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# FFAG Accelerator as a New Injector for the BNL-AGS*

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**Abstract.** It has been proposed recently to upgrade the Alternating-Gradient Synchrotron (AGS) of Brookhaven National Laboratory (BNL) to an average proton beam power of one MWatt at the top energy of 28 GeV. This is to be accomplished primarily by raising the AGS repetition rate from the present ~ 1/3 to 2.5 pulses per second, and by a relatively modest increase of beam intensity from the present 0.7 to about 1.0 x $10^{14}$ protons per cycle. The present injector, the 1.5 GeV Booster, has a circumference a quarter of that of the AGS, and four successive beam pulses are required for a complete fill of the AGS. The filling time at injection is thus at least 0.5 seconds, and it ought to be eliminated if one desires to shorten the AGS cycle period. Moreover, holding the beam for such a long period of time during injection causes its quality to dotoriate and beam losses. This report is the summary of the results of a feasibility study of a 1.5 GeV Fixed-Field Alternating-Gradient (FFAG) Accelerator as a new possible injection to the AGS.

**Keywords:** FFAG Accelerators, Upgrade, Synchrotrons, Proton Beams, High Intensity.
**PACS:** 29.20.-c

## 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 neither for bending nor for focusing. In principle, this mode of operation requires a large momentum excursion that, for instance, from 400 MeV to 1.5 GeV is about ±40% around the central momentum value.

Another feature of the FFAG accelerator is the use of magnets with combined function 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.

Recently, four major rules where devised [1] for the design of a compact and stable FFAG accelerator lattice. The rules are as follows: (1) Tune the ring lattice for stability at the lower end of the momentum range, that is at injection; (2) Use FDF triplets made of sector magnets; (3) Make use of the *Adjusted Field Profile* [2] for the compensation of the chromaticity; and (4) chose a large circumference and periodicity to reduce the effects of the magnets edges [3]. These rules have been applied consistently to the design of the 1.5-GeV FFAG accelerator for the AGS Upgrade.

## 1.5-GEV FFAG AS A NEW INJECTOR TO THE BNL AGS

The layout of the AGS facility is shown in Fig. 1. For the time being it has been proposed to replace the Booster with a 1.2-GeV Super-Conducting Linac (SCL) [4] that connects directly the 200-MeV room-temperature Drift-

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Tube Linac (DTL) to the AGS. At the same time it has also been suggested to upgrade the DTL energy to 400 MeV by replacing the last four tanks with a 805 MHz RF system as it was done at Fermilab [5].

It has also been found necessary to investigate alternative solutions like, for instance, the use of a 1.5-GeV FFAG accelerator replacing the Booster, instead of the SCL. For this purpose, the best scenario so far developed is to locate the new injector in the same tunnel on top of the AGS magnets. The circumference of the two rings would then be the same 807 m.

The 1.5-GeV FFAG injector to the AGS is made of an unbroken sequence of 136 periods each made of a FDF triplet as shown in Fig. 2. To be noticed is the double mirror symmetry of the lattice around the middle point of the long straight and the middle of the D-sector magnet. The main parameters are listed in Tables 1 and 2.

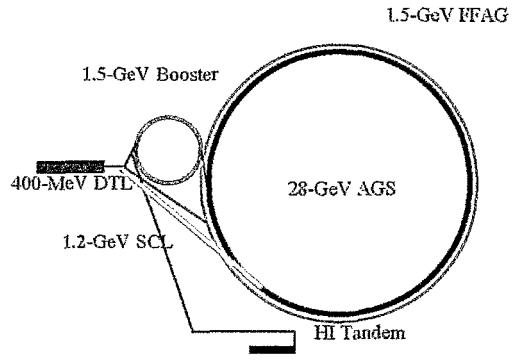


**FIGURE 1.** AGS Upgrade with 1.2-GeV SCL or 1.5-GeV FFAG

The lattice was tuned at the desired values at the low energy end of 400 MeV. The lattice functions across the period are plotted in Fig. 3. The lattice parameters are in Table 3. The amplitude β-functions are smaller than those in the present Booster, and the dispersion is considerably reduced to about 4.0 cm in the middle of the long straight. The phase advance per period is close to 100° in both planes. The transition energy is very large and imaginary because of the reverse bending. Moreover, the required field and gradient have modest values.

