FFAG Accelerators

CERN Specialised Accelerator School
on Accelerators for Medical Applicatons

Vosendorf, Austria, June 2015

Dr. Suzie Sheehy
University of Oxford and ASTeC/STFC/RAL

‘Fixed Field Alternating Gradient’ Accelerators

1. Another type of accelerator?
2. What is an FFAG?
   - Are FFAGs like a synchrotron or cyclotron?
   - Fixed field magnets
   - The “non-scaling” FFAG
   - Beam dynamics issues
   - The “scaling” FFAG
3. Designs for hadron therapy:
   - RACCAM project
   - The PAMELA project + `NORMA’
   - FFAG gantries

Another type of accelerator?

'Modern' Proton/ion therapy has seemingly conflicting requirements for the accelerator:

Size & cost

Rapid variable energy

Easy to operate & reliable

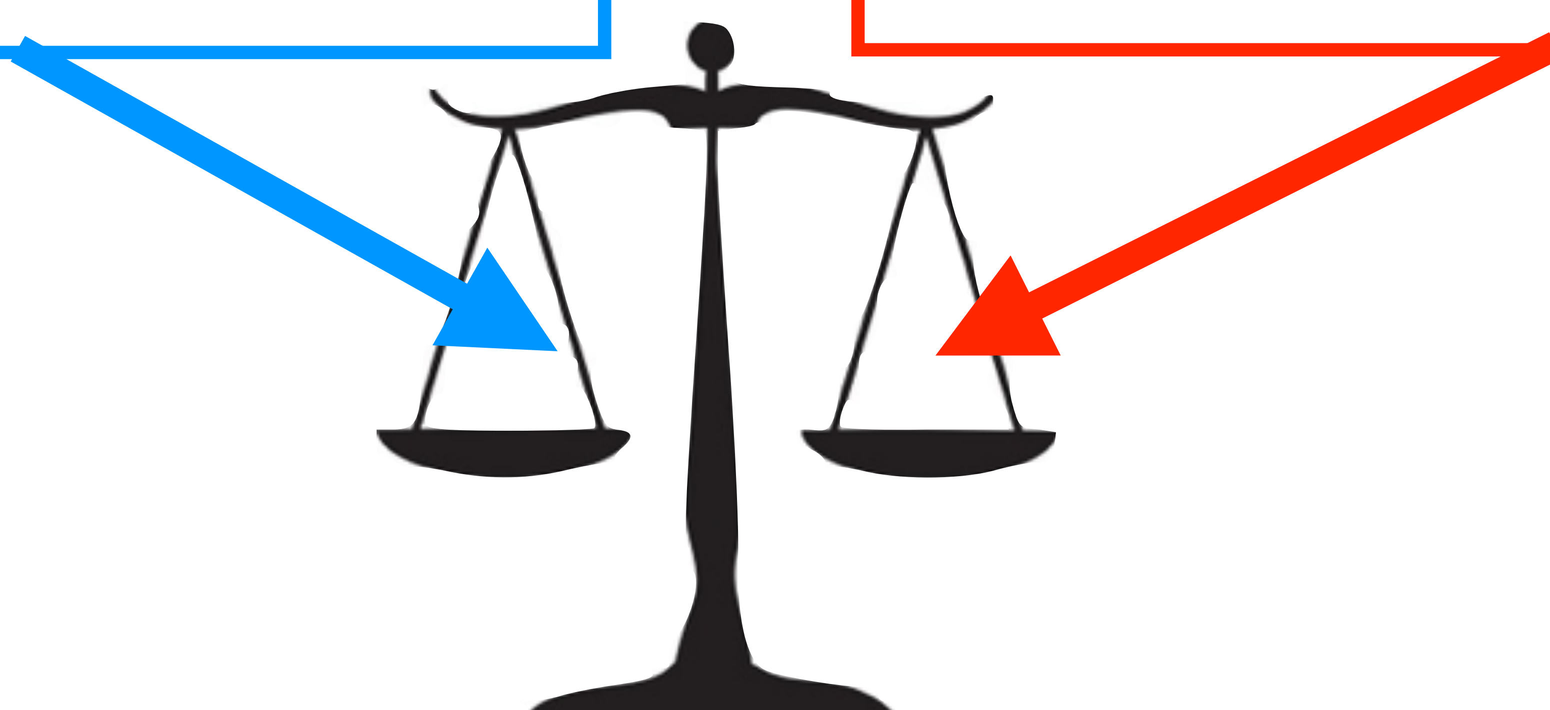
Relatively low intensity

Ability to deliver best treatment

Large range of energies

Precision required

Variation of intensity required



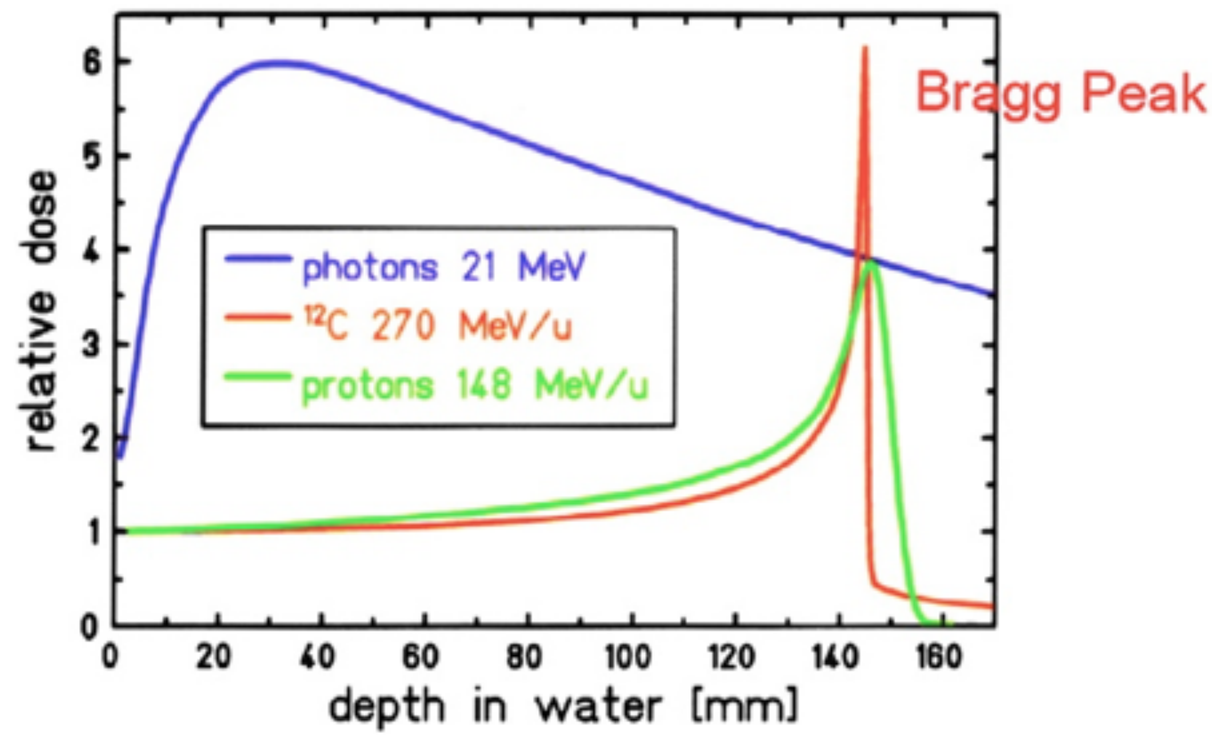
Another type of accelerator?

- Additional challenges still to be met:

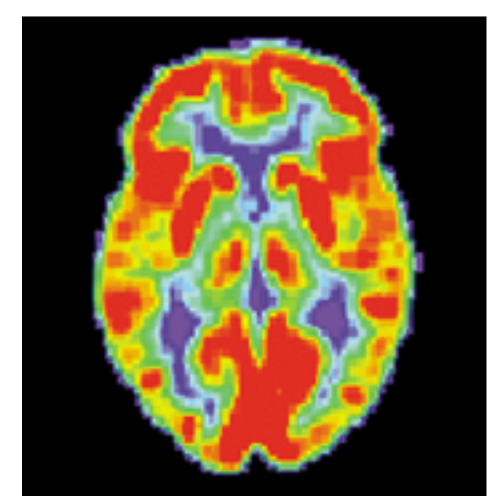
Image: GSI Heidelberg

How can we make smaller/ lighter/cheaper gantries?

- Particle species variation
- Online proton radiography



High intensity, compact sources for radioisotope production



‘Fixed Field Alternating Gradient’ Accelerators

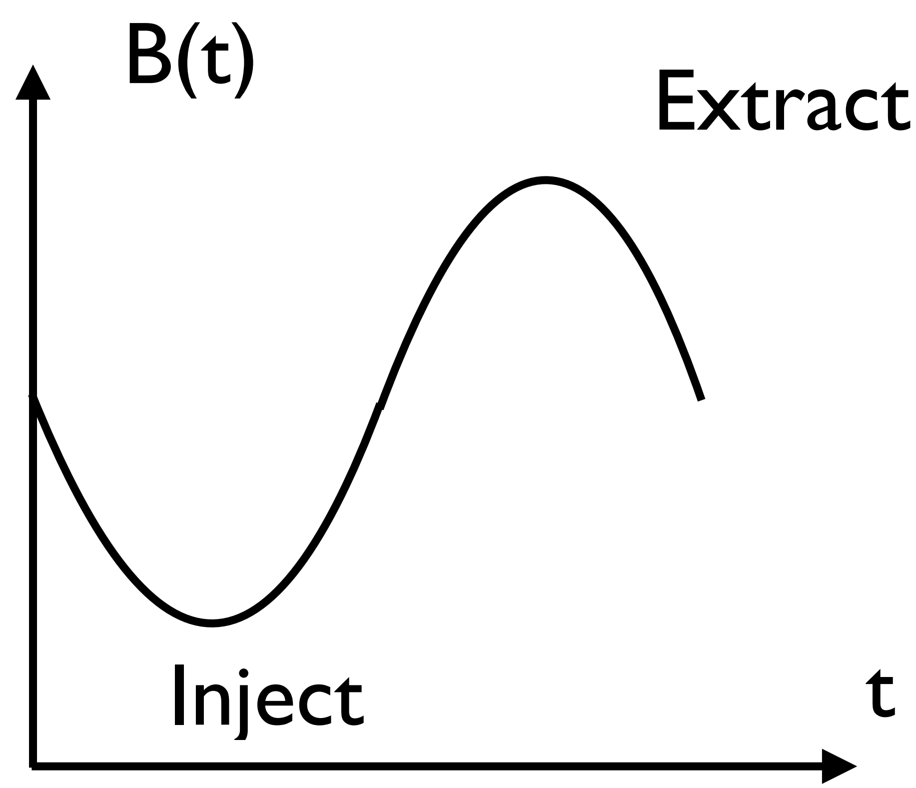
1. Another type of accelerator?
2. What is an FFAG?
    - Are FFAGs like a synchrotron or cyclotron?
    - Fixed field magnets
    - The “non-scaling” FFAG
    - Beam dynamics issues
    - The “scaling” FFAG
3. Designs for hadron therapy:
    - RACCAM project
    - The PAMELA project + `NORMA’
    - FFAG gantries

“Particles should be constrained to move in a circle of constant radius thus enabling the use of an annular ring of magnetic field …

which would be varied in such a way that the radius of curvature remains constant as the particles gain energy through successive accelerations.”

- Marcus Oliphant, 1943

Is an FFAG like a synchrotron? (1)



Synchrotron magnet cycle

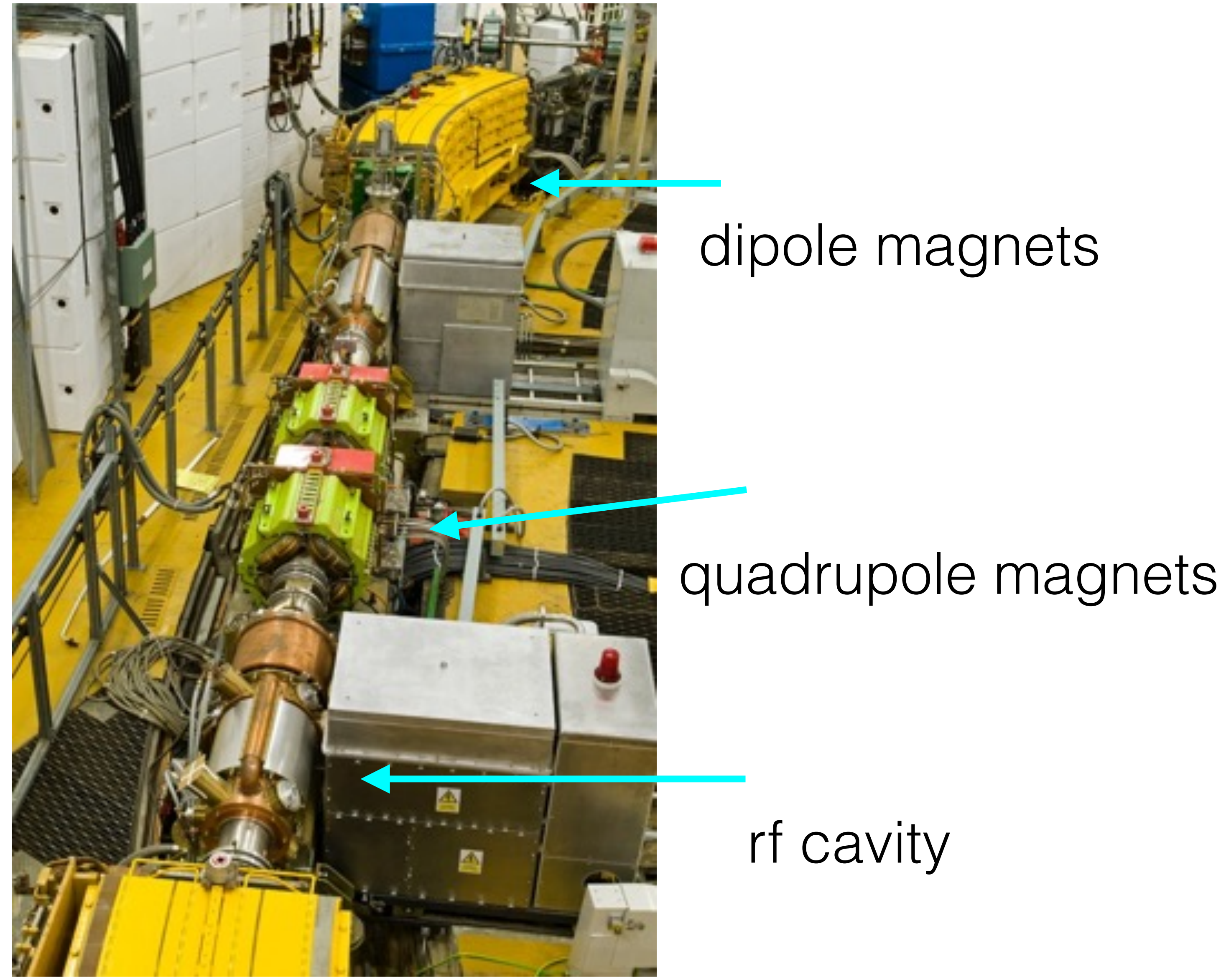
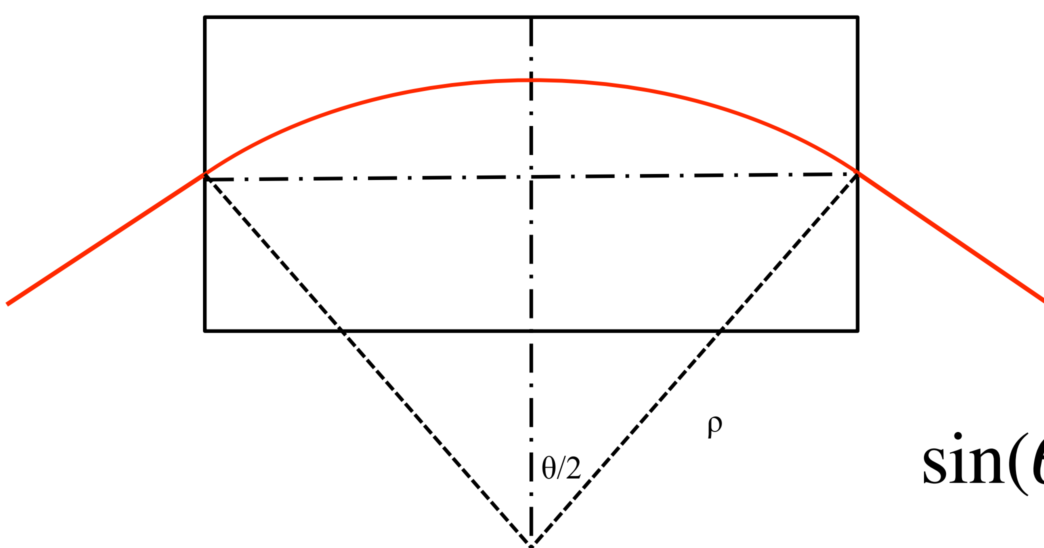


