FFAG development in the UK

David Kelliher (ASTeC/RAL/STFC)

with thanks to

R. Edgecock and D. Bruton (Huddersfield Uni)

S. Tygier and Hywel Owen (Manchester Uni)

J.B Lagrange and J. Pasternak (Imperial College)

S. Machida (ASTeC/RAL/STFC)

FFAG primer

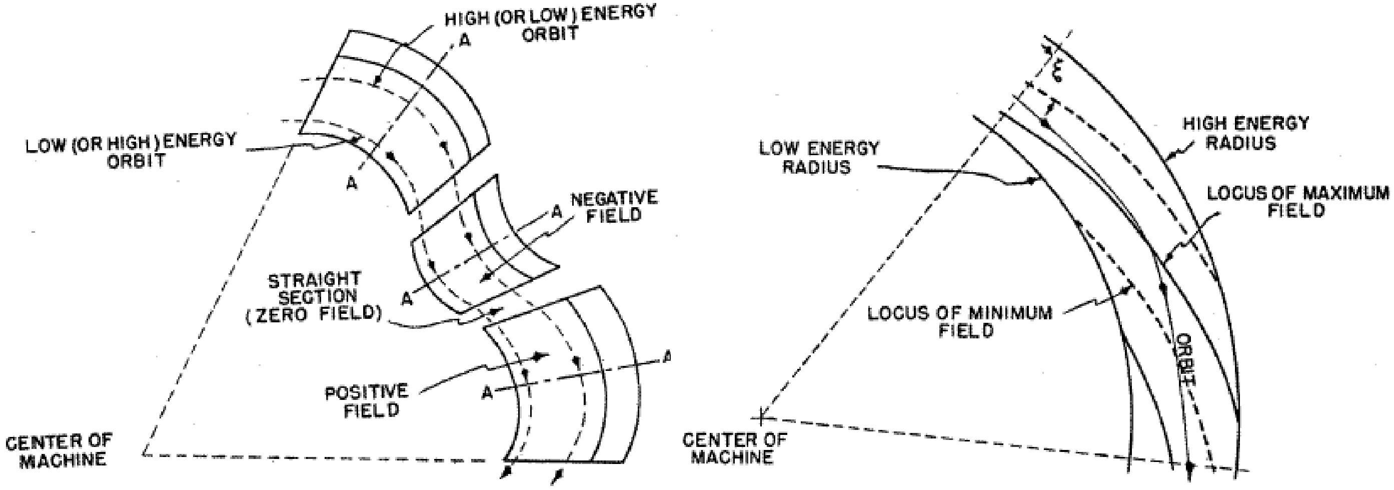
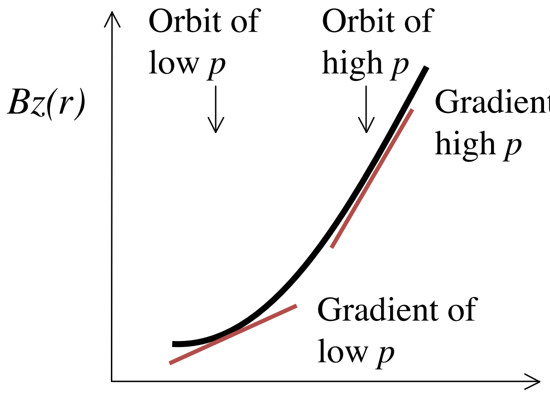


FIG. 2. Plan view of radial-sector magnets. FIG. 3. Spiral-sector configuration.

K.R. Symon, D.W. Kerst, L.W. Jones, L.J. Laslett and K.M. Terwilliger, *Phys. Rev.* **103**, 1837 (1956)



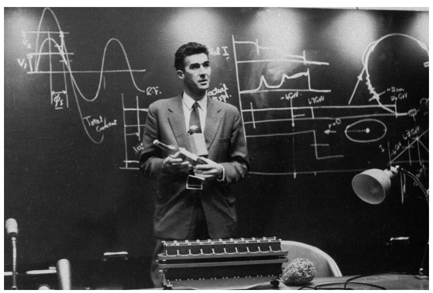
- FFAG – strong focusing machine in which the field is fixed in time.
- Scaling FFAGs were the first to be invented (1954).
- In order to maintain similar orbits and fixed tunes the field should follow the following profile.

$$B(r,\theta) = B_0 \left(\frac{r}{r_0}\right)^k F(\vartheta)$$

- Many other "non-scaling" FFAGs (and scaling variants) devised since then.

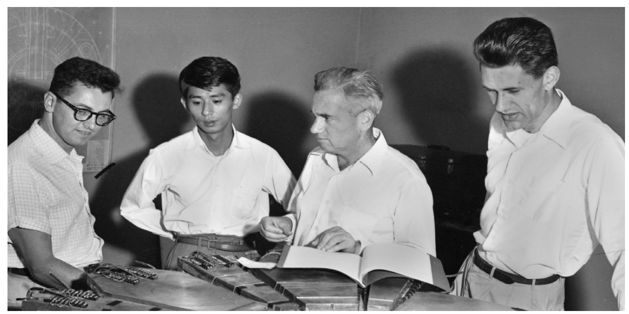
Strong focusing revolution

*(L to R) Brookhaven physicists **Ernst Courant, M. Stanley Livingston, and Hartland Snyde**r.*



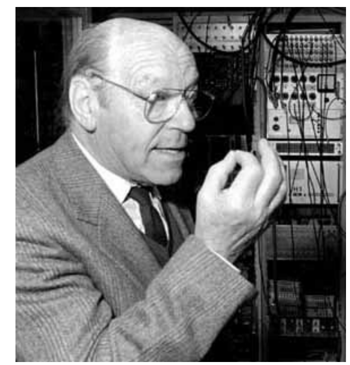
John Adams at CERN (1959)

AG synchrotrons



1955 Michigan MURA Summer Study; Ernest Courant, Tihiro Ohkawa, Otto Frisch, and Dave Judd by the Radial Sector Model (under construction)

FFAGs (Kolomensky, Okhawa, Symon)
The MURA years



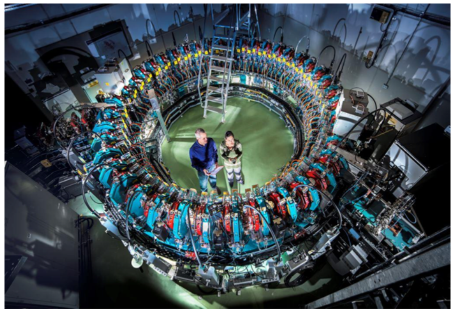
Wolfgang Paul

Paul traps

"the invention of strong focusing and the almost simultaneous gathering of the first believable experimental data on orbits in the Cosmotron began an explosion of thinking about particle accelerators that fired an enormous development in understanding of particle accelerators"
Fred Mills, "O Camelot: A Memoir of the MURA years"

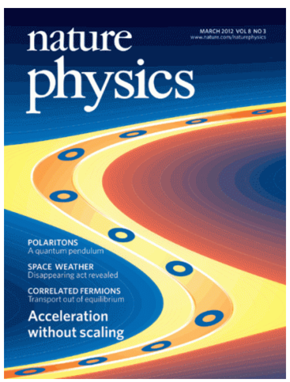
FFAGs in the UK: How it all started

- In the mid-2000s the BASROC consortium set up the CONFORM project to build and commission EMMA, fund the PAMELA design study and investigate other applications.
- EMMA is a linear non-scaling FFAG (NS-FFAG). Although in first instance a model for a muon accelerator, the lessons learned on EMMA are applicable to FFAGs for other applications.
- PAMELA was a design for a hadron therapy complex which leveraged the high repetition rate and variable energy extraction that an FFAG allows. A non-linear NS-FFAG design was adopted.
- In addition, the design for the muon FFAG which formed part of the UKNF Neutrino Factory, was studied by a number of UK (and US) researchers.
- These projects spurred further research into FFAGs at various universities and national labs around the UK which continues today.



