A NON-SCALING FIXED FIELD ALTERNATING GRADIENT ACCELERATOR FOR THE FINAL ACCELERATION STAGE OF THE INTERNATIONAL DESIGN STUDY OF THE NEUTRINO FACTORY*

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Abstract

The International Design Study of the Neutrino Factory (IDS-NF) has recently completed its Interim Design Report (IDR), which presents our current baseline design of the neutrino factory. To increase the efficiency and reduce the cost of acceleration, the IDR design uses a linear non-scaling fixed field alternating gradient accelerator (FFAG) for its final acceleration stage. We present the current lattice design of that FFAG, including the main ring plus its injection and extraction systems. We describe parameters for the main ring magnets, kickers, and septa, as well as the power supplies for the kickers. We present a first pass at an engineering layout for the ring and its subsystems.

INTRODUCTION

The goal of a neutrino factory is to produce a high energy, high intensity neutrino beam with a well-defined energy spread. This is accomplished by accelerating an intense muon beam to high energies, then storing it in a decay ring with long straight sections which are pointed downward toward far distant detectors. The baseline design for the machine is presented in the IDR [1].

For the IDS-NF, the final energy of the muon beam is 25 GeV. Acceleration to this energy is made more challenging by the large transverse and longitudinal emittance of the beam (required normalized acceptances of 30 mm transverse and 150 mm longitudinal, see [1] for definition). Acceleration must be rapid since the muons are decaying.

The cost of acceleration is generally dominated by the cost of the RF systems. Making more passes through the RF cavities generally reduces the cost of the acceleration. An FFAG allows a large energy range within a single beam line with fixed magnetic fields, allowing a large number of turns, limited only by phase slippage in fixed frequency RF arising from the time of flight variation with energy, and our desire to avoid decays. We can make more passes through the cavities than would be possible in a recirculating linear accelerator (RLA), since the number of turns in an RLA is limited by the difficulty in separating the beams into separate arcs at the linac ends.

Table 1: Main ring lattice parameters for the IDS-NF FFAG. The lattice consists entirely of FDF triplets, where each magnet is combined function with a straight axis. The angle and shift are defined such that on entering the magnet, the coordinate system rotates by half the angle then shifts by the shift value, and on exiting the magnet the coordinate system shifts by the negative of the shift angle then rotates by half the angle again. The angle and shift would be positive to give the usual sagitta correction for a dipole magnet bending by a positive angle. Precision in values is for reproducibility in simulations, and does not indicate required tolerances.

Long drift (m)		5.00
Short drift (m)		0.75
Cells		67
Circumference (m)		699
	D	**F**
Length (m)	1.986908	0.968982
Angle (mrad)	144.613	-25.417
Shift (mm)	38.452	14.284
Field (T)	4.35539	-1.33734
Gradient (T/m)	-14.13038	18.82272
Aperture radius (mm)	131	161
Max field (T)	6.2	4.4

MACHINE DESIGN

Main Ring Lattice

Prior to the IDR, several possible lattice designs were studied [2]. A triplet design was chosen for its symmetry properties for injection and extraction and superior performance compared to a FODO lattice. The drift space in the earlier designs was insufficient to have sufficiently low stray fields for the septum, so the long drift was extended to 5 m. The resulting lattice was presented in the IDR.

After the IDR was finalized, engineering studies indicated that additional space was needed between the mag-

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Table 2: RF Parameters for the FFAG Ring. The Cavity voltage is the maximum that the cavity can achieve; the ring voltage is the total voltage needed. Cavities are the two cell cavities described in Study II [3] with a 30 cm diameter aperture.

Cavities	50
Cavity voltage (MV)	25.5
Ring voltage (MV)	1195.609
Turns	11.8
Decay (%)	7.1

