# FFAG Accelerators

## CERN Introductory Accelerator School
## Prague, September 2014


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STFC Rutherford Appleton Laboratory, UK



Many thanks to Dr. S. Machida for his advice and previous lecture materials

# Motivation

- Many challenges for future hadron accelerators:

| High power | Reliable | Flexible |
|---|---|---|
| Neutrons, muons, ADS | Medical, ADS | Is industry limited by existing technology? |

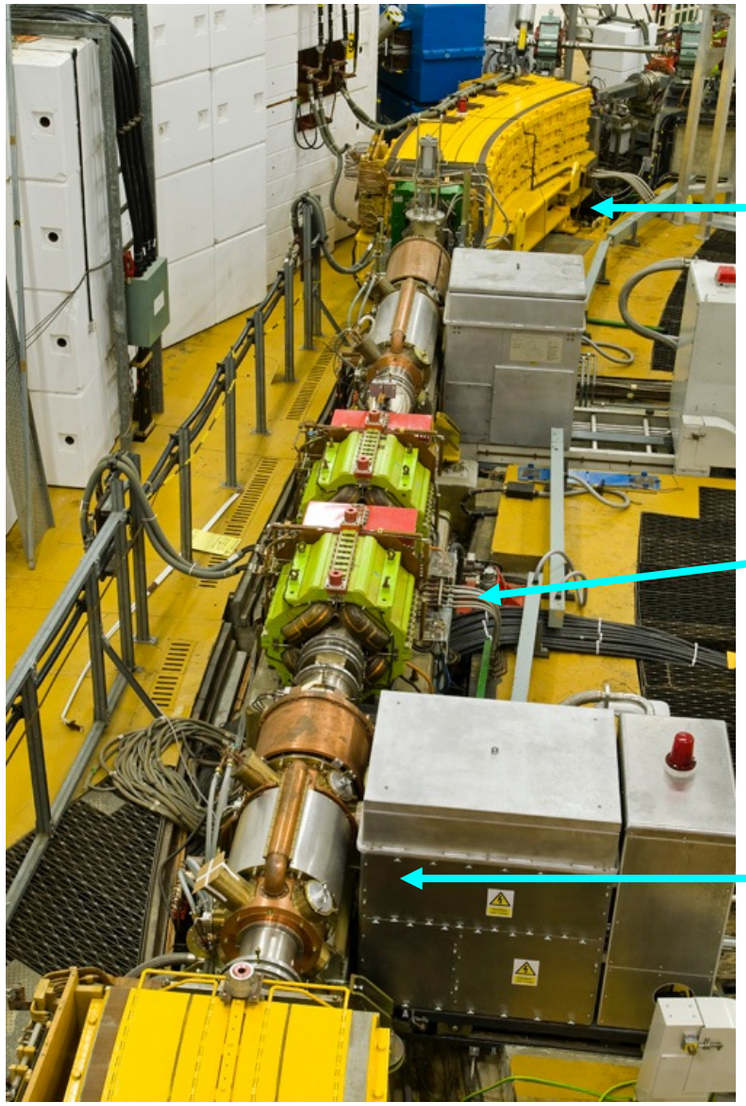
| Rapid acceleration | Cheap |
|---|---|
| Muon beams<br>Unstable nuclei | Hadron accelerators aren't known for being cheap |

# ‘Fixed Field Alternating Gradient’ Accelerators

- Are FFAGs like a synchrotron or cyclotron?
  - EMMA non-scaling FFAG
- Fixed field magnets
- Beam dynamics
- Scaling FFAGs
- Advanced FFAG types and optics

# Is an FFAG like a synchrotron? (1)

"*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



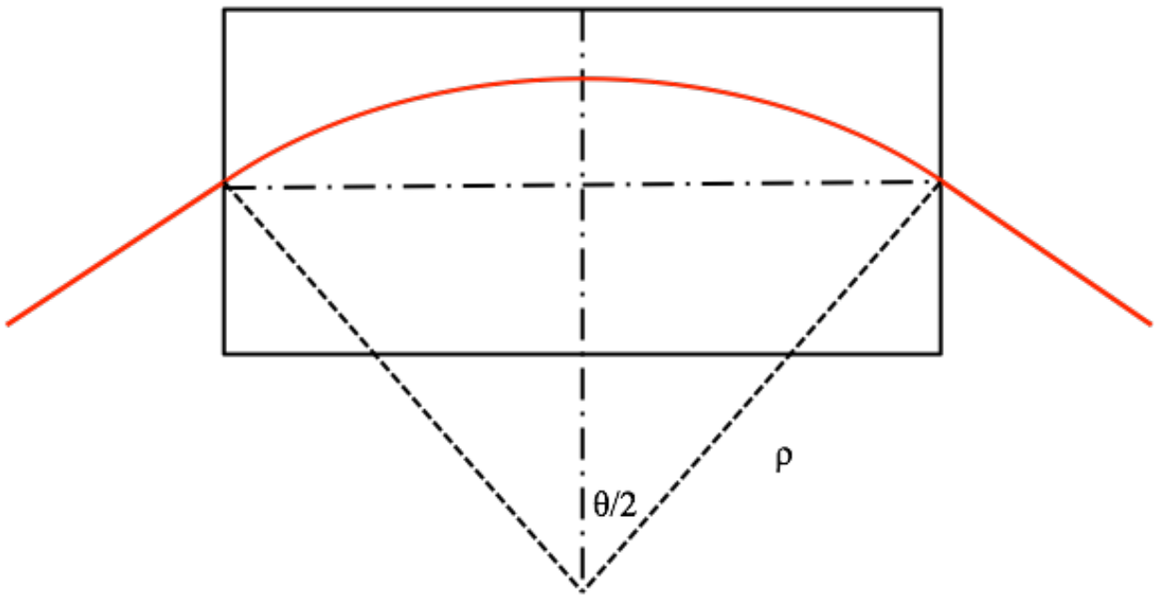
dipole magnets

quadrupole magnets

rf cavity

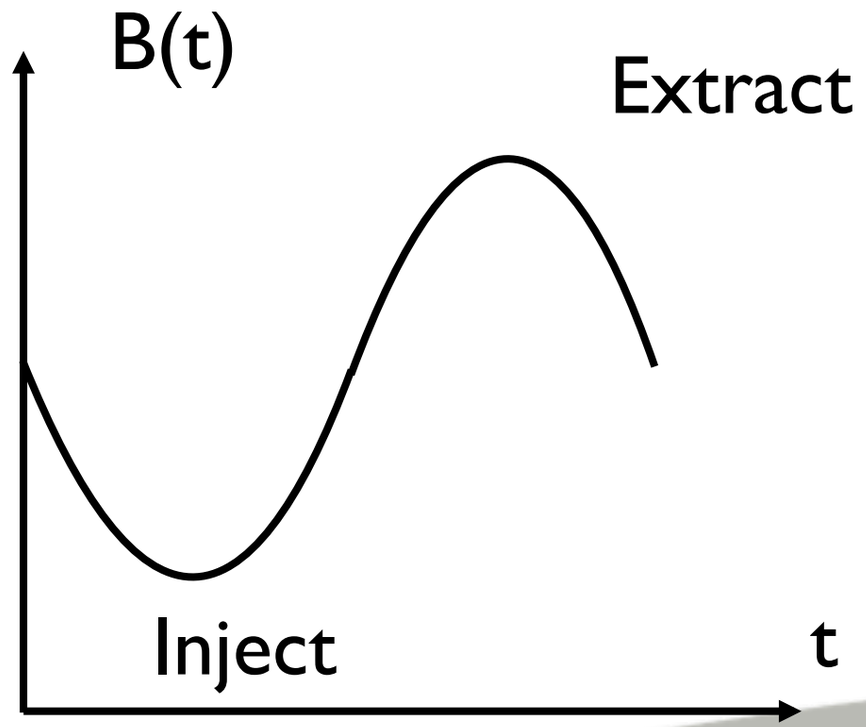
*Image courtesy of ISIS, STFC*

# Is an FFAG like a synchrotron? (2)




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

$$\theta \approx \frac{B(t)L}{p(t)/q}$$




**What happens if I don't ramp the B field with E?**

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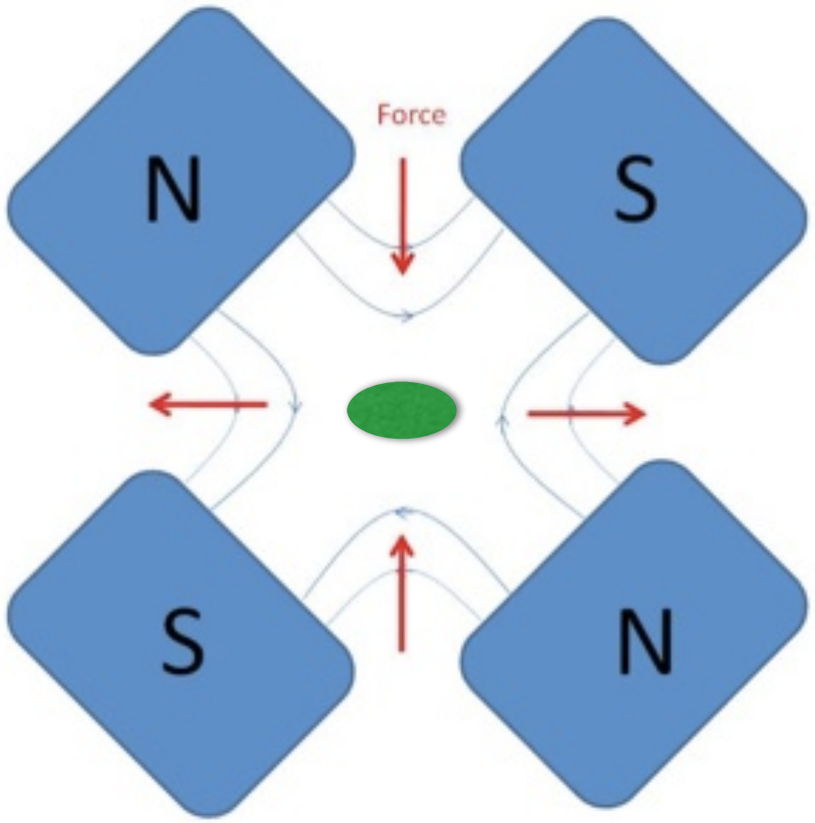
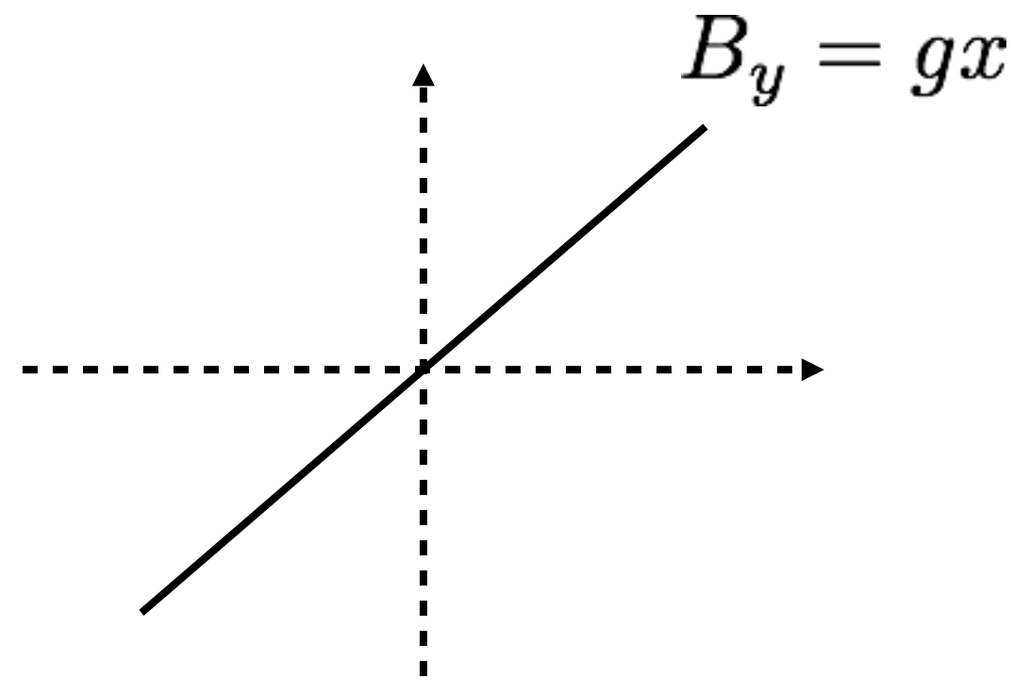
# Is an FFAG like a synchrotron? (3)




