ENERGY DEPOSITION IN MAGNETS AND SHIELDING OF THE TARGET SYSTEM OF A STAGED NEUTRINO FACTORY*

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Abstract

In the Neutrino Factory and Muon Collider muons are produced by firing high energy protons onto a target to produce pions. The pions decay to muons which are then accelerated. This method of pion production results in significant background from protons and electrons, which may result in heat deposition on superconducting materials and activation of the machine preventing manual handling. In this paper we discuss the design of a secondary particle handling system. The system comprises a solenoidal chicane that filters high momentum particles, followed by a proton absorber that reduces the energy of all particles, resulting in the rejection of low energy protons that pass through the solenoid chicane. We detail the design and optimization of the system and energy deposition and shielding analysis in MARS15(2012).

INTRODUCTION

The baseline target concept for a Muon Collider or a Neutrino Factory [1] is a free jet of mercury impacted by a 4-MW, 8-GeV proton beam at 50 Hz within a 20-T magnetic field [2]. The magnetic field is produced by a coaxial array of cryogenically cooled superconducting (SC) coils and water-cooled resistive magnets. The superconducting coils are protected from secondary radiation from the target by internal shielding of He-gas-cooled tungsten beads.

The design proton beam energy and power will be approached in stages [2], beginning with a 1-MW, 3-GeV proton beam. A solid carbon target can be used in the initial stage, and replaced with a mercury target module at a later stage when higher beam power is utilized.

The 20-T field on the target is reduced to 1.5 T in a tapering field profile over $\approx$ 5 m, beyond which is an $\approx$ 60-m-long, 1.5-T solenoidal Decay Channel where secondary pions decay to form the muon beam. Roughly 10% of the proton beam power is transported into the Decay Channel [3, 4], mainly via soft protons from breakup of target nuclei, and energetic protons scattered from the beam. These protons would be transported by the Decay Channel into subsequent components of the Muon Collider/Neutrino Factory Front End [5], the Buncher, Phase Rotator, and Ionization Cooling sections. To minimize radiation damage to these components, and to keep their activation low enough that hands-on maintenance is feasible, the secondary protons should be removed from the Decay Channel. This is to be accomplished via a bent-solenoid chicane [6], sketched in Fig.1, in which most proton of energy above 500 MeV are deflected out of the Decay Channel, and by a 10-cm-thick Be absorber which removes most protons of lower energy.

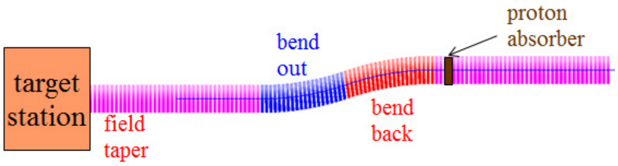

Figure 1: Sketch of the pion-production and Decay Channel, including a chicane to suppress energetic protons and an absorber for soft protons.

ENERGY DEPOSITION STUDIES

The higher-energy particles (mostly protons) which leave the beam in the chicane would pass through the coils of the bent solenoids unless the latter have adequate internal shielding. As for the superconducting coils of the target-system upstream of the chicane, we desire that the maximum energy deposition in the coils be less that 0.1 mW/g to permit an operational lifetime greater than 10 years of 10^7 s. This criterion is taken from studies [7] conducted for the ITER project.

To evaluate the amount of shielding required for the magnets of the Decay Channel chicane, we used a MARS15(2012) [8] simulation with field maps generated by G4beamline [9]. A preliminary version of these studies was reported in [10].

Given the complicated geometry of the chicane, adding tungsten shielding was not straightforward using only MARS extended geometry. However, a recently developed ROOT-based geometry framework [11] for MARS has made the task manageable with a wide variety of basic volumes provided by the ROOT TGeo module. The

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TGeoCtub elementary volume (cut tubes with arbitrary entrance and exit angles) proved to be the most important for seamless shielding. The fact that the volume of each shielding or coil segment can be calculated precisely in ROOT removes the uncertainty intrinsic to MARS Monte-Carlo based volume calculation. Parts of the chicane as defined using ROOT are shown in Fig. 2.

