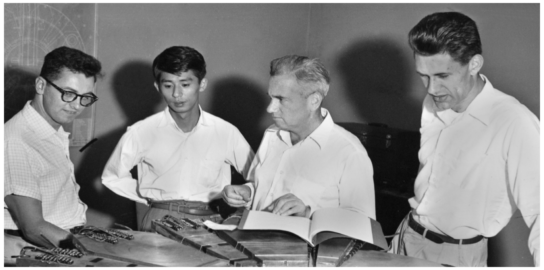
Introduction to non-scaling FFAGs

David Kelliher
ASTeC/STFC/RAL

With thanks to S. Machida

Scaling FFAGs

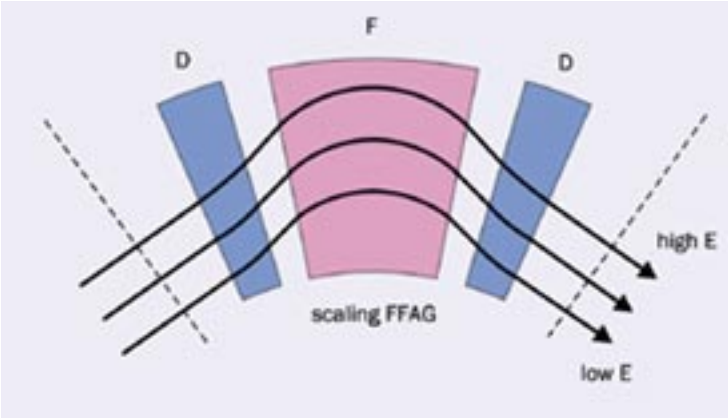


1955 Michigan MURA Summer Study; Ernest Courant, Tihiro Ohkawa, Otto Frisch, and Dave Judd by the Radial Sector Model (under construction)

Cardinal conditions of scaling FFAG

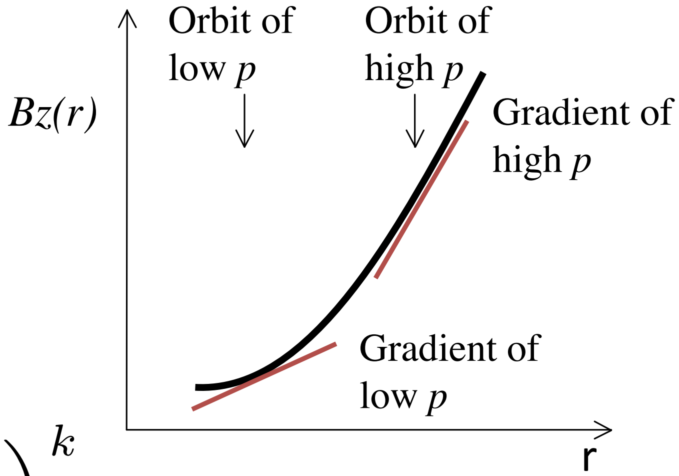
1. Geometrical similarity of orbits

$$\frac{\delta}{\delta p}\left(\frac{\rho}{\langle\rho\rangle}\right)\bigg|_{\vartheta=\text{const.}} = 0$$



2. Similarity of field index

$$\frac{\delta k}{\delta p}\bigg|_{\vartheta=\text{const}} = 0 \text{ where } k = \frac{r}{B}\left(\frac{\delta B}{\delta r}\right)$$



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

Non-scaling FFAG

noun

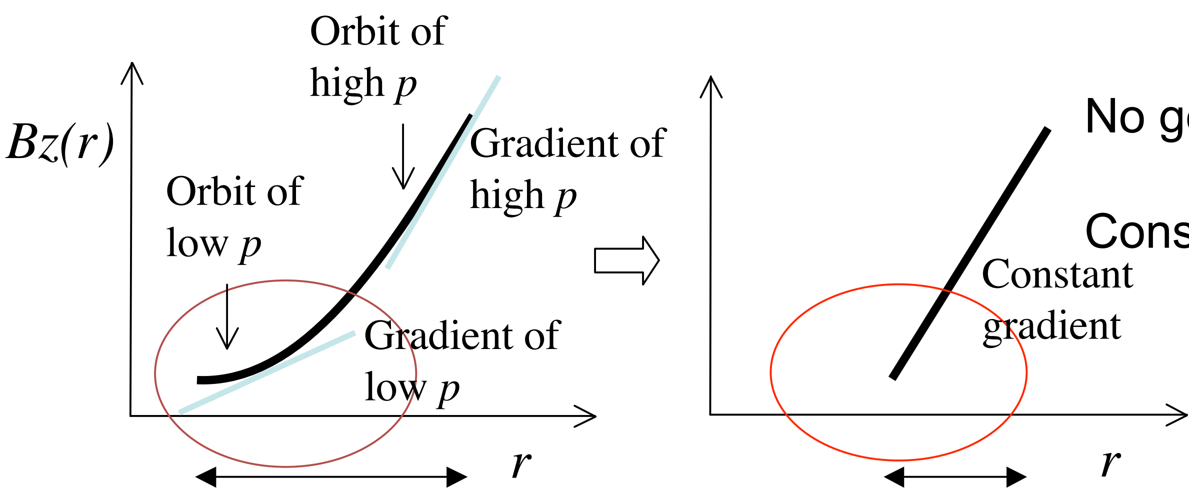
An FFAG that doesn't satisfy the cardinal conditions of a scaling FFAG.

abbrev: NS-FFAG, ns-FFAG, NSFFAG, nsFFAG.

BREAK THE SCALING RULES TO MAKE THE MAGNETS MORE COMPACT AND SIMPLE.

Make the magnets more compact

- If we could break cardinal conditions (scaling law), FFAG would be much simpler and magnet would be smaller.



No gentle slope at low momentum.
- Orbit excursion is shorter.

Constant gradient.
- Linear magnet.

- Use magnets that produce a linear (or uniform) magnetic field – dipoles and quadrupoles
- This is known as a **linear non-scaling FFAG**.

Accelerator Physics: Natural chromaticity

- The tune varies with momentum according to the chromaticity ξ,

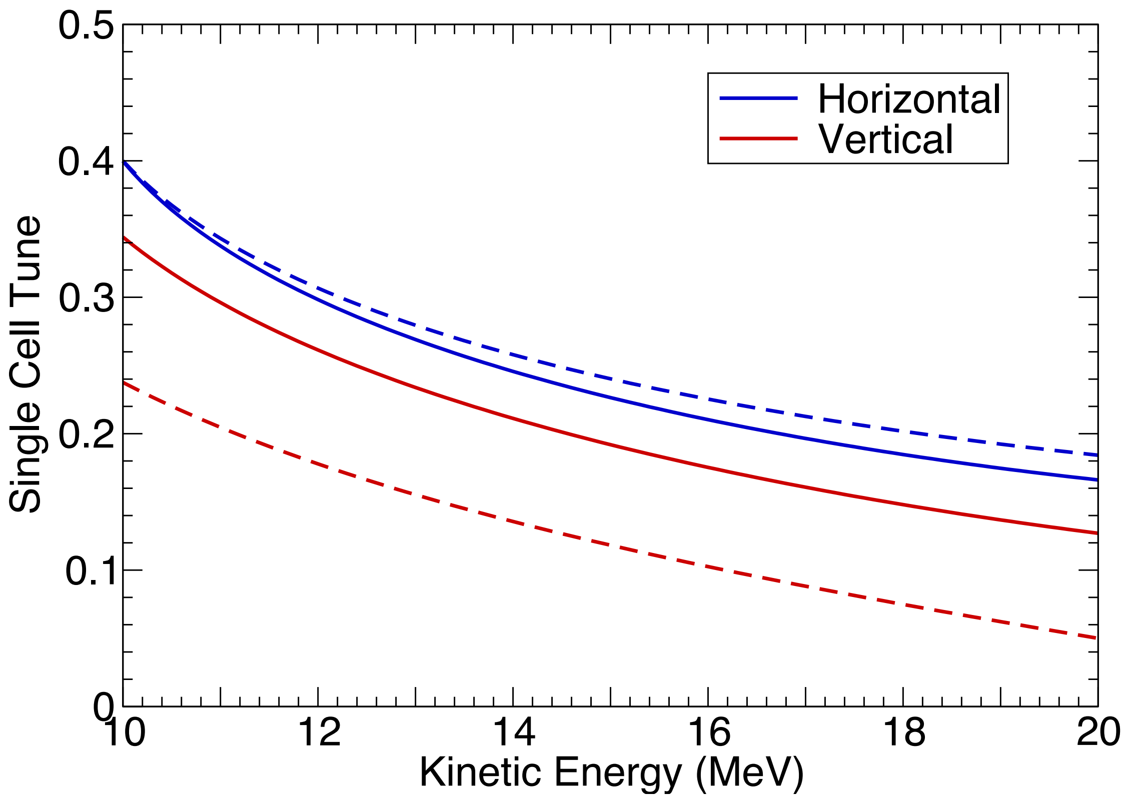
$$\Delta Q_{x,y} = \xi_{x,y} \frac{\Delta p}{p}$$

- The natural chromaticity in the linear lattice is always negative in both transverse planes.

$$\xi_{x,y} = -\frac{1}{4\pi} \oint \beta_{x,y} k_{x,y} ds$$

- The tune decreases with momentum in a linear lattice.

