Workshop Summary

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FFAG Workshop ’05
9 December 2005

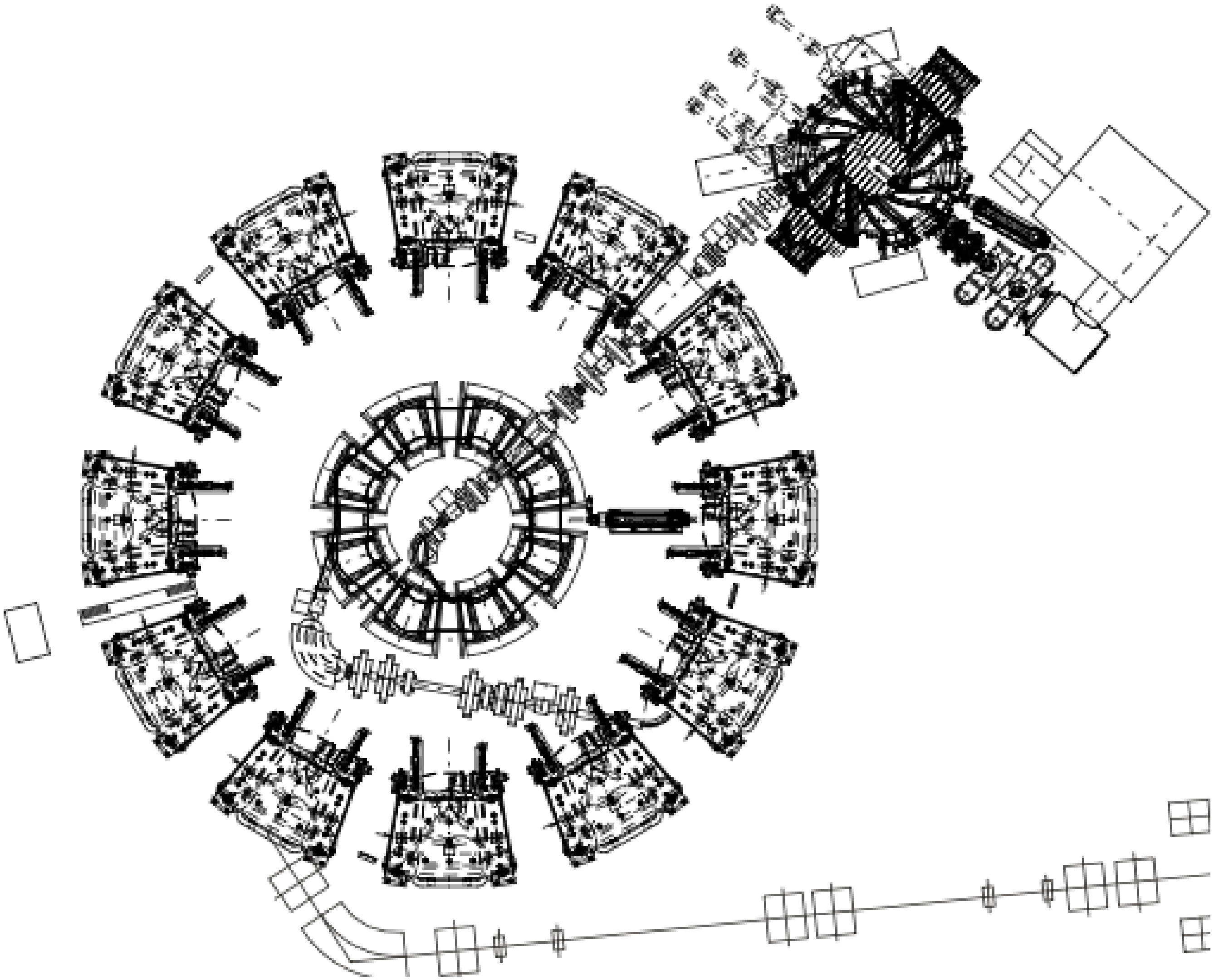
FFAG Applications

- FFAG proton beam driving a subcritical reactor
- Energy Recovering Internal Target: Boron neutron capture therapy
- Ibaraki proton therapy facility
- PRISM
- 150 MeV FFAG
- Non-sclaing proton FFAGs: AGS injector, high power proton driver, proton driver for neutrino factory, non-scaling model for proton machine
- 5-magnet cell nonlinear FFAGs: some isochronous, some allowing insertions
- Muon acceleration
- EMMA non-scaling electron model
- Prototype non-scaling proton medical machine

FFAG Applications
Driving Subcritical Reactor (KURRI)

