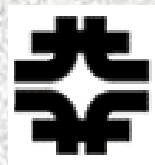




FFAG

Fermilab



Isochronous (CW) High Intensity Non-scaling FFAG Proton Drivers

C. Johnstone

Fermilab/Particle Accelerator Corporation

PAC'11

Marriott Marquis

New York City, New York

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New Directions in Accelerators: FFAGs: (Fixed-field Alternating Gradient)

- *Accelerators are playing increasingly important roles in science, technology, and medicine, with demands for*
 - *higher beam currents, duty factors, and precision beam control,*
 - *All (of course) in the context of affordable and reliable technology.*
 - *This drive has generated world-wide interest in FFAGs. FFAGs have the high repetition rates characteristic of cyclotrons, yet they embody the advantages of the synchrotron:*
variable energy, low losses, compact footprint, high energy reach.
- ➡ *Combining the best features of the cyclotron and synchrotron, **FFAG accelerators represent new directions in accelerator science and are presently under international development.***



FFAG

The International FFAG Collaboration: International Accelerator Laboratories and Universities

U.S.

Fermilab

Brookhaven National Lab

Lawrence Berkeley National
Laboratory

University of California: L.A., Riverside

Michigan State University

Canada

TRIUMF

University of British Columbia

Switzerland

CERN

France

LPS

Grenoble

U.K.

Daresbury Laboratory.

Manchester, Liverpool, Leeds, and
Lancaster and Oxford University

Imperial College

Rutherford Appleton Laboratory

John Adams Institute, Oxford

Birmingham University

Clatterbridge Centre for Oncology

Beatson Oncology Centre

Gray Cancer Center

Japan

KEK

Kyoto University (KURRI)

Osaka University





FFAG

Motivation – CW (isochronous operation)

- Cyclotrons dominate the commercial/applied market
 - Modest acceleration systems, both RF and magnetic
 - Constant CW beam – instantaneous and integrated beam control
- As the energy crosses into the relativistic regime
 - Isochronous orbits become increasingly difficult to maintain (~250 MeV for protons)
 - Machine size increases rapidly and field gradients are imposed
 - Decreased separation of orbits and no extraction straight generate high losses
 - Eventually a synchro-cyclotron is required with swept-frequency RF initially to constrain machine size
 - Eventually the energy is too relativistic and particularly weak vertical envelope control breaks down

**600 MeV (PSI) does not scale to 1 GeV (ADS) the next step is a
FFAG**



Quick Guide to Fixed-Fielding Alternating Gradient FFAGs

- Simplest Dynamical Definition:
 - FFAG is ~ a cyclotron with a gradient; beam confinement is via:
 - Strong alternating-gradient (AG) focusing, both planes: **radial sector FFAG**
 - normal/reversed gradients alternate (like a synchrotron)
 - Gradient focusing in horizontal, edge focusing in vertical: **spiral sector FFAG**
 - vertical envelope control is through edge focusing (like a cyclotron)
 - the normal gradient increases edge focusing with radius /momentum (unlike a cyclotron)
 - A cyclotron can be considered the lowest-order FFAG
- Types of FFAGs:
 - **Scaling:**
 - B field follows a scaling law as a function of radius - r^k (k a constant;) present-day scaling FFAGs: Y. Mori, Kyoto University Research Reactor Institute
 - **Nonscaling:**
 - Linear (quadrupole) gradient; beam parameters generally vary with energy (EMMA FFAG, Daresbury Laboratory, first nonscaling FFAG)
 - Nonlinear-gradient; beam parameters such as machine tune can be fixed (as in a synchrotron)



Thin lens transverse focusing terms

- The relevant strength terms, therefore, in an arbitrary-order multipole CF magnet used in a FFAG are:
 - For the horizontal, the three terms are

$$1/f_F = \overset{\text{synchrotron}}{\underbrace{k_F l}_{\text{red circle}}} + \overset{\text{cyclotron}}{\underbrace{\left(\frac{\mathcal{G}}{\rho_F} + \frac{\eta}{\rho_F} \right)}_{\text{blue circle}}}$$

with $\mathcal{G}$ is the sector bend angle, η the edge angle (edge angle is assume small so tangent is approximated), length, l , is the F half - magnet length and k_F is the "local" gradient for an arbitrary order field.

- For the vertical only the quadrupole gradient, $k_D l$, and the edge term are available
 - The different focusing terms can be varied independently to optimize machine parameters such as footprint, aperture, and tune in a FFAG



More on gradient/edge-focusing

- Understanding the powerful interplay between gradient and edge focusing is critical to understanding the potential of FFAGs
 - In cyclotrons,
 - horizontal envelope control is through the centripetal term
 - Centripetal term increases with radius/pathlength/momentum in the cyclotron magnets
 - Vertical envelope control is through edge focusing / field shaping at the magnet edges
 - proportional to the constant dipole field; more difficult to increase, much weaker than horizontal focusing in cyclotrons
 - In FFAGs,
 - the gradient increases both the horizontal (centripetal) and vertical (edge focusing) with radius/momentum
 - This last point is very important for FFAGs because it allows the field, orbit location, and important machine parameters such as tune to be more independent and strongly controlled than in cyclotrons



FFAG

To summarize beam envelope control (in the thin Lens Limit):

1. Centripetal (*Cyclotrons* + *FFAGs*) :

- bend plane only, horizontally defocusing or focusing
 - Strength $\propto \theta/\rho$ (bend angle/bend radius of dipole field component on reference orbit)

2. Edge focusing (*Cyclotrons* + *FFAGs*) :

- Horizontally focusing / vertically defocusing, vice versa, or no focusing depending on field at entrance and entrance angle
 - Strength $\propto \tan \eta/\rho$, (or $\sim \eta/\rho$ for reasonably small edge-crossing angles)

