

ENERGY FLOW AND DEPOSITION IN A 4-MW MUON-COLLIDER TARGET SYSTEM*

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Abstract

The design of the target station for a 4-MW Muon Collider or a Neutrino Factory is evolving to include more space for services to the magnets and internal tungsten shielding, as well as consideration of removing the 5-T resistive copper coils, thereby reducing the peak field from 20 to 15 T. Simulations with MARS15 have been performed to verify that these revisions preserve sufficient shielding that the peak power deposition everywhere in the superconducting magnets will be less than 0.1 mW/g, permitting at least a 10-year operational lifetime against radiation damage to the organic insulators.

INTRODUCTION

The 4-MW target station for a Muon Collider or a Neutrino Factory [1] requires an array of cryogenically cooled superconducting (SC) coils and water cooled resistive (RS) coils to produce a magnetic field of ~ 20 T around the free-mercury jet target, of which about 5 T is generated by the resistive coils. The field will gradually decrease over 15 m downstream from the target to 1.5 T in the pion-decay channel. Subsequently the muons, produced by the pion decay, will be cooled by ionization, accelerated and stored in a ring either for $\mu^+\mu^-$ collisions or for intense neutrino beams via muon decay.

Most of the 4-MW power of the proton beam will end up in the target station, although some 800 kW escapes in various directions. While the resistive copper magnet is largely immune to effects of radiation and energy deposition, if insulated with MgO or spinel, superconducting magnets will fail (due to radiation damage to organic insulation) if the radiation dose exceeds about 10 MGy. This translates to a limit of about 0.1 mW/g of energy deposition over an operational life of 10 years of 10^7 s each [2]. Internal shields consisting of He-gas-cooled tungsten beads will protect the SC coils from radiation damage. However, shielding in a 4-MW beam requires the outer radius of the shield/inner radius of the SC coils near the target to be ≈ 120 cm [3]. Here, we report progress in optimizing and refining the geometry of the shielding inside the SC coils.

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THE IDS120j CONFIGURATION

This paper reports results for the so-called IDS120j target-station geometry (Fig. 1, left), which has 12 cable-in-conduit SC coils (Nb₃Sn insert, NbTi outset) and 5 copper, hollow-conductor resistive magnets. Under present consideration is the elimination of the resistive coils, reducing the central field to 15 T, to simplify the mechanics of the inner target module that contains the mercury target and mercury-pool beam dump [4] (Fig. 1, right). There are four cryostats with 3 SC coils in each. The inner radii of the coils in the cryostats are 120/90/70/50 cm. There are gaps of 137/96/71 cm between the last coil of an upstream cryostat and the first coil in the following cryostat to accommodate the cooling components of the two cryostats and of their internal shielding. To maintain smooth variation of the on-axis magnetic field, the SC coils that flank each gap are of large radial depth [5].

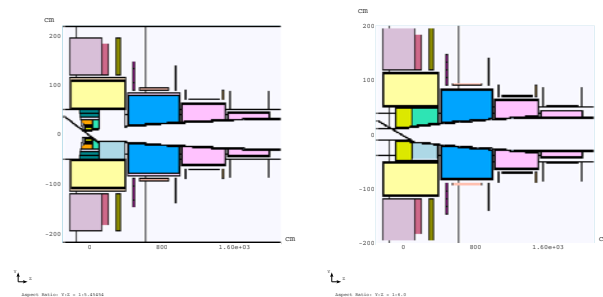


Figure 1: y - z (vertical plane) cross sections for the IDS120j geometry with (left) and without (right) resistive coils (RS). The beam (and mercury target) are tilted vertically with respect to the magnetic axis so the spent beam and jet can be absorbed in a pool of mercury.

The internal tungsten-bead (W) shielding is contained within stainless-steel vessels whose walls must support the ≈ 200 ton weight while limiting stresses and consequent deformations to acceptable values [5].

The vessel that contains the mercury jet target and collection pool was modeled as a cylindrical stainless-steel shell with ≈ 50 -cm outer radius. The pool extends to ≈ 3.8 m downstream of the target, roughly to the end of the first cryostat. The inner mercury containment vessel

has a ≈ 5 -mm-thick Be beam window on its downstream face. The inner wall of the outer shielding vessel serves as the secondary mercury containment vessel, which vessel also has a Be beam window on its downstream face. Rapidly flowing He gas cools the inner containment vessel and the downstream Be windows. In the variant without resistive coils, the volume previously occupied by these coils is filled with tungsten-bead shielding, and shielding is added above the mercury pool (Fig. 1, right).