**Do we also ramp the quadrupoles in a synchrotron?**

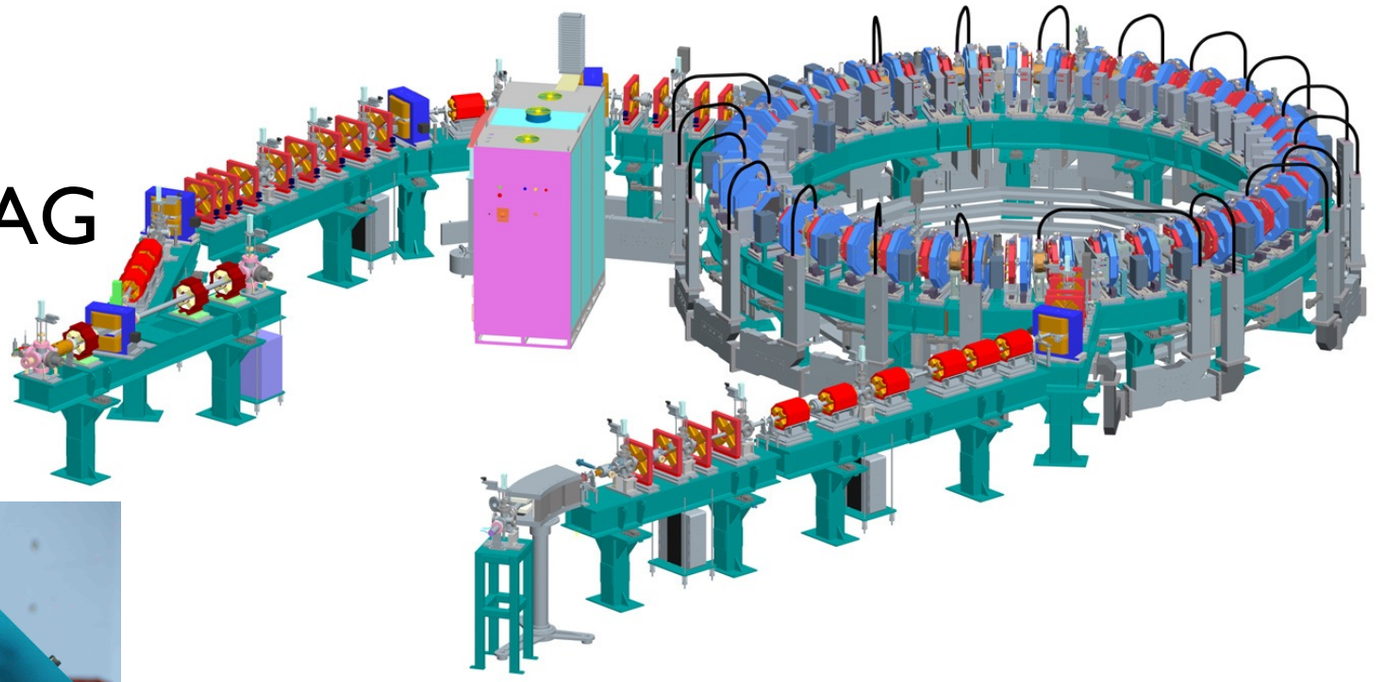
$$k = \frac{g}{p/q}$$

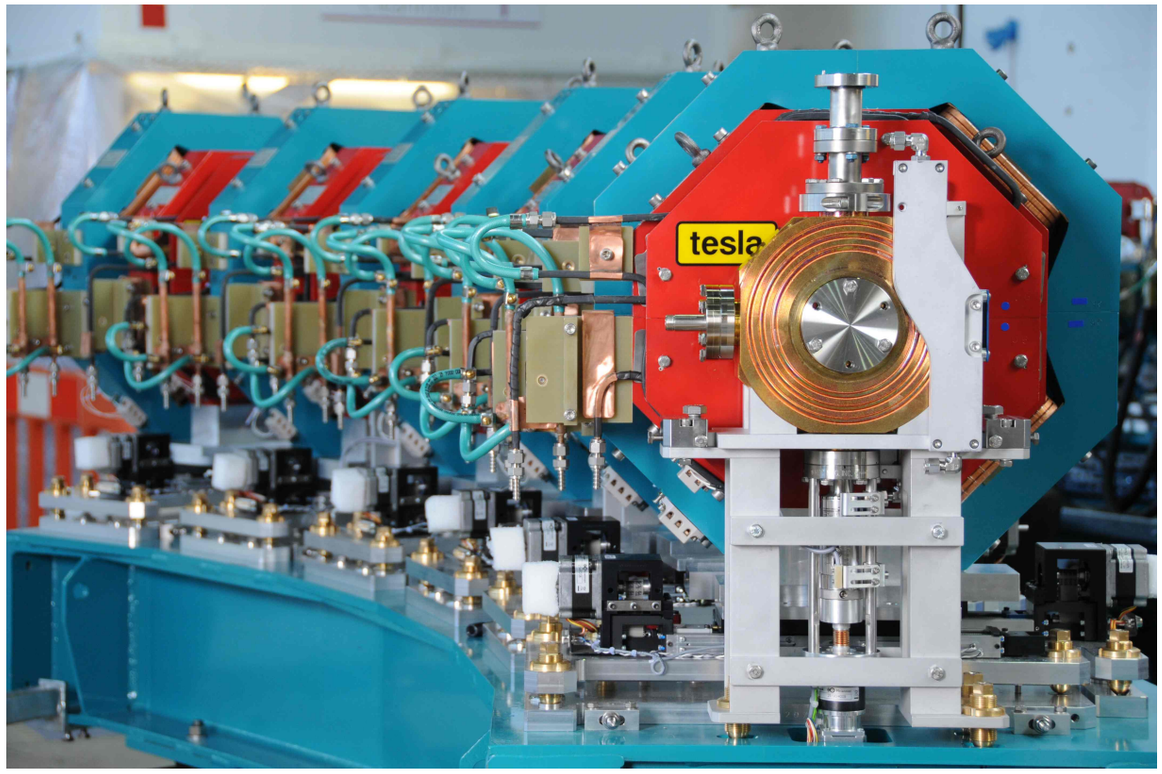
'normalised gradient' of quad

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

# The ‘EMMA’ accelerator

42 Quadrupole doublets
10-20 MeV e-
Demonstrates ‘non-scaling’ FFAG

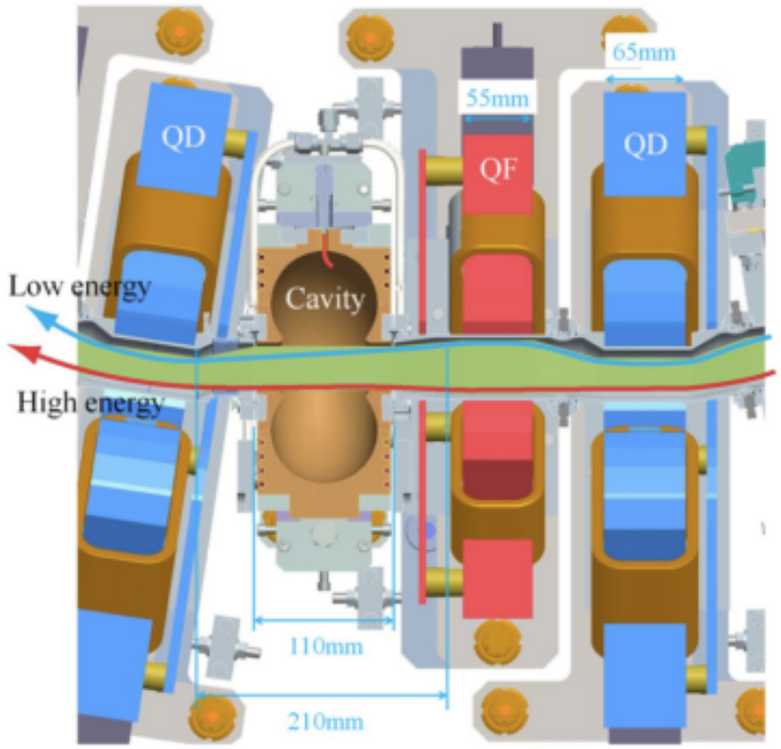





‘Electron Model for Many Applications’ = EMMA
Built and commissioned at STFC Daresbury Laboratory, UK

