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

Alessandro G. Ruggiero

Brookhaven National Laboratory, Collider-Accelerator Department,

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 detoriate 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.
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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 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.

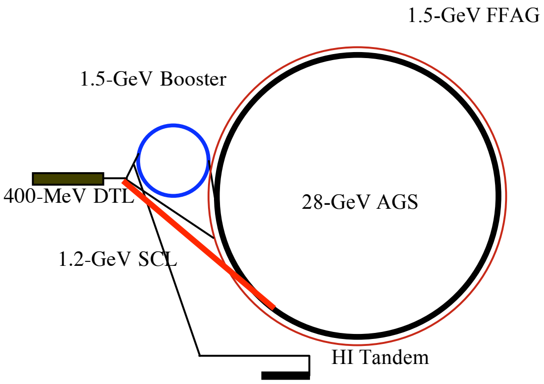

FIGURE 1. AGS Upgrade with 1.2-GeV SCL or 1.5-GeV FFAG

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^o 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

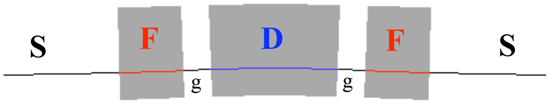

FIGURE 2. The AGS-FFAG Period (FDF) and the Injection Trajectory.

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 π 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
β	0.713056	0.922996
γ	1.42632	2.59868
Momentum, MeV/c	954.263	2,250.51
Magn. Rigidity, kG-m	31.8308	75.0691
Momentum δ	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 ρ, m	–40.5958	17.3512
Bending Angle, mrad	–17.2432	80.6862
Bending Ratio (D/F)	2.43	

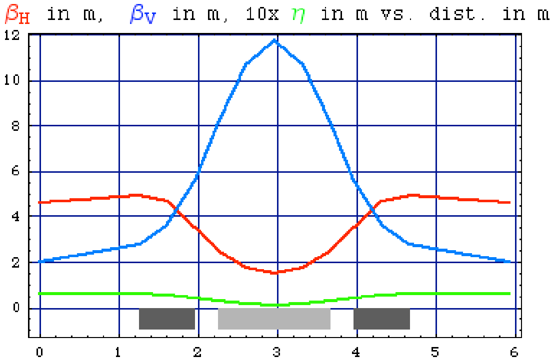

FIGURE 3. The AGS-FFAG Lattice Functions for the Injection Orbit (δ = 0)

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
β_H max (in S)	4.5733 m
β_V max (in D)	11.7902 m
η max (in S)	0.060 m
Phase Adv. / Period, H/V	105.23^o / 99.935^o
Betatron Tunes, H/V	39.755 / 37.755
Natural Chromaticity, H/V	–0.926 / –1.805
Transition Energy, γ_T	105.482 i

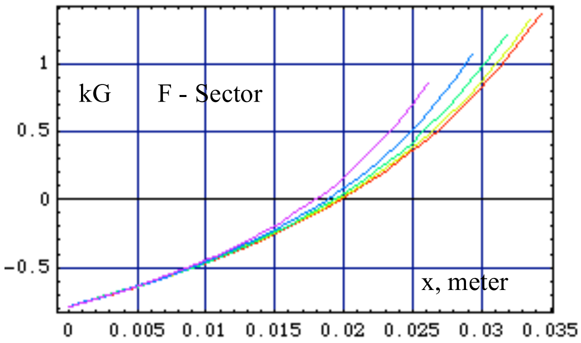

FIGURE 4. Field Profiles vs. Radial (x) Position In the F-Sector Magnet

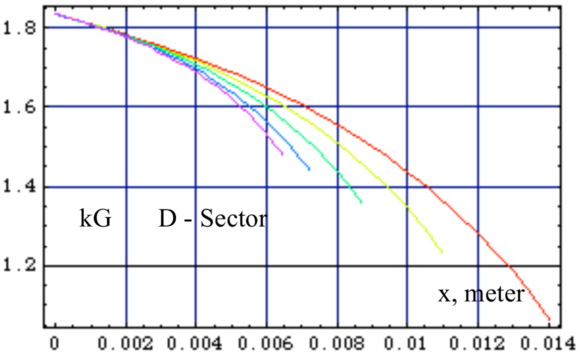

FIGURE 5. Field Profiles vs. Radial (x) Position in the D-Sector Magnet

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 μs. The main parameters of extraction are summarized in Table 8 and the layout is shown in Fig. 11.

