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FFAG-Based High-Intensity Proton Drivers*

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Abstract. This paper is the summary of a feasibility study of a Fixed-Field Alternating-Gradient (FFAG) Accelerator for Protons in the one-to-few GeV energy range, and average beam power of several MWatt. The example we have adopted here is a beam energy of 1 GeV and an average power of 10 MWatt, but of course the same design approach can be used with other beam parameters. The design principles, merits and limitations of the FFAG accelerators have been described previously [1]. In particular, more advanced techniques to minimize magnet dimension and field strength have been recently proposed. The design makes use of a novel concept by which it is possible to cancel chromatic effects, thus making betatron tunes and functions independent of the particle momentum, with an *Adjusted Field Profile* [2]. The example given here assumes a pulsed mode of operation at the repetition rate of 1.0 kHz.

Keywords: FFAG Accelerators, Proton Driver, High-Intensity Beam, High-Power Beam, Proton Beam
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INTRODUCTION

There are several applications that may require high-intensity proton accelerators in the one to few GeV energy range capable to deliver an average beam power of several MWatt. Some of these applications are: Spallation Neutron Sources, Accelerator-Driven Tritium Production, Nuclear Waste Transmutation, Nuclear Energy Production, by either Nuclear Fission or Fusion methods, production of Radio-Isotopes and Exotic Nuclear Fragments, and intense beams of Mesons, Muons and Neutrinos for Nuclear and High-Energy Physics. Several proton accelerators architectures have been proposed and studied for all or some of these applications, namely: Cyclotrons, Rapid-Cycling Synchrotrons, Room-Temperature and Super-Conducting Linacs, Induction Linacs, and FFAG accelerators.

FFAG accelerators are an old technology proposed and demonstrated about a half a century ago [3]. They have been proposed in the past especially in connection of Spallation Neutron Sources [4]. But, despite a considerable amount of design and feasibility studies, FFAG accelerators were never endorsed by the scientific community, because they were perceived owing a too complex orbit dynamics, a too large momentum aperture required for acceleration, and consequently too expensive magnets. RF acceleration was also considered problematic over such a large momentum aperture. Moreover, the FFAG accelerator was always coupled to large injection energy (of few hundred MeV) at one end, and to the need of stacking/accumulating devices at the other end of the accelerating cycle.

Recently, there is a renewed interest in FFAG accelerators, first of all because of the practical demonstration [5] of a 150-MeV proton accelerator at KEK, Japan, and secondly because of a more modern approach to beam dynamics and magnet lattice design, and of some important innovative ideas [1, 2] concerning momentum compaction and magnet dimensions. Because of the more recent development, FFAG accelerators are presently a very appealing and competitive technology that can allow a beam performance at the same level of the other accelerator architectures. Like all other technologies, FFAG accelerators have of course their own pro's and con's, but it is undoubted that they can fulfill the requirements set by the application.

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FEATURES OF THE FFAG ACCELERATORS

The main feature of the FFAG accelerators is that they are essentially based on conventional room-temperature magnet technology with constant field. As the beam is accelerated by RF cavities, its trajectory spirals from an inner orbit where injection occurs toward an outer orbit from which the beam is extracted. The radial extension of trajectories is entirely confined within the magnet aperture, and the field does not need then to be ramped either for bending or for focusing.

In principle, this mode of operation requires a large momentum excursion that, for instance from 200 MeV to 1.0 GeV is about ±40% around the central momentum value. To avoid that the momentum range gets exceedingly too large, FFAG accelerators require large injection energy, of few hundred MeV, for instance as delivered by a Drift-Tube Linac (DTL).

Another feature of the FFAG accelerator is the use of magnets with combined functions for simultaneous bending and focusing. The field *profile* is not constant but varies across the magnet width and may vary from magnet to magnet. Moreover, the bending and the focusing alternate providing strong focusing and a more compact momentum aperture when compared to cyclotrons. Nevertheless the reverse bending subtracts from the total bending increasing the circumference of the ring.

