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FFAG Accelerator Proton Driver for Neutrino Factory

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Abstract

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 and of 1.5, 4.45 and 11.6 GeV. The average proton power at the top energy can be as large as 20 MWatt at a repetition rate of 100 Hz. A Continuous Wave (CW) mode of operation with a 100% duty cycle has also been studied.

FFAG Accelerators

There is recently a renewed interest in FFAG Accelerators [1] for a varied of applications in Nuclear and High-Energy Physics, Energy Technology and Medical Therapy. FFAG Accelerators have the capability to accelerate charged particles over a large momentum range (±30-50%) and the feature of constant bending and focusing fields. Thus magnets do not need to be ramped and particles can be accelerated very fast at the rate given by the limitation of the accelerating field from RF cavities placed in proper location between magnets. The performance of FFAG accelerators is thus to be placed between that of Super-Conducting Linear Accelerators (SLC), with which they share the fast acceleration rate, and Rapid-Cycling Synchrotrons (RCS), as they allow the beam to re-circulate over fewer revolutions. They are similar to Cyclotrons but also take advantage of alternating focusing and bending for a more radial compact geometry, and free themselves from a rigid RF frequency – Path Length relation.

BNL R&D Program on FFAG Accelerators

Brookhaven National Laboratory (BNL) 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 are:

– Upgrade of the Alternating Gradient Synchrotron (AGS) with a new FFAG injector [2] spanning over the energy range of 400 MeV to 1.5 GeV corresponding to a momentum excursion of ±40%. The ring would be housed in the AGS tunnel and has henceforth a circumference of 807 m. The repetition rate is 2.5 or 5.0 Hz. The aim of the Upgrade is an average proton beam power of 1 to 2 MWatt at 28 GeV.

– A site-independent 1.0-GeV Proton Driver [3] capable to deliver as much as 10-MW of average beam power at the high repetition rate of 1 kHz. The injection energy is assumed at 200 MeV and the corresponding momentum excursion is then 45%. The circumference is 201 m.

The Neutrino Factory Project

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 decay reaction shown in Figure 1, 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.

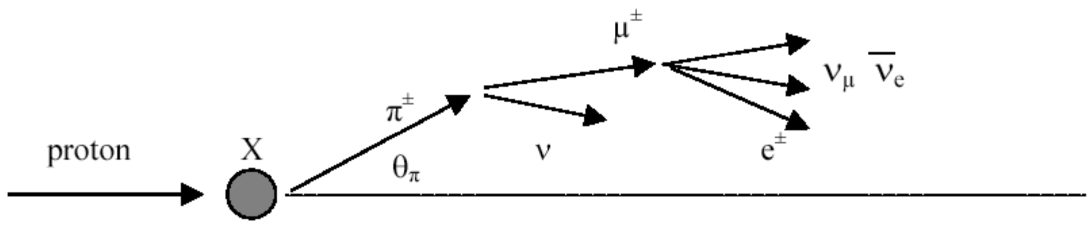

Figure 1. Impact-Decay Reaction p + X -> $\pi^{\pm}$ -> $\mu^{\pm}$ -> ν

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 (SCL) [4] or a Rapid-Cycling Synchrotron (RCS) [5]. Both of these accelerators have their own merits and limitations when they are compared to each other for cost and performance. 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 Target Issue

Another performance parameter to take into account in the design of the Proton Driver is the beam repetition rate. The commonly accepted requirement is the delivery of protons for an average proton 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 limit of present accelerator technology. The just cited figures are consistent with the presently perceived limitations of the target upon which the proton beam is to impinge. The main issue is the resistance of the material to the thermal shock wave upon impact especially in the pulsed mode of operation when the beam pulse has a very brief duration of only few microseconds. To reduce the disruptive effects of the shock wave it is desirable to increase the duty cycle with a longer beam duration per pulse, for instance with a slow spill from the accelerator. At the same average beam power level, that will reduce the peak power to a more tolerable amount. In the limit of the Continuous Wave (CW) mode of operation with a

100% duty cycle, the shock wave issue is entirely eliminated and one is only left with the static heating effects that can be coped with cooling techniques. A CW mode of operation is possible with SCL and FFAG Accelerators but not with RCS. Another advantage of CW mode of operation is that with the thermal shock wave issue removed, it is possible to raise the average beam power well above the 4 MW level, for instance possibly by an order of magnitude. That will either yield an increase of neutrino production rate or, conversely, a reduction of the acceptable phase space (momentum spread and transverse emittance) at the phase of production, with reduced requirements on production and transport channels, and on cooling. Of course all this assumes that the time sequence of neutrinos on the distant detector has no consequences on the experimental program, with the possible exception of beam background.

