An Energy Upgrade from TESLA to a High-Energy $\mu^+\mu^-$ Collider

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ABSTRACT

We discuss the possible extension of a TESLA 250×250 GeV SRF e^+-e^- linear collider to a multi-TeV μ^+-μ^- collider, by future addition of a muon source, return arcs for recirculation and a collider ring. The TESLA SRF systems are potentially also suitable for multiturn acceleration of muon bunches, and could be adapted for use in a recirculating μ-linac. Many problems and design issues would need to be resolved, and further study is needed.

I. INTRODUCTION

The TESLA collaboration is developing a proposal for a 250×250 GeV e^+-e^- linear collider based on superconducting rf (SRF) acceleration.[1] In this concept two 250 GeV linacs, for electrons and positrons, respectively, are directed collinearly into an interaction point for high-energy (500 GeV) single-pass collisions. In this note we comment that these same linacs could also be used for accelerating muons, and multiple recirculations of muons through the linacs could permit acceleration to many TeV in energy. The muons could then be transferred into a storage ring for multiturn ultrahigh energy collisions (up to ~10 TeV or more). If a suitable muon source is developed, the scenario would give TESLA a unique opportunity for a future energy upgrade by an order of magnitude or more. This arrangement would take great advantage of a previous investment in TESLA, which would provide the tunnel and SRF, (probably) the most expensive components of the upgraded facility. The phased approach of first e^+e^-, then μ^+-μ^-, allows physics to be carried out in a facility with more realizable technology in the short term, yet have the long-term potential for much higher-energy μ^+-μ^- collisions, if the difficult μ-source and design issues can be solved.

II. GENERAL DESCRIPTION

As presently envisioned the TESLA facility would have two 250 GeV linacs pointed toward each other, each ~ 15 km long and with ~10 km of active accelerating cavities. Each of these linacs would consist of relatively large aperture (7cm diameter) 1300 MHz cavities, and be capable of handling large beam power. The overall capabilities of the rf system are quite similar to the capabilities needed for the accelerator of a $\mu^+\mu^-$ Collider system. Therefore, these same linacs could also be used to accelerate muons, with the important difference that the muons could be returned in a circular transport to the linac(s) for several passes of acceleration.

Figures 1A and 1B outline conceptual configurations for the $\mu^+\mu^-$ collider upgrade. In both Figures 1A and 1B we show a collider storage ring in the center of the facility, where it could use the same detector used for the e^+-e^- linear collider. (In an optimal configuration, the collider might be at the end of the facility, with a separate detector, as in figure 2.) Muons from a muon source would be injected into a TESLA linac and accelerated to the end of the facility to an energy-matched return arc returns them for another pass through both linacs, where at the other end another energy-matched transport returns the muons through both linacs. The muons gain ~250 GeV in each passage of a linac, or 500 GeV when passing through both linacs. The process can continue through multiple passes of both linacs, with separate return transports for each pass.

This arrangement is extremely flexible in that it permits gradual energy upgrades. For example, a single pass through both linacs into a storage ring would convert the e^+e^- collider into a $\mu^+\mu^-$ collider at twice the energy. Further energy upgrades could be accomplished by additions of more passes obtained by adding more return arcs with a full-energy collider ring. The actual number of passes would be determined by physics requirements. The cost of the return arcs would be a fraction of the cost of the accelerating structures, rf power and support infrastructure. Energy upgrades by large factors are possible. For instance, 10 passes would obtain 5 TeV muons (10 TeV collisions).

In Figure 1A the muons are turned completely around in a circular path and injected backwards through the same linacs on each end. 10 linac passes would require only 5 return paths at each end. In figure 1B the beams are bent 180° and transported back to the beginning of the linacs for another 180° bend; 10 passes would require 10 complete return loops (although the long return straight path could be shared).

For a $\mu^+\mu^-$ collider both μ^+ and μ^- bunches must be accelerated. In configuration 1A the beams will be matched in energy in each return path if they start at the same point and propagate in the same direction through the linacs (circulating through the return arcs in opposite directions). In this configuration it is more natural to place the source and collider at the ends of the double linac (see figure 2).

In configuration 1B the μ^+ and μ^- bunches must propagate through the linacs in opposite directions in order to arrive at the arcs at the same energy. In this configuration it is more natural to place the source and collider at the center; the μ^+ and μ^- bunches could counterpropagate through ten passes of the linacs before being kicked into the collider ring, and be energy matched in each return arc. This configuration has the same bend length as 1A or 2 but has an increased time for acceleration because of the added return path.

