# FFAG R&D and the EMMA Experiment

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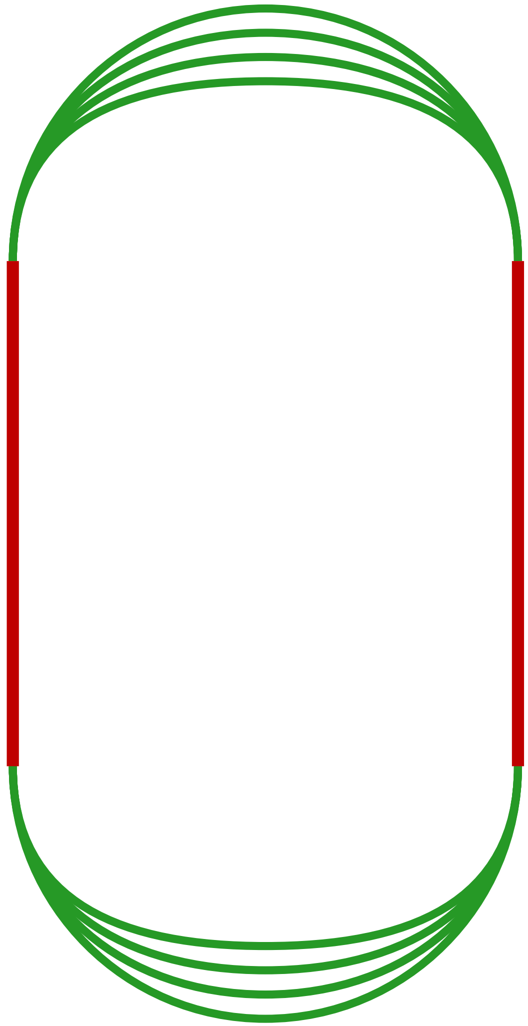
# Outline

- Introduction to FFAGs
- Theory and simulation work
- The EMMA experiment

# Reducing Muon Acceleration Cost

- Dominant cost: RF cavities and power
- Reduce cost: make many passes through RF
- RLAs: switchyard limits passes
- Eliminate switchyard, more passes
  - Single arc for all energies



# Fixed Field Alternating Gradient Accelerators

- Acceleration too fast to ramp magnets
- Keep magnetic fields fixed
  - Large energy acceptance in arc
  - At least factor of 2
- Alternating gradient focusing
  - Keep aperture “small”

# Scaling FFAGs

- Tune same at all energies
  - Large energy acceptance
- Disadvantages
  - Large superconducting magnet apertures
    - Lose cost advantage
  - Forced to low frequency RF (5 MHz)
    - Large voltage needed (GV)
    - Incompatible with cooling RF

