Recirculating Linacs for a Neutrino Factory – Arc Optics Design and Optimization §

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Abstract

A conceptual lattice design for a muon accelerator based on recirculating linacs [1] is presented here. The challenge of accelerating and transporting a large phase space of short-lived muons is answered here by presenting a proof-of-principle lattice design for a recirculating linac accelerator. It is the centerpiece of a chain of accelerators consisting of a 3 GeV linac and two consecutive recirculating linear accelerators, which facilitates acceleration starting after ionization cooling at 190 MeV/c and proceeding to 50 GeV. Beam transport issues for large-momentum-spread beams are accommodated by appropriate lattice design choices. The resulting 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 can be extended for all passes in both recirculating linacs.

Muon Acceleration Scheme

A proposed muon accelerator complex [2] features a 0.2-to-3 GeV straight "Preaccelerator" linac, a 3-to-11 GeV four-pass recirculating "Compressor" linac (RLA1), and finally an 11-to-50 GeV five-pass recirculating "Primary" linac (RLA2). The Preaccelerator captures a large muon phase space coming from the cooling channel and accelerates them to relativistic energies of about 3 GeV. It makes the beam sufficiently relativistic and adiabatically decreases the phase-space volume, so that further acceleration in recirculating linacs is possible. Increased muon lifetime ($\gamma\tau$) allows use of the first recirculating linac, the Compressor (RLA1). During compression, the longitudinal and transverse phase spaces are shaped (while further increasing the energy) for injection into the high-energy Primary (RLA2), which then generates the 50 GeV beam for the storage ring.

Beam Transport Issues – Design Choices

In a recirculating linac accelerator (RLA) 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 any RLA should be limited to about five. Here a single dipole spreader was chosen as a consequence of small energy difference between injection and extraction energy (5 times) and because of rather high injection energy into RLA. For further discussion of recirculating linac dynamic range (injected-to-final energy ratio) see Ref. [3].

For multiple practical reasons horizontal rather than vertical beam separation was chosen. One of the drawbacks would be an enormous vertical aperture of the vertical spreader/recombiner dipole, if the vertical separation were chosen. Furthermore, rather

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than suppressing vertical dispersion created by the spreaders and recombiners we chose the horizontal separation with no dispersion suppression; it is matched to the horizontal dispersion of the arc. Finally, to assure compact arc architecture very short matching sections in spreaders and recombiners are desired.

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 (unbroken periodic symmetry) and small beta functions in that plane

Furthermore, to assure appropriate longitudinal acceptance of the arcs there is a need for momentum compaction management and to account for nonlinear effects. As for the transverse acceptance consideration one needs to limit momentum-driven mismatch in the horizontal plane.

Finally, 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 via three families of sextupoles to control the horizontal emittance blow-up.

Arc Optics - Proof-of-Principle Lattice Design

The RLA1 recirculator uses a horizontal separation of beams at the end of the linacs to allow independent recirculation of each pass. Individual arc optics 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/Recombiner design by maintaining similar betatron periodicity in linacs and arcs. It also reduces vertical beam envelopes and alleviates chromatic effects.

To perform bunch compression in RLA1 the beam is accelerated off-crest with phase offsets in the range of 22 to 45 deg for different passes and M_{56} in the range of 60 to 110 cm for different arcs.

Lattice for two arcs of the RLA1 (arc1 and arc3) are illustrated in terms of the beta functions and dispersion in Figures 1and 2. Short matching sections in spreaders and recombiners (consisting of six quads) allow us to match all TWISS functions and to join 'smoothly' regions of different optics (focusing periodicity). The resulting uniform focusing optics including spreaders and recombiners are summarized in Figures 1 and 2.

The number of periodic cells in the arc was chosen and tuned, so that the desired value of momentum compaction factor required for optimum longitudinal phase space compression (M_{56} = 1.1 m) is built into the arc optics, (see Figure 2).

The required large momentum acceptance necessitates introduction of two-sextupole families in spreaders and recombiners to facilitate orbit and path length correction for off-momentum particles.