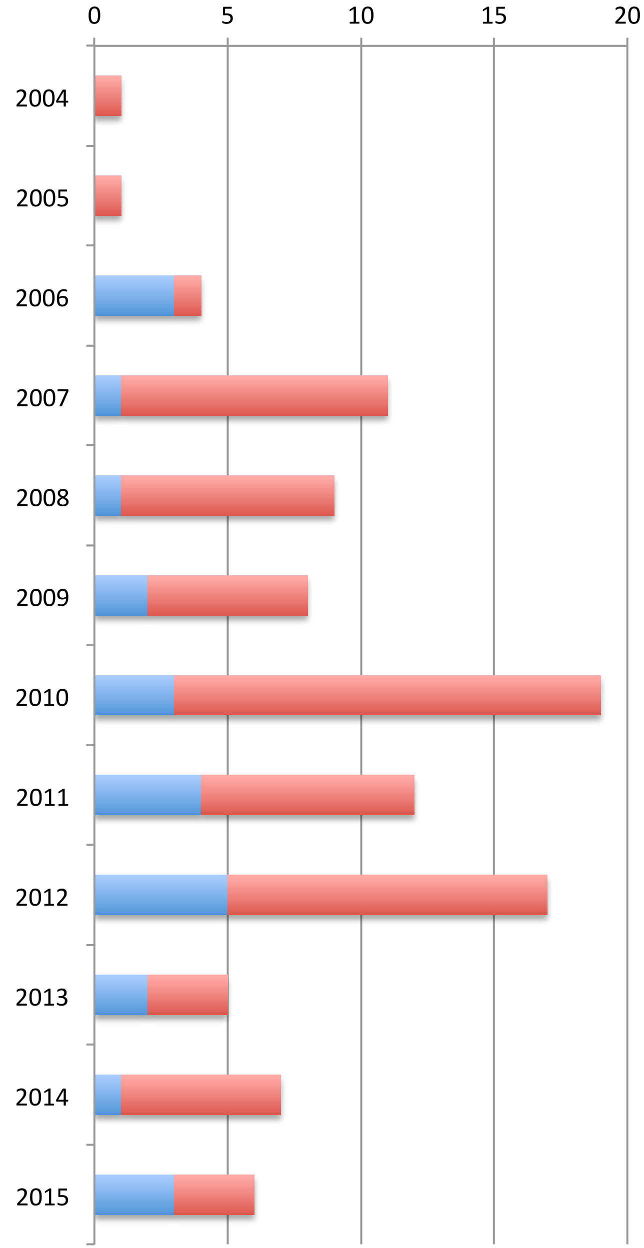
CONFORM project 2007

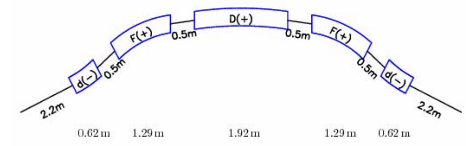
FFAG08, Manchester University



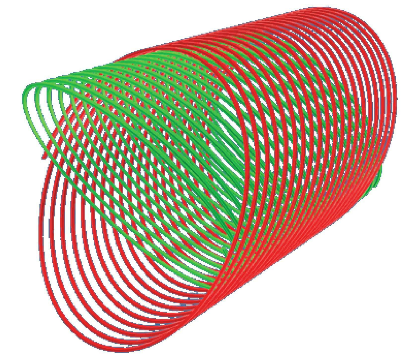
EMMA experiments 2010-2012

KURRI collaboration (2012-)





G. Rees “pumplet”



PAMELA CDR (2012)

FFAG11, Trinity College Oxford

IDS-NF IDR (2011)

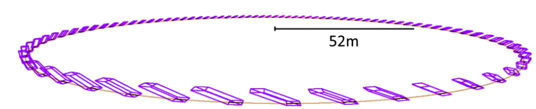


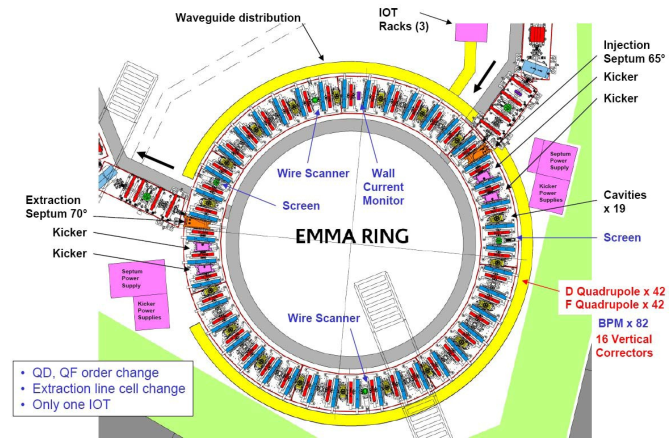
FIG. 8. Perspective view of the 12 GeV ring.

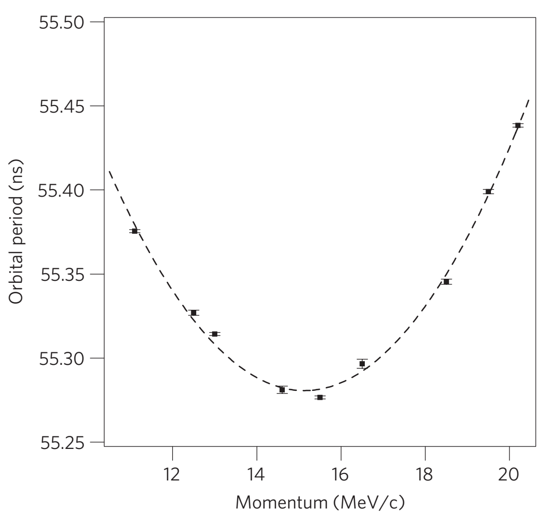
Vertical FFAG (Brooks, 2013)

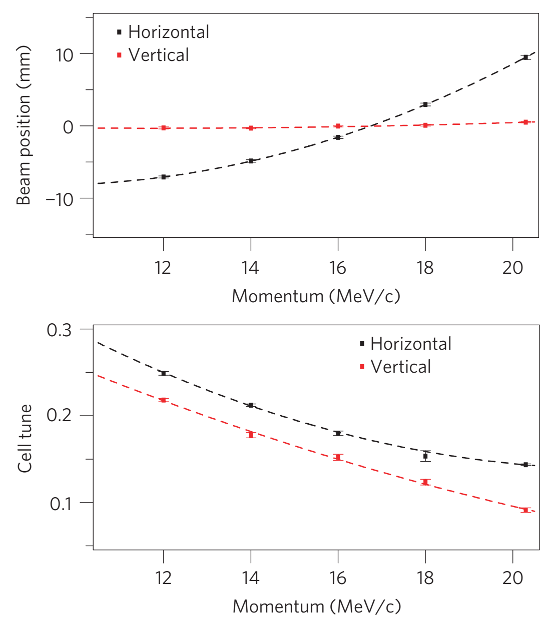
Number of publications on FFAGs by UK-based authors as found on epubs.stfc.ac.uk (apart from the 2004-2005 period where records were separately found).

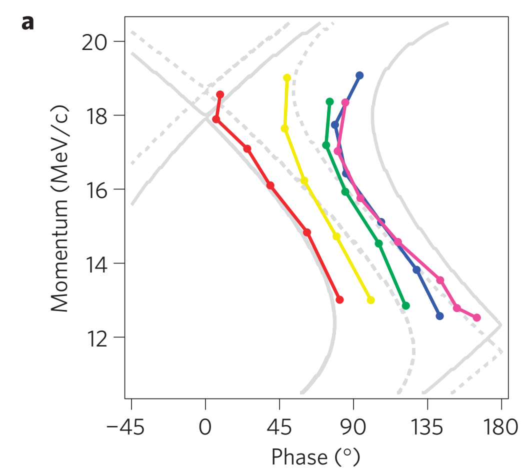
EMMA (Daresbury, UK)

- EMMA is a linear, non-scaling FFAG. It is a densely packed ring consisting of 84 quadrupoles (offset to get bending).
- Experiments demonstrated that beam is accelerated through integer tunes in the serpentine channel without significant growth in oscillation amplitude.





