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1.5-GEV FFAG ACCELERATOR AS INJECTOR TO THE BNL-AGS*

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Abstract

A 1.5-GeV Fixed-Field Alternating-Gradient (FFAG) proton Accelerator is being studied as a new injector to the Alternating-Gradient Synchrotron (AGS) of Brookhaven National Laboratory (BNL). The major benefit is that it would considerably shorten the overall AGS acceleration cycle, and, consequently, may yield to an improvement of beam stability, intensity and size. The AGS-FFAG will also facilitate the proposed upgrade of the AGS facility toward a 1-MW average proton beam power at the top energy of 28 GeV. This paper describes the FFAG design for acceleration of protons from 400 MeV to 1.5 GeV, with the same circumference of the AGS, and entirely housed in the AGS tunnel.

THE BNL-AGS FACILITY

The present BNL-AGS accelerator complex is shown schematically in Figure 1. The 1.5-GeV Booster plays a central role for the collection and preparation of all types of particle beams before they are transferred to the AGS. The AGS circumference is four times that of the Booster, so that a complete fill of the AGS requires also four Booster beam pulses. Presently, the repetition rate of the Booster and the AGS are 7.5 Hz and 0.5 Hz, respectively. That requires a filling time of the AGS to be about 0.5 second, followed by about one second for acceleration to the top energy, and another second for resetting the AGS field cycle. At best, the overall cycle period is 2.5 seconds. Moreover, a filling time of 0.5 second is a long period where several effects on the stored beam may occur, with consequent losses and size deterioration. One would expect a great improvement on the beam quality and performance if the filling time can be shortened so that particles do not have to wait too long before they are accelerated.

THE AGS UPGRADE PROGRAM

It has recently been proposed to upgrade the AGS facility for an average proton beam power of at least one MW. This can be accomplished in two steps: (1) the replacement of the main magnet AGS power supply with one operating at 2.5 Hz, and (2) a Super-Conducting Linac (SCL) for direct acceleration of protons from the 200-MeV Drift-Tube Linac (DTL) to 1.2 GeV. This mode of operation completely bypasses the Booster, and eliminates the 0.5 s long injection period. A feasibility study of the 1.2-GeV SCL has already been done. Such a device is relatively expensive, and is a technology that still needs to be completely demonstrated. On the other end, a 1.5-GeV FFAG accelerator represents a valid alternative to the 1.2-GeV SCL, fulfilling the same power requirements. To ease the design of the SCL proper, it has also been proposed to raise the energy of the DTL from 200 to 400 MeV. We shall assume such upgrade in energy of the DTL also with the study of the FFAG injector.

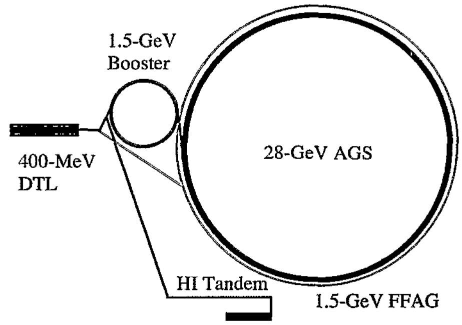

Figure 1. AGS Upgrade with 1.5-GeV FFAG

MODE OF OPERATION

The FFAG accelerator by definition has the bending and focusing fields constant during acceleration. The magnets are not ramped, so that the resulting cycle can be made considerably shorter. Assuming the FFAG ring has the same size of the AGS and is installed in the same tunnel, with an energy gain of one MeV/turn the total acceleration cycle takes about 8.0 msec. Only a single acceleration cycle in the FFAG is required to get a desired intensity proton beam, transferred in a single turn to the AGS. The proton beam will be provided by the Linac upgraded to 400 MeV. The full intensity of 1.0 x 10^{14} protons per FFAG pulse can be attained with multi-turn injection at 400 MeV by charge exchange with a Linac pulse 1.0 ms long at the rate of 2.5 cycles/second.

FFAG ACCELERATOR ISSUES

The most important issue is the search for an ideal lattice that accommodates a large momentum aperture that in our case extends over ±40%. Without entering too much in the detailed discussion of *scaling* versus *non-scaling* lattices, it will suffice to say here that it is certainly highly desirable to find a magnet arrangement where the lattice functions, for instance the betatron tunes, do not change too much over the required momentum range. It is almost impossible to find a *scaling* FFAG lattice for a 1.5 GeV proton, especially if one wants to limit the strength of the bending and focusing fields, that otherwise may require magnets with too large radial aperture. We adopted a *non-scaling* lattice based on the FDF triplet that requires only modest fields.

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THE LATTICE OF THE AGS-FFAG

The FFAG ring has a circumference of 807.091 m, equal to that of the AGS, and is made of 136 identical periods, each 5.935 m long. The period, shown in Figure 2, is made of three combined-function sector magnets in the symmetric FDF arrangement. The trajectory shown is that of the reference momentum value p_0 taken at injection. The parameter δ is used to define the momentum of any particle $p = p_0 (1 + \delta)$. At injection $\delta = 0$, and $\delta = 1.36$ at 1.5 GeV.

