

# MULTI-PASS ERL IN A ‘DOGBONE’ TOPOLOGY\*

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## Abstract

The main thrust of a multi-pass Recirculating Linear Accelerator (RLA) is its very efficient usage of expensive linac structures. That efficiency can be further enhanced by configuring an RLA in a ‘dogbone’ topology, which ‘boosts’ the RF efficiency by factor close to two (compare to a corresponding racetrack). However, the ‘dogbone’ configuration requires the beam to traverse the linac in both directions, while being accelerated. This can be facilitated by a special ‘bisected’ linac optics, where the quadrupole gradients scale up with momentum to maintain periodic FODO structure for the lowest energy pass in the first half of the linac and then the quadrupole strengths are mirror reflected in the second linac half. The virtue of this optics is the appearance of distinct nodes in the beta beat-wave at the ends of each pass (where the droplet arcs begin), which limits the growth of initial betas at the beginning of each subsequent droplet arc. Furthermore, ‘bisected’ linac optics naturally supports energy recovery in the ‘dogbone’ topology. Here, we present a-proof-of-principle lattice design of a multi-pass energy recovery linac (ERL) in a ‘dogbone’ topology.

## ‘DOGBONE’ ERL – OVERVIEW

Energy Recovery Linacs (ERLs) accelerate electron bunches of linac quality, and then recover beam energy by deceleration through the same linac, before dumping the bunches at low (injection) energy. Energy recovery has the benefits of supporting high beam energy and power, while maintaining high beam quality, including small beam sizes as delivered by linacs; minimizing activation by dumping low-energy (and thus low-power) beam; and ensuring power-efficient accelerator operation, e.g. for collider applications [1].

A dog-bone-shaped RLA was first considered for rapid acceleration of fast decaying muons, as part of Neutrino Factory design [2]. Here, we propose a multi-pass electron ERL consisting of a single superconducting linac configured with elliptical twin axis cavities [3], capable of accelerating (or decelerating) beams in two separate beam pipes (see Figure 1a). Such cavity, features opposite direction longitudinal electric fields in the two halves of the cavity, as illustrated schematically in Figure 1b.

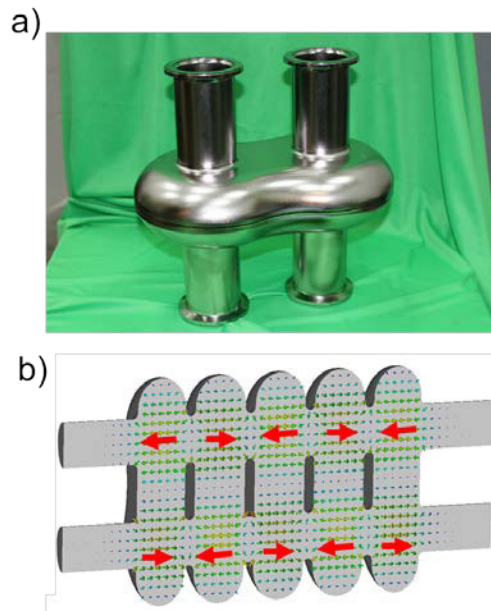


Figure 1: Elliptical twin axis cavity: a) Single cell Niobium cavity; b) Configuration of electric fields with opposing directions in two halves of a multi-cell cavity.

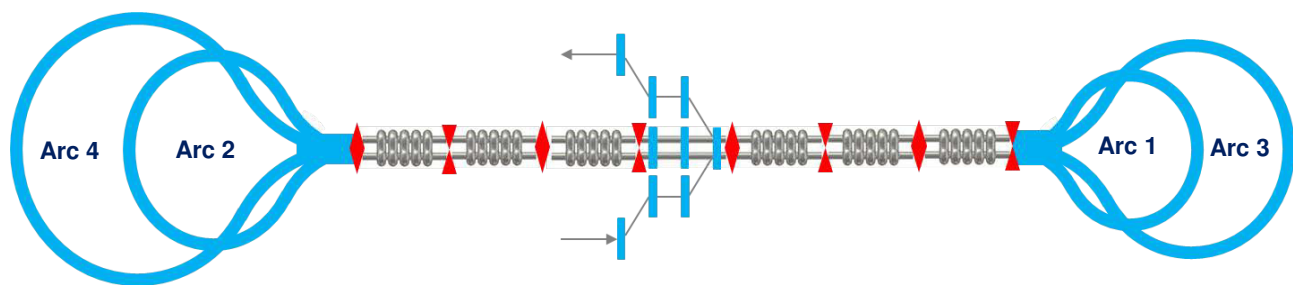


Figure 2: Multi-pass ‘Dogbone’ ERL – Schematic view of the accelerator layout; featuring a single SRF linac based on elliptical twin axis cavities, four return ‘droplet’ arcs and a pair of injection/extraction chicanes.

