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Shielding Aspect of High Current Proton Linear Accelerator (KOMAC)

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Proton Engineering Frontier Project (PEFP) is building the Korea Multipurpose Accelerator Complex (KOMAC), which consists of a high current 100 MeV proton linear accelerator and various particle beam facilities during the period from 2002 to 2012. As an interim goal for the project, 20 MeV linac will be built in 2007. This presentation provides a preliminary estimate of shielding required for the 20 mA proton linac, the beam dump, and its beam facility. Required thickness of concrete was assessed by a simple line-of-sight model for the lateral shielding of beam line and beam dump both on normal and accident conditions. For actual shielding design calculation, a code system consisting of the MCNPX, DORT and DUCT-III was established, and their validation calculations were performed for the attenuation coefficients, beam line shielding, and duct streaming.

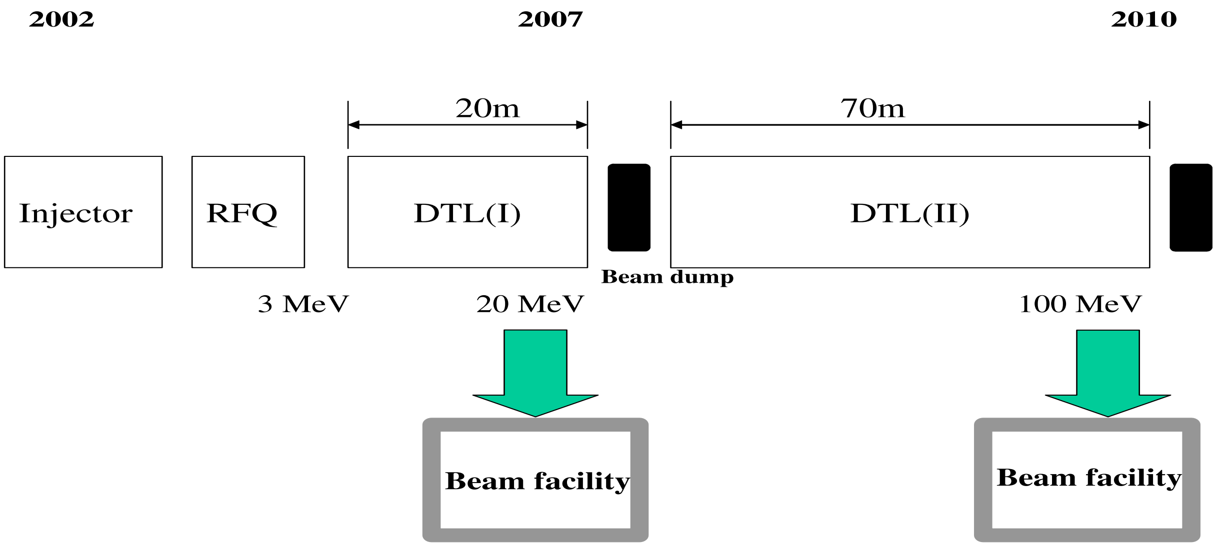

Figure 1: A schematic diagram of the KOMAC with the construction time-line

1 Introduction

PEFP (Proton Engineering Frontier Project) is building the KOMAC (Korea Multipurpose Accelerator Complex), which consists of a proton linear accelerator with 100 MeV energy, 20 mA current, and various particle beam facilities during the period from 2002 to 2012. In the meantime, as an interim goal for the project, 20 MeV linac will be built in 2007. Table 1 lists key parameters of the KOMAC, and Fig. 1 shows a schematic diagram of the KOMAC with the construction time-line. One of the KOMAC's unique characteristics is its high average beam current, 4.8 mA which is 3 times high as compared with the ORNL's Spallation Neutron Source (SNS), 1.4 mA at 1 GeV. This high current is very challenging not only for the accelerator design itself, but also for the shielding design.

