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DESIGN OF THREE RECIRCULATING-LINAC SRF SYSTEMS FOR A 4-TeV μ^+-μ^- COLLIDER

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Abstract

In a conceptual design of the accelerating systems for a 4-TeV μ^+-μ^- collider, three recirculating superconducting linacs (with energies reaching 70 GeV (with 350 MHz SRF), 250 GeV (800 MHz) and 2000 GeV (1300 GHz), respectively) are used. We briefly describe design concepts for the acceleration features, superconducting RF cavities, input couplers, RF control and RF power systems.

1 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]. In this paper, we explore the superconducting RF (SRF) components of a possible μ-acceleration system. 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.

In an accelerator the decay and acceleration rates can be combined to obtain an expression for beam survival:

$$N_{final} = N_{initial}\left[\frac{E_{initial}}{E_{final}}\right]^{\frac{m_\mu c^2}{L_\mu (dE/ds)}},$$

where N, and E are the number and energy of muons before and after acceleration, L_μ = 660 m is the μ decay length, and dE/ds is the acceleration gradient (including all lengths). Small decay loss requires dE/ds >> $m_\mu c^2/L_\mu$ = 0.16 MeV/m, which is relatively large, but can be reached in multipass systems with moderately high gradient.

In the feasibility study, an acceleration scenario is presented which consists of an ~1 GeV linac injecting into a sequence of four recirculating linacs (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. Figure 1 shows a conceptual overview of a 4-RLA system.

The basic accelerating unit in this scenario is the 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 (9–16 turns).

For high luminosity, the μ^+-μ^- collider will require a

short-range wake-field effects and higher-order mode (HOM) loads will be enlarged. Also the μ-beam will decay throughout the system, producing electrons with a mean energy of 1/3 E_μ. The mean e-beam energy deposition is a constant: dE/ds = $m_\mu c^2/(3L_\mu)$ per μ (0.053 MeV/m/μ). Beam can be accelerated from 1 GeV to 2 TeV with <20% decay loss and <10% longitudinal phase-space dilution. [2]

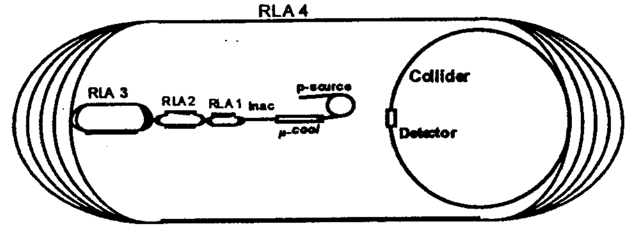

Figure 1. Overview of a μ^+-μ^- collider system.

There are many possible variations in RLA scenarios. The present case is simply an initial example, from which more detailed specifications of rf and transport systems may be developed, with eventual reoptimization.

2 SRF ACCELERATION SYSTEMS

2.1 Basic Design Considerations

The RLA permits economic multipass acceleration, but the separate transport for each turn with cost and complexity considerations limits the number of turns to ~10–20 per RLA, which is very compatible with the μ lifetime constraint. Counterrotating μ^+ and μ^- bunches can be accelerated in the same RLAs. In the baseline

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

	RLA 1	RLA 2	RLA 3	RLA 4
Beamenergy (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 (GV)	1.0	6	16	11.2
$L_{turn}(2L_{linac}+2\pi R)$(km)	0.26	0.95	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
Temp. K		4.2	2	2

scenario, the RF frequency increases from RLA to RLA as the beam increases in energy, and the bunch length is correspondingly shortened to match final collider requirements. Table 1 displays system parameters. In this scenario, RF systems at 100, 350, 800 and 1300 MHz are needed. While Cu cavities are suitable for the ~100 MHz RLA, the higher-energy RLAs require a relatively long multipass pulse and high efficiency. The relatively large apertures of SRF cavities can contain the large-emittance μ-beams (with decay products) and reduce the wake-fields. Significant difficulties in the adaptation of SRF technology to μ^+-μ^- acceleration exist. High-power HOM loads will be needed and the beam transport and SRF cavities must accommodate any spillage from μ-decay.

If the total RF voltage and beam current are fixed, the total investment costs depend on three items: 1. total length L of the cavities and cryostat-'linear cost', 2. total RF power to be transferred to the beam, and 3. total RF power dissipated in the SRF cavities: 'cryogenic cost'. Also, we must take into account the five-year operational cost of RF generator power and cryogenic power.

