1.5-GeV FFAG Accelerator as Injector to the BNL-AGS

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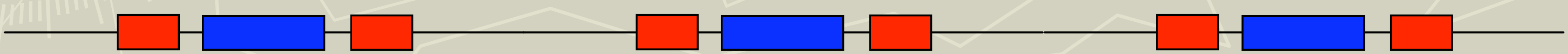
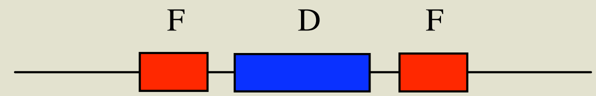
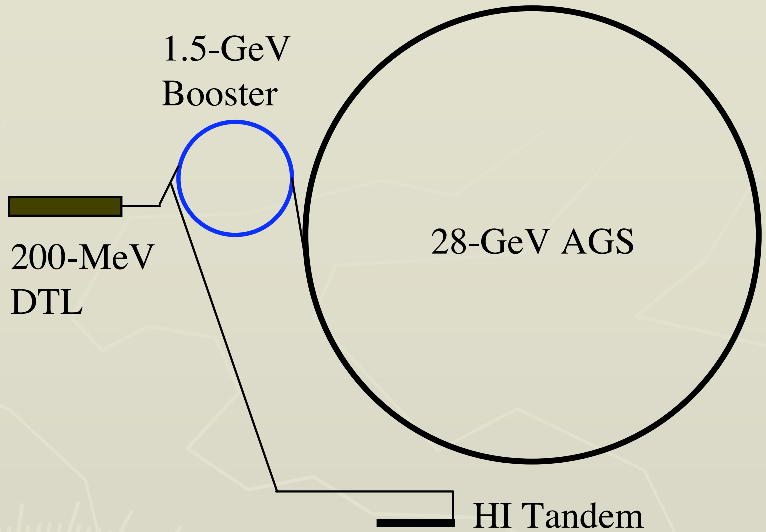
BROOKHAVEN NATIONAL LABORATORY

Jefferson Lab Presentation. September 20, 2004



Present BNL - AGS Facility

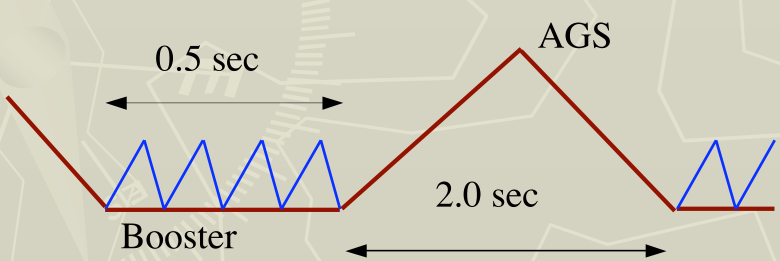




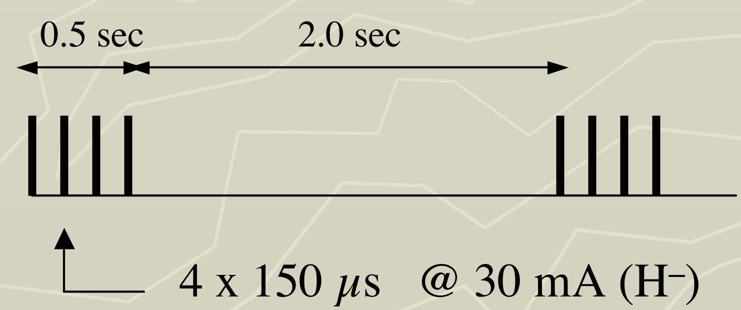
Performance

Rep. Rate	0.4 Hz
Top Energy	28 GeV
Intensity	7 x 10^{13} ppp
Ave. Power	**125 kW**

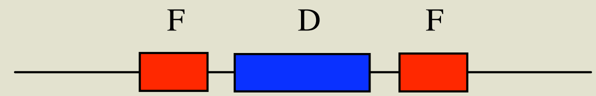
Typical AGS cycle for Protons



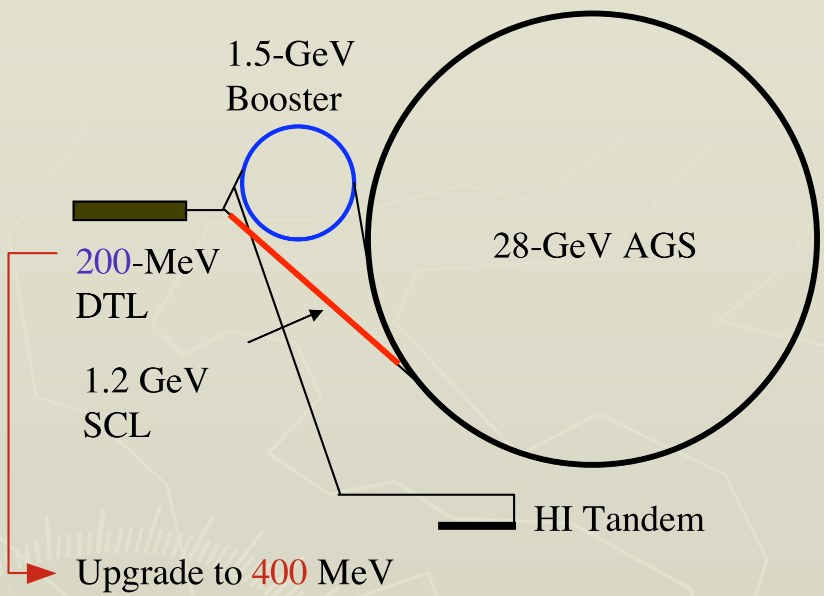
Typical DTL cycle for Protons



AGS Upgrade with 1.2-GeV SCL



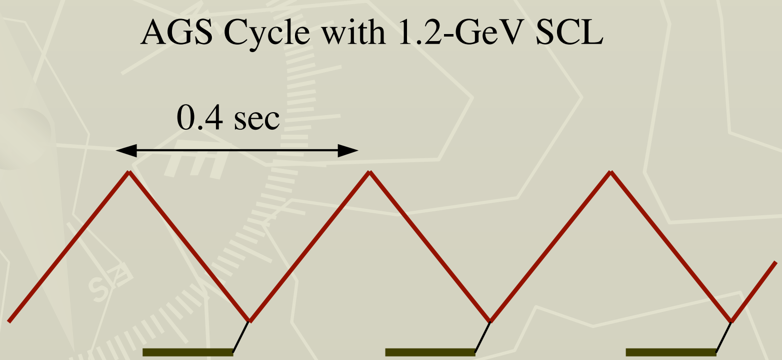
BNL- C-A/AP/151

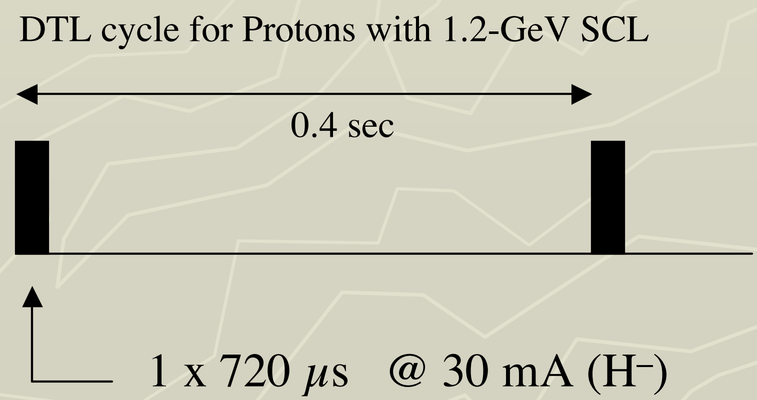


Performance

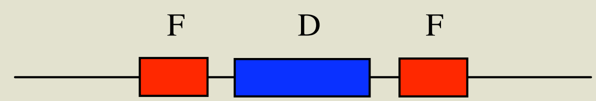
Rep. Rate	2.5 Hz
Top Energy	28 GeV
Intensity	1.0 x 10^{14} ppp
Ave. Power	**1.0 MW**

