RECIRCULATING LINEAR MUON ACCELERATOR WITH RAMPED QUADRUPOLES*

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Abstract

Neutrino Factories and Muon Colliders require rapid acceleration of short-lived muons to multi-GeV and TeV energies. A Recirculating Linear Accelerator (RLA) that uses a single linac and teardrop return arcs (the so called 'Dogbone' RLA) [1] 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. Since muons are generated as a tertiary beam they occupy large phase-space volume and the accelerator must provide very large transverse and longitudinal acceptances. The above requirements drive the design to low RF frequency. 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. We have developed the optics and technical requirements for RLA designs, using superconducting RF cavities capable of simultaneous acceleration of both μ^+ and μ^- species, with pulsed linac quadrupoles to allow the maximum number of passes.

INTRODUCTION

A new concept of rapidly changing the strength of the linac quadrupoles as the muons gain energy will be presented. This increases the number of passes that each muon will make in the RF cavities, leading to greater cost effectiveness. The design will include the optics for the multi-pass linac and droplet-shaped return arcs, including chromatic compensation [1].

Future large scale facilities such as Neutrino Factories and Muon Colliders will benefit from more effective use of RF cavities by having RLA designs with more recirculation passes [2].

MULTI-PASS LINAC OPTICS

Superconducting accelerating structure is by far the most expensive component of the accelerator complex. Maximizing number of passes in the RLA has significant impact on cost-effectiveness [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.
- Favorable optics solution for simultaneous acceleration of both species, μ^+ and μ^- can be supported by the 'Dogbone topology', which allows both charge species to traverse the RLA linac in the same direction while passing in the opposite directions through the mirror symmetric optics of the return 'droplet' arcs.

The key element of the transverse beam dynamics in a multi-pass 'Dogbone' RLA is an appropriate choice of multi-pass linac optics. The focusing profile along the linac (quadrupole gradients) need to be set, so that one can transport (provide adequate transverse focusing for given aperture) multiple pass beams within a vast energy range. Obviously, one would like to optimize the focusing profile to accommodate maximum number of passes through the RLA.

Two styles of linac focusing lattice (FODO and Triplet) were studied for the lattice design of the RLA [1]. The focusing symmetry between the horizontal and vertical planes in the FODO lattice guarantees uniformly decreasing betatron phases in both planes while the energy increases in higher linacs passes. This yields a linac optic design that is well balanced in terms of Twiss functions and beam envelopes, which supports twice as many passes through the Dogbone RLA

Since the beam is traversing the linac in both directions throughout the course of acceleration, the best choice is a 'flat' focusing profile for the entire linac. That is, the quads in all cells are set to the same gradient. This gradient was chosen to corresponding to a 90° phase advance per cell as determined for the injection energy. There is no scaling of the quad gradients for increasing energy along the linac as this scaling would be incorrect for subsequent passes.

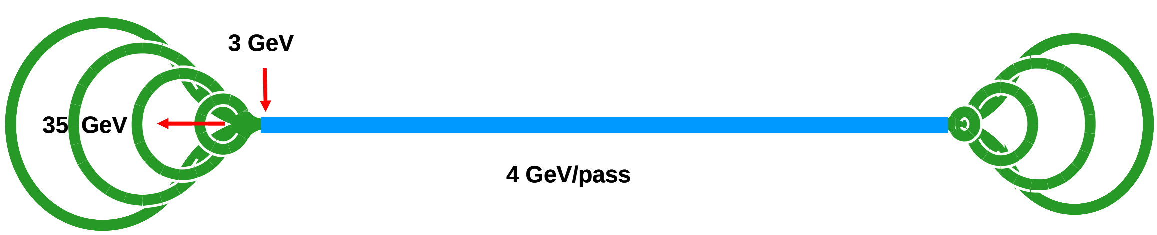

Figure 1: Layout of an 8-pass 'Dogbone' RLA with the top-to-injected energy ratio of 12.

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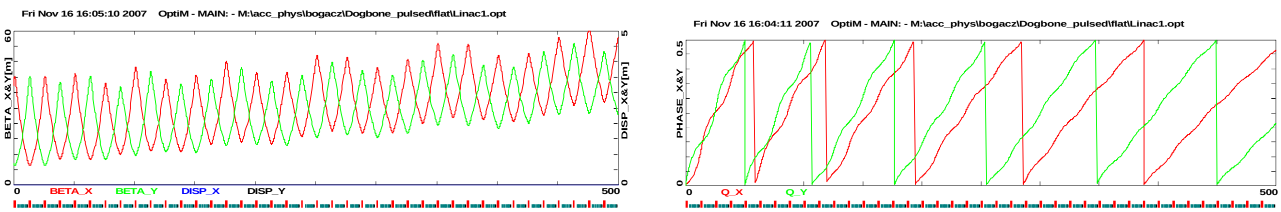
The RLA layout illustrated in Figure 1, features a ‘Dogbone’ based on a 500 meter long (20 FODO cells with 8 RF cavities/cell) 4 GeV linac with the injection energy of 3 GeV .

