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FLUKA-MARS15 SIMULATIONS TO OPTIMIZE THE FERMILAB PIP-II MOVABLE BEAM ABSORBER

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Abstract

PIP-II is the Fermilab's flagship project to provide powerful, high-intensity proton beams to the laboratory's experiments. The heart of the PIP-II project is an H- 800 MeV superconducting linear accelerator. In order to commission the beam and operate safely the linac, several constraints were evaluated. The design of a movable 5 kW beam absorber was finalized to allow staged beam commissioning in different linac locations. Prompt and residual radiation levels were calculated, and radiation shields were optimized to keep those values within the acceptable levels in the areas surrounding beam absorber. Monte Carlo calculations with FLUKA and MARS15 codes are presented in the paper to support these studies.

INTRODUCTION

The Proton Improvement Plan II project (PIP-II [1]) is an essential upgrade to the Fermilab accelerator complex. As an immediate goal, PIP-II is focused on upgrades capable of providing 120 GeV proton beam power in excess of 1 MW on a target at the start of the Long-Baseline Neutrino Facility/Deep Underground Neutrinos Experiment (LBNF/DUNE) program, currently anticipated for the mid-2020's. The central element of PIP-II is a brand-new, leading-edge superconducting linear accelerator (see Fig. 1 as a reference for its 3D model). The linac is followed by a beam transfer line that brings the beam to the existing Booster. Upgrades to a number of systems in the Fermilab Booster, Recycler and Main Injector are required to accommodate the new higher injection energies and beam intensities in each machine. Thanks to these upgrades, PIP-II will enable to provide beam to DUNE and an extensive suite of on-site particle physics experiments, intended to search for new particles and new forces in our universe.

PIP-II LINAC

The PIP-II linear accelerator is based on Continue Wave (CW) capable accelerating structures and CryoModules (CMs). The H^- beam from one of the two Ion Sources is transported through the Low Energy Beam Transfer (LEBT) section to the Radio Frequency Quadrupole (RFQ) for bunching and acceleration. At the extraction of the RFQ, the beam passes through a Medium Energy Beam Transport (MEBT) line for transport and matching to the linac SuperConducting (SC) part. The beam leaves the Warm Front End (WFE) at the MEBT exit and is accelerated from 2.1 MeV to 800 MeV thanks to five different types of SC CMs. The acceleration starts with Half Wave Resonators (HWR), operating at 162.5 MHz, followed by two types of Single Spoke Resonators (SSR1 and SSR2), operating at 325 MHz. The last two sections, LB650 and HB650, are composed of two types of elliptical 5-cell cavities. The latter will operate at 650 MHz. The lattice of the Linac is composed of SC solenoids and normal conducting quadrupoles. The HWR, SSR1 and SSR2 use three types of solenoids (one type for each section), while the last two sections use normal conducting quadrupoles arranged in doublet formation to provide transverse beam focusing.

At the end of the HB650 section the beam leaves the linac tunnel and enters the Beam Transfer Line (BTL) before reaching the Booster. If necessary, the beam can be aborted in the main 50 kW absorber located in the BTL. For beam commissioning/linac optimization studies an additional low power 5 kW absorber will be permanently located at the end of the Linac tunnel.