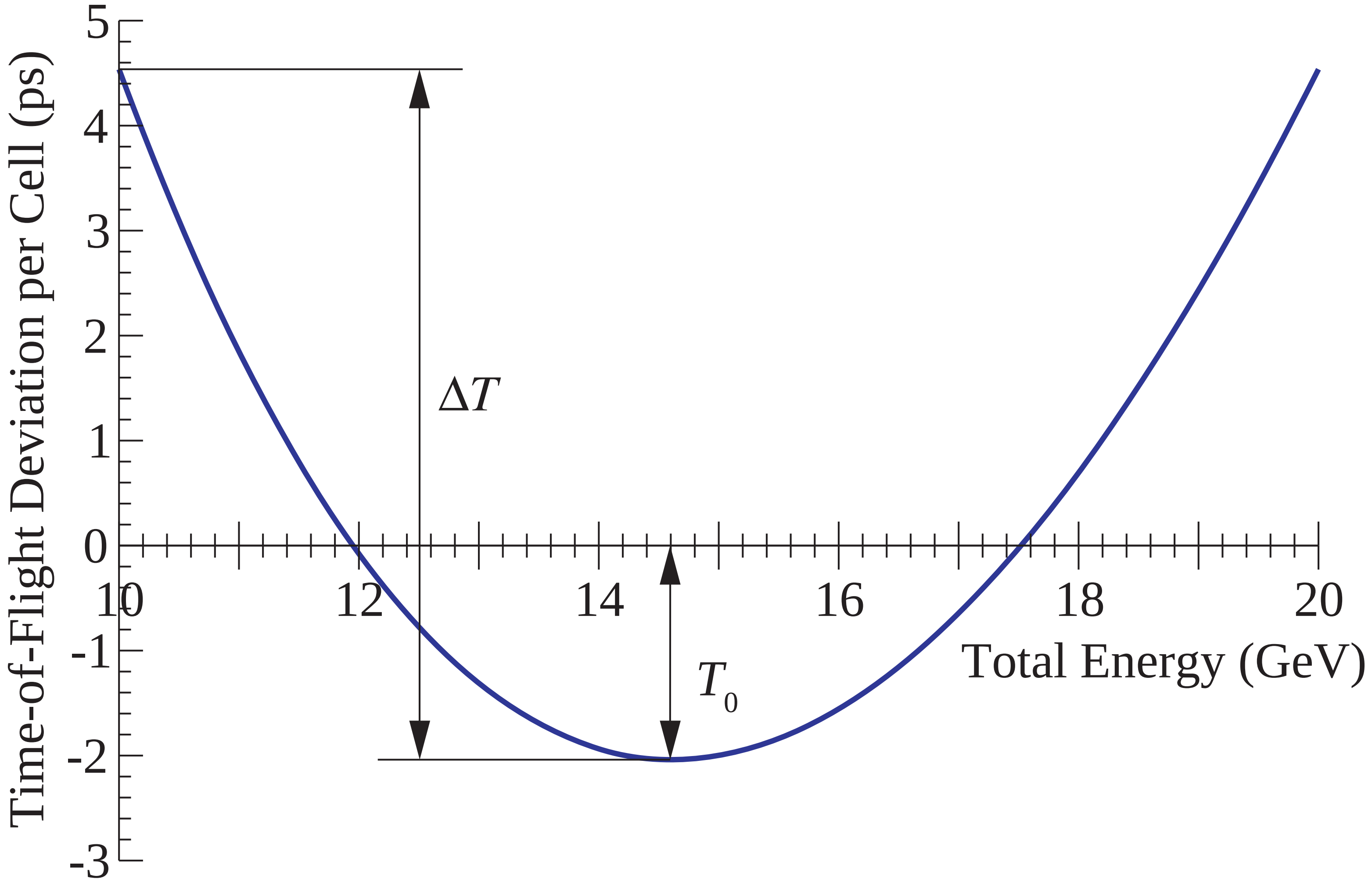
# Non-Scaling FFAGs

- Tunes depend on energy
- To achieve energy acceptance:
  - Simple cells, all identical
  - Magnets linear
  - Rapid acceleration
- Advantages
  - Smaller magnet apertures
  - High-frequency RF (200 MHz)

# Time of Flight

- Different energies, different times of flight
  - Single arc
  - Can't rapidly vary RF frequency
  - RF synchronization limits turns
- Forces scaling FFAG to low frequency
- Non-scaling FFAGs
  - Isochronous near central energy
  - Serpentine longitudinal phase space

# Non-Scaling FFAG
# Time of Flight vs. Energy

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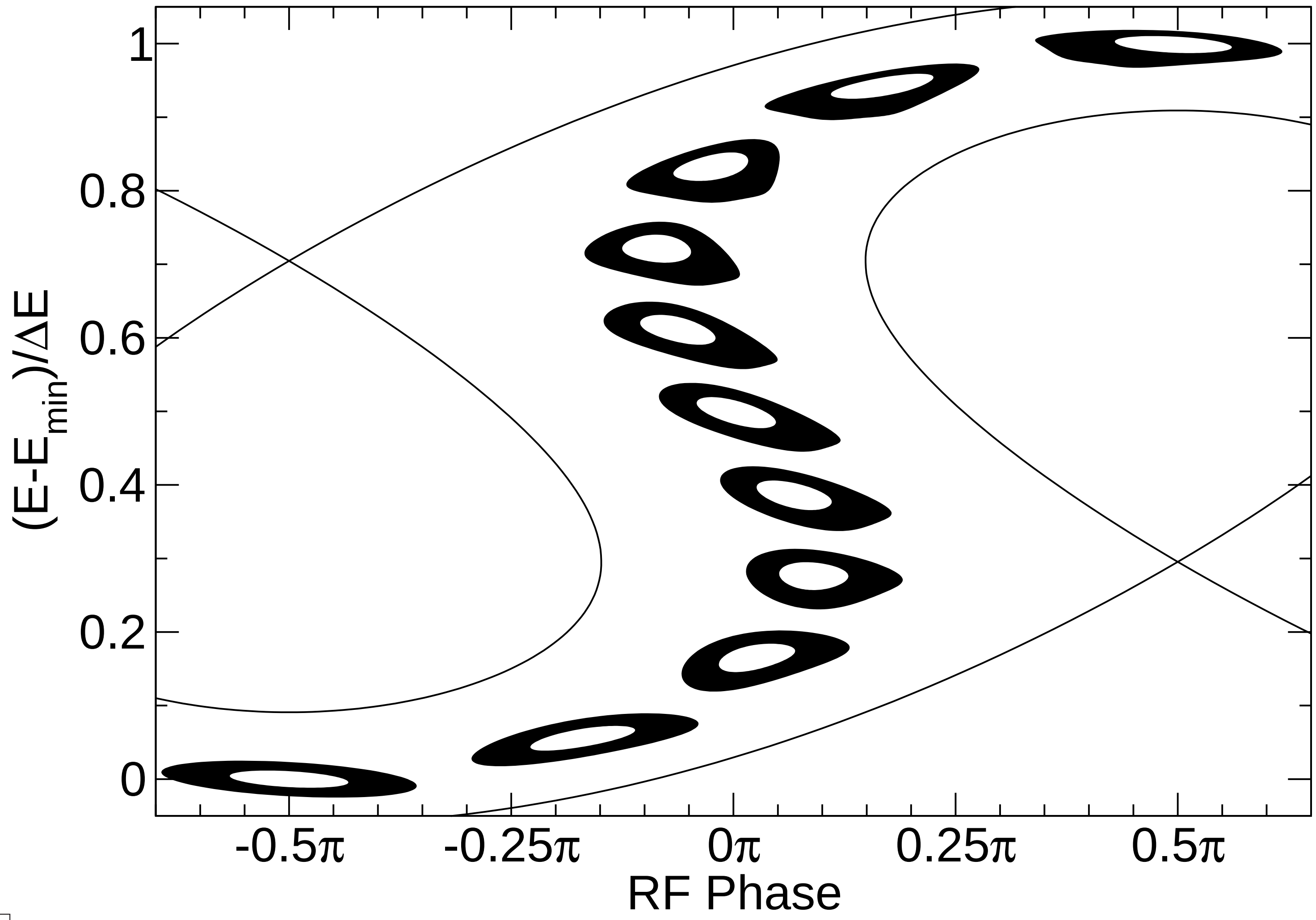
Neutrino Factory Muon Collider