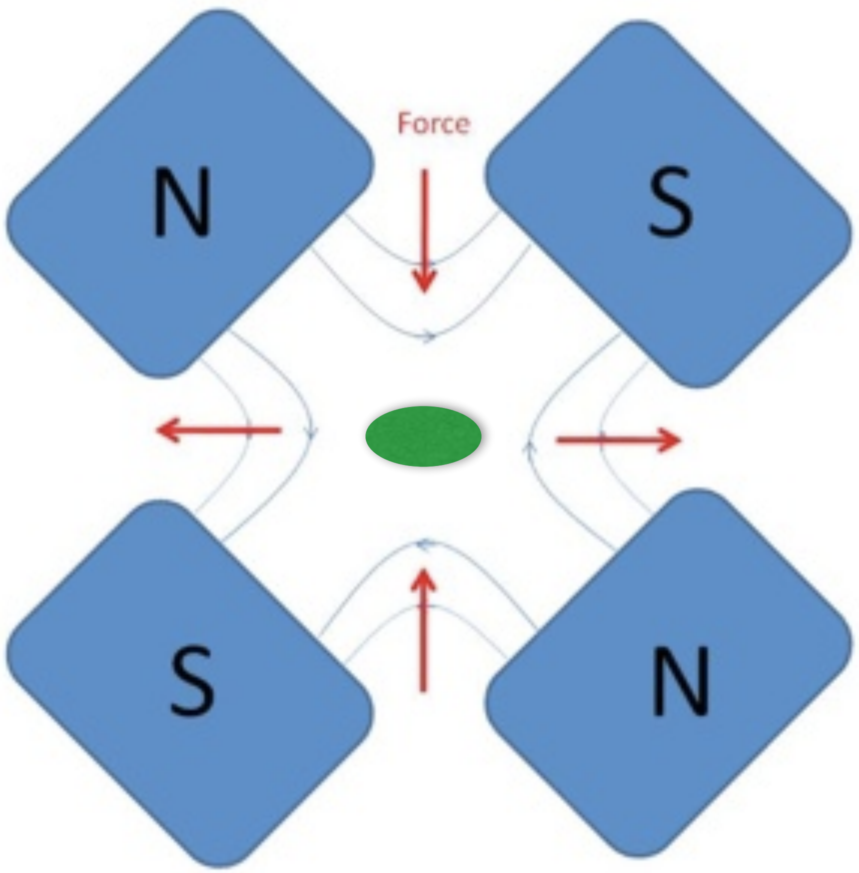
Image courtesy of ISIS, STFC

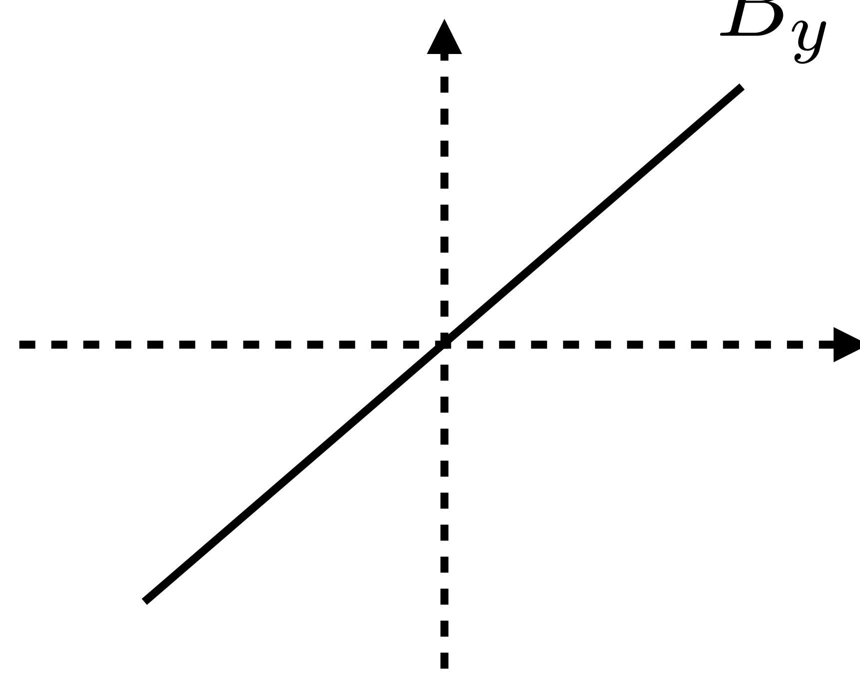


Bending angle in dipole magnet

$$\sin(\theta/2) = \frac{B(t)L}{2(B(t)\rho)} \qquad \theta \approx \frac{B(t)L}{p(t)/q}$$

Is an FFAG like a synchrotron? (2)





$$k = \frac{g}{p/q}$$

'normalised gradient' of quad

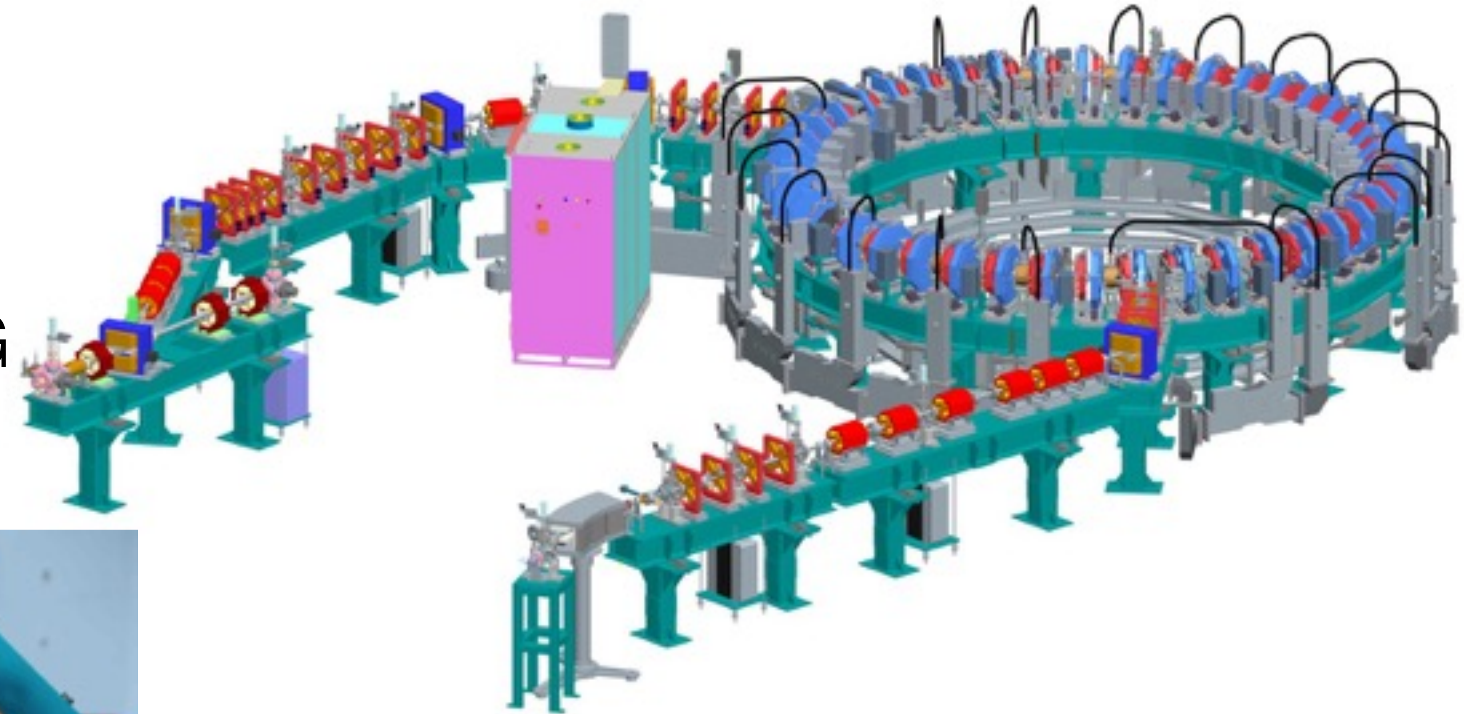
$$\frac{1}{f} = \frac{L(dB(t)/dx)}{p(t)/q}$$

