High-Power FFAG-based Heavy-Ion and Proton Drivers

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Proton and Heavy-Ion Drivers

High-Power Proton and Heavy-Ion Drivers **Proposals** for:

Spallation Neutron Sources;

Tritium Production;

Nuclear Waste Transmutation;

Energy Production;

Production of Radio-Isotopes and Exotic Nuclear Fragments;

High-Intensity Beams (Kaons, Mesons, Muons and Neutrinos);

Proton and Heavy-Ion Beam **Energy** ranges from ~ 1 to about 10 GeV.

Average Beam **Intensity** ranges from 1 to possibly 10 MWatt, and more.

Different **Modes of Operation** are also considered:

low repetition rate of a few tens of pulses per second (Hz);

high repetition rate of a few thousand pulses per second (kHz);

continuous mode of operation (CW).

Available Accelerators

There are several types of Particle Accelerator that can be used for the acceleration of intense hadron beams:

Rapid-Cycling Synchrotrons (RCS),

Super-Conducting Linacs (SCL),

Cyclotrons, (don't forget old-fashion Microtrons)

Fixed-Field Alternating Gradient (FFAG) Accelerators.

Cyclotrons are similar to FFAG accelerators, but have also some major differences and limitations.

SCL's represent the ideal configuration for a high-power Proton and Heavy-Ion Driver, and are the most straightforward solution to adopt. However, they require considerable cryogenic and RF systems, and are expensive.

RCS's are expected to be more economical but are limited in repetition rate, and therefore require more beam intensity per pulse.