Tune variation

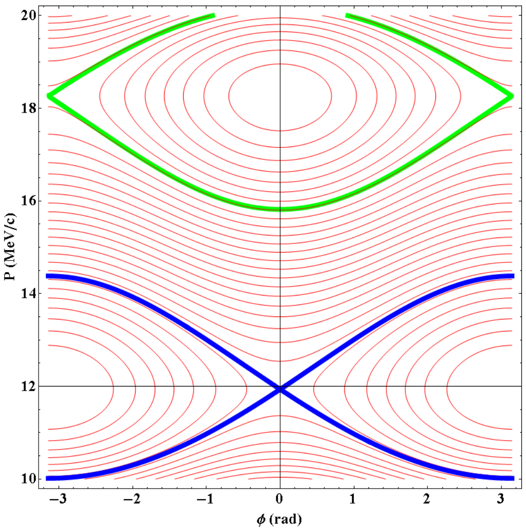


- Many tunes that may corresponds to resonances crossed during acceleration (e.g. integer tunes).
- Accelerate through them quickly!

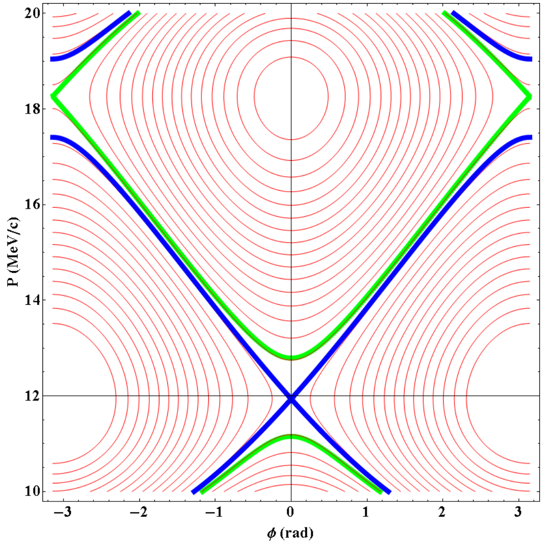
Credit: J.S. Berg

ACCELERATE RAPIDLY IN THE SERPENTINE CHANNEL

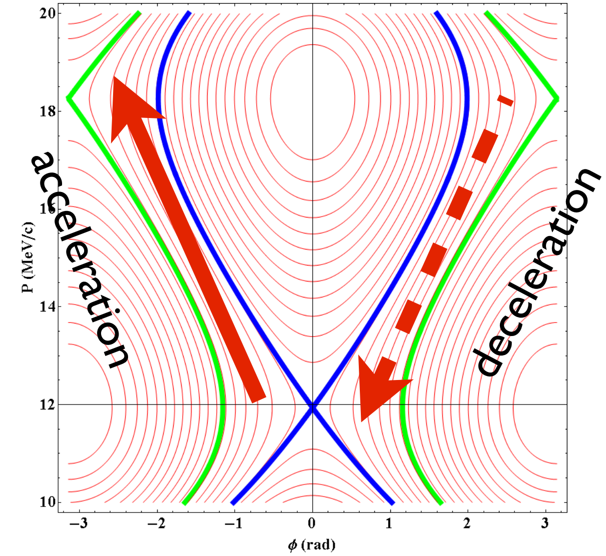
Longitudinal dynamics



V_{RF} too low



Critical V_{RF}

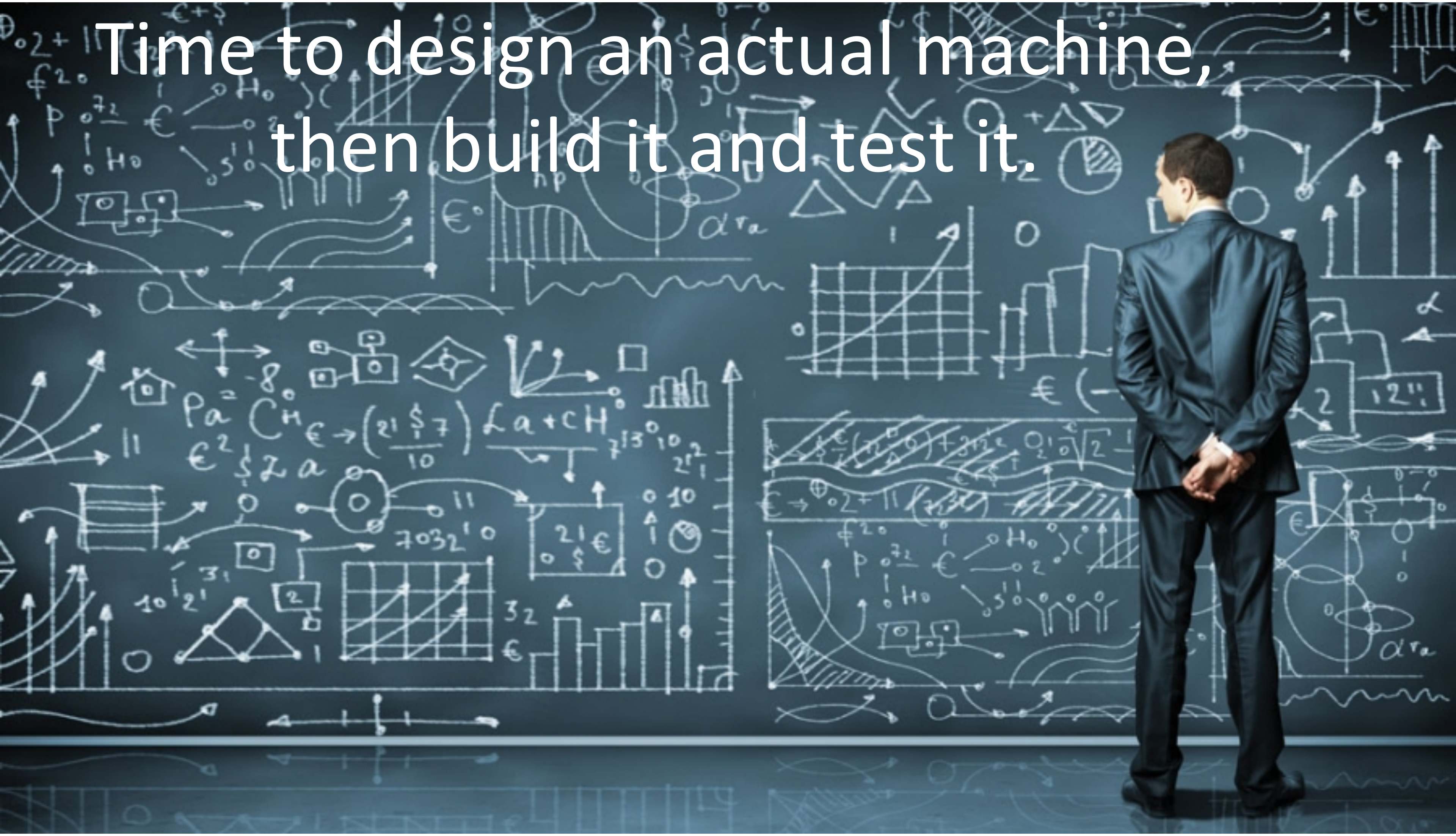


Sufficient V_{RF} to open channel

- With sufficient voltage, a channel opens up between stable buckets
- Fix the RF parameters (voltage, phase and frequency) and accelerate rapidly in this channel (out-of-bucket, gutter or serpentine acceleration).