## ADJUSTED FIELD PROFILE

**FIGURE 2.** The AGS-FFAG Period (FDF) and the Injection Trajectory.

When applying the *Adjusted Field Profile* rule [2] for the chromaticity compensation, the field distribution versus the radial displacement x at five different equally spaced longitudinal locations is determined, shown in Fig.s 4 and 5 respectively for the F and half of the D sector magnets. There is a considerable amount of non-linearity involved. Still the strength across the radial extension remains limited to only few kGauss. In particular the F-magnet looks more like a quadrupole, and the D-magnet a typical combined-function sector magnet. The magnets have been conceptually designed and judged feasible, as they are shown in Fig.s 6 and 7 with their parameters listed in Table 4. Supplementary coils are located surrounding the vacuum chamber for the creation and control of the desired field profile. The shape and separation of the magnet poles have also to be tapered properly.

The betatron tune variation during acceleration with the *Adjusted Field Profile* is shown in Fig. 8. The variation is less than 0.1, mostly caused by the entrance and exit angles trajectories make with the magnets [3]. The actual *Bundle* of trajectories covering the full momentum range is shown in Fig. 9. The radial extension is of only 3.6 mm at the entrance of the F-magnet and drops down to less than a millimeter in the middle of the D-magnet.

The vacuum chamber has an elliptical cross-section 18 cm wide and 9 cm high. It is made of a 2 mm stainless steel, since the requirements on the vacuum pressure are relaxed. Assuming a beam full emittance of 100 $\pi$ mm-mrad, the actual location and dimension of the beam during acceleration in the vacuum chamber is shown in Fig. 10. Shown is also a similar 10-cm diameter circular pipe that can be located in the long straights where RF cavities are needed.

## ACCELERATION CYCLE IN THE FFAG INJECTOR

To get the desired intensity of $10^{14}$ protons per pulse, multi-turn injection of negative ions ($H^-$) is needed. The injection parameters are given in Table 5 and the layout of the injection components is shown in Fig. 12. The entire

injection process takes about one millisecond at the 2.5 Hz repetition rate to be sustained by the present DTL with proper modifications.

During multi-turn injection the beam is captured by the standing-by RF cavity system at the harmonic number h = 24 with about 500 kVolt of peak voltage. The resulting bunch area at the end of the RF capture is 0.4 eV-sec as it was determined by computer simulation including space-charge forces. No beam losses were noticed. At most the space-charge tune depression was estimated to be 0.5, a value that should not present any major concern. The beam is then accelerated to the top energy (1.5 GeV) by a peak RF voltage of 1.2 MVolt in 2,200 revolutions taking about 7 milliseconds. Thus the total acceleration cycle, including multi-turn injection is 8 milliseconds. The main acceleration and RF parameters are given in Tables 6 and 7.

Table 1. Proton Beam Kinematic Parameters

| | Injection | Extraction |
|---|---|---|
| Kinetic Energy, MeV | 400 | 1,500 |
| $\beta$ | 0.713056 | 0.922996 |
| $\gamma$ | 1.42632 | 2.59868 |
| Momentum, MeV/c | 954.263 | 2,250.51 |
| Magn. Rigidity, kG-m | 31.8308 | 75.0691 |
| Momentum $\delta$ | 0 | 1.36 |

Table 2. Magnet Parameters for the Injection Orbit

| Magnet Type | F | D |
|---|---|---|
| Arc Length, m | 0.70 | 1.40 |
| Bending Field B, kG | – 0.78409 | 1.8345 |
| Gradient G, kG/m | 26.5817 | –23.2956 |
| Bending Radius $\rho$, m | –40.5958 | 17.3512 |
| Bending Angle, mrad | –17.2432 | 80.6862 |
| Bending Ratio (D/F) | 2.43 | |