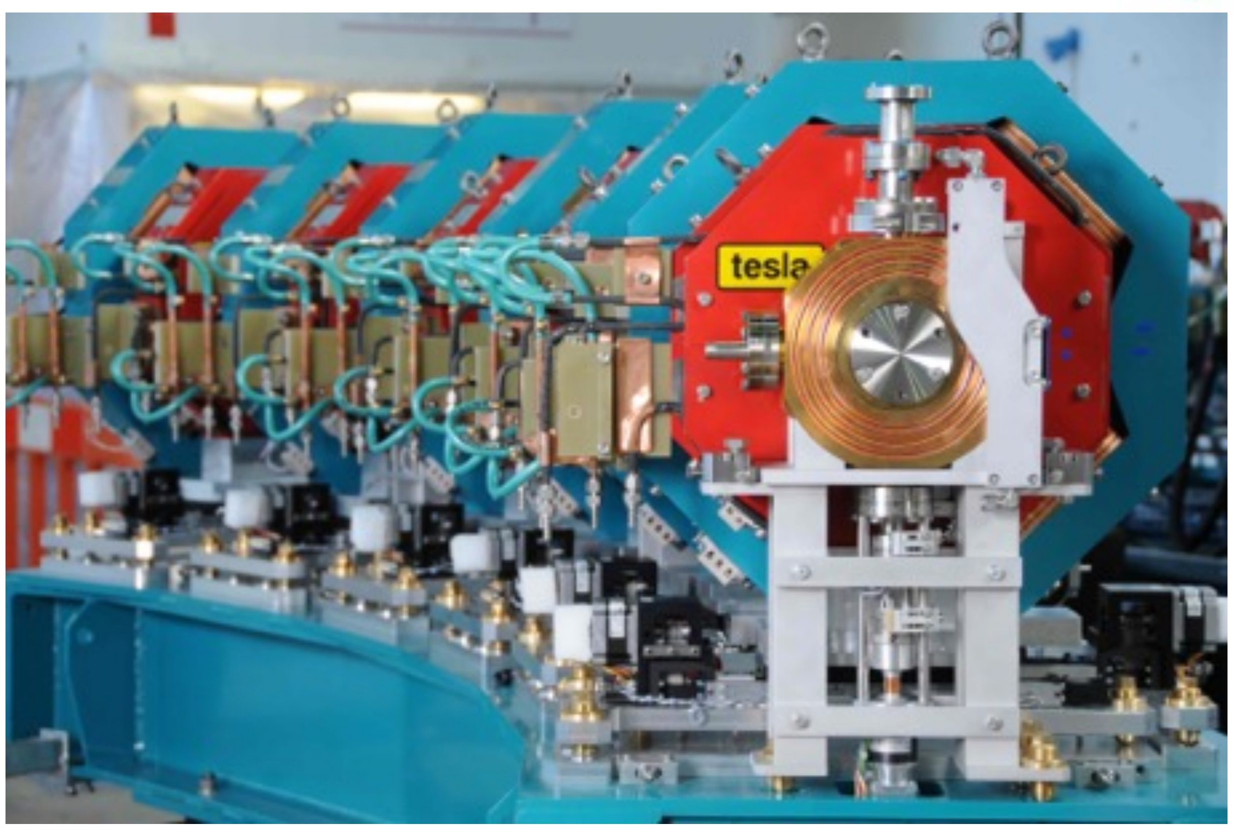
The ‘EMMA’ accelerator

42 Quadrupole doublets

10-20 MeV e-

Demonstrates ‘non-scaling’ FFAG



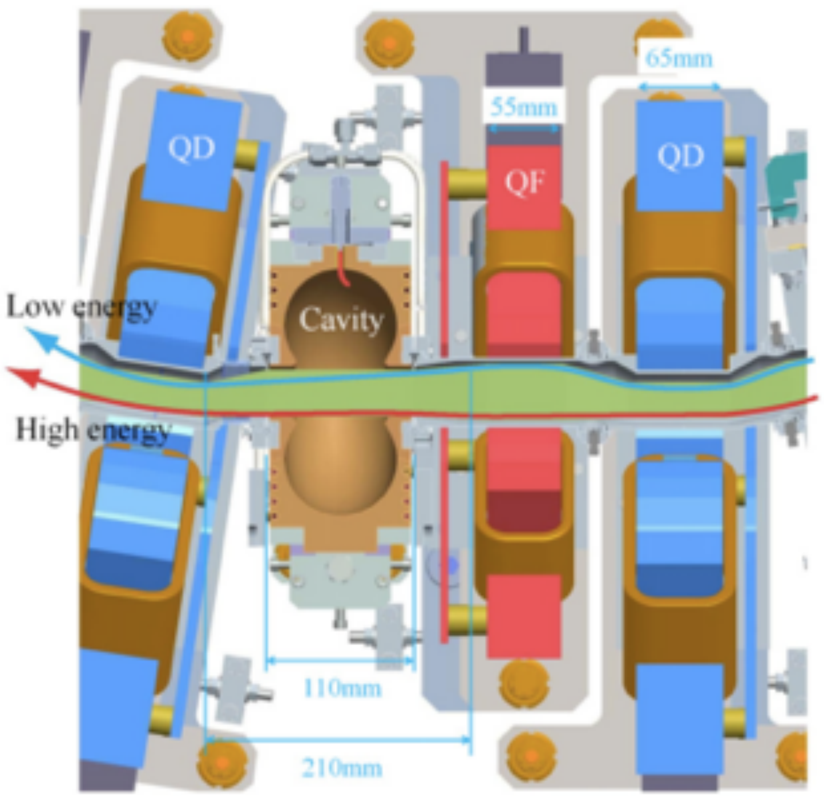


‘Electron Model for Many Applications’
= EMMA

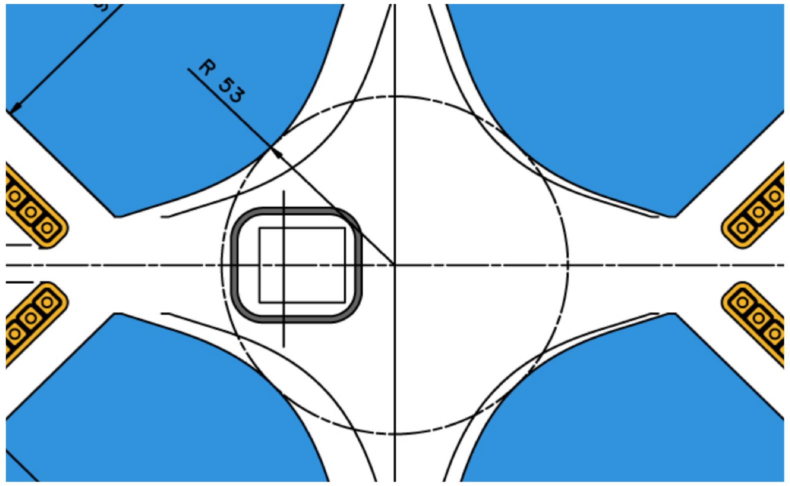
Built and commissioned at STFC
Daresbury Laboratory, UK

EMMA doesn't ramp the B field with time

'Fixed Field Alternating Gradient' = FFAG



Quadrupole with radial offset creates bending component



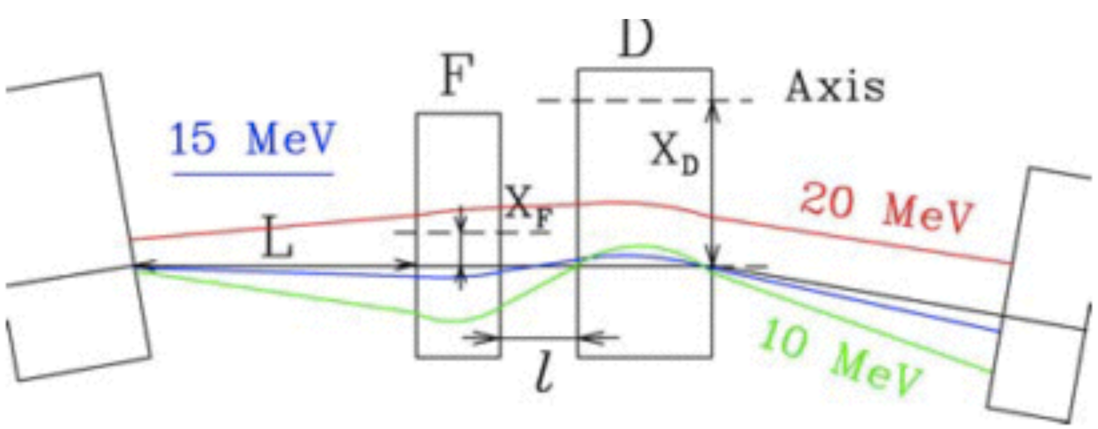


Figure 2: Orbits in a quadrupole doublet cell.

M. Craddock, PAC'07

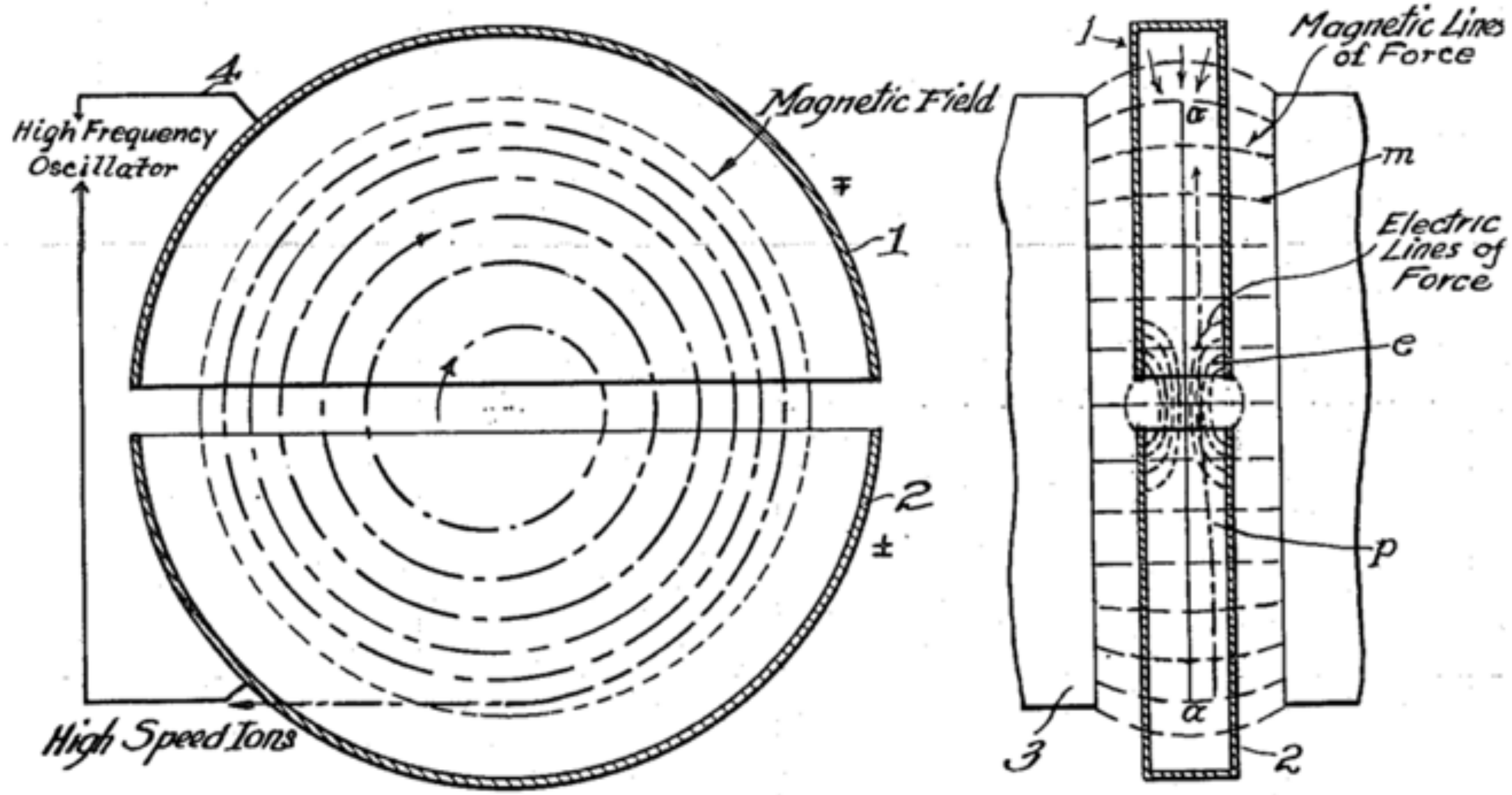
Note: this is just like a 'combined function' magnet

Fixed-field magnets have advantages

- Simple power supplies and no synchronisation issues
- You can accelerate very quickly (as fast as your RF allows…)
    - in EMMA and in muon FFAGs this is ~10 turns
- Higher repetition rate, so higher average current.

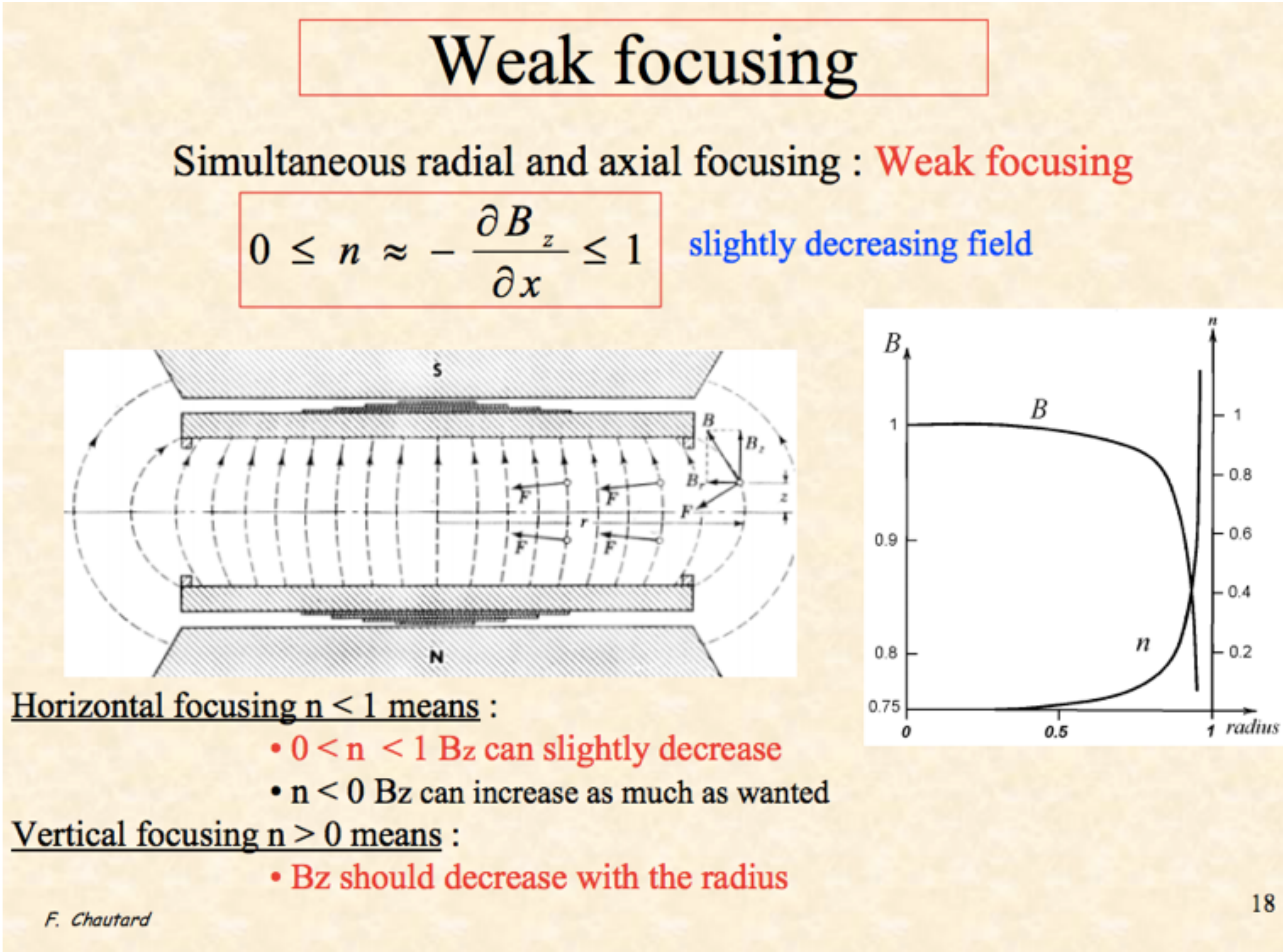
Is an FFAG like a cyclotron? (1)

It has fixed field magnets too



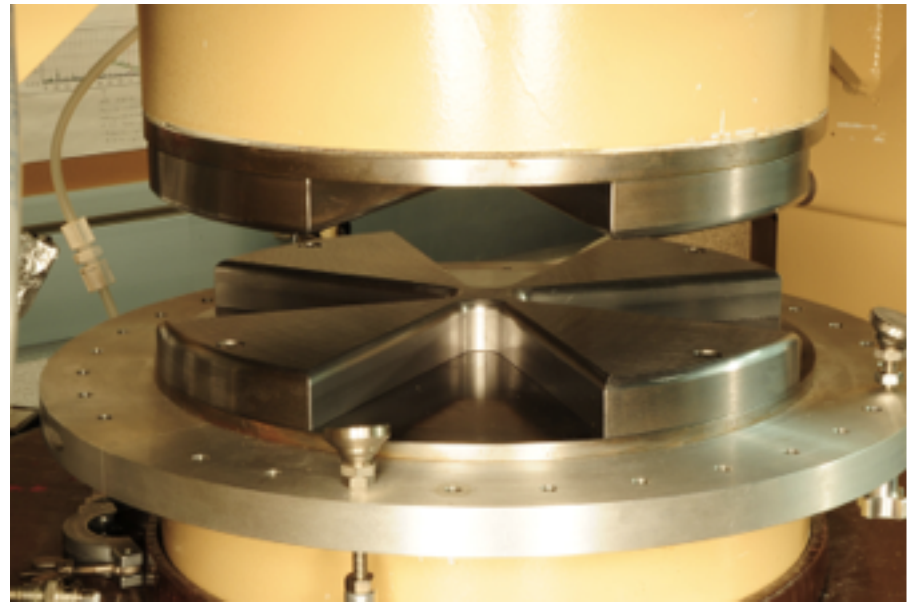
The particles spiral outward as they gain energy

Is an FFAG like a cyclotron? (2)



Slide source: F. Chautard, 2012 CAS

Is an FFAG like a cyclotron? (3)



