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

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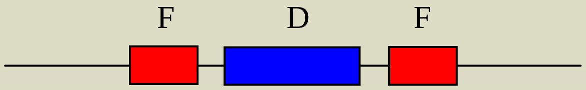
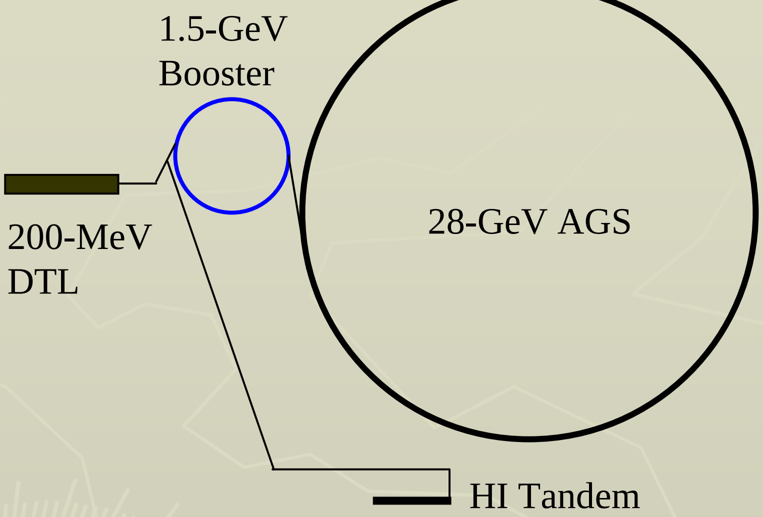
Present BNL - AGS Facility