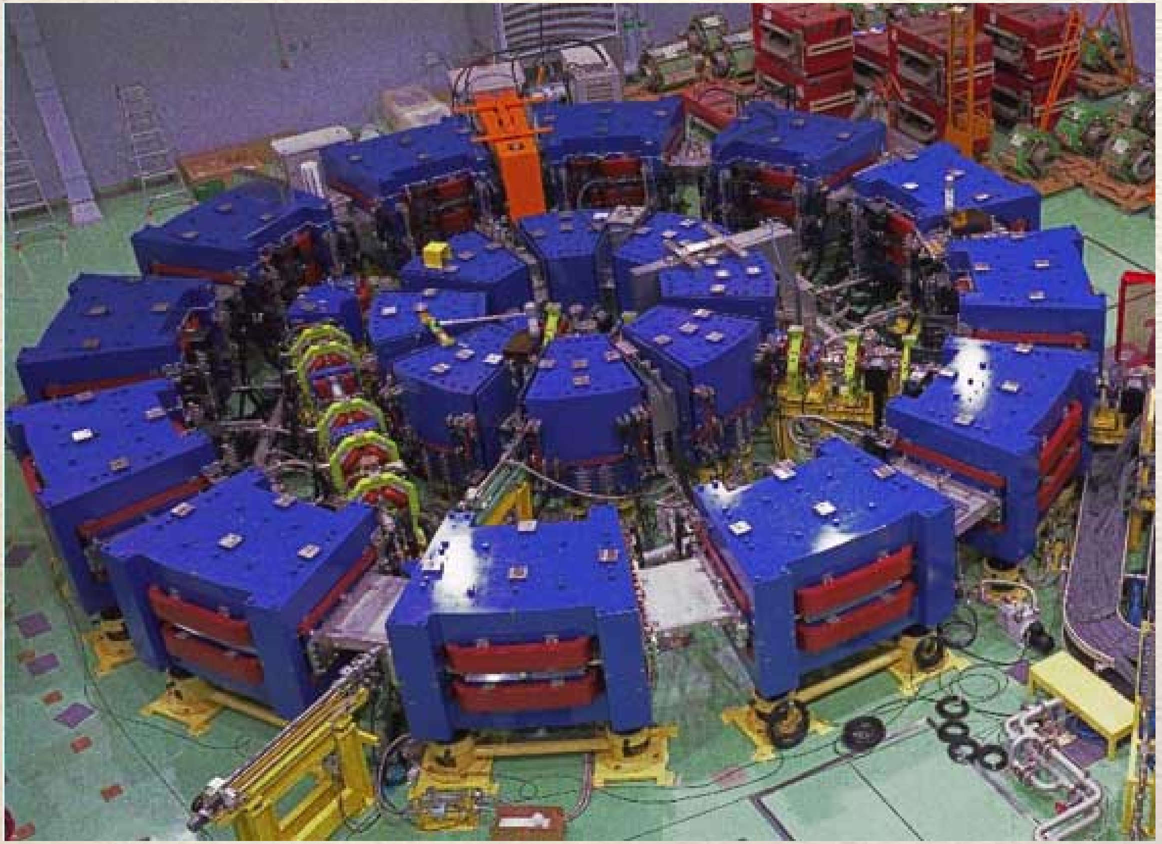
FFAG Accelerators

FFAG accelerators are expected to perform in between SCL's and RCS's. Whereas the beam is accelerated in one single pass in the SCL, and circulates for several thousand revolutions in the RCS, the beam is accelerated in the FFAG accelerator over a few tens or at most a few hundreds of revolutions.

The most important feature of the FFAG accelerator is that the guiding magnetic field is kept constant with time. Thus the acceleration rate is not limited by the magnetic field but by the accelerating RF system itself. Because of the higher repetition rate, higher beam power can be achieved with lower beam intensity.

At the same time, because the magnetic field is kept constant, and has a limited range across the radial aperture, the momentum excursion between injection and extraction is reduced. Depending on the ring lattice choice, the momentum range accepted in the acceleration cycle is at most $\Delta p/p = \pm 30$ to $\pm 50\%$. Thus depending on the application and the required energy range, the accelerator complex can be made of a single or two or even three FFAG rings of the same circumference and structure concentric to each other, to ease the transfer, and all located in the same enclosure.

