ENERGY DEPOSITION IN THE TARGET SYSTEM OF A MUON COLLIDER/NEUTRINO FACTORY*

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Abstract

Much of the energy of the primary proton beam of Muon Collider/Neutrino Factory would be deposited in the superconducting coils that provide a solenoid-magnet transport channel for secondary particles, unless those coils are protected by massive internal shielding. Studies are reported of energy deposition in such shielding, with the goal of permitting 10 years operational life at 4-MW beam power. The graphite target should be able to withstand the "thermal shock" induced by the pulsed beam; further study is needed to confirm this.

INTRODUCTION

In a muon accelerator complex such as a Muon Collider [1, 2, 3] or a Neutrino Factory [4, 5, 6], a target is bombarded by a multi-MW proton beam to produce pions that decay into muons, which are thereafter bunched, cooled, and accelerated. The present concept for the Target System [7] is for a graphite (or carbon-carbon composite) target and proton beam dump inside a 20-T solenoid field, which field tapers down to 2 T, used throughout the rest of the Muon Collider/Neutrino Factory Front End [5], over 5 m [8, 9]. The yield of muons from the target is maximal at low kinetic energies, roughly $40 < \mathrm{KE} < 180$ MeV, which particles emerge at large angles to the proton beam, favoring a cylindrical target of small radius, and tilted slightly with respect to the magnetic axis to minimize reabsorption of particles if their helical trajectory passes through the target a second time [10].

The solenoid field is to be provided by superconducting coils (with cable-in-conduit conductor as used in the ITER project [11]), except for a 5-T resistive coil insert (with Mg)/spinel insulation as used at J-PARC [12]) near the target [13]. Radiation damage (particularly to organic insulators) limits the dose on the superconducting coils to about 10 MGy [14], which translates to a peak power deposition of about 0.1 mW/g for a 10-year operations lifetime of 10^7 s/year. To achieve this performance, superconducting coils must have internal shields, here taken to be tungsten beads cooled by He gas flow. The required shielding

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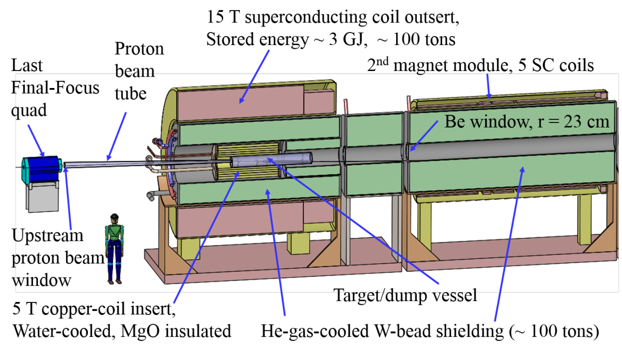

Figure 1: Sketch of the Target System concept, including the second magnet module that completes the field taper from 20 T on the target down to 2 T in the Decay Channel.

is substantial, and leads to an inner radius of the superconducting coils of 1.2 m near the target; consequently the energy stored in the 20-T coils is about 3 GJ.

The target (and beam dump, shown in Fig. 2) will also suffer radiation damage and must be replaced periodically. Operation at high temperature provides annealing of radiation damage and substantially longer target lifetime (as demonstrated at the CERN CNGS neutrino target [**?**]). The target will be radiation cooled, operating at about 1700° C for a carbon-based target at 1-MW beam power. It is encased in a double-walled stainless-steel vessel with intramural He-gas flow for cooling, shown in Fig. 2. The upstream proton beam window (Fig. 1) will be of Ti or Al, and the downstream (double) window will be of Be to minimize degradation of the secondary-particle beam.

The use of short proton pulses (3 ns rms) leads to severe stress (thermal shock) on a solid target, which is mitigated by use of materials with high strength, high heat capacity and low thermal-expansion coefficient. A carbon-carbon composite can have thermal-expansion coefficient 1/5 that of graphite and may be favored for operation at beam power higher than 1 MW or at repletion rates less than the nominal 60 Hz.

The paper reports on studies of the energy/power deposited in various elements of the Target System, based on a MARS15(2014) simulations [15]

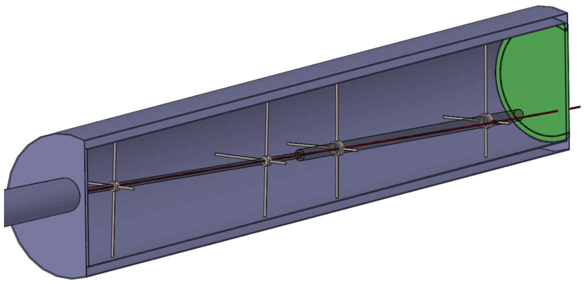

Figure 2: Target vessel with graphite target and proton beam dump. The downstream beam window (green) is of Be.