This presentation provides a preliminary estimate of shielding required for the 100 MeV, 20 mA proton linac, 20 MeV beam dump, and its beam facility. Required thickness of concrete was assessed by a simple line-of-sight model for the lateral shielding of beam line on nominal and accident conditions, and the beam dump. For an actual shielding design, a code system consisting

Table 1: Key parameters of the KOMAC

Proton beam energy on target	20 MeV (2007) , 100 MeV (2012)
Pulse repetition rate	120 Hz
Proton pulse length on target	2 ms
Average linac macro-pulse current	20 mA
Linac duty factor	24 %
Average proton current	3.0 x 1016 ptns/secs
Average beam current	4.8 mA

*Average beam current of SNS is 1.4 mA at 1 GeV

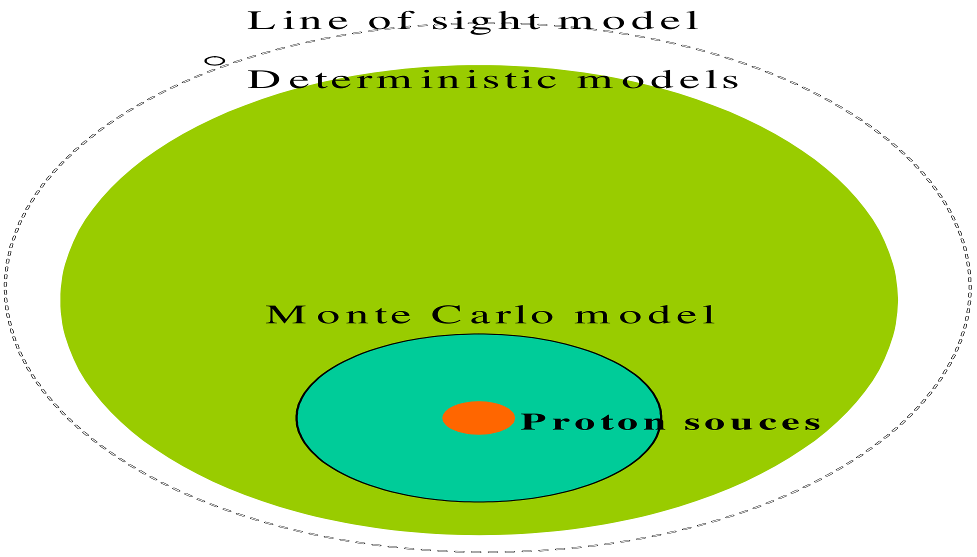

Figure 2: Design strategy of the KOMAC shielding

of the MCNPX [1], DORT [2], DUCT-III [3] was established, and its validation calculations were performed for the attenuation coefficients, beam line shielding, and duct streaming.

2 Design assumptions, requirements and strategy

As for the design assumptions, normal linac operation and accidental beam loss were taken into account in the shielding calculations. Beam losses for normal operation were assumed as 1 W/m, a widely accepted figure which should keep the induced radioactivity in the machine at a level sufficiently low to permit hands-on maintenance. This value corresponds to a proton beam loss of $3x10^{11}$ and $6x10^{10}$ 6x109 protons per meter and per second at 20 MeV and 100 MeV, respectively.

For the shielding design, the dose equivalent rate limit was taken as 0.1 μSv/h for public areas and 10 μSv/h for controlled areas. These figures assures that the annual dose equivalent limit [4] of 1 mSv for the public, and 20 mSv limit for the KOMAC staffs with an operating time 2000 hours per year, will not be exceeded.

An accident scenario considers a full loss of the 480 kW beam (100 MeV) at a single point. A tentative design requirement for full beam loss is quoted from CERN stating that [5]

> “A full beam loss at a localized point must not give rise to a dose equivalent rate outside the shielding exceeding 100 mSv/h and the accelerator control system must be capable of aborting the beam in a time short enough that the integral dose caused by such an accidental condition remains negligible”

At the initial stage of the shielding design, a preliminary estimate of the shielding thickness for the linac and beam dump is performed first by a simple line-of-sight model. Subsequent design will utilize both accurate Monte Carlo model (MCNPX) and fast deterministic model (DORT and DUCT-III). As shown in Fig. 2, Monte Carlo model maps boundary surface leakage to boundary source for multi-dimensional discrete ordinate model such as DORT, or simple semi-empirical model such as DUCT-III.

Table 2: Minimum shielding thickness required to reduce the dose equivalent rate to below 0.1 μv/h (the limit for public exposure) and 10 μv/h (controlled radiation area) for a continuous loss of 1 W/m.

E_p (MeV)	I_p	Required shielding (cm)	Required shielding (cm)
20	2.2 x 10^{12}	203	148
100	4.5 x 10^{11}	305	210
1000	4.5 x 10^{10}	595	375

3 Line-of-sight model

Preliminary shielding calculations were performed using a simple point source and line-of-site model. This model assumes a localized radiation source (i.e., a localized beam loss) and requires the knowledge of the source (i.e., the number and energy distribution of the neutrons generated by the interaction of the proton beam with accelerator components or a target) and of the attenuation length (which accounts for the shielding properties of the material). For lateral shielding (i.e., 90 to the proton beam) and pure cylindrical geometry, the model takes the simple form:

$$H = H_0 \frac{exp(-d/\lambda)}{r^2} \tag{1}$$

in which H is the dose equivalent past the shield, H_0 is the source term (the dose equivalent at unit distance from the unshielded source), d is the thickness of the shield, λ is the attenuation length of the shielding material and $r = r_0 + d$, where r_0 is the distance from the radiation source to the inner wall of the shield. Below 1 GeV, H_0 and vary with neutron energy and depend on target material.