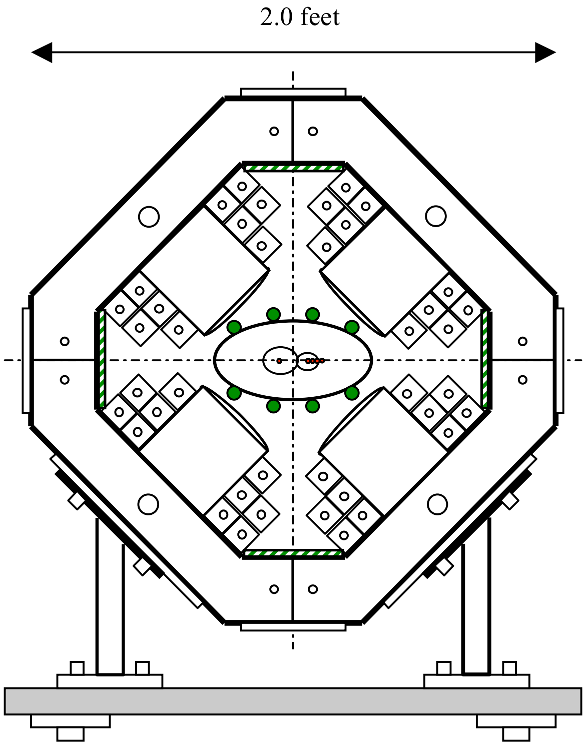

FIGURE 6. Conceptual Design of the F-Magnet

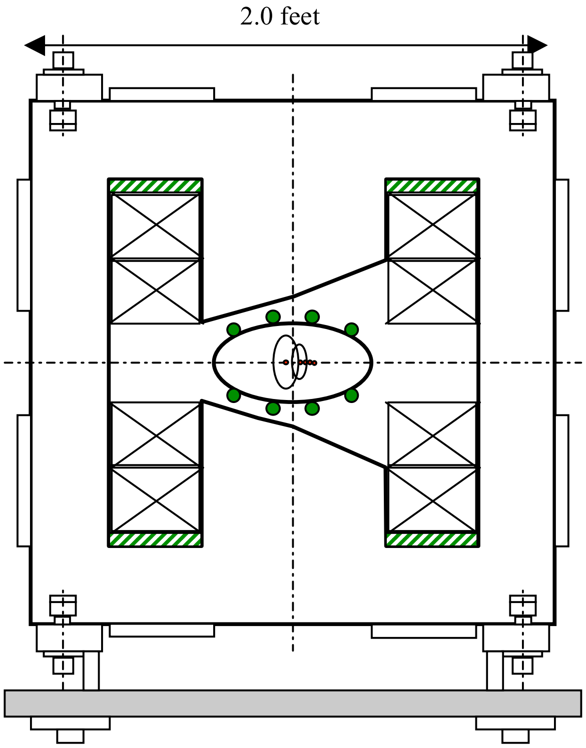

FIGURE 7. Conceptual Design of the D-Magnet

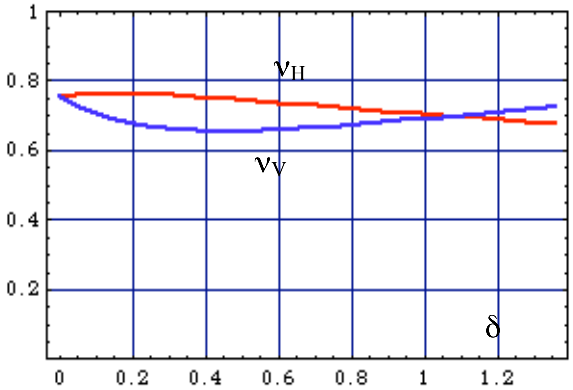

FIGURE 8. Fractional Tune versus Momentum δ

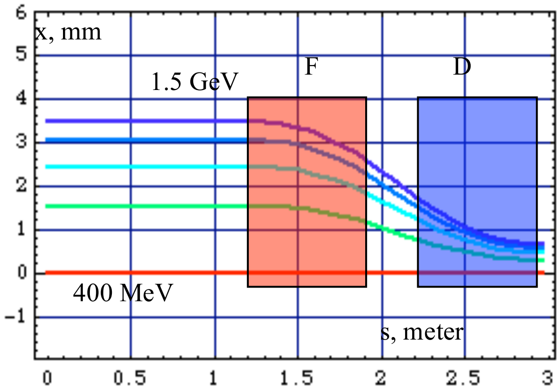

FIGURE 9. Orbit Trajectories along half of a Period at different energies

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.

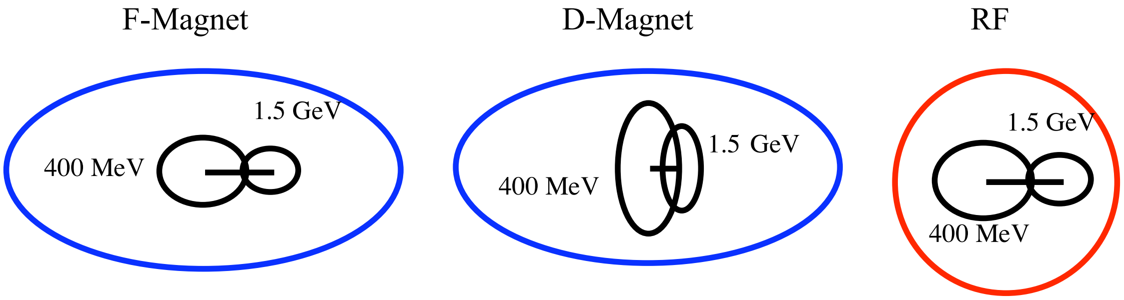

FIGURE 10. 18 cm x 9 cm Vacuum Chamber in F and D Magnets, and 10 cm for RF Cavities

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.