FFAG KURRI Complex



2.5 MeV

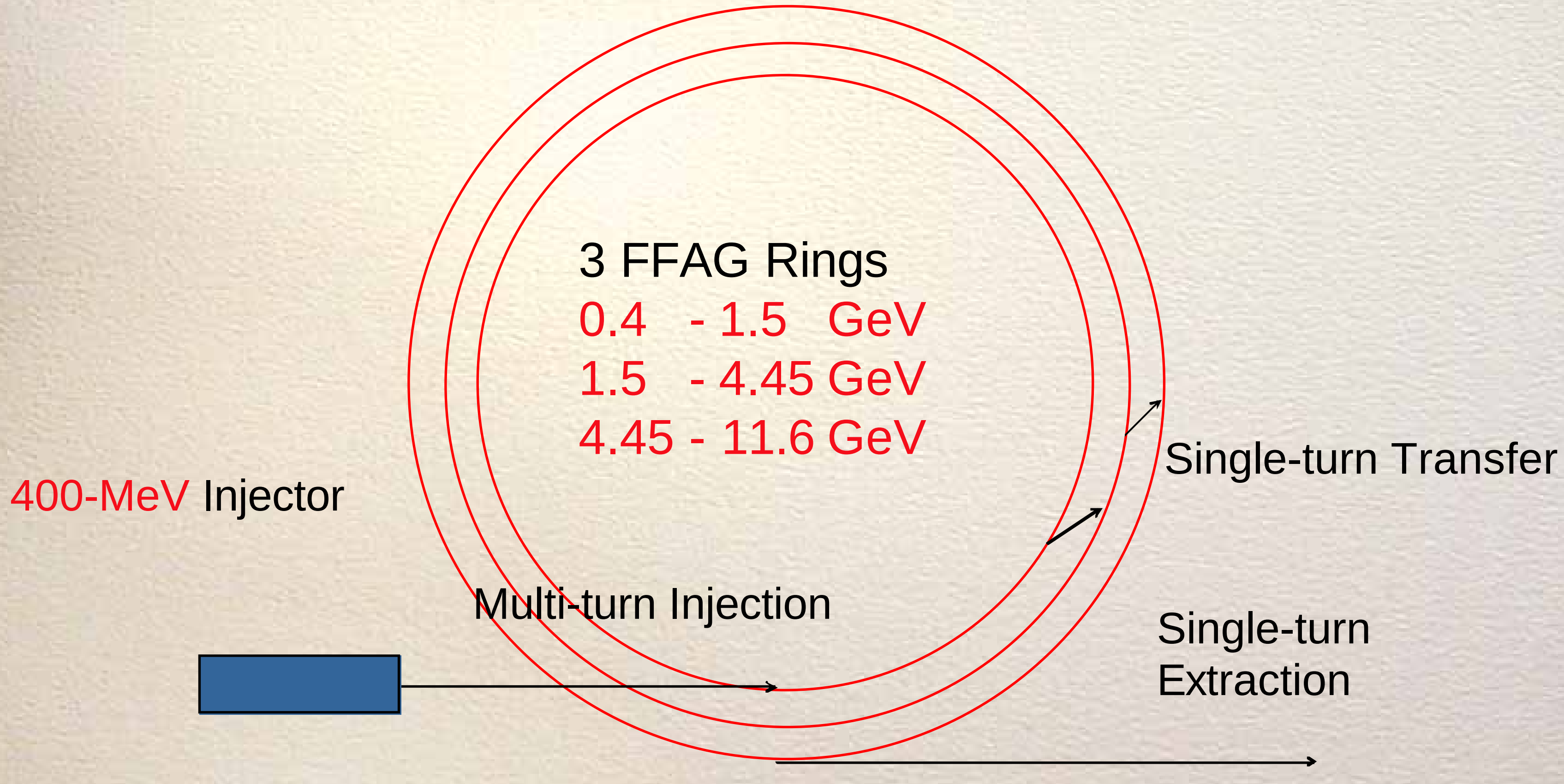
25 MeV

150 MeV

…

1 GeV (?)

Example of High-Power Proton Driver



Examples of proposed FFAG-based Proton and Heavy-Ion Drivers

Project	**A**	**B**	**C**	**D**	**E**
	Protons	Protons	Protons	Protons	H.I.
Top Energy, GeV(/u)	1.5	12	12	1	0.40
Inj. Energy, MeV(/u)	400	400	400	50	15
Rep. Rate	2.5-5.0 Hz	50 Hz	CW	1 kHz-CW	1 kHz-CW
Ave. Power, MW	0.050	4	100	10	0.40
Ave. Curr., mA(-ion)	0.033	0.33	8.5	10	0.0042
No. of Rings	1	3	3	2	2
Circumference, m	807	807	807	204	204

A - AGS Upgrade **B**, **C** - Neutrino Factory, Muon Collider, …

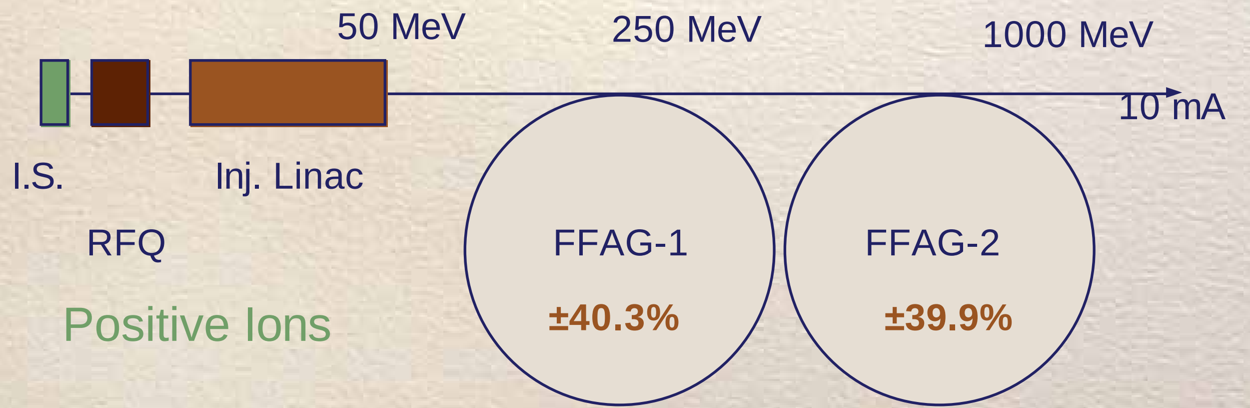
D - Neutron Source, Energy Production, … **E** - Radio-Isotopes Production

2-FFAG Rings -- Proton Driver

Three possible modes of operation:

A. Acceleration with Broadband RF Cavity — f_{rep} = 1 kHz
B. Pulsed Mode with Harmonic Number Jump — f_{rep} = 10 kHz
C. CW Mode with Harmonic Number Jump — f_{rep} = CW