Final details in the design of the inner target module that will include Hg jet nozzle, Be window, shielding, Hg pool and its draining system are yet to be determined. See [4] for the present vision of this complex subsystem.

POWER DEPOSITION STUDIES

The latest version of the MARS code (MARS1510) [6], utilizing MCNP cross-section libraries [7] for proper treatment of low-energy neutrons (less than ≈ 5 MeV), was used for simulations of energy deposition (DP) in the target station. The simulations reported here are for an 8-GeV proton beam, which maximizes the yield of low-energy secondary pions from a mercury target [8]. The beam protons have a transverse Gaussian profile with $\sigma_x = \sigma_y = 0.12$ cm, and interact with a 20-m/s, 0.4-cm-radius Hg jet, whose velocity permits the ≈ 30 -cm-long interaction region of the target to be replaced every pulse at 50-Hz operation. The proton beam and Hg-jet parameters (beam angle, beam/jet crossing angle, Hg-jet radius) have been optimized for maximum pion yield [8].

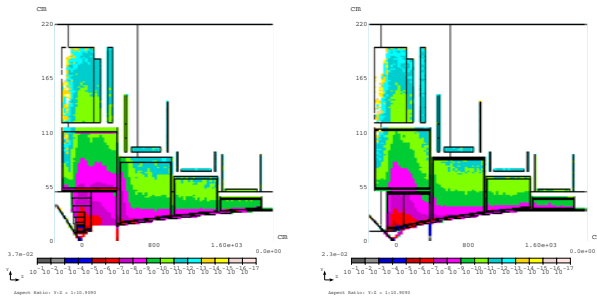


Figure 2: y - z projection of azimuthally averaged deposited-power (DP) for the IDS120j configuration with (left) and without (right) resistive coils (RS). The power deposition in the SC coils is everywhere less than 0.1 mW/g.

The DP distribution for the two cases, with 20-cm axial gaps between shield modules, and for the lowest-grade of W beads (15.8 g/cm³), appears in Fig. 2, while details for the DP distribution in the station are given in Table 1. The total DP in the SC coils without resistive coils will be less than 1 kW. In both cases the DP in the first SC coil, the largest in the configuration, will be roughly equal to the power deposited in the other 11 SC coils.

About 2.2 MW of power will be deposited in shielding material and surrounding vessels (which include the beam

Table 1: Deposited power (DP) in kW in the superconducting coils (SC), shielding (SH), resistive magnets (RS), beam pipe (BP), shielding vessels (SHVS), Hg target, Hg pool, Hg pool vessel, and the Be window.

COMPONENT	RS	NO RS
SC	1.3	0.79
SH	1443	1519
RS	311	---
BP	414	724
SHVS	281	19.25
Hg TARG.	400	396
Hg POOL	436	444
POOL VES.	15.4	6.45
Be WIND.	5.95	7.57
TOTAL	3307	3119

pipe). Removing the heat load from these materials will be a challenging task.

The target and mercury collection pool each will receive about 400 kW, which must be dissipated in a heat exchanger in the mercury flow loop. The downstream Be window will receive about 6-7 kW.

Some 450 kW (mostly energetic scattered protons) will continue into the downstream π/μ beam-transport system, where a chicane and beam absorber will remove most of this power [9]. About 200 kW (mostly low-energy neutrons) will escape radially from the SC coils, and another 200 kW (mostly soft protons) will escape upstream.

AZIMUTHAL DISTRIBUTIONS

In Fig. 2 and Table 1 the power deposition was azimuthally averaged. However, the geometry of the mercury collection pool introduces a significant azimuthal asymmetry in the power deposition in the vicinity of SC 4. Therefore a study of the azimuthal dependence of the power deposition in this coil was performed to verify that there are no regions in this coil with DP greater than 0.1 mW/g. These studies included simulation of two different densities of the W beads, and for various axial gap size between shielding modules. Some analysis was also performed for coils SC 3 and 7.

The azimuthal segmentation of SC 4, located just downstream of the first axial gap in the W shielding, is shown in Fig. 3. The bin sizes in r , z and ϕ were 14.4 cm, 21.3 cm and 30° , respectively; the coil was segmented into 48 volumes. Angle $\phi = 0$ is to the right of Fig. 3(right), such that the region $0 < \phi < 180^\circ$ corresponds to the region above the mercury pool, where there is less shielding material.

