Superconducting Technologies and Materials for Muon Collider Magnets

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The energy reach for discovery of a muon collider (MC) is an order of magnitude higher than that of a *pp*-collider with the same collision energy [1]. Muon colliders have been proposed with collision energy between 125 GeV for Muon Collider Higgs Factories (MCHF), to 6 TeV for the Energy Frontier (EF) machines. Based on the muon beam parameters established by the Muon Accelerator Program (MAP), the average luminosity is planned to be 10^{32}/cm^2/s in the former case and 10^{35}/cm^2/s in the latter case. For the MCHF collider ring and superconducting (SC) magnet design of [2, 3], the power deposited in these magnets by the electrons from muon decay was calculated to be 300 kW with heat deposition reaching 1 kW/m in the magnet cold mass along the collider ring, i.e. several MW at room temperature. However, thanks to an accurately designed multicomponent protection system [3], the heat load on the magnet cold components can be reduced below 15 W/m, which is acceptable for modern cryogenic systems. Management of radiation loads in multi-TeV EF colliders needs instead to be resolved.

All three deleterious effects induced by the muon decay electrons in SC magnet components are vital for magnet design and performance: (1) Heat load drives the cryogenic system design and collider operational cost, (2) Peak energy deposition in SC coils is taken into account while studying the quench stability of the magnets, and (3) peak energy deposition (or absorbed dose) in magnet components defines the component lifetime, which is critical for organic materials.

Similarly, detectors are also sensitive to muon decay products. Optimization of the lattice design is very important to reduce as much as possible radiation on magnets and detectors. In addition, an appropriate machine-detector interface design helps in reducing the detector background generated by muon decays. Magnets are protected by tungsten masks in the interconnect regions and by allowing apertures large enough to use internal protective liners to reduce energy deposition of muon decay products in the cold masses [3]. Within the interaction region (IR), those protective elements along with the carefully designed tungsten nozzles placed inside the detector very close to the interaction point are used to protect the IR magnets and trap most of the decay electrons and incoherent e+e- pairs before they reach the detector [4, 5]. In short, the background load on the detector can be reduced by more than three orders of magnitude by this and other sophisticated shielding methods [3]. Note that all those findings were based on sophisticated modeling with the MARS code [6]. At the same time, the high energy accelerator magnets, which are either made of superconducting Nb_3Sn, or of both high-temperature (Bi2212 or ReBCO HTS) and low-temperature (Nb_3Sn LTS) superconductors, still see a large fraction of the radiation loads.

The standard fabrication process for Nb_3Sn accelerator magnets includes coils' reaction at high temperature and their impregnation with CTD-101K epoxy to reinforce the electrical and mechanical properties of the brittle cable insulation, which is typically E or S2-glass. CTD-101K epoxy has a relatively low radiation resistance. For instance, its common limit in the Hi-Lumi LHC type magnets is 25 MGy, which confines the lifetime of accelerator magnets operating in severe radiation environments, such as the Nb_3Sn focusing quadrupoles in the collider IR. The proposed white paper will focus on the protection of HTS/LTS magnets at high energy/high luminosity muon and hadron colliders. It will focus on study and selection of radiation resistant impregnation materials. Physical, electrical and mechanical properties of available resins will be obtained, including parameters bound to technological specifications, such as viscosity and pot life. Monte Carlo MARS15 simulations of radiation load and peak energy deposition in these resins will be performed. MARS15 tabulates the particles passing through any complex 3D geometry, material and electromagnetic field distribution, and produces results on particle fluxes, spectra, energy deposition, material activation, displacement per atom, etc. in order to produce power density (mW/g), absorbed dose (Gy/year), and potential instantaneous temperature rise.

A magnet impregnation material of potential interest is an organic olefin-based thermosetting dicyclopentadiene $C_{10}H_{12}$ (DCP) resin, commercially available in Japan as PENTAM®8000 by RIMTEC Corporation. This resin has a low dielectric permittivity and a low moisture absorbency. The radiation strength of the DCP resin was studied and compared with epoxy resin (bisphenol-A type) for resistance to ^{60}Co gamma radiation up to a dose of 3.3 MGy with a dose rate of 2 kGy/h [7]. The DCP resin had a superior gamma ray resistance compared to the epoxy. Also, whereas for non-organic materials there is a dependence of material response on the type of beam irradiation, such a dependence can be modest for organic materials, which respond to the absorbed dose, and not as much to the beam current. Therefore, resistance to gamma irradiation is a promising indicator. Another impregnation material under study is radiation-resistant polyimide Matrimid® 5292, a hot-melt bismaleimide solution by Huntsman Corporation, which has been tested in Nb_3Sn dipole and quadrupoles short models [8].

The Brookhaven LINAC Isotope Producer (BLIP) offers a unique facility for the study of materials relevant to the high energy accelerators needed for the study of the particle physics EF. BLIP provides proton beams of 66-200 MeV with currents up to 170 μA that can be focused or rastered for irradiation studies. These beams have been used to study the performance of a wide range of accelerator structural materials, including high power targets [9-16] and materials for use in the LHC [17-18] as well as superconductors [19-20], as a function of radiation dose. The hot cells and instrumentation available at the Medical Isotope Research Program (MIRP) facility support detailed characterization of the mechanical properties of the irradiated materials. Furthermore, detailed microstructural analysis of irradiated samples can be carried out on beamlines at the NSLS-II. Detailed superconductor characterization is available at the Superconducting Magnet Division. The studies proposed here would continue Brookhaven's long engagement with delivering irradiation capabilities to support HEP needs.

Complementary irradiation facilities under consideration include the Fermilab NOvA Target Hall.

While the motivation for this effort is to conduct a broad range of beam irradiation tests to determine the most promising materials required for a future muon collider, this research will have applicability to a wide range of accelerator facilities utilizing high-power beams. Thus, we also aim to collaborate with other accelerator collaborations that require next-generation materials to guarantee successful delivery of physics results.

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