Final Energy	1 GeV
Average Power	10 MWatt
Average Current	10 mA



2-FFAG Rings -- Heavy-Ion Driver

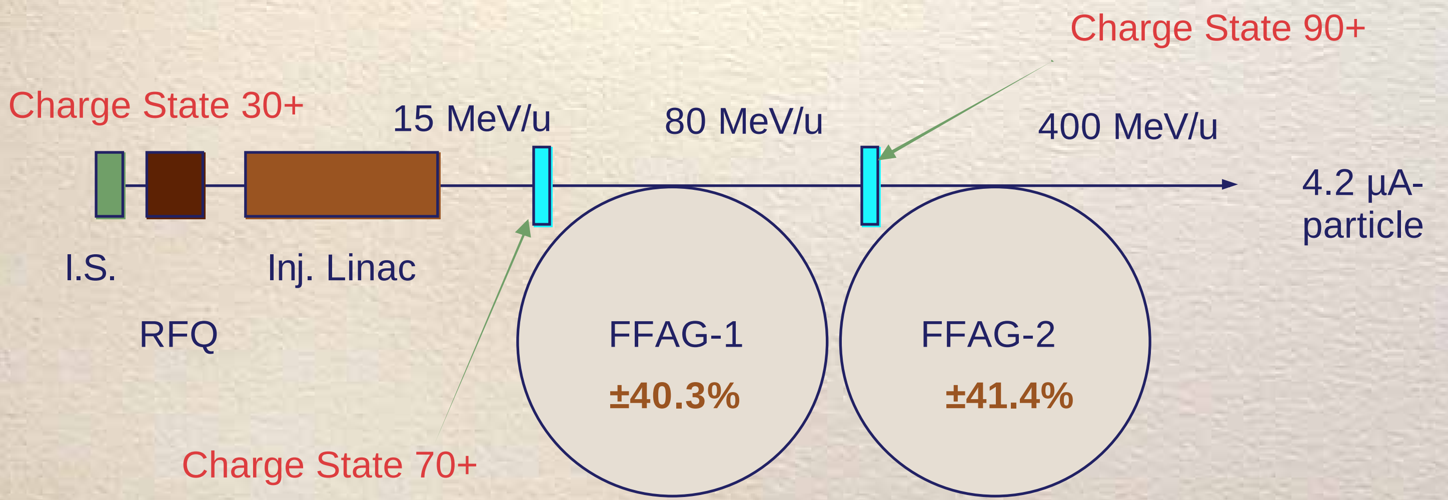
Three possible modes of operation;

A. Acceleration with Broadband RF Cavity f_{rep} = 1 kHz

B. Pulsed Mode with Harmonic Number Jump f_{rep} = 10 kHz

C. CW Mode with Harmonic Number Jump f_{rep} = CW

Final Energy	400 MeV/u
Average Power	400 kWatt
Average Current	4.2 μA-particle



FFAG Magnet Configurations

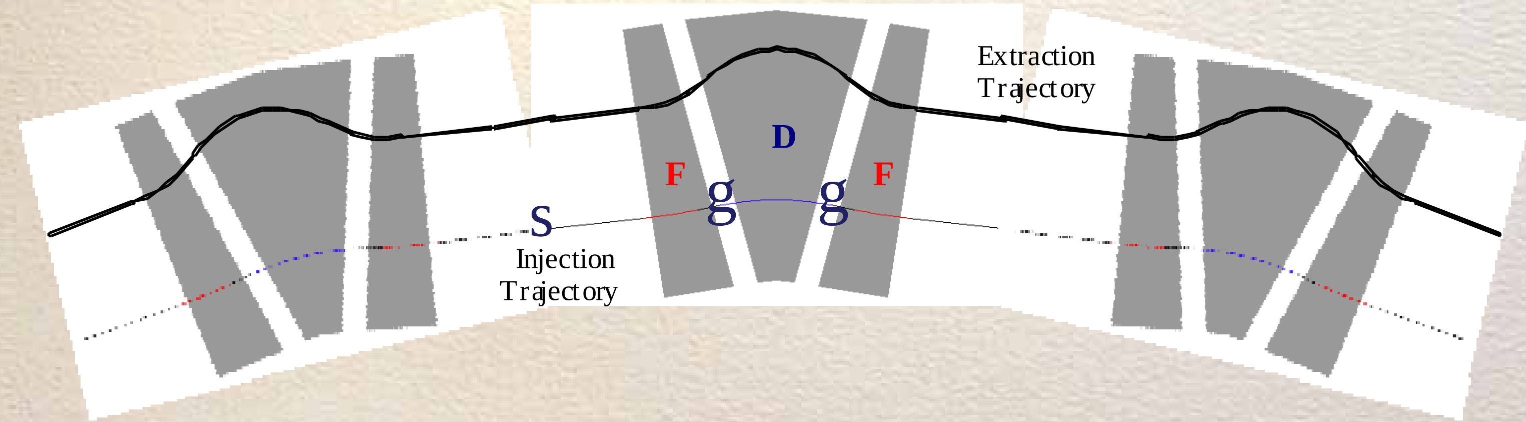
There are several types of FFAG configuration, but mostly they fall into two categories: *Spiral* and *Radial* FFAG's, and sometime a combination of both. In the *Radial* configuration, magnets are typically sector-shaped with a radial field profile in the body of the magnet itself.

