Proton FFAG Accelerator Work at Brookhaven National Laboratory

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Summary

- Design of a Proton FFAG Accelerator
- FFAG Accelerator for AGS Upgrade
- 1-GeV 10-MW FFAG Proton Driver
- FFAG Proton Driver for Neutrino Factory
- FFAG Medical Accelerator
- e-RHIC
- FFAG for Synchrotron Light Source
- FFAG Electron Model (for Protons)
- Acceleration by Harmonic-Number Jump
- RIA

Acceleration by Harmonic-Number Jump

A.G. Ruggiero "RF Acceleration with Harmonic-Number Jump", BNL Internal Report, C-A/AP 237, May 2006

To avoid the problem of frequency modulation for acceleration of low-energy beams over a too short period of time, and to boost acceleration rate.

The method allows the use of constant frequency acceleration using superconducting cavities, despite the fact that the beam velocity may vary considerably.

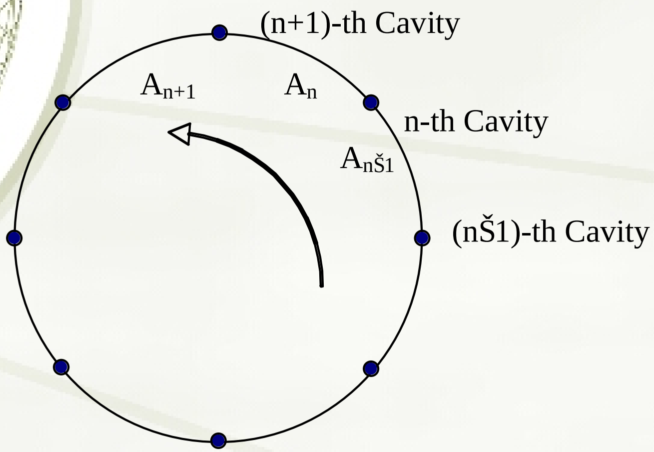
The accelerating voltage and RF phase need to be programmed accordingly.

We studied first the motion of *Synchronous* particles, and then of those with deviating initial conditions.

We estimated the area and height of the RF buckets that are to contain the beam bunches with the added condition of the **HNJ**.

We determined methods to create the program of energy gain as required by the **HNJ** method, including the effect of the cavity Transit Time Factor (**TTF**).

Acceleration of Synchronous Particles



The ring is made of N RF cavities equally spaced.

$\mathbf{E}_n$ = total energy

$\mathbf{T}_n = h_n T_{RF}$

$\Delta\mathbf{E}_n = (Q\, eV_n / A) \sin(\omega_{RF}\, \mathbf{t}_n)$

$= (Q\, eV_n / A) \sin(\phi_n)$

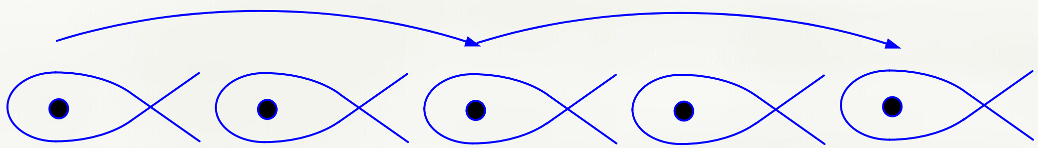
Assume the beam as a sequence of point-like bunches (*synchronous*, *reference*).

The energy gain is adjusted for a change in the travel period $\mathbf{T}_n$ in the following arc so that the *reference* particle is pushed forward or back exactly by Δh harmonics.

$\mathbf{T}_n = h_n T_{RF}$ $\mathbf{T}_{n-1} = h_{n-1} T_{RF}$ $h_n - h_{n-1} = -\Delta h$

$$\Delta\mathbf{E}_n = \beta_n^2 \gamma_n^3 E_0 \Delta h / h_n (1 - \alpha_{pn} \gamma_n^2)$$

Acceleration of Non-Synchronous Particles



Any other particle $t_n = \mathbf{t}_n + \tau_n$ $\Delta E_n = (Q\, eV_n / A) \sin(\omega_{RF}\, t_n)$

$$\varepsilon_n = E_n - \mathbf{E}_n$$

$$\Delta\varepsilon_n = (Q\, eV_n / A)\,[\sin(\phi_n + \omega_{RF}\,\tau_n) - \sin(\phi_n)]$$

$$\sim (Q\, eV_n / A)\ (\cos\phi_n)\ \omega_{RF}\,\tau_n$$

$$\Delta\,\tau_n = \tau_n - \tau_{n-1}$$

$$= -(1 - \alpha_{pn}\,\gamma_n^2)\ \mathbf{T}_n\,\varepsilon_n / \beta_n^2\,\gamma_n^3\,E_0$$

