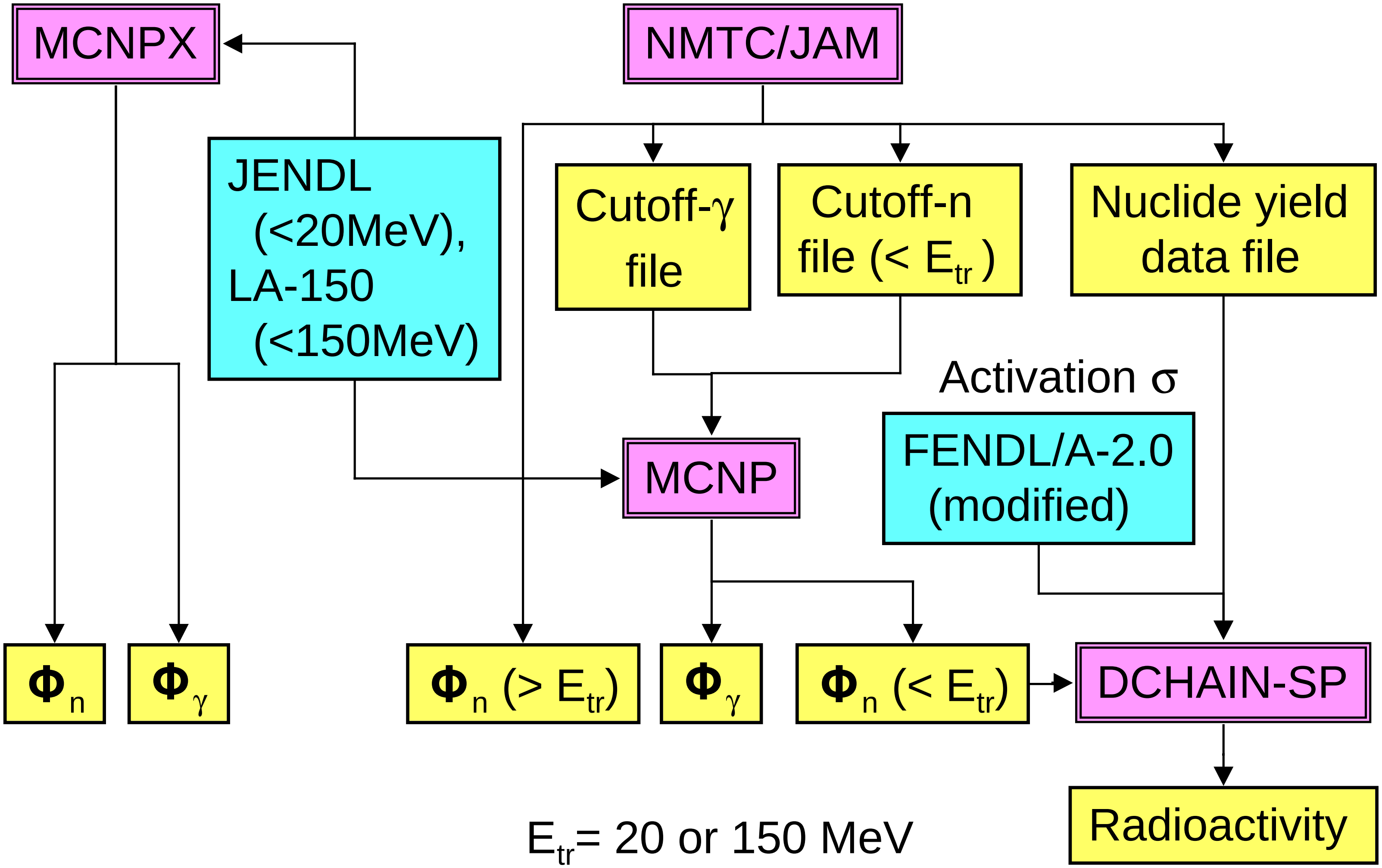
Masayoshi KAWAI (KEK)

Code & Data



MCNPX

NMTC/JAM

JENDL (<20MeV), LA-150 (<150MeV)

Cutoff-γ file

Cutoff-n file (< E_{tr})

Nuclide yield data file

Activation σ

MCNP

FENDL/A-2.0 (modified)

Φ_n

Φ_γ

Φ_n (> E_{tr})

Φ_γ

Φ_n (< E_{tr})

DCHAIN-SP

Radioactivity

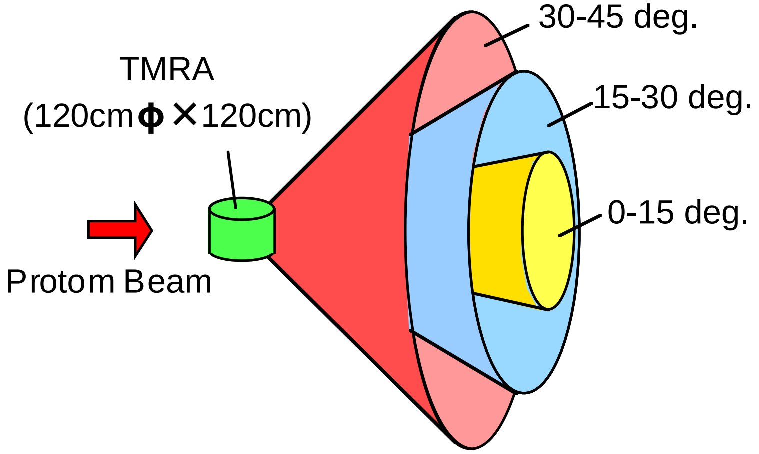
E_{tr}= 20 or 150 MeV

Biological Shield (1-D): Objectives

- Conceptual design for the biological shield
  - Learn about transmission phenomena of neutron and photon in shield materials
  - Select appropriate shielding materials
  - Determine approximate shield thickness

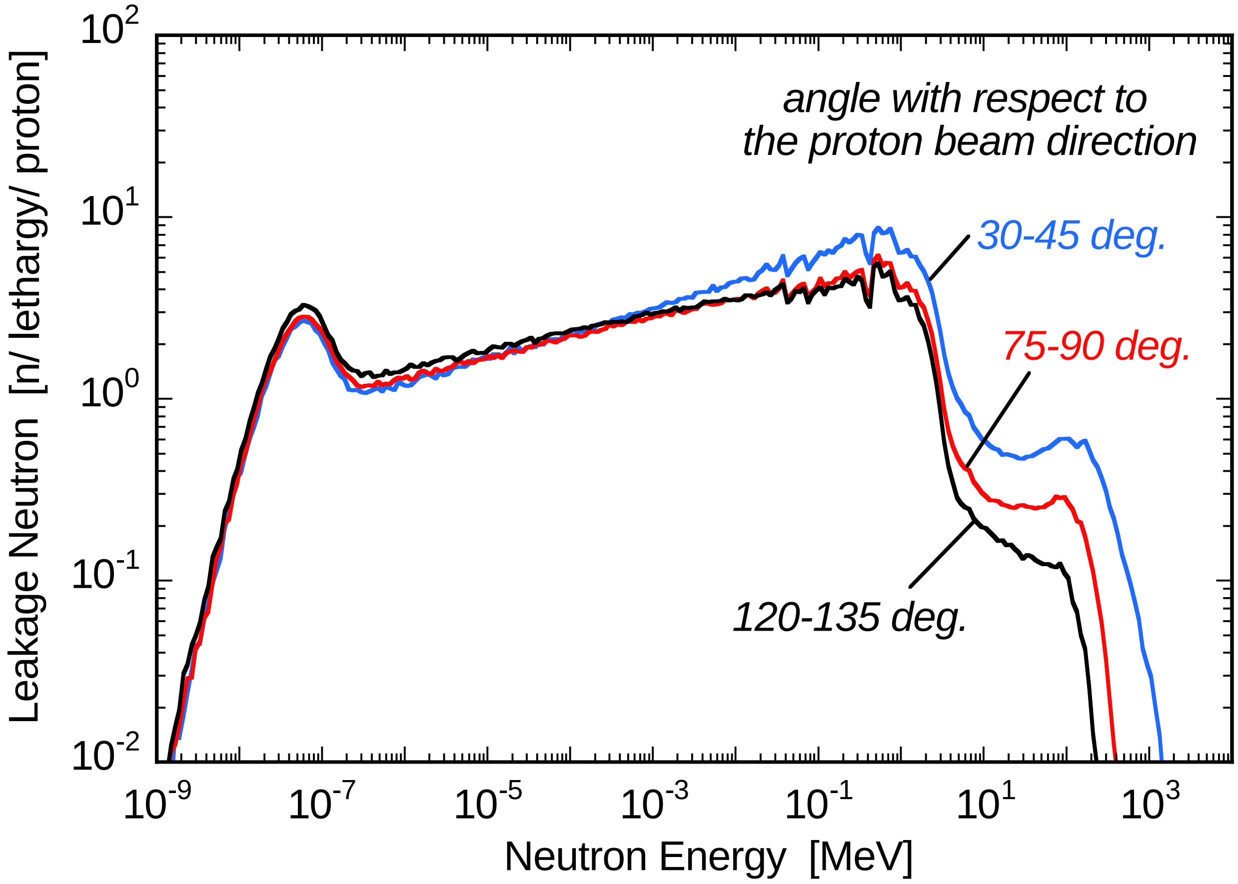
Biological Shield (1-D): Step-1

- Source Term Calculation
  - Model 3-dimensional TMRA in detail
    - Mercury target, Lead reflector, Moderators, Beam holes, etc.
  - Impinge a proton beam of 3GeV & 1MW to the mercury target
  - Calculate neutron energy spectra leaking from the TMRA
    - Every 15 degree angle ranges
    - Total 12 (=180/15) spectra



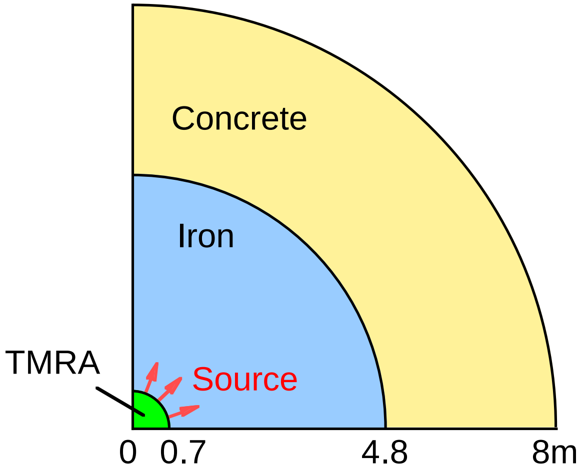
Biological Shield (1-D) : Source Spectra from TMRA

- Low-energy	(< 1 MeV)	almost isotropic
- High-energy	(> 10 MeV)	enhanced strongly to forward direction



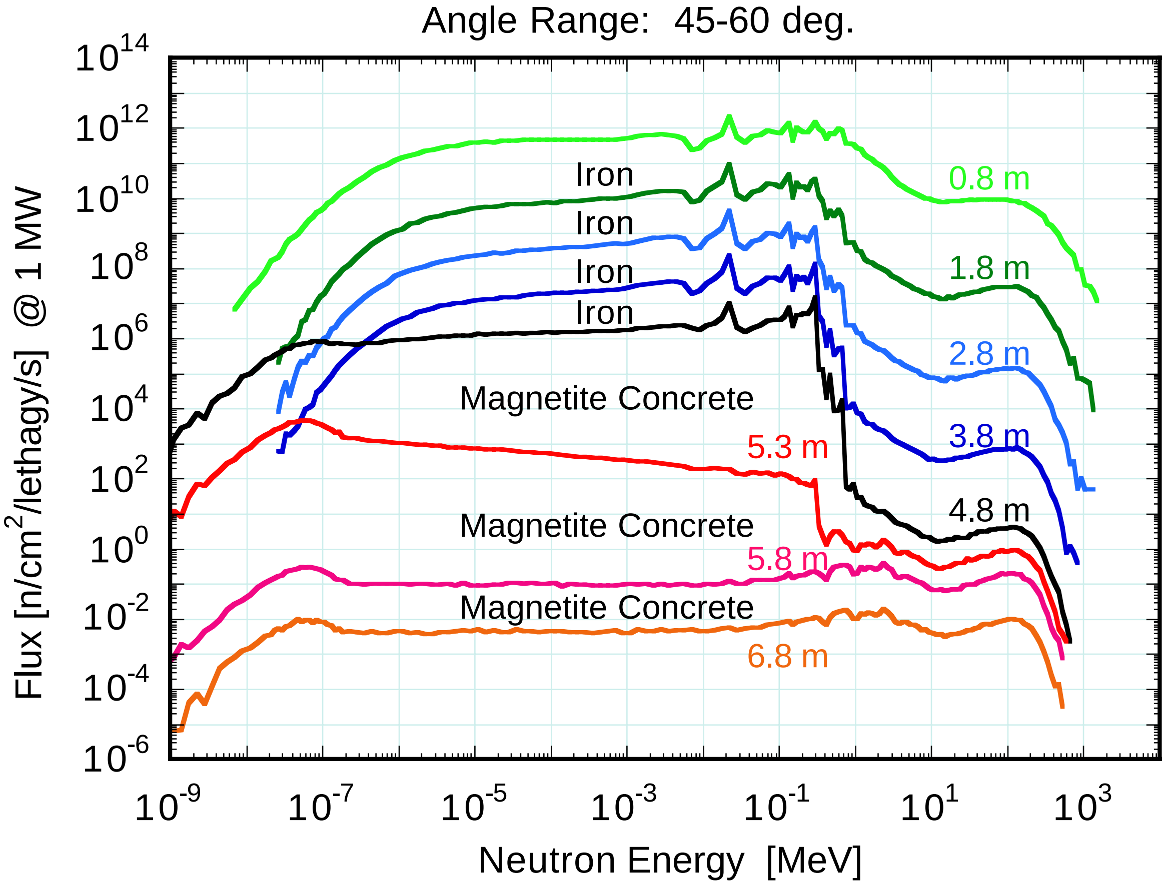
Biological Shield (1-D) : Step-2

- Deep Penetration
  - 1-Dimensional spherical model
  - One of 12 source spectra
  - Materials
    - Pure iron
      - Density: 7.2 g/cm^3 (void included)
      - Thickness: 4.8m, 5.0m, 5.2m from the center
    - Concrete
      - Ordinary concrete (2.2 g/cm^3)
      - Magnetite concrete (3.4 g/cm^3)
      - Steel punched magnetite concrete (4.6 g/cm^3)
  - Variance reduction by weight window
  - CPU Time: 500 min. with Pentium-III (784 MHz) for 1 angle range
  - Target dose: 0.1 μSv/h to achieve 12.5 μSv/h with considering
    - a safety factor of ~10
    - a correction factor of ~10 for omission of streaming effects

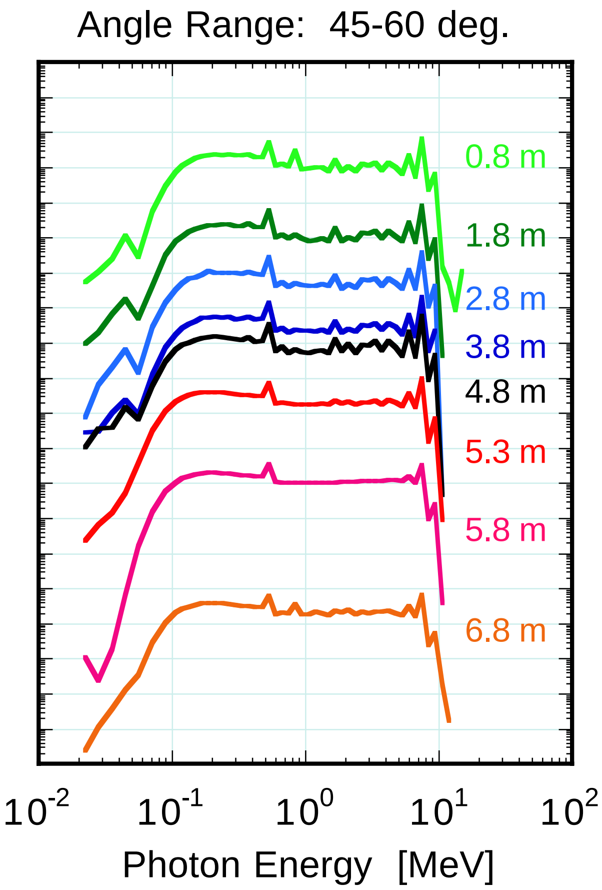


Biological Shield (1-D) : Energy Spectra

Neutron

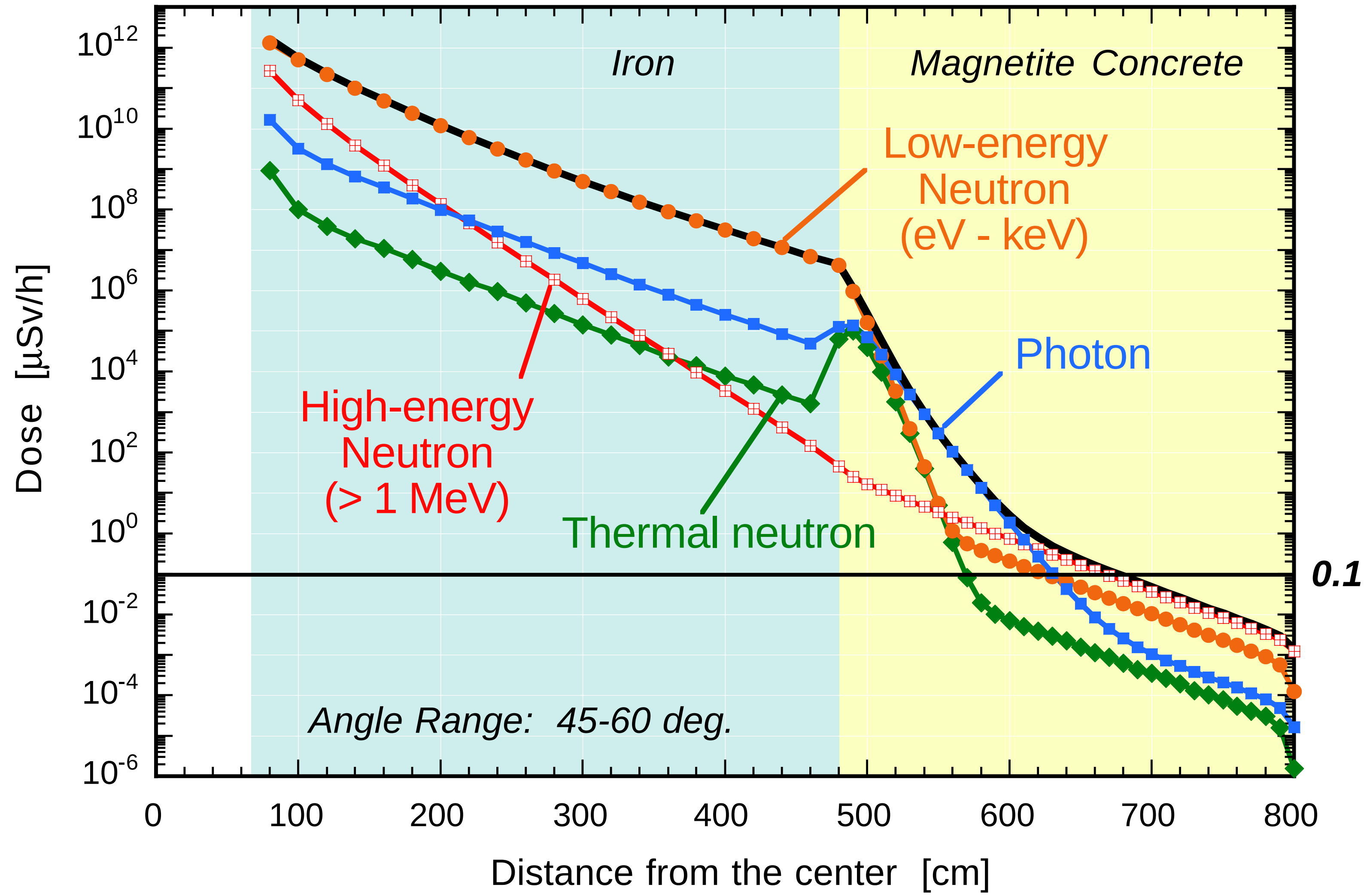


Photon



- Monte Carlo simulation can be used for bulk shielding calculation.