# EMMA doesn't ramp the B field with time

## 'Fixed Field Alternating Gradient' = FFAG



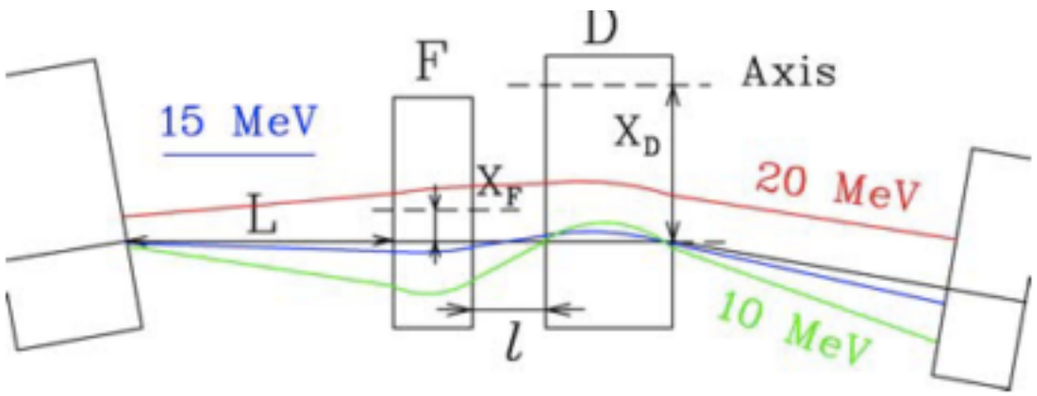
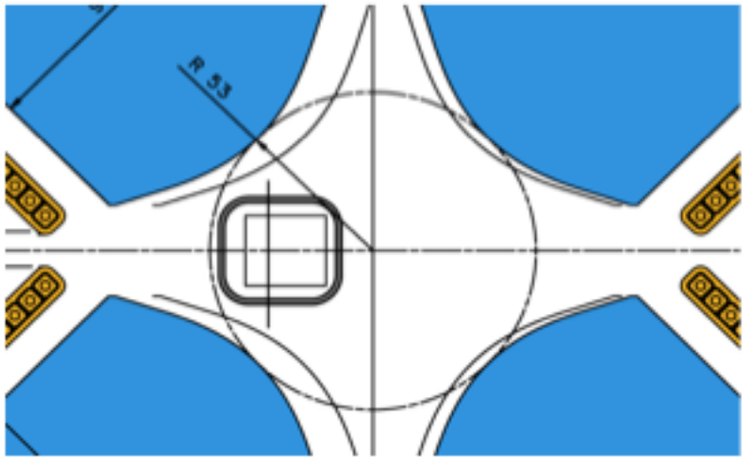




Figure 2: Orbits in a quadrupole doublet cell.

M. Craddock, PAC'07

Quadrupole with radial offset creates bending component



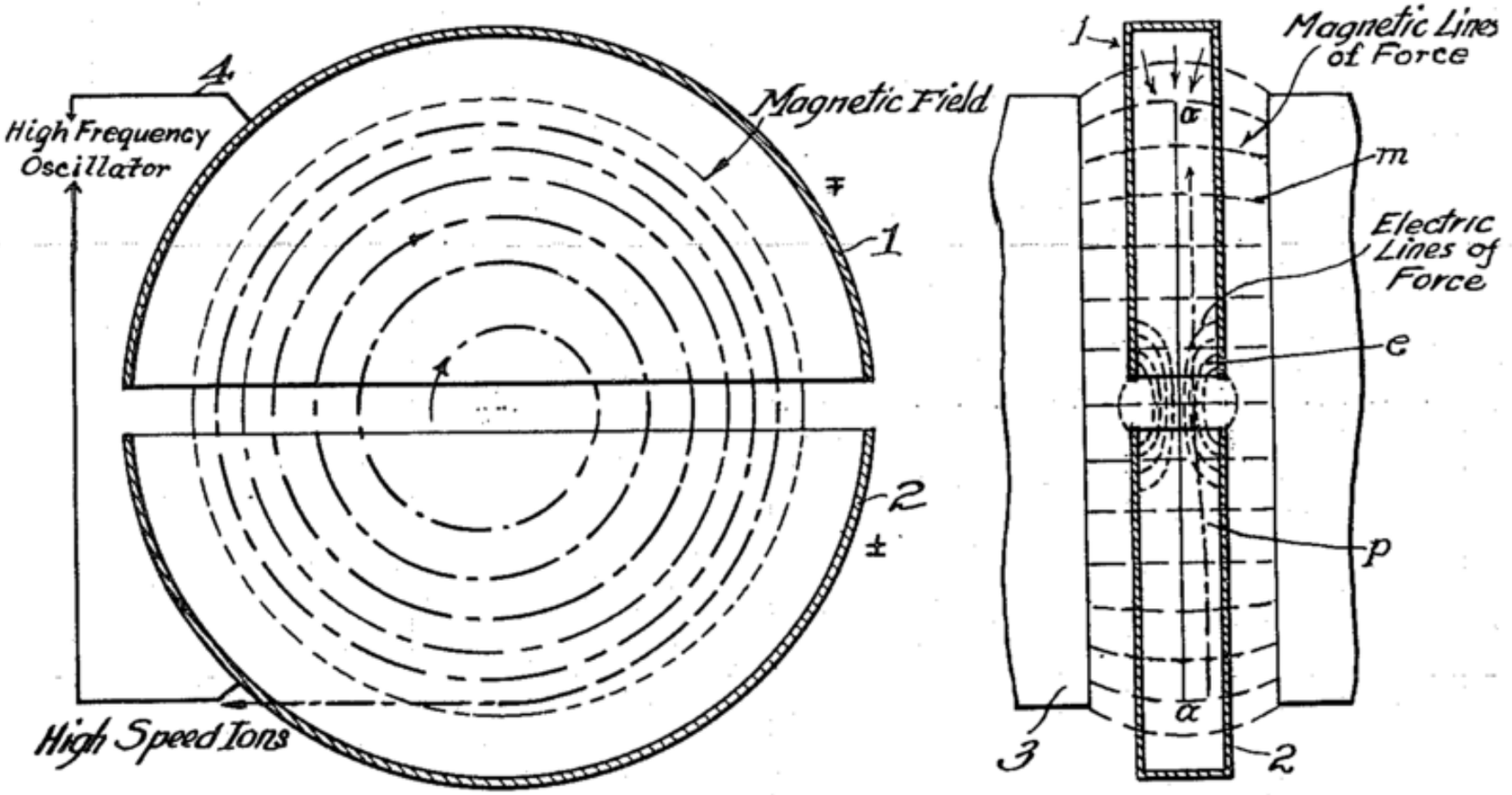

Note: this is just like a 'combined function' magnet

# 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

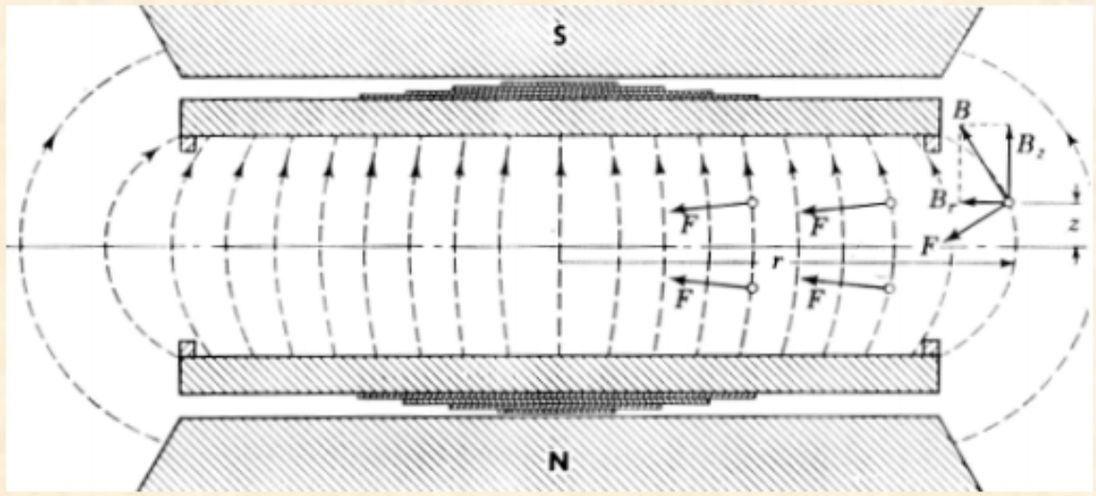
# Is an FFAG like a cyclotron? (2)

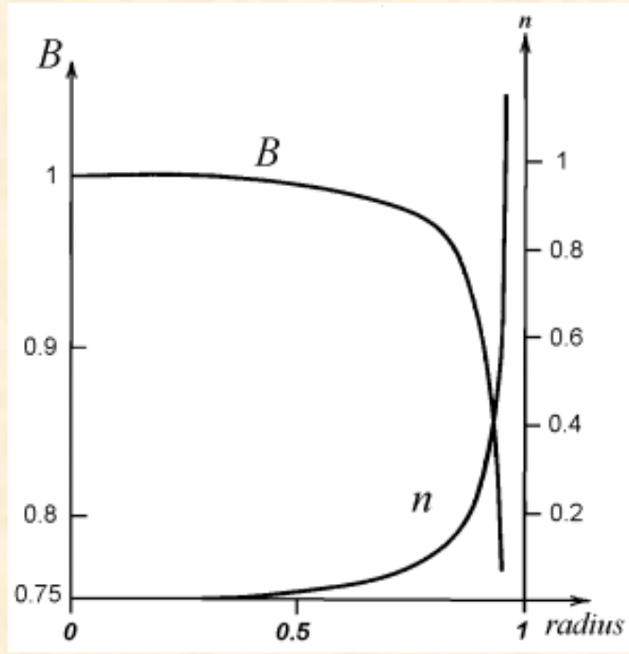
## Weak focusing

Simultaneous radial and axial focusing : Weak focusing

$$0 \leq n \approx -\frac{\partial B_z}{\partial x} \leq 1$$

slightly decreasing field




Horizontal focusing n < 1 means :

- 0 < n < 1 Bz can slightly decrease
- n < 0 Bz can increase as much as wanted

Vertical focusing n > 0 means :