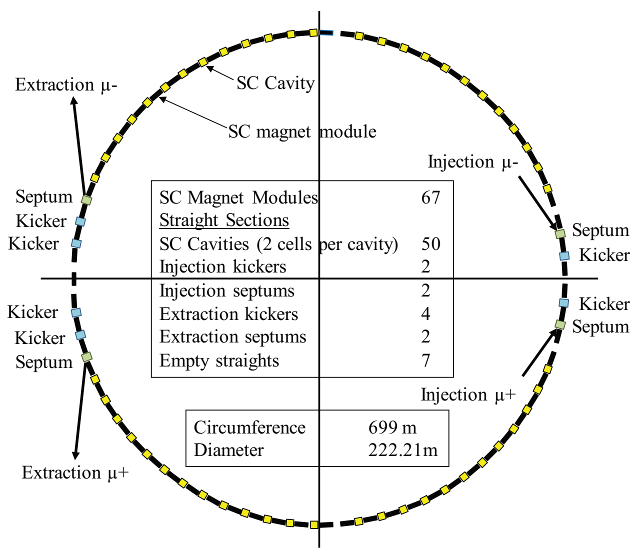

Figure 1: Layout of the FFAG ring.

nets. Since the injection and extraction systems have an odd number of cells, a lattice with an odd number of cells was designed. The parameters for this lattice are given in tables 1 and 2, and a layout of the ring is shown in Fig. 1.

Injection and Extraction

The general method for the design of the injection and extraction system is described in [4]. The parameters of that system were updated to correspond with updated designs for the main ring and were given in the IDR. The

Table 3: Magnet parameters for the injection/extraction system. The pattern is the arrangement and polarity of kickers in sequential cells: - or + for inward and outward kicks, respectively, in 0 for an empty cell.

	Injection	**Extraction**
Kickers	2	4
Pattern	-0-	++00++
Kicker field (T)	0.089	0.067
Septum field (T)	0.92	1.76
Magnet length (m)	4.4	4.4

Table 4: Aperture requirements for the magnets in the injection and extraction regions.

Type	**Count**	**Radius (mm)**
Injection D	4	161
Injection F	4	208
Extraction D	2	155
Extraction F	8	198

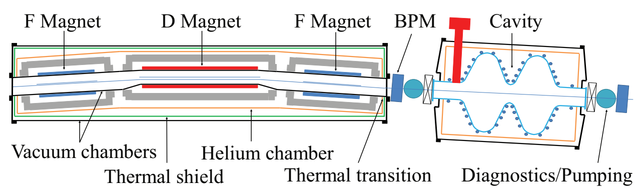

Figure 2: Layout of a single lattice cell containing an RF cavity.

magnet parameters are given in table 3. We desired to keep the septum fields below 2 T to reduce the septum stray field, and this necessitated the 5 m drift length in the lattice cell. We required that the kicker fields remain below 0.1 T.

The induced injection oscillation requires larger aperture magnets in the injection and extraction regions, to the inside for injection and the outside for extraction. The aperture requirements are given in table 4.

Both the kicker and the septum magnets would have 30 cm $\times$ 30 cm square apertures. We propose using traveling wave kickers with at least 4 sub-kickers. These will likely require extensive pulse forming networks (PFNs), since a separate PFN would be required for each of the three bunch trains coming in rapid succession, times the 6 kickers, times 4 sub-kickers. In addition, 3 PFNs will likely be needed in parallel to produce the necessary current.

PRELIMINARY ENGINEERING

A first pass engineering study of the accelerator is underway with the objective of establishing:

- Technology choices for the various accelerator components
- That there is enough space in the lattice drift sections for injection and extraction magnets, RF cavities, cryostats, beam diagnostics and vacuum equipment.
- Enough detail in the engineering design to provide a credible cost estimate for construction.

For a lattice cell with an RF cavity, Fig. 2 shows a simplified engineering layout and Fig. 3 shows a CAD model. The 201.25 MHz Nb-Cu cavity structure design is taken from neutrino factory feasibility study II [3].

Warm sections on both sides of the two cryostats that house the magnets and cavities allow diagnostics and vacuum equipment to be at room temperature, with conventional construction and easy access for maintenance.

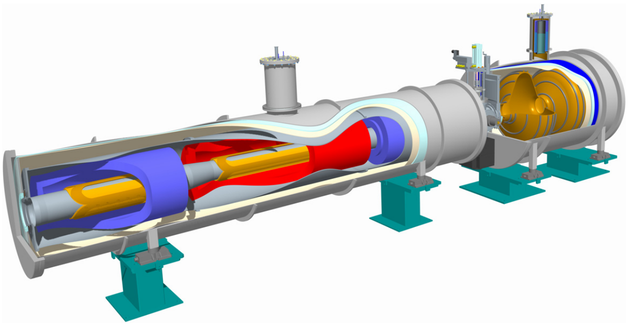

Figure 3: Conceptual engineering of magnet module and RF cavity straight.