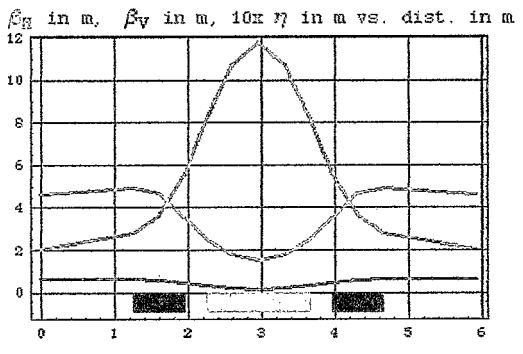


**FIGURE 3.** The AGS-FFAG Lattice Functions for the Injection Orbit ($\delta$ = 0)

Table 3. The AGS-FFAG Parameters for the Reference Trajectory

| | |
|---|---|
| Circumference | 807.091 m |
| Number of Periods | 136 |
| Period Length | 5.93449 m |
| Period Structure | S F g D g F S |
| Short Drift, g | 0.30 m |
| Long Drift, S (total) | 2.53450 m |
| $\beta_H$ max ( in S) | 4.5733 m |
| $\beta_V$ max (in D) | 11.7902 m |
| $\eta$ max (in S) | 0.060 m |
| Phase Adv. / Period, H/V | 105.23° / 99.935° |
| Betatron Tunes, H/V | 39.755 / 37.755 |
| Natural Chromaticity, H/V | –0.926 / –1.805 |
| Transition Energy, $\gamma_T$ | 105.482 i |

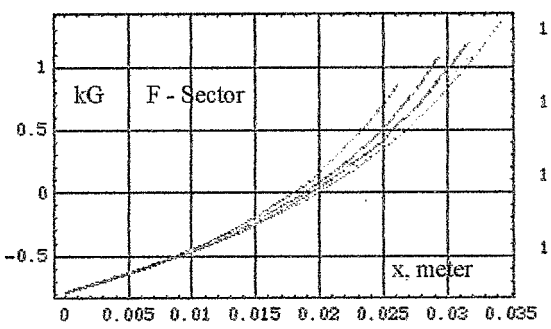


**FIGURE 4.** Field Profiles vs. Radial (x) Position In the F-Sector Magnet

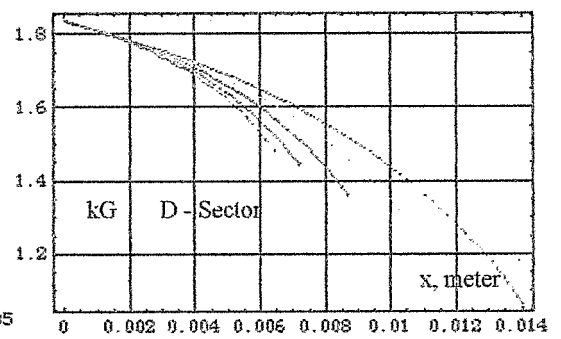


**FIGURE 5.** Field Profiles vs. Radial (x) Position in the D-Sector Magnet

The last step in the cycle is extraction from the FFAG accelerator and transfer to the AGS. The two rings are located in the same tunnel on top of each. Extraction is of a single turn. At that purpose three missing bunches are created in the beam during injection to allow a fast kicker rise time of 0.3 $\mu$s. The main parameters of extraction are summarized in Table 8 and the layout is shown in Fig. 11.