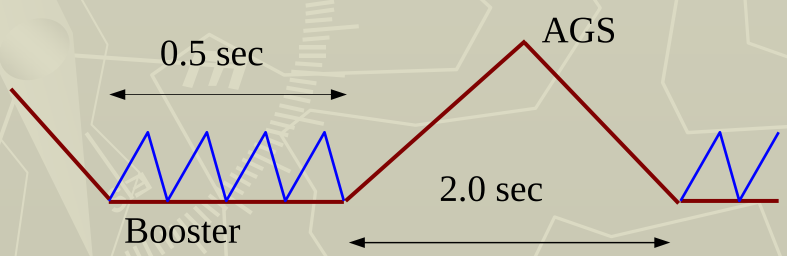




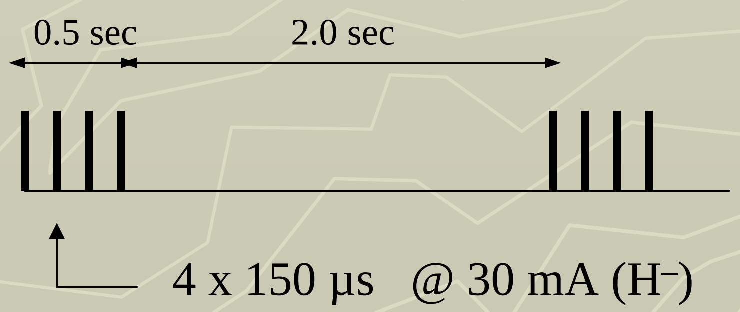
Performance

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

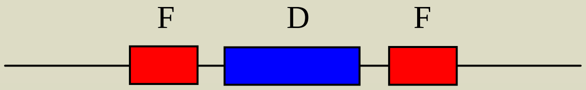
Typical AGS cycle for Protons



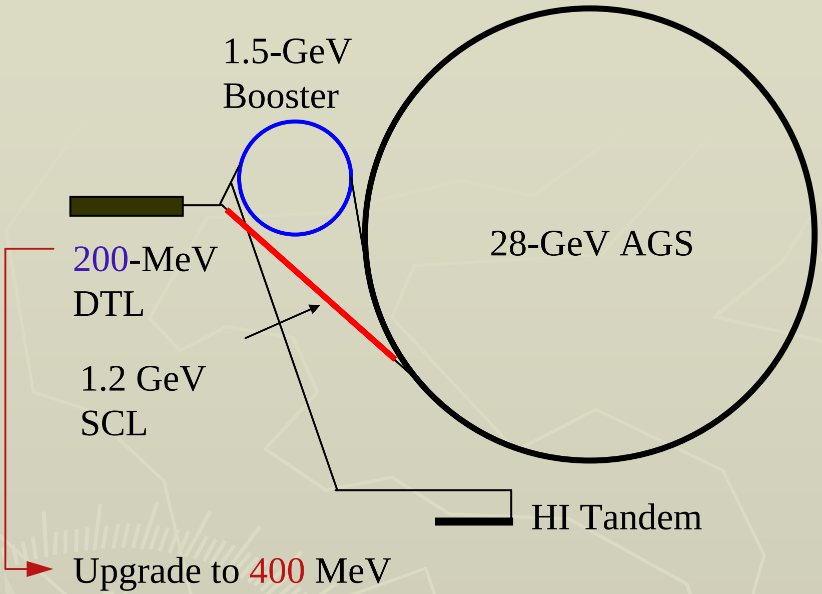
Typical DTL cycle for Protons



AGS Upgrade with 1.2-GeV SCL



BNL- C-A/AP/151

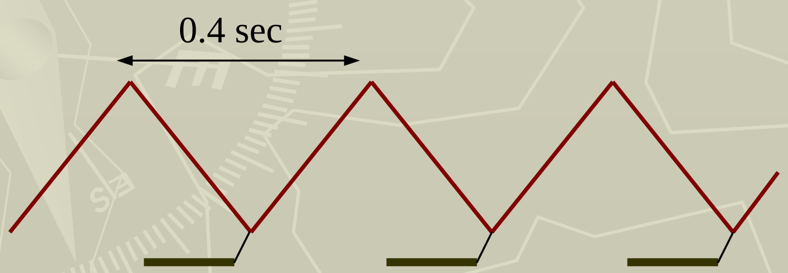


Performance

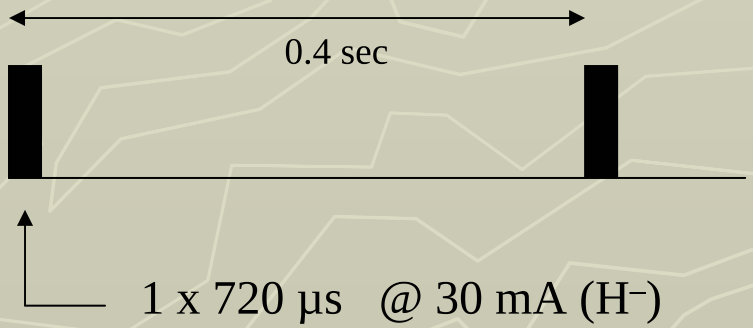
Rep. Rate	2.5 Hz
Top Energy	28 GeV
Intensity	1.0 x 10^{14} ppp
Ave. Power	**1.0 MW**