FFAG Accelerators for Proton Beams

Two lattice configurations and magnet arrangements have been proposed for an FFAG Accelerator [1]:

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. This lattice has been experimentally demonstrated at KEK [6] with a pair of FFAG proton rings that have been commissioned.

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 also expected to be more economical [7]. Yet there is the concern of the beam stability when crossing a large number of resonances, some linear and others not, some driven by errors, misalignment and magnet imperfections, and others that appear to be structural. A *Non-Scaling* FFAG Accelerator has never been practically demonstrated.

In the 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 CW mode of operation [8] with a continuous circulating beam that may avoid the need of negative ions and charge exchange at injection.

The lattice of the FFAG Proton Driver we opt for is a *Non-Scaling* type made of a continuous sequence of FDF triplets as shown in Figure 2. 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 and can be thought as the superposition of a dipole and quadrupole field. During acceleration the magnetic fields remain constant and the magnets are not ramped. The beam is injected on an injection orbit placed toward the inside of the ring. The beam is accelerated and its trajectory moves radially toward 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 also continuously tuned in frequency with the assistance of ferrite that limits the amount of voltage and acceleration rate. In the CW mode of operation [8], 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.

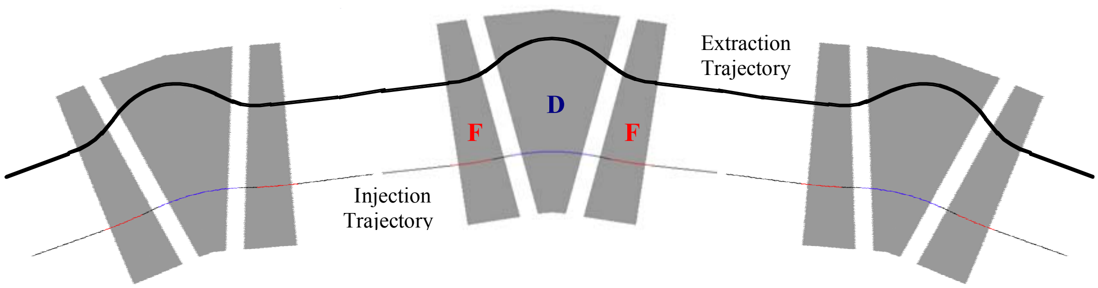

Figure 2. A sequence of FDF Triplets making a *Non-Scaling* FFAG Lattice

FFAG Accelerators Design

We explored the possibility of using FFAG Accelerators for the acceleration of protons up to an energy of 12 GeV. Clearly 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 3. We assume that each ring can only accelerate over a momentum range of ±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 [2] with a circumference of 807 m to fit in the AGS tunnel. 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 injection energy to the first ring has been taken to be 400 MeV to control

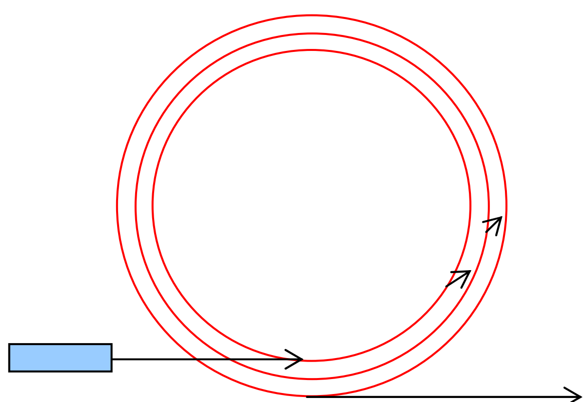

Figure 3. Proton Driver with 3 FFAG Rings

the amount of space-charge forces. The 400-MeV injector could be a room-temperature or superconducting linac, a RCS, a Cyclotron, or eventually one more FFAG accelerator. The major parameters of the three rings are listed in Table 1. We have assumed the same RF wavelength (λ = 5.9345 m) for acceleration in all of them. There is an increment of two harmonic numbers from one ring to the next to allow a change a circumference so that there is about 2 m separation between rings. It is then possible with this arrangement to operate at any energy up to 11.6 GeV. In case a lower energy is sufficient then it may also be possible to build and operate only the first two rings and add the last one in a later stage. The approach is clearly modular, cost effective and programmatic.