Biological Shield (1-D) : Dose



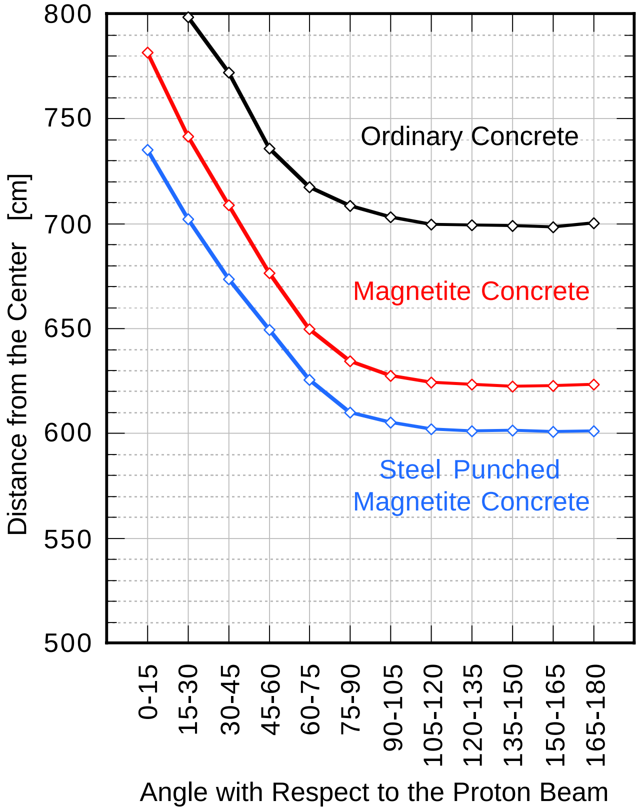
Biological Shield (1-D) : Results

- Magnetite concrete is very effective to reduce total shield thickness when compared to ordinary concrete.

- No remarkable benefit is found in use of steel punched magnetite concrete.

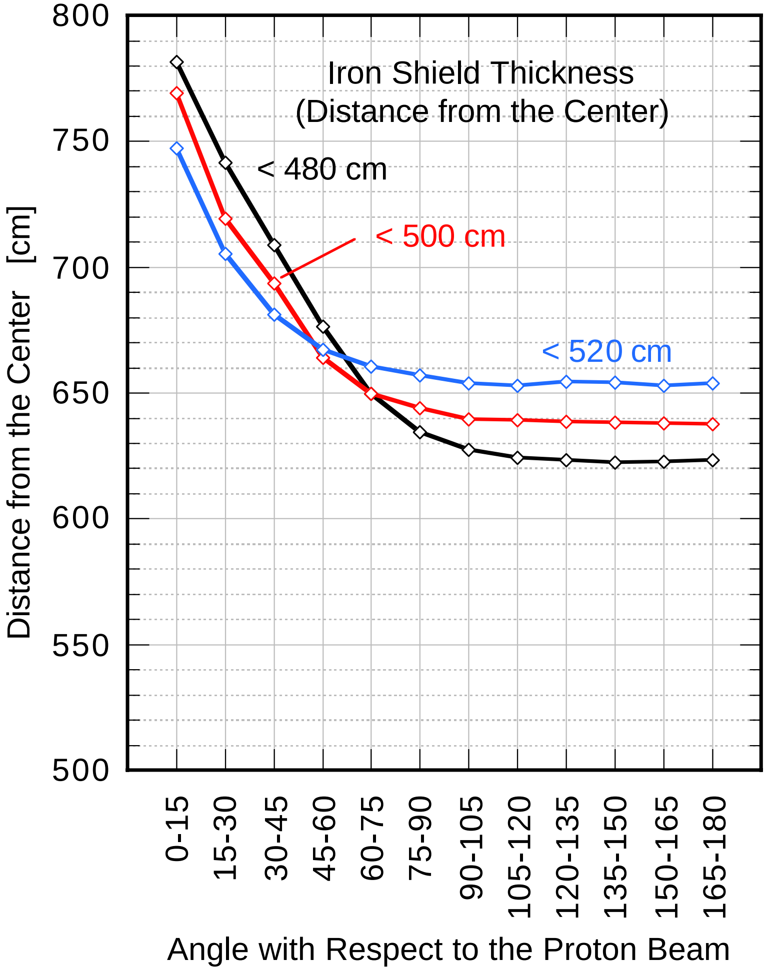
Magnetite concrete was selected for lateral outer region of the biological shield.

Total shield thickness to attain 0.1 μSv/h
(Iron shield up to 480 cm)

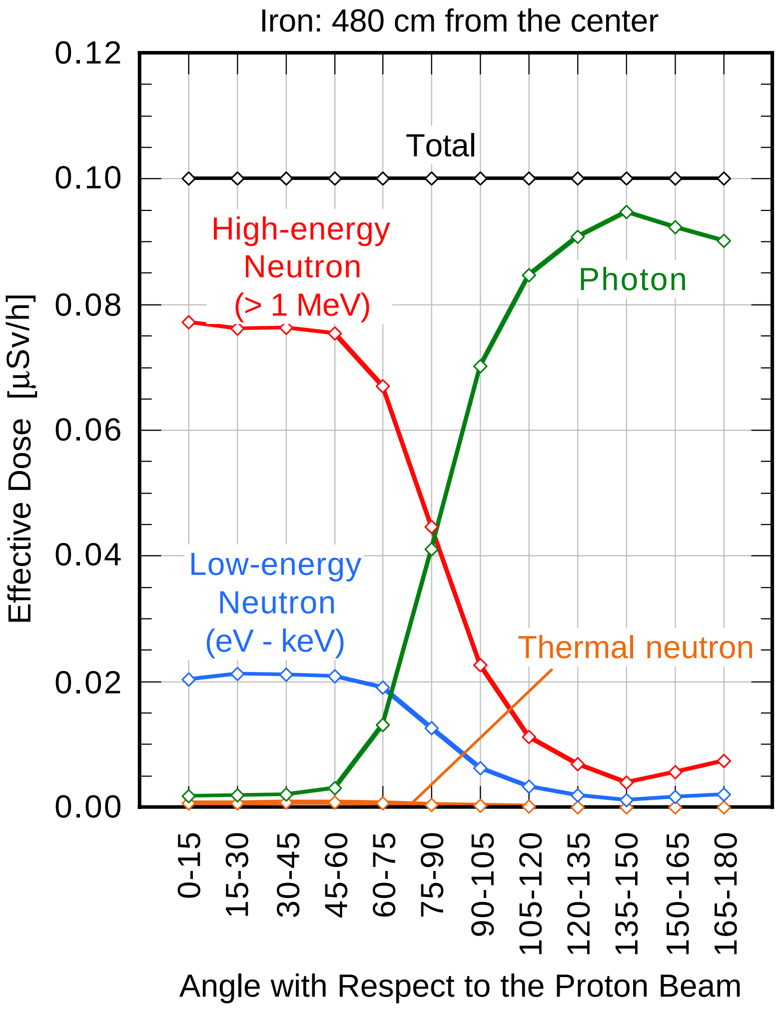


Biological Shield (1-D) : Results

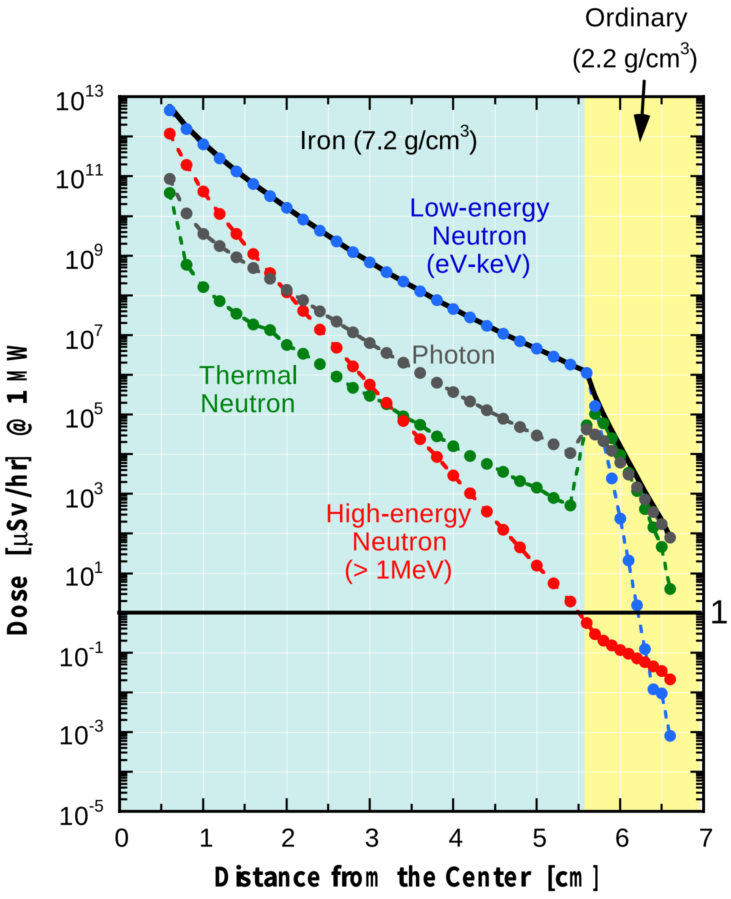
Total shield thickness to attain 0.1 μSv/h
(Magnetite Concrete)

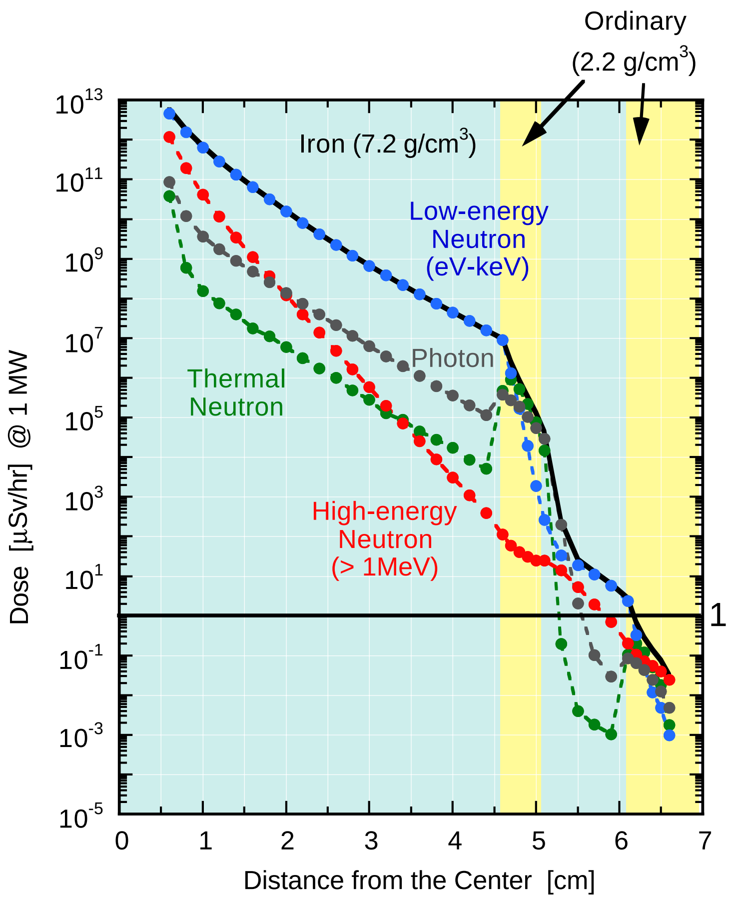


Breakdown


Iron: 480 cm from the center

Biological Shield (1-D) : Optimization

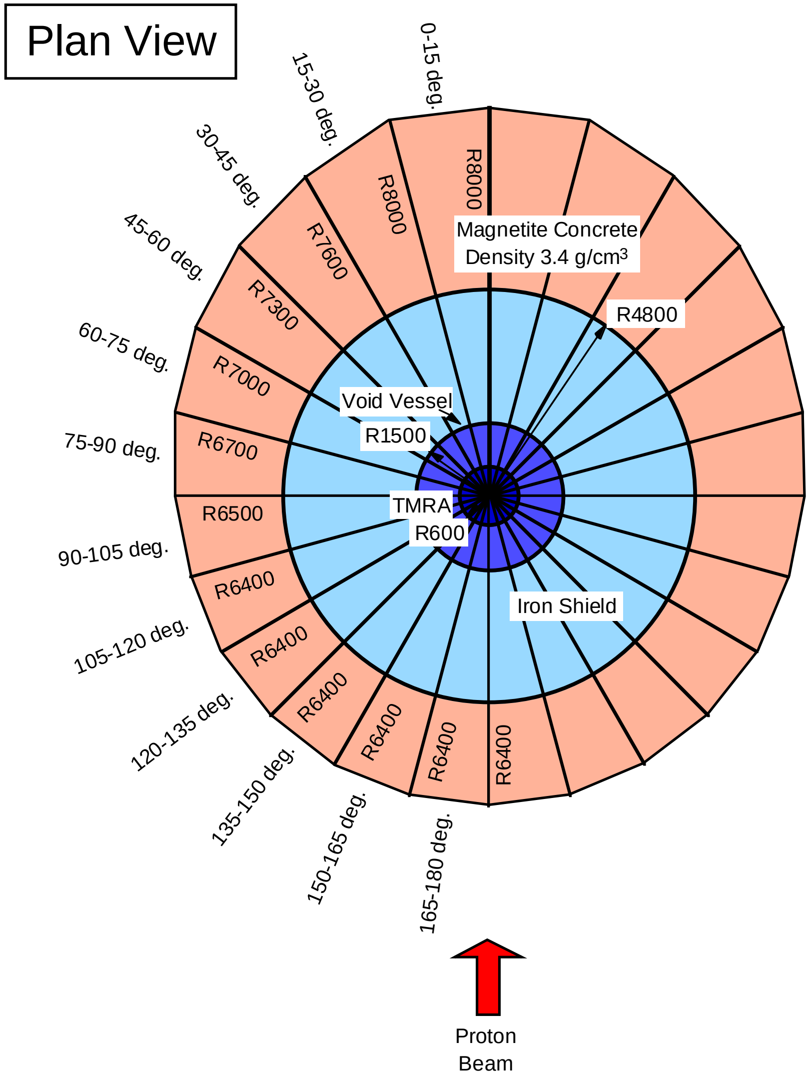




- A thin concrete layer in the steel shield is very effective to attenuate low energy neutron fluxes.
- This idea was adopted for the biological shield for the vertical direction.

Biological Shield (1-D) : Final Results

- Preliminary shield thickness was determined.
  - Backward:
    - Iron up to 4.8 m
      magnetite concrete up to 6.4 m
    - Secondary gamma-rays are dominant to the total.
  - Forward
    - Iron up to 4.8 m
      magnetite concrete 6.5 ~ 8.0 m
    - High-energy neutrons are dominant to the total.



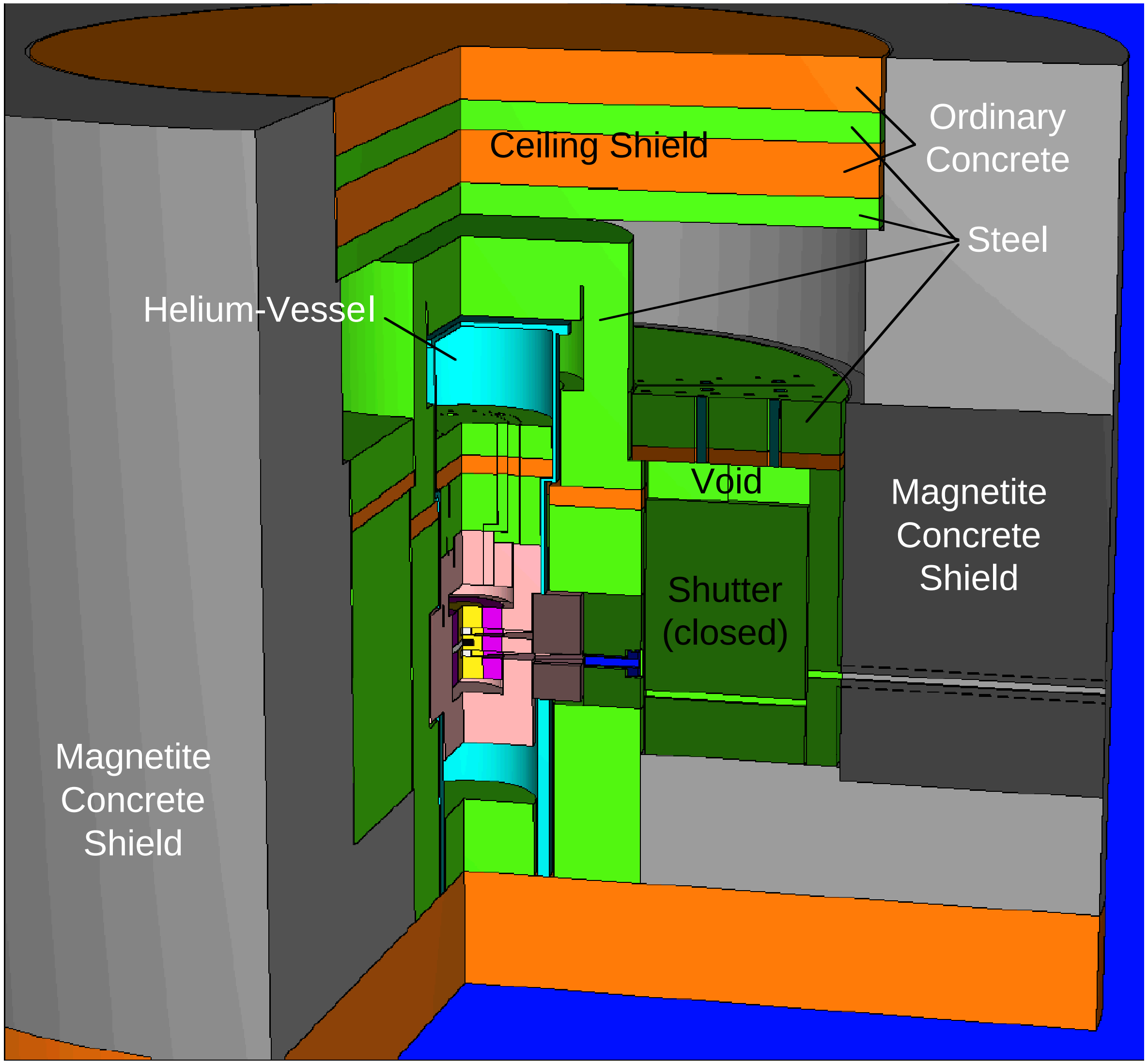
Biological Shield (3-D): Introduction

- Objective
  - Design a target station layout that satisfies the radiation dose regulation

