Results from the EMMA Experiment

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NuFact 2012
July 27, 2012

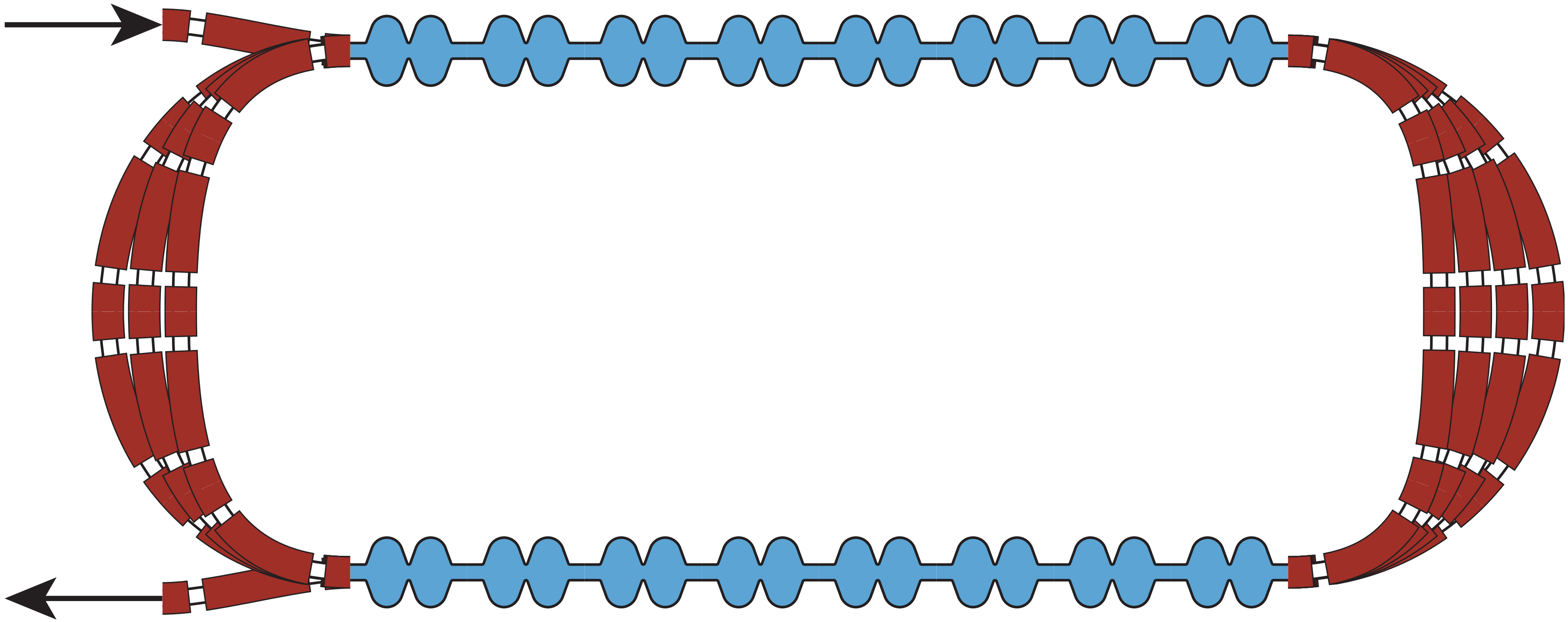
Outline

- Accelerators
- FFAGs
  - Introduction
  - Scaling and non-scaling FFAGs
  - Serpentine acceleration
  - Muon acceleration
- EMMA accelerator: goals and parameters
- EMMA results
  - Measurement of acceleration
  - Other measurements
- EMMA plans

Types of Accelerators

- Linacs
  - Very rapid acceleration: magnet fields fixed
  - Large acceptance
  - Very expensive: only one pass through RF
- Recirculating linear accelerators (RLAs)
  - Make multiple passes through linac
  - Arcs return beam to linac
    - Different arc for each energy
    - Arc switchyard limits number of passes
    - Adjust arc length to ensure RF synchronization
  - Small magnet apertures
    - But lots of arc length

Types of Accelerators



Types of Accelerators

- Synchrotrons
  - Ramp magnet fields in proportion to momentum
  - Accelerate slowly, limited by magnet ramp rate
  - Very efficient, allow may passes through RF
  - Small magnet apertures
  - Vary RF frequency with time of flight
    - Sufficient time due to slow acceleration
- Cyclotrons
  - Fixed magnetic fields, allow rapid acceleration
    - Beam moves across aperture during acceleration
  - Only work well for nonrelativistic energies
  - Large magnet apertures
  - Isochronous: fixed RF frequency

Introduction to FFAGs

- Fixed Field Alternating Gradient accelerators
- Magnet fields fixed: beam moves across aperture
  - Acceleration rate limited only by
    - Installed RF voltage
    - RF frequency sweep rate to keep beam synchronized to RF
- In contrast to cyclotron
  - Alternating gradient focusing keeps apertures small
  - Works at relativistic energies
  - Time of flight varies with energy
- Useful when you want
  - Rapid acceleration
  - High efficiency by making many RF passes
  - Apertures that aren't too large