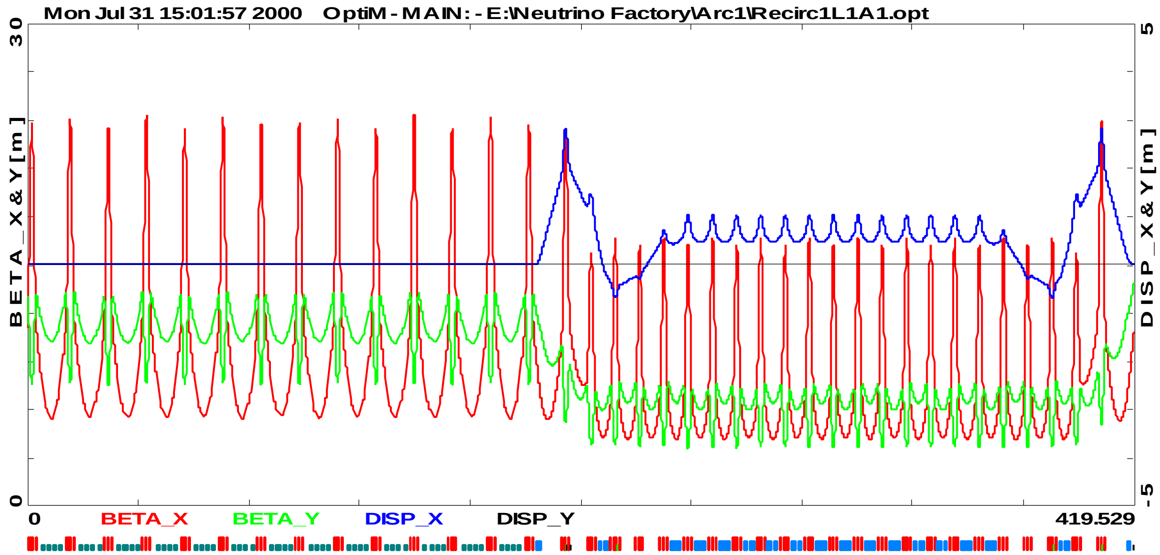

Figure 1 1L-S1-Arc1-R1'smooth periodic transition' lattice connected by compact spreader/recombiner optics) – acceleration from 2856 MeV to 3972 MeV

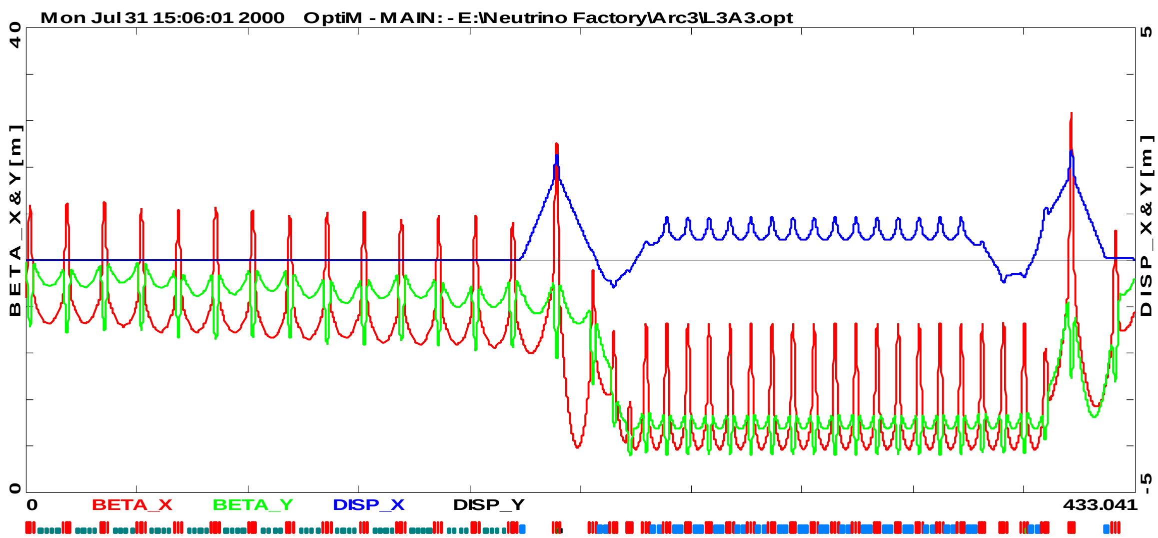

Figure 2 3L-S3-Arc3-R3'smooth periodic transition' lattice connected by compact spreader/recombiner optics) – acceleration from 4526 MeV to 6142 MeV

