Muon (FFAG) Accelerators

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http://www.astec.ac.uk/intbeams/users/machida/proc/pac07/machida_20070628.pdf & ppt

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- Summary (1)

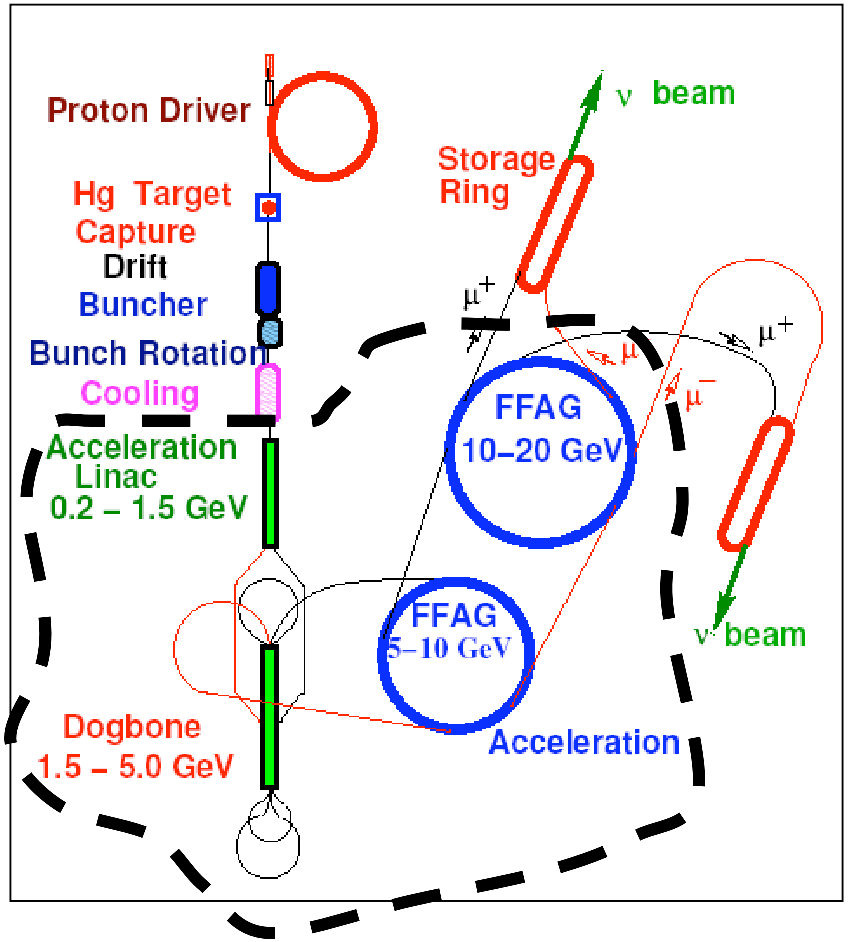
Muon accelerators in a neutrino factory

Muon accelerators in a neutrino factory (1)

a whole complex

- Neutrino Factory: 20 to 50 GeV muon beam.
  - c.f. Muon Collider: a few TeV muon beam.
- Accelerators are the most costly part of the machine complex.
- Proposals
  - Feasibility study I and II
  - European neutrino factory complex
  - Neutrino factory in Japan
  - Study 2-A
  - International Scoping Study (ISS)

neutrino factory complex



Muon accelerators in a neutrino factory (2)

requirements of muon accelerator

- Quick acceleration
  - Short lifetime of 2.2 μs.
  - In particular, when γ (Lorentz factor) is small.

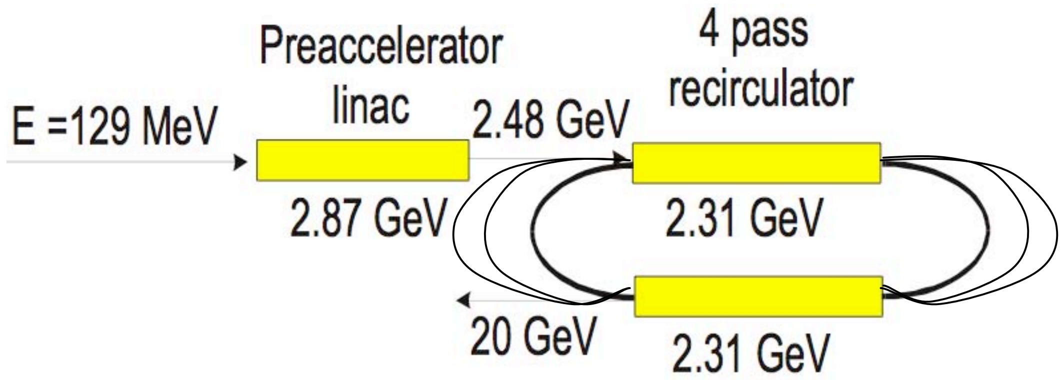
- Large acceptance
  - Muon is a tertiary particle.
  - Muon emittance is a few tens of thousand π mm mrad.
  - e.g. 30,000 π mm mrad (or 30 π mm)

- Cost consideration
  - Accelerators are the most costly part of a neutrino factory.
  - In particular, efficient use of rf system is essential.

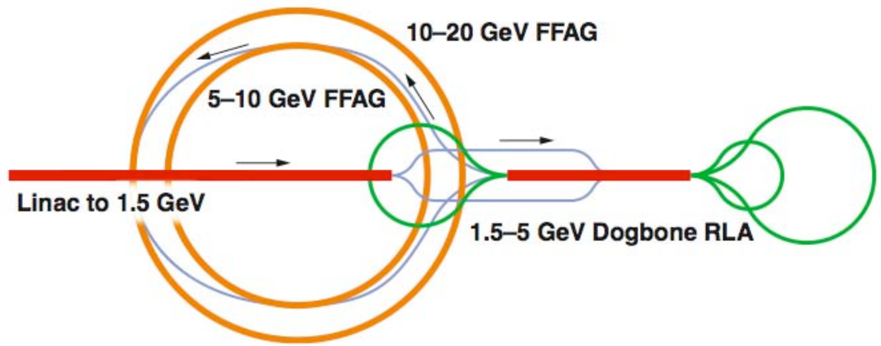
Muon accelerators in a neutrino factory (3)

choice of main accelerator

- Feasibility Study II
  - Use of linac several times -- re-circulating Linac (RLA).

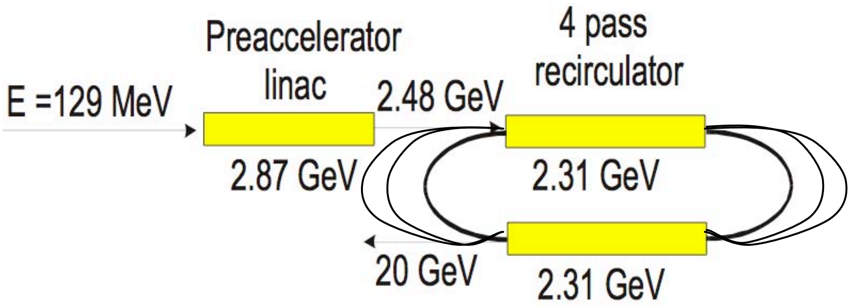


- Study 2-A
  - Nonscaling FFAG from 5 GeV to the top energy.

