Fixed Field Alternating Gradient Accelerators (FFAG)

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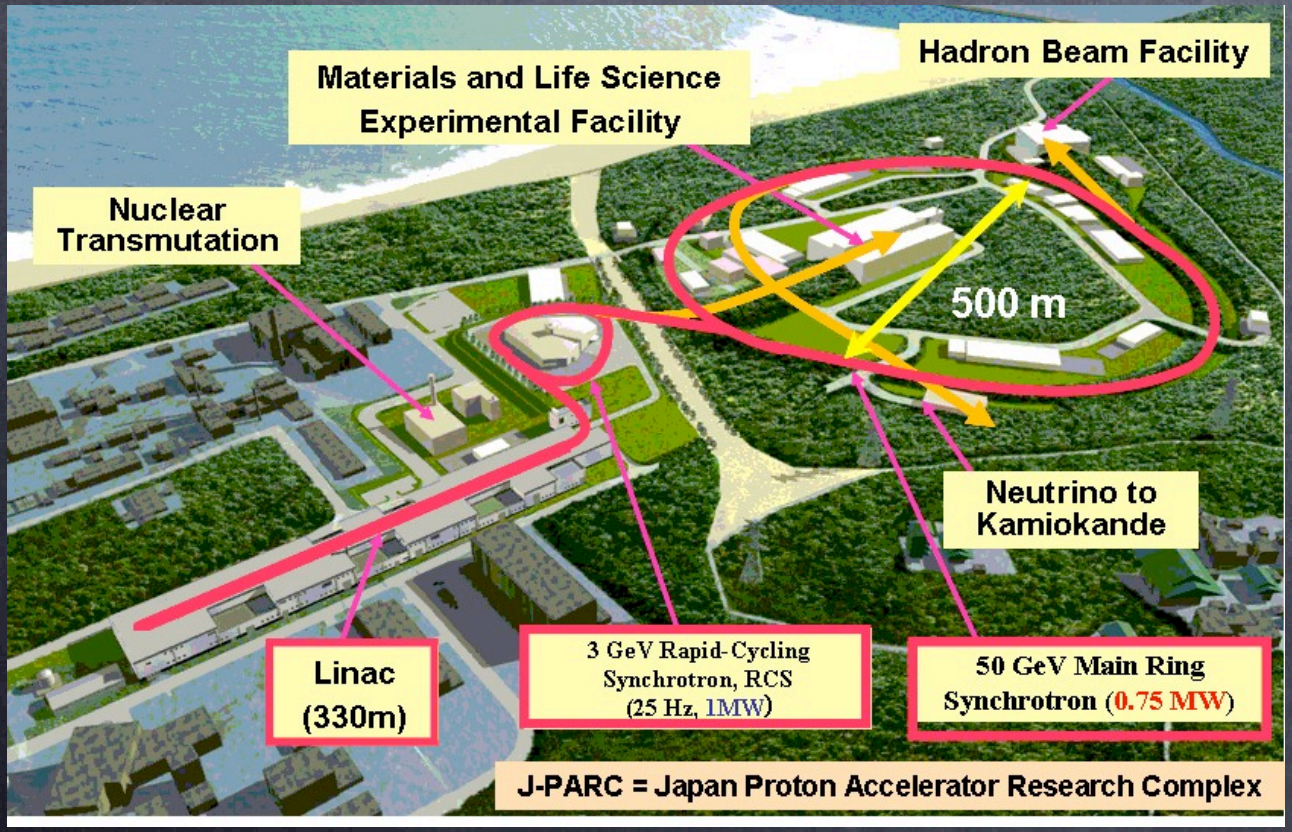
- Introduction (6 slides)
  - Future directions of (hadron) accelerators
- FFAG without constraint of tune (28 slides)
  - non-scaling machine
- Scaling FFAG and “tune stabilised” FFAG (18 slides)

Future directions of (hadron) accelerators

High beam power

- Neutron, Muon source, MW or more
  - Synchrotron based facility: ISIS, J-Parc
  - Linac based facility: SNS, ESS
- Accelerator driven system (ADS)

J-Parc



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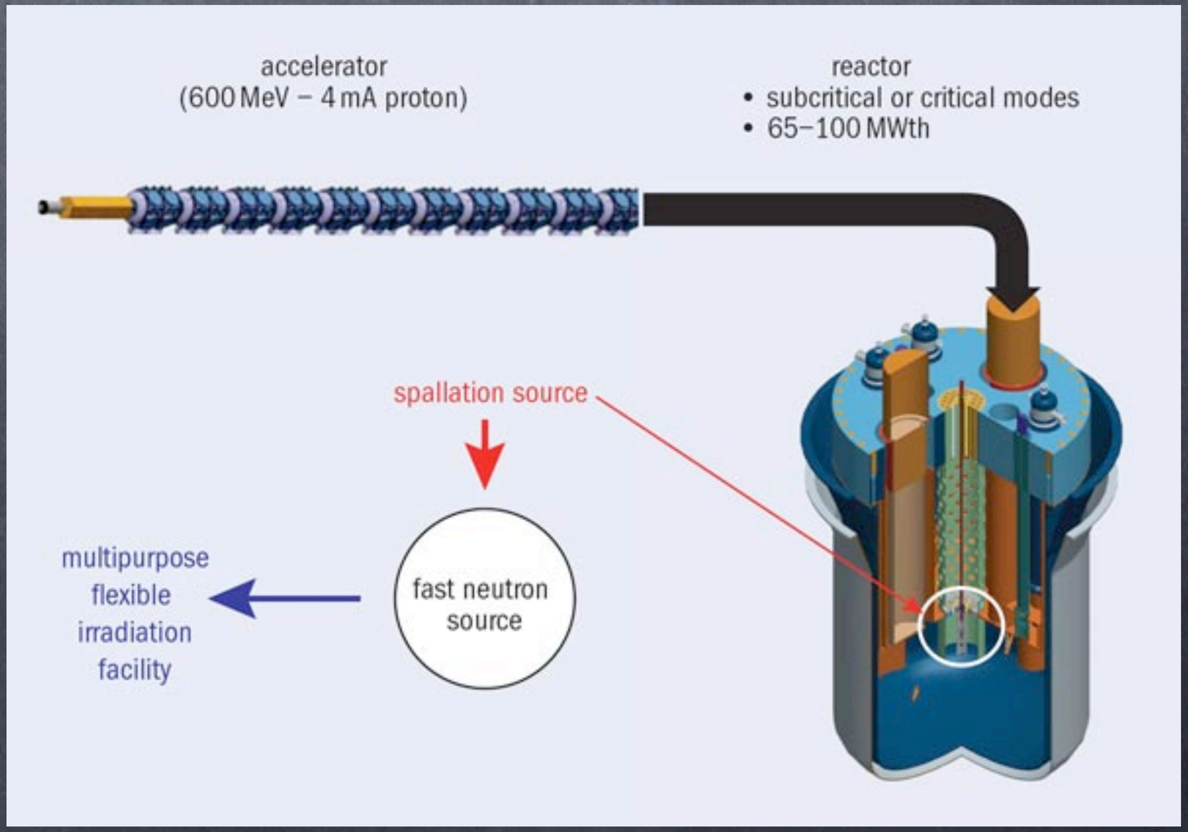
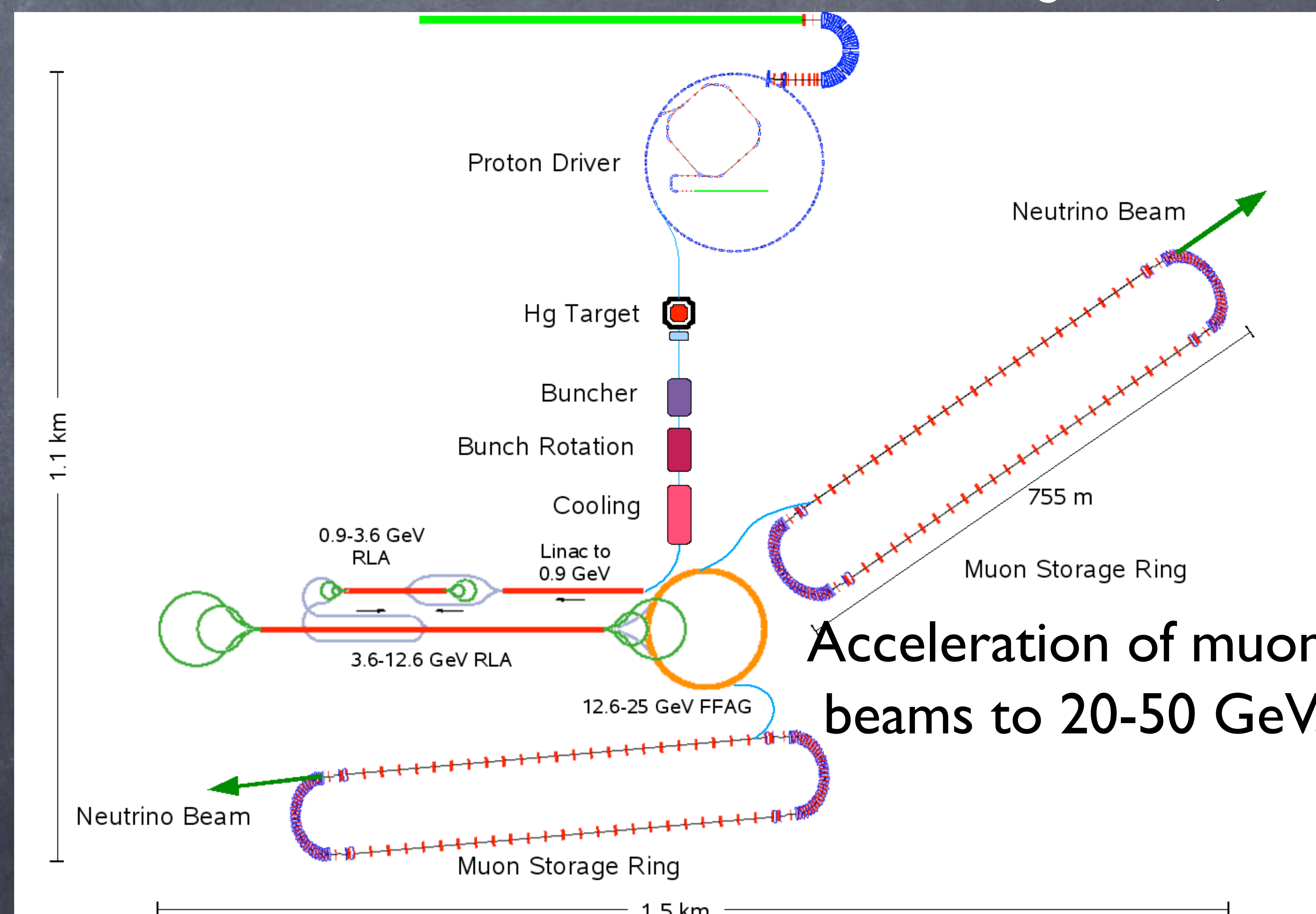


Acceleration of short lived particles

- Neutrino factory, Muon collider
  - Linac or re-circulating linac to accelerate muons
- Accelerator of unstable nuclei

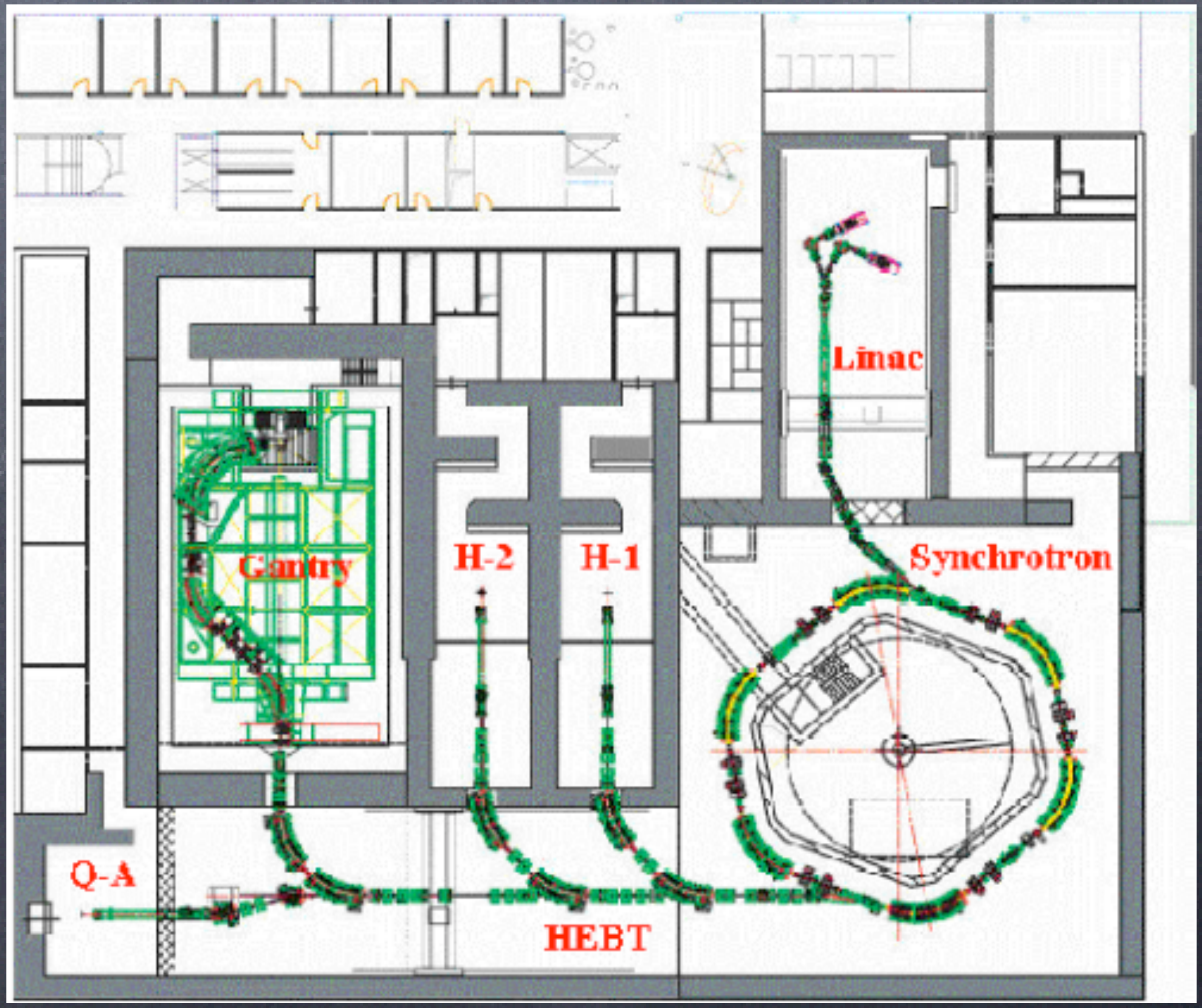
Neutrino factor (original layout)



Accelerator for many other applications

- Particle therapy
  - Cyclotron based: proton therapy
  - Synchrotron based: proton and ion therapy
- Industrial use
  - sterilisation
  - cargo scan for security

Particle therapy



Questions

- Are the accelerators available today good enough?

- Any other options without making a huge jump?

