Fixed Field Alternating Gradient Accelerators: The Future Challenges

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Beam dynamics meets Magnets 2014

Outline

Brief introduction to FFAG

Challenges of FFAG accelerators in 4 area

- as an alternative to linacs
- as an alternative to synchrotrons
- as an alternative to cyclotrons
- as a beam transport line

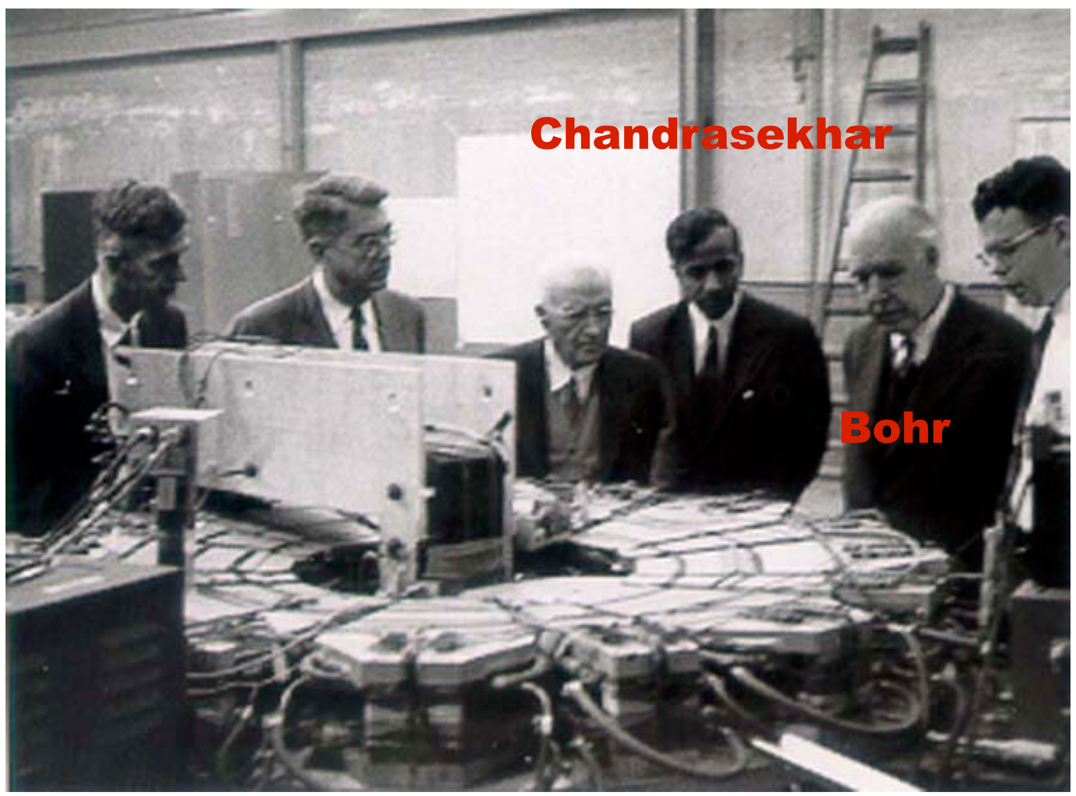
Challenge of FFAG magnets

Summary

Introduction

simple question

Is FFAG (Fixed Field Alternating Gradient) accelerator one family of cyclotron?



FFAG

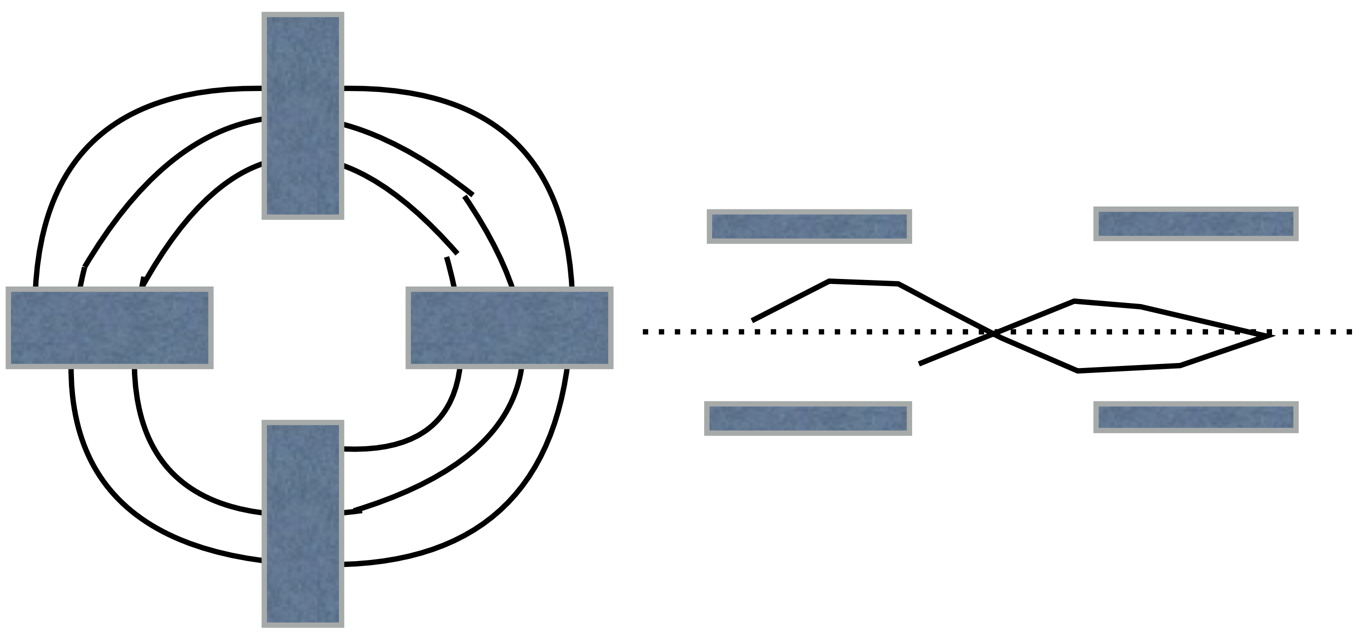
Cyclotron

Introduction

no simple answer

Yes, but someone says cyclotron is one family of FFAG.

top view side view



In both accelerators,

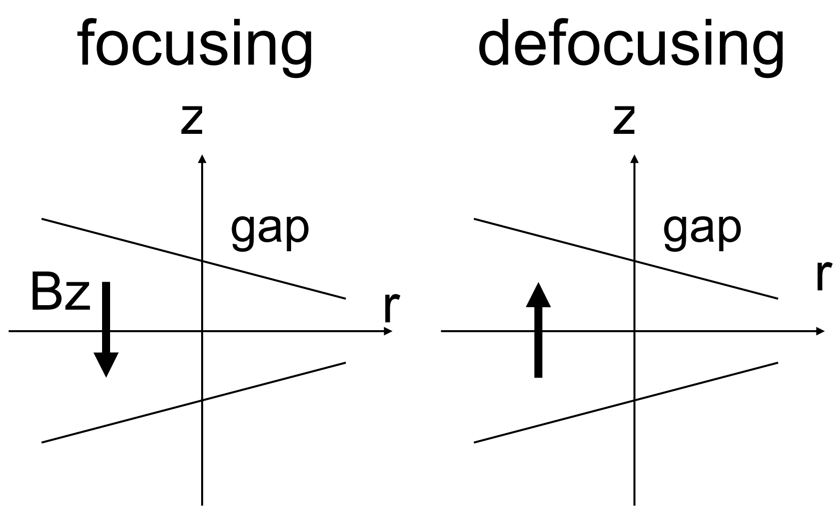
- Orbits spiral out with acceleration.
- Beams stay around median plane by transverse focusing.
- Have wide aperture in horizontal than vertical.

Pulsed beam FFAG ⟷ Synchro cyclotron

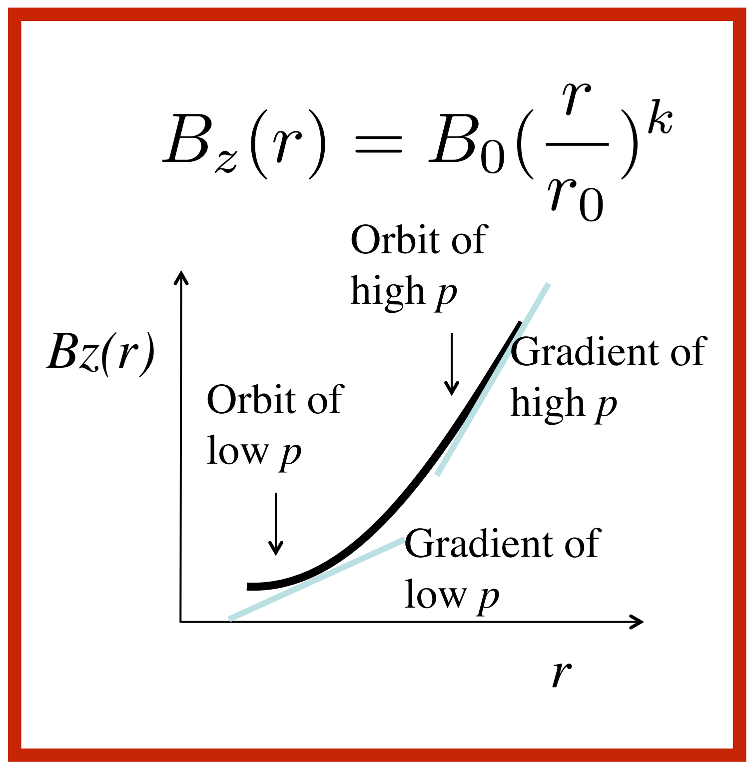
CW FFAG ⟷ Isochronous cyclotron

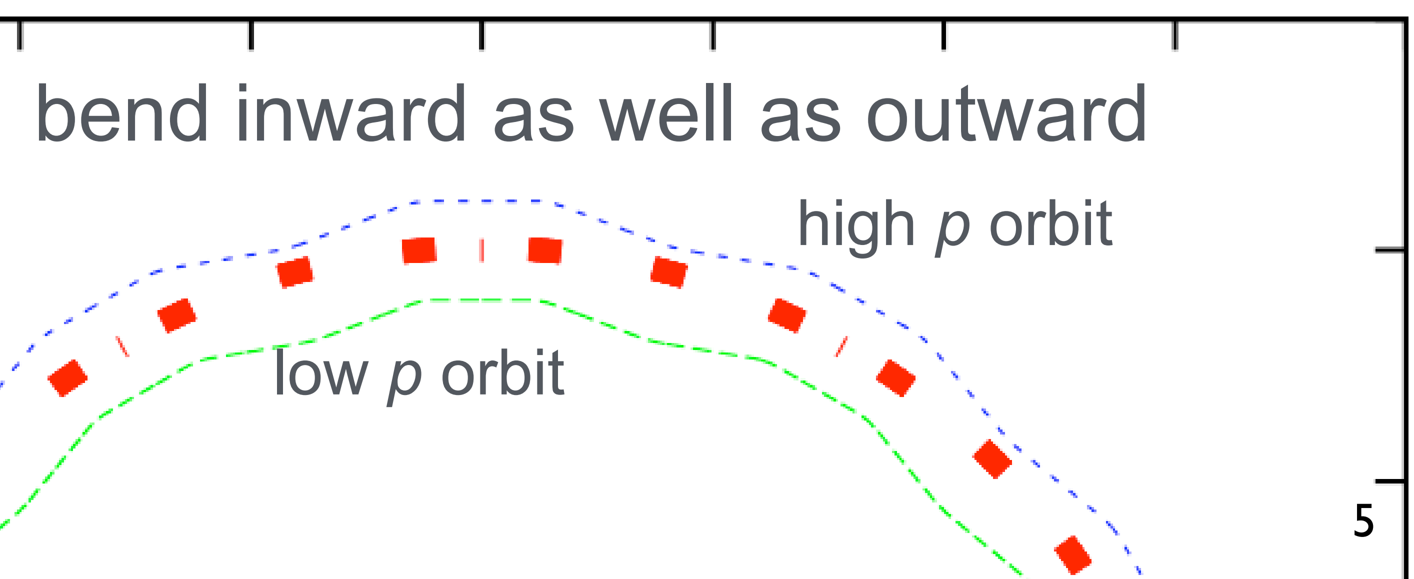
Introduction
one difference

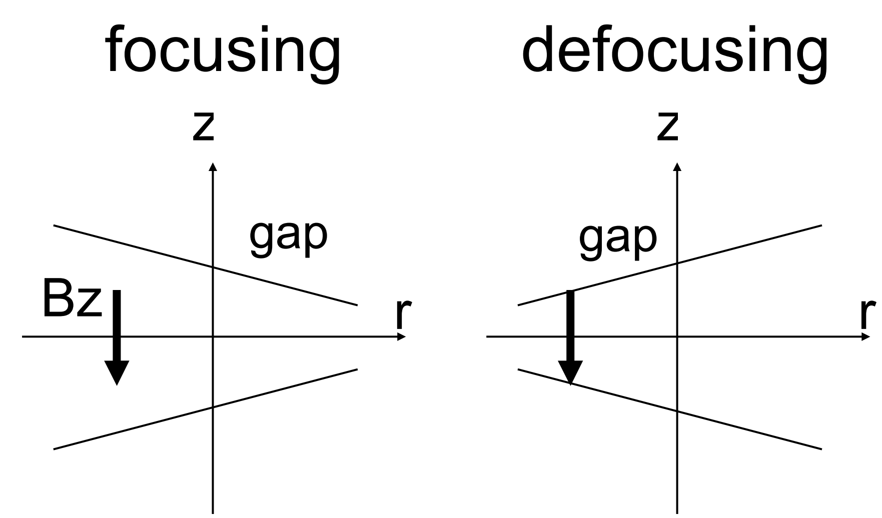
Alternating gradient (or strong focusing) makes FFAG different from cyclotron.



