RADIATION SHIELDING STUDIES FOR SUPERCONDUCTING MAGNETS IN MULTI-TEV MUON COLLIDERS[*][†]

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Abstract

Circular muon colliders provide the potential to explore center-of-mass energies at the multi-TeV scale within a relatively compact footprint. Because of the short muon lifetime, only a small fraction of stored beam particles will contribute to the physics output, while most of the muons will decay in the collider ring. The resulting power carried by decay electrons and positrons can amount to hundreds of Watt per meter. Dedicated shielding configurations are needed for protecting the superconducting magnets against the decay-induced heat and radiation damage. In this paper, we present generic shielding studies for two different collider options (3 TeV and 10 TeV), which are presently being explored by the International Muon Collider Collaboration. We show that the key parameter for the shielding design is the heat deposition in the magnet cold mass, which will be an important cost factor for facility operation due to the associated power consumption.

INTRODUCTION

The International Muon Collider Collaboration (IMCC) studies the design and technology for multi-TeV muon colliders with $\sqrt{s}$ =3 TeV and 10 TeV [1–3]. One of the technical challenges is the protection of superconducting magnets in the collider ring against the heat deposition and radiation damage by muon decay products. The beam and collider parameters are chosen such that the decay-induced power load on the machine does not exceed ~500 W/m for both collider options (see Table 1). This takes into account that decay electrons and positrons carry on average 35% of the muon energy, while the remaining 65% of the energy is carried away by neutrinos, which are irrelevant for the radiation load to the machine. Shielding studies for muon colliders have been previously carried out within the US-Muon Accelerator Program (MAP) [4–8], indicating that a continuous liner (few centimeters of tungsten) is needed inside magnets and magnet interconnects. A first assessment of the shielding requirements for the arcs of a 3 TeV and a 10 TeV collider has been performed more recently within the IMCC [9] using the FLUKA code [10–12]. In the present paper, we extend our previous arc studies by evaluating the power load and radiation damage for different shielding thicknesses. In addition, we discuss in more depth the radial build of arc dipoles.

Table 1: Muon decays in the collider ring for two beams with one bunch/beam, assuming an injection frequency of 5 Hz and 1.2×10^{7} s (≈140 days) of operation per year.

	3 TeV	**10 TeV**
Muons per beam	2.2×10^{12}	1.8×10^{12}
Circumference	4.5 km	10 km
Av. muon lifetime	0.031 s	0.104 s
Av. decay rate	4.9×10^{9} m^{-1}s^{-1}	1.8×10^{9} m^{-1}s^{-1}
Power ($e^{\pm}$)	0.411 kW/m	0.505 kW/m
Annual decays	5.87×10^{16} m^{-1}	2.16×10^{16} m^{-1}

RADIAL BUILD FOR ARC DIPOLES

One of the key challenges for the collider shielding design is the overall optimization of geometrical aspects (beam aperture, shielding thickness, coil aperture) and thermal aspects (shielding and magnet temperature, thermal insulation, cooling scheme). This optimization critically depends on technology choices, e.g., low-temperature versus high-temperature superconductors, and requires a multi-disciplinary design approach including radiation and beam physics, magnet engineering, cryogenics and vacuum. A careful optimization of the shielding thickness is important since it significantly impacts the aperture requirements for magnets.

An essential design parameter for the shielding of arc magnets is the maximum allowed heat deposition in the cold mass and the resulting cooling requirements, which will be an important cost factor for collider operation due to the associated power consumption. Other design criteria are the particle-induced power density in the coils, which must remain below the quench level of magnets, as well as cumulative radiation damage in different magnet components.

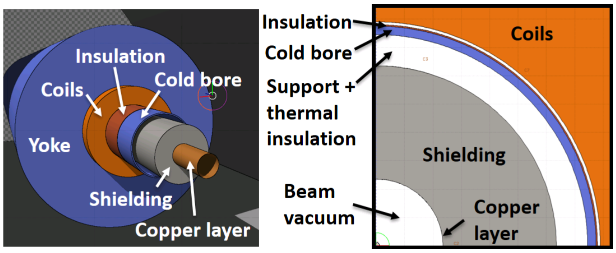

Figure 1: Arc dipole model used in the radiation studies.

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[*] Funded by the European Union (EU). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.

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Table 2: Tentative 1D radial build of the collider arcs, defining the inner aperture of dipole coils.

Description	**r**
Beam aperture	23.49 mm
Coating (Cu)	0.01 mm
Radiation absorber (W)	20-40 mm
Shielding support and thermal insulation	11 mm
Cold bore	3 mm
Cold bore insulation	0.5 mm
Clearance to coils	1 mm
Total (=inner coil radius)	59-79 mm

The latter includes the cumulative displacement damage in the superconductor, as well as the total ionizing dose in organic materials like the coil insulation and spacers [13]. If the radiation damage is too high, this can lead to magnet failures during the lifetime of the collider.