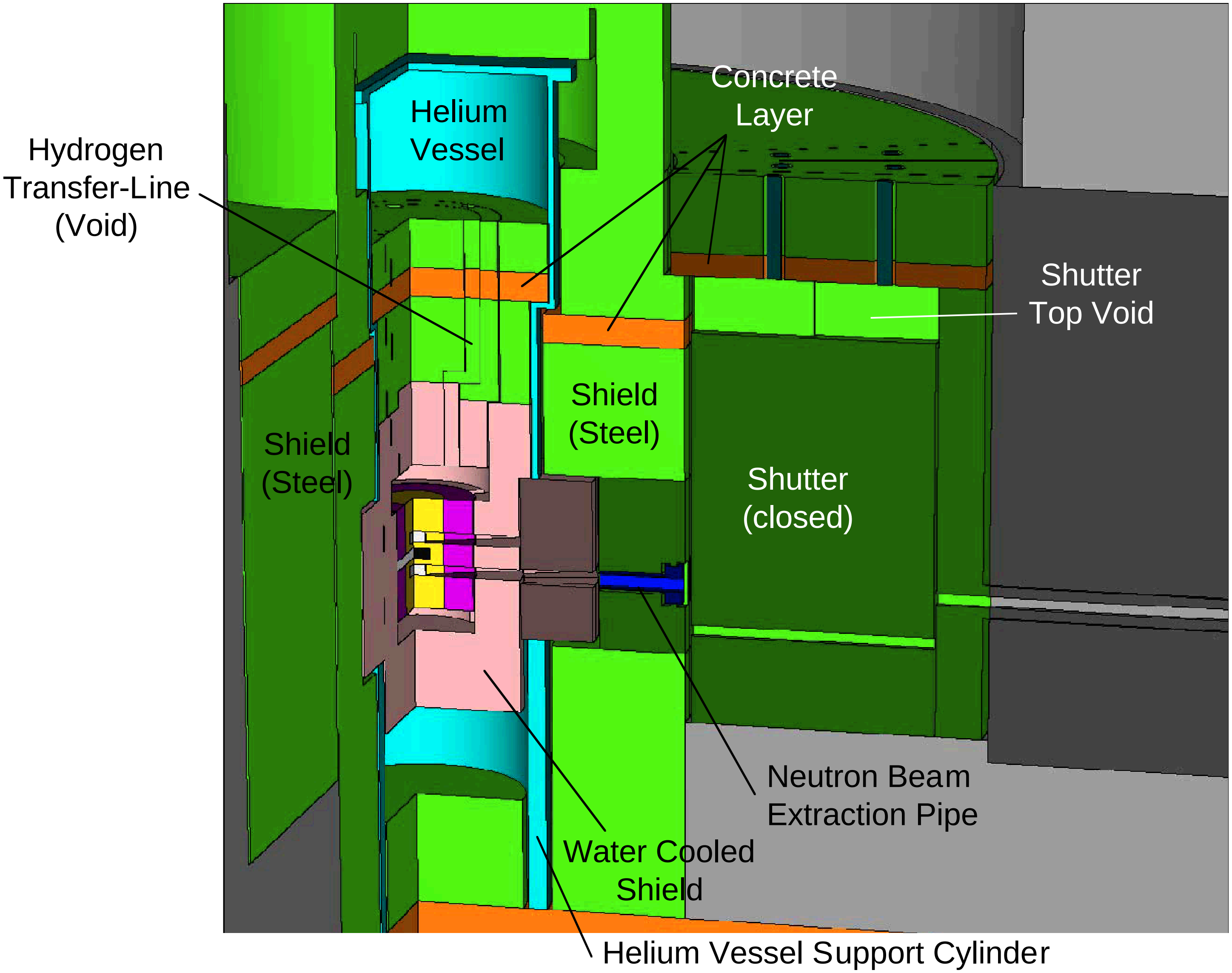
- Approach
  - Three-dimensional Monte Carlo calculation
  - Consider various components in the target station in a model, especially major gaps and void spaces to treat streaming effects precisely

- Design items
  - Materials & dimensions of shield blocks
  - Location & dimensions of components
  - Widths of gaps between neighboring components
  - Shutter stroke, positions of top & bottom void for shutter movement
  - Heating & activation in the shield region, etc.

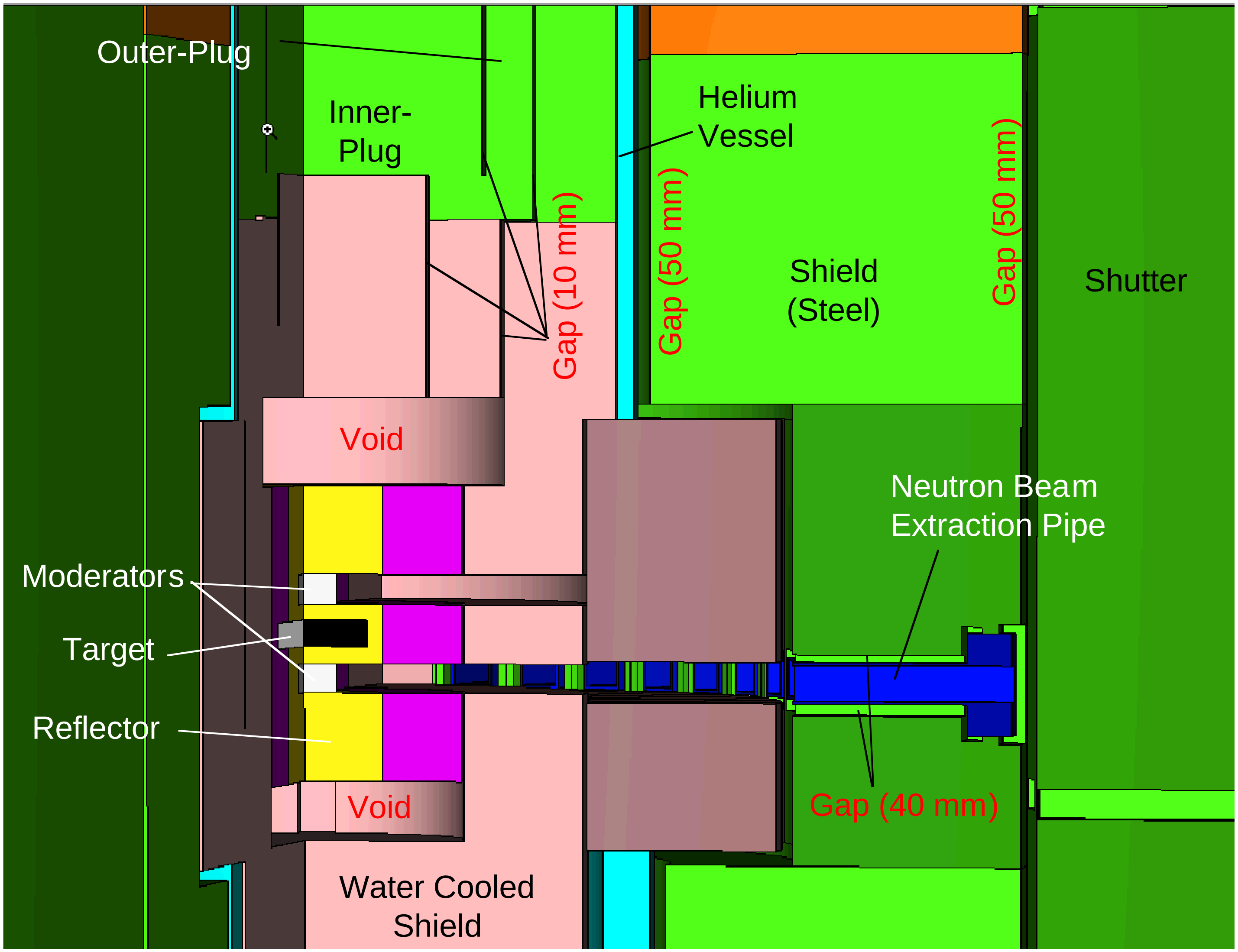
Biological Shield (3-D): Model-1



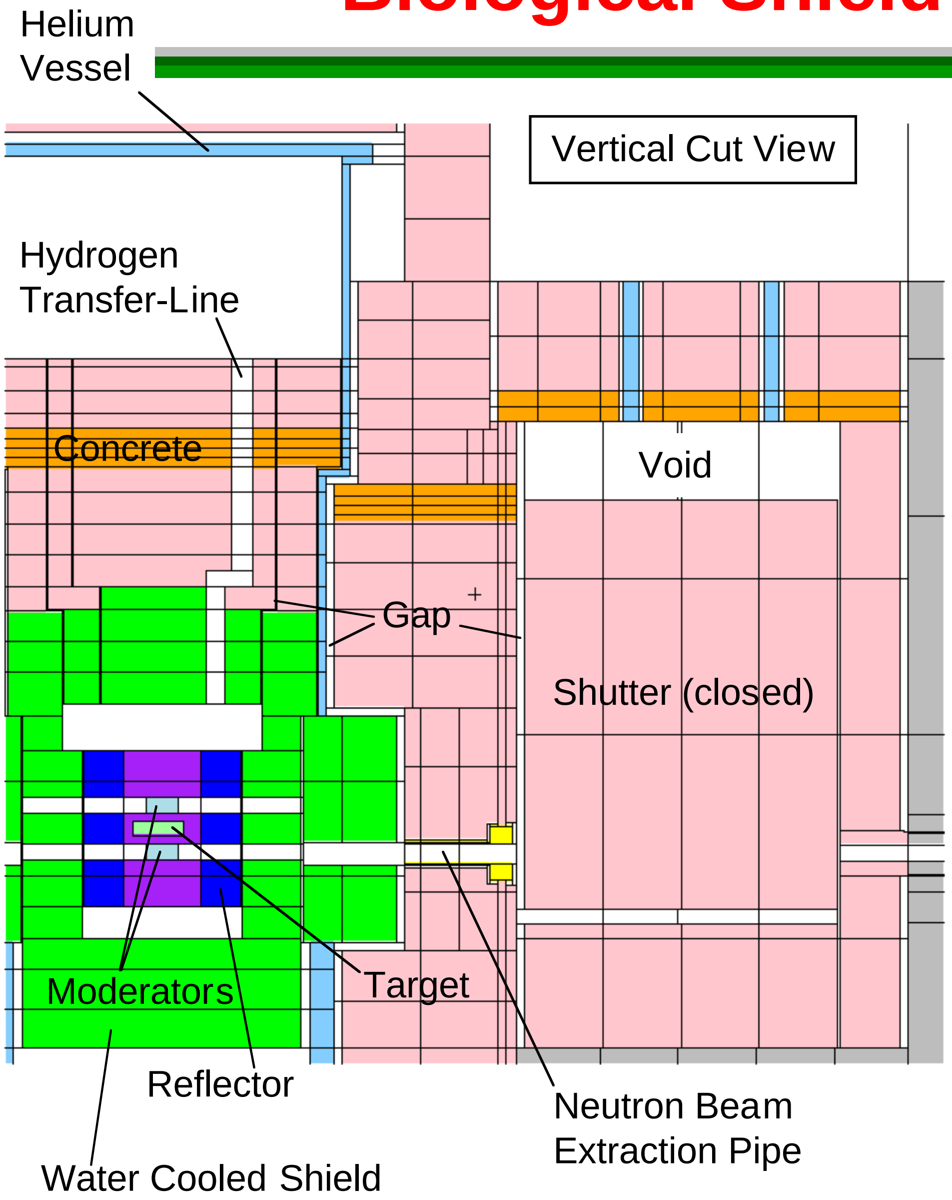
Biological Shield (3-D): Model-2

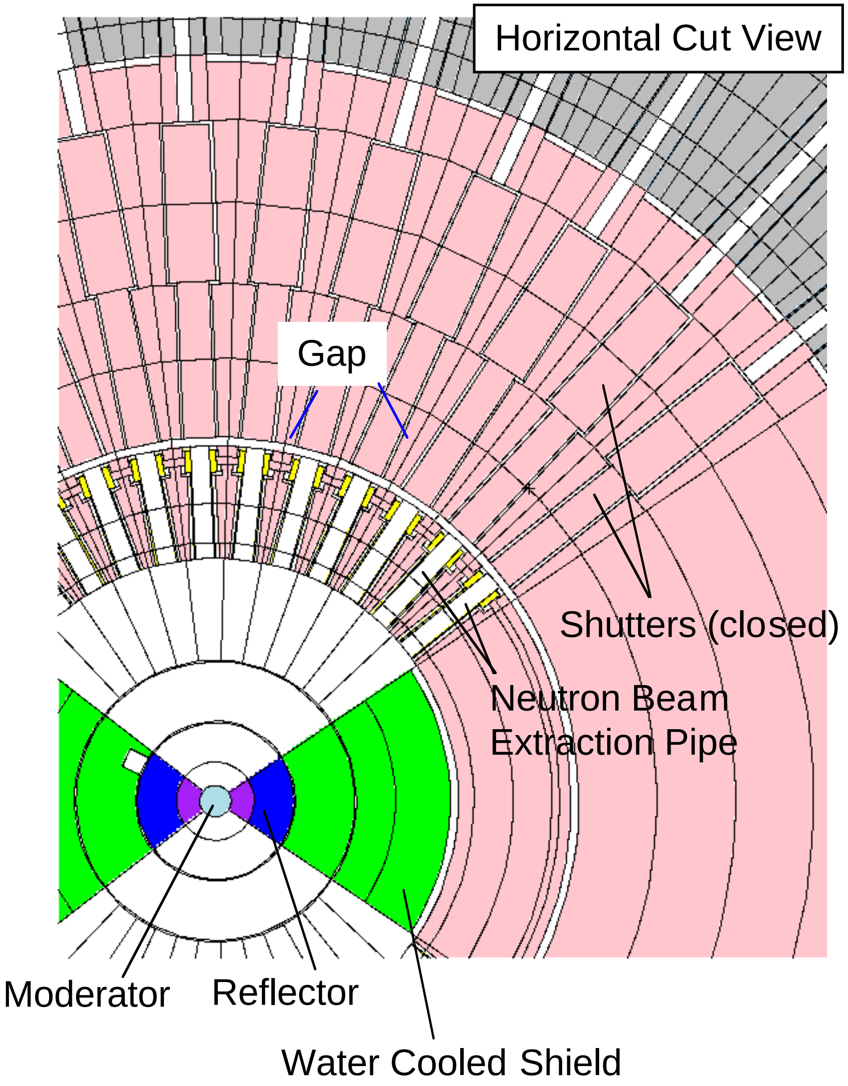


Biological Shield (3-D): Model-3



Biological Shield (3-D): Model-4



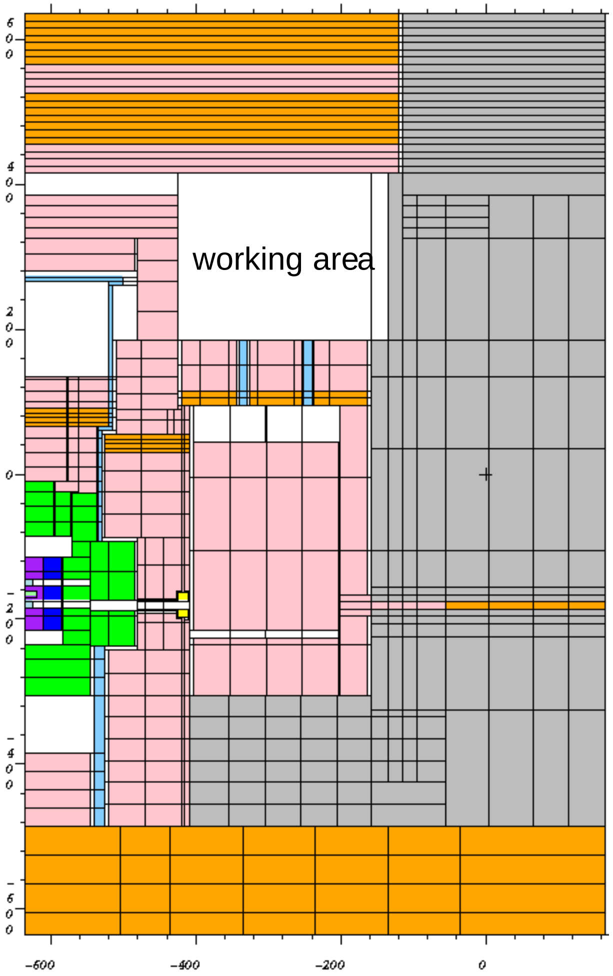


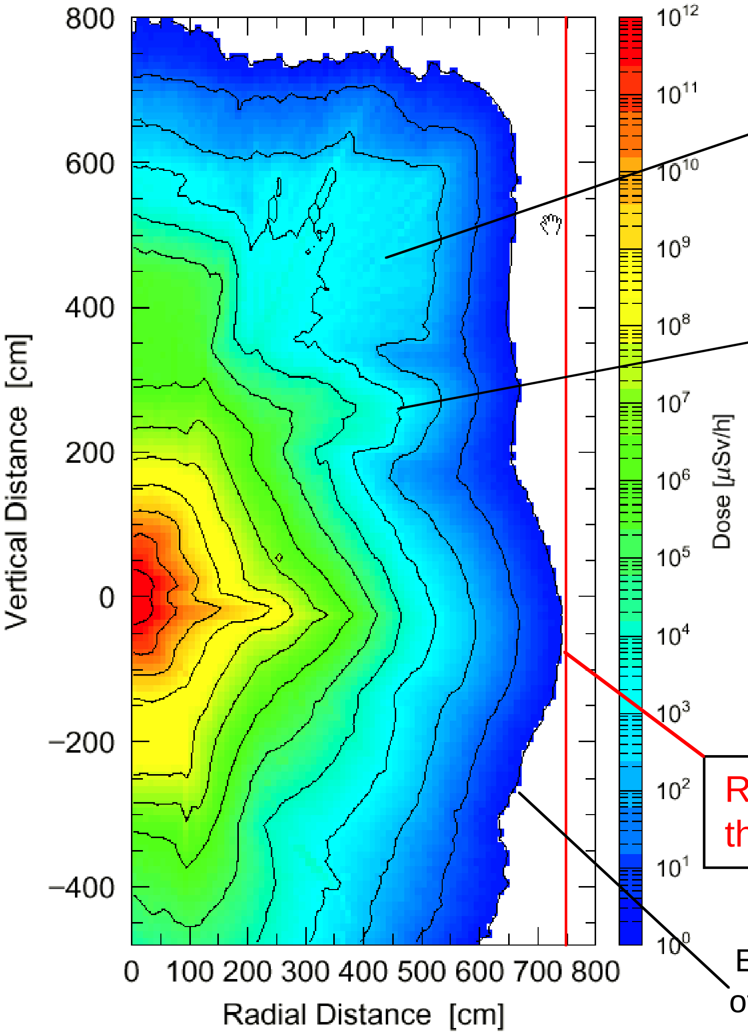
Biological Shield (3-D): Conditions

- Code & Data
  - MCNPX 2.2.6 + LA-150
- Density
  - Usual steel: 7.7 g/cm^3
  - Steel shield blocks: 7.4 g/cm^3 (including unavoidable vacancies)
  - Ordinary concrete: 2.2 g/cm^3
  - Magnetite concrete: 3.4 g/cm^3
- Source
  - 3 GeV, 1 MW proton beam on the Hg-target
- Design goal for dose rate: 1 μSv/h by neutrons > 10 MeV
  - Correction for underestimation of high-energy neutron fluxes by MCNPX+LA150 for steel (underestimation of 20% / m, 4.8 m thickness, $0.8^{4.8} \sim 1/3$): 3
  - Correction for dose by neutrons < 10 MeV and photons: 2
  - A priori safety factor for MC calculation: 2
    - 3 x 2 x 2 x 1 μSv/h = 12 μSv/h, not to exceed the dose limit of 12.5 μSv/h