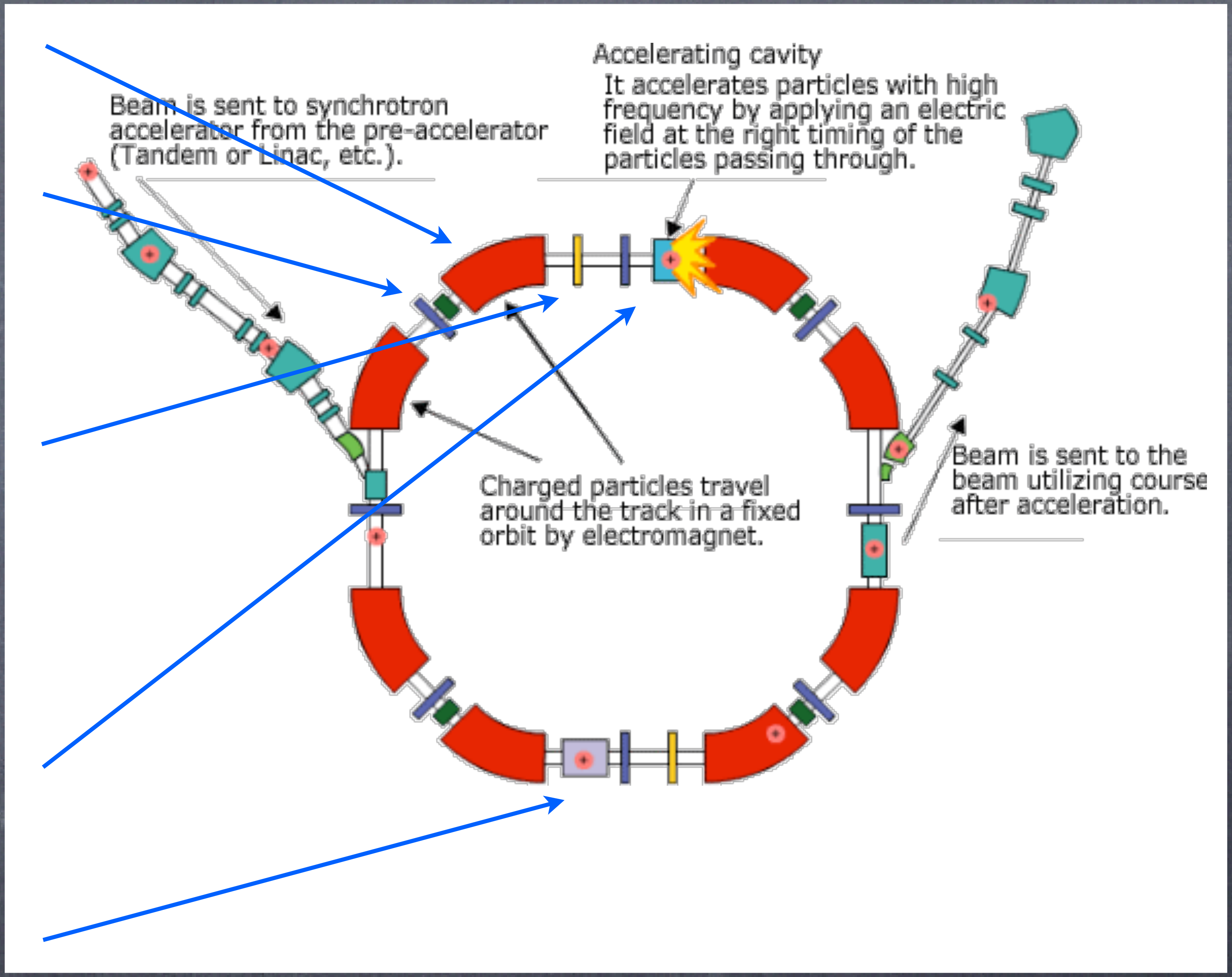
Fixed Field Alternating Gradient (FFAG)?

FFAG without constraint of tune

non-scaling machine

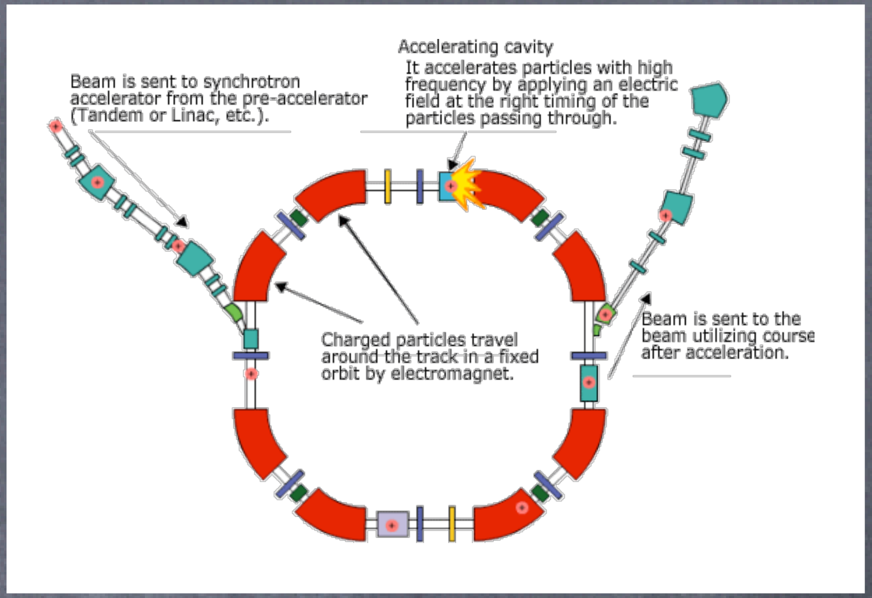
Synchrotron (1)

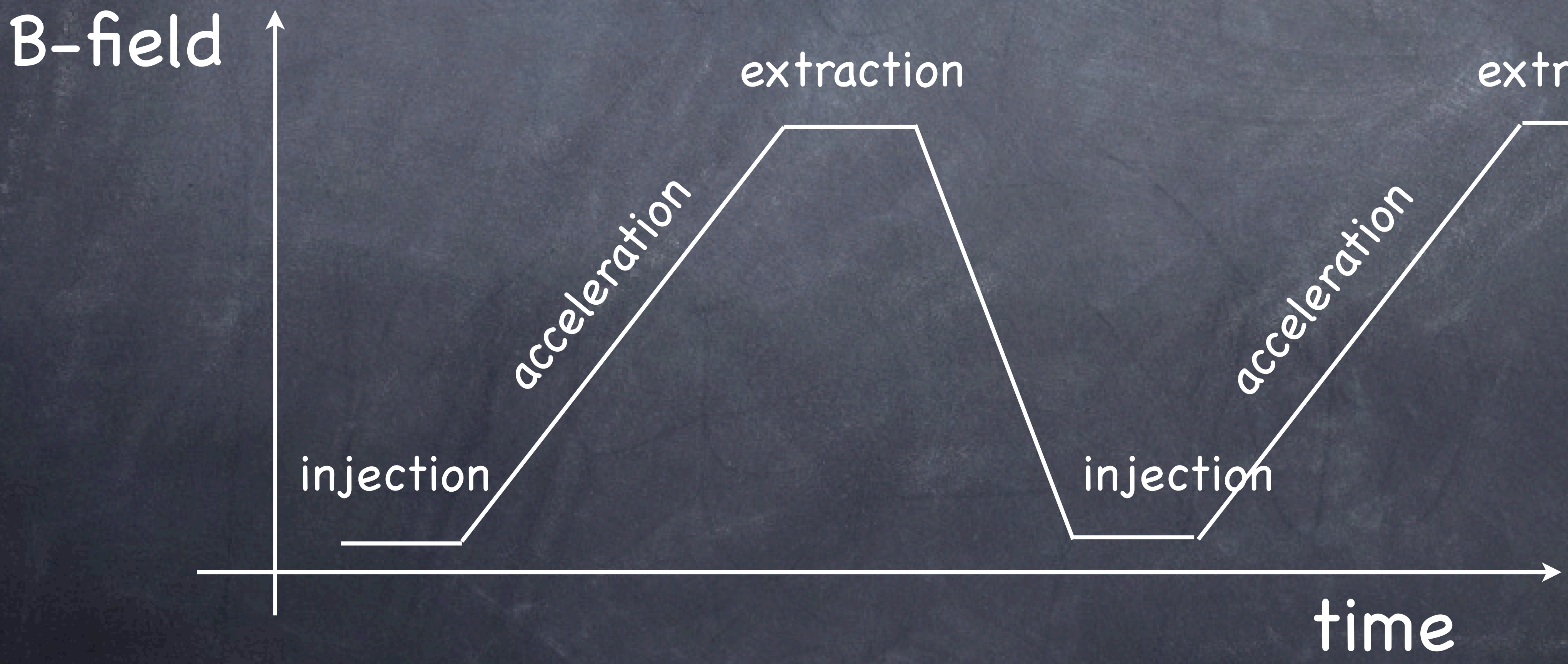
- Bending magnet
- Quadrupole magnet
- Multipole magnet for special purpose
- rf cavity
- Diagnostic



Synchrotron (2)

- When a beam is accelerated at rf cavity, magnetic field is increased to keep the orbital shape constant.





Synchrotron (3)

- Circulating radius (orbit) becomes constant.

$$\theta = \frac{B(t)L}{p(t)/e}$$

- Transverse focal length (optics) becomes constant.

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

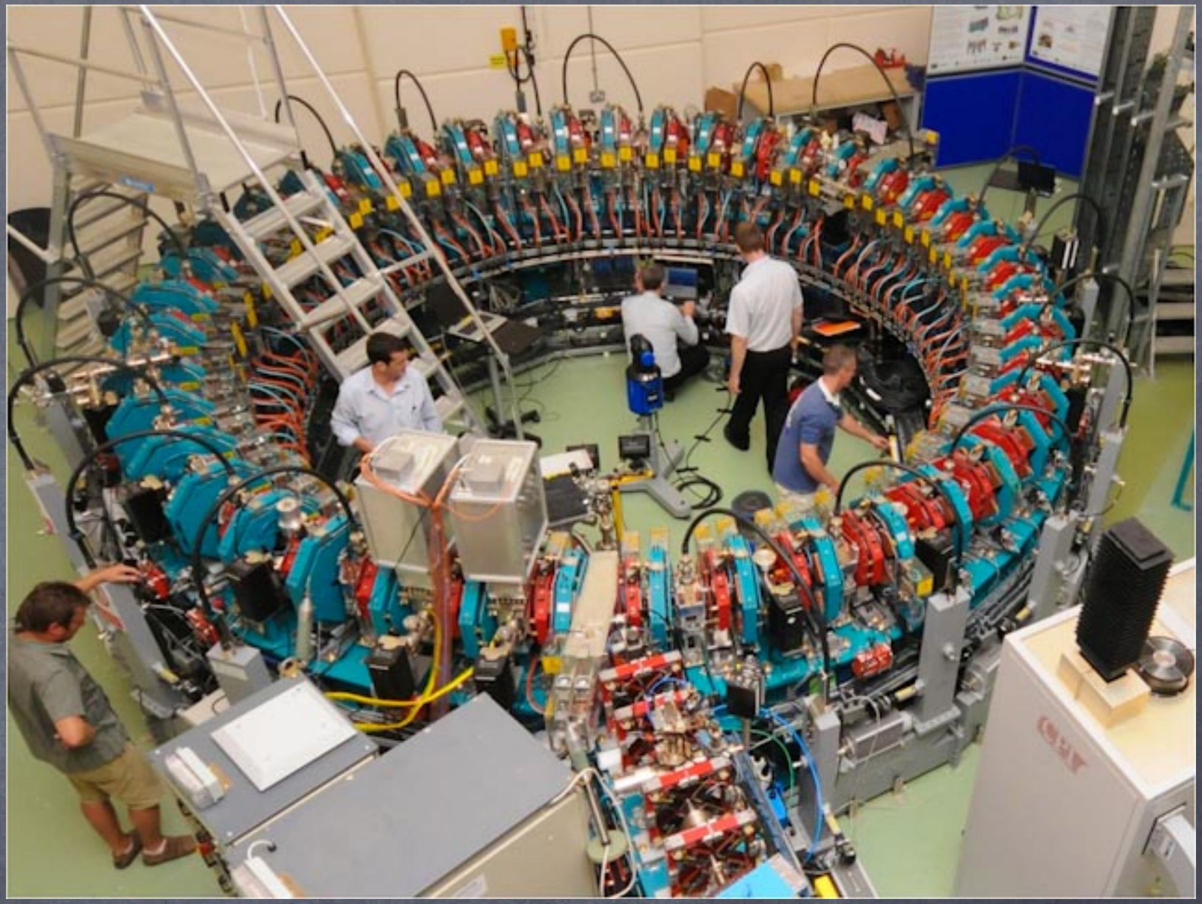
> small aperture magnets.

Have you heard EMMA?

the first non-scaling FFAG
"Electron Model for Many Applications"

EMMA lattice (1)

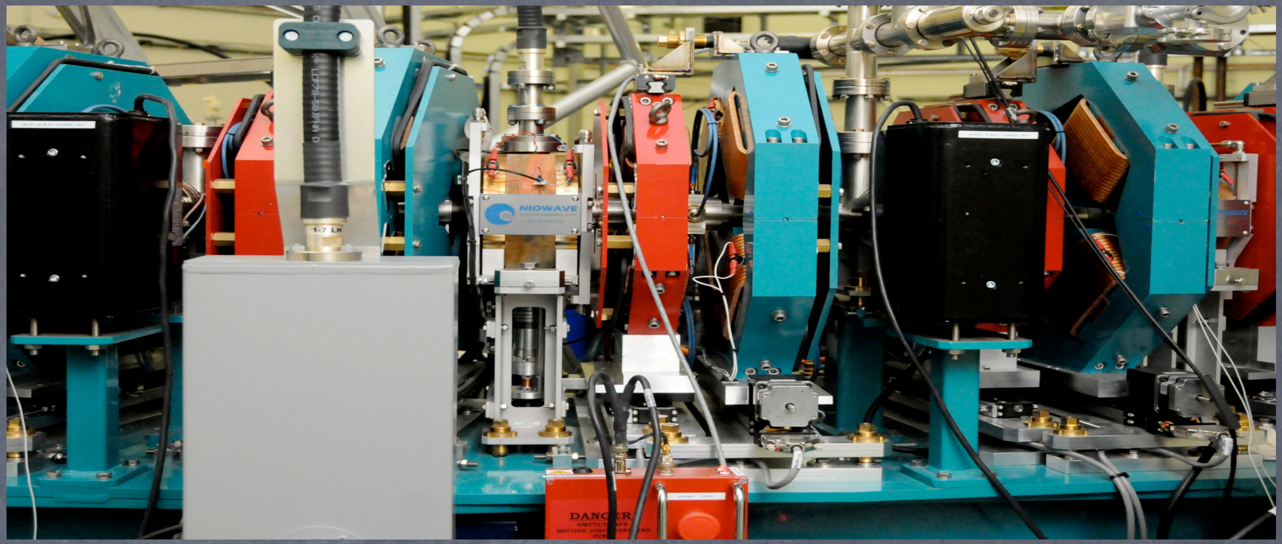
- EMMA at Daresbury ->
- Lattice with very regular 42 doublet cell.

