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# FFAG for high power applications

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This is not a talk of high power FFAG “design”, but a proposal of “a new way to design” FFAG.

# Background philosophy
## *toward high power FFAG*

High power FFAG needs innovative design.

- CW (fixed frequency) operation
- Fixed transverse tune
- Vertical excursion
- Minimise loss at injection and extraction

However, the machine should be easy to construct/operate.

- Not too tight specification of hardware
- Be able to cope with "unexpected"
- Enough knobs to optimise operational condition

# Looking back for last 10 - 15 years

## *issues of fixed field accelerators*

Principle works

- Scaling design gives almost constant transverse tune.
- Parabolic shape of orbital period creates serpentine channel.

Did we pay much attention to the operation aspect?

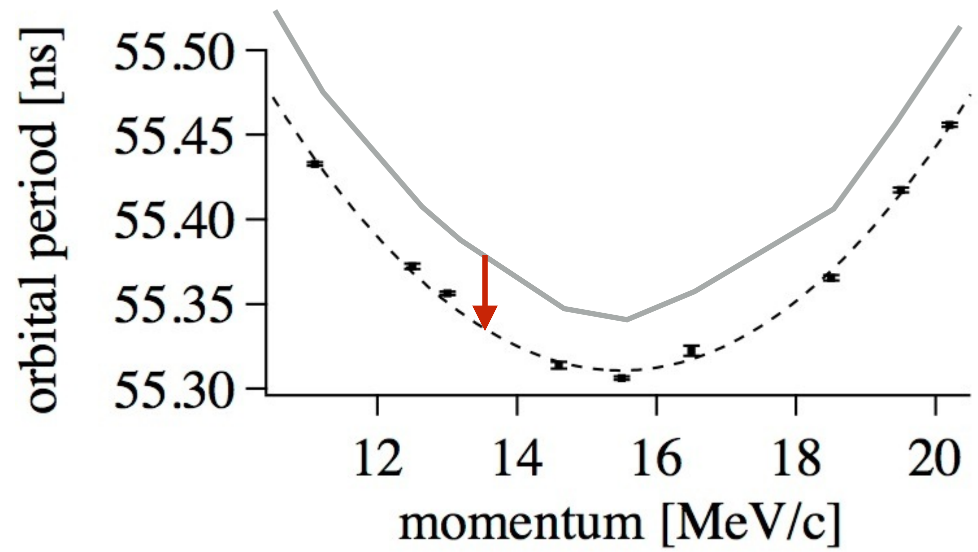
- I am not sure!
- Some observations tell us the answer is probably “No”.

# Lesson we learn
*in EMMA*

Measured orbital period was off by ~50 ps.

RF frequency range could not cover the whole serpentine channel parameters we wanted to explore.

We did not prepare for this difference.




Fortunately, the slider of the magnet base could be used to enlarge the whole ring to increase orbital period.

## Lesson we learn

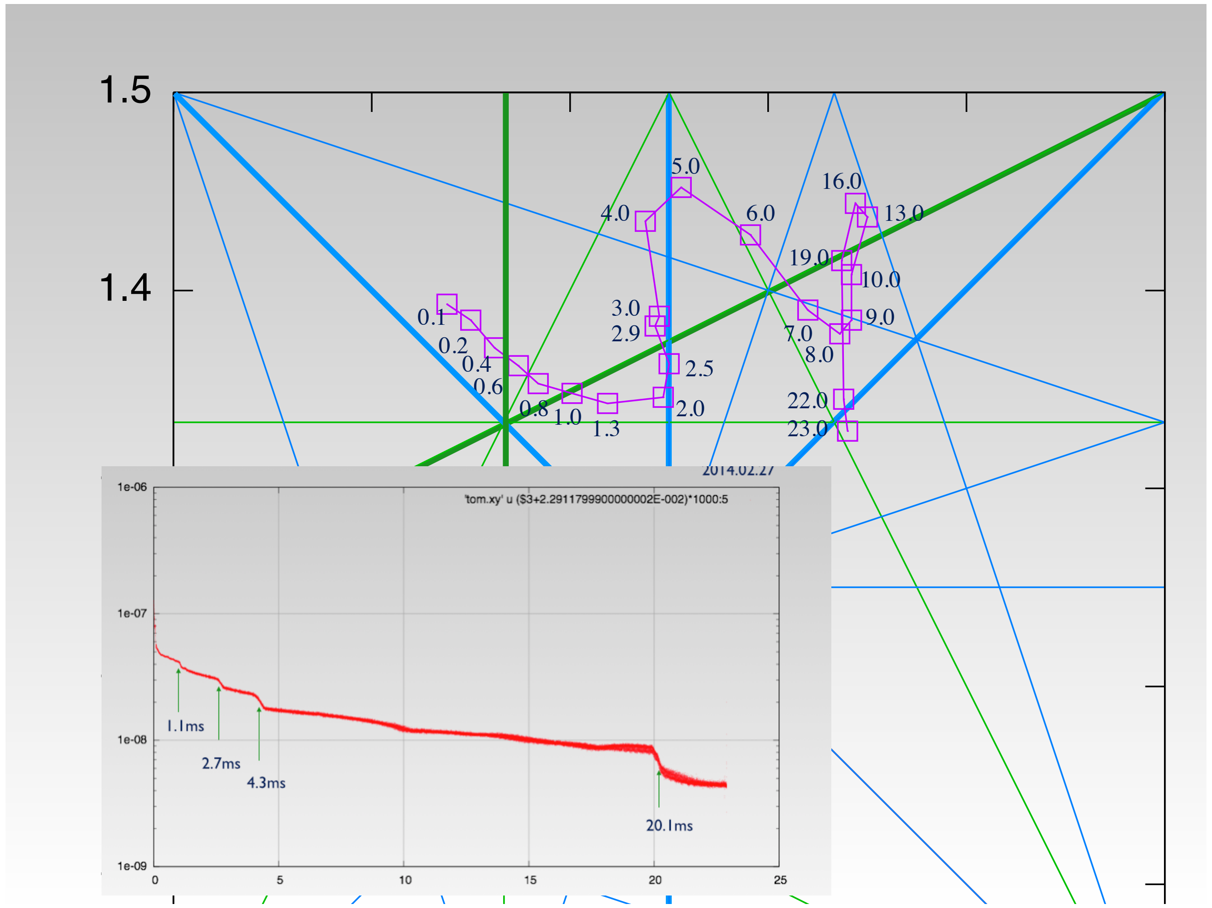
- Fundamental parameter such as orbital period could be off by “unexpected” reason.
- We need to prepare knobs to correct it.

# Lesson we learn

*in KURRI scaling FFAG*

Scaling magnet does not necessarily give the fixed tune.

Tedious procedure to shim the magnet pole face is necessary.