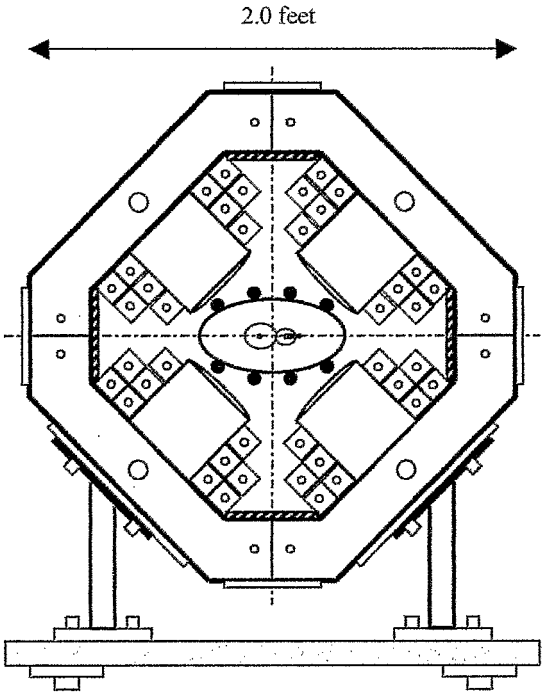


**FIGURE 6.** Conceptual Design of the F-Magnet

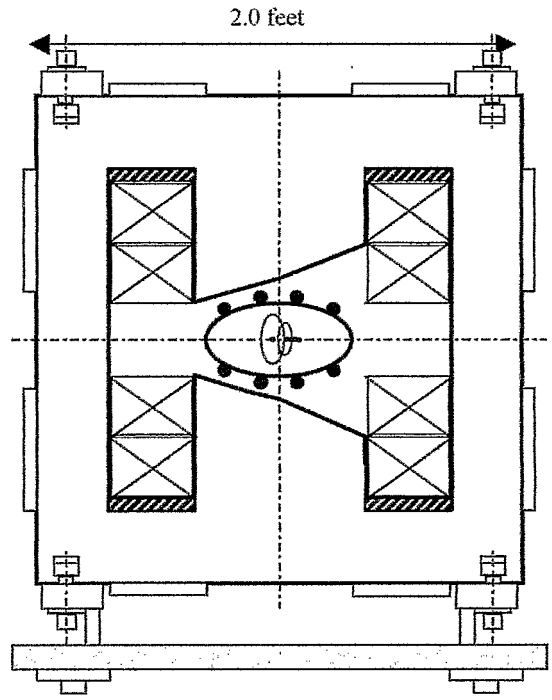


**FIGURE 7.** Conceptual Design of the D-Magnet

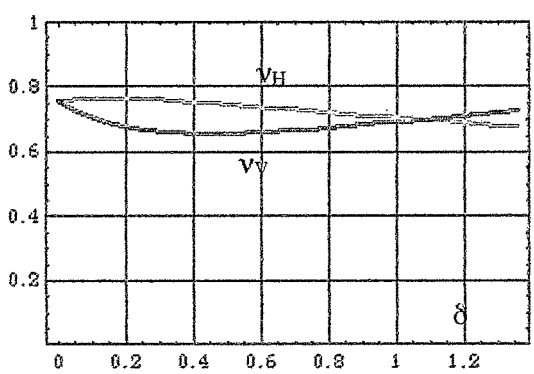


**FIGURE 8.** Fractional Tune versus Momentum δ

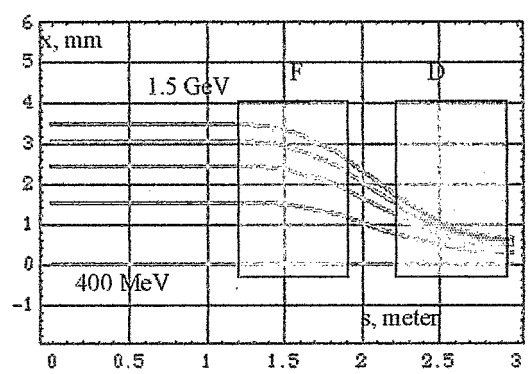


**FIGURE 9.** Orbit Trajectories along half of a Period at different energies

Table 4. List of the AGS-FFAG Magnet Parameters

| Parameter | Unit | F-Sector Magnet | D-Sector Magnet |
|---|---|---|---|
| Type | | Quadrupole | Comb. Function |
| Number of Magnets | | 2 x 136 | 136 |
| Core Length | m | 0.65 | 1.35 |
| Magnetic Length | m | 0.70 | 1.40 |
| Pole Tip Radius | cm | 8.0 | -- |
| Gap Height | cm | -- | 15 |
| Pole Width | cm | 10.5 | 21 |
| No. Pancakes / Magnet | | 4 | 4 |
| No. Turns per Pancake | | 5 | 4 |
| Pole Tip Gradient | kG/ m | 30 | -- |
| Max. Field B | kG | 2.4 | 3.0 |
| Transfer Function B / I | G / I | 1.5 | 2.2 |
| Coil Current I | A | 1,600 | 1,350 |
| Conductor Dimension | mm | 30 x 30 | 25 (H) x 50 (V) |
| Current Density | $A/cm^2$ | 180 | 108 |
| Resistance / Magnet | mΩ | 1.26 | 0.88 |
| Resistance / Total | mΩ | 343 | 120 |
| Inductance / Magnet | mH | 0.50 | 1.87 |
| Inductance/ Total | mH | 136 | 254 |
| Coil Insulation | kV | (20) | (20) |
| Total Voltage, IR | V | 550 | 162 |
| Dissipated Power | kW | 880 | 225 |
| Stored Energy | kJ | 174 | 232 |