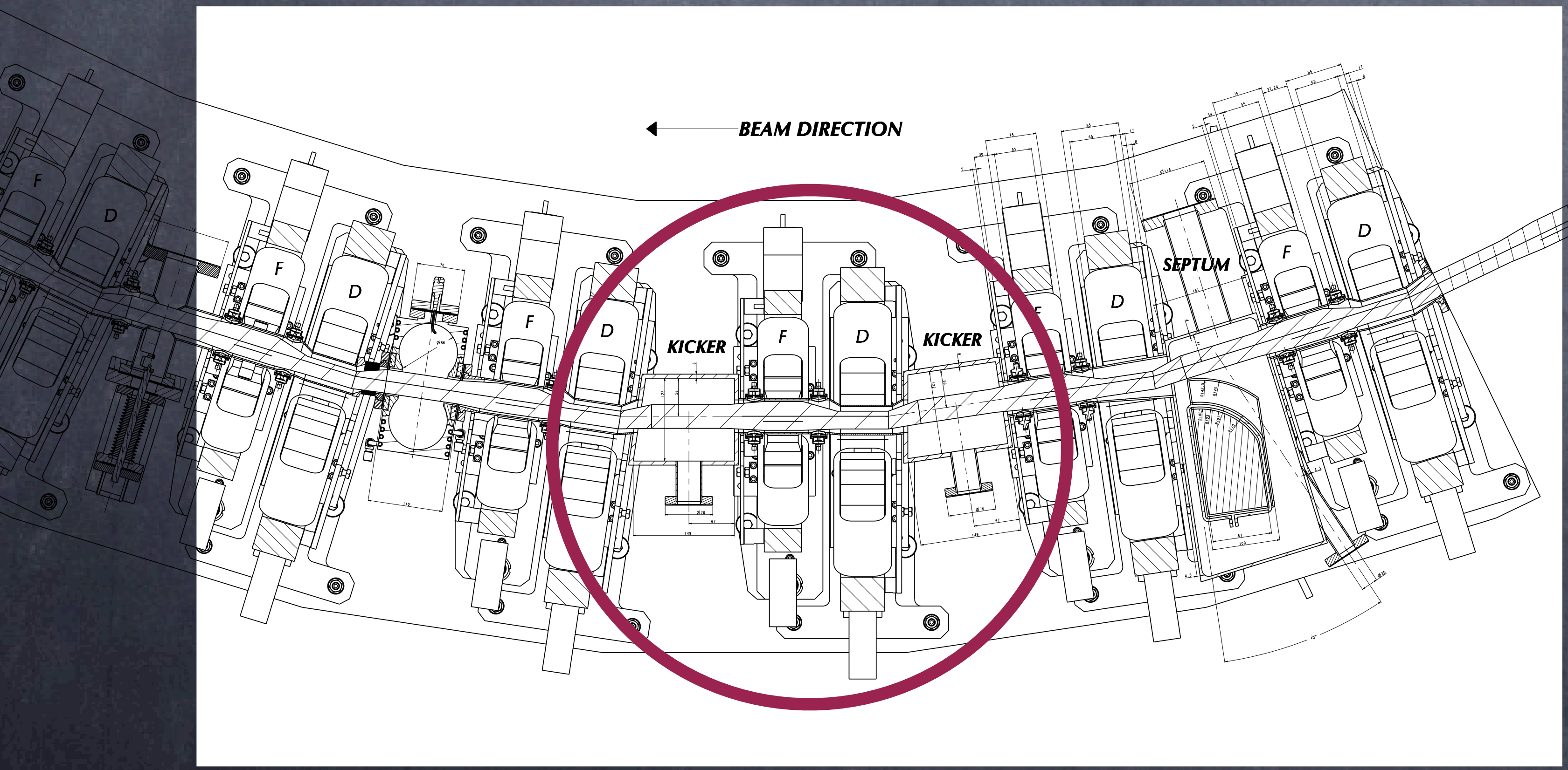


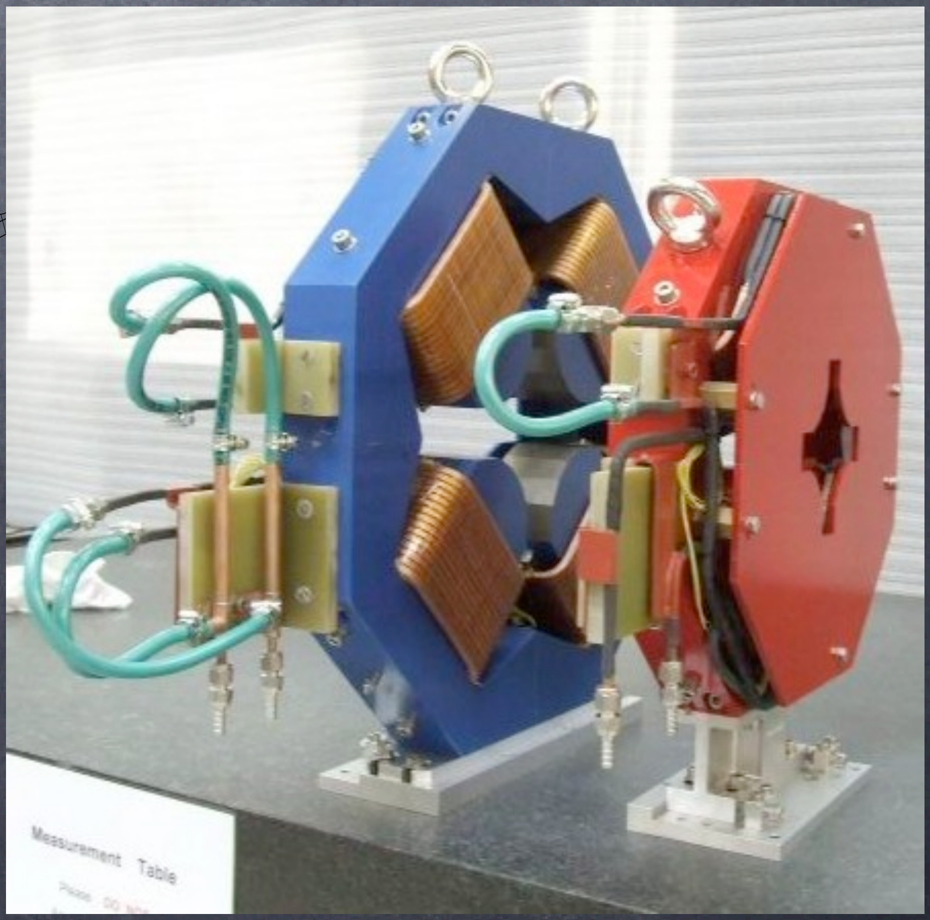
- Diamond light source lattice as a comparison.

EMMA lattice (2)

- Quadrupole only.
- Radially shifted quadrupole to create bending component.

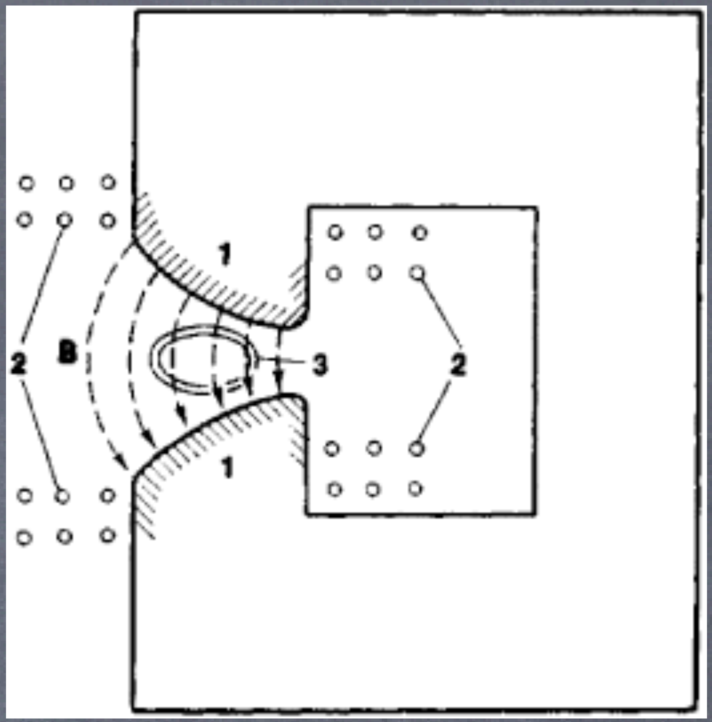






EMMA lattice (3)

- Synchrotron magnets are used to be all "combined function" type.
  - BNL AGS, CERN PS, etc.



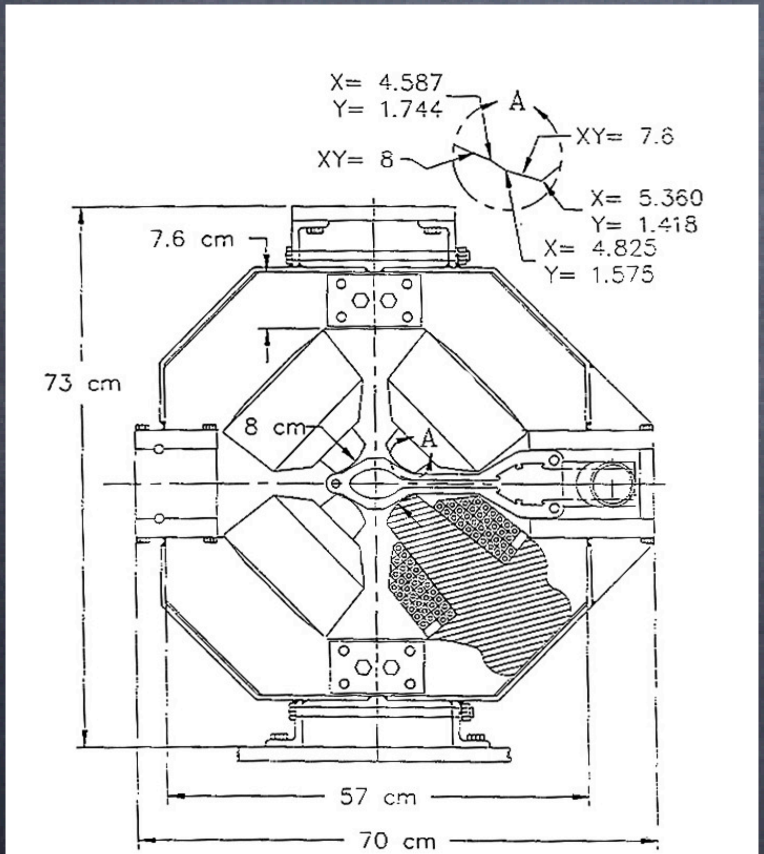


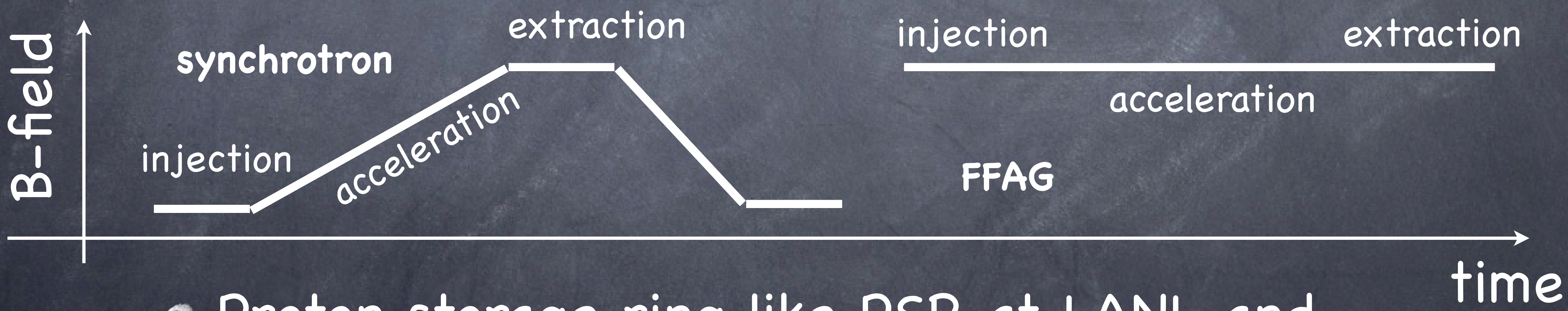
Figure 1.3.1.1.2-010 Cross Section of the Storage Ring Quadrupole Magnet

- "Separated function" magnets (separate bending and quadrupole magnets) were later invented.

SNS ring

EMMA lattice (3)

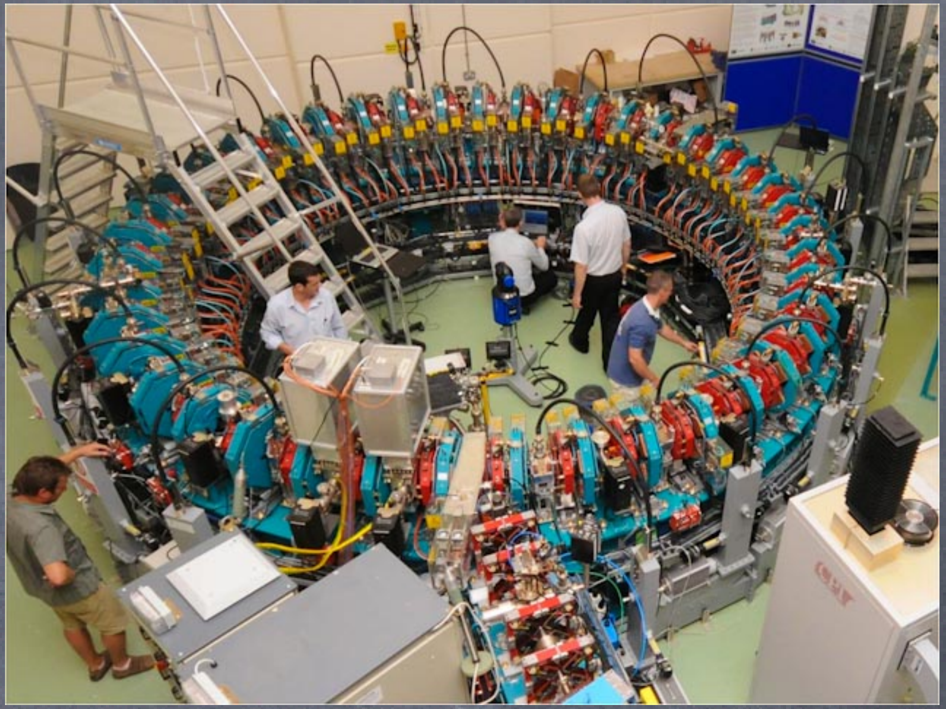
- What is special in EMMA ?
- The only difference from a synchrotron is
  - Magnetic field does not ramp while a beam is accelerated, i.e. fixed field lattice.

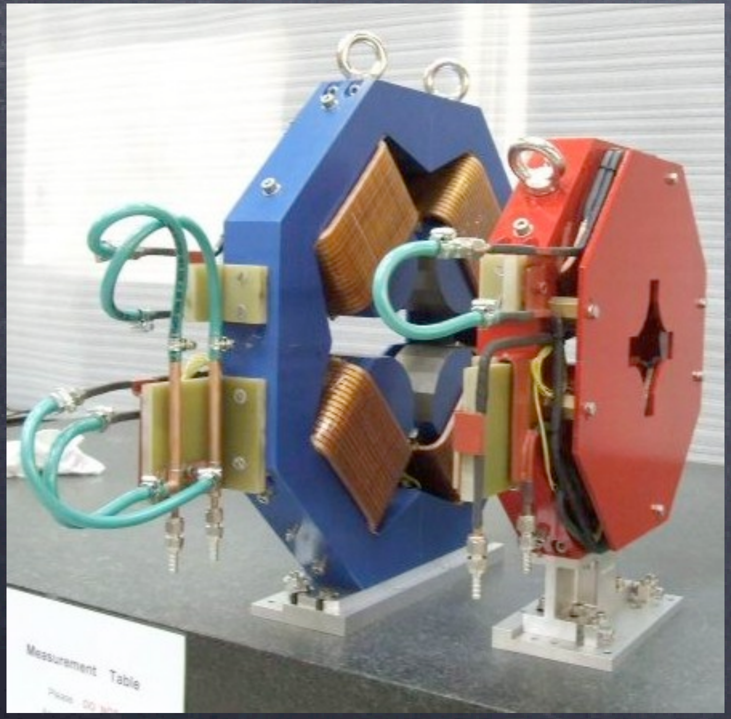


- Proton storage ring like PSR at LANL and SNS at ORNL uses fixed field, but does not accelerate a beam.

EMMA lattice (4)

- EMMA is one family of Fixed Field Alternating Gradient (FFAG) accelerator.





- This family of FFAG, in particular, uses the same type of lattice magnets and has very similar optical property as an ordinary synchrotron.

Operation with fixed field magnets.

Advantage to use fixed field magnet (1)

- Hardware point of view
- Operation point of view
- Beam dynamics point of view

Advantage to use fixed field magnet (1)
hardware point of view

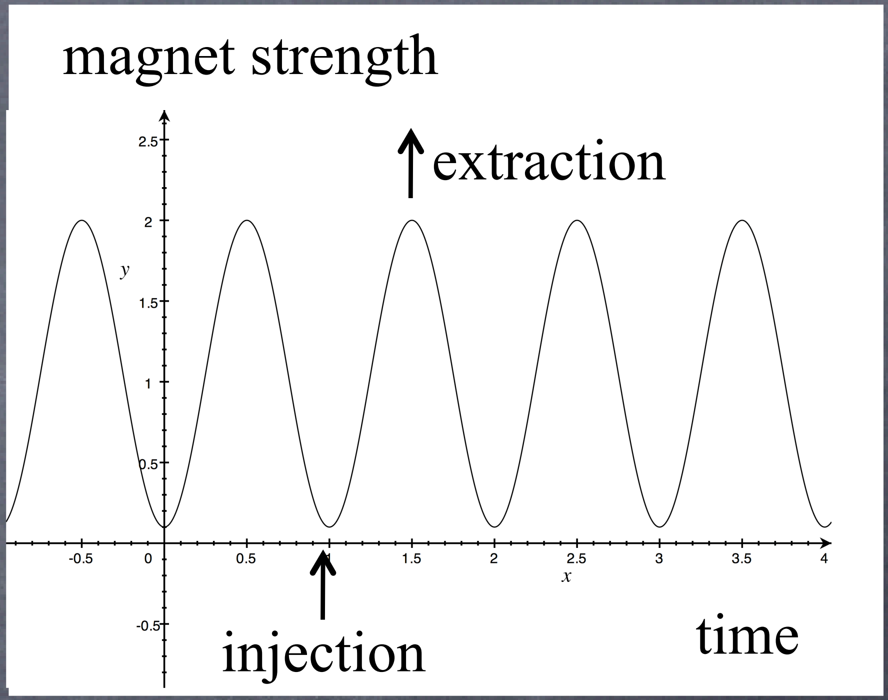
- Power supply is simpler and cheaper.
  - No programming and feedback.
- No eddy current in magnet or on vacuum chamber.

$$V_{ind} = -\frac{dB(t)}{dt}$$

- No synchronisation loop between magnets and rf.
- More reliability compared with machine with pulsed magnets.

Advantage to use fixed field magnet (2) operational point of view

- In a synchrotron, time to complete one acceleration cycle is determined by ramping of magnets.
  - ISIS operates with 50 Hz.
  - 10 ms or ~10,000 turns.



- In FFAG, it is possible to accelerate a beam very fast. Only limited by available rf voltage (power).
  - ~10 turns (for muon acceleration).