Biological Shield (3-D): Results-1

Beam-Line #2 47.5 degrees with respect to the proton beam direction





Streaming due to working area

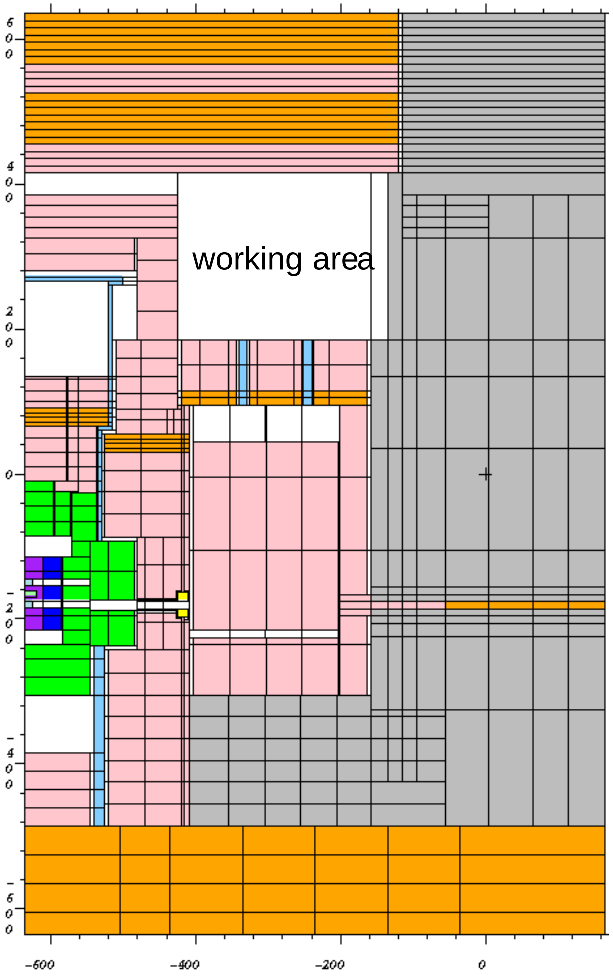
Streaming due to shutter top void

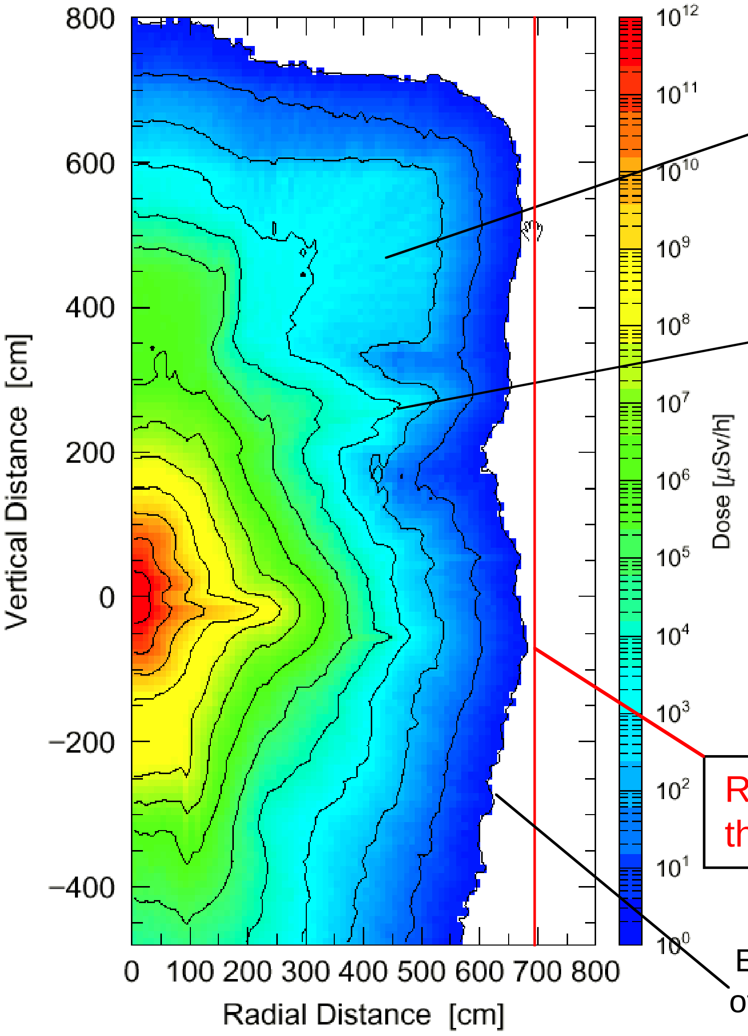
Required shield thickness: 7.5 m

Envelope of 1 μSv/h

Biological Shield (3-D): Results-2

Beam-Line #7 90.8 degrees with respect to the proton beam direction





Streaming due to working area

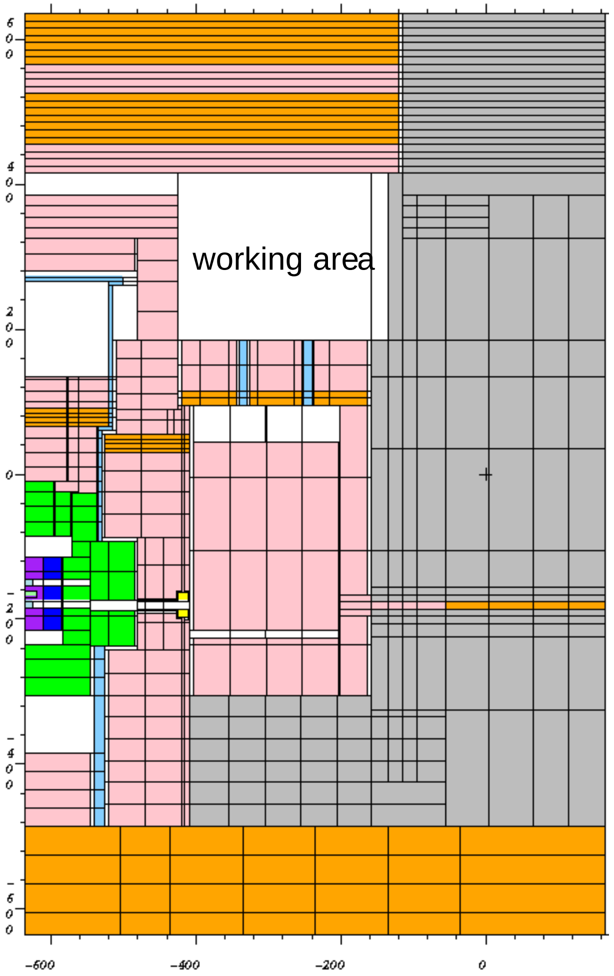
Streaming due to shutter top void

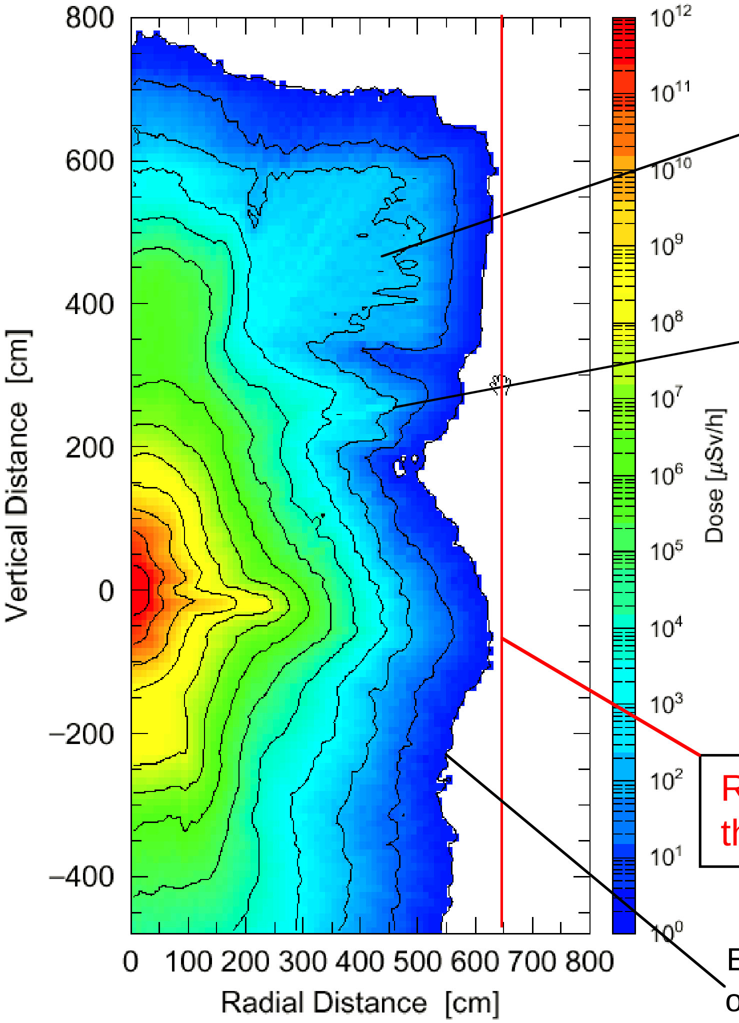
Required shield thickness: 7.0 m

Envelope of 1 μSv/h

Biological Shield (3-D): Results-3

Beam-Line #12 134.0 degrees with respect to the proton beam direction





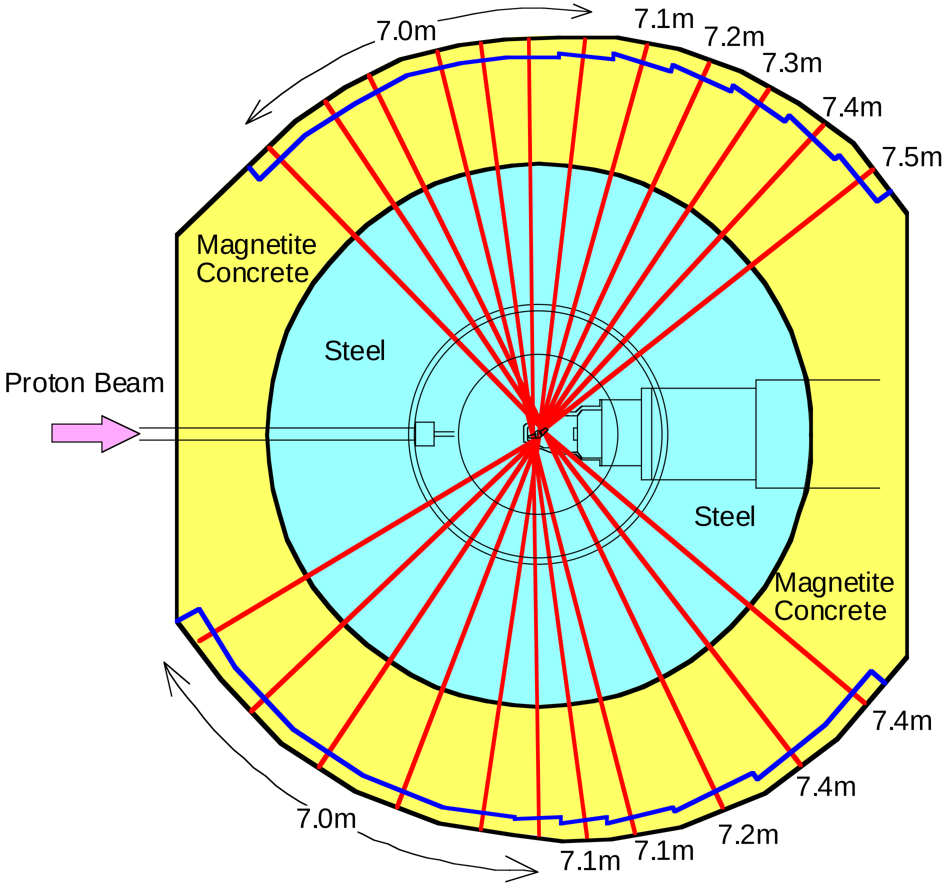
Streaming due to working area

Streaming due to shutter top void

Required shield thickness: 6.5 m

Envelope of 1 μSv/h

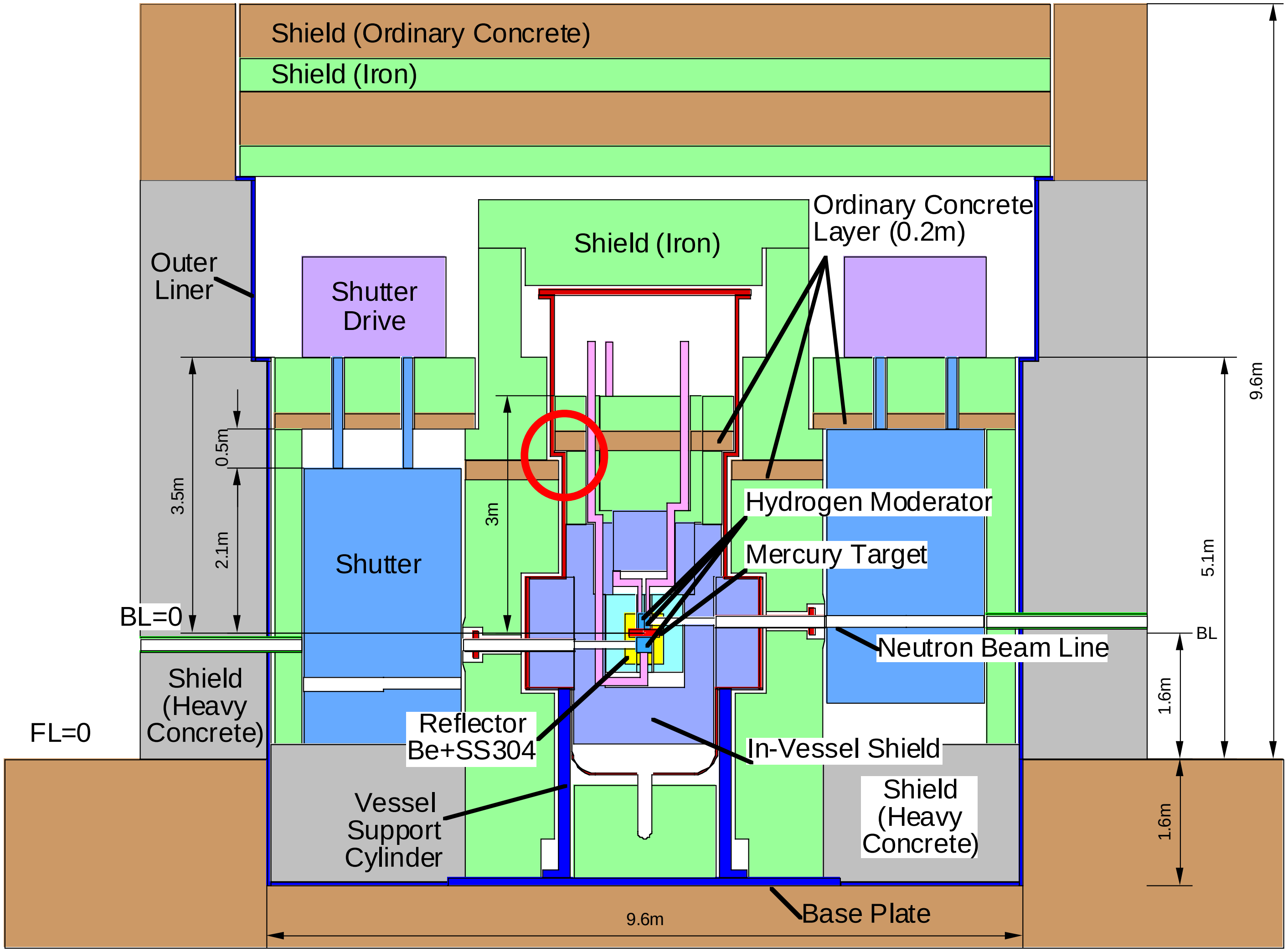
Biological Shield (3-D): Horizontal Layout



Thickness of 6.5m is required for backward angles, but increased to 7.0 m.

- No strong request to reduce the thickness to 6.5 m from users
- Save construction cost for future beam-line shielding

Biological Shield (3-D): Vertical Layout



Biological Shield (3-D): Summary-1

- Steel is basically used inside of the outer-liner ($R < 4.8$ m).
- A 200 mm thick horizontal layer of ordinary concrete is introduced in the steel shield at a height about B.L.+2500 mm to attenuate low-energy neutron flux to reduce radiation dose for shutter drives and activation levels of components in the working area around top of the helium-vessel by 2 ~ 3 orders of magnitude.
- For shutter bottom shield, steel is replaced by magnetite concrete ($\rho = 3.4$ g/cm^3) to reduce construction cost.
- For outside of the outer-liner, magnetite concrete is selected instead of ordinary concrete to reduce total shield thickness.
  (Use of the magnetite concrete is also required for adequate shielding against neutrons passing through neutron-beam-lines.)
- Total lateral shield thickness measured from the target station center ranges from 7.0 m to 7.5 m (4.2 ~ 4.4 kg/cm^2).

Biological Shield (3-D): Summary-2

- Top of the target station is covered with fifteen ceiling shield blocks composed of 800 mm thick steel and 1400 mm thick ordinary concrete.
- Thick concrete shields for both upward and lateral directions surrounding the target station attenuate low-energy neutron fluxes below 1 MeV accumulated in the steel shields effectively.
- Height of the reflector plug is minimized to suppress its weight for easy remote handling under a condition that activation dose at top of the plug is lower than 100 μSv/h.
- Shutter stroke is determined as 400 mm (+100 mm margin).
  A beam-line is closed when a shutter goes down.
- Heights of shutter and shutter top shield are minimized for precise alignment and easy remote handling of shutters without increasing shield thickness.

- Finally, a target station layout that satisfied the radiation dose regulation was determined.