Small-Amplitude Oscillations

$$\Delta^2\tau_n / \Delta n^2 + \Omega_n^2\,\tau_n = 0 \quad \text{with} \quad \Omega_n^2 = 2\,\pi\,\Delta h / \mathrm{tg}\,\phi_n$$

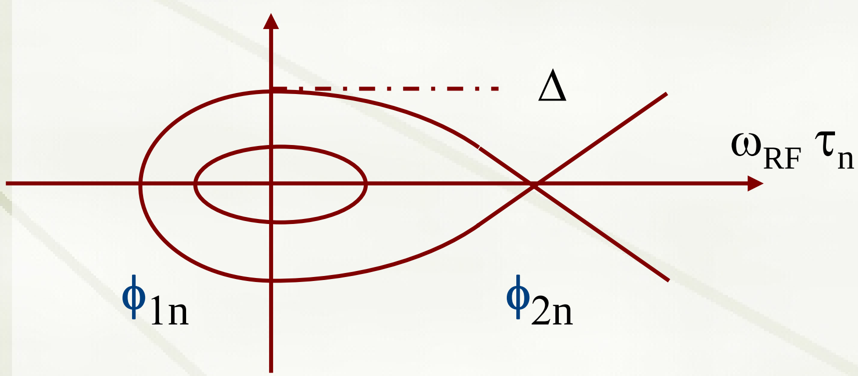
RF Buckets with Harmonic-Number Jump

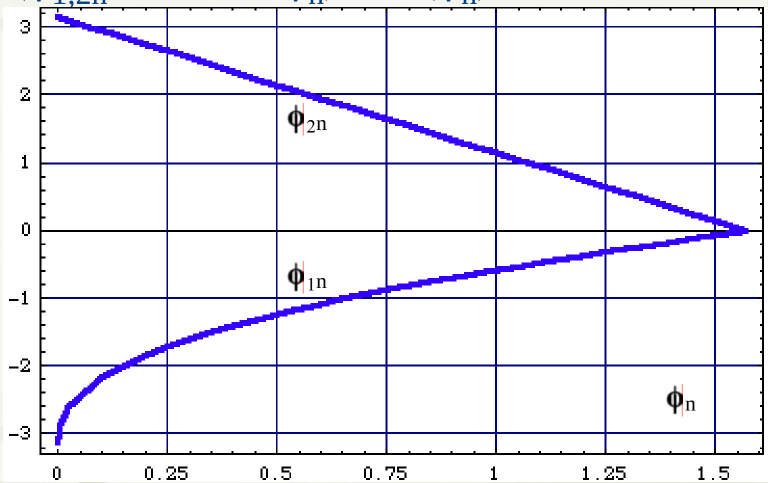
The Hamiltonian

$$H = (Q\, eV_n / A\, \omega_{RF}) \; [\cos(\phi_n + \omega_{RF}\, \tau_n) + \omega_{RF}\, \tau_n \sin(\phi_n)] +$$

$$- \; (1 - \alpha_{pn}\, \gamma_n^2) \; \mathbf{T}_n\, \varepsilon_n^2 \; / (2\, \beta_n^2\, \gamma_n^3\, E_0)$$

$$\cos(\phi_n + \phi_{1,2n}) + \cos(\phi_n) + (\phi_{1,2n} - \pi + 2\,\phi_n) \sin(\phi_n) = 0$$





RF Buckets with Harmonic-Number Jump

Bucket Area

$$B_n = (8 / w_{RF})[\, 2\, Qe\, V_n\, b_n^{\,2}\, g_n^{\,3}\, E_0 \;/\; A\, \pi\, h_n\, (1 - a_{pn}\, g_n^{\,2})\,]^{1/2}\, I(\phi_{1n}, \phi_{2n})$$

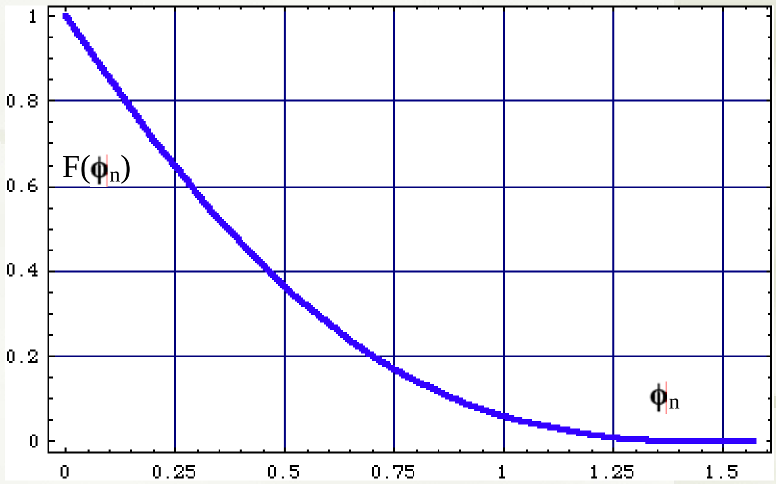
$$I(\phi_{1n}, \phi_{2n}) = \int [\cos(\phi_n + \phi) + \phi \sin(\phi_n) + G(\phi_n)]^{1/2} / 4\sqrt{2}\; d\phi$$