In this paper, we present a first-order evaluation of the shielding efficiency based on a simple 1D radial build of arc dipoles (see Fig. 1 and Table 2). The maximum horizontal beam size and hence the inner shielding aperture is determined by the optics dispersion and the relatively large momentum spread (0.1%). Here we assume an inner shielding radius of 23.5 mm for the 10 TeV collider, in order to accommodate at least $5\sigma_x$, where σ_x is the RMS beam size in the horizontal plane. The beam aperture requirements might, however, evolve with the optics design [14, 15]. For simplicity, the same aperture is used for the 3 TeV collider. The shielding is assumed to be made of tungsten, with a thin layer of copper on the inner side. The copper improves the transverse beam stability and hence reduces the emittance growth [16]. As radial shielding thickness, we assume 20–40 mm. Considering also the required space for shielding supports, thermal insulation, cold bore and coil insulation, the resulting coil radius ranges from 59 mm for a 20 mm shielding to 79 mm for a 40 mm shielding. The FLUKA studies presented in the following are based on a generic string of 6 m long dipoles, with a field strength of 10 T (16 T) for the 3 TeV (10 TeV) collider. The interconnects between dipoles are assumed to be fully shielded with tungsten in order to reduce the radiation load to the magnet front faces.

SECONDARY PARTICLE SPECTRA

The electrons and positrons produced by muon decay in the collider ring can have TeV energies and emit synchrotron radiation while travelling inside the magnetic fields. Their energy is then dissipated through electromagnetic showers in surrounding materials. In addition, secondary hadrons can be produced in photo-nuclear interactions, in particular neutrons, which dominate the displacement damage in magnet coils. Figure 2 shows the electron/positron, photon and neutron spectra in the dipole coils of a 10 TeV collider. The different blue curves correspond to the different tungsten shielding thicknesses described in the previous section. For comparison, the figure also shows the spectra of decay electrons/positrons and synchrotron photons when they impact on the vacuum aperture (red curves). The energy of synchrotron photons emitted by the decay products can reach very high values in a 16 T dipole, up to the TeV regime.

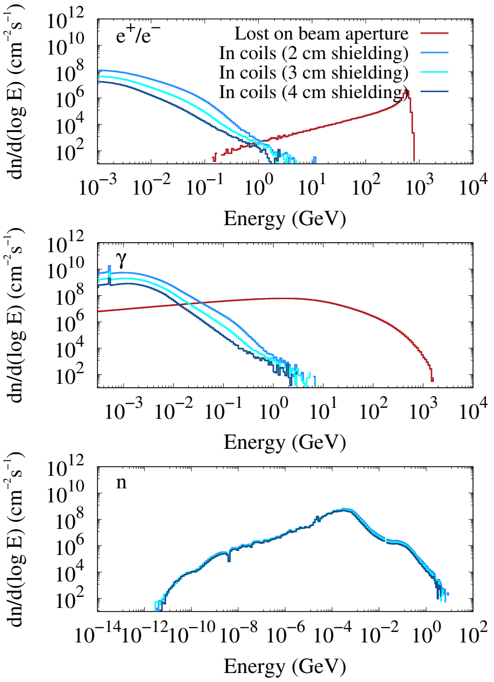

Figure 2: Secondary particle flux due to muon decay (10 TeV collider). Red curves: spectra of decay products (electrons/positrons) and synchrotron photons lost on the beam aperture of arc dipoles. Blue curves: the resulting secondary spectra in the dipole coils for different shielding thicknesses.

As demonstrated by the blue curves, the shielding transforms the electron and photon spectra into much softer ones, with a high abundance of MeV particles and maximum energies of a few GeV. The curves for different shielding thicknesses are qualitatively very similar, but the number of electrons and photons in the coils decreases visibly when increasing the radial shielding layer from 2 cm to 4 cm. On the other hand, the neutron spectra in the coils depend very little on the shielding thickness.

POWER DEPOSITION

Depending on the tungsten thickness, the shielding absorbs between ~96% (2 cm) and ~99 % (4 cm) of the power originally carried by decay electrons and positrons. The relative power deposition in the shielding is found to be similar for the 3 TeV and 10 TeV colliders despite the harder decay spectrum in the latter case. Figure 3 summarizes the power escaping from the shielding and the power deposition in the magnet cold mass and cold bore as a function of the shielding thickness. As illustrated by the figure, the cold elements dissipate most of the power leaking from the shielding, while only a small fraction is deposited in the environment like the tunnel walls and surrounding soil. As a design criterion for the 10 TeV collider, the beam-induced heat load in cold elements due to muon decay shall not exceed O(5 W/m) for