Only Protons, **no** HI

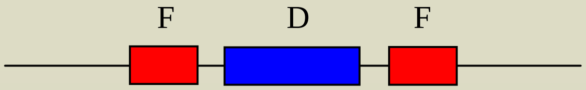
AGS Cycle with 1.2-GeV SCL



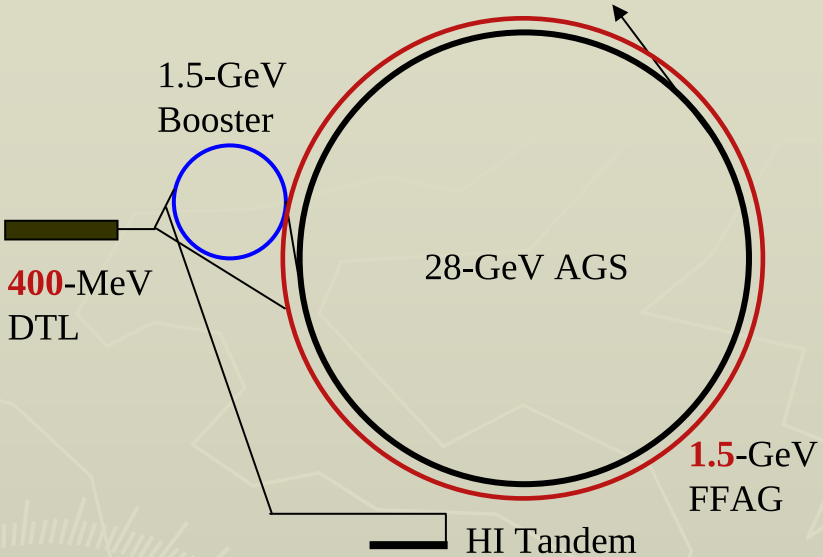
DTL cycle for Protons with 1.2-GeV SCL



AGS Upgrade with 1.5-GeV FFAG



BNL - C-A/AP/157

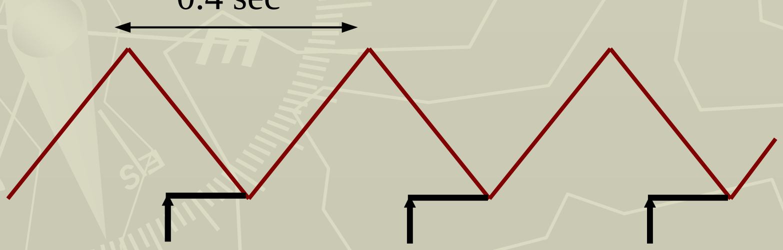


Performance

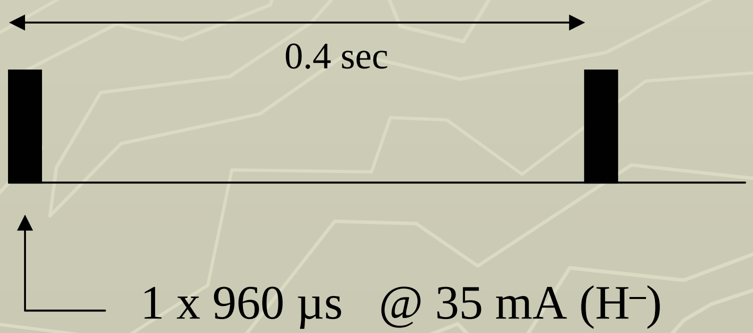
Rep. Rate	2.5 Hz
Top Energy	28 GeV
Intensity	1.0 x 10^{14} ppp
Ave. Power	**1.0 MW**

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

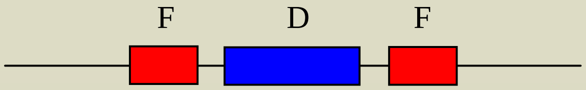
AGS Cycle with 1.5-GeV FFAG



DTL cycle for Protons with 1.5-GeV FFAG



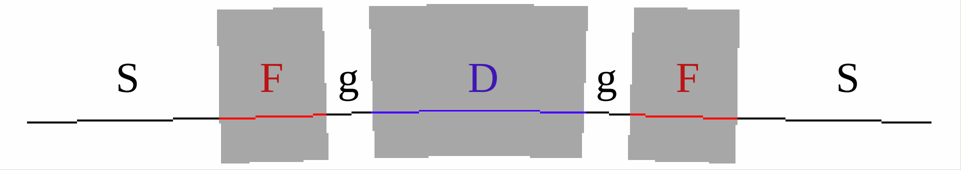
1.5-GeV FFAG Lattice Design



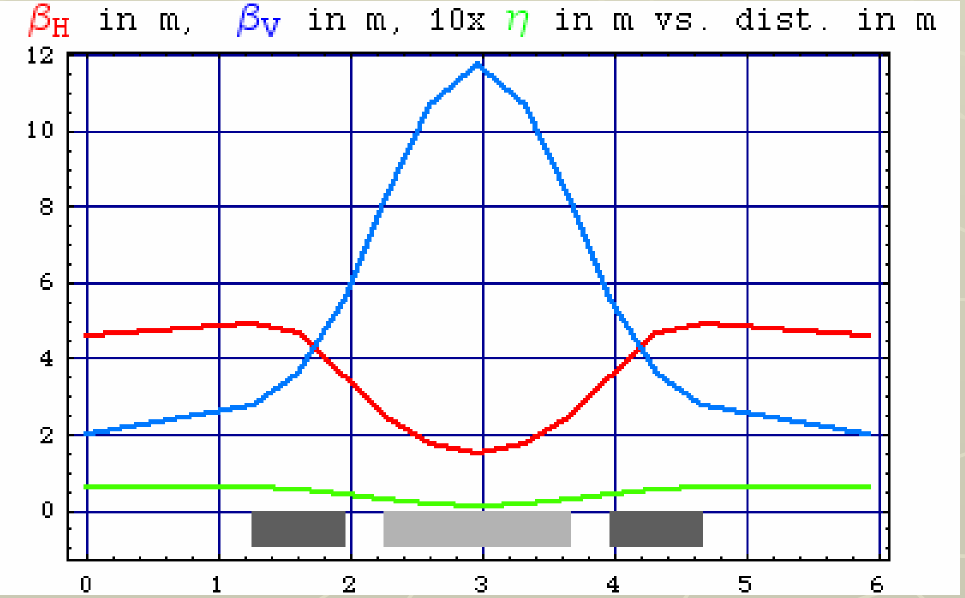
Energy Range 400 MeV - 1.5 GeV

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

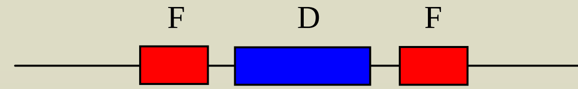
Reference Momentum, $\mathbf{p_0}$		954.263 MeV/c
Momentum Range, δ		0 - 1.36
Circumference		807.091 m
No. of Periods		136
Period Length		5.9345 m
Drifts:	Long (S)	2.5345 m
	Short (g)	0.3 m
F-sector:	Length	0.70 m
	Field	– 0.7841 kG
	Gradient	26.58 kG/m
D-sector:	Length	1.40 m
	Field	1.8345 kG
	Gradient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



