A NON-SCALING FFAG FOR RARE ISOTOPES PRODUCTION *

A.G. Ruggiero, T. Roser, D. Trbojevic, BNL, Upton, New York, 11973, USA

Abstract

This is a report to demonstrate use of Non-Scaling Fixed-Field Alternating-Gradient (FFAG) accelerators [1] in acceleration of partially stripped ions of Uranium-238 for Rare Isotopes Production. This example assumes a beam final energy of 500 MeV/u with an average beam output current of 1 µA-particle and a beam average power of 120 kWatt.

INTRODUCTION

The scope of this design is similar to the Rare Isotopes Accelerator project (RIA) [2] for the same application that makes use of a long Super-Conducting Linac (SCL). The RIA project makes use of a large number of superconducting RF cavities divided in Low-, Medium-, and High-β sections. Use the FFAGs proposed here, could be economical since it uses considerably less RF cavities, though it is made of a long magnetic structure but believed easier to built and less expensive [3]. The layout comprising three FFAG rings is shown in Figure 1. The three rings have about the same circumference and, though in the figure they are shown next to each other for logistic comparison, they can be housed in the same tunnel either on top of each other or concentric to each other. The front-end is a combination of ECR source, an RFQ and a 10 MeV/u superconducting Linac in all similar to that proposed for the equivalent RIA project. At the exit of the Linac a first foil will strip the ions to a charge state of about Q = 70. Acceleration in the first and second FFAG ring will occur at that charge state. A second stripping target is located at the exit of FFAG-2 for a final charge state Q = 90, at which the beam is finally accelerated in the third ring. The main parameters are summarized in Table 1.

THE LATTICE OF THE FFAG RINGS

The three rings have the same circumference of 204 m. They accelerate beam over about the same moment range of ± 31-35%. The three rings have about the same lattice made of a sequence of FDF triplets, shown in Figure 2, separated by a drift long enough for insertions of RF cavities, of collimation devices, and of the components for injection and extraction. The Lattice is of the *Non-Scaling* (NSL) type [4,5] where the FDF triplets are made of sector combined-function magnets with a linear field profile, essentially a pure dipole field superimposed on a quadrupole field. This lattice has been chosen for this design because it is expected to reduce the size and the field of the magnets, to allow long drift insertions, and consequently to be more economical. Magnets are current driven, operated at room temperature, and run at constant field. Alternatively they can also be permanent magnets.

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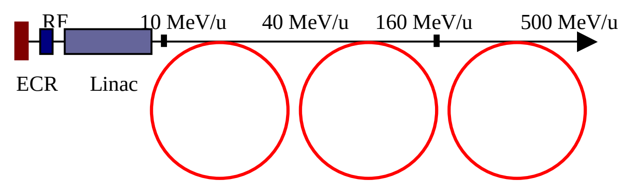

Figure 1: Layout of FFAGs for Rare Isotopes Production.

Table 1. Main Beam and Acceleration Parameters

	FFAG-1	FFAG-2	FFAG-3
Injection Energy	10 MeV/u	40 MeV/u	160 MeV/u
Extraction Energy	40 MeV/u	160 MeV/u	500 MeV/u
Charge State	+70	+70	+90
Δp/p	±33.7 %	±34.7 %	±31.3 %
Δx	13 cm	14 cm	11 cm
RF	175 MHz	350 MHz	700 MHz
Group of Cavities	4	2	1
Cavities / Group	2	8	18
βc	0.173	0.337	0.7245
Cavity Gap	15 cm	14 cm	12.5 cm
Axial Aver. Field	12.3 MV/m	14.0 MV/m	19.6 MV/m
Δh	1	2	4
Number of Revol.	26	49	73
Harm. Number	824 - 420	842 - 458	916 - 628
Accelerat. Period	90 µs	90 µs	80 µs

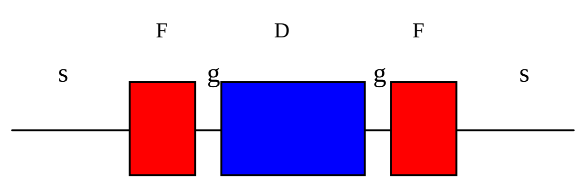

Figure 2: The FDF Triplet Period of each FFAG Ring.

The lattice main parameters are given in Table 2, and the lattice functions across the length of a single period are shown in Figure 3 at injection and extraction. A major concern with the *Non-Scaling Lattice* choice is the property that the betatron tunes vary considerably during acceleration as it is shown in Figure 4. The momentum compactness of the closed orbits is shown in Figure 5 for the FFAG-3 ring, with a similar behavior for the other rings. The radial separation Δx across the full momentum range Δp/p is shown in Table 1. The field profile in each of the magnets of the three rings, shown in Figure 6, is modest and the magnitude does not exceed 12 kGauss.