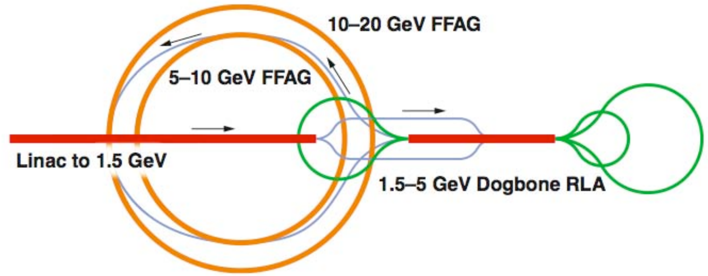


Muon accelerators in a neutrino factory (4)

why FFAG?



vs.



- Number of turns (or arcs) in RLA is limited, ~ 5.
  - We have to use a different arc for each turn.
  - Design of switchyard (split/combine at the end of arc) is difficult because muon beam size is huge.
- FFAG can have more numbers of turns in a single arc.
  - No switchyard is necessary.
  - Requirement of rf voltage reduces. It is a cost effective option.
  - Lorentz factor γ is already high when a muon is injected to FFAG.
  - A knob which compromises between cost and muon yield.

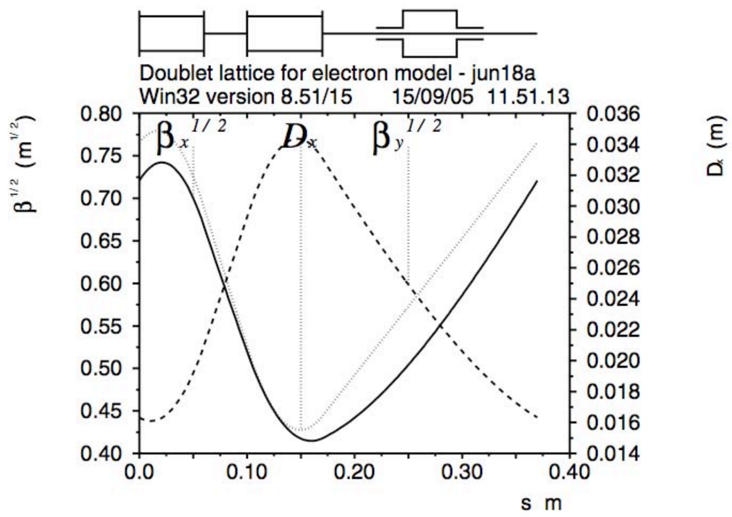
Nonscaling FFAG

Nonscaling FFAG (1)

FFAG in one word

- FFAG is a Fixed Field Alternating Gradient accelerator.
  - It separates the guiding field from the acceleration process.
  - Quick acceleration is possible. The rate only depends on voltage.

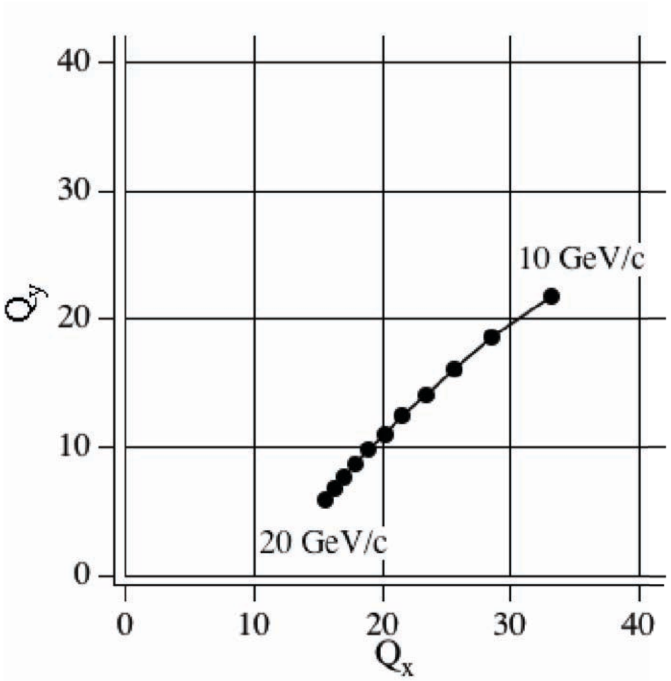
- Nonscaling FFAG looks as a “storage ring”.
  - Lattice with ordinary dipoles and quadrupoles.
  - Dispersion function is small enough to give large momentum acceptance.
  - Orbit excursion from injection to extraction is small.



lattice functions of 10 to 20 MeV electron model

Nonscaling FFAG (2)

tune excursion due to natural chromaticity



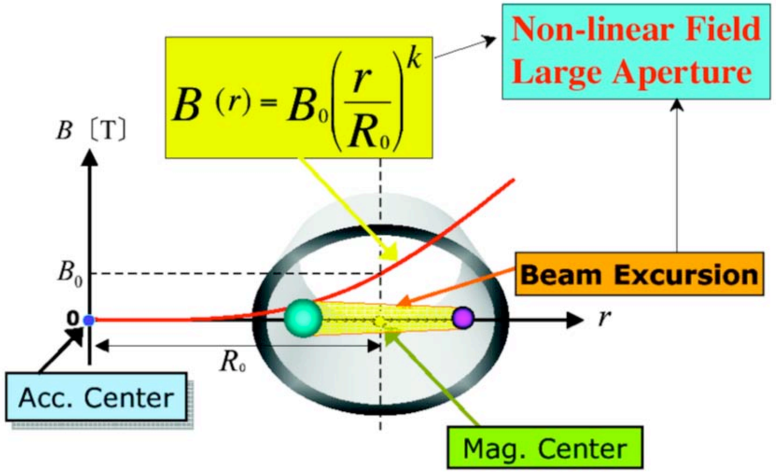
Tune excursion from 10 to 20 GeV/c muon ring.

- Orbit excursion can be small by tiny dispersion function.
- Tune excursion is, however, large because of no chromaticity correction.
- Crossing of many integer and half-integer tune values.
  - Is it harmful?

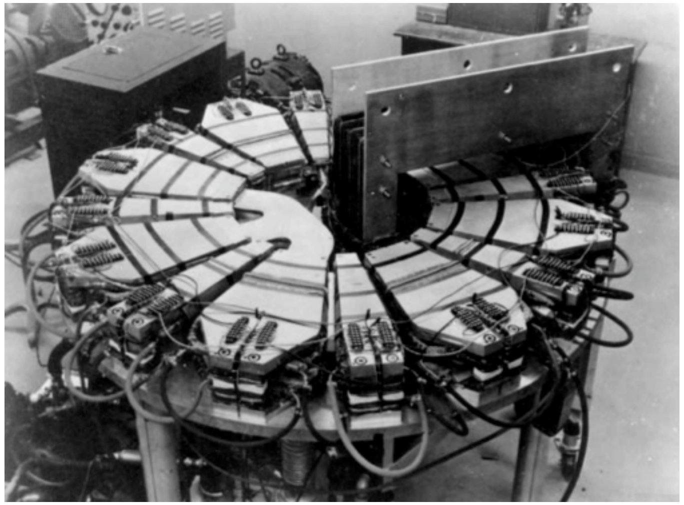
Nonscaling FFAG (3)

nonscaling *vs.* *scaling*

- Why not chromaticity correction?
  - FFAG with full chromaticity correction is called a scaling FFAG.
  - The original type of FFAG invented in 1950's.



Nonlinear field profile cancel chromaticity.