3. Gradient focusing (*Synchrotrons* + *FFAGs*) :

- Body gradient, fields components > dipole:

$$B = a + bx + cx^2 + dx^3 + \dots \Rightarrow B' = b + 2cx + 3dx^2 + \dots$$

- Linear field expansion, constant gradient
 - » **Synchrotrons + linear-field nonscaling FFAGs (muon accelerators)**
- Nonlinear field expansion up to order k, magnitude of gradient increases with r or energy:
 - » **Scaling FFAGs**
- Arbitrary nonlinear field expansion, magnitude of gradient increases with r or energy:
 - » **Nonlinear Non-scaling FFAGs**

Edge crossing angles are kept deliberately small in large multi-cell synchrotron rings. This term becomes increasingly important for and causes problems in small synchrotron rings.

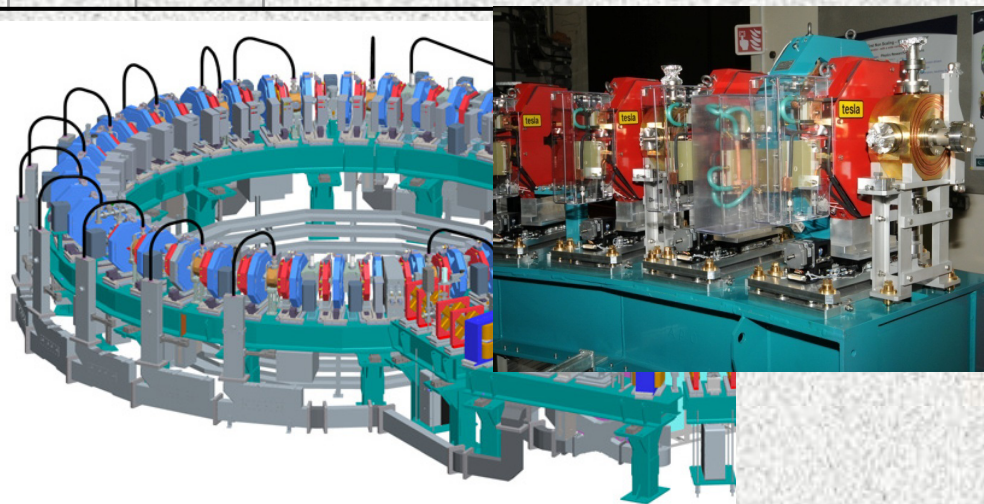


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Operating Scaling FFAGs or scaling FFAGs under construction

	<i>Ion</i>	<i>E (MeV)</i>	<i>Cells</i>	<i>Spiral Angle</i>	<i>Radius (m)</i>	<i>First Beam</i>	<i>Technical</i>
KEK-PoP	p	1	8	0°	0.8-1.1	2000	
KEK	p	150	12	0°	4.5-5.2	2003	100 Hz, 90% ext.
KURRI -ADSR (Figure 1)	p	2.5	8	40°	0.6-1.0	2006	Initial spec: 120 Hz, 1μA Now: 1kHz, 100μA, @200 MeV
	p	20	8	0°	1.4-1.7	2006	
	p	150	12	0°	4.5-5.1	(2007)	
NEDO-ERIT	p	11	8	0°	2.35	(2008)	70mA ionization cooling ring
PRISM study	α	0.8	6	0°	3.3	(2008)	Phase space rotator
Radiatron	e	5	12	0°	0.3-0.7	(2008)	24 kW, 10 kHz, betatron acc.

EMMA – world's first nonscaling FFAG, @Daresbury Laboratory, being commissioning, presently functioning as a storage ring





FFAGs in Industry

- Mitsubishi – hand-held 1 MeV electron accelerator (spiral sector FFAG)
- NHV Corporation
 - Developing several commercial electron FFAGs to replace Rhodotron, for example
- Number of proton FFAG designs have been completed for medical use (RACCAM, PAMELA projects)



FFAG

Progression of the NS FFAG Design

- **Linear (constant gradient)**
 - Rectangular magnets EMMA machine at Daresbury Laboratory
 - Non-constant machine tune, significant investment in high-power rf
 - EMMA has 19 rf cavities in a 42-cell ring.
 - Maximum acceleration range: factor of 4 (practically 2-3)
- **Linear (constant) gradient + edge contour**
 - Edge contour on magnets to stabilize tune
 - Increase of momentum range to a factor of 6
- **Nonlinear gradient + edge contour**
 - Arbitrary order combined with magnet edge contour
 - Ultra-constant tune
 - Slow acceleration supported - low-power, but swept-frequency rf system
 - Increase of momentum range as high as 44 in a more compact footprint
- **Nonlinear gradient – isochronous**
 - Ultra-constant tune
 - Gradient/magnet shape adjusted for isochronous orbits - simple low-power fixed-frequency rf system



FFAG

The Future Generation of FFAGs –

Applying a Nonlinear Gradient to the Nonscaling FFAG

- Compact machines; i.e. footprint, aperture and tune control required higher-order, tailored field profiles
- An arbitrary field expansion has been exceptionally successful
 - Order of magnitude increase in momentum range over initial NS concept
 - an acceleration range of a factor of 44 has been achieved.
 - Large Dynamic Acceptance in predominately nonlinear fields
 - Strong focusing, 90° cell tunes (or higher) achieved in both horizontal and vertical well into the relativistic regime
- Isochronous orbits have been achieved in a nonscaling FFAG by applying an nonlinear gradient and edge contour
- *Isochronous implies CW operation and simple rf systems*



