MUON ACCELERATORS FOR PARTICLE PHYSICS — MUON

The Higgs Factory muon collider superconducting magnets and their protection against beam decay radiation

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ABSTRACT: A low-energy medium-luminosity Muon Collider (MC) is being studied as a possible Higgs Factory (HF). Electrons from muon decays will deposit more than 300 kW in superconducting (SC) magnets of the HF collider ring. This imposes significant challenges to SC magnets used in the HF storage ring (SR) and interaction regions (IR). Conceptual designs of SC dipole and quadrupole magnets are described which provide high operating gradient and field in a large aperture to accommodate the large size of muon beams (due to low $\beta^*$), as well as a cooling system to intercept the large heat deposition from the showers induced by decay electrons. The distribution of heat deposition in the main elements of HF SR lattice requires large-aperture magnets to accommodate thick high-Z absorbers to protect the SC coils. Based on the developed MARS15 model and intensive simulations, a sophisticated protection system from radiation was designed for the collider SR and IR to bring the peak power density in the SC coils well below the quench limit and reduce the dynamic heat deposition in the cold mass of SC magnets by a factor of 100. The radiation protection system consists of tight tungsten masks in the magnet interconnect regions and elliptical tungsten liners in the magnet aperture optimized for each magnet. These elements reduce also the background particle fluxes in the collider detector.

KEYWORDS: Accelerator Applications; Accelerator modelling and simulations (multi-particle dynamics; single-particle dynamics); Accelerator Subsystems and Technologies

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Contents

Introduction 1

1 Magnets 2
  1.1 Design constraints 2
  1.2 Requirements 2
  1.3 Storage ring 4
  1.4 Interaction region 5
  1.5 Implementation in MARS15 model 8

2 Magnet protection system 8
  2.1 Concept 8
  2.2 Reducing heat load on cold mass 11
  2.3 Machine-detector interface 13

3 Conclusions 14

Introduction

The discovery of the Higgs boson boosted interest in a low-energy medium-luminosity Muon Collider (MC) as a Higgs Factory (HF). A preliminary design of the 125 GeV c.o.m. HF muon Storage Ring (SR) lattice, the Interaction Region (IR) layout and superconducting (SC) magnets, along with the first results of heat deposition simulations in SC magnets, are described in refs. [1–3]. The large normalized beam emittance and $\beta_{\text{max}}$ as well as the necessity to protect the SC magnets and detector from showers generated by muon decay products, require SC magnets with very large apertures in both the IR and the rest of the storage ring. A preliminary design of the HF storage ring is based on Nb$_3$Sn SC magnets with the coil aperture ranging from 50 cm in the interaction region to 16 cm in the arc [2]. The coil cross-sections were generated based on the considerations related to the magnet operating fields as well as margins, field quality and quench protection to provide an adequate space for the beam pipe, helium channel and inner absorber (liner).

The high level of Lorentz forces in large-aperture coils, operating at relatively high fields, requires stress management in the coil to avoid large degradation or even damage of brittle Nb$_3$Sn superconductor. Stress management concepts for shell-type coils have been recently proposed for high-field accelerator magnets based on Nb$_3$Sn superconductor [4, 5]. Both concepts use special metallic structure with radial shells and azimuthal bars to intercept and transfer Lorentz forces inside the coil. The experimental studies and optimization of these concepts, however, are still at a very early stage. Therefore, the stress management elements are not included in the described HF magnet design concepts. The main objective of the described SC magnets for HF SR and IR is just providing realistic field maps for the analysis and optimization of the SR lattice and IR design, as well as for studies of beam dynamics and magnet protection against radiation [3, 6]. Stress management elements will be included in the energy deposition simulations once the magnet and machine designs mature.
At the 62.5 GeV muon energy and $2 \times 10^{12}$ muons per bunch intensity, the electrons from muon decays deposit more than 300 kW in the SC magnets of the HF IR and SR. This heat deposition corresponds to an unprecedented average dynamic heat load of 1 kW/m around the 300-m long ring, a multi-MW room temperature equivalent if the heat is deposited at liquid-helium temperature. This paper presents the results of a thorough optimization of the protection system to substantially reduce radiation loads on the HF magnets as well as particle backgrounds in the collider detector. It brings together in a coherent form the results of our previous papers on that subject published in several PAC Proceedings [1–3] and expands the magnet radiation protection concept. New thoughts with corresponding recent references are added through the text.