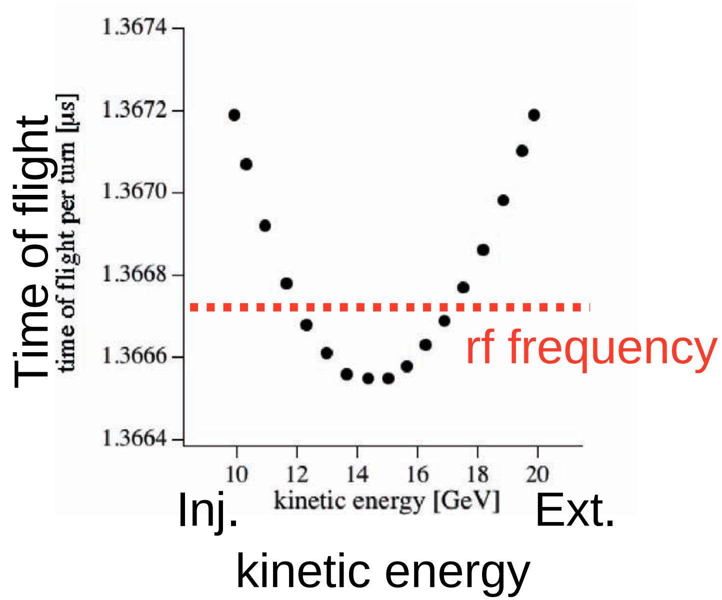


radial sector model (from K. Symon, "MURA DAYS", PAC03)

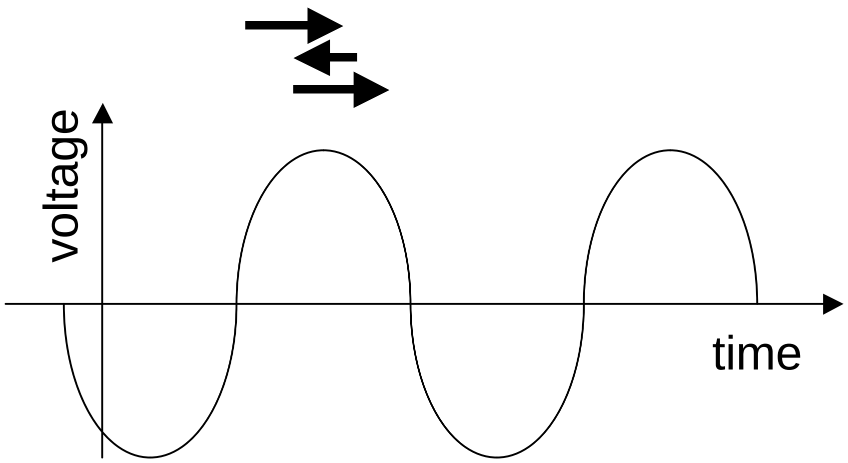
- Nonscaling FFAG with sextupole for partial correction does not give enough acceptance for a muon beam.

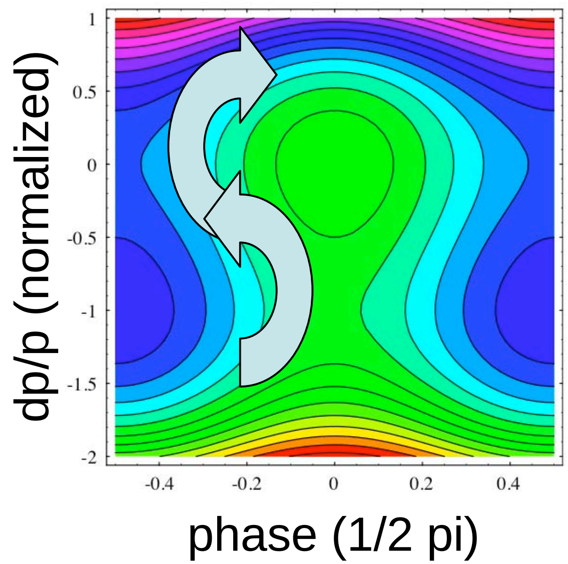
Nonscaling FFAG (4)

rf acceleration



- No time to modulate rf frequency.
  - Use fixed frequency (FFFFAG !).
- Cannot be isochronous, but almost isochronous.
- Inject a beam near a rf crest and finish acceleration before too much phase slip accumulated.





Beam dynamics issues

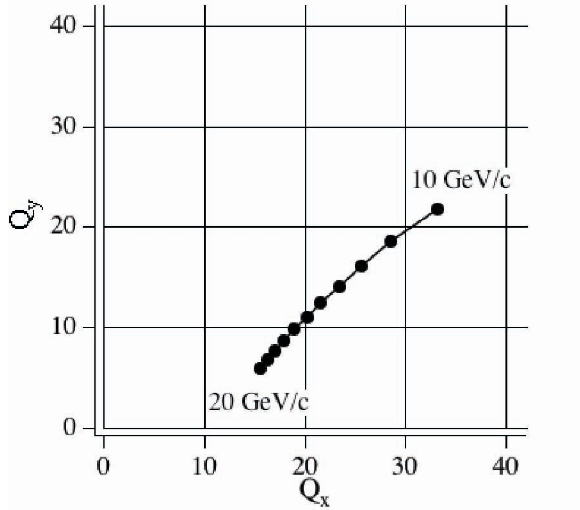
- Transverse tune excursion
- ToF dependence on transverse amplitude

Transverse tune excursion (1)

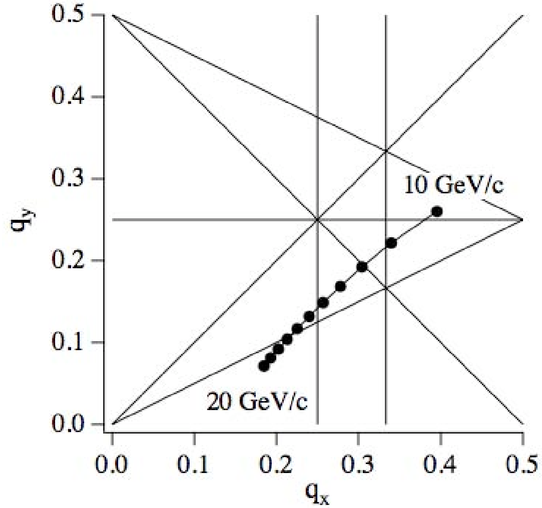
excursion of cell tune

- Total tune of integers and half-integers are crossed.
  - If not much errors, they should not be any problem.
- Cell tune is between 0 and 0.5.
- Cell tune of 1/3 and 1/4 are crossed.
  - If not much nonlinearities, they should not be any problem.