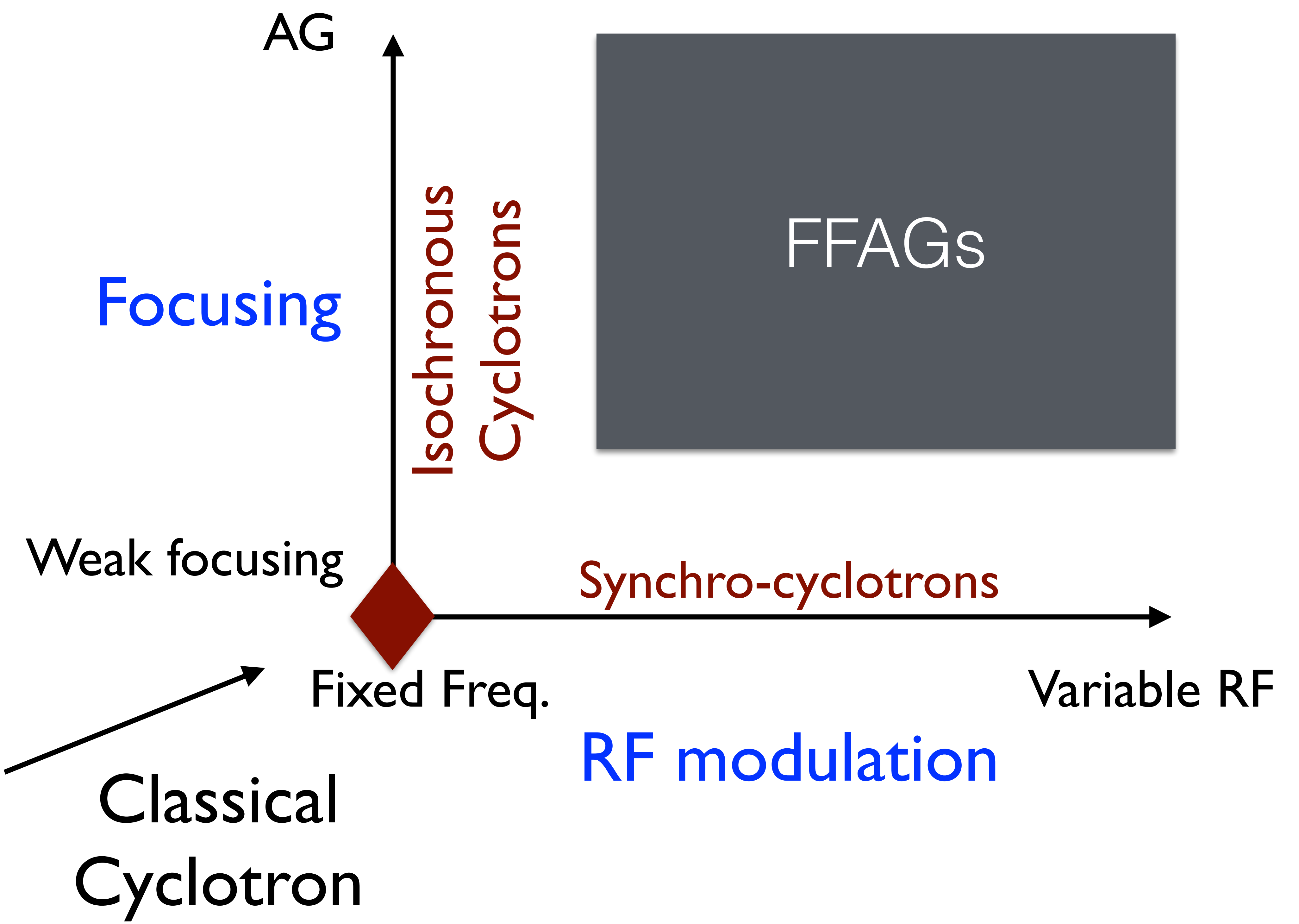
What about the AVF cyclotron?

You may have heard of ‘flutter’ in an AVF cyclotron

An FFAG has a flutter so large that the field *reverses sign* between ‘hills’ and ‘valleys’.

In the AVF cyclotron the weak focusing is still important, but in the FFAG the dynamics is controlled by the strong focusing.

The circular fixed-field accelerator family



But that's not the whole story…

- So an FFAG is like a synchrotron but with fixed-field magnets

- OR like a cyclotron with a field gradient and strong focusing, (and variable RF frequency**)

But that's not all there is to it…

**FFAGs do not always have variable RF frequency…

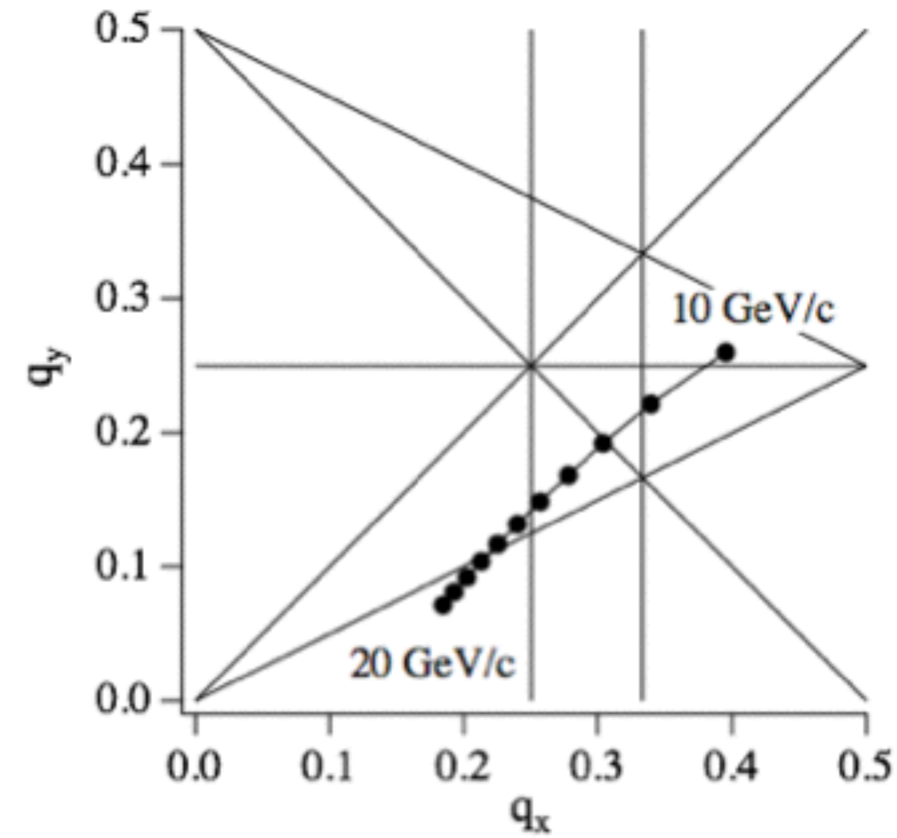
‘Fixed Field Alternating Gradient’ Accelerators

1. Another type of accelerator?
2. What is an FFAG?
    - Are FFAGs like a synchrotron or cyclotron?
    - Fixed field magnets
    - The “non-scaling” FFAG
    - <u>Beam dynamics issues</u>
    - The “scaling” FFAG
3. Designs for hadron therapy:
    - RACCAM project
    - The PAMELA project + `NORMA’
    - FFAG gantries

Circular Accelerators

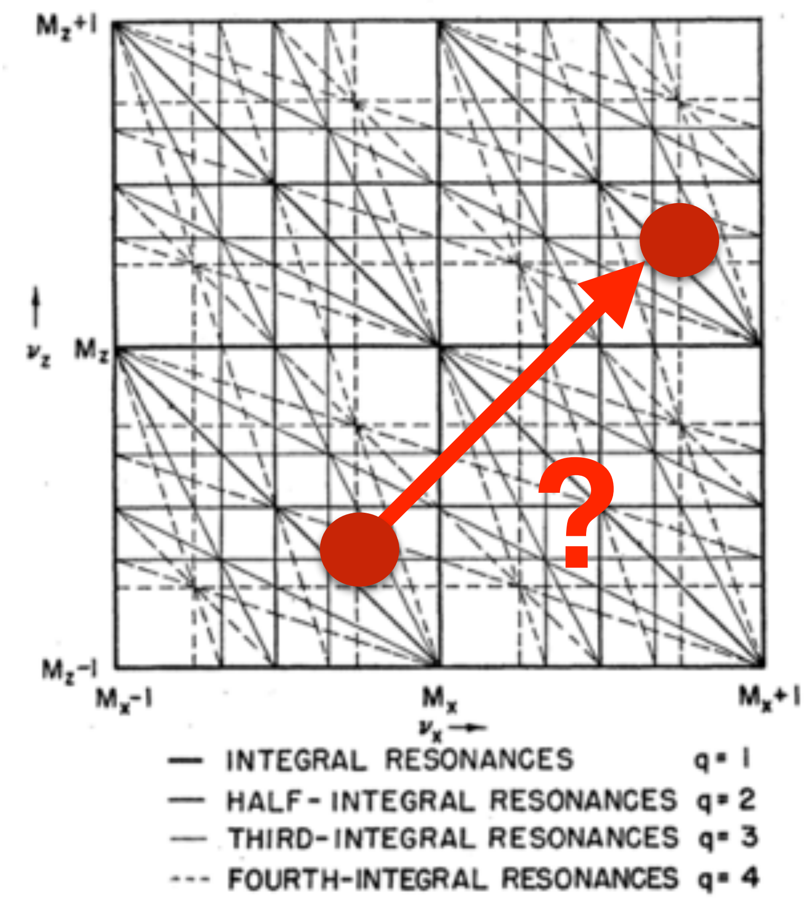
	Cyclotron	Synchrotron	FFAG
Revolution time	Constant	Variable (except relativistic)	Variable
Orbit radius	Variable	Constant	Variable
Transverse focusing	Variable	Constant	Variable

What does variable focusing mean?



- In a synchrotron the tune is fixed away from resonance lines
- But in an FFAG, the betatron tunes can vary…

Resonance crossing

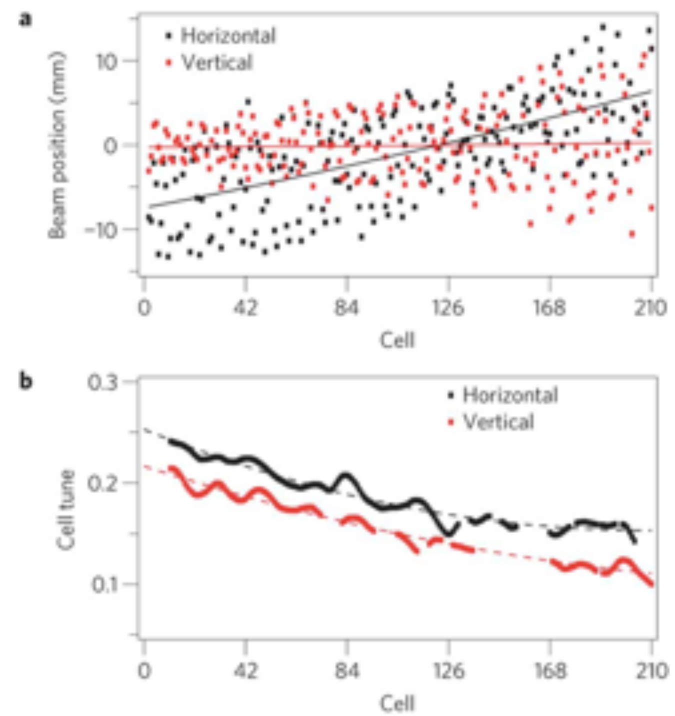


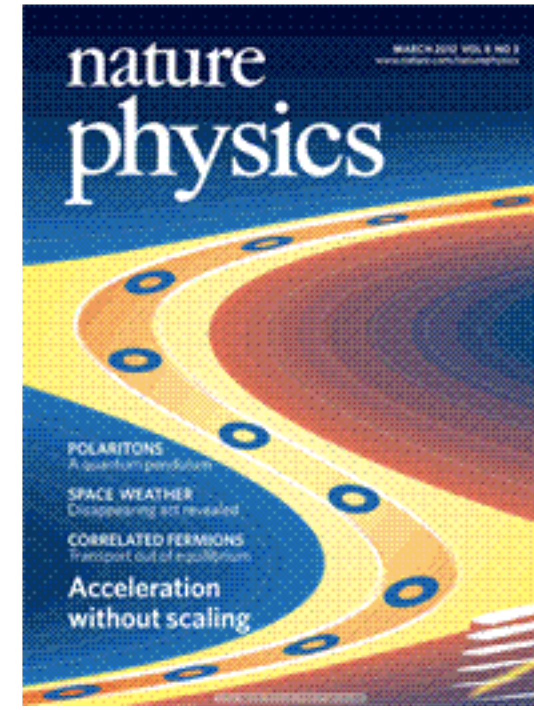
$$n\nu_x + m\nu_y = 0,1,2...$$

- There are many resonance lines in tune space
- Normally, particles would be lost on resonance, but if the resonance is <u>weak</u> and the crossing is <u>fast</u> the beam can survive.

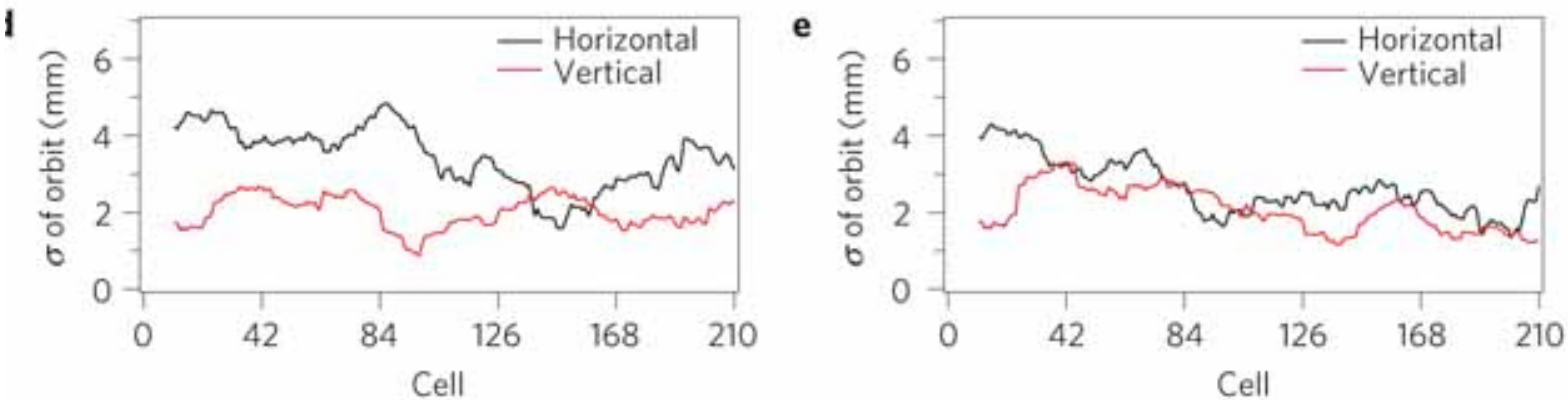
Results from EMMA

Orbit and tune shift with momentum





No beam 'blowup' despite resonance crossing



S. Machida et. al., Nature Physics 8, 243–247 (2012)

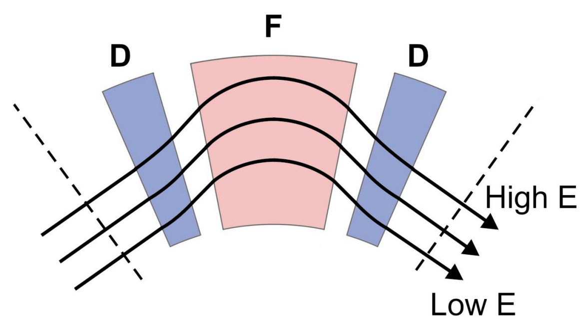
But that's not the whole story…

- Electrons & muons are easy to accelerate quickly, but for hadrons it's harder…
- If resonance crossing could be harmful for hadron FFAGs, what can we do to fix it?
    - In a synchrotron, we call off-momentum tune variation "chromaticity", can we correct it?
- Can we have stable tunes in an FFAG?