$$G(\phi_n) = \cos(\phi_n) - (\pi - 2\,\phi_n) \sin(\phi_n)$$

Bucket Height

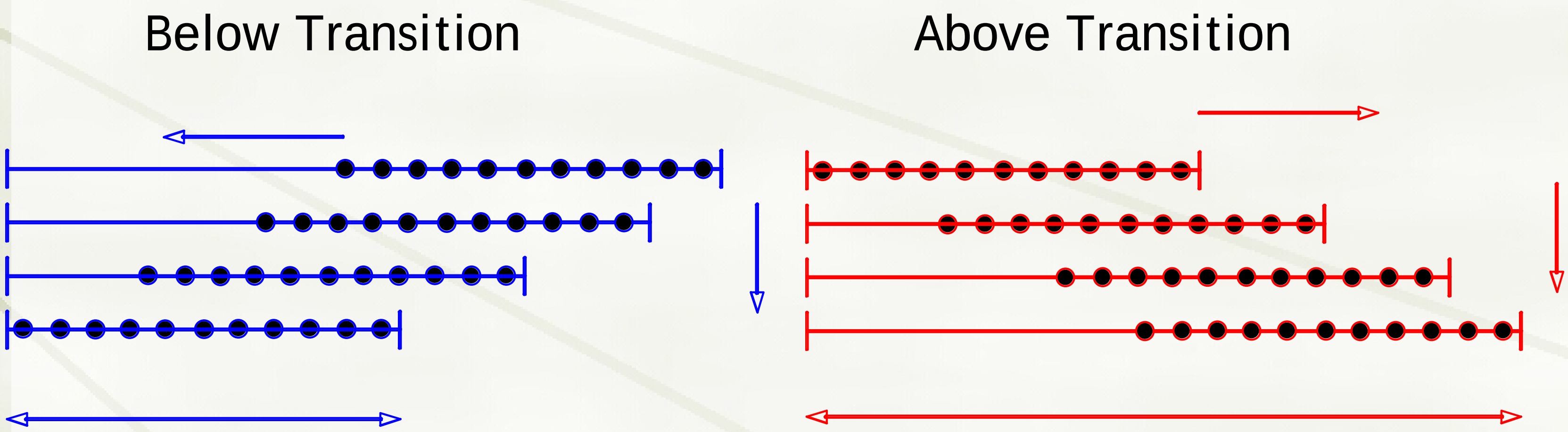
$$\Delta^2 = 2\, Qe\, V_n\, \beta_n^{\,2}\, \gamma_n^{\,3}\, E_0\, F(\phi_n) \,/\, A\, \pi\, (1 - \alpha_{pn}\, \gamma_n^{\,2})\, h_n$$

$$F(\phi_n) = \cos(\phi_n) - (\pi/2 - \phi_n) \sin(\phi_n)$$



Consequences of Harmonic-Number Jump

To avoid beam losses, the number of bunches ought to be less than the harmonic number at all time. On the other end, because of the change of the revolution period, the number of RF buckets will vary. There is a difference between the case of acceleration below and above transition energy. Below transition energy the beam extension at injection ought to be shorter than the revolution period. That is, the number of injected bunches cannot be larger than the RF harmonic number at extraction. The situation is different when the beam is injected above the transition energy. In this case the revolution period decreases and the harmonic number increases during acceleration.



Energy Gain Programming

Energy gain at the n-th cavity

$$\Delta \mathbf{E_n} = eV_n \sin(\phi_n) \quad = \quad A\, \beta_n^2\, \gamma_n^3\, E_0\, \Delta h \,/\, Q\, h_n\, (1 - \alpha_{pn}\, \gamma_n^2)$$

$$V_n \quad = \quad n_c\, g\, \xi_n\, TTF(\beta_0/\beta, n_c) \qquad TTF(x, 1) = \sin(\pi x/2) \,/ (\pi x/2)$$

$$g \;=\; \lambda\, \beta_0 / 2 \qquad\qquad \xi_n \;=\; \text{average axial field}$$

Two Programming Methods:

1. Constant RF Phase ϕ_n

   It requires the design of a RF Cavity with proper radial field profile

2. Constant average axial Field ξ_n

   It requires a RF phase modulation

Radio-Isotopes Acceleration (RIA)

We have studied the use of FFAG's for the acceleration of U-238 with charge state +28 to produce radioisotopes and exotic nuclear fragments.