Different types of magnet lattice configuration have been proposed and investigated; but a lattice made of triplets has been found to be the most advantageous, especially in the FDF configuration. Though there is some freedom in choosing the magnet edge configuration and the relative orientation of the magnets with respect to each other, we have only considered the case that the magnets are combined-function sector magnets with the exit plane of one parallel to the entrance plane of the next. For a certain reference momentum p_0, that we chose to correspond to the injection orbit [1], the entrance and exit angles the corresponding reference trajectory makes with each magnet vanish.

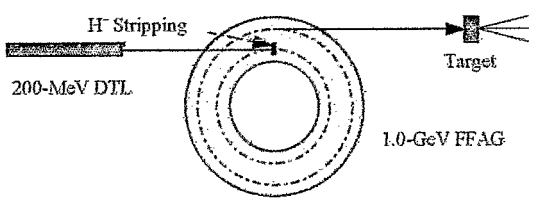

FIGURE 1. Layout of a site-independent 1-GeV 10-MWatt Power Proton Driver.

Four major rules [1, 2, 6] have been proposed for the design of the lattice of the FFAG accelerator to insure stability of motion over the required momentum range for acceleration and a compact magnet configuration. The design of the Proton Driver described here makes use of these major rules.

FFAG ACCELERATOR AS A 1.0-GEV AND 10-MWATT PROTON DRIVER

The average beam proton power from any proton accelerator is given by

$$P = N e F U_f \qquad (1)$$

with e the elementary electric charge, N the number of protons per cycle, F the repetition rate, and U_f the final kinetic energy.

A site independent example of a High-Power Proton Driver based on the use of a FFAG accelerator is described in Fig. 1. The example assumes acceleration between U_i = 200 MeV and U_f = 1.0 GeV. The injector could be a 200-MeV Drift Tube Linac (DTL). Multi-turn injection by stripping of negative ions (H^-) is done over a period of time T_{inj} to reach the desired number of protons N per FFAG cycle. Acceleration proper takes T_{acc} so that the total cycle period is $t = T_{inj} + T_{acc}$, and the repetition rate is $F = 1/t$. The average proton beam current is $I_p = NeF$. The main kinematics parameters are listed in Table 1.

INJECTION, ACCELERATION AND RF CONSIDERATIONS

Let I_L be the peak current from the DTL, and α the ratio of beam chopping required to eliminate potential losses of beam that will not fit in the capturing RF buckets. Let also $\beta_i c$ be the beam velocity at injection, and C the circumference of the FFAG accelerator. The revolution frequency $f = \beta_i c/C$, and the revolution period $T = 1/f$. The number of protons injected per turn is $N_p = \alpha I_L T/e$. We can derive the total number of injected turns required to reach the final intensity $n = N/N_p = Ne/\alpha I_L T$, and the injection period $T_{inj} = n\,T = Ne/\alpha I_L$ that does not depend on the accelerator circumference or on the injection energy.

Let also W be the average energy gain per turn, and $m = (U_f - U_i)/W$ the number of revolutions during acceleration. If T_{ave} is the average revolution period, the acceleration period is $T_{acc} = m\,T_{ave} = (T_{ave}/W)(1 - U_i/U_f)(1 + \eta)\,U_f$, where η is the acceleration time dilation factor that includes, for instance, the

transition between RF capture during multi-turn injection and the onset of the acceleration proper. We can assume $(1 - U_i / U_f)(1 + \eta) \sim 1$ that yields

$$T_{acc} = T_{ave} P \tau / W Ne \quad (2)$$

By combining this to the injection period T_{inj} to get the FFAG cycle time $\tau = T_{inj} + T_{acc}$, we finally have

$$\tau = Ne / a I_L (1 - P / P_B)$$

$$= T_{inj} / (1 - P / P_B) \quad (3)$$

where $P_B = W Ne / T_{ave}$ is the average circulating beam power during acceleration. Clearly one requires $P < P_B$. For instance, with $P_B = (3/2) P$, the total FFAG cycle period $\tau = 3 T_{inj}$. For stable beam RF loading operation, we should add to the RF power P_{RF} an amount about equal to P_B being dissipated in the RF cavity system. Since the RF power by far dominates all other power consumptions in the ring we can infer that the overall efficiency $P / P_{RF} \sim 33\%$.