Scaling FFAGs

- FFAGs originated in the 1950s
- Midplane field is $B_0(\theta)(r/r_0)^k$
  - Alternating gradient from $B_0(\theta)$ changing sign
- Closed orbit properties
  - Tunes are constant
  - Constant momentum compaction of $1/(k+1)$
  - Orbits geometrically similar, sizes scaling as $p^{1/(k+1)}$
- Scaling FFAGs designed & built in Japan recently
  - NuFactJ neutrino factory design (2001)
  - Three-ring proton accelerator for ADS (KART, 2008)
  - ERIT neutron production ring (2008)
  - PRISM muon phase rotator

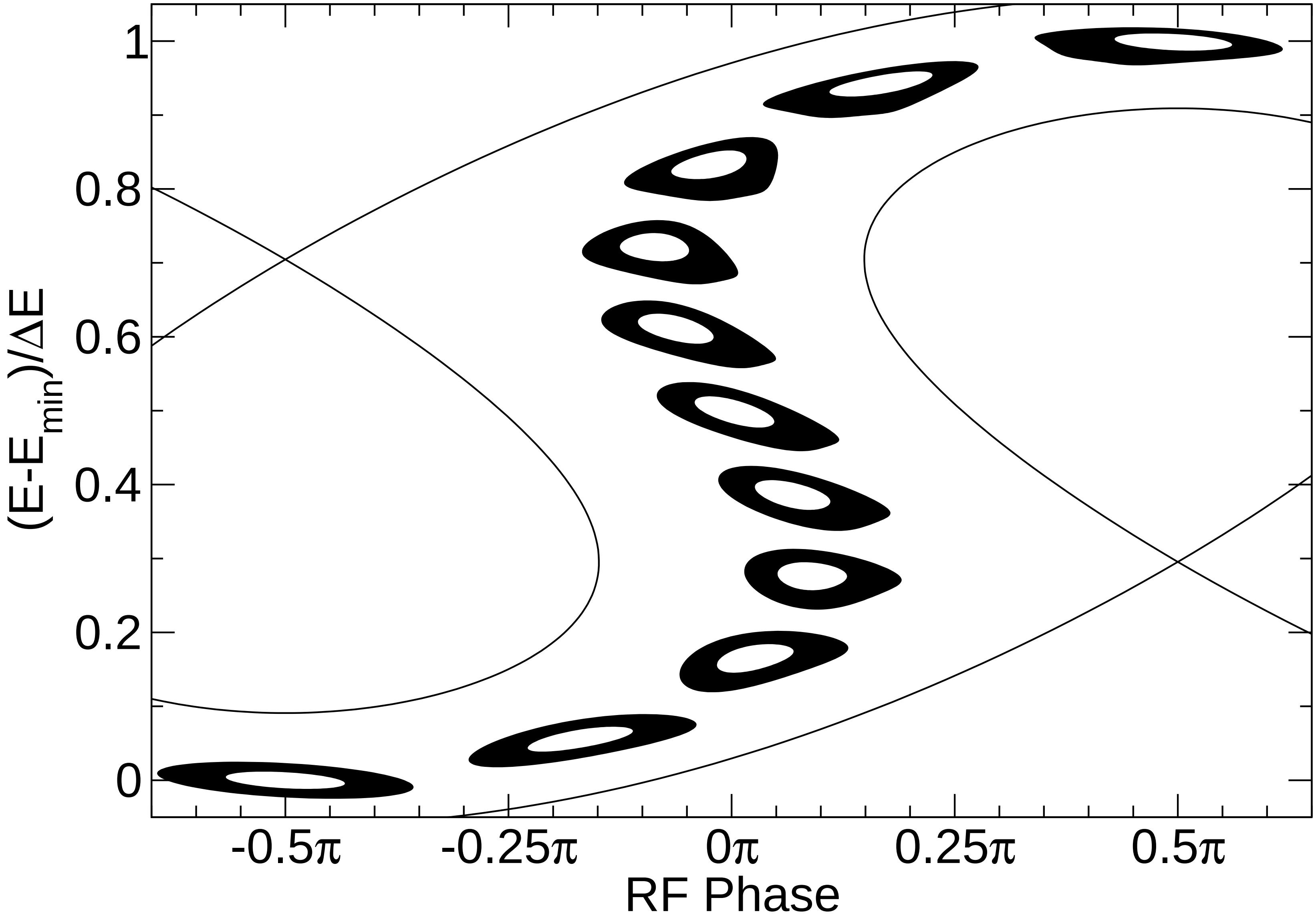
Non-Scaling FFAGs

- Desire to improve some FFAG properties
  - Physical magnet aperture
  - Dynamic aperture
  - Longitudinal beam dynamics
- Break the symmetries that give “scaling”:
  - Tune depends on energy
- Early ideas in this direction
  - Use linear magnets (Mills & Johnstone, 1997)
    - Large dynamic aperture
  - Flexible momentum compaction lattice with strong sextupoles (Trbojevic, Courant, & Garren 1999)
    - Very small physical aperture
    - Smaller dynamic aperture