AG magnets in FFAG







AG magnets in synchrotron

Brief introduction to FFAG

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Challenge of FFAG magnets

Summary

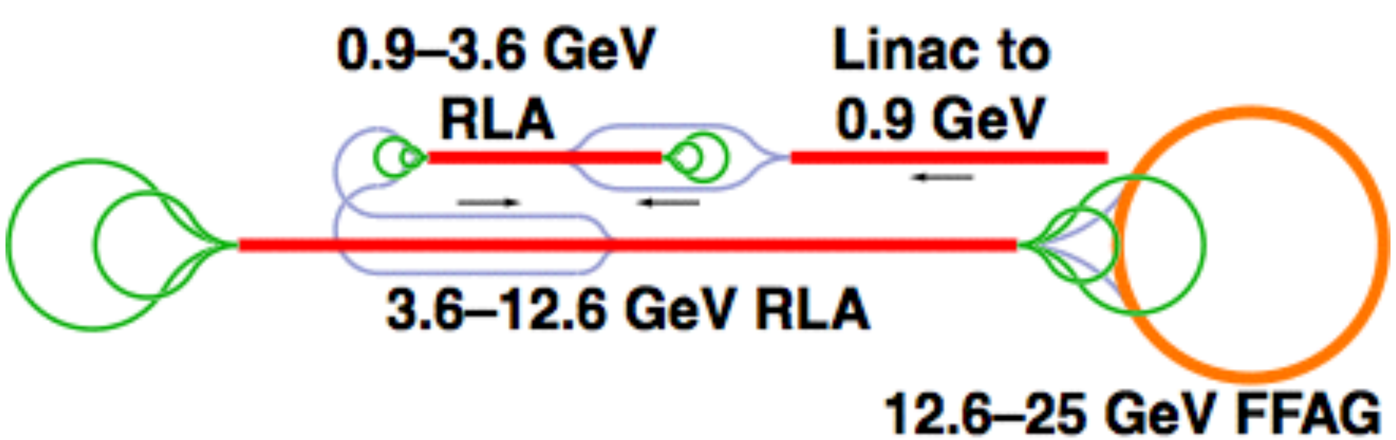
FFAG as an alternative to linac *demands*

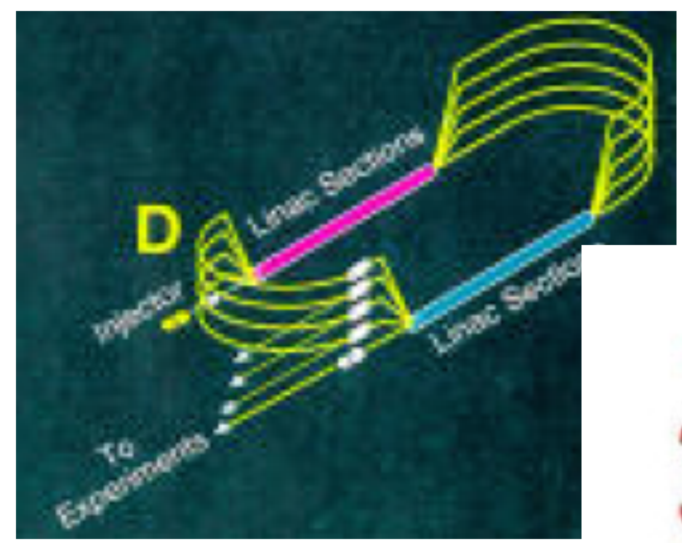
Short lived particles like muons and unstable ions have to be accelerated as quick as possible.

Linac is the obvious solution, but using accelerating structure more than once is a cost effective alternative.

One option is Recirculating Linear Accelerator (RLA). The other is FFAG.

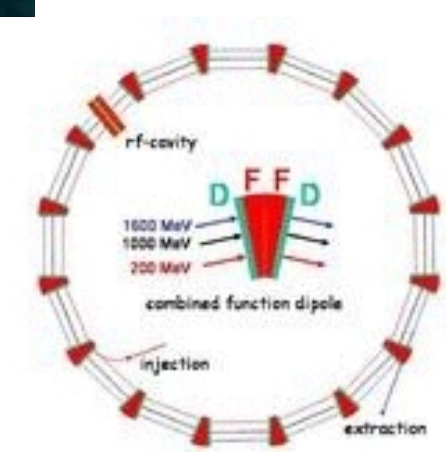
Neutrino Factory design





RLA

FFAG



RLA needs several arcs for each momentum. FFAG has single ring.

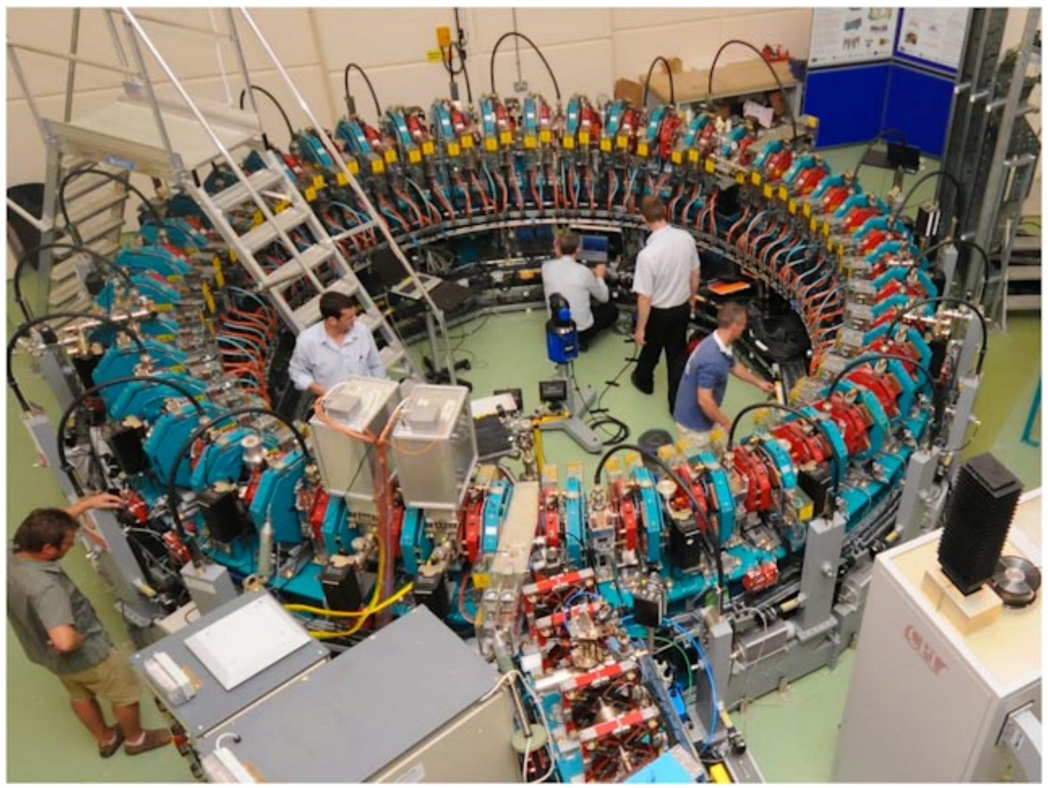
Beams circulates only 10 turns or less.

Ref. Machida, et.al., Nature Physics, Vol. 8, No. 3 (2012) 243.

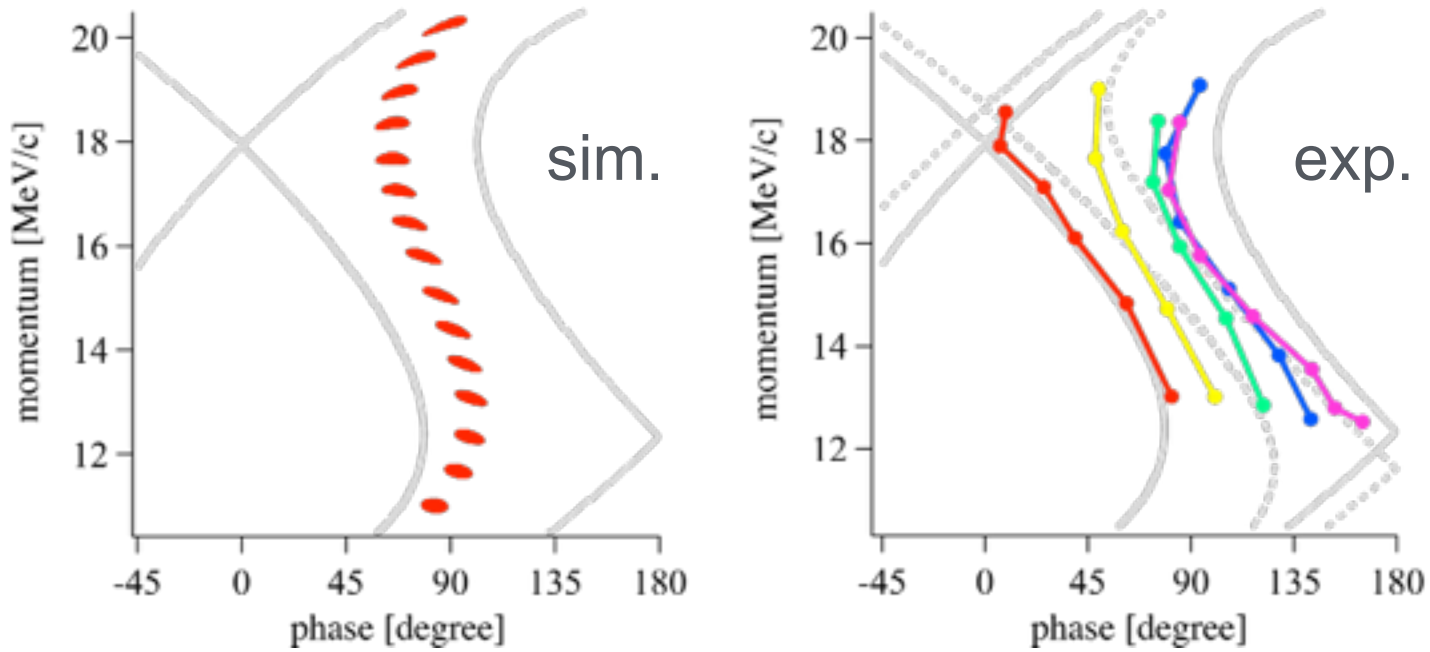
FFAG as an alternative to linac

what has been done

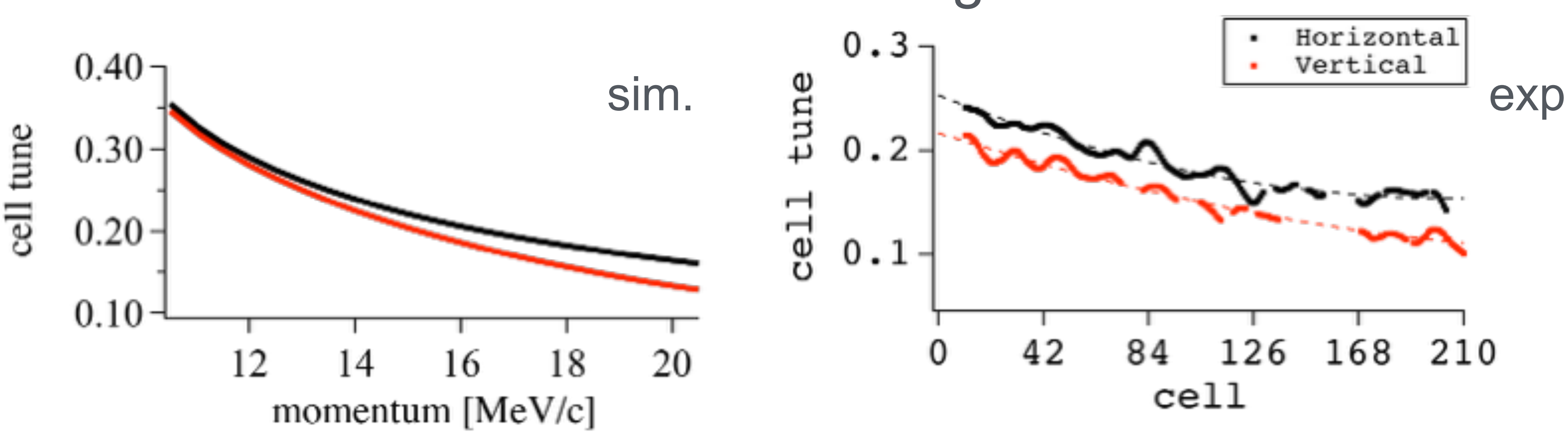
EMMA at Daresbury lab as demonstration of principle.



serpentine channel acceleration



resonance crossing



Ref. Berg, et.al., PRST-AB 9, 011001 (2006).

FFAG as an alternative to linac

challenge of injection and extraction

As in the case of any circular accelerator, injection and extraction are one of issues.

