MUON ACCELERATION CONCEPTS FOR FUTURE NEUTRINO FACTORY*

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Abstract

We summarize current state of concept for muon acceleration aimed at future Neutrino Factory. To ensure adequate survival of the short-lived muons, acceleration must occur at high average gradient. The need for large transverse and longitudinal acceptances drives the design of the acceleration system to initially low SRF frequency, e.g. 325 MHz, and then increased to 650 MHz, as the transverse size shrinks with increasing energy. Here, we considered two cost effective schemes for accelerating muon beams for a stagable Neutrino Factory: Exploration of the so-called 'dual-use' linac concept, where the same linac structure is used for acceleration of both H^- and muons and alternatively, the SRF efficient design based on multi-pass (4.5) 'dogbone' RLA, extendable to multi-pass FFAG-like arcs.

MUON ACCELERATOR COMPLEX

The proposed muon accelerator complex consists of a single-pass, superconducting linac with 325 MHz RF cavities, accelerating muons to 1.25 GeV that captures the large muon phase-space coming from the bunch rotator. The large acceptance of the linac requires large apertures and tight focusing. This, combined with moderate beam energies, favors solenoid rather than quadrupole focusing for the entire linac [1]. The initial single-pass linac accelerates muons to sufficiently relativistic energies, 1.25 GeV, beyond which acceleration using more efficient and compact higher frequency, 650 MHz, linac structure becomes feasible.

Then for further acceleration (from 1.25 GeV to 5 GeV), our design study branches into two alternative paths: Scheme I, where the linac is followed by a 4.5-pass, recirculating linear accelerator (RLA) in a 'dogbone' configuration and Scheme II where a single pass linac shared between muons and H^- is being used - the so called 'dual-use' linac. In both schemes, acceleration beyond 1.25 GeV continues using more compact and efficient 650 MHz SRF structure, while adiabatically decreasing the phase-space volume.

INITIAL SINGLE-PASS LINAC

A single-pass linac starting at 255 MeV/c raises the total energy to 1.25 GeV. This makes the muons sufficiently relativistic to facilitate further acceleration in the RLA or in the dual-use linac. The initial phase-space of the beam, as delivered by the muon front-end, is characterized by significant energy spread; the linac has been designed so that it first confines the muon bunches in longitudinal phase-space, then adiabatically super-imposes acceleration over the confinement motion, and finally boosts the confined bunches to 1.25 GeV. To

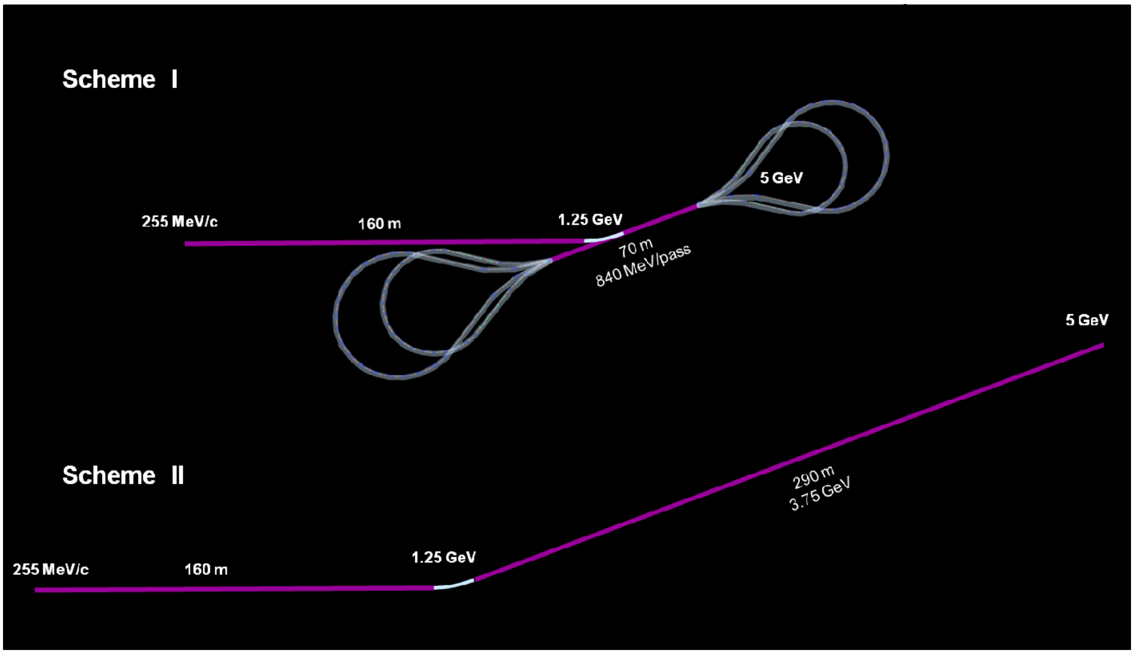

Figure 1: Two design options for 5 GeV Neutrino Factory – Schematic view of the overall accelerator complex.