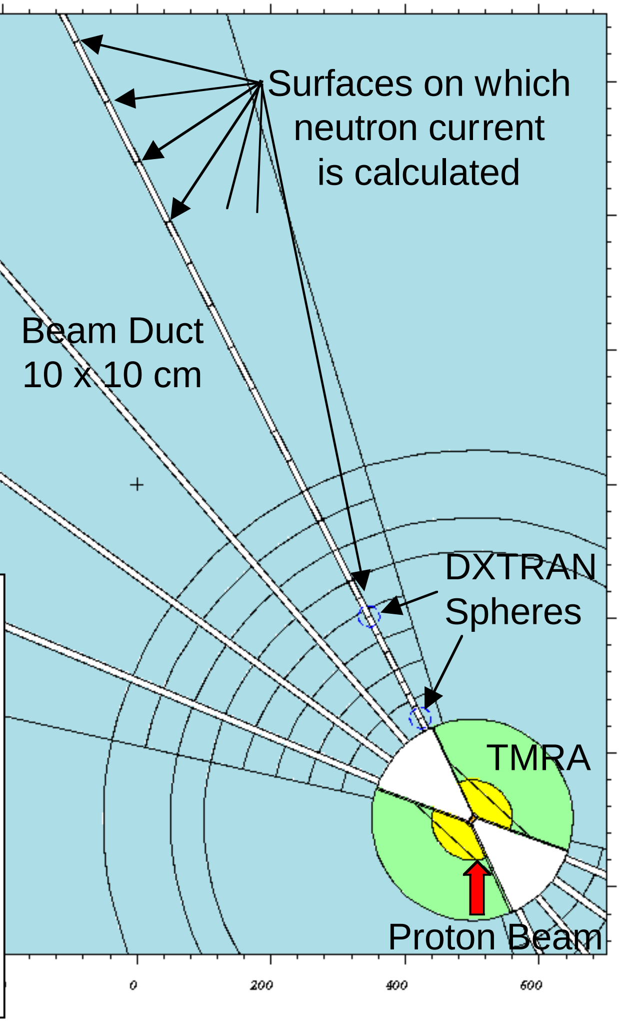
Methodology for NBL Calculation

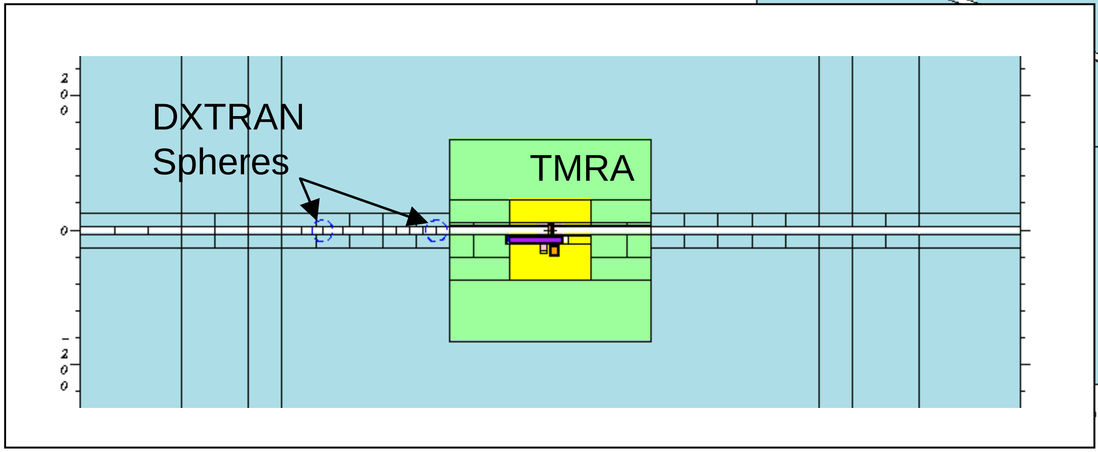
- NBL Source Term
  - Neutronics calculation for neutron beam lines (NBL) starting with a proton beam bombardment of the mercury target is not practical because
    - a great amount of computation time is needed, &
    - modeling of the whole system, TMRA, bulk shield and NBL, is too complicated.
  - If an NBL source term that represents accurately neutrons traveling through a beam line is obtained, NBL calculation will be very efficient.
  - 2-Step calculation

- Objective
  - To create a methodology for NBL calculation
    - a suitable NBL source term
    - a subroutine to generate neutrons in Monte Carlo calculations

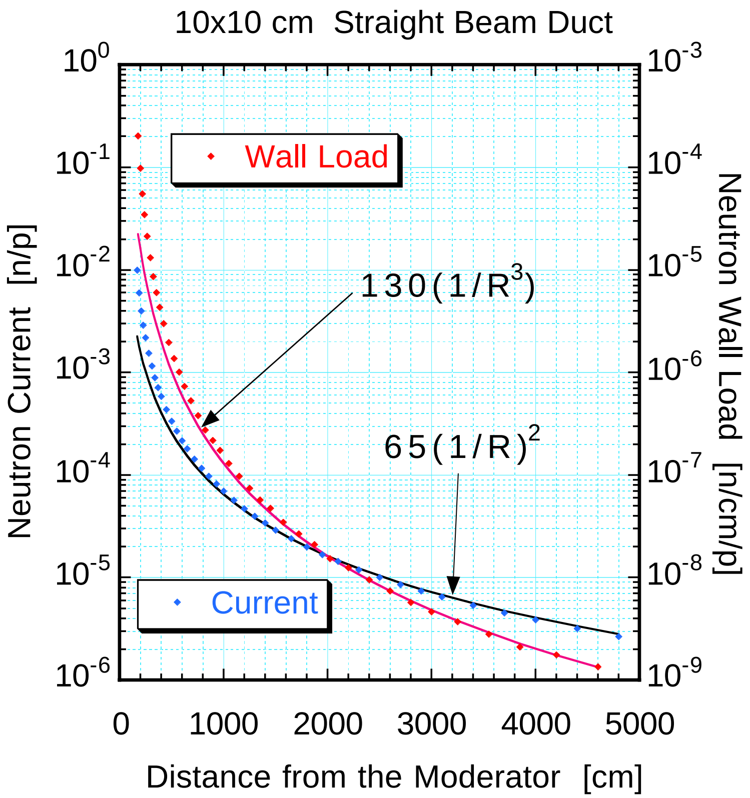
Methodology: Source Term Calculation

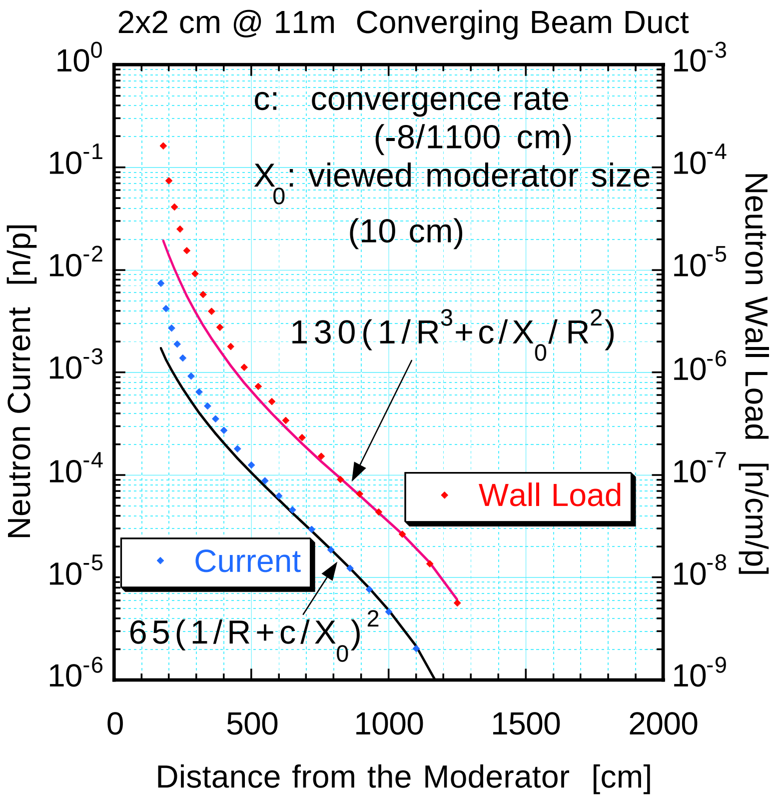
- Model TMRA & beam lines
- Calculate neutron current *J(E,R)* in an NBL at many positions from the moderator by using the DXTRAN spheres of the MCNPX code (source term)
- Two Duct Configurations
  - 10 x 10 cm Straight
  - Converging from 10 x 10 cm at the moderator to 2 x 2 cm at 11 m





Methodology: Calculated Results



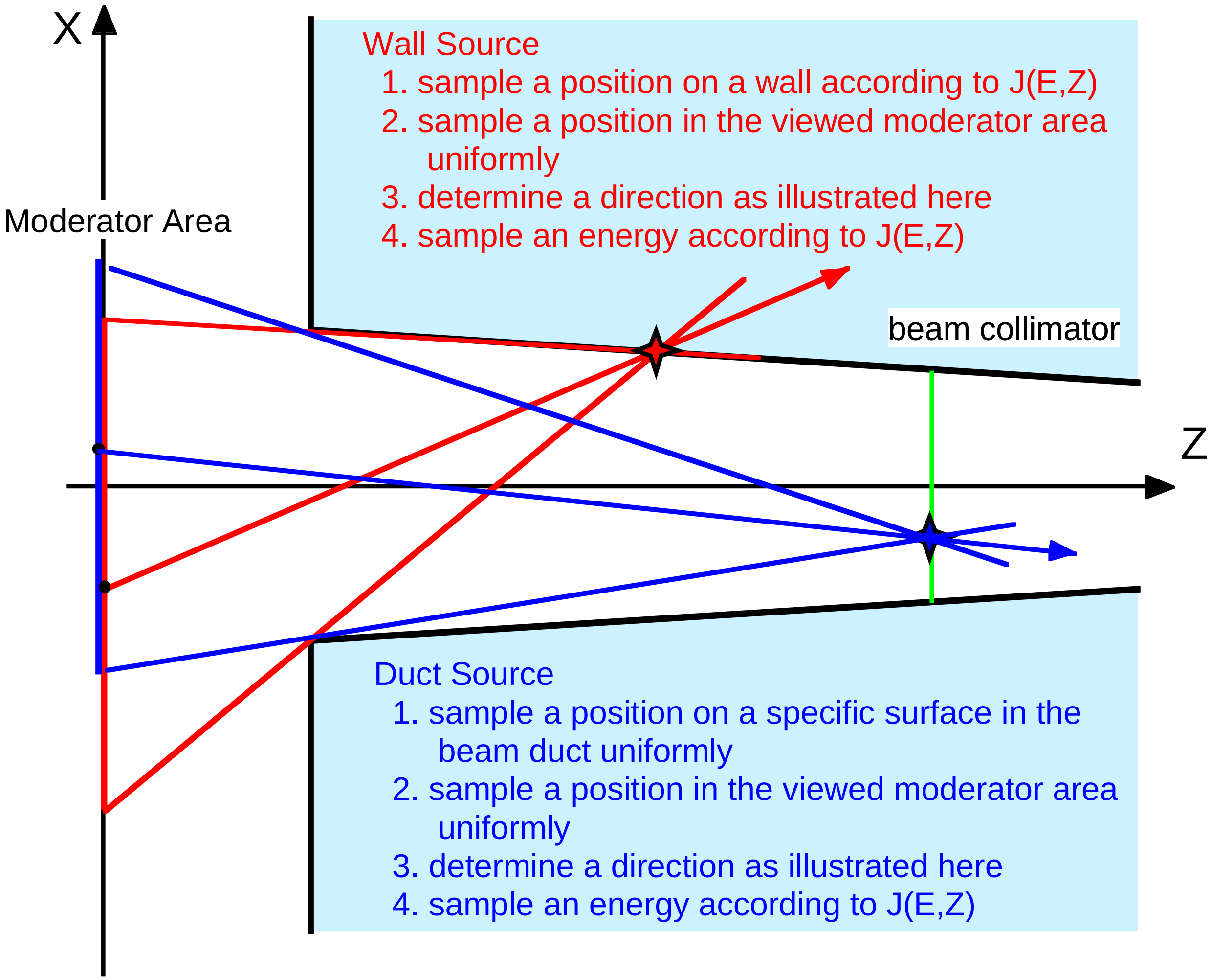


Current: J(R)
Wall Load: -dJ(R)/dR

Symbols: Monte Carlo calculation
Lines: Theoretical estimation

A decrease of neutron current between both ends of an interval just corresponds to a neutron wall load in the interval.

Methodology: Sampling



Wall Source
1. sample a position on a wall according to J(E,Z)
2. sample a position in the viewed moderator area uniformly
3. determine a direction as illustrated here
4. sample an energy according to J(E,Z)

Duct Source
1. sample a position on a specific surface in the beam duct uniformly
2. sample a position in the viewed moderator area uniformly
3. determine a direction as illustrated here
4. sample an energy according to J(E,Z)

Wall Source
- beam line shield
- shutter

Duct Source
- To-chopper
- beam stop
- shutter
- sample

A source subroutines for MCNPX that generate source neutrons for NBL calculations by using the NBL source term was produced.

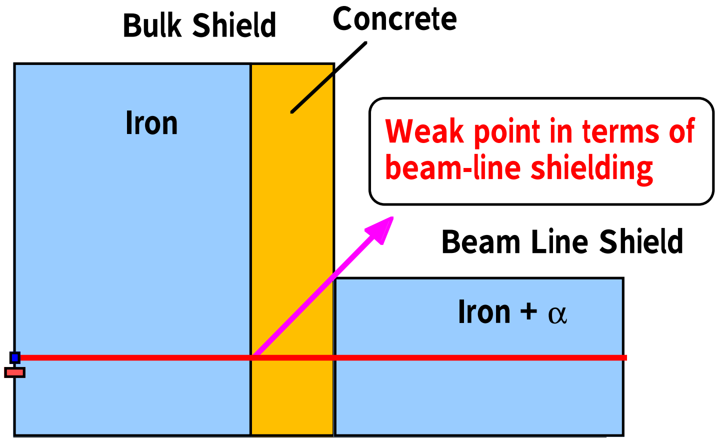
Methodology: Summary

- A new method for NBL shielding calculation has been established.

- Feature:
  - In the 2nd step calculation, source neutrons are
    - not generated on a certain plane across the NBL,
    - but on beam duct walls along the NBL.
  - This method enables us to treat a neutron wall load distribution, that is, a source term, accurately in the NBL shielding calculation.

Junction: Objectives

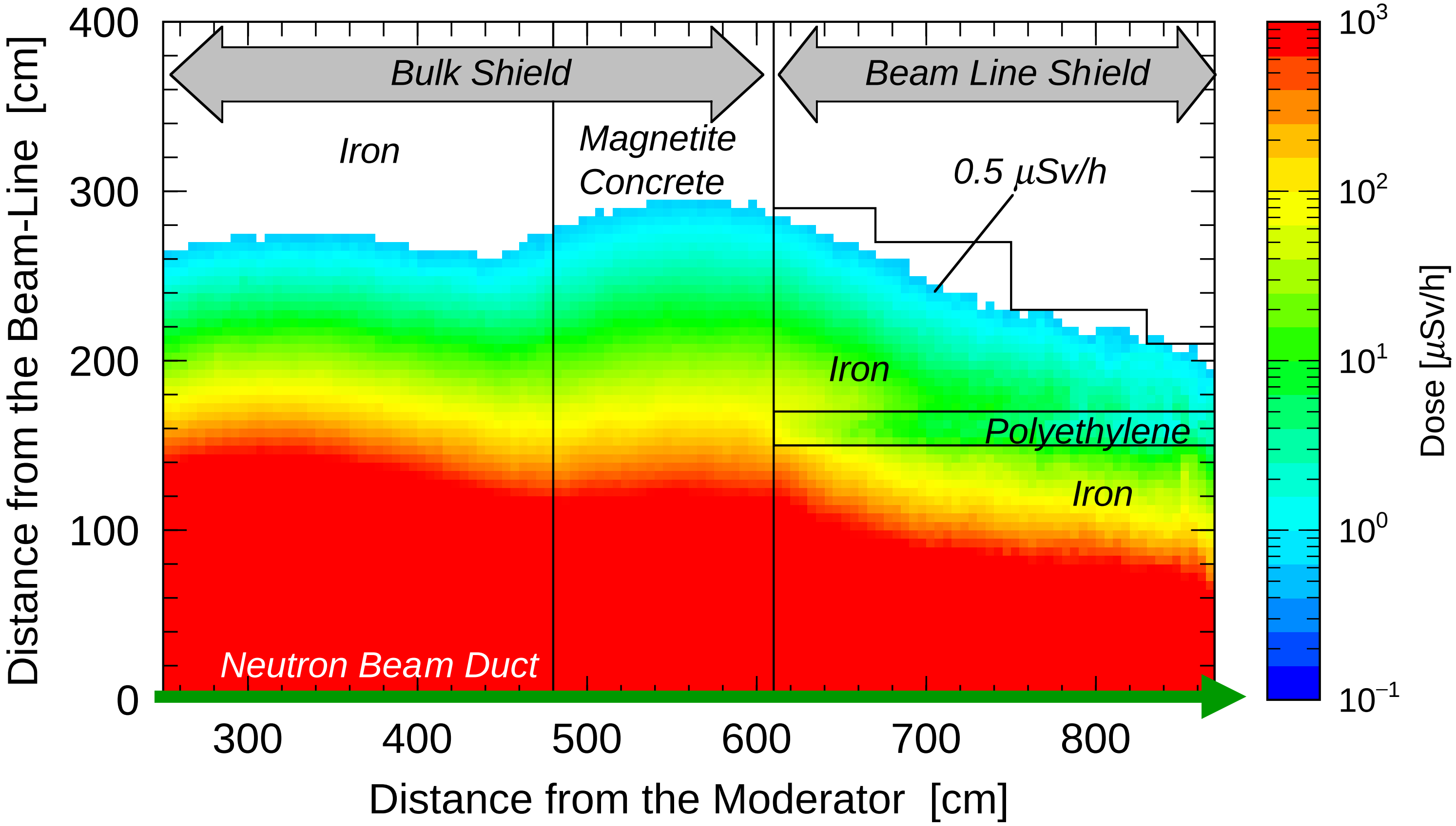
- Bulk shield
  - Iron + Concrete
- Weak point in terms of beam-line shielding
  - The concrete layer is needed for the bulk shield to stop low-energy neutrons penetrating through the thick iron shield.
  - The concrete layer is, however, a weak point in terms of beam-line shielding.
- Objectives
  - To determine an appropriate structure for the junction between the bulk shield and NBL



Junction: Calculation

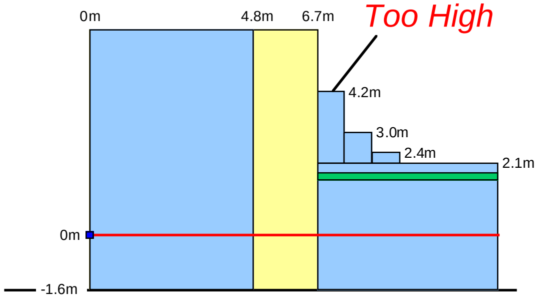
- R-Z model
  - Iron for bulk shield up to 4.8 m from the center
  - Concrete 1.3 or 1.9 m thickness
  - Beam-line shield Iron (1.8m) + Polyethylene (0.3m)
- The NBL source term along the beam line
- Material
  - Iron (7.2 g/cm^3, including void spaces)
  - Concrete
    - Ordinary concrete (2.2 g/cm^3)
    - Magnetite concrete (3.5 g/cm^3)
    - Steel punched magnetite concrete (4.6 g/cm^3)
  - Polyethylene (0.9 g/cm^3)
- Target dose: 0.5 μSv/h by neutrons > 1 MeV
  - assuming that the total dose < 1 μSv/h can be attained under this condition