The TESLA e^+e^- linear collider also calls for a large-circumference damping ring. Two configurations are under conideration: a large circular ring with 1km radius or a long "dog-bone" shaped ring. The circular ring tunnel and infrastructure could also be used in a $\mu^+\mu^-$ return arc or collision ring at suitable energies.

The collider ring (or rings) would be a high-field fixed-field ring. With a 6.7T mean bending field a 2 TeV ring would be 1 km in radius (Tevatron-sized) and a 5 TeV ring would have a 2.5 km radius (~Fermilab site-filler). In principle, storage rings of increasing radius can be built around the same detector as the energy is upgraded.

In table 1 we have compiled parameters for TESLA and a TESLA-based $\mu^+\mu^-$ collider. For the muon collider we have assumed a μ-source similar to the concept under development by the $\mu^+\mu^-$ collider studies. In table 1 we use round beams for the $\mu^+\mu^-$ collider ($\sigma_x=\sigma_y$, $\varepsilon_x=\varepsilon_y$, etc.), while beamstrahlung constraints require asymmetric collisions in the e^+e^- collider, with much smaller vertical beam sizes.

SRF has several qualitative technical advantages over room-temperature copper rf, and these are utilized to full advantage in this arrangement. The larger beam apertures used in SRF cavities are required to accommodate the large μ beam size (from larger emittance). Also SRF allows an rf pulse long enough to accommodate the several passes of muons; in fact, the time required for ~ten passes of a μ bunch is approximately the same as the design active pulse length in the TESLA cycle. (In TESLA a train of ~1000 e-bunches are single-passed through the linacs.)

As shown in Table 1, The overall power demands and accelerating pulse structure requirements for the SRF are quite similar in e^+e^- and $\mu^+\mu^-$ modes. The relatively large aperture of the TESLA structure reduces the longitudinal and transverse wakes (compared to room-temperature high-frequency rf) to a level that may tolerate the large-charge bunches of the $\mu^+\mu^-$ collider.

III. SCENARIO CONSTRAINTS/ PROBLEMS

A major difficulty is that the $\mu^+\mu^-$ collider will require a high-intensity, high-quality muon source. In the presently developed scenarios this would consist of a KAON-class proton source, target and collector for π production, high acceptance transport for $\pi\Rightarrow\mu$ decay with rf bunch rotation, μ-cooling system, and μ-linac/recirculator injector for the TESLA-scale accelerator. A μ-source concept of this type is being developed in the $\mu^+\mu^-$ collider design collaboration, but considerable R&D is needed to develop and validate that concept.[2,3] An additional fundamental difficulty is the muon decays and the resulting radiation and detector background; this is also discussed in reference 3.

A. TESLA-related Issues - Bunch Structure and Power

We discuss in more detail issues that are related to TESLA utilization.

A significant complication is the somewhat different pulse structure of a $\mu^+\mu^-$ collider. TESLA uses a train of relatively closely-spaced lower-intensity bunches, while the muon collider would have a few high-intensity bunches with multiple but widely-spaced bunch passages. The muon collider could have single-bunch current limitations, but TESLA (e^+-e^-) is relatively tolerant of total current and peak-current limitations. It is unclear whether the same cavity and coupler designs and rf systems could provide optimal performance for both acceleration modes.

As a first example of bunch spacing scenarios, we consider a scenario of the type displayed in Figure 2 but choose 18 km as the return arc lengths, and 30 km as the total double linac length, or 96 km for a total cycle with two passes through the double linac (1 TeV acceleration). With 2 bunches (each) of 2×10^{12} μ^+ and μ^- and a 24 km bunch spacing, we obtain a linac current of 8 ma from both beams, similar to the TESLA 11.3ma single-beam current.[4] Acceleration to 2 TeV would take two full turns or 0.64ms, and acceleration to 5 TeV would take 5 turns or 1.6 ms. These times could be compared to the TESLA design cycle of 0.8ms active (1.3 ms total with fill and decay). The beam power is also larger (6.4 MJ/pulse for 5×5, compared to 4.5 MJ for TESLA). The muon accelerator also has the added complication of acceleration of both-sign beams in the same structure, possibly in opposite directions, and the arrival times of bunches at individual cavities will not be evenly spaced. (An alternative configuration in which each linac separately accelerates only one sign of μ's is of course possible.) The relatively large charge per bunch for μ's will cause a large voltage drop in the cavities (of up to ~10%) as the bunches pass through extracting energy; the rf controls and beam dynamics must be designed to handle this.

