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AGS-less RIA with FFAG Accelerators

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Abstract

We have studied the use of Fixed-Field Alternating-Gradient (FFAG) accelerators for the acceleration of heavy ions to produce radioisotopes and exotic nuclear fragments. We have taken as reference a beam of nuclei of Uranium 238 partially stripped to +28 charge state.

Introduction

We found that a convenient layout is made of two identical FFAG rings of the same size matching the circumference of the Alternating-Gradient Synchrotron (AGS) tunnel at Brookhaven National Laboratory (BNL), though the present scheme does not involve the AGS for the beam acceleration. The acceleration ranges between 6 and 50 MeV/u in the first ring, and between 50 and 300 MeV/u in the second. The mode of operation is pulsed at the repetition rate of 1,000 pulses per second (or less if desired) with a maximum average beam power of 200 kWatt. 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 have proposed and investigated acceleration with the method of *Harmonic-Number Jump* (HNJ) that employs constant-frequency superconducting cavities [1]. The ion source is an ECR type capable of 30mA-electric in continuous wave mode. At such intensity only one turn of ion beam needs to be injected in the first ring. Multi-turn injection can then be avoided as well electron or other methods of beam cooling. Space charge tune depression at injection is kept to $\Delta\nu = 0.3$ assuming a betatron emittance of 5.0 p mm-mrad (full value, normalized). Both FFAG rings are made of a periodic sequence of FDF triplets that result in a *Non-Scaling* Lattice [2].

Outline of the Scheme

The proposed scheme for the acceleration of Uranium 238 in a pair of FFAG accelerators is shown in Figure 1. The ion source is of ECR type that generates a continuous beam of 30mA-electric of partially stripped ions with charge state Q = +28 at the energy of 12 keV/u. To avoid losses at high energies, the beam is pre-bunched and chopped at 201.34 MHz, the RF in both FFAG rings, accelerated in one RFQ to 200 keV/u, and to 6 MeV/u in a Linac made of quarter-wavelength or spoke cavities also operating at 201.34 MHz. Overall transmission of the beam from the ion source to injection into the first ring (FFAG-1) is conservatively taken to be 70%. The two rings have about the same circumference, equal to that of the AGS. The revolution period at injection into the first ring is 24 µs. With the beam pulse current from the injector of 20mA-electric, one full turn injected would correspond to 1.0×10^{11} ions. The method of acceleration proposed is HNJ in both rings. Since the beam energy is constantly below the transition energy at all times, the number of bunches injected in the first ring is no more than the RF harmonic number at the end of the acceleration cycle in the second ring [1]. Thus the beam pulse length from the injector is only a fraction of the revolution period at injection. The main beam parameters are given in Table 1.

Table 1. Beam Parameters at Injection into FFAG-1

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 p mm-mrad
Bunch Area (full)	10 μeV/u-s

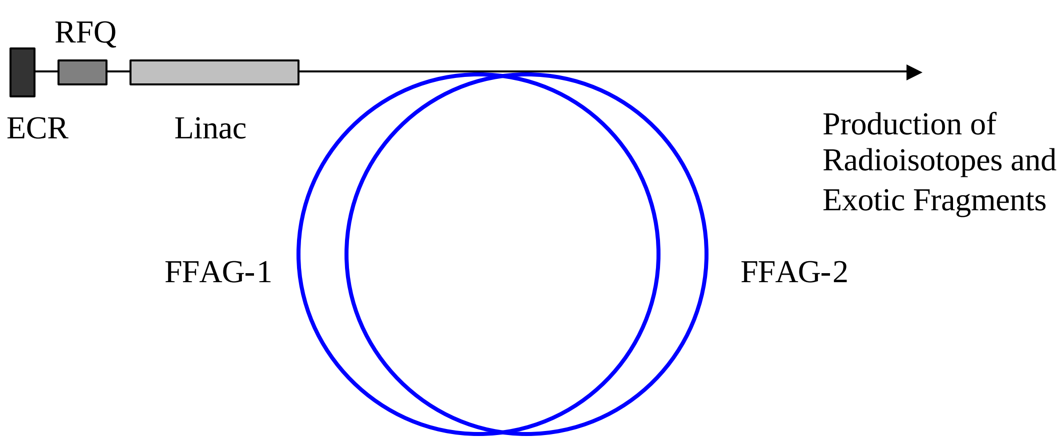

Figure 1. Layout of Injector and two FFAG Rings for RIA

FFAG Ring Lattice

The two rings not only have about the same circumference but have also about the same identical lattice configuration. We have opted for a *Non-Scaling* Lattice made of a sequence of FDF triplets as shown in Figure 2, with a Linear Field Profile, since it provides a most compact beam and magnet dimension. The design procedure is outlined in [2]. The main magnet parameters are given in Table 2, and those of the lattice functions in Table 3.