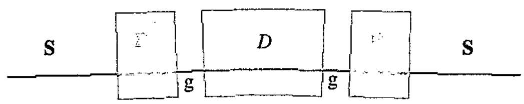

Figure 2. The AGS-FFAG Period.

The entrance and exit faces of the D-sector magnet are geometrically parallel to the neighboring ones of the two F-sector magnets. Thus, the entrance and exit angles the injection trajectory makes with each magnet are identically equal to zero. This is not true for an off-momentum trajectory. The lattice parameters are shown in Tables 1 and 2.

Table 1. Magnet Parameters for the Injection Orbit

Magnet Type	F	D
Arc Length, m	0.70	0.70
Bending Field, kG	– 0.78409	1.8345
Gradient, kG/m	26.5817	–23.2956
Bending Radius, m	–40.5958	17.3512
Bending Angle, mrad	–17.2432	80.6862

The lattice functions across one period on the injection trajectory are displayed in Figure 3. The lattice parameters are summarized in Table 2. The phase advance per period is around 100° in both planes, and the betatron tunes differ from each other by two units to avoid the effect of a coupling resonance. Because of the reverse bending the transition energy is pure imaginary.

ADJUSTED FIELD PROFILE

We succeeded in finding a stable solution with a linear field profile adopting a *non-scaling* FFAG lattice. The fixed gradient makes variations in tunes per cell between 0.4 at injection and 0.1 at top energy. The vertical amplitude lattice function has large variations at the beginning and at the end of the cycle. We have devised a method [1] to adjust the magnetic field profile to cancel this momentum dependence. The relationship between closed orbit $x = x(\delta)$ and momentum deviation $\delta$was used to derive by an inversion a dependence of momentum $\delta = \delta(x)$. With the use of the powerful symbolic language of MATHEMATICA [2], it is possible to invert relationships and to derive δ as a function of displacement x and obtain the actual field profile versus radial aperture. The results are shown in Figure 4. The bending field is plotted versus the radial location x. The central orbit ($x = 0$) is the beam orbit with the kinetic energy of 400 MeV. The magnetic field profile is nonlinear transversely and in addition varies along the length of the magnet. The F-sector magnet is essentially a quadrupole with a field range between –0.8 and +0.8 kGauss centered about $x = 1.85$ cm on top of which nonlinearities are added. The D-sector magnet has the typical profile of a combined function magnet extending over a narrower radial excursion between $x = 0$ and 1.4 cm.

Table 3. The AGS-FFAG Parameters at Injection

Circumference	807.091 m
Number of Periods	136
Period Length	5.9345 m
Period Structure	S F g D g F S
Short Drift, g	0.30 m
Long Drift, S (total)	2.5345 m
β_H max (in S)	4.5733 m
β_V max (in D)	11.7902 m
η max (in S)	0.060 m
Phase Advance, H/V	105.234° / 99.9345°
Betatron Tunes, H/V	39.755 / 37.755
Chromaticity, H/V	–0.9263 / –1.8052
Transition Energy, γ_T	105.482 i

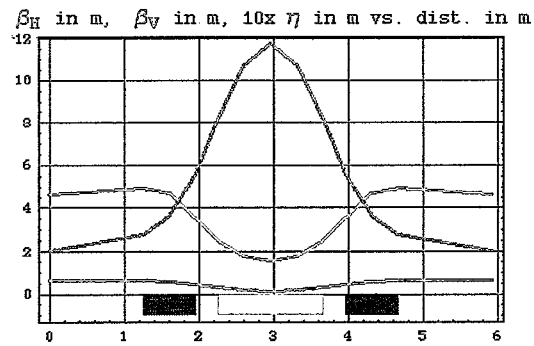

Figure 3. The AGS-FFAG Lattice Functions for the Injection Orbit ($\delta = 0$)

MOMENTUM DEPENDENCE

The closed orbits x_P for momentum values in the range $\delta = 0 - 1.36$ are plotted in Figure 5 versus the longitudinal coordinate s across half of a period. The derivative x_P' gives the entrance and exit angles the off-momentum trajectories make with each of the sector magnets. They have a focusing/defocusing effect, and their contribution to the lattice functions has been properly included in our calculation. Finally the fractional part of the betatron tunes ν_H and ν_V are plotted in Figure 6 versus the momentum deviation δ. During the entire acceleration cycle each tune does not vary by more than 0.1.