total tune = 84 x cell tune



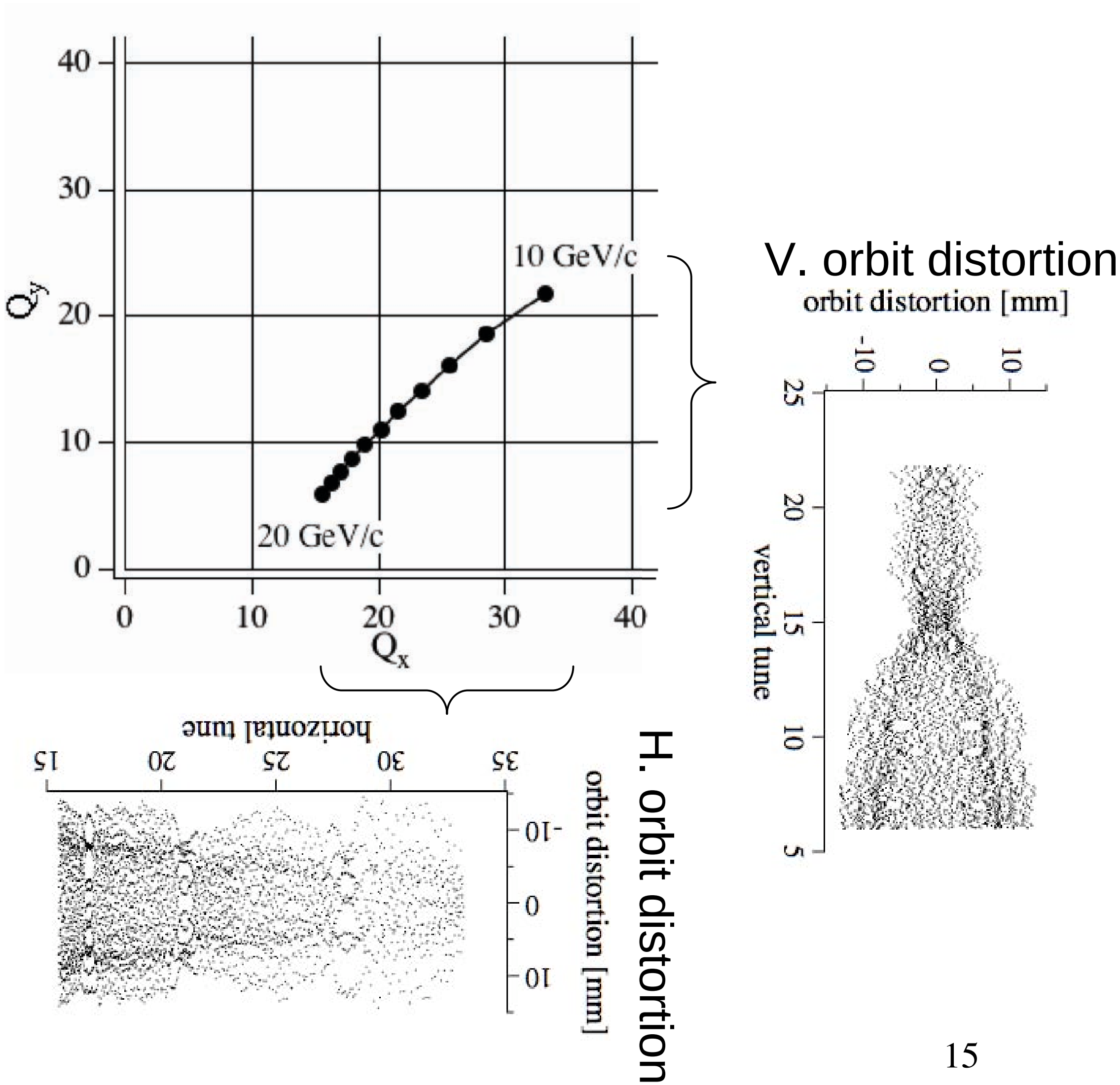
cell tune



Transverse tune excursion (2)

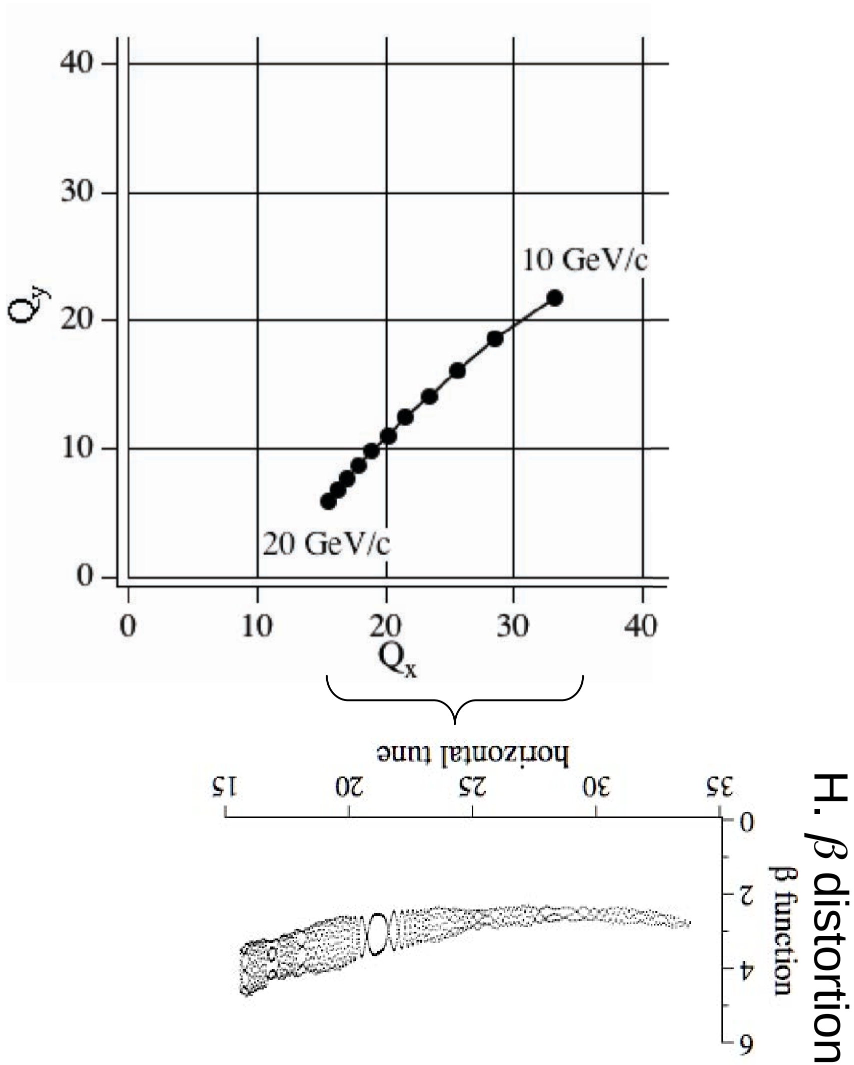
orbit distortion

- Orbit distortion occurs due to alignment errors.
- But it shows no structure which depends on total tune.
- Orbit distortion is caused by random dipole kicks. Integer resonance is not correct physics to apply in this case.



Transverse tune excursion (3)

optics distortion

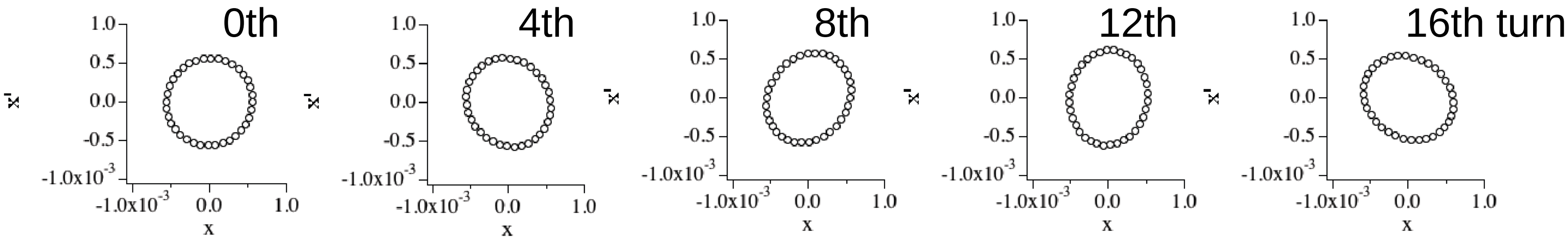


- Optics distortion occurs due to gradient errors.
- But it shows no structure which depends on total tune.
- Optics distortion is caused by random quadrupole kicks. Half integer resonance is not correct physics to apply in this case, either.