Non-Scaling FFAG Lattice

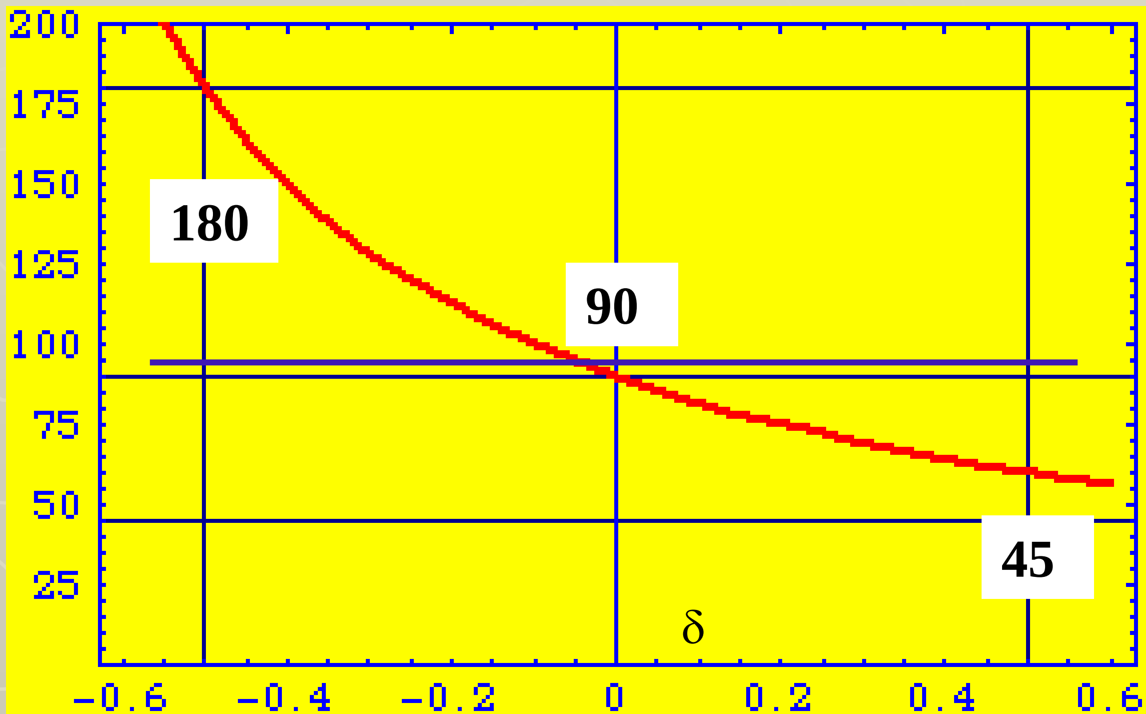


Chromaticity with Linear Gradient



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

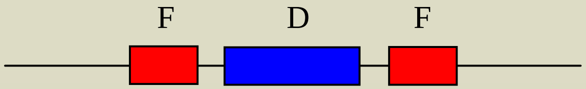
$h^2 n / (1 + \delta)$



Scaling FFAG Lattice: Large p-Aperture, Large Field, Constant Tune

Non-Scaling Lattice: Narrow p-Aperture, Lower Field, Varying Tune

Adjusted Field Profile



BNL - C-A/AP/148

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

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

- 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:

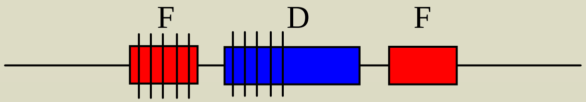
$$n(x, s) = n_0 [1 + \delta(x, s)] \quad \text{-->} \quad G(x, s) = G_0 [1 + \delta(x, s)] \quad \text{<---}$$

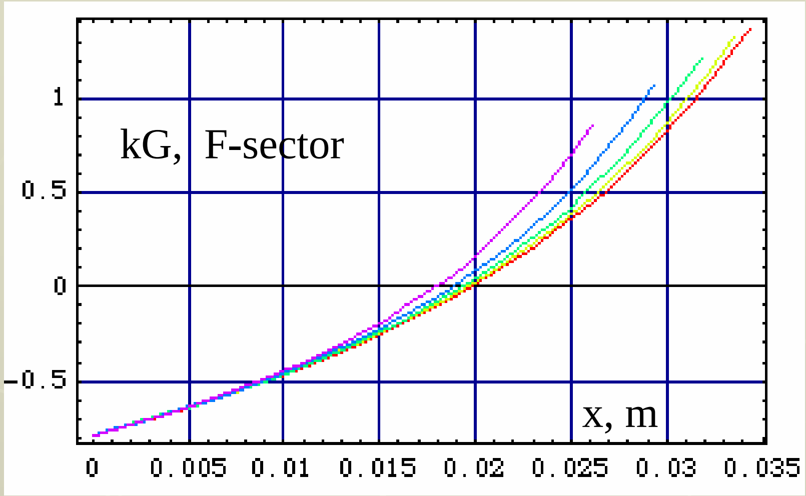
where n_0 is related to the gradient $G_0 = n_0 h B_0$ on the reference trajectory.