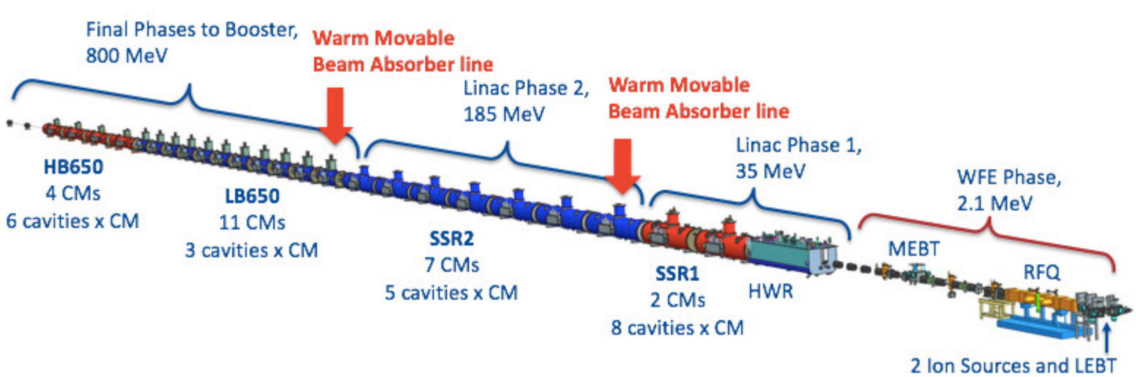

Figure 1: 3D Model of the ~215 m long PIP-II accelerator from the two H^- ions sources (right) to the HB650 section (left). Beam Commissioning Phases are shown as well as the proposed Warm Movable Beam Absorber locations: at the first SSR2 CM (to allow the Linac Phase 1 Beam Commissioning) and at the first LB650 CM (to allow the Linac Phase 2 Beam Commissioning).

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BEAM COMMISSIONING PHASES

Presently, the Linac beam commissioning is envisioned to be divided into four major phases (see Fig. 1):

- **WFE Phase**: including beam commissioning of the 2 Ion Sources, LEBT, RFQ, and MEBT up to an energy of 2.1 MeV;
- **Linac Phase**: including the SC Linac part beam commissioning. The multi-stage approach is dictated by the large betatron phase advance per CM at low energy. Two locations are identified as critical: at the end of SSR1 section (Linac Phase 1 up to 35 MeV) and at the end of SSR2 section (Linac Phase 2 up to 185 MeV). The Linac phase will be completed when the whole linac is installed and commissioned at the 5 kW absorber.
- **Final Phase (a):** including beam commissioning of the Linac and its BTL to the main 50 kW absorber.
- **Final Phase (b):** including injection to the Booster and reaching the nominal parameters.

PIP-II MOVABLE BEAM ABSORBER

The multi-stage approach to the beam commissioning of the SC Linac requires a warm moveable beam absorber equipped with the appropriate diagnostic. In order to minimize its cost impact on the PIP-II project, the present proposal is to use the same core part of the 5 kW absorber with shielding sized to the Linac energies and intensities of Phases 1 and 2.

BEAM COMMISSIONING OPERATIONAL SCENARIOS

The PIP-II Linac is built to operate with an averaged H^- beam current of 2 mA and a beam duty factor of 1.1%. Initially the accelerator will provide pulsed beams for the neutrino program. The absorber shields have been simulated for the nominal beam parameters in Table 1 and the pulse beam commissioning parameters in Table 2.

Table 1: Beam Parameters Used

MeV	**35**	**185**
RMS Energy Spread [MeV]	0.0524	0.098
RMS Momentum Spread [MeV/c]	0.196	0.179
Horizontal RMS size [mm]	1.73	1.5
Horizontal RMS angle [mrad]	0.56	0.26
Vertical RMS size [mm]	1.7	1.5
Vertical RMS angle [mrad]	0.58	0.26

Table 2: Pulse Parameter Scenarios

MeV	**35**	**185**
Scenario A	-	-
Pulse width [ms]	0.1	0.1
Repetition Rates [Hz]	20	10
Scenario B	-	-
Pulse width [ms]	0.55	0.55
Repetition Rates [Hz]	1	1

METHODOLOGY

Detailed Monte-Carlo simulations using the FLUKA code [2,3] have been performed and the relevant physics quantities, such as particle fluences, residual and ambient dose equivalent rates have been calculated for different irradiation profiles and several radiation cooling times in order to optimize the choice of shielding materials and design. For the most promising design, FLUKA results were intercompared to the MARS15 code [4,5] results.