Figure 2 illustrates the multi pass optics case, which supports a maximum number of 8 passes through the RLA. The highest pass is limited by the linac phase advance falling below 180 deg.

Pass 1 (3-7 GeV)



Pass 8 (31-35 GeV)

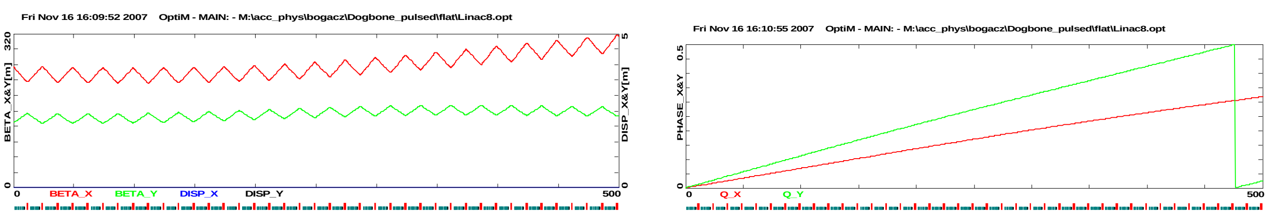


Figure 2: The first pass and the last one (8-th) of a FODO based multi-pass linac optics. In each set, the left plot represents beta functions, and the right plot describes betatron phase advance. Red is horizontal and green is vertical**.**

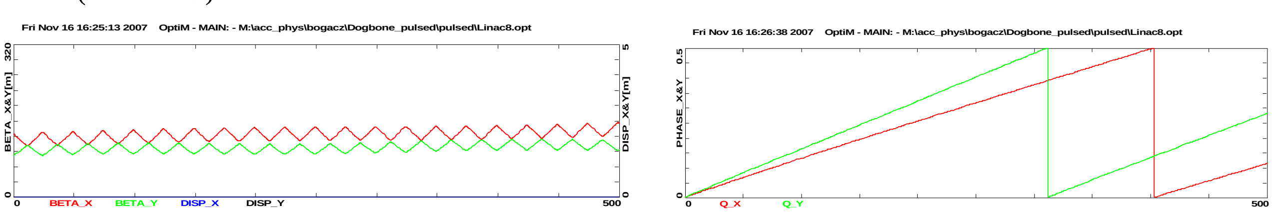
Now we consider a ‘Pulsed’ linac Optics for the same RLA layout. Here we assume a time varying quad strength in the RLA linac described in the previous section. A feasible quad pulse would assume 500 Hz cycle ramp with the top pole field of 1 Tesla. That would translate to a maximum quad gradient of G^{max} =2 kGauss/cm (5 cm bore radius) ramped over τ = 1 msc from the initial gradient of G_0 =0.1 kGauss/cm. We have used a fairly conservative rise time based on similar applications for ramping the new corrector magnets for the Fermilab Booster that have 1 kHz capability [3].

For simplicity, we consider a linear ramp according to the following formula:

$$G(t) = G_0 + \frac{G^{max} - G_0}{\tau} t \qquad (1)$$

A single bunch travelling with a speed of light along the linac with quads ramped according to Eq.(1), ‘sees’ the following quad gradient passing through i-th cell along the linac (i = 1,…20)

Pass 8 (31-35 GeV)



Pass 12 (47-51 GeV)

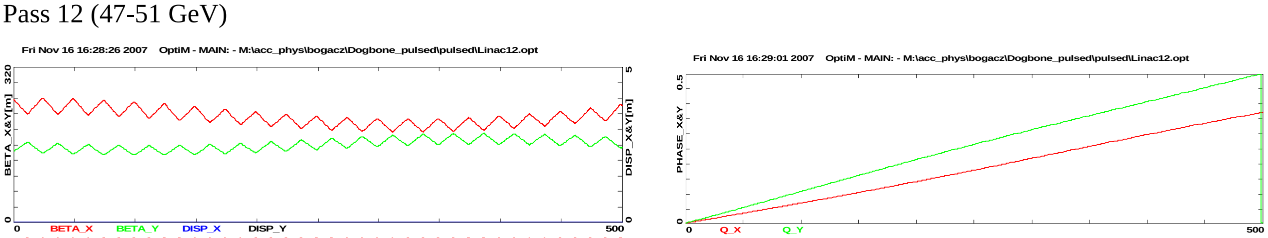


Figure 3: The 8-th pass and the last one (12-th**)** of the pulsed linac optics. By pulsing the focusing quads as described in Eq.(3), the additional 4 passes increase the output energy from 35 to 51 GeV. In each set, the left plot represents beta functions, and the right plot describes betatron phase advance. Red is horizontal and green is vertical**.**

$$G_i = G_0 + \frac{G^{max} - G_0}{\tau}\frac{\ell_{cell}}{c}i \qquad (2)$$

where ℓ_{cell} is the cell length and i defines the bunch position along the linac.