1 Magnets

1.1 Design constraints

Rather high magnetic fields and operating margins required for HF SR magnets call for advanced superconductor and accelerator-magnet technologies beyond the traditional Nb-Ti magnets. The Nb-Ti superconductor used in all present accelerators has a critical temperature $T_{c0}$ of about 9.8 K and an upper critical magnetic field $B_{c2}$ of about 14.5 T. These parameters limit the operating magnetic fields in accelerator magnets based on this superconductor to 6–7 T at 4.5 K or 8–9 T at 1.9 K. A practical alternative to Nb-Ti is Nb$_3$Sn superconductor, which has a critical temperature $T_{c0}$ of about 18 K and an upper critical magnetic field $B_{c2}$ of about 28 T. Thanks to its superior superconducting properties, Nb$_3$Sn allows reaching operating fields up to 15 T at 4.5 K.

Significant progress in raising the performance parameters of commercial Nb$_3$Sn composite wires in the late 1990s–early 2000s [7] and impressive achievements of accelerator magnet technologies based on this superconductor during the past two decades [8] make it possible to consider Nb$_3$Sn accelerator magnets for MC storage rings. Due to the considerable challenges and uncertainties in operating conditions of SC magnets in the MC SR, it is reasonable to choose a nominal operating field at the level of 10 T to provide large (up to 50%) operating margin for HF SR magnets. Conceptual designs and performance parameters of HF SR and IR magnets based on Nb$_3$Sn superconductor are described below. The coil cross-sections were optimized to achieve the necessary field level and quality in the area occupied by beams using the ROXIE code [9].

The next subsection discusses the conceptual designs and parameters of the HF SR and IR magnets. The lattice parameters are those of ref. [6]. The large beam size in the IR quadrupoles, as well as the requirements for magnet and detector protection from muon decay showers, leads to very large magnet apertures, which in turn imposes challenging engineering constraints on the magnet design and creates beam dynamics issues with magnet field quality and fringe fields. These issues are not discussed in this paper.

1.2 Requirements

Table 1 summarizes the specifications of the IR magnets. The orbit sagitta in the IR dipoles is rather large, 8.1 cm. Nevertheless, it does not affect the bore size of the IR dipoles, which is determined by the large vertical beam size.

Tables 2 and 3 present the maximum values of the main parameters for the dipoles (B) and quadrupoles (Q) used in the chromaticity correction section (CCS), the matching section (MS) and
the arc (ARC). The most challenging magnets are the CCS dipoles ($B_{CS}$), some MS dipoles ($B_{MSI}$) and the arc dipoles ($B_{ARC}$), which need high nominal operating field up to 10 T.

The magnet aperture outside the IR reduces from 231 mm in the CCS quadrupoles to 92 mm in the arc dipoles. Note that the aperture size in the arc is defined by the arc dipoles due to a relatively large beam sagitta. To standardize the magnet designs in the various sections it was decided to use for this study two different aperture sizes: large (~231 mm) in the CCS and adjacent part of the MS, and small (~130 mm) in the ARC and adjacent part of the MS.

### Table 1. IR magnet specifications.

| Parameter       | Q1  | Q2  | Q3  | Q4  | B1  |
|-----------------|-----|-----|-----|-----|-----|
| $10\sigma_{\text{max}}$ (mm) | 234 | 411 | 339 | 415 | 405 |
| $G_{\text{nom}}$ (T/m)      | 74  | -36 | 44  | -25 | 0   |
| $B_{\text{nom}}$ (T)        | 0   | 2   | 0   | 2   | 8   |
| $L_{\text{mag}}$ (m)        | 1.00| 1.40| 2.05| 1.70| 4.10|
| Coil aperture (mm)          | 267 | 444 | 372 | 448 | 438 |
| Quantity               | 1   | 2   | 1   | 1   | 2   |

### Table 2. SR dipole magnet parameters.

| Parameter       | $B_{CS}$ | $B_{MSI}$ | $B_{MSII}$ | $B_{ARC}$ |
|-----------------|----------|-----------|------------|-----------|
| $10\sigma_{\text{max}}$ (mm) | 225 | 222 | 127 | 92 |
| $B_{\text{nom}}$ (T)      | 10 | 10 | 6.4 | 10 |
| $L_{\text{mag}}$ (m)      | 1.8 | 2.4 | 3.6 | 3.0 |
| Coil aperture (mm)        | 258 | 255 | 160 | 120 |
| Quantity               | 13 | 2   | 3   | 8   |