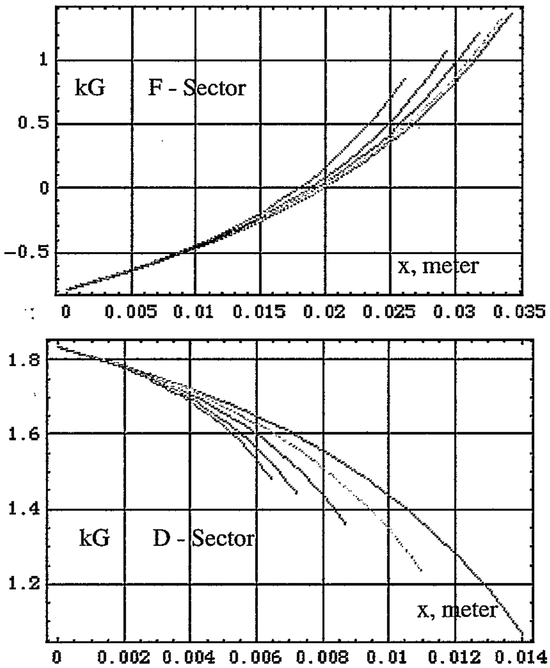

Figure 4. Field Profiles vs. Radial (x) Position

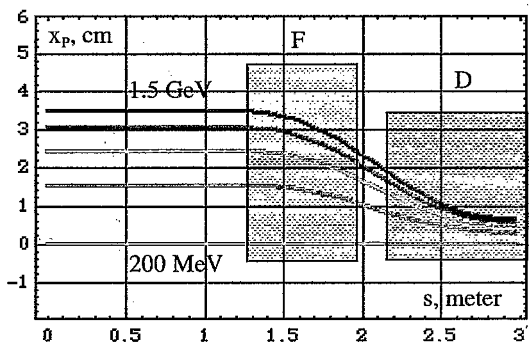

Figure 5. Closed Orbit vs. Path Length

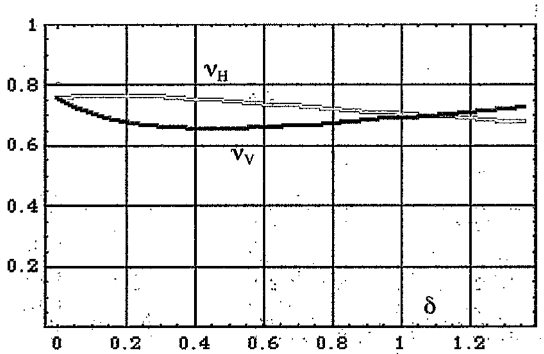

Figure 6. Fractional part of ν_H and ν_V versus δ

INJECTION INTO THE AGS-FFAG

About 260 turns of negative-ions H^- are to be injected from the 400-MeV DTL into the AGS-FFAG. Multi-turn injection last about 1.0 ms. At the end of the process the beam extends over the length of one turn, with a gap of about 300 ns. To avoid unnecessary beam losses, the beam is pre-chopped at the beginning of the DTL for the duration of about 50% of the revolution period. Table 4 gives the summary of the beam parameters at injection. The maximum tune-depression is reached at the end of multi-turn injection. The unperturbed tunes have been chosen to avoid the crossing of any major systematic resonance up to order 15th included.

Table 4. Beam Parameters at Injection into the FFAG

Linac Peak Current	35 mA
Revolution Period	3.78 μs
No. of Protons / FFAG pulse	1.0 x 10^{14}
Chopping Ratio	0.50
Chopping Frequency	6.357 MHz
Single Pulse Length	0.96 ms
No. of Turns Injected / pulse	255
Linac/FFAG repetition rate	2.5 Hz
Linac Duty Cycle	0.24 %
Linac Beam Emittance, rms norm.	1 π mm-mrad
Final Beam Emittance, full norm.	100 π mm-mrad
Bunching Factor	3
Space-Charge Tune-Shift	0.50

ACCELERATION IN THE AGS-FFAG

We opted for the RF modulation. We assumed a constant energy gain of 0.5 MeV/turn and harmonic number h = 24. To create a beam gap of 300 nsec for the extraction kicker, two consecutive out of the 24 RF buckets are void of any beam. Table 5 gives a summary of the RF acceleration parameters. It is possible to add more cavities in the future for a shorter acceleration period.

Table 5. Parameters of Acceleration in the AGS-FFAG

Harmonic Number, h	24	
Energy Gain	0.5 MeV / turn	
Acceleration Period	7.0 msec	
No. of Revolutions	2,200	
Peak RF Voltage	0.8 MVolt	
Number of full Buckets	22 out of 24	
Total Number of Protons	1.0 x 10^{14}	
Protons / Bunch	4.6 x 10^{12}	
No. of RF Cavities	20	
Peak Voltage / Cavity	40 kVolt	
Power Amplifier / Cavity	250 kW	
Energy Range, MeV	**400**	**1,500**
Revol. Period, μs	3.78	2.92
RF Frequency, MHz	6.357	8.228
Peak Beam Current, Amp	4.24	5.49
Peak Beam Power, MW	2.12	2.75

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[1] A.G. Ruggiero, BNL Int. Rep., C-A/AP/#148. 4/2004.
[2] MATHEMATICA, http://www.wolfram.com