The significance of CW Accelerators

- A CW accelerator implies:
 - Fixed magnetic fields
 - 50 Hz is the ~ practical technical limit for pulsed magnet systems
 - Stored power and expense of pulsed supplies can be commercially prohibitive
 - The simplicity of fixed-frequency rf
 - the rotational frequency of orbits is a constant at all energies
- Consequences of non-isochronous orbits
 - Beam is pulsed at the rf sweep rate, not continuous
 - Swept-frequency rf (rf timing is changed to match the revolution time of the beam – the synchrotron and synchro-cyclotron)
 - 50-100 Hz sweep rate for rf frequencies $\geq$ tens of MHz
 - KHz sweep rate for broad-band rf ($\sim$ MHz)
 - slow acceleration, high power consumption



The Isochronous Condition

- Dipole fields, i.e. cyclotrons, maintain isochronicity at nonrelativistic energies - that is, at nonrelativistic energies velocity is proportional to momentum and path length is proportional to momentum in a constant B field, therefore path length is proportional to velocity.
- Isochronism can be imposed on the orbits in FFAGs into nonrelativistic energies by requiring the path length remain proportional to velocity, which has an increasingly nonlinear dependence on momentum. The average B field which determines path length as a function of momentum must increase nonlinearly in this energy regime according to:

$$\overline{R}_{extraction} - \overline{R}_{injection} = Aperture$$

$$\overline{R}_{injection} = \frac{\beta_{injection}}{\beta_{extraction}} \overline{R}_{extraction}$$

$$\left(1 - \frac{\beta_{injection}}{\beta_{extraction}}\right) \overline{R}_{extraction} = Aperture$$

*Note that in the nonrelativistic regime, β_{inj} can be $\ll \beta_{ext}$ and aperture $\cong$ machine radius, at relativistic energies, aperture $\ll$ machine radius

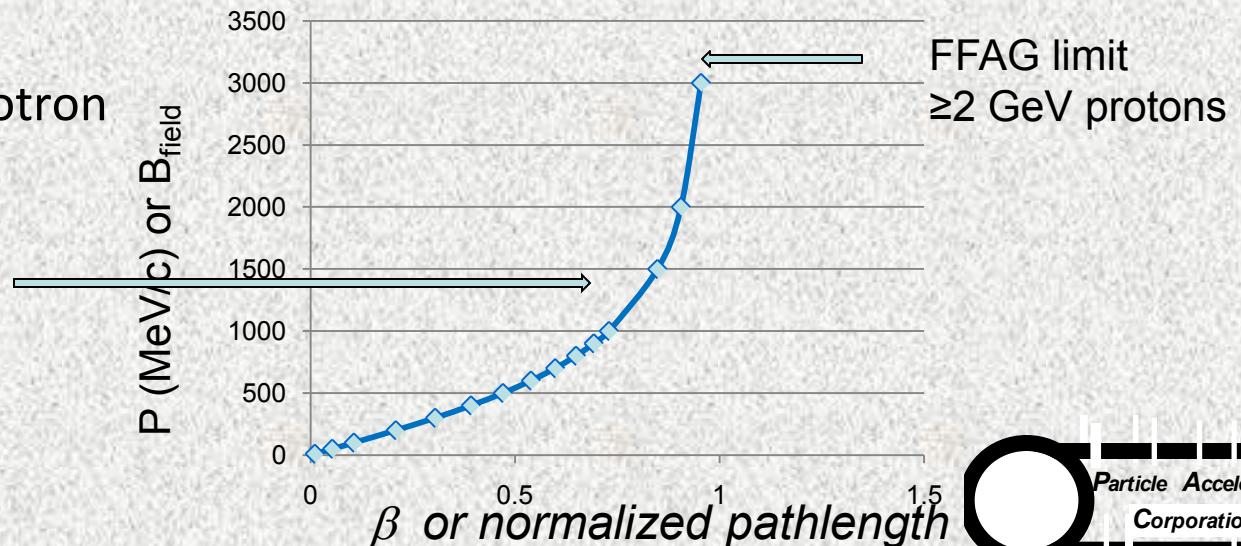


FFAG

Relativistic Isochronous NS FFAGs -

- NS FFAG can retain isochronicity even at relativistic energies
 - Isochronous orbits are proportional to velocity
 - Orbital path length, however, follows the B field proportional momentum not velocity
 - At relativistic energies, momentum is an increasingly nonlinear function of velocity
 - Arbitrary nonlinear field expansion/edge angle can constrain the tune and the orbit/momentum to be proportional to velocity
 - Nonlinear gradient provides very strong focusing at high energy in both planes,
unlike the cyclotron

Cyclotron limit
~ 1 GeV protons





FFAG

Summary of Nonscaling FFAG properties

- By utilizing all conventional modes of transverse focusing for beam and machine parameter control the FFAG can be a powerful hybrid of the cyclotron and synchrotron
 - The FFAG has the potential to combine the best features of the synchrotron and cyclotron
 - **Strong focusing allows synchrotron-like straights – and therefore the low losses associated with synchrotrons especially at extraction**
 - Variable energy extraction – elimination of degraders (to be discussed further)
 - **The simplicity of fixed magnetic fields rather than pulsed operation**
 - Very recently - the simplicity of *fixed-frequency* rather than swept-frequency rf systems; producing reliable, continuous, cyclotron-like beam
- ➡
- **The low operational overhead and simplicity of the cyclotron**