- Bz should decrease with the radius

F. Chautard

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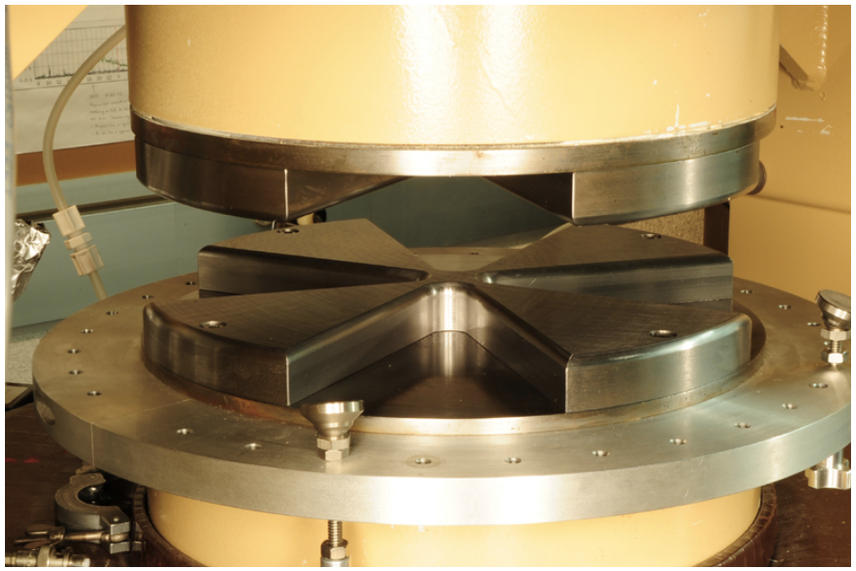
Slide source: F. Chautard, 2012 CAS

# Is an FFAG like a cyclotron? (3)

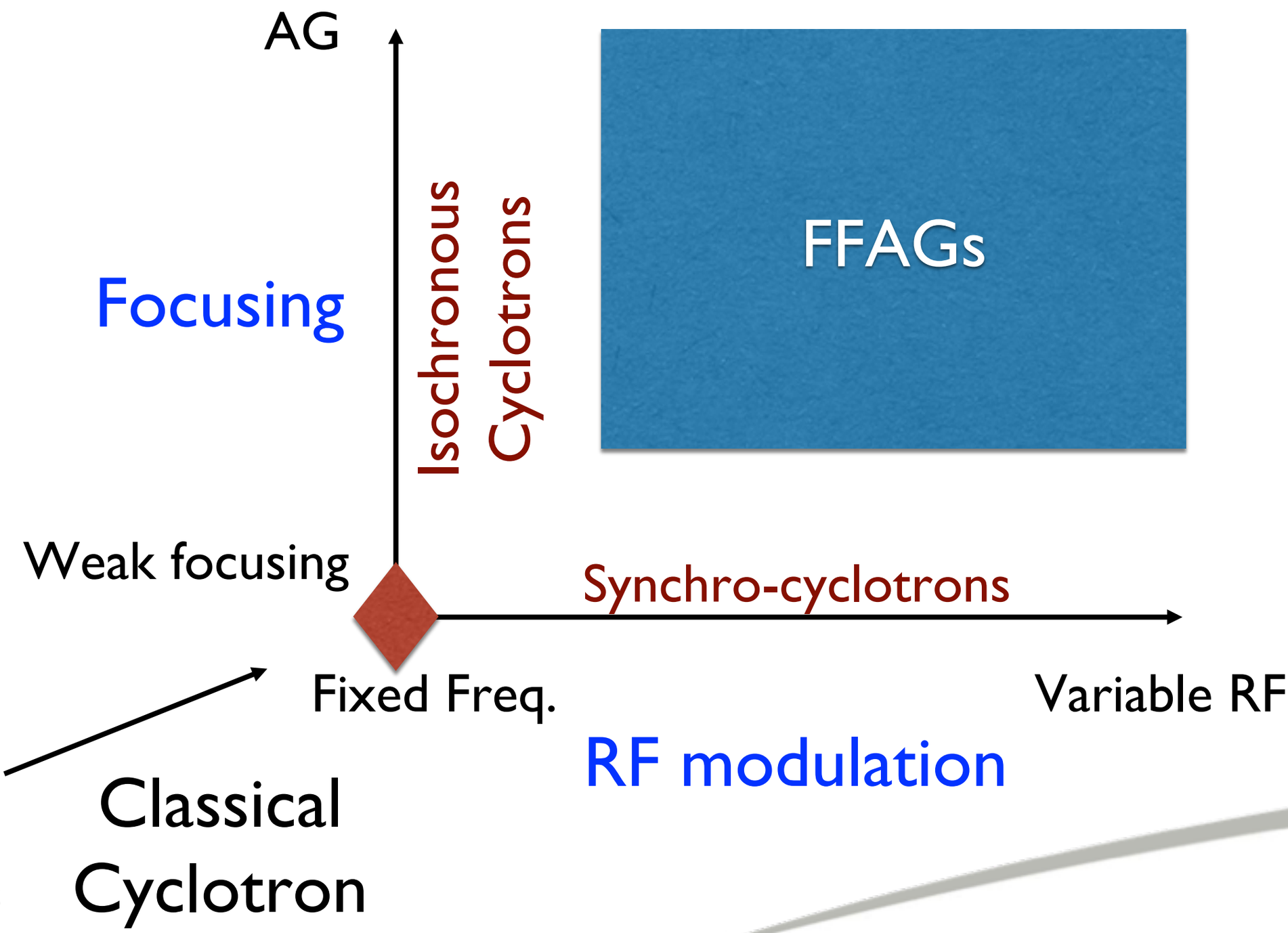


**What about the AVF cyclotron?**

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



- 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…

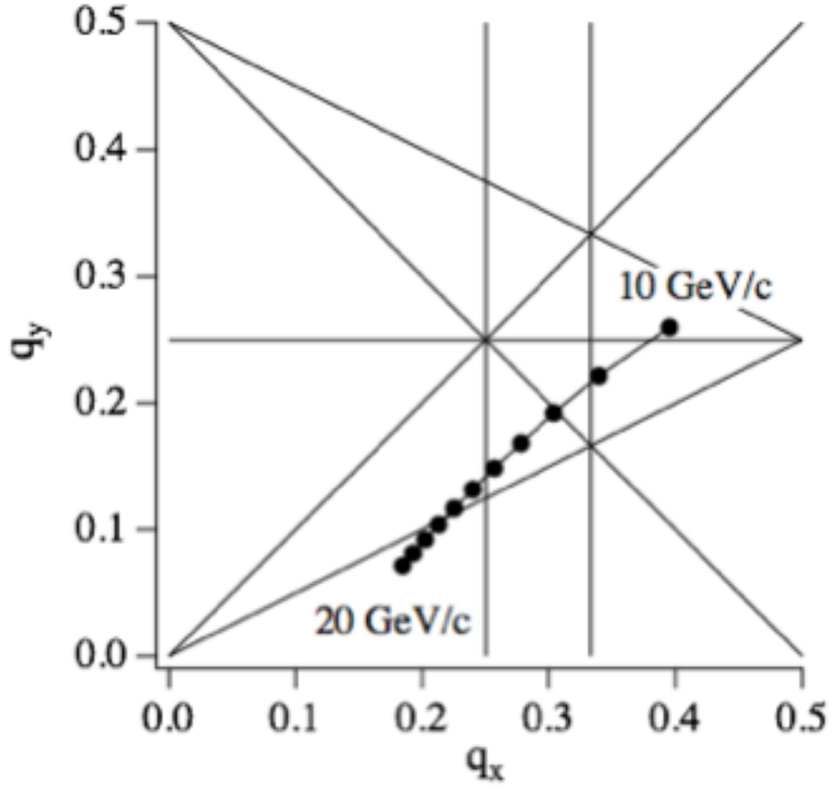
**FFAGs do not always have variable RF frequency…

# Circular Accelerators

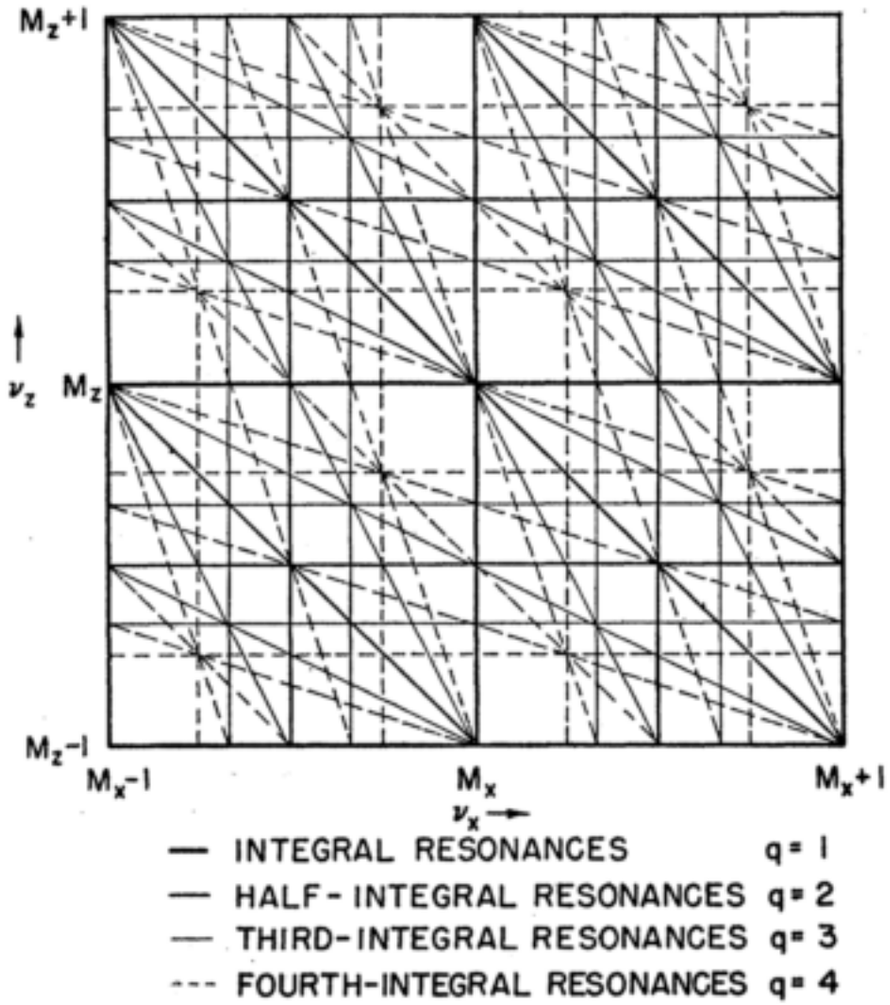
| | Cyclotron | Synchrotron | FFAG |
|---|---|---|---|
| Revolution time | Constant | Variable (except relativistic) | Variable |
| Orbit radius | Variable | Constant | Variable |
| Transverse focusing | Variable | Constant | Variable |