Credit: S. Machida

Time to design an actual machine, then build it and test it.

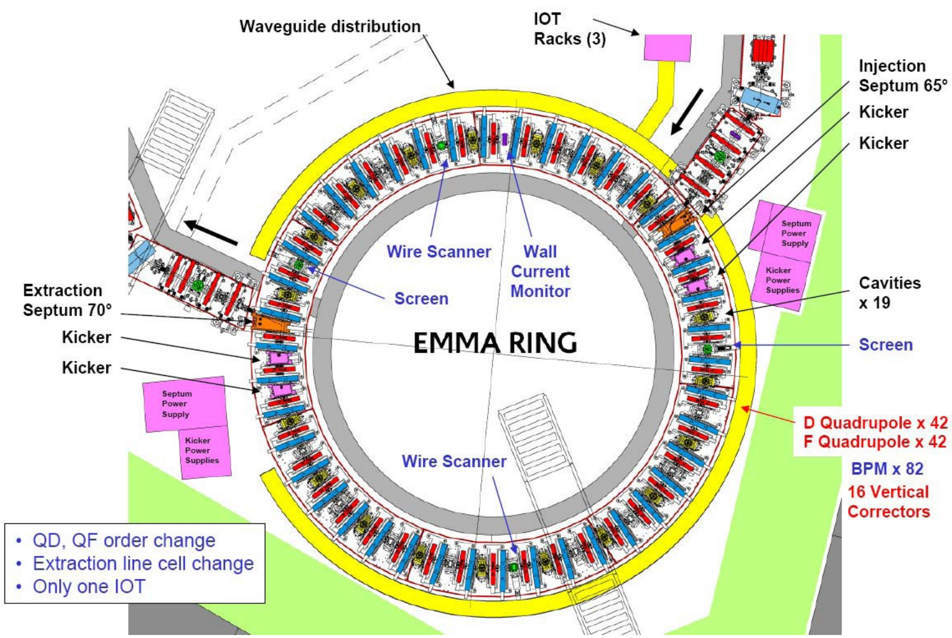


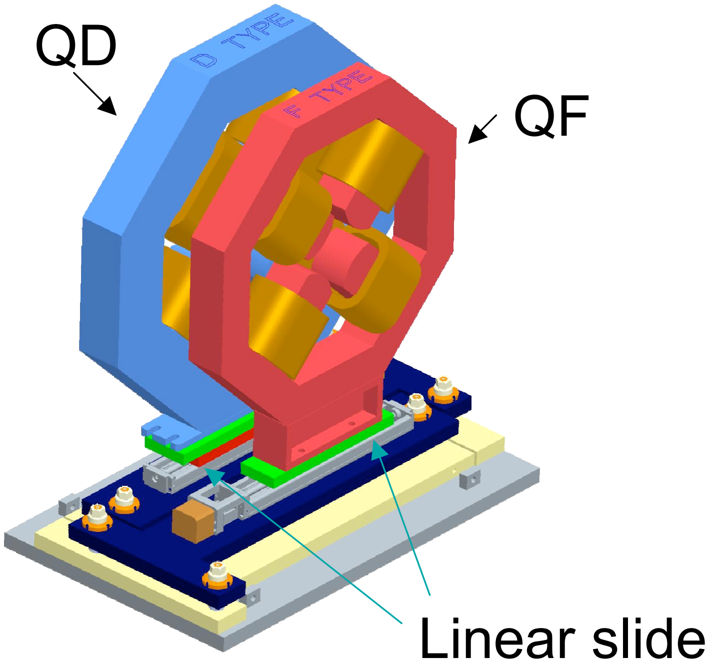
Linear non-scaling FFAG: Design Process

- Ensure cell tunes are in stable region $0 < Q_{x,y} < 0.5$ throughout acceleration.
- A ring consisting of many identical cells is preferred – high degree of symmetry improves dynamic aperture.
- Minimise magnet apertures: keep betatron functions and dispersion under control.
- Optional for very rapid acceleration: Ensure a (roughly) parabolic time of flight (TOF) to allow serpentine acceleration.
- Design a realistic injection and extraction scheme.
- Perform error study to check feasibility w.r.t. alignment tolerances etc.
- ….

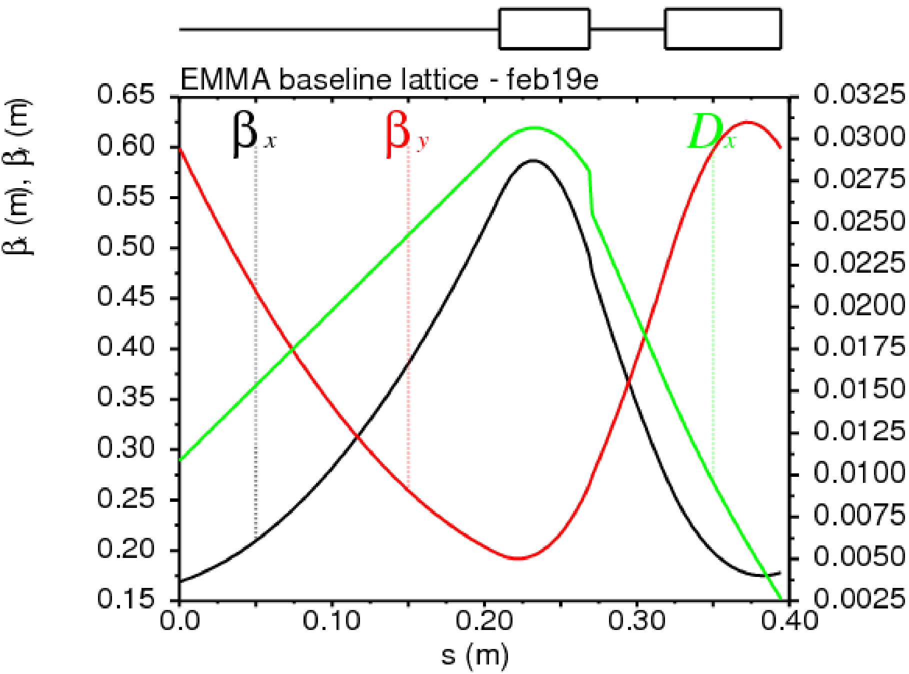
Electron Model for Many Applications: (EMMA)

- A proof-of-principle 10-20 MeV electron FFAG.
- A densely packed ring consisting of 42 DF doublets.
- Quadrupoles are shifted to get the bending component.





