# LINACS FOR FUTURE MUON FACILITIES*

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*Abstract*

Future Muon Colliders (MC) and Neutrino Factories (NF) based on muon storage rings will require innovative linacs to: produce the muons, cool them, compress longitudinally and 'shape' them into a beam and finally to rapidly accelerate them to multi-GeV (NF) and TeV (MC) energies. Each of these four linac applications has new requirements and opportunities that follow from the nature of the muon in that it has a short lifetime ($\tau$ = 2.2 μsec) in its own rest frame, it is produced in a tertiary process into a large emittance, and its electron, photon, and neutrino decay products can be more than an annoyance. As an example, for optimum performance, the linac repetition rates should scale inversely with the laboratory lifetime of the muon in its storage ring, something as high as 1 kHz for a 40 GeV Neutrino Factory or as low as 20 Hz for a 5 TeV Muon Collider. A superconducting 8 GeV Linac capable of CW operation is being studied as a versatile option for muon production [1] for colliders, factories, and muon beams for diverse purposes. A linac filled with high pressure hydrogen gas and imbedded in strong magnetic fields has been proposed to rapidly cool muon beams [2]. Recirculating Linear Accelerators (RLA) are possible because muons do not generate significant synchrotron radiation even at extremely high energy and in strong magnetic fields. We will describe the present status of linacs for muon applications; in particular the longitudinal bunch compression in a single pass linac and multi-pass acceleration in the RLA, especially the optics and technical requirements for RLA designs, using superconducting RF cavities capable of simultaneous acceleration of both $\mu^+$ and $\mu^-$ species, with pulsed linac quadrupoles to allow the maximum number of passes. The design will include the optics for the multi-pass linac and droplet-shaped return arcs.

## MUON PRODUCTION AND COOLING

### *Proton Driver Linac*

The first linac in the accelerator chain for intense muon beams is for the proton driver. Proposals for various types of linacs and synchrotrons for this purpose have been to use charge exchange injection of $H^-$ ions to overcome the Laslett space charge tune spread. The ultimate expression of this idea is to eliminate acceleration in the synchrotron, such that it becomes an accumulation and bunching ring, and provide all of the acceleration in an 8 GeV linac [1]. To provide sufficient muon flux for a collider of acceptable luminosity will require over 4 MW of beam power at some energy greater than 6 GeV [3].

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### *Multi-Megawatt Target*

Once the intense proton bunches have been formed at 8 GeV they are tightly focused onto a target capable of many MW operation [4] 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 of the 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 be formed to fit into reasonable accelerating structures, depending on their intended NF or MC use.

### *Ionization Cooling and Emittance Exchange*

The only method fast enough to cool a muon beam is ionization cooling in which the muons pass through a low Z material to lose energy in all three directions, have only the longitudinal component replenished by RF, and thereby reduce their angular divergence. Doing the same thing after ninety degrees in betatron phase advance allows the transverse dimensions of the beam to be reduced, but to reduce the bunch length by ionization cooling requires the longitudinal emittance to be exchanged with the transverse emittance. This exchange can be accomplished by placing the energy absorbing material in a dispersive region, either as a wedge-shaped absorber or as a continuous homogeneous absorber [5].

### *Linacs for Bunching and Cooling*

The reduction in each transverse emittance by a factor of 1/e from ionization cooling requires that the energy lost in the absorber be equal to the energy of the beam. Thus for a 250 MeV beam, a linac of about 7×250 = 1750 MeV energy would be needed to achieve a factor of a thousand in each transverse plane, or a factor of a million in six-dimensional emittance reduction as is required for a MC. In muon ionization cooling, intense magnetic fields are required which imply either sequential energy absorption and RF segments or the use of normal conducting RF filled with high-pressure gas [6].

## CHOICE OF ACCELERATION TECHNOLOGY

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, as low as 200 MHz for the initial bunching and cooling sections. If normal-conducting cavities were used, the required high gradients of order of ~15 MV/m would demand uneconomically high peak power of RF sources. Superconducting RF (SRF) cavities are a much more attractive solution. RF power can then be delivered to the cavities over an extended time, and thus RF source peak power can be reduced. Another important advantage of SRF cavities is that their design is not limited by a requirement of low shunt impedance and therefore their aperture can be significantly larger.