# 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

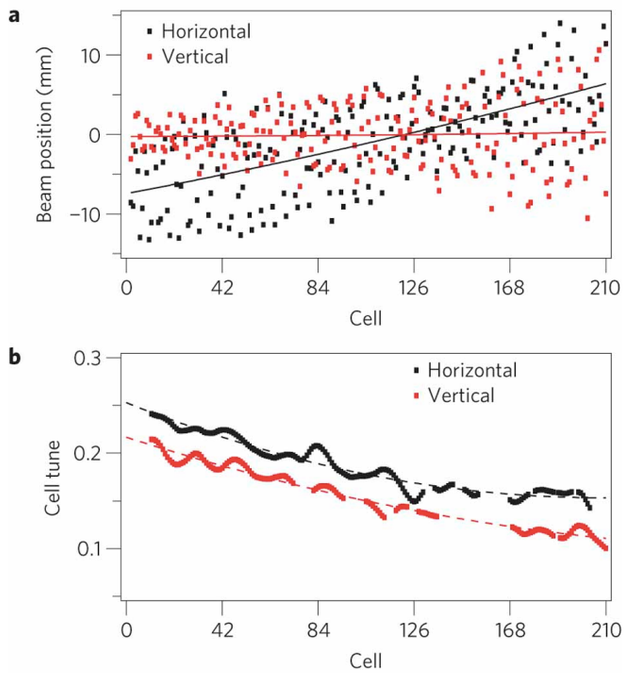


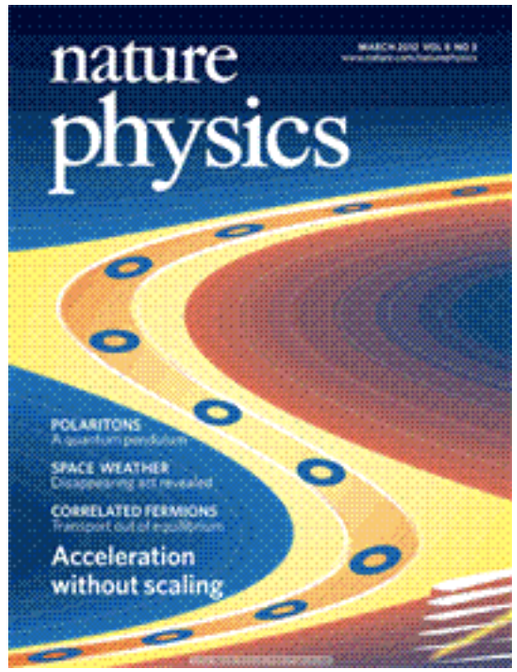

$$n\nu_x + m\nu_y = 0,1,2...$$

- 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.

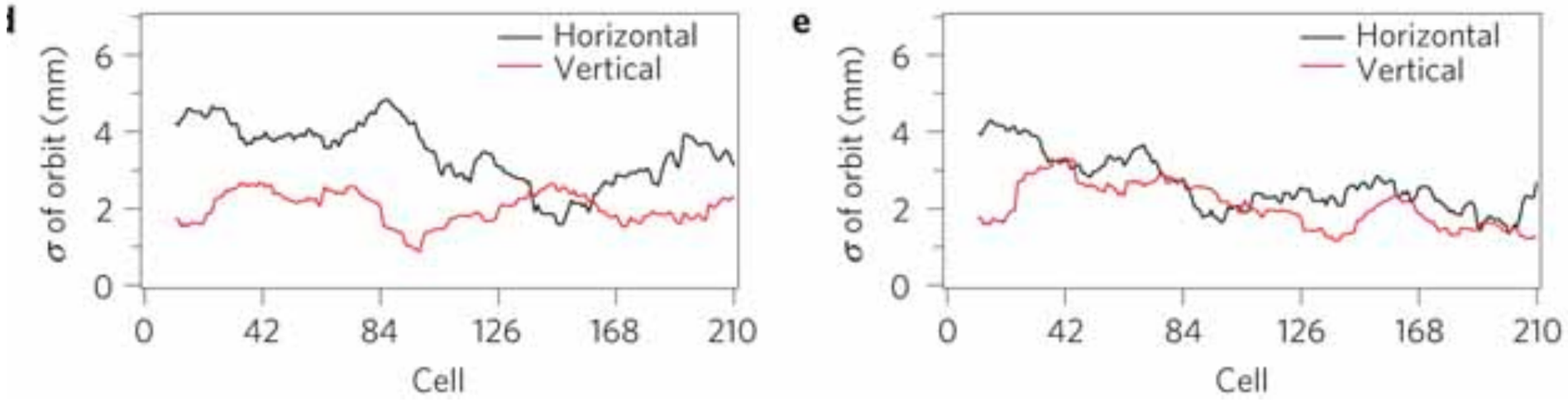
# Results from EMMA

Orbit and tune shift with momentum




No beam ‘blowup’ despite resonance crossing




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



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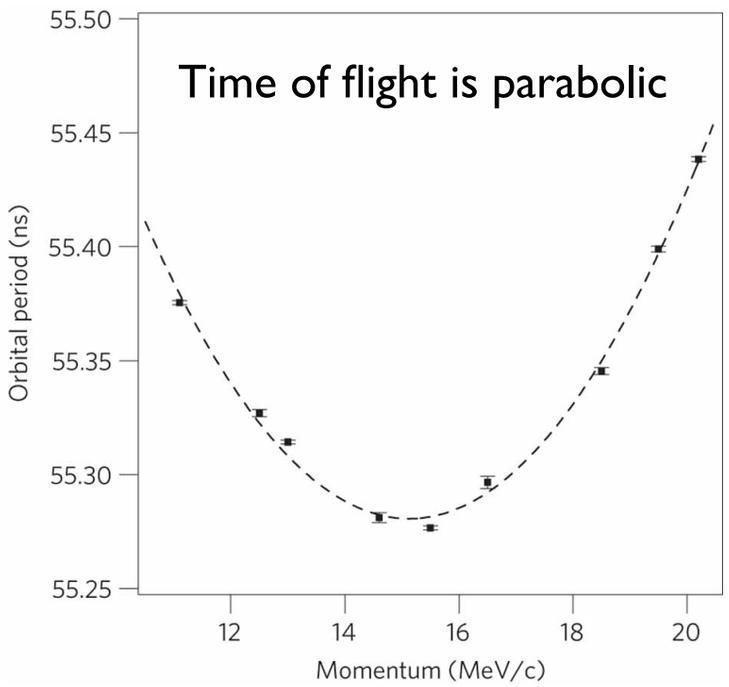
# EMMA - longitudinal

**Can you have an FFAG with fixed RF frequency?**

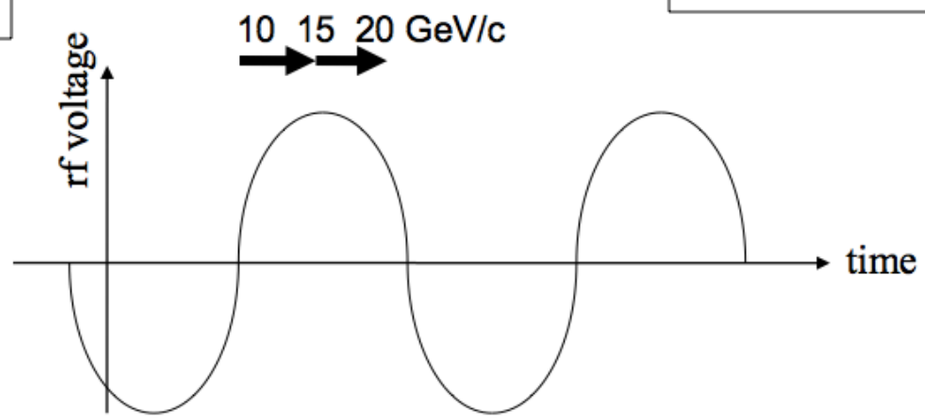



- Suppose we choose rf frequency that is synchronized with revolution frequency at the center.

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.



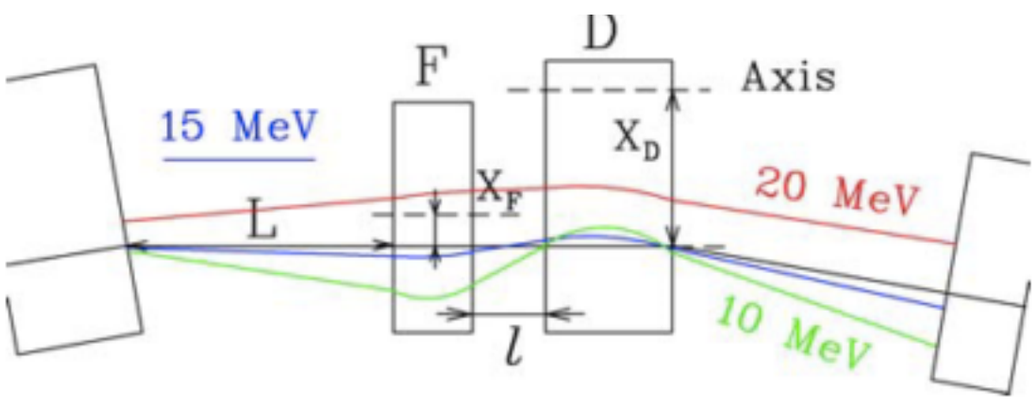




Figure 2: Orbits in a quadrupole doublet cell.