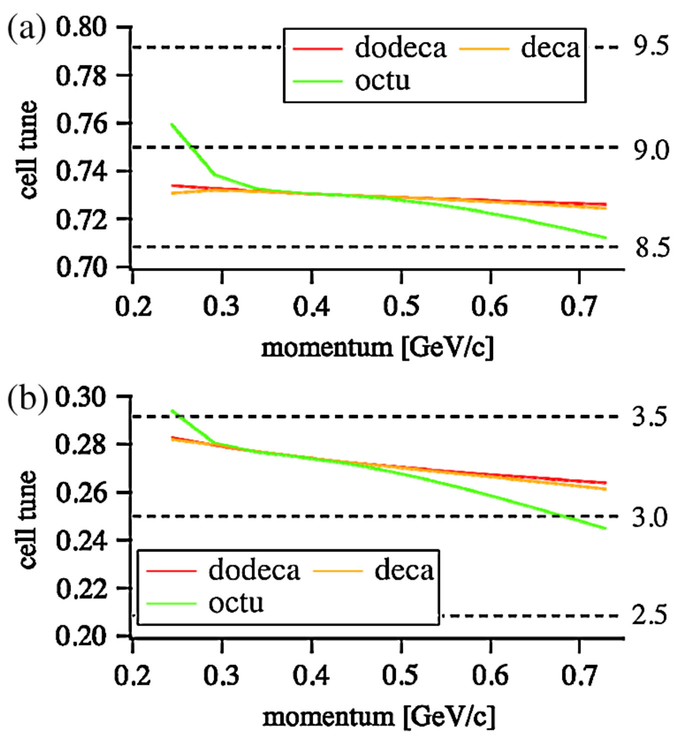


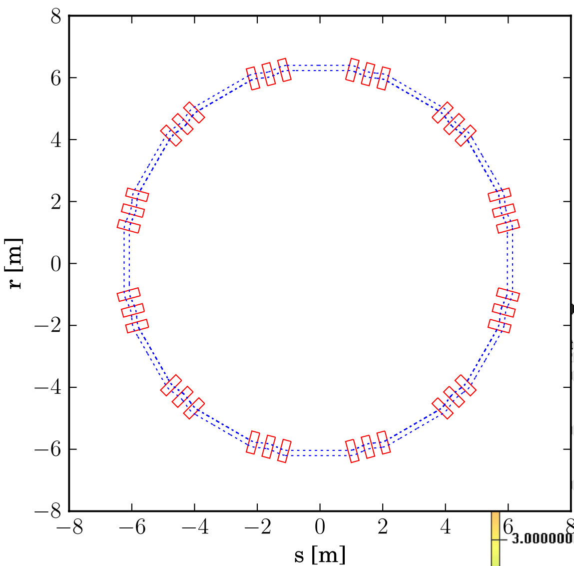


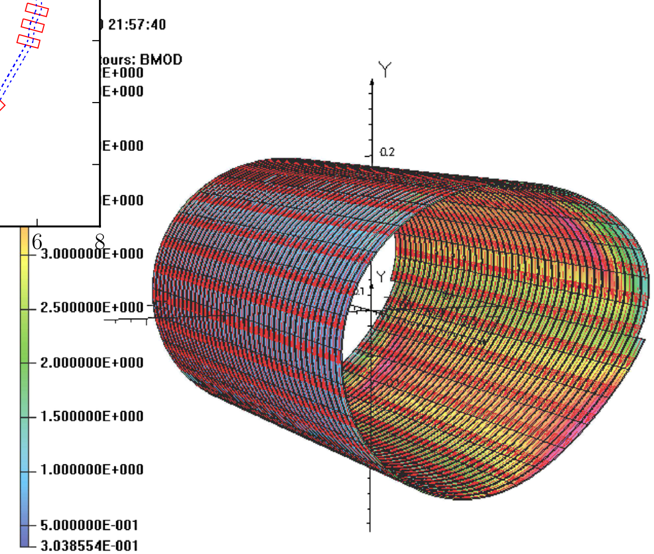
S. Machida et al, Nat. Phys. (2012)

PAMELA (JAI, Oxford)

- Approximate scaling field - retain just enough multipole components to keep the tune variation within a half-integer.
- Fix working point in second stability region of Hill's equation to reduce magnet aperture.
- Novel double-helix SC magnets developed.







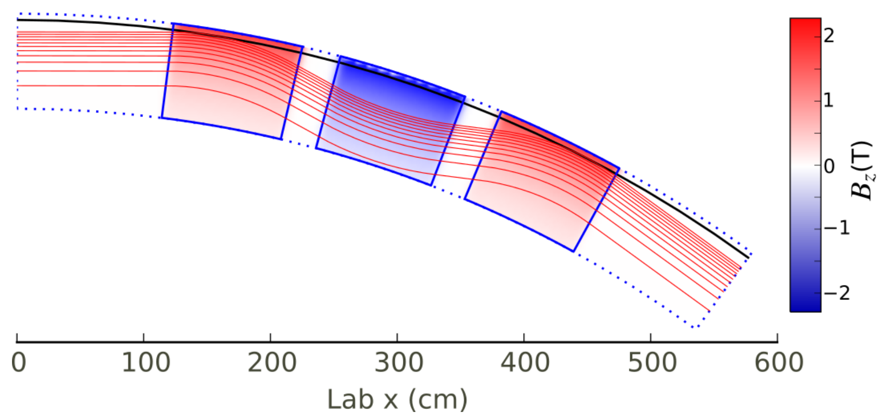
S.L. Sheehy et al, PRST-AB (2010), K. J. Peach et al, PRST-AB (2013)

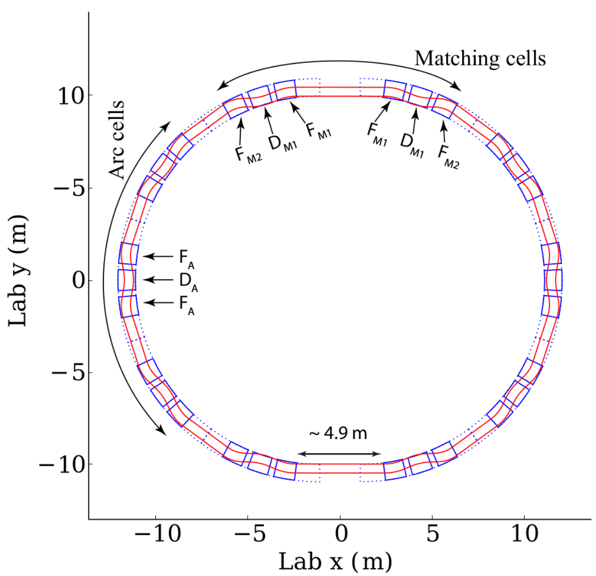
FFAGs: Issues being addressed

Issue	Description	Projects/Designs
Matching	Allow insertions for injection/ extraction, racetrack lattices	NORMA, NuSTORM
Characterisation	Measure lattice properties. Injection matching. Diagnostics.	KURRI collaboration
Iso-everything	Isochronous, zero-chromaticity design for cw operation.	Vertical FFAG, Pumplet, (PIP)
Compactness	Eliminate reverse bends or reduce packing factor to reduce circumference.	Spiral FFAG, racetracks with packed arcs, PIP.
Collective effects	High intensity machines.	KURRI collaboration, Simulation/Ion traps.

