BNL-96525-2011-CP
MAP-doc-4321
IDS-NF-AWG-006

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. The beam dynamics studies including the process of acceleration are discussed. The first pass at engineering for the layout of the ring cell is described. The progress of studies on the main machine subsystems is discussed. The future plans for the study are drawn.

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) is capable to produce 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 comleted Interim Design Report [3].

Muon acceleration, which is necessary in order to obtain a well focused neutrino beam as its angular divergence is inversely proportional to the relativistic γ of the parent muons, 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 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

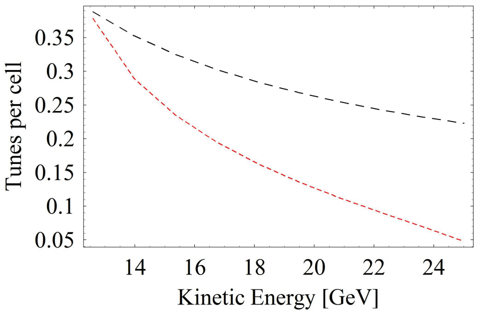

Figure 1. The cell tunes (horizontal-black and vertical-red lines) as a function of energy in the NS-FFAG.

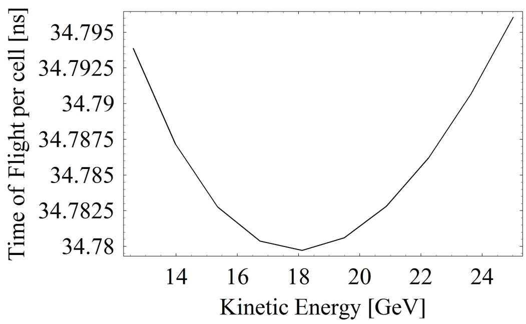

Figure 2. The time of flight per cell as a function of muon energy in the NS-FFAG.

order to further improve the efficiency of acceleration and reduce the cost, a Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) ring is assumed at the final stage of acceleration to the final energy of 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 positive and negative bending angles with strong focusing.

2. Non-Scaling FFAG lattice description

The current baseline NS-FFAG lattice [4] is based on an FDF triplet lattice using 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 a large dynamical acceptance needed for muon beams, but introduces a time of flight variation as a function of the transverse amplitude. This may result in longitudinal emittance blow up, which may be prevented by introducing chromaticity correction. The detailed 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.

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

3. Preliminary engineering

Engineering studies have been initiated resulting in a preliminary conceptual layout of the NS-FFAG

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

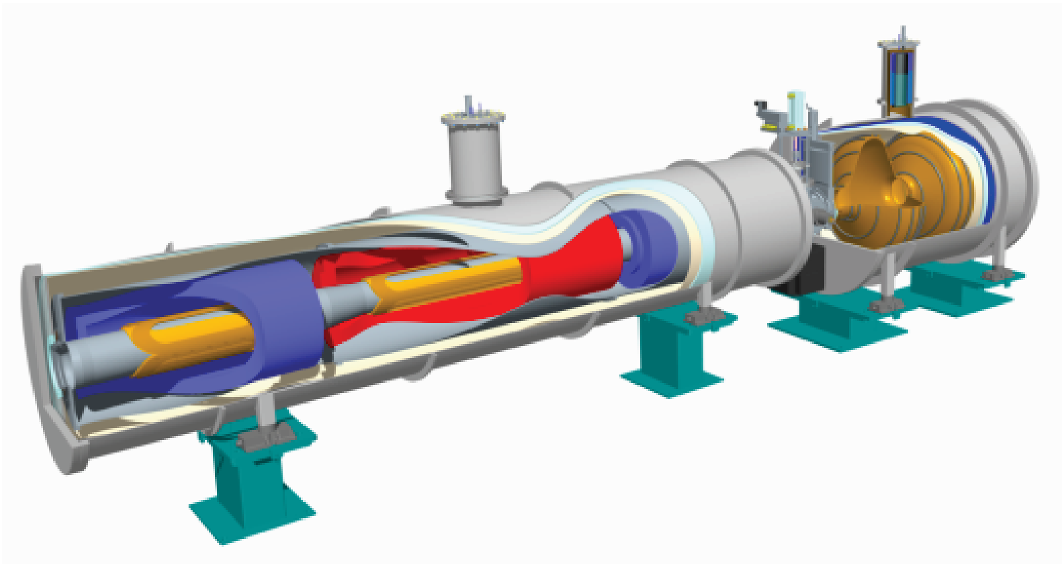

Figure 3. The layout of NS-FFAG machine cell containing the RF cavity. The F and D magnets with coils and yokes (red and blue, respectively) placed in the common cryostat are shown on the left. The RF cavity enclosed in a separate cryostat is shown on the right.