Table 1. Major Parameters of the 3 FFAG Rings (Proton Driver)

		Inj. Ring	*LE Ring*	*HE Ring*
Energy: Inj. Ext.	GeV	0.40 1.50	1.50 4.45	4.45 11.6
β Inj. Ext.		0.7131 0.9230	0.9230 0.9847	0.9847 0.9972
Δp/p	±%	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. Ext.	MHz λ = 5.9345 m	36.02 46.03	46.03 49.75	49.75 50.38

The three rings have the same periodicity and about the same circumference. They have thus also about the same lattice behavior, shown in Figure 4 across the length of one of the periods. The main magnet, drift and beam width parameters are listed in Table 2. The global lattice parameters are shown in Table 3. The beam width Δx shown in Table 2 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 exception of the magnets in the HE ring where a field in excess of 2 Tesla is needed.

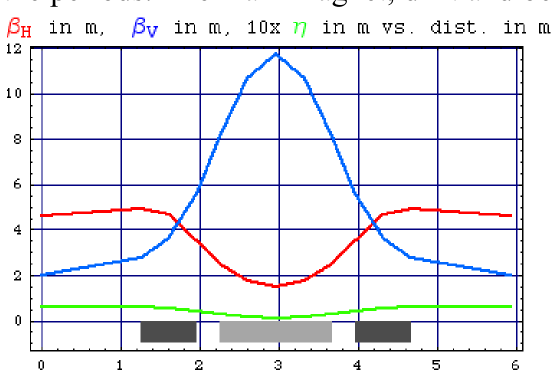

Figure 4. Lattice Functions along the Length of a Period

Injection for the Pulsed Mode of Operation

In the Pulsed Mode of Operation the charge exchange method with negative ions (H^-) is required for injection in 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 4. The beam size and intensity at the space-charge limit are given in Table 5. The layout of the injection components has already been described in [2] and there is no need to repeat it here. We only note that one needs a rectangular vacuum chamber 30cm x 10cm to surround the beam at injection including the space for the foil and the orbit bump as shown in Figure 5.

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. Global Lattice Parameters

Phase Adv. / Cell	H	105.234°
	V	99.9395°
Betatron Tune,	H	39.755
	V	37.755
Nat. Chromaticity,	H	-0.9263
	V	-1.8052
Transition Energy,	γ_T	105.482 i

Table 4. 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

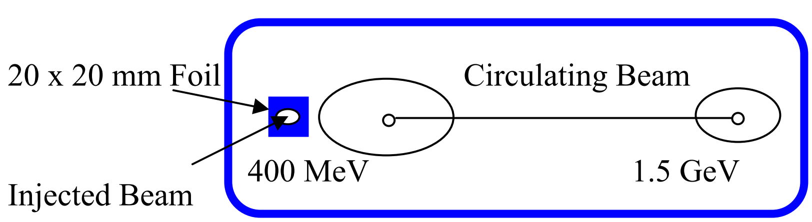

Figure 5. Beam Footprint in the Injection area with a 30 x 10 cm Vacuum Chamber

Table 5. 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}
Average Beam Current	mA	1.60	1.60	1.60
Average Beam Power	MW	2.40	7.12	18.56
Full Nor. Emittance	π mm-mrad	100	100	100
Actual Inj. Emittance	π mm-mrad	98.32	41.69	17.68
Bunching Factor		4.0	4.0	4.0
Tune-Shift		0.343	0.188	0.085
Half Vert. Beam Size	cm	2.12	1.38	0.90
Half Hor. Beam Size	cm	3.41	2.22	1.46

The design of the 400-MeV injector Linac can be scaled from that of the corresponding section of the SNS Linac [9]. The beam at the moment of transfer to the Injector Ring is already pre-bunched at 201.25 MHz and captured by standing by RF cavity system soon after injection in a box car fashion (one bunch per bucket). During multi-turn injection the RF voltage is constant and set at zero phase with no resulting acceleration. The injection period is over one millisecond that at the repetition rate of 100 Hz yields a duty factor of 11.5%. Once reached the full intensity, after 303 injected turns, the maximum tune depression from space-charge forces is about 0.35. The beam is pre-chopped at the exit of the ion source by 50% at the injection RF frequency to avoid unnecessary losses that may cause latent activation of the ring components. A number of missing bunches are also created for a time duration required for injection and extraction kickers.

RF Acceleration in the Pulsed Mode of Operation

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 that may change by an addition of 2 RF wavelengths to allow for the increase in circumference. The beam bunches are transferred from one ring to the next in the box-car fashion, one bunch in one bucket. The main acceleration parameters are given in Table 6. Figure 6 gives the RF frequency modulation and the beam RF power versus the number of turns around the ring during acceleration. The average beam power at the exit of each ring is given in Table 5. 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 mode.