EMMA cell



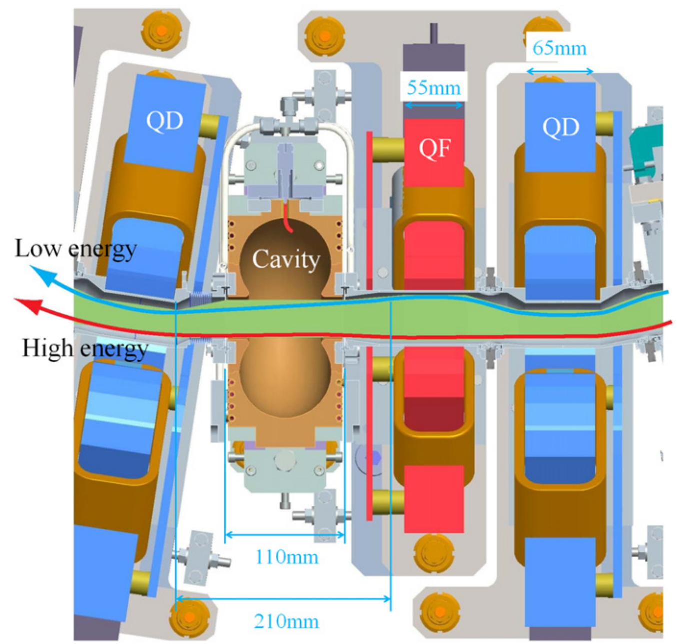
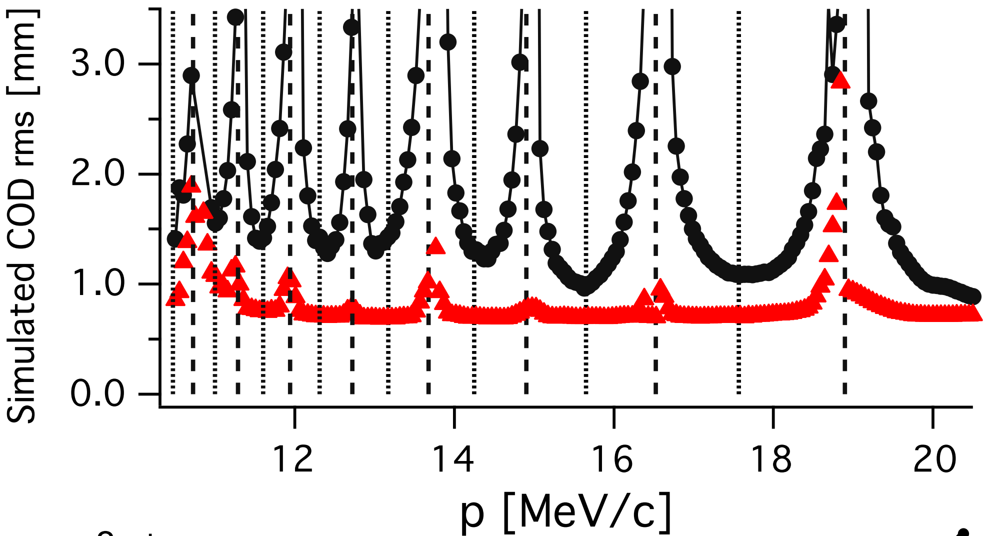
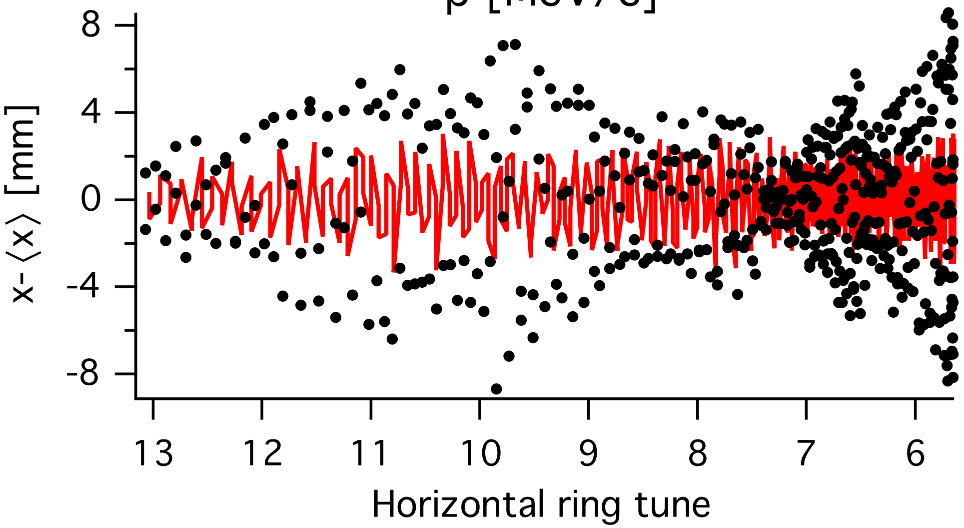


Fig. 5. Plan section of the EMMA cell showing the quadrupole doublet and RF cavity.

Goals – Ensure betatron function and dispersion allow a compact magnet. Ensure a low momentum compaction factor and parabolic time of flight.

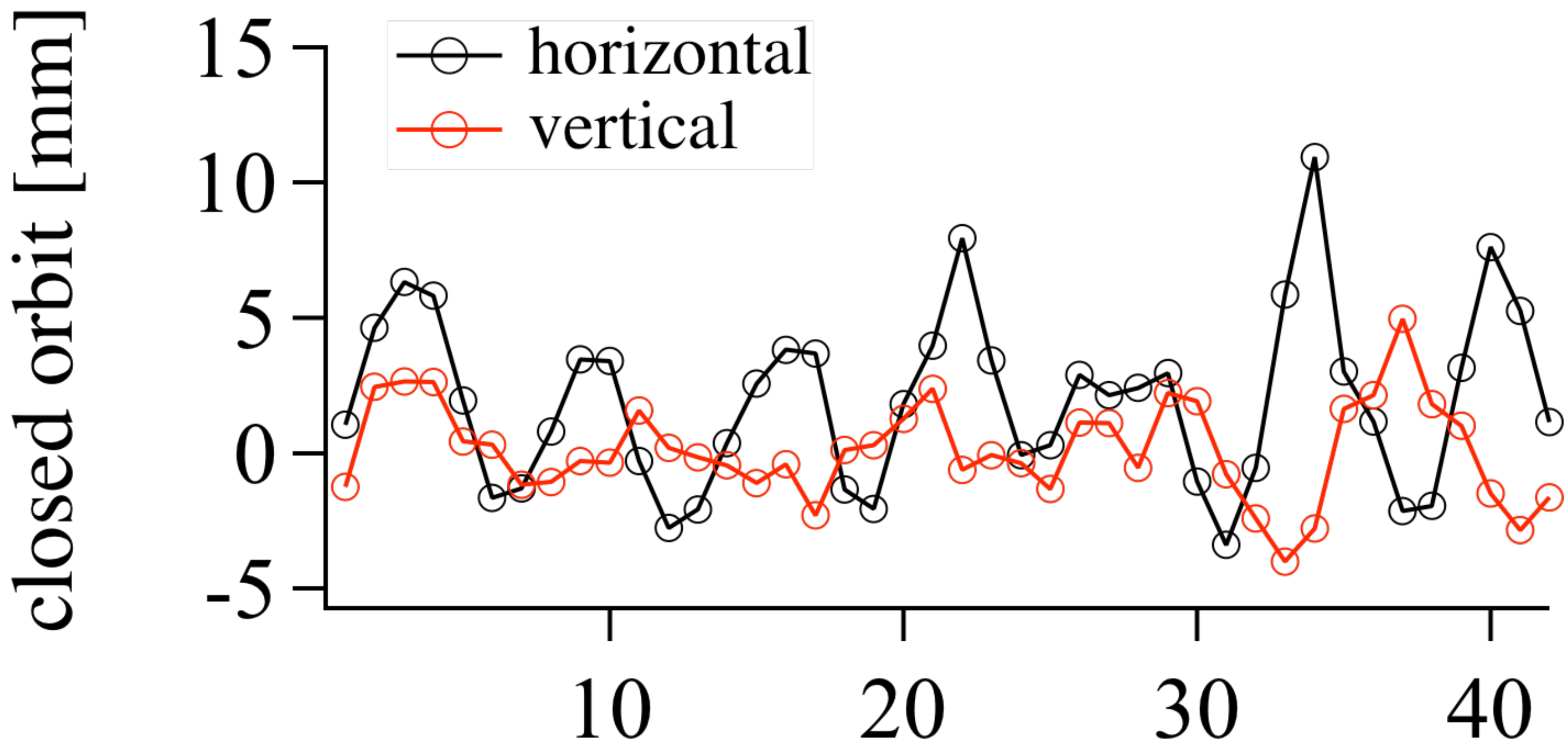
COD in EMMA





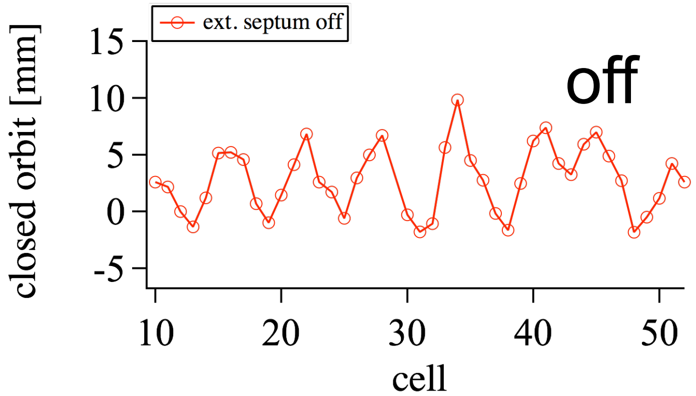
Correcting the harmonics of the magnet misalignments reduces both the COD and the accelerated orbit across the momentum range.

