RECIRCULATING LINEAR ACCELERATORS FOR FUTURE MUON FACILITIES*

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Abstract

Neutrino Factories (NF) and Muon Colliders (MC) require rapid acceleration of short-lived muons to multi-GeV and TeV energies. A Recirculating Linear Accelerator (RLA) that uses superconducting RF structures can provide exceptionally fast and economical acceleration to the extent that the focusing range of the RLA quadrupoles allows each muon to pass several times through each high-gradient cavity. A new concept of rapidly changing the strength of the RLA focusing quadrupoles as the muons gain energy is being developed to increase the number of passes that each muon will make in the RF cavities, leading to greater cost effectiveness.

ACCELERATION SCHEME OVERVIEW

To provide sufficient muon flux for either a MC or NF will require a high power proton driver over 4 MW of beam power at some energy greater than 6 GeV.

Intense proton bunches are tightly focused onto a target capable of many MW operation to produce an intense pion beam. The pions are captured in a strong solenoidal field where they decay into muons (and neutrinos). At the end a 40 m pion decay channel the muon beam has transverse normalized emittances of around 40,000 mm-mr and is spread in time over tens of ns. The transverse dimensions of the beam must be cooled to be small enough and bunches must formed to fit into reasonable accelerating structures. For a MC, this is about a factor of a thousand in each transverse plane, or a factor of a million in six-dimensional emittance reduction.

3 GEV LINEAR PRE-ACCELERTOR

A single-pass linac "pre-accelerator" raises the beam energy to 3 GeV. This makes the muons sufficiently relativistic to facilitate further acceleration in a RLA. In addition, the longitudinal phase space volume is adiabatically compressed in the course of acceleration [1]. The large acceptance of the pre-accelerator requires large aperture and tight focusing at its front-end. Given the large aperture, tight space constraints, moderate beam energies, and the necessity of strong focusing in both planes, we have chosen solenoidal focusing for the entire linac [3]. The beam size is adiabatically damped with acceleration, and that allows the short cryo-modules to be replaced with the intermediate and finally long cryo-modules as illustrated in Fig. 1. In the initial part of the linac, when the beam is still not completely relativistic, the offcrest causes synchrotron motion which allows bunch compression in both length and momentum spread. The synchrotron motion also suppresses the sag in acceleration for the bunch head and tail.