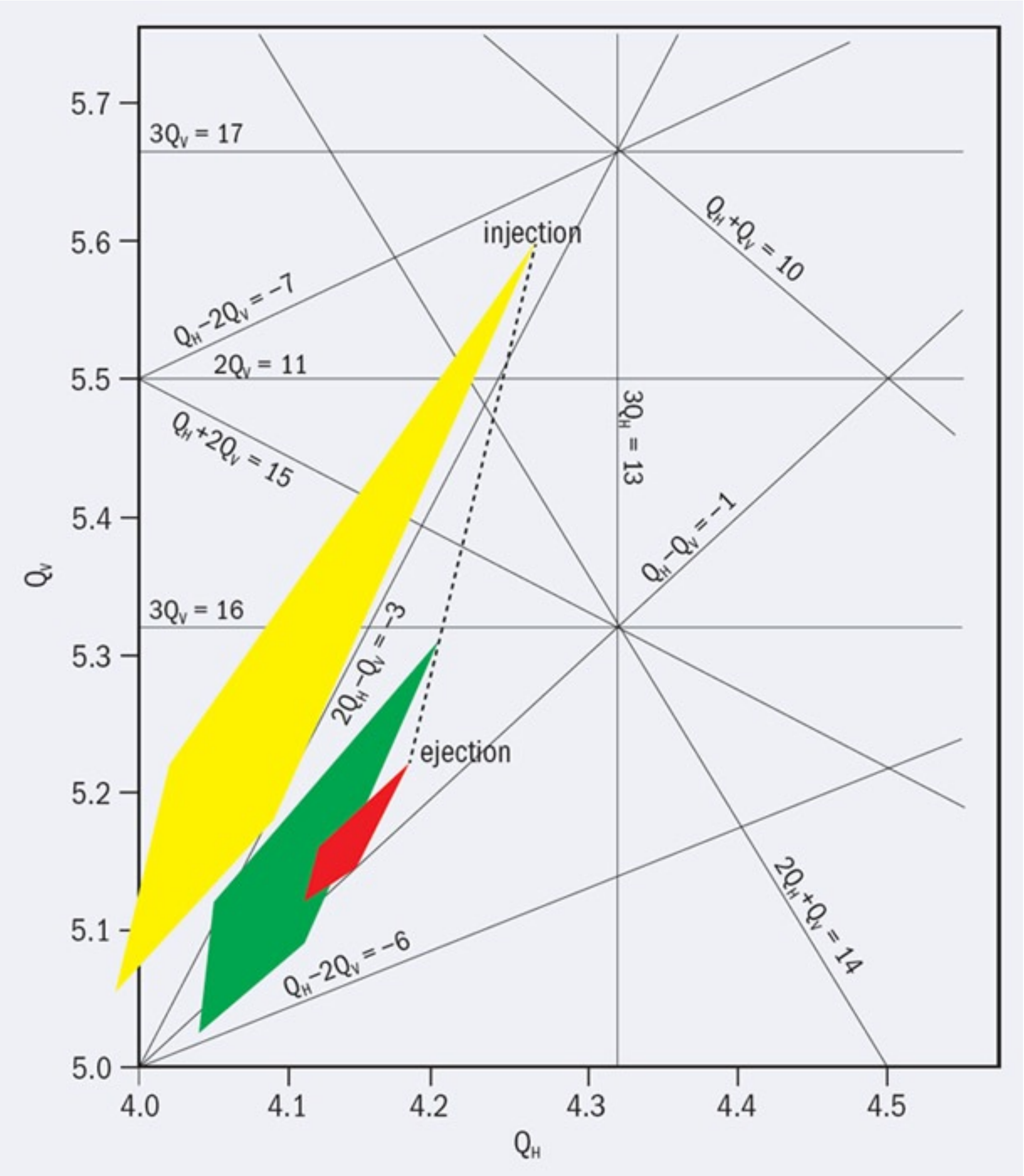

## Lesson we learn

- Fundamental parameter such as tune could be off by “unexpected” reason.
- We need to prepare knobs to correct it.

# Lesson we learn

It is not always optimum to fix the tune.

e.g. Space charge tune spread becomes less as the beams are accelerated.




Common practice in synchrotrons

## Lesson we learn

- Transverse tune should be adjusted according to the beam intensity.
- We need to prepare knobs to do this.

# Lesson we learn

*tracking with 3D field map*

Particle tracking with 3D magnetic field map is possible.

However, we never be able to precisely predict accelerator parameters (closed orbit, orbital period, tune, for example) on the design stage.

Modelling with 3D magnetic field map is used to understand what has been measured.

## Lesson we learn

- Fundamental parameter cannot be precisely predicted by 3D field map in advance.
- We need to prepare knobs for some flexibility.

# Lesson we learn

*injection and extraction*

70 degree septum magnet is required in EMMA.

Difficult to predict orbit with large fringe fields.

Stripping foil inside the main magnet in KURRI MR.

Space for inj/ext device and turn separation are always the issue.

## Lesson we learn

- Injection and extraction are always crucial parts.
- Some of adjustment are expected in-situ and need knobs to make it possible.

# Accelerator not for its own sake

*requirement*

FFAG development for the last 10 -15 years were mostly for its own sake.

KURRI and Kyushu FFAGs are giving beams to users.

It was possible by Mori-san (Ishi-san, Ikeda-san, Yonemura-san and others).

They will, however, retire eventually.

Unless FFAG has well defined flexibility (knobs) which can be used at daily operation by “users”, it never be adapted as a “tool” for research or applications.

FFAGs still do not have “citizenship” in accelerator community.

# What is missing?

## *let us learn from synchrotron!*

Excitation of the main dipole and quadrupole can be controlled as a function of time with programmable power supply.

Additional steering magnets, trim quadrupoles, or trim coils in the main magnets can be used to optimise daily operation.

How can we implement the similar flexibility in FFAGs?

> Programmable power supply is not useful for fixed field machines.

# Tuning of orbit and optics

## *synchrotrons vs fixed field accelerators*

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 cyclotrons and FFAGs

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.

c.f. Frequency and voltage of rf cavity is adjusted as a function of time in both cases. This determines acceleration pattern.

# Proposal

## *control knobs in fixed field accelerators*

Cyclotron has trim coils, which control orbital period and harmonic components of orbit.

Extend the concept of trim coils and define available knobs from the machine design to operation stage consistently.

Let us use "strength of individual multipole (normal and skew)"!

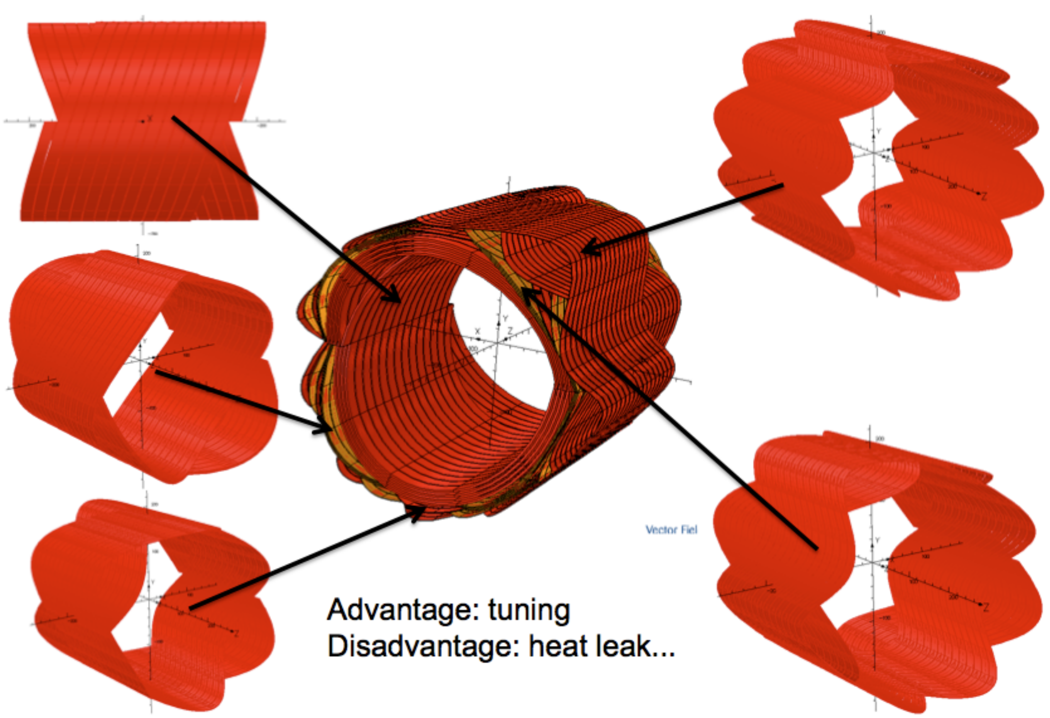
Edge angle is a useful parameter for design but cannot be altered after construction.

# Magnetic field profile
## *multipole expansion*

Any magnetic field profile can be decomposed completely by multipoles.

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

PAMELA magnet is an example.




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

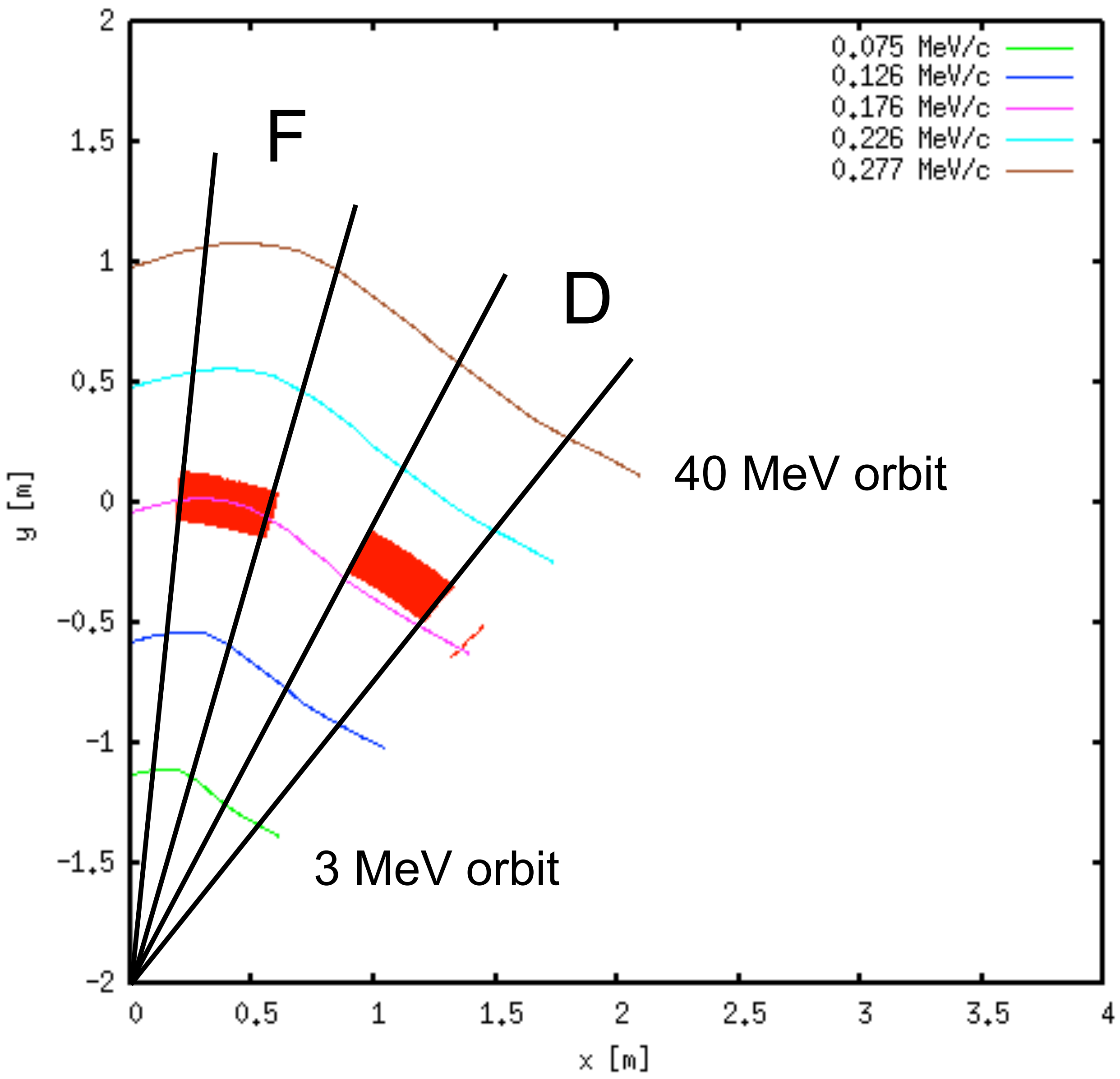
dipole, quadrupole, sextupole, decapole, dodecapole