3.1 Normal operation

The calculations were performed at 20, 100 and 1000 MeV. Source terms and attenuation lengths from ref. [6] were used for three energies, taking data for a thin copper target. The use of thin target data is a conservative assumption, as the neutron spectrum from a thick target would be softer, i.e, less penetrating through the shield. The minimum shielding thicknesses required to reduce the ambient dose equivalent rate to below the public limit and to below the design value of a controlled radiation area are given in Table 3.1. The distance from the source to the outer surface of the shield (the parameter r in eq. (1)) was taken as 5 m for proton energies of 25 and 100 MeV and 10 m for 1000 MeV.

3.2 Full beam loss

A loss of the entire beam (4.8 mA average current) corresponds to 3 x 10^{16} lost protons per second. If such loss is localized at one point, the source term for $Ep = 100$ MeV is approximately 1.3 x 10^6 Sv m^2/h, which would produce an instantaneous dose equivalent rate outside a shielding designed for public occupancy ($d/\lambda = 12.2$ and $r = 10$ m) of 80 mSv/h. If the beam is cut within 100 ms, the integrated dose equivalent would be less than 2.6 μv, a perfectly acceptable figure, when compared with the annual dose equivalent of 1 mSv for the public occupancy.

Therefore a shield designed for a continuous beam loss of 1 W/m during routine operation is also adequate for an accidental loss of the full beam at a localized point, provided that the linac can be stopped within 100 ms, which is well within the capabilities of the accelerator control system. The integral dose delivered to the public area in this time interval is of the order of μv, based on the fact that the loss is localized at one point.

3.3 20 MeV beam dump

20 MeV beam dump should be capable of absorbing the full 4.8 mA beam, which corresponds to 3 x 10^{16} protons per second. If they are localized at one point inside the beam dump, the source term for Ep = 20 MeV is approximately a dose equivalent rate of 17.4 Sv m^2/s. The minimum shielding thicknesses (concrete) required to reduce the ambient dose equivalent rate to below the public limit area (2.8 x 10^{11} Sv/s) are calculated as about 6.5 m, using $r = 5$ m and $\lambda = 29$.

4 Validation of code system

More detailed calculation will be inevitable as the design stage proceeds. Monte Carlo models are considered most reliable, and are able to model radiation fields in complex geometry. However they consumes significant amounts of resources, even with today's computers, and may give solutions with poor statistics even when variance reduction methods are heavily applied. On the other hand, discrete ordinate models and simple semi-empirical models have been applied for many of the complex shielding tasks, coupled with the Monte Carlo code. Since they are not only fast but also capable of parametric studies, with an appropriate validation, those models are the best choice when sensitivities of many factors are required in the shielding design.

A code system consisting of the MCNPX, DORT and DUCT-III was established, and its validation calculations were performed for the attenuation coefficients, two-dimensional beam line shielding, and duct streaming.

4.1 Attenuation coefficients

Attenuation coefficients as a function of each thickness were calculated using MCNPX and MCNPX/DORT in the shielding of 16 GeV protons incident on dirt tunnels (specifications were excerpted from proton driver of FNAL). In the MCNPX/DORT calculations, neutron and photon sources were provided by MCNPX and fed into the DORT system, as shown schematically in Fig. 4.1.

It has been shown that the calculation time of MCNPX/DORT is about one fourth of MCNPX case's, while the attenuation curves calculated from two methods shows about 20 % overestimation by MCNPX/DORT as shielding becomes thicker. Further validation calculations are planned with actual KOMAC specifications.

4.2 Two-dimensional shielding

Shielding of a virtual beam line was modeled in two-dimensional geometry where protons of energies 100 MeV and 20 MeV, are lost through the dipole magnet in the tunnel, as shown in Fig. **??**. MCNPX and MCNPX/DORT calculations were performed to produce attenuation coefficients, and to study sensitivities of the locations and shapes of the components. As shown in Figs. 4.2 relative differences are within 10 % between MCNPX and MCNPX/DORT, while MCNPX-DORT always overestimates.