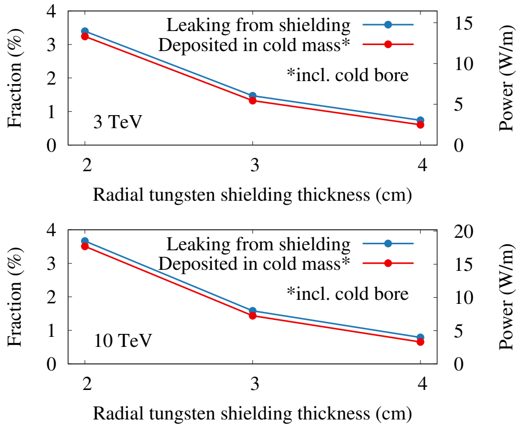

Figure 3: Power leaking from the tungsten shielding (blue lines) and power deposition in the magnet cold mass including cold bore (red lines). The upper and lower plot correspond to the 3 TeV and 10 TeV colliders, respectively. The relative fraction (left axis) is wrt the power in Table 1.

magnet operation in the vicinity of liquid helium (4.2 K), but could be up to O(10 W/m) for operation in the range of 20 K. This is to limit the cooling requirements and power consumption to acceptable levels, also considering additional static heat loads [17]. This suggests that a shielding thickness of 2 cm is not sufficient for 10 TeV since the power leaking from the tungsten amounts to almost 20 W/m. The tungsten shielding layer likely needs to be in the range of 3–4 cm, for which the escaping power decreases to 8–4 W/m.

CUMULATIVE RADIATION DAMAGE

In order to quantify long-term radiation effects magnets, we assume an average operational time of 1.2×10^7 s per year (≈140 days, see Table 1). Figure 4 illustrates the cumulative ionizing dose in the dipole coils (10 TeV) after five years of operation. Dose hot spots can be observed on the horizontal plane due to the overbent decay electrons and positrons, and the emitted synchrotron photons (see also Ref. [9]). The figure corresponds to the magnet front, where the dose is the highest. This illustrates the importance of radiation shielding in the magnet interconnects. At the magnet center, the peak dose is found to be a few 10% lower.

Figure 5 summarizes the maximum dose in the cold bore insulation and in the coils after 5 years of operation. For shielding thicknesses ≥3 cm, the ionizing dose remains within acceptable limits of typically used insulation and spacer materials, with some margin to increase the operational time of the collider beyond 5 years. On the other hand, for a 2 cm-thick shielding, the values are at or even exceed typical material limits already after 5 years, in particular for the 10 TeV collider. The figure also shows the maximum Displacement per Atom (DPA) in the coils (also for 5 years). The latter was calculated with the Norget-Torrens-Robinson (NRT)-model in FLUKA. The DPA estimates are conservative as they neglect any recombination due to annealing during warm-up of the magnets in shutdowns. Previous irradiation experiments showed that the critical temperature T_c of Nb_3Sn starts to be affected above 10^{-3} DPA [18]. A change of T_c was also found for high-temperature superconductors in the 10^{-3} DPA regime [19]. The DPA values predicted for the dipole coils remain comfortably below these values for the considered shielding thicknesses and are less critical for the magnet lifetime than the dose.

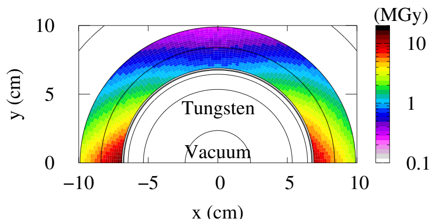

Figure 4: Cumulative ionizing dose in the dipole coils after five years of operation with 140 days/year (10 TeV collider). The figure assumes a 3 cm thick tungsten shielding.

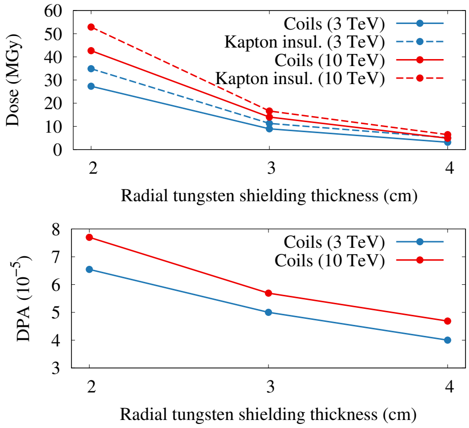

Figure 5: Maximum dose in the cold bore insulation and in the coils (top), and maximum Displacement Per Atom (DPA) in the coils (bottom). The figures assume 5 years of operation with about 140 days of running time per year.

CONCLUSION

This paper showed that the decay-induced heat load in the cold mass of superconducting magnets determines the shielding requirements for arc magnets in a multi-TeV muon collider. The studies demonstrated that 3–4 cm of tungsten is needed in order to reduce the power deposition below 5–10 W/m. With such a thickness, the cumulative radiation damage in magnets (dose and DPA) is expected to be acceptable, even for more than 5 years of operation. Together with the required beam aperture (here 2.35 cm) and other space requirements for supports etc., the inner coil radius of arc magnets needs to be about 7–8 cm, which is a key figure for the magnet design. Besides the conceptual shielding considerations discussed here, one also faces different engineering challenges, like the heat extraction from the shielding. In addition, the vacuum chamber needs to support the weight of the shielding (>100 kg/m). Another important aspect is the raw material cost of the shielding, which requires a careful optimization of the shielding cross section.

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