Table 6. RF Acceleration Parameters for the Pulsed Mode

		Inj. Ring	*LE Ring*	*HE Ring*
Energy Gain per Turn	MeV/turn	0.60	0.90	2.00
No. of Revolutions		1834	3278	3576
RF Peak Voltage	MVolt	1.20	1.80	4.00
Acceleration Period	ms	6.137	9.398	10.001
Injection Period	ms	1.144	--	--
Max. Repetition Rate	kHz	0.137	0.106	0.100
Gap Voltage	kVolt	20	30	40
Gaps / Cavity		2	2	2
Number of Cavities		30	30	50

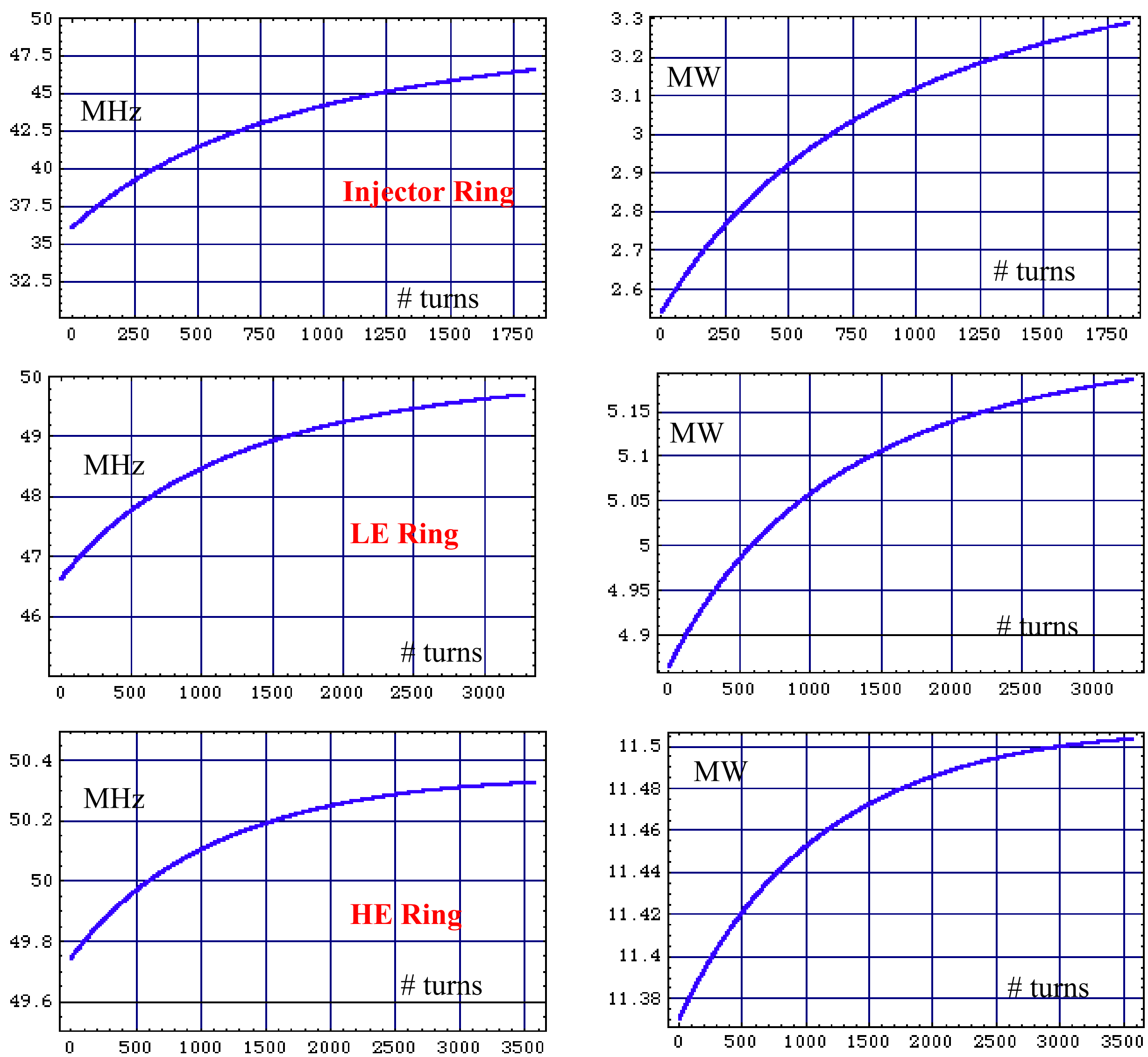

Figure 6. RF Frequency Modulation (MHz) and RF Beam Power (MW) vs. Number of Revolutions in the Acceleration Cycle for each of the three FFAG Rings

