FFAG Design for a 10 GeV Neutrino Factory for the IDS-NF

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Abstract. I give the design parameters for a linear non-scaling FFAG optimized to accelerate the IDS-NF muon beam from 5 to 10 GeV. The results are given for several values of the long drift length. The corresponding parameters for a 12.6 to 25 GeV FFAG are also given. For a 10 GeV neutrino factory, I analyze the choice between scenarios with or without an FFAG in the acceleration chain.

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5–10 GEV FFAG DESIGN

In [1], a design for a 12.6–25 GeV FFAG for a neutrino factory is described. Recent physics results [2, 3] have led to a reduction in the maximum energy of a neutrino factory to 10 GeV [4].

I designed an optimized lattice for a 5–10 GeV FFAG using an identical optimization procedure to the lattice in [1]. The choice of a factor of 2 in energy is based on past studies which indicated that a factor of 2 was near optimal: when a sequence of 2, 3, or 4 FFAGs was used to accelerate a neutrino factory beam by a factor of 8 in energy, each FFAG accelerating by an equal factor in energy, the sequence of 3 had the lowest cost, the sequence of 4 had a somewhat higher cost, and the sequence of 2 had a significantly higher cost.

Due to the smaller energy range, the a parameter (see [5]) needs to be 0.1120, higher than the 0.074827 that was used for the 12.6–25 GeV FFAG (these both correspond to approximately a 5% longitudinal emittance distortion in the approximation that the time of flight is perfectly parabolic). In both cases we leave 17 drifts free for injection, extraction, and utilities (4 drifts are allocated to this). One may be able to accomplish injection and extraction with fewer cells in the 5–10 GeV case than in the 12.6–25 GeV case; that should be investigated. All remaining cells contain an RF cavity to maximize the average accelerating gradient per cell, so as to minimize the effect of transverse amplitude on the time of flight [6]. The cost described in [7] is minimized. With a double cell cavity, engineering drawings indicate that it would be difficult to make the long drift much less then 4.3 m. The design for a machine with this drift length is given in Table 1, and compared with the design for a 12.6–25 GeV FFAG. I also give designs for reduced long drift lengths to indicate the benefit of reducing that drift length. Note that for the design with the 4.3 m drift, the beam may be too large to fit within the 30 cm aperture of the 25.5 MV cavities, and we may therefore require lower gradient cavities.

While one could make a design which has more turns, that would require an increase in the circumference and a reduction in the amount of RF in the machine. This would reduce the machine cost, both due to less RF and a reduction in the magnet apertures and fields (which overcomes the cost of additional magnets). However, this would further reduce the energy gain per cell, (already lower than what we had for the 12.6–25 GeV FFAG), thus increasing the effect of the transverse amplitude on the longitudinal motion [6]. This effect is already difficult to deal with based on our tracking results thus far, and I think it is a bad idea to exacerbate it.

We wish to compare the cost of an acceleration system with a linac and two RLAs to the cost of an acceleration system with a linac, one RLA, and an FFAG. Starting with the energy breakpoints for the IDS-NF baseline linac and RLA designs [8], I estimate that for the acceleration scenario without an FFAG, the linac will accelerate to a total energy of 0.8 GeV and the first RLA to 2.8 GeV. With the FFAG, the linac will instead accelerate to 1.2 GeV. Starting on a preliminary costing [9, 10] of the 25 GeV facility, I scale the FFAG cost according to the cost line in Table 1; for the linac I divide the cost by the number of cells, then multiply by the ratio of the difference in energy gain to the energy gained in the final cell of the IDS-NF design. This is used because the beam is close to the crest near the end of the linac. For the RLAs, I linearly interpolate the cost per GeV in the inverse of the high energy value, then multiply by the actual energy gain. The results are shown in Table 2. The difference between the costs for the two scenarios accelerating to 10 GeV is much less than the uncertainty of this calculation. I therefore see no cost advantage in using an FFAG. Applying this same cost scaling to a scenario accelerating to 25 GeV with either two or three RLAs shows a clear advantage in using the FFAG.

Table 1 gives stored energies for the magnets for both systems. The stored energies in the magnets appears to

TABLE 1. Parameters for the FFAG designs.