GEOMETRY MODELS

Four different beam absorber shielding configurations were separately evaluated, taking into account space constraints inside the accelerator tunnel. All the proposed designs have the same Graphite core of cylindrical shape and aluminum jacket. The jacket covers the core and also incorporates a water-cooling system. The dimensions of the core, its aluminum jacket and backstop are based on the requirements for the low-power absorber, designed to handle 1 GeV beam up to 5 kW beam power deposited [6,7] (see Fig. 2).

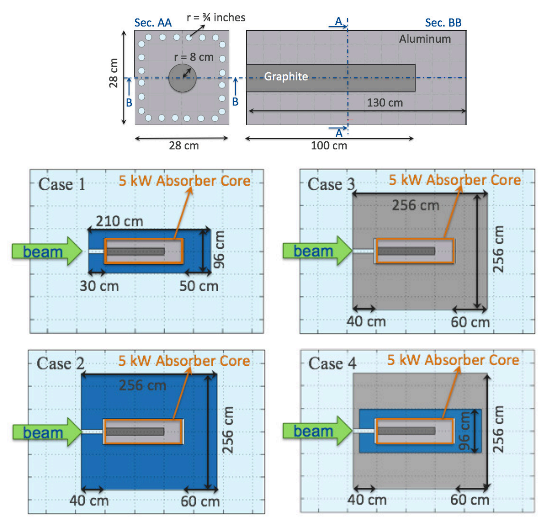

Figure 2: Cross and transverse sections of the beam core absorber geometry: the channels with cooling water are drilled inside the aluminium (top). Transverse sections of the four different shielding designs around the beam core absorber (bottom). Case 1 uses A36 steel for average thickness of 20 cm around the absorber core; Case 2 enlarges the A36 steel shielding to 1 m; Case 3 substitutes the A36 steel with Concrete; Case 4 is a combination of Case 1 with additional concrete shielding around the A36 steel layer up to 1 m.

PHYSICS SETTINGS

Both FLUKA and MARS15 are set with a 100 keV energy transport cut-off for all particles, except for neutrons and photons for which the cut-off was set to 10^{-5} eV and 10 keV, respectively. In addition, to achieve accurate results for residual nuclei production, the evaporation model of the heavy fragments and the coalescence mechanism were activated for all the FLUKA simulations. The same is a default in the MARS15 simulations.

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RESULTS

Prompt Radiation

Ambient dose equivalent rates inside a portion of the Linac tunnel are shown in Figure 3 and Figure 4 and referred to the most extreme beam parameter conditions at 185 MeV. Results imply that the beam-on access permit is not allowed in the tunnel, accordingly to the Fermilab dose rate limits area classifications [8]. Case 4 represents the best layout to reduce radiation impact in the tunnel areas surrounding the absorber. Figure 5 compares the two beam commissioning pulse scenarios for Case 4.

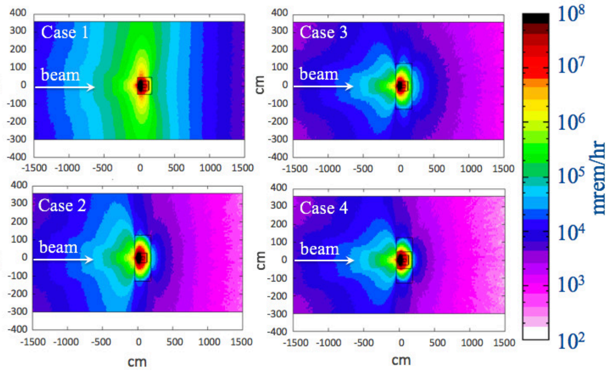

Figure 3: FLUKA results comparison between the ambient dose equivalent rates due to prompt radiation at 2 mA, 185 MeV and *Scenario A* for the four shielding cases.

