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Pros and Cons of the Acceleration Scheme (NF-IDS)

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The overall goal of the acceleration systems: large acceptance acceleration to 25 GeV and 'beam shaping' can be accomplished by various fixed field accelerators at different stages. They involve three superconducting linacs: a single pass linear Pre-accelerator followed by a pair of multi-pass Recirculating Linear Accelerators (RLA) and finally a non–scaling FFAG ring. The present baseline acceleration scenario has been optimized to take maximum advantage of appropriate acceleration scheme at a given stage. Pros and cons of various stages are discussed here in detail. The solenoid based Pre-accelerator offers very large acceptance and facilitates correction of energy gain across the bunch and significant longitudinal compression trough induced synchrotron motion. However, far off-crest acceleration reduces the effective acceleration gradient and adds complexity through the requirement of individual RF phase control for each cavity. Close proximity of strong solenoids and superconducting cavities requires effective magnetic shielding. The RLAs offer very efficient usage of high gradient superconducting RF and ability to adjust path-length after each linac pass through individual return arcs with uniformly periodic FODO optics suitable for chromatic compensation of emittace dilution with sextupoles. However, they require spreaders/recombiners switchyards at both linac ends and significant total length of the arcs. The non-scaling Fixed Field Alternating Gradient (FFAG) ring combines compactness with very large chromatic acceptance (twice the injection energy) and it allows for large number of passes through the RF (at least eight, possibly as high as 15). However, injection/extraction system would require very strong large aperture kickers. The most serious drawback is no correction mechanism for time of flight dependence on transverse amplitude and the energy loss down the bunch train due to inherent lack of synchrotron motion along the accelerating cycle.

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[1] Speaker

1. Introduction

The overall goal of the acceleration systems is to accept muons coming out of the cooling section with a kinetic energy of around 138 MeV and to accelerate them to the final energy of 25 GeV. Present baseline accelerator design emerged from the Neutrino Factory International Scoping Study. Their design choices are driven by the fact that the muons are decaying, and thus must be accelerated as rapidly as reasonably possible and that the beam sizes, both transverse and longitudinal, are very large. The above requirements drive the design to low RF frequency, as low as 200 MHz. If normal-conducting cavities were used, the required high gradients of order of ~17 MV/m would demand uneconomically high peak power of RF sources. Superconducting RF cavities are a much more attractive solution, since RF power can then be delivered to the cavities over an extended time.

The superconducting accelerating structure is by far the most expensive component of the accelerator complex. 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.

2. Baseline Acceleration Scenario

The acceleration systems consist of several different components. It involves three superconducting linacs (200 MHz): a single pass linear Pre-accelerator followed by a pair of multi-pass ‘Dogbone’ recirculating linacs (RLA). In the presented scenario, acceleration starts after ionization cooling at 244 MeV/c in a single pass linac to about 0.9 GeV, then the recirculation becomes possible; first to 3.6 GeV in a 4-5pass RLA I (of 0.6 GeV/pass), followed by the second 4-5pass RLA II (of 2 GeV/pass) to 12.6 GeV. Finally, the beam is injected into a non–scaling FFAG ring for further acceleration to about 25 GeV. The Pre-accelerator captures a large muon phase space coming from the cooling channel. It accelerates muons to relativistic energies, while adiabatically decreasing the phase-space volume, so that effective acceleration in the RLAs is possible. They further compress and shape-up the longitudinal and transverse phase-spaces, while increasing the energy. The proposed ‘Dogbone’ RLA configuration facilitates simultaneous acceleration of both μ^+ and μ^- species. The acceleration complex is illustrated schematically in Figure 1.

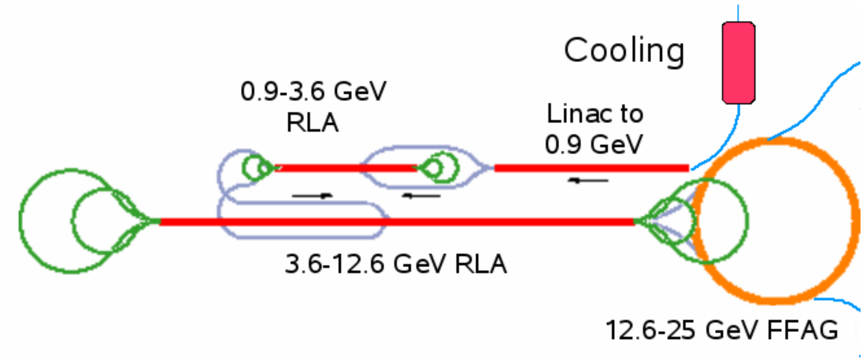

Figure 1: Layout of the baseline acceleration system.

