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SUPERCONDUCTING RF CAVITIES AND MAGNETS FOR A 4-TeV ENERGY MUON COLLIDER

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ABSTRACT

The accelerators must take the muon beams from ~100 MeV to 2 TeV energies within the muon lifetime for a 4 TeV energy muon collider. These constraints plus the muon decay heating seriously challenge the designs of the superconducting RF (SRF) cavities and magnets in the accelerators and collider ring. The multiple superconducting recirculation linac and the very rapid-cycling superconducting synchrotron approach are both studied. We briefly introduce the technical considerations and preliminary designs of the SRF systems and magnets.

INTRODUCTION

Muon colliders can provide strong potential advantages in high-energy physics, but also present serious technical challenges, as described in the Snowmass feasibility study[1]. A muon collider would use the superconducting RF (SRF) cavities for accelerating and superconducting (SC) magnets for bending the μ-beams throughout the machine. The central difficulty in the μ^+-μ^- collider is the muon decay, with a lifetime of $2.2\times10^{-6}\gamma_\mu$ s (where $\gamma_\mu = E_\mu/m_\mu c^2$) that implies a requirement for very rapid increases in muon energies. At the design luminosity, the SC dipoles and quadrupoles must contain muon beams (up to

2×10^{12} muons per bunch) that will deposit over 1.8 kW of energy per meter into the storage ring.

First, we introduce a 20-Tesla (T) hybrid capture solenoid system[2] (combining a Bitter type water-cooled solenoid with a superconducting solenoid) that captures the pions and transfers the pions to a decay and phase rotation channel producing muons. Muons will then be accelerated in SRF accelerating structures. To do so, we have developed two accelerating scenarios. One of the options is a Rapid Cycling Synchrotron (RCS)[3], where two hybrid rings (2200m radius) of fixed SC magnets alternating with iron magnets ramping at 200Hz and 330 Hz between full negative to full positive field bending the muons. Muons are given 25 GeV of RF energy (700 MHz) per orbit by accelerating cavities. As an alternative we also discuss another option to RCS, where three recirculating superconducting linacs (respectively with energies reaching 70 GeV (with 350 MHz SRF), 250 GeV (800 MHz) and 2000 GeV (1300 MHz)) are used in a sequence of four recirculating linacs (RLAs)[4], each of which increases beam energy by ~ an order of magnitude, they accelerate beams up to 2 TeV for injection into a collider ring.

At 2 TeV the mean muon lifetime is 41.6 ms. To achieve high luminosity (higher number of turns and shorter orbit), the dipole should be over 8 T carrying muon over 1000 turns in a short-diameter orbit[5].

SC MAGNETS FOR MUON CAPTURES

The pions produced by a target[1] must be captured by solenoid magnets during their decay into muons. A possible layout of a 20-T hybrid solenoid magnet with a clear bore of 150 mm is shown in Fig. 1, which is designed to capture particles with a transverse momentum of 225 MeV/c or less. The hybrid magnet option was selected for the following reasons: 1) The operating power for the water cooled solenoid is substantially lower if a superconducting outer-magnet is used. 2) The current density in the water-cooled Bitter solenoid can be low enough to insure that its lifetime will be long enough. (A reasonable lifetime goal might be 25000 hours.) 3) Additional space inside the Bitter solenoid can be made available for a heavy metal water-cooled shield. This reduces the incident energy from