In the latter case there are two possible choices of magnet configuration: the *Scaling Lattice* (**SL**) and the *Non-Scaling Lattice* (**NSL**). The **SL** has a hyperbolic field profile with a field index set such that the chromaticity, that is the variation of the lattice functions with beam momentum, is fully compensated.

The **NSL** does not compensate for the chromaticity since the Field Profile is Linear (**LFP**) with a constant gradient in each magnet. As a consequence, there is a large variation of betatron tunes with the beam momentum. All the examples of previous Table are of the **NSL** type. They make use of **FDF** Triplets that have been proven to be very effective in strong focusing systems, with very low amplitude and dispersion functions.

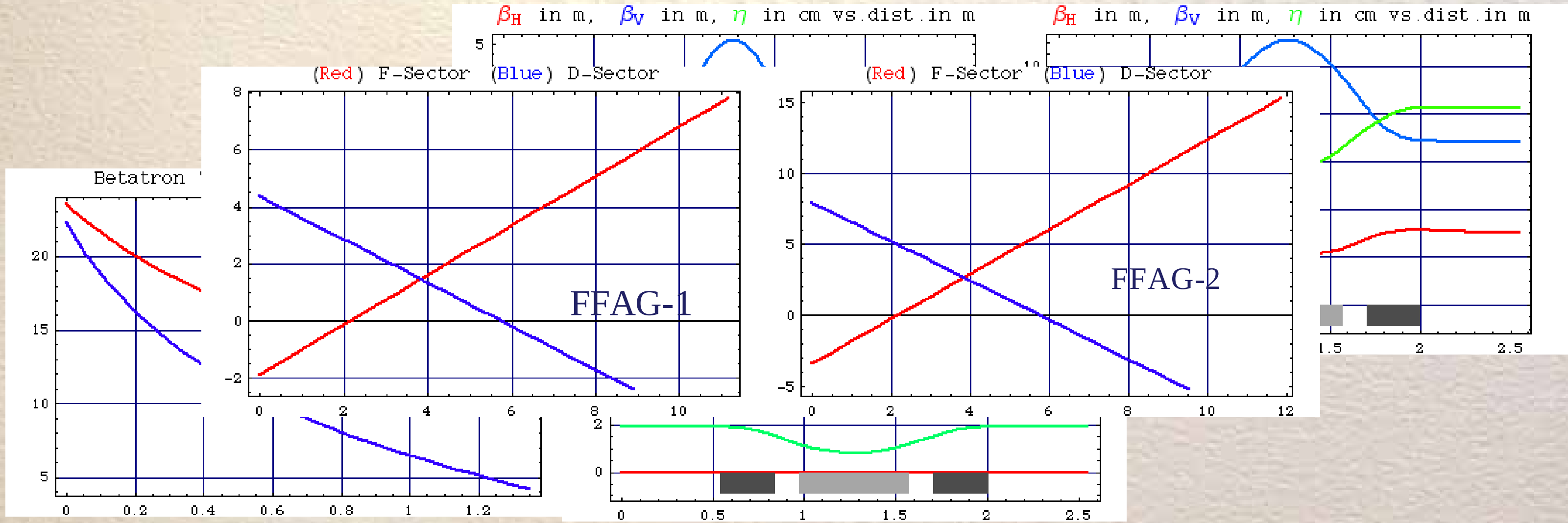
Non-Scaling FFAG Accelerators

The lattice of a **NLS** FFAG with **LFP** is a sequence of **FDF** Triplets. The beam is injected on an orbit placed on the inside of the ring, spirals during acceleration toward the outside, and is extracted from an outer orbit. There are two major drifts: a long one, *s*, and a minor one, *g*.