Considering our example of proton driver with an average beam power of 10 MWatt, a consistent set of parameters is $a = 0.5$, $I_L = 60$ mA and $N = 6.25 \times 10^{13}$ protons per cycle that yields $T_{inj} = 0.333$ ms and $T_{acc} = 0.667$ ms. In this case $P_{RF} = 2 P_B = 30$ MWatt. From Eq. (3) the average energy gain per turn is

$$W/C = (5.0 \text{ keV/turn}) / \beta_{ave} \quad (4)$$

where $c \beta_{ave}$ is the average value of the beam velocity $c\beta$ during acceleration.

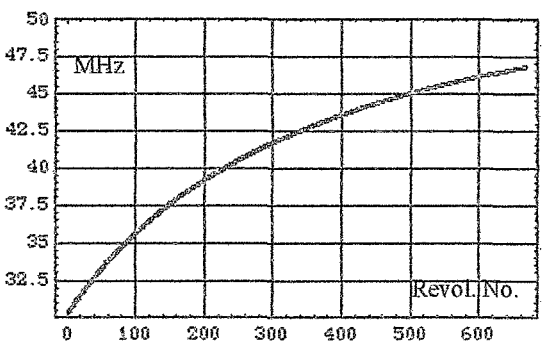

FIGURE 2. RF Modulation, Harmonic Number h = 36.

We have designed an FFAG lattice described next with a circumference C = 201 m. Since $\beta_{ave} \sim 0.75$ the required energy gain is W = 1.2 MeV/turn and the RF peak voltage 1.8 MVolt. Acceleration can be accomplished with ferrite-driven single-gap cavities, each about 1 m long, with an internal diameter of 10 cm. Assuming a gap voltage of 45 kVolt, 40 cavities are needed. Each cavity is to be driven by a 0.8 MWatt power amplifier. With the harmonic number h = 36, the RF frequency modulation is as shown in Fig. 2. A major concern is of course the cavity ferrite operating in that frequency range and that is to be swept in about one third of a millisecond. Tables 5 and 6 give respectively a summary of the Acceleration Parameters and of the RF Cavity System.

TABLE 1. Proton Driver Kinematic Parameters

	Injection	Extraction
Kinetic Energy, MeV	200	1,000
β	0.56616	0.87503
Momentum, MeV/c	644.44	1,696.04
Magn. Rigidity, kG-m	21.496	56.574
Beam Ave. Power	10 MWatt	
Repetition Rate	1.0 kHz	
Beam Ave. Current	10.0 mA	
Total Protons / Cycle	6.25×10^{13}	

TABLE 2. Magnet Parameters for the Injection Orbit

Magnet Type	F	D
Arc Length, m	0.35	0.70
Bending Field B, kG	– 2.118	4.956
Gradient G, kG/m	71.12	–23.2956
Bending Radius ρ, m	–40.5958	62.65
Bending Angle, mrad	–34.49	80.69
Bending Ratio (D/F)	2.34	

DESIGN OF THE FFAG LATTICE

The design is made considerably easier with a large ring circumference and periodicity [1]. We believe nevertheless that such a Proton Facility should be as compact as possible. We have found a reasonable solution with a circumference C = 201.8 m and a periodicity of 68 identical FDF triplets. We have of course followed the procedure described in [1, 2 and 6]. In particular we have adopted a *Non-Scaling Lattice*. The period, shown in Fig. 3, is similar to the one we have adopted for the AGS Upgrade [7] and already represents a solution close to optimization, and from which we have scaled the new design with different injection energy and circumference. The dimensions of the Drifts and of the Sector Magnets have also been scaled accordingly as described in [1]. The lattice functions, estimated at the injection energy, are shown in Fig. 4. The magnet and lattice parameters, on the injection orbit, are summarized in Tables 2 and 3. The long drift S is 1.25 m long, enough to accommodate a single-gap RF cavity.