Injection energy (GeV)	12.6	5	5	5	5	5	5	5
Extraction energy (GeV)	25	10	10	10	10	10	10	10
Long drift (m)	5.0	4.3	4.0	3.8	3.6	3.4	3.2	3.0
Short drift (m)	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Cells	67	55	53	53	53	53	51	51
D length (m)	1.994466	1.620155	1.407454	1.481612	1.550139	1.614460	1.375857	1.437968
D angle (mrad)	147.626	179.015	184.550	183.086	181.829	180.725	186.552	185.440
D shift (mm)	39.012	44.874	43.635	43.414	43.224	43.069	41.563	41.277
D field (T)	4.43410	2.60811	3.07698	2.91080	2.77279	2.65478	3.19420	3.04971
D gradient (T/m)	−14.0598	−7.3583	−9.0320	−8.4690	−7.9849	−7.5614	−9.5610	−9.0156
F length (m)	0.965155	0.756990	0.641052	0.703935	0.769636	0.837441	0.684476	0.753383
F angle (mrad)	−26.924	−32.388	−32.999	−32.268	−31.639	−31.087	−31.676	−31.120
F shift (mm)	14.371	17.141	16.322	15.893	15.450	14.986	14.245	13.747
F field (T)	−1.43705	−0.87525	−1.05424	−0.94040	−0.84563	−0.76625	−0.95533	−0.85640
F gradient (T/m)	18.8800	10.1626	12.9054	11.5936	10.4508	9.4611	12.6004	11.2634
Cavities	50	38	36	36	36	36	34	34
RF voltage (MV)	1212.571	905.740	859.522	864.833	871.983	880.459	826.089	835.383
turns	11.6	6.4	6.7	6.7	6.6	6.6	7.0	6.9
D radius (mm)	130	175	169	167	165	163	157	156
D max field (T)	6.3	3.9	4.6	4.3	4.1	3.9	4.7	4.5
D stored energy (kJ)	899	473	534	489	451	419	480	450
F radius (mm)	160	205	195	198	201	204	192	195
F max field (T)	4.5	3.0	3.6	3.2	2.9	2.7	3.4	3.1
F stored energy (kJ)	204	117	130	121	114	107	121	113
Circumference (m)	699	492	434	434	434	434	380	380
Decay (%)	7.0	6.8	6.4	6.3	6.3	6.2	5.8	5.7
Energy gain/cell (MV)	15.9	14.2	14.0	14.1	14.2	14.3	14.0	14.1
Cost (A.U.)	162	130	128	124	122	120	118	115

TABLE 2. Cost comparison of acceleration scenarios. Numbers in the first column are percentage values from [10]; other numbers are scaled from them as described in the text.

Linac	11	16.9	9.0	10.0	14.0
Energy (GeV)	0.9	1.5	0.7	0.8	1.2
RLA 1	18	25.2	13.1	14.8	22.5
Energy (GeV)	3.6	6.0	2.3	2.8	5.0
RLA 2	43	83.7	28.0	35.8	
Energy (GeV)	12.6		7.6		
RLA 3			76.6		
Energy (GeV)					
FFAG	29				23.3
Energy (GeV)	25.0	25.0	25.0	10.0	10.0
Total	101	125.8	126.7	60.7	59.8

vary more strongly than the costs for the systems. This is partly due to the cost model used [7]: in that model, the cost of a magnet does not go to zero as its length goes to zero, which is based on the observation that a short, large aperture magnet is dominated by the cost of the magnet ends.

There are (at least) two deficiencies in this design that need to be corrected. The first is that the number of turns should be a half integer. The second is that the design has not been properly optimized for a time of flight which is not a purely parabolic function of energy. Nonetheless, I expect the final designs to be similar to the ones shown here.

SYSTEM WITH A 4 GEV BREAKPOINT

Instead of completely constructing a 10 GeV neutrino factory in one shot, one might like to have intermediate stages where one could perform useful physics. In the scenarios above, the FFAG-based scenario has a natural breakpoint at 5 GeV. In addition, there are natural breakpoints at 1.2 GeV, 1.6 GeV, 3.3 GeV (corresponding to 0, 0.5, and 2.5 passes through the linac in the first RLA) corresponding to delays in constructing parts of the second RLA. In fact, any intermediate energy in that first RLA should be achievable.

However, the question was raised whether one could have a lower cost option by choosing a breakpoint at 4 GeV. The argument (J. Pasternak) is that the reduction in cost of the relatively inefficient lower energy stages outweighs the increase in cost of the FFAG, even if the FFAG becomes less efficient.