Fig. 4 presents the simulated azimuthal DP distribution at four radii in SC 4, with and without the resistive magnet. This plot shows that the peak power densities would be in the upper half of the coil, towards the negative- x direction

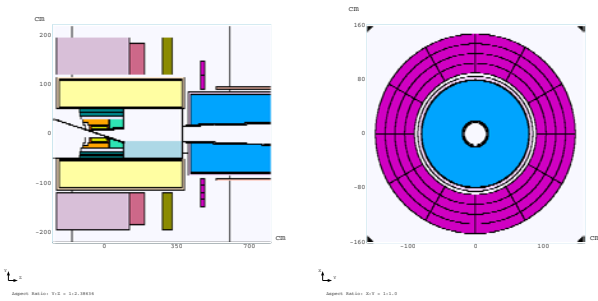


Figure 3: y - z (left) and y - x (right) cross sections of the target station, showing details of the segmentation of SC 4.

for the case with resistive coils. These peak values, close to 0.1 mW/g, could be mitigated by including W-bead shielding above the mercury pool, as considered in [4].

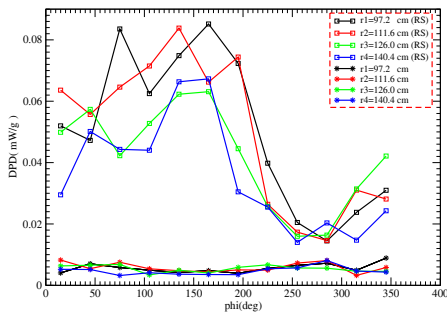


Figure 4: Azimuthal deposited-power distributions for four radii in coil SC 4 with and without resistive magnets.

In the configuration where the resistive magnets are replaced by W-bead shielding, the peak deposited power in SC 4 would be relatively modest everywhere.

Figure 5 presents a comparison of the peak power densities (DP) in coil SC 4, and the total DP in all SC coils as a function of the axial gap size between shielding modules, for the two W-bead densities. The top plot shows that for W beads of density 15.8 g/cm³ the power-density limit of 0.1 mW/g will be satisfied for axial gaps less than 20 cm. With 20-cm axial gaps and low-density W beads, the total deposited power in all 12 SC coils would be slightly over 1 kW, as shown in Fig. 5(bottom).

CONCLUSIONS

The design of the IDS120 baseline configuration for the MC/NF target station has been refined over the past 6 months with more realistic spacing of magnet coils to make room for services to them, and to the internal shielding. The shielding material has been changed to He-gas-cooled tungsten beads (from lower-density tungsten-carbide beads). Azimuthal analysis of power deposited in the superconduction coils verifies that this is everywhere below the limit [2] of 0.1 mW/g. A simpler design of the

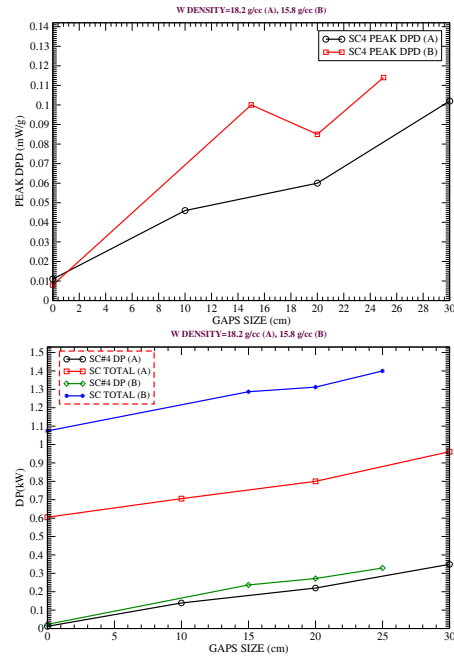


Figure 5: Peak deposited power density in coil SC 4 (top), and total deposited power in SC 4 and in all SC coils (bottom), vs. axial gap in the shielding. Both plots show results for W densities of 15.8 and 18.2 g/cm³.

mercury containment vessel has been considered, and although it implies less than maximal internal shielding, the power deposited in the superconducting coils would still be acceptable. Replacement of the 5-T resistive coils by W-beads improves the shielding as expected.

With a basic concept for the shielding now validated, future studies will emphasize the engineering challenges of realizing the configuration of the 4-MW target station.

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