Junction: 2D-Map

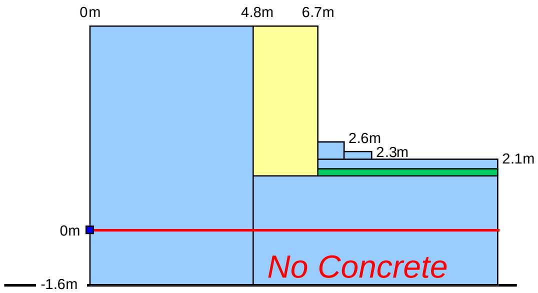

Dose by Neutrons above 1 MeV,   d205

Junction: Results

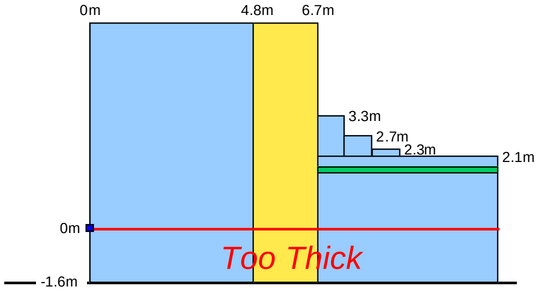
Ordinary Concrete



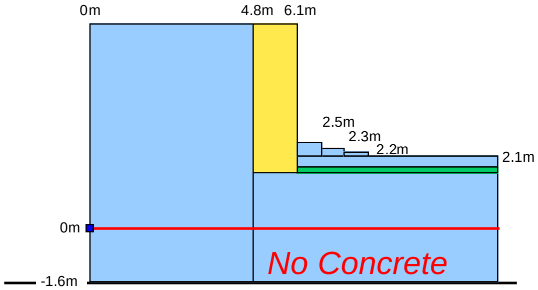
Ordinary Concrete



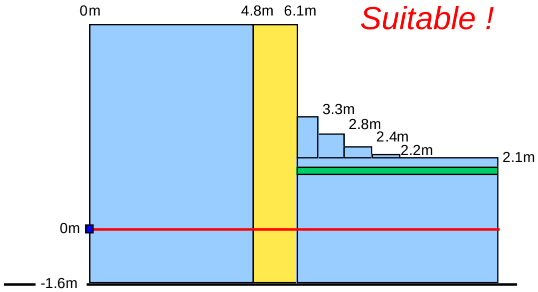
Magnetite Concrete



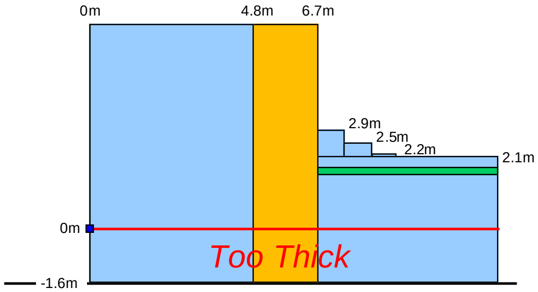
Magnetite Concrete



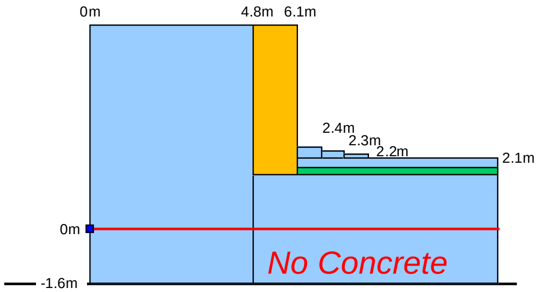
Magnetite Concrete



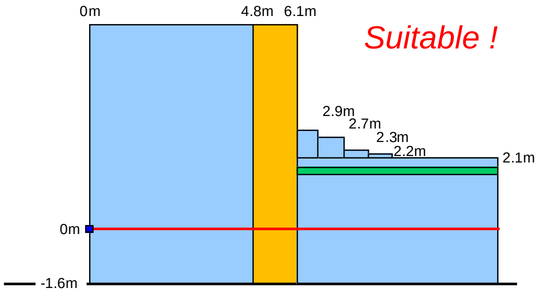
Steel Punched Magnetite Concrete



Steel Punched Magnetite Concrete

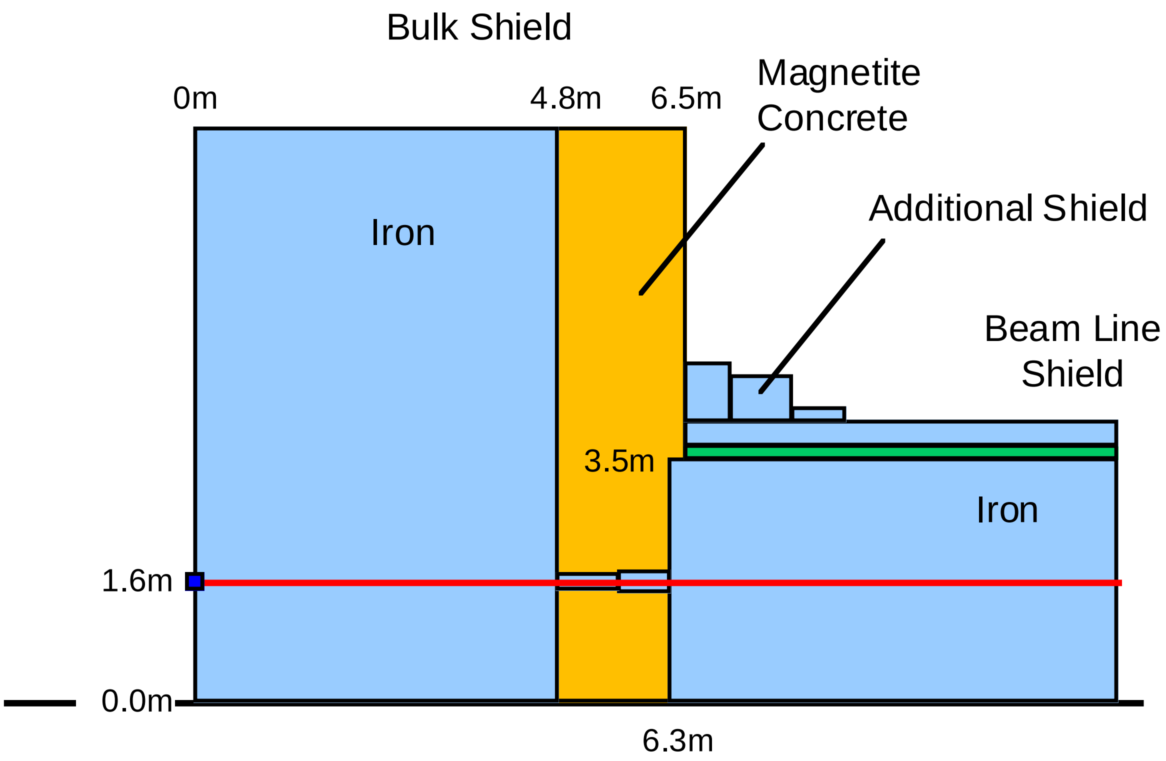


Steel Punched Magnetite Concrete



Junction: Summary

- Magnetite concrete is suitable for the outer layer of the bulk shield to reduce additional shield on the NBL.



NBL: Objectives

- To provide rough estimates of beam line shield thickness for arranging beam lines in the experimental hall
  - Straight duct / Converging duct
  - Dependence on duct size
  - Dependence on distance from the moderator
  - Empirical formula

- Detailed shielding design for each beam line --> Future work

NBL: Calculation

- R-Z model
  - IRON + POLYETHYLENE (30 cm)

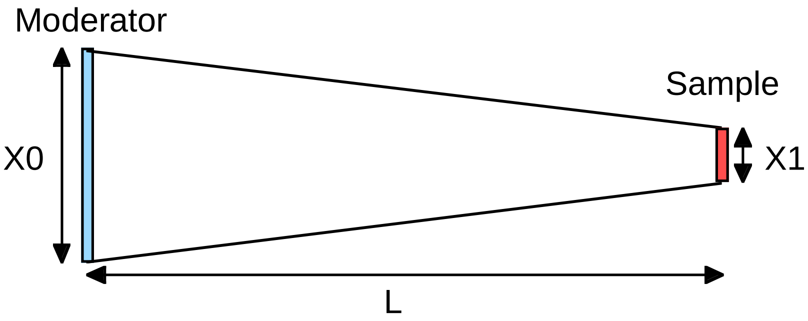
- The NBL source term along the beam line
- Material
  - Iron (7.2 g/cm^3, including void spaces)
  - Polyethylene (0.9 g/cm^3)
- Target dose: 0.2 μSv/h by neutrons > 10 MeV
  - assuming that the total dose < 1 μSv/h can be attained under this condition

- An empirical formula was derived from the calculated results.

NBL: Empirical Formula

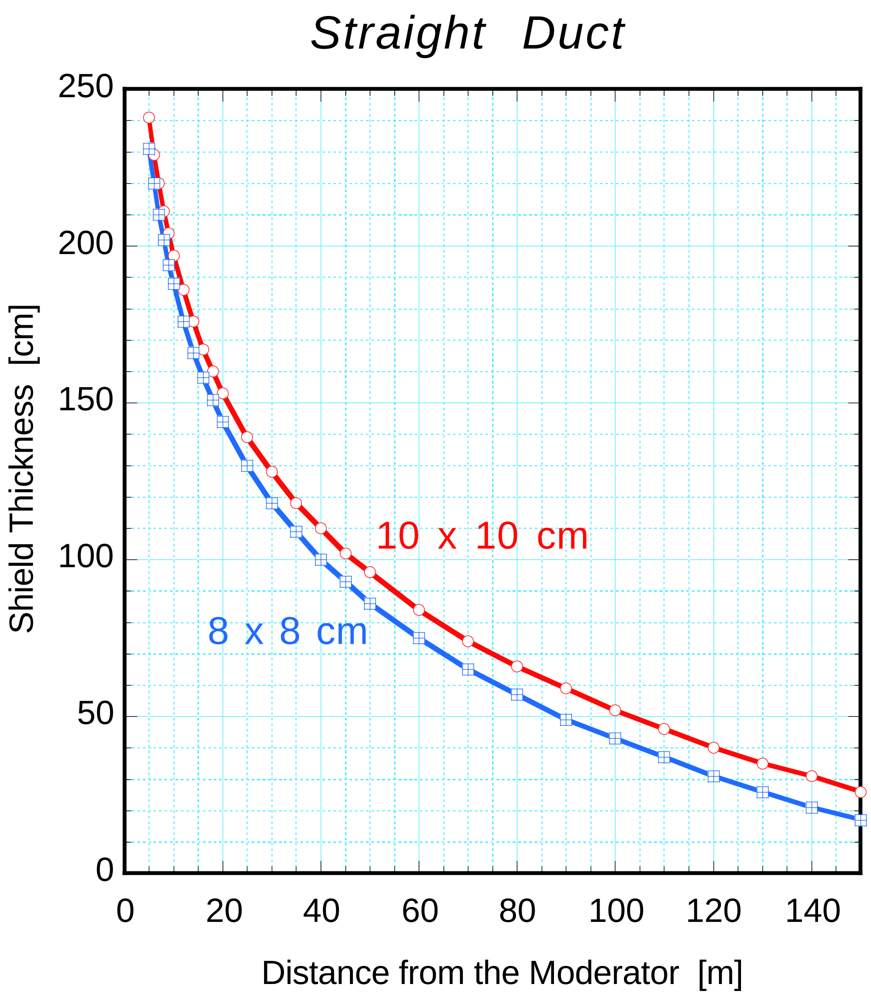
$$T = 530 + 21 \cdot \ln\left\{130 \cdot P \cdot \left(\frac{X_0}{10}\right)^2 \cdot \left(\frac{1}{L^3} + \frac{C}{X_0 L^2}\right)\right\}$$

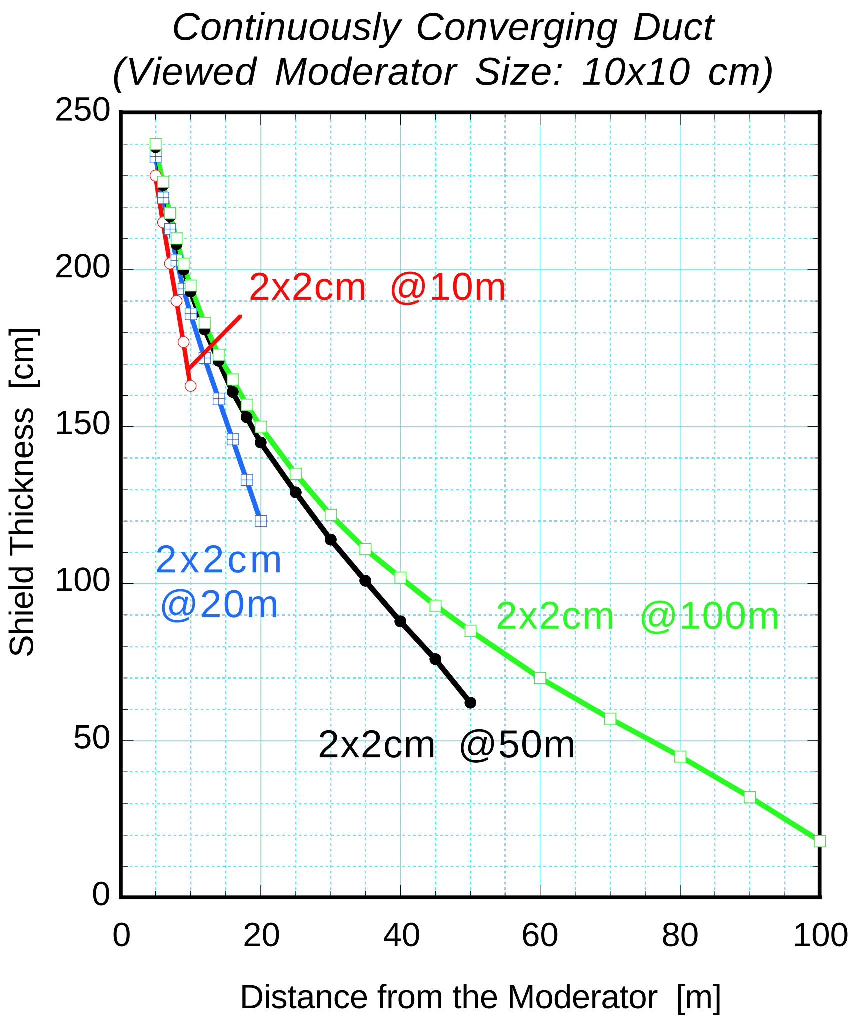
T:	*NBL shield thickness [cm]*
P:	*proton beam power [MW]*
X_0:	*viewed moderator size [cm]*
X_1:	*converged beam size at the sample [cm]*
L:	*distance between the moderator and the sample [cm]*
C:	*convergence rate [$=(X_1-X_0)/L$]*



This formula was used to estimate approximate dimensions of NBL shields for arranging NBLs in the experimental hall.

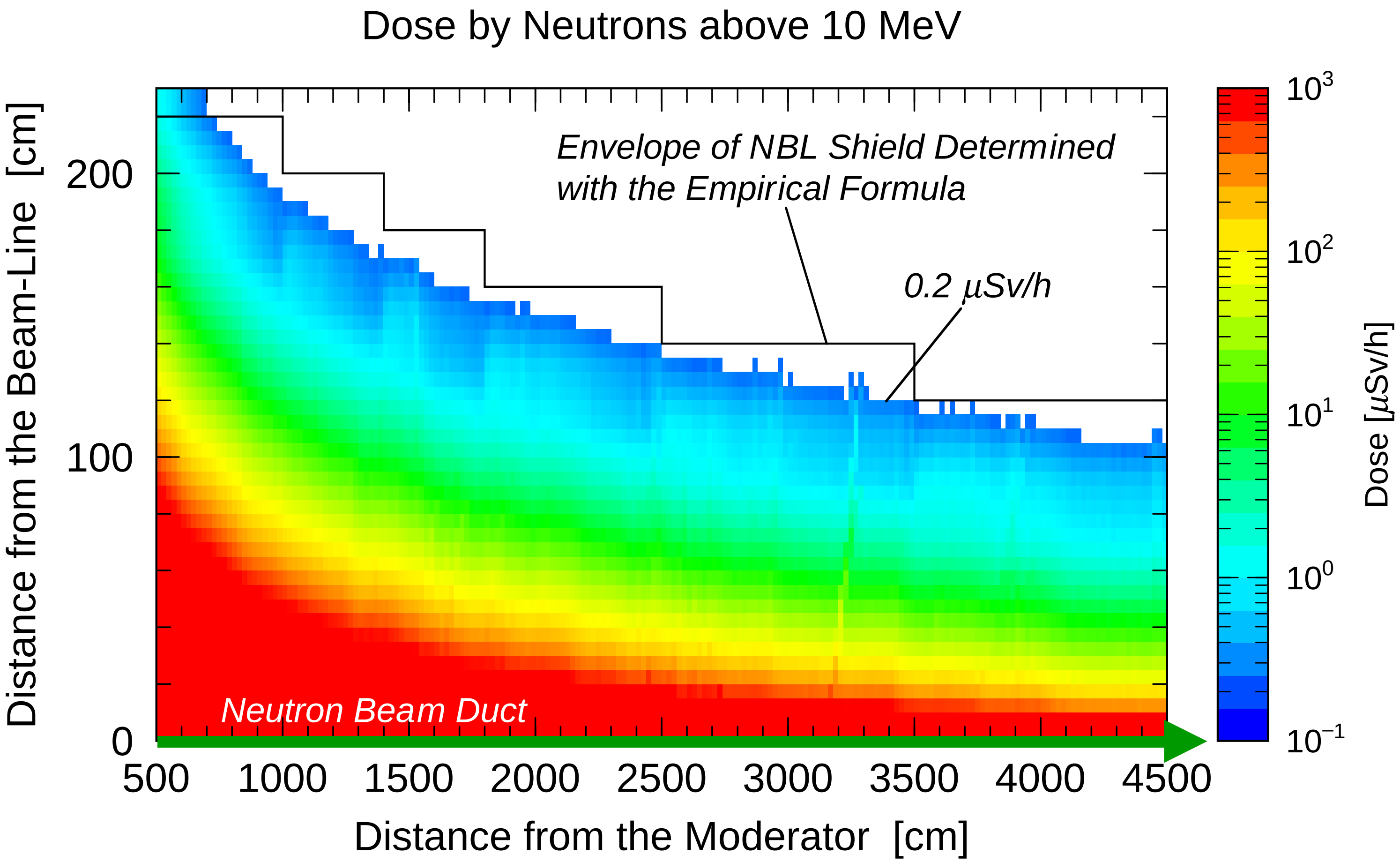
NBL: Estimated Thickness





NBL: Validation

The empirical formula predicts adequately the NBL shield thickness.



NBL: Validation == LASCE Experiment ==

The methodology will be validated by using the LANSCE neutron beam-line shielding experiment.

Beam Stop: Objectives

- To provide rough estimates of neutron beam stop size for arranging beam lines in the experimental hall
  - Dependence on incident neutron flux
  - Empirical formula

- Optimization of a neutron beam stop for each beam line

  --> Future work

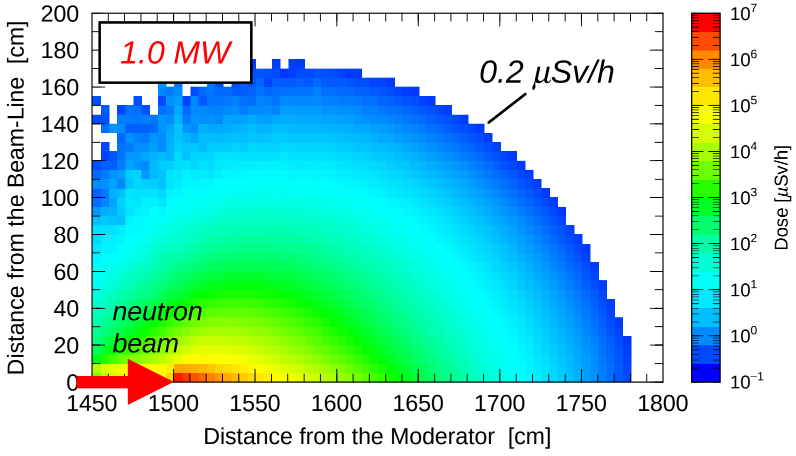
Beam Stop: Calculation

- R-Z model
  - IRON only
  - Increase of shield thickness due to hydrogen-containing plates is assumed to be 15 % of iron thickness.
- The NBL source term along the beam line
- Material
  - Iron (7.2 g/cm^3, including void spaces)
- Target dose: 0.2 μSv/h by neutrons > 10 MeV
  - assuming that the total dose < 1 μSv/h can be attained under this condition

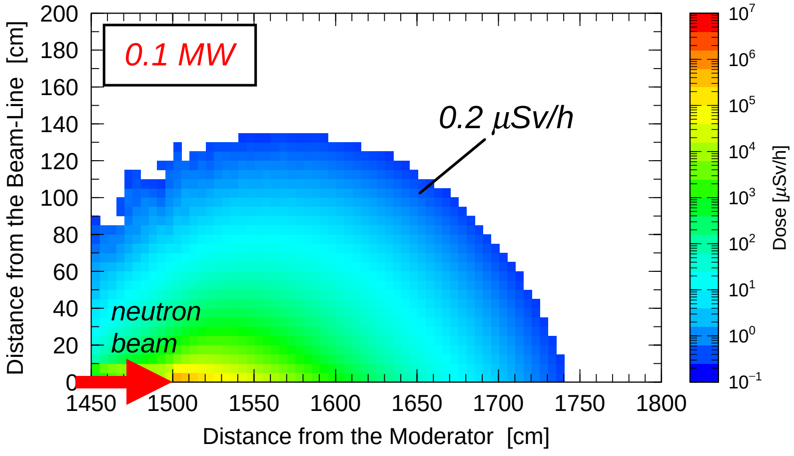
- An empirical formula was derived from the calculated results.