## TUNEABILITY OF THE EXTRACTION ENERGY IN THE FFAG ACCELERATOR

One interesting feature of FFAG Accelerators is their flexibility and tuneability of the final energy. With the same design geometry, design procedure, and tuning conditions at the 400-MeV injection energy, it is possible to extend the final energy up to a value of 3.0 GeV. Of course in the meantime the field range and the radial excursion changes. In Fig. 13 we show the field profiles required for 2.0. 2.5 and 3.0 GeV. The bending field at injection of course is unchanged but the field range has increased, though well within acceptable values.

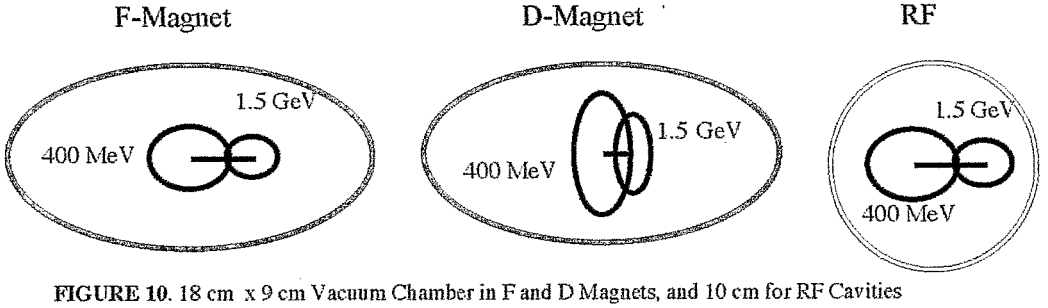


**FIGURE 10.** 18 cm x 9 cm Vacuum Chamber in F and D Magnets, and 10 cm for RF Cavities

Figure 14 shows the fractional part of the betatron tunes across the momentum aperture. It is seen that even at 3.0 GeV the variation of the tunes has increased but still does not exceed 0.2. The same Fig. 14 shows also the required radial aperture to accommodate the full energy range that at most is 4.6 mm.

The energy tuneability is useful if the FFAG is operated as the Injector to the AGS. Indeed in order to squeeze the beam size at the exit of the FFAG acceleration cycle into the transverse aperture of the AGS, it may be beneficial to increase the final energy since the beam physical size would also decrease accordingly. But if the energy gain per

turn during acceleration is kept to 500 keV, the beam average power will not increase by raising the final energy since the acceleration period would correspondingly lengthen and lower the repetition rate. Nevertheless, the acceleration rate is limited by the choice of the RF that operates at harmonic number h = 24 in order to match the acceleration cycle of the AGS.