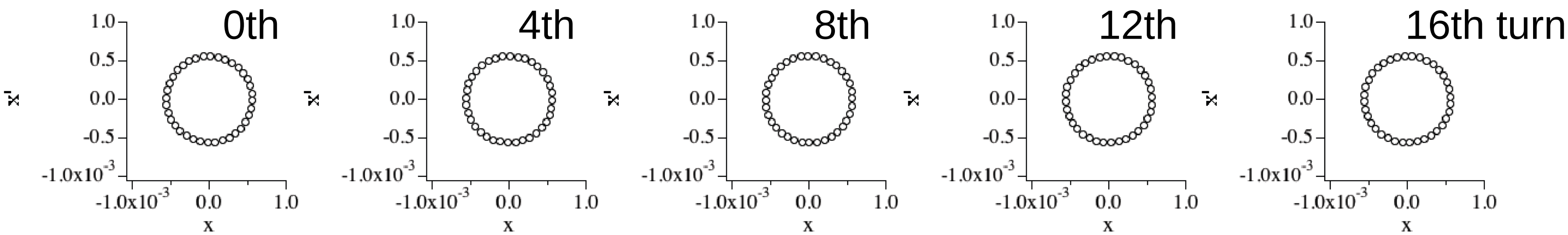
Transverse tune excursion (4)

emittance evolution

- Evolution of emittance ellipse normalized by lattice β without taking into account of errors.



- Evolution of emittance ellipse normalized by lattice β with taking into account of errors.



- No emittance growth, but beam size growth due to tumbling.

Transverse tune excursion (5)

summary

- Resonance is not correct physics in a nonscaling muon FFAG. Random dipole and quadrupole kicks introduce continuous orbit and optics distortion.

- In 10 to 20 GeV muon ring,
  - 0.050 mm alignment errors: 7 mm OD (max.)
  - 0.1% gradient errors: 10% beam size growth.

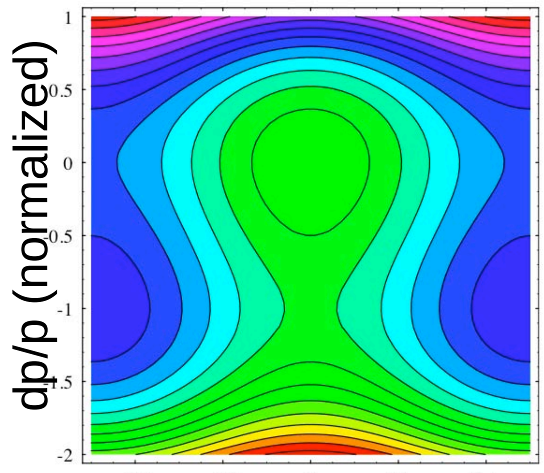
- Nonlinearities exist due to kinematic terms and fringe fields.

- Tune excursion is tolerable.

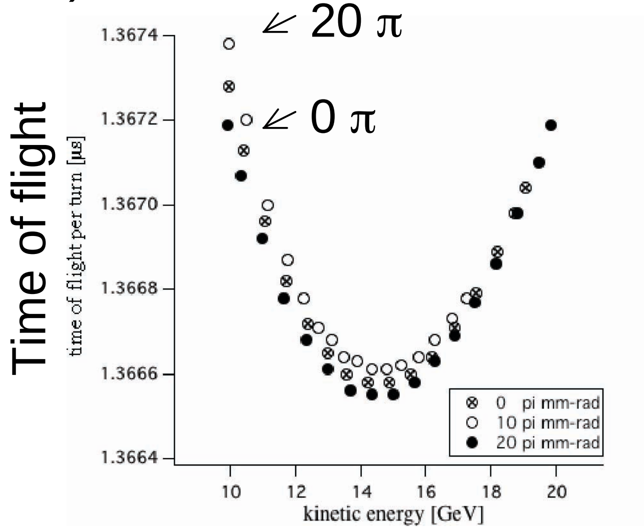
ToF dependence on transverse amplitude (1)

- Time of flight is a function of transverse amplitude as well as momentum.
- Large amplitude particles have too much phase slip to be accelerated to the maximum energy.

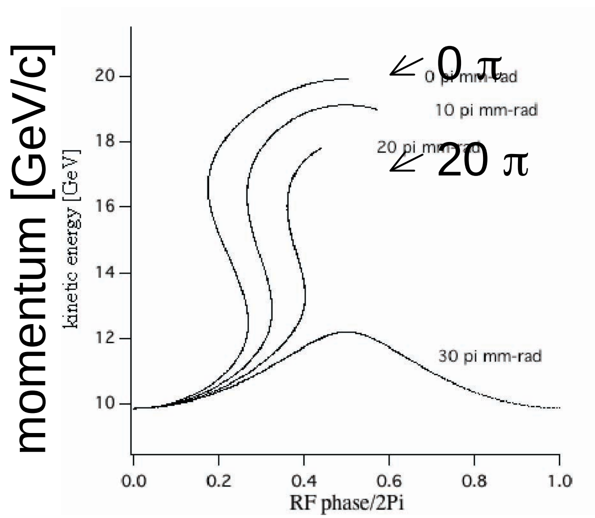
(This is only for zero amplitude.)



phase (1/2 pi)



kinetic energy

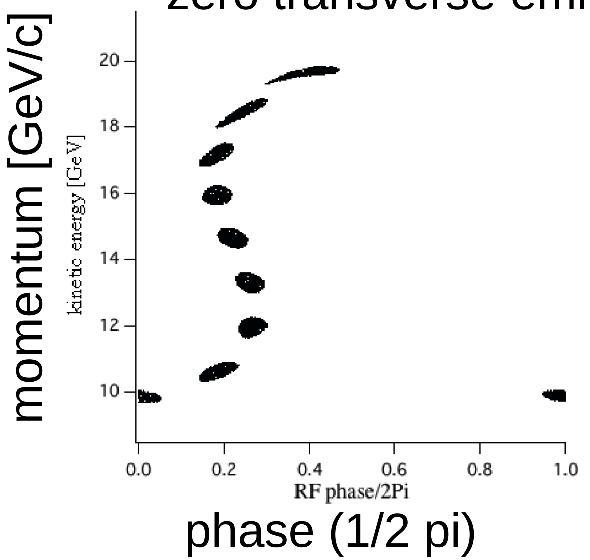


phase (1/2 pi)

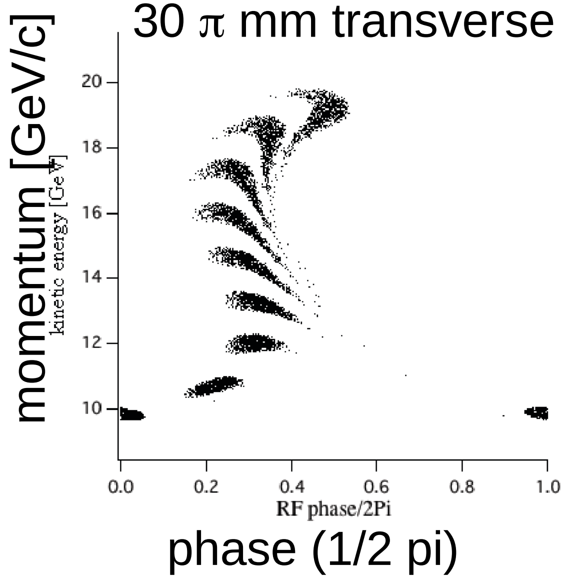
ToF dependence on transverse amplitude (2)