Muon beam emittance is large even after cooling.

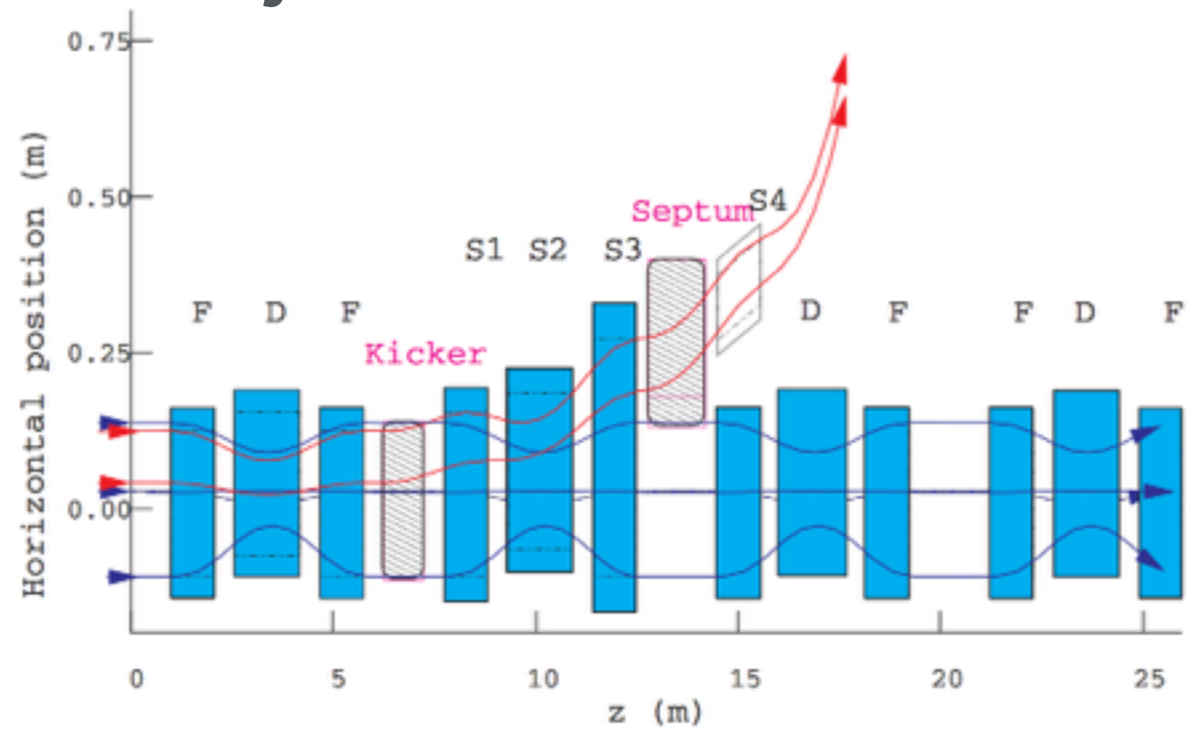


TABLE VII. Parameters for FFAG injection and extracting kickers.

Energy (GeV)	5	10	10	20
Type	Inject	Extract	Inject	Extract
Length (m)	1.5	1.5	1.5	1.5
Kick field (T)	0.37	0.51	0.78	0.58
Maximum field at the coils (T)	3.6	2.6	4.2	5.6
Vertical aperture (cm)	10	10	7.6	7.6
Horizontal aperture (cm)	25	25	19.5	19.5
Current (kA)	44	60	71	53
Supply voltage (kV)	±58	±60	±52	±48
Rise/fall time (ns)	640	950	875	1270
Pulse length (ns)	300	300	300	300
Stored energy (J)	850	1620	2280	1260

Brief introduction to FFAG

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Challenge of FFAG magnets

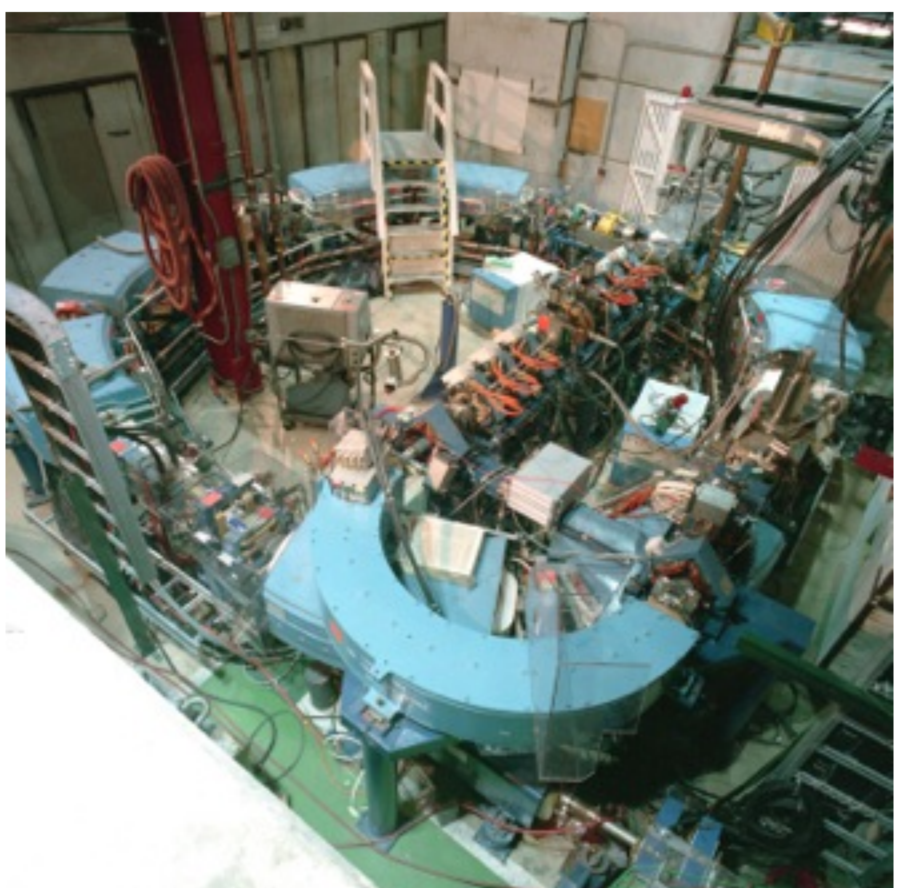
Summary

FFAG as an alternative to synchrotron *demands*

Need of high power pulsed beams for neutron and muon production.

Accelerators beyond ISIS, SNS, J-Parc and ESS

J-Parc



Loma Linda Proton Therapy Centre

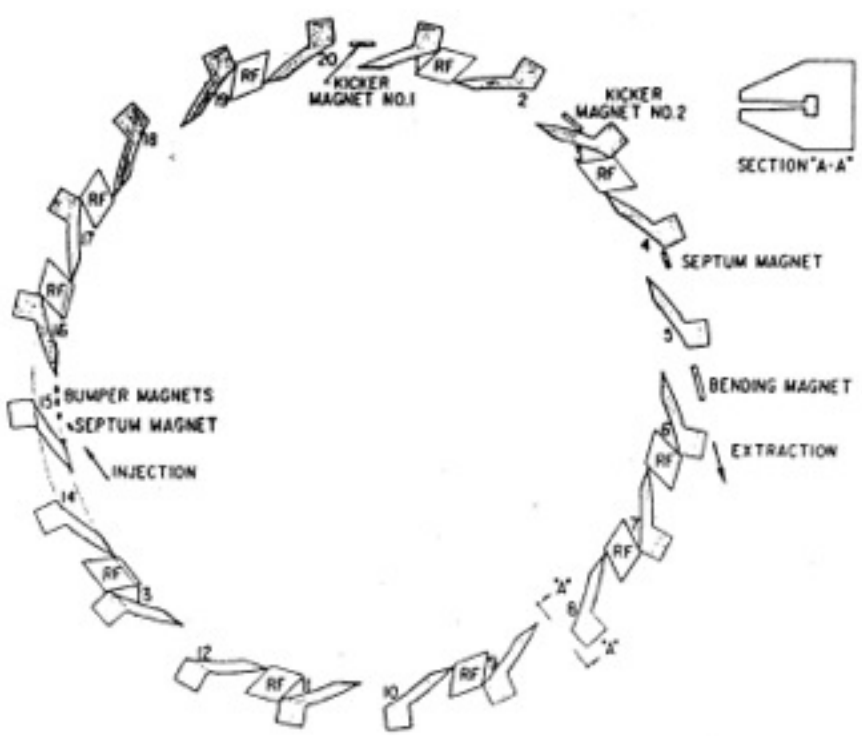
Compact, easy operation, and flexible accelerators for cancer therapy.

FFAG as an alternative to synchrotron

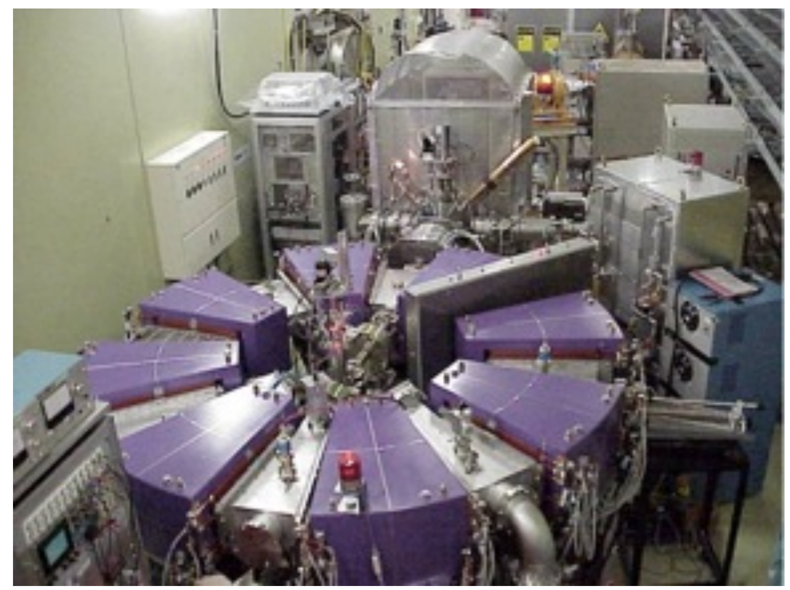
what has been done

R&D as an alternative to medium energy synchrotron.

Design work started in 1980s for spallation neutron source



Aspen at ANL



PoP 1 MeV proton FFAG with 1 kHz operation in 1999

150 MeV prototype FFAG

FFAG as an alternative to synchrotron

challenge of high power operation

High bunch charge

Fixed field magnets → increase repetition rate to obtain high beam power

However, high bunch charge (same level of synchrotron) is necessary to aim at higher beam power.

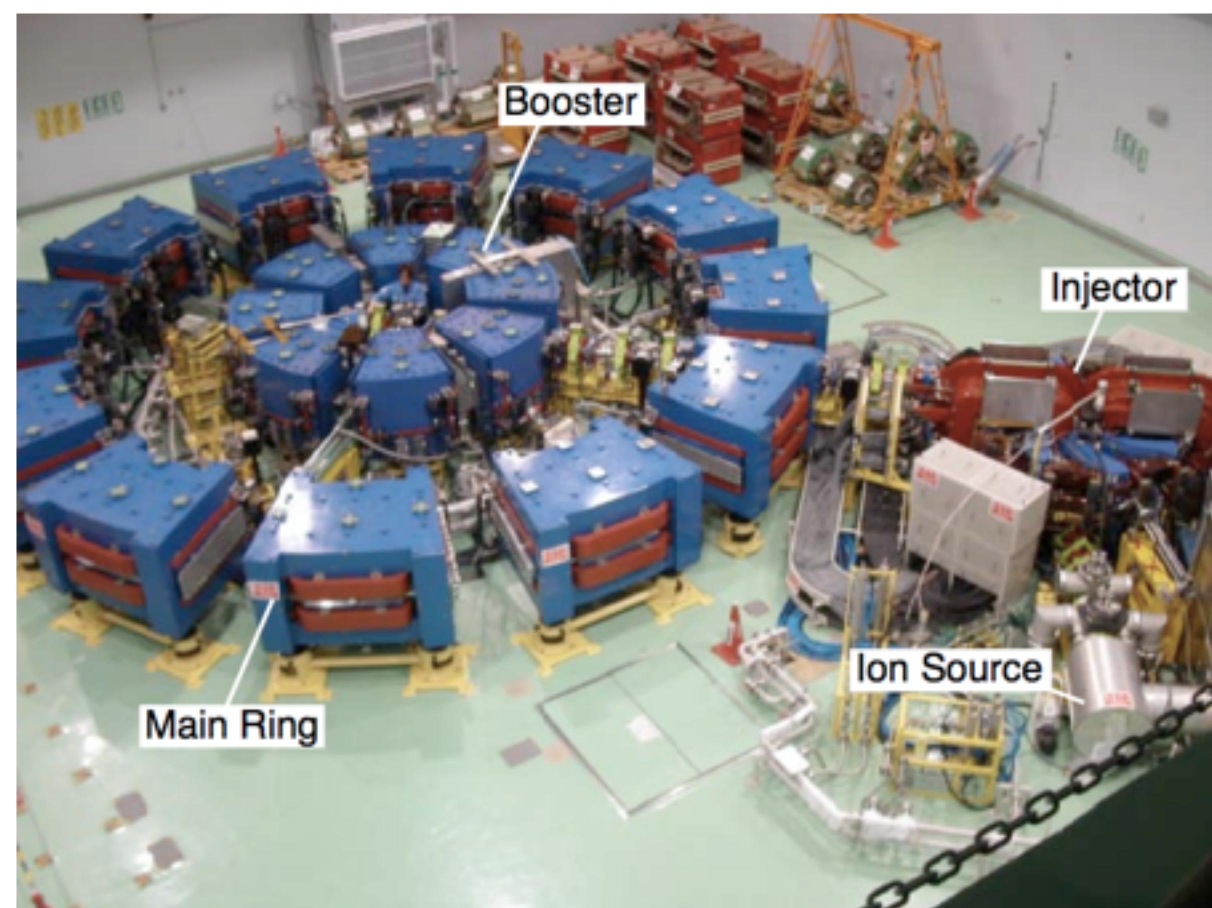
Experiments at KURRI

- Does FFAG can have the same level of tune spread as in synchrotron despite highly nonlinear lattice?