### Table 3. SR quadrupole magnet parameters.

| Parameter       | $Q_{CS}$ | $Q_{MS}$ | $Q_{ARC}$ |
|-----------------|----------|----------|-----------|
| $10\sigma_{\text{max}}$ (mm) | 231 | 130 | 46 |
| $B_{\text{nom coil}}$ (T) | 5.3 | 5.5 | 3.3 |
| Length (m)      | 1.0 | 1.0 | 1.0 |
| Coil aperture (mm) | 264 | 163 | 79 |
| Quantity | 5 | 5 | 4.5 |

The aperture of magnet coils in this analysis was defined as the maximum beam size ($10\sigma_{\text{max}}$, i.e. ± $5\sigma_{\text{max}}$ from the beam axis) plus 30 mm for the beam pipe (BP) and absorber (ABS) plus 3 mm for the BP insulation and helium channel. In the IR magnets, the coil aperture was increased by
Table 4. Nominal magnet parameters at $T_{\text{op}} = 4.5$ K.

| Parameter          | Dipole | Quadrupole |
|--------------------|--------|------------|
| Coil ID (mm)       | 270    | 160        |
| Max $B_{\text{op}}$(T) | 10.0   | —          |
| $B_{\text{max}}$ (T)     | 14.1   | 14.2       |
| Max $G_{\text{op}}$(T/m) | —      | 33         |
| $G_{\text{max}}$ (T/m)   | —      | 96.6       |
| $B_{\text{max}}$ coil (T) | 15.8   | 15.6       |
| Fraction of SSL    | 0.71   | 0.34       |
| $L$ (mH/m)         | 54.1   | 20.5       |
| $E_{\text{op}}$ (MJ/m) | 4.33  | 0.59       |
| $F_{x_{\text{op}}}$ (MN/m) | 9.25  | 0.89       |
| $F_{y_{\text{op}}}$ (MN/m) | -3.96 | -0.93      |

~50 mm with respect to this definition and limited by two sizes, 320 mm in Q1 and 500 mm in Q2–Q4 and B1–B2, to reserve extra space for IR magnet protection against radiation. The coil aperture of the CCS and adjacent MS magnets was increased to 270 mm, and in the ARC magnets and adjacent MS magnets to 160 mm. This allows using thicker inner absorbers in the arc magnets if necessary.

1.3 Storage ring

All the magnets are based on two-layer, shell-type coils with the iron yoke used mainly to reduce the fringe fields. It allows a sufficient space for the coil support structure. The cross-sections of dipole and quadrupole coils were optimized to achieve the required nominal operating field or gradient with margin and good field quality corresponding to $8\sigma$ of the full beam size. The conceptual designs of the HF SR magnets are based on a 42-strand Rutherford cable, 21.6 mm wide and 1.85 mm thick, made of a 1 mm diameter Nb$_3$Sn composite wire with Cu/nonCu ratio of 1.0. The cable is insulated with a 0.2 mm thick insulation.

The optimized cross-sections of the CCS, MS and ARC dipole and quadrupole coils are shown in figure 1. The main magnet parameters at 4.5 K are summarized in table 4. The magnet operating margin is a ratio of magnet nominal field or field gradient to the corresponding maximum values defined by the magnet short sample limit (SSL). The Nb$_3$Sn dipoles operate at 71% and the quadrupoles at 22–34% of their SSL at 4.5 K.

The relatively low fields in the CCS, MS and ARC quadrupoles allow using the traditional Nb-Ti technology, which would simplify the magnet fabrication process and reduce their cost. Using the same cable with Nb-Ti strands in both quadrupoles reduces $G_{\text{max}}$ to 54 and 90 T/m. However, the magnets still have a sufficient operating margin as they operate at 61% and 40% of the SSL for the 270 mm and 160 mm quadrupoles respectively. The final choice of superconductor for the SR quadrupoles will depend on the results of radiation studies for these magnets.
Geometric field harmonics at the corresponding reference radii in the SR magnets are reported in table 5. With optimized coil cross-sections the relative field errors in the area occupied by muon beams are $\sim 10^{-4}$ or less (dark blue area in figure 1). Since the SR magnets will operate at a fixed nominal field, the contributions to the normal sextupole $b_3$ from the coil magnetization due to the persistent currents in superconductor and from the iron saturation can be compensated by introducing the appropriate geometrical components of the opposite sign, as it is shown in [10].

