Beam Dynamics Issues of Muon Acceleration in RLA ♣

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A conceptual design of a muon acceleration based on recirculating superconducting linacs is proposed. In the presented scenario, acceleration starts after ionization cooling at 210 MeV/c and proceeds to 20 GeV, where the beam is injected into a neutrino factory storage ring. The key technical issues are addressed; such as: the choice of acceleration technology (superconducting versus normal conducting) and the choice of RF frequency, and finally, implementation of the overall acceleration scheme: capture, acceleration, transport and preservation of large phase space of fast decaying species. Beam transport issues for large-momentum-spread beams are accommodated by appropriate lattice design choices. The proposed arc optics is further optimized with a sextupole correction to suppress chromatic effects contributing to emittance dilution. The presented proof-of-principle design of the arc optics with horizontal separation of multi-pass beams is extended for all passes.

1. Muon Acceleration Scheme

A neutrino factory [1] is aimed to produce narrow neutrino beams via decay of muons in long straight sections of a storage ring. As illustrated schematically in Figure 1, a proposed muon accelerator complex features a 0.2-to-2.8 GeV straight pre-accelerator linac and a 2.8-to-20 GeV four-pass recirculating linac accelerator (RLA).

The pre-accelerator captures a large muon phase space coming from the cooling channel and accelerates them to relativistic energies of about 2.8 GeV. It makes the beam sufficiently relativistic and adiabatically decreases the phase-space volume, so that effective acceleration in recirculating linacs is possible. The RLA further compresses and shapes the longitudinal and transverse phase spaces, while increasing the energy.

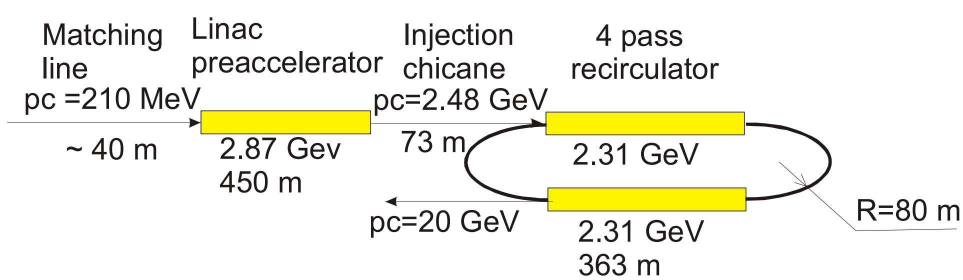

Figure 1: 20 GeV muon accelerator complex based on RLA – machine layout.

2. Accelerating Technology – Design Choices

To ensure adequate survival rates of short-lived muons, acceleration must occur at high average gradient. Our estimate [2] shows that a "real estate average" RF gradient of 15 MV/m will allow survival of about 80% of source muons throughout the RLA. Since muons are generated as a secondary beam they

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occupy large phase-space volume (even after the most optimistic stages of ionization cooling). The accelerator must provide high average gradient, while maintaining very large transverse and longitudinal accelerator acceptances. The above requirement drives the design to low RF frequency, e.g. 200 MHz. If normal-conducting cavities at that frequency were used, the required high gradients would demand unachievably high peak RF sources. Superconducting RF is a much more attractive solution. The RF power can then be delivered to the cavities over an extended time, and thus RF source peak power can be reduced.

3. Machine Architecture

At low energy, 210 MeV/c, muon beam is not sufficiently relativistic, which would yield a phase slip for beams at higher passes, significantly reducing acceleration efficiency for subsequent passes. Here we choose a linear pre-accelerator to about 2.8 GeV, which makes the beam sufficiently relativistic and adiabatically decreases the phase space volume, so that further acceleration in recirculating linacs is possible.

In a recirculating linac accelerator one needs to separate different energy beams coming out of a linac and to direct them into appropriate arcs for recirculation. Experience at Jefferson Lab suggests that in order to manage initially large emittance and energy spread, a ratio of final to injected energy should be well below 10. In addition, the number of passes in the RLA should be limited to about four. Here a single dipole spreader is chosen as a consequence of small energy difference between injection and extraction energy and because of rather high injection energy into RLA.

For multiple practical reasons horizontal rather than vertical beam separation was chosen. One of the