SUPERCONDUCTING COILS

As noted above, radiation damage (particularly to organic insulators) limits the dose on the superconducting coils to about 10 MGy [14], which translates to a peak power deposition of about 0.1 mW/g for a 10-year operations lifetime of 10^7 s/year.

The simulated power deposition from a 4-MW proton beam in the W-bead shielding, in the 5-T resistive coil insert, and the various superconducting coils of the first three magnet modules is summarized in Fig. 3, averaged over azimuth. The upper edge of the magenta band in the figure corresponds approximately to 0.1 mW/g, the nominal safe limit, indicating that the first two superconducting coils are not shielded quite enough for operation at 4 MW.

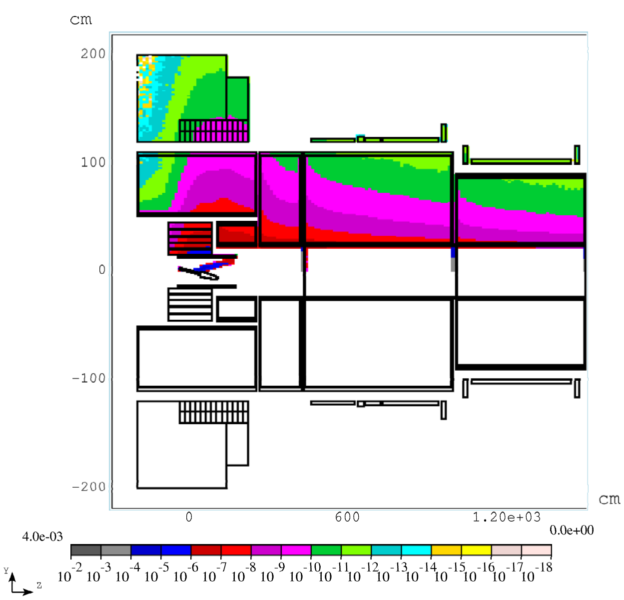

Figure 3: Simulated power deposition in the Target System for a 4-MW proton beam, averaged over azimuth.

Further details of the power deposition in superconducting coils 1 and 2 are shown in Fig. 4, as a function of azimuth and z for the region $120 < r < 140$ cm. The azimuthal dependence arises because the tilted proton beam follows a helical trajectory such that secondary particle production in the target peaks at $\phi \approx 235°$. The present shielding configuration is sufficient for operation at 2 MW, but would provide only a 5-year life of coils 1 and 2 with 4-MW operation. The present shielding configuration differs from that previously considered [16, 17] by the removal of some 10 cm of radial shielding inside the 5-T resistive coils, to permit a larger target module inside them.

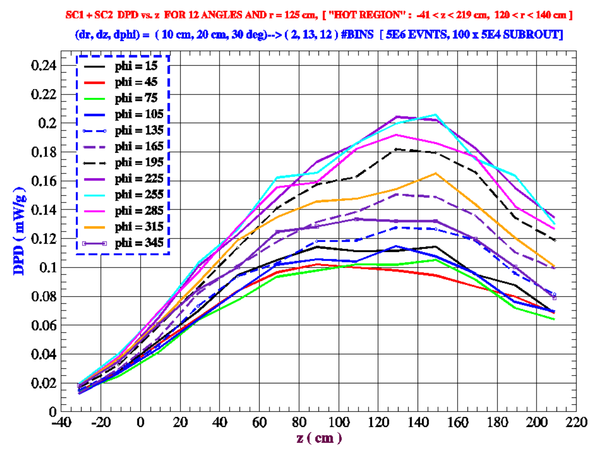

Figure 4: Power deposition in superconducting coils 1 and 2 as a function of z for $120 < r < 130$ cm, for 12 bins of 30° in azimuth, for 4-MW proton beam power.

