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Factory***

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FFAG Accelerator Proton Driver for Neutrino Factory*

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1. Introduction

This paper is the summary of a conceptual study of a Proton Driver for Neutrino Factory based on the use of a Fixed-Field Alternating-Gradient (FFAG) Accelerator. The required proton energy range for an optimum neutrino production is 5 to 12 GeV. This can be accomplished with a group of three concentric rings each with 807 m circumference [1].

FFAG Accelerators [2] have the capability to accelerate charged particles over a large momentum range (± 30 -50%) and the feature of constant bending and focusing fields. Particles can be accelerated very fast at the rate given by the accelerating field of RF cavities placed in proper locations between magnets. The performance of FFAG accelerators is to be placed between that of Super-Conducting Linear Accelerators (SCL), with which they share the fast acceleration rate, and Rapid-Cycling Synchrotrons (RCS), as they allow the beam to re-circulate over fewer revolutions.

Brookhaven National Laboratory is involved in the study of feasibility of FFAG Accelerators to accelerate intense beams of protons in the GeV energy range for a variety of applications the most important of which is the Upgrade of the Alternating Gradient Synchrotron (AGS) with a new FFAG injector [3] accelerating from 400 MeV to 1.5 GeV. The ring would be housed in the AGS tunnel and has henceforth a circumference of 807 m.

2. Neutrino Factories

A Neutrino Factory has the main goal to produce 10^{21} neutrino/a. This is done by having an intense beam of protons of energy between 5 and 12 GeV impinging on a radiation-resistant target, and by collecting μ -mesons emerging from the reaction

$$p + X \rightarrow \pi^{\pm} \rightarrow \mu^{\pm} \rightarrow \nu$$

and storing them in a storage ring where they decay in neutrinos in one long straight section directed toward the location of a massive detector placed at a very long distance.

Thus a main component of the Factory is the Proton Driver capable to deliver the required proton intensity at the proper energy. The proton accelerator could be a Super-Conducting Linac or a Rapid-Cycling Synchrotron. FFAG Accelerators can also be thought as Proton Drivers at high intensity and in the specified energy range as we shall show in this paper.

The requirement is the delivery of protons with an average beam power of 4 MW at the repetition rate of 25 Hz that gives 10^{14} protons per pulse at 10 GeV that is certainly within the capability of present accelerator technology. These figures are consistent with the presently perceived limitations of the target upon which the proton beam is to impinge.

3. FFAG Accelerators for Proton Beams

Two configurations and magnet arrangements have been proposed for an FFAG Accelerator [2]:

-- *Scaling Lattice* that has the advantage of constant orbit parameters across the large momentum aperture but at cost of high bending fields, large magnet aperture and a limitation on available drift space.

-- *Non-Scaling Lattice* where orbit parameters vary considerably across the momentum aperture but with the benefit of lower bending fields, smaller magnet aperture and allowance for more drift space. The engineering and construction of a FFAG Accelerator based on this principle are greatly simplified and expected to be more economical.

In case of proton beams, the concern of multiple resonance crossing is to be coupled to the presence of large space-charge forces at injection that, despite the fast rate by which the region of relevance is traversed, still may be significant. Moreover the longitudinal beam dynamics requires a careful analysis because of the fast frequency-varying RF cavity system needed for acceleration. It is also possible to operate the accelerator in a Continuous Wave (CW) mode of operation [4] with a continuous circulating beam.

The lattice of the FFAG Proton Driver we opt for is a *Non-Scaling* type made of a continuous sequence of FDF triplets. Each magnet has a combined bending and focusing function. The bending and the focusing alternate in sign between the three magnets of the triplet. The field profile in each magnet is purely linear. The beam is injected on an injection orbit placed toward the inside of the ring. The beam is accelerated and its trajectory spirals to the outside. Once the top energy is reached the beam is located on the far outmost orbit, the extraction trajectory, from which is extracted in a single turn. In the pulsed mode of operation there is only a single beam being accelerated that occupies only one trajectory. In this case multi-turn injection of negative ions is required to achieve the design intensity. Also, because the beam changes velocity continuously during acceleration, the RF cavity system is continuously tuned in frequency with the assistance of ferrite that limits the amount of voltage and acceleration rate. In the CW mode of operation,

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on the contrary, the beam is continuously accelerated and is present on every trajectory. In this case the beam is continuously injected turn-after-turn. The RF cavity system is tuned to a constant frequency and the beam is accelerated with a special voltage program designed to allow a programmable harmonic number jump from one turn to the next.

4. FFAG Accelerators for Neutrino Factory

We explored the possibility of using FFAG Accelerators for the acceleration of protons up to an energy of 12 GeV. This can be accomplished only with multiple rings that we assume to be concentric to each other and installed in the same tunnel, as shown in Figure 1. We assume that each ring can only accelerate over a momentum range of $\pm 40\%$. There are then three of such rings. The first ring (*Inj. Ring*) accelerates protons from 400 MeV to 1.5 GeV and for its design we essentially copy that proposed for the AGS Upgrade program [3] with a circumference of 807 m. The second ring (*LE Ring*) accelerates to 4.45 GeV, and the last one (*HE Ring*) to 11.6 GeV. They both have about the same circumference of the first ring. The transfer from one ring to the next occurs fast, in a single turn. The major parameters of the three rings are listed in Table 1. We have assumed the same RF wavelength ($\lambda = 5.9345$ m) for acceleration.

The three rings have the same periodicity and about the same circumference. They have thus also about the same lattice behavior, shown in Figure 2. The main magnet, drift and beam width parameters are listed in Table 2. The beam width Δx is the range that covers just the momentum excursion. To that one should add the contribution of betatron emittance at injection and extraction. The magnetic field strength required to cover the momentum range during acceleration is within the limit of room-temperature magnet technology with the possible

Figure 1. Proton Driver with 3 FFAG Rings

Figure 2. Lattice Functions along the Length of a Period

exception of the magnets in the HE ring where a field in excess of 2 Tesla is needed.