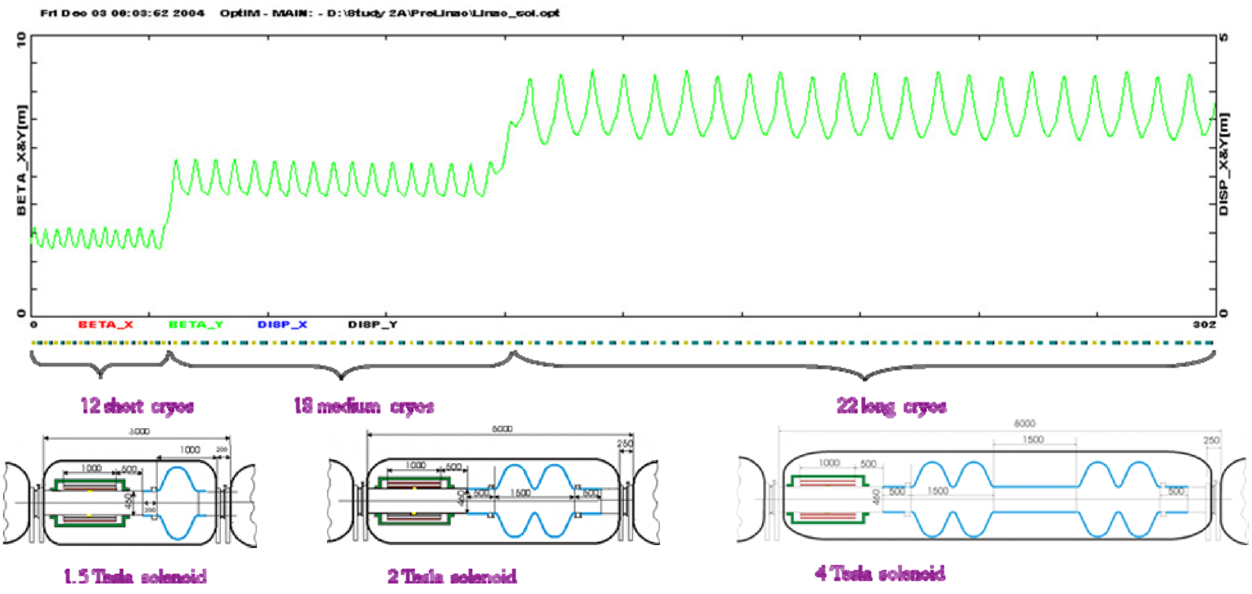

Figure 1: Transverse optics– uniform periodic focusing with 12 short, 18 medium, and 22 long cryo-modules.

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There is a 0.4% beam loss coming mainly from particles at the longitudinal phase space boundary.

MULTI-PASS LINAC OPTICS

The superconducting accelerating structure is by far the most expensive component of the accelerator complex. Maximizing the number of passes in the RLA can significant lower the cost [2] of the overall acceleration scheme.

There are two notable advantages of the 'Dogbone' configuration compared to the 'Racetrack': better orbit separation at the linac ends resulting from larger (factor of two) energy difference between two consecutive linac passes. Furthermore, more favorable optics solution for simultaneous acceleration of both $\mu^{\pm}$ species can be supported by the 'Dogbone topology', which allows both charge species to traverse the RLA linac in the same direction.

The key element of the transverse beam dynamics in a multi-pass 'Dogbone' RLA is an appropriate choice of multi-pass linac optics. Since the beam is traversing the linac in both directions throughout the course of acceleration, one would like to maintain a 90° phase advance per cell for the lowest energy pass (the initial half-pass) by scaling the quad gradients with increasing energy along the linac. In order to mitigate the beta beating due to reduced focusing for the subsequent passes, the other half of the linac would have the inverted scaling of the quadrupole gradients, as illustrated in Figure 3.

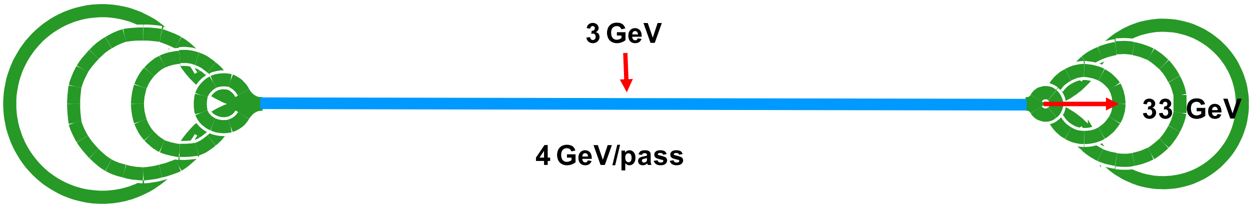


Figure 2: The RLA layout features a 'Dogbone' based on a 250 meter long linac (20 FODO; 4 RF cavities/cell).