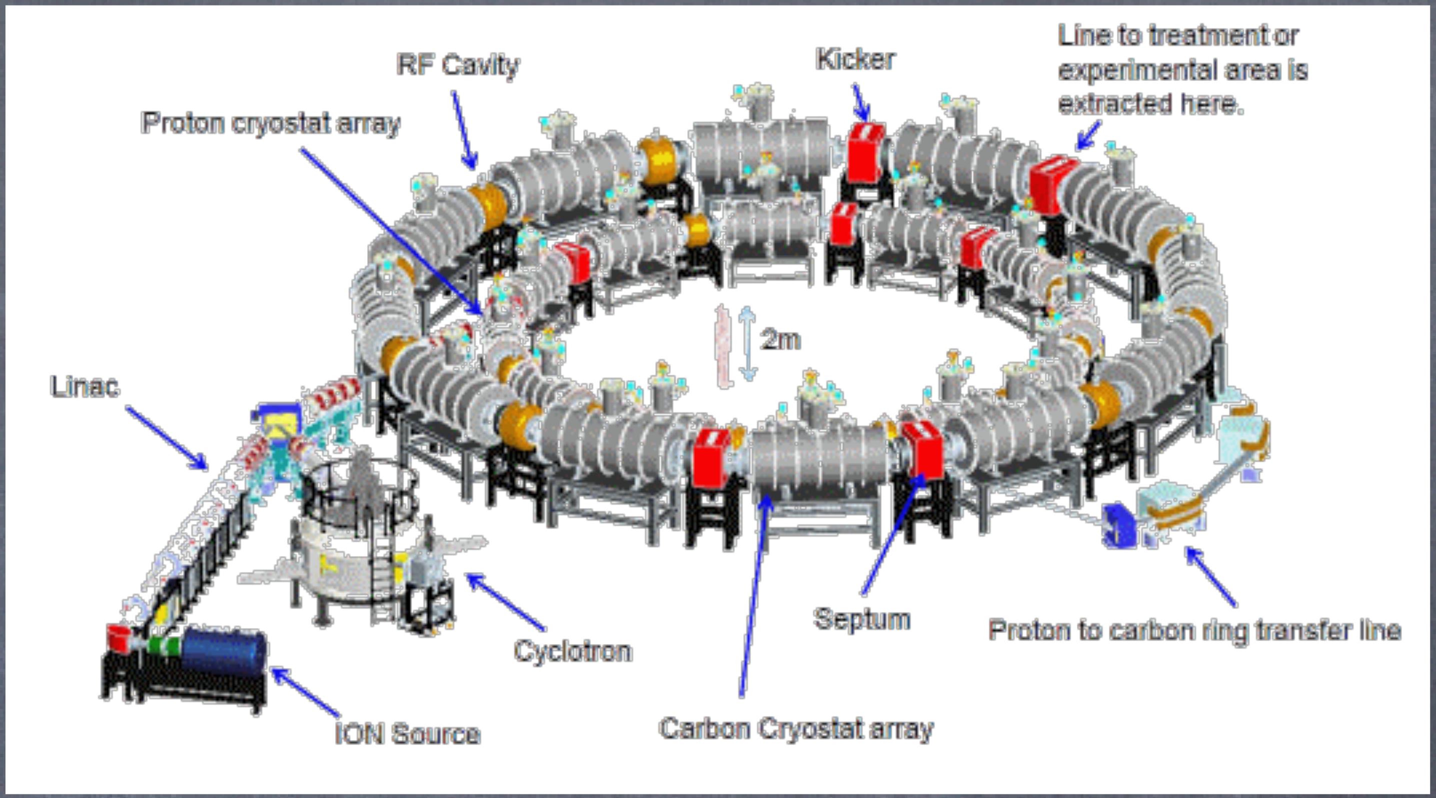
Advantage to use fixed field magnet (3) beam dynamics point of view

- Higher repetition makes the high average current.
  - Beam power = Energy x NofP x Rep.
- High "Rep." can reduce "NofP" to get the same beam power. Space charge effect is a single bunch effect and proportional to "NofP" only.

$$\Delta Q = -\frac{r_p n_t}{2\pi\beta^2\gamma^3\varepsilon_t B_f}$$

Advantage to use fixed field magnet (4) altogether

PAMELA



- Easy to handle
- Inexpensive
- Compact
- Accelerators for medical and security use.
  - spot scanning

- Muon acceleration.
- Accelerator of short lived particles.

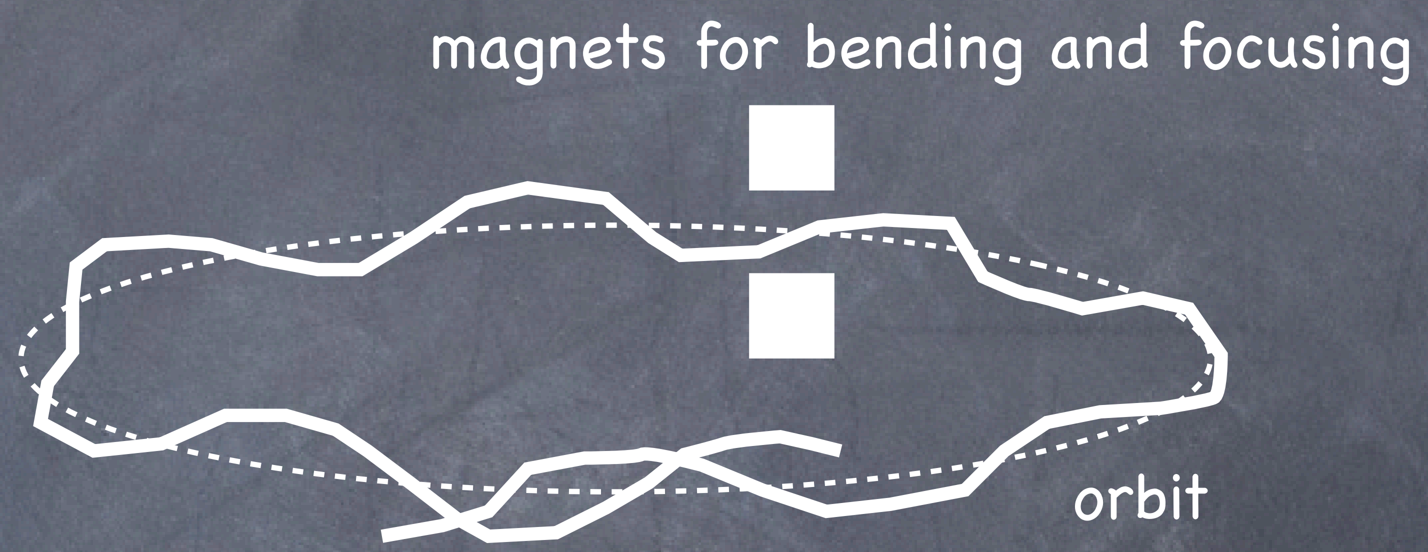
- High power accelerators for n, m and ADSR.

Summary so far (1)

- FFAG accelerators are similar to synchrotron, but operated with fixed field magnets, which give many advantages.
- What is the disadvantages?

Three basic parameters of circular accelerators (1)

- Revolution time
  - rf frequency
- Circulating radius
  - vacuum chamber size
- Transverse focal length or effective strength
  - beam dynamics



Three basic parameters of circular accelerators (2)

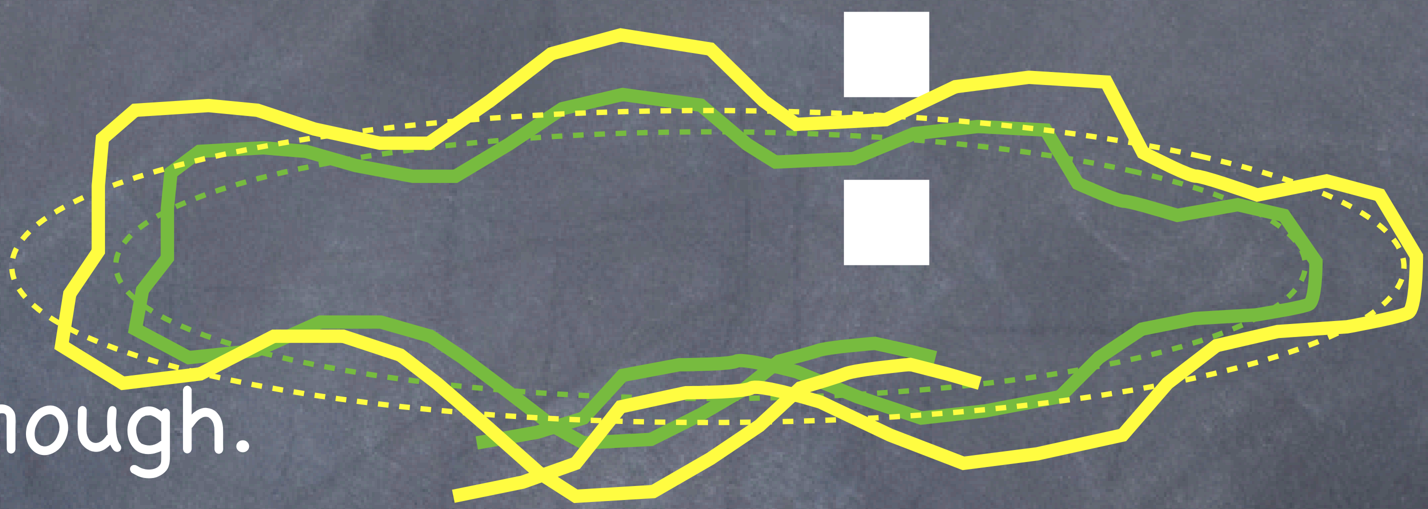
	Cyclotron	Synchrotron	FFAG
Revolution time	constant fixed frequency rf	varies const for relativistic beams	varies
Circulating radius	varies	constant	varies
Transverse focusing	varies	constant	varies

FFAG seems most ambitious or crude approach?

Dispersion function (1)

- Change of circulating radius can be small with small dispersion function.

$$\Delta R = D(dp/p)$$



- How small is small enough.
  - dp/p ~ +/-33% (factor 2) to +/-50% (factor 3).
  - To make the orbit shift within a few cm, dispersion function should be less than 10 cm.
    - D = dR/(dp/p)
  - In an ordinary synchrotron, it is > 1 m.

Dispersion function (2)

- H-function defined as

$$H = X_d^2 + P_d^2$$

$$X_d = D/\sqrt{\beta_x} = \sqrt{2J_d}\cos\phi_d$$

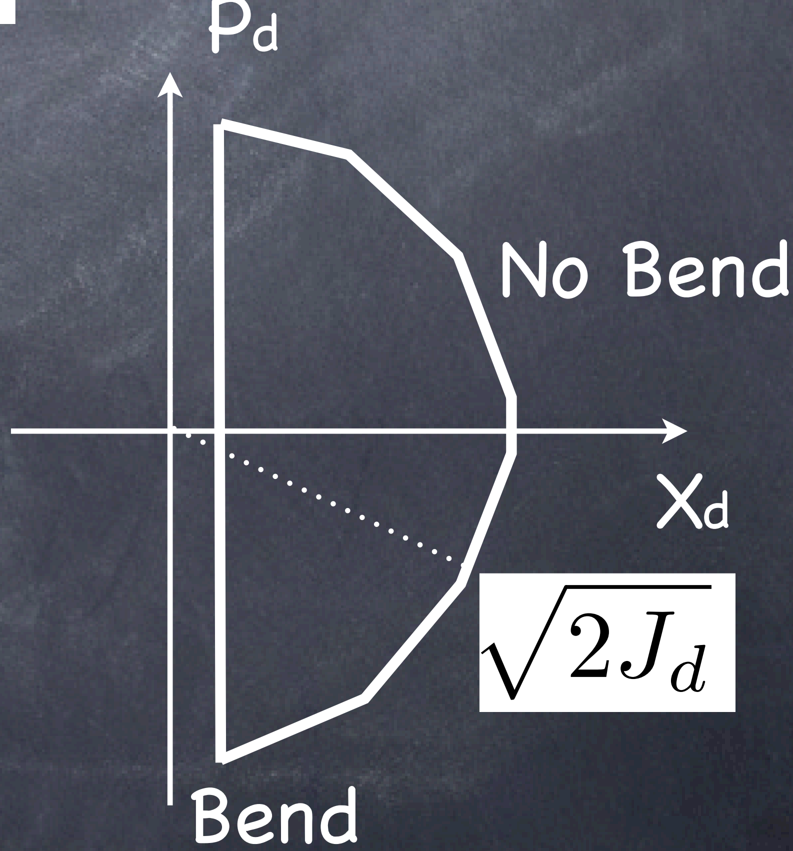
$$P_d = (\alpha_x D + \beta_x D')/\sqrt{\beta_x} = -\sqrt{2J_d}\sin\phi_d$$

- Without bending, J_d is invariant and ϕ_d is identical to the betatron phase advance.

- With bending (thin lens), J_d changes.

$$\Delta X_d = 0$$

$$\Delta P_d = \sqrt{\beta_x}\Delta D = \sqrt{\beta_x}\theta$$



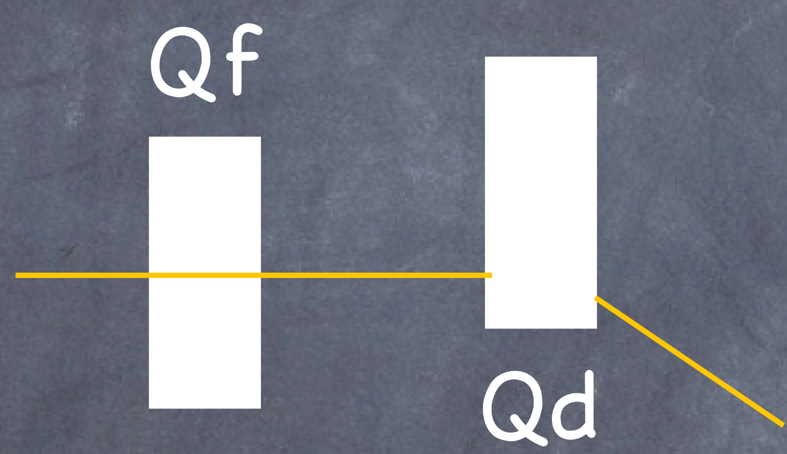
Dispersion function (3)

- Trick is to bend where the horizontal beta is small.

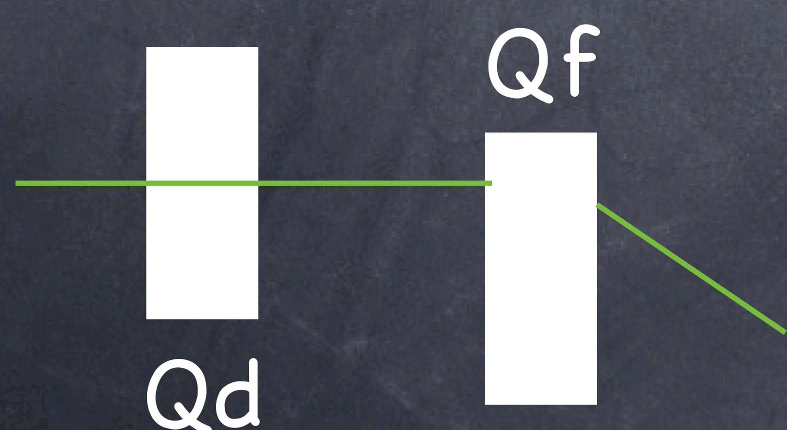
$$\Delta P_d = \sqrt{\beta_x}\Delta D = \sqrt{\beta_x}\theta$$

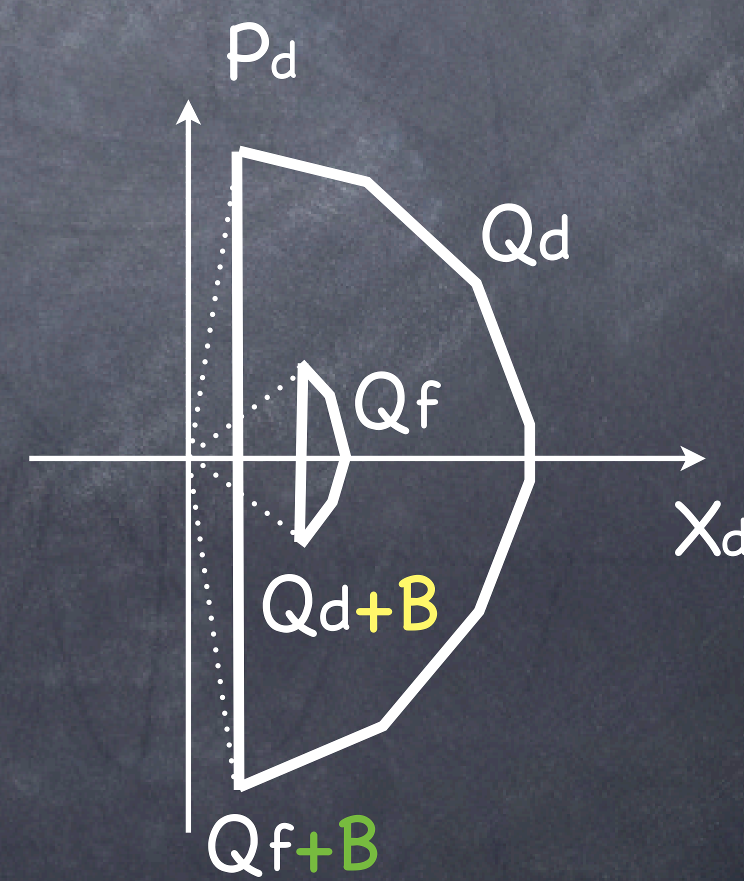
$$\phi = \int \frac{ds}{\beta_x}$$

- Bend in Qd gives small ΔP_d and phase advance in Qf is small.