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

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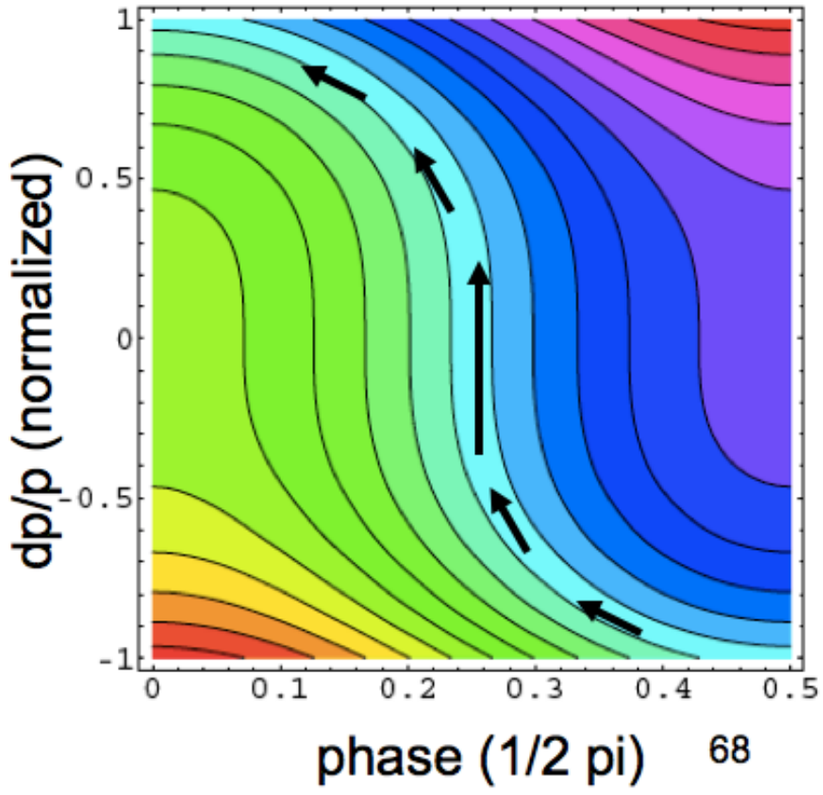
# EMMA - longitudinal

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

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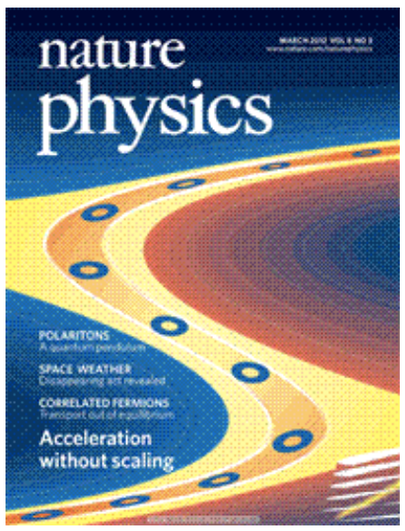
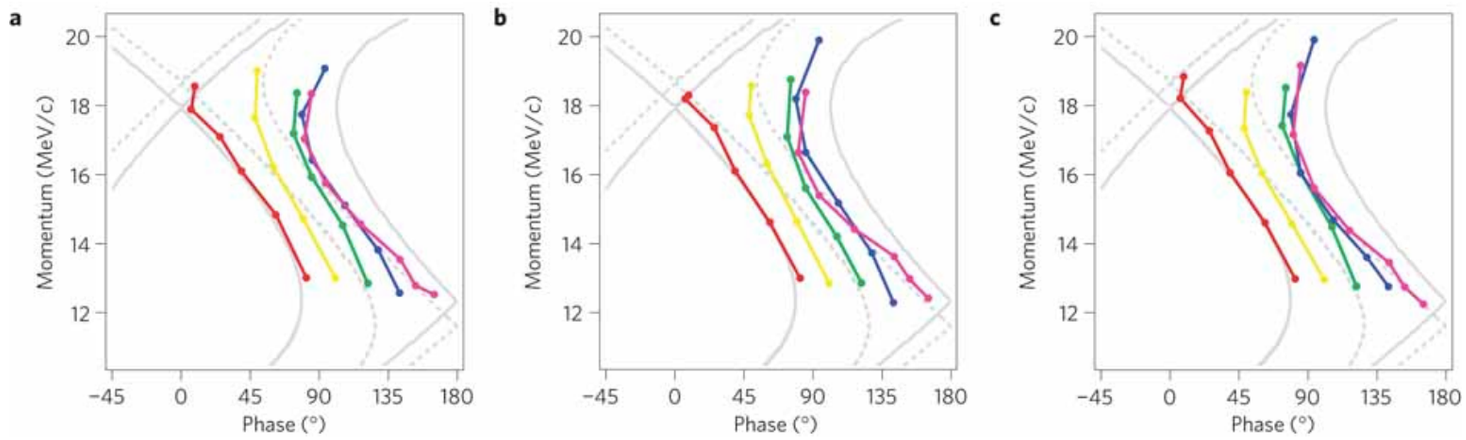



S. Machida et. al., Nature Physics 8, 243–247 (2012)

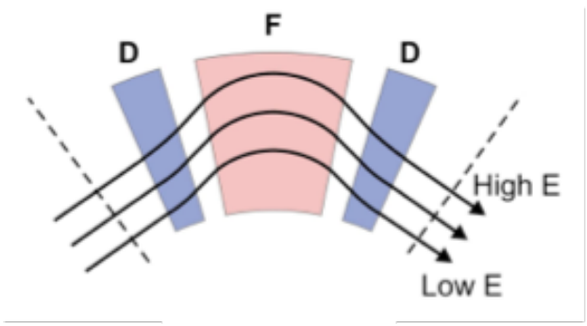
- Electrons & muons are easy to accelerate quickly, but for hadrons it's harder…
- If resonance crossing could be harmful for hadron FFAGs, what can we do to fix it?
- In a synchrotron, off-momentum tune variations = chromaticity
- Can we have stable tunes in an FFAG?

# Scaling FFAG

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

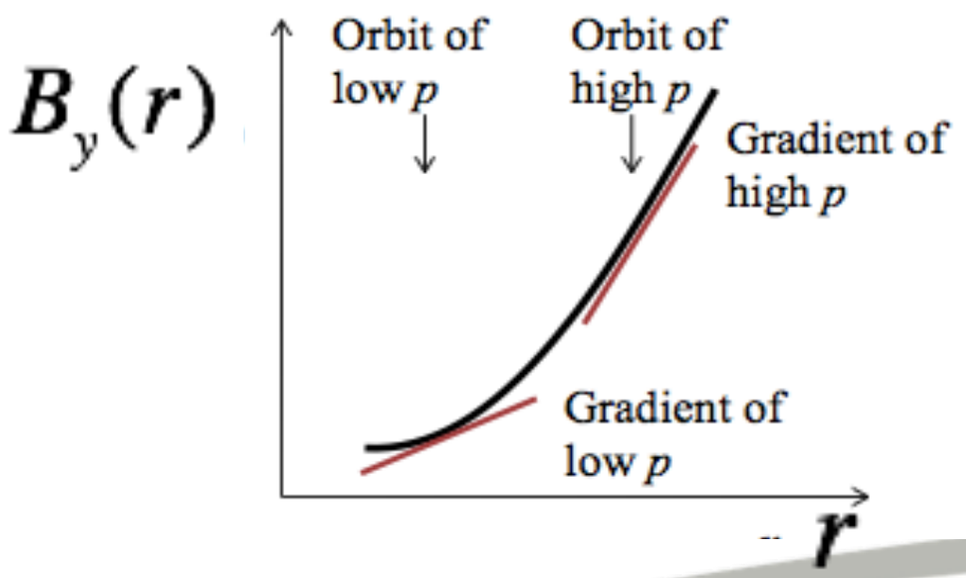
The orbits are made ‘similar’