# Non-Scaling FFAG Longitudinal Phase Space



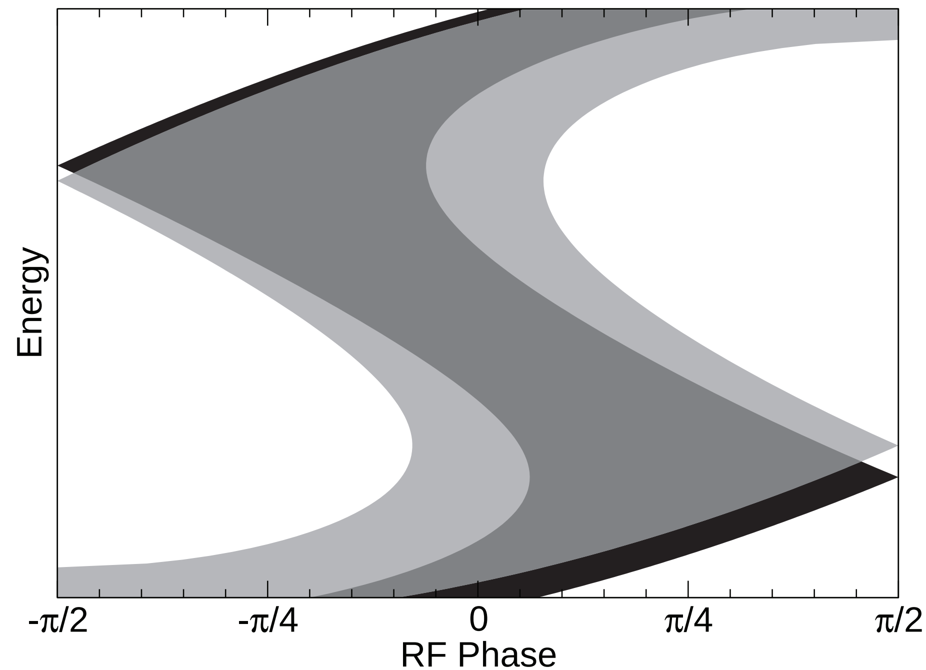
# Theory and Simulation Outline

- Time of Flight and Transverse Amplitude
- Scaling FFAGs at Low Energy
- Error Studies

# Time of Flight and Transverse Amplitude

- Larger transverse amplitude, longer time

- Different transverse amplitudes, different longitudinal phase space
- Beam loss
- Emittance growth