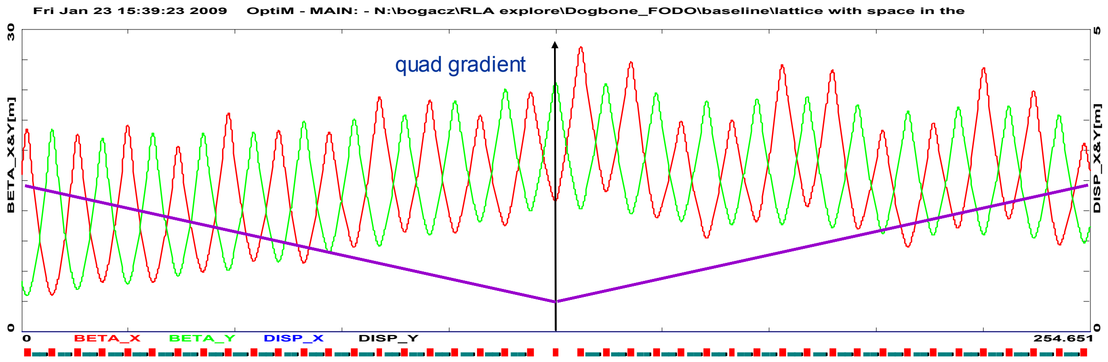
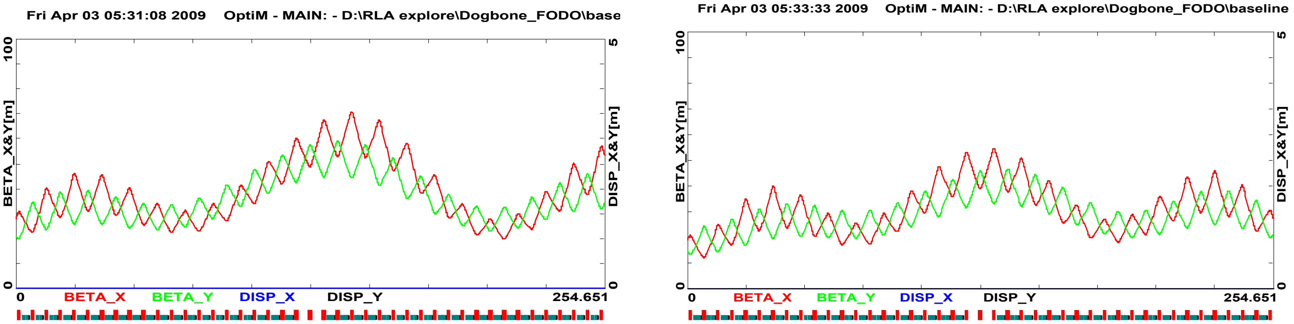


Figure 3: Bisected linac Optics – mirror symmetric quadrupole gradient profile minimizing under-focus beta beating.

Now we consider a 'Pulsed' linac Optics for the same RLA layout. Here we assume a time varying quad strength in the RLA linac described in the previous section. A feasible quad pulse would assume a 500 Hz cycle ramp with the top pole field of 1 Tesla. That would translate to a maximum quad gradient of G^{max} =2 kGauss/cm (5 cm bore radius) ramped over τ = 1 ms from the initial gradient of G_0 =0.1 kGauss/cm.

Figure 4 illustrates the multi pass optics for the pulsed linacs. As one can see below, there is sufficient phase advance to support up to 12 passes.

Pass 8 (31-35 GeV): Fixed Pulsed



Pass 12 (47-51 GeV): Fixed Pulsed

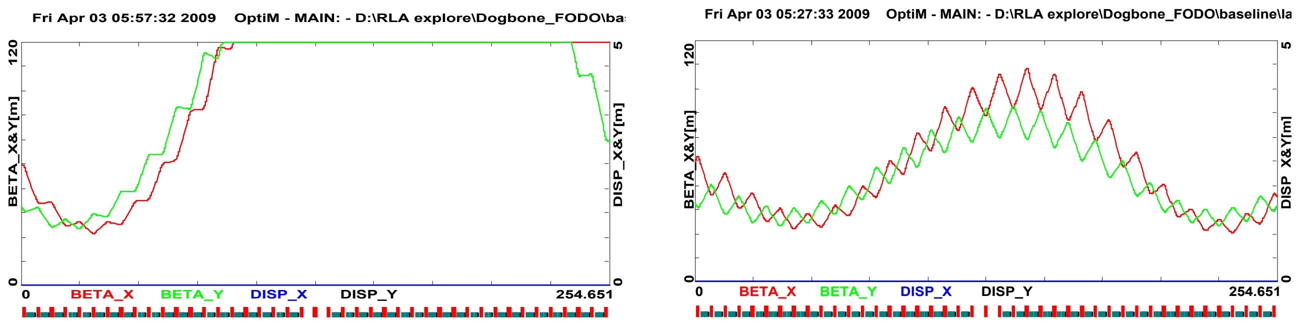


Figure 4: The 8-th pass and the last one (12-th**)** of the 'fixed' vs 'pulsed' linac optics - additional 4 passes gained**.**