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




The ‘field index’ is constant

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



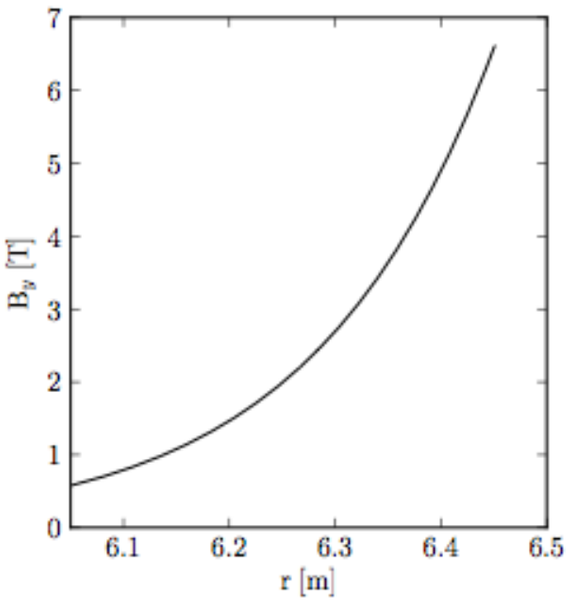

$\rho_0$ Average bending radius

$\rho$ Local bending radius

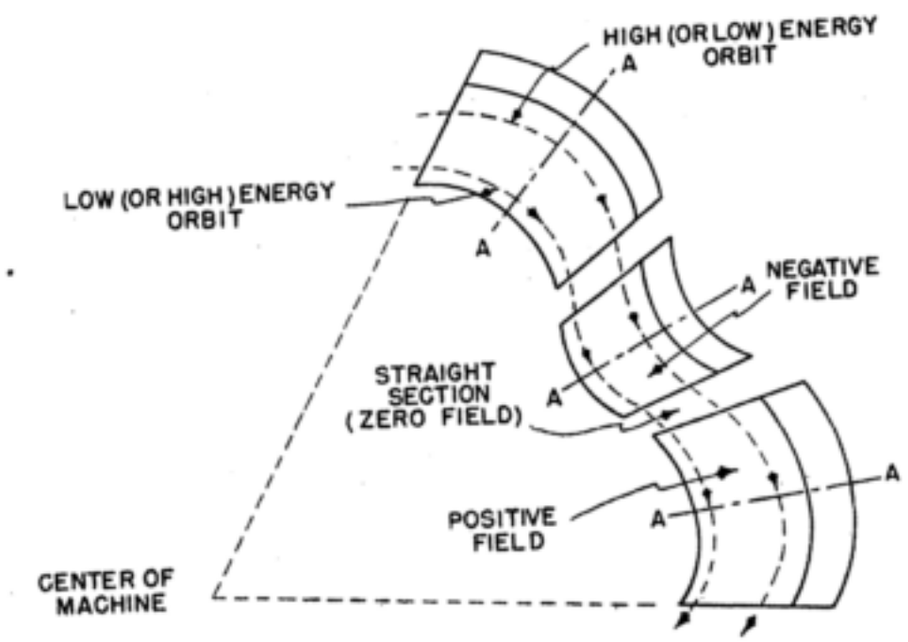
$\theta$ Generalised azimuth

# 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




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

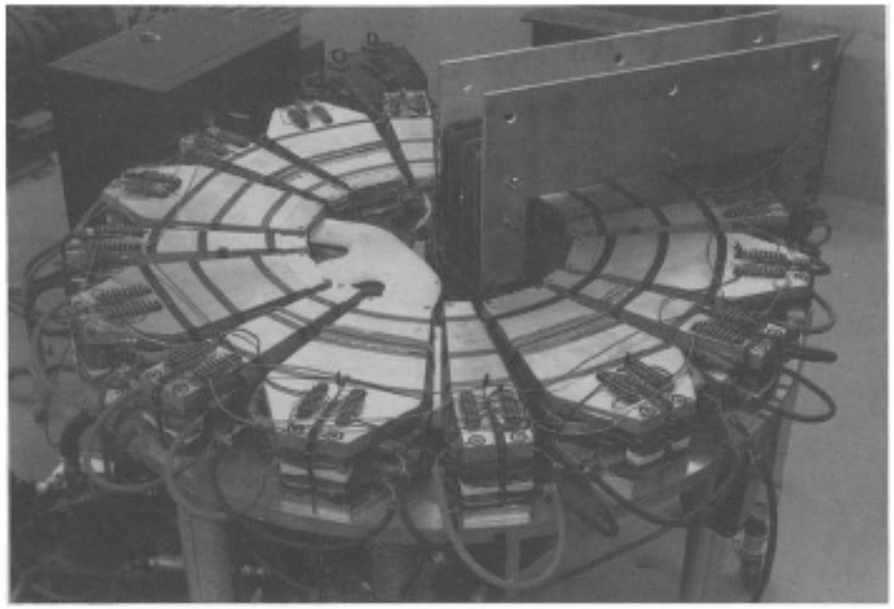


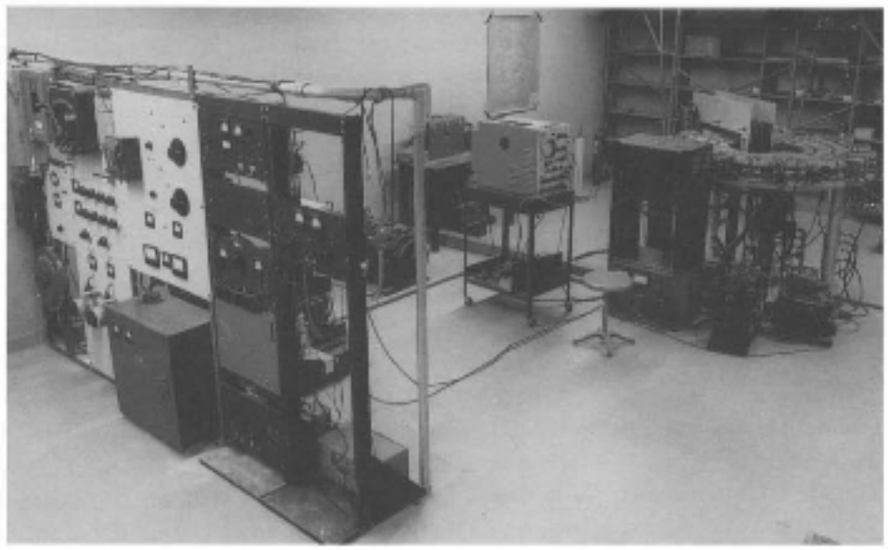

$$\omega = \frac{eB}{m\gamma} \neq const.$$

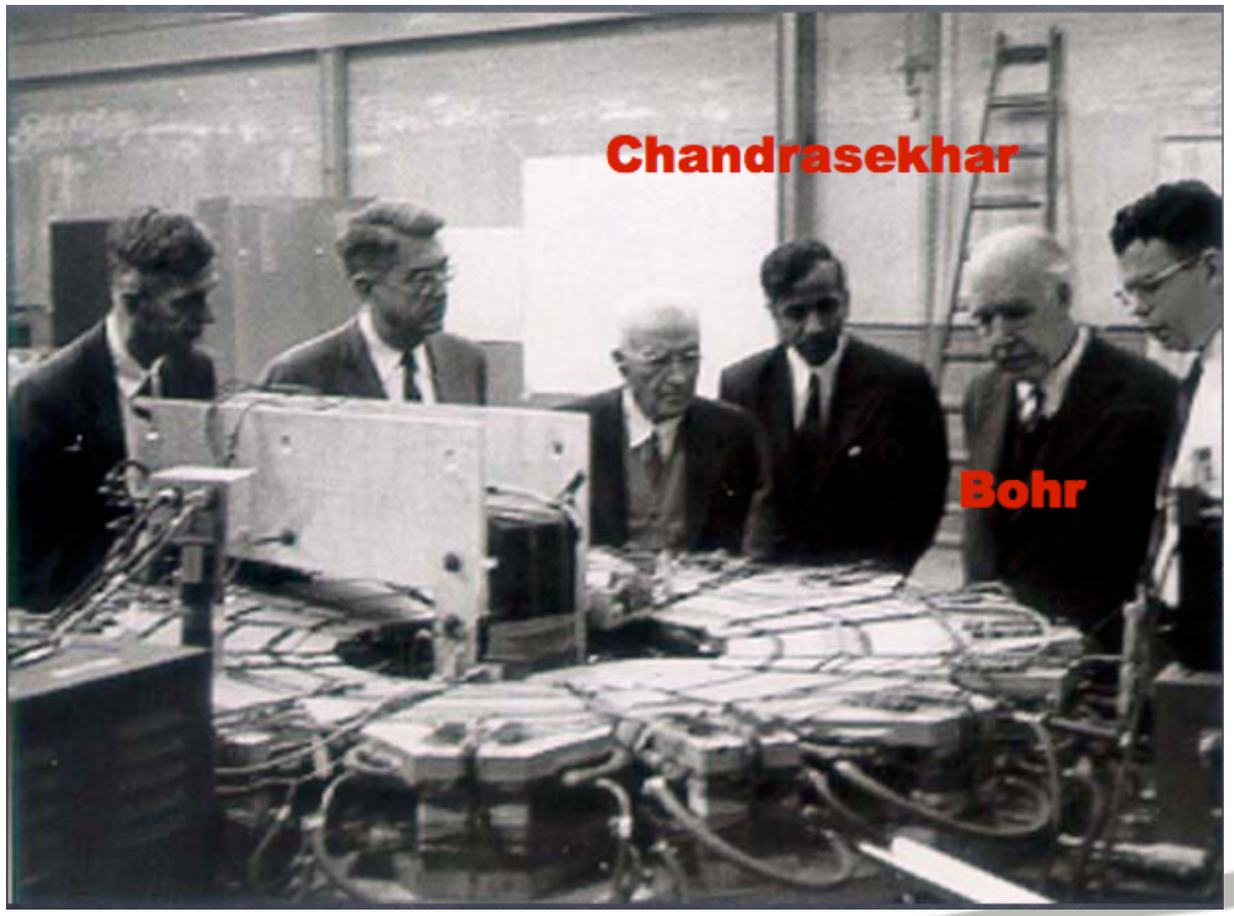
- Note that this field profile does NOT satisfy isochronicity (see M. Seidel’s cyclotron lecture)

# The FFAG is not so new…

1956








L. W. Jones, AIP Conference Proceedings, 237, 1 (1991)

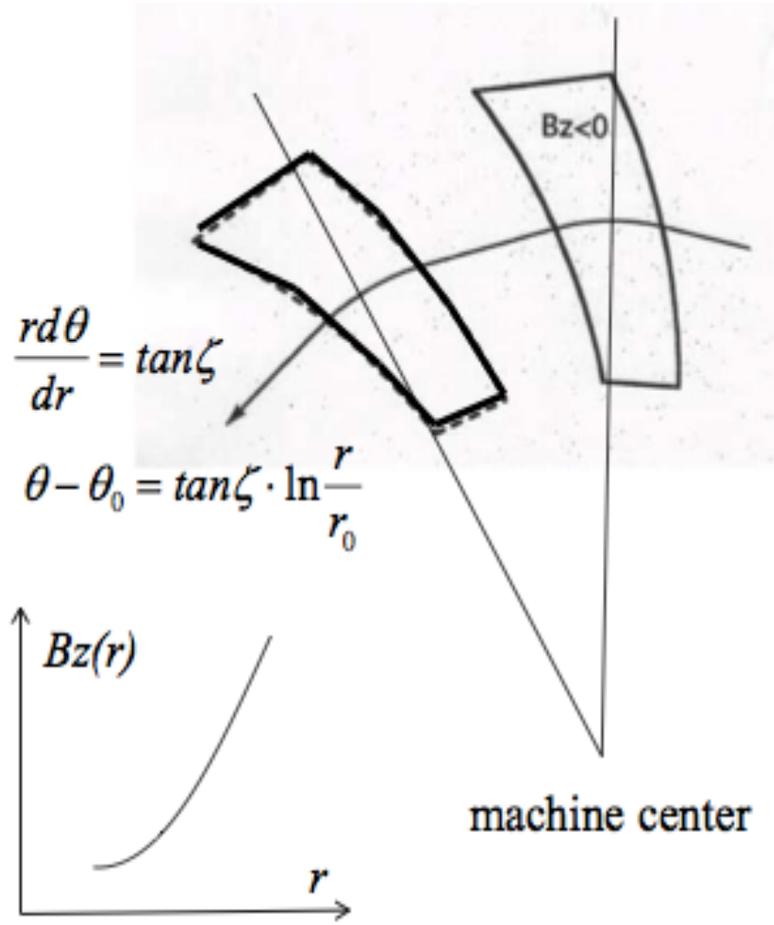
# Scaling FFAG types

- There is also another way the field can satisfy this condition

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

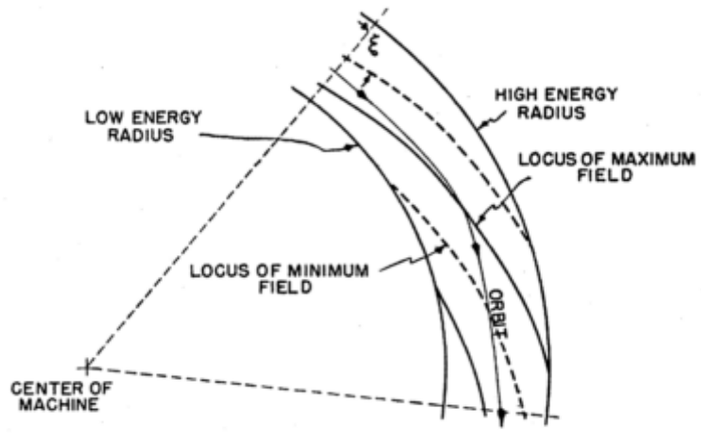
$$F(\vartheta) = F\left(\theta - tan\zeta \cdot \ln\frac{r}{r_0}\right)$$

Spiral sector type




Spiral angle gives strong edge focusing.