NORMA: Normal-conducting Racetrack Medical Accelerator

- Scaling FFAG
- 30→350 MeV protons
- Normal conducting magnets
- Therapy & Tomography
- Straight section to give 'racetrack' shape for injection and extraction
- Matching cells have same geometry, but different fields





	Ring	Racetrack
Cell Radius (m)	9.6	10.55
Circumference (m)	60.4	70.7
Orbit excursion (cm)	43	49
Ring tune	7.72, 2.74	7.71, 2.68
Peak field (T)	1.57	1.74
DA (mm mrad)	68.0	57.7
Max drift (m)	2.4 (x10)	4.9 (x2)

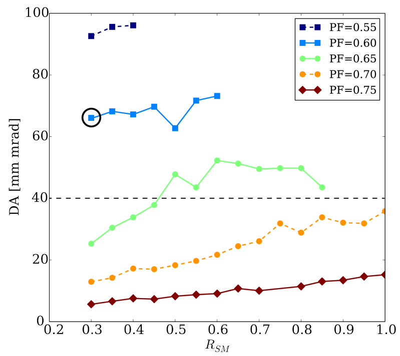
Rob Appleby, James Garland, Kiril Marinov, Hywel Owen, Sam Tygier

The Cockcroft Institute of Accelerator Science and Technology

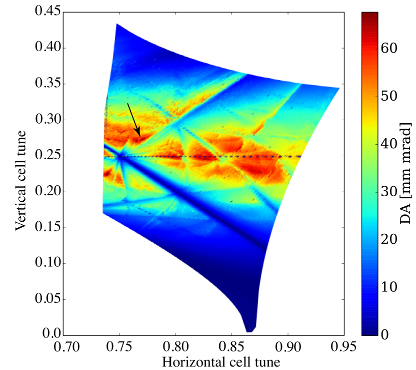
MANCHESTER 1824 The University of Manchester

NORMA: Design and optimisation

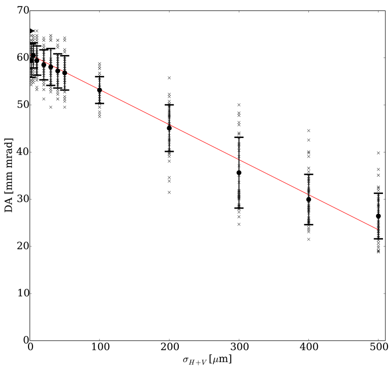
Optimise ring for size, fields and DA



Geometry

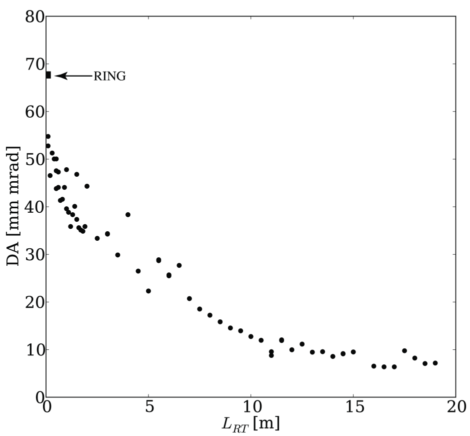


Tune

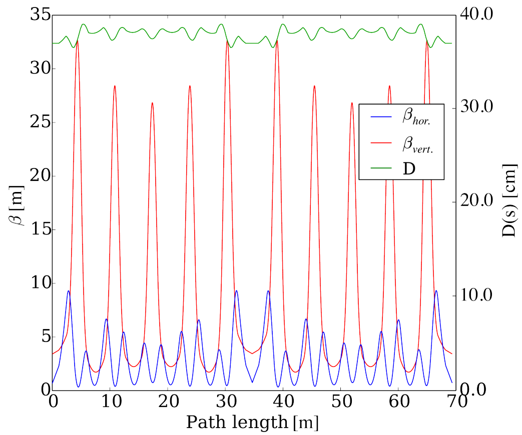


Misalignments

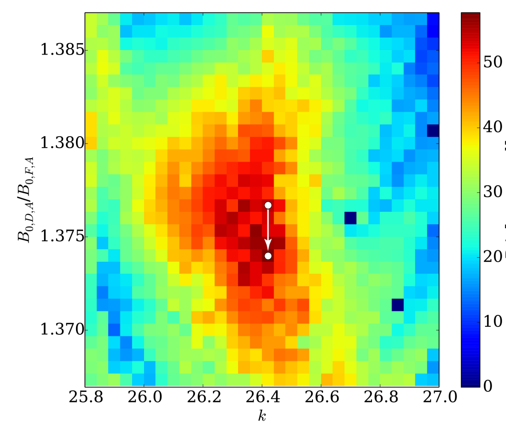
Add straight sections. Re-optimise after adding matching section.



Extend drift



C-S parameters



Fine tune

http://dx.doi.org/10.1103/PhysRevSTAB.18.094701

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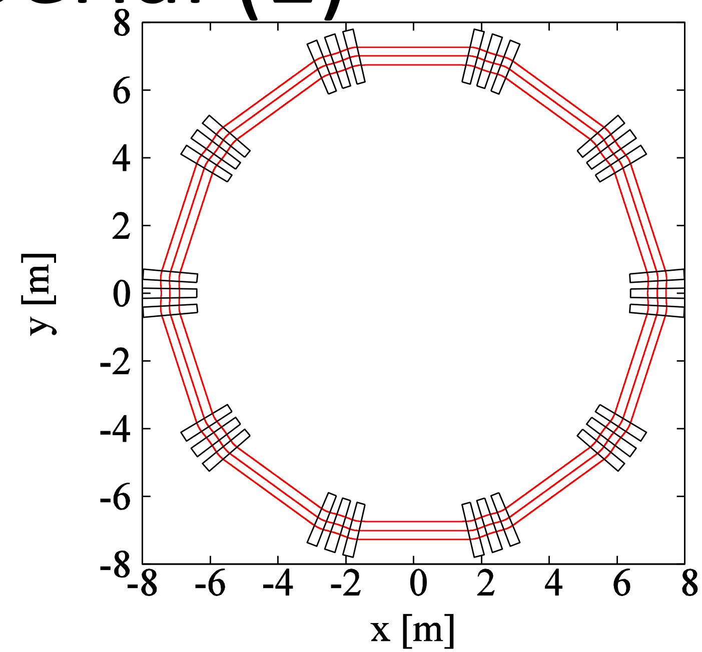
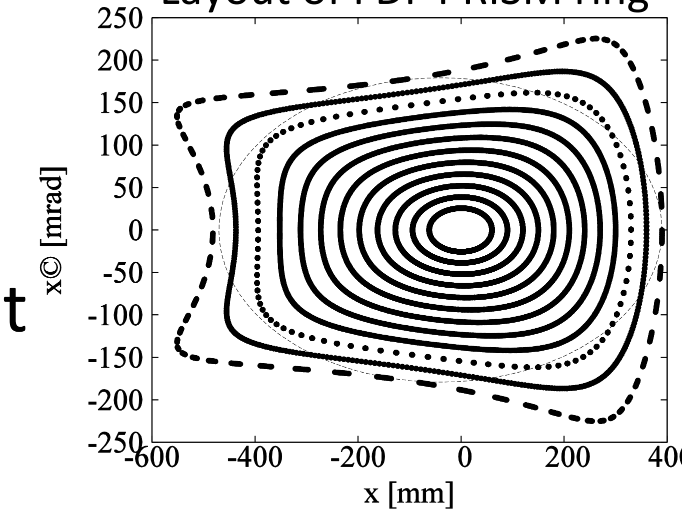
FFAG R&D at Imperial (1)

- Applications in fundamental physics:
  - Substantial effort on applications in novel neutrino beam generation (nuSTORM and nuPIL) -> J-B. Lagrange talk
  - Design work for PRISM FFAG - next generation muon to electron conversion experiment