Serpentine Acceleration

- Non-scaling FFAGs try to reduce magnet aperture
  - Reduced dispersion, thus small momentum compaction
  - Relativistic: isochronous at one point in energy range
- Time of flight parabolic-like function of energy
  - Synchronized to fixed-frequency RF at two energies
  - Cross RF crest three times during acceleration
  - S-shaped path in longitudinal phase space: serpentine acceleration
    - Minimum voltage for channel to open
    - More voltage widens central channel
  - Extends time that beam is synchronized to RF

Serpentine Acceleration



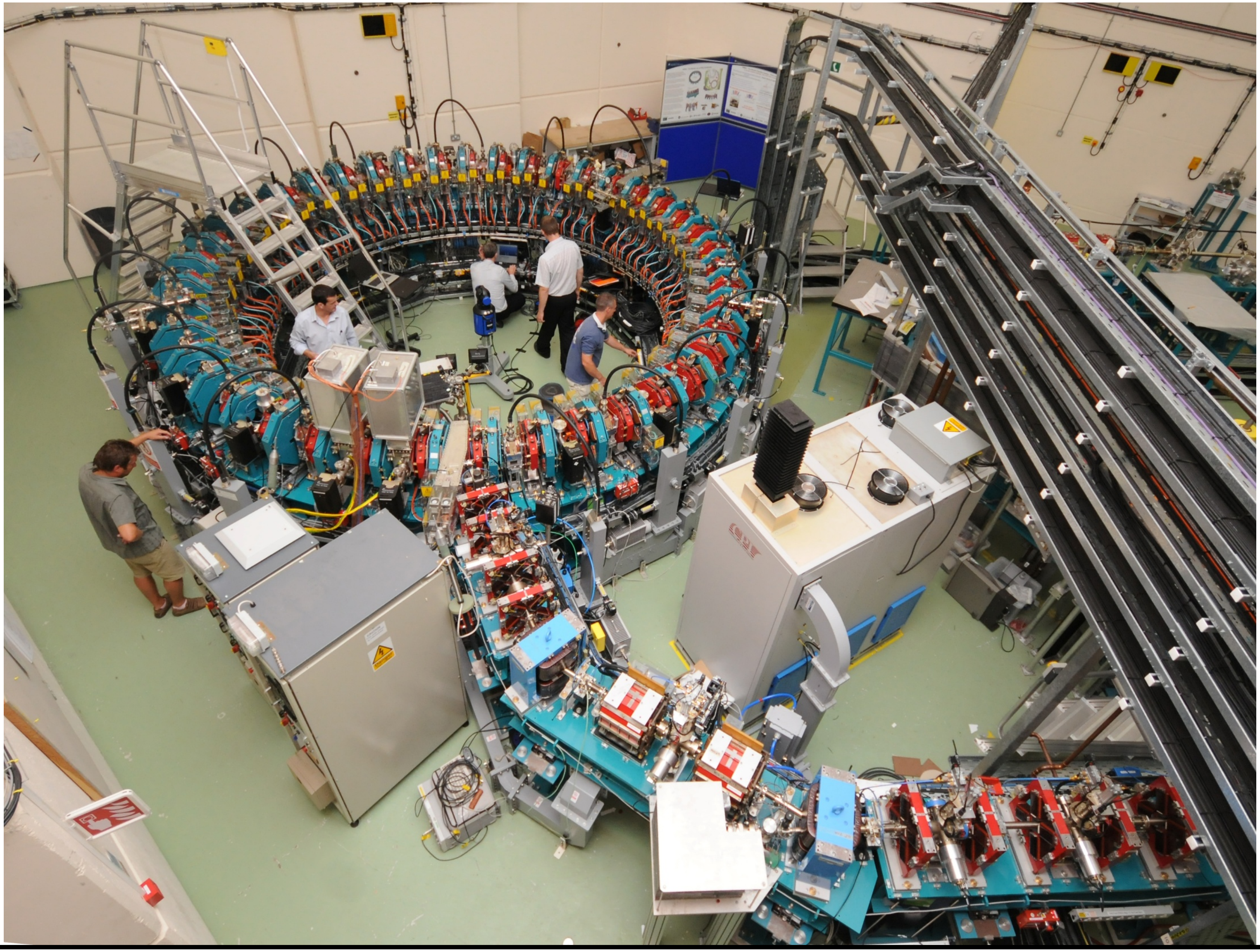
Muon Acceleration

- Rapid acceleration required
  - High average gradient: high (200+ MHz) frequency RF
  - No time to shift RF frequency
  - No time to ramp magnets
- More passes through RF for efficiency
- RLAs have limited number of turns: switchyard
- Linear non-scaling FFAGs good at higher energies
  - FFAG to get many passes in same beamline
    - Serpentine acceleration helps this
  - Non-scaling to keep magnet costs down
    - Time of flight range less than scaling: more turns
  - Linear non-scaling to get large dynamic aperture
    - Very important for neutrino factory