- As a whole beam, longitudinal emittance blows up and momentum spread increases.
- Chromaticity correction cures the problem (S. Berg, Nucl. Instrum. Methods, 2006), but it reduces aperture.

zero transverse emittance



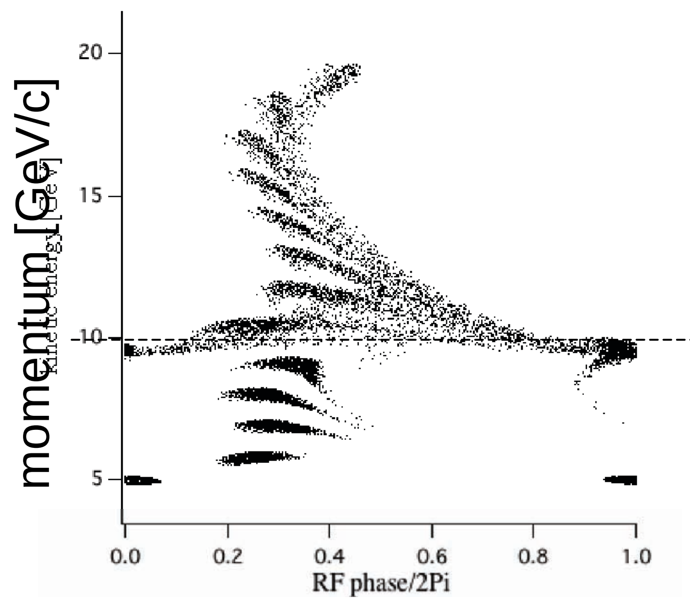
30 π mm transverse emittance



ToF dependence on transverse amplitude (3)

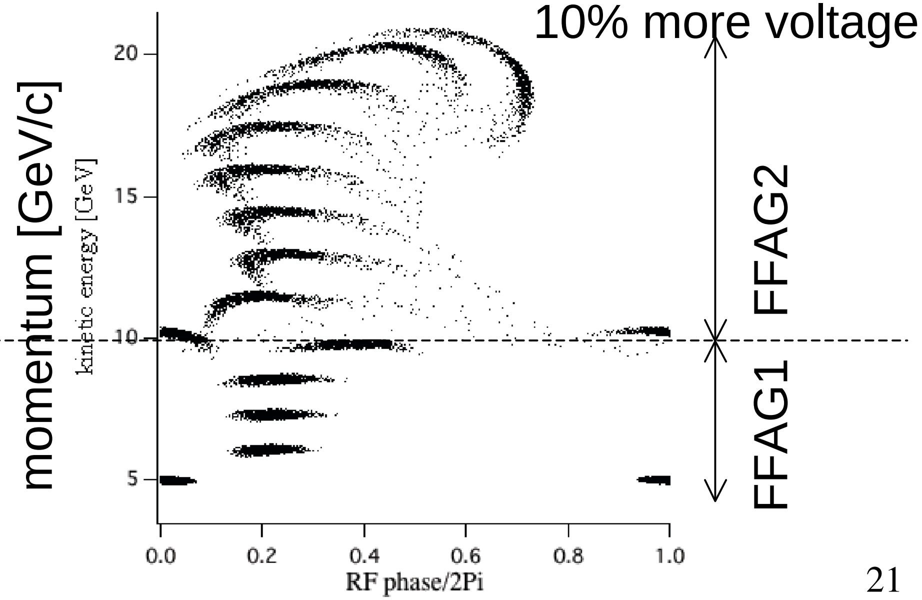
- Either increase voltage and finish acceleration before building up phase slip,
- Or introduce higher harmonic rf and make an rf crest flatter mitigates blow-up.
- In a cascade of FFAGs, effects are enhanced.

without any cures



phase (1/2 pi)

With 2nd harm. rf and 10% more voltage



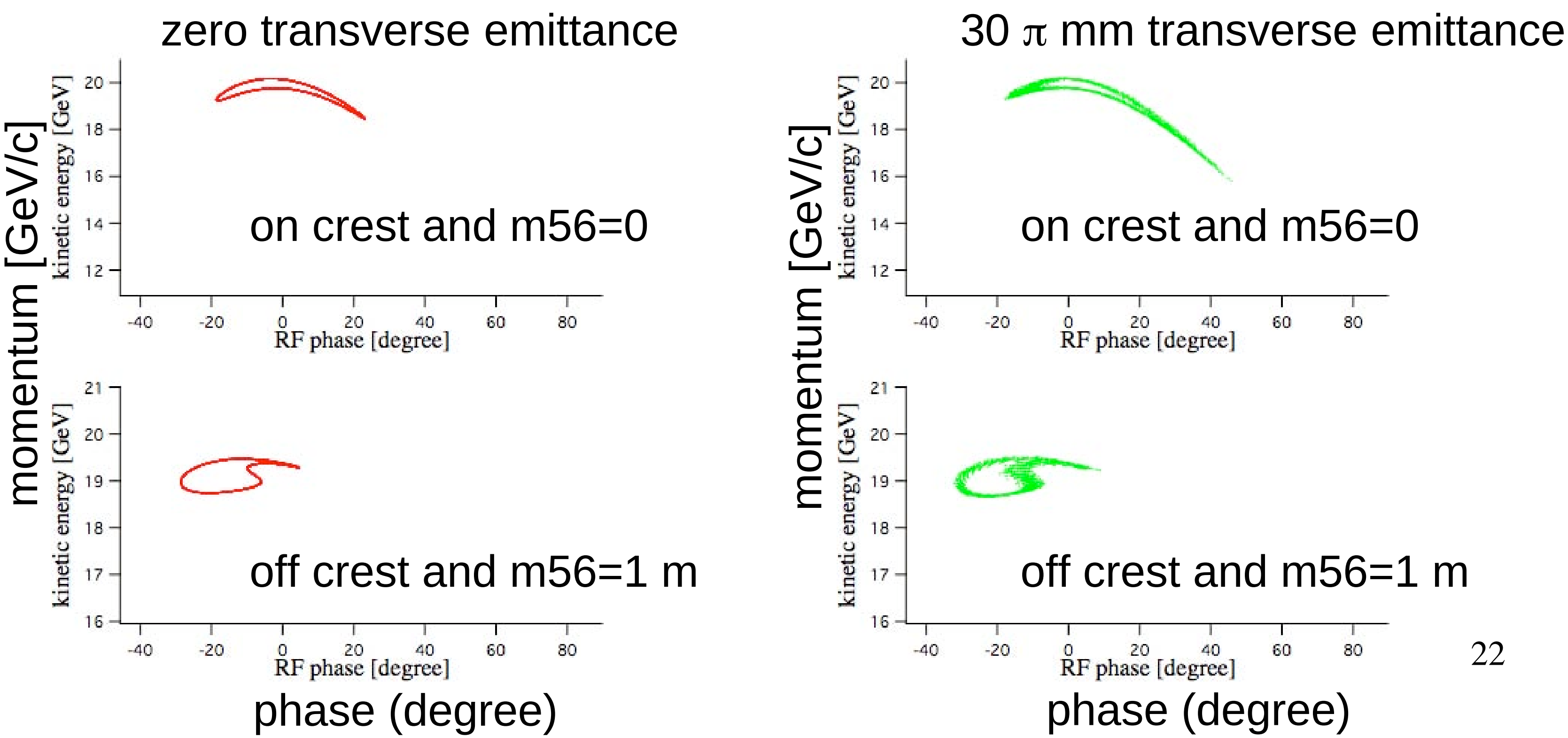
phase (1/2 pi)

ToF dependence on transverse amplitude (4)

- Re-circulating Linear Accelerator (RLA) has a knob, m_{56} [m], in each arc.

$$\Delta s = m_{56} \frac{\Delta p}{p}$$

- Together with off crest rf phase, synchrotron oscillations mix ToF dependence on amplitude.