RF Acceleration in the CW Mode of Operation

The possibility to operate a FFAG Accelerator in a Continuous Wave (CW) Mode of operation, for the delivery of a continuous beam on the target, is discussed in [8] 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 during the entire acceleration cycle. In this mode of operation the acceleration cycle is considerably shorter as it is possible to see by inspection of Figure 7 that shows the energy gain ΔE program versus number of revolutions. 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. To be observed is the large RF voltage required especially in the HE Ring. The variation of the Harmonic Number h turn after turn is shown in Figure 8. It jumps down by one unit every turn. Figure 9 gives the radial profiles of the RF cavities voltage versus beam position for each of the three rings.

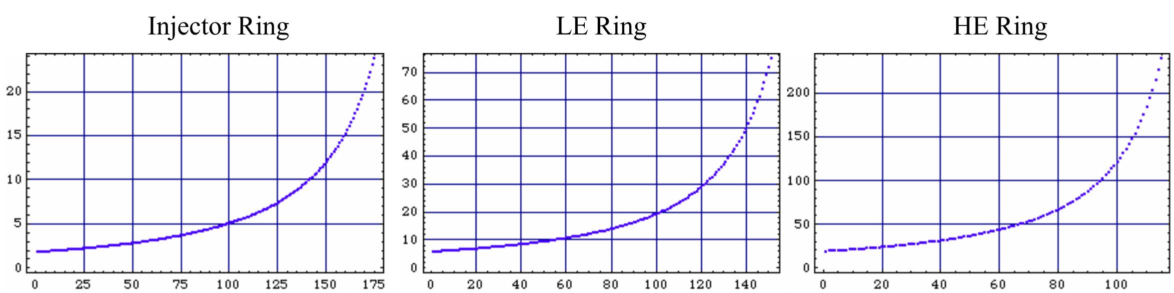

Figure 7. Energy Gain ΔE (MeV) vs. Number of Revolutions for the CW Mode of Operation

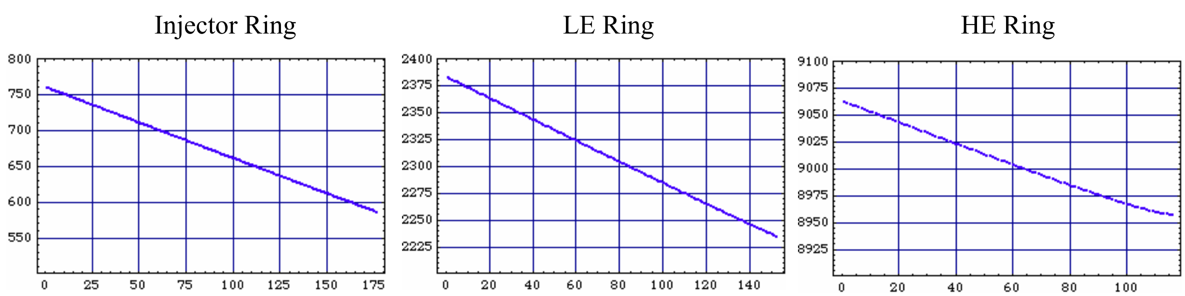

Figure 8. Harmonic Number h vs. Number of Revolutions for the CW Mode of Operation

In the CW mode of operation the beam is *continuously* transferred from one ring to another. Moreover injection into the Injector Ring has to occur also continuously and that may be problematic because one desires enough orbit separation so one injected turn can be avoided by the subsequent one as it is done for instance in Cyclotrons. This issue requires a particular analysis and design that is not done here. It may be that, in order to facilitate the operation, after all injection and stripping of negative ions may still be required.