- Bend in Qf gives large ΔP_d and phase advance in Qd is large.





Focusing force (1)

- Focusing due to quadrupole magnets.
  - Example: FODO lattice.

$$\sin\frac{\phi}{2} = \frac{L}{2f} \qquad \frac{1}{f} = \frac{(dB/dx)L_m}{B\rho}$$

ϕ : phase advance, L : half cell, L_m : quad length, $B\rho$: rigidity

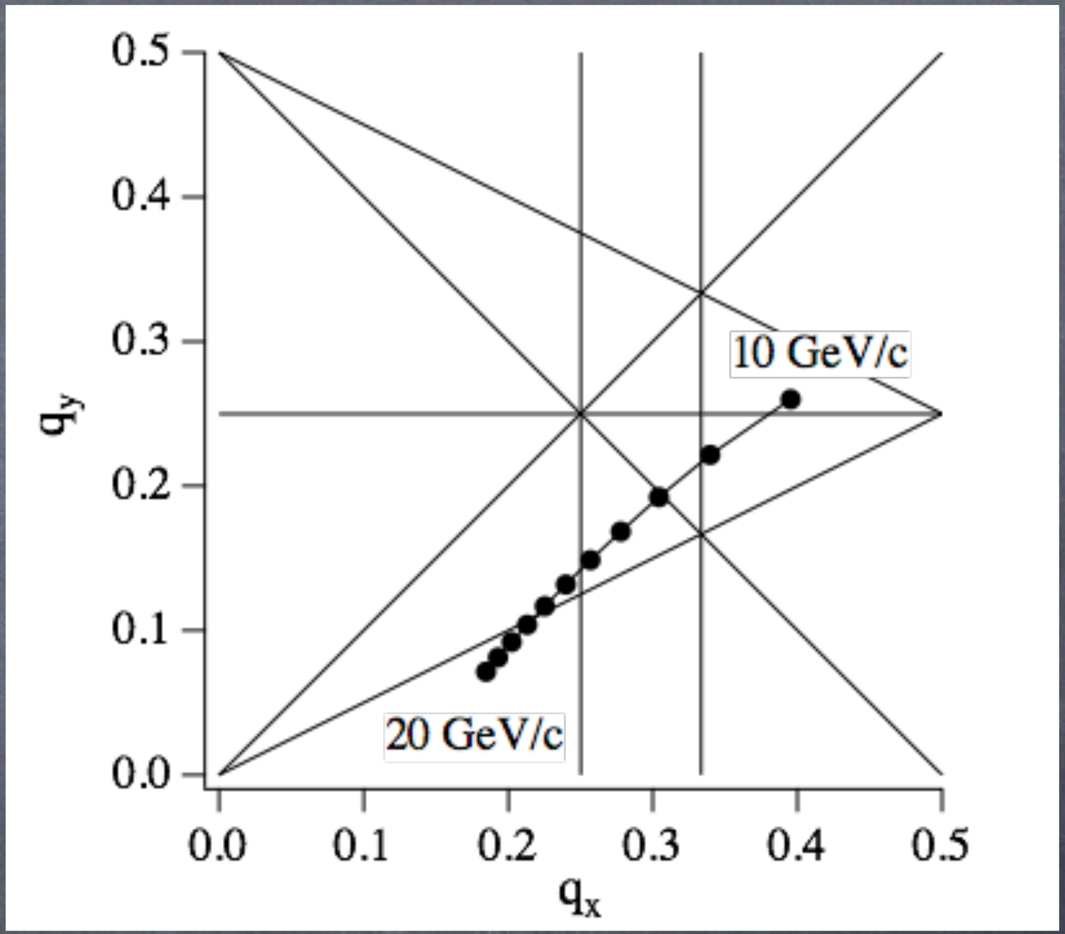
  - Beta function becomes large with high momentum.

$$\beta_F = \frac{2L[1+\sin(\phi/2)]}{\sin\phi}$$

β_F : beta function

Focusing force (2)

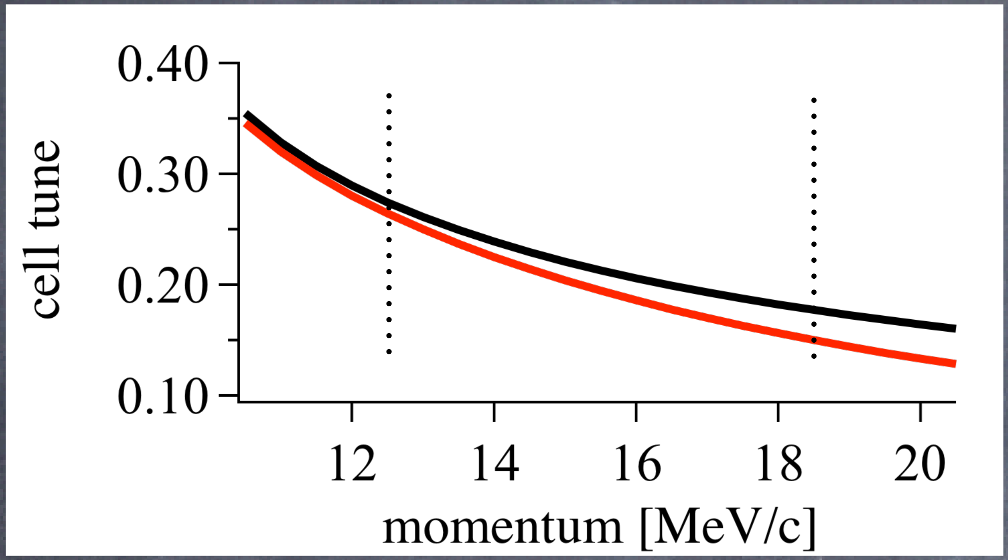
- In a synchrotron, tune is fixed and away from resonance lines.
- In a FFAG, tune moves through acceleration.
- The number of resonance lines is minimised by high periodic lattice.



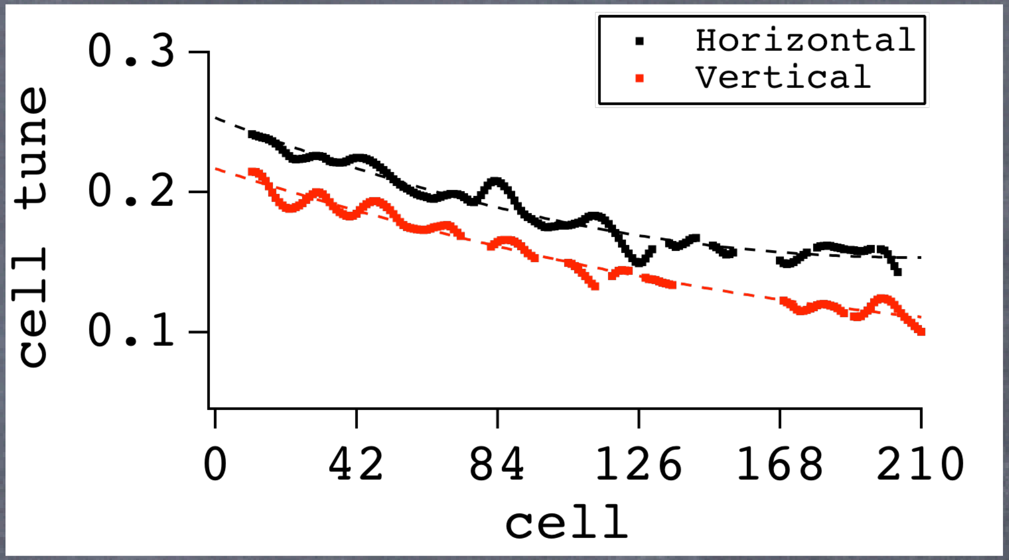
- How harmful to go through "resonances" at rational tunes? This depends on other parameters.
  - In EMMA, a beam goes through very quickly.

EMMA results (1)

- When a beam is accelerated, tune decreases.

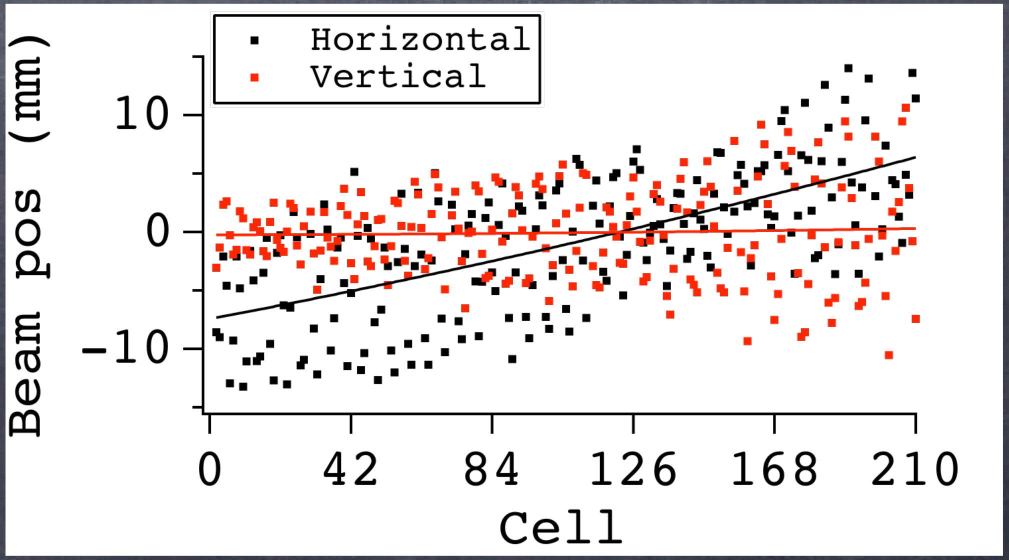


simulation



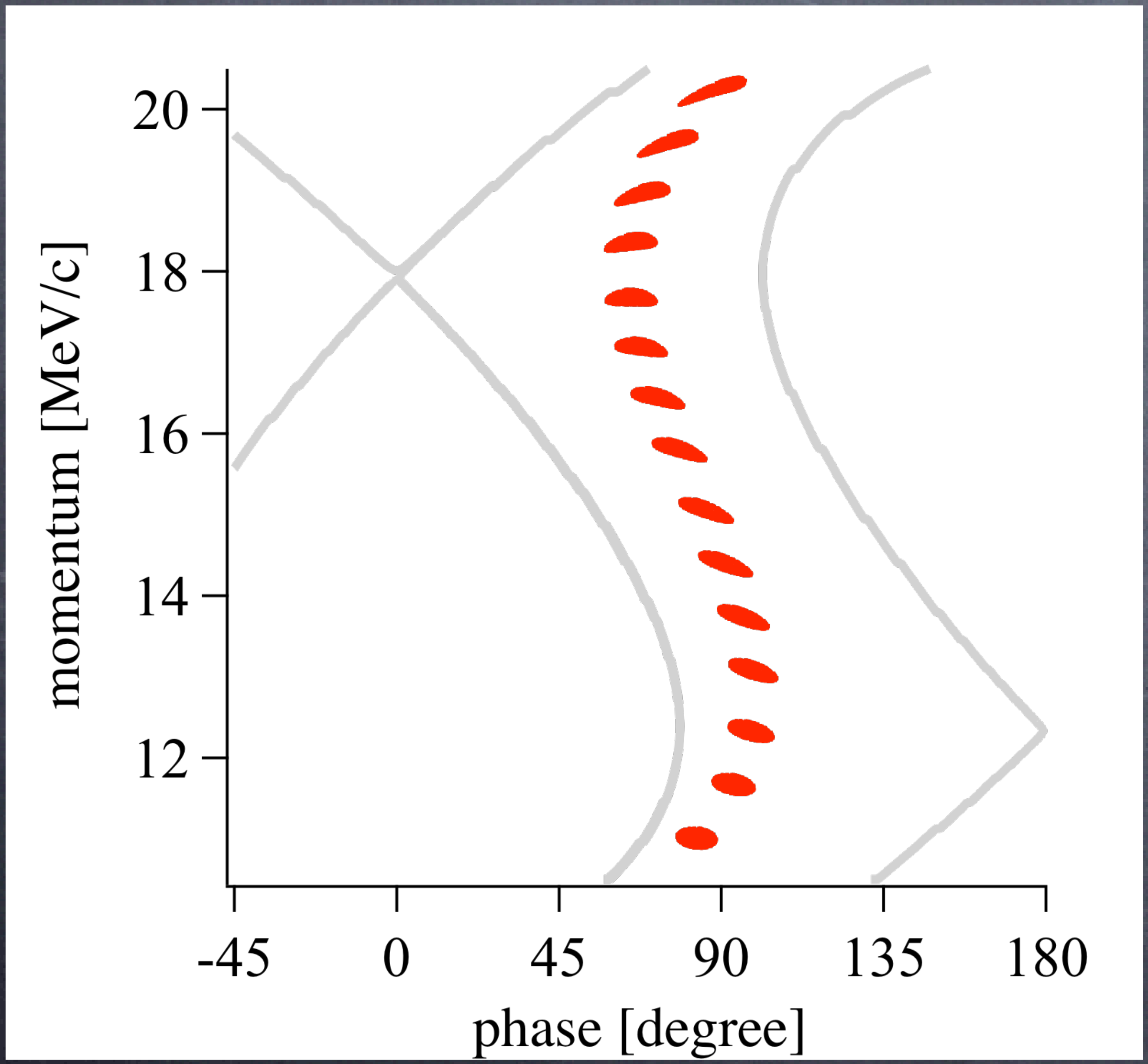
experiment (12.5 to 18.5 MeV/c)

- When a beam is accelerated, orbit expands horizontally, but not in vertical.