For a CW machine the cost minimum is located where the first item is equal to the third, but not the maximum attainable gradient. However, the use of pulsed RF can reduce the 'cryogenic cost' and allow for us to choose higher E_{acc}. The remaining issues for a 'pulsed' muon collider are: (1) should we cut the Linac length while keeping the same number of beam transport components in the arcs, or vice versa, and (2) what is the highest Eacc which we expect will be used in a pulsed operation in the future.

2.2 1300 MHz (RLA4) SRF

In RLA4, the muon energy increases from 250 GeV to 2000 GeV. As a baseline design 25 MV/m (Q_0=5 x 10^9) and 16 turns are chosen that need about 112 GV of cavities at 2 K, 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. The HOM load requirements for the 1300 MHz SRF can be estimated using the formula:

$$P_{HOM} = k_{HOM} Q^2 f_{rf}$$

With $k_{HOM} \approx$ 4 V/pC/m for μ-TESLA cavities, Q is the charge per bunch (3 x 10^{-7} C) and f_{rf} is the frequency of bunch passages through the cavity (15×4×16 =960). For 16 passes, 4 bunches, 15 Hz cycles, we obtain ~300 W/m. This compares with the TESLA 1995 design HOM load of ~4.6W/m. Therefore a substantially different HOM coupling system should be developed, with ~99% of the energy coupled out at higher temperatures. One alternative will be to enlarge the aperture of the cavity from existing 70 mm to 102 mm. That will help the HOM mode damping (reduce the k_{HOM} by 50%). This change, of course, will cost the ratio of E_{pk}/E_{acc} (17%) and R/Q (-33%). Figure 2 shows a modified arrangement of the TESLA type cryomodule [3].

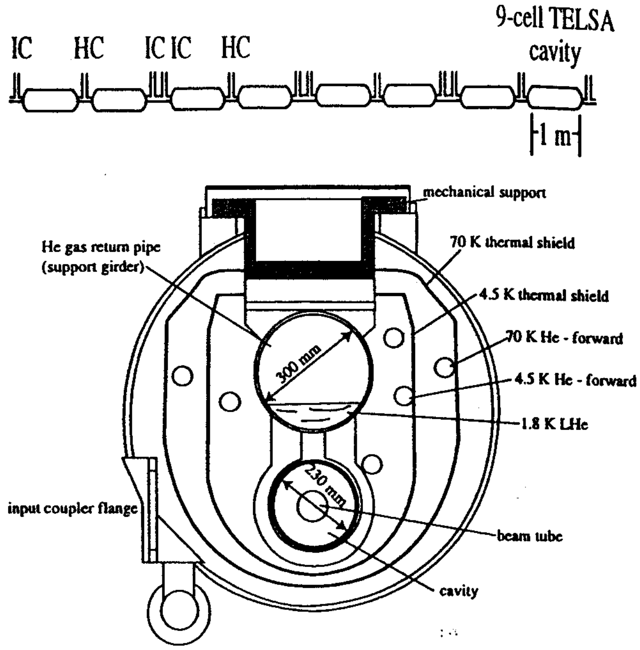

Figure 2. A cryomodule based on the TESLA cavities; input couplers - IC and HOM couplers - HC.

2.3 800 MHz (RLS3) & 350 MHz (RLA2) SRF

Because of larger apertures and longer bunches, k_{HOM} is expected to decrease as ~ $1/\lambda_{RF}^3$ so HOM loads at 800 MHz and 350 MHz should be much less (~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 this at 2 K (1.6 W/m); the remainder would be absorbed at higher temperature.

The 800 MHz RLA3 requires 16 GV of SRF or 1.07 km of linac at 15 MV/m (Q_0=5 x 10^9) and 2 K. These are modeled on the LANL PILAC SRF test module which obtained 15 MV/m in a pulsed mode.