by Holger Witte

# Demonstration of FFAG design, construction and operation with multipoles

# Toy model as a start
*8 cell lattice*

Simple FODO lattice with 8 cell per ring




energy: 3 - 40 MeV

field: 1.5 T max

packing factor: 0.5

Start from scaling FFAG optics.

Then control individual multipoles.
(as we did for PAMELA.)

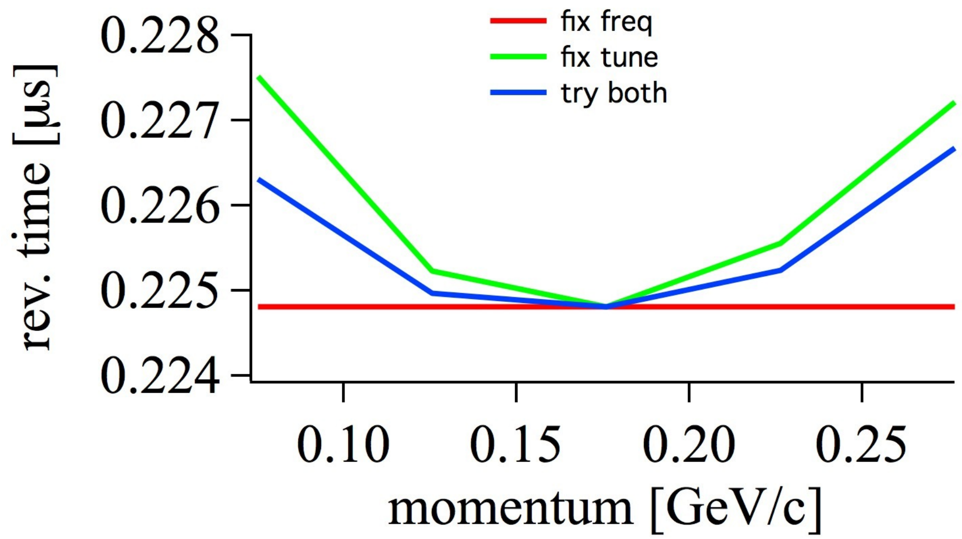
# With normal multipoles

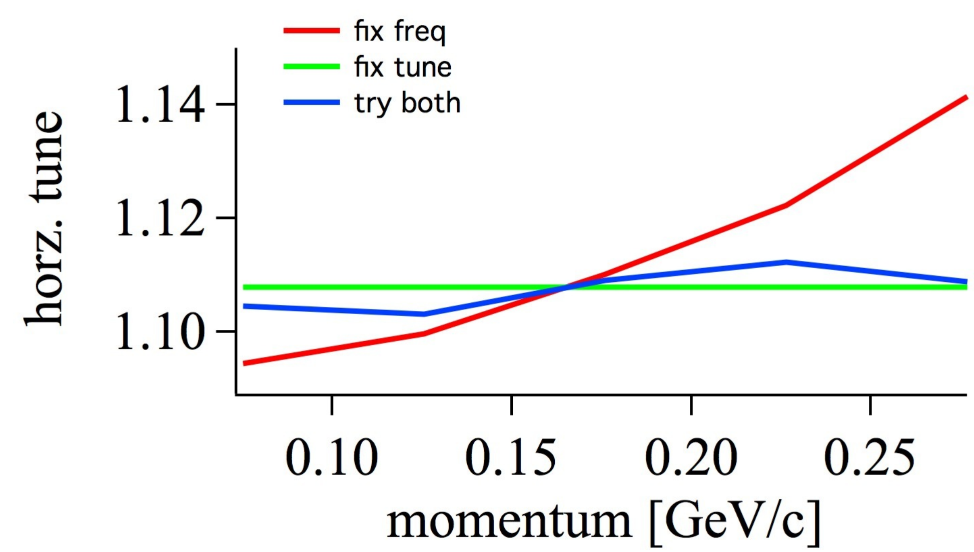
*change mode between cyclotron and FFAGs*

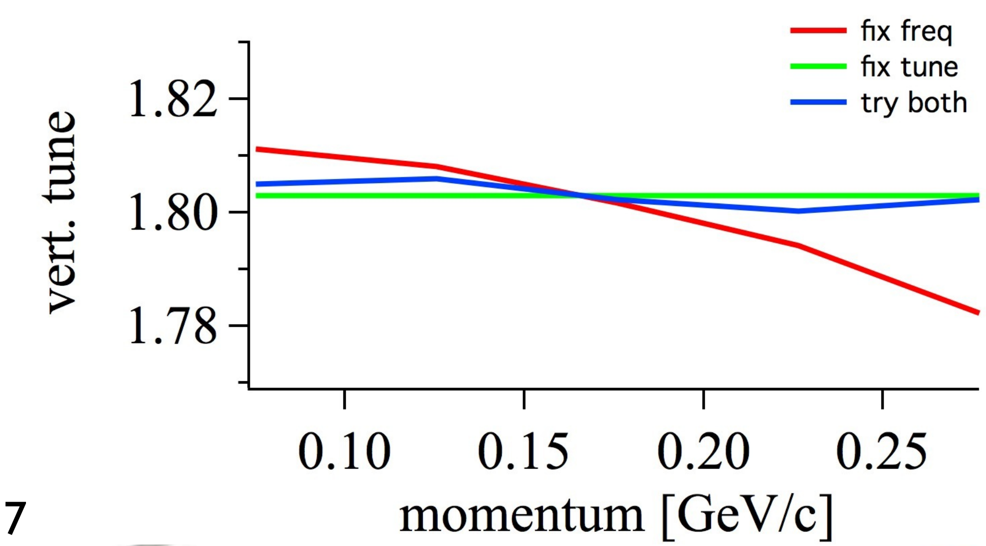
Taking the first 5 multipoles (knobs), adjust the lattice either cyclotron like (fixed frequency) or FFAG like (fixed tune) or in between.

cyclotron mode
(fixed frequency)

FFAG mode
(fixed tune)



# How accurately do we fix tune and rev. time?

1. Large tune shift causes resonance crossing.

2. Large variation of revolution time breaks isochronous condition.

Is “< 1%” enough?

# Required accuracy of Tune

Distance between n-th order resonance is 1/n.

When n=4, dQ=0.25

Space charge tune shift is the same magnitude.

dQ=0.1 may be too large.

dQ=0.01 or a few of 0.01?

# Required accuracy of revolution time

Acceleration with fixed frequency basically uses serpentine channel!

Minimum required voltage is

ref. J. S. Berg, EPAC02 and FFAG03

$$V_{min} = \frac{\omega_{rf} \Delta T \Delta E}{(1/a)}$$

where $\Delta T$ is the spread of rev. time.

$\Delta E$ is the total energy range.

$(1/a)$ ~12.

Introduce normalised spread $\delta T = \Delta T / T_{rev}$

$$V_{min} = \frac{2\pi h \delta T \Delta E}{(1/a)}$$

is proportional to harmonic number, spread of rev. time and total energy range.