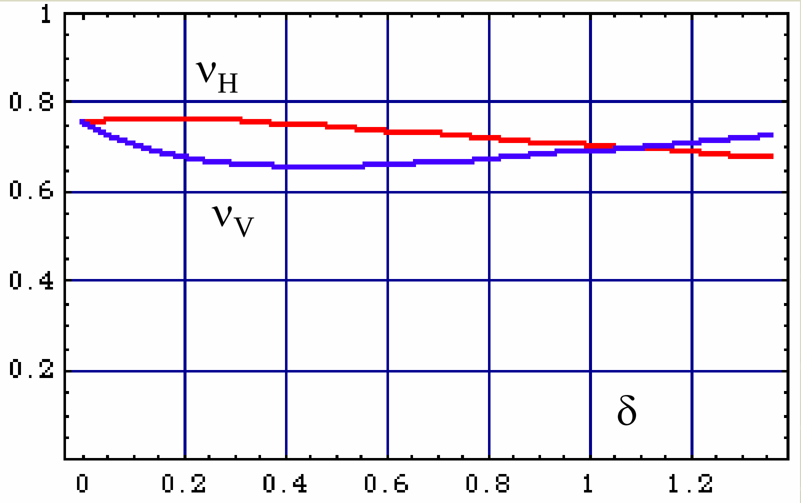
- Then the equations of motion reduce to

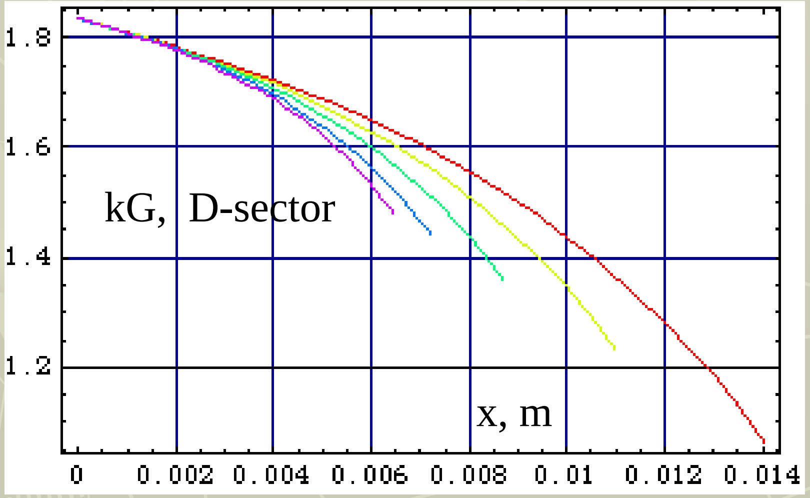
$$x'' + h^2 x / (1 + \delta) + h^2 n_0 x = h\, \delta / (1 + \delta) \quad \text{-->} \quad x = x(\delta, s) \quad \text{-->} \quad \delta = \delta(x, s)$$
$$y'' - h^2 n_0\, y = 0$$

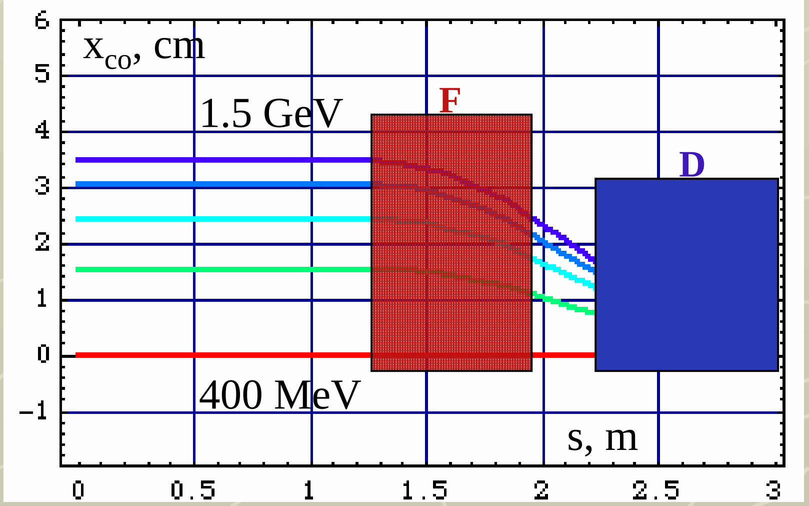
Magnet Field Profiles -- β-Tunes
p-Bundle