The 350 MHz RLA2 requires 6 GV of SRF cavities, or 600 m at 10 MV/m. Our model for the 350 MHz RF system is the CERN cavity, which obtains 6 MV/m in CW mode at 4 K [4]. An experiment was proposed for a CERN 350 MHz SRF cavity (Figure 3) to br operated in pulsed mode to determine its gradient limit (which will develop guidelines for the RLA2 SRF design). Preliminary tests of the pulsed behavior of a 350 MHz a

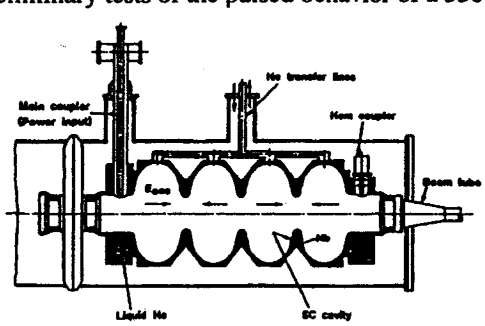

Figure 3. Cross-section of a CERN 350 MHz SRF cavity

superconducting LEP cavity were conducted at CERN. The maximum peak RF power reached was 507 kW for 1 ms pulse. At that incident power a maximum field of 7.9 MV/m could be reached without field degradation [5].

2.4 Input Couplers Design Concepts

RF input couplers and HOM couplers are very important components in the acceleration systems. Our strategy is to apply the experience obtained in development at the leading labs to the concept design . The design features are (1) co-axial structure with two warm windows to isolate the cavity vacuum, (2) use of DC bias on the center conductor and proper dimensions of the co-axial structure to suppress multipacting, and (3) baking the assembly with ceramic windows.

3 RF CONTROLS & RF SYSTEMS

Important constraints on the RF system derive from the large charge per bunch. The voltage droop from a bunch passage could be as large as ~10%, and that droop must be recovered before the next bunch passage. However uneven spacing of multiple bunches should be avoided, since the following bunch would not receive the same energy. Other problems may occur from uneven beam loading due to simultaneous acceleration of counterrotating μ^+ and μ^- bunches, but this effect should average to zero. Other effects that must be considered are effects of momentum fluctuations on arrival time in each pass, bunch charge fluctuations from pulse to pulse, differential fluctuations for μ^+ and μ^- bunches, microphonic effects, and control of multiple cavities by single klystrons.

3.1 RF System Design

The RF system (Figure 4) for the three multiturn RLAs must provide RF power for acceleration of the μ- and μ+ bunch and maintain constant energy at the output of each RLA from pulse to pulse. During the multiturn acceleration a cavity voltage droop is acceptable but must well defined and controlled. Due to the large stored energy in the cavities it is possible to reduce the power requirements in all RLAs to 200 kW/m. A digital feedback system will sample the cavity field every bunch revolution period and provide (time-varying) gradient and phase control for consecutive bunch acceleration cycles. Differential bunch charge fluctuations are not controlled because of excessive power requirements. A worst case scenario of ±10% bunch charge fluctuation will result in only ±0.27% energy gain fluctuation in RLA2.

3.2 RF Power Requirements

The RF power requirement is dominated by the power needed for the acceleration of the beam. Additional power is required for RF control. The control power needed depends on the magnitude of perturbations to be controlled.

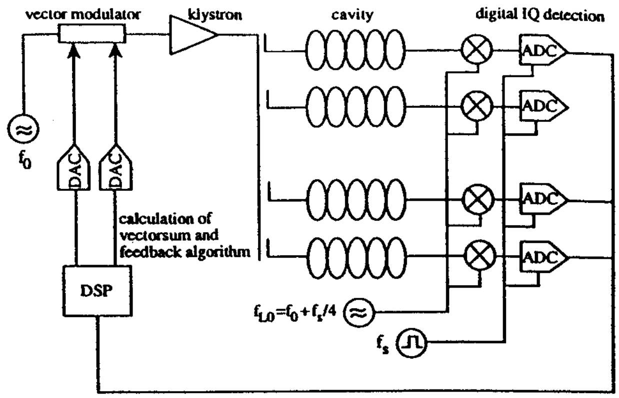

Figure 4. RF system design.

A voltage droop during consecutive intra-pulse acceleration cycles of the μ- and μ^+ bunch is permissible but must be reproducible from pulse to pulse. In the recirculating linacs RLA2 and RLA3 a considerable voltage droop of 8.6% and 11.9 % respectively is tolerated to reduce the power required for acceleration. Stored energy in the cavities is used for acceleration. In RLA4 the average current is sufficiently low (due to the large circumference of the accelerator) that a constant gradient can be maintained with moderate power. Table 2 presents some of the RF parameters.

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	200
Voltage drop	0.086	0.12	0.00
RF on - cryogenic loss, W/m	119	71	78
Ave. wall power for RF, kW/m	5.2	2.6	5.25

4 ACKNOWLEDGMENTS

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