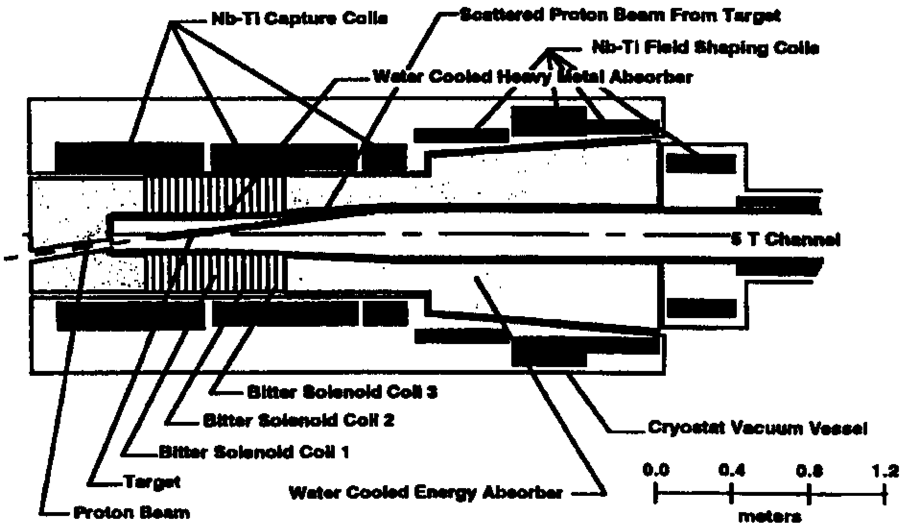

Figure 1. A 20T hybrid capture solenoid with a transfer solenoid system of 5T in phase rotation section (inside is a tilted target).

the target into the water-cooled solenoid and the surrounding superconducting solenoid.

The water-cooled Bitter solenoid insert has an inner radius of 120 mm. The extra inner bore radius allows a heavy metal (tungsten or some other high Z, high density metal) shield that is 30mm thick to be inserted around the target region. The Bitter solenoid insert outer radius has been set at 345 mm. The cryostat of the SC outer-magnet (solenoid) starts at a radius of 370 mm.

The SC outer-magnet coil alone is designed to produce a central field of about 7.5 T. Operating under this condition, the outer-magnet solenoid can be made from Nb-Ti operating at 2.0 K. The outer-magnet has three coils with an inner radius of 400 mm. The outer radius of these coils is about 540 mm. The peak magnetic field in the outer-magnet coil is about 8.3 T when the coils are fully powered.

Other superconducting solenoids downstream from the outer-magnet coils form the transition region that shapes the magnetic field between the target and the phase rotation system. The decay of the pions to muons will occur at the 5 T region.

RECIRCULATION SRF ACCELERATOR

In a muon accelerator the decay and acceleration rates require a small decay loss that means $dE/ds \gg m_\mu c^2/L_\mu = 0.16$ MeV/m (including all lengths), which is relatively large, but can be reached in multipass systems with moderately high gradient.

SRF Acceleration Systems

The basic accelerating unit in this scenario is the recirculation linear accelerator (RLA), which consists of two linacs with return arcs in a racetrack configuration. The beams are accelerated and returned for several passes in the same linacs, but with separate return arcs (10-20 turns). There are four RLAs, each of which increases beam energy by ~ an order of magnitude, and which accelerates beam up to 2 TeV for injection into a collider ring[4]. Figure 2 shows a conceptual overview of a 4-RLA system. The RLA permits economic multipass

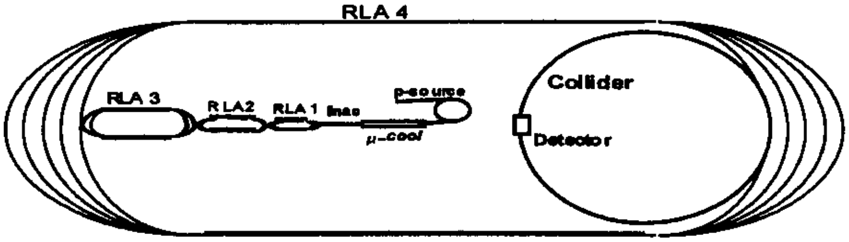

Figure 2. Overview of a μ^+-μ^- collider system.

Table 1. Parameters of a 4-RLA μ-accelerating system.

	RLA 1	RLA 2	RLA 3	RLA 4
Beam energy (GeV)	1→9.6	9.6→70	70→250	250→2000
RF frequency (MHz)	100	350	800	1300
N turns	9	11	12	16
V_{rf} /turn	1.0	6	16	11.2
$L_{turn}(2L_{linac}+2\pi R)$(km)	0.26	.095	2.32	12.6
Beam Survival	91%	94.8%	97.6%	96.4%
$\sigma_{z,beam}$ (cm)	8.3→4.8	1.3	0.6	0.3
Cavity temp. K		4.2	2	2

acceleration, but the separate transport for each turn with cost and complexity limits the number of turns to ~10–20 per RLA. In this scenario, RF systems at 350, 800 and 1300 MHz are SRF cavities. Table 1 gives the main parameters of the SRF system.

