Recent developments on the muon Non-Scaling FFAG for the Neutrino Factory and its subsystems

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Abstract. The current status and recent developments on the muon non-scaling FFAG for the Neutrino Factory studied in the framework of the EUROnu/IDS-NF projects are presented. Beam dynamics studies, including the process of acceleration, are discussed. A first pass at engineering for the layout of the ring cell is described. Progress of studies on the main machine subsystems is discussed. The future plans for the study are described.

1. Introduction

The International Design Study of the Neutrino Factory (IDS-NF) [1], together with the EUROnu Project [2], seek the complete end-to-end conceptual design for the Neutrino Factory, a potential future facility for precision neutrino experiments. The Neutrino Factory (NF) produces a high quality neutrino beam with a well known energy spread and flavour content by injecting muons accelerated to high energy into a decay ring equipped with long straight sections pointing towards far neutrino detectors. This facility aims for an unprecedented precision for a discovery of CP violation in the leptonic sector and is currently recognized as the best facility for this ambitious goal. The current baseline for the NF is described in detail in the recently completed Interim Design Report [3].

Muon acceleration, which is necessary for the neutrino factory to achieve its high performance, represents a challenge for the accelerator system. Firstly, the muon beam produced as tertiary beam has a very large initial transverse emittance and energy spread. Even after applying the RF phase rotation and ionization cooling, assumed in the muon front end, the required accelerator normalized acceptances at the input are as high as 3 π cm rad and 150 mm in transverse and longitudinal phase spaces, respectively. Secondly, a short muon lifetime (2.2 μs at rest) dictates a need for a very fast acceleration. As the first stage of acceleration from 150 MeV to 0.9 GeV, a superconducting (SC) linac is proposed. At higher energy up to 12.6 GeV, the baseline uses recirculating linacs, where the beam passes a few times through the same accelerating RF structure (4-5 times) reducing the cost of the accelerator. In order to further improve the efficiency of acceleration and reduce the cost, a Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) ring is used for the final stage of acceleration to 25 GeV. The NS-FFAG ring allows one to perform more than 11 turns through the same accelerating system using 201 MHz superconducting (SC) RF cavities. This is possible due to the quasi-isochronous optics, which allows the time of flight difference as a function of energy to be minimized by combining the positive and negative bending angles with strong focusing.

2. Non-Scaling FFAG lattice description

The current baseline NS-FFAG lattice [4] is based on FDF triplet lattice using combined SC magnets with superimposed dipole and quadrupole magnetic field components. This magnetic field configuration results in a machine with the so-called "natural" chromaticity, which means that the tunes change as a function of beam energy, as can be seen in Fig. 1. The absence of higher order multipoles simplifies the magnet design and allows for the large dynamic acceptance needed for muon beams, but introduces a time of flight variation as a function of the transverse amplitude. This may result in the longitudinal emittance blow up, which may be prevented by introducing chromaticity correction. A scheme for this correction still needs to be identified in future studies. The time of flight variation as a function of energy has a parabolic behaviour, which is shown in Fig 2.

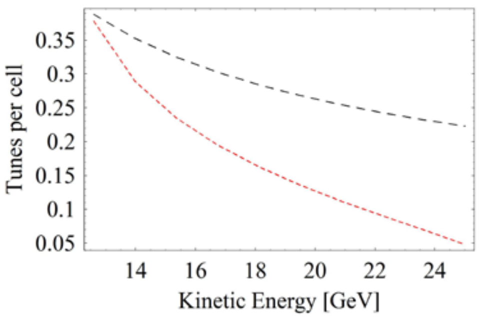

Figure 1. The cell tunes (horizontal-black and vertical-red lines) variation as a function of energy in the NS-FFAG.