In the pulsed mode of operation injection of negative ions (H^-) is required into the *Injector Ring* to reach the desired beam intensity. We take as a goal the acceleration of 10^{14} protons per pulse. The main injection parameters are listed in Table 3. The beam size and intensity at the space-charge limit are given in Table 4.

Table 1. Major Parameters of the 3 FFAG Rings

		<i>Inj. Ring</i>	<i>LE Ring</i>	<i>HE Ring</i>
Energy:	Inj.	0.40	1.50	4.45
	Ext.	1.50	4.45	11.6
β	Inj.	0.7131	0.9230	0.9847
	Ext.	0.9230	0.9847	0.9972
$\Delta p/p$	$\pm\%$	40.45	40.43	40.41
Circumference	m	807.091	818.960	830.829
No. of Periods		136	136	136
Period Length	m	5.934	6.022	6.109
Harmonic No.		136	138	140
RF	Inj.	36.02	46.03	49.75
	Ext.	46.03	49.75	50.38

5. RF Acceleration

At the end of the injection period, the beam is immediately accelerated by a RF cavity system that is ferrite tuned, at constant peak voltage. The frequency is chosen to be a sub-multiple of 201.25 MHz at injection. The RF is also matched from one ring to the next with about the same harmonic number. It remains to be proven that the range of RF chosen is suitable for the fast tuning of ferrite over a period of 6 – 10 msec required for acceleration. Other concerns are the amount of voltage that a cavity gap can sustain and the capability of coping with beam loading with such large beam power.

Table 2. Field Parameters

		Inj. Ring	LE Ring	HE Ring
Drifts: S	m	1.26725	1.28588	1.3045
g	m	0.30	0.3044	0.3088
F-sector: Length	m	0.70	0.71029	0.72059
Field min	kG	-0.78409	-1.84918	-4.23518
Field max	kG	3.79445	8.94876	20.4415
Gradient	Kg/m	26.5817	60.8858	139.476
D-sector: Length	m	1.40	1.42058	1.44118
Field min	kG	1.83450	4.32645	9.90888
Field max	kG	-1.39962	-3.30084	-7.51787
Gradient	Kg/m	-23.2956	-53.3590	-122.236
Δx max, in F	cm	17.22	17.46	17.69
in D	cm	13.88	14.07	14.26

Table 3. Injection Parameters

Injection Energy	MeV	400
H ⁺ Source Current	mA	35
RFQ Transmission	%	80
Chopping Ratio	%	50
Inject. Beam Current	mA	14
Inj. Protons / turn		3.3×10^{11}
Injected Turns		303
Pulse Length	ms	1.144
Repetition Rate	Hz	100
Duty Cycle		0.1144

Table 4. Space-Charge, Beam Size and Beam Intensity

		Inj. Ring	LE Ring	HE Ring
Protons / pulse		1.0×10^{14}	1.0×10^{14}	1.0×10^{14}
Ave. Beam Current	mA	1.60	1.60	1.60
Ave. Beam Power	MW	2.40	7.12	18.56
Full Nor. Emittance	$\pi \mu\text{m}$	100	100	100
Act. Inj. Emittance	$\pi \mu\text{m}$	98.32	41.69	17.68
Bunching Factor		4.0	4.0	4.0
Tune-Shift		0.343	0.188	0.085
Half Vert. Size	cm	2.12	1.38	0.90
Half Hor. Size	cm	3.41	2.22	1.46

The possibility to operate a FFAG Accelerator in a CW mode of operation, for the delivery of a continuous beam on the target, is discussed in [4] and is based on the so-called principle of *Harmonic Number Jump* from one revolution to the next with a proper energy gain program and constant RF frequency. In this mode of operation the acceleration cycle is considerably shorter. We have assumed an RF of 201.25 MHz for the Injector Ring, 805 MHz for the LE Ring, and 3.2 GHz for the HE Ring, that

require a lower amount of voltage per turn and that eventually can be made of superconducting cavities. All these frequencies are equal or multiple of the bunching frequency (201.25 MHz) as the beam is delivered from the Injector Linac. The number of revolutions that the acceleration cycle takes in each of the three rings is respectively 175, 151 and 115.

Because we have adopted a *Non-Scaling* FFAG lattice with a *Linear* Field Profile there is a considerable large betatron tune shift during acceleration. Several integral tune values are crossed. The situation is the same for both Pulsed and CW Mode of operation, except to note that traversal of possible resonances is done considerably faster in the CW Mode of operation and that therefore is to be preferred.

6. Conclusions

Our feasibility studies show that FFAG Accelerators are suitable as Proton Drivers for beam power up to and exceeding 20 MW, beam energy up to 12 GeV, and repetition rate of 100 Hz. There are nonetheless some issues that need to be addressed with a more careful study in the near future. They are: Large Space Charge Forces at Injection. To reach the high beam intensity multi-turn Injection of H⁺ is needed. Both of these issues need a high energy Injector Linac. Magnets need to be designed properly showing capability to control misalignment and manufacturing imperfections. The fast acceleration rate in the pulsed mode of operation need a RF tunable system that can only be driven with ferrite. Finally with adoption of the *Non-Scaling* FFAG Lattice the beam will cross several resonances especially of first and second order. The beam stability in this case may be established only with careful computer simulations and tracking.

The capability to accelerate high-intensity proton beams of FFAG Accelerators is of the same level of that of SCL, and likely superior to that of RCS and Cyclotrons. But most important, because of the use of conventional room-temperature magnets, FFAG Accelerators could also be comparatively more economical.

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