1.4 Interaction region

Conceptual designs of the HF IR magnets are also based on a 1 mm diameter Nb$_3$Sn composite wire with a critical current density of 2.7 kA/mm$^2$ at 12 T and 4.2 K, and a Cu/nonCu ratio of 1.15. The Q1–Q4 and B1 coils use, as the SR magnets, a 42-strand Rutherford cable, 21.6 mm wide and 1.85 mm thick. The cable in the dipole coil Bq (in Q2 and Q4) has 22 1-mm diameter strands. The cable is 11.3 mm wide and 1.77 mm thick. Both cables are insulated with a 0.2 mm thick insulation.

Figure 1. Coil cross-sections of HF SR dipoles and quadrupoles.
Table 5. Geometric harmonics at $R_{\text{ref}}$ ($10^{-4}$).

| ID | $R_{\text{ref}}$, mm | $b_3$ | $b_5$ | $b_6$ | $b_7$ | $b_9$ | $b_{10}$ |
|----|----------------------|-------|-------|-------|-------|-------|---------|
| D  | 270                  | -0.2  | -0.1  | —     | 0.2   | 1.2   | —       |
|    | 160                  | 53    | 0.0   | -0.1  | —     | 0.5   | 1.1     |
| Q  | 270                  | —     | —     | 0.2   | —     | —     | 0.0     |
|    | 160                  | 53    | —     | —     | 0.1   | —     | 0.0     |

Table 6. IR magnet parameters at $T_{\text{op}} = 4.5$ K.

| Parameter                  | Q1 | Q2* | Q3 | Q4* | Bq** | B1 |
|----------------------------|----|-----|----|-----|------|----|
| Aperture (mm)              | 320| 500 | 500| 500 | 780  | 500|
| $B_{\text{max}}$ (T)       | —  | —   | —  | —   | 4.18 | 16.3|
| $G_{\text{max}}$ (T/m)     | 94.9| 58.2| 62.9| 58.2| —    | —  |
| $B_{t_{\text{max}}}$ coil (T) | 16.4| 17.2| 16.9| 17.2| 15.0 | 17.7|
| Operating margin           | 0.78| 0.62| 0.70| 0.62| 0.48 | 0.50|
| $L$ (mH/m)                 | 177 | 454 | 454| 454 | 65   | 1188|
| $E_{\text{op}}$ (MJ/m)    | 10.4| 11.3| 16.8| 5.5 | 1.6  | 13.8|
| $F_x(I_{\text{op}})$ (MN/m) | 5.8 | 7.3 | 6.5 | 4.1 | 0.7  | 9.7 |
| $F_y(I_{\text{op}})$ (MN/m) | -12.3| -12.6| -14.2| -6.8| -4.7  | -8.9|

* calculated for nominal Bq = 2 T.

** calculated for $G_{\text{nom}} = 35$ T/m (Q2).

The coil aperture of the IR magnets was increased by 50 mm, to 320 mm in Q1 and to 500 mm in Q2–Q4 and B1, to provide adequate space for the beam pipe, helium channel and inner absorber (liner). The number of layers in the coils was chosen based on the operating margin and quench protection considerations. The coil cross-sections were optimized to achieve the required field quality in the beam area.

The IR magnets use 6-layer, shell-type coils, whereas the dipole coil Bq in Q2 and Q4 has only one layer. Q1 and Q2(1) do not have an iron yoke since they will be installed inside the detector field. In Q2(2)–Q4 and B1 the iron yoke is used mainly to reduce fringe fields. The optimized cross-sections of the Q1–Q4 and B1 coils are shown in figure 2. The main magnet parameters at 4.5 K are summarized in table 6. The parameters for Q2 and Q4 with dipole coil Bq include the combined dipole and quadrupole fields. The Bq parameters include the field from the main quadrupole coil Q2 at $G_{\text{nom}} = 35$ T/m. In Q4, the Bq parameters are better due to the lower $G_{\text{nom}} = 25$ T/m.