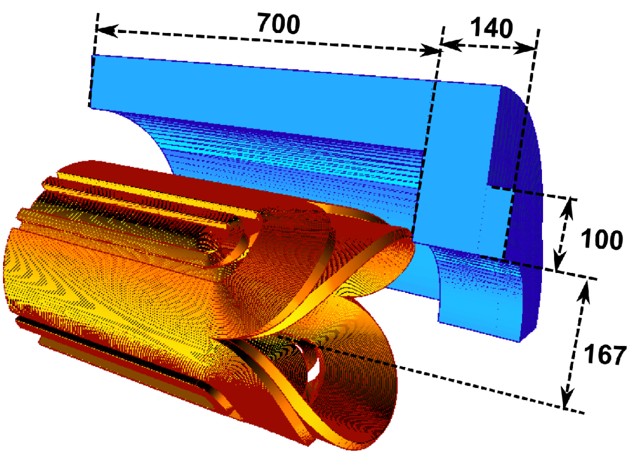

Figure 4: A design for the F magnet, showing half the magnet with dimensions in mm. Coils and an iron yoke are shown.

We have produced a design for the F magnet that has separate dipole and quadrupole layers. It uses Ni-Ti Rutherford cable in 3 conductor blocks for the dipole and 2 blocks for the quadrupole layer.

The FDF magnet coils inside their iron yokes can be seen around a circular cross-section vacuum chamber in Figs. 2 and 3. The vacuum chamber is manufactured from 316LN stainless steel with very low magnetic permeability and high proof stress. Transition tapers in the chamber between the D and F magnets deal with the angle changes, offsets and difference in apertures.

The liquid helium chamber is shown constructed from 3 welded sections to reduce the volume of liquid helium required for the 67 superconducting magnet modules, each 6.3 m in length. In kicker locations, BPMs are being considered between the F and D magnets in the cryostat. This will lengthen the available space for the kicker magnets to help reduce the very challenging power supply ratings.

Kickers

A conceptual design of the kicker magnet assembly is shown in Fig. 5 with the kicker split in to 4 sub-units. High voltage feedthroughs can be seen on the top of the vacuum

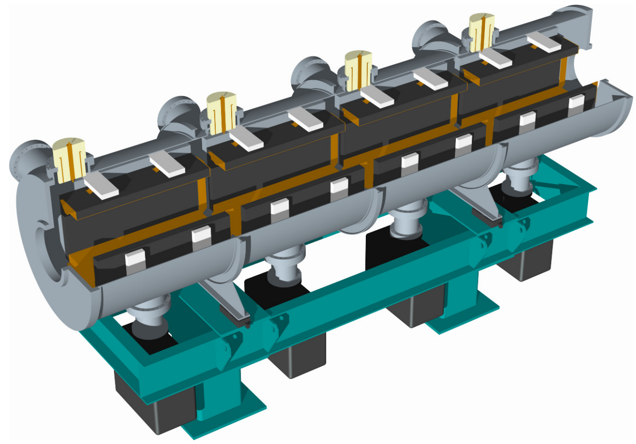

Figure 5: Conceptual engineering of kicker magnet.

chamber, ion pumps underneath and side ports for access to electrical connections from the kicker units to the HV electrical feedthroughs. With short alignment bellows at each end of the kicker straight section, 3.74 m is available for the 4 0.86 m long sub units with 0.1 m space between.

FUTURE PLANS

The design should be updated to accelerate in precisely an integer and a half turns. More beam dynamics studies are needed to reduce the beam distortion in the longitudinal plane, and determine the optimal longitudinal phase space distribution (energy spread, ellipse tilt, etc.) so that matches can be designed to upstream and downstream systems. We will need to determine error tolerances. We will track through the full machine, taking into account the actual layout of cavities and perturbations in the injection and extraction regions. We need to make a final decision as to whether we can successfully incorporate chromaticity correction, and if so how much.

We would like to study a single layer combined function design (which would have a small correction coil, either dipole or quadrupole). We need to compute the energy deposition from muon decays, since this will be important for designing the cryogenic system and diagnostics.

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