Muon survival practically excludes use of conventional circular accelerators and demands either a high-gradient conventional or recirculating linac. While recirculation provides significant cost savings over a single linac, it cannot be used at low energy since the beam is not sufficiently relativistic and will therefore cause a phase slip for beams in higher passes, thus significantly reducing acceleration efficiency for subsequent passes.

## LONGITUDINAL BUNCH COMPRESSION

Initial pre-acceleration in a single-pass linac (to about 3 GeV) is necessary to make the beam sufficiently relativistic, so that further acceleration in RLA is possible. In addition, the muon's longitudinal phase space volume is adiabatically compressed in the course of acceleration.

The large acceptance of the accelerator requires large aperture and tight focusing at its front-end. The above requirement combined with necessity of strong focusing in both planes at moderate energy makes the solenoidal focusing superior to the quadrupole one and hence has been chosen for the entire linac [7]. To achieve a manageable beam size at the linac front-end short focusing cells are used for the first 12 cryo-modules. The beam size is adiabatically damped with acceleration, and that allows one to replace short cryo-modules with 18 intermediate-length cryo-modules and then, with 22 long cryo-modules as illustrated in Figure 1.

The initial bunch length and energy spread are very large, so that the bunch length is more than half a wave length ($\Delta\phi$ =±89 deg) and the momentum acceptance is about ±21%.

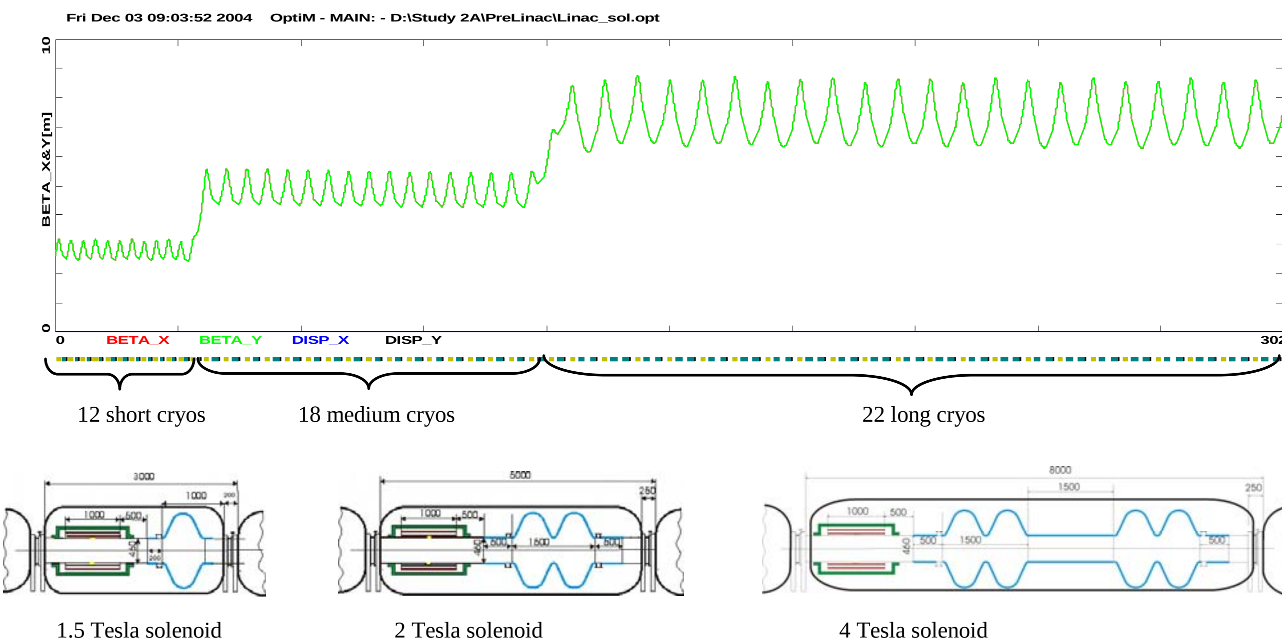



Figure 1: Top, transverse optics of the linac – uniform periodic focusing with three styles of cryo-modules. Below, layout of short, intermediate and long cryo-modules along with the required solenoid fields for each style.