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achieve a manageable beam-size in the front-end of the linac, short focusing cells (with one 2-cell cavity) are used for the first 22 cryomodules. The beam size is adiabatically damped with acceleration, allowing the short cryomodules to be replaced with 30 intermediate length cryomodules (with one 4-cell cavity). Each linac section is configured with periodic FOFO cells, matched at the section junctions, as illustrated in Figure 2. Periodicity within each section is maintained by scaling the solenoid fields in consecutive cryomodules linearly with increasing momentum [2]. The cavity iris radius limits the physical aperture of the linac. The radius of 15 cm matched with 2.5×sigma beam envelope defines the transverse acceptance (normalized) of the linac as 20 mm rad, se Figure 2 (bottom).

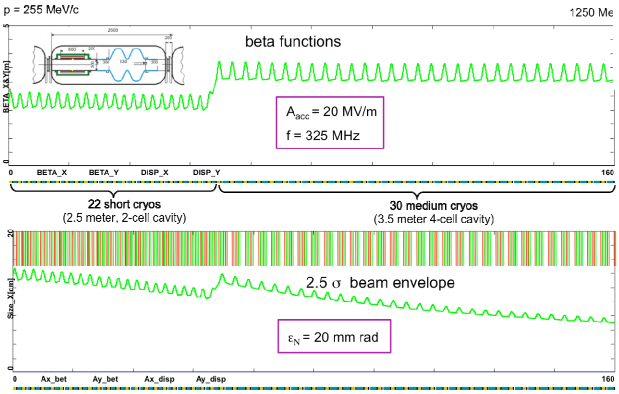

Figure 2: Transverse FOFO optics and the beam envelope of the initial linac.

In the initial part of the linac, when the beam is still not relativistic, the far-off-crest acceleration induces rapid synchrotron motion (one and a half of the full period along the linac), which allows bunch 'head' and 'tail' to switch places within the RF bucket three times during the course of acceleration. This process [3] is essential for averaging energy spread within the bunch, which ultimately yields desired bunch compression in both bunch-length and momentum spread.

DELAY/COMPRESSION CHICANE

For simultaneous acceleration of both muon charge species, transition to 650 MHz linac requires a half-wavelength path length delay for one of the muon species. This is facilitated by a double chicane, where muons of different charges follow alternative chicane legs, different in length by the half-wavelength at 650 MHz, and with negative M_{56} to facilitate longitudinal ¼-wave rotation.

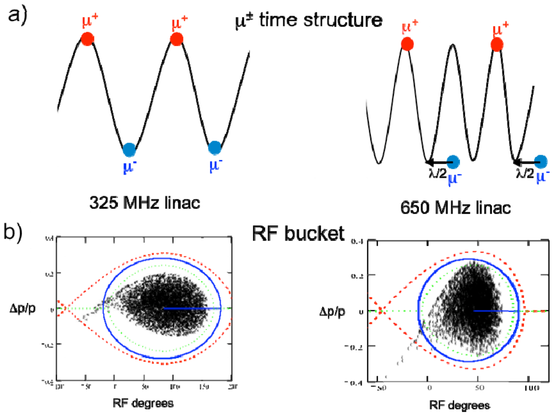

Figure 3: a) Time structure of muon bunches; doubling the RF frequency requires path-length delay of $\lambda/2$ for μ^-, to put them into accelerating buckets for the new frequency, b) Change of the bucket length (factor of 2 shorter when RF frequency doubled) requires significant compression of the bunch-length (about factor of 2) in order to fit the bunch into the new bucket.