Only Protons, **no** HI

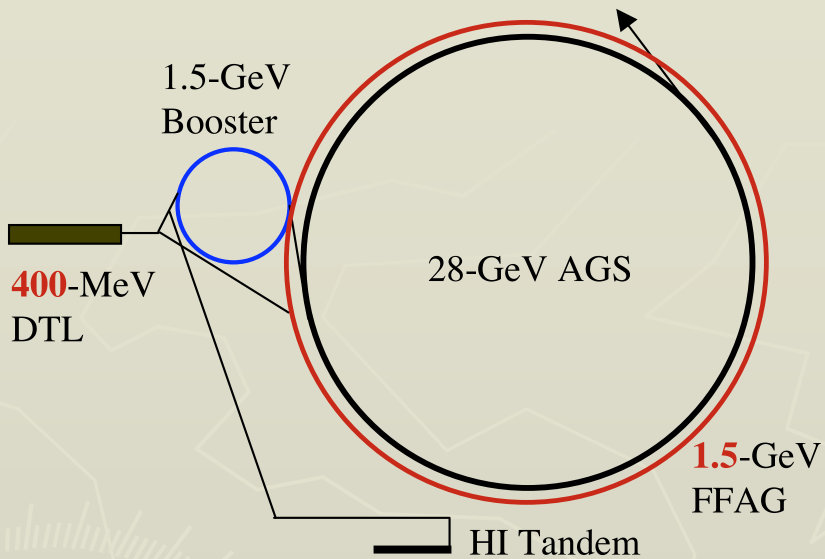




AGS Upgrade with 1.5-GeV FFAG



BNL - C-A/AP/157

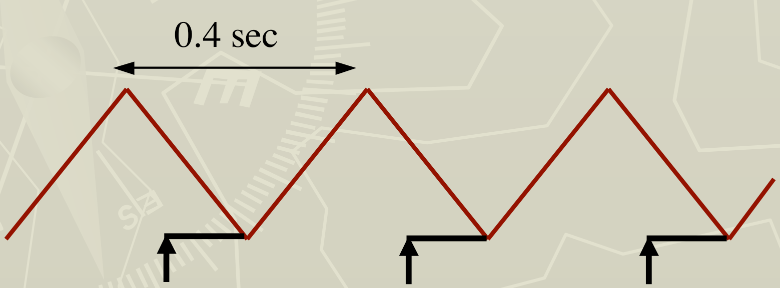


Performance

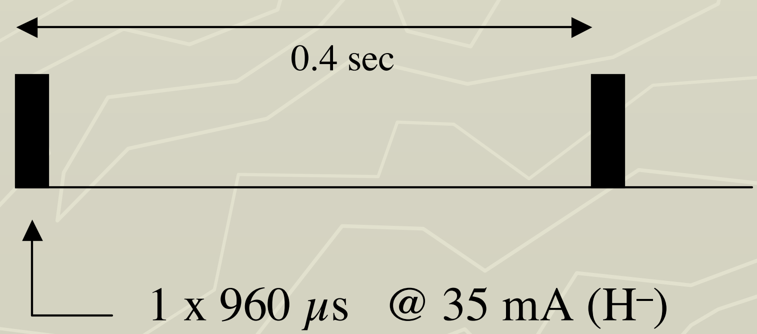
Rep. Rate	2.5 Hz
Top Energy	28 GeV
Intensity	1.0 x 10^{14} ppp
Ave. Power	**1.0 MW**

Protons, **and** HI (??)

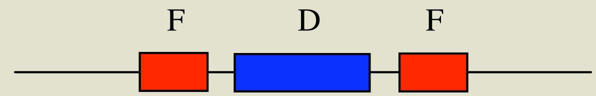
AGS Cycle with 1.5-GeV FFAG



DTL cycle for Protons with 1.5-GeV FFAG



Considerations of FFAG

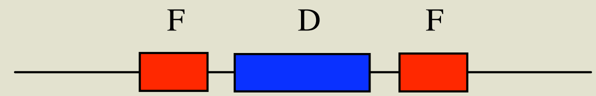


FFAG accelerators are an old technology proposed and demonstrated about a half a century ago. They have often been proposed especially in connection of Spallation Neutron Sources. But, despite a considerable amount of design and feasibility studies, they were never successfully endorsed by the scientific community, because they were perceived with 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 the need of a relatively large injection energy (of few hundred MeV) at one end, and the need of stacking/accumulating device 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 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 concerning momentum compaction and magnet dimensions. Because of these 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.

FFAG Accelerators have also been extensively studied as possible storage and accelerators of intense beams of Muons in the several GeV energy range

Main Features of FFAG



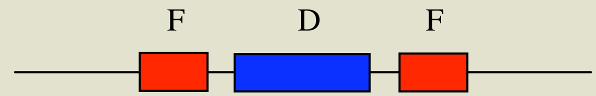
The main feature of the FFAG accelerators is that they are essentially based on conventional room-temperature magnet technology with constant field. As the beam is accelerated by RF cavities, its trajectory spirals from an inner orbit where injection occurs toward an outer orbit from which the beam is extracted. The radial extension of trajectories is entirely confined within the magnet aperture, and the field does not need to be ramped neither for bending nor for focusing.

In principle, this mode of operation requires a large momentum excursion that, for instance from 200 MeV to 1.0 GeV or from 400 MeV to 1.5 GeV is about **±40%** around the central momentum value. To avoid that the momentum range gets exceedingly too large, FFAG accelerators require a relative large injection energy, of few hundred MeV. The injector could be a Linac or a smaller scale FFAG with a cycle matching that of the main accelerator.

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.

Different types of magnet lattice configuration have been studied: FODO, Doublets, and Triplets. Triplets have been found to be the most advantageous, especially in the FDF configuration.

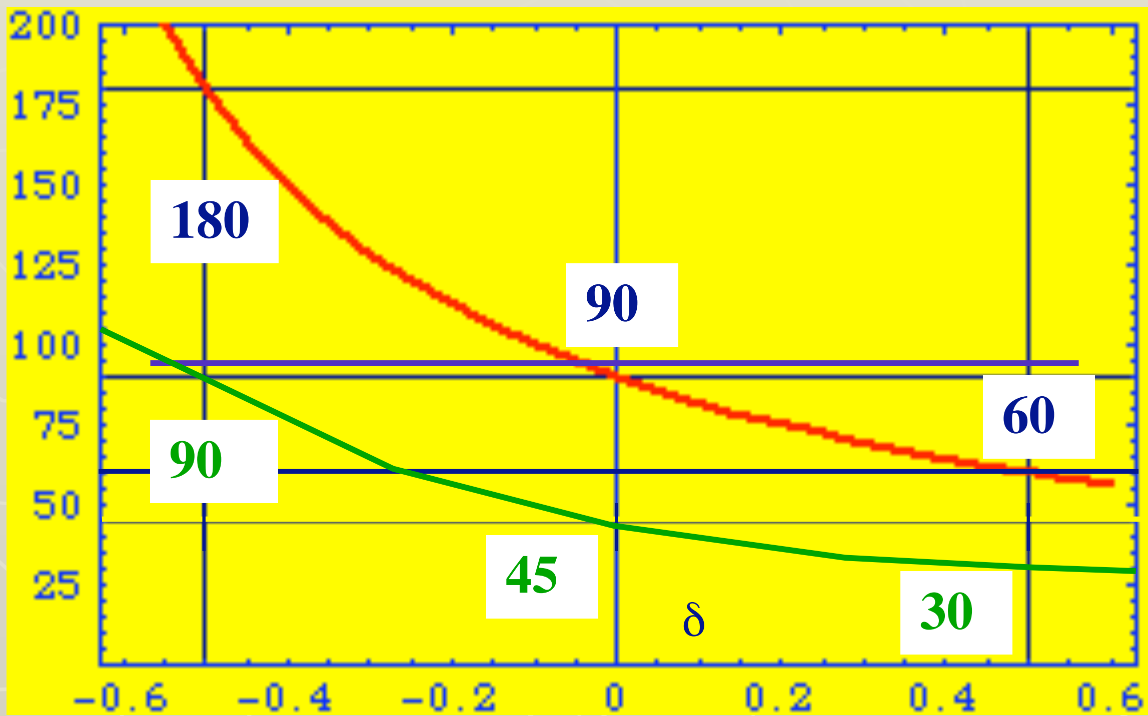
Chromaticity with Linear Gradient



$$x'' \quad + \quad h^2 (1 + n)\, x / (1 + \delta) \quad = \quad h\, \delta / (1 + \delta)$$
$$y'' \quad - \quad h^2\, n\, y / (1 + \delta) \quad = \quad 0$$

$h^2 n / (1 + \delta)$

$p = p_0 (1 + \delta)$

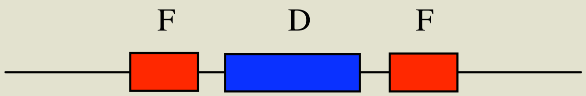


δ = 0 *δ = 2*

Rule # 1: Tune the lattice at the low energy end (Injection) for Phase Advance 90-100⁰

(Courant) *δ = 0*

Second Rule (Johnston, Trbojevic)



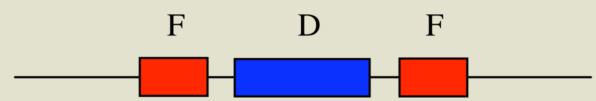
Employ the **FDF** arrangement of the triplets since this, as it was well known from the lattice studies of electron storage rings for the production of synchrotron radiation, yields a considerable lower dispersion when compared to the DFD arrangement, and thus a more compact momentum spread and smaller magnet width. At the same time most of the bending ought to be done by the central **D** magnet, while the two F magnets at the ends of the triplet provide reverse bending, that is have the polarity inverted with respect to that of the **D** magnet.