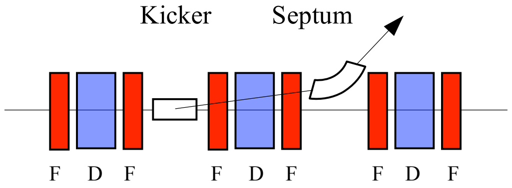

FIGURE 11. Extraction from the FFAG

Table 5. Parameters at Injection into the FFAG

Linac Peak Current	35 mA
Revolution Period	3.78 μs
No. of Protons / FFAG pulse	1.0×10^{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, γ_T	105.5 i
Peak RF Voltage	1.2 MVolt
Number of full Buckets	22 out of 24
Total Number of Protons	1.0×10^{14}
Bunch Area, full	0.4 eV-sec
Protons / Bunch	4.6×10^{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

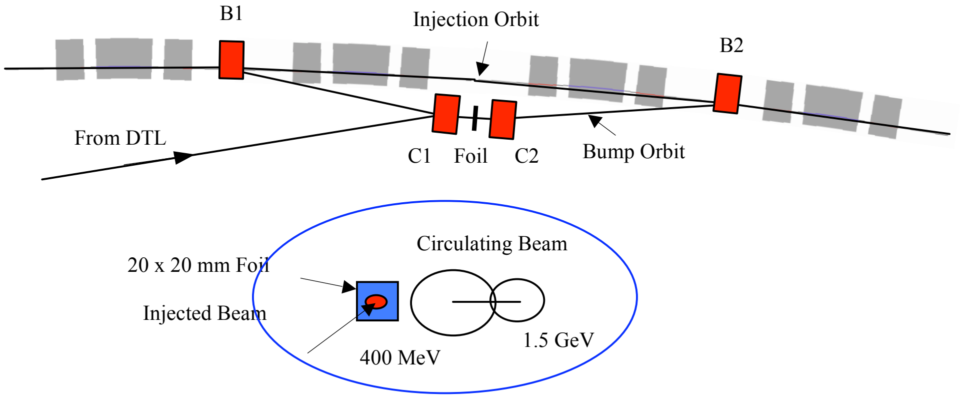

FIGURE 12. Injection Transfer Line and Beam Cross-Section at the Foil

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.

