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RADIATION LOAD STUDIES FOR SUPERCONDUCTING MAGNETS IN A 10 TeV MUON COLLIDER

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Abstract

Among the various future lepton colliders under study, muon colliders offer the prospect of reaching the highest collision energies. Despite the promising potential of a multi-TeV muon collider, the short lifetime of muons poses a severe technological challenge for the collider design. In particular, the copious production of decay electrons and positrons along the collider ring requires the integration of continuous radiation absorbers inside superconducting magnets. The absorbers are needed to avoid quenches, reduce the heat dissipation in the cold mass and prevent magnet failures due to long-term radiation damage. In this paper, we present FLUKA shower simulations assessing the shielding requirements for high-field magnets of a 10 TeV muon collider. We quantify in particular the role of synchrotron photon emission by decay electrons and positrons, which helps in dispersing the energy carried by the decay products. For comparison, selected results for a 3 TeV muon collider are also presented.

INTRODUCTION

Circular muon colliders offer the prospect of reaching significantly higher center-of-mass energies than electron-positron colliders, since the latter option is limited by the synchrotron radiation emission. The design of muon colliders is, however, less mature and involves various technical challenges [1]. The recently formed International Muon Collider Collaboration [2] aims to address key design questions for a multi-TeV collider, with a center-of-mass energy $\sqrt{s}$ of 10 TeV or even higher. Despite the Lorentz boost, multi-TeV muons still have a relatively short mean lifetime in the laboratory frame 0.1 s for $\sqrt{s}$=10 TeV and hence they rapidly decay while circulating in the collider ring. The decay electrons and positrons carry on average around one third of the muon energy, while the rest escapes in the form of neutrinos. Contrary to e^-/e^+ colliders, where the heat load is from synchrotron radiation from the primary beam, in the muon collider case it is arising from secondary particles generated by the decay. The resulting power dissipated by those amounts to several 100 W per meter [2]. This poses a significant challenge for the collider design due to the instantaneous heat deposition and cumulative radiation damage in the collider equipment. To sustain the radiation load, superconducting magnets need to be protected with a continuous absorber. The absorber must fulfil different purposes, as preventing beam-induced quenches, reducing the thermal load to the cryogenic system, and avoiding magnet failures due to the cumulative dose in insulators and atomic displacements in superconductors [3].

Radiation load studies for muon collider magnets have been previously carried out in the scope of the US Muon Accelerator Program (MAP) [4]. These studies [5–10] focused, however, on lower center-of-mass energies $\sqrt{s}$=0.125-4 TeV. In this paper, we present a first generic shielding assessment for the arc magnets of a higher-energy collider with a center-of-mass energy of $\sqrt{s}$=10 TeV. For comparison, we also show results for a $\sqrt{s}$=3 TeV machine. The studies were carried out with the FLUKA particle shower code [11–13], which is the standard code at CERN for accelerator shielding applications. The beam parameters considered in this paper (see Table 1) have been scaled from the design parameters previously adopted by the MAP collaboration. The collider design foresees two counter-rotating muon bunches of opposite charge, which share the same vacuum chamber. To reach the desired design luminosity, new bunches need to be injected multiple times per second. We assume that bunches are injected with a frequency of 5 Hz and that all injected muons decay in the collider ring. This assumption is justified since the luminosity burn-off in the collision point is small compared to the number of decays. We also neglect possible beam halo losses on the aperture.

SIMULATION MODEL

To derive general conclusions, we do not consider a specific arc lattice, but we model a generic string of dipoles, with magnetic fields of 7 T and 10.4 T for the 3 TeV and 10 TeV machines, respectively. The power dissipated by decay electrons and positrons per unit length is comparable in both colliders (about 500 W/m) due to the different ring circumferences. Previous shielding studies for muon colliders considered different magnet design options, including open mid-plane dipoles, where the decay products impact on an absorber located at a larger radius than the coils [5–7]. This design has some advantages in terms of heat load management, but adds some complexity to the magnet design.