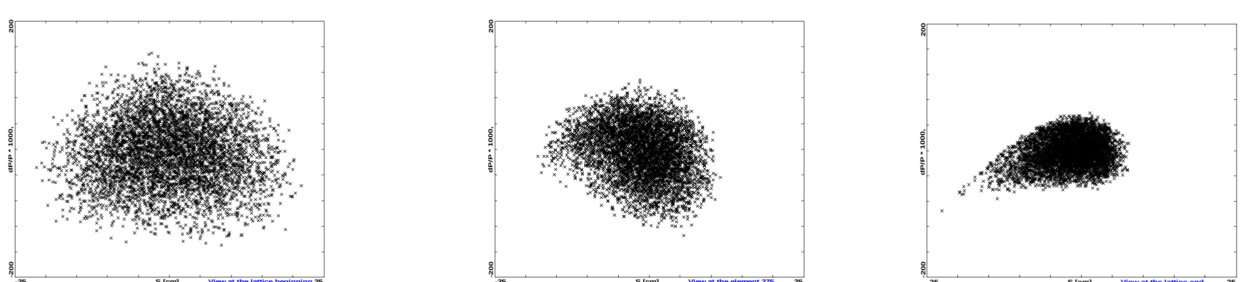



Figure 2: Adiabatic bunch compression along the linac – Longitudinal phase-space (s, Δp/p): at the beginning, half-way through and at the end of the pre-accelerator, as illustrated by particle tracking, axis range: s = ±25 cm, Δp/p = ±0.2 .

To perform adiabatic bunching, the RF phase of the cavities is shifted by 72 deg at the beginning. of the pre-accelerator and gradually changed to zero by the linac end. In the first half of the linac, when the beam is still not sufficiently relativistic, the offset causes synchrotron motion, allowing bunch compression in both length and momentum spread to $\Delta p/p = \pm 7\%$ and $\Delta\phi = \pm 29$ deg. The synchrotron motion also suppresses the sag in acceleration for the bunch head and tail. Figure 2 illustrates adiabatic bunch compression along the linac.

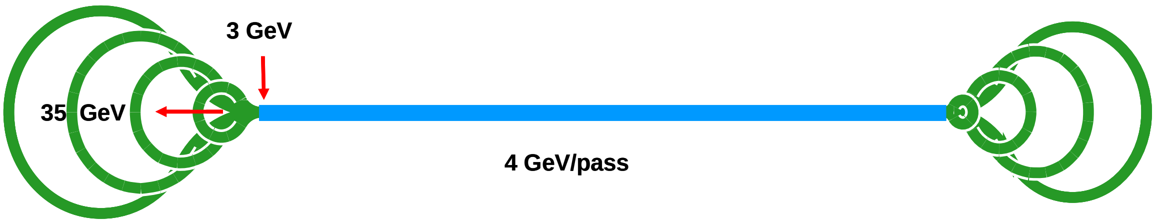



Figure 3: Layout of an 8-pass 'Dogbone' RLA with the top-to-injected energy ratio of 12.

## 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 has significant impact on cost-effectiveness [8] 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 $\mu^{\pm}$ species 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 '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. The RLA layout illustrated in Figure 3, 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. The alternative structure is called a racetrack, where the CEBAF machine at Jefferson Lab is an example.

Two styles of linac focusing lattice (FODO and Triplet) were studied for the lattice design of the RLA [9]. 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.