Scaling FFAG

The orbits are made 'similar'

$$\left.\frac{\partial}{\partial p}\left(\frac{\rho}{\rho_0}\right)\right|_{\theta=const.} = 0$$



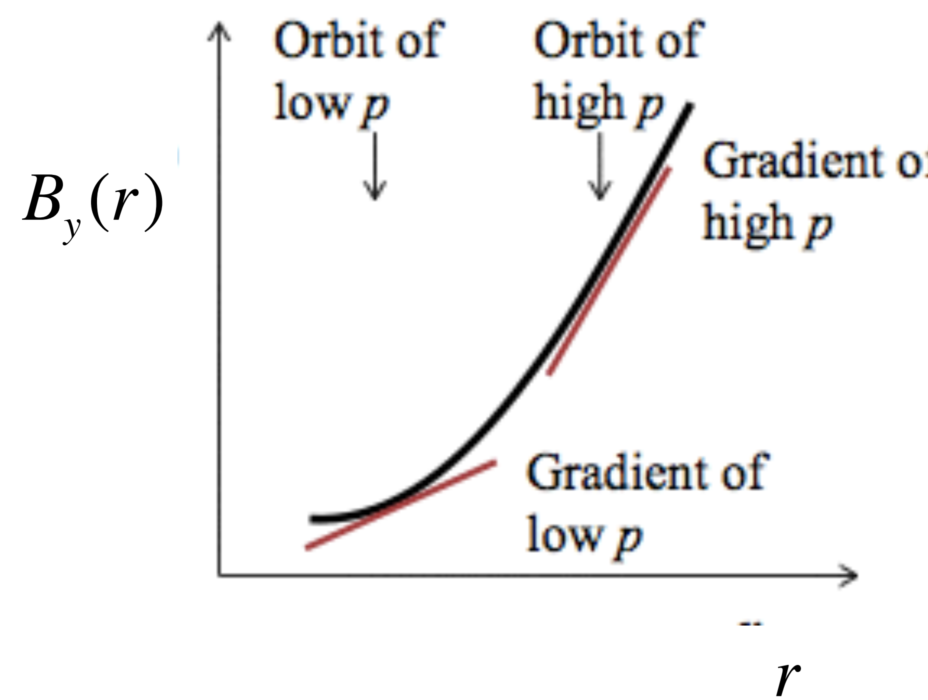
ρ_0 Average bending radius

ρ Local bending radius

θ Generalised azimuth

The 'field index' is constant

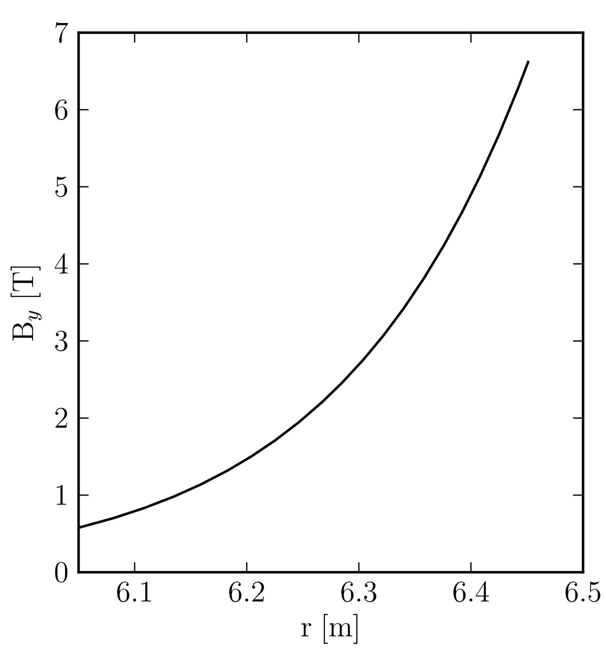
$$\left.\frac{\partial k}{\partial p}\right|_{\theta=const.} = 0 \qquad k = \frac{r}{B}\left(\frac{\partial B}{\partial r}\right)$$



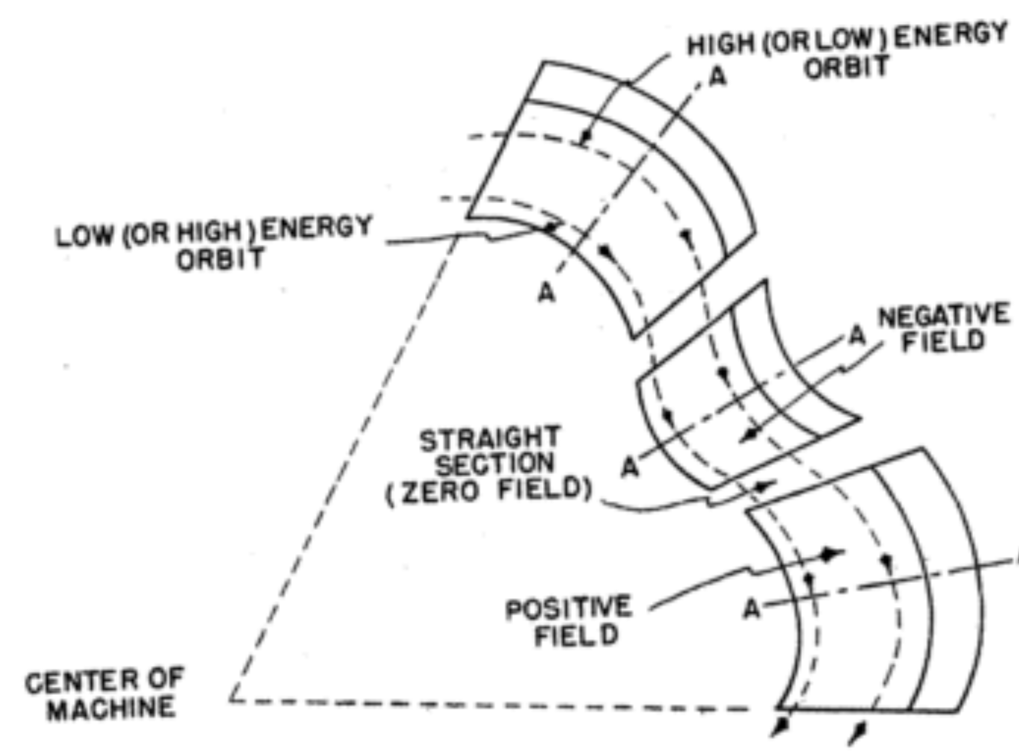
- In fact, the first FFAGs had constant tunes and were designed not to cross resonances, we call them 'scaling' FFAGs

Scaling FFAG

- If the field profile is of this form, the 'cardinal conditions' are satisfied.
- We call this type of FFAG a 'scaling' type.
- Alternating magnets have opposite bending fields



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

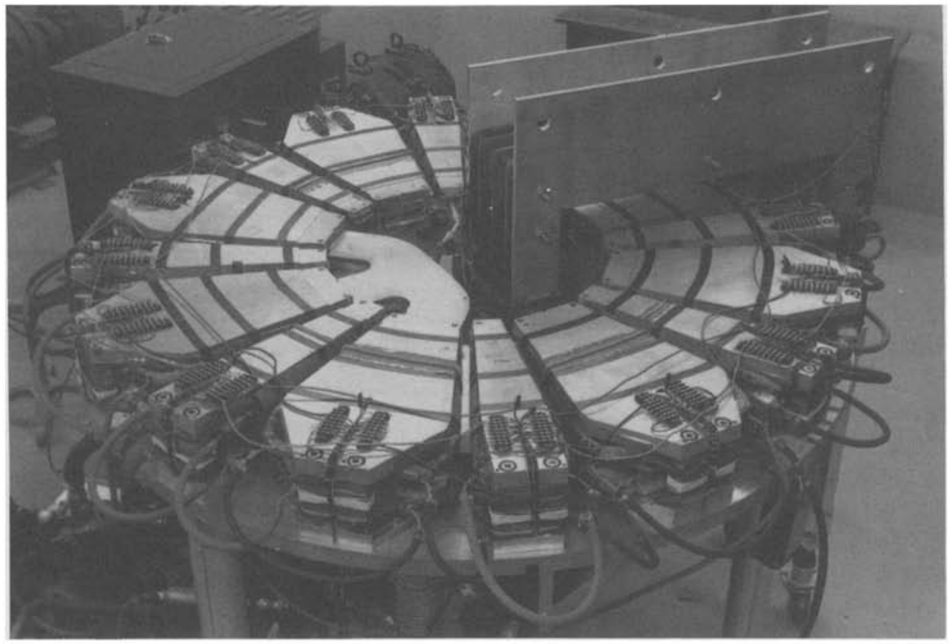


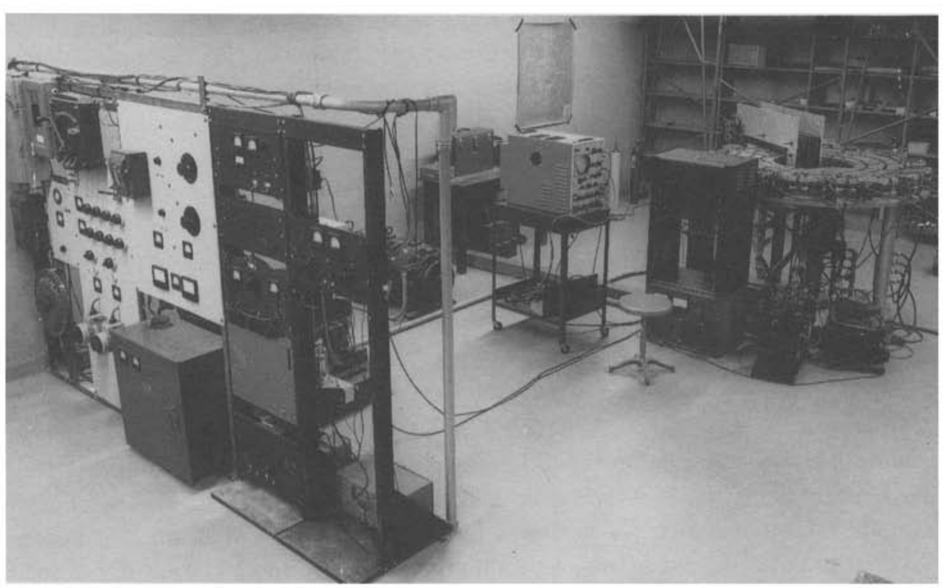
Note that this field profile does NOT satisfy isochronicity (see cyclotron lecture)

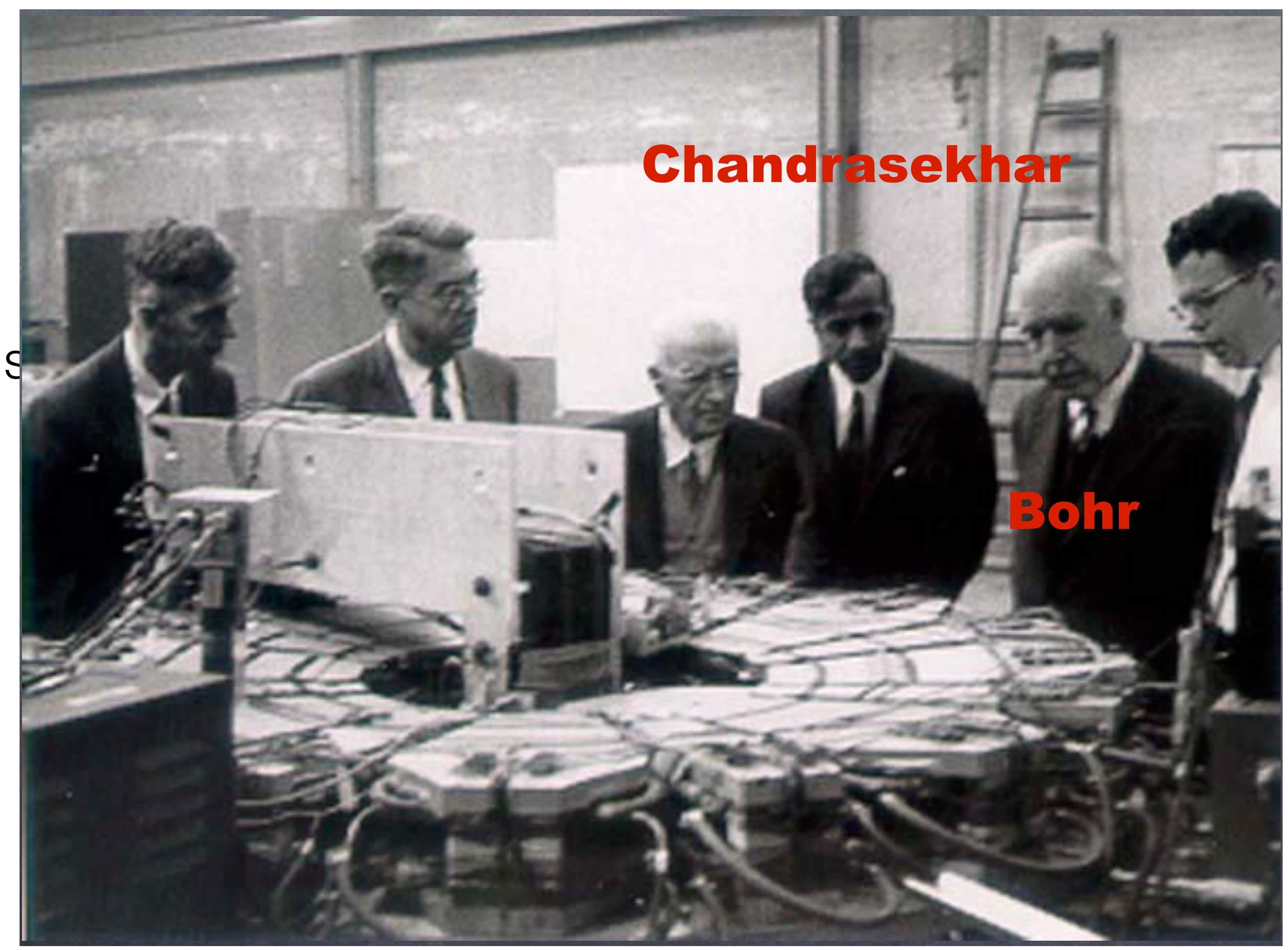
$$\omega = \frac{eB}{m\gamma} \neq const.$$