Table 2. Main Lattice Parameters

Circumference	204 m
Number of Periods	60
Period Length	3.4 m
Long Drift (2s)	1.452 m
Shirt Drift(g)	0.172 m
F-Sector Length	0.401 m
D-Sector Length	0.802 m

ACCELERATION

Acceleration is done with the method of *Harmonic Number Jump* (HNJ) [5] that only needs constant frequency RF superconducting cavities. The frequency varies from a ring to the next to allow a large diameter cavity bore for the containment of the full momentum acceleration range. To boost the acceleration rate RF cavities are grouped in few locations around each ring, and each group can be made of few single-cell, individually powered cavities. They have elliptical shape and work in π-mode. The number of groups, the number of cavities per group, the cell gap, the reference βc values, and the average axial field values are also shown in Table 1. Aside from their design simplicity, the total number of cavities in the whole FFAG accelerator is considerably smaller than that in the RIA SCL equivalent. That is 36 cavities in the FFAG rings against 360 in RIA SCL. A radial energy gain profile at each cavity is estimated that allows a harmonic number jump Δh between two consecutive groups of cavities. The resulting number of

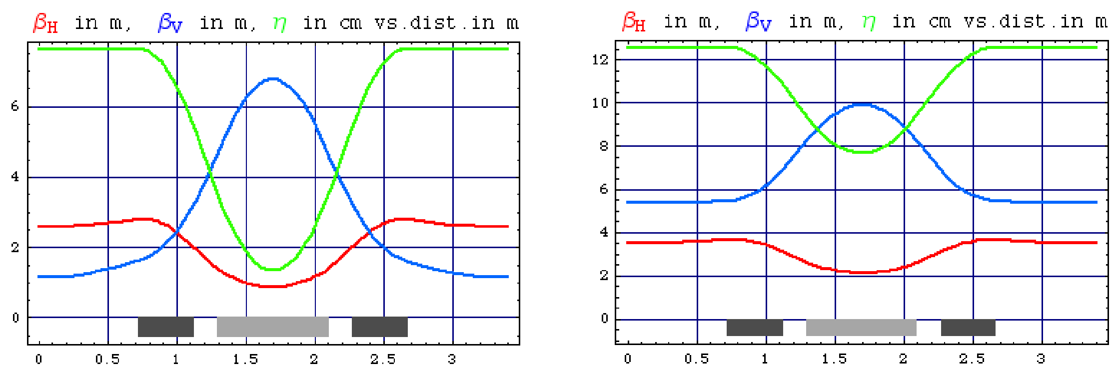

Figure 3: Lattice Functions along a Period at Injection (left) and Extraction (right).

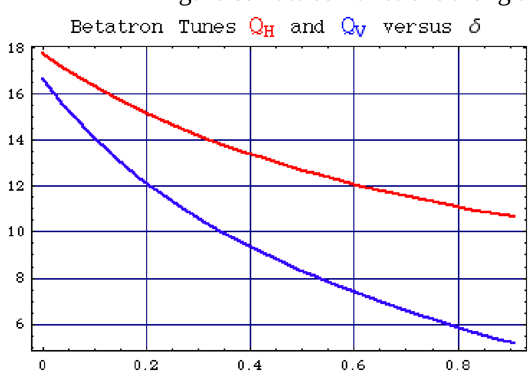

Figure 4: Betatron Tunes during acceleration

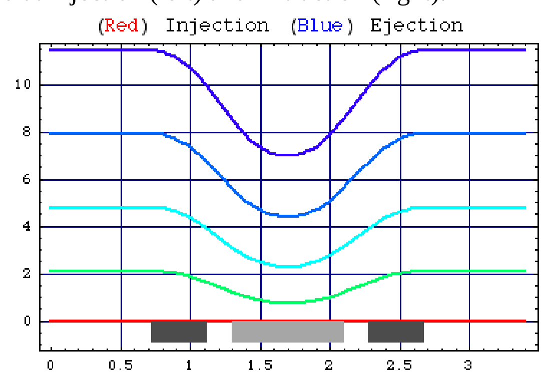

Figure 5: Momentum Closed Orbits

FFAG-1 FFAG-2 FFAG-3

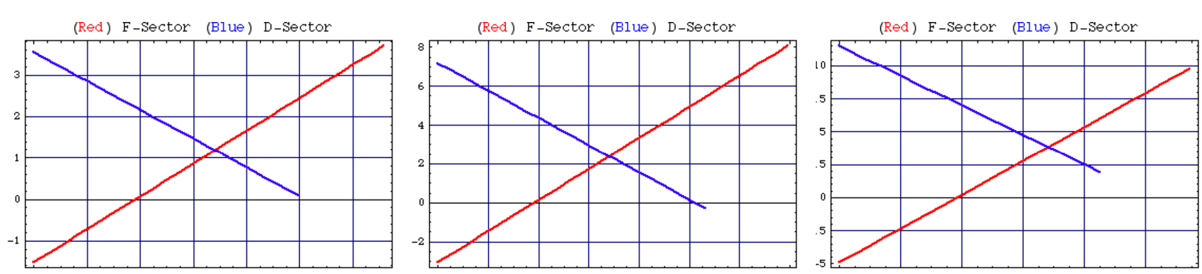

Figure 6: Field Profile (kG vs. cm) of the Sector Magnets in the three FFAG Rings.