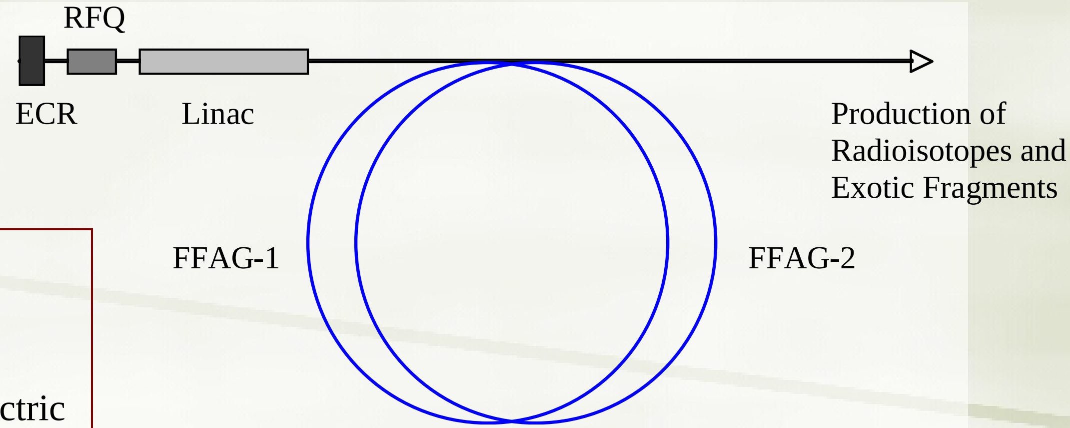
A.G. Ruggiero "AGS-less RIA with FFAG Accelerators", BNL Internal Report, C-A/AP 238, May 2006

Because of the large variation of the beam velocity in each ring, to avoid the use of ferrite or other techniques for RF modulation, we proposed acceleration with the method of *Harmonic-Number Jump* (HNJ).

The ion source is an ECR capable of 30mA-electric (CW). Only one turn needs to be injected. Multi-turn injection can be avoided as well methods of beam cooling.

Space charge tune depression is less than $\Delta\nu = 0.3$ with a betatron emittance of 5.0 π mm-mrad (full value, normalized).

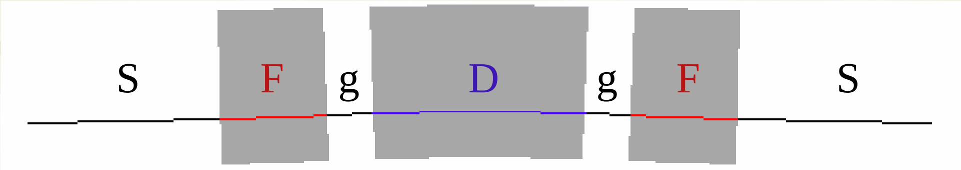
Outline of the Scheme



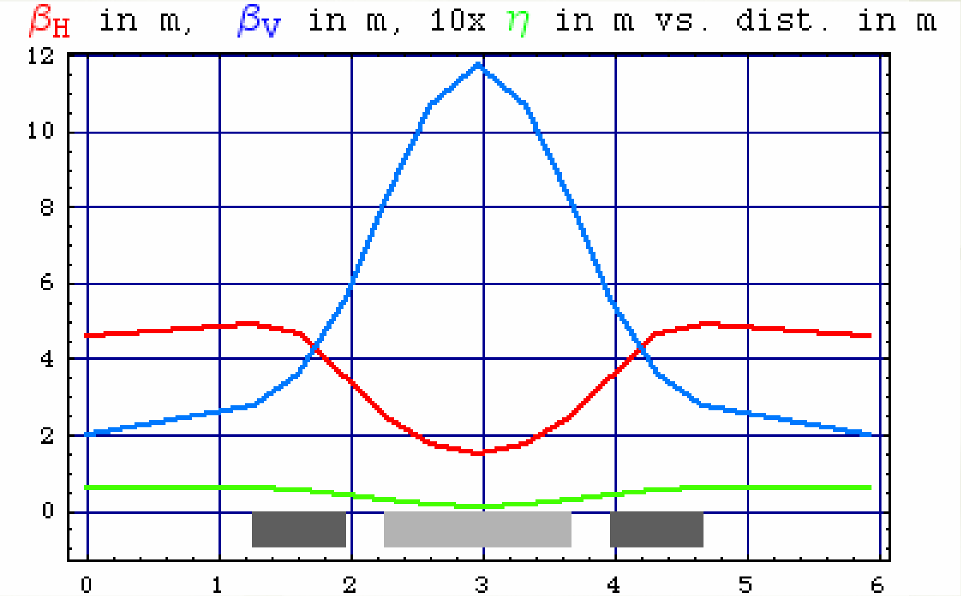
Type of Ions	Uramium
Charge State, Q	+28
Mass Number, A	238
ECR current	30 mA-electric
Injector Linac Energy	6 MeV/u
Beam Bunching Frequency	201.34 MHz
Chopping Ratio	80%
Transmission Efficiency	80%
Injected Current	20 mA-electric
Linac Pulse Length	4.13 µs
Repetition Rate	1,000 pulses/s
Linac Duty Cycle	0.413 %
No. of Injected Turns	1
No. of Ions / Cycle	1.8×10^{10}
No. of Bunches	831
No. of Ions/Bunch	2.13×10^{7}
Norm. Emittance (full)	5.0 π mm-mrad
Bunch Area (full)	10 µeV/u-s