2.1 Pre-Acceleration Linac

Initial pre-acceleration in a single-pass linac is necessary to make the beam sufficiently relativistic, so that further acceleration in the RLA is possible. 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.

The initial bunch length and energy spread are very large, so that the bunch occupies significant fraction of the RF bucket. To perform adiabatic bunching, the RF phase of the cavities is shifted far off-crest at the beginning of the linac and gradually changed to zero by its end [1]. This way induced synchrotron motion suppresses the sag in acceleration for the bunch head and tail leading to adiabatic bunch compression along the linac as illustrated in Figure 2.

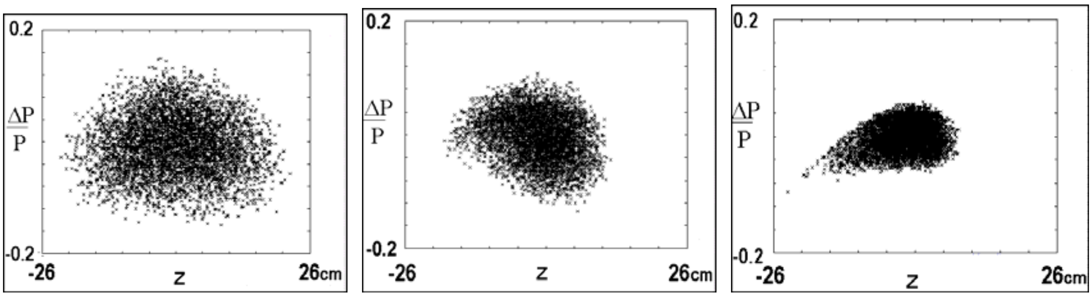

Figure 2: Particle tracking results showing adiabatic bunch compression along the linac. The longitudinal phase-space (z, $\Delta p/p$) is shown before (left), in the middle (center), and at the end (right) of acceleration.

However, off-crest acceleration reduces the effective acceleration gradient and adds complexity through the requirement of individual RF phase control for each cavity. Close proximity of strong solenoids and superconducting cavities requires effective magnetic shielding via counter wound solenoid coils.

2.2 Recirculating Linear Accelerator (RLA)

The superconducting accelerating structure is by far the most expensive component of the accelerator complex. Therefore, maximizing the number of passes in the RLA has a significant impact on the cost-effectiveness [2] of the overall acceleration scheme. The injection energy into the RLA and the energy gain per RLA linac were chosen so that a tolerable level of RF phase slippage along the linac could be maintained. Proposed ‘Dogbone’ configuration for the RLA offers two major advantages (compared to a ‘Racetrack’):

(1) Better orbit separation at the linac ends resulting from a larger (factor of two) energy difference between two consecutive linac passes.

(2) Favorable optics solution for simultaneous acceleration of both μ^+ and μ^- in which both charge species traverse the RLA linac in the same direction while passing in the opposite directions through the mirror symmetric optics of the return ‘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 [3]. 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 transition cells one ‘flips’ the dispersion for the inward bending 300^0 arc, etc. The resulting ‘droplet’ Arc optics [3] based on 90^0 phase advance FODO cells with uniform periodicity of Twiss functions is illustrated in Figure 3.

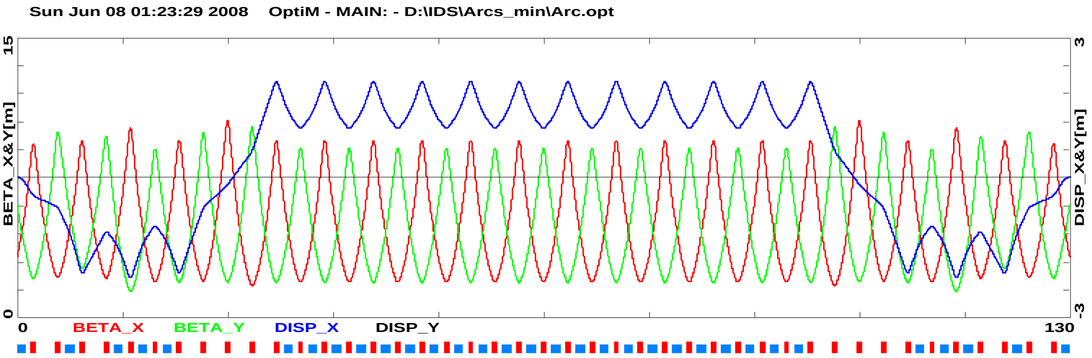

Figure 3: ‘Droplet’ Arc optics – uniform periodicity of beta functions and dispersion.