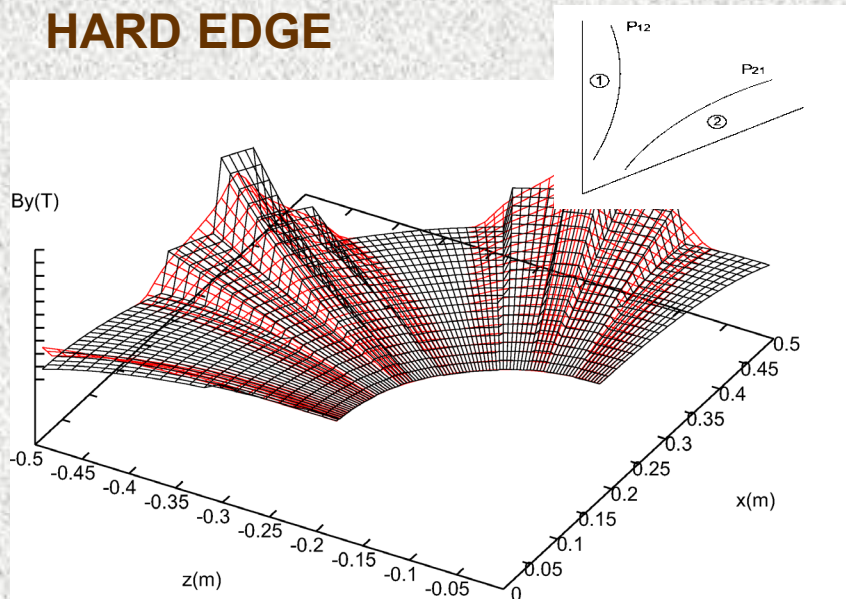
FFAG

Advanced Modeling Simulations in COSY INFINITY

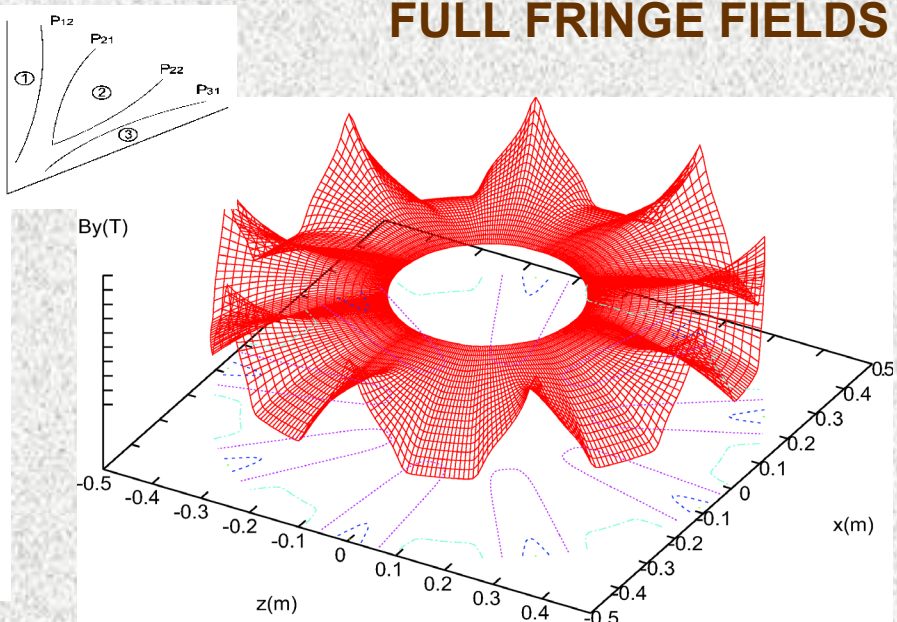
- As conventional accelerator codes provide too-little flexibility in field description and are limited to low order in the dynamics, new tools were developed for the study and analysis of FFAG dynamics based on transfer map techniques unique to the code COSY INFINITY.
- Various methods of describing complex fields and components are now supported including representation in radius-dependent Fourier modes, complex magnet edge contours, as well as the capability to interject calculated or measured field data from a magnet design code or actual components.