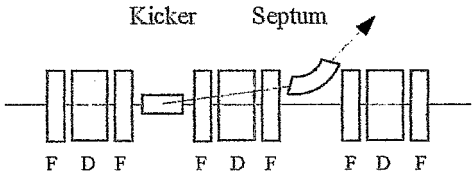


**FIGURE 11.** Extraction from the FFAG

Table 5. Parameters at Injection into the FFAG

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

Table 6. Acceleration in the AGS-FFAG

| | |
|---|---|
| Circumference | 807.091 m |
| Harmonic Number, h | 24 |
| Energy Gain | 0.5 MeV / turn |
| Transition Energy, $\gamma_T$ | 105.5 i |
| Peak RF Voltage | 1.2 MVolt |
| Number of full Buckets | 22 out of 24 |
| Total Number of Protons | $1.0 \times 10^{14}$ |
| Bunch Area, full | 0.4 eV-sec |
| Protons / Bunch | $4.6 \times 10^{12}$ |
| Injection Period | 1.0 ms |
| Acceleration Period | 7.0 ms |
| Total Cycle Period | 8.0 ms |

Table 7. RF Cavity System

| | | |
|---|---|---|
| No. of RF Cavities | 30 | |
| No. of Gaps per Cavity | 1 | |
| Cavity Length | 1.0 m | |
| Internal Diameter | 10 cm | |
| Peak Voltage / Cavity | 40 kVolt | |
| Power Amplifier / Cavity | 250 kW | |
| Energy Range, MeV | 400 | 1,500 |
| β | 0.713 | 0.9230 |
| Rev. Frequency, MHz | 0.265 | 0.3428 |
| Revolution Period, μs | 3.78 | 2.92 |
| RF Frequency, MHz | 6.357 | 8.228 |
| Peak Current, Amp | 4.24 | 5.49 |
| Peak Beam Power, MW | 2.12 | 2.75 |

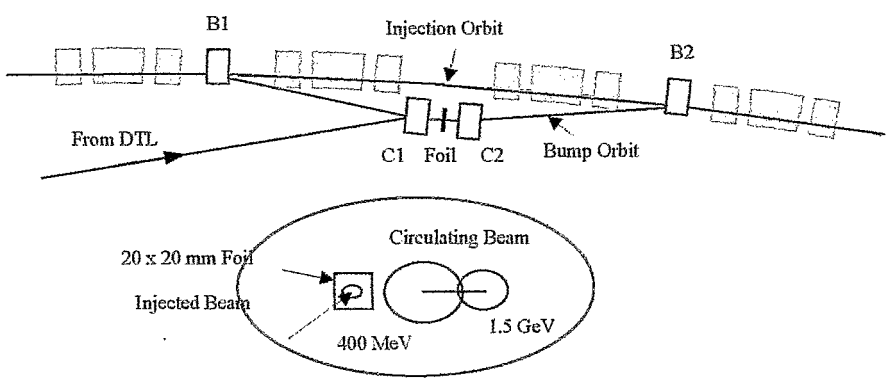


**FIGURE 12.** Injection Transfer Line and Beam Cross-Section at the Foil

Table 8. Parameters of Extraction from the FFAG

| | |
|---|---|
| Revolution Period | 2.92 μs |
| Beam Gap | 300 ns |
| Kicker Magnet, Length | 1.5 m |
| Field | 1 kG |
| Rise-Time | < 300 ns |
| Septum Magnet, Length | 1.5 m |
| Field | 10 kG |
| Repetition Rate | 2.5 Hz |

The Kicker field remains constant for the duration of the beam pulse, and it is finally reset to zero-value in about 400 ms, to be fired again the next cycle.

## CONCLUSIONS

In conclusion, the design of the 1.5-GeV FFAG injector for the AGS appears to be very feasible. Possible concerns are the design and manufacturing of the triplet magnets and the control of imperfections and errors. These issues require a more careful and detailed analysis including numerical tracking, in order to determine tolerances. It may also be possible to replace the non-linear field distribution derived from the *Adjusted Field Profile* with a more simplified model as long this does not influence too much the beam orbit dynamics and the dynamical aperture.