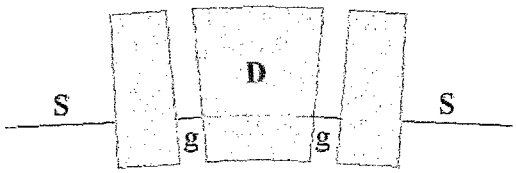

FIGURE 3. Period of the FFAG Proton Driver

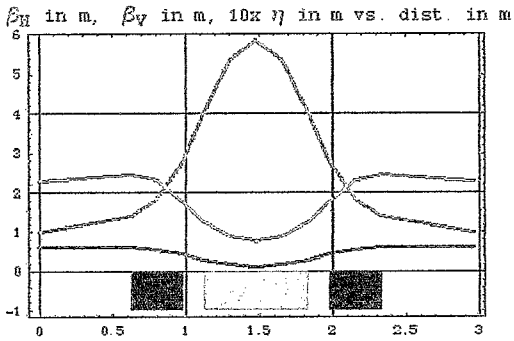

FIGURE 4. Lattice Function at Injection

ADJUSTED FIELD PROFILE

To compensate for the chromatic effects we have adopted *Adjusted Field Profiles* [1, 2] that are shown along the length of the magnets in Fig.s 5 and 6. The Magnetic Fields have strength within acceptable range.

The variation of the fractional betatron tunes during acceleration is shown in Fig. 7. There is a change of about 0.2 caused by the entrance and exit angles the particle trajectory makes with the edges of the magnets [6]. We believe the change to be acceptable. The compactness of the trajectories at different momentum values along the length of half a period is shown in Fig. 8. The orbit separation is less than 4 cm in the middle of the long straight section. The magnet design is then very compact and feasible. The technical feasibility of the sector magnets that include properly the *Adjusted Field Profiles* needs careful study and a practical demonstration.

BEAM AND MAGNET DIMENSIONS

The parameters at injection are listed in Table 4. The beam emittance at the space-charge tune-shift of 0.5 is 150 π mm-mrad; but because the betatron beta functions are also small, the overall beam dimensions during acceleration are modest and can be safely fit in an elliptical vacuum chamber 20 cm wide and 10 cm high. The overall magnet dimensions are thus about 2 feet x 2 feet. The design procedure to be followed is thus essentially the same as described in [7]. It is seen that the power consumption for the magnets is modest (~ 1 MWatt), and considerably smaller than that required for the RF acceleration.

There is enough drift space for the accommodation of magnet components for injection and extraction that follow closely the layout described in the similar note [7] of the 1.5-GeV FFAG for the BNL-AGS Upgrade.