Table 1: Parameters

	$\sqrt{s}$=3 TeV	$\sqrt{s}$=10 TeV
Beam energy	1.5 TeV	5 TeV
Bunch intensity	2.2×10^{12}	1.8×10^{12}
Number of bunches	1	1
Injection frequency	5 Hz	5 Hz
Circumference	4.5 km	10 km
Arc dipole strength	7 T	10.4 T
Power lost in e^+/e^- per beam	400 W/m	500 W/m

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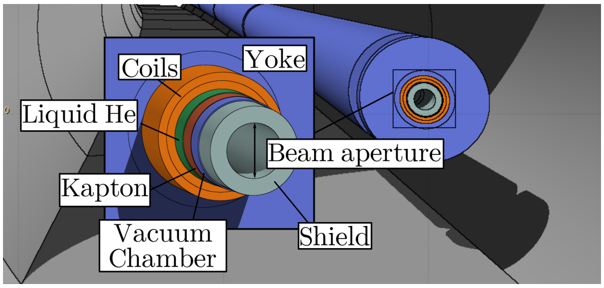

Figure 1: Geometry of the arc section. In detail, the different components of the dipole magnets are reported.

In this paper, we consider a conventional magnet design like in the LHC, with coils on the mid-plane.

For each study ($\sqrt{s}$=3 TeV and $\sqrt{s}$=10 TeV), a dedicated FLUKA model was implemented, consisting of a sequence of 9 dipole magnets separated by 20 cm long drift regions. Each dipole magnet was assumed to be 6 m long and straight. The magnet string is long enough to model the longitudinal build-up of particle impacts on the aperture. In absence of a detailed magnet engineering design, a cylindrical symmetry was assumed for the dipole geometry. As depicted in Fig. 1, the innermost element is a tungsten shield with an internal radius of 5 cm and a thickness of 3 cm. This approach follows previous studies within MAP, where such tungsten absorbers were first proposed [5–10]. The assumed shielding aperture shall be considered as tentative as the actual aperture requirements still have to be studied. The aperture will depend on the necessary beam clearance and must be large enough to properly fit the beam. For simplicity, we did not include any beam screen in the calculations.

The shielding needs to be kept at a higher temperature than the magnet cold mass to evacuate the shower-induced heat load efficiently. Here we assume a gap of 1 mm between the W shielding and the cold bore of the magnet. This gap and the thermal separation of the shielding and cold mass require further studies, which are out of the scope of this paper. The assumed gap is certainly insufficient for thermal evacuation purposes, but shall represent a conservative scenario for the radiation load studies. We further model a 0.5 mm thick Kapton insulation layer between the cold bore and the coils, which is the closest organic material to the beam. This insulation is followed by a 1.5 mm liquid helium layer impregnating the inner and outer coils, whose thicknesses are 1.5 cm each. Those dimensions follow typical accelerator magnets. The coils are embedded in stainless-steel collars, which are surrounded by the magnet yoke. The tungsten liners continue in the interconnects and are complemented by 5 cm thick tungsten shields protecting the magnet front faces.

Considering the generic nature of this study, we model a fixed-size Gaussian beam envelope with σ=100 μm, without any beam divergence. During the muon decay process, two neutrinos and a first generation lepton (e^+/e^-) are emitted. Neutrinos do not cause any harm to accelerator components and they are neglected here. On the contrary, the charged products interact with the elements of the collider, depositing their energy locally in downstream magnets. With ultra-relativistic muon beams, the produced electron/positrons will follow Michel's spectrum [14]. The decay electron and positrons are overbent by the strong dipole fields due to their lower magnetic rigidity compared to the stored muons. Consequently, they impact on the inner edge of the shielding within a few tens of meters from the decay position. While travelling inside the beam vacuum of a magnet, the electrons and positrons emit synchrotron photons and therefore lose energy. Due to their small mass, this is a non-negligible effect. Considering a charged particle moving in a magnetic field, the energy emitted per unit length is [15]:

$$\Delta E = \frac{e^2}{6\pi\epsilon_0 (m_0 c^2)^4} \frac{E^4}{\rho^2} \tag{1}$$

This means that a 1 TeV electron traveling in a 10 T field will radiate 1.26 GeV per centimeter, a substantial amount of energy. The emitted photons travel almost parallel to the electron trajectory, with a very small angular divergence. Contrary to the electrons/positrons, the synchrotron photons are spread over the external and internal sides of the magnet aperture. An accurate account of synchrotron photon emission by the decay particles is hence important in the simulation study. This feature has been added recently in the FLUKA code [12] and has been used here. We adopted 1 MeV and 300 keV transport cuts for electrons/positrons and photons, respectively. This choice is an adequate tradeoff between an accurate simulation and fast CPU times. All results reported below include the contribution of both beams.

POWER DEPOSITION

With the 3 cm-thick tungsten shielding considered in this study, the total heat deposition in the dipole cold mass is found to be 5 W/m for the 3 TeV collider and 7 W/m in the 10 TeV collider, respectively (compared to the initial 500 W/m). This shows that the harder decay spectrum in the 10 TeV machine does not significantly increase the amount of direct heat deposition in cryogenic magnets. Figure 2 displays the transverse power density distribution in the most loaded coil cross section close to the magnet end (the values are about 15-20% lower in center). In the 10 TeV machine, the power density distribution is more dispersed between the internal and external sides due to the synchrotron photons emitted by the decay electrons and positrons. The power density on the external side (due to photons) is almost as high as the power density on the inner side, where decay electrons and positrons are lost. On the contrary, with a 1.5 TeV beam in the 3 TeV machine, the synchrotron radiation contribution is not as prevalent. Instead, the dominating component of heat deposition is the direct impact of e^+/e^- on the shielding.

The figure of merit to quantify the quench margin is the radially averaged power deposition density in the inner coils. For both collider energies, the maximum averaged power density is less than 1.5 mW/cm^3. For comparison, the quench levels is about 15-20 mW/cm^3 for the bending

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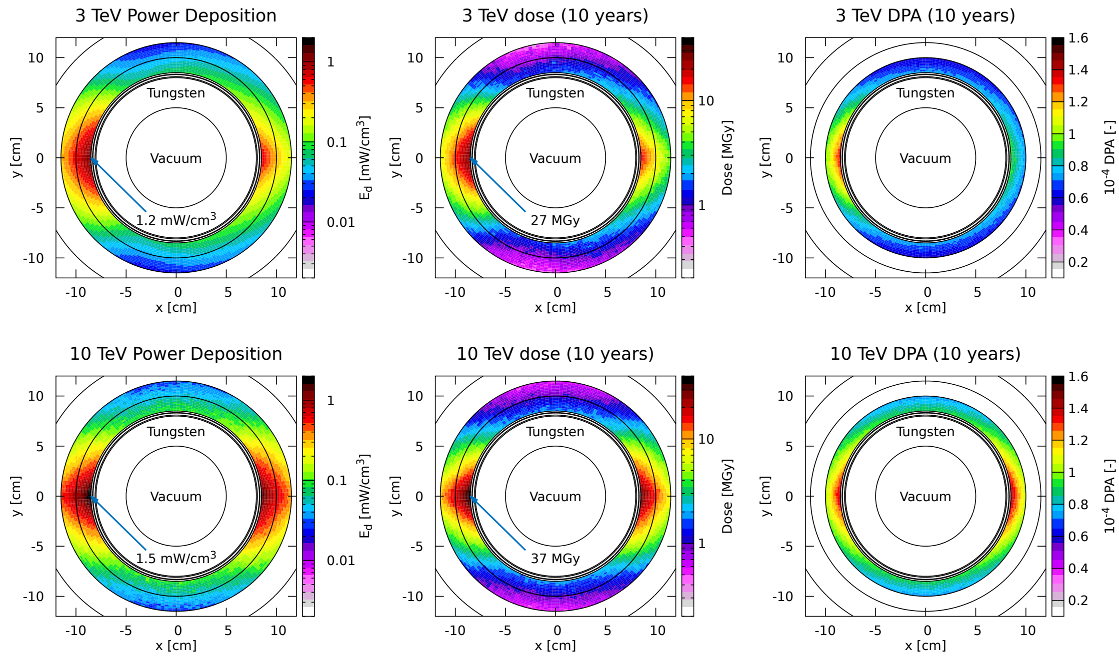