A 6-layer coil design provides large operating margin in the IR magnets at a relatively low current density in the coil. All the magnets operate at 50–80% of the short sample limit at 4.5 K. Conductor grading in the coil can be used to provide an additional margin, if needed.
Geometric field harmonics for Q1–Q4, Bq and B1 at corresponding $R_{\text{ref}}$ are shown in table 7. Optimization of the coil cross-section provided the relative field errors in the area occupied by muon beams at the level of $10^{-4}$ (dark blue area in figure 2). As the SR magnets, IR magnets will operate at fixed nominal fields. Thus, the contributions to $b_3$ from the superconductor magnetization and from the iron saturation (in those magnets where it is used) can be compensated by introducing the appropriate geometrical components of the opposite sign. Notice, that in the magnets, placed inside the detector solenoid, the coil magnetization effect has to be estimated including the field from the detector magnet.

Analysis of the Dynamic Aperture (DA) with the MADX PTC code and harmonics from table 7 shows that field errors in the straight sections of the IR magnets reduce the DA by a factor of 2 so that it coincides with the good field region shown in figure 2.
Table 7. Geometric harmonics at $R_{\text{ref}} \times 10^{-4}$.

| Parameter | Q1 | Q2–Q4 | Bq  | B1  |
|-----------|----|-------|-----|-----|
| $R_{\text{ref}}$ (mm) | 135 | 225   | 225 | 225 |
| $b_3$     | —  | —     | 0.08| -0.07|
| $b_5$     | —  | —     | 0.05| -0.06|
| $b_6$     | -0.56| -0.18| —   | —   |
| $b_7$     | —  | —     | 0.34| 0.12 |
| $b_9$     | —  | —     | 0.57| 0.02 |
| $b_{10}$  | -0.47| -0.57| —   | —   |
| $b_{11}$  | —  | —     | 2.55| 0.91 |
| $b_{13}$  | —  | —     | -2.89| 1.58|
| $b_{14}$  | 3.45| -0.94| —   | —   |

1.5 Implementation in MARS15 model

The MARYS15 Monte Carlo code [11] was used to address the key issues related to magnet and detector protection from radiation in the HF muon collider. A detailed 3D model of the entire collider ring was built for the first time. It allowed us realistic modelling of the beam-induced heat load to each of the machine components and contribution to the detector backgrounds from the entire ring. It included the layouts of the interaction region, the chromaticity correction and matching sections, the arc, and the machine-detector interface (MDI) as well as the SR tunnel and detector hall [3]. In each area the model incorporated the described above magnet geometries, materials and magnetic field maps. Figures 3 and 4 show the model of the 300-m circumference HF with the SiD-like detector at the interaction point (IP). The silicon vertex detector and tracker are based on the design proposed for the CMS detector upgrade. The detector geometry in GDML format was promptly imported into the MARS15 model.

The cross-sections of the IR quadrupoles Q2 and Q4 with dipole coils Bq as designed and implemented in the MARS15 model are shown in figure 5. The inner and outer radii of the SC coils, which are composed of 31% Nb$_3$Sn (the superconductor), 36% Cu (the composite wire stabilizer) and 33% G10 (the epoxy-impregnated S2-glass insulation), and the bronze poles are 25 cm and 40.5 cm, respectively. The coils and poles are embedded into the stainless steel external support structure with the outer radius of 55 cm. The 50-cm ID 8-Tesla IR dipoles as designed and implemented in the MARS15 model are shown in figure 6.

2 Magnet protection system

2.1 Concept

The first studies of radiation heat depositions and doses in the HF SR have shown [1–3] that, to provide the required cooling and adequate lifetime of the HF SC magnets, the values of radiation
load should be reduced by at least a factor of 100. As it was shown in early studies [12, 13], the practical ways to protect SC magnets in a MC storage ring against electromagnetic showers induced by electrons from muon decays include the following three measures: a) the reduction of the magnet lengths to 2 to 4 m; b) the installation tight tungsten masks in the magnet interconnect regions; and c) the use of thick tungsten liners inside the magnet apertures.
Such a radiation protection system concept allows reaching the following objectives:

• providing the reduction of the peak power density in the Nb$_3$Sn cable to $\sim$1.5 mW/g which is below the Nb$_3$Sn superconductor quench limit with an appropriate safety margin [14];

• keeping the lifetime peak dose in the innermost layers of insulation below 20–40 MGy;

• reducing the average dynamic heat load in the cold mass to the level of $\sim$10 W/m, which is acceptable for a cryogenic system;

• suppressing the long-range component of the detector background.
As a result of comprehensive MARS15 simulations, such a magnet protection system (MPS) was designed for the HF muon collider to achieve these objectives and to provide at least a $8\sigma_{x,y}$ full beam envelope ($\pm 4\sigma_{x,y}$ from the beam axis) for muons for up to 2000 turns.