Pass 1 (3-7 GeV)

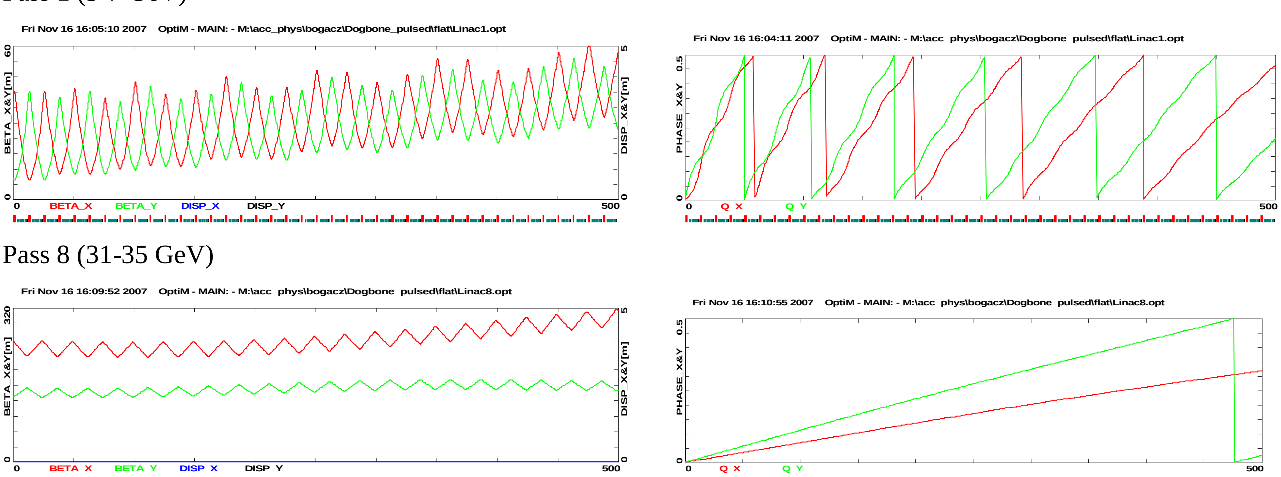
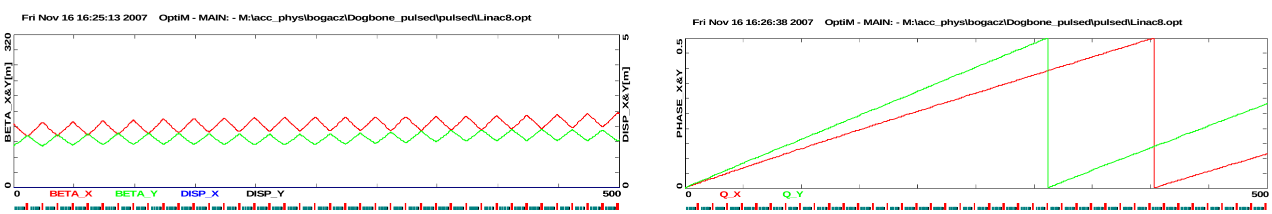



Figure 4: The first pass and the last one (8-th) of a FODO based multi-pass linac optics. In each set, the left plot represents beta functions, and the right plot describes betatron phase advance. Red is horizontal and green is vertical.

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 correspond 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 4 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.

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 $\tau$ = 1 ms 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 [10].

Pass 8 (31-35 GeV)




Pass 12 (47-51 GeV)

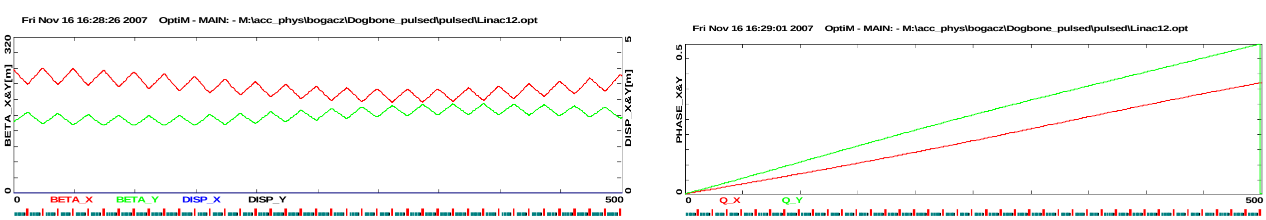



Figure 5: The 8-th pass and the last one (12-th**)** of the pulsed linac optics. By pulsing the focusing quads as described in Eq.(3), the additional 4 passes increase the output energy from 35 to 51 GeV. In each set, the left plot represents beta functions, and the right plot describes betatron phase advance. Red is horizontal and green is vertical**.**

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)

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

where $\ell_{cell}$ is the cell length and i defines the bunch position along the linac.