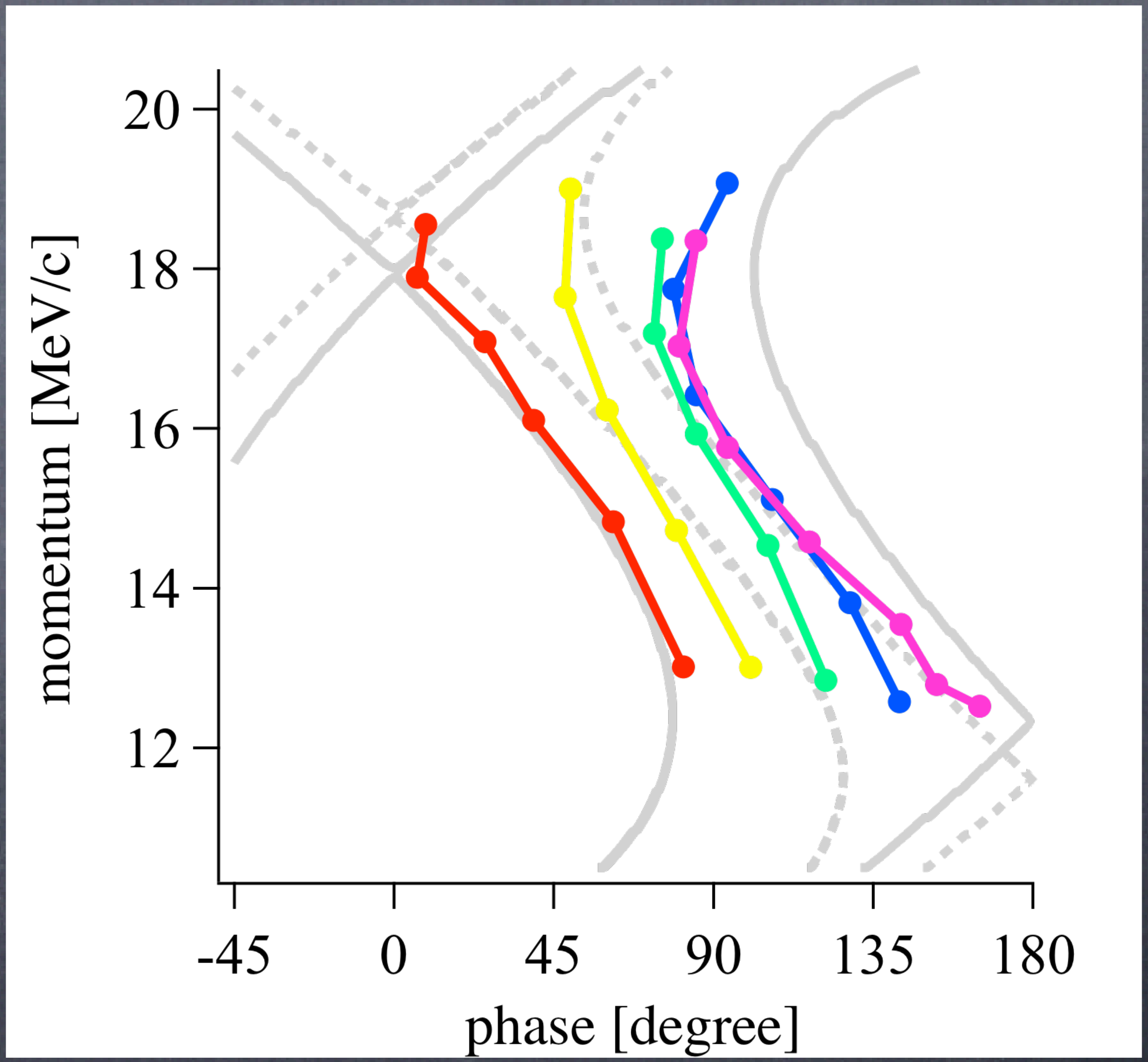


EMMA results (2)

- Reconstruction of longitudinal phase space.
  - “Serpentine channel acceleration”



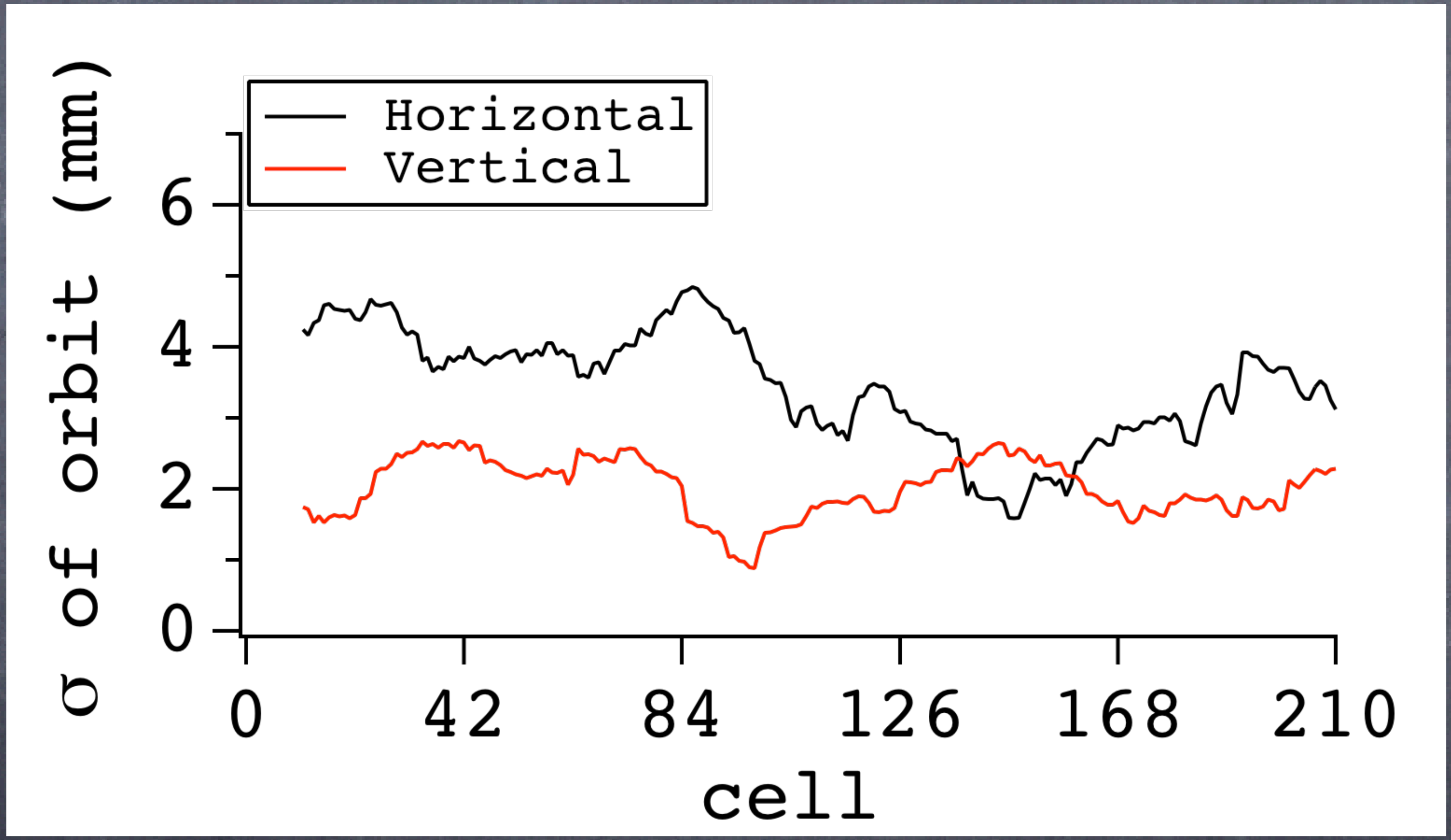
simulation



experiment (12.5 to 18.5 MeV/c)

EMMA results (3)

- No blowup of beam size despite crossing of resonances.



experiment (12.5 to 18.5 MeV/c)

Ref: S. Machida et al., Nature Physics 8, 243 (2012)

Summary so far (2)

- FFAG accelerators are similar to synchrotron, but operated with fixed field magnets, which give many advantages.
- Specific optics and orbit design for FFAG overcomes potential disadvantages as being fixed field operations.

FFAG family

- Non-scaling FFAG like EMMA is in fact a new comer in the FFAG family.
- Original FFAG design has orbit shift, but tune is fixed by "scaling" principle, invented in 1950s.

FFAG with constant tune

scaling machine

Three parameters of circular accelerators (3)

	Cyclotron	Synchrotron	FFAG
Revolution time	constant	varies (const for relativistic)	varies but small range
Circulating radius	varies	constant	varies but small range
Transverse focusing	varies	constant	**varies**

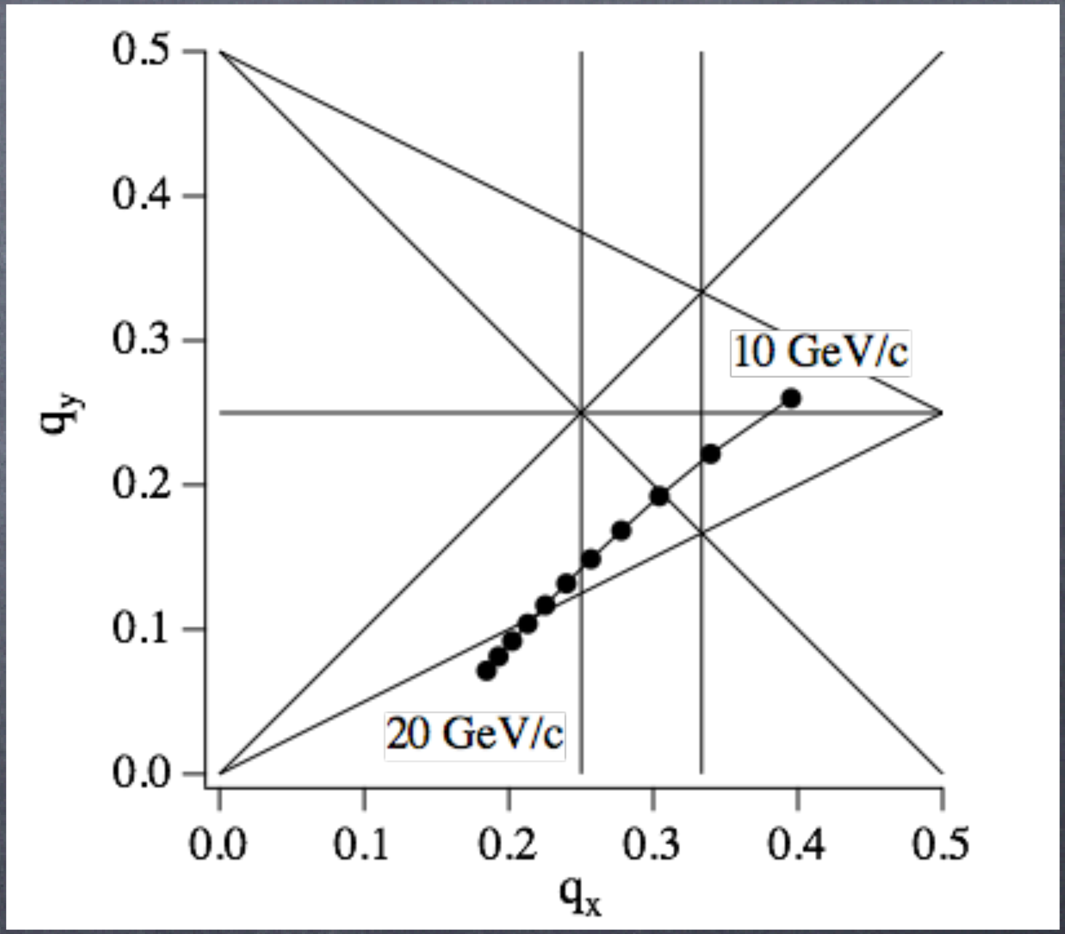
FFAG seems most ambitious or crude approach?

Focusing force

- For muon acceleration, a beam goes around only ~10 turns.

- Large tune shift during acceleration is very scary for other applications.

- Larger resonant build up may happen.

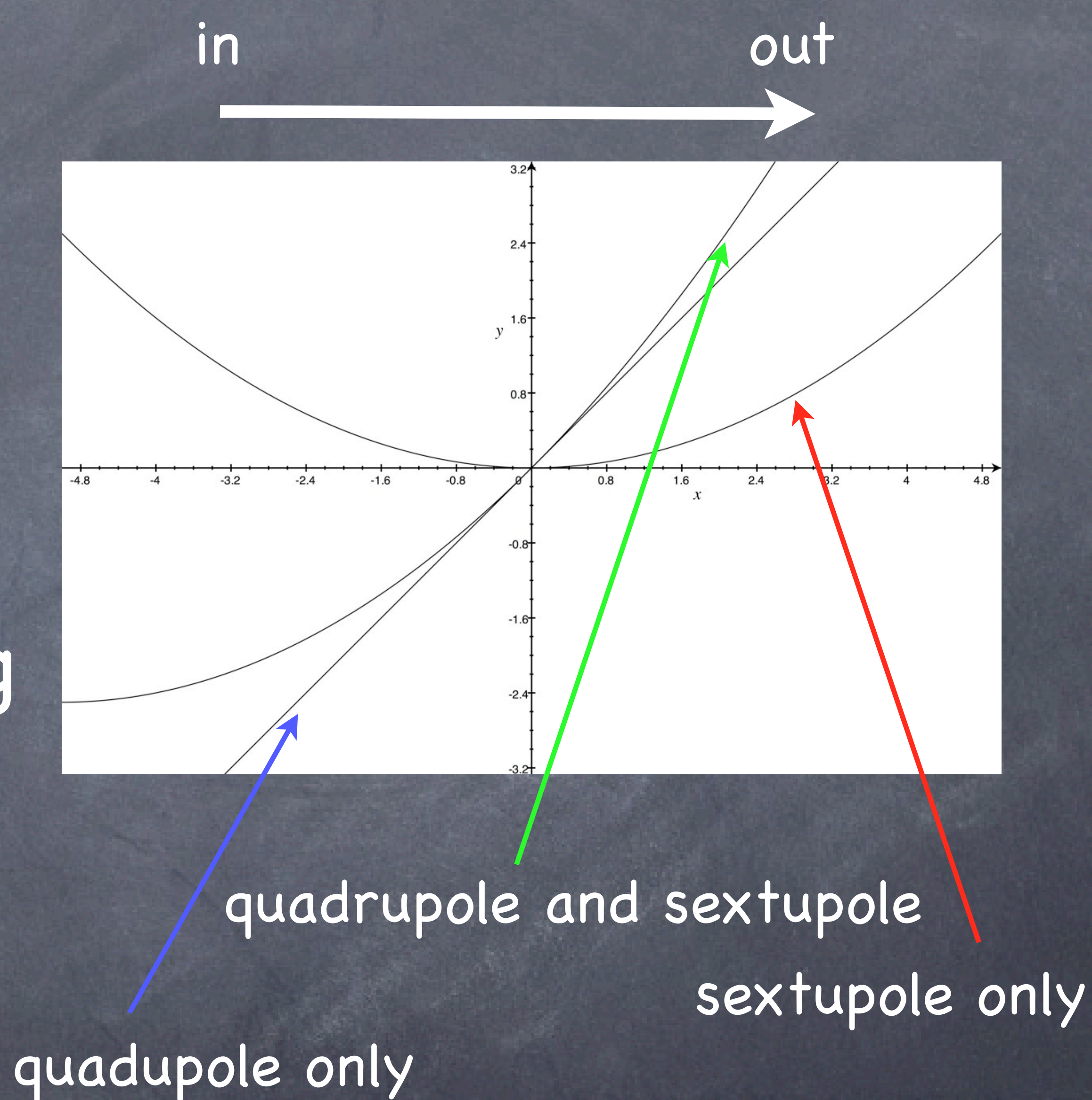


Chromaticity correction (1)

- In an ordinary synchrotron, small shift of tune due to off-momentum particles (< 1%) could be a big problem.
- Sextupole for chromaticity correction is a common practice to compensate it.

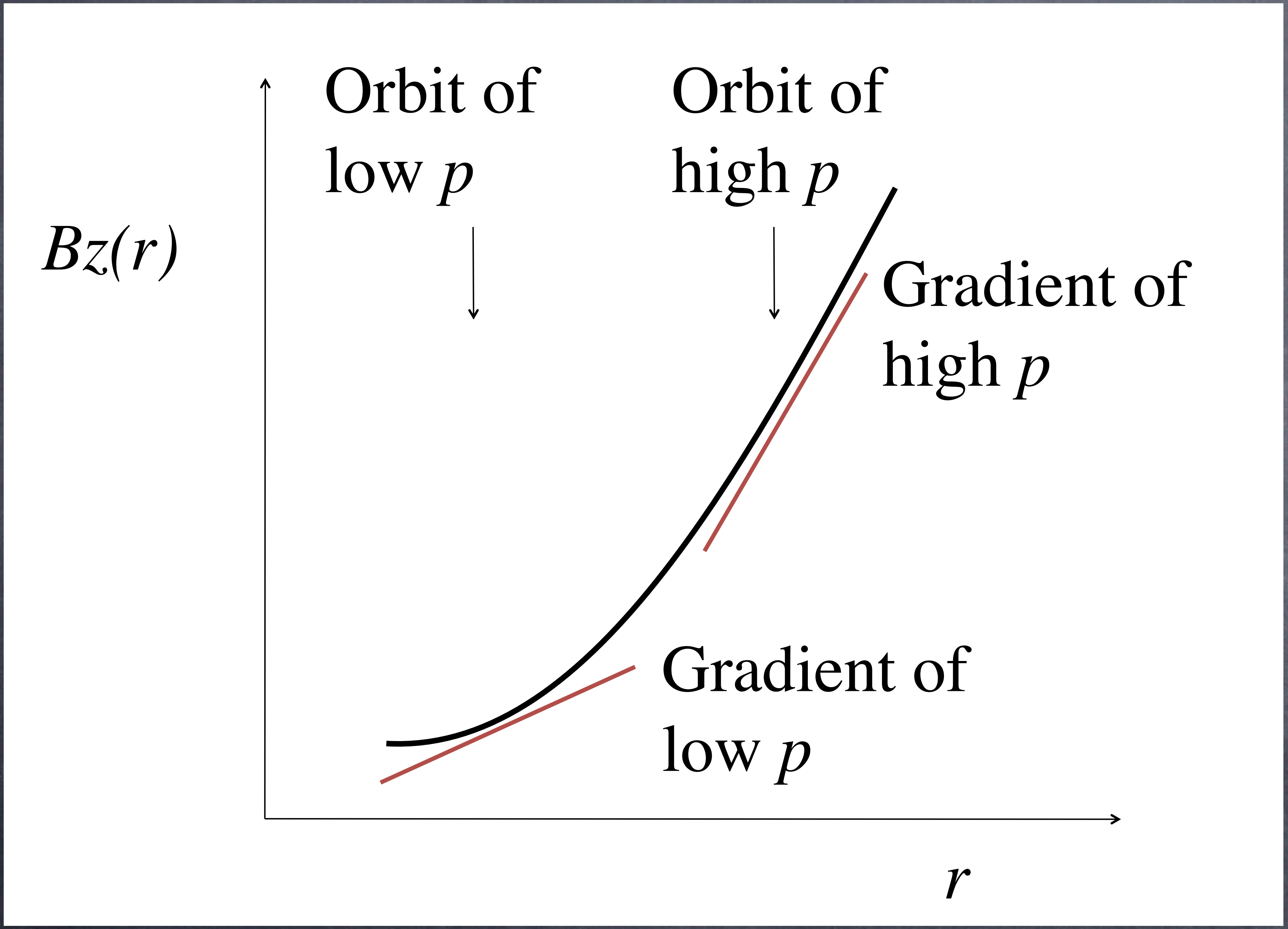
Chromaticity correction (2)

- Off-momentum particle circulates outer orbit.
  - make a magnet which has gradient depending on its radial position.