$$B_z = B_{z0}\left(\frac{r_0 + r}{r0}\right)^k$$
$$= B_{z0}\left(1 + \sum_{n=1} \frac{1}{n!} \frac{k(k-1)\cdots(k-n+1)}{r_0{}^n} r^n\right). \quad (3)$$

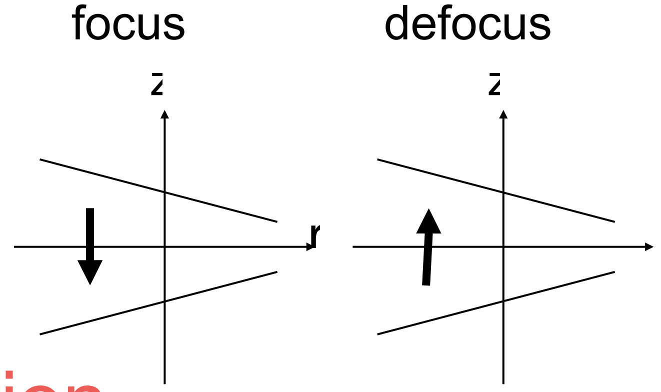
- Can we keep horizontal emittance larger than vertical to reduce space charge effects?

KURRI FFAG



FFAG as an alternative to synchrotron

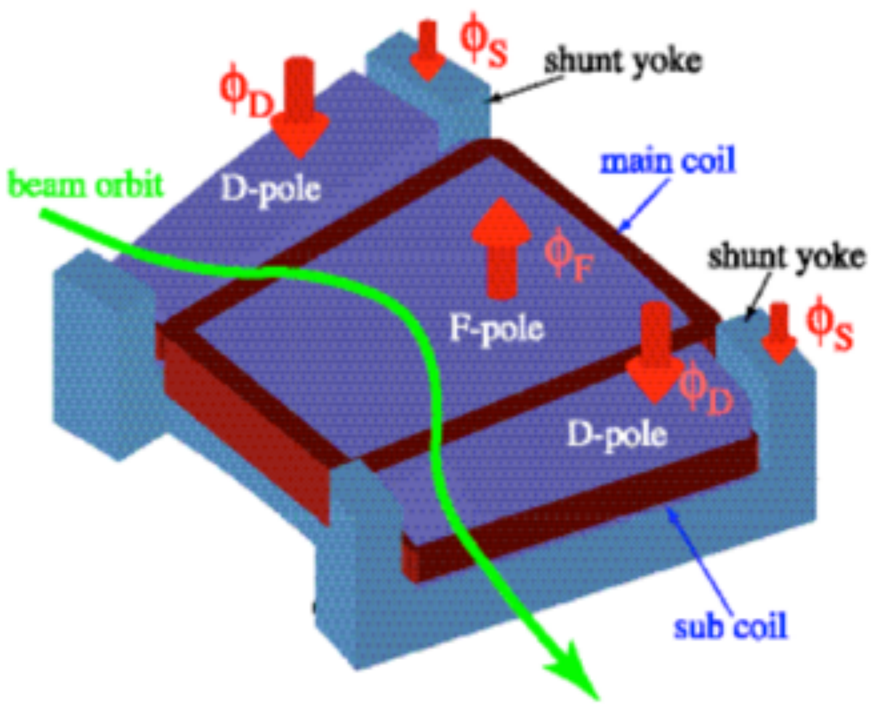
good challenge, but…



“York free” magnet

- Make it lighter
- Open space for injection/extraction

3D-view



It worked as we expected, but a lot of fringe field leakage.

Makes a problem when it coupled with magnetic material in the straight section.

Brief introduction to FFAG

Challenges of FFAG accelerators in 4 area

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- as an alternative to synchrotrons
- **as an alternative to cyclotrons**
- as a beam transport line

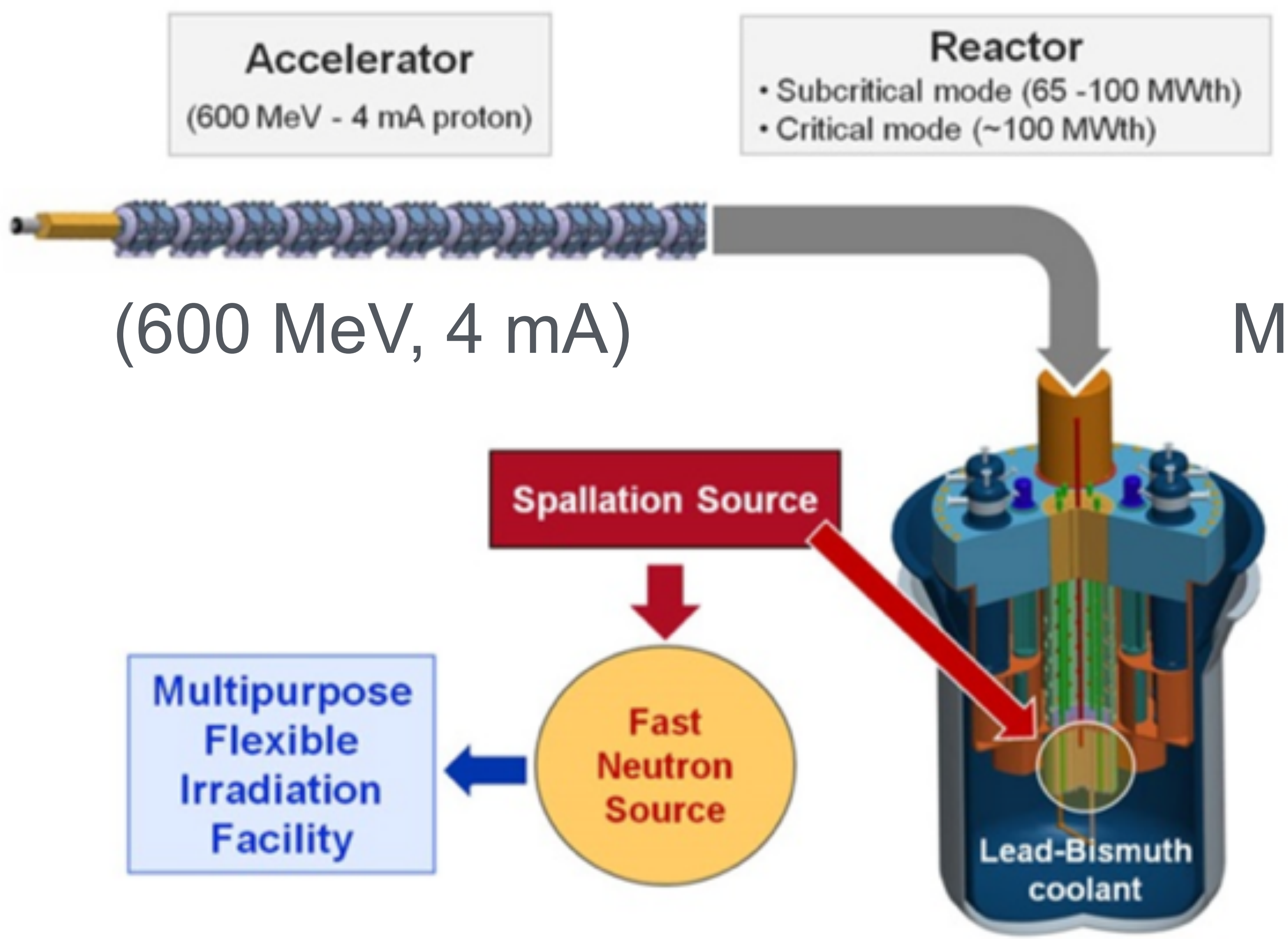
Challenge of FFAG magnets

Summary

FFAG as an alternative to cyclotron
demands

ADS needs >10 MW continuous beams with high reliability.

Superconducting linac and cyclotron are present option.

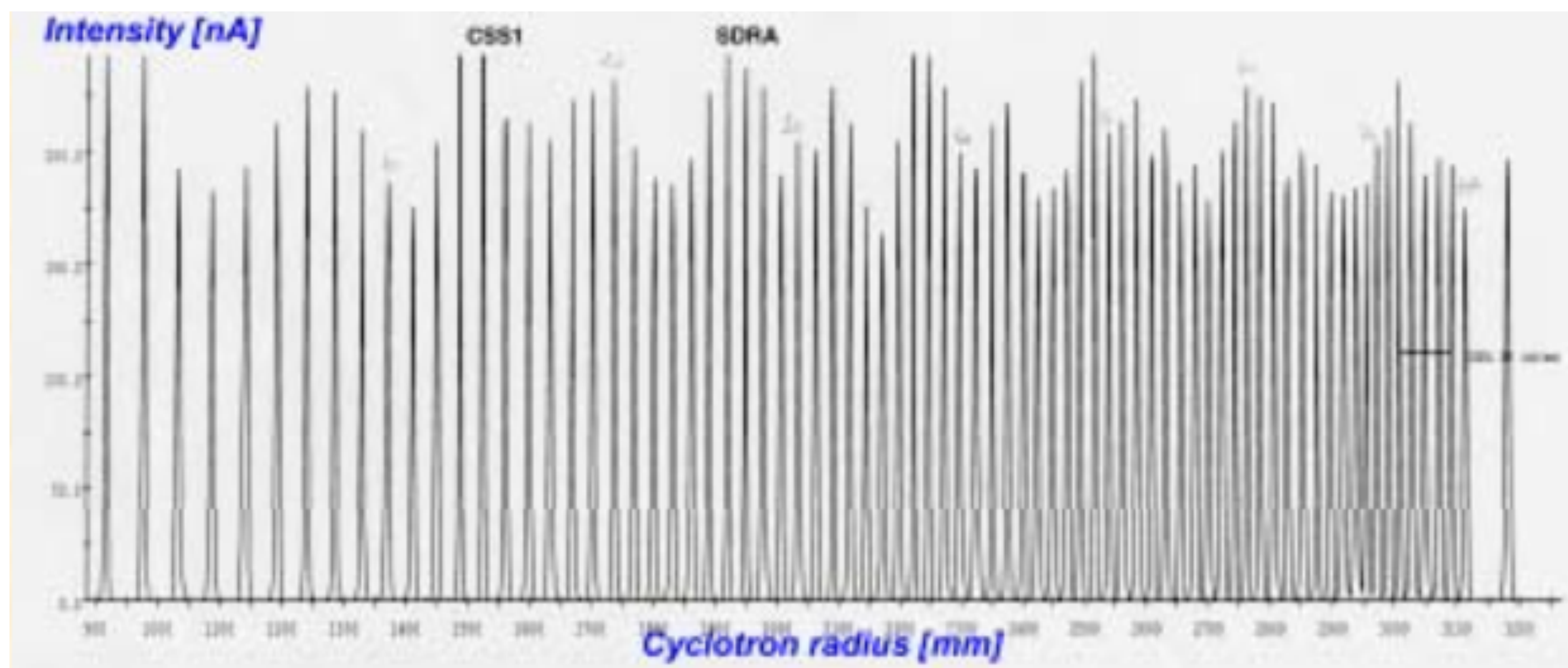


FFAG as an alternative to cyclotron
difficulties in cyclotrons

Beam loss at extraction due to small turn separation

High energy around or more than 1 GeV

Chautard, CAS “Small Accelerators” (2005)



FFAG may be able to overcome those problems.