# Time of Flight and Transverse Amplitude: Reducing Effect

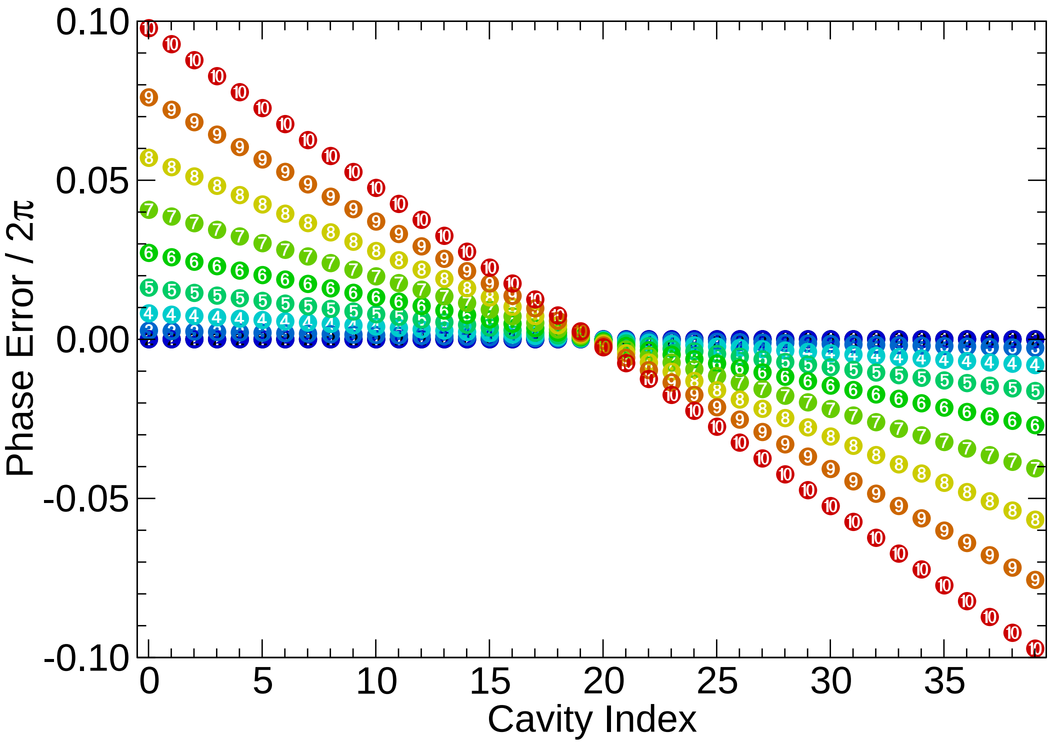
- Reduce tune range during acceleration
  - Nonlinear magnets reduce dynamic aperture
  - 20–30% possible?
- Increase energy gain per cell
  - 25% cut free, 60% cut for 45% cost
  - Low energy (5–10 GeV) ring less than 6 turns

# Time of Flight and Transverse Amplitude: Reducing Effect

- Add higher harmonic RF
  - Beam loading, reduced gradient
- Optimize machine parameters, initial conditions
- More cooling!
- Put everything together