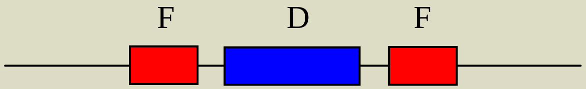






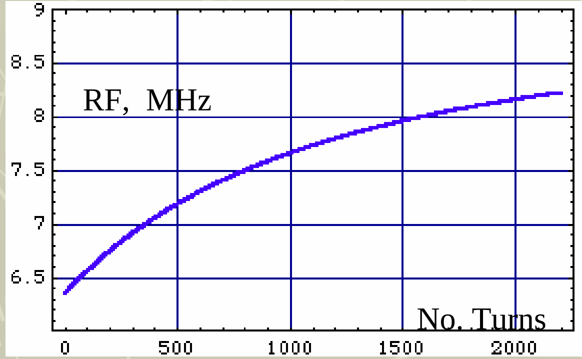


RF Cavity System



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
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

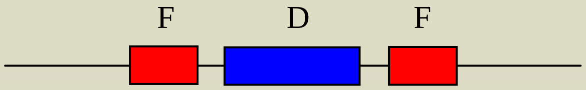


RF Cavity System

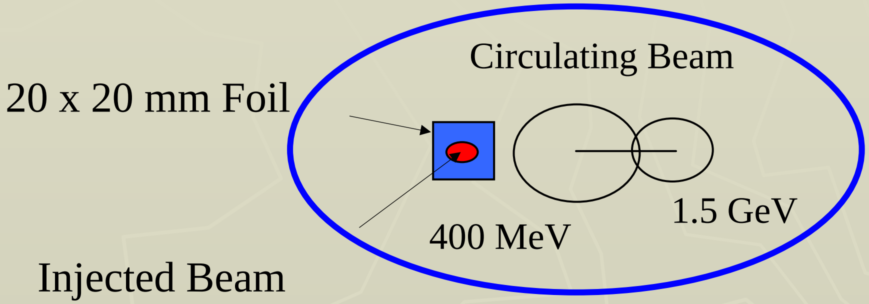
Peak RF Voltage	0.8 MVolt	
No. of RF Cavities	20	
No. of Gaps per Cavity	1	
Cavity Length	1.0 m	
Internal Diameter	10 cm	
Peak Voltage / Cavity	40 kVolt	
Power Amplifier / Cavity	250 kW	
Energy Range, MeV	**400**	**1,500**
β	0.7131	0.9230
Revol. Frequency, MHz	0.2649	0.3428
Revolution Period, μs	3.78	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

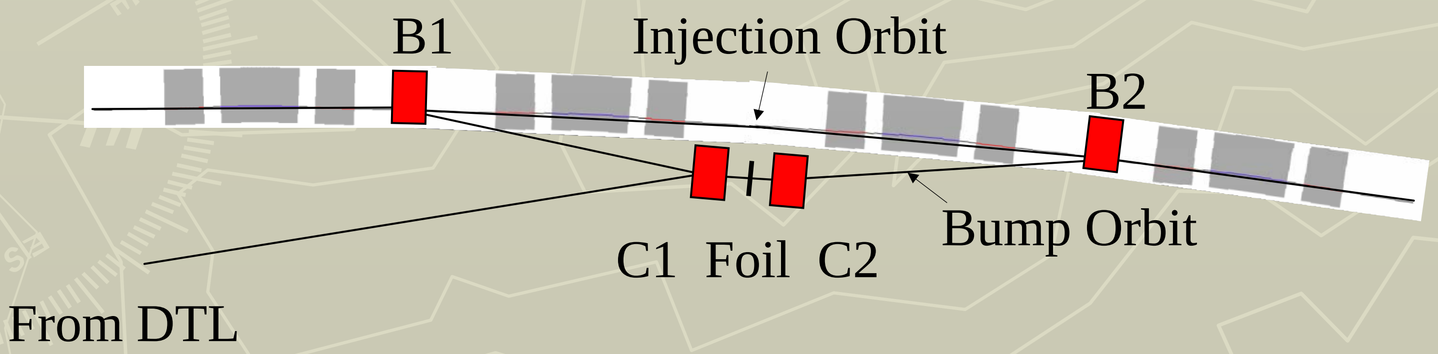
Multi-Turn Injection (H^-)



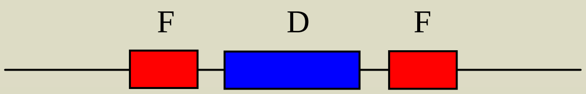
Linac Peak Current	35 mA
Revolution Period	3.78 μs
No. of Protons / FFAG pulse	1.0 x 10^{14}
Chopping Ratio	0.50
Chopping Frequency	6.357 MHz
Single Pulse Length	0.96 ms
No. of Turns Injected / pulse	255
Linac/FFAG Rep. Rate	2.5 Hz
Linac Duty Cycle	0.24 %
Linac Beam Emittance, rms norm.	1 π mm-mrad
Final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