EMMA Goals

- Before EMMA, a non-scaling FFAG had never been built
- Study beam dynamics in non-scaling FFAGs
  - Resonance crossing
  - Serpentine acceleration
- Study parametric behavior
  - Which major resonances are crossed
  - Shape of time of flight curve
  - Acceleration rate
  - RF synchronization energies

EMMA Goals



EMMA Design

- Accelerate electrons from 10 to 20 MeV
  - Inject and extract anywhere in this range
- 16.6 m circumference
- 42 identical doublets of combined-function magnets
  - Offset quadrupoles, remotely movable
    - Shifters can be used for closed orbit correction
  - Independently vary dipole and quadrupole components
- 19 1.3 GHz RF cavities
  - Around 2 MV of RF voltage
  - >6 MHz tuning range
- Injection and extraction each with septum and two kickers

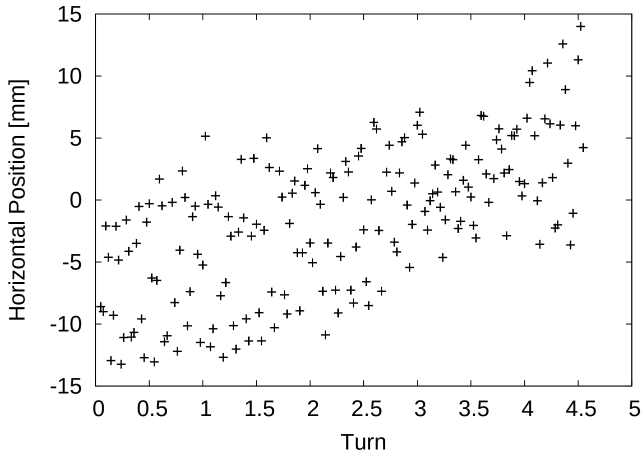
EMMA Design

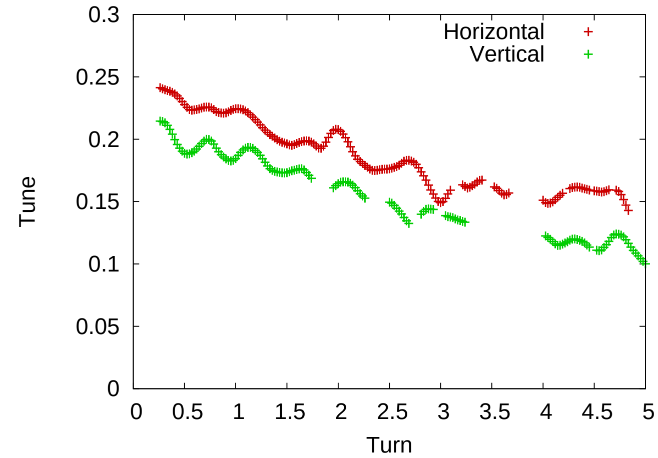
- Extensive diagnostics
  - 2 sets of BPMs in (almost) every cell
    - Turn-by-turn data
    - One set in same spot in each cell
      - Closed orbit distortion
      - Tune measurements when lack many turns
    - Pairs of BPMs across drifts
    - Time of flight measurement
  - Wall current monitor (new!)
    - Current
    - Time of flight
  - 2 YAG screens
    - Finding the beam at injection

Results from Last Year

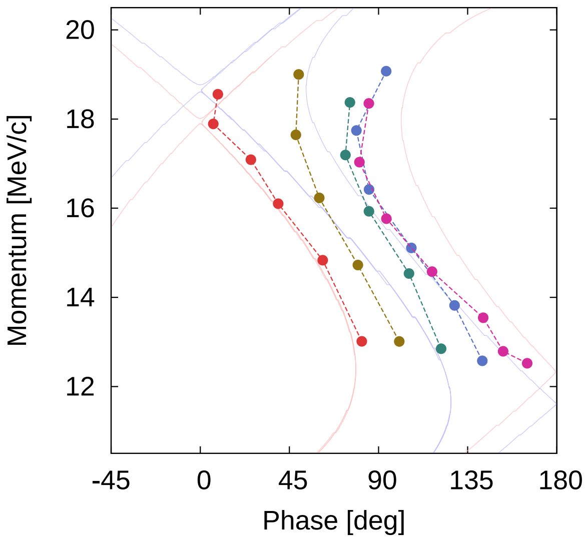
- Measurements at fixed energy
  - Horizontal and vertical tunes
    - Fourier analysis of a sequence of cells
  - Time of flight
    - See expected parabolic shape
  - Orbit position
    - Large orbit distortion observed: ± 5 mm, expected ± 1 mm
      - Horizontally, septum stray field a major contributor
      - Horizontal and vertical distortions similar scale
- Measured about 6 MV of acceleration
  - Energy measured indirectly via tunes or orbit position
    - Consistent whichever we use
    - Verified (roughly) energy gain with extracted beam
  - Use time of flight curve to find serpentine channel
    - Consistent with acceleration seen