Layout of FDF PRISM ring

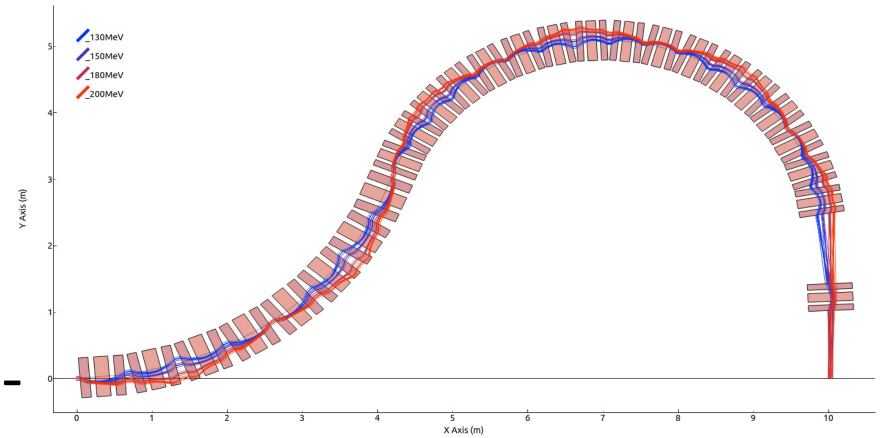


...and its huge acceptance

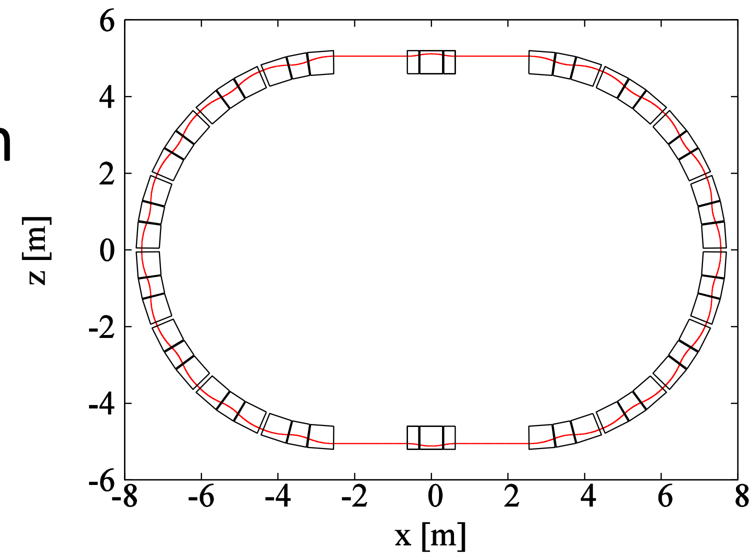
Imperial College London

FFAG R&D at Imperial (2)

- Applications in medicine and applied science:
  - Design work for the novel zero-chromatic NS-FFAG proton gantry
  - Investigations on medical racetrack allowing for proton radiography (in collaboration with Manchester University)
  - Developing novel solutions for spallation neutron production.



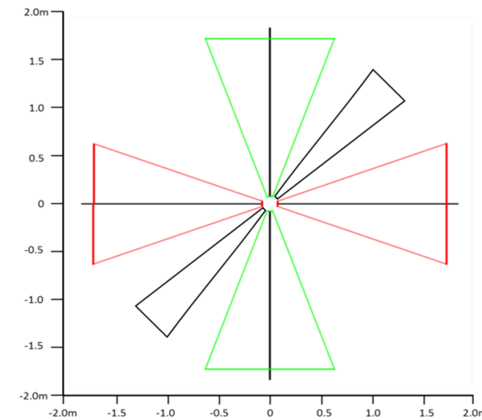
Layout of the novel FFAG gantry

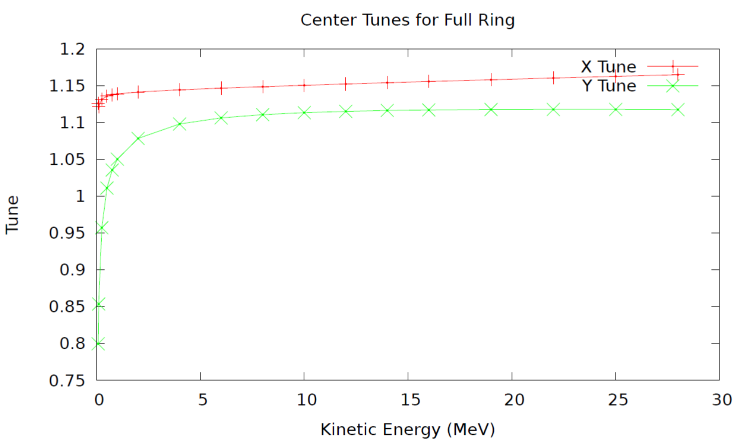


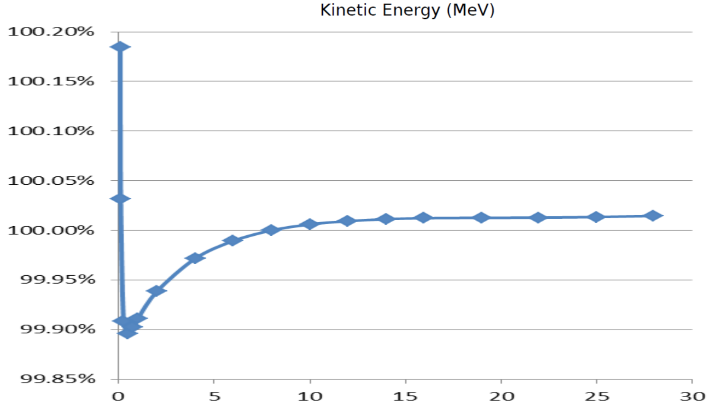
350 MeV ring for proton radiography

PIP: Compact radioisotope source

- 4 sector FFAG/strong focusing proton cyclotron for isotope production. Design by Carol Johnstone.
- Focusing both from field profile and edge effects. No reverse bends
- 2 RF cavties, 200 kV per turn.
- Injection at 75 keV. Extraction at 14 MeV (^{99m}Tc) and at 28 MeV (therapeutic isotopes).







Chromaticity/TOF

- Vertical tune passes an integer but resonance crossing is quick (within a turn).
- TOF variation within 0.3%.

Injection

- Radial injection septum capture simulated in Opal

Extraction

- Electrostatic deflector and septum looks feasible

Currently studying internal target for ^{99m}Tc production

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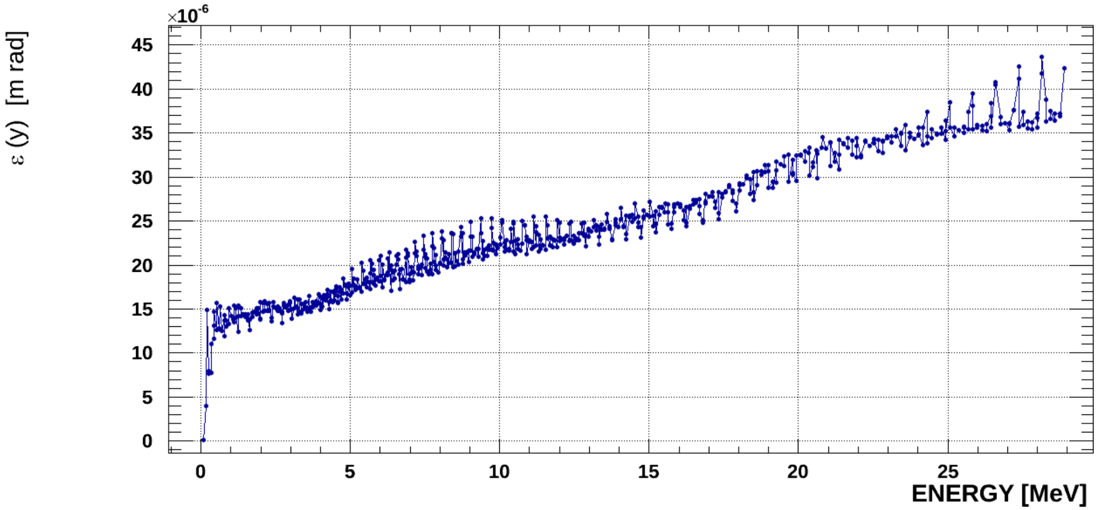
PIP: Compact radioisotope source

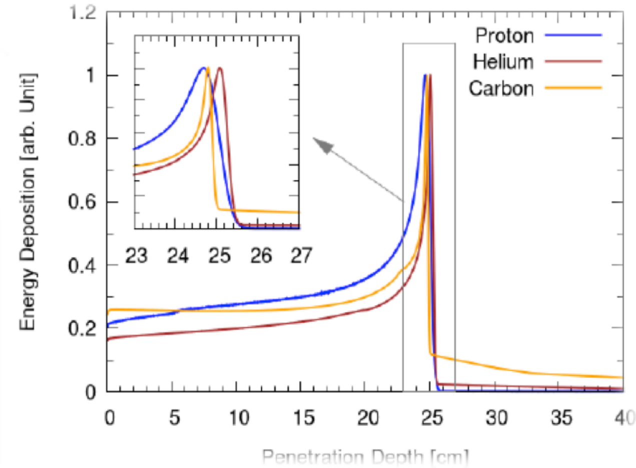
- 20mA tracked to 28 MeV in Opal
- 20 x any existing commercial radioisotope cyclotron!
- Losses: currently 1.3%, too large
- **no optimisation yet done (can open vertical aperture if required)**



Vertical emittance growth

FFAG for Ion Beam Therapy

• **Design of helium beam facility for cancer therapy:**
- half way between protons and carbon
- much smaller fragmentation tail than carbon
•- much smaller facility/cost than carbon!