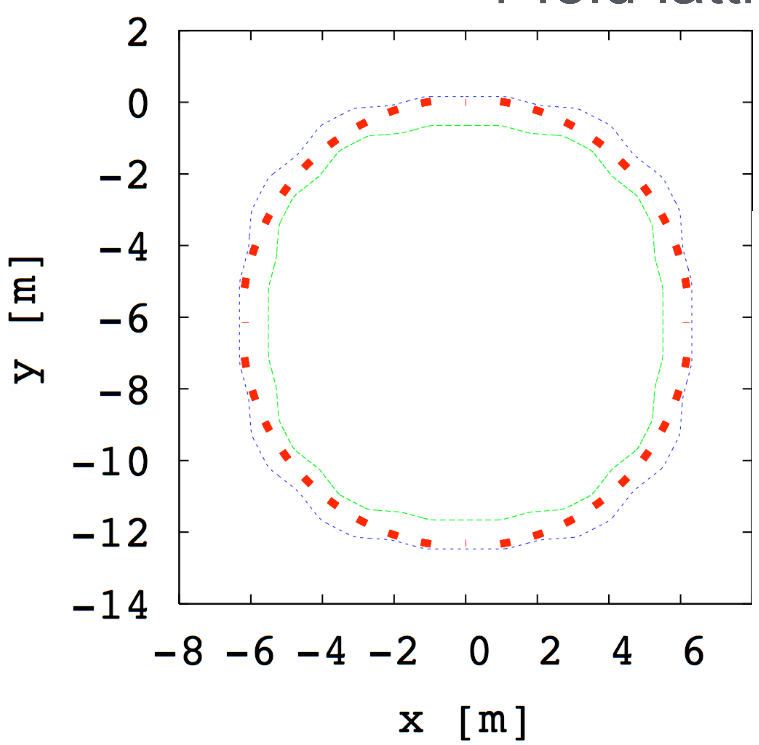
FFAG as an alternative to cyclotron

challenge of reducing beam loss

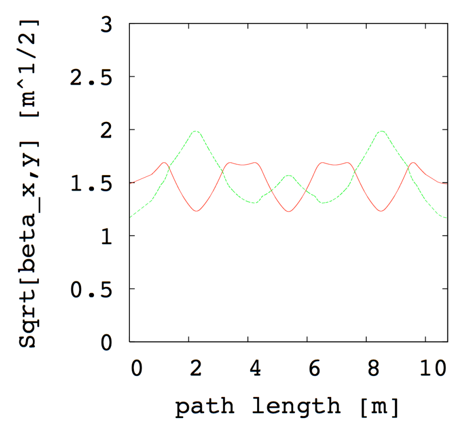
Synchrotron lattice evolved from circular to polygon with a concept of superperiodicity.

Similarly, FFAG lattice can design superperiod with long straight section.

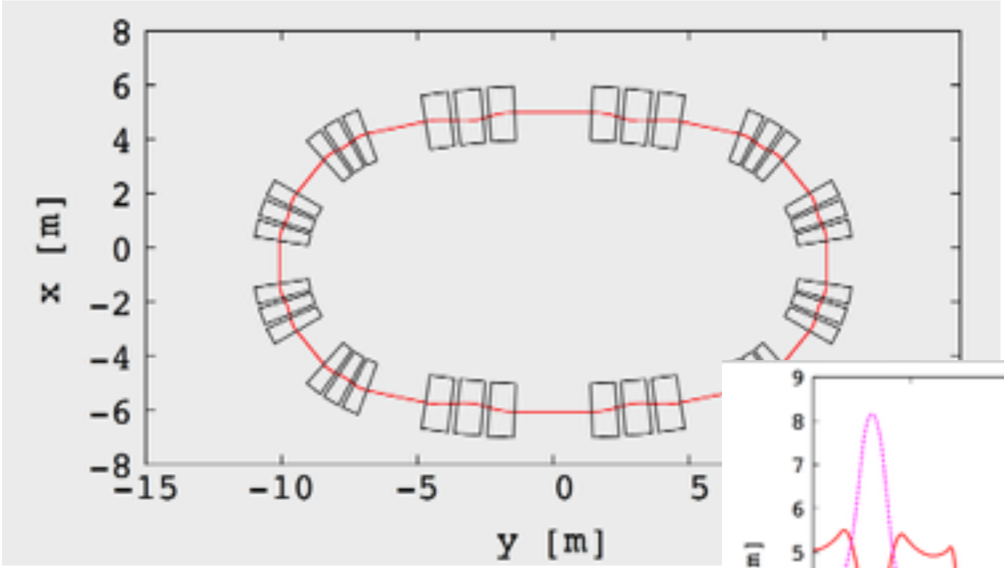
4-fold lattice



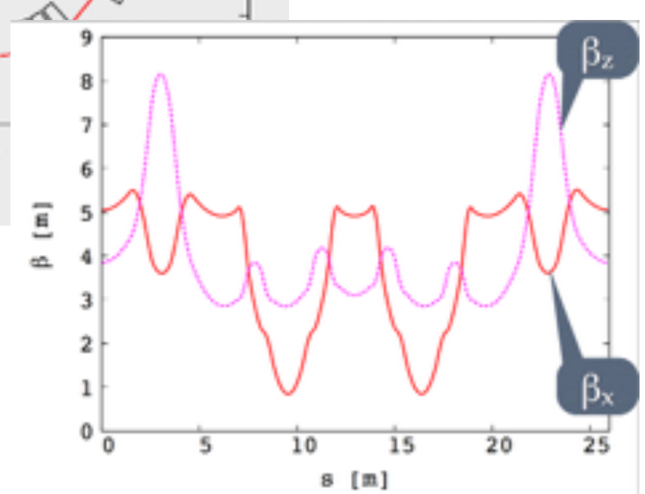
beta function



egg shape lattice (J.B.Lagrange)



beta function



Because of alternating gradient magnets, more freedom of the lattice structure, having insertion is easy and that gives more space for extraction.

FFAG as an alternative to cyclotron

challenge of increasing energy

The maximum energy of cyclotron is limited by transverse focusing field.

Mean field $B_z = \gamma B_0$, where $B_0 = \dfrac{mc}{eR}$ and $R = \dfrac{c}{2\pi f}$

R is the radius when $v \to c$

Focusing field as a derivative of mean field with respect to radius

$$\frac{dB_z}{dr} = \frac{B_0}{R}\frac{d\gamma}{d\beta} = \frac{B_0}{R}\beta\gamma^3 \text{ , where } r = \beta R$$

However, beam momentum increases as $\beta\gamma$

Therefore, focusing becomes too strong at high energy.

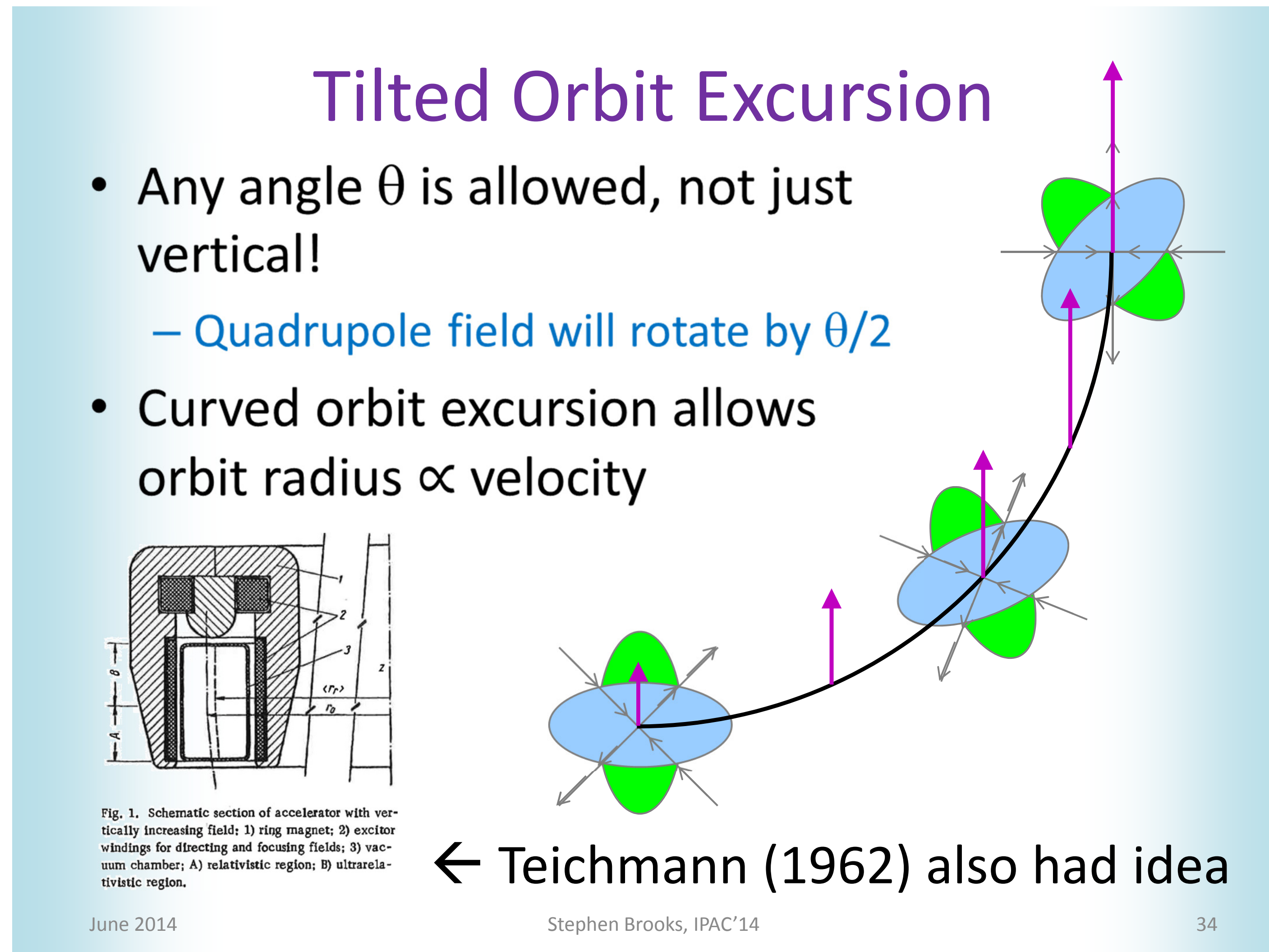
$$\frac{1}{B\rho}\frac{dB_z}{dr} = (\frac{\gamma}{R})^2$$

FFAG as an alternative to cyclotron

challenge of increasing energy

One way to overcome the maximum energy of cyclotron.

3D cyclotron (or FFAG)
by Stephen Brooks



Similar idea exited before

Ref. Teichmann, *Atomnaya Energiya* 12 (1962) 475.

FFAG as an alternative to cyclotron

challenge of increasing energy

How the magnetic field is specified?

Maxwell's equations in free space,

$$\partial_y \mathbf{B} = \begin{pmatrix} 0 & \partial_x & 0 \\ -\partial_x & 0 & -\partial_z \\ 0 & \partial_z & 0 \end{pmatrix} \mathbf{B}$$ rearranged from $\nabla \cdot \mathbf{B}=0$ & $\nabla \times \mathbf{B}=0$

In flat surface case, off surface field can be obtained as Taylor series,

$$\mathbf{B}(x,y,z) = \sum_{n=0}^{\infty} \frac{y^n}{n!} \partial_y^n \mathbf{B}(x,0,z)$$

In curved surface case, off surface field can be also obtained as Taylor series,

$$\mathbf{B}(x,y,z) = \sum_{n=0}^{\infty} \frac{(y-Y(x,z))^n}{n!} \partial_y^n \mathbf{C}(x,0,z)$$

where $\mathbf{C}(x,y,z) = \mathbf{B}(x, y+Y(x,z), z)$ with curved surface $Y(x,z)$

and

$$\partial_y \mathbf{C} = \begin{pmatrix} 1 & Y_x & 0 \\ -Y_x & 1 & -Y_z \\ 0 & Y_z & 1 \end{pmatrix}^{-1} \begin{pmatrix} 0 & \partial_x & 0 \\ -\partial_x & 0 & -\partial_z \\ 0 & \partial_z & 0 \end{pmatrix} \mathbf{C}$$

where $Y_x = \frac{\partial Y}{\partial x}$ etc.

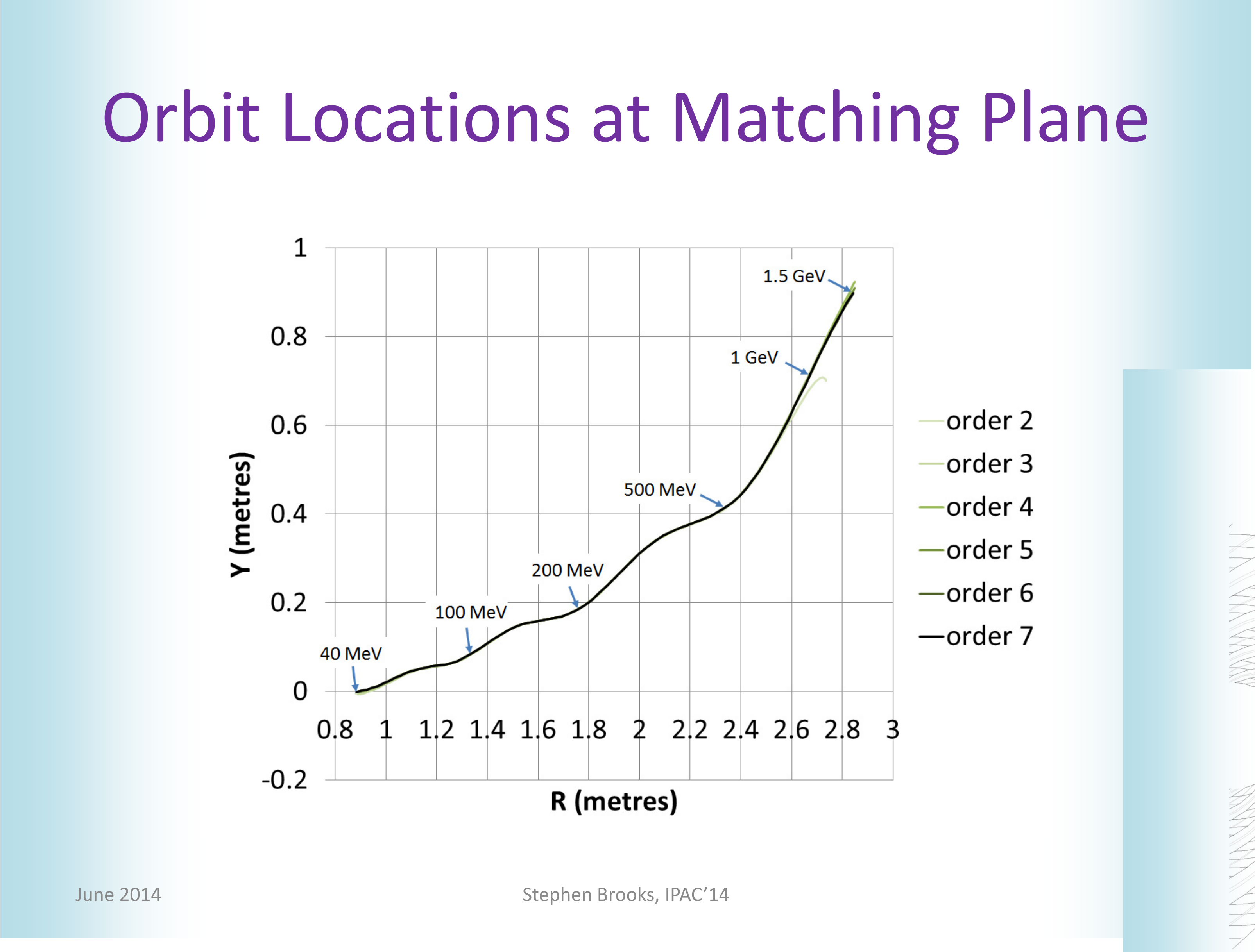
Ref. http://stephenbrooks.org/ap/report/2014-2/offsurface.pdf