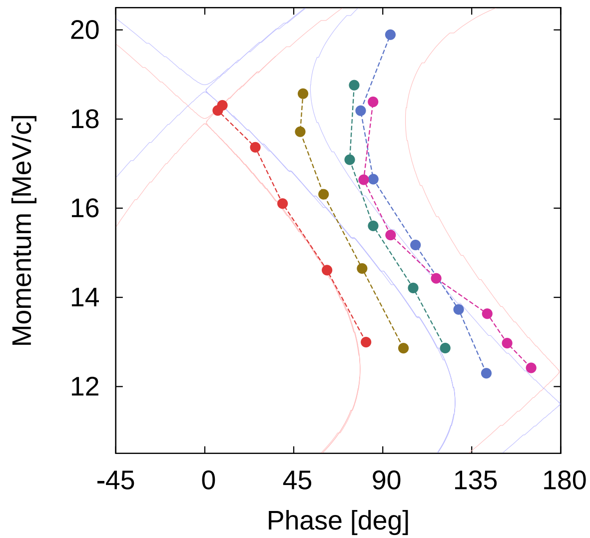
Results from Last Year

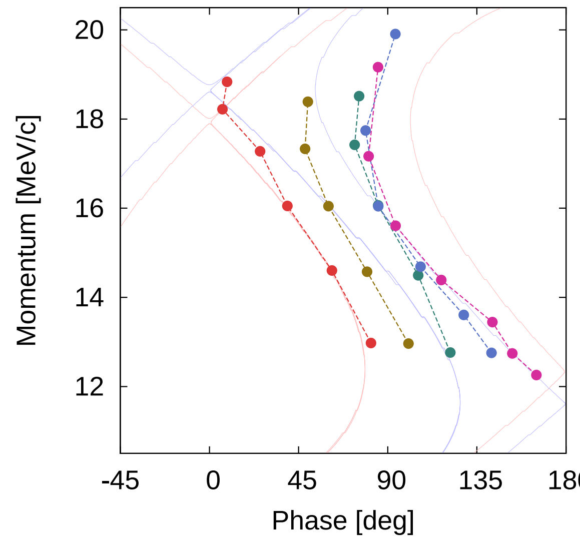




Horizontal Position Horizontal Tune Vertical Tune







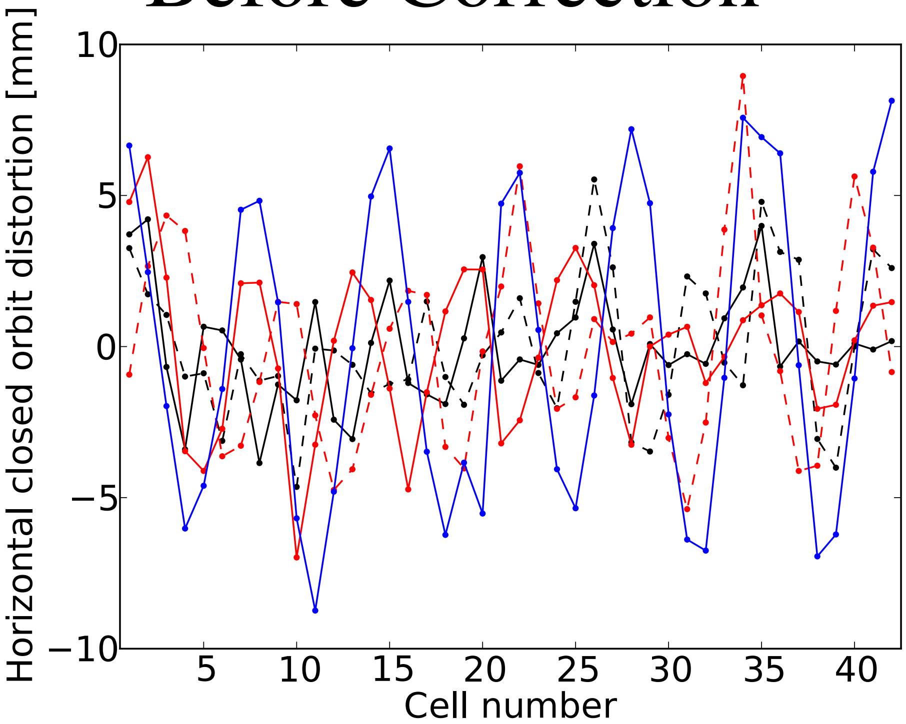
S. Machida *et al.*, Nature Phys. **8** (2012) 243