The major concern of any type of FFAG accelerator is the variation of the betatron tunes and functions that can be exceedingly too large for the required momentum aperture. There are two methods to reduce and to control such large tune variation.

Scaling FFAG Lattice:
- Large Dispersion.
- Magnets with Large Aperture and High Field.
- Constant Tune. Prefers DFD Triplet.

Non-Scaling FFAG Lattice:
- Small Dispersion.
- Magnet with smaller Aperture and Lower Field.
- Large Chromaticity. Prefers FDF Triplet.

Scaling Lattice



Conceive an arrangement of trajectories so that the momentum dependence is absorbed by the curvature h

$$x'' = q B_y (1 + hx) / pc$$

The Lorentz condition imposes that at any location

$$q B_y / pc = 1 / r$$

With an arbitrary origin corresponding to $h = 1 / r_0$, assume that B_y is a function of r, and by expansion

$$B_y = B [1 + (r - r_0) dB / B dr]$$

By insertion

$$x'' = h^2 (1 + K) x \qquad \text{with} \qquad x = r - r_0$$

The focusing parameter is then

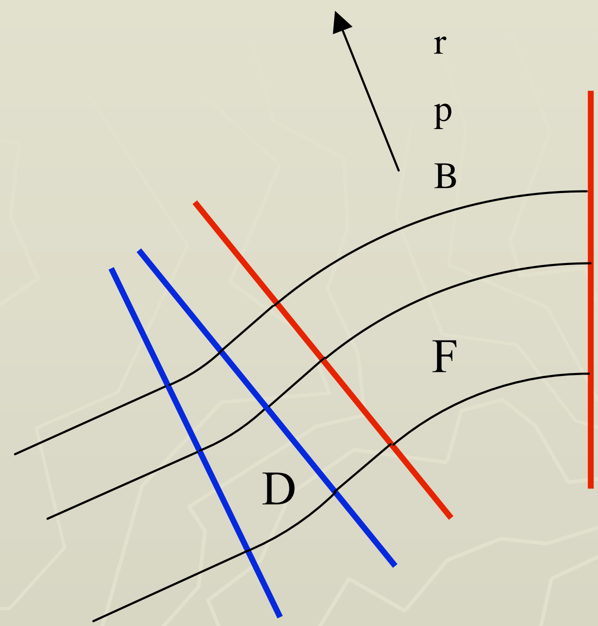
$$K = (r dB / B dr)$$

If one requires that K is independent of location and of the particle momentum, then the field index

$$n = - r dB / B dr$$

must be constant across the momentum (radial) aperture. The corresponding field profile

$$B = B_0 (r / r_0)^{-n}$$

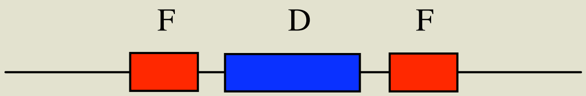


Trajectories are parallel to each other.

Trajectories are Arcs of Circle.

Entrance and Exit Angles = 0

Non-Scaling Lattice

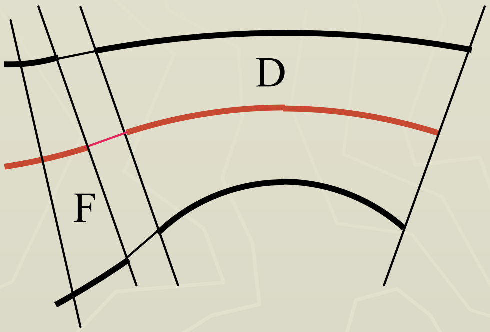


This is one by which only for the reference trajectory corresponding to the curvature h and momentum p_0 the *Lorentz condition* is exactly satisfied uniformly along the length of a sector magnet. On the reference trajectory there is a uniform constant curvature h and bending field B_y. Moreover, this reference trajectory makes zero angle at the entrance and exit of the magnets. But this is not true for any other particle with a different momentum value $p = p_0 (1 + \delta)$. For this particle the trajectory is not an arc of circle with constant curvature, but crosses regions with varying bending and focusing field.

In the special case of a constant field gradient $G = dB / dr$ it is then not possible to preserve constant tunes and lattice functions across the momentum aperture.

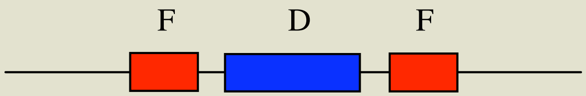
It is nevertheless possible to find an *Adjusted Field Profile* within each of the magnets that cancels the chromatic behavior of the lattice functions over the desired momentum range. The *Adjusted Field Profile* causes the gradient to vary in a specific manner so that the resulting field index at a particular longitudinal location s is now a function of the radial displacement x; that is $n = n(x, s)$ that cancels the momentum dependence at the denominator of the focusing parameter K).

The field so derived satisfy the Maxwell equations correctly. Because now the field configuration varies with the path length s, there is also a solenoid field component B_s that can nevertheless be ignored.



Very important are the magnet edge effects, because for a Non-Linear Scaling Lattice the trajectories make non vanishing entrance and exit angles with the magnets, unless $\delta = 0$.

3rd Rule: Adjusted Field Profile (Ruggiero,Teng)



BNL - C-A/AP/148

- Linearized Equations of Motion
- Introduce the *field index* $n(x) = G(x) / h\, B_0$

$$x'' \quad + \quad h^2 (1 + n)\, x / (1 + \delta) \quad = \quad h\, \delta / (1 + \delta)$$
$$y'' \quad - \quad h^2\, n\, y / (1 + \delta) \quad = \quad 0$$

- Consider the general case where the field index is a nonlinear function of both x and s, namely $n = n(x, s)$. At any location s, for each momentum value δ there is one unique solution $x = x(\delta, s)$, and by *inversion* δ is a function of x and s, namely $\delta = \delta(x, s)$. We pose the following problem: Determine the field distribution, namely $n = n(x, s)$, that compensates the momentum dependence of $(1 + \delta)$ at the denominator:

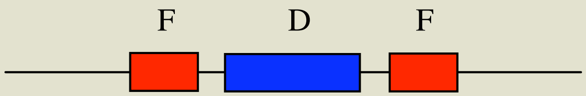
$$n(x, s) \;=\; n_0\, [1 + \delta(x, s)] \qquad \text{-->} \qquad G(x, s) = G_0\, [1 + \delta(x, s)] \qquad \text{<--}$$

where n_0 is related to the gradient $G_0 = n_0\, h\, B_0$ on the reference trajectory.

- Then the equations of motion reduce to

$$x'' + h^2\, x / (1 + \delta) \;+\; h^2 n_0\, x \;=\; h\, \delta / (1 + \delta) \quad \text{-->} \quad x = x(\delta, s) \quad \text{-->} \quad \delta = \delta(x, s)$$
$$y'' - h^2 n_0\, y \;=\; 0$$