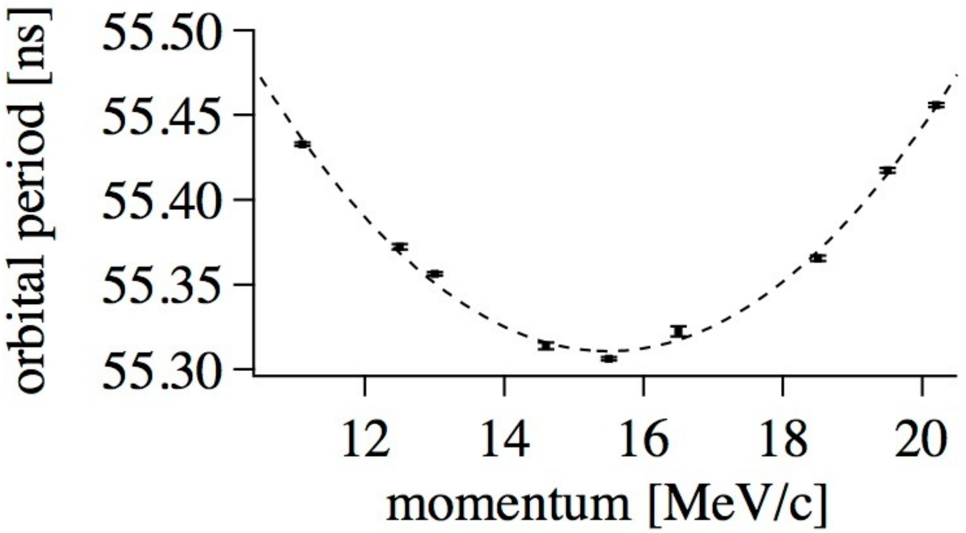
# Just check with EMMA parameters

In EMMA

$h$ = 72

$\delta T = \Delta T / T_{rev}$ =3 x $10^{-3}$

$\Delta E$ = 10 MeV




Therefore

$$V_{min} = \frac{2\pi h \delta T \Delta E}{(1/a)}$$ = 1.1 MV as expected!



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# Rule of thumb

$$V_{min} = \frac{2\pi h \delta T \Delta E}{(1/a)} \sim \frac{h}{2} \delta T \Delta E$$

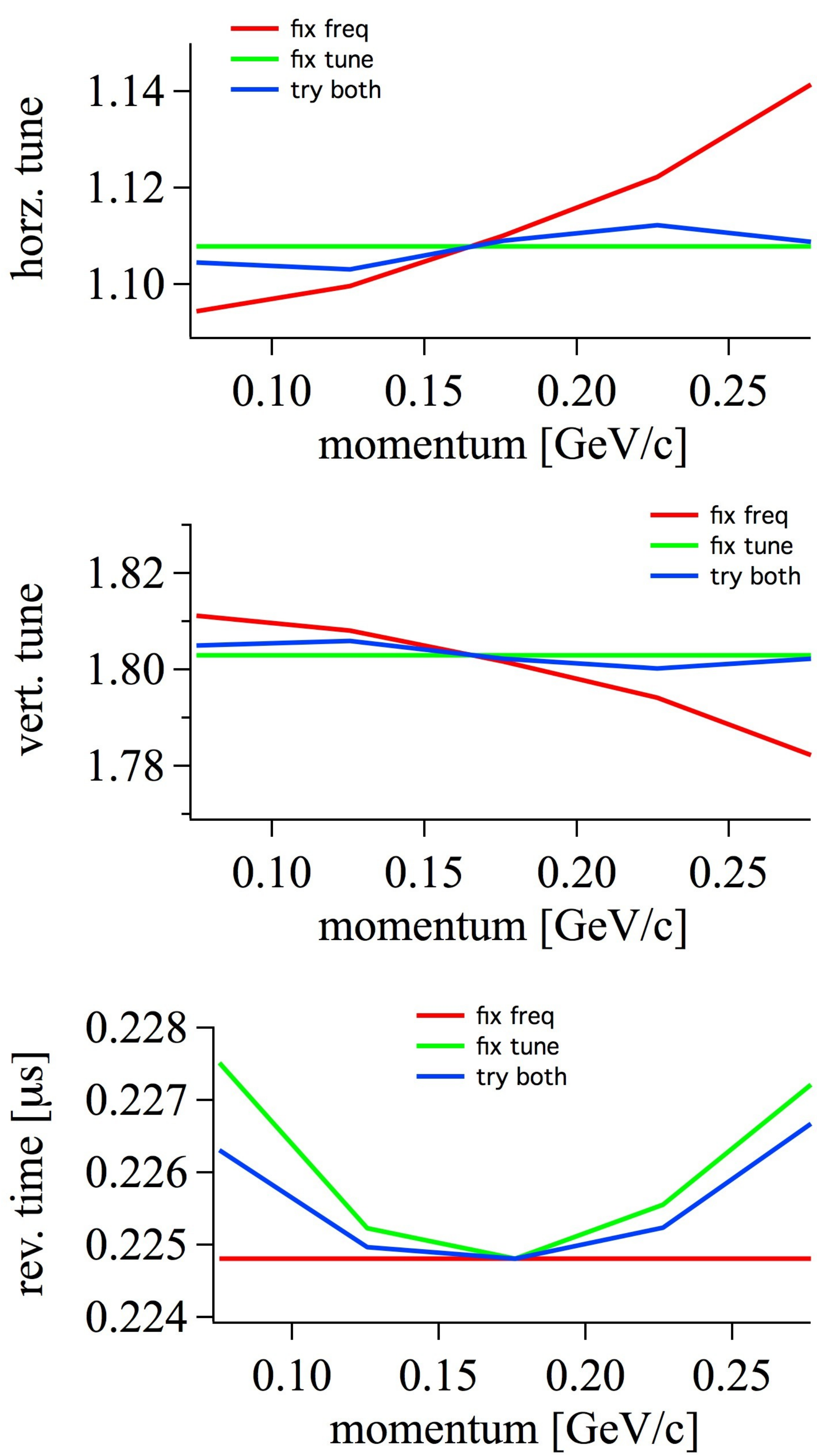
or

$$\delta T \sim \frac{2}{h} \frac{V_{min}}{\Delta E} \sim \frac{1}{turns}$$

example

The machine which takes 100 turns to the top energy needs 1% level of isochronous.

look at blue line




# In “optimised” lattice

Tune spread seems small enough.

Rev. time spread is relatively large.

$$\delta T = \Delta T / T_{rev} = 8.3 \times 10^{-3}$$

In order to accelerate from 3 to 40 MeV

$$\Delta E = 37 \text{ MeV}$$

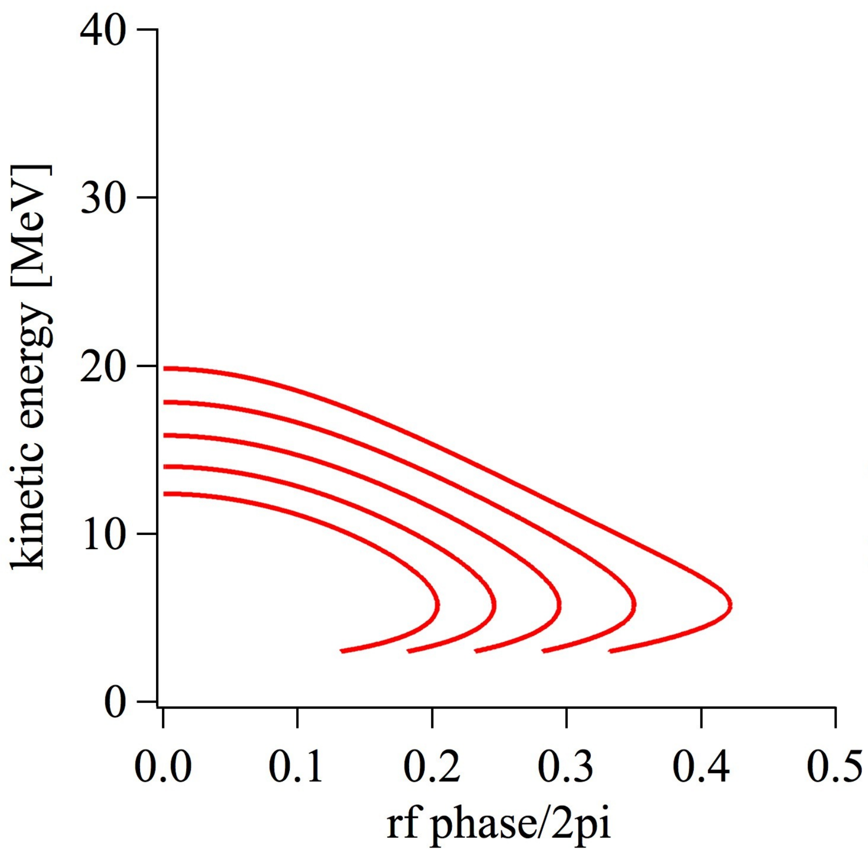
$$V_{min} = \frac{2\pi h \delta T \Delta E}{(1/a)} = 160 \text{ kV}.$$

Possible in this small energy range, but better to have smaller $\delta T$ .