Figure 2: Power deposition density (left), cumulative dose (center) and DPA (right) in the coils of a generic arc dipole in muon collider (top: $\sqrt{s}$=3 TeV, bottom: $\sqrt{s}$=10 TeV). The center of the collider ring is on the left side. The dose and DPA values were scaled to 10 years of collider operation.

dipoles of the LHC (8.3T, NbTi cables) [16, 17], and is expected to be 70 mW/cm^3 for the future 11 T Nb_3Sn HL-LHC magnets [18]. We hence conclude that the found values are safely below the quench level. The actual margin will depend on the choice of coil technology and operating temperature.

CUMULATIVE RADIATION DAMAGE

The ionizing dose deposited in organic components of collider ring magnets can lead to a degradation of material properties, with loss of bonding strength and embrittlement. This increases, for example, the risk of mechanical failure or premature quenches [19]. The tolerable dose limit depends on the choice of materials for coil impregnation, insulation, spacers etc and is typically estimated to be a few 10 MGy [19]. Figure 2 shows the cumulative dose distribution in the coils after 10 years of collider operation. We consider 200 days of operation per year with the parameters reported in Table 1, under the conservative assumption of 100% machine availability. The simulations indicate that the peak dose at the inner edge of the coil reaches almost 30 MGy for the 3 TeV collider and almost 40 MGy for the 10 TeV collider, respectively. About 20% higher values can be observed for Kapton insulation around the cold bore. These values are at or even exceed the acceptable limits of typically used materials [3]. Despite the small cross section of photonuclear interactions, secondary photons can give rise to a sizeable number of neutrons in a muon collider. These neutrons are the main source of atomic displacements in magnet coils, which can affect the properties of the superconductor. Experimental irradiation studies showed that the critical temperature of Nb_3Sn samples starts to degrade above ~10^{-3} Displacements per Atom (DPA) [20]. In both collider options, the simulated peak DPA in the coils remains below this value, within a range of $1 - 2 \times 10^{-4}$ DPA accumulated over 10 years. For comparison, similar values are reached in the inner triplet magnets of the HL-LHC after 3000 fb^{-1} and they are considered acceptable [3]. Since displacement phenomena are dominated by neutrons, they have a lower dependence on the shielding thickness.

CONCLUSIONS

This paper presented a first generic shielding study for the dipole arc magnets of a 10 TeV muon collider. The study showed that the absorber requirements are similar for a 10 TeV and a 3 TeV machine if the power loss per unit length is similar in both cases. The increased dispersion of the energy by synchrotron photons is beneficial in a 10 TeV collider as it reduces the peak load on the inner side of the aperture. The study shows that the cumulative dose in organic magnet components (insulators, spacers etc.) is one of the most limiting factors, which guides the shielding requirements. With a 3 cm W absorber and a beam aperture of 5 cm, the ionizing dose is expected to reach critical values after 10 years of operation. A slightly thicker shielding is hence needed to allow for some safety margin. Although the studies in this paper were based on generic assumptions and without a real accelerator lattice, they provide a first numerical estimate of the expected radiation load in the arcs of a 10 TeV muon collider.

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