The FFAG is not so new…

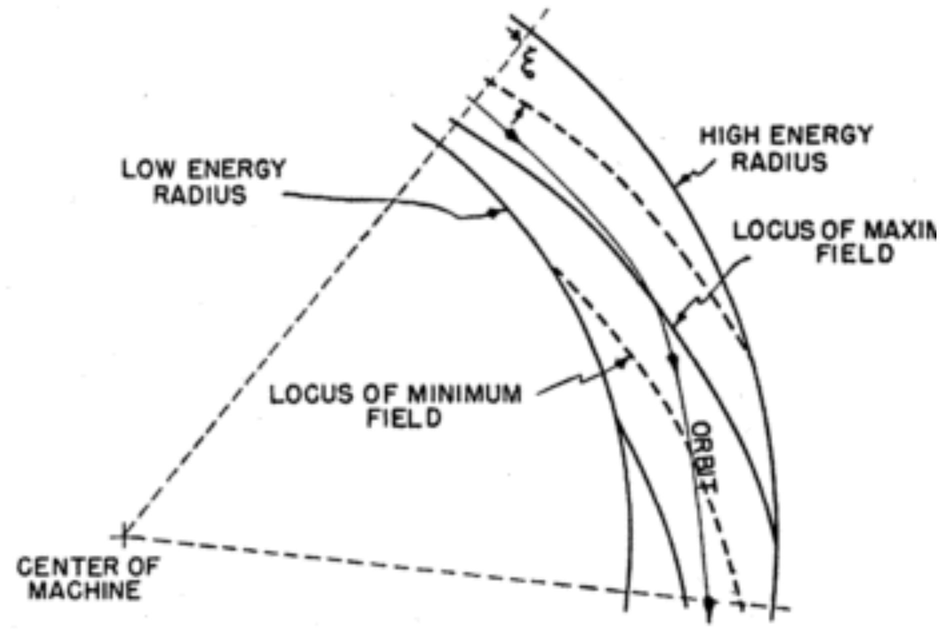
1956







Scaling FFAG types



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

$$F(\vartheta)=F\left(\theta-\tan\zeta\cdot\ln\frac{r}{r_0}\right)$$

Spiral sector type

Spiral angle gives strong edge focusing.

$$\therefore \Delta p_z=\frac{e}{v_x}\int_{-\infty}^{\infty}\left(-v_y B_x\right)dx=-eB_{z0}\tan\zeta\cdot z$$

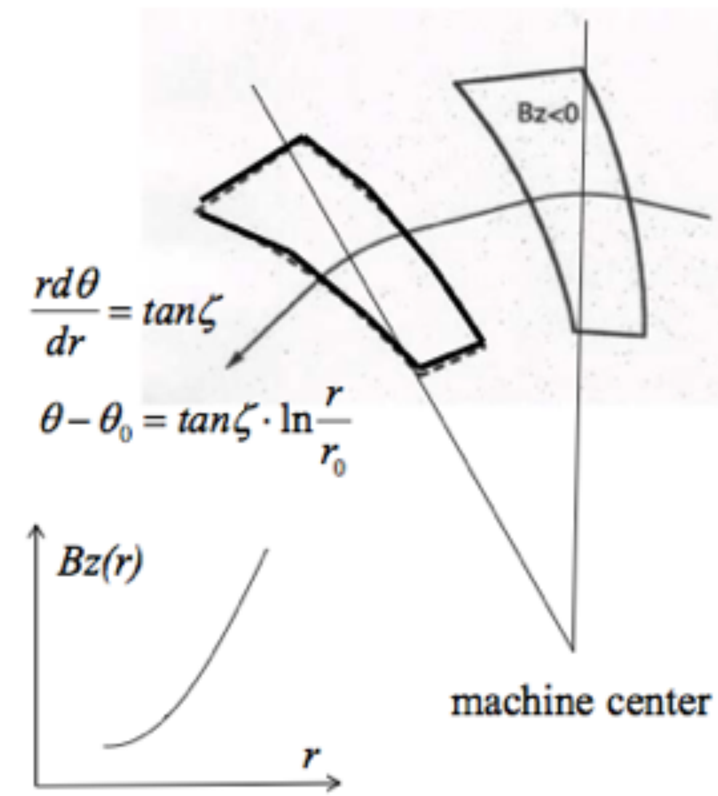


Image source: K. Symon, D. Kerst, L. Jones, L. Laslett, and K. Terwilliger, "Fixed-Field Alternating-Gradient Particle Accelerators," Phys. Rev., vol. 103, no. 6, pp. 1837–1859, Sep. 1956.

S. Machida, CAS 2012

Recent Scaling FFAGs

- In the late 90's and in 2000's, the FFAG idea was re-awakened in Japan,
- Particular focus on hadron FFAGs of scaling type

Proof of Principle machine finished in 1999 at KEK, demonstrated 1kHz rep. rate

3-stage FFAG for ADSR studies

2.5 MeV spiral (ion beta) FFAG with induction cores

25 MeV radial (booster) FFAG with RF

150 MeV radial (main) FFAG with RF

Circular Accelerators

	Cyclotron	Synchrotron	Non-scaling FFAG	Scaling FFAG
Revolution time	Constant	Variable (except relativistic)	Variable (small)	Variable
Orbit radius	Variable	Constant	Variable (small)	Variable
Transverse focusing	Variable	Constant	Variable	Constant

A quick summary so far…

'Scaling' type is a very specific type of FFAG. Anything else is the 'non-scaling' type.

EMMA is a linear non-scaling FFAG, which again is quite specific.

…Are there any other possibilities?

> *"There are other variations of these designs which preserve betatron oscillation stability, hold ν_x and ν_y constant, but do not retain the property of similar of equilibrium orbits."*
>
> *"The magnet edges of focusing and defocusing sectors can be made non-radial, and the fields in positive- and negative- field magnets made different functions of radius"*

- K. Symon, D. Kerst, L. Jones, L. Laslett, and K. Terwilliger, "Fixed-Field Alternating-Gradient Particle Accelerators," Phys. Rev., vol. 103, no. 6, pp. 1837–1859, Sep. 1956.

‘Fixed Field Alternating Gradient’ Accelerators

1. Another type of accelerator?
2. What is an FFAG?
    - Are FFAGs like a synchrotron or cyclotron?
    - Fixed field magnets
    - The “non-scaling” FFAG
    - Beam dynamics issues
    - The “scaling” FFAG
3. Designs for hadron therapy:
    - RACCAM project
    - The PAMELA project + `NORMA’
    - FFAG gantries

Medical FFAG Design Studies

Have been many and varied.
I’ve chosen a few to highlight… but it is a wide topic

RACCAM
Spiral (scaling) FFAG

2006 - 2008 Design Study

150 MeV protons
Magnet designed & built
Many useful studies on optimal throughput of facility etc…

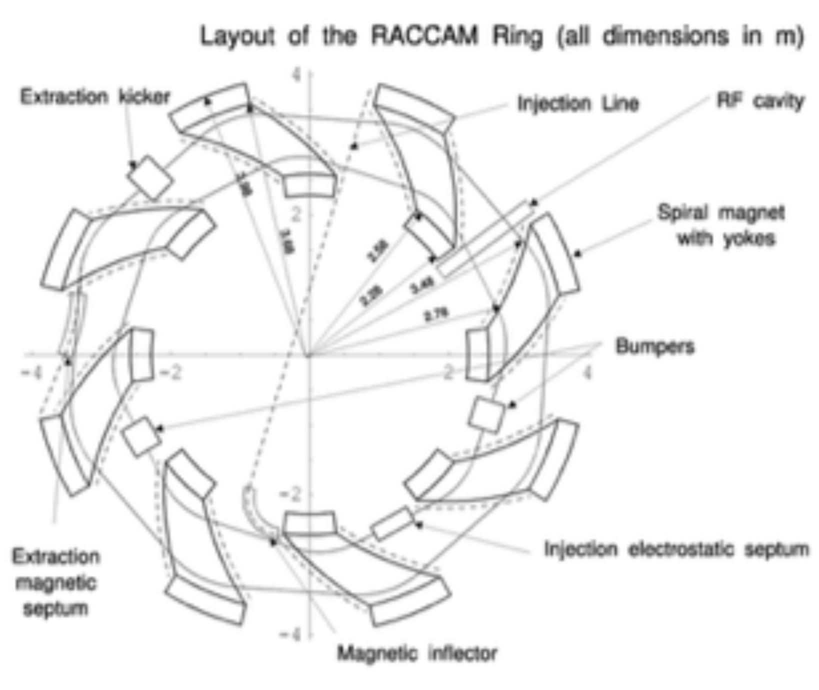
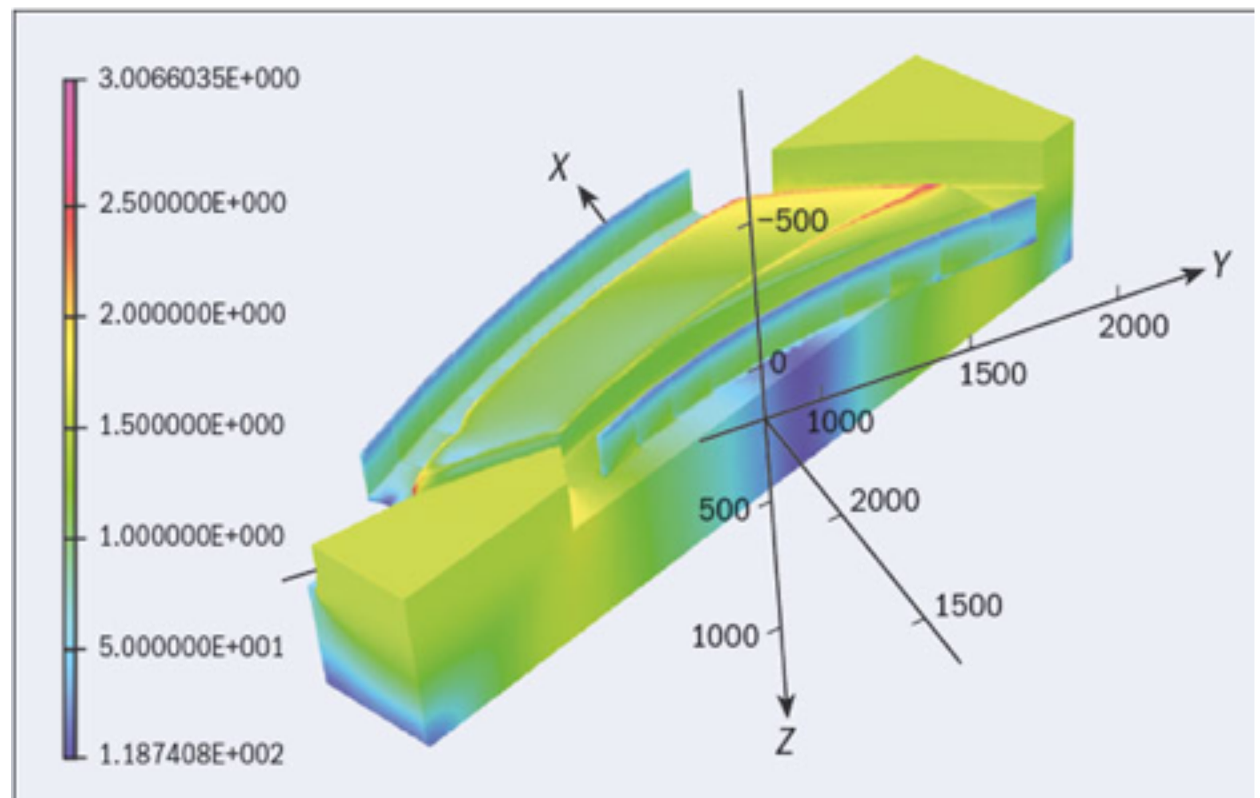


FIGURE 3.



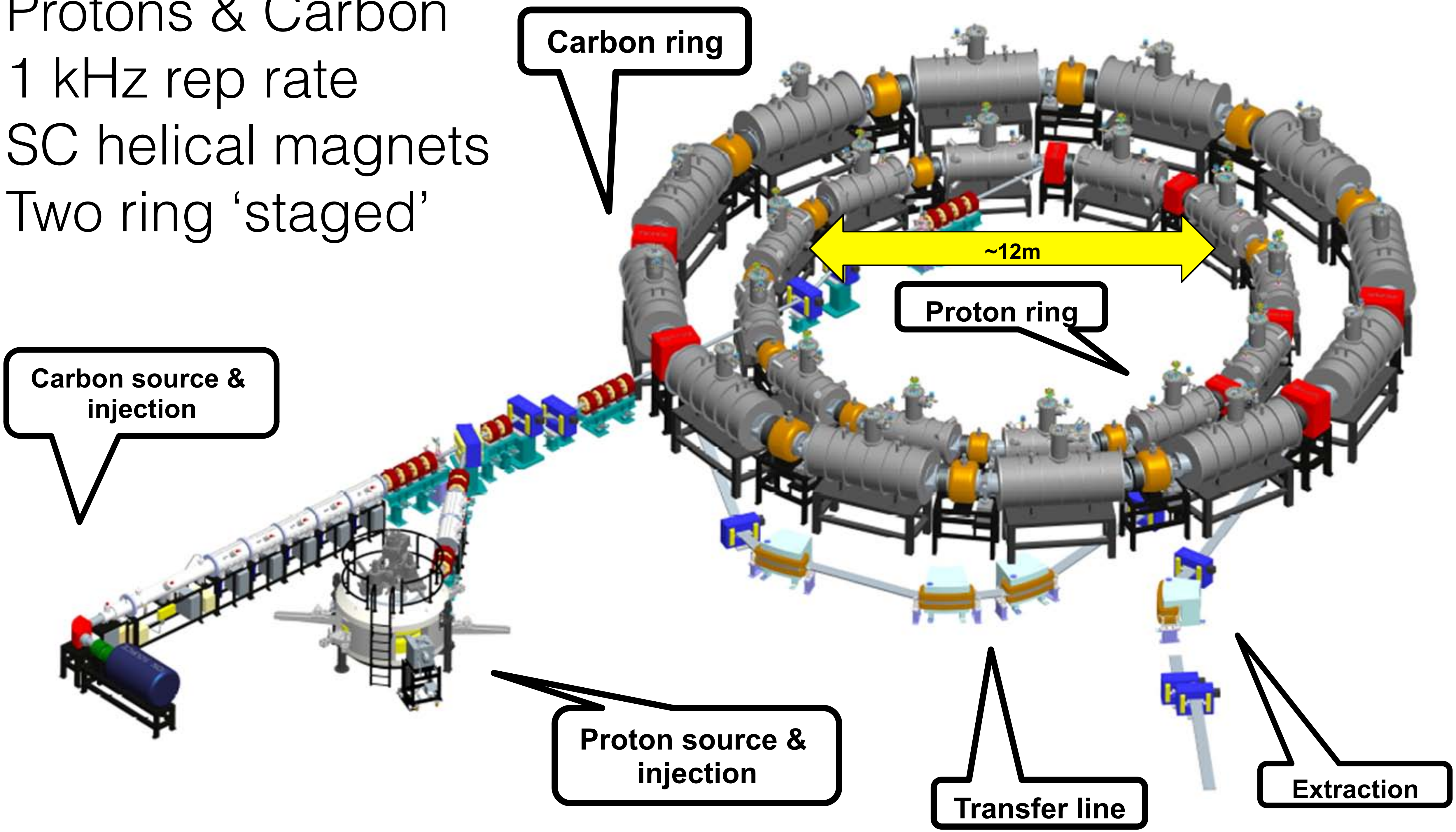
F. Méot, the RACCAM FFAG project, http://dx.doi.org/10.1063/1.2898985