The longer pulse needed for acceleration to 5 TeV would require more rf input power, and it is important that the rf system be extendable to supply this. Luminosity increases would require acceleration of more muons (more bunches, increased repetition rate), and the rf system should be designed to support maximal beam power increases. (Some TESLA design variations tend toward lower power (less charge, 5 Hz, etc.); the present extension would indicate enabling higher power capacity.)

B. Wake Potential and HOM Considierations

In TESLA the longitudinal wake loss factor W_L is calculated to be 10.6 V/pC/m in the rf structure with σ = 1 mm bunch lengths. With 5×10^{10} electrons/bunch this results in a suppression of the cavity acceleration field of 85 kV/m at the bunch center, which is compensated by operation at 3° off crest. For 2×10^{12} μ/bunch and σ = 5mm, this becomes 4.5 V/pC/m ($W_L \propto \sigma^{-1/2}$), and this results in a 1.4 MV/m suppression. The energy spread and bunch length can be controlled by operation at ~25° off crest with nonsynchronous return arcs which enable synchrotron oscillations.[5]

Because of the higher peak currents the higher-order-mode (HOM) power is expected to be an order of magnitude larger for the muon collider case. In TESLA the HOM losses are estimated to be 4.6 W/m. One of the TESLA test facility goals is to determine how much of the HOM power is absorbed at 2K, with a design goal of < 7 to 10%; the total power load at 2K is budgeted at 2.2 W/m. We estimate HOM losses of ~100W/m would be obtained for the 5TeV (4 bunch) acceleration, and 7% of that (7W/m) would be too much for the 2K cryogenic system.

A clear R&D design goal is to see how large the loads are, and how to handle them. Options include larger apertures to facilitate energy transport from the cavities, increased cryogenics, and HOM load modifications from the initial TESLA design. Calculations by Q. S. Shu and Ming Zhao indicate that TESLA HOM couplers for up to 400 W/m can be designed,[6] and I. R. Campisi has promised to develop specific HOM designs for this purpose.[7]

C. Transverse Focussing Considerations

The muons will pass through the linacs at substantially different energies from the TESLA electrons, and it may be necessary to change the focusing system for stable focusing of the different energies. This may require new magnets or an entirely new lattice, which must be designed and verified in the multipass mode. Transverse wake-fields in a reduced focusing lattice must also be considered.

Muons will decay within the acceleration process; however the acceleration is sufficiently fast that only ~5% will decay. (This is less than the ~20% or more decay in the scenarios of ref. 2, which economize by relatively reduced SRF linac length, and more recirculating passes.) The μ-decay, $\mu \rightarrow e\nu\nu$, creates an electron (or positron) with ~1/3 of the initial μ energy. The total production will be ~10W/m of electron(positron) beam power. Most of these electrons will remain within an accelerating phase and continue to the end of the linac, where they will be lost by energy mismatch and/or synchrotron radiation in the return arcs. (Synchrotron radiation is not a serious problem for the muons themselves; energy loss at 5TeV is only ~10 MeV/turn with 5T bending fields.) Some of the electrons may be lost within the linac. It is important to verify whether the losses are acceptable; this will be true if the beam power deposited in the 2K cryogenic system is small. Collimation systems for the arcs and within the linac may be desired. μ-decay will occur within the collider ring, and shielding and collimation will be needed to handle these, particularly in cryogenic magnets and near the detectors (see ref. 2, 3).

IV. CONCLUSIONS

The TESLA linacs have much potential for reconfiguration as a high-energy μ-recirculator. Many problems and design issues would need to tbe resolved, and these issues are important in either application. It will be useful to carry out a design study to sufficient detail to understand what design changes may be needed in TESLA to make it optimal for a future upgrade to a $\mu^+\mu^-$ Collider.

Table: Parameters for TESLA[4] and a TESLA-based $\mu^+\mu^-$ Collider. TESLA (e^+-e^-) luminosity includes a factor of ~2 enhancement from disruption.

Parameter	**TESLA Collider**	**TESLA $\mu^+\mu^-$ Collider**
Collision energy	500 GeV	10 TeV
Beam energies	250×250 GeV	5×5 TeV
Number of passes	1	10
Particles/bunch	5×10^{10}	2×10^{12}
Bunches/train	1130	2–4 (1–2 per beam)
Energy to both beams	4.5 MJ	3.2—6.4 MJ
Beam pulse length	0.8 ms	1—2ms
repetition rate	10 Hz	10 Hz
Collision Parameters		
Collision turns	1	1200
ε, Normalized emittance	20×1	30 mm-mrad
β_X,β_Y	25×2 mm	3 mm
σ_x, σ_y	$1 \times 0.064\ \mu$	$1.4\ \mu$
Luminosity	6×10^{33}	2—4×10^{35}