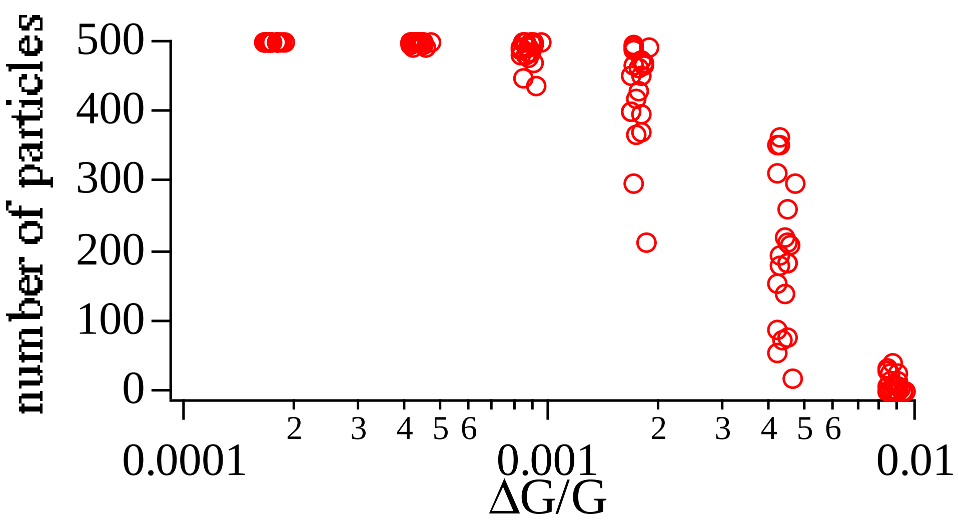
# Low-Energy Scaling FFAG

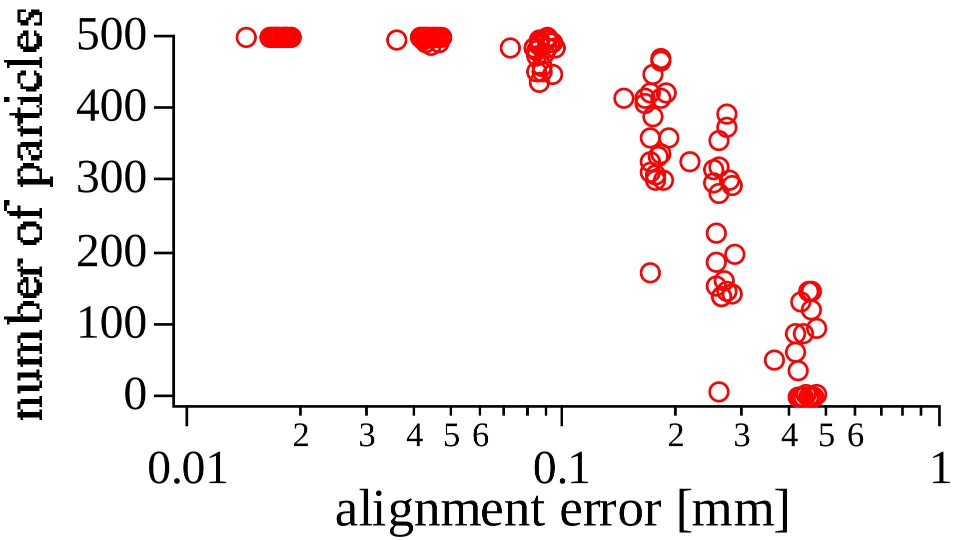
- No transverse amplitude problem
- Wide warm magnets at lower energy, OK cost
- Harmonic number jump: high frequency RF
- Only one sign
- Bunch train?



# Error Studies (Machida)

- Example 10–20 GeV linear nonscaling FFAG
- Acceptable error levels
  - 100 $\mu$m RMS displacements
  - $10^{-3}$ fractional gradient error