Table 2. Magnet Parameters of the FFAG Rings at Injection

	FFAG-1	FFAG-2
Circumference, C	807.091 m	808.304 m
Periodicity, P	136	136
Period Length, L	5.9345 m	5.9434 m
Long Drift, S	2.5345 m	2.5383 m
Short Drift, g	0.300 m	0.300 m
Magnetic Rigidity, $B\rho$	30.13 kG-m	87.00 kG-m
F-Sector Magnet		
Length, L_F	0.700 m	0.701 m
Bending Field, B_F	-0.7423 kG	-2.1644 kG
Gradient, G_F	25.1641 kG/m	73.2661 kG/m
D-Sector Magnet		
Length, L_D	1.400 m	1.402 m
Bending Field, B_D	1.7367 kG	5.0640 kG
Gradient, G_D	-22.0533 kG/m	-64.2089 kG/m

Table 3. Lattice Parameters of the FFAG Rings at Injection

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	4.9 m / 11.8 m
Max dispersion, η	6.0 cm
Chromaticity, H / V	-0.925 / -1.814

The lattice functions are about the same for both rings. They are displayed in Figure 3 for injection and extraction energy. Since we are adopting a *Non-Scaling* Lattice, there is a noticeable variation of the lattice functions over the acceleration cycle as it is also possible to notice from Figure 4 that shows the variation of betatron tunes. Such variation crosses indeed several major half-integral and integral resonances. The momentum compactness of the beam is shown in Figure 5. The contribution of the momentum interval for acceleration to the magnet horizontal aperture is 26 cm in the F sector magnet for the FFAF-1 ring, and 21 cm for the FFAG-2 ring. The aperture requirement in the D-sector magnet is somewhat less. To this one should add the contribution from the betatron beam size that is expected to be ± 5 mm. Figure 6 gives the plots of the magnetic field in both F and D sector magnets. The field values are very reasonable, and the magnets can be made with conventional warm technology. Aside from the large variation of betatron tunes that may raise some concern about beam stability and losses, the design looks to be well behaved. The other major parameters that describe the acceleration cycle are listed in Table 4.