### 2.2 Reducing heat load on cold mass

The parameters of the radiation protection system were individually optimized for each magnet and interconnect region in the 300-m circumference HF collider ring and IR. Figure 7 shows a fragment of the radiation protection system built in MARS15 for the IR. The aperture sizes of the tungsten nozzle and the interconnect region masks are location-dependent since they are defined as $\pm 4\sigma_{x,y}$ from the beam axis. It was found in the MARS15 simulations that the mask thickness has to be 15 cm and its outer radius should coincide with the SC coil outer radius at each location.

The thicknesses of tungsten liners inside the magnets are also dependent on the magnet location in a ring. As an example, the thickest tungsten liner for one of the hottest dipole magnets in the CCS at 24.2 m from the IP is shown in figure 8. The liner is 4.1 cm thick horizontally and 2 cm thick vertically, and it operates at 60–80 K. It is followed radially by the support structure, stainless steel beam pipe, Kapton insulation, liquid helium channel and 4.5 K Nb$_3$Sn coil.

**Figure 7.** MDI MARS15 model with tungsten nozzles on each side of IP, tungsten masks in interconnect regions and tungsten liners inside each magnet. The collider sub-detectors and iron-concrete shielding around the magnets are also shown.

The 15-cm long tungsten masks are installed in every interconnect region around the machine (see, e.g., figure 7). Their apertures are at $\pm 4\sigma_{x,y}$ from the beam axis or farther. Figure 9 (left)
shows the geometrically tightest mask at the IP end of the hottest BCS1 dipole at 24.2 m from the IP. Calculated isocontours of the power density at its longitudinal maximum in this BCS1 dipole are shown in figure 9 (right). The shielding effect of the tungsten mask and liner in the magnet aperture is clearly seen. The peak power density in the BCS1 dipole SC coil is reduced from ~150 mW/g to less than 1 mW/g. The reduction of heat load to the target value of 1.5 mW/g or less is achieved in the IR magnets (figure 10) as well as in all the SC coils around the ring.

Figure 9. Tungsten mask at the IP end of the BCS1 8-T dipole (left) and power density isocontours in this dipole (right). The ring center is to the right in these figures.
Dynamic heat loads on the SC magnet cold mass define the capacity of the collider cryoplant and its operating costs. An acceptable level of dynamic heat load is 10 W/m or less at the liquid helium temperature of 4.5 K. It means that the magnet protection system needs to reduce the average heat load to the cold mass by a factor of 100 from the original 1 kW/m. The system described above was designed under this constraint. The distribution of the dynamic heat load along half of the HF SR with optimized tungsten masks and liners is shown in figure 11. The average heat load to the cold mass at 4.5 K is below the desired value of 10 W/m. Although in some magnets the heat load level is up to 15 W/m which is higher than the average, it is still tolerable for a cryogenic system at 4.5 K. The remaining average power dissipation of ~990 W/m is intercepted by the tungsten masks and liners at 60–80 K.

The designed tungsten masks and liners are positioned at $\pm 4\sigma_{x,y}$ from the beam axis or farther. The analysis of related resistive wall impedance and beam stability has shown [15] that one can expect some small (few percent) growth of an initial perturbation after 1000 turns. Thus, there is a safety factor of about one hundred for transverse-plane instabilities. For the longitudinal plane, the magnet protection system from radiation can result in up to ~30% energy broadening. This effect could probably be mitigated by means of a second-harmonic RF. In any case, thin conducting tapers will be included in the system for a smooth transition between masks and liners.

2.3 Machine-detector interface

The above MPS design also helps reduce the long-range background particle load on the HF detector [16]. It includes an additional crucial element: a nozzle inside the detector to intercept the products of shower development in the IP vicinity. Figure 12 shows that, thanks to the MPS described in this paper, only energetic photons and Bethe-Heitler muons come to the nearest to the...
Figure 11. Dynamic heat load in SC magnets along half of the HF collider for tungsten masks and liners at 60–80 K (red) and cold mass at 4.5 K (blue).

The nozzle design and its effect on the reduction of the background particle flux in the detector are described in ref. [16].