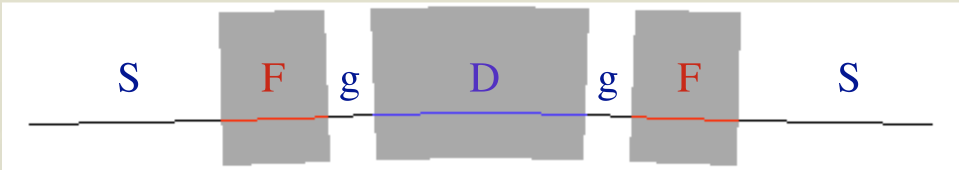
1.5-GeV FFAG Lattice Design



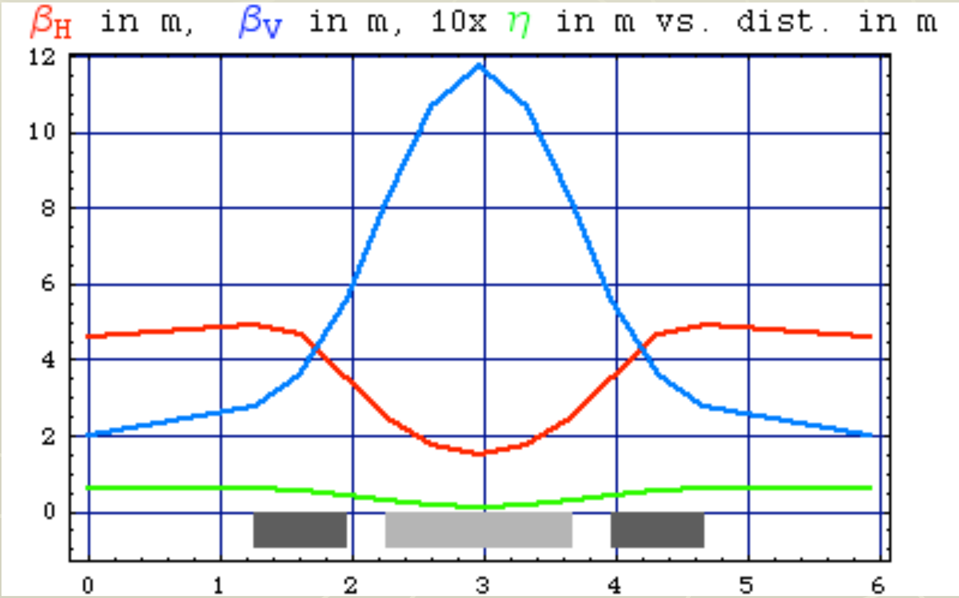
Energy Range		400 MeV - 1.5 GeV	

$p = \mathbf{p_0}\,(1 + \delta)$

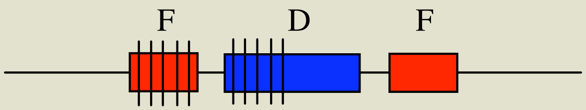
Reference Momentum, $\mathbf{p_0}$		954.263 MeV/c
Momentum Range, δ		0 - 1.36
Circumference		807.091 m
No. of Periods		136
Period Length		5.9345 m
Drifts:	Long (S)	2.5345 m
	Short (g)	0.3 m
F-sector:	Length	0.70 m
	Field	– 0.7841 kG
	Gradient	26.58 kG/m
D-sector:	Length	1.40 m
	Field	1.8345 kG
	Gradient	– 23.30 kG/m
Phase Advance / Period		105.23° / 99.93°
Betatron Tunes, ν_H / ν_V		39.755 / 37.755
Transition Energy, γ_T		105.482 i

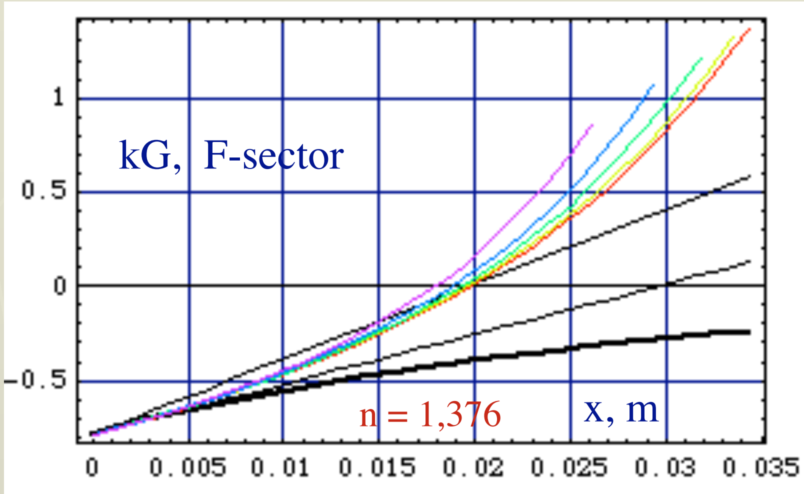


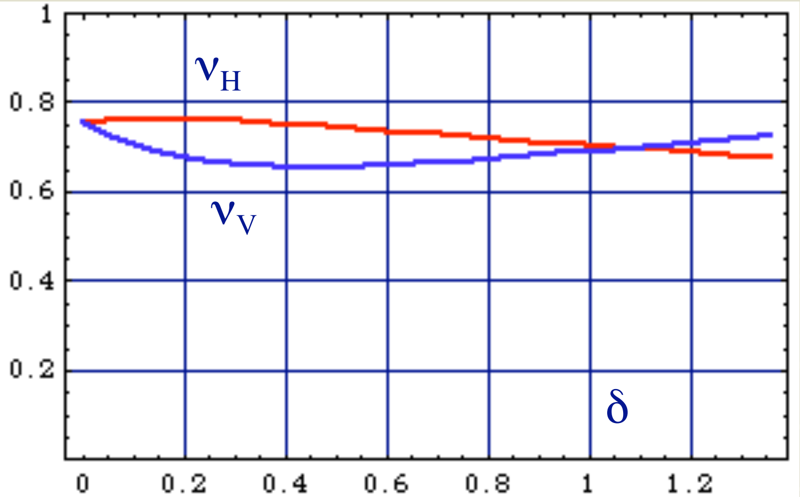
Non-Scaling FFAG Lattice

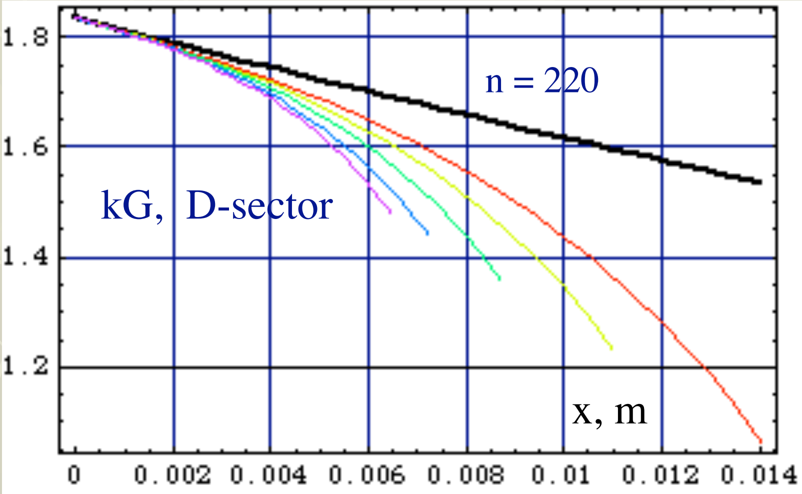


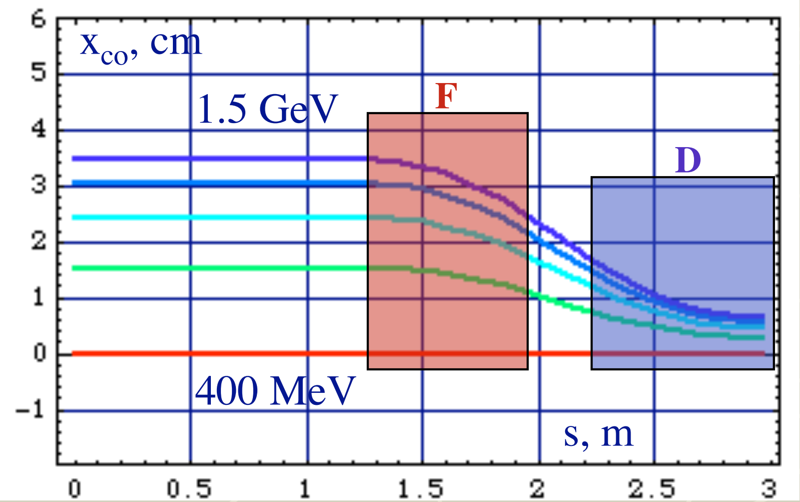
Magnet Field Profiles -- β-Tunes
p-Bundle