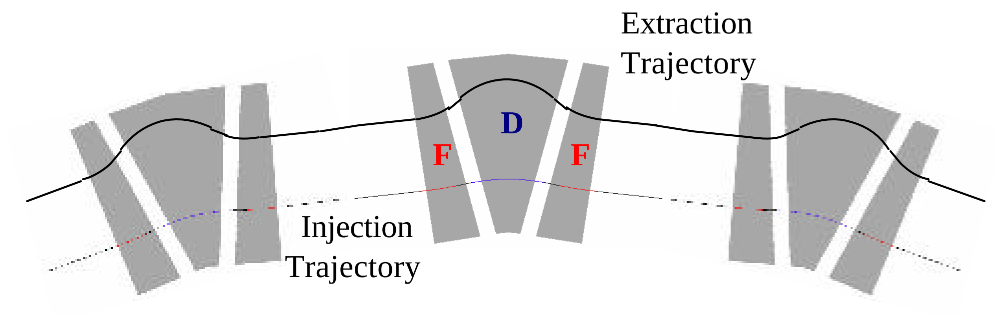

Figure 2. A Sequence of FDF Triplets making a FFAG Ring

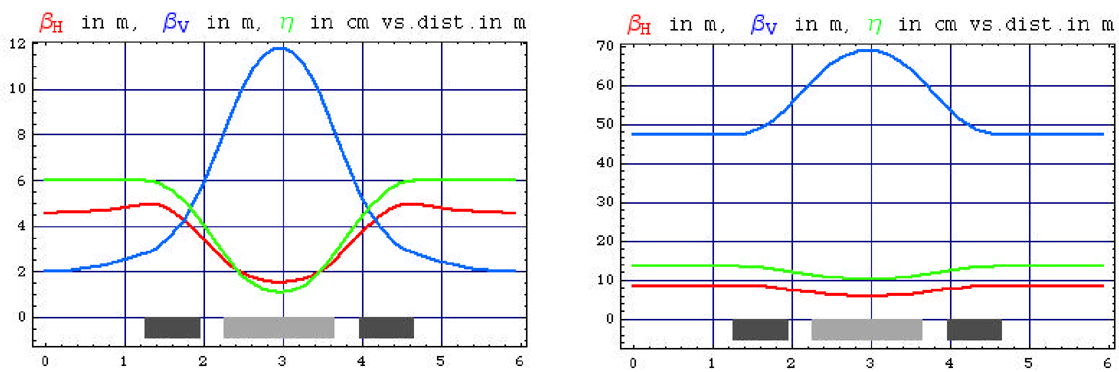

Figure 3. Lattice Functions at the Injection and Extraction Energy for both Rings

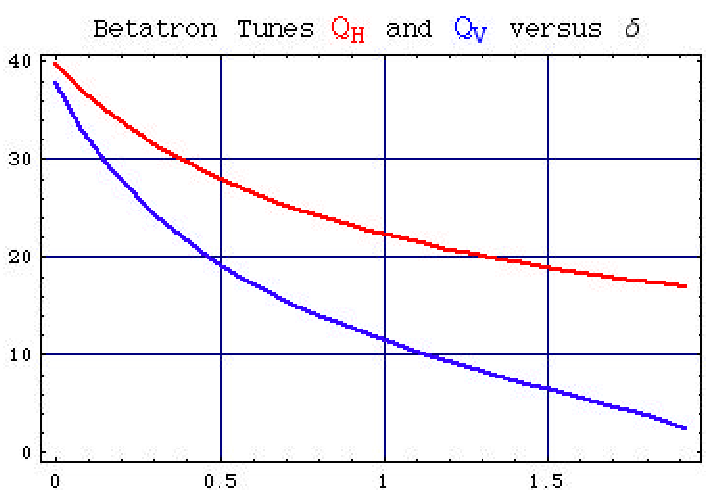

Figure 4. Betatron Tunes Q_H and Q_V versus Momentum Deviation $d = 1 - p/p_{inj}$

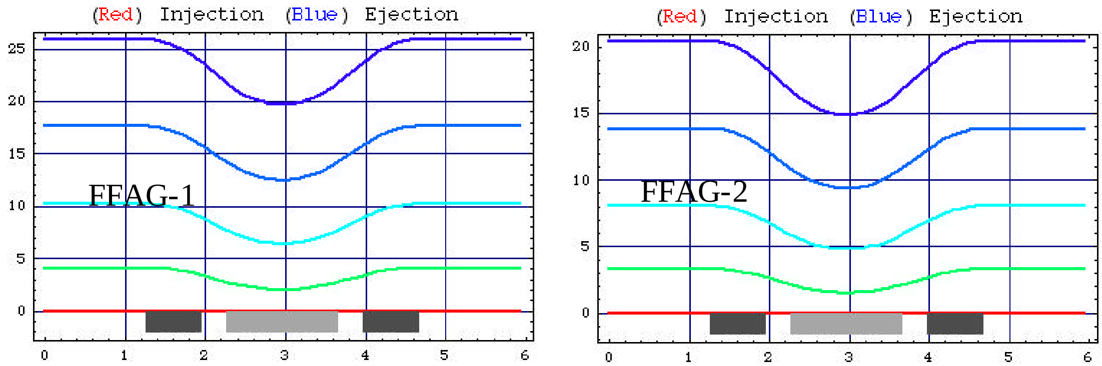

Figure 5. Momentum Closed Orbits (cm) along one Period (m)