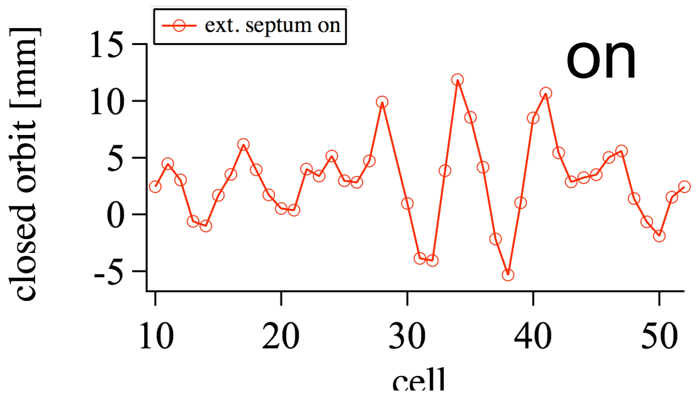
Measured COD

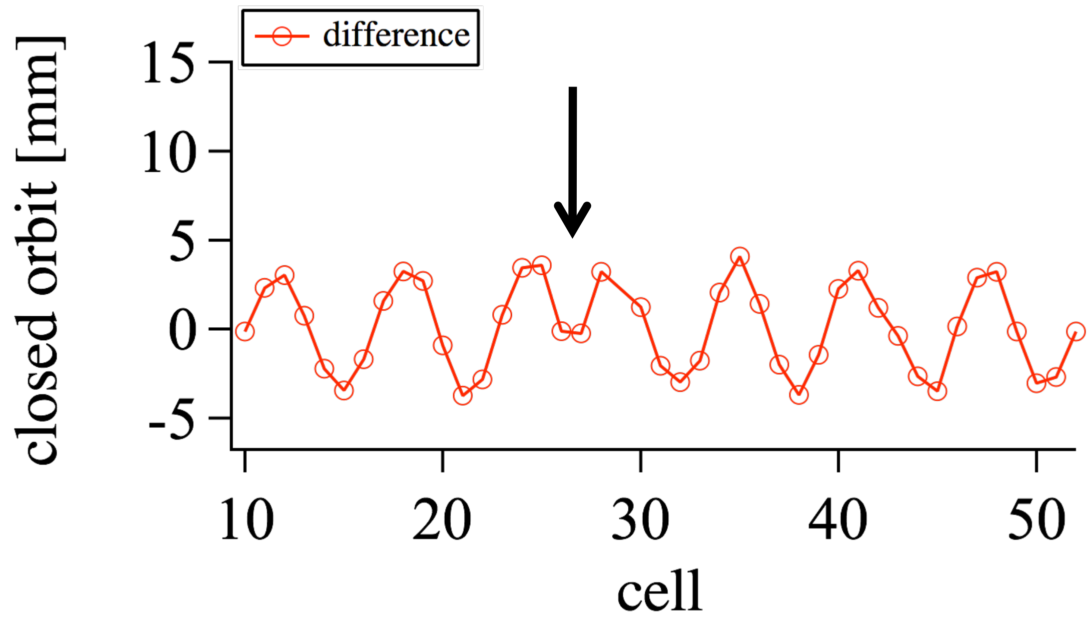


Source of horizontal COD

- Difference between on and off tells COD by extraction septum.







- Kink at extraction septum (between cell 26 and 27)
- COD amplitude is ~8 mm.

The culprit – Septum stray field.

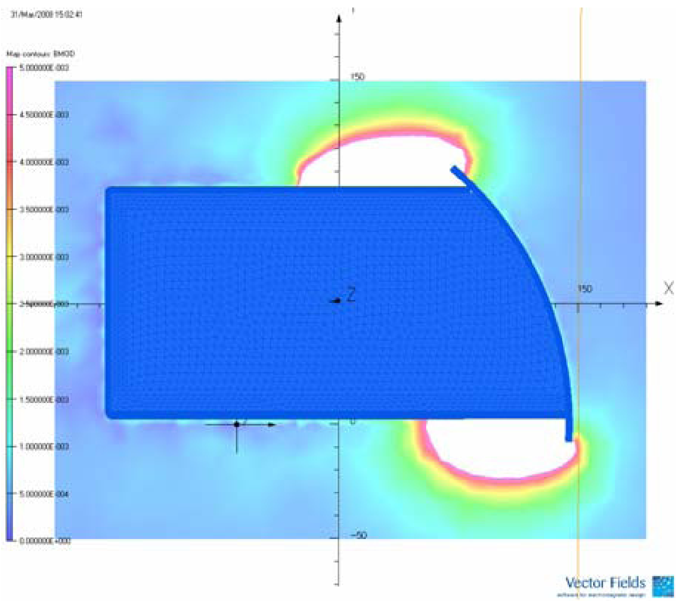
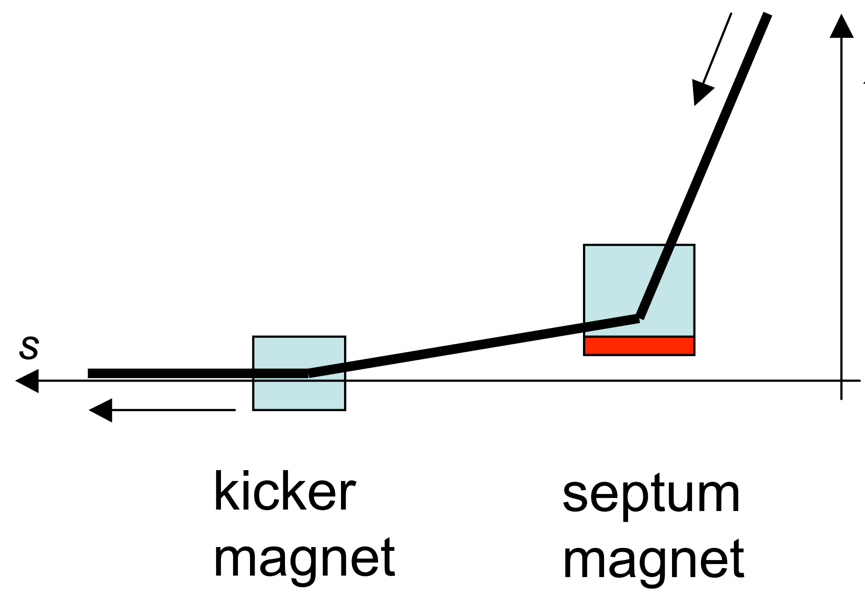


Figure 2: Septum, showing magnetic field magnitudes [5]. Transition to white is at 5 mT.



Because of the short drift space, a 65 degree injection septum is required.