As illustrated in Figure 2, the beam is injected via a fixed field chicane at the middle of the linac to minimize the effect of phase slippage for the lowest energy beam accelerated in the linac, which is phased for the speed-of-light particle. At the linac ends the beams need to be directed into the appropriate energy-dependent (pass-

dependent) ‘droplet’ arc for further recirculation [4] (a pair of droplet arcs at each end of the linac). Reusing the same linac for multiple (3.5) beam passes provides for a more compact and efficient accelerator design and leads to significant cost savings [5]. Furthermore, this scheme is well suited to operate in the energy recovery mode.

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## OPTICS ARCHITECTURE

The proposed accelerator complex consists of a single linac equipped with two pairs of return ‘droplet’ arcs (a pair on each end) to facilitate recirculation and energy recovery of different energy beams, with the beam being injected via a fixed field chicane at the middle of the linac.

For the remainder of this paragraph, we will present a detailed description of the proposed accelerator complex in the energy recovery mode.

### Multi-pass Linac

The focusing profile along the linac was chosen so that energy recovered beams with a large energy spread could be transported within the given aperture. Since the beam is traversing the linac in both directions (as being accelerated, or decelerated) two consecutive passes are accommodated in different ‘halves’ of elliptical twin axis cavities. To assure adequate focusing for counter propagating beams a ‘bisected’ focusing profile was chosen for the multi-pass linac [6]. Here, the quadrupole gradients were set to scale up with momentum to maintain  $90^\circ$  phase advance per cell for the first half of the linac and then they were mirror reflected in the second half to mitigate the beta beating resulting from under-focusing for the first full pass through the linac, as illustrated in Figure 3. Multi-pass linac optics for all 3.5 passes is illustrated in Figure 4.

One can notice the ‘bisected’ linac optics naturally supports energy recovery, providing an extra path length delay of one half of the RF wavelength is added to the highest energy arc (Arc 4), which will put the beam into a decelerating mode. The linac optics for 3.5 decelerating passes (energy recovery) follows a mirror symmetric optics to the one illustrated in Figure 4.

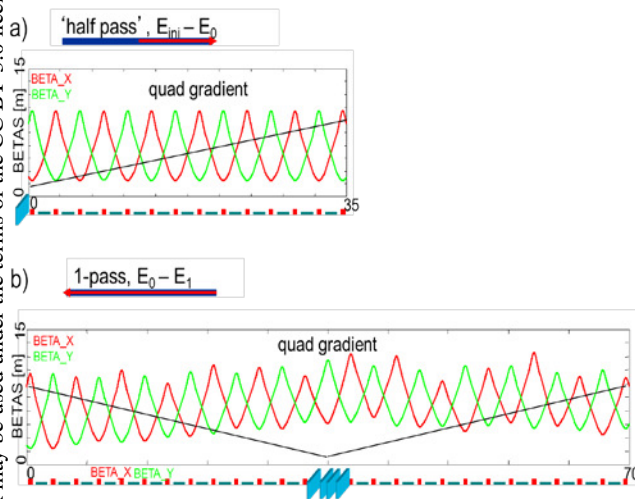


Figure 3: “Bisected” linac optics: (a) periodic FODO structure set for the lowest energy ‘half-pass’ through the linac; (b) linac optics for the first ‘full pass’; the under focusing effects in the first half of the linac are mitigated by reversing the focusing profile in the second half.

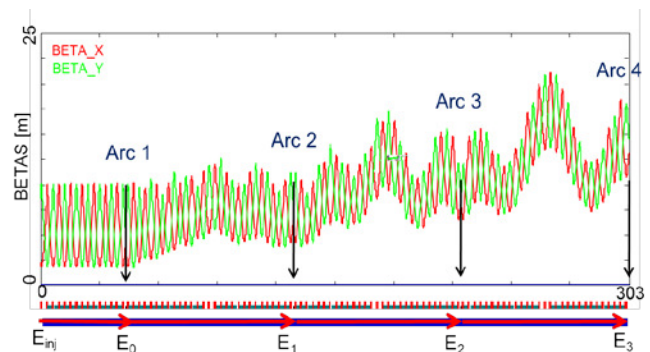


Figure 4: Multi-pass linac optics for all passes, with mirror symmetric arcs inserted as point matrices (arrows). The virtue of the optics is the appearance of distinct nodes in the beta beat-wave at the ends of each pass (where the arcs begin), which limits the growth of initial betas at the beginning of each subsequent droplet arc (Arc 1–4), hence eases linac-to-arc matching.