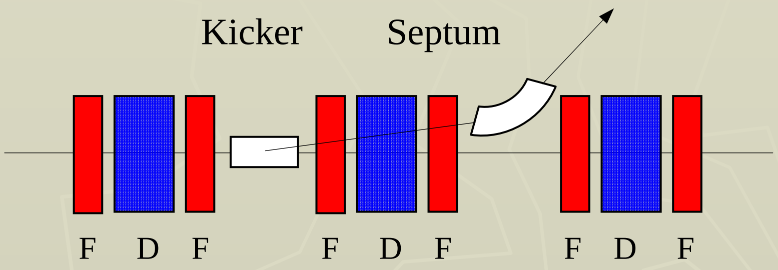
10 cm x 20 cm Vacuum Chamber



Single-Turn Extraction

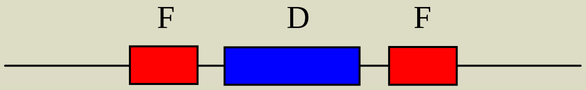


Revolution Period	2.92 μs
Beam Gap	300 ns
Kicker Magnet, Length	1.5 m
Field	1 kG
Rise-Time	< 300 ns
Septum Magnet, Length	1.5 m
Field	10 kG
Repetition Rate	2.5 Hz

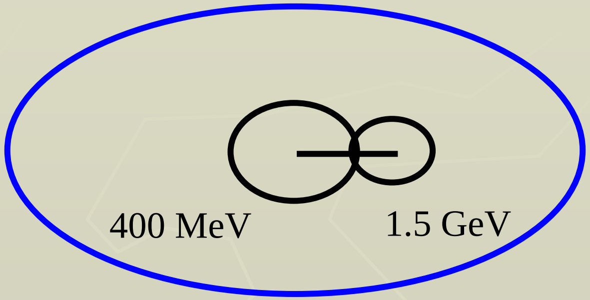


The Kicker field remains constant for the duration of the beam pulse (about 2.6 μs), and it is finally reset to zero-value in about 100 ms, to be fired again the next cycle.