- Sextupole (x^2) is enough to correct for small dp/p (< 1%).

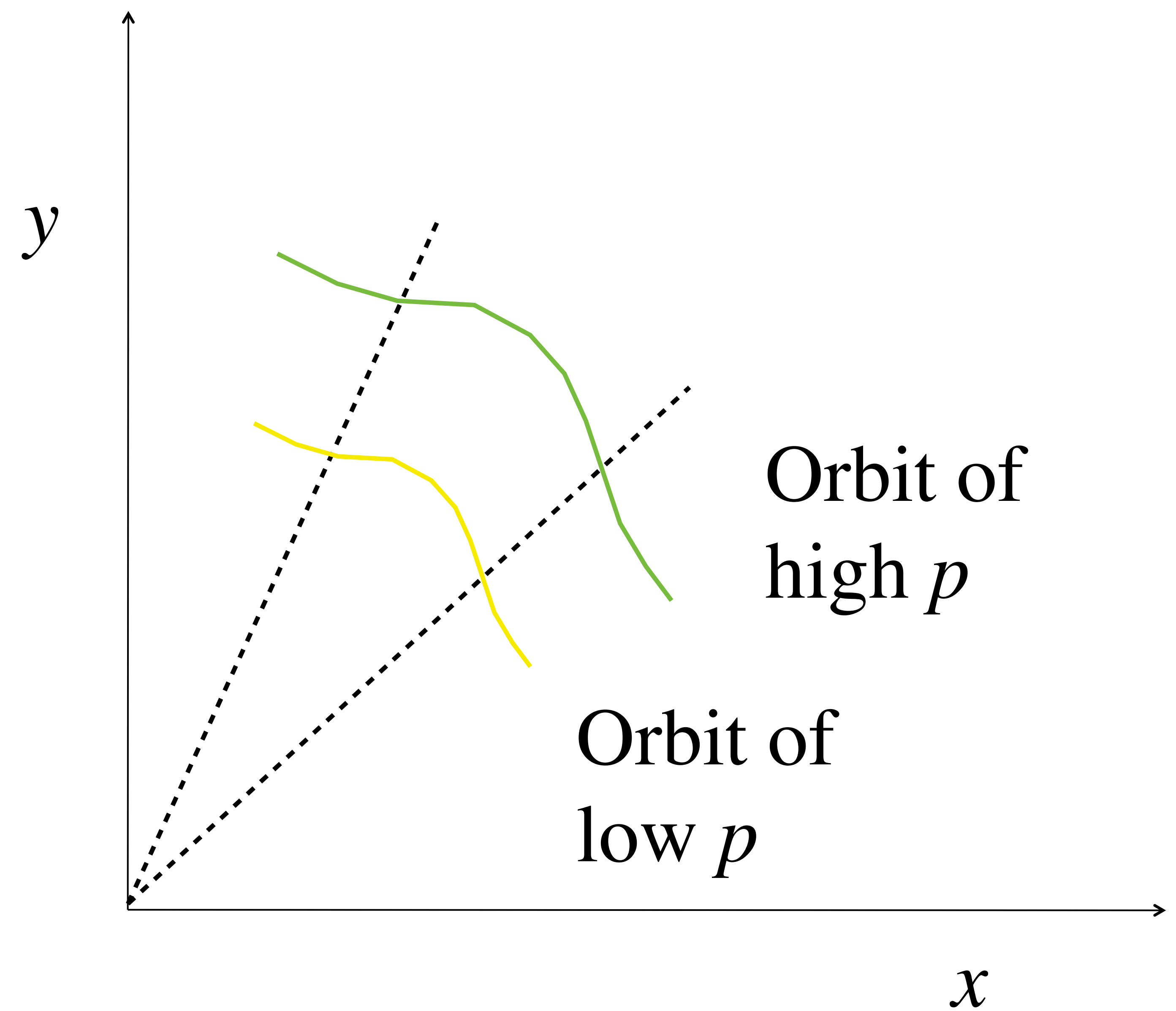
Cardinal condition of scaling FFAG (1)
"constancy of field index"



$$\left.\frac{\partial k}{\partial p}\right|_{\vartheta = const.} = 0$$

$$k = \frac{r}{B}\left(\frac{\partial B}{\partial r}\right)$$

Cardinal condition of scaling FFAG (2) "geometrical similarity"



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

ρ_0 : average curvature

ρ : local curvature

ϑ : generalised azimuth

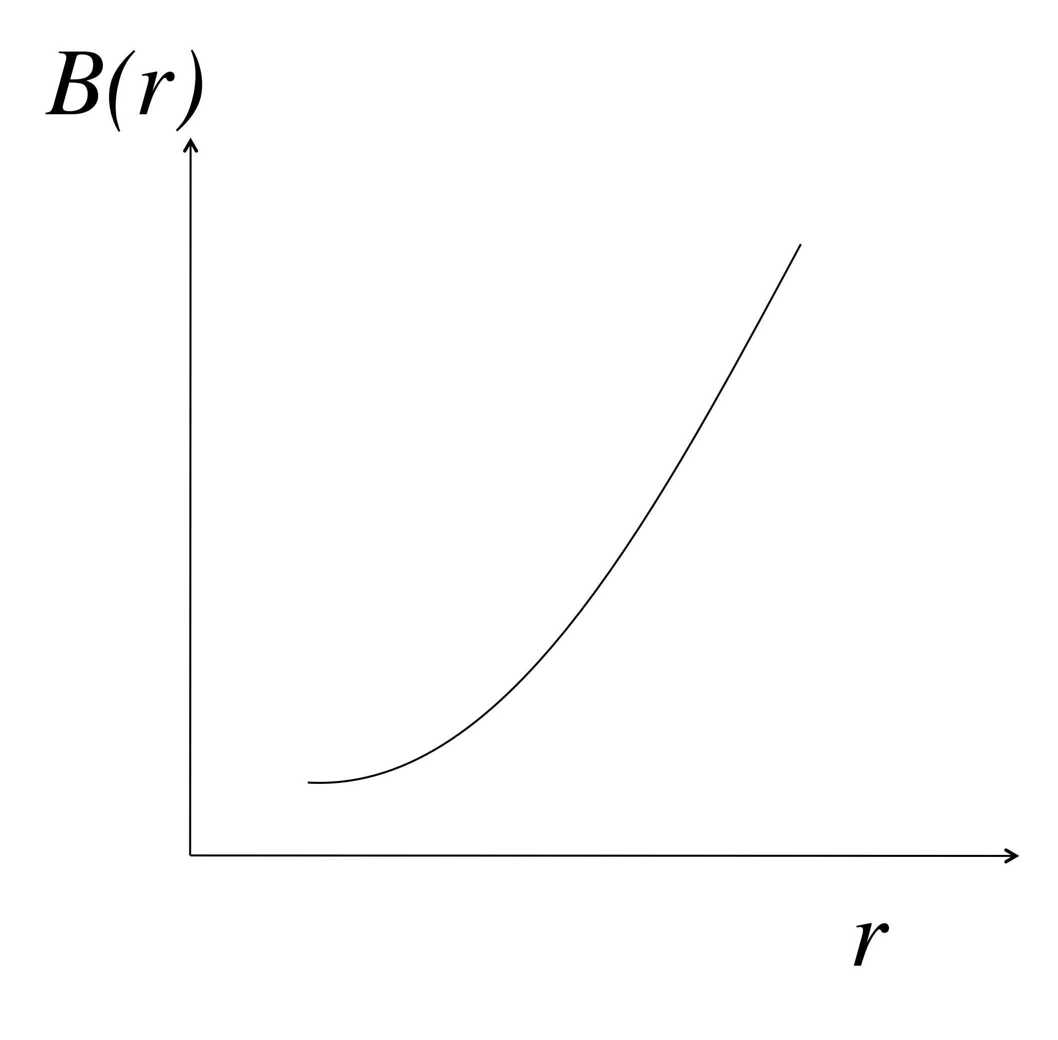
Field profile in radial direction

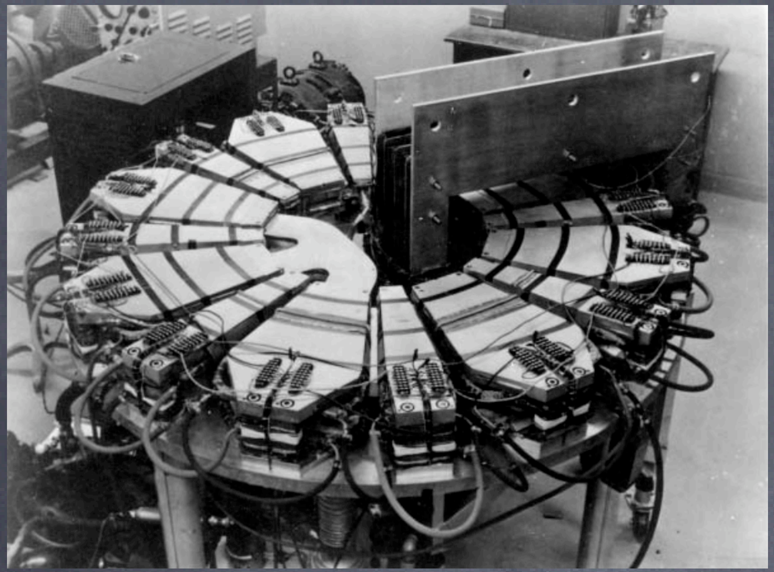
- If the field profile has the following shape, cardinal conditions are satisfied.

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

- Field shape is determined by focusing condition, not by isochronous condition.

$$\omega = \frac{eB}{m\gamma} \neq \text{constant}$$





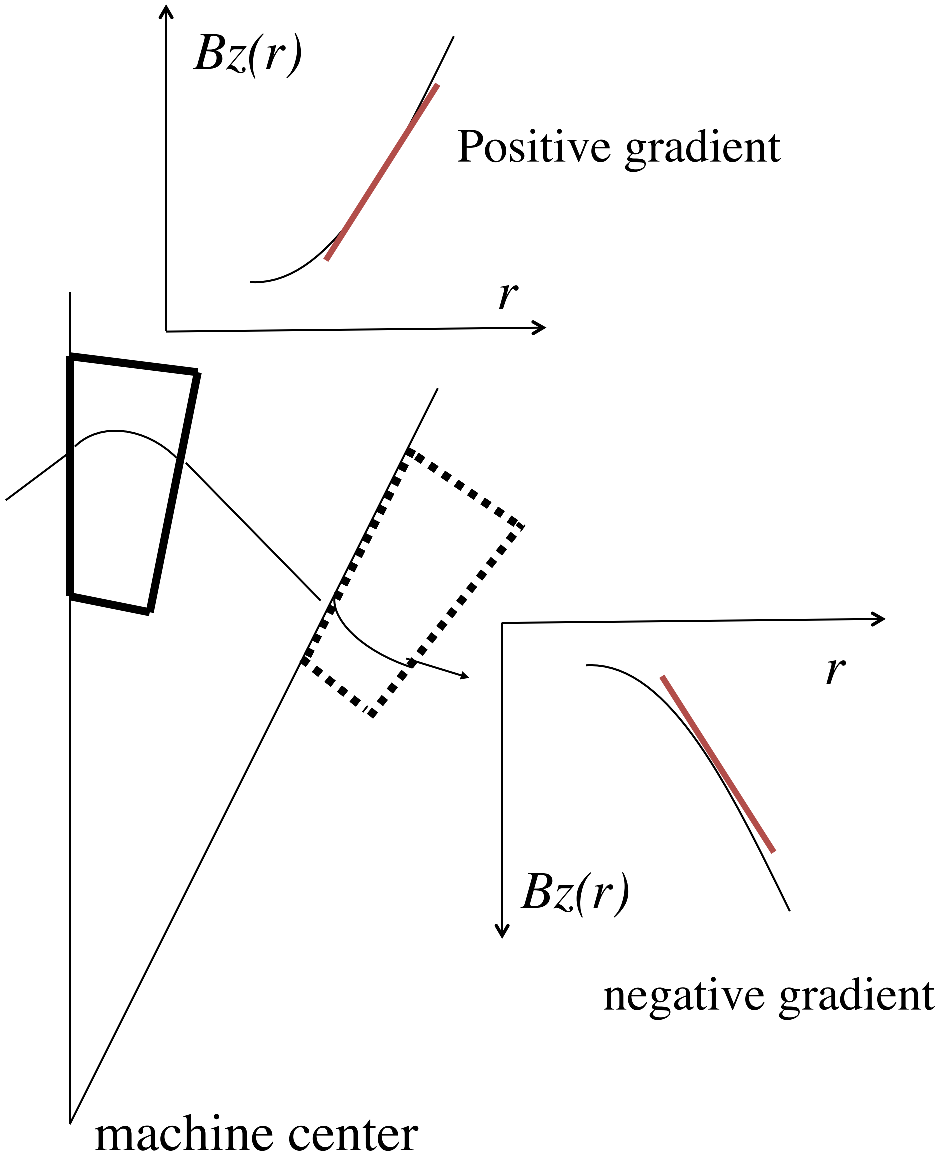
Radial sector

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

$$F(\vartheta) = F(\theta)$$

Radial sector type

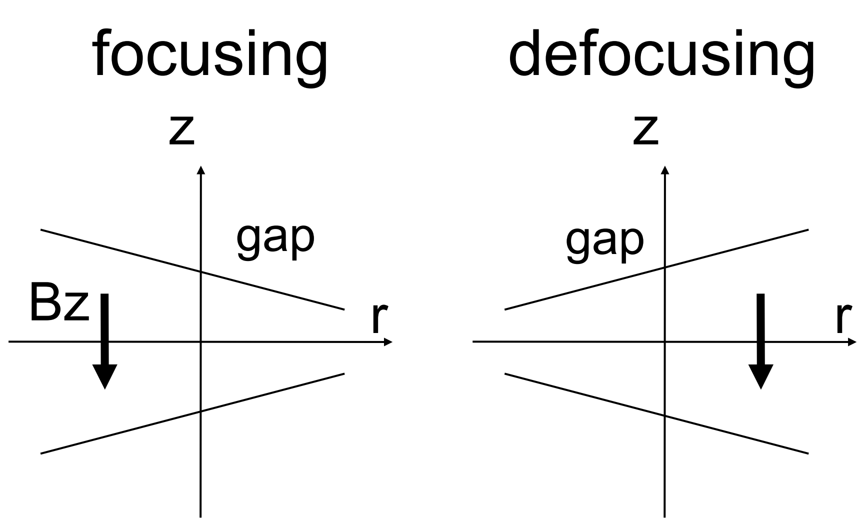
Alternating magnet has opposite sign of bending.



AG focusing in synchrotron and FFAG

Conventional strong focusing synchrotron

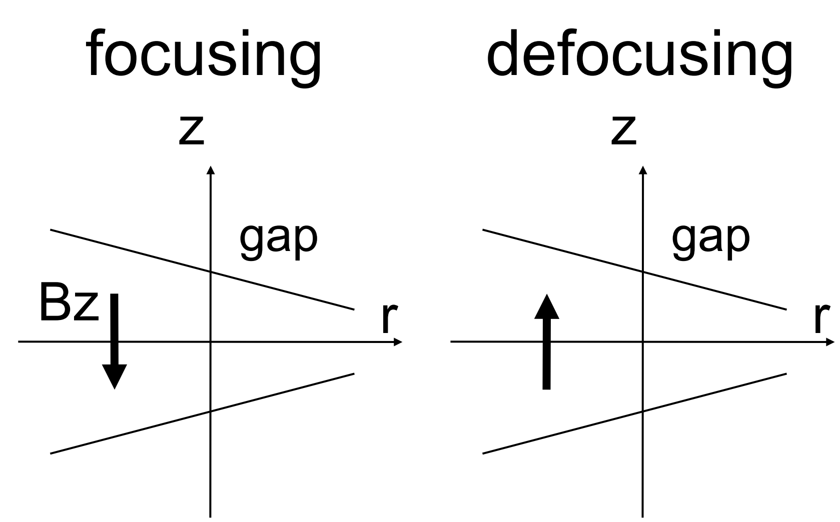
Bending a beam in the same direction.