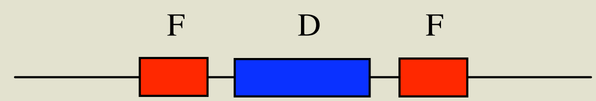






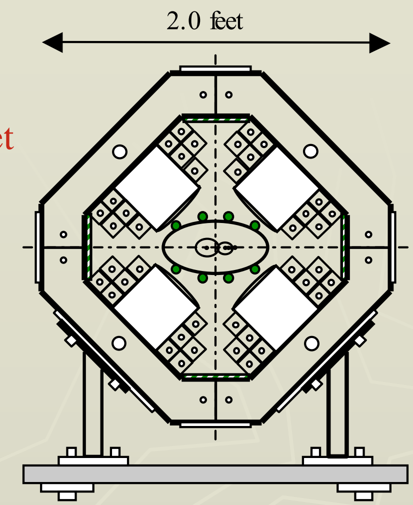


Magnet Design

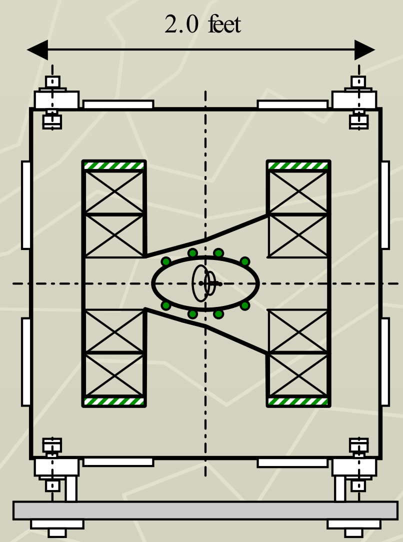


Parameter	Unit	F- Magnet	D- Magnet
Type		Quadrupole	Comb. Function
Number of Magnets		2 x 136	136
Core Length	m	0.65	1.35
Magnetic Length	m	0.70	1.40
Pole Tip Radius	cm	8.0	--
Gap Height	cm	--	15
Pole Width	cm	10.5	21
No. Pancakes / Magnet		4	4
No. Turns per Pancake		5	4
Pole Tip Gradient	kG/ m	30	--
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	mW	1.26	0.88
Resistance / Total	mW	343	120
Inductance / Magnet	mH	0.50	1.87
Inductance/ Total	mH	136	254
Total Voltage, IR	V	550	162
Dissipated Power	kW	880	225
Stored Energy	kJ	174	232

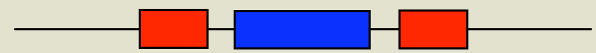
F-Magnet



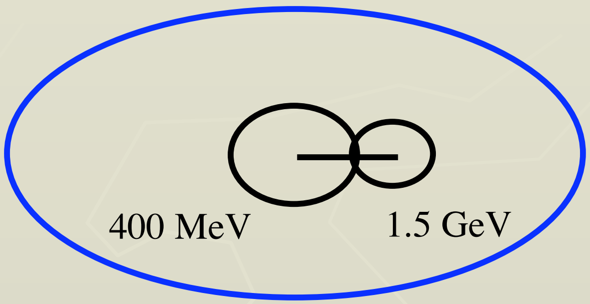
D-Magnet



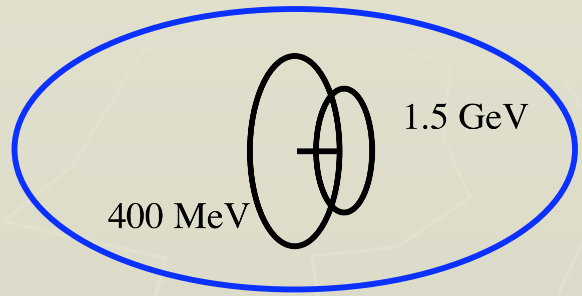
Magnet Design



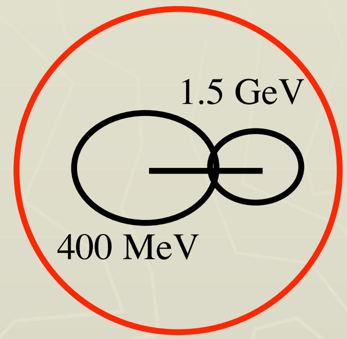
F-Sector



D-Sector



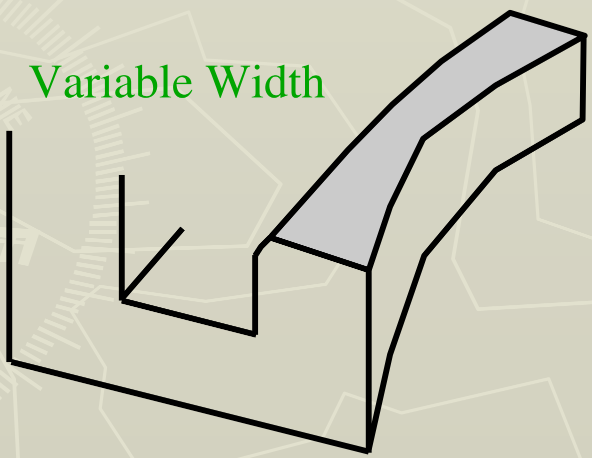
RF Long Straight



10 cm x 20 cm Elliptical Vacuum Chamber

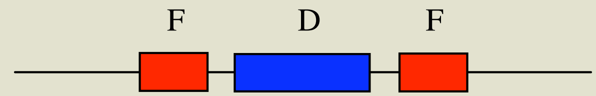
10 cm Diameter Circular Vacuum Chamber

Variable Width

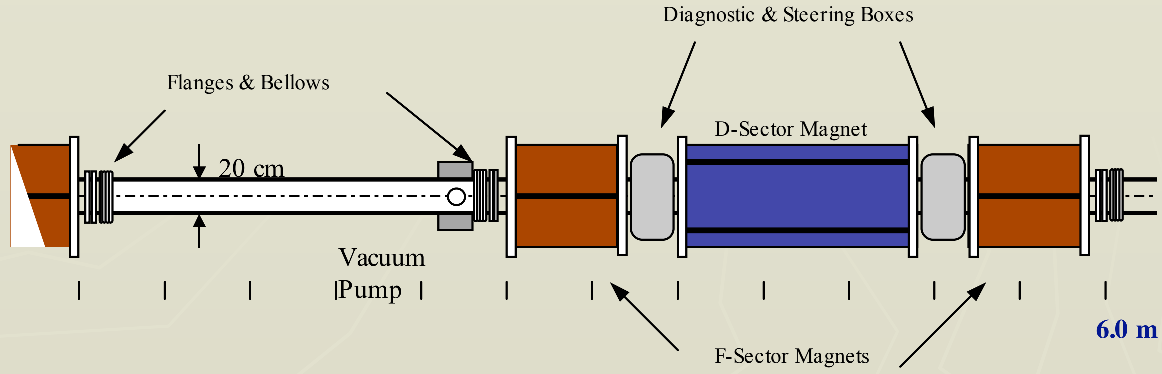


Variable Gap

Period Layout (136 Cells)