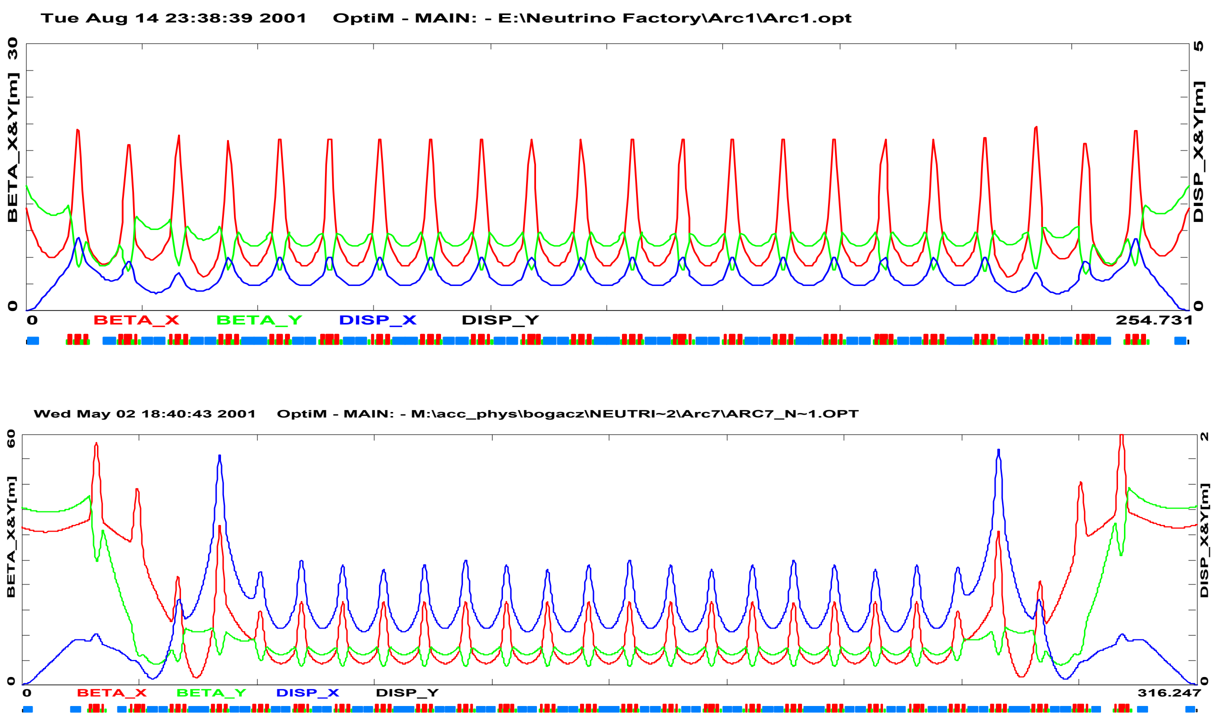

Figure 2: Optics of Arc1 (top) and Arc7 (bottom) – beta-functions and the horizontal dispersion matched to both adjacent linacs, Much larger difference (compared to Arc 1) between the values of beta functions in the adjacent linacs and Arc7, A quest to maintain 'smooth' transition of beta functions across spreaders and recombiners.

drawbacks would be an enormous vertical aperture of the vertical spreader/recombiner dipole, if the vertical separation were chosen. Furthermore, rather than suppressing vertical dispersion created by the spreaders and recombiners we chose the horizontal separation with no dispersion suppression; it is smoothly matched to the horizontal dispersion of the arc. Finally, to assure compact arc architecture very short matching sections in spreaders and recombiners are desired (see Figure 2).

Another crucial beam transport issue is to maintain manageable beam sizes in the arcs. This calls for short cells and for putting stringent limits on dispersion and beta functions (beam envelope). Since spreaders and recombiners were chosen in the horizontal plane, the uniform focusing and lattice regularity was broken in that plane and the horizontal beam envelope requires special attention. On the other hand, the vertical beam size remains small due to maintaining uniform focusing and small beta functions in that plane.

4. Arc Optics – Proof-of-principle Lattice Design

Focusing in all arcs is based on a periodic triplet focusing structure, rather than a FODO lattice, which allows use of longer straight sections as in the linacs. This simplifies spreader and recombiner design by maintaining similar betatron periodicity in linacs and arcs. It also reduces vertical beam envelopes and alleviates chromatic effects.

In addition, there is a need for high periodicity and smooth transition between different types of optics, e.g. linac-arc-linac, to alleviate emittance dilution due to chromatic aberrations (second order dispersion). Suppression of chromatic effects via sextupole corrections in spreaders and recombiners was implemented [3] via three families of sextupoles to control the horizontal emittance blow-up.To perform bunch compression in RLA the beam is accelerated off-crest with phase offsets in the range of 5 to 23 deg for different passes The number of periodic cells in the arcs was chosen, so that the desired value of momentum compaction factor required for optimum longitudinal phase space compression (M_{56} = 1.4 m in all arcs) is built into the arc optics.

Lattices for two extreme arcs of the RLA (Arc1 and Arc7) are illustrated in terms of the beta functions and dispersion in Figures 2. Short matching sections in spreaders and recombiners (consisting of six quads) allow one to match all TWISS functions and to join ‘smoothly’ regions of different optics.

5. Conclusions

Results of this study suggest there are no obvious physical, or technical limitations precluding construction of an RLA for acceleration of muons to 20 GeV. The use of 200 MHz accelerating frequency and superconducting RF technology seems well justified.

The resulting optics is well suited for transporting large phase space beams. Proposed chromatic corrections via two families of sextupoles in spreaders/recombiners are proven to be very effective in emittance dilution control.

References

[1] R. Raja et al. “The Program in Muon and Neutrino Physics”, Proceedings of Snowmass 2001

[2] V.A Lebedev et al. “Muon Accelerator for Neutrino Factory”, Proceedings of NuFACT’00, May 2000

[3] S.A. Bogacz and V.A. Lebedev, “Recirculating Linacs for Neutrino Factory – Arc Optics Design and Optimization”, Proceedings of NuFACT’00, May 2000