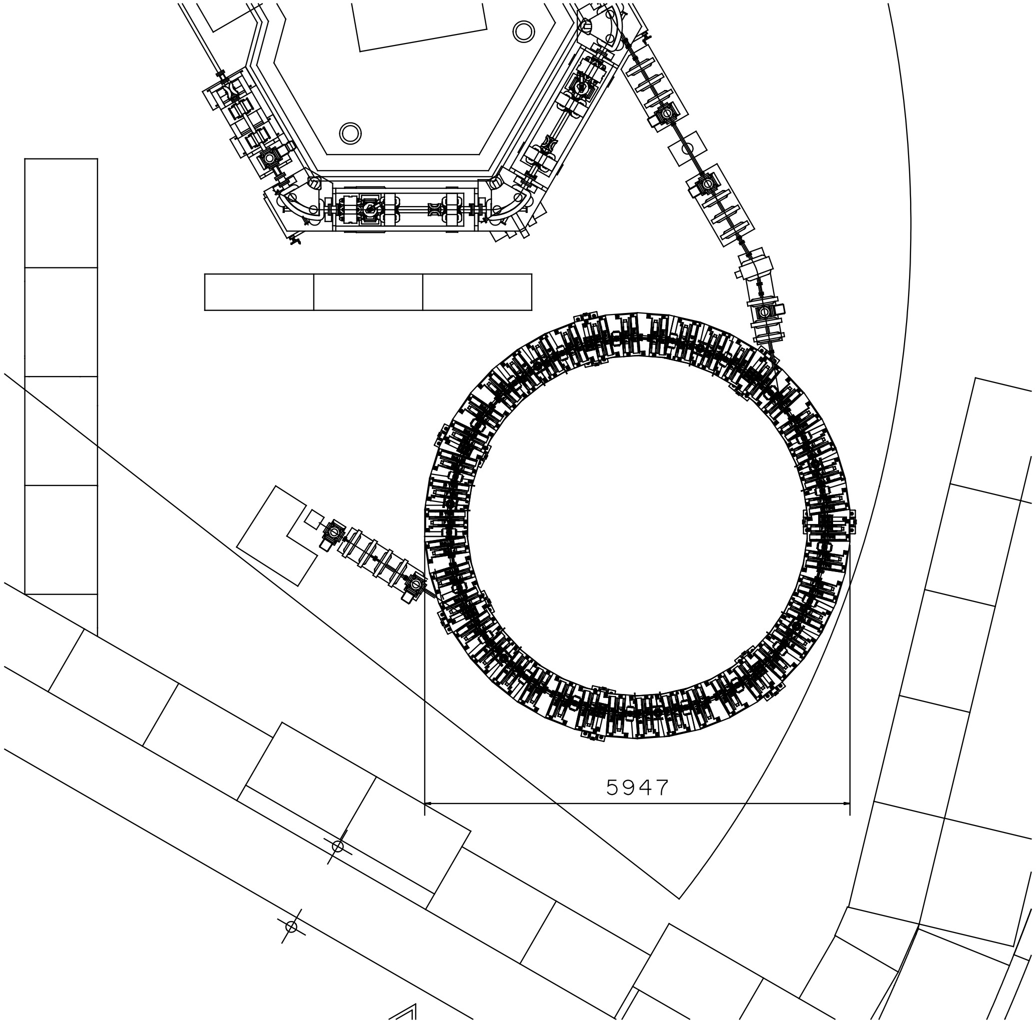
# EMMA
# Experimental Goals

- Not just a demonstration: study
- Longitudinal dynamics in linear non-scaling FFAGs
- Crossing of resonances
- Effect of errors

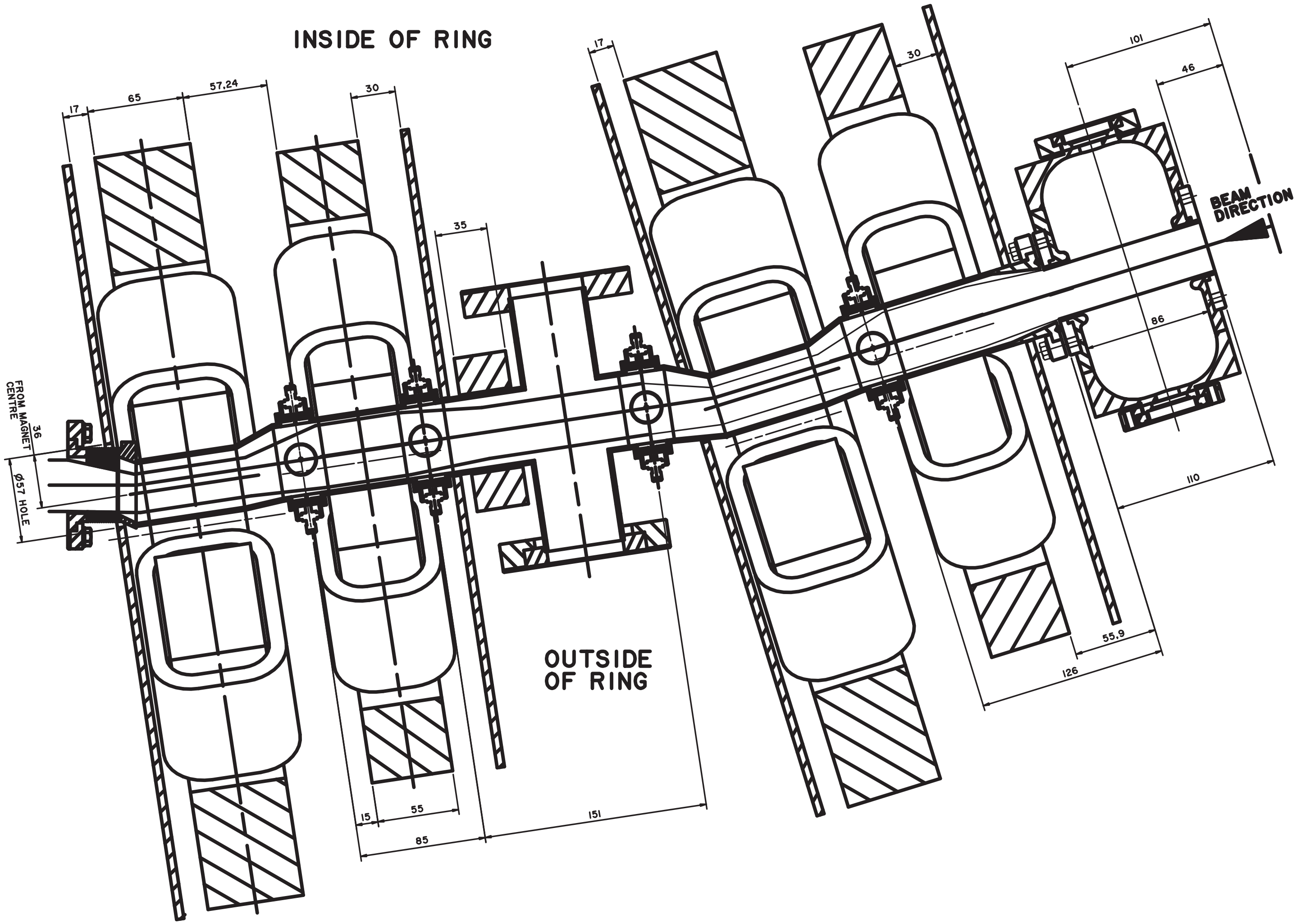
# EMMA
# Machine Overview

- Accelerate electrons from 10–20 MeV
- Electron beam injected from ERLP (Daresbury)
- 42 doublet cells, 16.6 m circumference
- 19 1.3 GHz RF cavities
- Accelerate in around 10 turns (varies)
- Small beam paints phase space