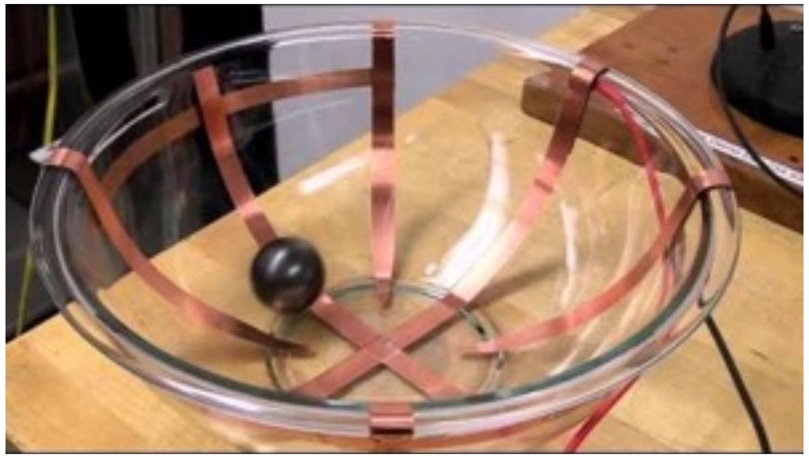
FFAG as an alternative to cyclotron

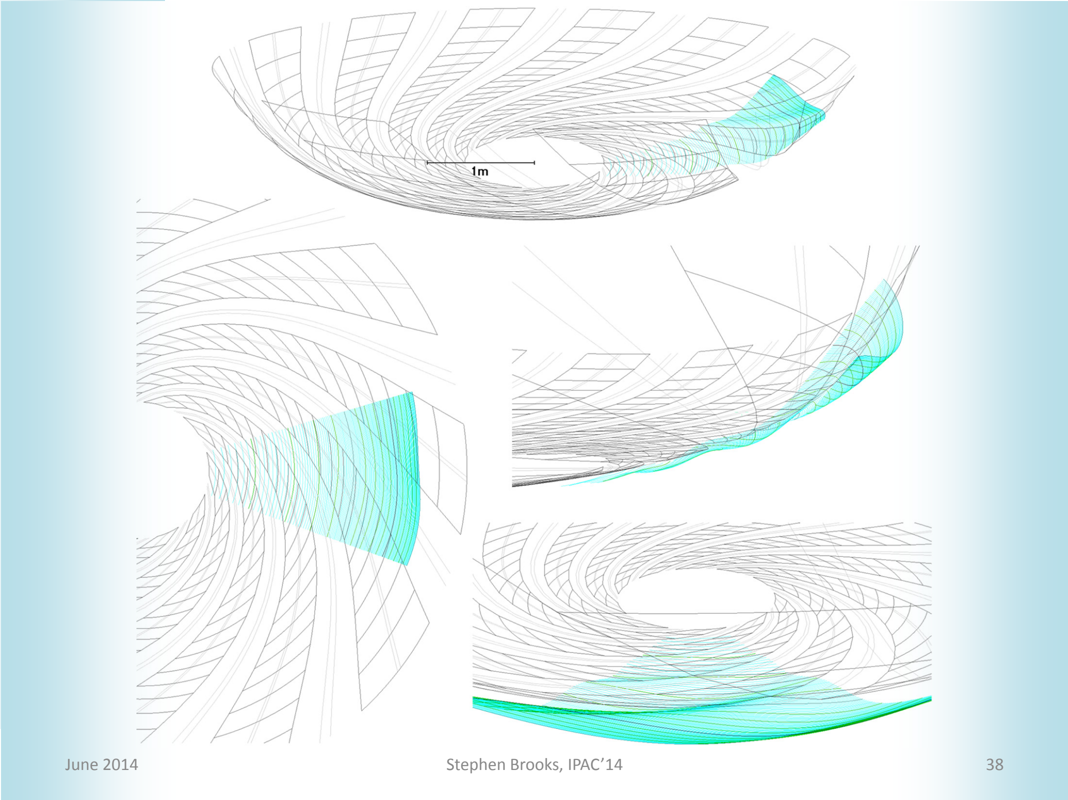
challenge of increasing energy

Orbit moves vertically as well as horizontally.

ping pong ball accelerator!







Science & Technology Facilities Council

Brief introduction to FFAG

Challenges of FFAG accelerators in 4 area

- as an alternative to linacs
- as an alternative to synchrotrons
- as an alternative to cyclotrons
- as a beam transport line

Challenge of FFAG magnets

Summary

FFAG as a beam transport line

demands

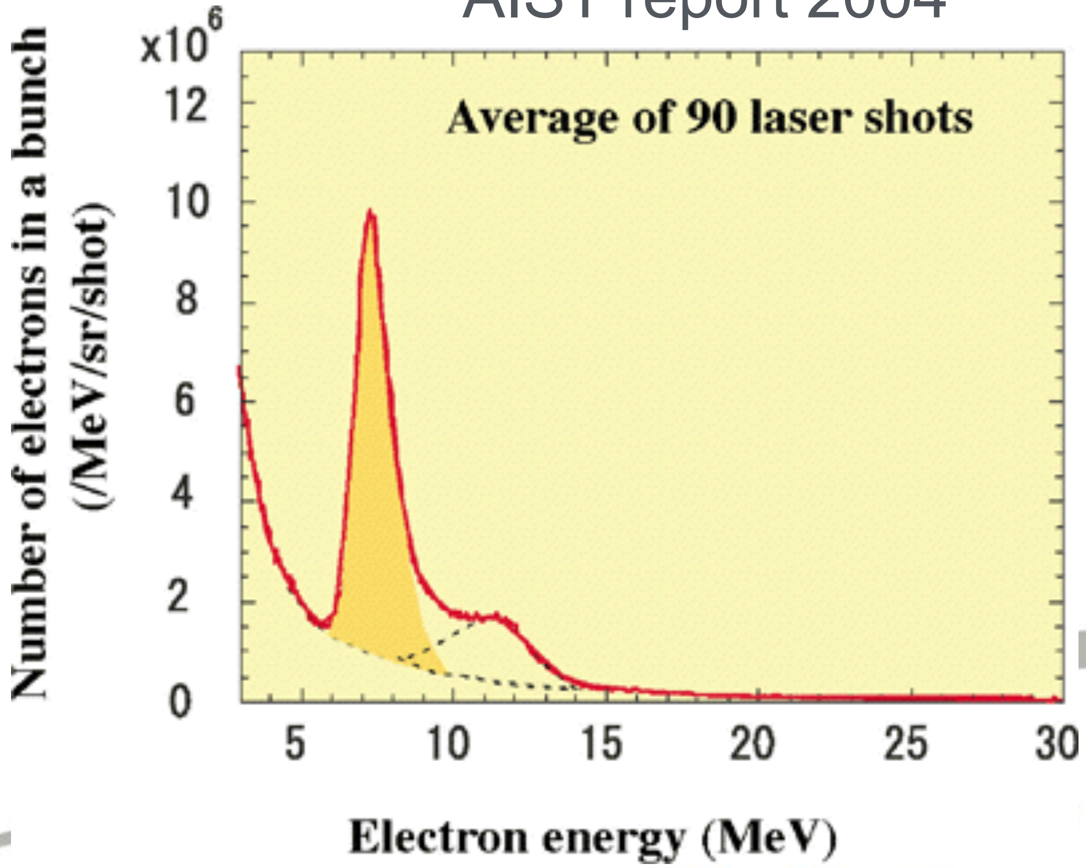
There are demands for large momentum acceptance in beam transport line.

Gantry: does not have to reset magnet strength to transport particles with different momenta.

Muon and secondary beams: momentum spread is large due to production process.

Beams from laser plasma accelerators: momentum spread is large due to acceleration mechanism.

AIST report 2004



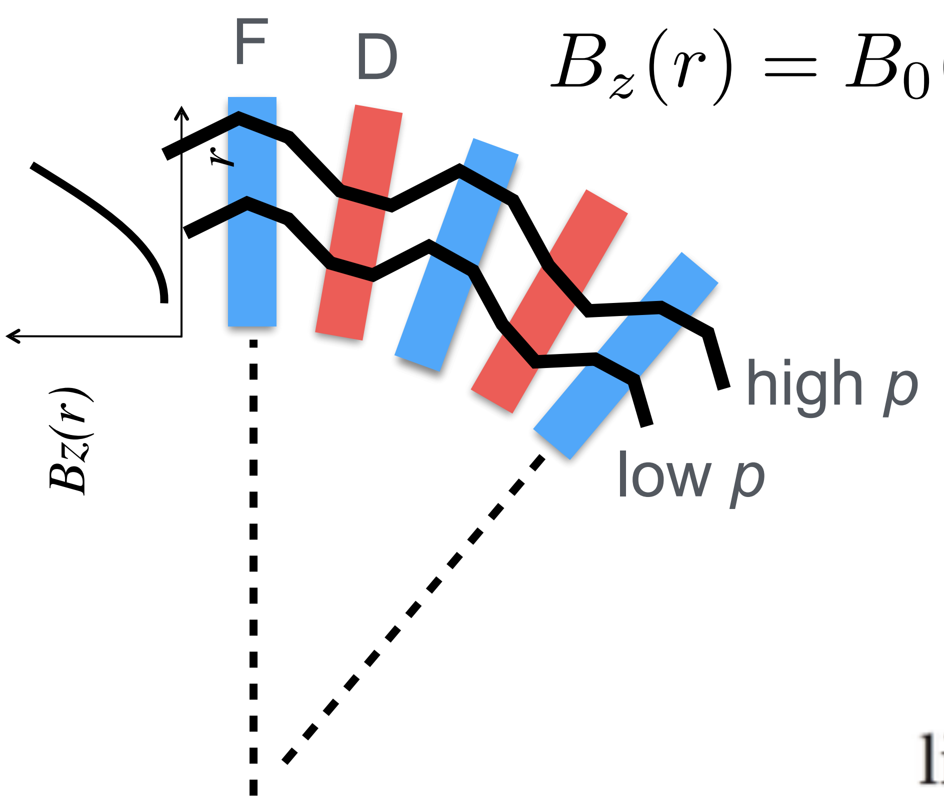
Ref. Machida, et.al., PRST-AB 13, 084001 (2010).

FFAG as a beam transport line

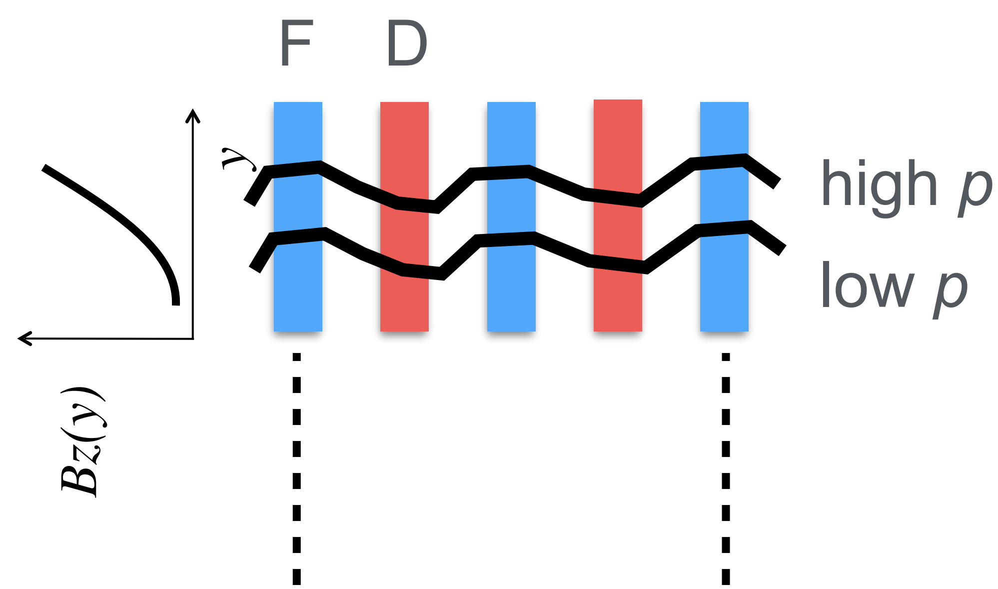
idea

FFAG magnets can be placed in straight line.

$$B_z(r) = B_0\left(\frac{r}{r_0}\right)^k$$



radius $\longrightarrow \infty$



$$\lim_{y_0\to\infty}\left(\frac{y_0+y}{y_0}\right)^k = \lim_{y_0\to\infty}\left[\left(1+\frac{y}{y_0}\right)^{y_0/y}\right]^{(k/y_0)y}$$

$$= \lim_{y_0\to\infty}\left[\left(1+\frac{y}{y_0}\right)^{y_0/y}\right]^{(n/\rho)y} = \exp\left(\frac{n}{\rho}y\right)$$

This can been seen as the limit of infinitely large radius.