Closed Orbit Correction

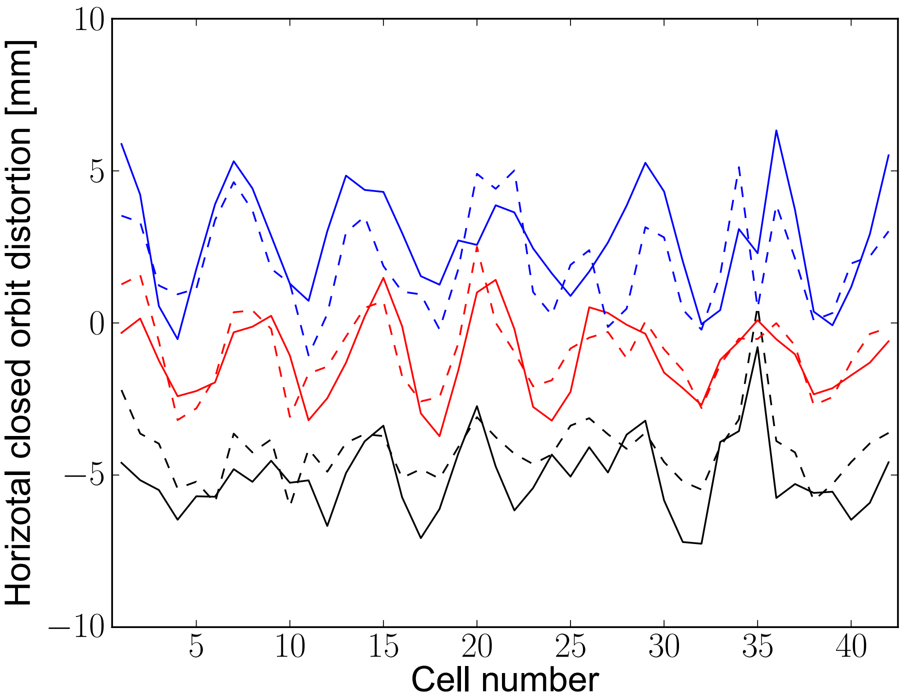
- Closed orbit distortion our primary problem
  - Limits acceleration range
  - May be preventing injection at lower energies
- Have 84 horizontal and 16 vertical correctors
  - Horizontal correctors are moving main magnets
- Correct using response matrix from simulation
  - Tune simulated lattice to measured tune
    - Difficult to get precise tune measurements: tune signal decoheres from chromaticity
  - Including F quadrupole displacements didn't work
  - Reduced RMS distortion from 3.0 mm to 1.3 mm
- Next step: measure response matrix, use to correct
  - Did trial run for one F quad