Arbitrary shapes, field content, contours

HARD EDGE



FULL FRINGE FIELDS

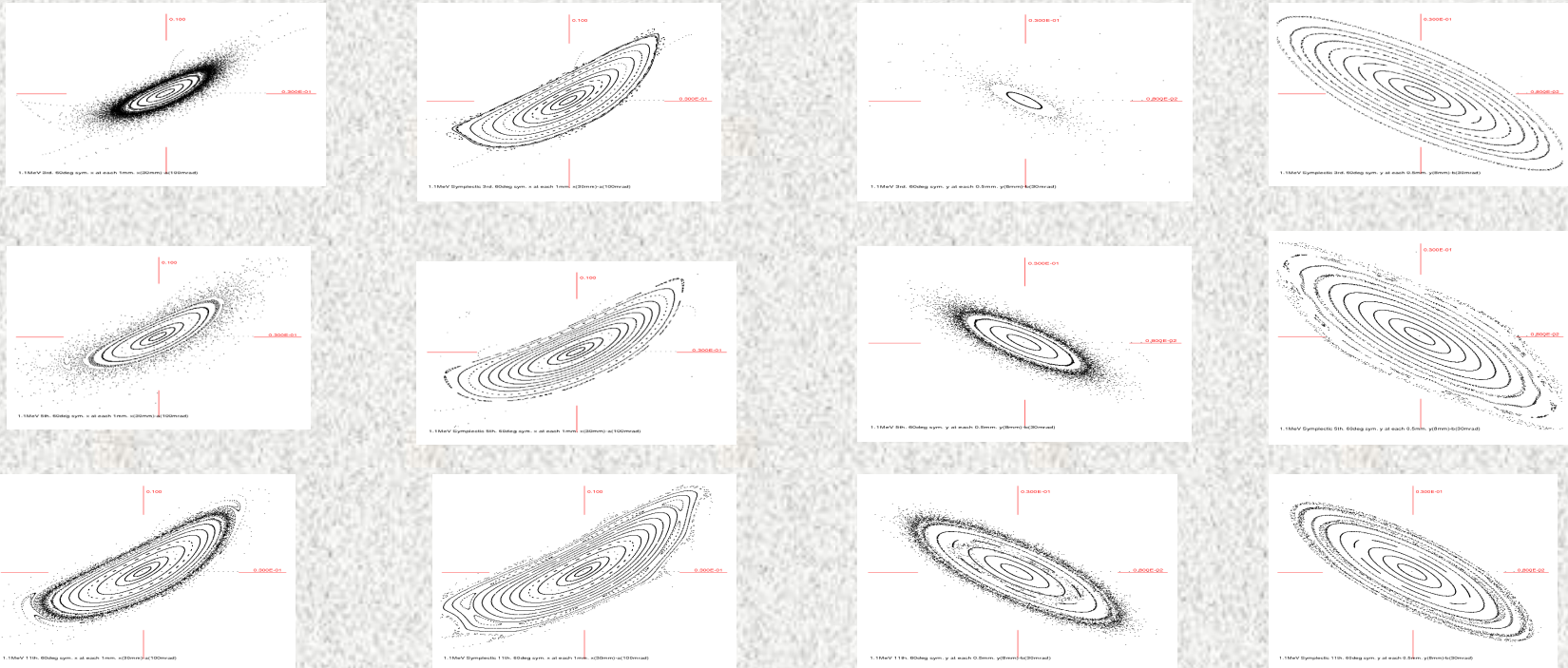




FFAG

Example of dynamics studies of fixed-field accelerators using new tools in COSY

- Below is a sample FFAG having sixfold symmetry, with focusing stemming from an azimuthal field variation expressed as a single Fourier mode as well as edge focusing. The system is studied to various orders of out-of-plane expansion with the results for orders three and five shown below (typical of a conventional out-of-plane expansion in codes like Cyclops).



Tracking in a model non-scaling six-fold symmetric FFAG for horizontal (left pairs) and vertical (right, pairs) with 3rd (top), 5th (middle), and 11th (bottom) out of plane expansion, with focusing from an azimuthal field variation expressed as a single Fourier mode as well as edge focusing. With (left) and without (right) Expo symplectification is shown.

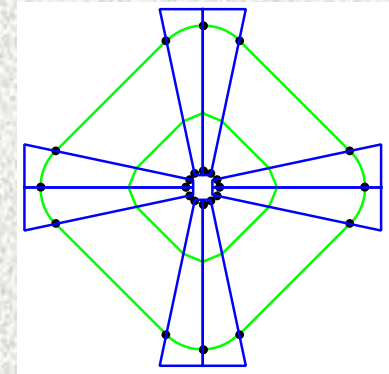
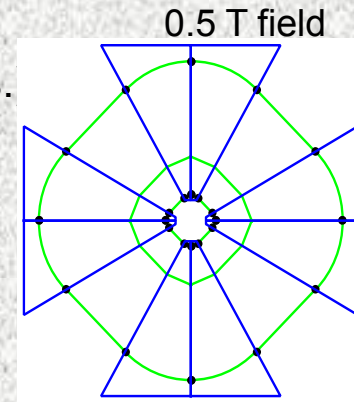


FFAG

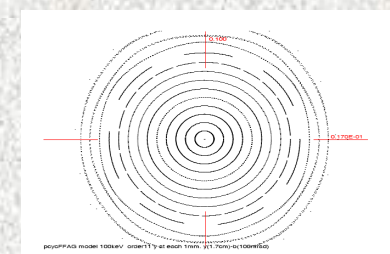
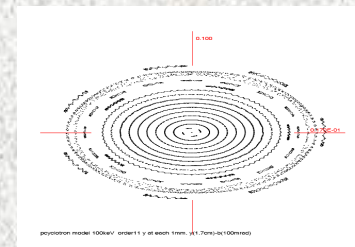
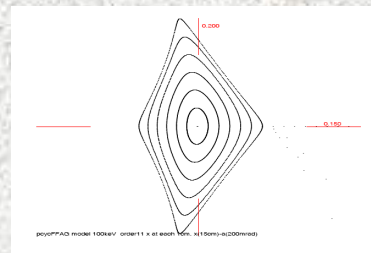
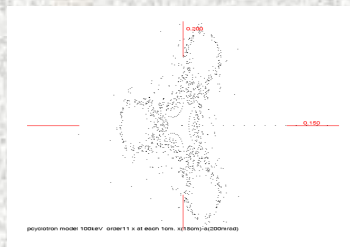
Comparison of a sector cyclotron with a FFAG using advanced design and simulation tools

- Study of a low-energy cyclotron vs. FFAG equivalent designs:

- 5 kG field at injection;
(For cyclotron implies a 5 kG field at all energies.)
- 1T limit on the extraction field in the FFAG
- ≥ 10 cm magnet @injection (to achieve 5 kG)
- ≤ 5 cm between magnets at injection.
- Same footprint: an ~ 0.9 m radius
- No reverse bends in the FFAG
- vertical focusing is through edge crossing.
- 4 sectors both designs



Low-energy cyclotron (left) and equivalent FFAG (right)



Subtleties in transverse dynamics of cyclotron and FFAG at 100 keV:
Horizontal cyclotron and FFAG (left pair) and vertical cyclotron and
FFAG (right pair) as observed in advanced simulations



Application: Accelerator-Driven Subcritical Reactor: CW beam is a requirement + duplication of accelerator for reliability