3 Conclusions

Preliminary design concepts of superconducting magnets based on the Nb$_3$Sn superconductor for the Higgs Factory Muon Collider were generated. These magnets provide required high operating gradients and dipole fields in appropriate apertures sufficient to accommodate the large size of muon beams as well as the beam liners and cooling system to intercept the large heat deposition from the showers induced by the decay electrons.

The magnet geometry, materials and magnetic field maps were implemented in a detailed 3D MARS15 model of the entire HF collider ring including IR, chromaticity correction, matching sections, arc, and machine-detector interface. A sophisticated radiation protection system based on tight tungsten masks in the magnet interconnect regions and optimized elliptical tungsten liners in the magnet apertures was designed for the HF collider. This system allows reduction of the peak power density in the superconducting coils to below their quench limit and the dynamic heat deposition in the magnet cold masses to a level tolerable by the cryogenic system. The results obtained confirm the possibility of radiation protection of Nb$_3$Sn superconducting magnets in a Higgs Factory muon collider.
The coil stress management structures, required for large-aperture high-field magnets made of the brittle Nb$_3$Sn superconductor, were not considered in the presented analysis. However, it is clear that they will reduce even more the radiation and heat load on the magnet coils.

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References

[1] A.V. Zlobin et al., Preliminary design of a Higgs Factory muon storage ring, in Proc. of IPAC2013, Shanghai, China, May 2013, pg. 1487.
[2] A.V. Zlobin et al., Storage ring and interaction region magnets for a muon collider Higgs Factory, in Proc. of NA-PAC2013, Pasadena, CA, U.S.A., (2013), pg. 1271.
[3] N.V. Mokhov et al., Mitigating radiation impact on superconducting magnets of the Higgs Factory muon collider, in Proc. of IPAC2014, Dresden, Germany, June 2014, pg. 1084.
[4] S. Caspi et al., Canted-Cosine-Theta magnet (CCT) — a concept for high field accelerator magnets, IEEE Trans. Appl. Superconduct. 24 (2014) 4001804.
[5] A.V. Zlobin, V.V. Kashikhin and I. Novitski, *Large-aperture high-field Nb$_3$Sn dipole magnets*, in *Proc. of IPAC2018*, Vancouver, Canada, (2018), pg. 2738.

[6] Y. Alexahin, E. Gianfelice-Wendt and V. Kapin, *Muon collider lattice concepts*, arXiv:1806.08717.

[7] E. Barzi and A.V. Zlobin, *Research and development of Nb$_3$Sn wires and cables for high-field accelerator magnets*, *IEEE Trans. Nucl. Sci.* 63 (2016) 783.

[8] G. Apollinari, S. Prestemon and A.V. Zlobin, *Progress with high-field superconducting magnets for high-energy colliders*, *Ann. Rev. Nucl. Part. Sci.* 65 (2015) 355.

[9] ROXIE webpage, http://cern.ch/roxie.

[10] V.V. Kashikhin and A.V. Zlobin, *Persistent current effect in 15–16 T Nb$_3$Sn accelerator dipoles and its correction*, in *Proc. of NAPAC2016*, Chicago, IL, U.S.A., (2016), pg. 1061.

[11] N.V. Mokhov and C.C. James, *The MARS code system user’s guide*, Fermilab-FN-1058-APC, https://mars.fnal.gov, Fermilab, Batavia, IL, U.S.A., (2018).

[12] C.J. Johnstone and N.V. Mokhov, *Optimization of a muon collider interaction region with respect to detector backgrounds and the heat load to the cryogenic systems*, in *Proc. of Snowmass-1996 DPF/DPB Summer Study on New Directions for High-Energy Physics*, Snowmass, CO, U.S.A., (1996), pg. 226.

[13] N.V. Mokhov et al., *Radiation effects in a muon collider ring and dipole magnet protection*, in *Proc. of PAC2011*, New York, U.S.A., (2011), pg. 2294.

[14] I. Novitski and A.V. Zlobin, *Thermal analysis of SC quadrupoles in accelerator interaction regions*, *IEEE Trans. Appl. Supercond.* 17 (2007) 1059.

[15] A.V. Burov, *Beam stability for Higgs Factory parameters*, report MAP-doc-4376, Fermilab, Batavia, IL, U.S.A., (2014).

[16] N.V. Mokhov, S.I. Striganov and I.L. Tropin, *Reducing backgrounds in the Higgs Factory muon collider detector*, in *Proc. of IPAC2014*, Dresden, Germany, June 2014, pg. 1084.