Conclusions

The presented lattice design for one of higher arcs (3L-Arc3) serves as a proof-of-principle arc optics template. Its architecture can be extended for all higher arcs in both recirculating linacs (RLA1 and RLA2). A single dipole horizontal separation of multi pass beams was chosen (rather than separating in the vertical plane). If the vertical plane were chosen one would need to deal with both the horizontal and vertical dispersion, which is not practical for compact matching sections.

The resulting optics illustrated in Figure 2 was put to test for beam transport properties. A multi particle simulation was carried out with a realistic large momentum spread (10%) particle distribution. The results are summarized in Figures 3 and 4. The simulation also shows that the chromatic corrections via two families of sextupoles in spreaders/recombiners are very effective means of emittance dilution control.

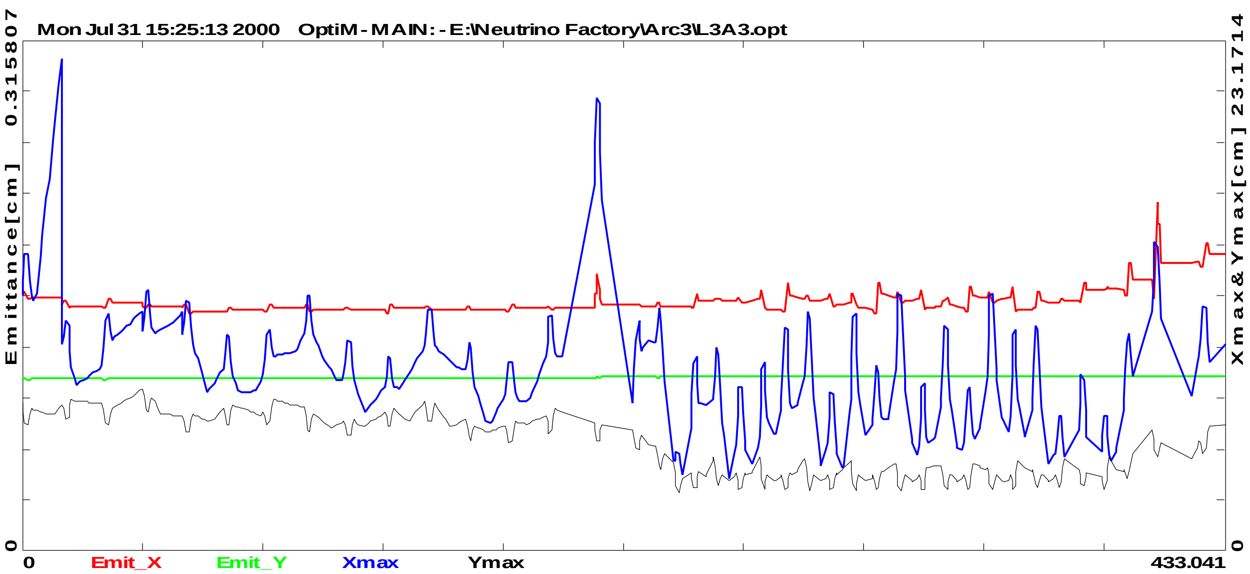

Figure 3 Beam envelops (maximum beam size) and the rms. beam emittances – particle tracking through 3L-S3-Arc3-R3 (from 4526 MeV to 6142 MeV)