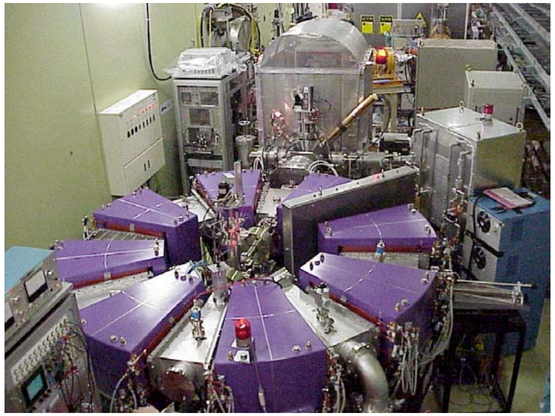


ToF dependence on transverse amplitude (5)

summary

- Time of flight depends on transverse amplitude.
  - It is not negligible because of large muon emittance.
- That can be mitigated with either higher voltage or higher harmonic rf components.
- The issue becomes more serious in a cascade of FFAGs.
- Re-circulating Linear Accelerator (RLA) and Linac have the same problem. However, RLA can mix the unwanted phase accumulation by synchrotron oscillations.

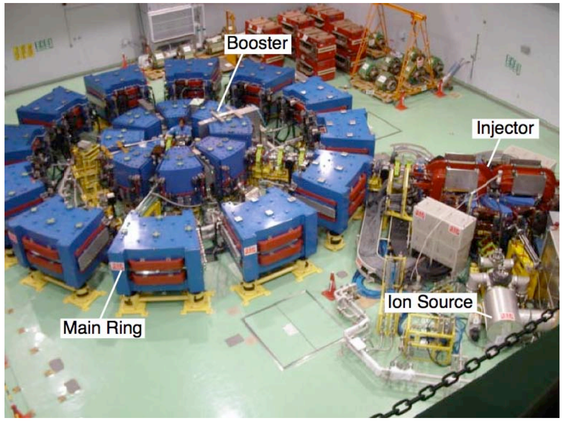
Development of scaling FFAG

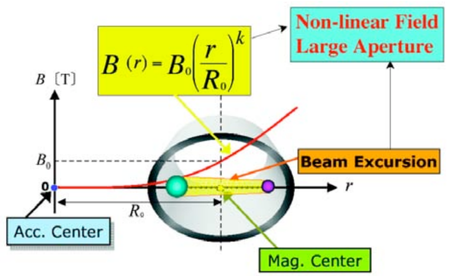


<u>PoP FFAG (2000)</u>: The world’s first proton FFAG with MA rf cavity.

<u>150MeV FFAG (2005)</u>: A prototype for medical use.

Development of scaling FFAG (1)





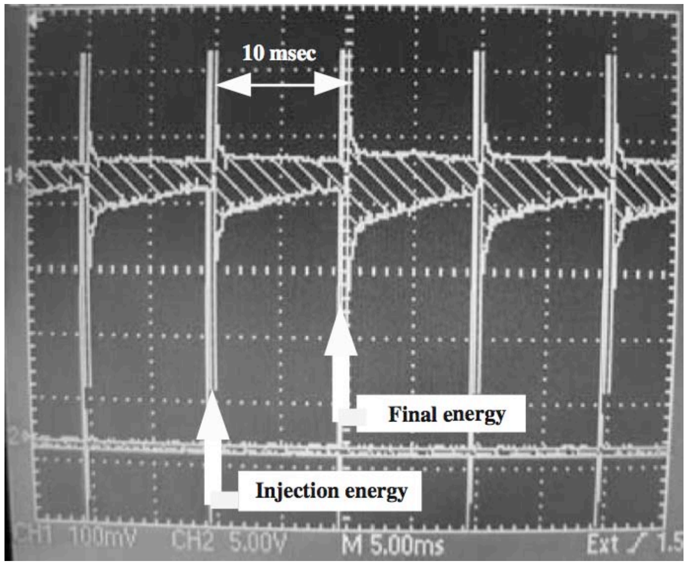
<u>ADSR FFAG (present)</u>: Combined with a reactor, it demonstrates Accelerator Driven System.

<u>PRISM FFAG (present)</u>: Muon phase rotator to reduce momentum spread.

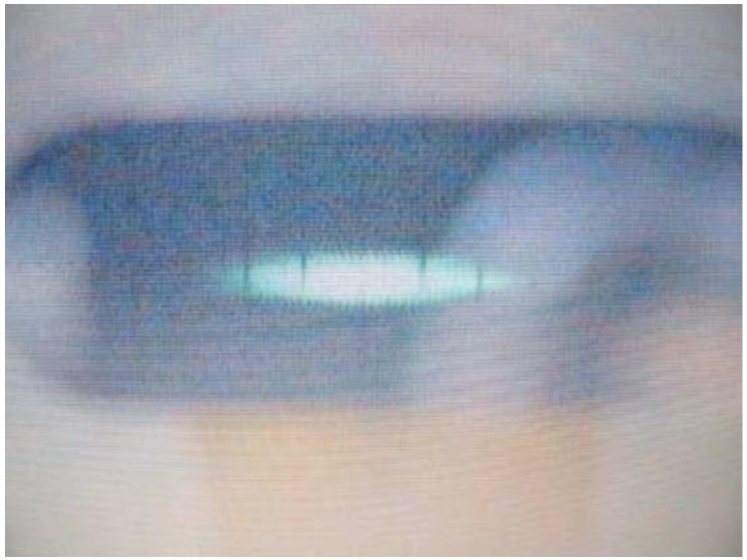
Development of scaling FFAG (2)

150 MeV FFAG at KEK

- A prototype of the medical use.
- 100 Hz operation.
  - Voltage of 6 kV.
  - Frequency from 1.5 to 4.6 MHz.
- 90% extraction efficiency.



100 Hz operation

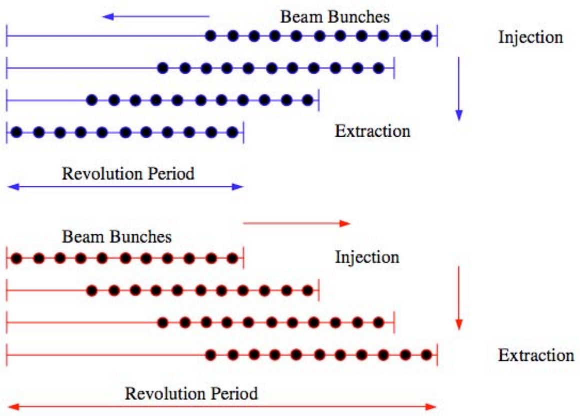


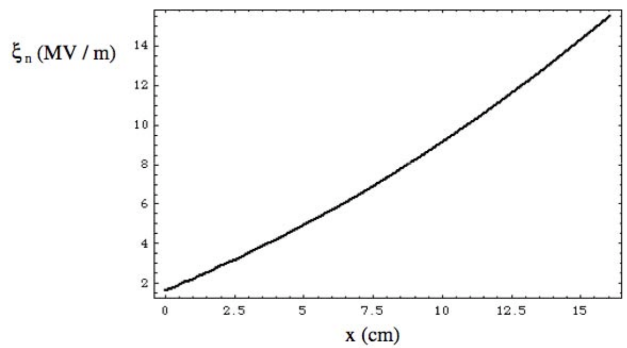
beam extraction

Development of scaling FFAG (3)

as a muon accelerator

- 5 to 10 GeV spiral FFAG for muon acceleration.
- Acceleration with Harmonic Number Jump
  - A bunch is captured in a bucket with different harmonic number turn by turn.
- Continuous operation with constant rf frequency is possible (A. G. Ruggiero, Phys. Rev. ST 100101, 2006).
- Energy gain has to be adjusted in radial direction.