An FFAG was designed at this energy, and its parameters are given in Table. There was a significant cost increase from the 5 GeV FFAG, and the design could only achieve a small number of turns. The reason for this is

TABLE 3. Parameters of a 4-10 GeV FFAG design

Injection energy (GeV)	4
Extraction energy (GeV)	10
Long drift (m)	4.3
Short drift (m)	0.75
Cells	83
D length (m)	1.608696
D angle (mrad)	113.489
D shift (mm)	45.220
D field (T)	1.58481
D gradient (T/m)	-5.9657
F length (m)	0.763496
F angle (mrad)	−18.894
F shift (mm)	11.476
F field (T)	−0.52225
F gradient (T/m)	7.6329
Cavities	67
RF voltage (MV)	1637.213
turns	4.1
D radius (mm)	203
D max field (T)	2.8
D stored energy (kJ)	269
F radius (mm)	241
F max field (T)	2.4
F stored energy (kJ)	109
Circumference (m)	742
Decay (%)	7.4
Energy gain/cell (MV)	17.4
Cost (A.U.)	206

TABLE 4. Costs of acceleration scenarios with a 4 GeV breakpoint.

Linac	12	12
Energy (GeV)	1	1
RLA 1	19.2	19.2
Energy (GeV)	4	4
RLA 2	29.8	
FFAG		36.9
Energy (GeV)	10	10
Total	61.0	68.1

likely twofold: first, that the increase in the energy range increased the time of flight range (which is a quadratic function of the energy range). This requires more RF voltage in proportion to that time of flight increase to have a tolerable longitudinal emittance distortion [5]. The second reason for the cost increase is that the tune range has increased, meaning that the beta functions will be larger at the two energy extremes: at the low end because one approaches the half integer resonance, and at the high end due to the weaker focusing. The result is an increased magnet aperture and therefore an increased cost.

Table 4 shows a cost comparison between acceleration scenarios with a 4 GeV breakpoint. The cost of an RLA scenario is similar to what one would have with the 5 GeV breakpoint. However, the FFAG scenario suffers a significant cost increase. The scenarios are relatively close in cost considering the accuracy of this estimate, but the fact that the cost of the FFAG scenario increases when reducing the lower energy from 5 to 4 is clear.

The cost comparison implicitly assumed that the RLA-only scenario used 4.5 linac passes for the second RLA. However, due to the relatively small energy range (only a factor of 2.5), the switchyard might get too dense with 4.5 passes. Thus one might be forced to fewer passes (if 4.5 passes were possible, one might question whether more passes would be possible with a larger energy range in the RLAs), and the cost would rise. Thus, 4 GeV appears to be a particularly inconvenient energy breakpoint in the acceleration scenario.

CHOICE OF AN ACCELERATION SCENARIO

- A higher energy is preferable to a lower one for detector performance.
- The choice between a RLA-only scenario and a scenario with an FFAG with a 5 GeV breakpoint is cost-neutral
- The performance concerns with an FFAG, namely the longitudinal distortion resulting from the time of flight dependence on transverse amplitude, may very well appear in the RLAs as well, since they have no chromaticity correction (though they do have some synchrotron oscillation, which will change the nature of the effect). We have not done sufficient tracking studies at this point to know one way or another.
- The scenario with a acceleration 5 GeV breakpoint provides a set of convenient intermediate breakpoints where one could stop construction (before installing RLA arcs) and do physics.
- The RLA-only scenario would require either partially constructing the second RLA to get to the 5 GeV energy, or would require that the first RLA be designed to 5 GeV, then some of the linac from the first RLA would be moved to the second RLA.

The primary argument against the scenario with an FFAG is that it adds a different type of accelerator to the machine, without a well-defined cost benefit. The last bullet above provides a path to accelerate to 5 GeV with the same cost as the FFAG scenario. However, the cost to reach 10 GeV will be somewhat higher in this scenario, since the arcs will need to be designed for 5 GeV instead of 2.8 GeV and there will be a longer focusing channel in the straight of the first RLA. In addition, there will be more decays. Furthermore, the modifications to that first RLA will require re-commissioning that machine when moving to the 10 GeV, potentially negating some of the operational benefit of not having an FFAG. FFAGs are also likely to be useful for a muon collider, so one will need to gain operational experience with them eventually. An additional concern is the longitudinal distortion from one FFAG stage making the next FFAG stage more difficult, but as pointed out above, it is not clear that this effect is absent from the RLAs.

Post-Conference Discussions

At an IDS-NF plenary meeting following the NuFact conference, discussions within the physics and detector community led to the conclusion that having an intermediate energy breakpoint below 10 GeV was not of interest. This eliminated the primary benefit of having the FFAG in the acceleration scenario for a 10 GeV neutrino factory. It was therefore decided to have an acceleration scenario with a linac and two RLAs for the IDS-NF neutrino factory (10 GeV) design.

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