# EMMA
# Floor Layout



# EMMA
# Cell Layout



# EMMA
# Funding and Schedule

- Funding: UK Research Councils Basic Technology
- Hardware 3.8 M£
- Staff 1.8 M£
- Funding starts now
  - Construction done at 2.5 years

# EMMA
# Variations to Study

- Tunes passed through during acceleration
- Shape/size of longitudinal phase space
- Magnitude of errors

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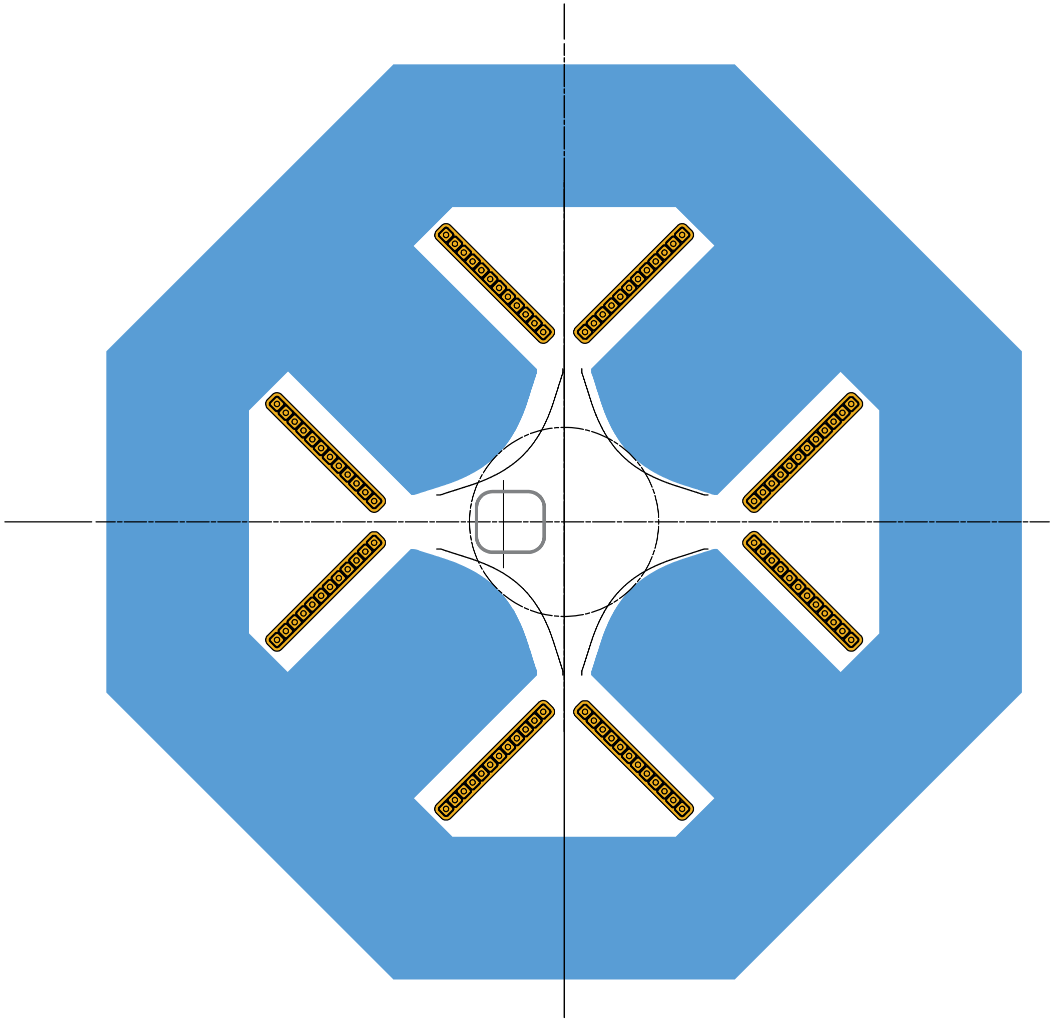
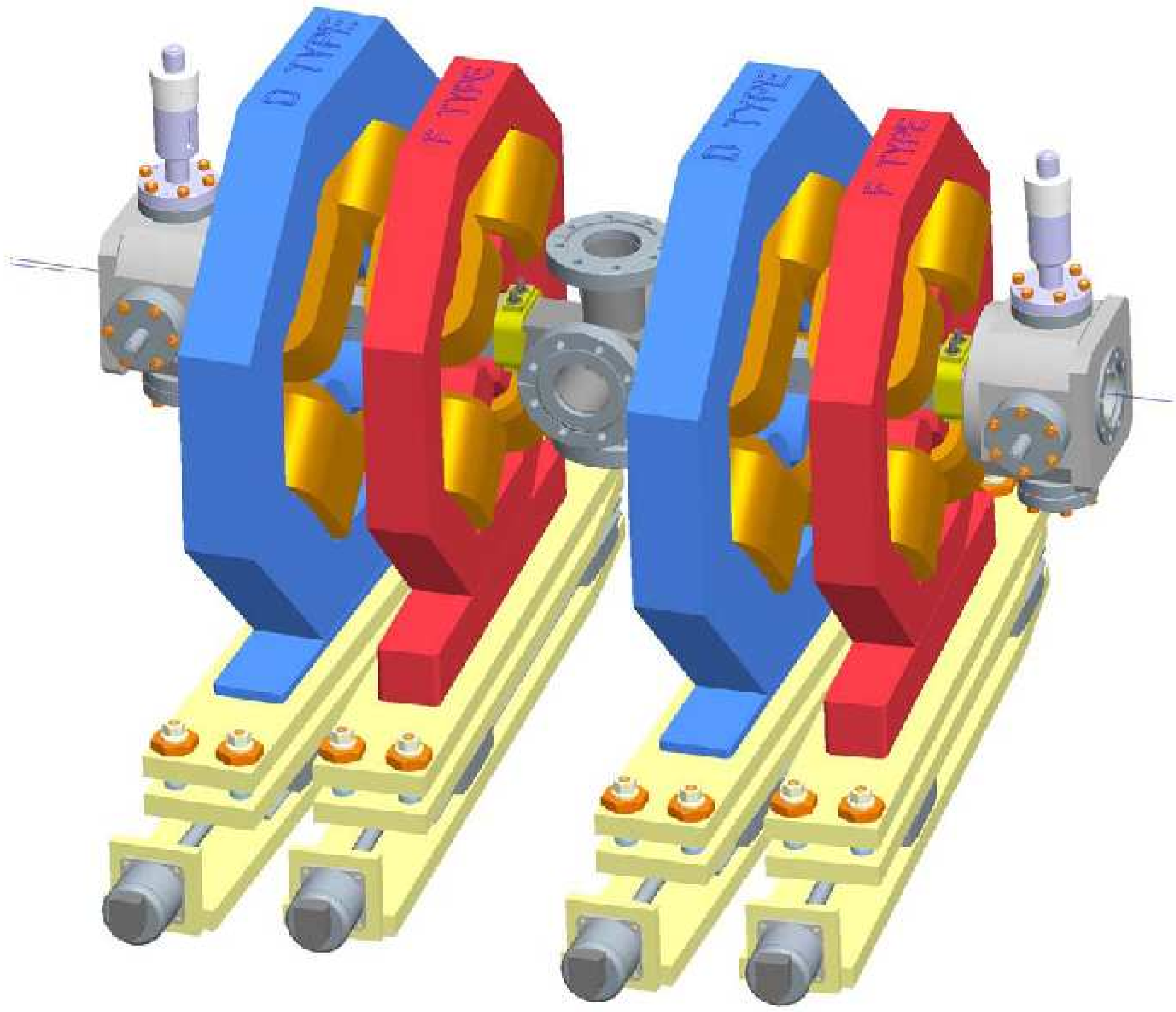
# EMMA
# Parameters to Vary

- Overall quadrupole field
- Overall dipole field
  - Sliders
- RF frequency
- RF voltage
- Individual magnet fields
- RF phases



# EMMA Cell



# EMMA
# Injection and Extraction

- Only major remaining design challenge
- Inject/extract over entire 10–20 MeV range
  - Commissioning
  - Study individual resonances
  - Difficult: phase advance variable
- Used to paint horizontal phase space
- Septum and two kickers
  - Separate sets for injection and extraction

# EMMA
# US Contribution

- Experiment specification (primary)
- Main ring lattice design (primary)
- Design of transfer lines (part)
- Injection/extraction design (part)
- Diagnostics (part)
- Simulation (future)
- Primarily Berg, Johnstone

# Conclusions

- FFAGs reduce acceleration costs for muon machines
- Theoretical and simulation studies are improving our understanding
- EMMA experiment will confirm our understanding