Beam Stop: Calculated Results

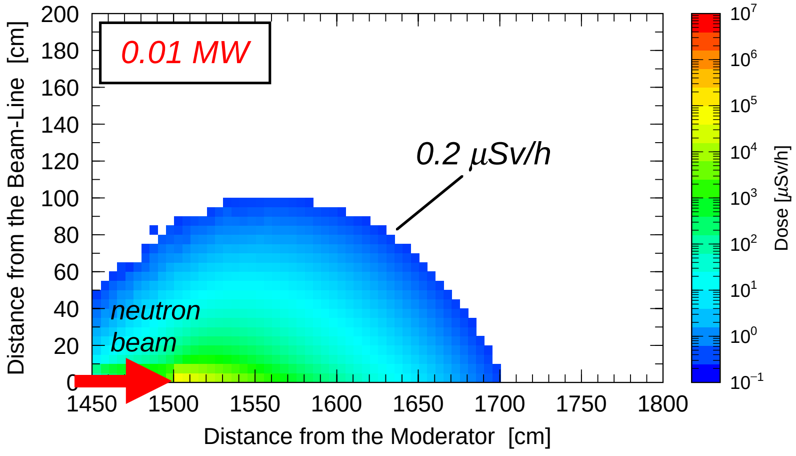
Dose by Neutrons above 10 MeV @ 1.0 MW



Dose by Neutrons above 10 MeV @ 0.1 MW



Dose by Neutrons above 10 MeV @ 0.01 MW



- Beam stop size depends on incident neutron flux.
- Change of incident neutron flux to beam stops is simulated by changing proton beam power in the calculation.

Beam Stop: Empirical Formula

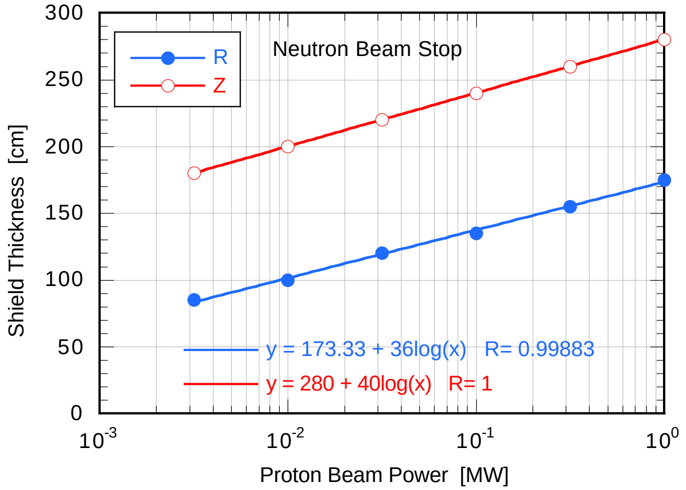
Z: along the neutron beam line

Shield Thickness = 322 + 20 ln (P)

R: direction perpendicular to the neutron beam line

Shield Thickness = 200 + 18 ln (P)

P: Incident neutron flux
1.0 for 10x10cm straight duct and a beam stop
at 15 m from the moderator



Example: 10x10cm straight duct @ 15 m from the moderator, proton beam power 1 MW

Length: {322 + 20 ln(1.0)} x 1.5 = 483 cm

(1.5=1.0+0.5, 1.0 for forward & 0.5 for backward)

Horizontal width: {200 + 18 ln(1.0)} x 2 = 400 cm

(2 for left & right)

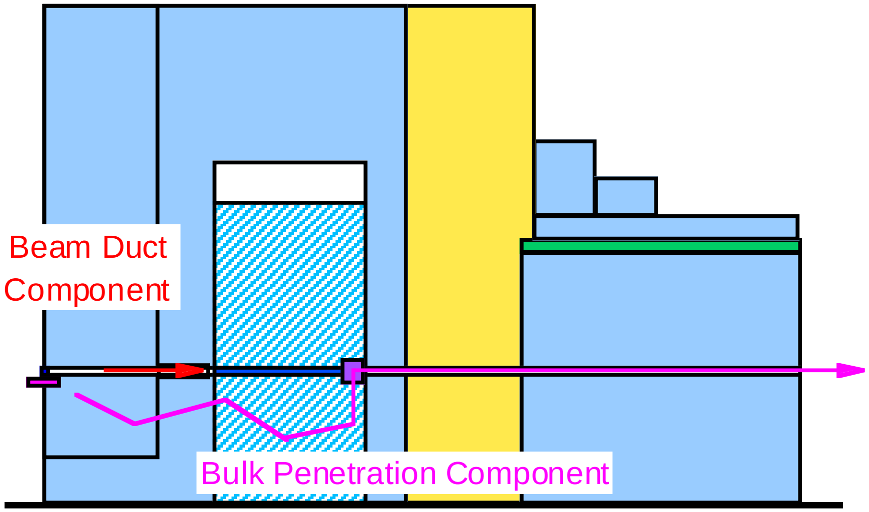
Height: {200 + 18 ln(1.0)} + 175 = 375 cm

(175 cm is the beam line height)

Shutter: Introduction

- Objectives
  - To optimize shutter configurations, i.e., material, size and location
  - To estimate radiation dose at a sample position

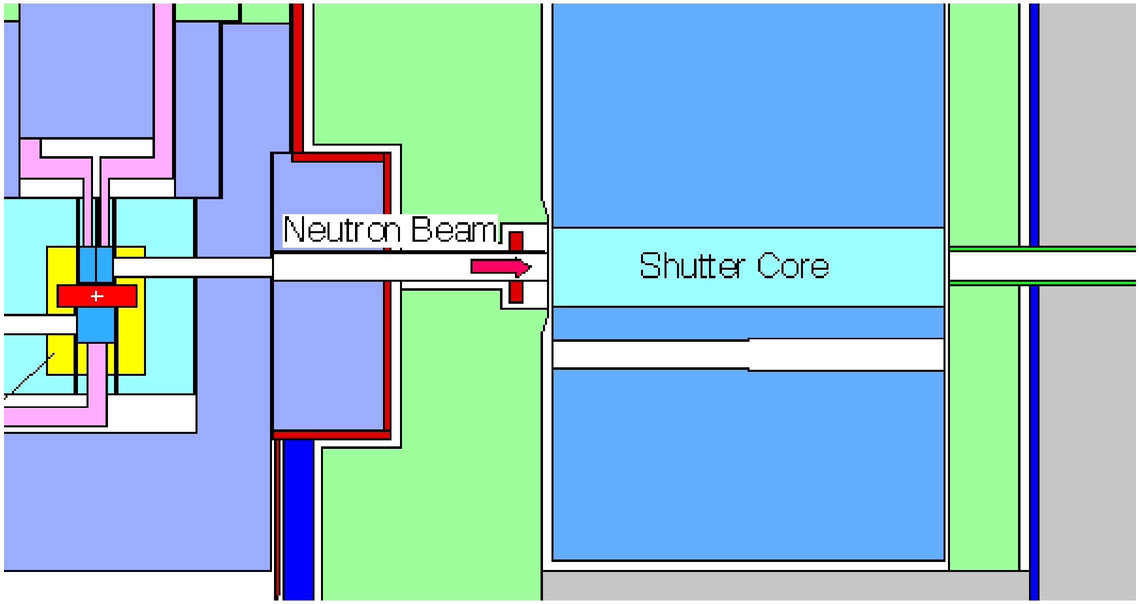
- Two Components to be Considered
  - Beam duct component
    - Uncollided part
    - Collided part
  - Bulk penetration component



Shutter: Need Hydrogen

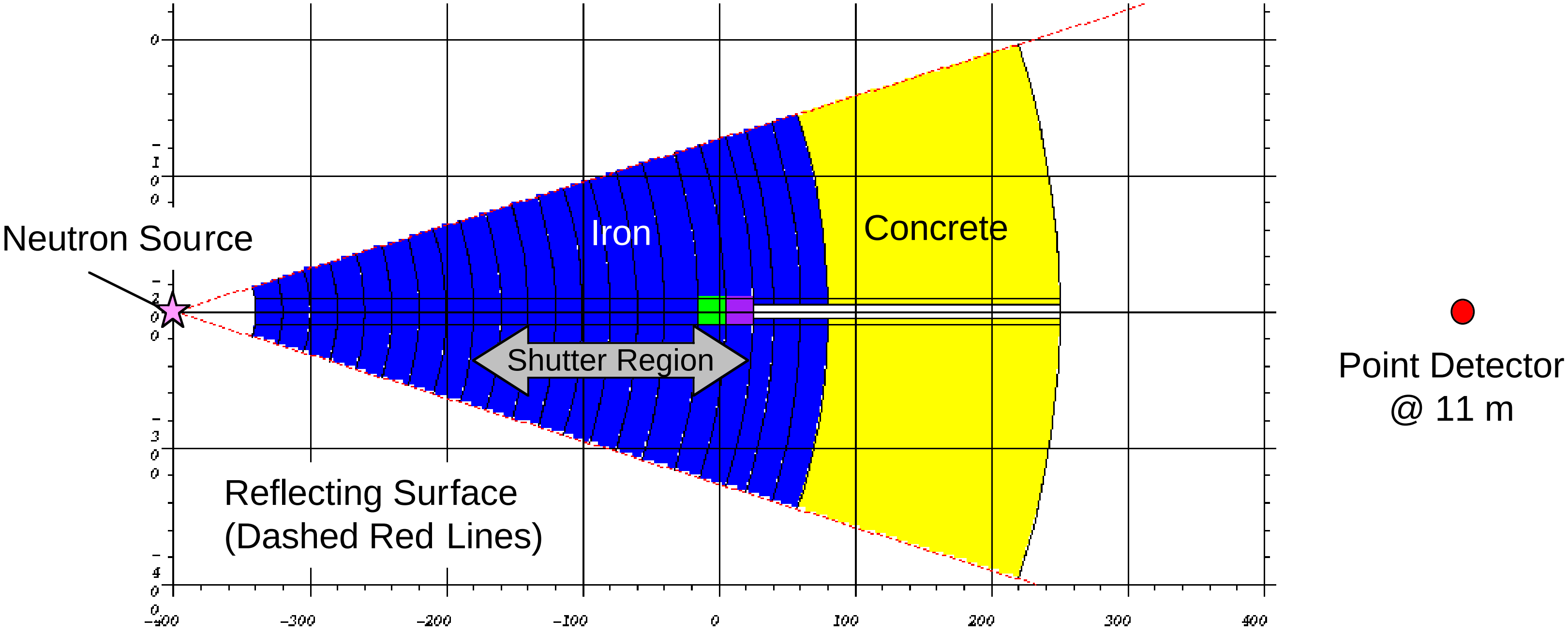
- According to a rough estimation, radiation dose at a sample position will be ~ 100,000 μSv/h mainly due to low-energy neutrons when steel is used solely for a shutter core material.

- Combination of steel and hydrogen-contained material, such as polyethylene, is required for the shutter core.



Shutter: Bulk Penetration Component

- Calculation
  - Source neutron for the 1-D bulk shielding calculation
  - Monte Carlo calculation
  - A spherical geometry with reflecting surface
  - Point detector at the sample position at 11 m from the moderator


Neutron Source

Iron

Concrete

Shutter Region

Point Detector
@ 11 m

Reflecting Surface
(Dashed Red Lines)

Shutter: Bulk Penetration Component

Total Shutter Length: 2.0 m (Iron 1.6 m + MAT-A 0.2 m + MAT-B 0.2 m)   unit: μSv/h

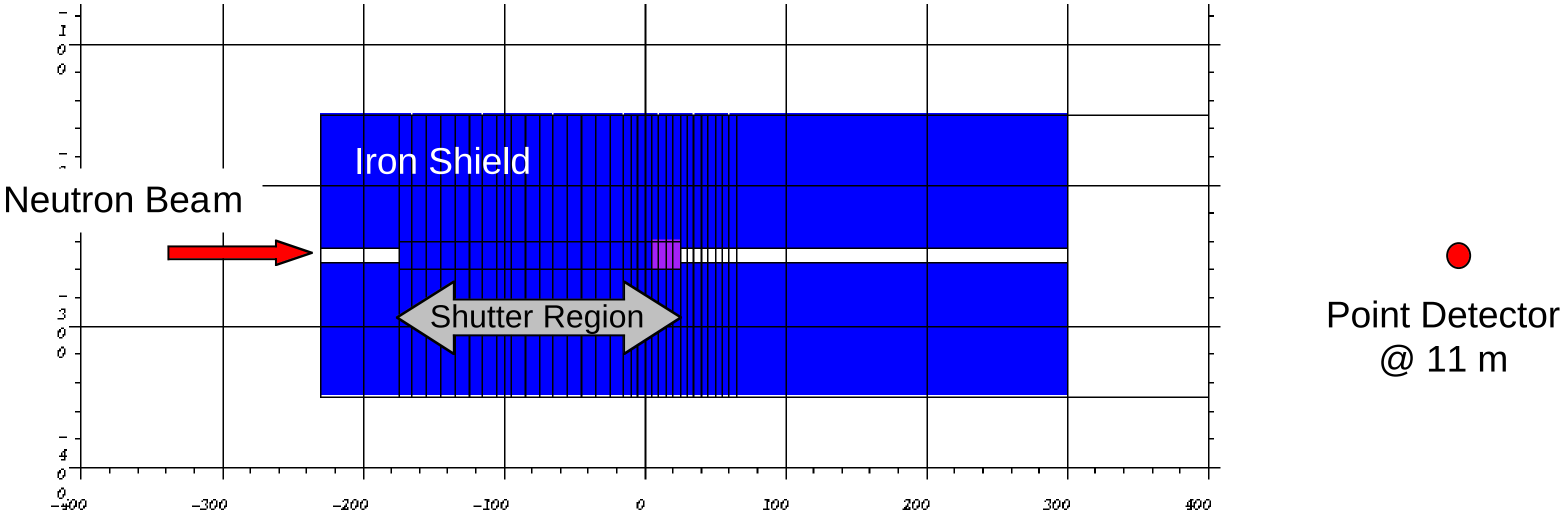
MAT-A	MAT-B	Thermal	eV - keV	> 1 MeV	Photon	Total
PE	Iron	0.6	385.0	0.6	6.3	392.5
B-PE	Iron	0.8	388.8	0.6	5.1	395.3
Iron	PE	35.5	78.1	0.6	69.4	183.5
Iron	B-PE	1.1	79.1	0.6	19.0	99.7
PE	SS-316	0.6	418.7	0.5	8.1	427.9
B-PE	SS-316	0.6	434.5	0.6	6.2	441.9
PE	Tungsten	0.4	297.3	0.3	8.0	305.9
B-PE	Tungsten	0.5	305.1	0.4	7.6	313.5
Iron	Tungsten	0.4	331.5	0.2	8.6	340.7
Tungsten	Tungsten	0.5	325.6	0.2	8.8	335.0
Iron	Ord. Conc.	60.1	257.2	0.5	33.4	351.2
Iron	Mag. Conc.	20.7	390.0	0.5	44.5	455.7
Ord. Conc.	Ord. Conc.	52.6	214.2	1.0	38.0	305.8
Mag. Conc.	Mag. Conc.	18.0	280.4	0.8	47.4	346.7
PE	PE	34.5	72.3	1.3	87.1	195.2
B-PE	B-PE	1.0	59.6	1.4	18.4	80.3

Shutter: Bulk Penetration Component

- Results
  - Low-energy neutrons and photons are the main contributor to the total dose.
  - Since these low-energy neutrons travel all around the steel shield region, enhancement of the shutter core material is not effective to reduce the dose rate at a sample position.
  - When polyethylene is used at the core end, the total dose is ~ 200 μSv/h. Hydrogen atoms in polyethylene attenuate effectively low-energy neutrons penetrating through the steel shield blocks.
  - Adding boron in polyethylene is further effective to reduce the dose due to thermal neutrons and photons, and the total dose is decreased to ~ 100 μSv/h.

Shutter: Beam Duct Component

- Uncollided Part
  - The NBL source term
  - Attenuation of neutron flux in the shutter due to total cross section was calculated by a simple exponential formula
- Collided Part
  - The NBL source term
  - Monte Carlo calculation with an R-Z model
  - Point detector at the sample position at 11 m from the moderator



Shutter: Beam Duct Component

unit: μSv/h

		Thermal	eV - keV	> 1 MeV	Photon	Total
Iron 180 cm + PE 20 cm	Uncollided	0.0	0.9	1.1	0.0	2.0
	Collided	0.4	10.5	1.9	1.1	13.9
	Total	0.4	11.4	3.0	1.1	15.9

		Thermal	eV - keV	> 1 MeV	Photon	Total
Iron 220 cm + PE 20 cm	Uncollided	0.0	0.3	0.0	0.0	0.3
	Collided	0.1	8.3	0.1	0.4	8.9
	Total	0.1	8.6	0.1	0.4	9.2

		Thermal	eV - keV	> 1 MeV	Photon	Total
Iron 180 cm + B-PE 20 cm	Uncollided	0.0	0.9	1.1	0.0	2.0
	Collided	0.0	8.6	1.6	0.3	10.5
	Total	0.0	9.5	2.7	0.3	12.5

		Thermal	eV - keV	> 1 MeV	Photon	Total
Iron 220 cm + B-PE 20 cm	Uncollided	0.0	0.3	0.0	0.0	0.3
	Collided	0.0	7.3	0.1	0.1	7.5
	Total	0.0	7.6	0.1	0.1	7.8

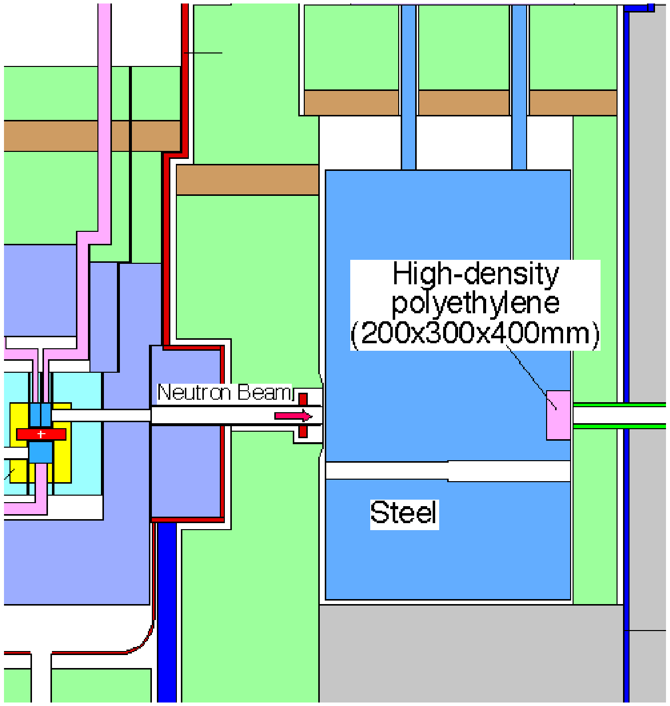
Shutter: Beam Duct Component

- Results
  - Dose rate due to the uncollided part is as small as 2 µSv/h for the 2.0 m length shutters.
  - Collided low-energy neutron in eV-keV region is the main contributor to the dose rate at the sample position. Use of polyethylene at the core end is effective to reduce the total dose rate.
  - When the total shutter length is 2.0 m (1.8 m steel + 0.2 m polyethylene), total dose rate is at most 20 µSv/h.

  - Dose rate due to the beam duct component is not significant when it is compared with that due to the bulk penetration component.

Shutter: Summary

- A combination of steel (1.8 m) & polyethylene (0.2 m) was selected finally for the shutter core. No high density material like tungsten will be used.
- Although borated polyethylene is effective to reduce the dose rate at a sample position, it is not adopted because the material swells a little.
- A dose rate at a sample position will be at most 200 μSv/h. The dose rate can be reduced easily to 10 μSv/h by adding an auxiliary shield because low-energy neutrons and photons are dominant in the total dose rate.