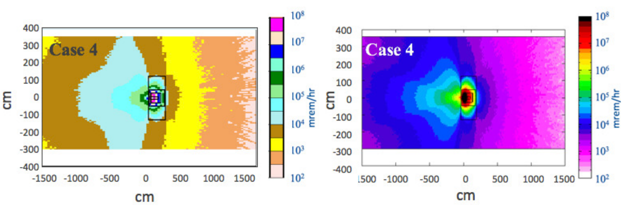

Figure 4: FLUKA and MARS15 Case 4 results. The two code results agree on the ambient dose equivalent rates due to due to prompt radiation at 2 mA, 185 MeV, *Scenario A*.

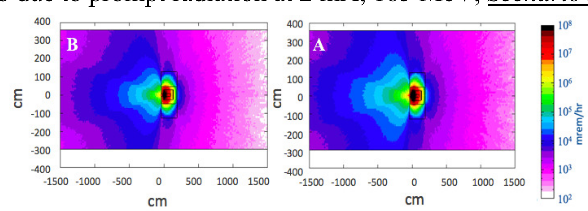

Figure 5: FLUKA Case 4 results comparison between beam pulsed *Scenario A* (right) and *Scenario B* (left) at 185 MeV. Restriction to access still applied, based on *Scenario B* results. However, access restricted to authorized personnel can be allowed during beam-on operation if a rigid barrier with locked gates is installed at approximately 15 m downstream the beam absorber.

Assuming *Scenario A* (Fig. 6 – right) for pulse parameter and 35 MeV, ambient dose equivalent results allow limited controlled occupancy at about 15 m downstream the beam absorber, during beam-on operation. Note that, in the 35 MeV case, only the A36 Steel shielding layer is used.

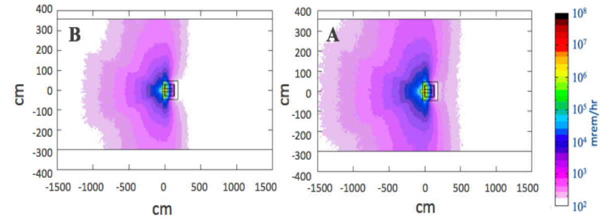

Figure 6: FLUKA Case 1 35 MeV results for *Scenario A* (right) and for *Scenario B* (left).

Residual Radiation

Residual dose rates maps have been calculated (see Fig. 7) for a conservative scenario corresponding to an irradiation profile of 1.15x10^{13} p/s at 185 MeV beam energy, for 100 days of irradiation and 4 hours of radiation cooling time. No major constraints are identified to access the areas at a distance of approximately 10 m from the beam absorber.

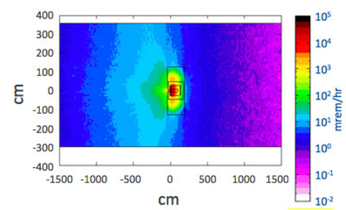

Figure 7: FLUKA Case 4 residual radiation results. 20 mrem/hr is considered a good practice limit for access the zone surrounding the beam absorber.

SUMMARY AND CONCLUSIONS

An extensive FLUKA and MARS15 simulation campaign was undertaken to evaluate the appropriate shielding for a movable beam absorber to allow its use during PIP-II beam commissioning. Starting from the 5 kW core absorber design, optimized on the basis of MARS15 and finite element calculations [6,7] to handle 1 GeV beam at the end of the Linac, several shielding configurations were taken into account with different beam and pulse parameter scenarios at 35 and 185 MeV beam energies.

Results show that a multi-layer shielding is the best choice in terms of maintaining acceptable levels for the prompt and residual radiation. This approach allows to add shielding during the various Phases of the Linac commissioning, taking into account the constraints of moving the absorber inside the Linac tunnel. Indeed, a first A36 Steel shielding layer is required for beam commissioning at 35 MeV beam energy, while an additional concrete layer is proposed to be added around the A36 steel once that the beam commissioning at 185 MeV will start.

The shielding performance could be improved by adding boron to the concrete layer to increment the neutrons absorption rate. In addition, an albedo trap in concrete can be introduced at the entrance to the absorber, to improve the neutron backscattering absorption. Detailed finite element analysis will follow to establish the possible need of an active water-cooling system during the beam commissioning Phases.

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