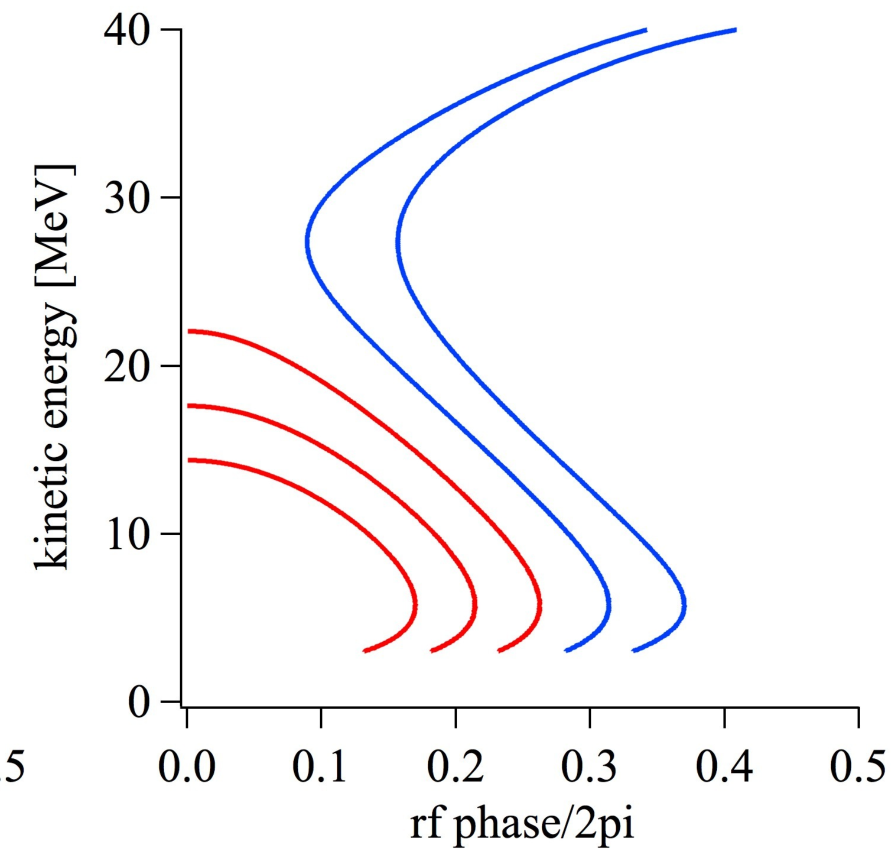
# Acceleration simulation
## *in serpentine channel*

The minimum voltage required to accelerate from 3 to 40 MeV is V = 160 kV indeed.

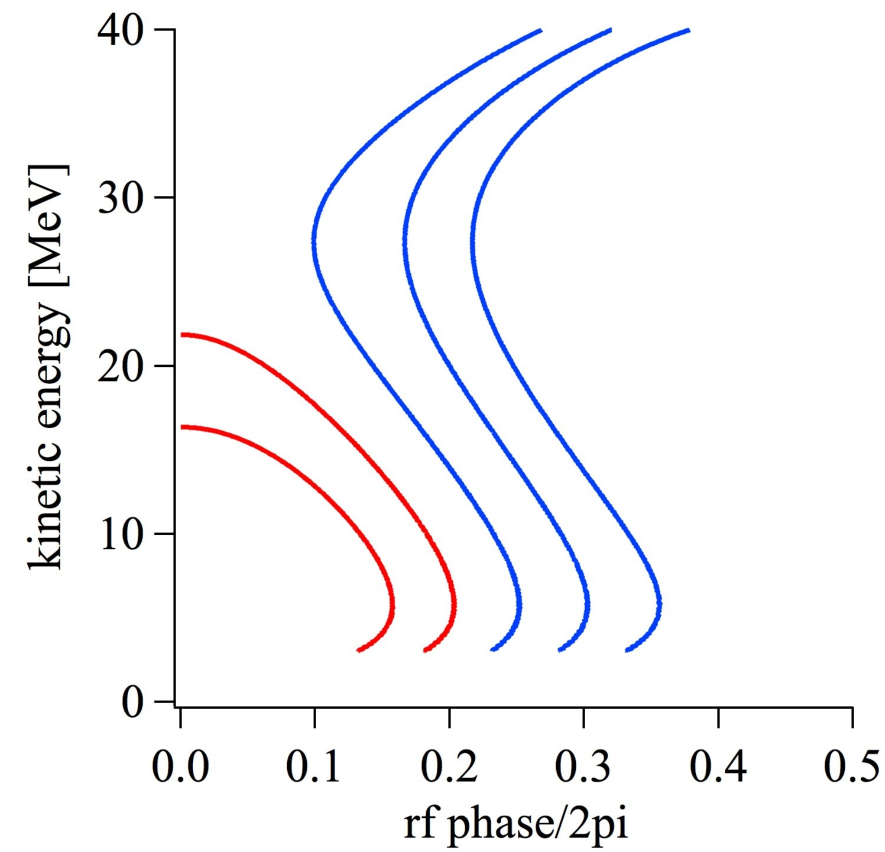
80 kV




160 kV




240kV



# Other possible knobs

*use of skew*

Other knobs we did not use at the time of PAMELA study is skew multipoles.

This is also the key ingredient of VFFAG and 3D cyclotron by S. Brooks.

# Orbit in vertical direction

In a synchrotron lattice, main source of the vertical dispersion is a skew field where horizontal dispersion is finite.

$$\frac{d^2 z}{ds^2} + K_z(s) z = \frac{1}{B\rho} \frac{\partial B_x}{\partial x} D_x \delta$$

Vertical dispersion is

$$D_z(s) = Q_z^2 \sqrt{\beta_z(s)} \sum_{k=-\infty}^{\infty} \frac{f_k \exp(ik\phi(s))}{Q_z^2 - k^2}$$

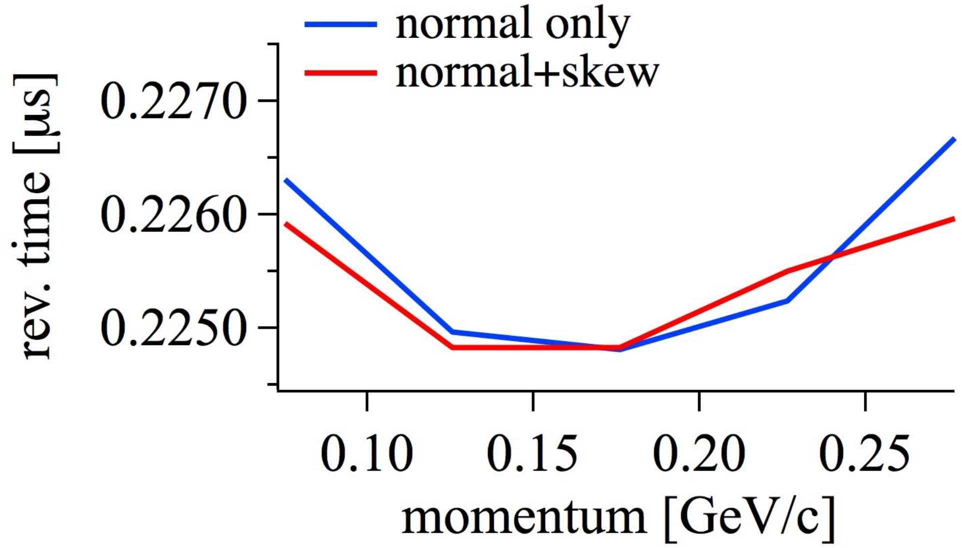
$$f_k = \frac{1}{2\pi B\rho} \int_0^{2\pi} \sqrt{\beta_z} D_x \frac{\partial B_x}{\partial x} \exp(-ik\phi(s)) ds$$