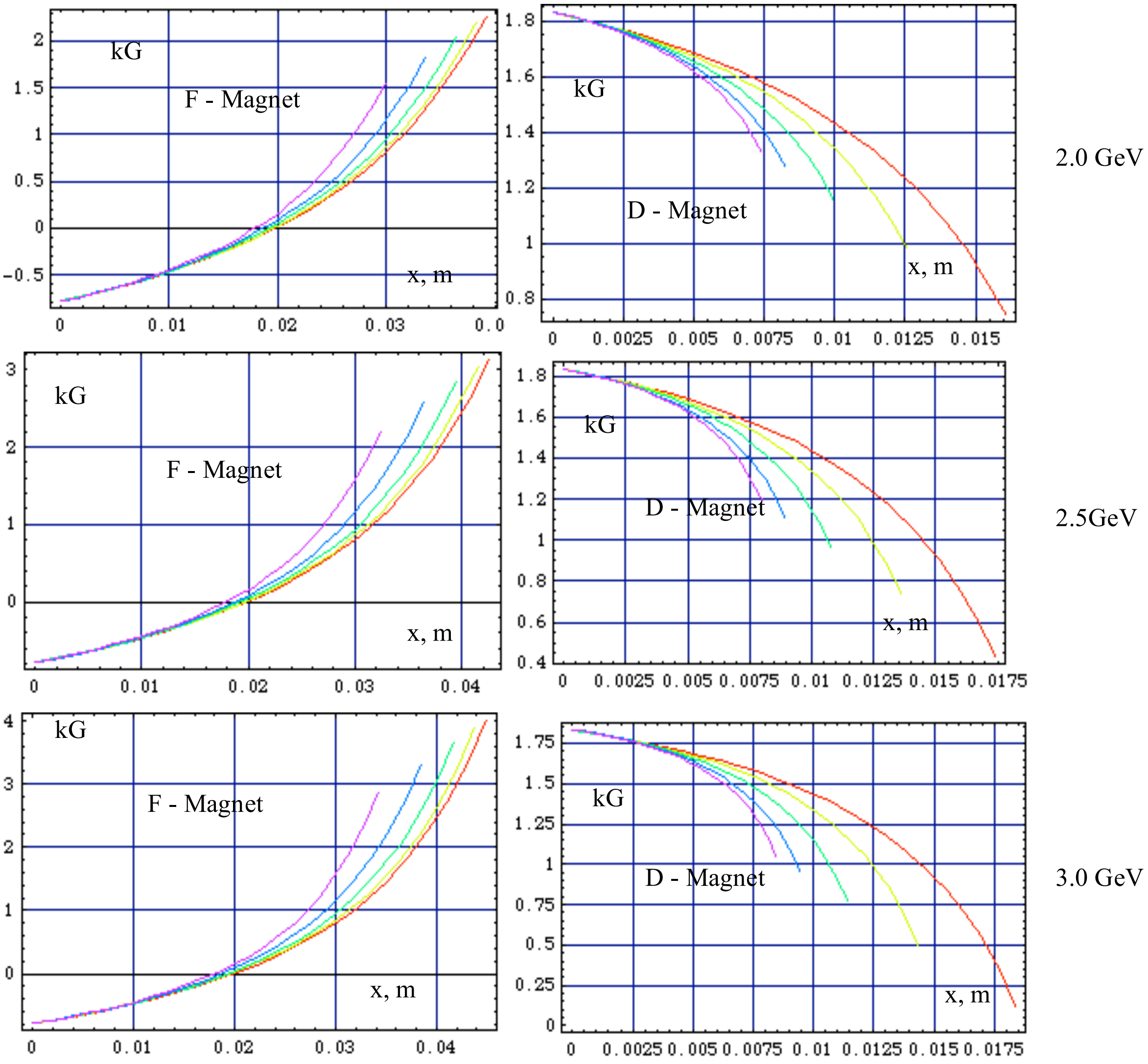

FIGURE 13. *Adjusted Field Profile* in the F and Sector Magnets at different final kinetic Energy.