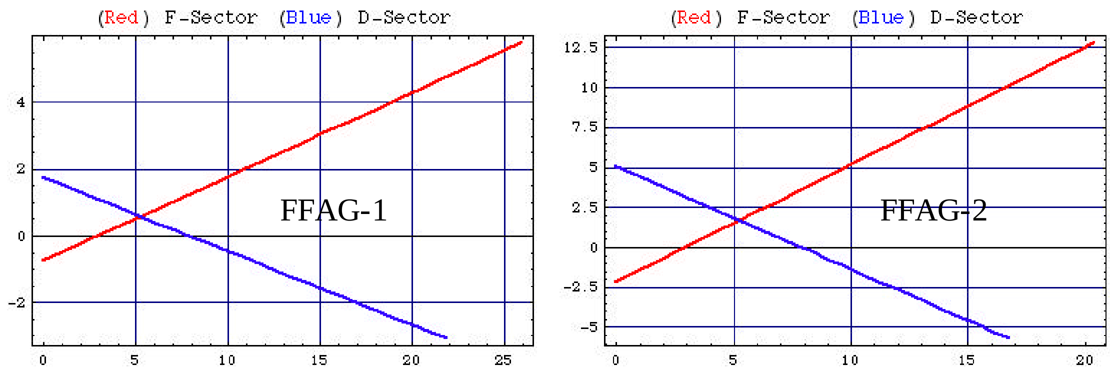

Figure 6. Magnetic Fields (kG) vs. Radial Position (cm)

Table 4. Parameters of the Acceleration Cycle

	FFAG-1		**FFAG-2**
	Injection	**Transfer**	**Extraction**
Circumference, m	807.091	808.304	8089.201
Kinetic Energy, meV/u	6	50	300
β	0.11255	0.3140	0.6526
Revolution Frequency, MHz	0.0418	0.1165	0.2422
Revolution Period, μs	23.9193	8.5853	4.1290
Harmonic Number	4816	1729	831
Energy Gain / Cavity, MeV/u	0.0201	0.494	3.301
Circulating Current, mA-e	3.3143	9.2340	19.2000
Beam RF Power, MWatt	0.0159	1.087	15.08
Average Beam Power, kW	**4.04**	**33.69**	**202.15**
Bunching Factor	4	8	16
Space-Charge Tune-Shift, Δν	0.29	0.068	0.020

Acceleration by Harmonic-Number Jump

Because of the large range and of the fast rate of change of the beam velocity, it is not easy to operate RF cavities in a frequency modulation mode where ferrite or other media should be used with reasonable high voltage and fast enough. The only other method we could think of for acceleration is to use constant-frequency RF superconducting cavities. Instead of modulating the frequency, the alternative is to modulate the energy gain from one cavity to the next [1]. The energy gain at one cavity should be set so that there is a change of beam speed in the following arc joining two cavities such that the local RF harmonic number has skipped by one or more RF wavelengths, so that the beam bunch falls in another bucket of identical properties. The energy gain can be modulated either with a proper voltage radial profile in the cavities or, by keeping the same field across, by adjusting the RF phase from one cavity to the next during the acceleration cycle. We have opted for this method because we though it is simpler and easier to realize. Moreover the beam acceleration is constantly below the transition energy in both rings. There is thus a limit on the maximum number of beam bunches at injection in FFAG-1 that cannot exceed the RF harmonic number at extraction from FFAG-2. Since both rings operate at the same RF of 201.34 MHz, the maximum number of bunches is 831. Using this method the acceleration period is predetermined and cannot be varied. The results of our calculations are shown in Table 5.

Table 5. RF Cavities Parameter

Type	Superconducting Elliptical Cells p-mode	
RF, MHz	201.34	
	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

The program of the energy gain per cavity is calculated with the HNJ method and plotted in Figure 7. The RF phase program, also calculated accordingly, is shown in Figure 8. That assumes a maximum phase of 60^o at the top of the acceleration cycle in both rings. Also the Transit Time Factor of the beam crossing the cavity at varying velocity β is taken into account. At that purpose all cavities in one ring are assumed with the same cell gap that is given by $\beta_0 \lambda/2$ with λ the constant RF wavelength, and β_0 a reference value. This mode of operation gives a constant average axial accelerating field that is the same to all cavities. All the relevant parameters are listed in Table 5 above. The results shown here are illustrative and have not yet optimized. Figure 9 shows the decrease of the local harmonic number during acceleration in both rings.