PAMELA

Particle Accelerator for Medical Applications

2007 - 2010 Design Study

Protons & Carbon
1 kHz rep rate
SC helical magnets
Two ring 'staged'

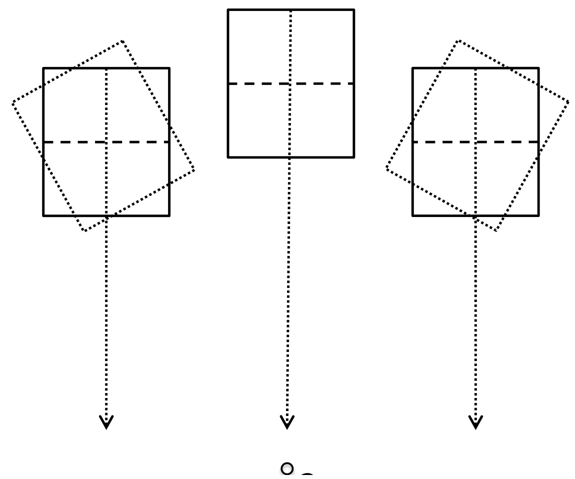


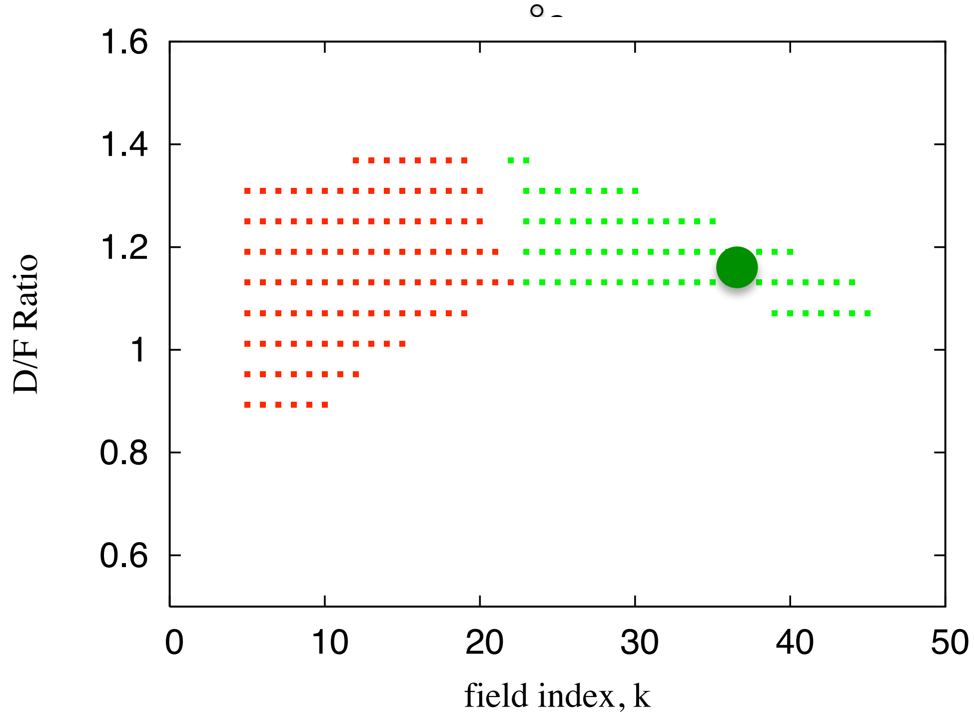
K. J. Peach, et al., Phys. Rev. ST Accel. Beams, vol. 16, no. 3, p. 030101, Mar. 2013.

PAMELA Lattice Concept

Tune-stable non-scaling FFAG designs have been developed

$$B_z = B_{z0}\left(\frac{r_0 + r}{r_0}\right)^k = B_{z0}\left(1 + \sum_{n=1} \frac{1}{n!} \frac{k(k-1)\cdots(k-n+1)}{r_0^n} r^n\right)$$





- Rectangular magnets,
- Simplified field profile
- Higher stability region
- (S. Machida, S. Sheehy)

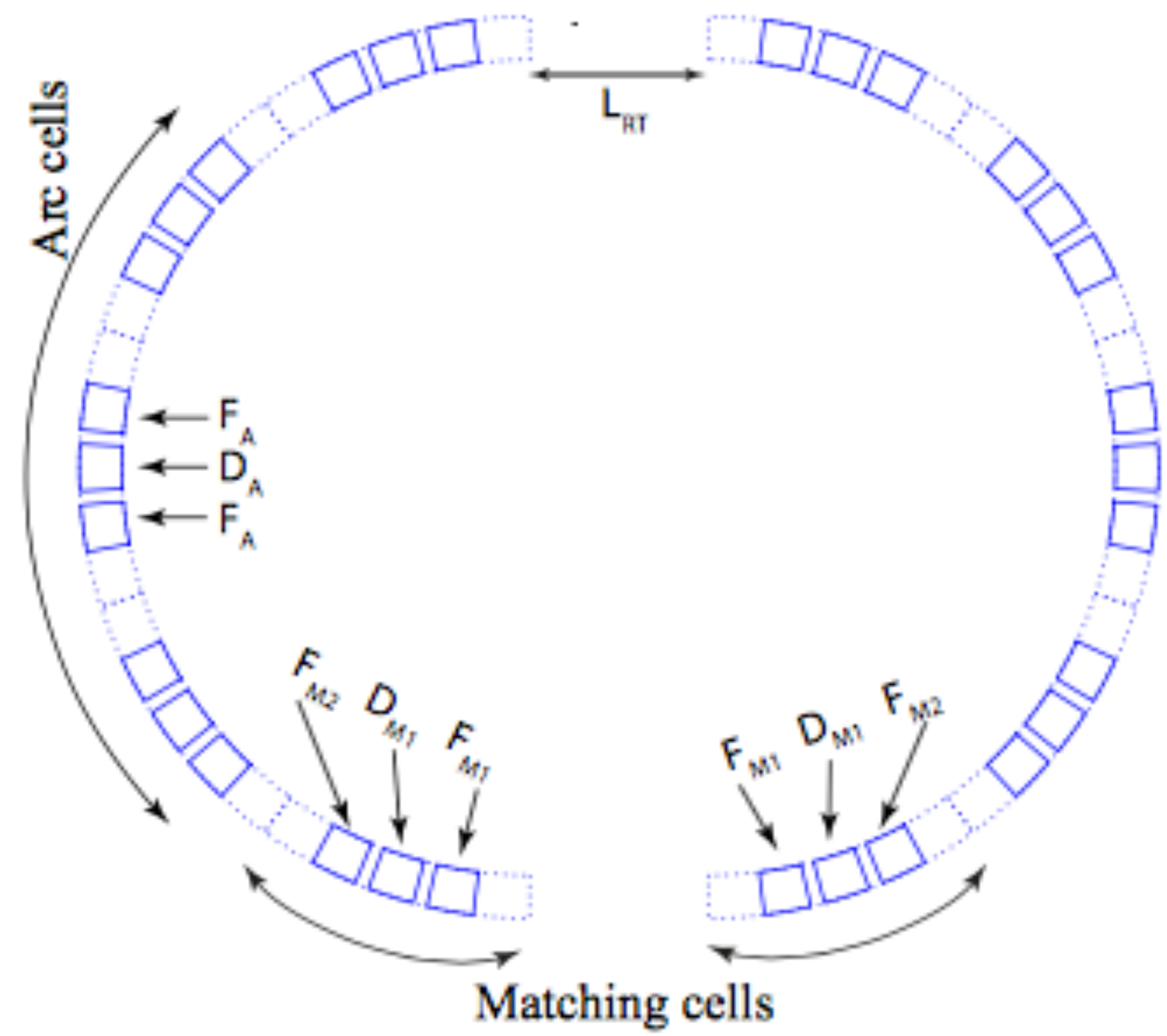
S. L. Sheehy, K. J. Peach, H. Witte, D. J. Kelliher, S. Machida, Fixed field alternating gradient accelerator with small orbit shift and tune excursion, Phys. Rev. ST Accel. Beams, 13, 040101, (2010).

NORMA

Normal Conducting Medical Accelerator

Similar principle to PAMELA, but:

- Compacted cells
- Insert long straights (inj/extr)
- Added matching sections
- Optimised design



J. Garland et al., IPAC 2015, TUPWI021

FFAG Gantries

Image: GSI Heidelberg

Gantries (particularly for Carbon) are:

- Large & heavy (630T total, 135T magnets)
- Expensive
- Slow to vary energy
- BUT required for treatment!

With an FFAG gantry:

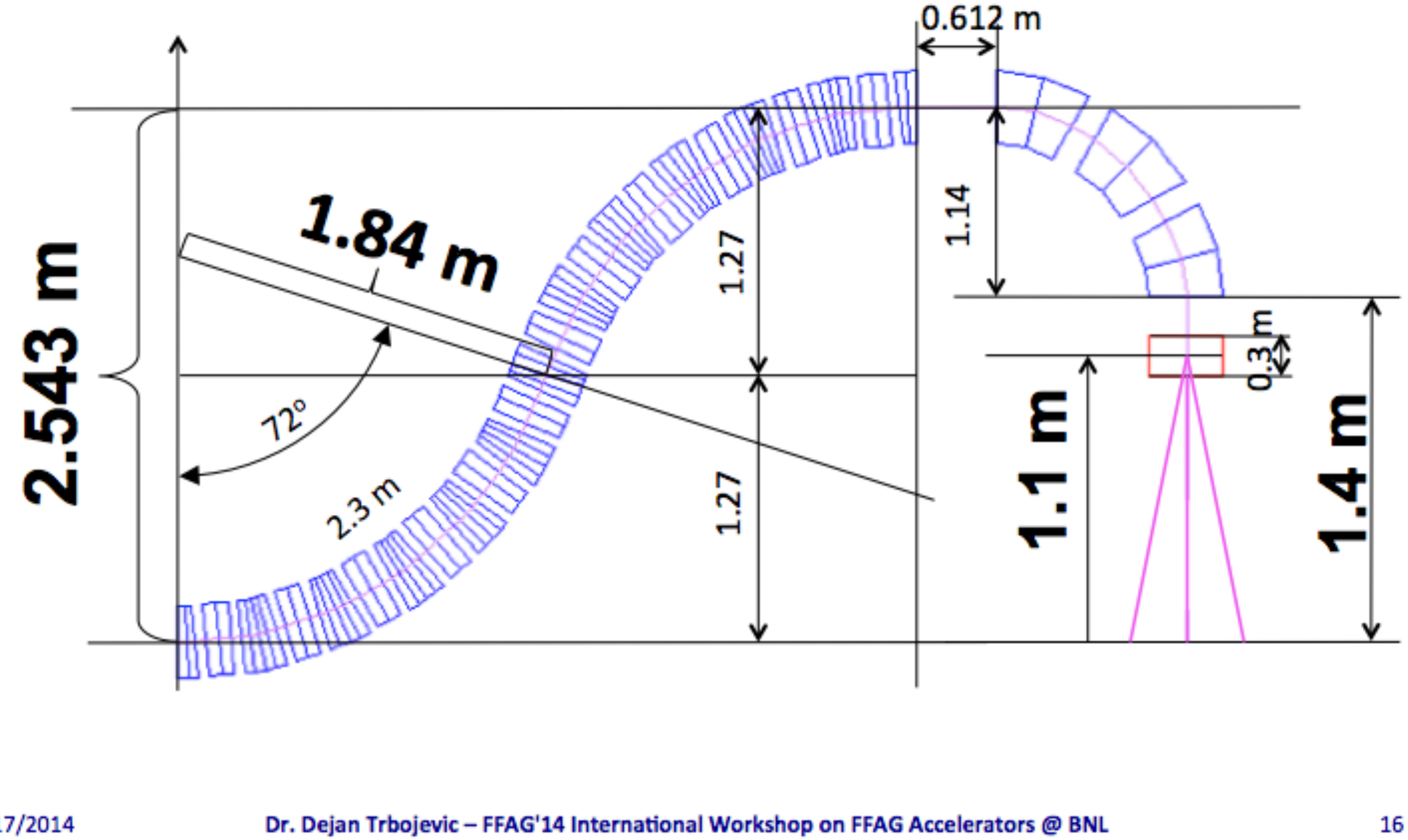
- Large energy acceptance (±50%)
- No limit on rapid variation of energy
- BUT challenging to design?