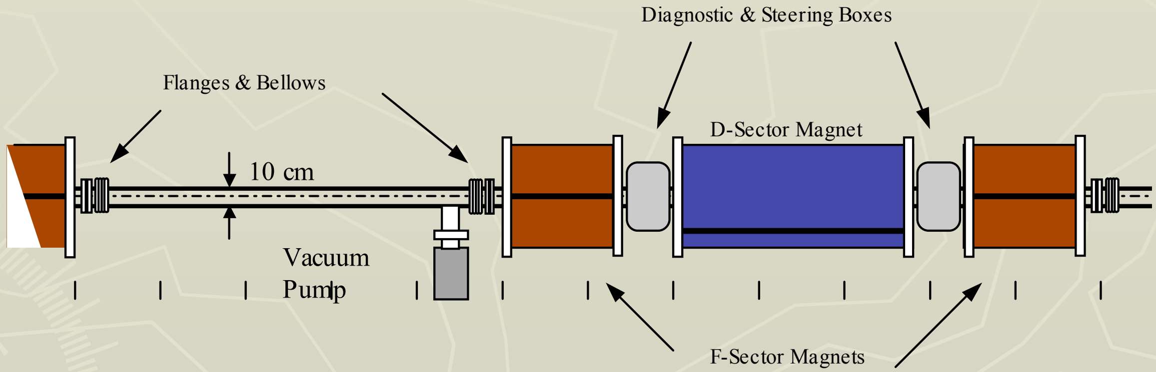


Top View



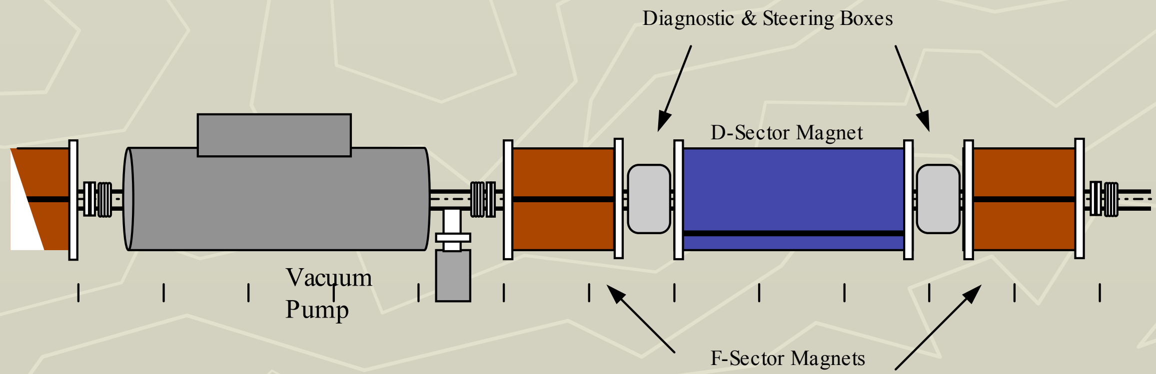
100 k$

Side View

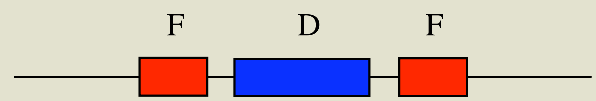


600 k$

RF Cavity

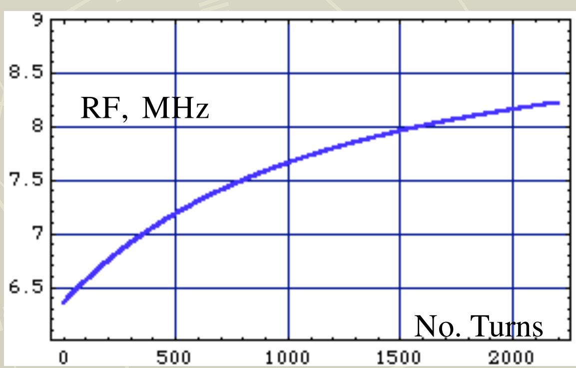


RF Cavity System



Parameters of Acceleration

Circumference	807.091 m
Harmonic Number, h	24
Energy Gain	0.5 MeV / turn
Transition Energy, γ_T	105.5 i
Number of full Buckets	22 out of 24
Bunch Area (full)	0.4 eV-sec
Total Number of Protons	1.0×10^{14}
Protons / Bunch	4.6×10^{12}
Injection Period	1.0 ms
No. of Revolutions	2,200
Acceleration Period	7.0 ms
Total Cycle Period	8.0 ms

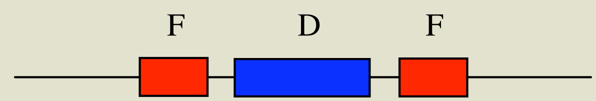


RF Cavity System

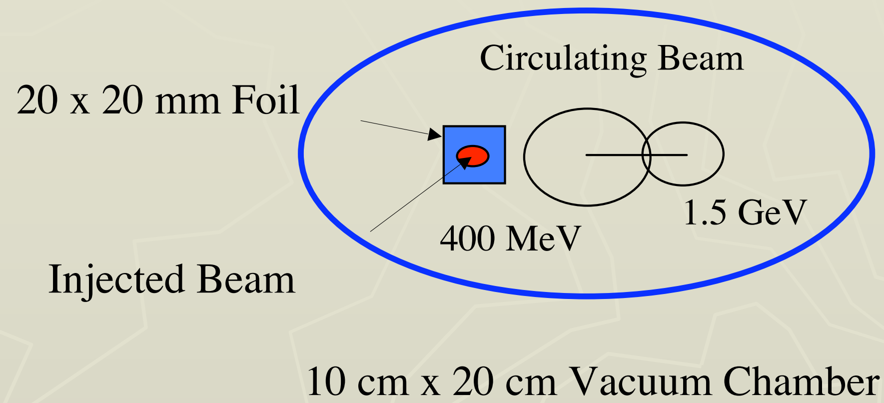
Peak RF Voltage	1.2 MVolt	
No. of RF Cavities	30	
No. of Gaps per Cavity	1	
Cavity Length	1.6m	
Internal Diameter	10 cm	
Peak Voltage / Cavity	40 kVolt	
Power Amplifier / Cavity	250 kW	
Energy Range, MeV	**400**	**1,500**
β	0.7131	0.9230
Revol. Frequency, MHz	0.265	0.343
Revolution Period, μs	3.78	2.92
RF Frequency, MHz	6.357	8.228
Peak Beam Current, Amp	4.24	5.49
Peak Beam Power, MW	2.12	2.75

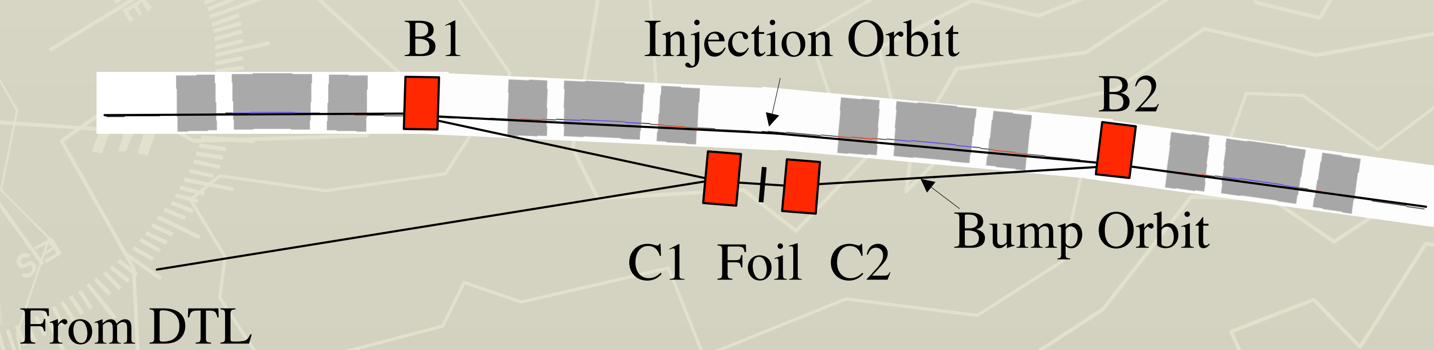
- One can add more Cavities later to shorten acceleration period
- Or start with fewer Cavities and longer acceleration period

Multi-Turn Injection (H^-)

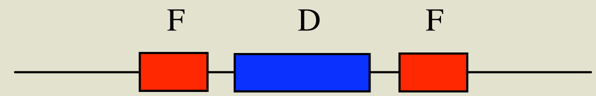


Linac Peak Current	35 mA
Revolution Period	3.78 μs
No. of Protons / FFAG pulse	1.0 x 10^{14}
Chopping Ratio	0.50
Chopping Frequency	6.357 MHz
Single Pulse Length	0.96 ms
No. of Turns Injected / pulse	255
Linac/FFAG Rep. Rate	2.5 Hz
Linac Duty Cycle	0.24 %
Linac Beam Emittance, rms norm.	1 π mm-mrad
Final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