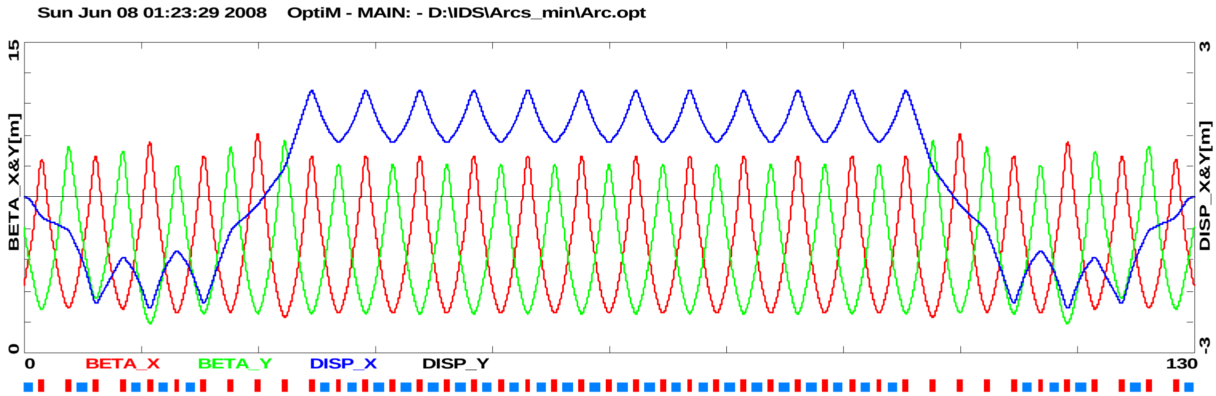
For multiple passes through the linac (the index n defines the pass number) the above formula can be generalized as follows:

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

where $\ell_{linac}$ is the full linac length and $\ell_{arc}$ 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 5 illustrates the multi pass optics for the pulsed linacs. As one can see, 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 [7]. 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 [8] is illustrated along with its 'foot print' in Figure 6.



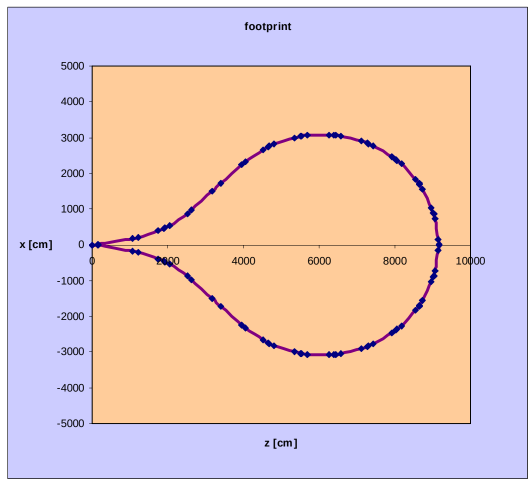




Figure 6: Top plot, 'Droplet' Arc optics – uniform periodicity of beta functions and dispersion. Bottom**,** horizontal layout of a 'Droplet' Arc – outward bending 60 deg. arc followed by 300 deg. inward bending arc.

## CONCLUSIONS

Intense muon beams for Muon Colliders, Neutrino Factories, and other physics and commercial ventures demand extensive use of linac technologies for their production, cooling, capture, beam formation/shaping and acceleration. The short muon lifetime drives the technology to the highest possible gradients for a wide range of frequencies. Furthermore, the accelerator must provide very large transverse and longitudinal acceptances. The above requirements drive the design to low RF frequency. If normal-conducting cavities at that frequency were used, the required high gradients would demand unachievably high peak power RF sources.

A TeV scale muon accelerator would consist of a single-pass linac that captures large muon phase space coming from the cooling channel and accelerates them to relativistic energies, while adiabatically decreasing the phase-space volume. It would be followed by an RLA that uses International Linear Collider (ILC) SRF structures in a single linac and 'droplet' return Arcs. The so called 'Dogbone' RLA 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. In addition a new concept of rapidly changing the strength of the linac quadrupoles as the muons gain energy is being developed to further increase the number of passes, leading to greater cost effectiveness.

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