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R&D Topics for Neutrino Factory Acceleration

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Abstract. The muons in a neutrino factory must be accelerated from the energy of the capture, phase rotation, and cooling systems (around 120 MeV kinetic energy) to the energy of the storage ring (around 25 GeV). This is done with a sequence of accelerators of different types: a linac, one or more recirculating linear accelerators, and finally one or more fixed field alternating gradient accelerators (FFAGs). I discuss the R&D that is needed to arrive at a complete system which we can have confidence will accelerate the beam and for which we can obtain a cost estimate.

Keywords: muon, acceleration, linac, recirculating linear accelerator, fixed field alternating gradient accelerator, neutrino factory
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MUON ACCELERATION

Muon beams in a neutrino factory are challenging to accelerate for two reasons. First, the beam must be accelerated rapidly, which only permits acceleration systems which have a relatively high average gradient (well over 1 MV/m). Second, the muon beams are much larger than the beams normally transported in accelerator systems.

One of the primary design goals in acceleration is cost reduction. Since the RF systems are generally the most expensive component of the acceleration system, one generally tries to reduce the amount of RF in the machine by making multiple passes through the RF cavities. The most straightforward way to accomplish this is by using a recirculating linear accelerator (RLA), which consists of one or more linacs which have several different arcs (one for each energy) connecting the end of one linac to the beginning of the next.

At low energies, an RLA becomes impractical for several reasons. First, since particle velocities vary with energy, and thus one cannot keep the beam synchronized with the RF in the same linac. Second, an RLA has a practical limit on the factor by which it can gain energy, and if one started at the cooling energy, that factor would limit you to a relatively small amount of RF while having a large amount of complexity in the arcs. Finally, the large relative energy spreads at low energies would make injection and beam separation difficult. Thus, a linac is generally used to get up to a certain intermediate energy before injecting into an RLA.

An RLA is limited by its switchyard to a relatively small number of passes though its linac(s). To get beyond this limit, the switchyard must be eliminated. Fixed field alternating gradient accelerators (FFAGs) have been considered for this purpose. They have a single arc with a large energy acceptance, avoiding the need for a switchyard. The number of turns one can make in an FFAG is limited because of the dependence of the time of flight on energy: fixed-frequency RF cannot remain synchronized with the bunches at all energies, and thus one will eventually leave the crest of the RF. As a result, FFAGs become more efficient in their RF use than RLAs only at higher energies [1, 2].

An example of a complete scheme for neutrino factory acceleration is shown in Fig. 1. It contains each of the machines described here: a linac, two RLAs, and an FFAG. The machines are chosen based on which is optimal in a given energy range.

This acceleration scenario for a neutrino factory is only an educated guess at this point. In the rest of this paper, I will discuss areas where these acceleration systems still need to be studied to bring this design to reality. I will describe research that needs to be done on the different types of machines: linacs, RLAs, and FFAGs. Finally I will discuss issues that are relevant to the entire system.

LINACS

Due to the large transverse emittances in a neutrino factory, we expect the effective longitudinal emittance to increase due to the dependence of time of flight on the transverse amplitude [3]. This should be simulated and taken into consideration when choosing the point of transition from the initial linac to the first RLA.

RLAS

For the RLAs, the first task is to complete a detailed lattice design for one configuration. Linear lattice designs have been done for several sample configurations ([4, 5] for example), but there are several significant pieces that have not been completed. Chromatic correction needs to be put into the lattices; this is especially

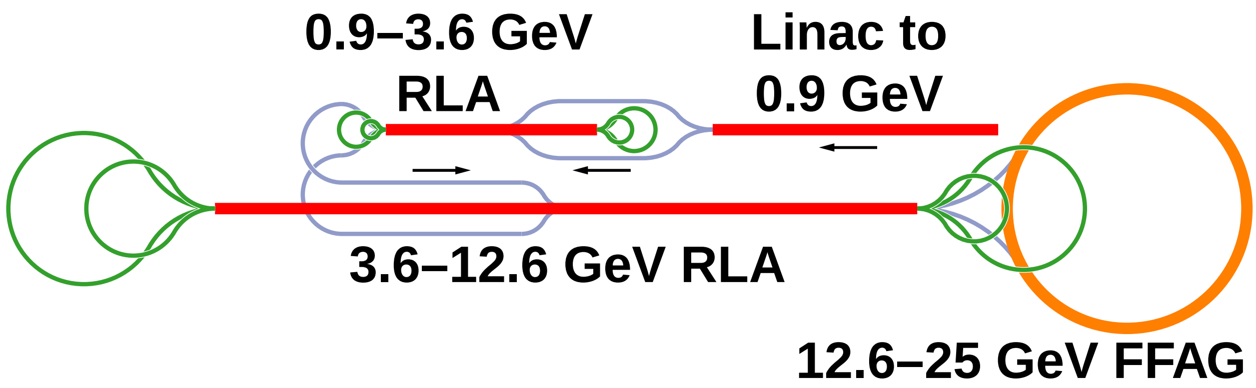

FIGURE 1. An example of a complete acceleration scheme for a neutrino factory.

important because of the relatively large energy spreads in these machines. A careful physical layout must be done of the switchyard to ensure that the beams can be separated into the individual arcs. Similarly, note that in Fig. 1, the most compact configuration for the arcs is to have the arcs cross. It should be determined how this is to be done, whether through vertical separation or an actual crossing, or if the low energy arcs should simply be made longer. It is necessary to understand the physical layout to ensure that whatever is chosen is possible in practice.