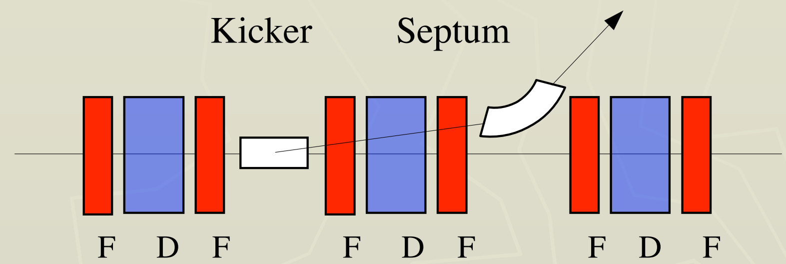




Single-Turn Extraction

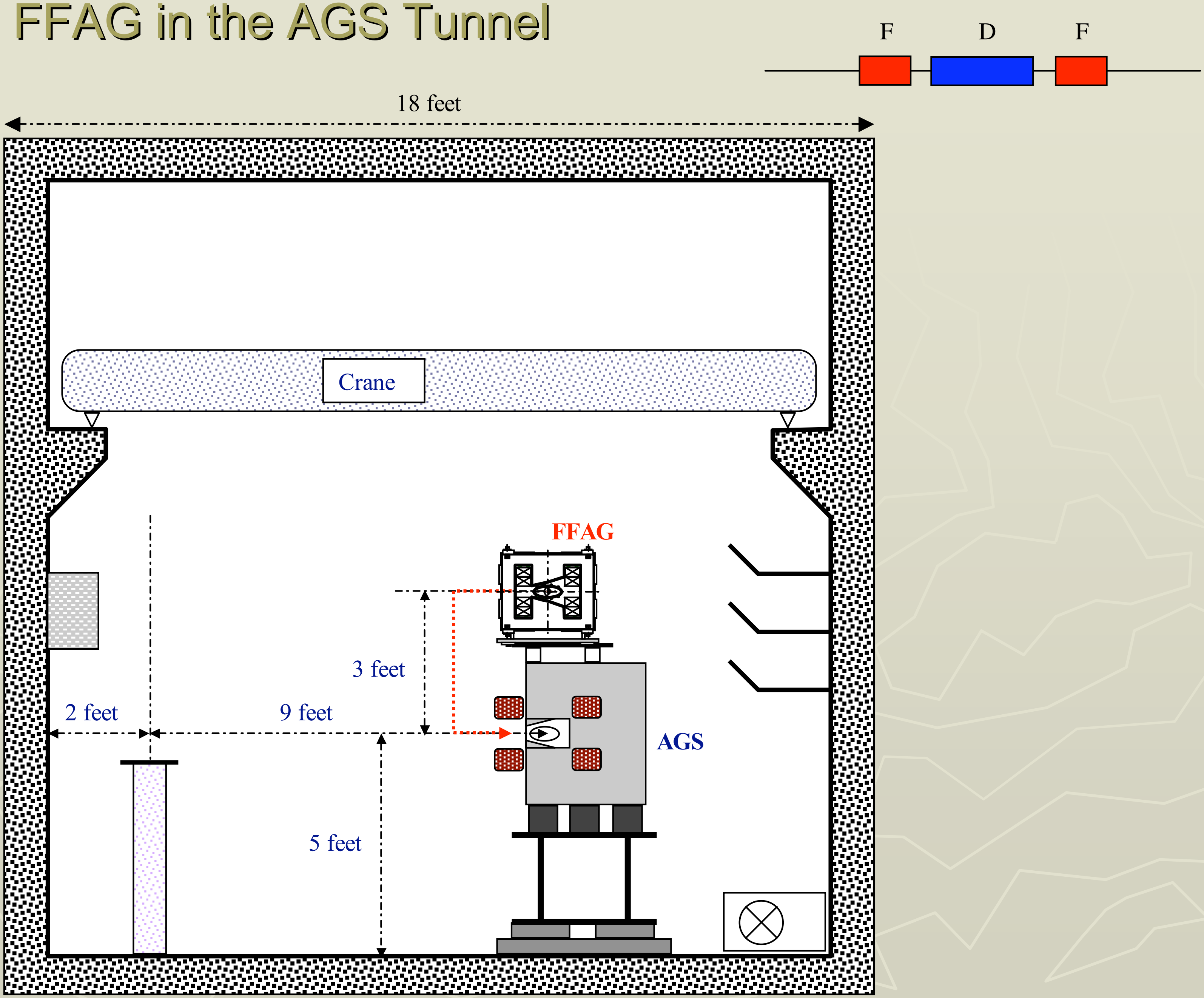


Revolution Period	2.92 μs
Beam Gap	300 ns
Kicker Magnet, Length	1.5 m
Field	1 kG
Rise-Time	< 300 ns
Septum Magnet, Length	1.5 m
Field	10 kG
Repetition Rate	2.5 Hz

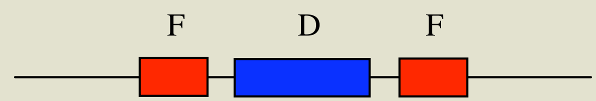


The Kicker field remains constant for the duration of the beam pulse (about 2.6 μs), and it is finally reset to zero-value in about 300 ms, to be fired again the next cycle.

FFAG in the AGS Tunnel



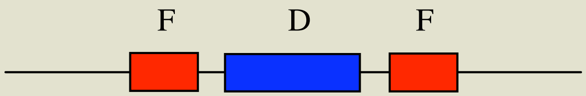
Space Charge at Injection



	FFAG	AGS
Kinetic Energy	400 MeV	1.5 GeV
Total no. of Protons	1×10^{14} (equiv. to 1.12 MW)	
Normalized Emittance	100 π mm-rad (5 x rms, full)	
Actual Emittance	98 π mm-rad	42 π mm-rad
Bunching Factor	3	4
Tune-Shift	**0.5**	**0.16**
β_V - max	12 m	22 m
$a_V = (\varepsilon\, \beta_V)^{1/2}$	34 mm	30 mm

FFAG final Energy can be increased (e.g. to 2.0 GeV)
to ease Injection into the AGS

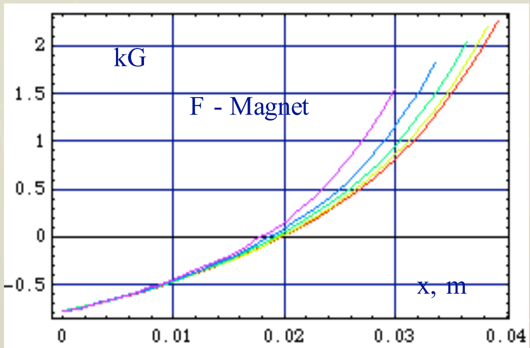
Final Energy Tunability (1 of 2)

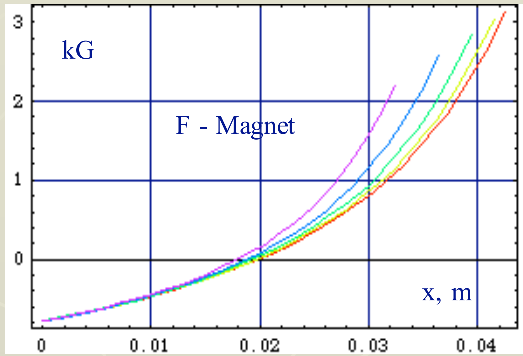


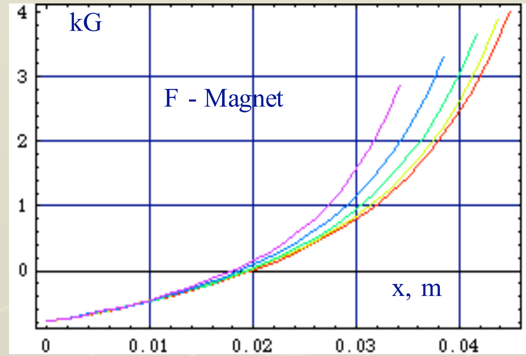
2.0 GeV

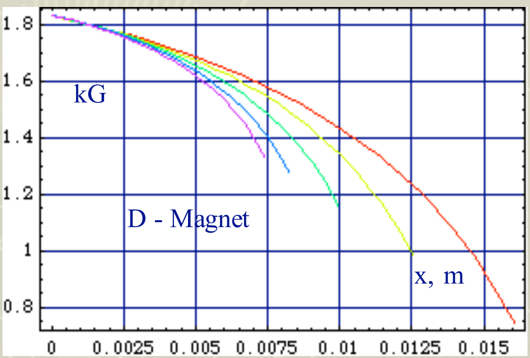
2.5 GeV

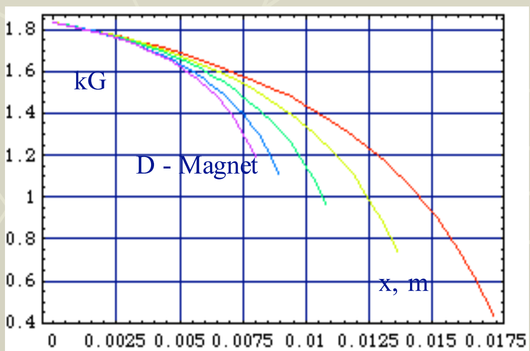
3.0 GeV

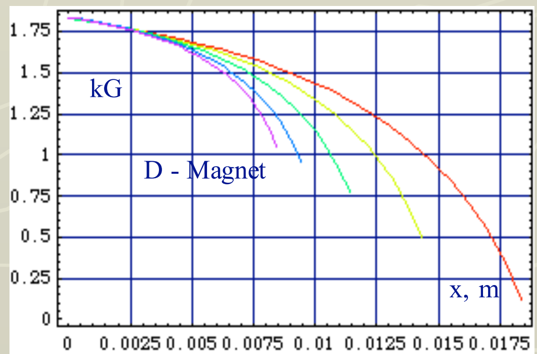




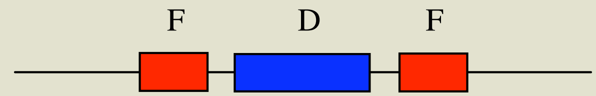




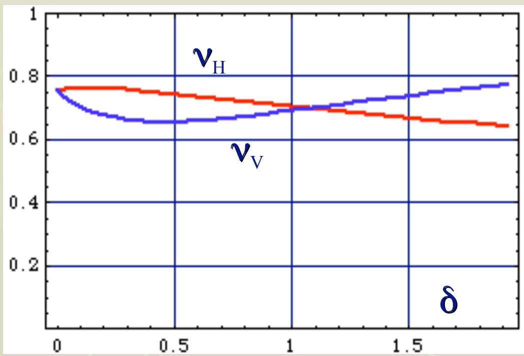


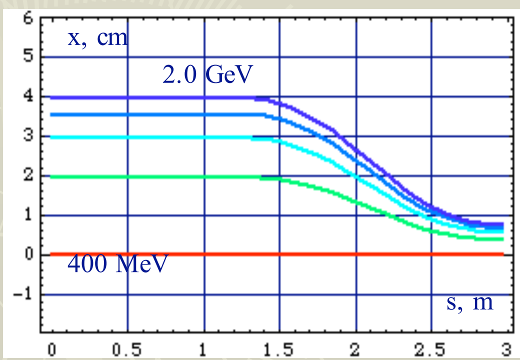


Final Energy Tunability (2 of 2)