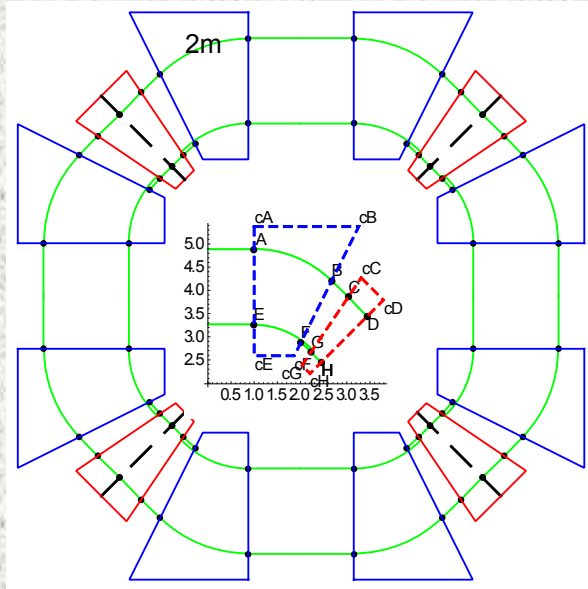
- Advantages
 - Injection through a lower-energy H^- ring or 250-MeV H^- linac
 - CW operation for high power output
 - Compact footprint (especially compared to a 1 GeV linac)
 - The simplicity of fixed-frequency rf system
 - Swept-frequency rf is required for a synchrotron or synchro-cyclotron
 - Isochronous cyclotron is large machine
 - Low losses
 - With strong focusing losses are comparable to a synchrotron
 - Critical for successful high-intensity operation (10 MW)
 - Strong focusing – strong vertical tunes
 - Mitigate impact of space charge
 - Promote increased stability at high intensities



FFAG

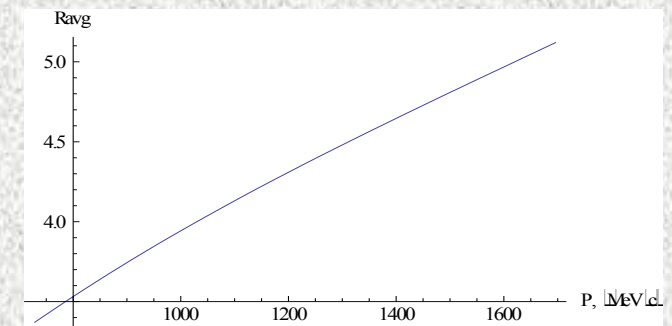
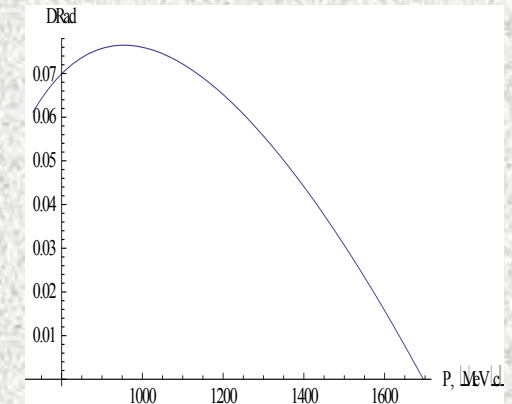
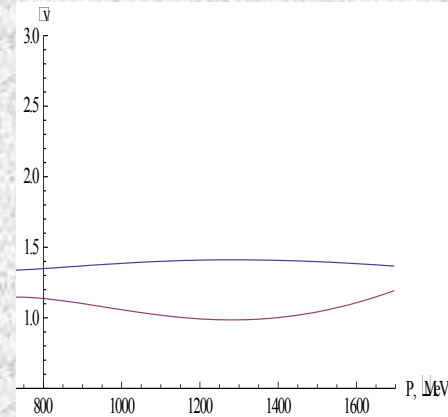


Advanced design and simulation of an Isochronous 250-1000 MeV Nonscaling FFAG



General Parameters of an initial 0.250 – 1 GeV non-scaling, near-isochronous FFAG lattice design

Parameter	250 MeV	585 MeV	1000 MeV
Avg. Radius (m)	3.419	4.307	5.030
Cell v_x / v_y (2π rad)	0.380/0.237	0.400/0.149	0.383/0.242
Ring.	1.520/0.948	1.600/0.596	1.532/0.968
Field F/D (T)	1.62/-0.14	2.06/-0.31	2.35/-0.42
Magnet Size F/D Inj	1.17/0.38	1.59/0.79	1.94/1.14



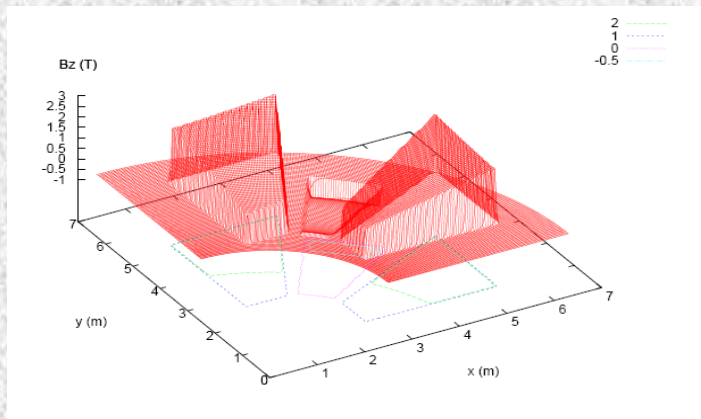
Clockwise: *Matemtica*: Ring tune, deviation from isochronous orbit (%), and radius vs. momentum