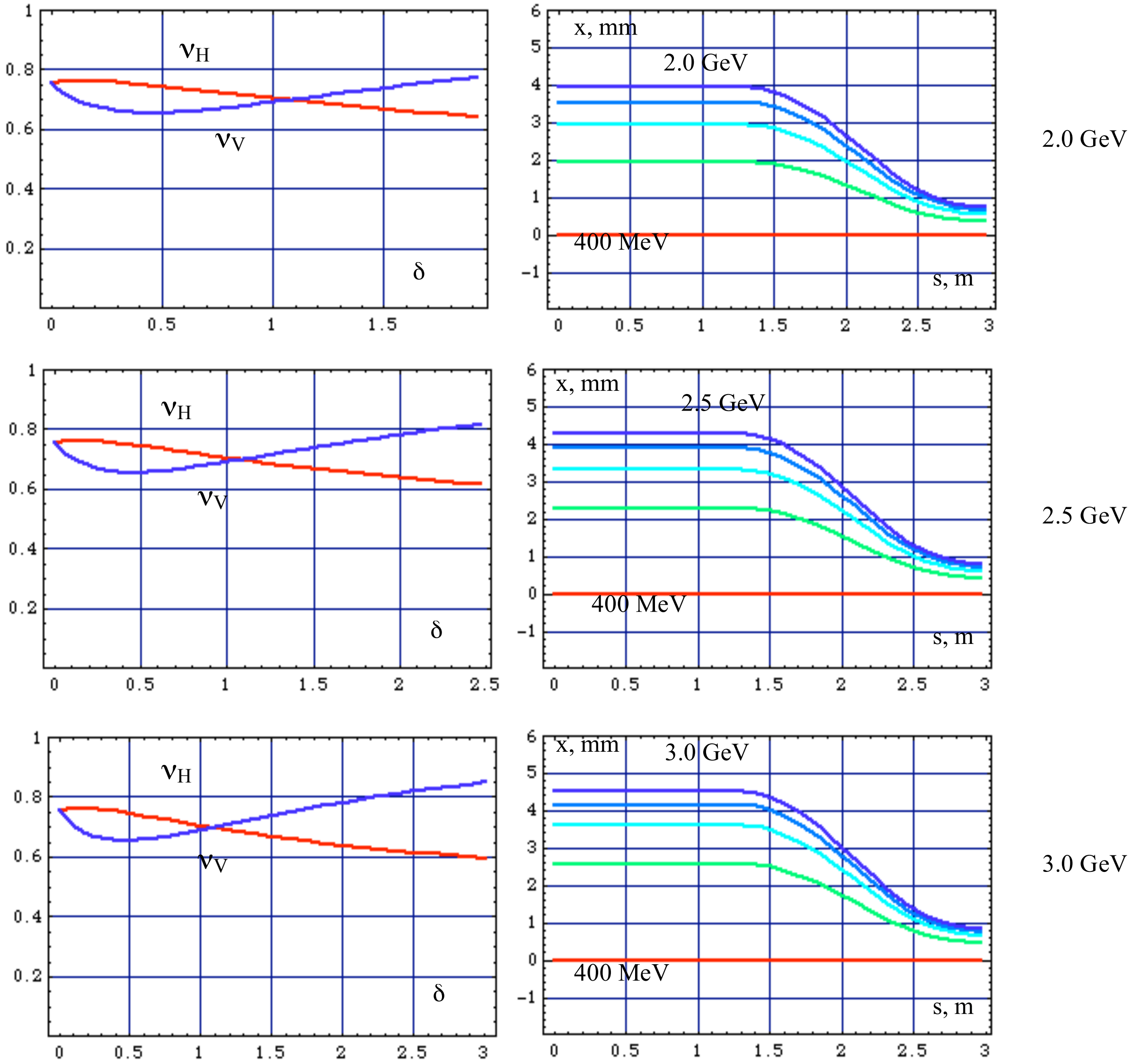

FIGURE 14. Tune Variation and radial Displacement across Momentum Aperture for different final Energy

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