	FFAG-1	**FFAG-2**	
	Inject.	**Transfer**	**Extract.**
Circumference, m	807.091	808.304	809.201
Energy, MeV/u	6	50	300
β	0.1126	0.3140	0.6526
Rev. Freq., MHz	0.0418	0.1165	0.2422
Rev. Period, µs	23.919	8.585	4.129
Harmonic No.	4816	1729	**831**
ΔE/ Cavity, MeV/u	0.0201	0.494	3.301
Circ. Current, mA-e	3.31	9.23	19.20
RF Power, MW	0.0159	1.087	15.08
Beam Power, kW	4.04	33.69	**202.15**
Bunching Factor	4	8	16
S. C. Tune-Shift	0.29	0.068	0.020

FFAG Rings at Injection

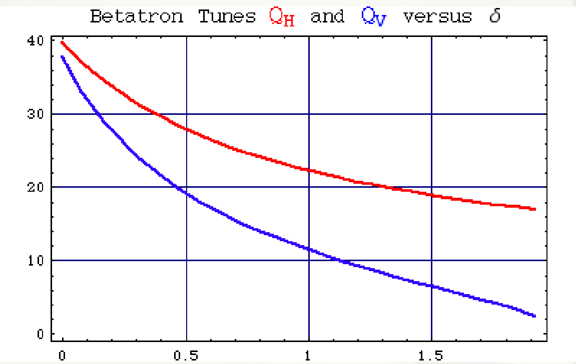


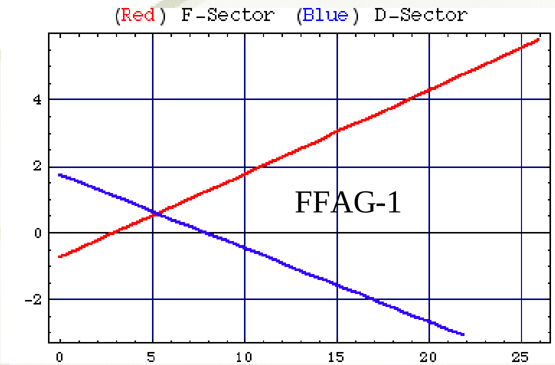
	FFAG-1	FFAG-2
Circumference, m	807.091	808.304
Periodicity	136	
Period Length, m	5.9345	5.9434
Long Drift S, m	2.5345	2.5383
Short Drift g, m	0.300	0.300
Bρ, kG-m	30.13	87.00
F-Sector Magnet		
Length, L_F, m	0.700	0.701
Bend Field, kG	-0.7423	-2.1644
Gradient, kG/m	25.164	73.2661
D-Sector Magnet		
Length, L_D, m	1.400	1.402
Bend Field, kG	1.7367	5.0640
Gradient, kG/m	22.0533	-64.2089

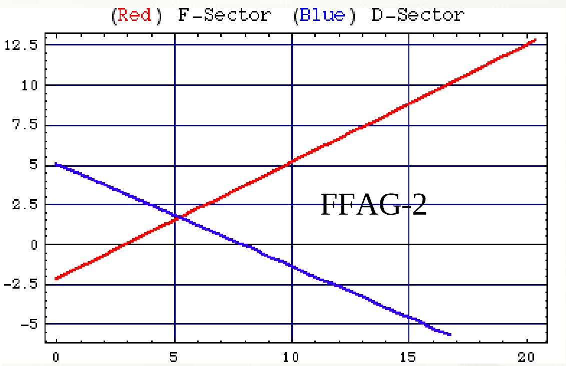


Phase Advance / Period, H / V	105^o / 100^o
Betatron Tunes H / V	39.76 / 37.75
Transition Energy, γ_T	-i105.5
Max β value, H / V, m	4.9 / 11.8
Max dispersion, η	6.0 cm
Chromaticity, H / V	-0.925 / 1.814