Comments and further work

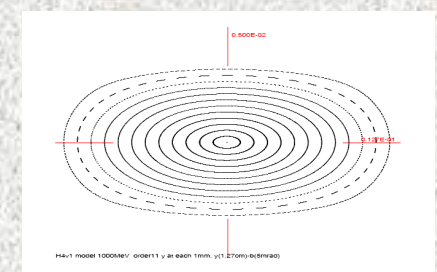
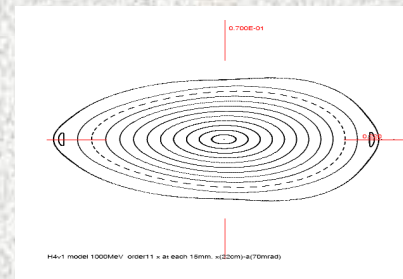
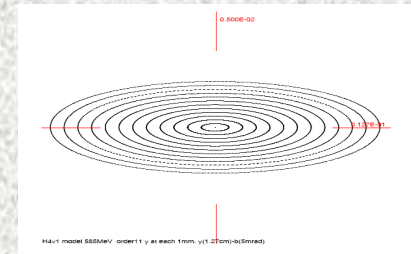
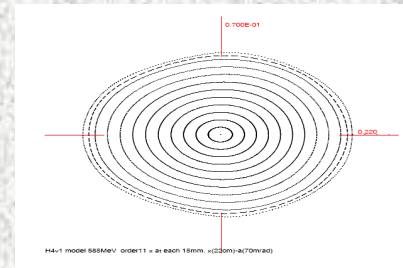
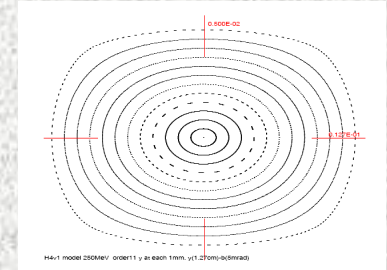
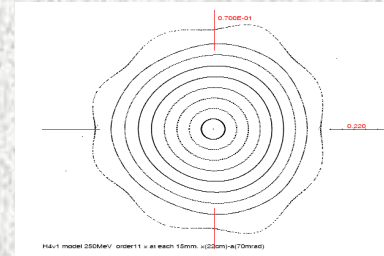
- Tracking results indicate $\sim 50\text{-}100\pi$ mm-mr; relatively insensitive to errors
- Low losses



Field Map and Tracking: 250-1000 MeV Proton Driver



- Immediate large DA aperture:
 - 50-100 mm-mr without correction
 - 0.1-1% error tolerance –typical magnet tolerances
- Final isochronous optimization will be performed using advanced optimizers in COSY

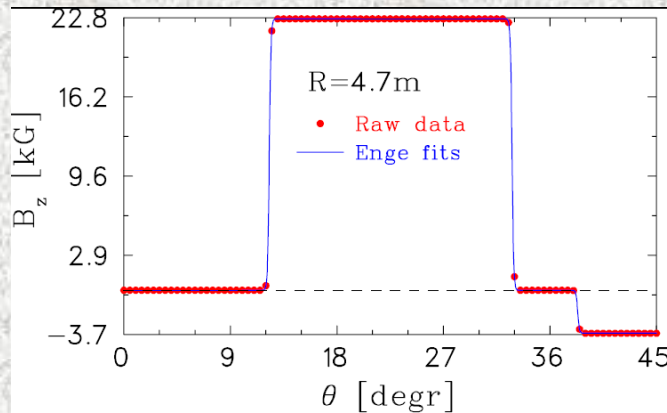


Dynamic aperture at 250, 585, and 1000 MeV – step size is 1.5 cm in the horizontal (left) and 1 mm in the vertical (right).



FFAG

1-GeV Proton Driver Modeled in CYCLOPS: fine mesh and fringe fields (Y.N Ray and M. Craddock, TRIUMF)

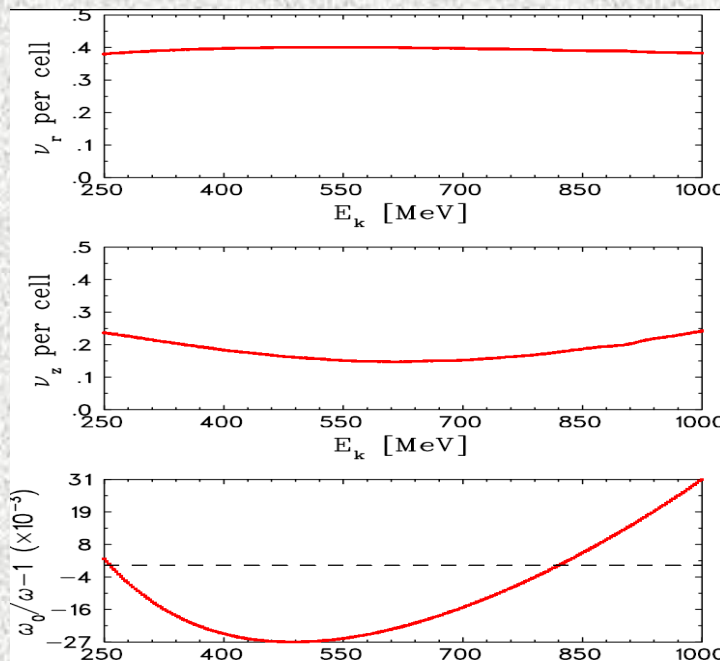


- B field with Enge function fall off

- tune per cell (radial, horizontal)

- tune/cell (z, vertical)