The field profile becomes exponential.

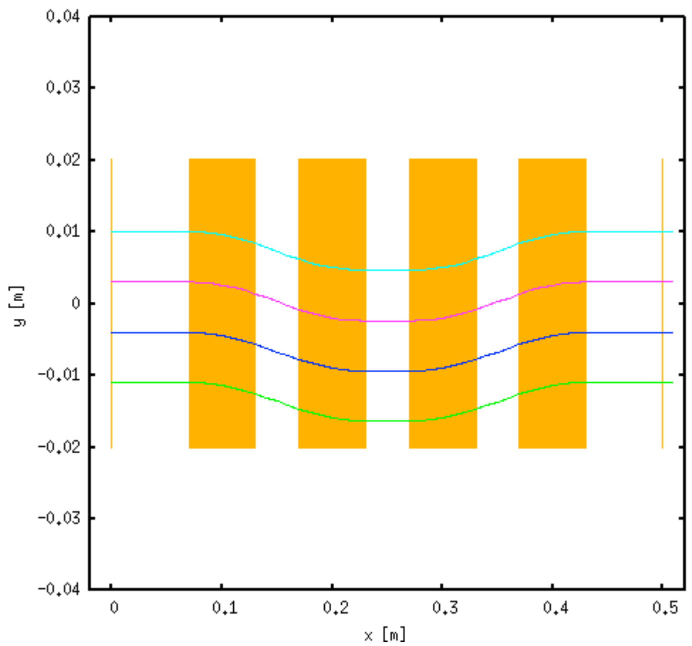
FFAG as a beam transport line

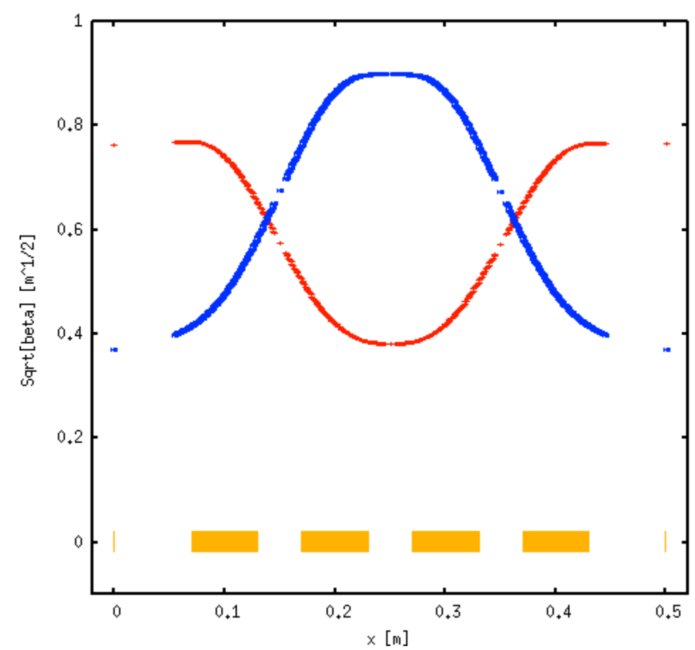
regular and dispersion matching cell

Alternating Gradient lattice (FDDF) with FFAG magnets can make beam transport line with large momentum acceptance.

Beta function for 0.1 ~ 0.8 GeV/c beams is identical.

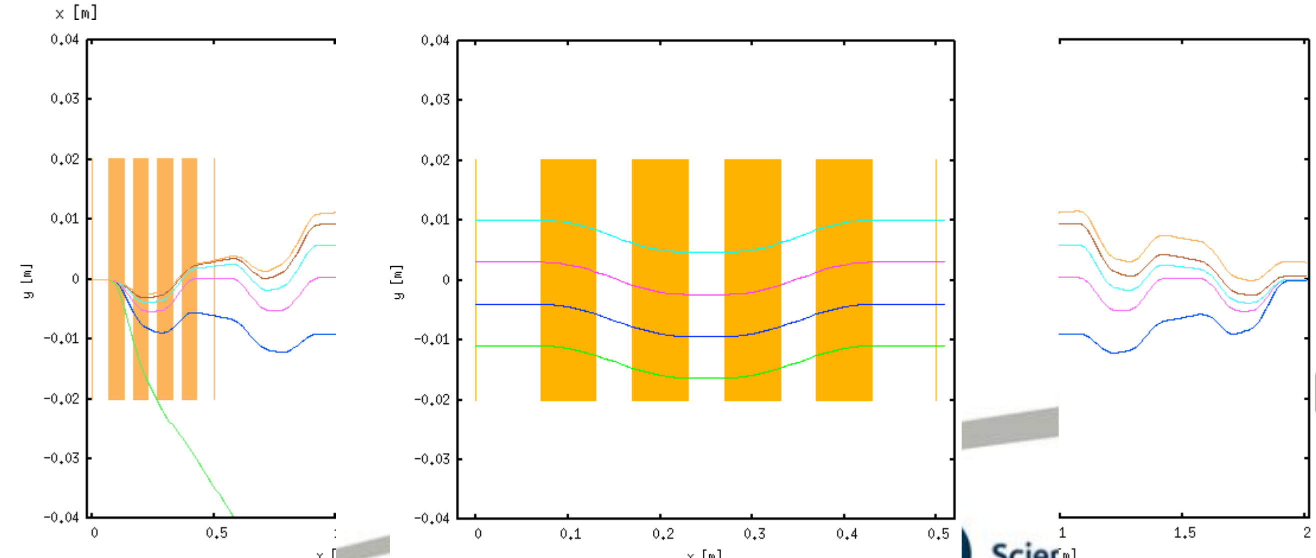
0.8 GeV/c
0.4 GeV/c
0.2 GeV/c
0.1 GeV/c





$$B_z(r) = B_0\left(\frac{r}{r_0}\right)^k$$

In the beginning and the end, we can insert dispersion matching section with as twice as much larger field index magnets.



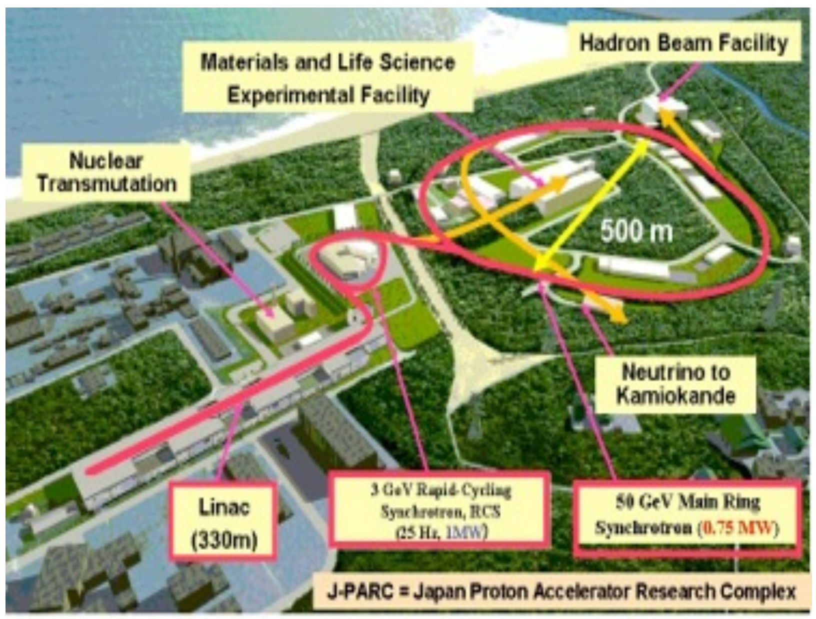
k=100 ~50 100

Ref. Lagrange, et.al., NIM A, Vol. 691 (2012) 55.

FFAG as a beam transport line

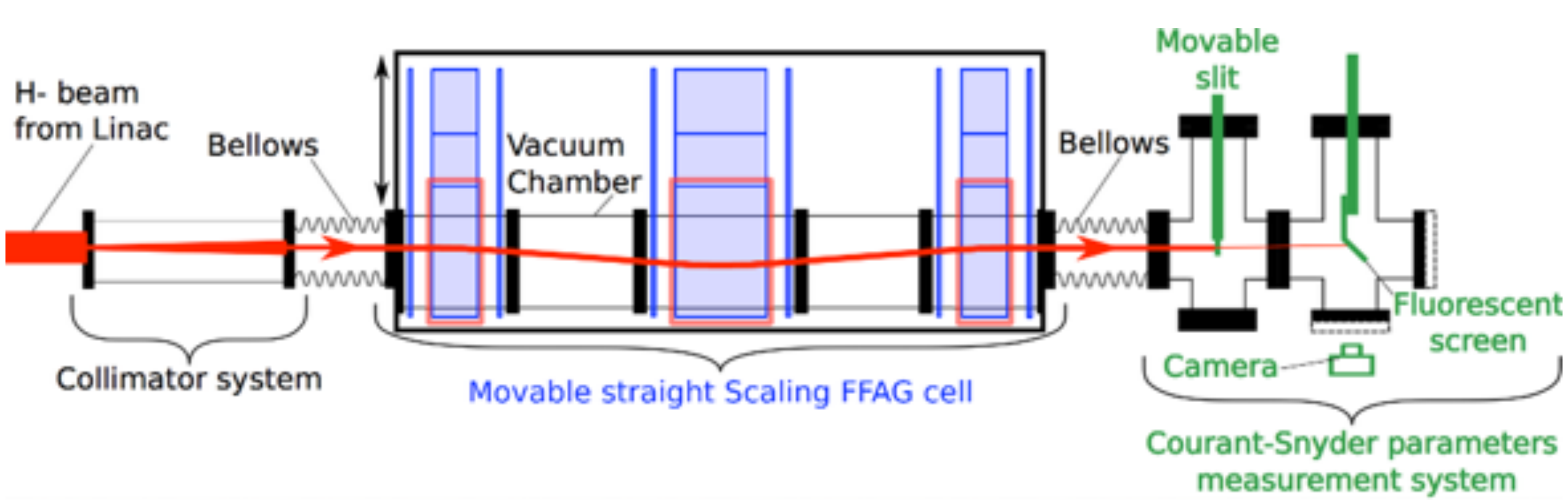
what has been done

Experimental large momentum acceptance has been validated at KURRI by J.B. Lagrange.