revolutions is only in the few tens, and the acceleration period does not exceed 100 μs that allows operation of all rings at the repetition rate of 10 kHz. Of course one of the features of the FFAG accelerators is that the magnets are constant in time, and the repetition rate applies only to the manipulation of the beam and of the RF cycle. The HNJ method causes the harmonic number to drop as acceleration proceeds. Thus the number of bunches injected in the first ring can be no larger than the harmonic number at extraction in the last ring. The corresponding fraction of the ring circumference at injection covered by the beam is thus only 19%.

PULSED AND CW MODE OF OPERATION

There are two possible modes of acceleration: (1) Pulsed Mode at the repetition rate of 10 kHz. Since we require a beam average current of 1 μA-p for an average power of 120 kW at top energy. The total number of ions accelerated per cycle is 6.25×10^8. The revolution period at injection into the FFAG-1 is 4.7 μs, and the beam pulse length from the injector is thus 0.9 μs that corresponds to the ion source current of 100 μA-p as mentioned above. This is a large current, one or two orders of magnitude above what present technology can provide. An accumulator ring would be required in the front stage for the accumulation of ten to a hundred turns before acceleration. An accumulator scenario proper with the FFAG approach outlined here remains to be investigated. (2) The Continuous Wave (CW) mode of acceleration [5,6] is possible depending on how the energy gain profile for the HNJ method of acceleration is realized in practice. In this case the beam can be continuously injected and accelerated. Again because of the reduction of the harmonic number during the process, the continuous beam from the source (in this case obviously an ECR) should be pre-chopped to a 19% ratio to preserve the space for the beam contraction from injection into the first ring to extraction from the last one. The corresponding ion intensity, before pre-chopping, should then be a more modest 5 μA-p. To maintain the space-charge tune-depression at injection into the low energy ring at a safe value $\Delta\nu = 0.25$, the full normalized emittance of the beam should be 1 π mm-mrad for the Pulsed Mode of operation. In the CW mode of operation the corresponding tune depression would be considerably smaller. Figure 7 shows the required energy gain for the FFAG-3 ring as an example. For the other rings we have similar curves. It could be achieved either with cavities having the properly designed dependence of the axial field with radius as given in Figure 8, or with an axial field constant across the aperture, the magnitude of which is shown in Table 1, and varying the RF phase of the cavities at each crossing as shown in Figure 9. The former method is desirable for the implementation of a CW mode of operation, the latter for the pulsed mode. Needless to say perhaps, but both of these methods need further investigation.

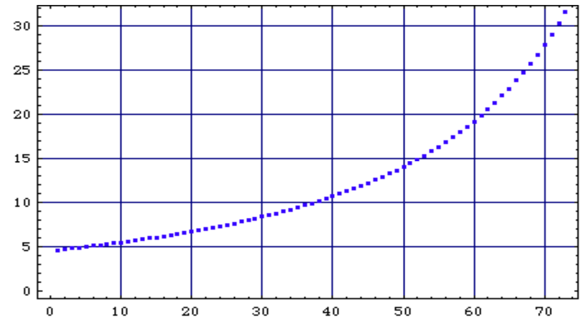

Figure 7: Energy Gain Profile per Cavity Group in FFAG-3 (MeV/u versus no. of crossings)

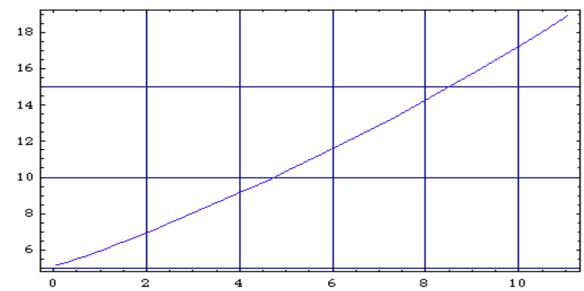

Figure 8: Radial Field Profile of Axial Field in a group of Cavities for FFAG-3 (MV/m vs cm)

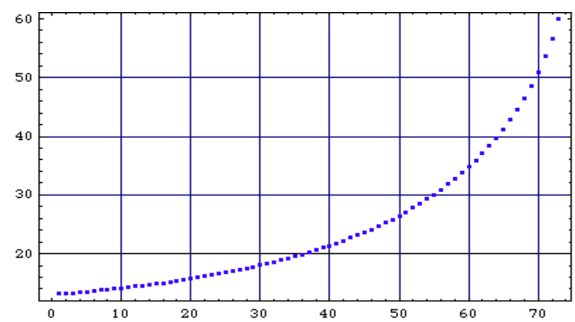

Figure 9: RF Phase Modulation during acceleration cycle (degrees vs. no. of crossings)

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