2.3 Non-scaling FFAG ring

Linear non-scaling FFAGs [4][5] attempt to address the two-fold difficulty of scaling FFAGs (large aperture and large time of flight variation with energy) by placing most of the bending in the defocusing magnets. As a result, for an equivalent energy range, magnet apertures can be reduced compared with a scaling FFAG. Furthermore, at least for high energies, the ring can be made isochronous at a single energy within the energy range of the machine. However, the time of flight is not completely independent of energy. Nonetheless, the relatively small time of flight variation with energy in these machines allows one to use relatively high frequency (200 MHz) RF to accelerate.

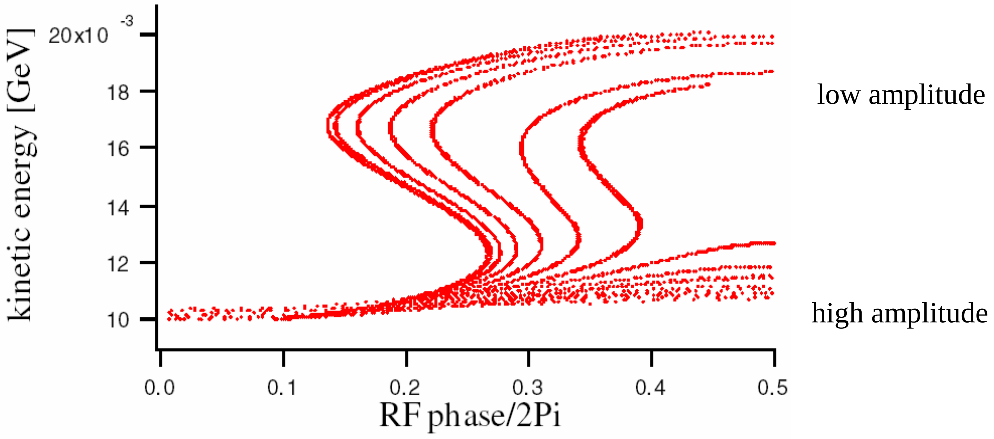

Figure 4: Phase space ‘channels’ for various amplitude particles. In the course of acceleration, particles start at low energy (bottom) and accelerated to high energy (top).

This allows for reasonably high accelerating gradients, and is compatible with the RF systems for the previous stage.

The primary difficulty with linear non-scaling FFAGs is that the time of flight depends on transverse amplitude [6]. Figure 4 illustrates time of flight dependence on the transverse amplitude in a linear non-scaling FFAG. This means that particles with different transverse amplitudes are guided through different regions of longitudinal phase space; there is only a limited region of initial phase for which particles with both low and high amplitudes will be accelerated. Once particles reach the final energy, low and high amplitude particles will have different phases, since the particles follow trajectories which are roughly parallel to the separatrices. In particular, large amplitude particles will be at a later RF phase than low amplitude particles. This will be problematic when one passes from one stage to the next, since large amplitude particles should arrive earlier, not later, than low amplitude particles for optimal transmission.

The non-scaling FFAG ring combines compactness with very large chromatic acceptance (twice the injection energy) and it allows for large number of passes through the RF (at least eight, possibly as high as 15). However, injection/extraction system would require very strong, large aperture kickers. The most serious drawback is no correction mechanism for: time of flight dependence on transverse amplitude and the energy loss down the bunch train due to inherent lack of synchrotron motion along the accelerating cycle.

3. Conclusions

The overall goal of the acceleration systems: large acceptance acceleration to 25 GeV and ‘beam shaping’ can be accomplished by various fixed field accelerators at different stages. The present baseline acceleration scenario has been optimized to take maximum advantage of appropriate acceleration scheme at a given stage. Pros and cons of varouous stages should guide the layout of the engineeting design foundation.

Despite these shortcomings the present NF-IDS scheme seems to be the best option for muon acceleration within 25 GeV energy range.

References

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