FFAG-1 **FFAG-2**

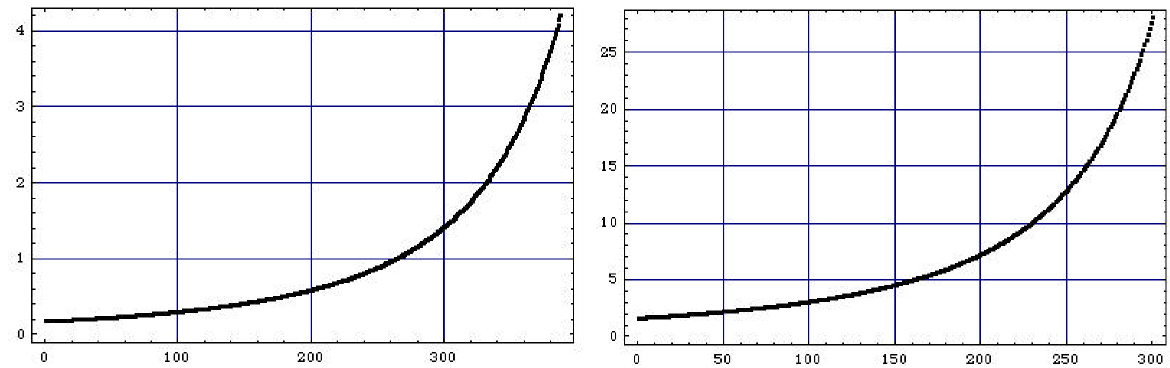

Figure 7. Energy Gain per Cavity (MeV) vs. Number of Cavity Crossings

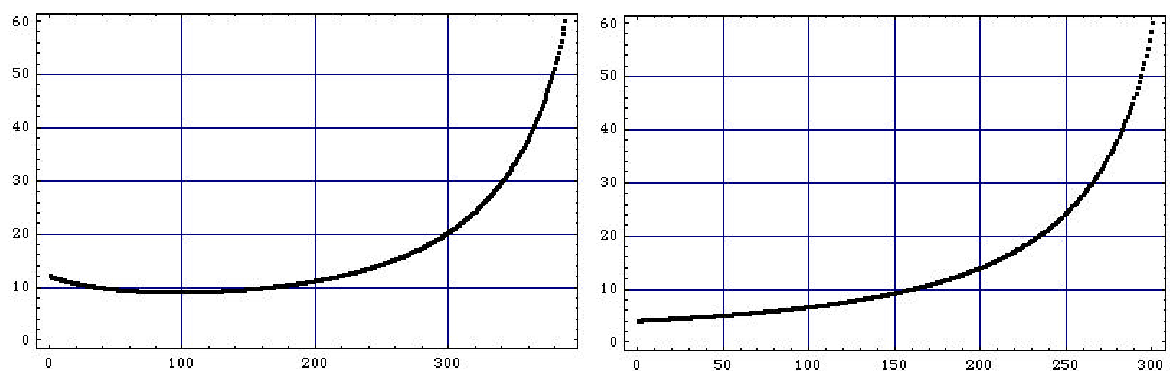

Figure 8. RF Phase Program (degrees) vs. Number of Cavity Crossings

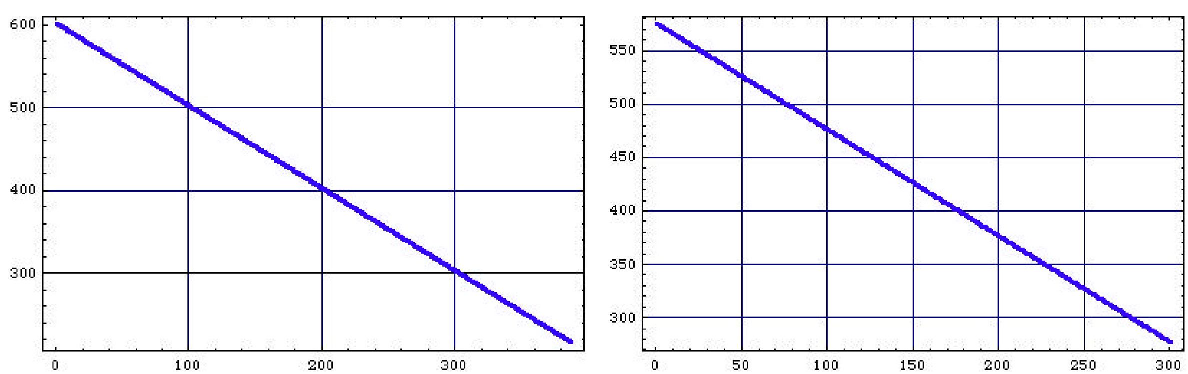

Figure 9. Variation of the Local Harmonic Number vs. Number of Cavity Crossings

We complete our analysis with the estimate of the RF bucket extension and height that are displayed in Figure 10 and 11 during the acceleration cycle. They seem more than adequate to capture and contain the beam bunches from the 6 MeV/u linac injector. The results depend on the choices available to provide the required program of energy gain per cavity, that here was by totally relying on the modulation of the RF phases. There are