For other FFAG gantry designs see:

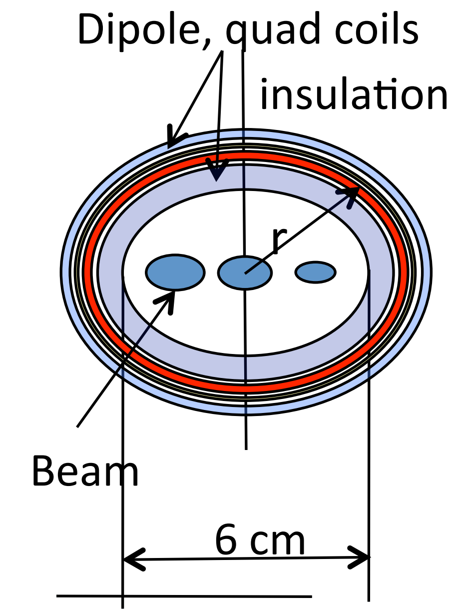
R. Fenning, PAMELA gantry design
J. Pasternak, FFAG'14 workshop

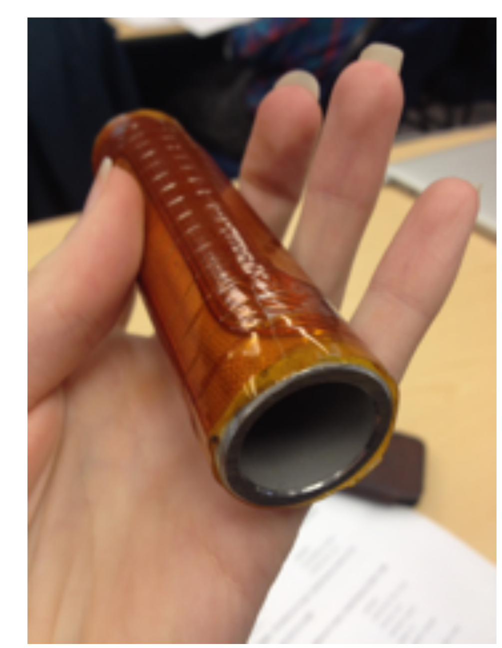
FFAG Gantries

Weight reduction: 135 Tons (HIT) -> 2 Tons (FFAG)



D. Trbojevic, superconducting non-scaling FFAG gantry
Work presented at FFAG workshop 2014, BNL





A prototype magnet made at BNL (hand to scale…)

Summary

- FFAGs are just a generalisation of synchrotrons or cyclotrons
- Two main types ‘scaling’ and ‘non-scaling’
  - Scaling: specific optics and orbit requirements put a strict requirement on the field profile
  - Non-scaling: removes these restrictions, very general type
- FFAGs may be suitable for many future applications, including medical applications

Reading List

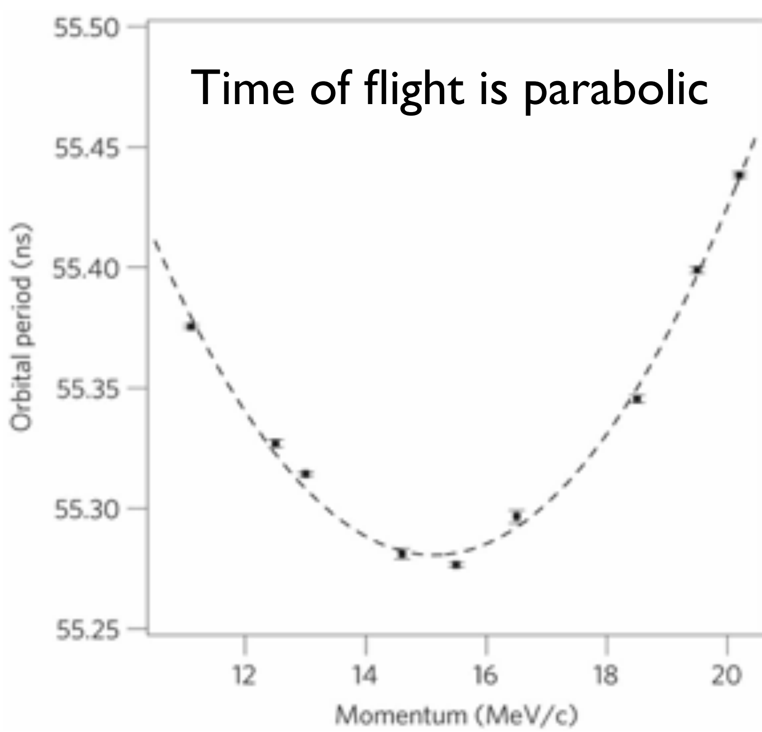
- CERN Courier, "Rebirth of the FFAG", 2004. http://cerncourier.com/cws/article/cern/29119
- K. Symon, D. Kerst, L. Jones, L. Laslett, and K. Terwilliger, "Fixed-Field Alternating-Gradient Particle Accelerators," Phys. Rev., vol. 103, no. 6, pp. 1837–1859, Sep. 1956.
- S. Machida,"Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA," Nat. Phys., vol. 8, no. 3, pp. 243–247, Jan. 2012.
- K. J. Peach, et al., Phys. Rev. ST Accel. Beams, vol. 16, no. 3, p. 030101, Mar. 2013.
- S. L. Sheehy, K. J. Peach, H. Witte, D. J. Kelliher, S. Machida, Phys. Rev. ST Accel. Beams, 13, 040101, 2010.
- D. Trbojevic, BNL-77556-2007-CP, http://www.bnl.gov/isd/documents/35754.pdf

+ Proceedings of the FFAG workshops

Additional Material

EMMA - longitudinal

Can you have an FFAG with fixed RF frequency?

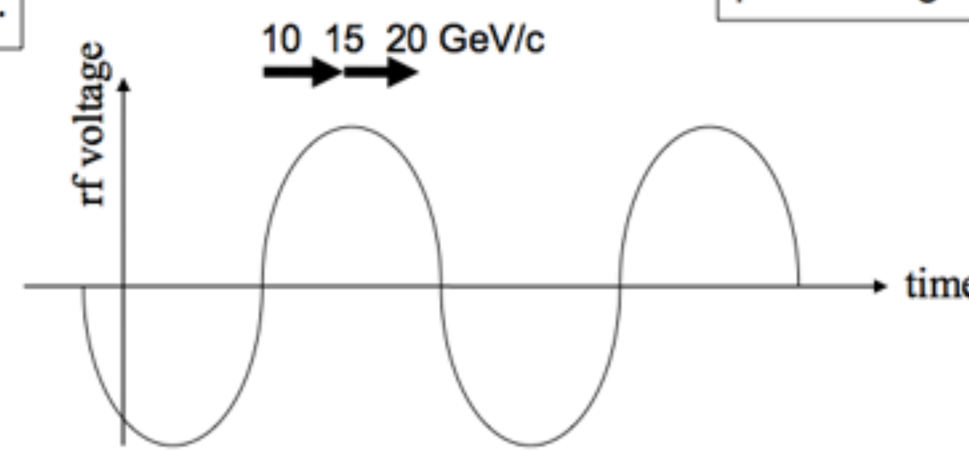


- Suppose we choose rf frequency that is synchronized with revolution frequency at the center.

In the first half of a cycle, a particle lags behind the rf.

At the center momentum, a particle is synchronized with rf.

In the second half, a particle lags again.



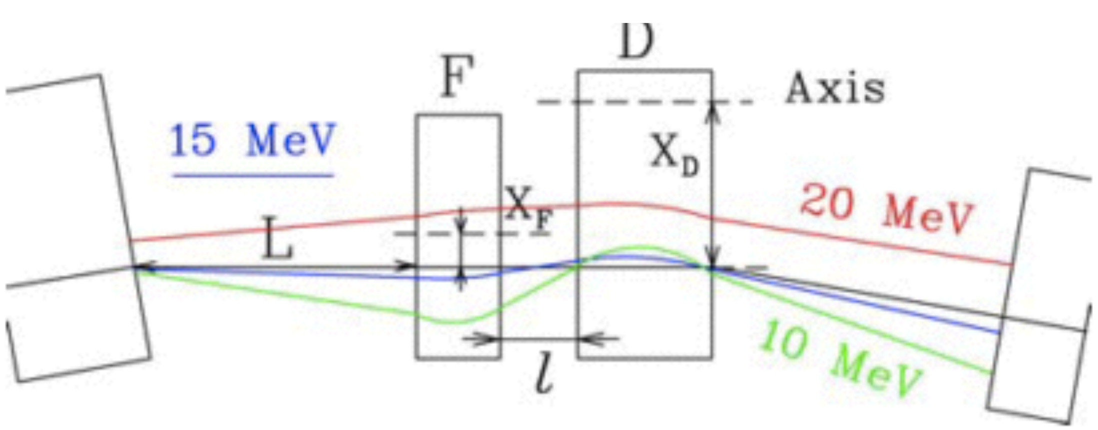


Figure 2: Orbits in a quadrupole doublet cell.

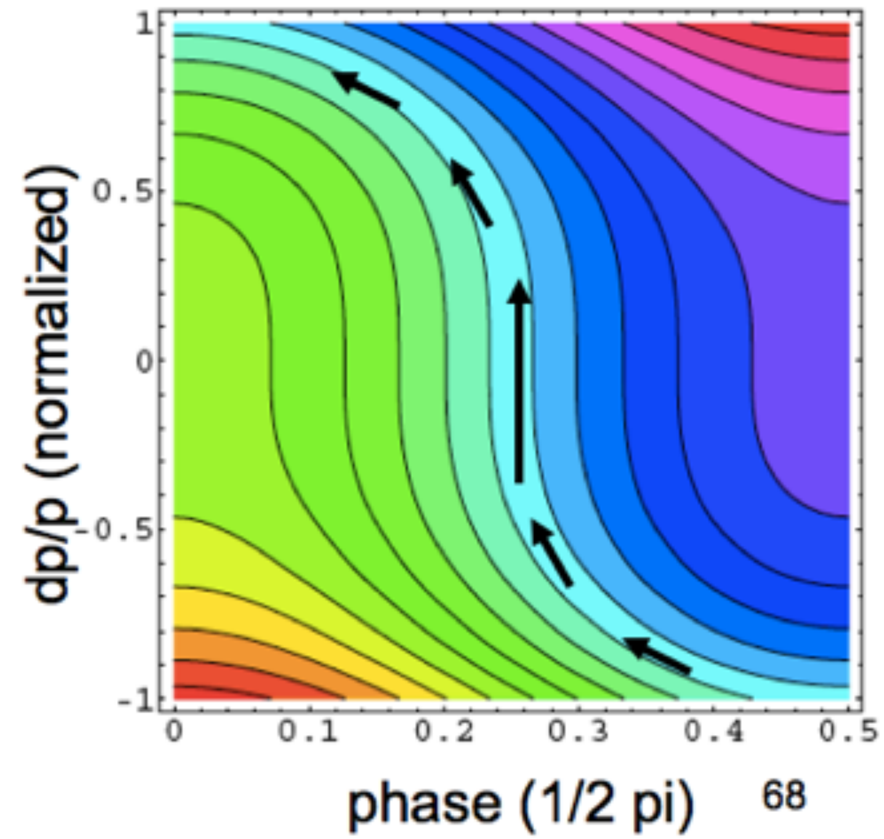
total time lag is less than a half of rf cycle, a beam has nergy gain.

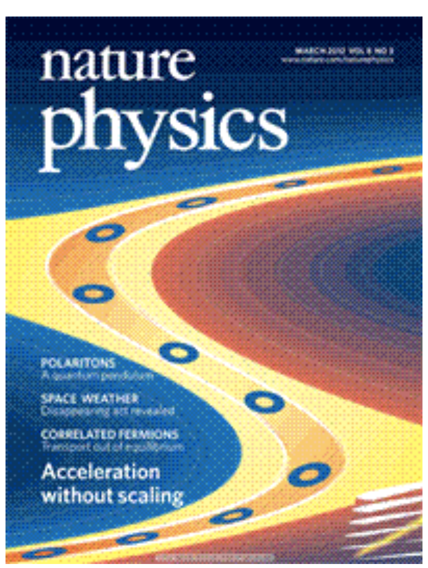
EMMA - longitudinal

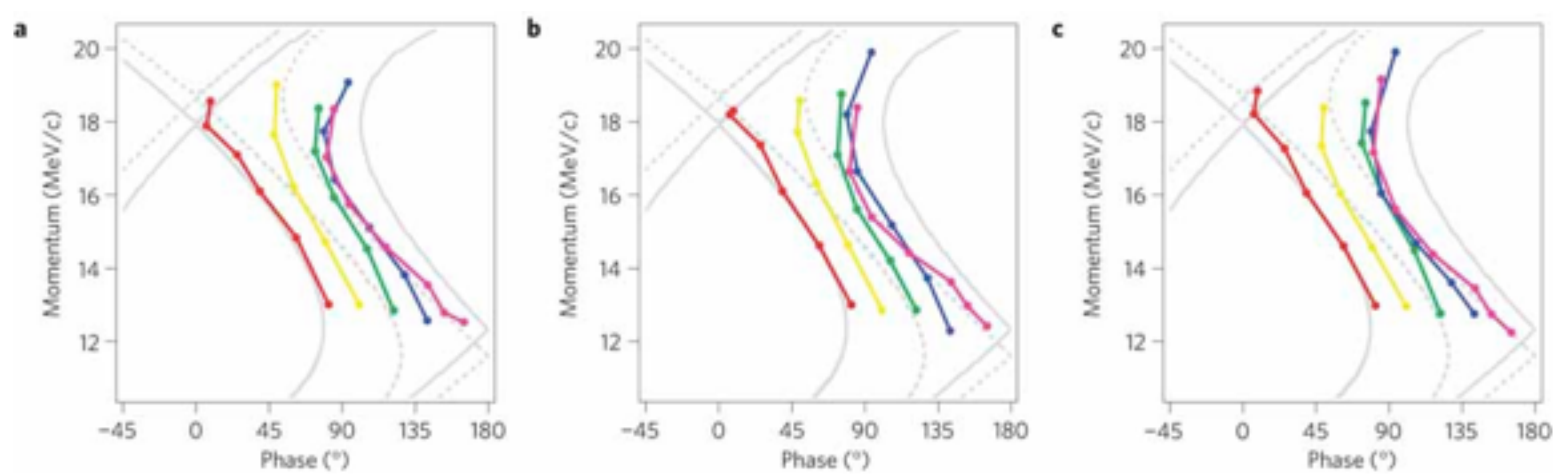
If the RF voltage is sufficient, we can accelerate over the whole energy range

Similar to acceleration in a cyclotron but with imperfect isochronicity

This is called ‘serpentine’ acceleration and was demonstrated in EMMA







S. Machida et. al., Nature Physics 8, 243–247 (2012)

Technology for scaling FFAGs

Image credit: A. Takagi

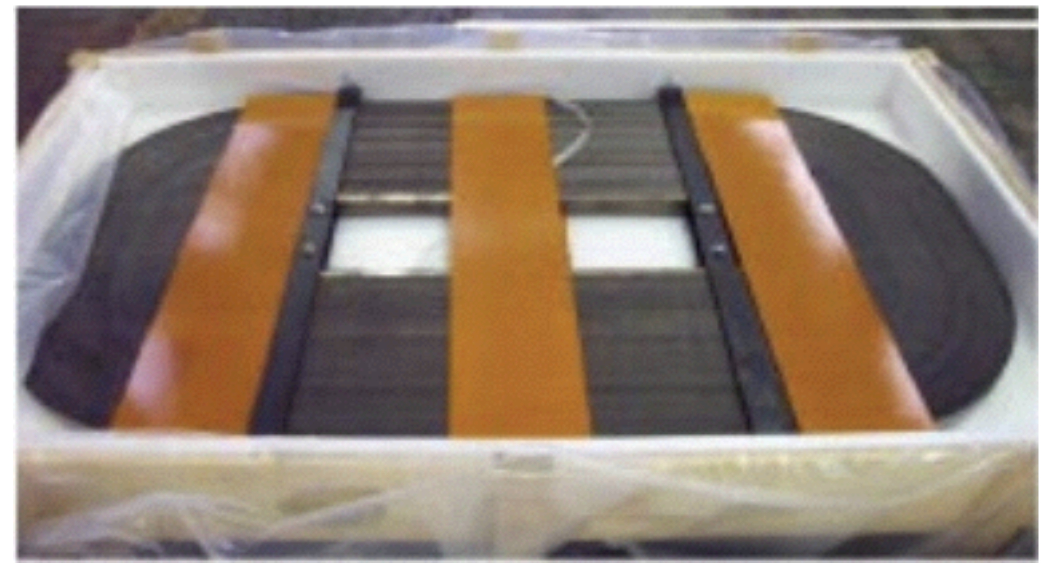


Image credit: Y. Mori,

Magnetic Alloy (MA) Cavity

High shunt impedance

Low Q - can cover large range of frequencies.