Injection/Extraction

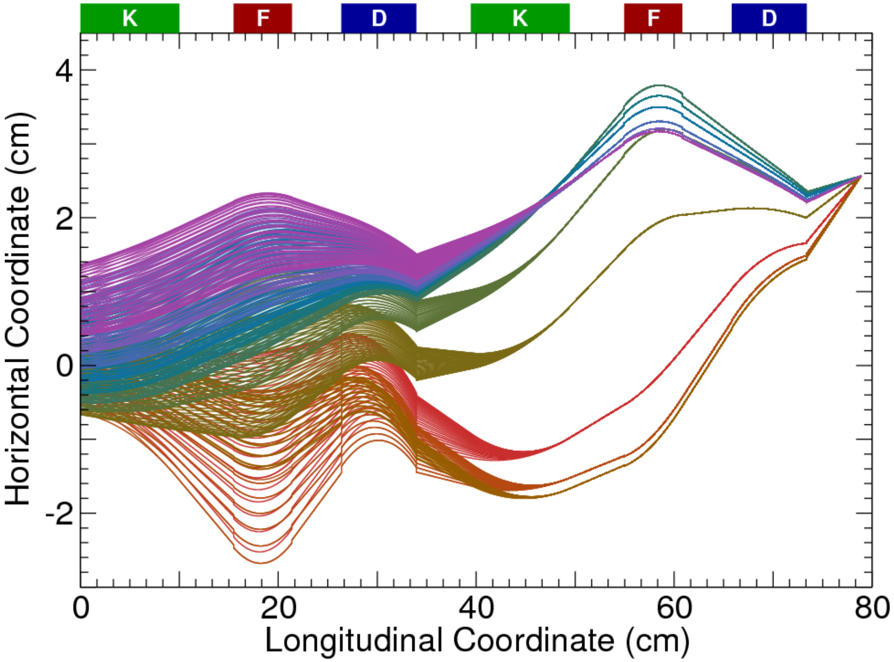
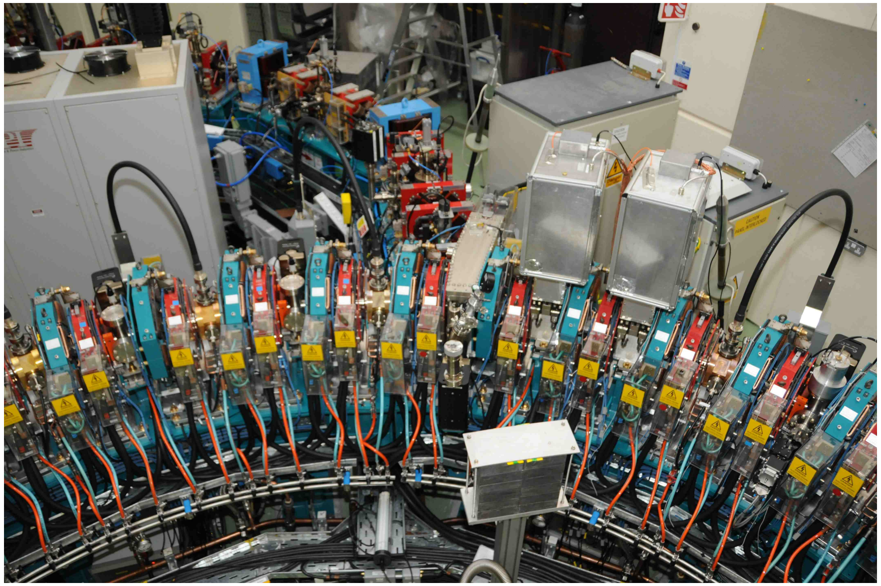
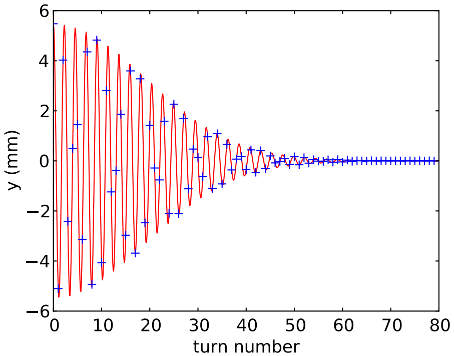


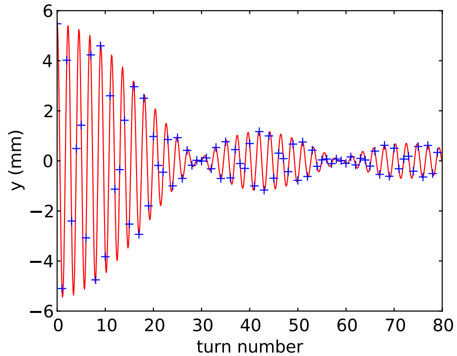
Figure 5: Injection of beams of various energies into EMMA. Energies are from 10 to 20 MeV in 1 MeV steps. Each color is a different energy: violet, toward the top, is the highest energy, and red, toward the bottom, is the lowest. For a given color, different lines are different initial conditions on the edge of an ellipse as in Fig. 3.



Natural chromaticity effects

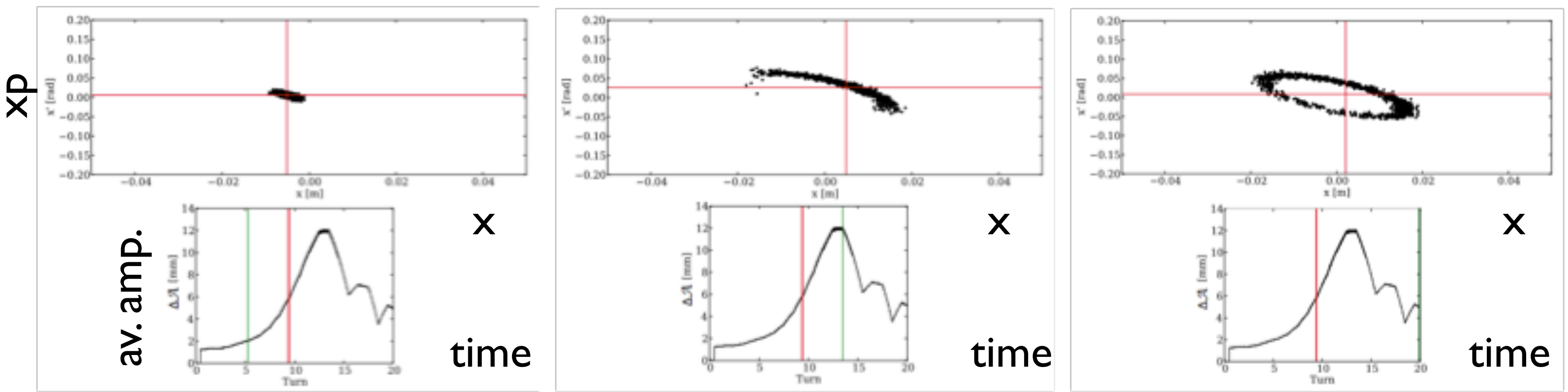


(a) Gaussian momentum distribution



(b) Uniform momentum distribution

Apparent decay in amplitude due to decoherence. Pattern of decoherence depends on the momentum distribution [C. Edmonds PRST-AB 17, 054401 (2014)]