A cost estimate of the technical components that make the FFAG injector gives a figure around 50 M$, that is at least half of that of the corresponding 1.2 GeV SCL. Also the FFAG requires only a conventional room-temperature magnet technology that may need less than the effort otherwise required for the design and construction of the superconducting RF cavities.

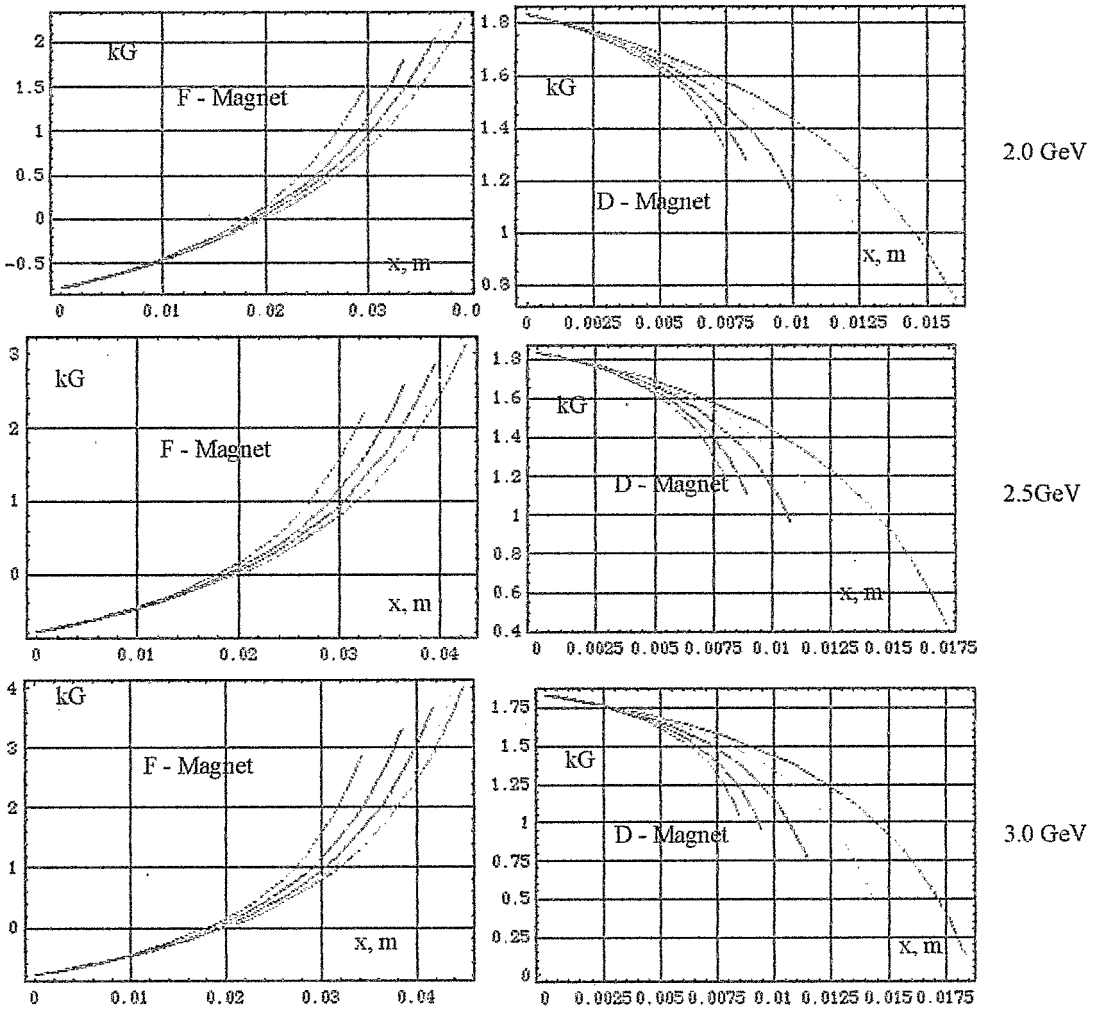


**FIGURE 13.** *Adjusted Field Profile* in the F and Sector Magnets at different final kinetic Energy.

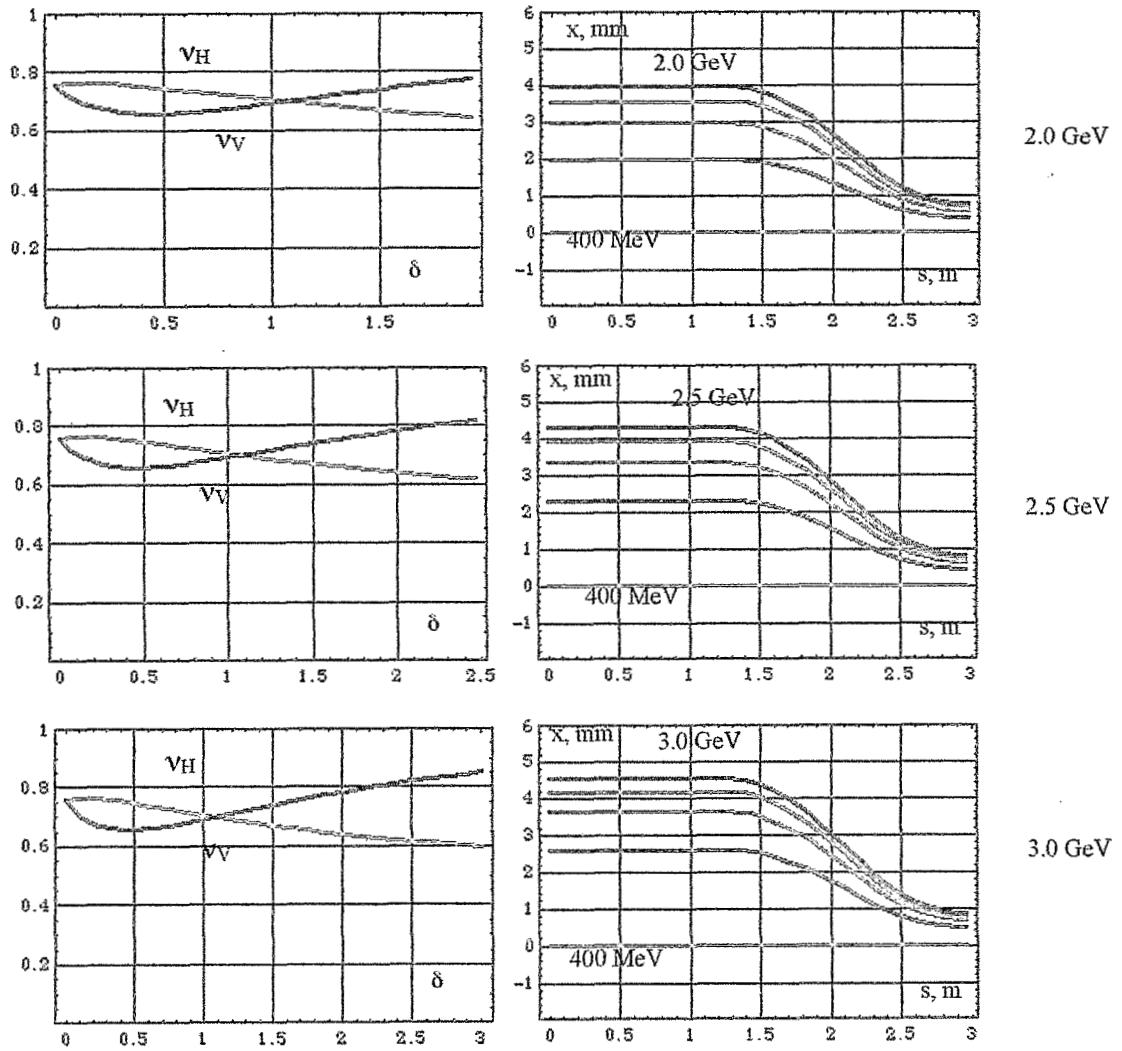


**FIGURE 14.** Tune Variation and radial Displacement across Momentum Aperture for different final Energy

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