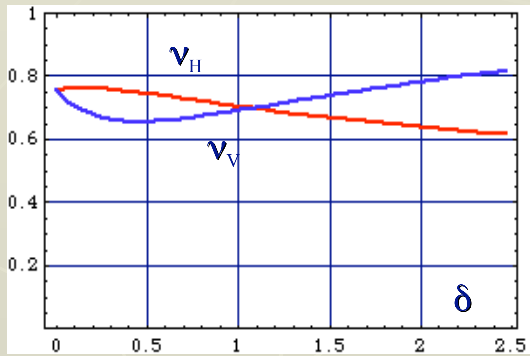


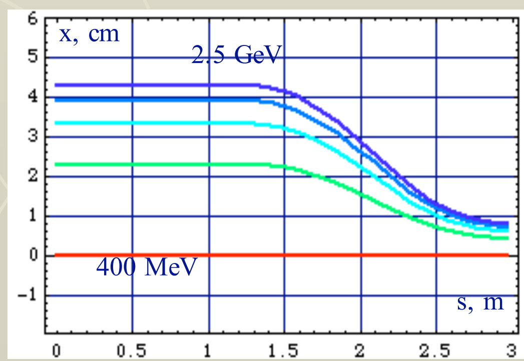
2.0 GeV



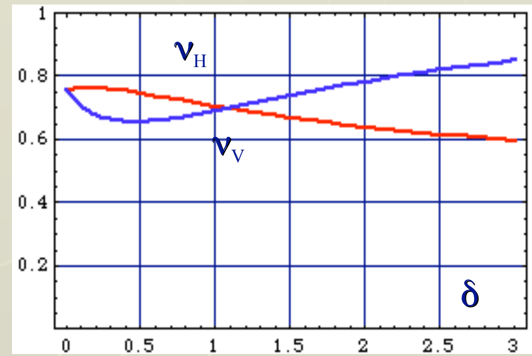


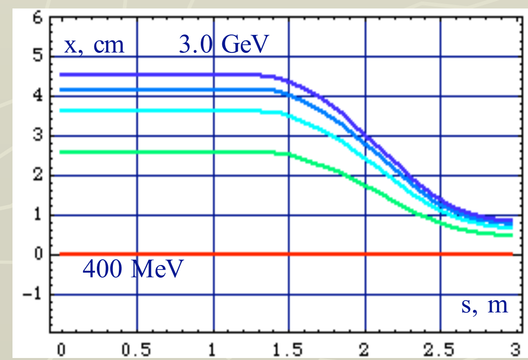
2.5 GeV



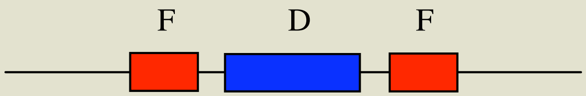


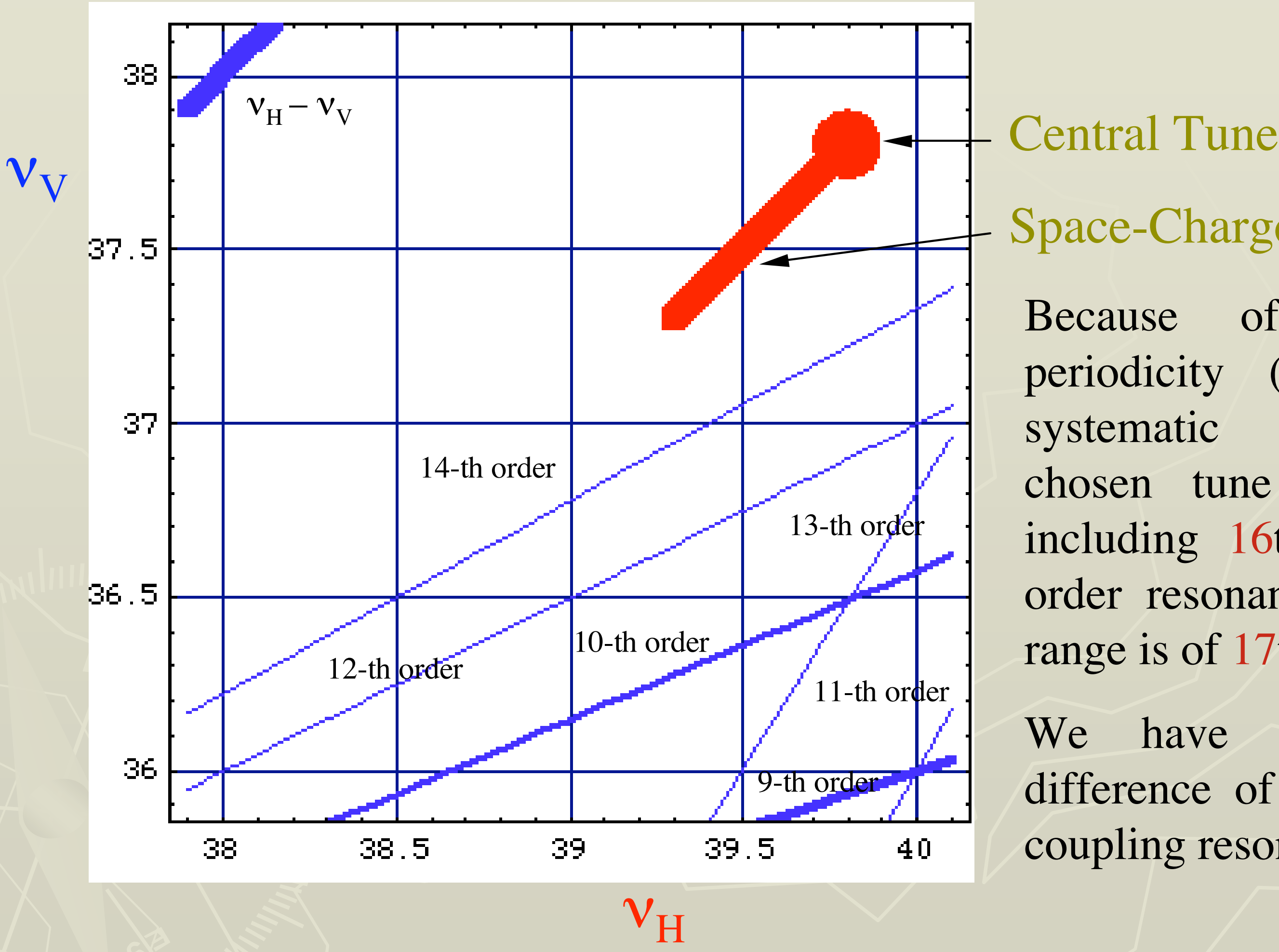
3.0 GeV





Tune Diagram



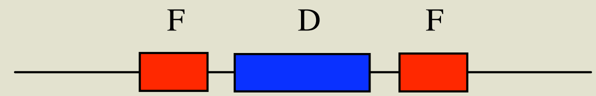


Because of the very large periodicity (136) there are no systematic resonances in the chosen tune region up to and including 16th order. The lowest order resonance to cross the tune range is of 17th order.

We have opted for a tune difference of 2 units to avoid the coupling resonance.

The main concern is the design and manufacturing of the Magnets, and the control of the *Adjusted Field Profile*. Numerical Tracking required to determine tolerances on the magnet imperfection errors.

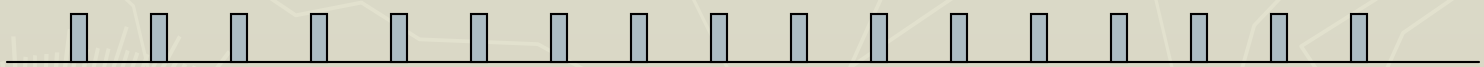
Conclusions



The **1.5-GeV FFAG** is an attractive alternative to the **1.2-GeV SCL** as the new injector for the **AGS Upgrade** program. The merits are:

- More familiar and conventional technology
- Less expensive (~ **50 M$**)
- Possibility of acceleration of Heavy Ions

More work has clearly to be done before it is considered as a substitute to the SCL.



By extrapolation, it is also a continuous high power **Proton Driver** for a variety of applications:

Final Energy	1.5 GeV
Repetition Rate	125 Hz
Protons / Pulse	1.0×10^{14}
Average Beam Power	**3.0 MWatt**