of course other possibilities to be explored, like for instance a superconducting cavity designed with a proper field profile, or a mixture of some RF phase modulation accompanied by a partial field profile. At the same time it is possible to change the final phase value that here has been assumed to be 60^o or the β-value that determines the cavity cell gap width.

FFAG-1 **FFAG-2**

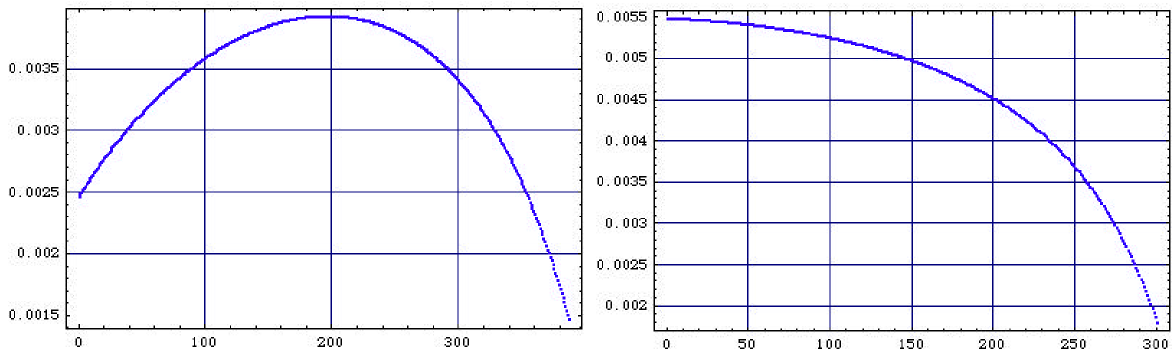

Figure 10. RF Bucket Half-Height, $\Delta p/p$ vs. Number of Cavity Crossings

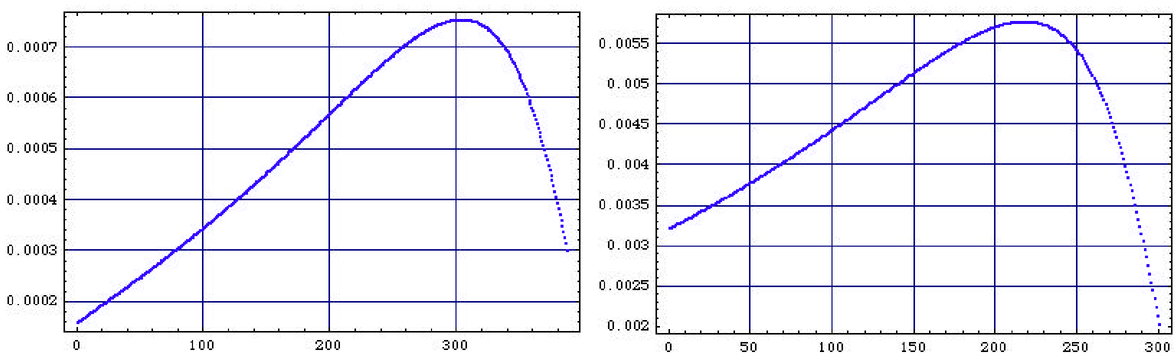

Figure 11. RF Bucket Area (eV/u – s) vs. Number of Cavity Crossings

References

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

[2] A.G. Ruggiero, "Design of Proton FFAG Accelerators", Proceedings of FFAG'05 Workshop, Osaka, Japan, Dec. 2005.