Structure of the FFAG Rings

Projects	**A**	**D & E**
No. of Periods	136	80
Period Length, m	5.93	2.55
Long Drift s, m	2,534	1.089
Short Drift g, m	0.30	0.129
F-Sector Arc Length, m	0.70	0.301
D-Sector Arc Length, m	1.40	0.602
Radial Width w, cm	17.3	11.2



Acceleration Methods

In the case of acceleration of low-energy protons and ions of Uranium, the beam velocity varies considerably during the cycle.

A frequency-modulated RF cavity system, like those using ferrite, will not do the job well, except for cases with low repetition rates.

An alternative is to use broad-band, constant frequency RF cavities, such as those used in the J-Parc accelerator complex. In this case the RF frequency is relatively low (a few MHz), and the voltage is only a few tens of kVolt per cavity.

Another approach that would allow a considerably higher repetition rate is the method of **Harmonic Number Jump** (HNJ).

Eventually, the HNJ method could also be used for a continuous beam mode of operation, since on a given orbit the beam is accelerated by a pre-programmed RF voltage, the profile being kept constant across the width of the cavity at all times, and all orbits can simultaneously be occupied by beam.

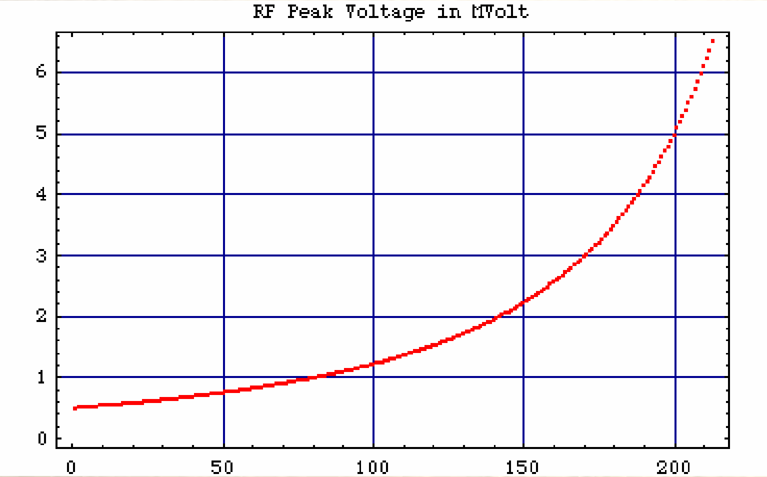
Acceleration by Harmonic Number Jump

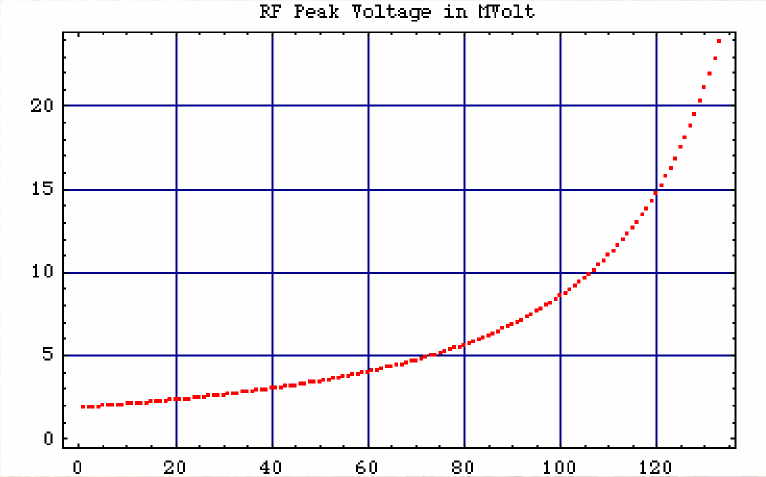
A higher repetition rate not only is desirable to boost the beam power and to avoid problems with space charge and with multiple resonance crossing in the NSL FFAG, but also to ease the performance requirements of the ion source and of multi-turn injection into the first FFAG ring. The **HNJ** method allows the use of superconducting RF cavities at very high constant frequency, in the range of several hundred MHz or even in the GHz range. Acceleration requires a programmed energy gain that varies between cavity crossings, to allow for the change of the transit time between cavities that corresponds to a *jump* of one or more RF harmonics. If f_{RF} is the RF frequency, obviously the relation $f_{RF} = h\,\beta c/C$ holds where h is the (local, that is between two consecutive cavity crossings) harmonic number, C the distance between cavities, and βc the beam velocity. In a synchrotron, the harmonic number h is kept constant; as the beam velocity βc varies, then the RF frequency f_{RF} is adjusted accordingly. The **HNJ** method, on the other hand, requires that f_{RF} is kept constant so that as the beam velocity βc changes the harmonic number h will have to vary accordingly. This can be achieved only with a proper program of energy gain between cavity crossings. It should be pointed out that, since the harmonic number h reduces during acceleration, the number of beam bunches at injection into the first ring cannot be larger than then harmonic number at extraction from the second ring.