- **Design uses two isochronous FFAGs:**
- **same basic design as for radioisotopes**
- **With straight sections to aid injection and extraction**
- **The design is in its early stages.**
- **Workshop planned:**
- **- 18th-20th January 2016**
- **- QE Hospital, Birmingham, UK**
- **- See: http://indico.cern.ch/event/456299/**
- **- All welcome**

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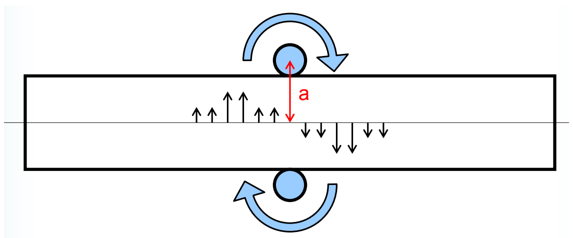
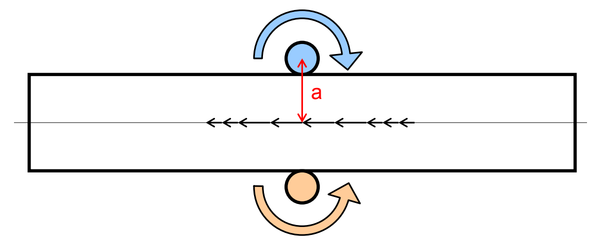
Vertical FFAGs (S. Brooks)

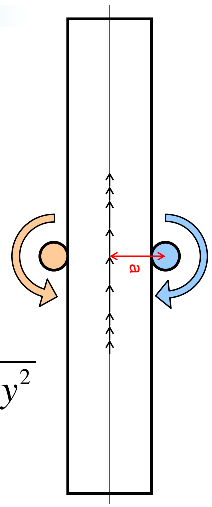
- In a SC (conductor dominated) magnet, it is more efficient to generate a magnetic field when the current windings are in the opposite direction.



$$B_y \propto \frac{x}{a^2 + x^2}$$



$$B_x \propto \frac{a}{a^2 + x^2}$$

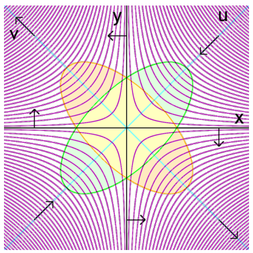


$$B_y \propto \frac{a}{a^2 + y^2}$$

- Rotate magnet so field is vertical. Now direction of increasing field is in vertical direction, i.e closed orbit moves upward/downward.
- The scaling law for VFFAGs

$$B_y = B_0 e^{ky} \cos kx \qquad B_x = -B_0 e^{ky} \sin kx$$

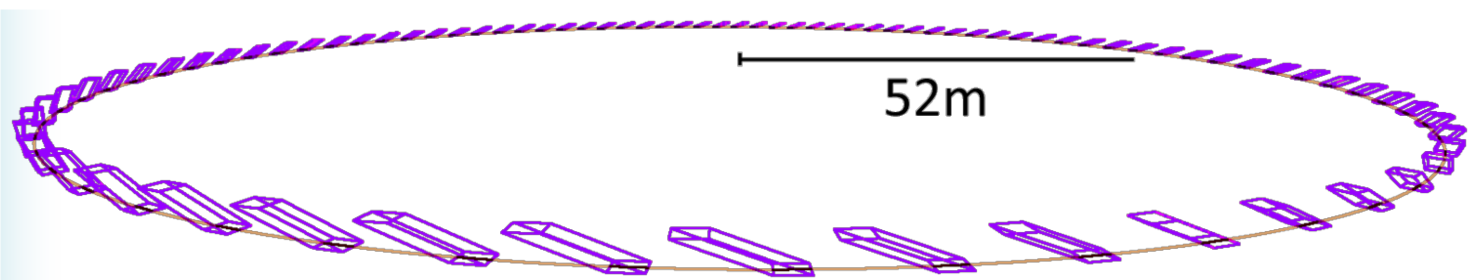
- This results in skew focusing optics.



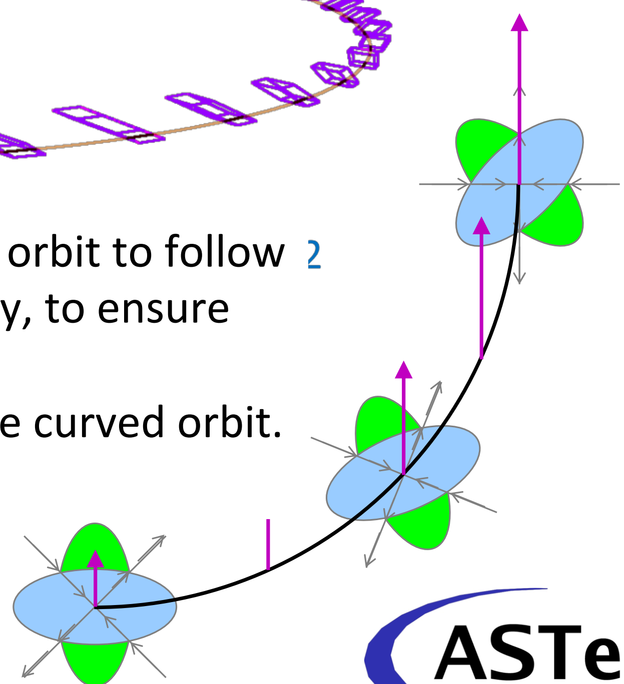
S. Brooks, PRST-AB (2013)

Vertical FFAG variants (S. Brooks)

- Spiral VFFAG: Edge angle eliminates reverse bending, and so reduces the circumference, required. This is introduced by tilting the magnets.
- 0.8-12 GeV, 2.5 MW spiral VFFAG design for an ISIS upgrade developed.



- Isochronism can be achieved but requires the closed orbit to follow 2 a curved path, moving both horizontally and vertically, to ensure orbit radius is proportional to velocity.
- In this case the field increases exponentially along the curved orbit.