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 the 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 a CAD model of the FFAG cell hosting the RF cavity as shown in Fig. 3.

4. Injection/extraction

The injection and extraction systems were designed using distributed kickers deflecting the beam in the 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. Existing technologies were used as much as possible, but clearly the aperture requirements are beyond those of currently used magnets. Also the fields in the extraction septa are higher than in conventional accelerator applications. Currently the extraction septa fields are limited to 2 T in order to minimize stray field leakage. The new assumptions on the available space in the straight section due to the necessary space for the cold/warm transitions resulted in an update of the injection/extraction system parameters, which are summarized in Table 2.

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

Beam dynamics simulations of the current baseline NS-FFAG lattice were performed in order to test the performance of the “serpentine” acceleration. Firstly, an initial 6D Gaussian distribution with longitudinal parameters close to the design ones, but with small transverse emittances, was launched,

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

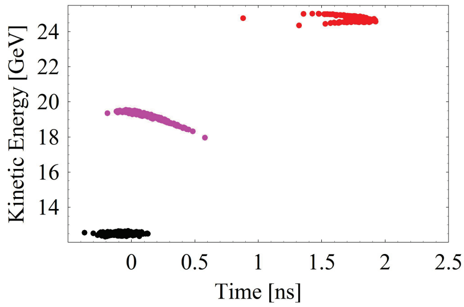

Figure 4. The injected (black), intermediate-after 5 turns (pink) and final (red) longitudinal phase spaces assuming small initial transverse emittances.

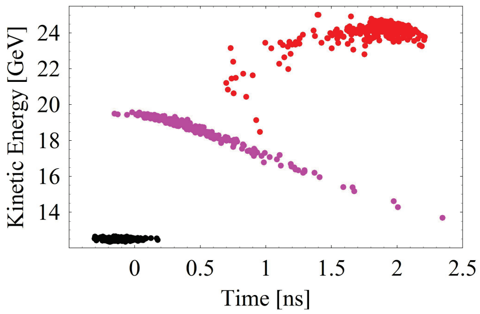

Figure 5. The injected (black), intermediate-after 5 turns (pink) and final (red) longitudinal phase spaces assuming large (design) initial transverse emittances.

and 11.8 turns in the machine were tracked. The RF cavities were distributed in all cells neglecting the effects of the empty spaces for injection/extraction. Secondly, similar tracking was performed with large (close to the 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 Figs. 4 and 5, 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 and additional energy spread. Longitudinal emittance blow up in the "serpentine" acceleration has been recognized in previous studies and possible cures identified [6].

6. Summary and future plans

The 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 a separate multipole conductor layers, the double helix, and the single layer combined function type. Chromaticity correction and its effect on the longitudinal and transverse beam dynamics will be studied and the conclusions on the final machine design drawn. The beam loss induced energy deposition including the muon decay needs to be studied, and its effect on the feasibility of the cryogenics understood, especially at the SC extraction septum. More engineering definitions for the machine subsystems need to be provided.

References

[1] http://www.ids-nf.org/
[2] http://www.euronu.org/
[3] The IDS-NF Collaboration, "Interim Design Report", IDS-NF-020, https://www.ids-nf.org/wiki/FrontPage/Documentation (2011).
[4] J. Scott Berg *et al.*, in *Proceedings of IPAC2011, San Sebastián, Spain* (IPAC'11/EPS-AG, 2011), p. 832.
[5] J. Pasternak *et al.,*. in *Proceedings of IPAC2011, San Sebastián, Spain* (IPAC'11/EPS-AG, 2011), p. 829.
[6] J. Scott Berg, Nucl. Instrum. Methods A **570** (2007), p. 15.