If the total RF voltage and beam current are fixed, the use of pulsed RF can reduce the 'cryogenic cost' and allow a higher E_{acc}.

SRF Cavities and SC Magnets

In RLA4, the muon energy increases from 250 GeV to 2000 GeV. As a baseline design 25 MV/m ($Q_0=5 \times 10^9$) at 2 K and 16 turns are chosen that requires about 112 GV per turn from cavities, or 4.5 km of active linac. Encouraged by the pulsed test results of the TESLA cavities, it is possible to use a higher E_{acc}. If 35 MV/m becomes realistic, the linac could be reduced to 3.2 km. For the 1300MHz SRF, 16 passes and 15Hz-RF pulses, the HOM power is ~300 W/m. One alternative will be to enlarge the aperture of the cavity from existing 70 mm to 102 mm. That will reduce the HOM mode damping requirements by a factor of 50%[6]. Fig. 3 shows a modified arrangement of the TESLA type cryomodule and Fig. 4 shows a cross-section of the multipass superconducting magnets.

Because of larger apertures and longer bunches, HOM power is expected to decrease as $\sim 1/\lambda^3_{RF}$ so HOM excitation at 800 MHz and 350 MHz should be much less (respectively, ~60 W/m and 2 W/m in this scenario). Decay losses at this intensity are ~16 W/m. We require that the cryogenic system tolerate ~10% of decay losses at 2 K (1.6 W/m) with the remainder absorbed at higher temperature.

The 800 MHz RLA3 requires 16 GV of SRF or 1.07 km of linac (12 turns) at 15 MV/m ($Q_0=5 \times 10^9$) and 2 K. The 350 MHz RLA2 requires 6 GV of SRF cavities, or 600m (11 turns) at 10 MV/m and 4K. Such values have been achieved in smaller testing structures. Figure 5 shows a candidate of the 350 MHz SRF cryomodule from CERN-LEPII[7].

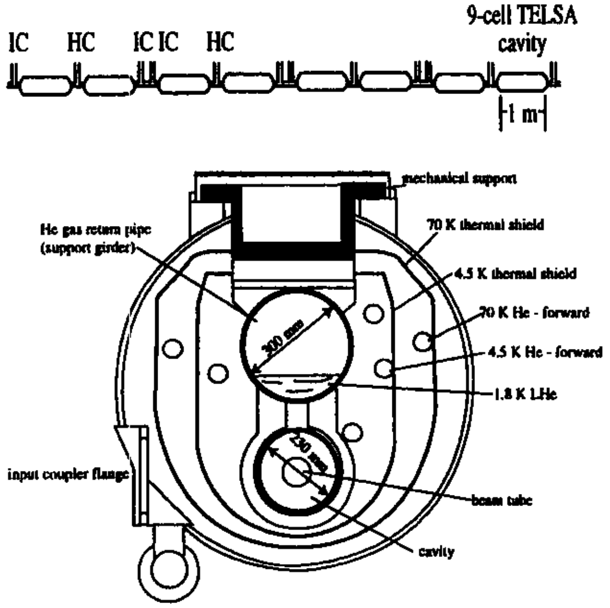

Figure 3. A cryomodule based on the TESLA cavities (couplers - IC and HOM couplers - HC).

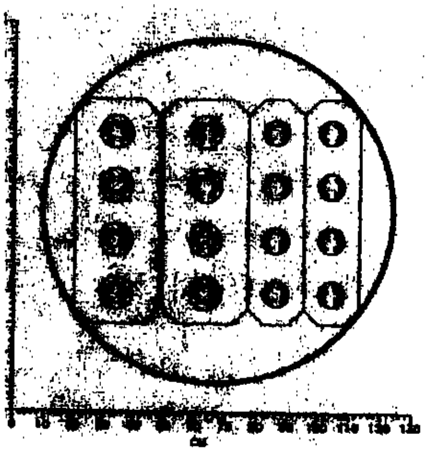

Figure 4. A cross-section of the multipass superconducting magnets.