before integer tune

right after integer

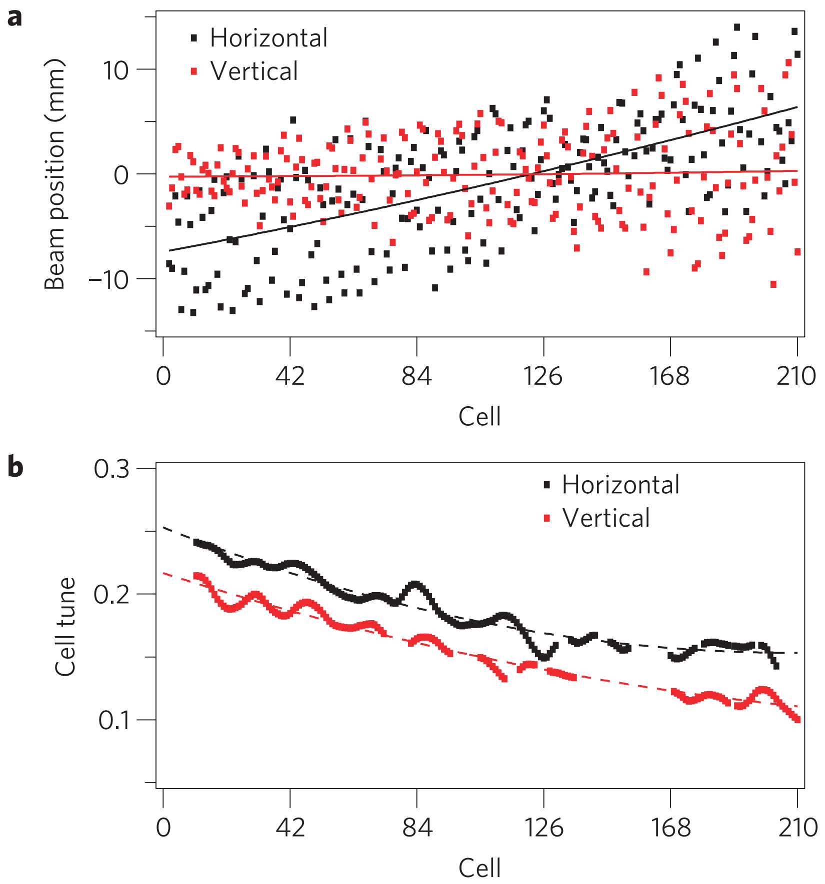
long after integer corssing

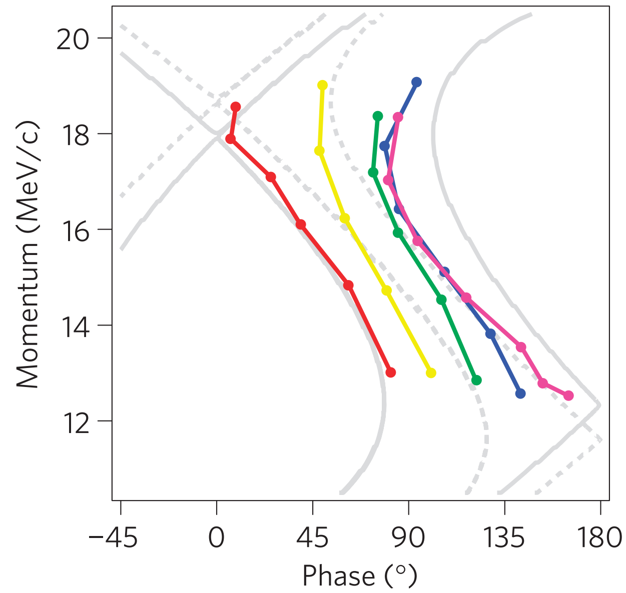
time

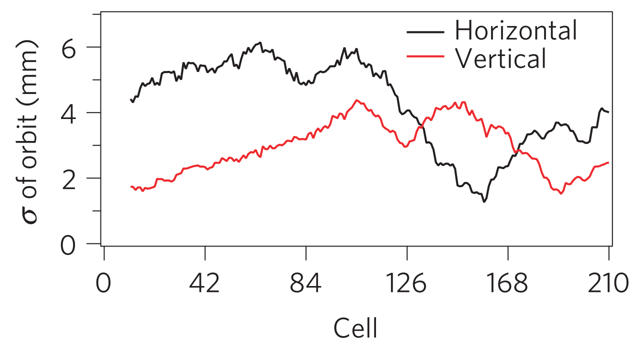
Integer crossing + chromaticity = emittance growth [J. Garland, FFAG13]

EMMA commissioning (2010 - 2012)

Acceleration results







It works!

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

BREAK THE SCALING RULES TO SIMPLIFY THE MAGNETS BUT KEEP THE TUNE ROUGHLY CONSTANT.

Towards flat tunes

- One approach to stabilising the tunes over the momentum range is to add higher order multipole components.
- Adding sextupoles to a linear non-scaling FFAG proved unsuccessful as chromaticity correction is most effective where the dispersion is large.
- Flat tunes were achieved using a wedge-shaped quadrupole design which utilised edge focusing (C. Johnstone].
- Another approach is to adopt a nonlinear field that approximates the scaling field but still results in a simpler magnet and allows longer straight sections to ease injection/extraction [S. Machida] .

PAMELA

A design study for a 250 MeV proton FFAG + 450 MeV/u carbon non-linear NS-FFAG for hadron therapy.

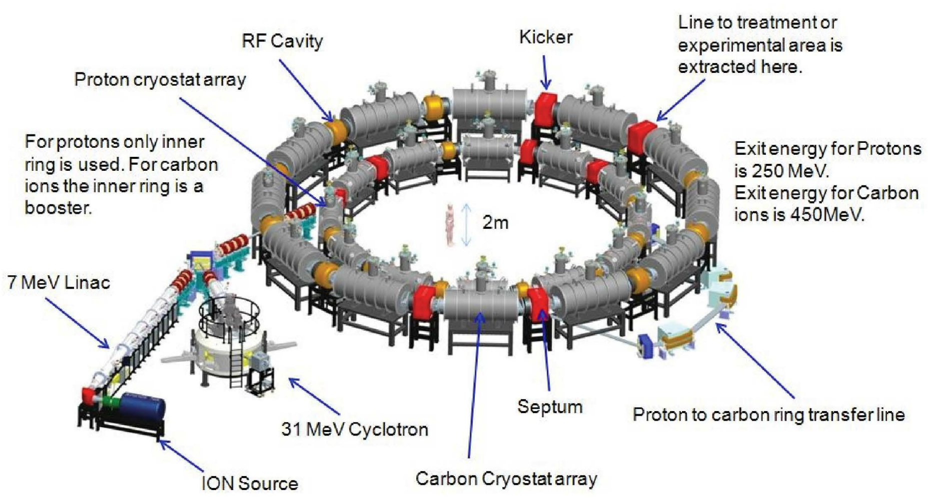
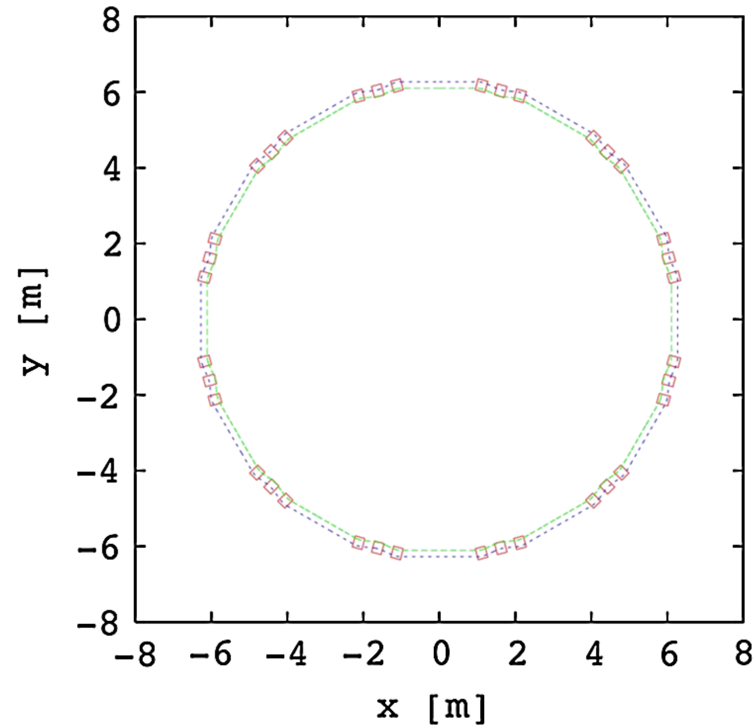


Figure 3.1: Proposed PAMELA layout.

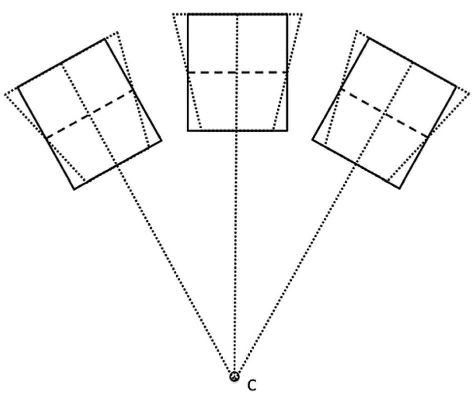


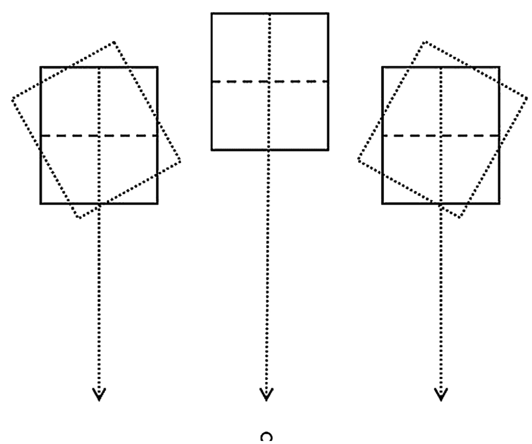
Proton ring footprint.

PAMELA design features.

$$B_y = B_0 \Big[1 + \frac{k(r-r_0)}{1!\, r_0} + \frac{(k-1)k(r-r_0)^2}{2!\, r_0^2} + \frac{(k-2)(k-1)k(r-r_0)^3}{3!\, r_0^3} + \frac{(k-3)(k-2)(k-1)k(r-r_0)^4}{4!\, r_0^4} \Big]$$

Truncated Taylor series approximating the scaling field.





Left: Rectangular instead of wedge-shaped magnets.
Right: Magnets aligned parallel rather than along an arc.