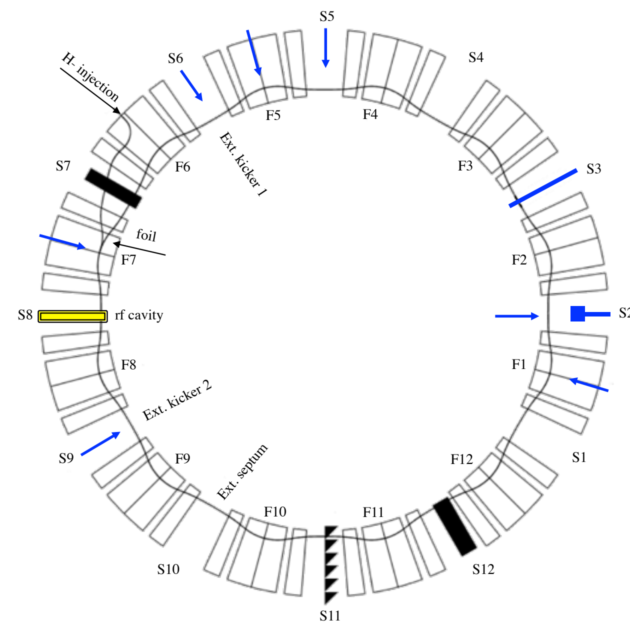
S. Brooks, PRST-AB (2013)

ASTeC

KURRI collaboration (2012 – ongoing)

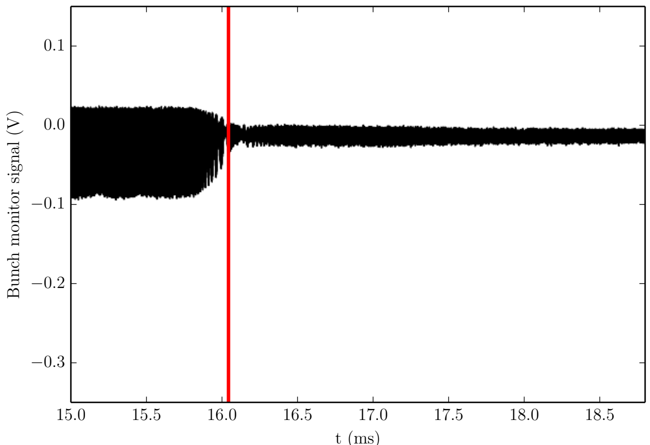
- International collaboration which was set up to conduct beam experiments using the scaling FFAGs at KURRI, Japan. The ultimate aim is to demonstrate the high beam power capability of FFAGs.
- Initial efforts have focusing on characterising the 150 MeV ADS ring at low intensity.

Parameter		Unit
R_0	4.54	m
Lattice	DFD	
N_{cells}	12	
Injection Energy	11	MeV
Extraction Energy	100-150	MeV
k (field index)	7.6	
f_{RF}	1.6-5.2	MHz
B_{max}	1.6	T



KURRI collaboration:

Measuring the radial position and field index



Radial probe measurement

→ $r_i(t)$

Algorithm: Find k(t) that minimises difference in momenta from

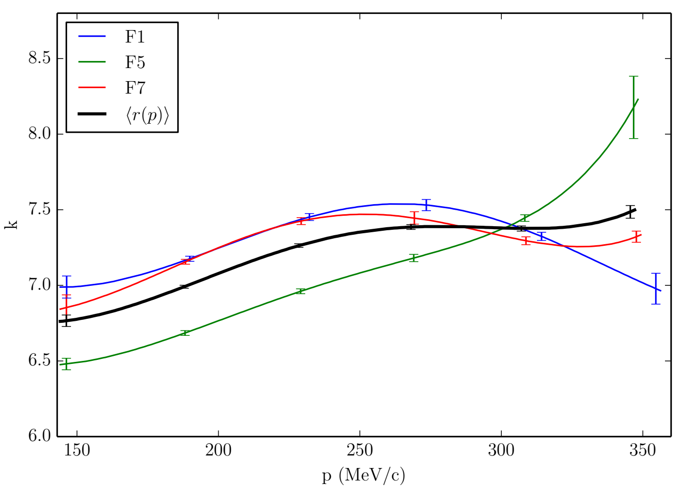
$$\alpha_c = \frac{1}{k+1}$$

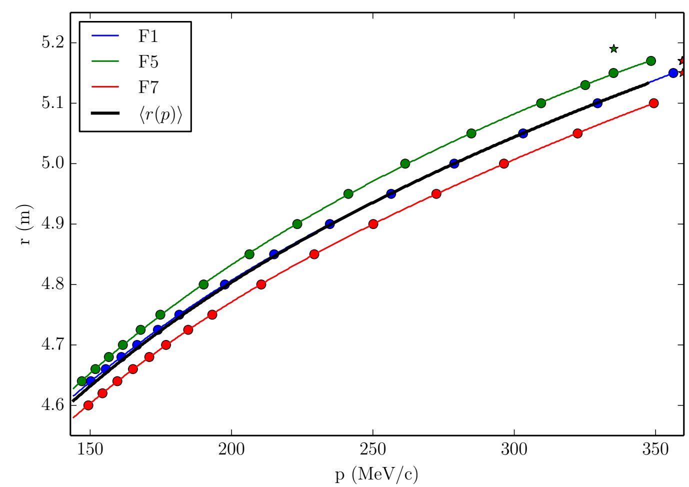
$$\frac{k(t)+1}{\gamma(t)^2} = \frac{\frac{1}{f(t)}\frac{df(t)}{dt}}{\frac{1}{r(t)}\frac{dr(t)}{dt}} + 1$$

$$p(t) = p(t_0)\exp[\int_{t_0}^{t}(k(t)+1)\frac{1}{r(t)}\frac{dr(t)}{dt}dt]$$

↙ $k_i(p)$

$r_i(p)$ ↓

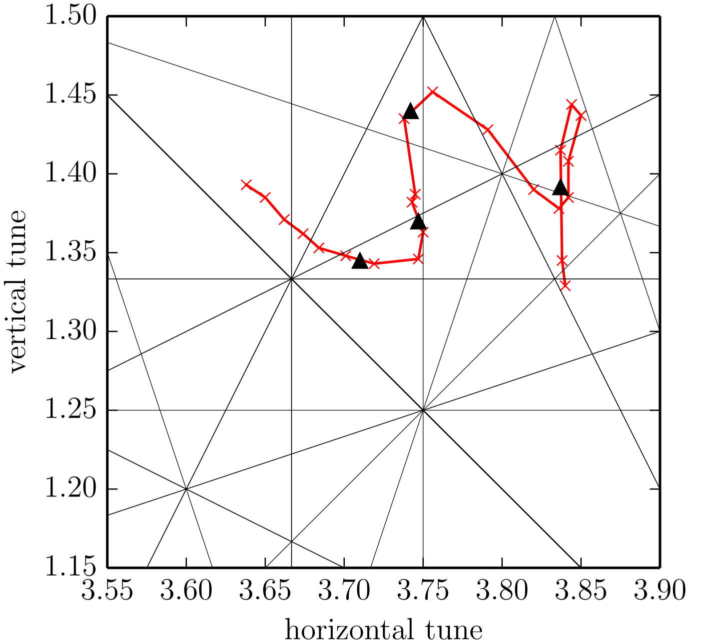




S. L. Sheehy et al, submitted for publication (2015), http://arxiv.org/abs/1510.07459≈

KURRI collaboration:
Summary of measurements

Measurement	Result/Utility
Radial position vs time	Field index, Dispersion, COD
Vertical coherent oscillations	Vertical orbit matching
Betatron tunes	Tune excursion
Dispersion at foil	Dispersion matching
Synchronous phase vs rf voltage	Foil thickness



Tune over momentum range

S. L. Sheehy et al, submitted for publication (2015), http://arxiv.org/abs/1510.07459≈

FFAG for high power spallation

- Higher powers can be reached by operating the FFAG at high rep rates (compared to RCS).
- The large horizontal aperture allows a larger emittance aspect ratio ε_h/ε_v and so a reduced space charge tune shift (all else being equal).

$$\Delta Q_v = -\frac{n r_p}{\pi \varepsilon_v \left(1+\sqrt{\varepsilon_h / \varepsilon_v}\right)\beta^2\gamma^3}\frac{1}{B_f}$$

- FFAG allows beam stacking at extraction energy (Ishi et al, HB2012). Can tailor pulse structure to meet requirements of multiple target stations.