Closed Orbit Correction

Before Correction



After Correction

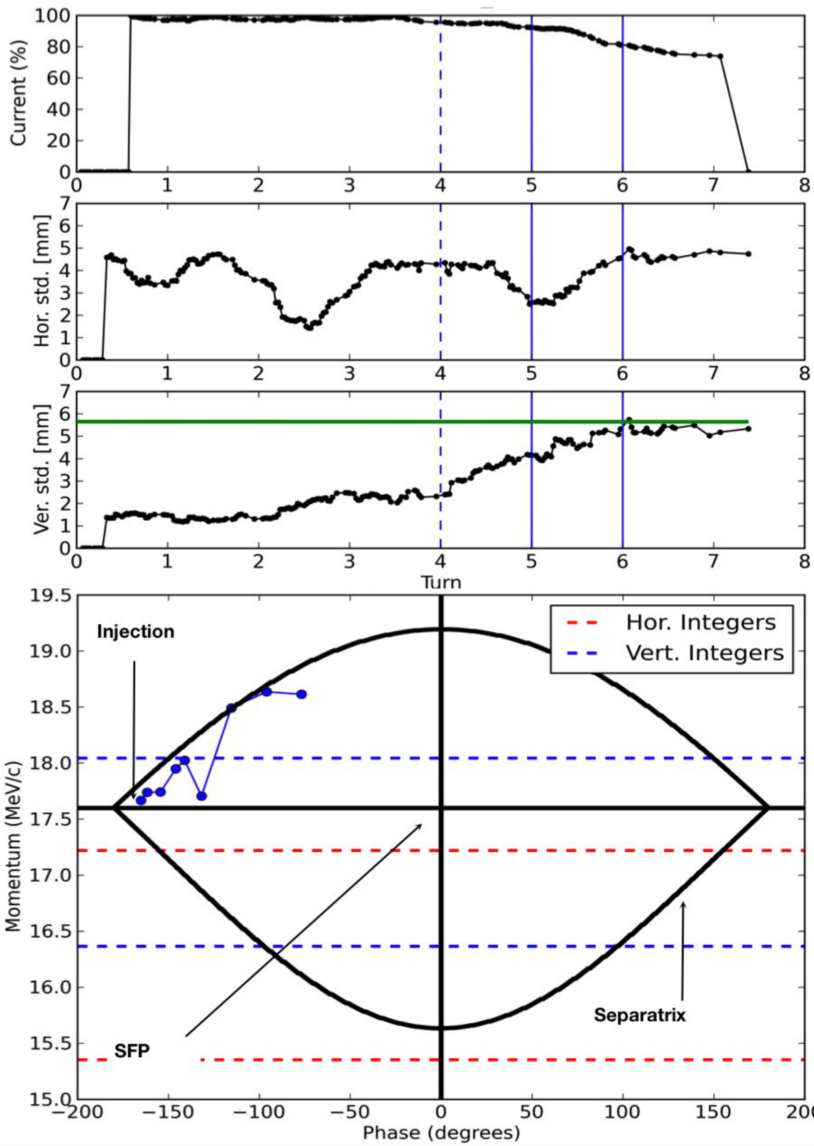


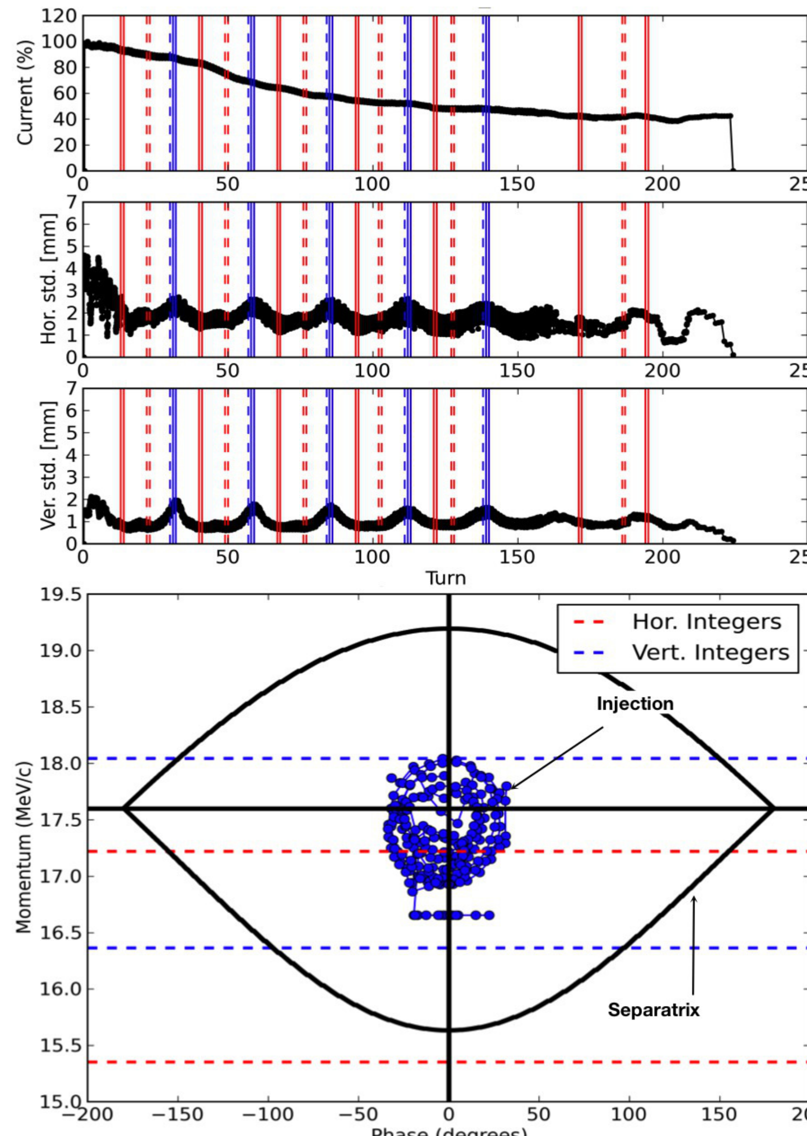
D. J. Kelliher *et al.*, IPAC12, 1455.

Resonance Crossing

- Non-scaling FFAG crosses many integer resonances
- Look at individual resonance crossing
- Inject in stable RF bucket
    - Control bucket energy with RF frequency
- Cross many times with oscillation
- Vary rate by varying position in RF bucket
- No noticeable growth when crossing rapidly (near stable fixed point)
- When crossing slowly near unstable fixed point, rapid beam growth and loss