From Study 2-A to ISS and beyond

From Study 2-A to ISS and beyond (1)

outcomes of the ISS studies

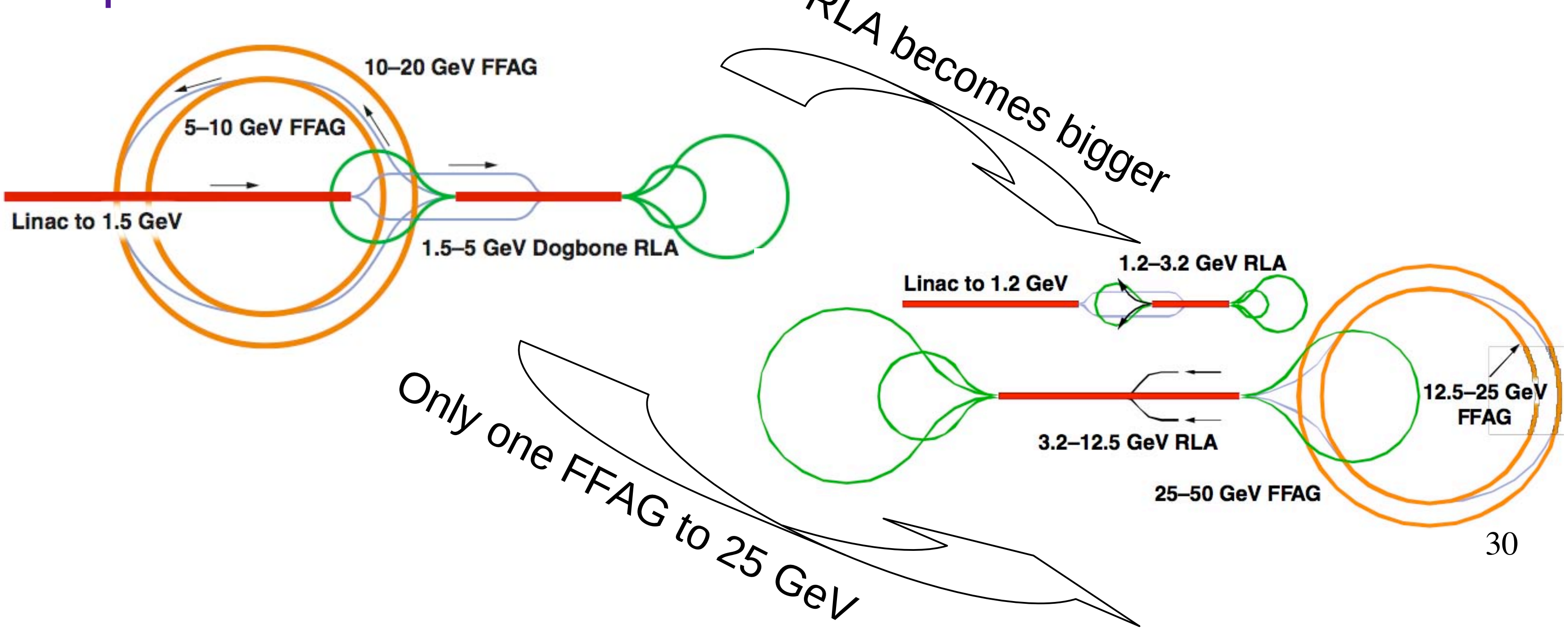
- Study 2-A may rely too much on FFAG.
- Integer and half-integer crossing seems to be no problem.
- Longitudinal emittance blown up by time of flight variation in a cascade of FFAGs is still an issue.
- On the other hand, RLA is in a better situation because of additional knob, m_{56} in the arc.

From Study 2-A to ISS and beyond (2)

recommendation by ISS

- No decision was made in the ISS on the transition energy among different structures.

- However, it recommends higher injection energy to a FFAG, keeping a second FFAG as an energy upgrade option to 50 GeV.

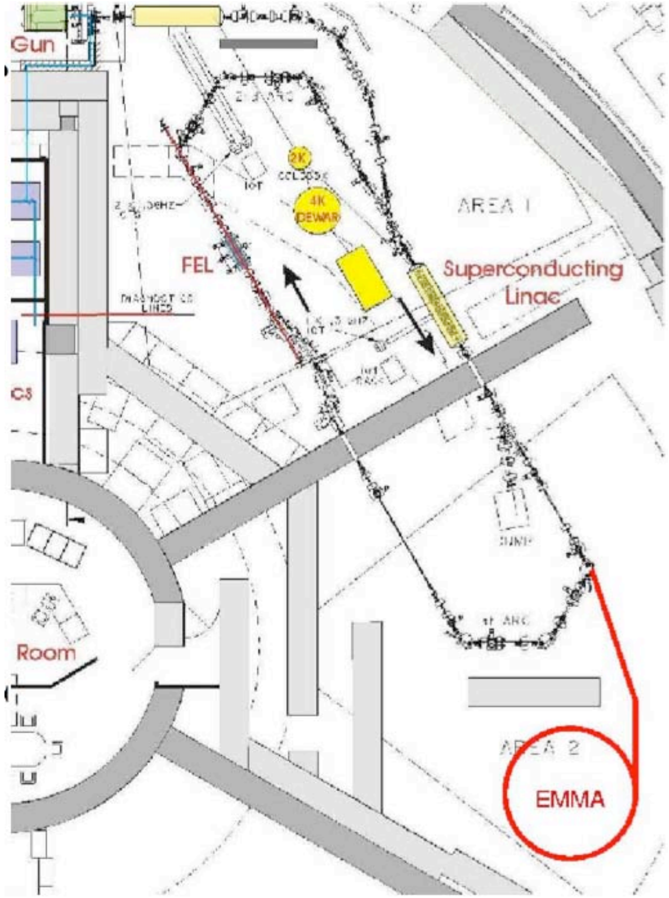


From Study 2-A to ISS and beyond (3)

EMMA

- Daresbury Laboratory hosts construction of an electron model of a nonscaling FFAG.
  - Acceleration outside buckets
  - Integer tune crossing
  - Large aperture

Energy:	10 to 20 MeV
Acceptance:	3,000 π mm mrad
Circumference:	16 m
# of cell:	42
# of turn:	12
rf voltage:	~30 kV/cell
rf frequency:	1.3 GHz



(a talk by R. Edgecock)

Summary

- Nonscaling FFAG has been studied as a strong candidate for the main accelerator of a muon beam.
  - Some issues still remain.

- Hardware development of a scaling FFAG goes on and experimental demonstration of a nonscaling FFAG has just started.