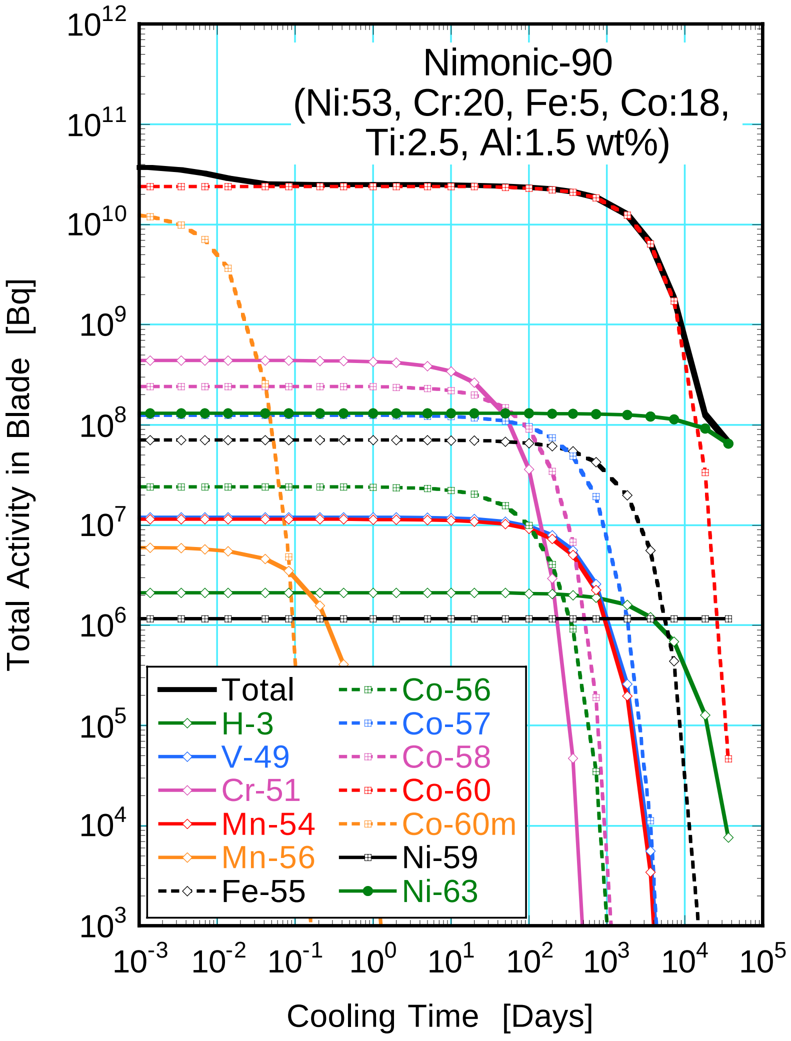


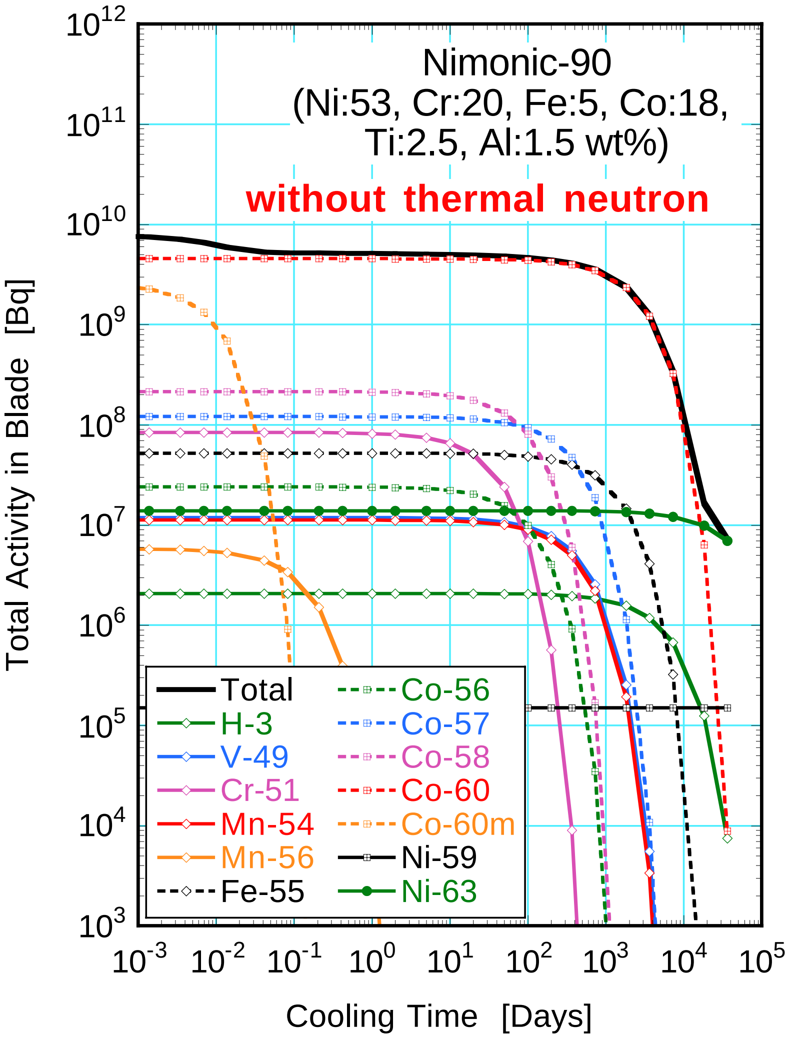
To-Chopper: Activation

- Objectives
  - To estimate radioactivity inventory in a chopper blade for maintenance
  - To give a guideline for selecting a chopper blade material

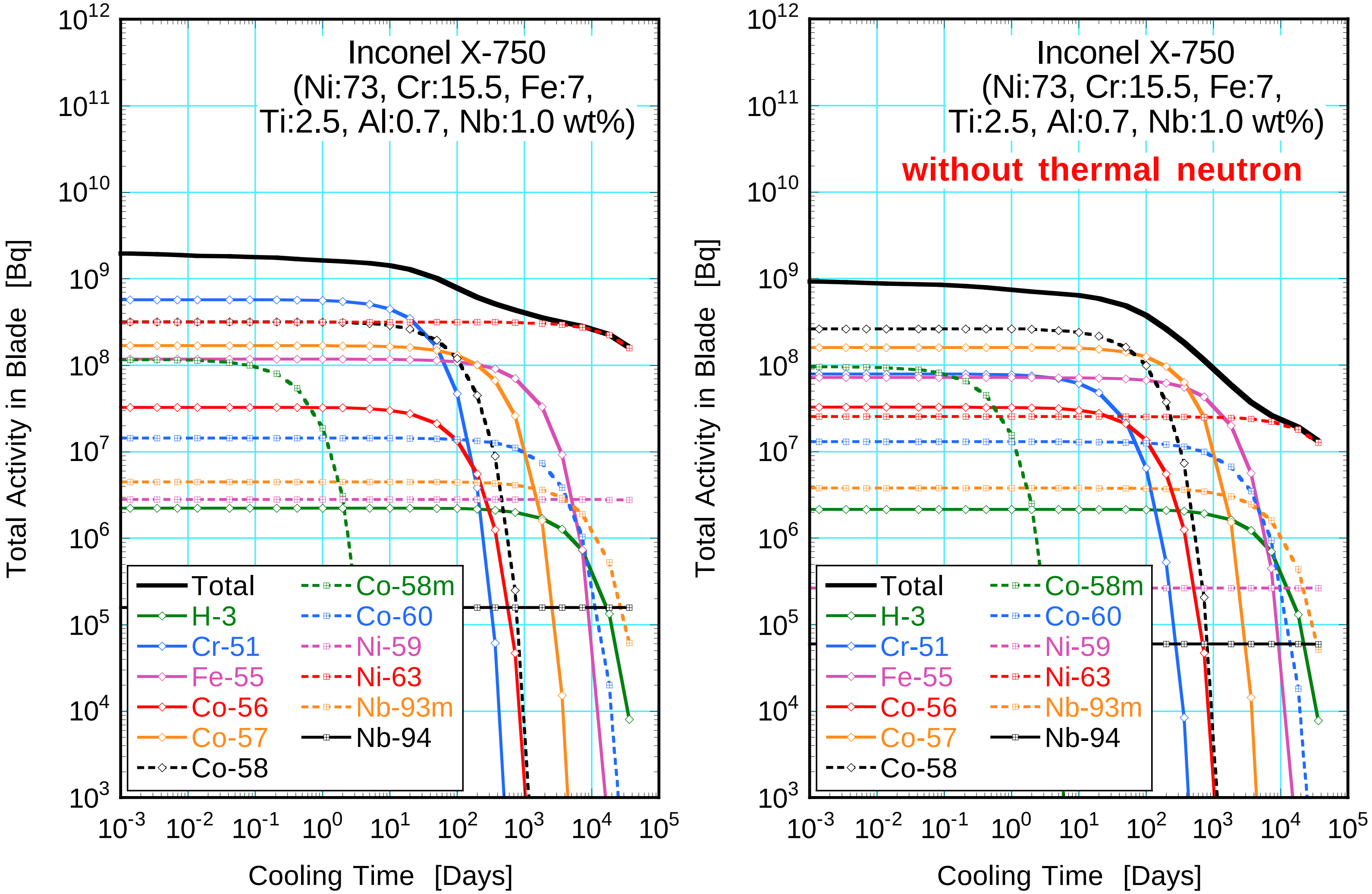
- Calculation Conditions
  - Blade size: 7 cm x 7 cm, 30 cm length
  - Material: Nimonic-90 or Inconel X-750
  - Position: 6.2 - 6.5 m from the moderator
  - Neutron beam size: 5.64 cm x 5.64 cm
  - Neutron flux: 4.1×10^9 n/s/cm^2
  - Operation: 1 MW, 5000 hours/year, 30 years

To-Chopper: Activation (Nimonic-90)





To-Chopper: Activation (Inconel X-750)



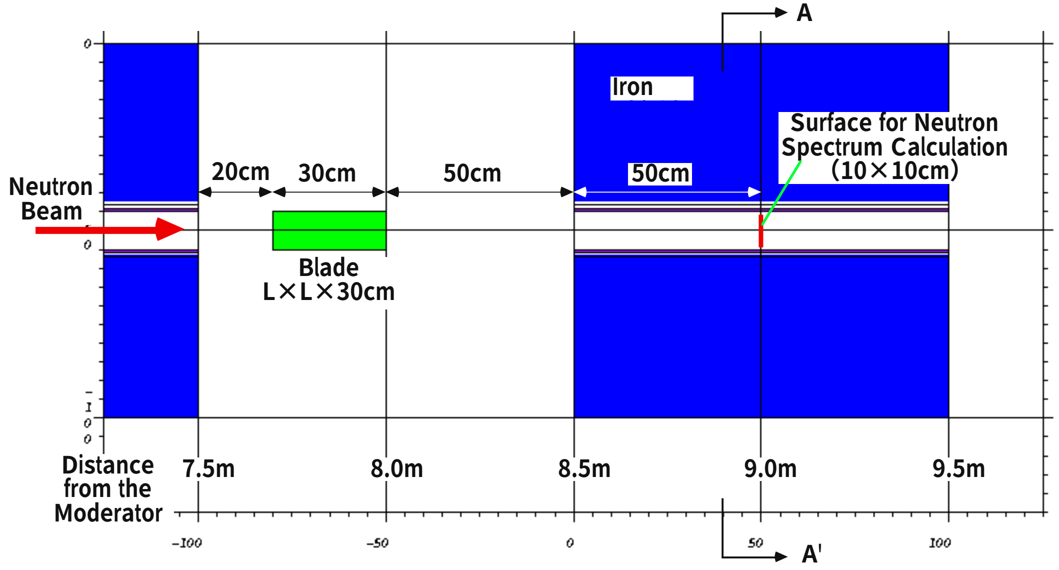
To-Chopper: Activation

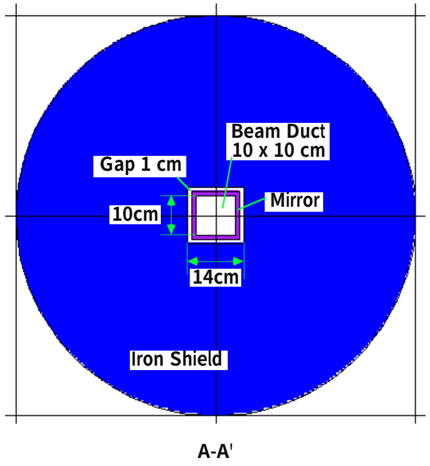
- Summary
  - Dominant radioactive nuclides are produced *via* the *(n,γ)* reactions.
    - $^{59}Co(n,\gamma)^{60}Co$, $^{50}Cr(n,\gamma)^{52}Cr$, $^{62}Ni(n,\gamma)^{63}Ni$, $^{54}Fe(n,\gamma)^{55}Fe$
  - Selecting a non-cobalt material is very effective to reduce total activity.
  - The total activity in Inconel X-750 is about 1/10 to that in Nimonic-90. Since main nuclides in Inconel X-750 do not emit gamma-rays as intensely and/or energetically as ^{60}Co, radiation dose from the Inconel X-750 blade is further less than that from the Nimonic-90 blade.
  - When a blade is made of Inconel X-750, total activity after 10 days cooling is approximately 10^9 Bq. This value is about 100 times less than the SNS estimation in a similar condition.

To-Chopper: Blade Size

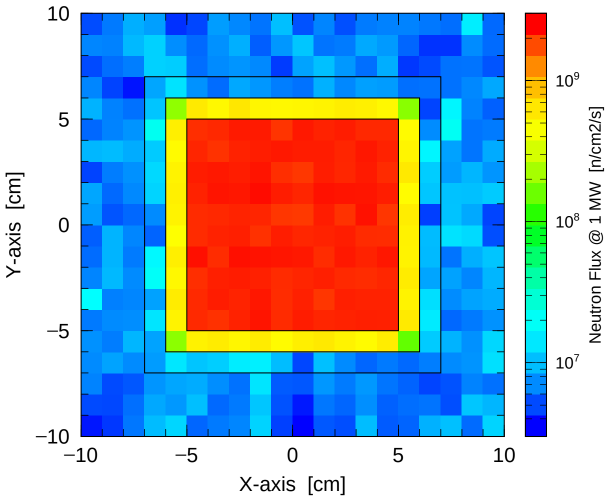
- Objectives
  - To give a guideline for a chopper blade size
    - Large enough in terms of shielding for high-energy neutrons
    - Small enough for short rise-time of neutron pulses and light weight

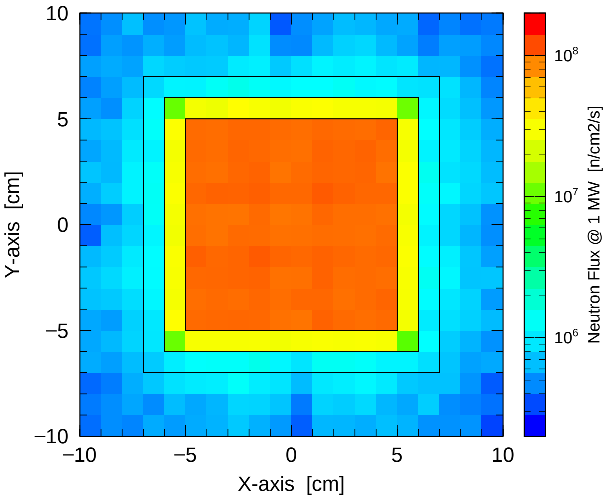
- Calculation Conditions
  - Blade size: L x L x 30 cm, L = 0, 10, 10.5, 11, 11.5, 12, 14, 16
  - Material: Inconel X-750, 8.5 g/cm^3

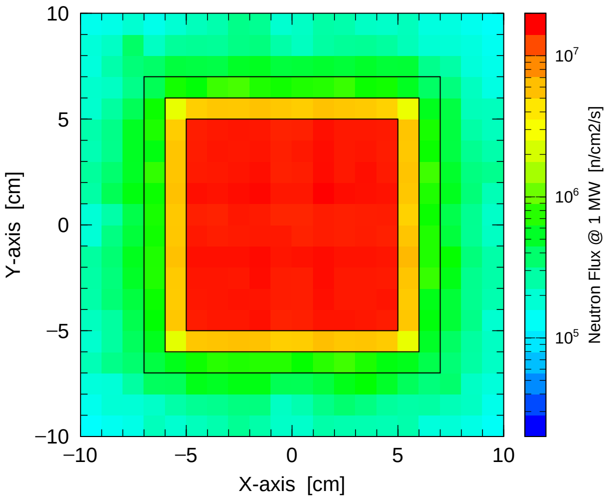


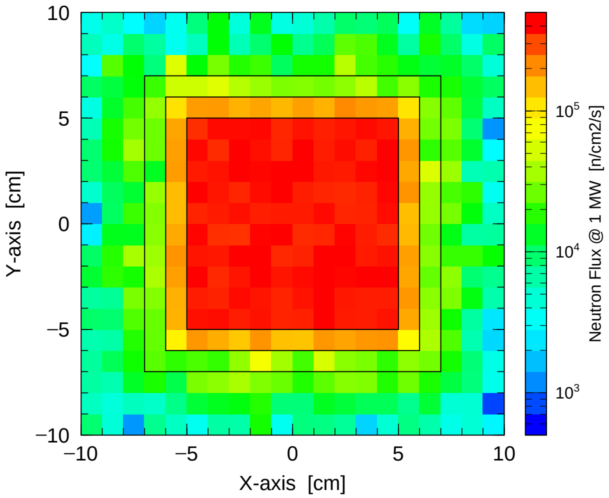


To-Chopper: Blade Size


Total Neutron Flux


Neutron Flux > 1 MeV


Neutron Flux > 10 MeV

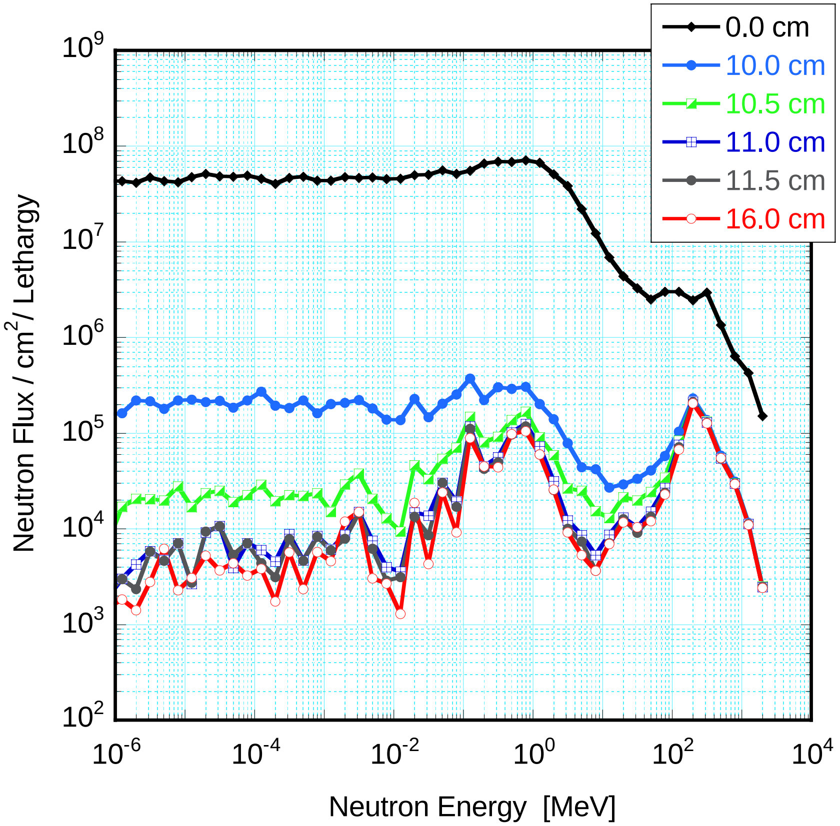

Neutron Flux > 100 MeV

Neutron flux distribution at the front end of the blade

Low-energy neutron flux is well collimated while high-energy neutrons are scattered significantly.

To-Chopper: Blade Size

- Results
  - When the blade size is large enough, high-energy neutron flux attenuates more than 10 times, and low-energy neutron flux 10^3 ~ 10^4 times.
  - When the blade size is just the same as the inner beam duct size, low-energy neutron flux increases more than 10 times.
  - The blade size of 11 cm, *i.e.*, 10 cm surrounded by an additional 0.5 cm layer, is enough.



Neutron flux spectra on the 10 x 10 cm plane
In the beam duct 1 m from the blade end as a
function of blade size