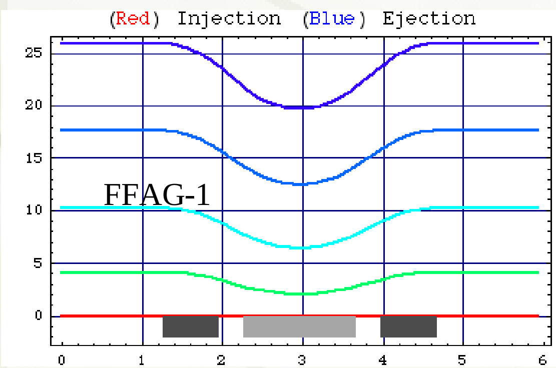
Non-Scaling Lattice with Linear Profile

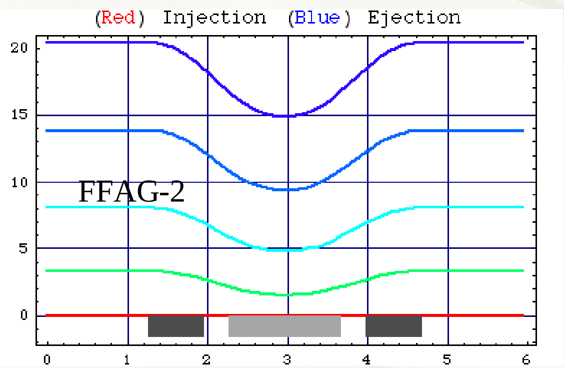






Magnetic Field B in kG vs. Radial Position x in cm





Momentum Closed Orbits x in cm vs. Path Length s in meter across one Period

RF Cavities Parameters

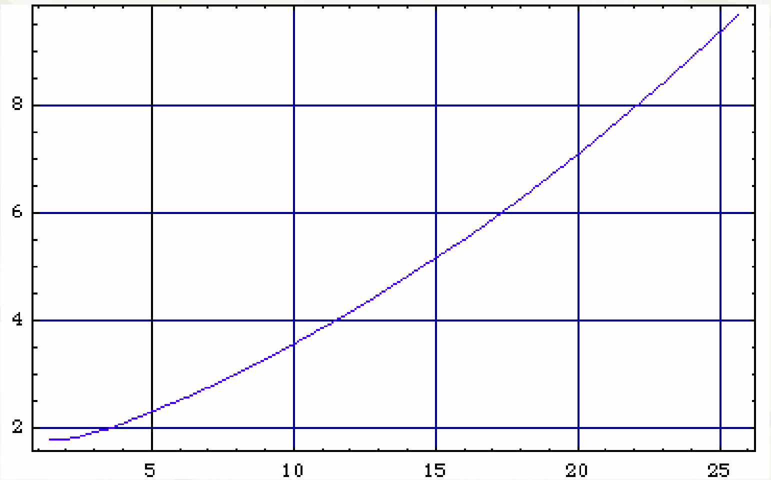
Type	Superconducting Elliptical Cells π-mode	
RF	201.34 MHz	
	FFAG-1	**FFAG-2**
Number of Cavities /Ring	8 equally spaced	3 equally spaced
Number of Cells / Cavity	4	4
Reference β Value, β_0	0.196377	0.314049
Cavity Cell Gap, cm	14.6267	35.5402
Cavity Diameter, cm	40	30
Cavity Length, m	2.0	2.0
Harmonic Number Jump, Δh	1	1
RF Phase, degrees	11.95 - 60	4.02 - 60
Average Axial Field, MV/m	9.792	25.102
Acceleration Period, ms	0.787	0.637
Number of Cavity Crossings	388	301
Number of Revolutions	**50**	**100**

Constant RF Phase

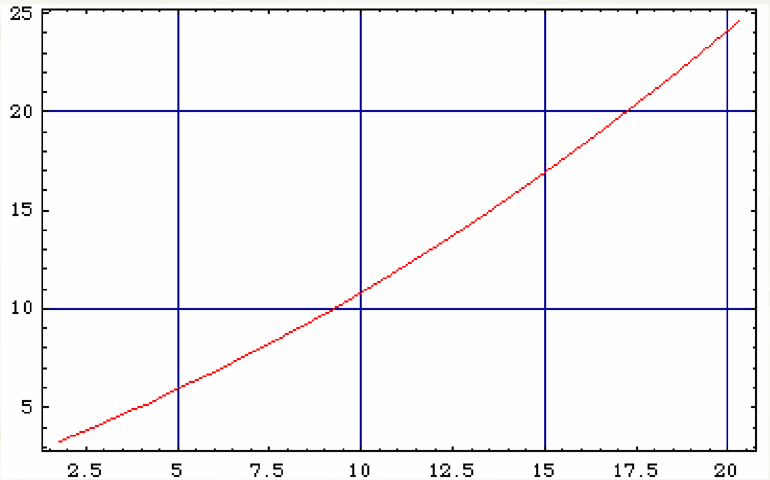
Average Axial Field in MVolt/m vs.