$\sqrt{\frac{\varepsilon_h}{\varepsilon_v}}$	**25 Hz**	**50 Hz**	**100 Hz**
1	1 MW	2	4
2	1.5	3	6
3	2	4	8

S. Machida, FFAG15 workshop

ASTeC

DF-Spiral FFAG (S. Machida)

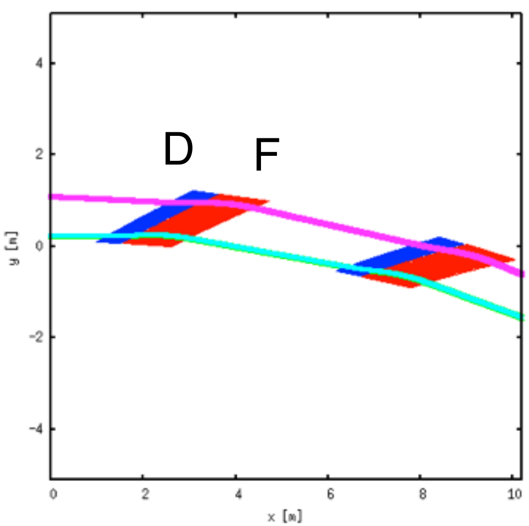
- Spiral sector FFAG has no reverse bends. However, spiral angle increases with number of cells and qx, qy cannot be independently varied

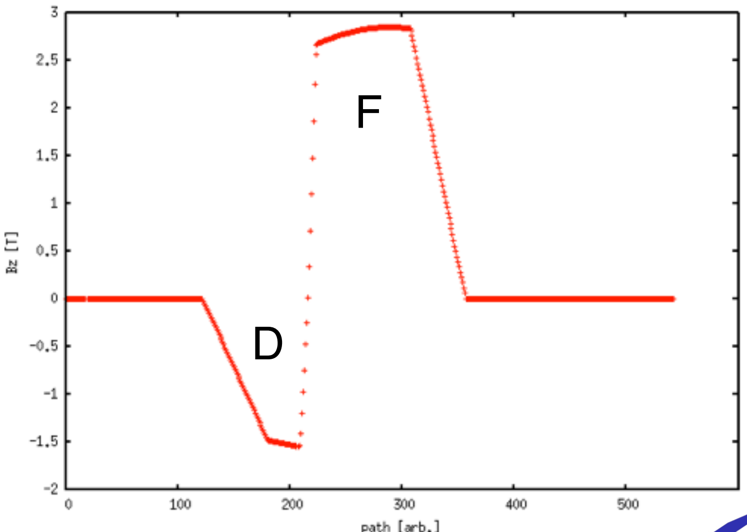
$$q_x^2 \approx k+1$$

$$q_y^2 \approx -k + f^2 \tan^2 \zeta$$

$$\text{where } \tan\zeta \approx \sqrt{k} \approx N, \quad f = \left\langle \left(B - B_{av}\right)^2 \right\rangle / B_{av}^2$$

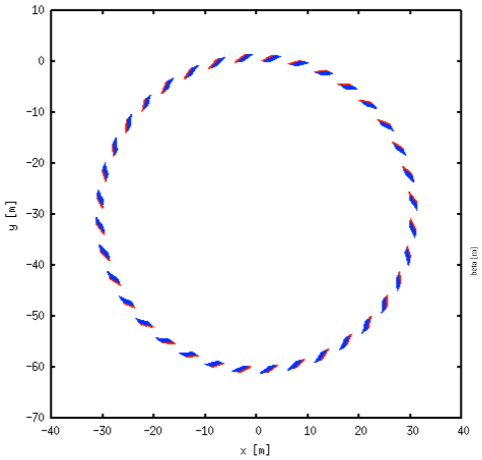
- To reduce required spiral angle, increase magnetic flutter. This can be done by introducing a negative field region at one edge of the spiral magnet. F/D ratio can be adjusted, so the lattice is tuneable.

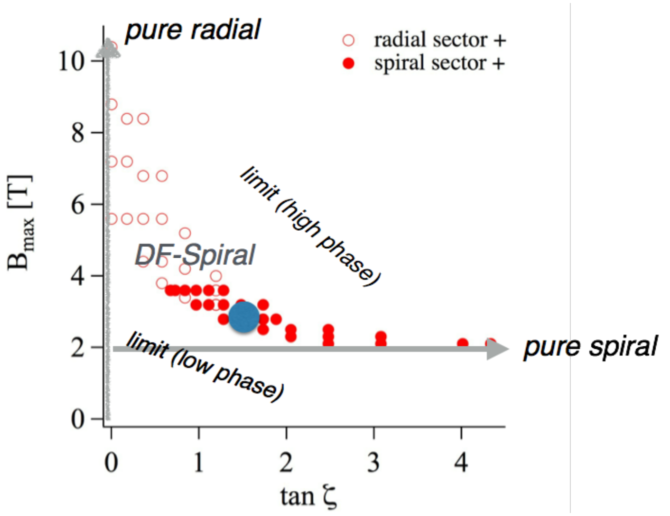




S. Machida, FFAG15 workshop

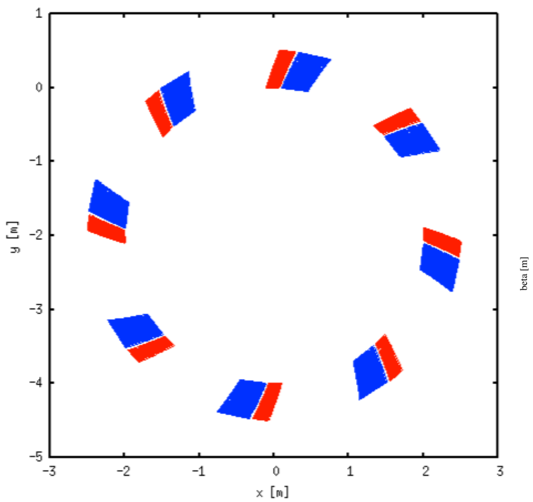
3 GeV DF-Spiral (S. Machida)

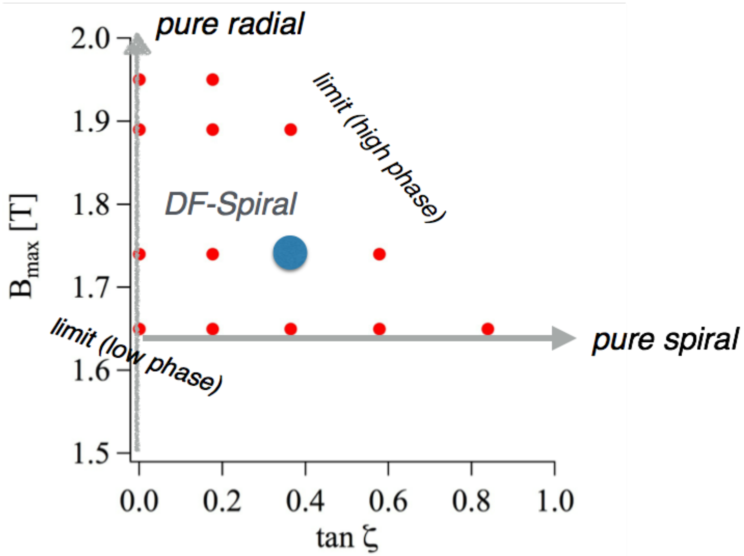




- Lattice layout and stability diagram of 3 GeV DF-Spiral shown above.
- Blue point shows the chosen working point where the spiral angle is low and the field acceptable.
- This is a candidate for an ISIS-II ring.

DF-Spiral "FETS FFAG" (S. Machida)





- 3-27 MeV DF-Spiral FFAG.
- The FETS DF-Spiral FFAG has the following goals
  - Demonstrate DF-Spiral optics and operation.
  - H- injection/extraction.
  - Tunability with additional trim coils.
  - Non-uniform painting at injection.
  - Operation with asymmetric emittance.
  - Beam stacking to shape time structure.

S. Machida, FFAG15 workshop

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Summary

- FFAG designs to meet various applications have proliferated in recent years.
- There has been a lot of progress in "Advanced FFAG" designs that allow more complex ring geometries (e.g. racetracks).
- Experimental methods to characterise scaling FFAGs have been developed.
- This lays the groundwork for high intensity beam physics experiments to follow in the near future.
- There is an possibility to use FETS as an injector for an FFAG. This opportunity should be used to test an FFAG design suitable for a high power proton ring.
- Finally, we are edging towards proving Symon was correct to assert

"FFAG synchrotrons have a number of important advantages over conventional synchrotrons. A major one is beam intensity." -K.R. Symon et al, Phys Rev 103 (1956)