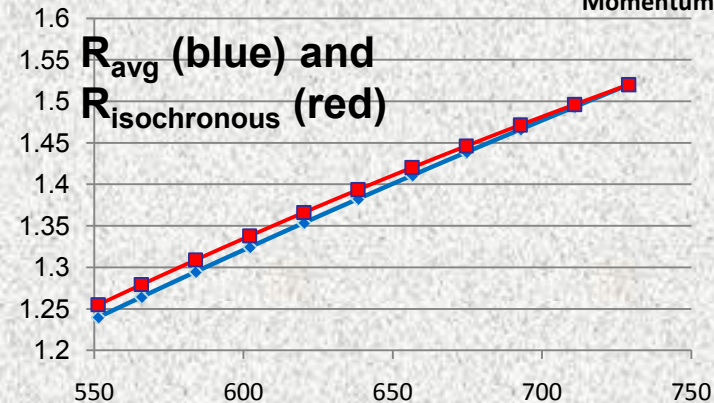
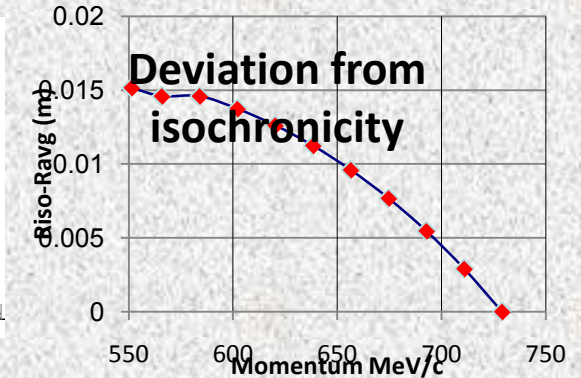
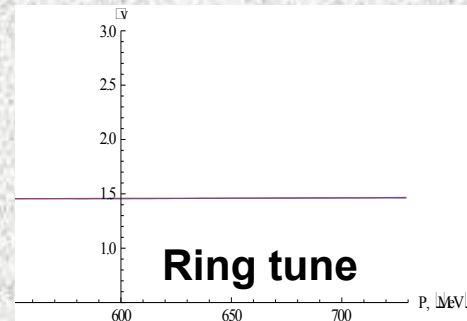
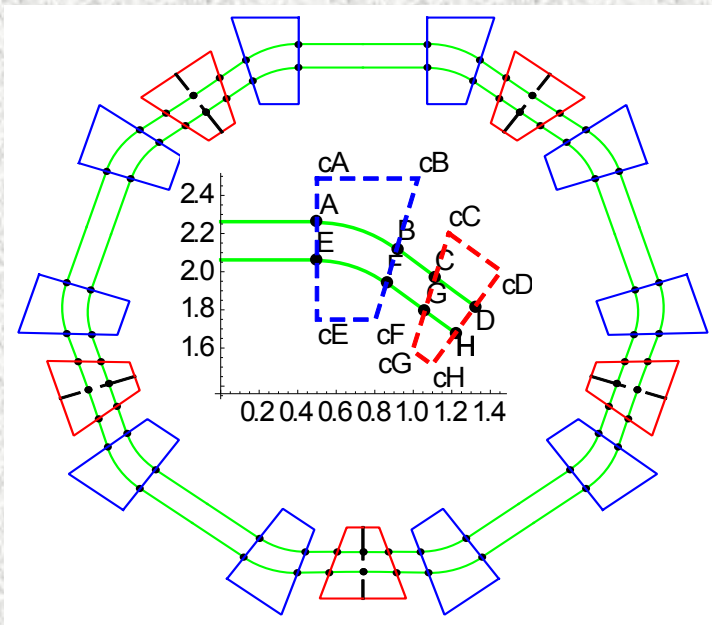
- frequency change, isochronous to +/- 3% using simple hard-edge model: progress will require the advanced codes; agrees with COSY results





FFAG

Example: lower-energy isochronous FFAG – preliminary 150-250 MeV SC Proton Ring



- Comments

- Peak field 3.5T @extraction in F;
- small 25 cm aperture
- Low losses



FFAG

Summary of advantages based on advances in FFAG technology

- CW operation (into relativistic energies) with new isochronous lattices
 - Simplicity and lower cost of fixed-frequency rf
- Strong focusing in a fixed field accelerator has demonstrated
 - Large, stable dynamical acceptance
 - Lower losses, particularly with smaller beam envelopes in vertical
 - Support of multiple long straights
 - Lowered extraction losses
 - Mitigation of space charge effects (strong tune in vertical), higher bunch intensities
 - Resonant and kicker-based extraction (horizontal and vertical)
 - Variable energy without use or reduced use of a degrader
 - Improved beam transmission at low energies
 - Respiration gating can be kicker based
 - Reduced shielding requirements – reduced civil costs
- Nested Rings
 - Compact footprint even for a multi-ion facility

Presently developing 3-8 GeV frequency-swept FFAGs (scaling and nonscaling) for the 2nd stage of acceleration for Project X (in collaboration with Imperial College, Fermilab, MSU, and ASTeC).



FFAG

General Comparative Comments

- Synchrotron duty cycle and beam control has improved significantly, however
 - Expert staff
 - Complex, expensive subsystems (swept-frequency rf and ramped magnets)
 - These factors tend to make them less attractive for many medical and commercial applications
- Cyclotron for many applications provide continuous beams
 - Single operator, simpler system to operate
 - Compactness leads to higher losses: proximity of high-energy orbits: little insertion space for a septum
 - Significant shielding required for the machine itself, energy degrading, collimation and energy selection: advantage in footprint is not as significant considering shielding requirements
- FFAG
 - No pulsed operation – simple operation like the cyclotron, can be CW
 - Synchrotron-like focusing and straights promote lower losses



FFAG

Concluding Remarks

- FFAG designs are advancing rapidly internationally, particularly for medical and high-energy applications with an isochronous nonscaling FFAG now designed and verified
- The first demonstration of Accelerator Driven Subcritical Reactor was performed this year at KURRI using the FFAG.
- Embedded rings supporting a compact multi-ion therapy facility are an exciting new direction for FFAGs.
- Highly advanced design and simulation tools have been developed and tested for FFAGs and cyclotrons and are ready for public distribution