The shielding is arranged in various modules, with small gaps in the axial coordinate z between them. Figure 3 indicates that these gaps results in higher energy deposition just down stream of them than would occur in their absence. In particular, the third superconducting coil (first coil in the second magnet module) receives a radiation dose that is marginal for operation at 4-MW beam power with the present shielding configuration, as shown in Fig. 5

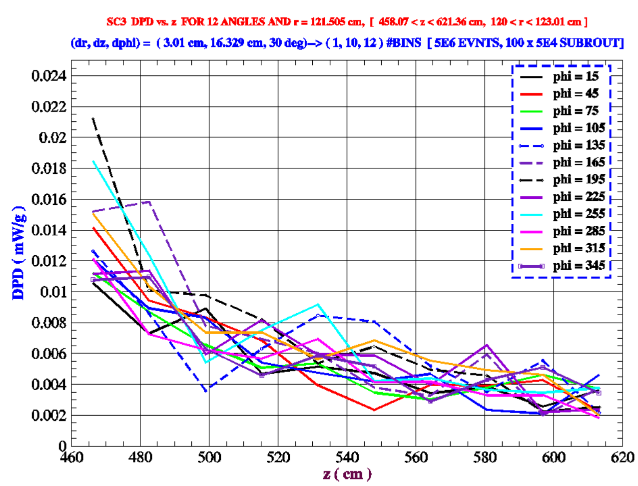

Figure 5: Power deposition in superconducting coil 3 as a function of z, for 12 bins of 30° in azimuth, for 4-MW proton beam power.

The general conclusion is that the present shielding configuration would be adequate for operation at 2 MW, but is marginal at 4 MW.

BE WINDOWS OF SHIELD MODULES

The secondary beamline, with 23-cm radius, is inside the W-bead shield modules. If this beamline is not to be in air, there must be windows as the beginning and end of each shield module. The heating of these windows by the secondary particles is not negligible, and they would need to be double windows with He-gas flow between them for cooling. If these are vacuum windows, their thickness would be substantial and their effect on the secondary muon beam needs further study.

Here, we report on power deposition as a function of radius in a possible 2.5-mm-thick Be window at the beginning of the second magnet module, $z = 430$ cm, as shown in Fig. 6.

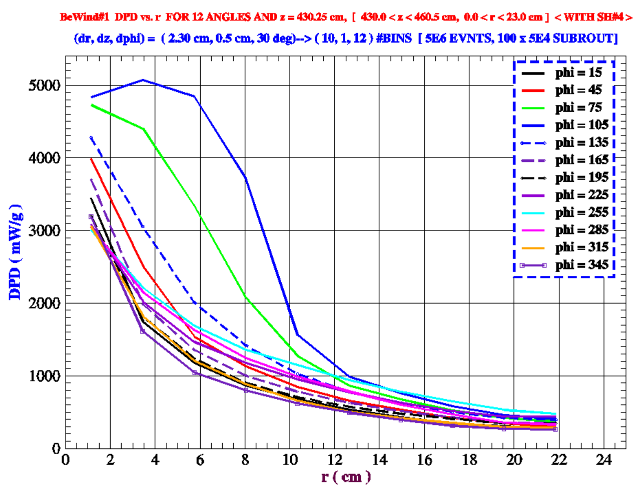

Figure 6: Power Deposition in a 2.5-mm-thick Be window at $z = 430$ cm, for 4-MW proton beam power.

TARGET

The peak energy deposition in the target determines its lifetime against radiation damage, and also the maximum incident beam power it can withstand without cracking due to pressure waves induced by transient heating.

In the case of a tilted proton beam, whose trajectory is helical, the point of peak energy deposition is not necessarily on the target axis, and our studies of this issue are still preliminary. Figure 7 shows our present results for energy deposition along the target axis, for both a tilt angle of 65 mrad, and for zero tilt. The power deposition can be converted to energy deposition per beam pulse by dividing by the beam repetition rate, nominally 60 Hz for a Neutrino Factory and 15 Hz for a Muon Collider. The estimated values of peak energy deposition appear to be insufficient to crack the target rod even at 4-MW beam power, but further study of this issue should be made.

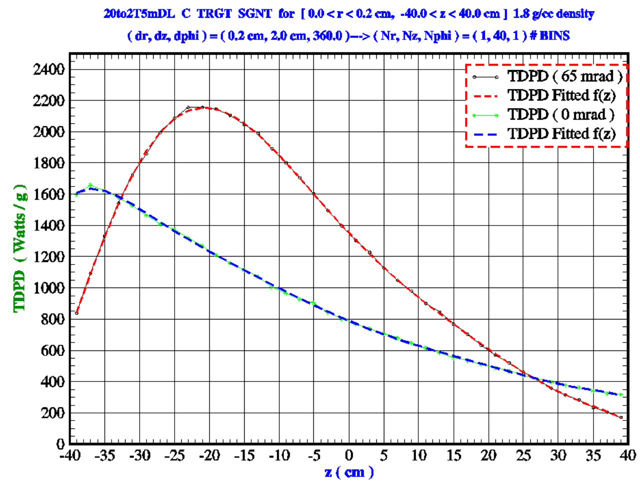

Figure 7: Power deposition on the axis of targets tilted at 0 and 65 mrad, for a 4-MW proton beam.

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