Radial Position x in cm

FFAG-1



FFAG-2



Acceleration by HNJ

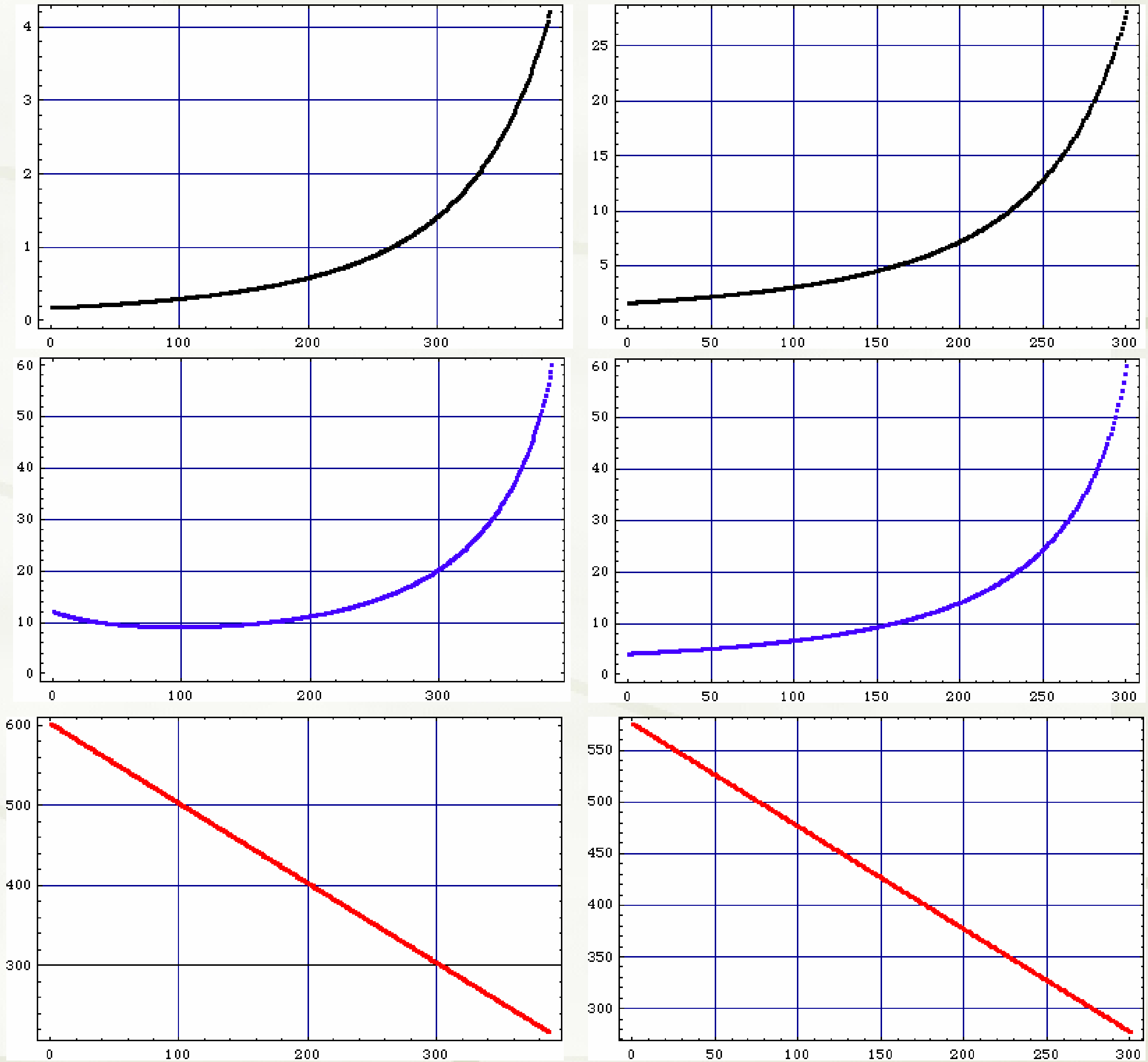
FFAG-1 FFAG-2

ΔE_n in MeV/u

ϕ_n in degrees

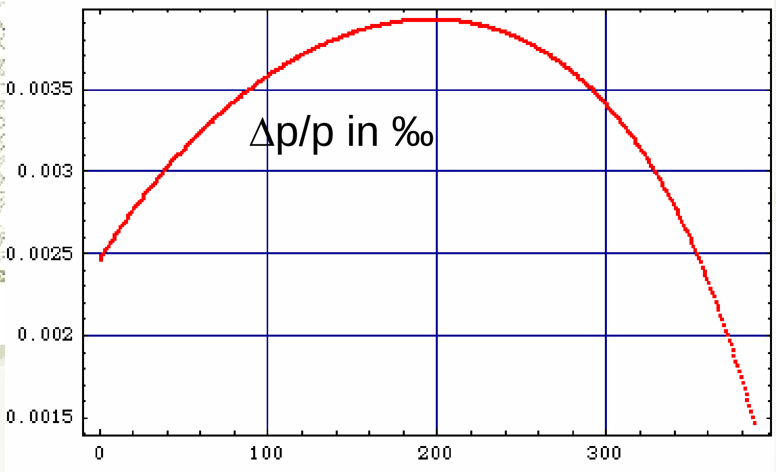
h_n