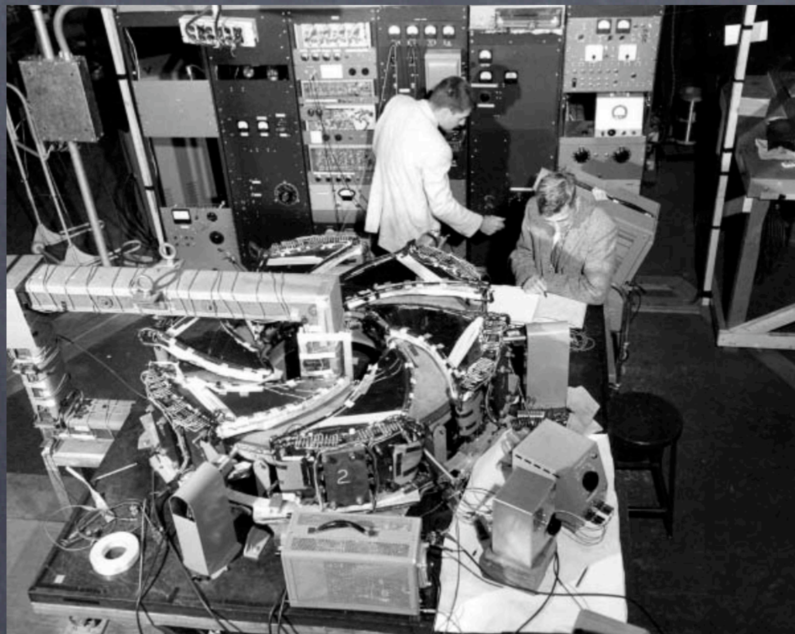


Does not satisfy the cardinal condition. Explain why.

FFAG

Bending a beam in the opposite direction to change the sign.





Spiral sector

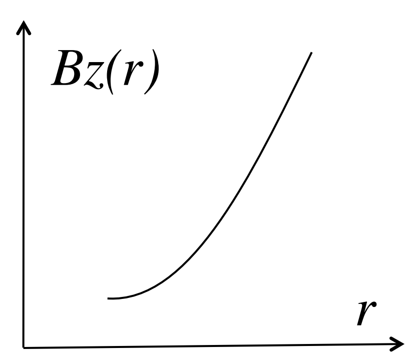
$$B(r,\theta) = B_0\left(\frac{r}{r_0}\right)^k F(\vartheta)$$

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

Spiral sector type

$$\frac{rd\theta}{dr} = tan\zeta$$

$$\theta - \theta_0 = tan\zeta \cdot \ln\frac{r}{r_0}$$



Spiral angle gives strong edge focusing.

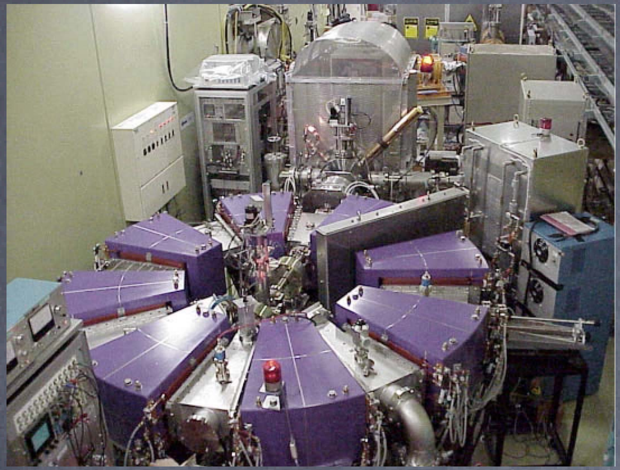
$$\therefore \Delta p_z = \frac{e}{v_x}\int_{-\infty}^{\infty}(-v_y B_x)dx = -eB_{z0}\tan\zeta \cdot z$$

Three variables of circular accelerators (3)

	Cyclotron	Synchrotro n	non-scaling FFAG	scaling FFAG
Revolution time	constant	varies (const for relativistic)	varies but small range	varies
Circulating radius	varies	constant	varies but small range	varies
Transverse focusing	varies	constant	varies	constant

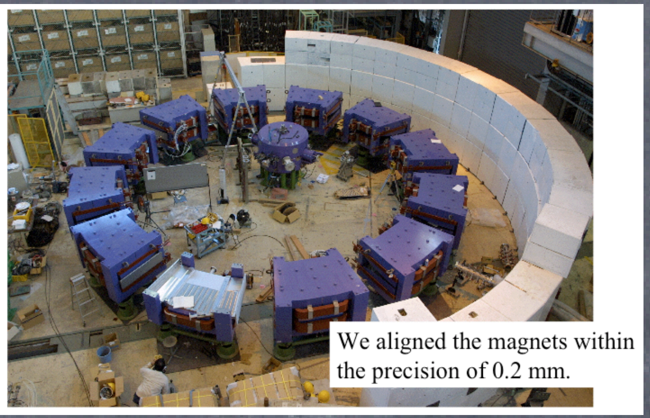
Re-birth of FFAG for the last few years

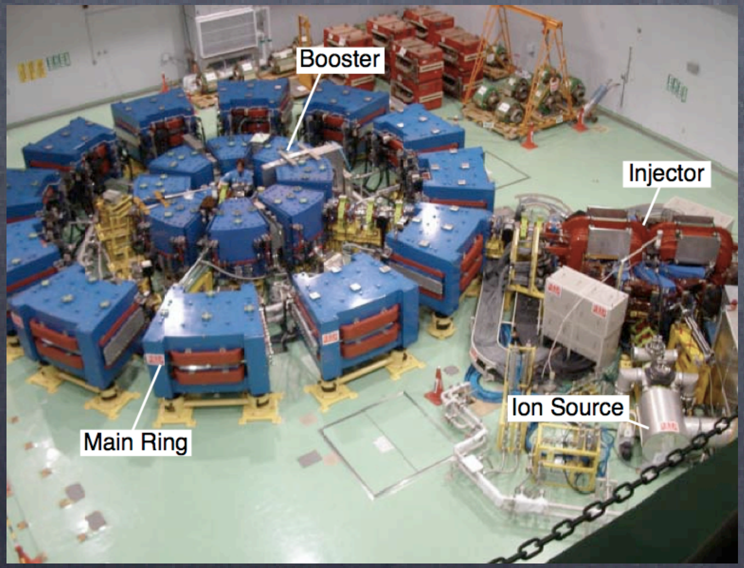
- 2000s



Proof of principle (proton acceleration with rf cavity) machine was constructed in 1999 and demonstrate rapid acceleration with 1 kHz.

Scale up version of PoP FFAG was constructed as a prototype of proton therapy machine.





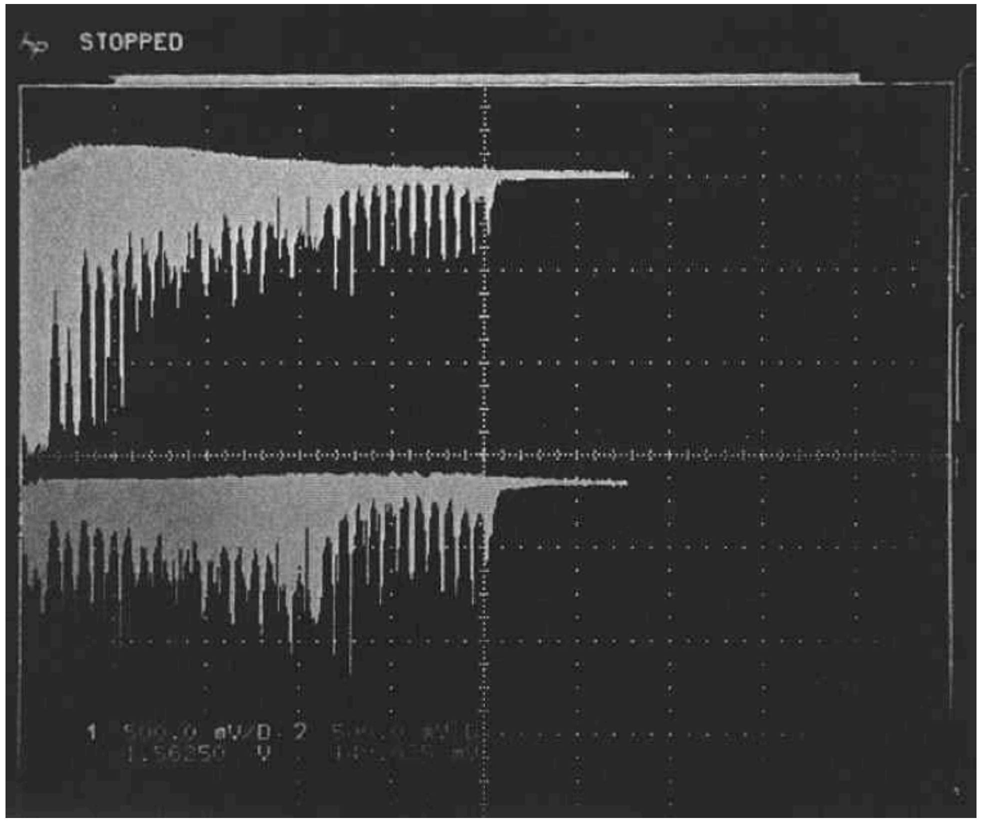
3 stage FFAG for ADSR

- 2.5 MeV spiral (ion beta) FFAG with induction cores
- 25 MeV radial (booster) FFAG with RF and flat gap
- 150 MeV radial (main) FFAG with RF and tapered gap

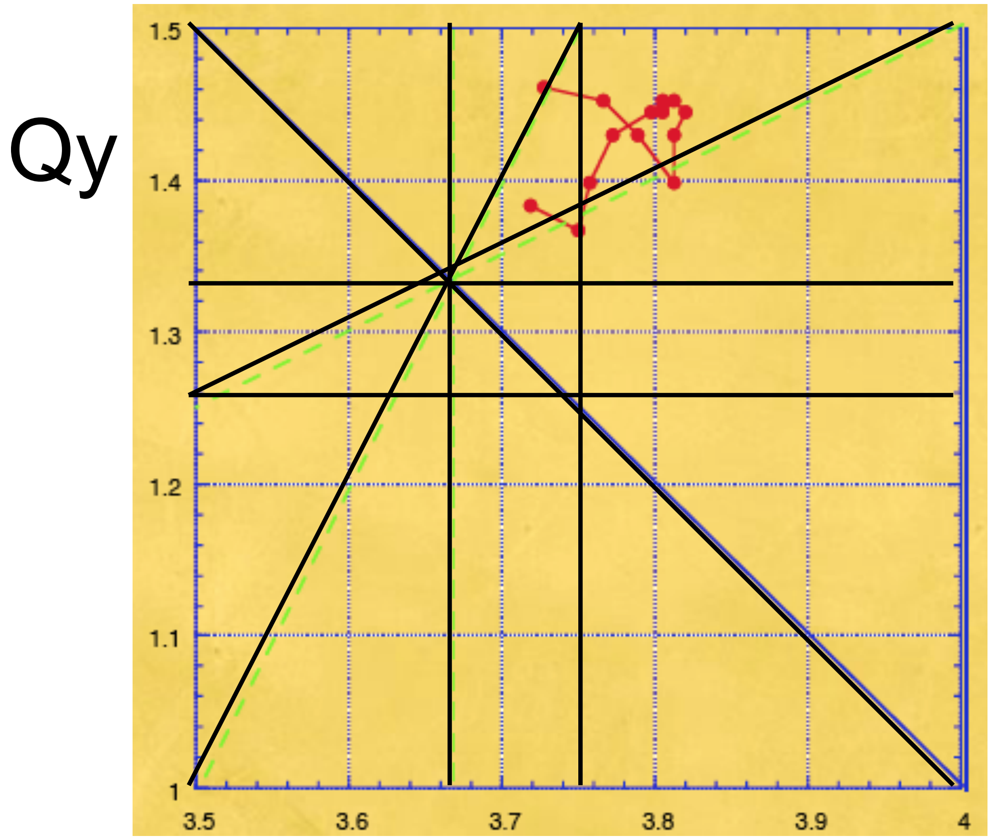
Beam power is still moderate.

Scaling FFAG results

- Demonstration of 1 ms acceleration (1 kHz equivalent).



Tune diagram of 150 MeV FFAG



- Tune excursion in 150 MeV FFAG.

Summary so far (3)

- FFAG accelerators are similar to synchrotron, but operated with fixed field magnets, which give many advantages.
- Specific optics and orbit design for FFAG overcomes potential disadvantages as being fixed field operations.
- Specific shape of field make the transverse tune constant.

Tune stabilised FFAG

- EMMA is a linear non-scaling FFAG.
- Original FFAG follows the scaling design.
- It is possible to fix the tune without following scaling principle.
  - Tune stabilised FFAG.
  - or Nonlinear non-scaling FFAG.

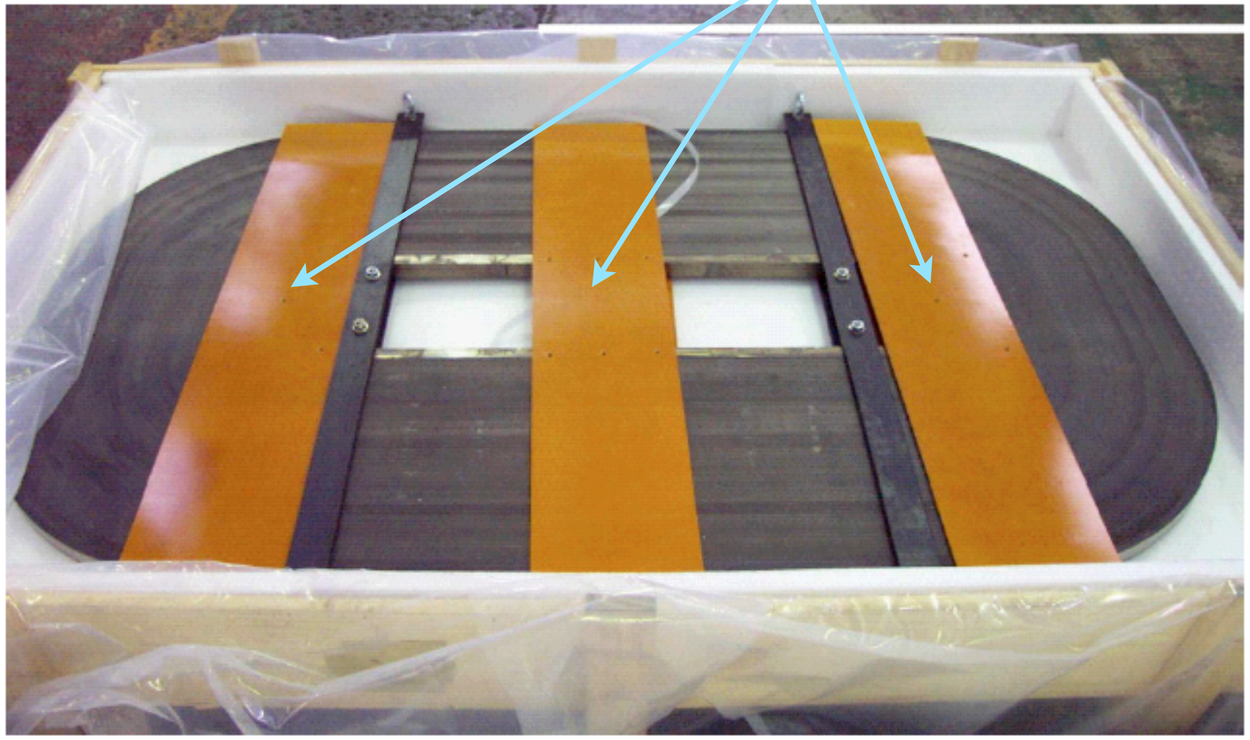
Scaling FFAG vs. synchro-cyclotron

- What is the difference between FFAG and synchro-cyclotron?
  - very similar
  - strong transverse focusing (alternating gradient)
  - transverse tune is constant
  - orbit does not move much
- probably there is no point to make a synchro-cyclotron now, it should be a FFAG.

One slide on hardware

- Magnetic Alloy (MA) cavity was the most crucial hardware part of recent scaling FFAG development.

- High shunt impedance for quick acceleration.
- Low Q for quick change of frequency.
- Arbitrary shape by thin tapes.



MA core for 150MeV FFAG
1.7m x 0.985m x 30mm

Summary

- FFAG accelerators are similar to synchrotron, but operated with fixed field magnets, which give many advantages.
- Specific optics and orbit design for FFAG overcomes potential disadvantages as being fixed field operations.
- Specific shape of field make the transverse tune constant.
- So far, it seems promising idea. However, we need to demonstrate high beam power operation.

Thank you for your attention.