### ‘Droplet’ Arcs

At the ends of the RLA linac, the beams need to be directed into the appropriate energy-dependent (pass-dependent) droplet arc for recirculation. The entire droplet-arc architecture [4] is based on  $90^\circ$  phase-advance cells with periodic beta functions. For practical reasons, horizontal rather than vertical beam separation has been chosen. Rather than suppressing the horizontal dispersion created by the spreader, it has been matched to that of the outward arc. This is partially accomplished by removing one dipole (the one furthest from the spreader) from each of the two cells following the spreader. To switch from outward to inward bending, three transition cells are used, wherein the four central dipoles are removed. The two remaining dipoles at the ends bend the same direction as the dipoles to which they are closest. The transition region, across which the horizontal dispersion switches sign, is therefore composed of two such cells. To facilitate subsequent energy recovery following acceleration, a mirror symmetry is imposed on the droplet arc optics. This puts a constraint on the exit/entrance Twiss functions for two consecutive linac passes, namely:  $\beta_{n \text{ out}} = \beta_{n+1 \text{ in}}$  and  $\alpha_{n \text{ out}} = -\alpha_{n+1 \text{ in}}$ , where  $n = 0, 1, 2, \dots$  is the pass index.

The complete droplet arc optics for the lowest-energy pair of arcs is shown in Figure 6. All higher arcs are based on the same principle as Arc 1, with gradually increasing cell length (and dipole magnet length) to match naturally to the increasing beta functions dictated by the multi-pass linac. The quadrupole strengths in the higher arcs are scaled up linearly with momentum to preserve the  $90^\circ$  FODO lattice. The physical layout of the above pair of droplet arcs is illustrated in Figure 5.

One additional requirement to support energy recovery in a linac configured with elliptical twin axis cavities is that the path-length of Arcs 1-3 has to be a multiple plus one half of the RF wavelength. Conversely, Arc 4 path-length should be just a multiple of the RF wavelength to switch the beam from the ‘accelerating’ to ‘decelerating’ phase in the linac.

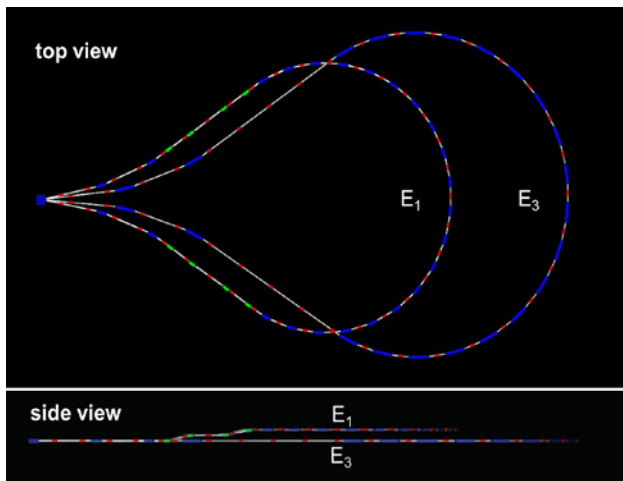


Figure 5: Layout of a pair of arcs on one side of the ‘dogbone’ RLA, Top and side views, showing vertical two-step ‘lift’ of the middle part of lower energy droplet arc to avoid interference with the larger droplet (1 meter vertical separation).

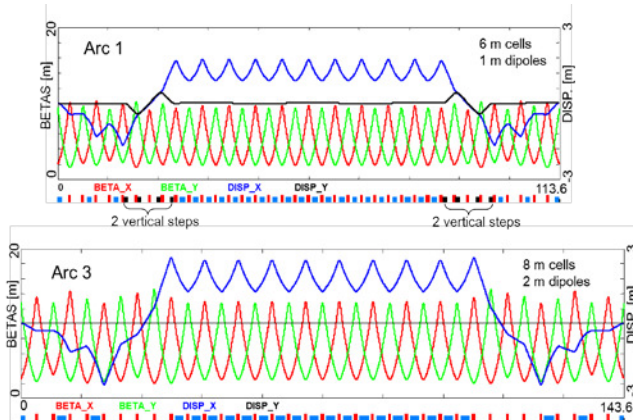


Figure 6: ‘Droplet’ arc optics for a pair of arcs on one side of the ‘dogbone’; Arc 1 and Arc 3.