V. REFERENCES

[1] TESLA design report, in preparation.
[2]. R. B. Palmer et al. “Muon collider design,” BNL - 62949, presented at the Third Workshop on Physics Potential and Development of $\mu^+\mu^-$ Colliders, San Francisco CA, Dec. 13-15, 1995.
[3] $\mu^+\mu^-$ Collider - A Feasibility Study, BNL-52503, Fermi-Lab-Conf.-96-092, LBNL-38946 (1996), presented at the Snowmass workshop.
[4] TESLA parameters are from the International Linear Collider Technical Review Committee Report 1995, SLAC. Parameters are not final design choices.
[5] D. Neuffer, to be published in NIM A (1996).
[6]. Q. S. Shu and Ming Zhao, unpublished communication, Snowmass Workshop (1996).
[7]. I. R. Campisi, private communication (1996).

Figure 1: Configurations for upgrading TESLA into a recirculating linac for injection into a $\mu^+\mu^-$ collider.
1A: In this configuration the μ^+ and μ^- beams are returned at the end of each linac and reinjected backwards through the same linacs, for several turns of back and forth recirculating acceleration before injection into opposing directions in a collider ring. The collider ring is in the center but could be at either end.
1B: In this configuration counter-rotating μ^+ and μ^- beams are bent 180° and transported back to the beginning of the (opposite) linacs for another 180° bend and recirculation; 10 passes would require 9 complete return loops (although the long return straight paths could be shared). We show a muon souce at the center which would launch oppositely charged bunches in opposite directions. After multipass acceleration the bunches are transferred into the collider for multiturn collisions.

Figure 1A

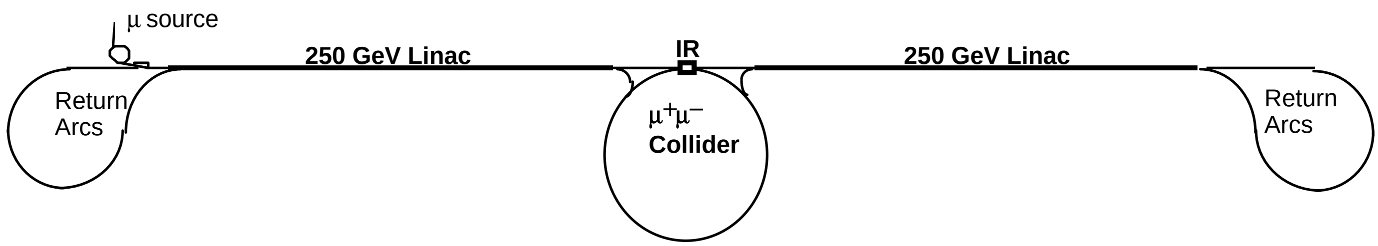

Figure 1B

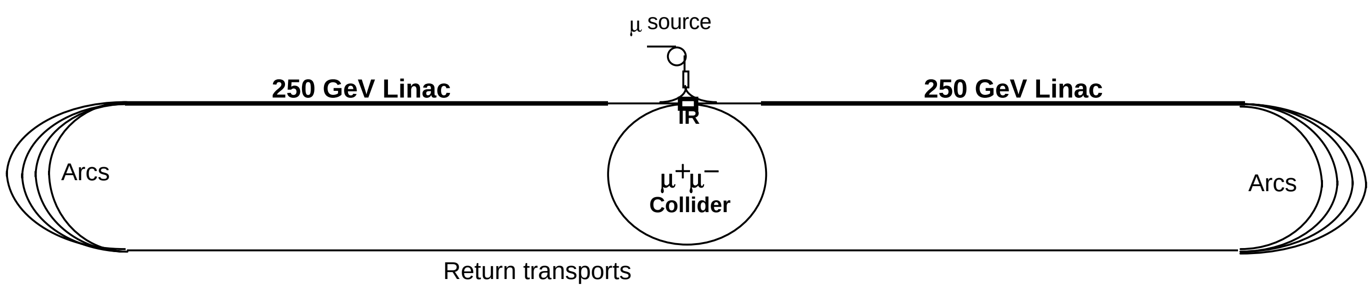

Figure 2: A variation of the figure 1A scenario. In this figure μ^+ and μ^- bunches are created at a source at the beginning of a linac, accelerated to the end of the double linac and returned back in a circular loop for a successive pass of acceleration in the opposite direction. Multipass acceleration would continue until extracted into a collider ring at the opposite (or the same) end of the linacs. (With the Collider at the opposite end an odd number of acceleration turns must occur.) 11 linac passes would require only 5 return paths at each end.