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




S. Machida, CAS 2012

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.

# 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

# Technology for scaling FFAGs

Image credit: A. Takagi

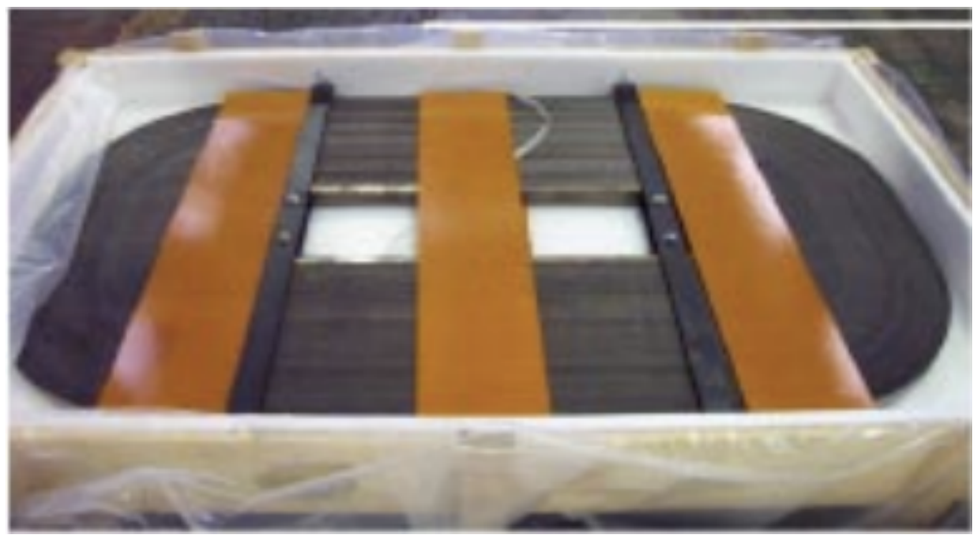


Image credit: Y. Mori,

Magnetic Alloy (MA) Cavity

High shunt impedance

Low Q - can cover large range of frequencies.

# 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…

- ‘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?

# Advanced FFAG optics (1)

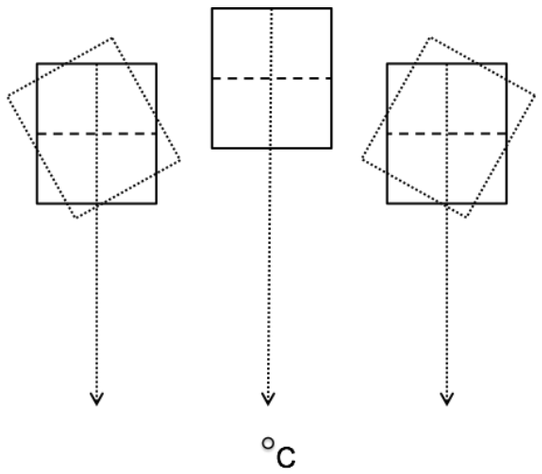
*"There are other variations of these designs which preserve betatron oscillation stability, hold $\nu_x$ and $\nu_y$ constant, but do not retain the property of similar of equilibrium orbits."*

*"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.

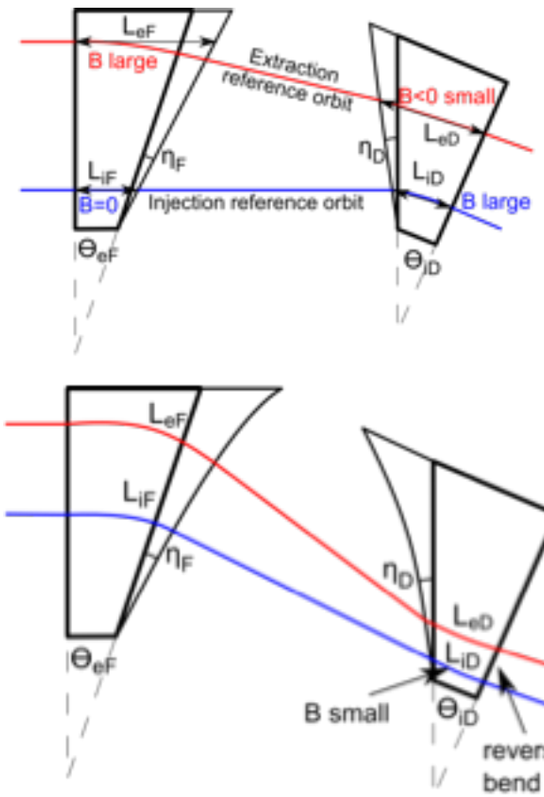
## Tune-stable non-scaling FFAG designs have been developed

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



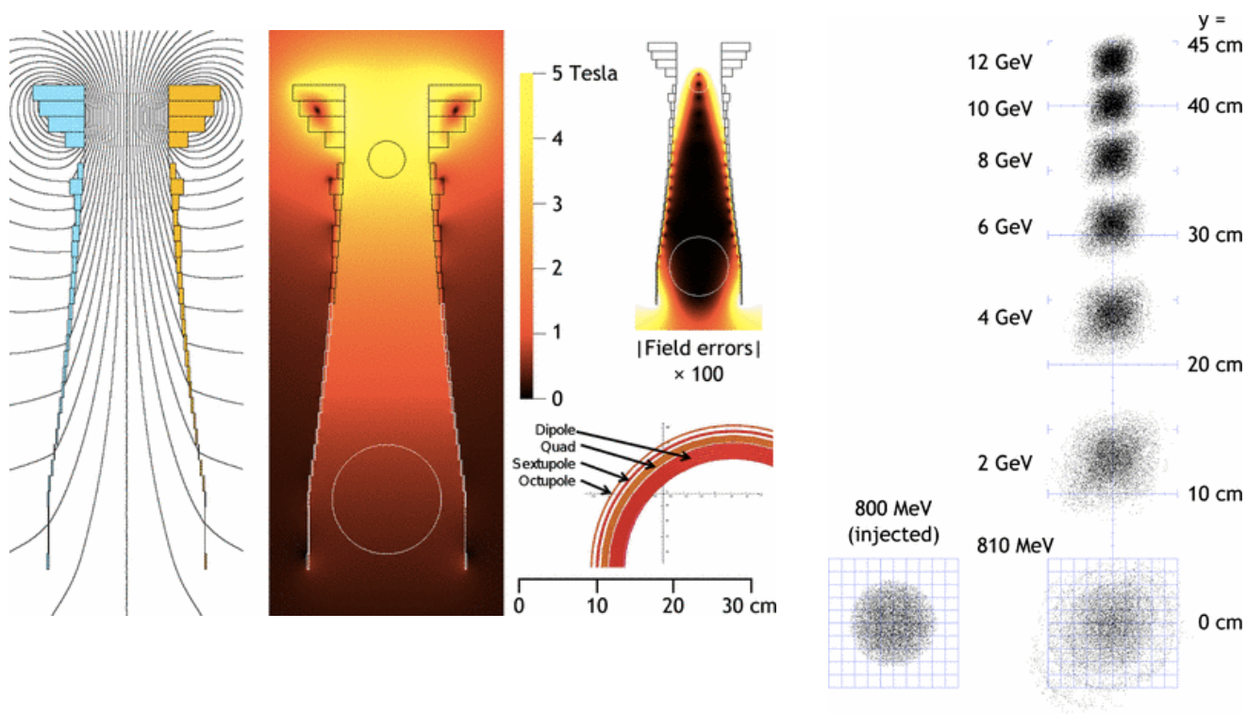

Rectangular magnets,
Simplified field profile
Higher stability region
(S. Machida, S. Sheehy)

# Advanced FFAG optics (2)




Radial designs with edge profiles
(C. Johnstone)

Vertical orbit excursion FFAG
(S. Brooks)



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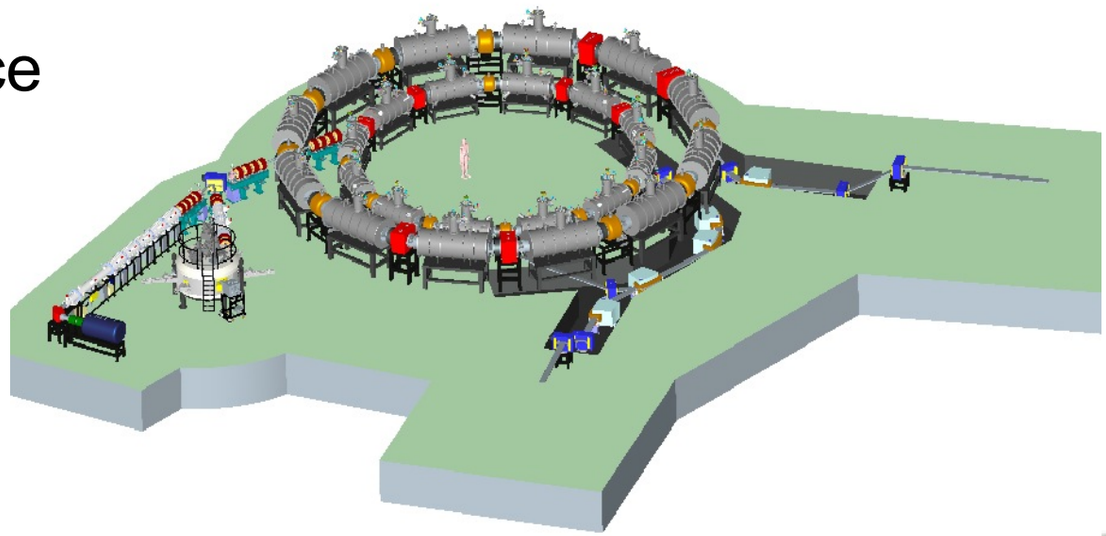
# Current status of FFAG designs

- A whole spectrum of designs have emerged in the last 5-10 years

Potential applications include:

- Accelerator Driven Subcritical Reactor
- Boron Neutron Capture Therapy
- Proton/carbon therapy
- Accelerator-based Neutron Source
- Emittance/Energy Recovery with Internal Target (ERIT)
- e-RHIC injector
- Muon or neutrino factory source
- + many more…



# 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
- In my view, the next big challenge is demonstrating high power operation

# 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.

Proceedings of the FFAG workshops