Resonance Crossing



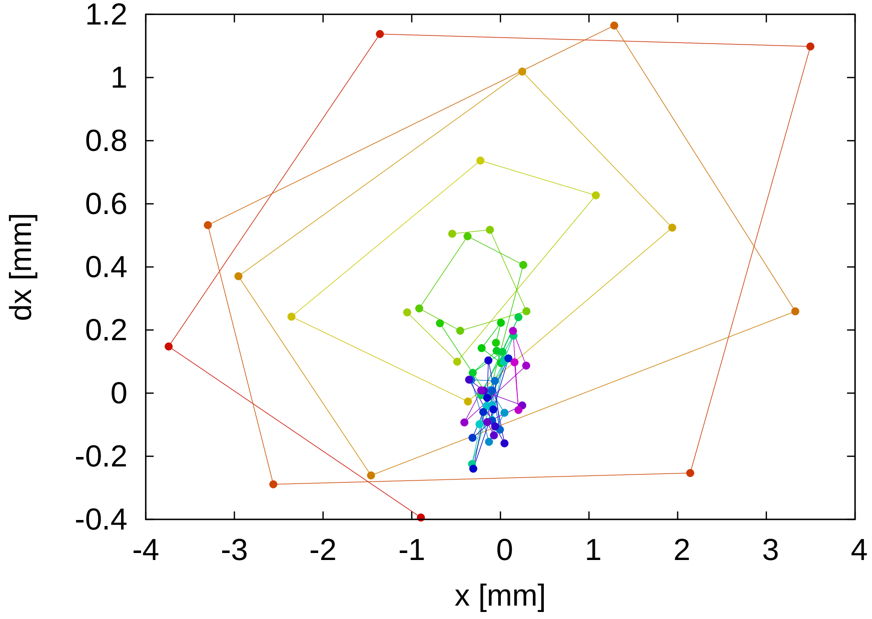


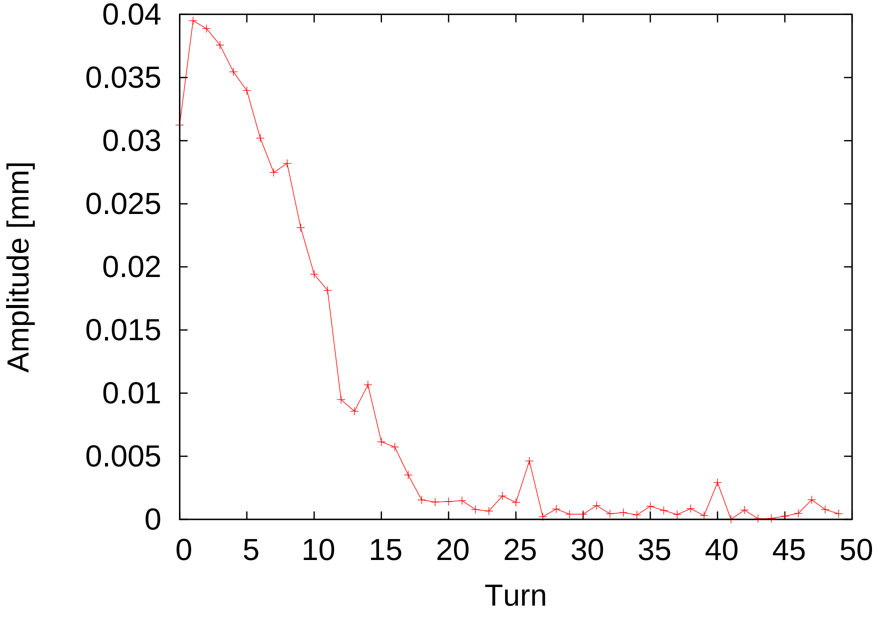
J. M. Garland *et al.*, IPAC12, 412

Poincare Maps

- Pairs of BPMs across longest drift (95 mm apart)
- Drifts nearly field-free: field clamps on magnets
- Give momentum and position: phase space
- Allow computation of amplitude
- Apparent decrease of amplitude
  - Decoherence due to energy spread and chromaticity
- Measure amplitude-dependent effects
  - Time of flight dependence on transverse amplitude
  - Dynamic aperture
- Extract energy distribution (C. Edmonds)
- Note shift in centroid
  - Maybe from BPM mapping of large distribution

Poincare Maps





Lessons for Muon FFAGs

- Ensure sufficiently low magnet-to-magnet field profile variation
- Injection and extraction are challenging
- Extensive diagnostics essential
  - Good timing
  - At least one BPM per cell
  - Extra BPMs in injection/extraction
- Precise magnet modeling and integration into simulations are necessary
- Individual control of field components (dipole/quadrupole) important

Future Directions

- Related to neutrino factory acceleration
  - Optimally correct closed orbit
  - Extend acceleration range
  - Probe important beam dynamics effects
    - Parametric dependence of serpentine acceleration
    - Time of flight vs. transverse amplitude
    - Transverse dynamic aperture
  - Study behavior with different lattice configurations
- Other areas of interest
  - Model phase rotation in PRISM (J. Pasternak *et al.*)
  - Space charge effects
  - Slow acceleration: rate limit
  - Many others

Concluding Thoughts

- Non-scaling FFAGs are a new type of accelerator which may benefit many applications, the clearest benefit being for muon acceleration
- We have built and operated the first non-scaling FFAG
- We have successfully accelerated beam
- We still have an extensive program to fully explore the behavior of this type of machine