For multiple passes through the linac (the index n defines the pass number) the above formula can be generalized as follows:

$$G_i^n = G_0 + \frac{G^{max} - G_0}{\tau c}\left[(n-1)\left(\ell_{linac} + \frac{n}{2}\ell_{arc}\right) + i\,\ell_{cell}\right] \qquad (3)$$

where ℓ_{linac} is the full linac length and ℓ_{arc} is the length of the lowest energy droplet arc. Here we also assume that the energy gain per linac is much larger than the injection energy. Figure 3 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.

‘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]. For multiple practical reasons horizontal rather than vertical beam separation was chosen. 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 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 ‘foot print’ in Figure 4.

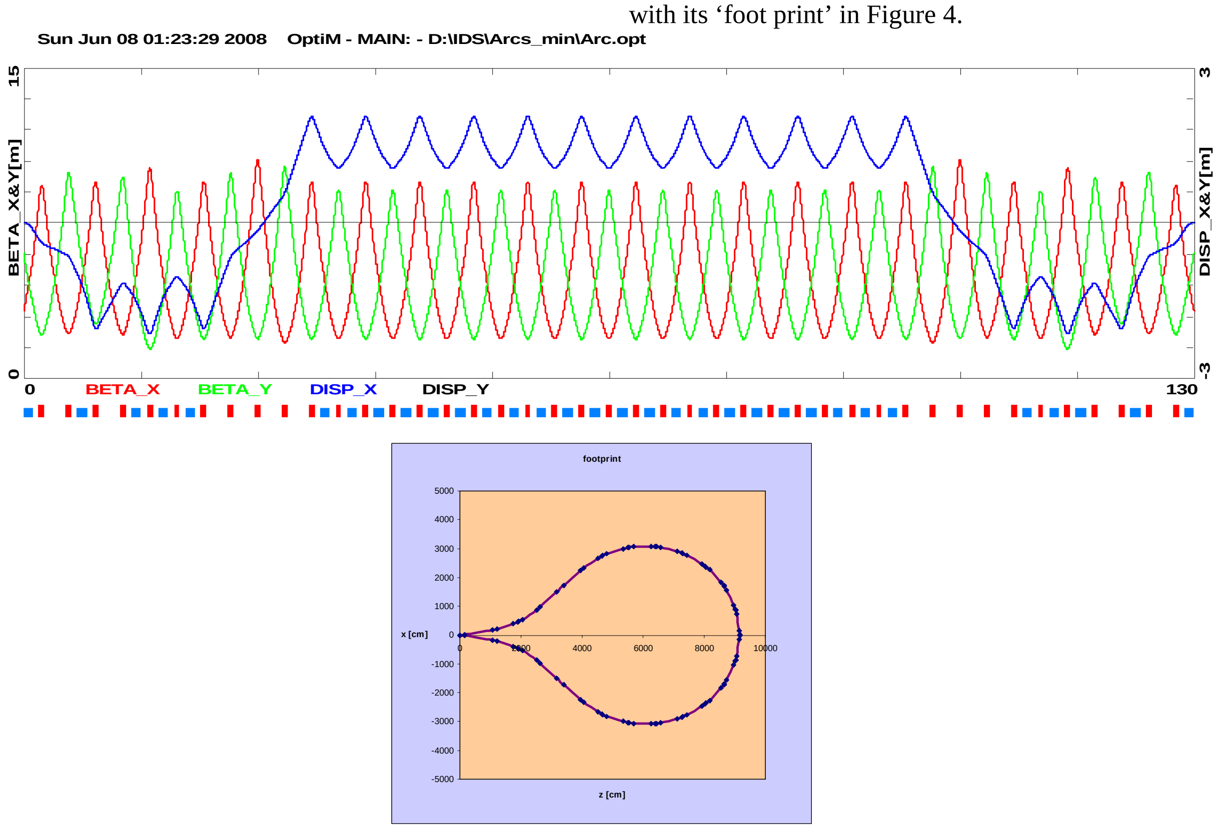


Figure 4: ‘Droplet’ Arc optics and its ‘footprint’ – uniform periodicity of beta functions and dispersion.

CONCLUSIONS

A Recirculating Linear Accelerator (RLA) that uses International Linear Collider (ILC) 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. However, the technical feasibility, ultimate limitations, and cost effectiveness of such schemes have not been fully developed.

REFERENCES

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[3] V.S. Kashikhin et al., “A New Correction Magnet Package for the Fermilab Booster Synchrotron”**,** PAC 2005.