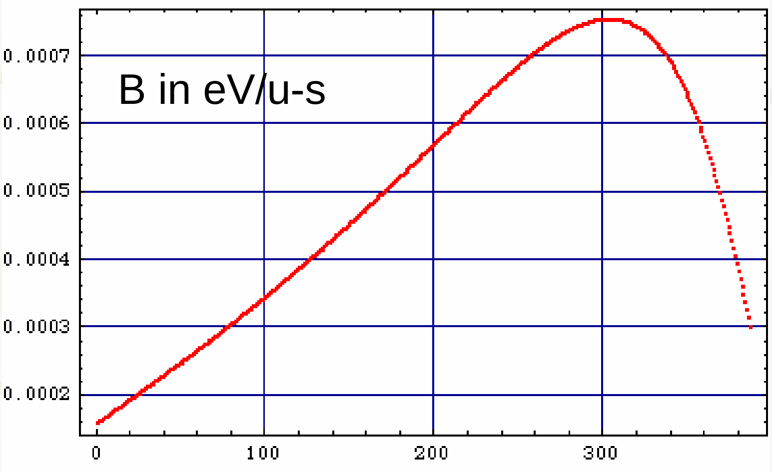
vs. no. of cavity crossings n



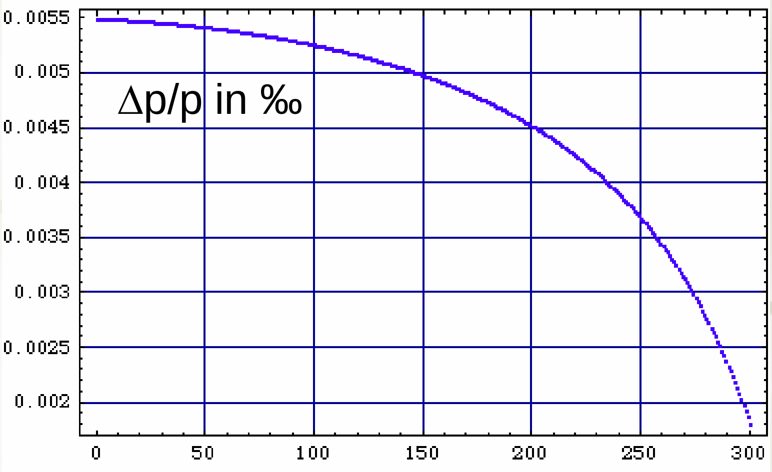
RF Buckets Height and Area

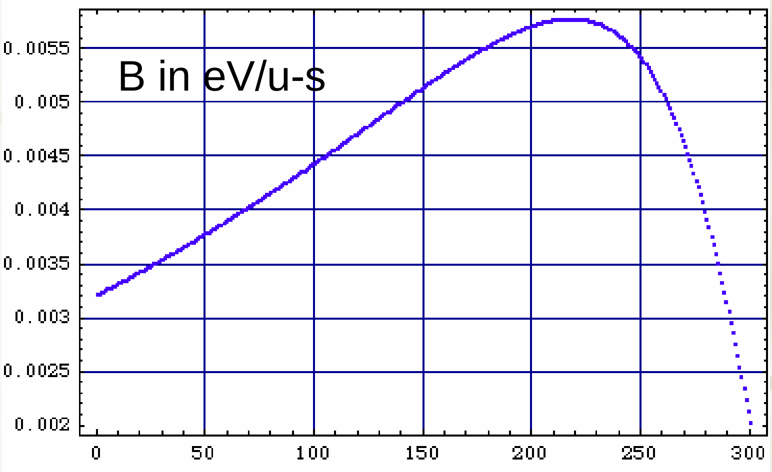
FFAG-1





FFAG-2





Number of Cavity Crossings, n