'DROPLET' ARCS

In a 'Dogbone' RLA one needs to separate different energy beams coming out of a linac and to direct them into appropriate 'droplet' arcs for recirculation [1]. Rather than suppressing horizontal dispersion created by the Spreader, it is smoothly matched to the horizontal dispersion of the outward 60^0 arc. Then by the appropriate pattern of removed dipoles in three transition cells, one 'flips' the dispersion for the inward bending 300^0 arc, etc. The entire 'droplet' Arc optics architecture is based on 90^0 betatron phase advance cells with uniform periodicity of Twiss functions. The resulting 'droplet' Arc optics based on FODO focusing [2] is illustrated along with its 'footprint' in Figure 5.

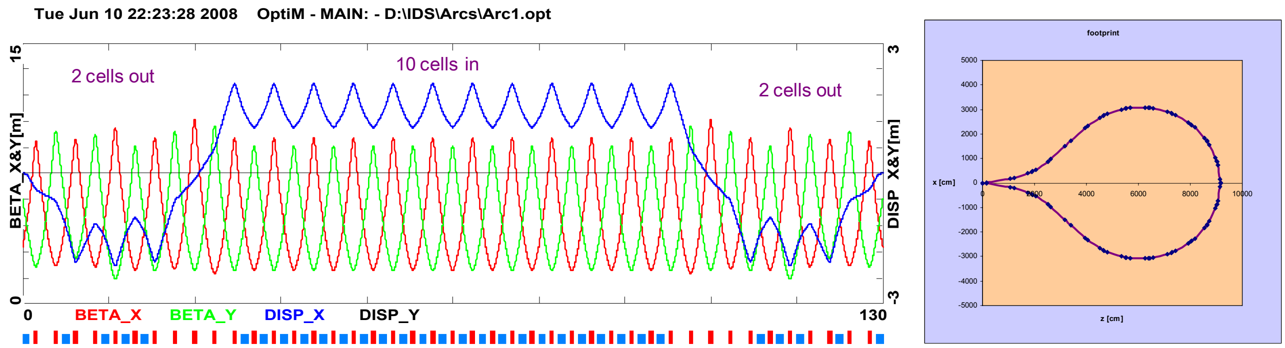


Figure 5: 'Droplet' Arc optics and its 'footprint' – uniform periodicity of beta functions and dispersion.

MULTI-PASS FFAG ARCS

Usage of pulsed quad focusing in the linac increased number of passes significantly, leading to cost savings. However, one needs to separate different energy beams coming out of a linac and to direct them into appropriate droplet-shaped arcs for recirculation. Each pass through the linac would call for a separate fixed energy droplet arc, increasing the complexity of the RLA. We also consider a novel return-arc optics design [4,5] based on a Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) lattice, which allows two (potentially even more) consecutive passes with very different energies to be transported through the same string of magnets.

CONCLUSIONS

Recirculating Linear Accelerators (RLAs) can provide exceptionally fast and economical muon acceleration. They are limited to the extent that the focusing range of the RLA quadrupoles allows each muon to pass several times through each high-gradient cavity and by the return arcs. The new concepts of rapidly changing the strength of the RLA focusing quadrupoles and use beta function beating as the muons gain energy has been developed that significantly increases the number of passes that each muon will make in the RF cavities

A droplet arc design based on a NS-FFAG lattice has been developed to transport muon beams of two passes for both charge species. This lowers the number of arcs and eases the design of a muon RLA. A droplet arc based on NS-FFAG lattice, allowing two consecutive passes with different energies to be transported through the same beamline is being considered.

REFERENCES

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