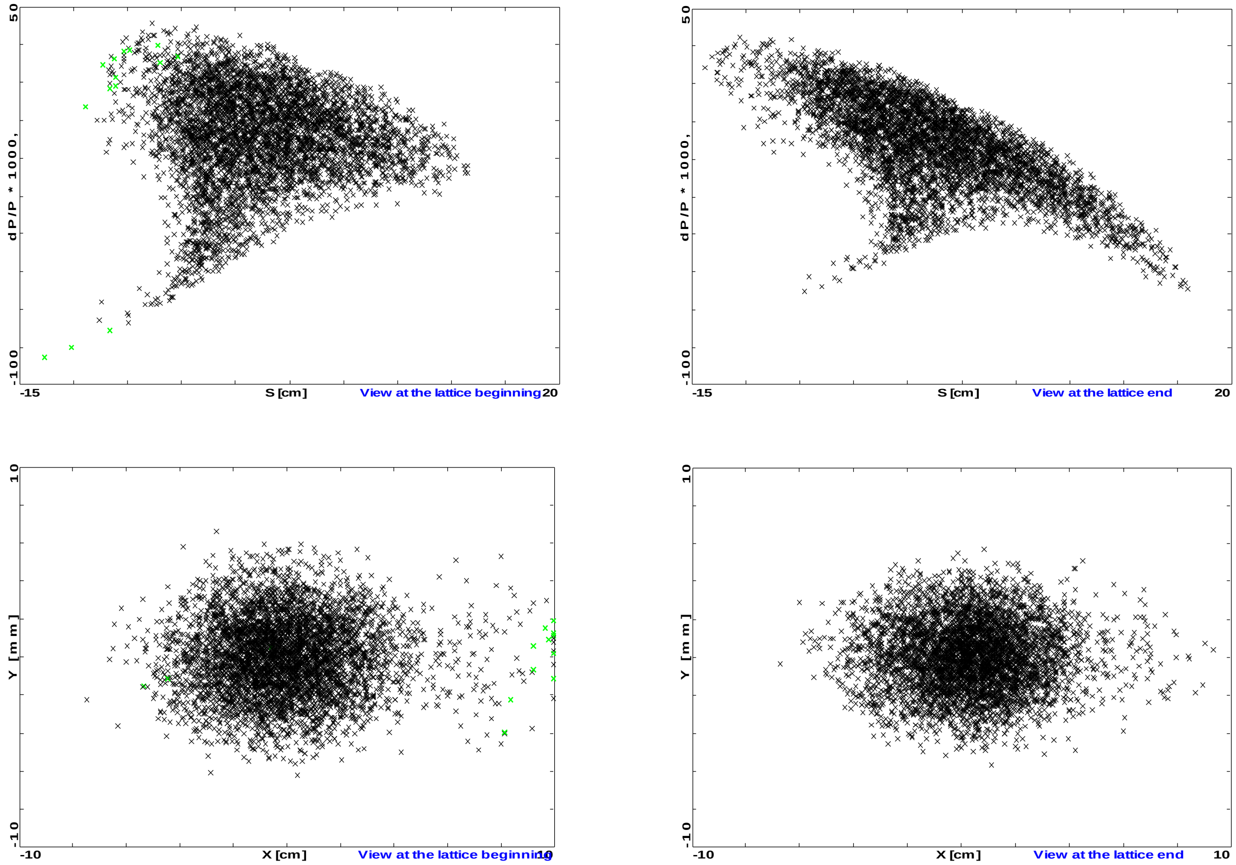

Figure 4 Longitudinal (top) and transverse (bottom) phase space tracking through 3L-S3-Arc3-R3 (from 4526 MeV to 6142 MeV)

Finally, as one can see in Figure 4, the longitudinal phase space is appropriately compressed by the momentum compaction built into the arc optics.

References

[1] V. Lebedev et al "Muon Accelerator for the Neutrino Factory", Proceedings of this conference

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[3] D. Douglas, "Lattice Design Principles for a Recirculated, High Energy, SRF Electron Accelerator", Proceedings of the 1993 Particle Accelerator Conference, IEEE Catalog No. 93CH3279-7, p. 584 (1993).