$$B_z(y) = B_0 \exp\left(\frac{n}{\rho} y\right)$$

y horizontal coordinate



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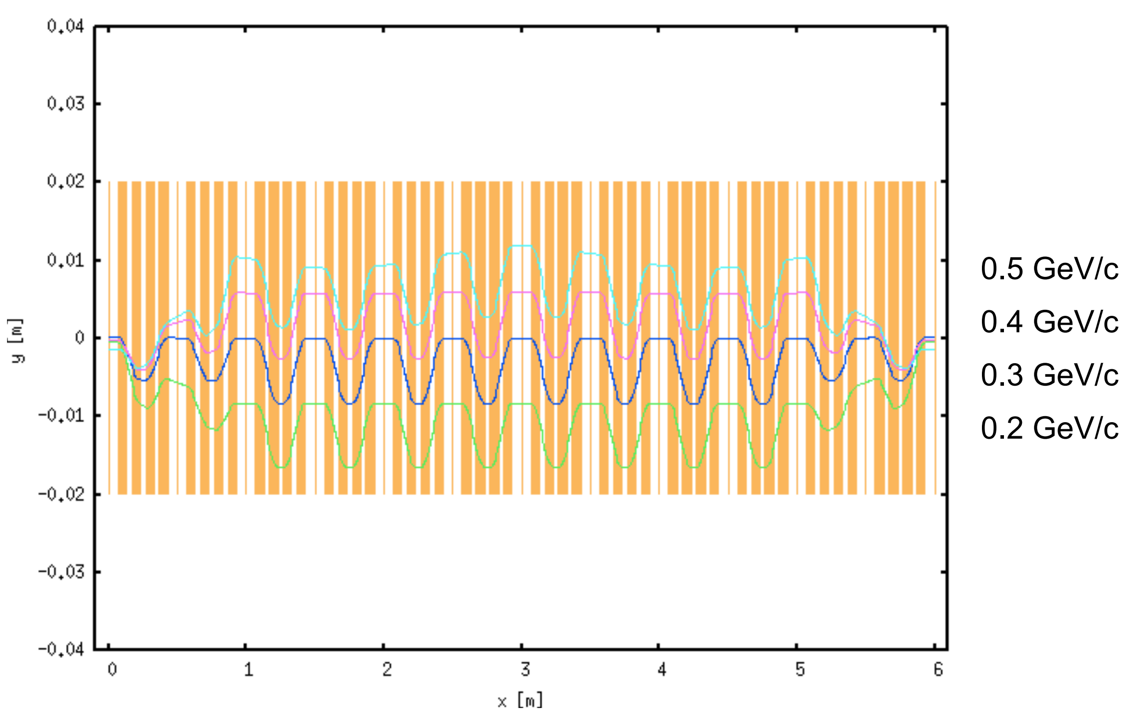
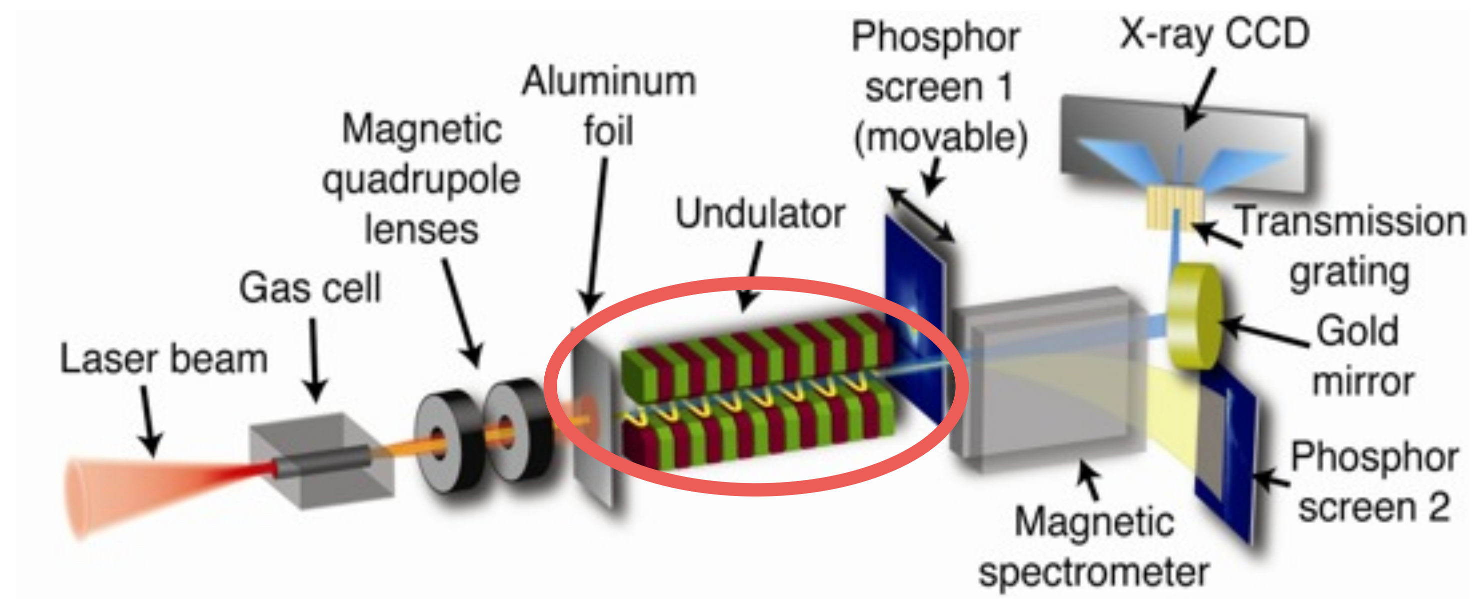
FFAG as a beam transport line

future challenge

FFAG undulator with large momentum acceptance for the beams from laser plasma accelerators?





Ref. Fuchs, et.al., Nature Physics, Vol. 5, No. 11 (2009) 826.

Ultimate undulator with field gradient!?

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Challenge of FFAG magnets

Summary

Challenge of FFAG magnets in all area

flexibility in operation

In synchrotrons

Orbit and optics are controlled as a function of time (t).

Dipole strength is adjusted as a function of time.

Gradient of quadrupole is adjusted as a function of time.

In FFAGs (and cyclotrons)

Orbit and optics are controlled as a function of space coordinates (x,y,z).

Field profile should be adjusted as a function of space coordinates.

FFAGs in particular, AG focusing means there are many azimuthal harmonics.

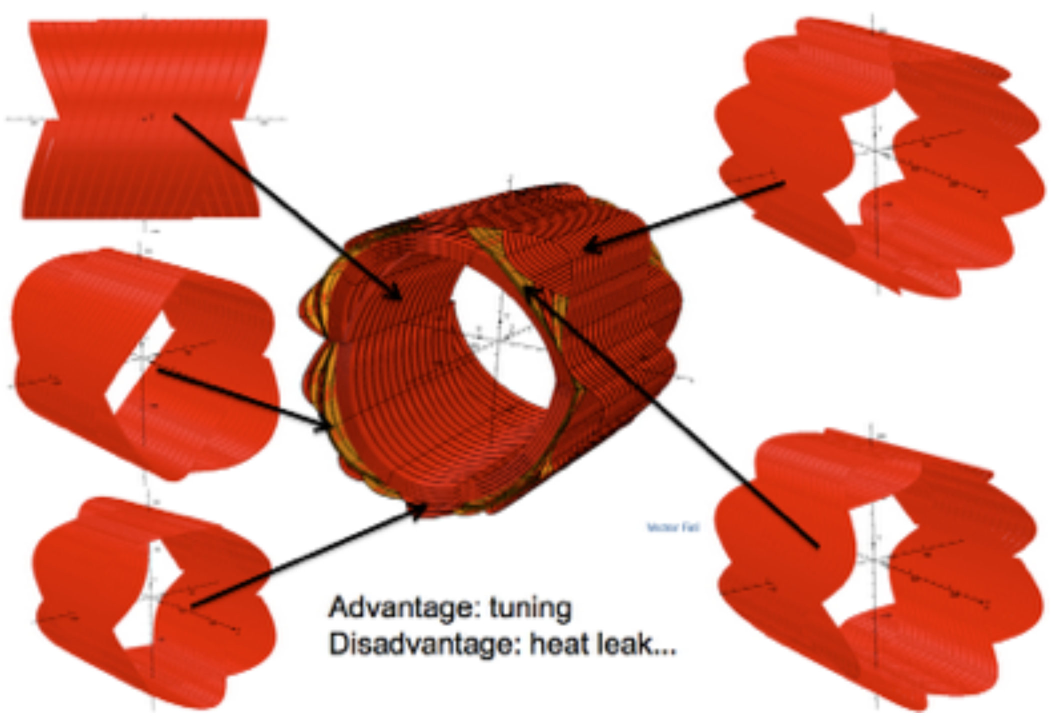
Ref. Sheehy, et.al., PRST-AB 13, 040101 (2010).

Challenge of FFAG magnets in all area

combination of multipoles

FFAG magnetic field profile is decomposed by multipoles and keep individual strength as a control knob.

In practice, the first few normal multipoles are enough to shape field profile which satisfies beam dynamics.



$$B_z = B_{z0}\left(\frac{r_0 + r}{r0}\right)^k = B_{z0}\left(1 + \sum_{n=1} \frac{1}{n!} \frac{k(k-1)\cdots(k-n+1)}{r_0{}^n} r^n\right). \quad (3)$$

dipole, quadrupole, sextupole, decapole, dodecapole

by Holger Witte

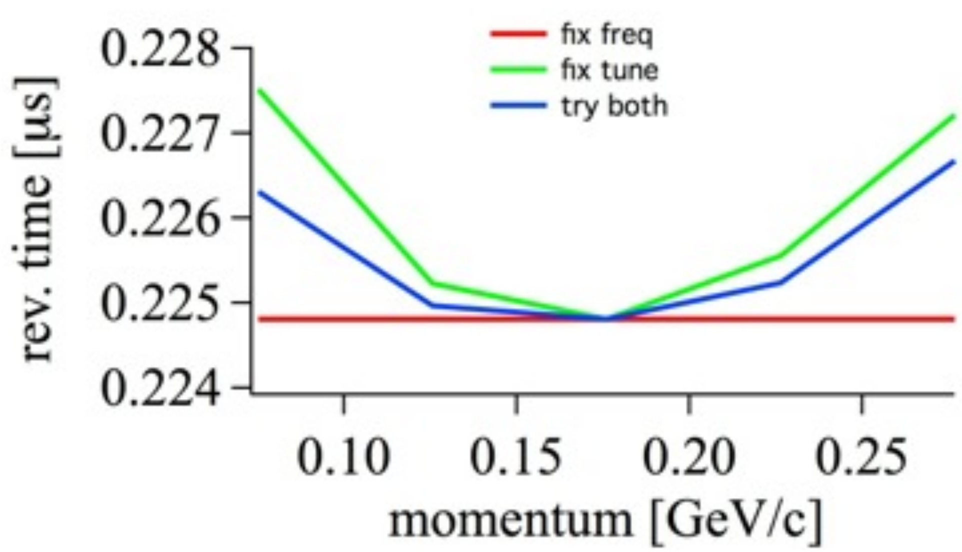
Challenge of FFAG magnets in all area

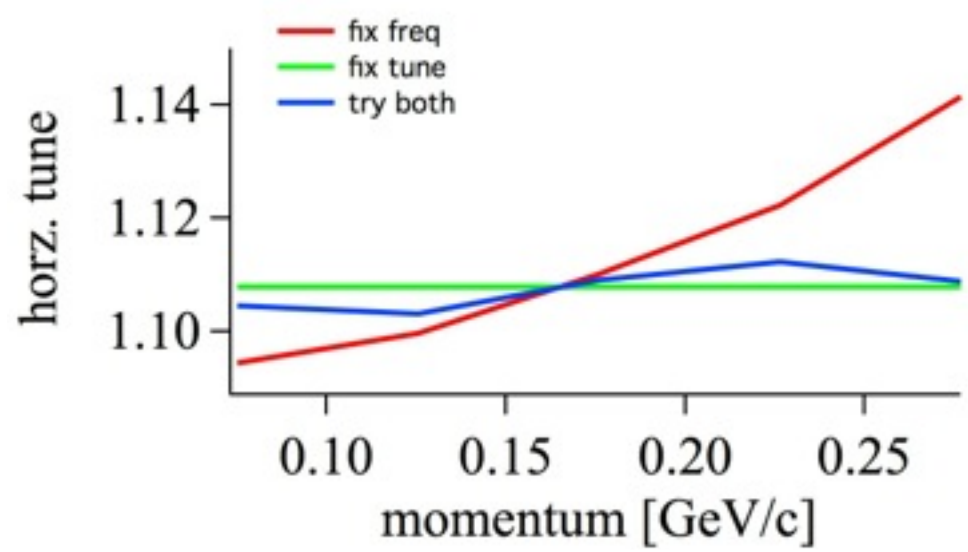
proposal of small test ring

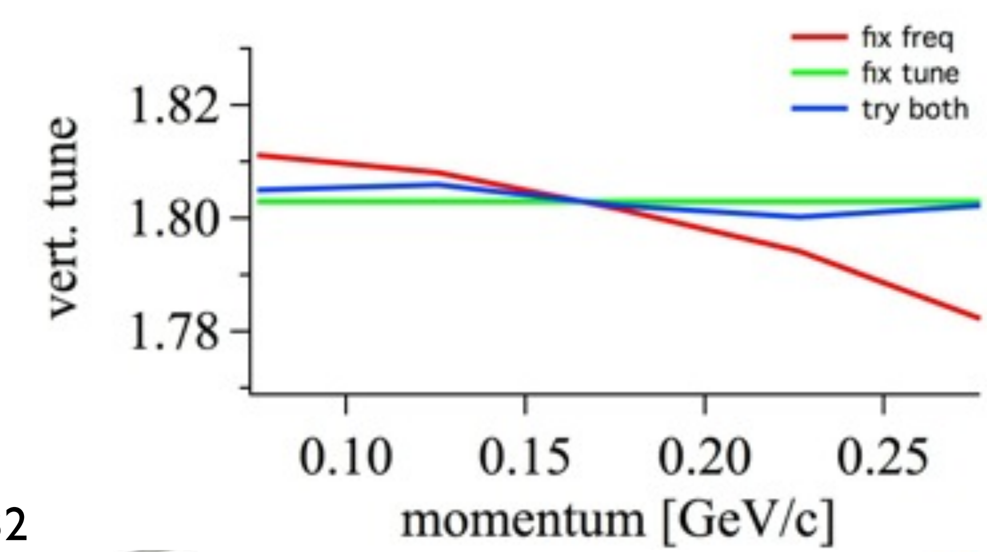
Taking the first 5 multipoles (knobs), adjust the lattice either cyclotron like (fixed frequency) or FFAG like (fixed tune) or in between.

cyclotron mode
(fixed frequency)

FFAG mode
(fixed tune)







Summary
challenges

As a linac

Large aperture devices for injection and extraction.

As a synchrotron

High bunch charge operation.

Experimental study is going on at KURRI.

As a cyclotron

Optics with idea borrowed from synchrotron (e.g. long straight).

Magnets which put the beam both in H and V directions.

As a beam transport

Large momentum acceptance beam line.

FFAG undulator

Magnet challenge

Do we have necessary and sufficient knobs?

Thank you for your attention.