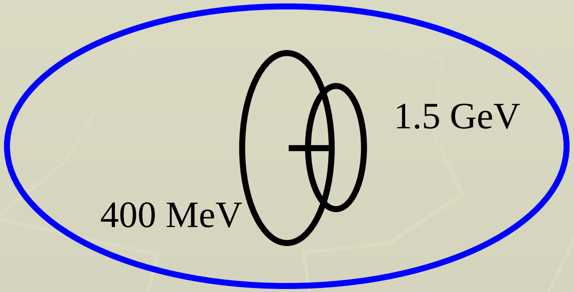
Magnet Design



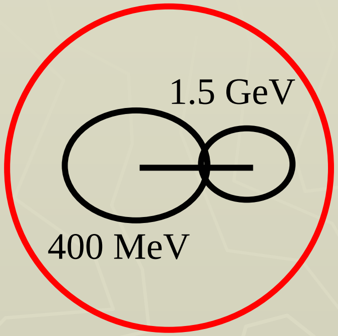
F-Sector



D-Sector



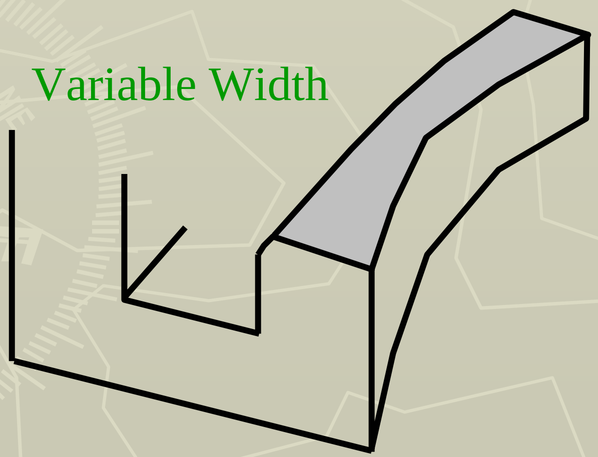
RF Long Straight



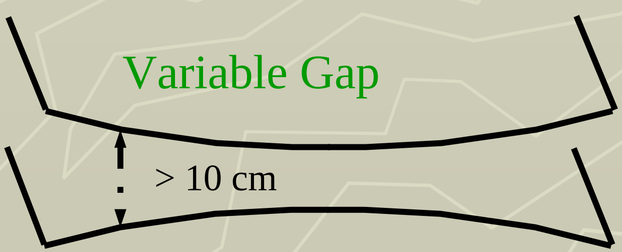
10 cm x 20 cm Elliptical Vacuum Chamber

10 cm Diameter Circular Vacuum Chamber

Variable Width



Variable Gap

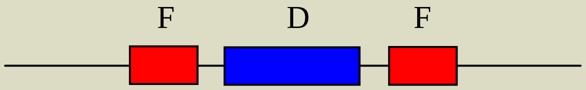


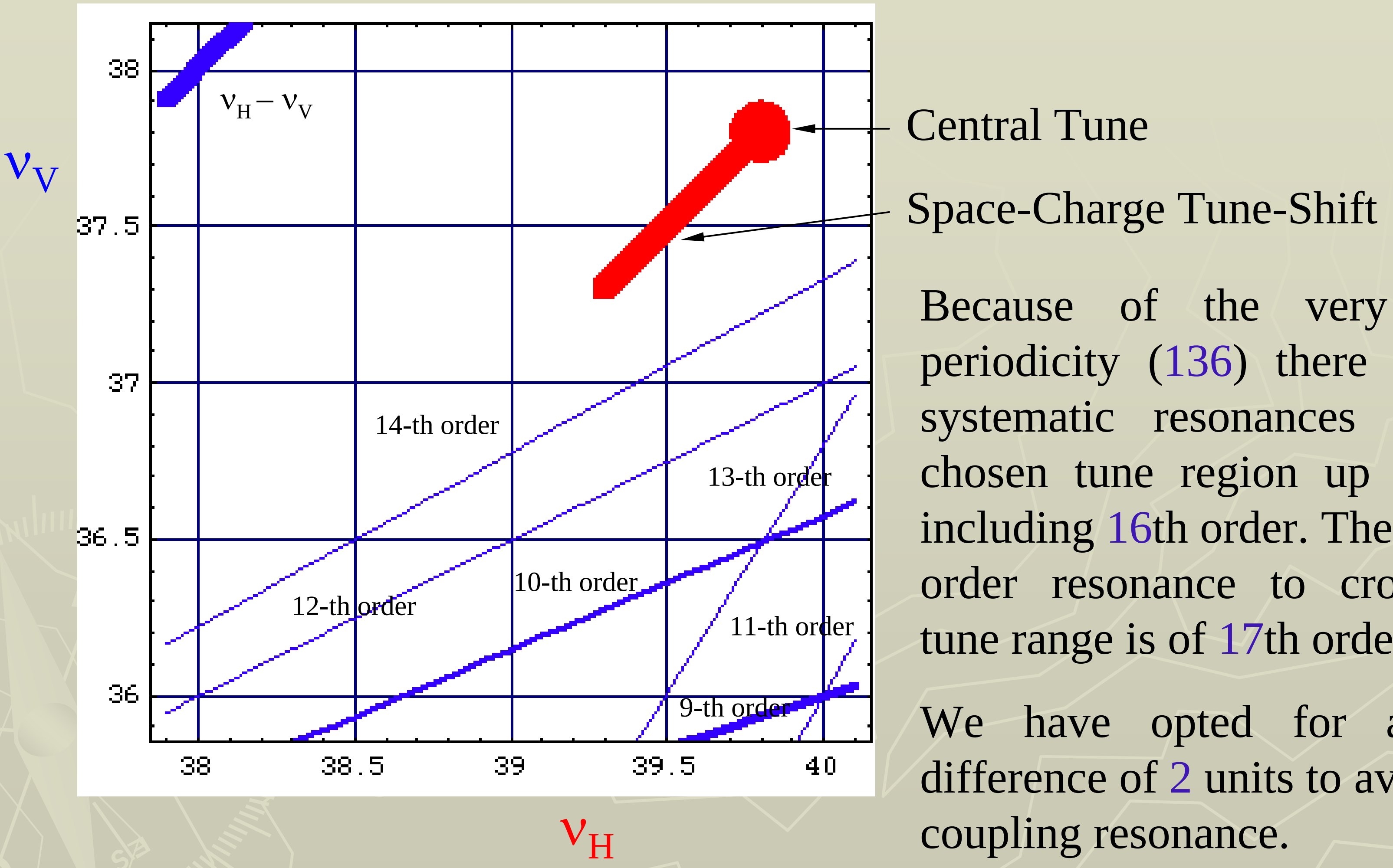
Space Charge at Injection

	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

Tune Diagram

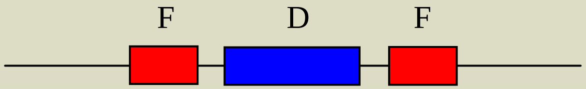




Because of the very large periodicity (136) there are no systematic resonances in the chosen tune region up to and including 16th order. The lowest order resonance to cross the tune range is of 17th order.

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

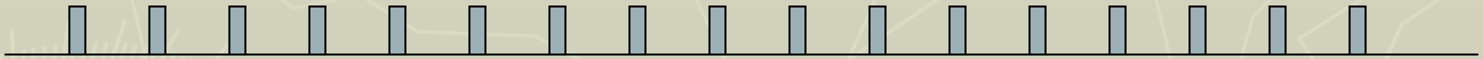
Conclusions



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
- 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**