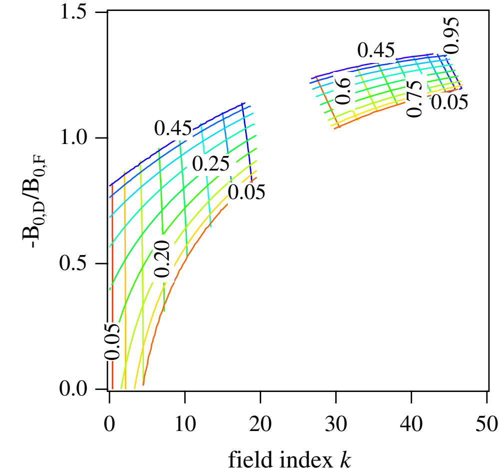
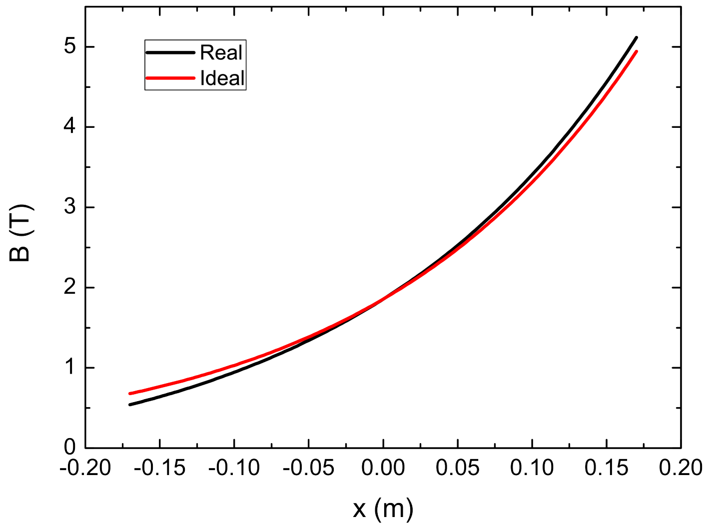
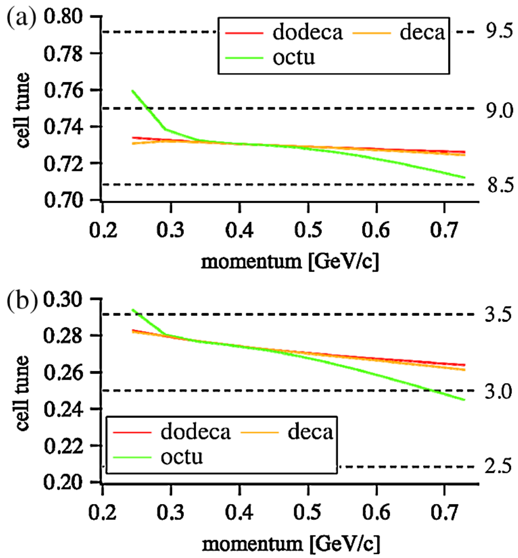


FIG. 1. (Color) From Ref. [13]. Stability diagram shows two stability regions. Upright numbers indicate vertical cell tune and vertically aligned numbers indicate horizontal cell tune. Lines are drawn with 0.05 step.

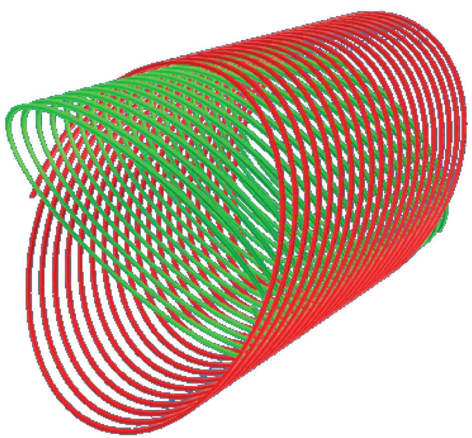
Second stability region of Hill's equation.

PAMELA magnets

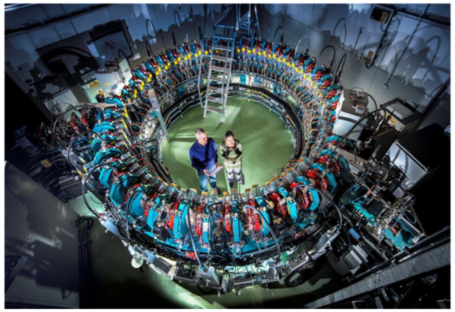




- Multipole components up to decapole found to be sufficient to stabilise the tunes.

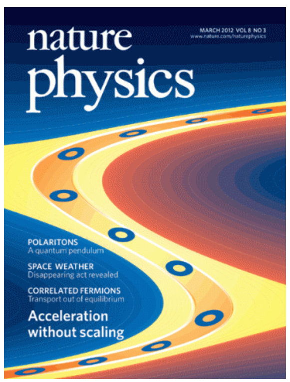


- Double-helix SC coils create each multipole component.



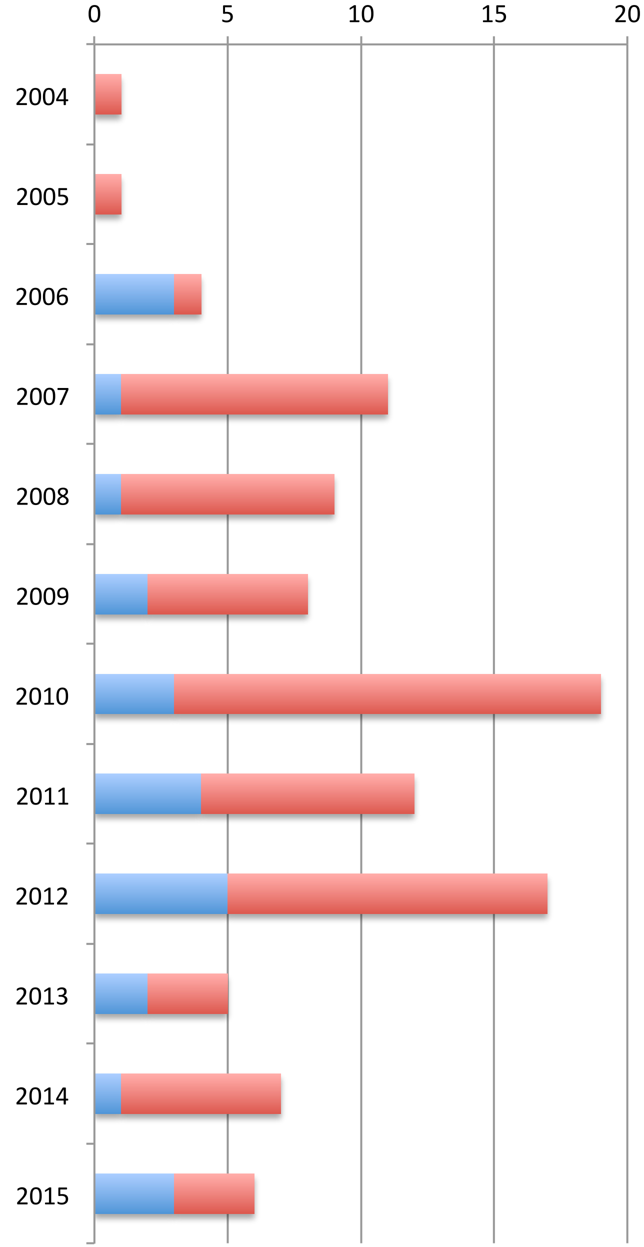
CONFORM project 2007

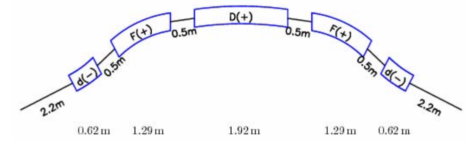
FFAG08, Manchester University



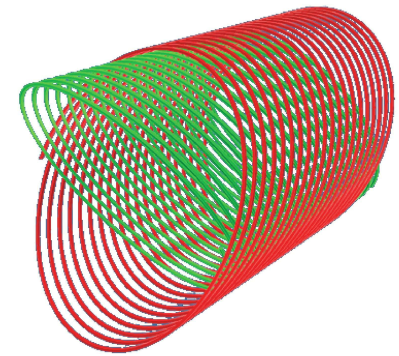
EMMA experiments 2010-2012

KURRI collaboration (2012-)





G. Rees "pumplet"



PAMELA CDR (2012)

FFAG11, Trinity College Oxford

IDS-NF IDR (2011)

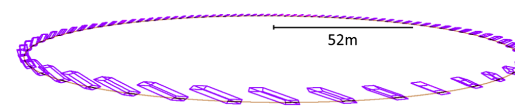


FIG. 8. Perspective view of the 12 GeV ring.

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).

Summary

- Since around the turn of the century FFAG designs to meet various applications have proliferated in recent years (scaling and non-scaling).
- We must build on these developments and continue to produce advances in accelerator physics.
- There is plenty of scope for further innovation in FFAG design.