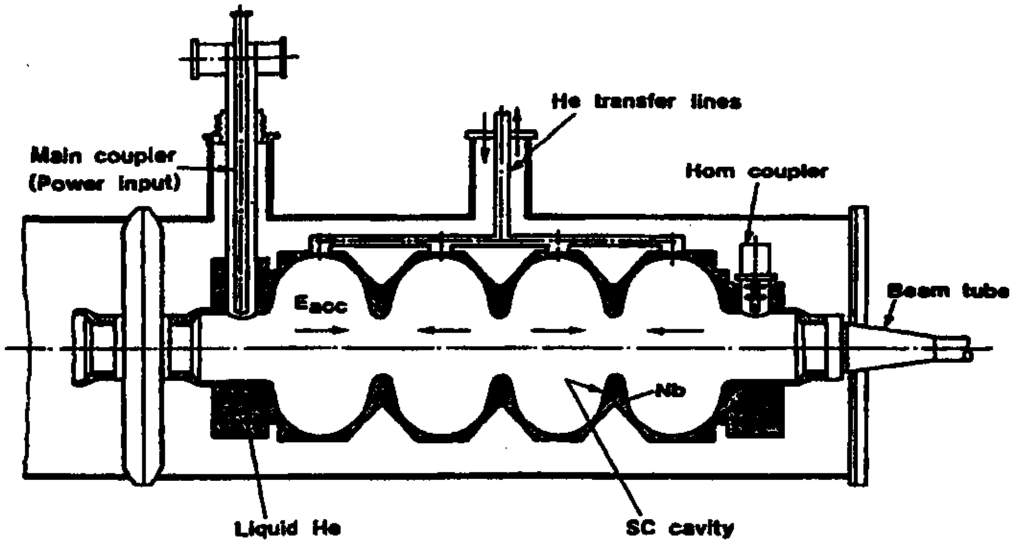

Figure 5. A candidate of the RLA2 cryomodule, based on a CERN 350 MHz SRF cavity.

Table 2. RF System and RF Power

	RLA2	RLA3	RLA4
RF pulse length, μs	35	84.2	672
Loaded Q to min. P	1×10^6	1×10^6	1×10^6
ΔEacc/Eacc	0.018	0.027	0.033
Average I, mA	100	45.6	7.6
Available RF Power, kW/m	200	200	400
Voltage drop	0.086	0.12	~0.0
RF on - cryogenic loss, W/m	119 (at 4K)	71 (at 2K)	78 (at 2K)
Ave. wall power for RF, kW/m	5.2	2.6	5.25

RF Power Requirements

The RF power requirements are dominated by the power needed for the acceleration of the beams. Additional power is required for RF controls. The control power needed depends on the magnitude of perturbations to be controlled to pass the muons 10 times through a pair of linacs. Table 2 lists the RF powers needed.

RAPID CYCLING SYNCHROTRON

Rapid-cycling approaches require innovations in magnet designs and layouts, but could be more affordable than a RLA version. Fig. 6. is a schematic layout of RCS and table 3 summarizes the parameters of the sub-systems.

100 MeV - 2 GeV Using RF=2GV: A single pass 2 GV linac is used.

2GeV - 25GeV Using RF = 2.5 GV/turn: This is the first recirculating ring and has 2.5 GV of 100 MHz RF. The superconducting magnets with 10 bores (each with a different fixed field) are used.

25 GeV - 250 GeV Using RF=6 GV/turn: This stage uses a single ring of fast ramping *cos θ* dipoles. Thin stranded copper conductor is used at room temperature to achieve a 4 Tesla field. The low duty cycle is exploited to keep the I^2R losses reasonable. A 6 GV of 350 MHz SRF system is distributed around the ring and accelerates the muons from 25 GeV to 250 GeV in 40 orbits.