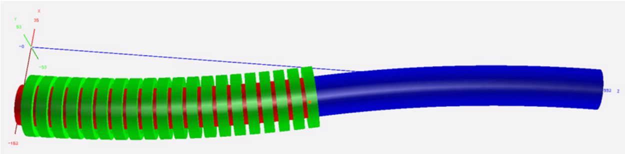

Figure 2: Chicane geometry as defined using ROOT. Red: shield, bend in; blue: shield, bend out; green: solenoidal coils of the bend-in.

In a straight solenoid with uniform field, particles move in helices about the (straight) trajectory of their “guiding center.” The magnetic field of a bent solenoid, as in each half of the chicane, is toroidal, and the guiding center undergoes “curvature drift” perpendicular to the plane of the toroidal field [12]. For the 1.5-T field of the decay channel, whose beampipe has 30 cm radius, the curvature drift deforms the shape of the beam into an ellipse with semimajor axis of length 42 cm at the center of the chicane.

In a first study of possible shielding configuration for the chicane, the beampipe was assumed to have radius 42 cm, and the thickness of the tungsten-bead shielding was 35 cm. Figure 3 shows a “horizontal” section of the model of the chicane, together with contours of energy deposition as simulated by MARS15(2012).

The average power deposition in the superconducting coils of the chicane, averaged over azimuth, for the model of Fig. 3 is shown as the blue curve in Fig.4 as a function of position along the chicane, and is everywhere less than the “ITER” limit of 0.1 mW/g. To estimate the peak energy deposition in the coils, the MARS model was segmented azimuthally, leading to the results shown in the blue curve of Fig. 5, where the deposition in a few regions remains above the “ITER” limit.

In a second iteration of the study, only the central 4 m of the chicane was modeled with a beampipe of 40 cm radius, with the outer segments having a beampipe of 30 cm radius, as shown in Fig. 6. The thickness of the shielding in the central portion of the chicane was taken to have 40 cm thickness, while the thickness of the shielding was only 30 cm in the outer portions of the chicane. Contours of energy deposition in the midplane of the chicane are shown in Fig. 6, with the azimuthally averaged energy deposition, and the peak energy deposition, shown in red in Figs. 4 and 5, respectively. The thickness of the shielding downstream of the chicane was only 5 cm, which is not quite adequate, as shown in Fig. 5.

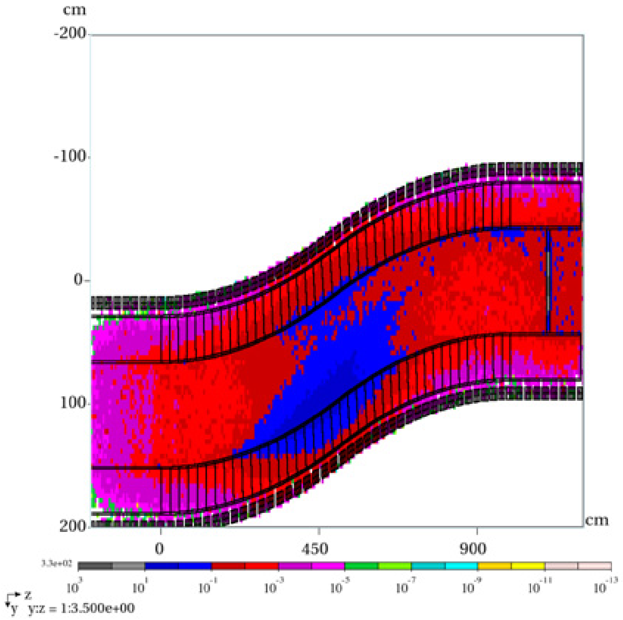

Figure 3: MARS15(2012) simulation of energy deposition in a model of the chicane with beampipe of 42 cm radius, surrounded by 35-cm-thick tungsten-bead shielding.