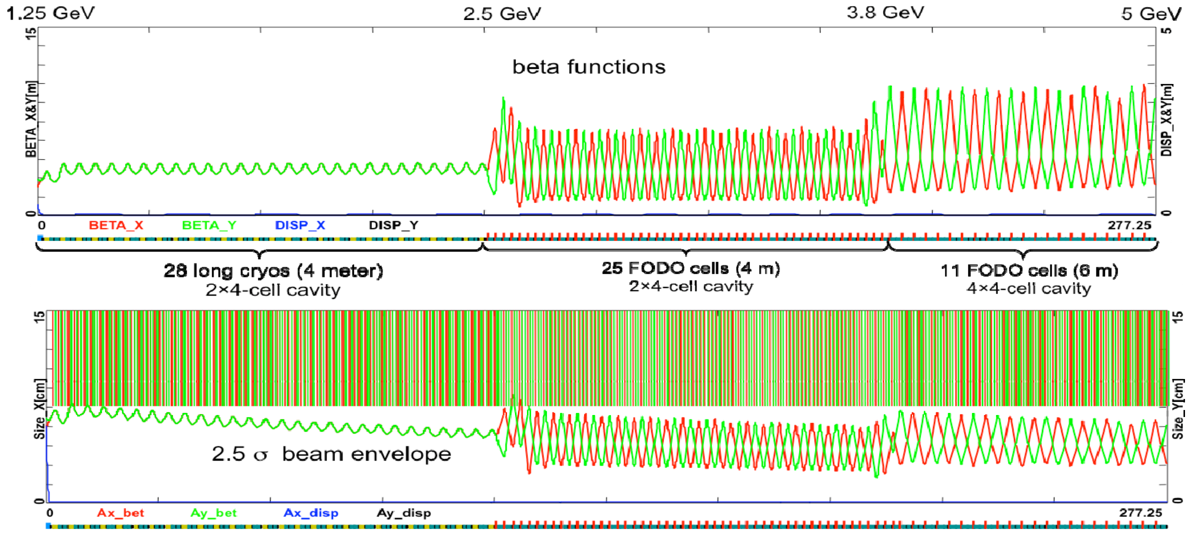

Figure 4: 'Dual-use' linac based on 650 MHz SRF: initial linac section with solenoid based FOFO optics, followed by two styles FODO sections with quadrupole focusing (top) and the beam envelope (bottom). The physical aperture radius of 7.5 cm is compatible with the transverse acceptance (normalized) of the initial single pass-linac, 20 mm rad.

'DUAL-USE' LINAC

The main thrust of the 'dual-use' linac is to re-use a large SRF linac structure, already needed for a proton driver (used for pion and ultimately muon production), to accelerate muons from 1.25 GeV to 5 GeV.This would offer significant cost saving measure providing muon and proton acceleration are compatible, which will be address at the end of this section. Following the double chicane, at 1.25 GeV, the transverse beam size is small enough, so the beam may be accelerated using more compact and efficient 650 MHz SRF structure with aperture radius of 7.5 cm (cavity iris). Initial beam condition at 1.25 GeV still favors solenoid rather than quadrupole focusing for the initial part of the linac. The front-end is therefore configured with 28, 4-meter long cryomodules; each containing two 4-cell cavities and a superconducting counter wound solenoid (similar in layout to previously described 325 MHz cryomodules). The beam size is further damped with acceleration and around 2.5 GeV; the quadrupole based FODO structure becomes more efficient than the solenoid FOFO optics.

Consequently, the linac continues; first with 28 shorter, 4-meter long, FODO cell, containing two 4-cell cavities and two quads. Then, around 3.8 GeV the transverse beam size becomes small enough, so one may switch to longer and more efficient FODO cells (6-meter long) with four 4-cell cavities; eleven such cells will complete the 5 GeV linac. Each of the linac sections, configured with periodic either FOFO or FODO cells, is uniformly matched at the junctions, as illustrated in Figure 4.

'DOGBONE' RLA

The main trust of the multi-pass RLA option is its very efficient usage of expensive SRF linac. The 'dogbone' RLA is designed to accelerate simultaneously the μ^+ and μ^- beams from 1.25 GeV to 5 GeV to further compress and shape the longitudinal and transverse phase-space [1] [2]. The beam is injected from the single-pass linac via the double chicane. The injection point into the 'dogbone' RLA coincides with the middle of the multi-pass linac to minimize the effect of phase slippage for initially 1.25 GeV muon beam accelerated in a linac phased for the speed-of-light particle. At the ends of the RLA linac the beams need to be directed into the appropriate energy-dependent (pass-dependent) 'droplet' arc for recirculation [3]. The above configuration has already been introduced in Figure 1 (top). The 650 MHz SRF linac is configured with smaller aperture (7.5 cm radius), higher gradient (25 MV/m) SRF cavities.

Multi-pass Linac

The focusing profile along the linac was chosen so that beams with a large energy spread could be transported within the given aperture. Since the beam is traversing the linac in both directions, a 'bisected' focusing profile was chosen for the multi-pass linac [1]. Here, the quadrupole gradients scale up with momentum to maintain 90° phase advance per cell for the first half of the linac and then are mirror reflected in the second half.

'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 [1] is based on 90° 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 simultaneous acceleration of both μ+ and μ− bunches; mirror symmetry is imposed on the droplet arc optics (oppositely charged bunches move in opposite directions through the arcs).

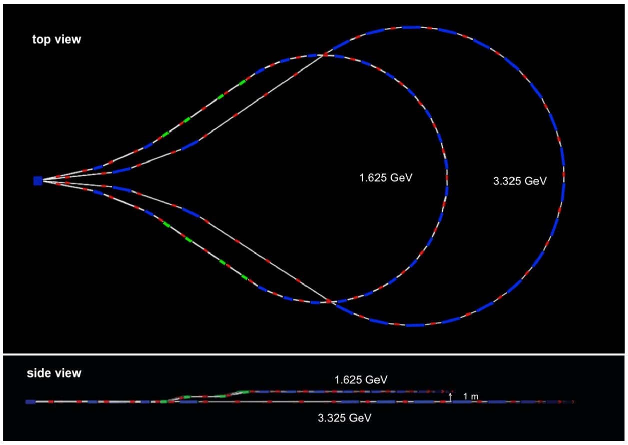

Figure 5: Layout of a pair of arcs on one side of the 'dogbone' RLA, Top and side views, showing vertical two-step 'lift' of the middle part of lower energy droplet arc to avoid interference with the larger droplet.

OUTLOOK

To reduce complexity of the above multiple return arcs, we have recently proposed a novel single arc design based on linear combined function magnets with variable dipole and quadrupole field components, which allows two consecutive passes with very different energies to be transported through the same string of magnets [4].

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