The primary motivation for the use of FFAGs at later stages is cost. However, there has been no attempt at a cost estimate of any recent RLA designs to form a point for comparison. Doing so will involve making a choice regarding the magnet technology used in the arcs and the linacs and detailed engineering studies of the switchyard and, if needed, arc crossings.

It is not completely clear what the maximum number of linac passes an RLA can be expected to make. This is related to both the linac dynamics and the details of the switchyard. Furthermore, it is not clear what the optimal energy range would be for an RLA: choosing the largest energy range is not always the best choice. Once a single design has been fully completed, there should be an optimization study to determine what is the best RLA configuration to use. Some consideration should be given to a more detailed comparison of racetrack and dogbone RLA configurations [6]. This is complicated by the experience that each machine must be designed by hand. Some attempts should be made to better understand the design principles of an RLA so that one can automate the design process, at least to some extent.

FFAGS

As mentioned, the primary motivation for the use of FFAGs is cost reduction. While it may initially appear that FFAGs have a cost advantage over RLAs, once one makes design adjustments to account for the complexity of their beam dynamics, one can quickly lose those advantages (see, for example, [7, 8]).

One of the primary concerns in any FFAG is longitudinal-transverse coupling. There is clearly linear coupling because there is dispersion in the RF cavities. Furthermore, in linear non-scaling FFAGs, there is a nonlinear coupling which is significant for muon beam sizes [3, 7]. The strength of these effects must be assessed, and designs must be made which give optimal and acceptable performance. At that point one will have a basis for comparing to the cost of an RLA which accelerates to the same energies. Some of these issues will likely be studied in the context of the EMMA experiment [9, 10].

Systems for injection into and extraction from FFAGs must be designed and engineered. This is critical since the breaking of symmetry in FFAGs generally leads to significant performance problems, and thus the injection and extraction systems must be particularly compact. The systems must be engineered to determine their cost, which is essential for the cost comparison to RLAs.

Alternative FFAG (other than linear non-scaling) designs should also be considered. This is particularly interesting since designs which have no tune variation with energy avoid the most serious longitudinal-transverse nonlinear coupling [3]. Scaling FFAGs using harmonic number jump acceleration [11] are one possibility [12]. Another possibility is a nonlinear non-scaling FFAG with constant tunes [13]. The former may have problems accelerating muons of both signs [14], while the latter may not have sufficient dynamic aperture [15]. However, these concerns are still at this point speculative.

GENERAL ISSUES

There are a number of issues that apply to the entire acceleration system. First, there is the optimization of the entire system. What types of machines should we use, and at what energies? How many RLA stages should be used? What should the energy transition points be between stages? Furthermore, how does the cost of the system depend on the incoming beam emittances?

At this point, no transfer lines have been designed between the machine stages. Transverse matching may be relatively straightforward, but longitudinal matching can potentially be very costly. One may want to re-design the subsystems to perform part of the matching themselves. One needs to determine the amount of losses in the transfer lines (including injection/extraction). Finally, the cost of these transfer lines need to be computed and included.

High gradient superconducting RF cavities at around 200 MHz are used in our accelerating systems. The high gradients are particularly important for the initial linac and the FFAGs [3]. Studies to this point have been very limited [16]. Furthermore, in FFAGs, one must operate with the highest field possible on the cavities. In principle, niobium-on-copper cavities can be operated in fields as high as 0.1 T if the cavity is cooled down before the field is applied [17], but this should be tested in long-term operation to ascertain how often a warm-up-cool-down cycle may be required.

One must consider beam loading in the RF cavities. This is a particular issue in the FFAGs, since multiple passes are made through the cavities, and there is no synchrotron oscillation (in linear non-scaling FFAGs). The first issue is that the bunches at the front of the train will see more voltage than the bunches in the back of the train. A potentially more significant issue is if bunches trains arrive in rapid succession, before there is time to re-fill the superconducting cavities [18]. One must come up with a plan to insure that all bunches have the same final energy (or sufficiently close to the same energy).

Finally, it is essential to perform tracking studies on the entire system to verify that the beam is transmitted with a tolerable level of emittance growth.

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