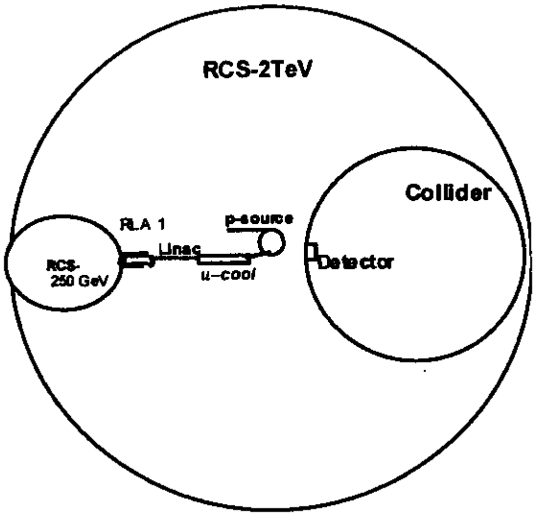

Figure 6. The Rapid -Cycling scenario of a muon accelerator and collider system

Table 3. The main parameter of the RCS system

	Linac	RLA	RCS1	RCS2
E (GeV)	0.1→2	2→25	25→250	250→2400
f_{rf} (MHz)	10→100	100	350	800
N_{turns}	1	10	40	86
V_{rf}(GV)	2	2.5	6	32
C_{turn}(km)	0.4	0.36	2.3	14
τ(ms)	0.0013	0.012	0.307	4.0
σ_{beam}(cm)	100→10	3	1	0.5
Survival	93%	92%	85%	82%

~60% survival over full cycle

260 GeV - 2 TeV Using RF=25 GV/turn: In the stage, we have two hybrid rings (2200m radius) of fixed superconducting magnets alternating with iron magnets ramping at 200 Hz between full negative and full positive field to bend the muons from the lower injection-energy to the higher extraction energy. Muons are given 25 GeV of RF energy (800 MHz) per orbit (tatol: 96 orbits). The SRF cavities are divided into multiple sections as at CERN-LEPII, so that magnetic fields and beam energies will match around the rings.

SC MAGNETS FOR COLLIDER RING

Special Considerations

Two factors govern the design of the collider ring magnets for a muon collider. (1) The decay of the muons within the ring can deposit up to 2 kW of beam energy per meter into the magnet bore in the form of high energy electrons, positrons and gamma rays. One must keep the muon decay products from depositing their energy into the superconductor of the collider ring magnets. (2) The luminosity at the collision point is inversely proportional to the ring circumference squared and it is inversely proportional to the beam size function squared. In order to get the circumference of the ring as small as possible, dipoles with a high central field are desirable. The strength of the quadrupoles should in some way be proportional to the collider ring dipole central field. A small beam size means that the beam beta function at the collision point must be very small. As a result, the focusing quadrupoles around the collision point must be strong with a large aperture. (The beam beta function in these quadrupoles is often very large in at least one direction.) Table 4 lists the muon decay parameters[5].

Magnet Design with an Absorbing Bore Tube

As shown in Fig. 7, to attenuate the decay product power by three orders of magnitude, about 65 mm of tungsten shield is required. Only about 1.8 W per meter will then be deposited into the superconducting coil while the remainder of the beam decay power will be absorbed by a cooled metal bore (shield) tube[5]. A copper bore tube would be twice as thick. The primary problem with the large aperture magnet design is the large forces because of the high magnetic fields and the large inner coil radius. These forces scale as the square of the central field times the inner coil radius. Test dipoles with a coil radius of 25 mm have been built and operated at central field as high as 10.2 T at a temperature of 1.8 K. Fig. 7 is a schematic layout of the magnet.

Table 4. Muon Decay Parameters in Various Components of a RLA scenario

Components	Peak Energy (GeV)	No. of Turns	Decay Rate $(\mu s^{-1}) \times 10^{13}$	Decay Power (kW)	Decay Power per unit L $(W\ m^{-1})$
First Ring	9.6	-NA-	1.9	0.6	-NA-
Second Ring	79	11	1.2	3.6	1.64
Third Ring	250	12	0.8	19.7	1.75
Fourth Ring	2000	16	0.4	36.8	1.26
Collider Ring	2000	1000	13.1	14600	1840

The Split Coil Design

In order for the muon decay products to leave the storage ring without colliding with the coil or a beam tube liner, there must be no material on the mid-plane of the magnet[5]. The muon decay products must pass the superconducting coil without interacting with any material. When the decay products are absorbed, they have to be absorbed in a way that prevents back scatter into the superconducting coils. A dipole using the split coil