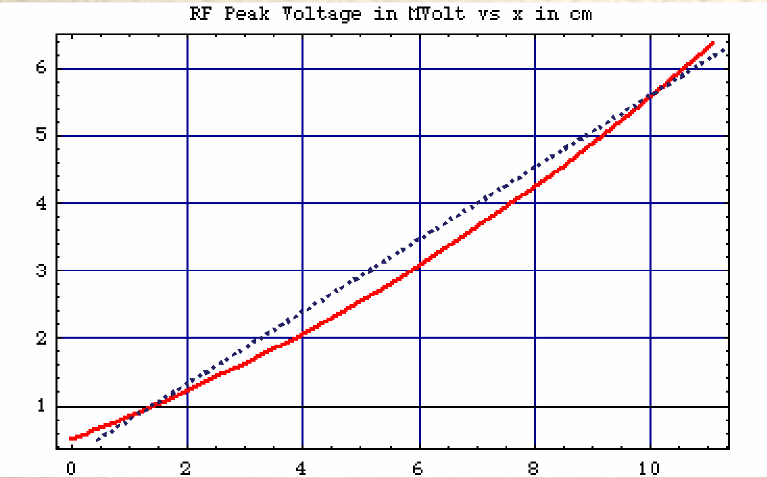
Profile of Energy Gain

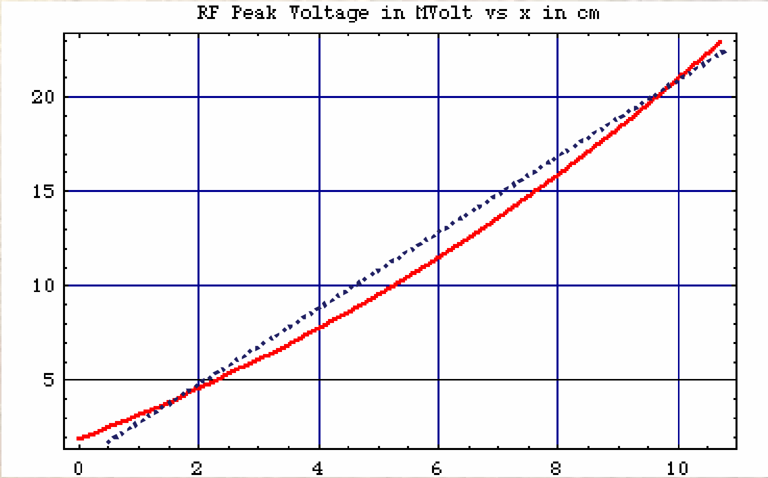
FFAG-1

FFAG-2

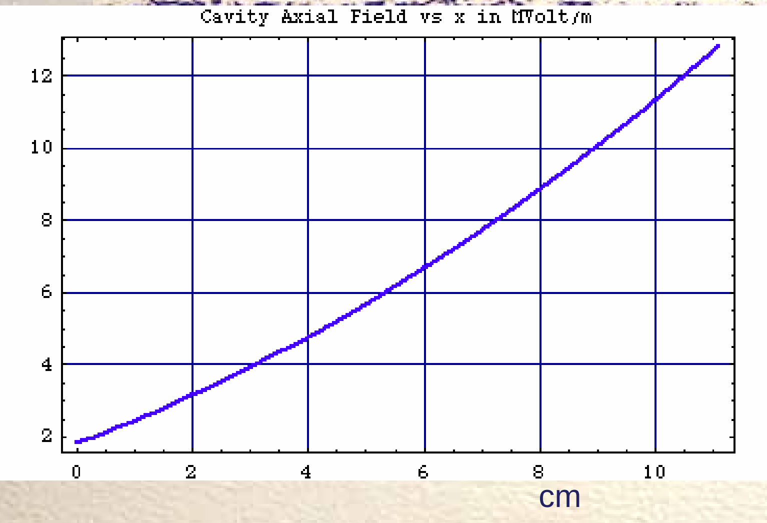


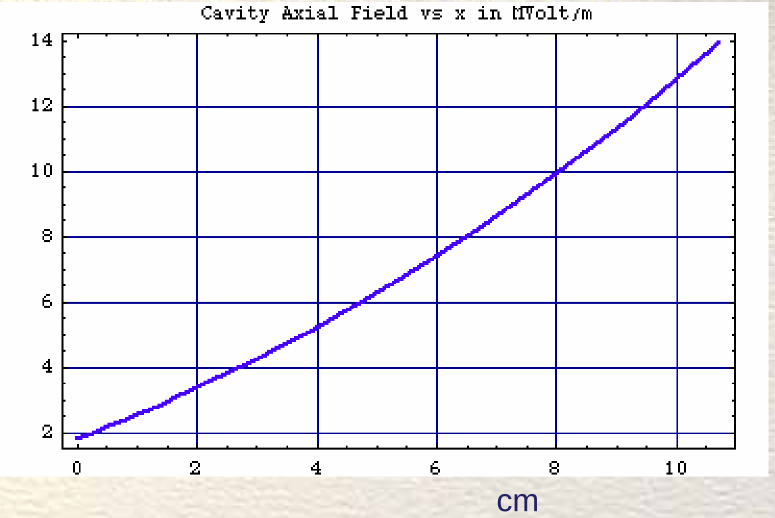






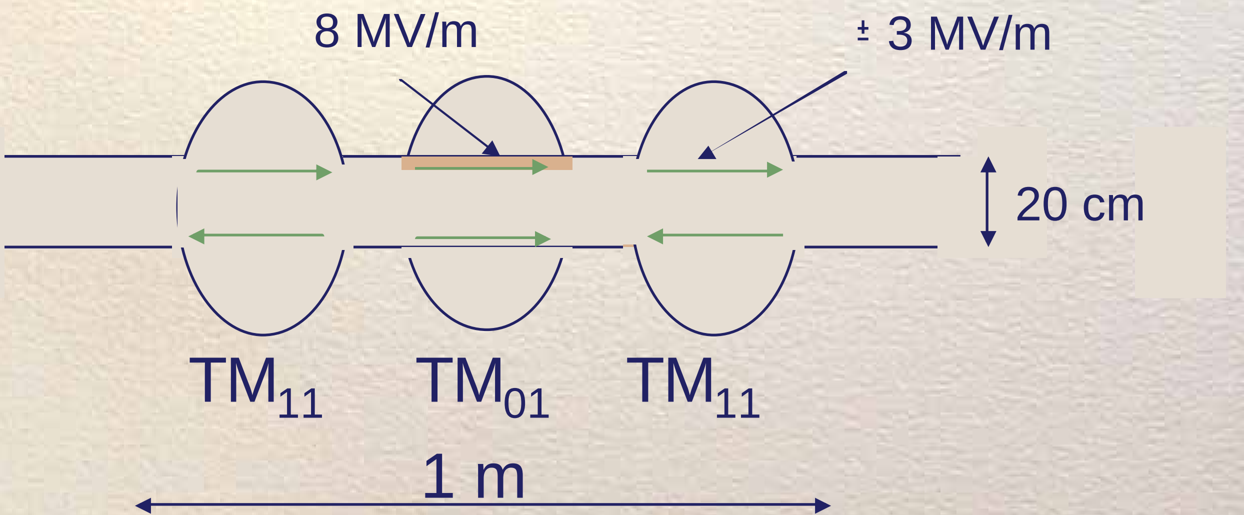
RF Cavities





805 MHz

Gap =7.5-15 cm



CW Mode of Operation

By extrapolation, the **HNJ** method of acceleration can be used for the more convenient and useful *Continuous Wave* (CW) mode of operation where the beam is continuously injected, accelerated and transferred to the Target. The continuous injection will require that ions occupy simultaneously all orbits as they move in a spiral way in and out from one ring to the next. This requires that the beam from the source, prior to injection into the first FFAG ring, is pre-chopped at the injection revolution frequency to allow for the gap corresponding to the ratio β_1/β_2 of the beam velocity at injection to the velocity at extraction.