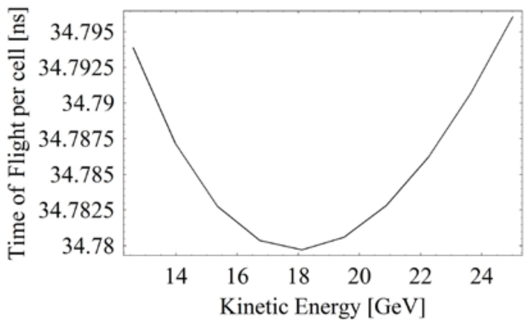

Figure 2. The time of flight per cell as a function of muon energy in the NS-FFAG.

The current lattice configuration has been chosen to allow for sufficient space in the long straight section (5 m) for the extraction septum, whose field is limited to ~2 T to reduce its stray fields. The main NS-FFAG ring parameters are summarized in Table. 1.

Table 1. Main NS-FFAG parameters.

Parameter	Value
Circumference [m]	699
Number of cells	67
Long drift length [m]	5
RF voltage per turn [MV]	1195.6
Max B field [T]	6.2
Max quadrupole gradient [T/m]	18.82
Turns for acceleration	11.8
Muon decay [%]	7.1

3. Preliminary engineering

Engineering studies have been initiated, resulting in a preliminary conceptual layout of the NS-FFAG cell. Attention has been drawn for the space requirements for the injection/extraction magnets, beam diagnostics, RF cavities, etc. The cold-warm transition between the SC magnet block and the long straight section was evaluated, resulting in the reduction of the available space from previously assumed 4.4 to 4 m. The parameters of the preliminary SC magnet design [5] together with the existing SC 201 MHz RF cavity structure were used to create the CAD model of the FFAG cell hosting the RF cavity as shown in Fig. 3.

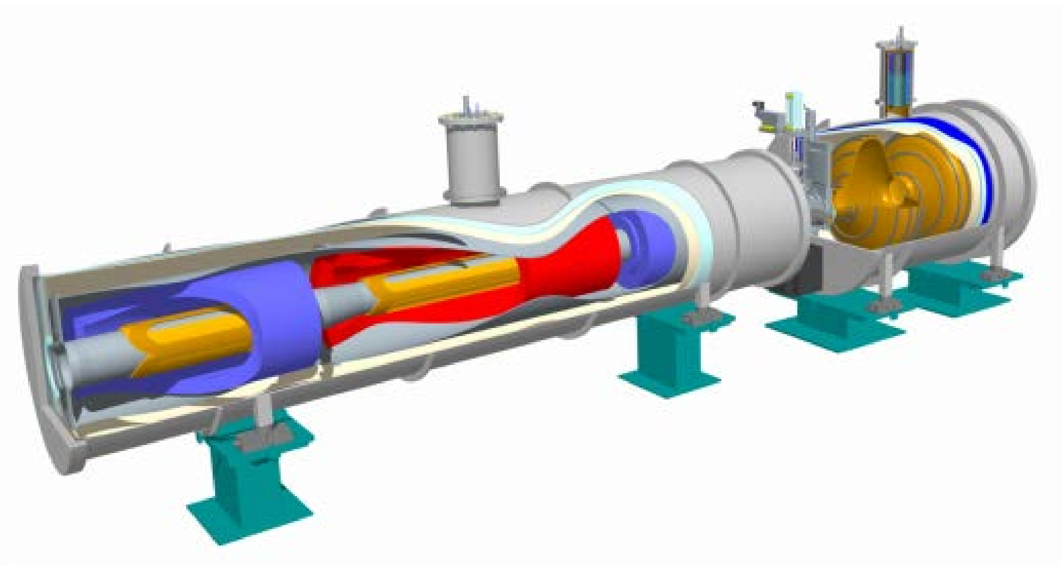

Figure 3. The layout of NS-FFAG machine cell containing the RF cavity. The F and D magnets with coils and yokes (red and blue, respectively) placed in a common cryostat are shown on the left. The RF cavity enclosed in a separate cryostat is shown on the right.