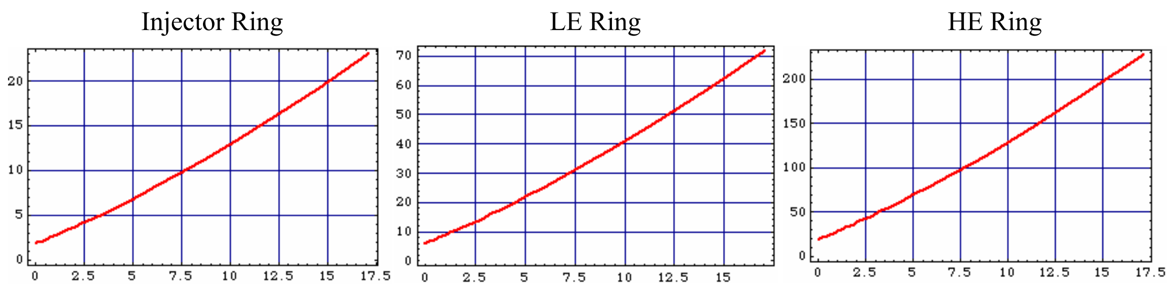

Figure 9. RF Total Voltage (MVolt) vs. Radial Beam Position (cm) for the CW Mode of Operation

One advantage of the CW Mode of operation is that, because of the 100% duty cycle, the current of the beam spill is 1.5 mA for a total power of 20 MW at 11.6 GeV. When this is multiplied by the number of beam turns actually circulating in any one the three rings the total circulating current varies between 0.2 and 0.3 mA from one to the other ring; that is considerably lower then the circulating peak current of 5.8 Amp in the Pulsed Mode. Correspondingly the space charge and beam loading effects are also commensurably lower. Moreover, since one expects that in the CW Mode there will be less destructive effects on the target, a considerably higher beam power can be sought for a more optimized neutrino production.

Betatron Tune Variation during Acceleration

Because we have adopted a *Non-Scaling* FFAG lattice with a *Linear* Field Profile there is a considerable large betatron tune shift during acceleration which because of the assumption of identical lattices is the same in all rings. That is shown in Figure 10. 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. Figure 11 shows the closed orbits at intermediate energy values between injection and extraction along the length of half the FDF period. Again, because of similarity between the lattices, that picture is about the same for all rings.

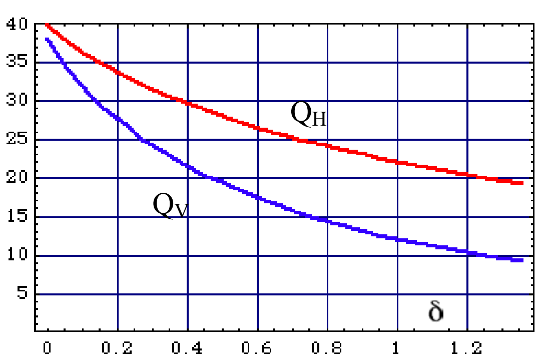

Figure 10. Tune Variation vs. Momentum

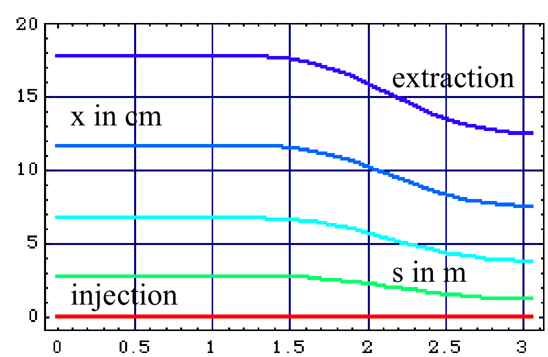

Figure 11. Closed Orbits vs Half-Period Length

Conclusions

Our feasibility studies show that FFAG Accelerators are suitable as Proton Drivers for beam power up to and exceeding 20 MW and beam energy up to 12 GeV. There are nonetheless some issues that need to be addressed with a more careful study in the near future. They are: The higher power mode corresponds to large Space Charge Forces at Injection. To reach the high beam intensity Multi-turn Injection of H^- is needed. Both of these feature need a high energy Injector Linac (400-MeV DTL or what else?). 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. Such tuneability need to be demonstrated especially at the required beam power level. Finally with adoption of the *Non-Scaling* FFAG Lattice that allows more compact and narrower magnet arrangement, and of the Linear Field profile, 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.

We have investigated a pulsed Mode of Operation for a beam repetition rate as large as 100 Hz. To alleviate the effects of thermal shock on the target a higher repetition rate is even more desirable, that though would be difficult to attain in practice. We have then investigated the possibility of CW Mode of Operation with the application of the *Harmonic Number Jump* method. This though would require a considerably higher constant-frequency RF voltage that may be attainable only with superconducting technology.

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 [10]. But most important, because of the use of conventional room-temperature magnets, that is of reliable state of the art of the technology involved, FFAG Accelerators could also be comparatively more economical.

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