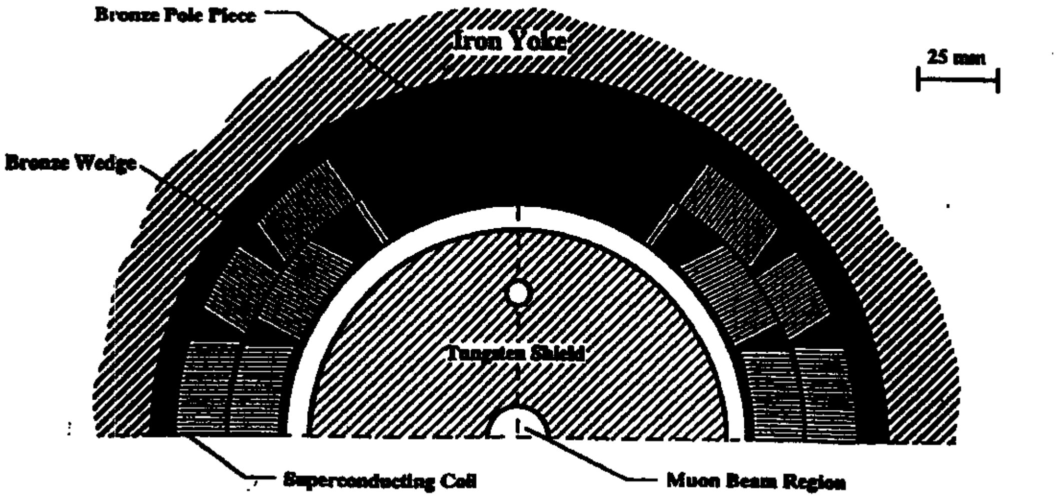

Figure 7. A cosine theta coil structure (muon decay energy is absorbed by a tungsten shield (65mm-thick).

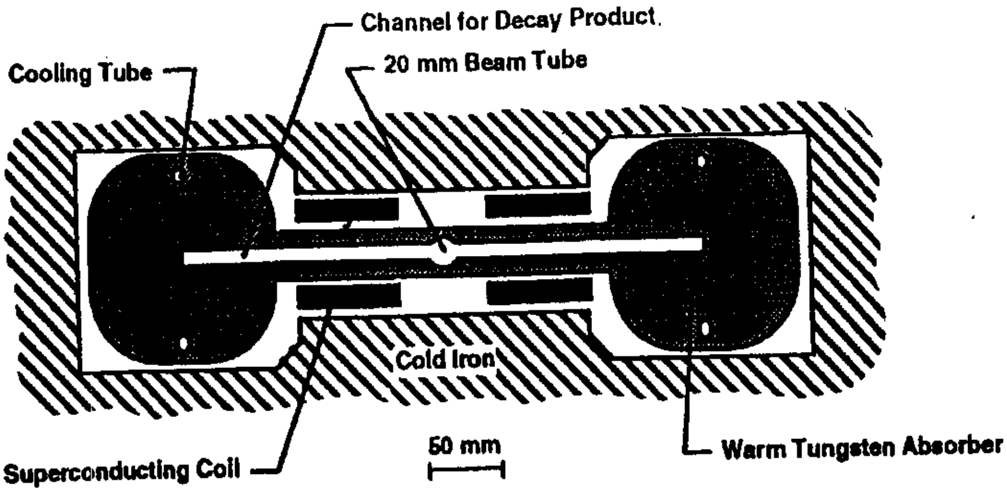

Figure 8. Separated coils on the mid-plane with a warm absorber for the muon decay products (an H magnet).

configuration can be fabricated in either a C or H configuration. Configured as an H magnet (see Fig. 8), the cold iron dimensions would be about 1060 mm wide by 700 mm high. The design shown in Fig. 8 has large forces that pull the coils together (across the mid-plane)[5]. The forces also push the coils apart parallel to the x-axis. In a cold iron configuration, the coil must be attached directly to the iron pole. Fig. 8 does not show this connection.

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