4.3 Duct streaming

DUCT-III is a simple design code to calculate duct-streaming radiations in nuclear facilities using the Shin's semi-empirical formula based on an albedo analytical method. Shielding of a

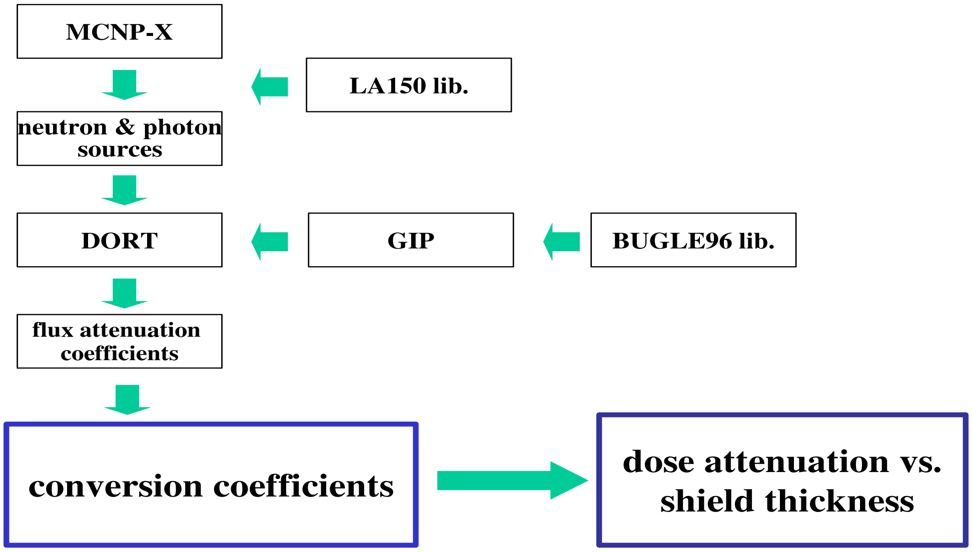

Figure 3: Structure of the MCNPX/DORT code system

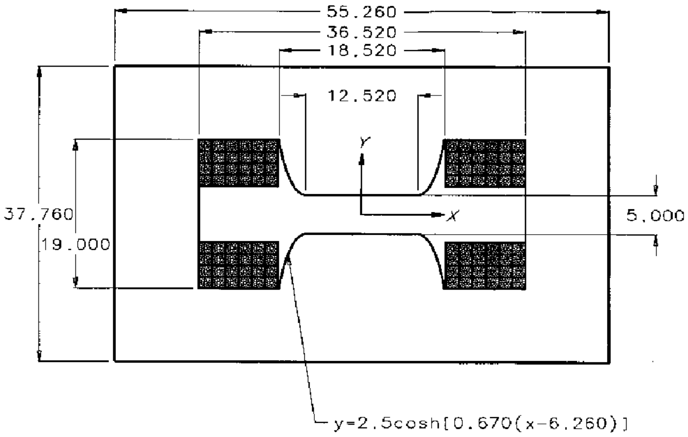

Figure 4: Two-dimensional modeling of beam line shielding: dipole cross section

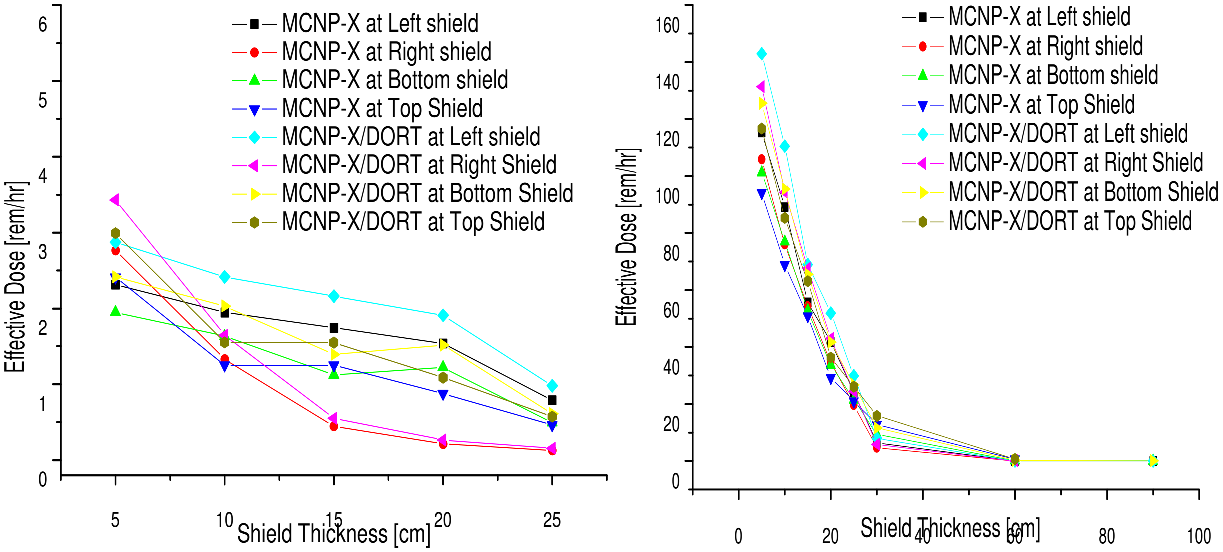

Figure 5: Results of the MCNPX/DORT validation calculations for two-dimensional shielding model

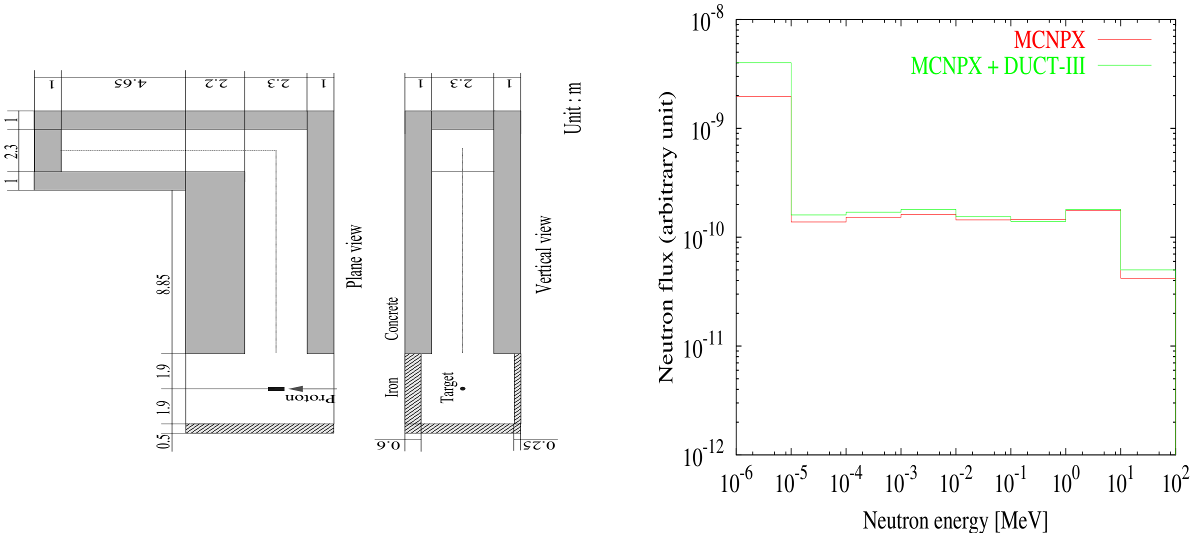

Figure 6: Results of the MCNPX/DORT validation calculations for two-dimensional shielding model

virtual beam facility whose geometric specifications are from NIMROD accelerator, was modeled by the MCNPX alone and MCNPX/DUCT-III. As shown in the left-hand side of Fig. 4.3, the proton was incident upon the copper target, and the tunnel contains two legs of 11 m and 8 m, respectively. In the MCNPX/DUCT-III model, the source neutron spectrum was provided by the MCNPX calculation. Neutron energy spectra the end of the 2nd leg were calculated and compared in the right-hand side of Fig. 4.3, showing a good agreement of DUCT-III results with the MCNPX's except for low neutron energy region.

5 Summary

For the shielding of the high current proton accelerator in the KOMAC project, we have provided preliminary shielding issues for 20 MeV proton linac as follows:

- Beam losses for normal operation were assumed as 1 W/m
- An accident scenario considers a full loss at a single point, with a tentative design requirement of the CERN
- MCNPX maps boundary surface leakage to boundary source for multi-dimensional discrete ordinate model such as DORT, or simple semi-empirical model such as DUCT-III.
- Line-of-sight model was used to estimate required thickness for the beam line in normal and accident conditions, as well as for the beam dump.
- MCNPX/ DORT/ DUCT-III code system was established and several validation calculations were performed.

Acknowledgements

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