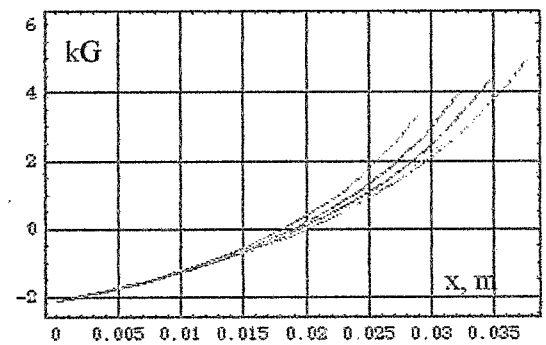

FIGURE 5. Field Profile in the F-Sector Magnet

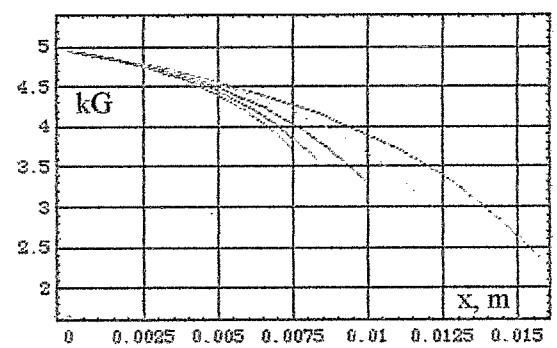

FIGURE 6. Field Profile in the D-Sector Magnet

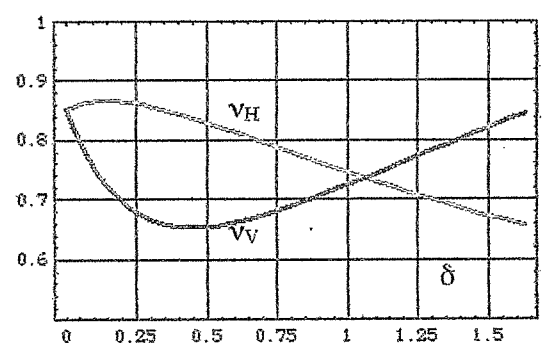

FIGURE 7. Tune Variation during Acceleration

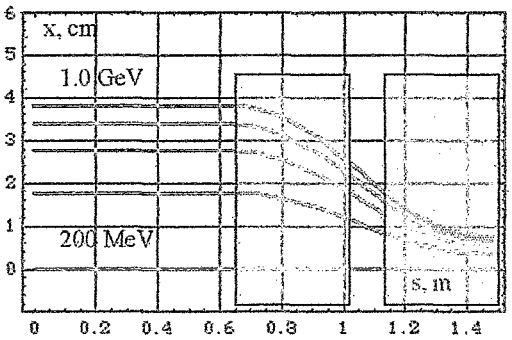

FIGURE 8. Trajectory Bundle in the Proton Driver

TABLE 3 Parameters for the Injection Trajectory

Circumference	201.773 m
Number of Periods	68
Period Length	2.96725 m
Period Structure	S F g D g F S
Short Drift, g	0.15 m
Long Drift, S (total)	1.26725 m
β_H max (in S)	2.27 m
β_V max (in D)	5.854 m
η max (in S)	0.0603 m
Phase Adv. / Period, H/V	105.10° / 99.802°
Betatron Tunes, H/V	19.8515 / 18.8514
Natural Chromaticity, H/V	–0.915 / –1.787
Transition Energy, γ_T	53.755 i

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TABLE 4. Injection into the FFAG Proton Driver

Linac Peak Current	60 mA
Revolution Period	1.888 μs
No. of Protons / FFAG pulse	0.94×10^{14}
Chopping Ratio	0.50
Chopping Frequency	30.283 MHz
Single Pulse Length	0.50 ms
No. of Turns Injected / pulse	265
Linac/FFAG repet. rate	1.0 kHz
Linac Duty Cycle	50 %
Linac Emittance, rms norm.	1 π mm-mrad
Final Emittance, full norm.	150 π mm-mrad
Bunching Factor	3
Space-Charge Tune-Shift	0.50

TABLE 5. Acceleration in the Proton Driver

Circumference	201.773 m
Harmonic Number, h	36
Energy Gain	1.2 MeV / turn
Transition Energy, γ_T	53.755 i
Peak RF Voltage	1.8 MVolt
Number of full Buckets	26 out of 36
Total Number of Protons	6.25×10^{13}
Bunch Area, full	0.4 eV-sec
Protons / Bunch	2.4×10^{12}
Injection Period	0.333 ms
Acceleration Period	0.667 ms
Total Cycle Period	1.0 ms

TABLE 6. RF Cavity System

No. of RF Cavities	40	
No. of Gaps per Cavity	1	
Cavity Length	1.0 m	
Internal Diameter	10 cm	
Peak Voltage / Cavity	45 kVolt	
Power Amplifier / Cavity	0.8 MW	
Energy Range, MeV	200	1,000
β	0.566	0.875
Rev. Frequency, MHz	0.841	1.300
Revolution Period, μs	1.189	0.769
RF Frequency, MHz	30.28	46.80
Peak Current, Amp	12.65	19.55
Peak Beam Power, MW	15.2	23.5

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