## OUTLOOK

The maximum number of passes through the RLA’s linac is often limited by design considerations for the switchyard, which first spreads the different energy passes to go into the appropriate arcs and then recombines them to align the beam with the linac axis. To reduce complexity of the above single energy return arcs, we have recently proposed a novel multi-pass arc design based on linear combined function magnets with variable dipole and quadrupole field components, which allows two consecutive passes with very different energies (factor of two, or more) to be transported through the same string of magnets [7]. Such a solution combines compactness of design with all the advantages of a linear, non-scaling FFA (Fixed Field Alternated) optics [8], namely, large dynamic aperture and momentum acceptance essential for energy recovery, no need for complicated compensation of non-linear effects, and one

can use a simpler combined-function magnet design with only dipole and quadrupole field components. The scheme utilizes only fixed magnetic fields, including those for injection and extraction.

## SUMMARY

The key advantage of a multi-pass RLA is its very efficient use of an expensive SRF linac. That efficiency can be further enhanced by configuring an RLA in a ‘dogbone’ topology, which almost doubles the RF efficiency (compare to a corresponding racetrack). Furthermore, the ‘dogbone’ RLA is well suited for operation in the energy recovery mode.

Here, we have presented a-proof-of-principle lattice design of a multi-pass energy recovery linac (ERL) in a ‘dogbone’ configuration.

Finally, the ‘dogbone’ ERL can be significantly simplified by replacing a pair of single energy ‘droplet’ arcs with the proposed FFA-like arcs, capable of transporting different energy beams through the same string of magnets. The multi-pass arc design has a number of advantages over separate-arc or pulsed-arc approaches. It eliminates the need for a complicated switch-yard, it reduces the total beam-line length, there is no need to accommodate multiple beam lines in the same tunnel or construct separate tunnels for individual arcs, there is no need for vertical bypasses, which may be required for separate arcs complicating the optics. This helps to increase the number of passes through the linac thus enhancing the top energy available with the same-size footprint.

## REFERENCES

- [1] D. Pellegrini, A. Latina, D. Schulte, and S.A. Bogacz, ‘Beam-dynamics Driven Design of the LHeC Energy Recovery Linac’, *Phys. Rev. ST-AB*, 121004 (2015).
- [2] S.A. Bogacz, ‘Beam Dynamics of Muon Acceleration for Neutrino Factory’, *Journal of Physics G: Nuclear and Particle Physics*, **29**, 1723, (2003).
- [3] H. Park, S. U. De Silva, J. R. Delayen, F. Marhauser, A. Hutton, ‘First Test Results of Superconducting Twin Axis Cavity for ERL Applications’, *Proceedings of LINAC 2018*, Beijing, China (2018).
- [4] C. Ankenbrandt, S.A. Bogacz, A. Bross, S.Geer, C. Johnstone, D. Neuffer, R. Palmer, M. Popovic, ‘Low Energy Neutrino Factory Design’, *Phys. Rev. ST-AB* **12**, 070101 (2009).
- [5] J.S. Berg, S.A. Bogacz, S. Caspi, J. Cobb, R. C. Fernow, J.C. Gallardo, S. Kahn, H. Kirk, D. Neuffer, R. Palmer, K. Paul, H. Witte, M. Zisman, ‘Cost-effective Design for a Neutrino Factory’, *Phys. Rev. ST-AB* **9**, 011001 (2006).
- [6] S.A. Bogacz, ‘Muon Acceleration Concepts for NuMAX: “Dual-use” Linac and “Dogbone” RLA’, *JINST*, **13**, P02002 (2018).
- [7] V.S. Morozov, S.A. Bogacz, Y.R. Roblin, K.B. Beard, ‘Linear Fixed-field Multi-pass Arcs for Recirculating Linear Accelerators’, *PRST-AB*, **15**, 060101 (2012).
- [8] V.S. Morozov, S.A. Bogacz, K.B. Beard, ‘Muon Acceleration with RLA and Non-scaling FFA Arcs’, in *Proc. IPAC’10*, Kyoto, Japan (2010).