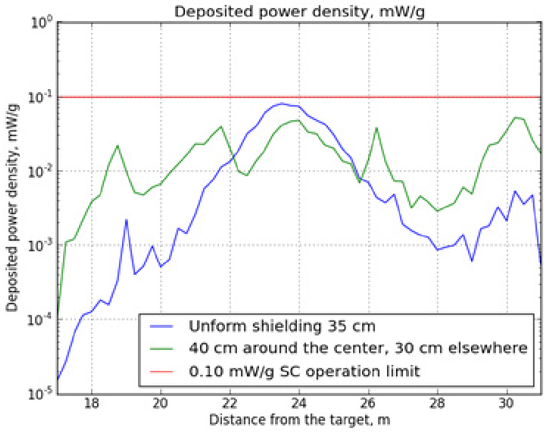

Figure 4: Simulated energy deposition in the superconducting coils of the chicane, average over azimuth.

SUMMARY

The models of shielding of the superconducting coils of the chicane investigated to date (based on MARS15(2012) simulations in the Default mode) appear to be close to providing sufficient protection against radiation damage for an operational lifetime in excess of 10 years. Simulations using MARS15 with MCNP data tables will be performed to evaluate better the energy deposition by low-energy neutrons, which may have been underestimated in the studies to date. Next steps in the studies are to introduce a beampipe which changes its cross section from circular to elliptical and back to circular along the chicane, along with shielding whose inner surface matches the beampipe

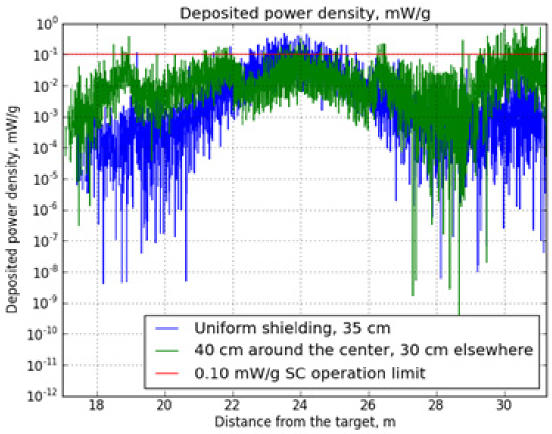

Figure 5: Simulated peak energy deposition in the superconducting coils of the chicane, based on an azimuthally segmented model.

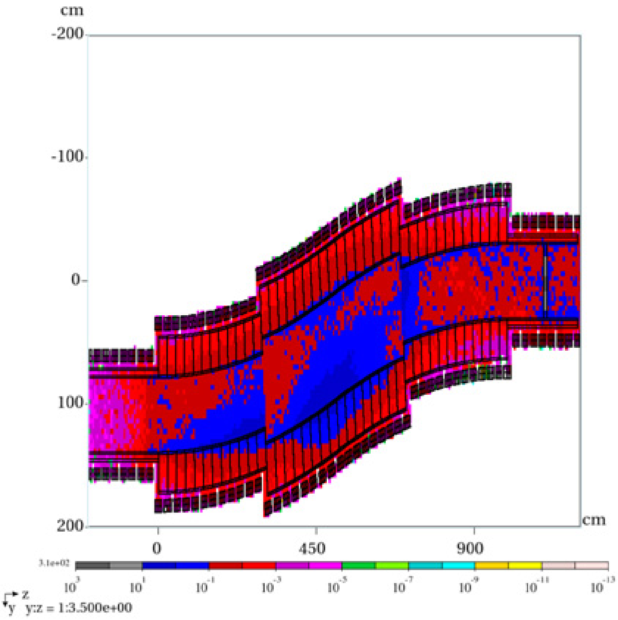

Figure 6: MARS15(2012) simulation of energy deposition in a model of the chicane with non-uniform beampipe of 42 cm radius around the central part of the chicane and 30 cm elsewhere, surrounded by 40 cm of tungsten-bead shielding around the central part of the chicane and 30 cm elsewhere.

and whose outer surface is circular, and with thickness that varies along the chicane.

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