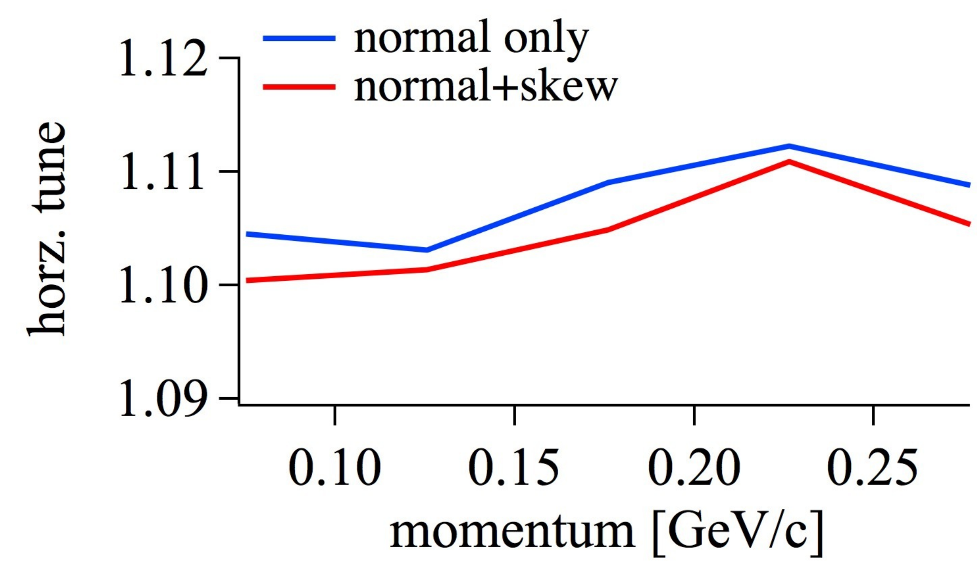
skew term

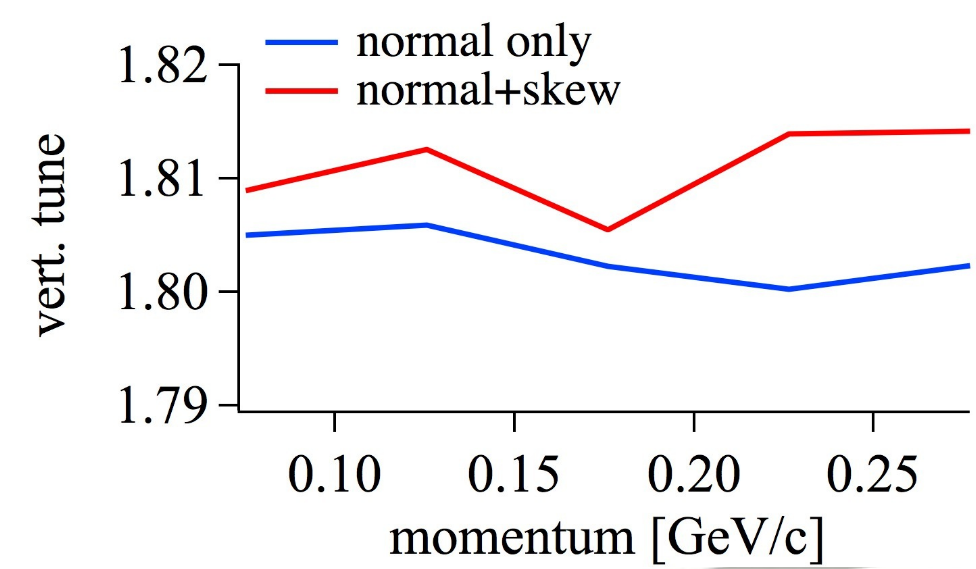
# With skew multipoles

## *toward "complete isochronism"*

Adding the first 5 skew multipoles (knobs), adjust the lattice to minimise transverse tune spread as well as revolution time spread.



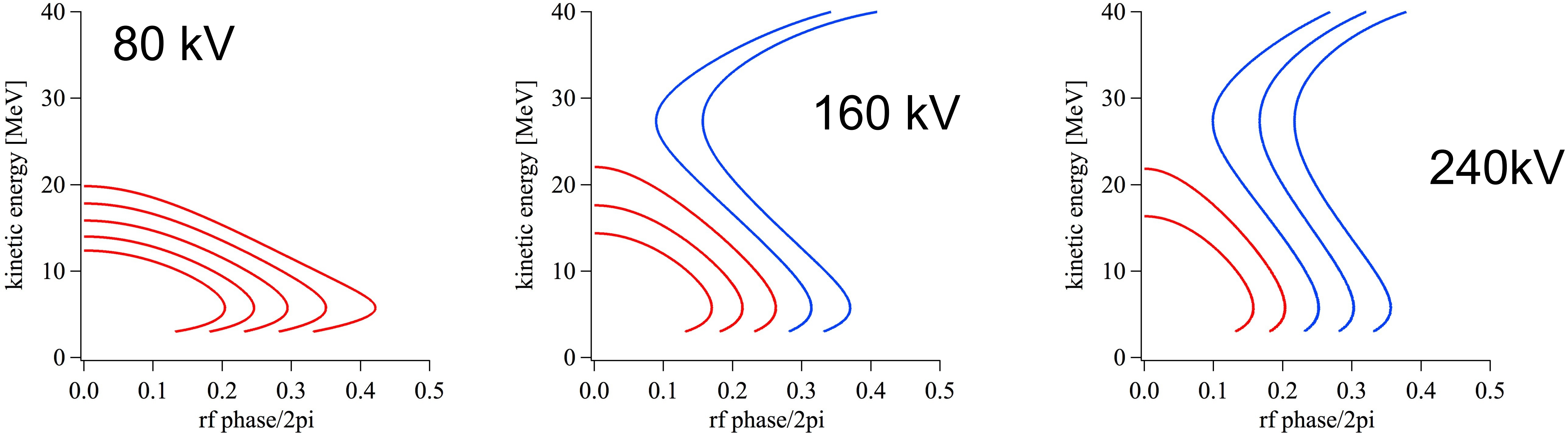




$$V_{min} = \frac{2\pi h \delta T \Delta E}{(1/a)}$$ = 99 kV.