4. Injection/extraction

The injection and extraction systems were designed using distributed kickers deflecting the beam in horizontal plane and placed symmetrically to serve both muon signs. In both systems the kickers are shared for positive and negative muons and are equipped with septum magnets for each polarity on each end of the system. The existing technologies were used as much as possible, but clearly the aperture requirements are beyond those of existing magnets. Also the fields in the extraction septa are higher than in conventional accelerator applications. Currently extraction septa of 2 T are assumed in order to minimize the stray field leakage. The new assumptions on the available space in the straight section, due to the necessary space for cold/warm transitions, resulted in the update of the injection/extraction system parameters, which are summarized in Table 2.

Table 2. Parameters of the injection and extraction systems.

Parameter	Injection	Extraction
Kickers	2	4
Kicker field [T]	0.106	0.8
Septum field [T]	1.2	1.94
Kicker/septum length [m]	3.7/3.4	3.7/4

5. Preliminary beam dynamics simulations with the "serpentine" acceleration.

Particles were tracked in the current baseline NS-FFAG lattice in order to test the performance of the "serpentine" acceleration. First, an initial 6D Gaussian distribution with longitudinal parameters close to the design ones, but with small transverse emittances were launched and 11.8 turns in the machine were tracked. RF cavities were distributed in all cells, neglecting the effects of empty spaces for injection/extraction. Then similar tracking was performed with large (close to design) initial transverse emittances. Both simulations showed a relatively large longitudinal emittance blow up but with almost lossless transport. As can be seen by comparing the Fig.1 and 2, the source of the longitudinal emittance increase is twofold: firstly the initial longitudinal distribution is stretched and filamented in the serpentine channel, secondly the time of flight variation for large transverse amplitude introduces an additional energy spread. The longitudinal emittance blow up in the "serpentine" acceleration has been recognized in previous studies and possible cures were identified [6].

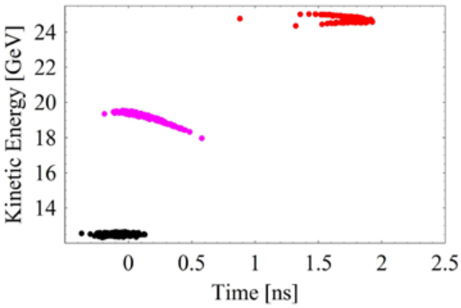

Figure 1. The injected (black), intermediate-after 5 turns (pink) and final (red) longitudinal phase spaces assuming small initial transverse emittances.

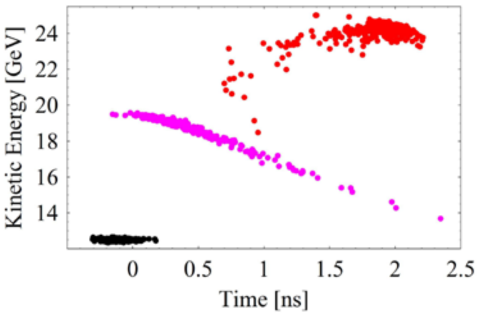

Figure 2. The injected (black), intermediate-after 5 turns (pink) and final (red) longitudinal phase spaces assuming large (design) initial transverse emittances.

6. Summary and future plans

Longitudinal emittance blow up needs to be minimized by optimizing the injection parameters and by altering the machine parameters, which need to be adjusted to give precisely 11.5 turns from injection to extraction. The effect of magnet errors and misalignments on the machine performance will be estimated and used to set the magnet tolerances. The magnet design will be updated to meet those specifications. Various technology solutions for the combined function SC main magnets should be compared including: the current design based on separate multipole conductor layers, a double helix, and a single combined function layer. Chromaticity correction and its effect on the longitudinal and transverse beam dynamics will be studied and the conclusions on the final machine design drawn. Beam loss induced energy deposition from muon decays needs to be studied, and its effect on the feasibility of the cryogenic systems understood, especially the SC extraction septum. More engineering studies of the machine subsystems is needed.

References

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