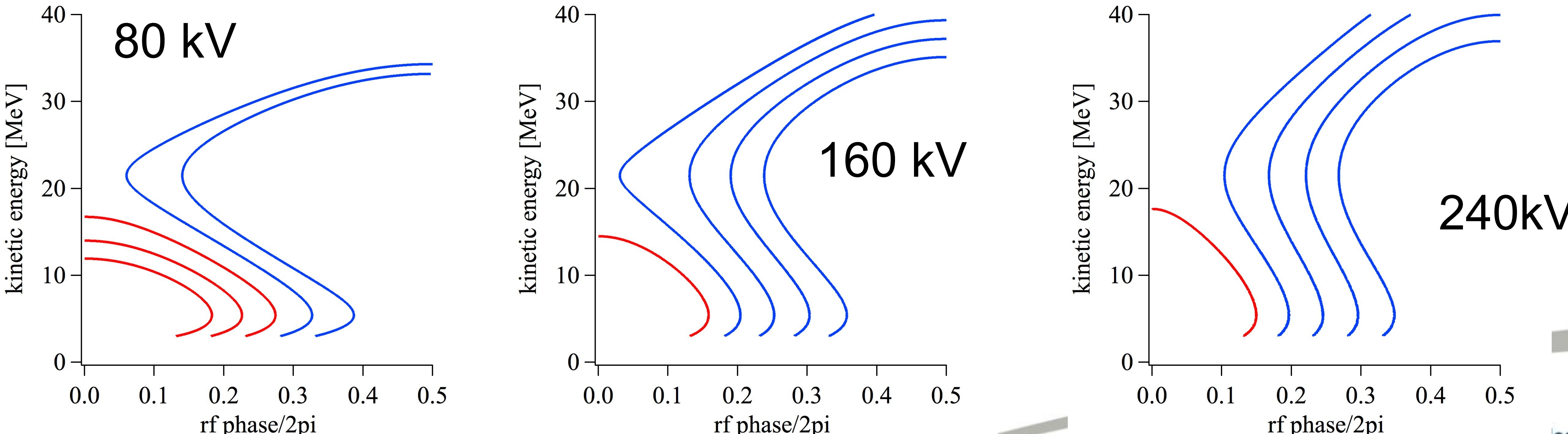
# Acceleration simulation

*in serpentine channel*

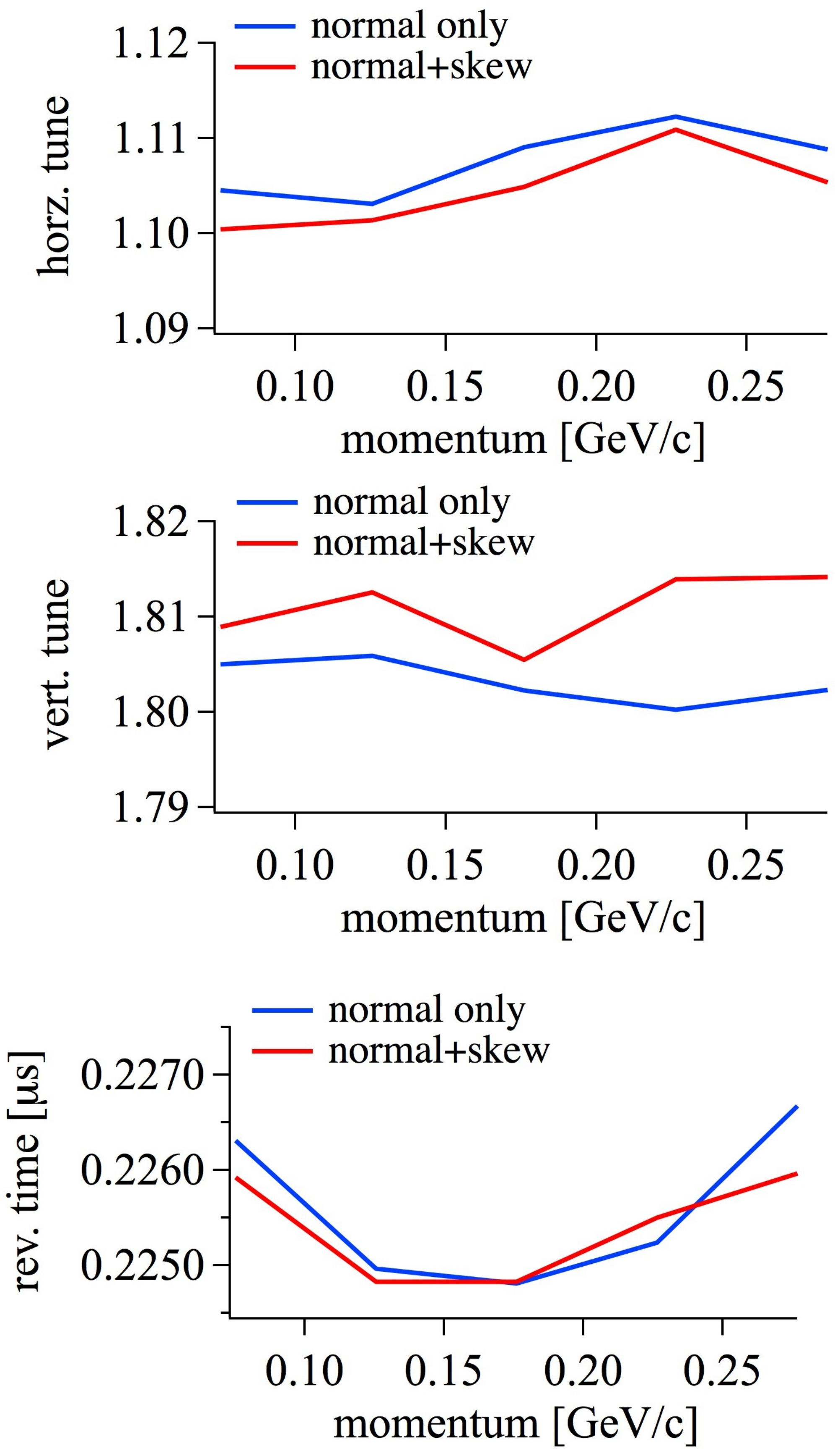
normal multipole only



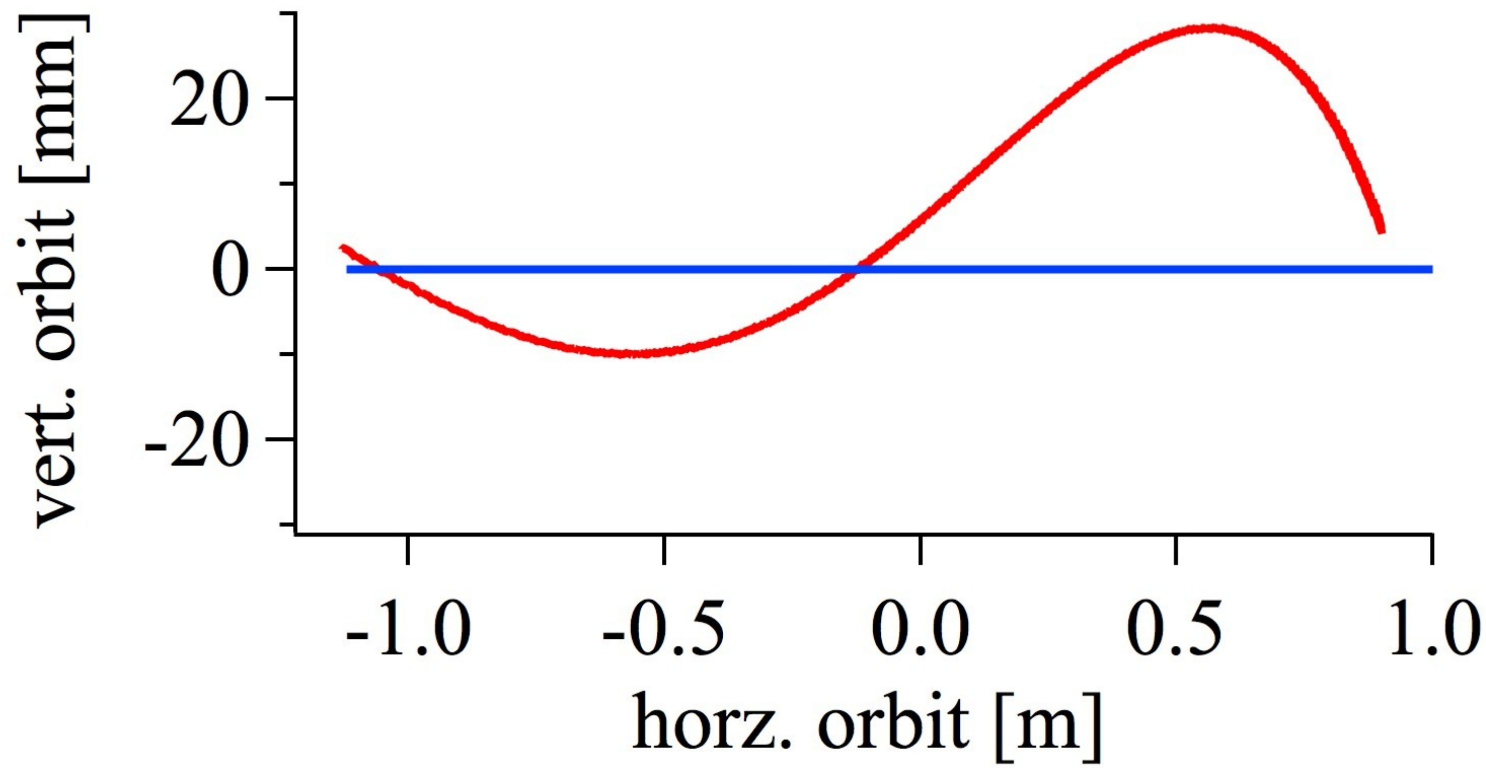

normal + skew



# Orbit excursion in vertical as well as in horizontal

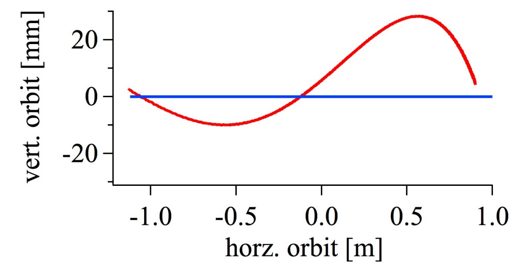


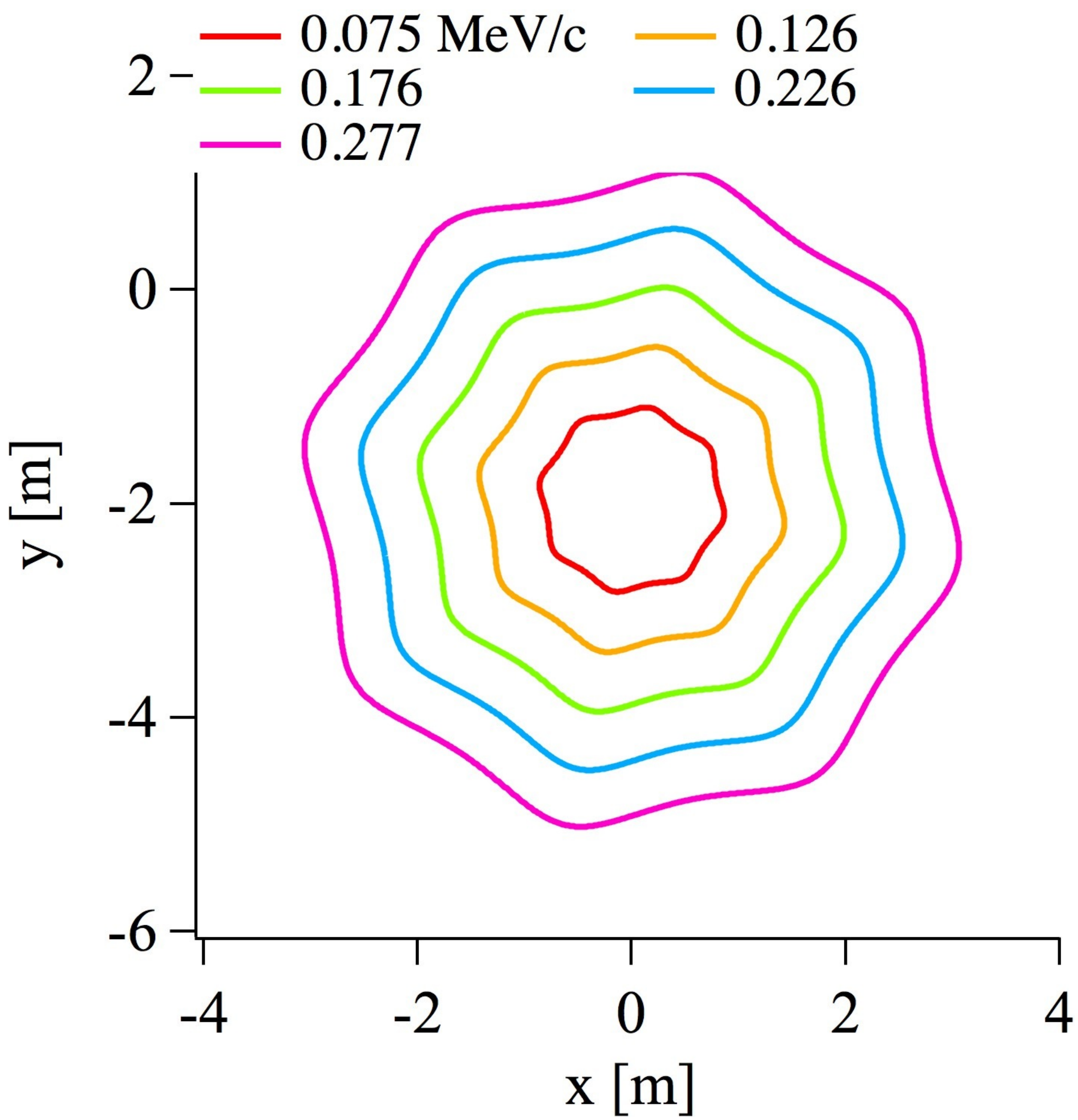

Vertical orbit becomes zero in the middle maybe because of the axis of multipoles (this should be further investigated).

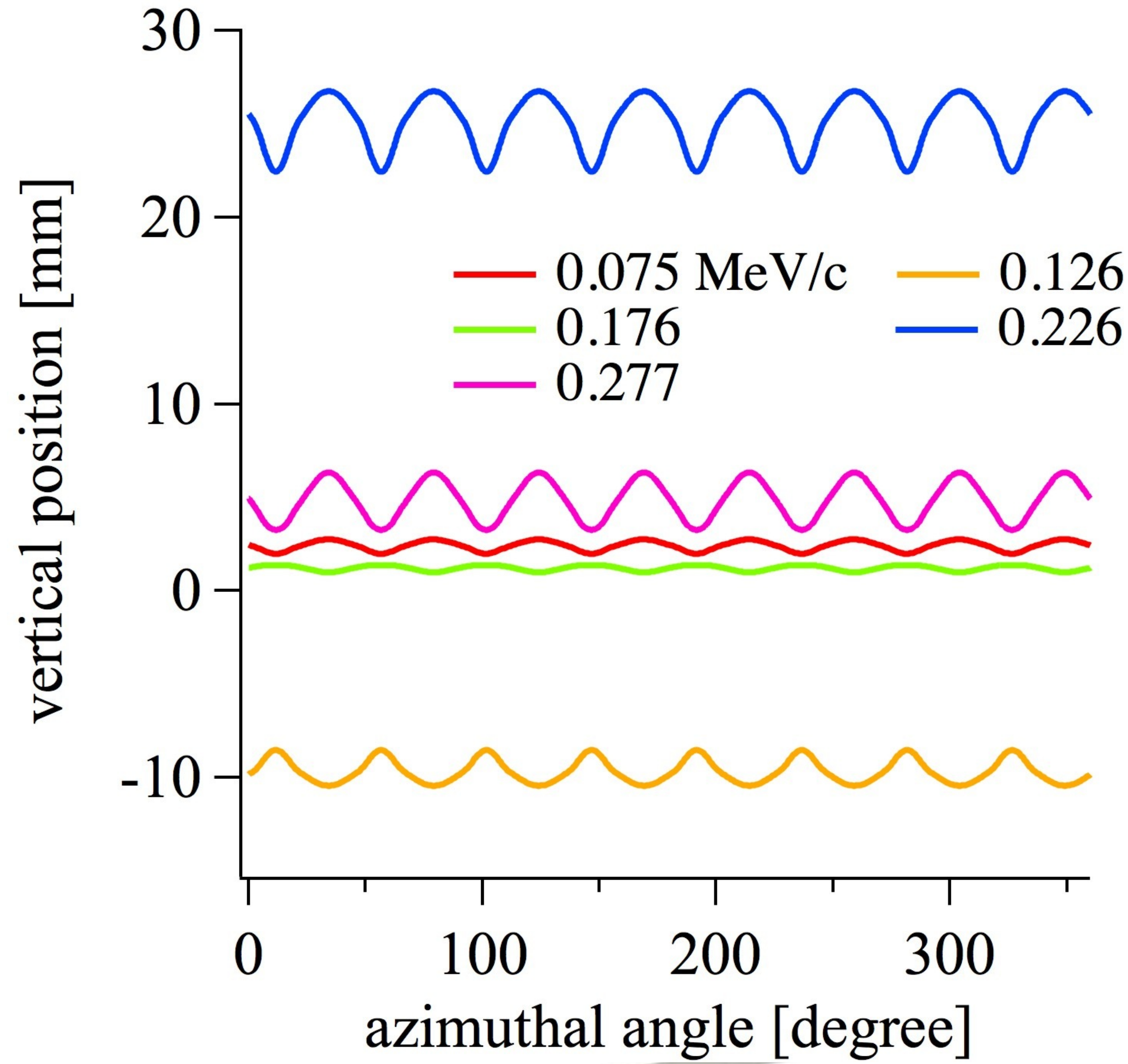


# Orbit excursion in vertical as well as in horizontal

## Closed orbit



# With normal and skew multipoles

*cyclotron, FFAGs or both*

We can minimise the spread of tune and revolution time at the same time with skew multipoles.

cyclotron mode
(fixed frequency)

FFAG mode
(fixed tune)

“complete isochronism" mode
(fixed frequency and fixed tune with fixed field)

named by J. Teichmann (1962)

# Injection/extraction

*only thoughts*

Injection/extraction is the most critical issue in fixed field accelerators.

Compact design with small turn separation makes it even harder.

We will use the multipoles strength so that complete isochronism condition breaks locally.

Large turn separation in vertical direction in final turns also helps.

# Engineering design of multipoles
*only thoughts*

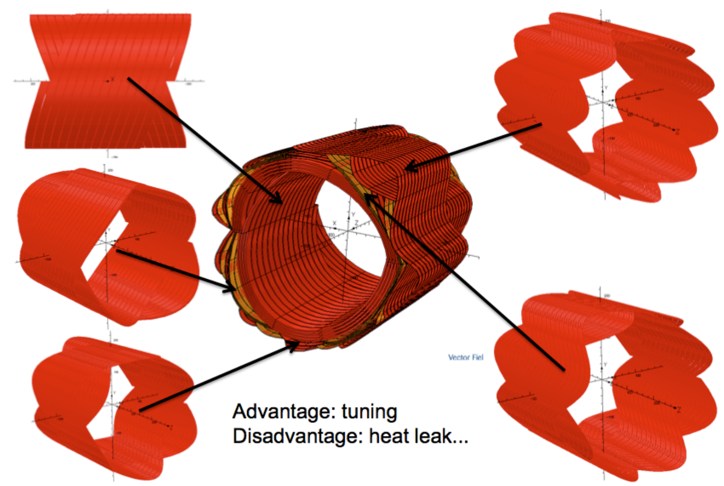
Easiest solution is PAMELA type magnets.

- No difference in terms of installing process for normal and skew.
- Aperture could be huge for machine like cyclotron orbit excursion.

Another way is distributed coils.

- Should be easy to establish matrix to relate multipole strength and individual coil current.
- Need more thought for skew components.

PAMELA




KURRI/IonBeta

# Summary (1)

We have now more than 10 years of experience of designing, construction and operation of FFAG.

It is always good to explore further novel concept and design, but also better to have some time to think

what is the crucial problems we had.

what is the lesson we learnt.

# Summary (2)

We emphasise operation aspect of fixed field accelerators.

Example here shows that we can use normal and skew multipoles as knobs from the design to the operation stage consistently.

We show these knobs will introduce a variety of operational modes.

# Summary (3)

I will propose a test facility of FFAG based on today's talk on Friday.

Stay tuned!

Thank you for your attention.

# Backups

# Immediate impact

Prototype of neutron source driver

e.g. 0.5 to 10+ MW ISIS upgrade

High intensity FFAG

Compact application machine

e.g. Isotope $^{99}$Tc production (40 MeV, 5 mA, D)

Should be industrialised following this project

Prototype of medical machine

Operation friendly machine with spot scanning