- Control extraction energy and beam current, thus control output power
- 150 MeV, 1 μA, 120 Hz
- Eventually 200 MeV, 100 μA, 1 kHz
- 3 stages
  - H^+ spiral induction, 100 keV–2.5 MeV
  - 2.5 MeV–20 MeV
  - 20 MeV–150 MeV, 12 cells
- Injector tested (w/o trim coils) to 250 keV, beam extracted
  - Crossed integer resonance
- Booster magnets being tested now, first beam spring 2006
- Maybe medical machine in the future

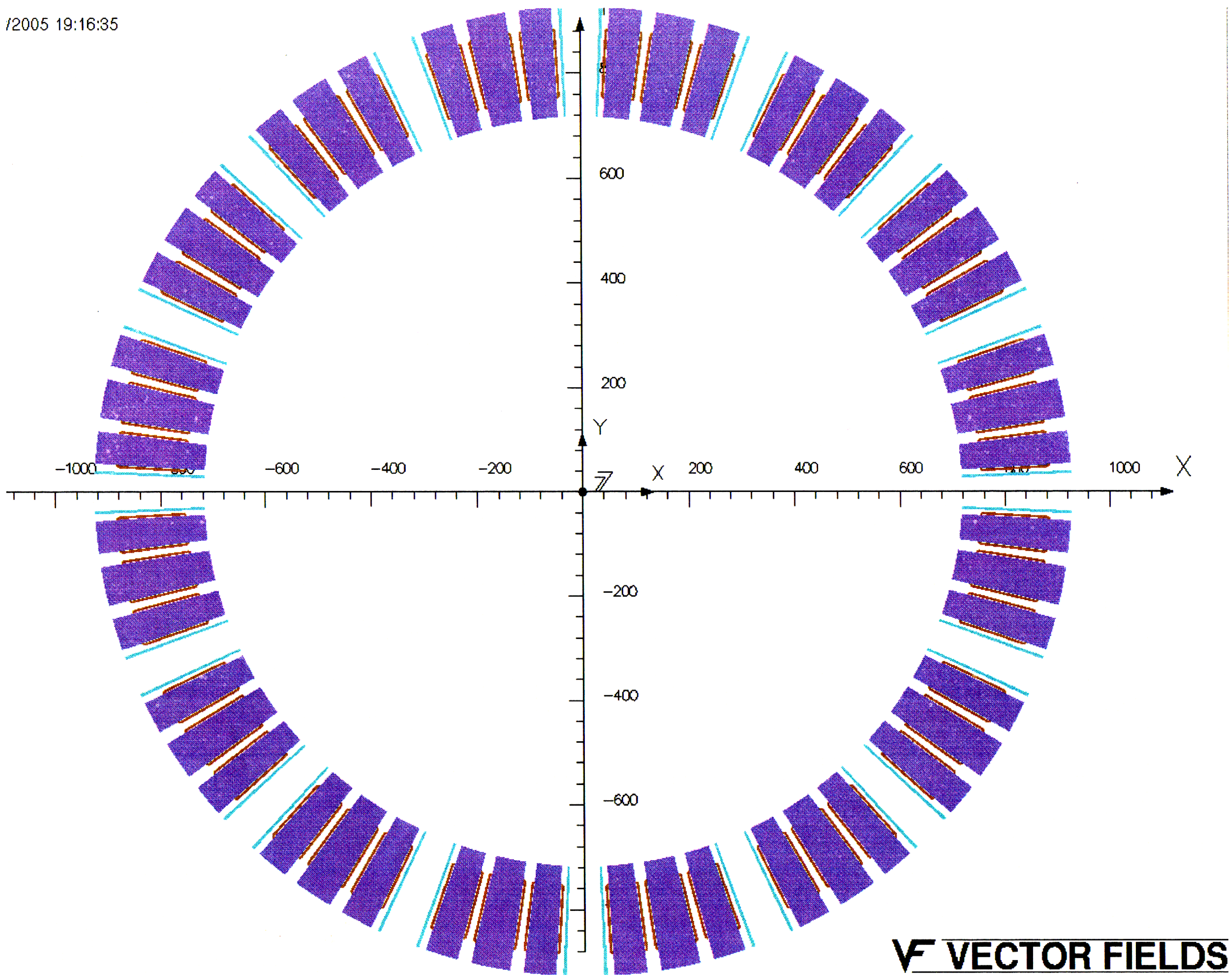
FFAG Applications
Driving Subcritical Reactor (KURRI)



FFAG Applications
Ibaraki Proton Therapy

- Studies have been done for the machine design, finalized in summer 2006
- Cyclotron injection, H$^+$, > 20 MeV
- Straights > 1 m
- Multi-port extraction: parallel treatments
- Pulsed beam for spot scanning
- Current specs: 230 MeV, 16 FDF cells, $k = 13$, 100 Hz, > 100 nA
- FDF for small orbit swing, ease of extraction
- Have funding to build

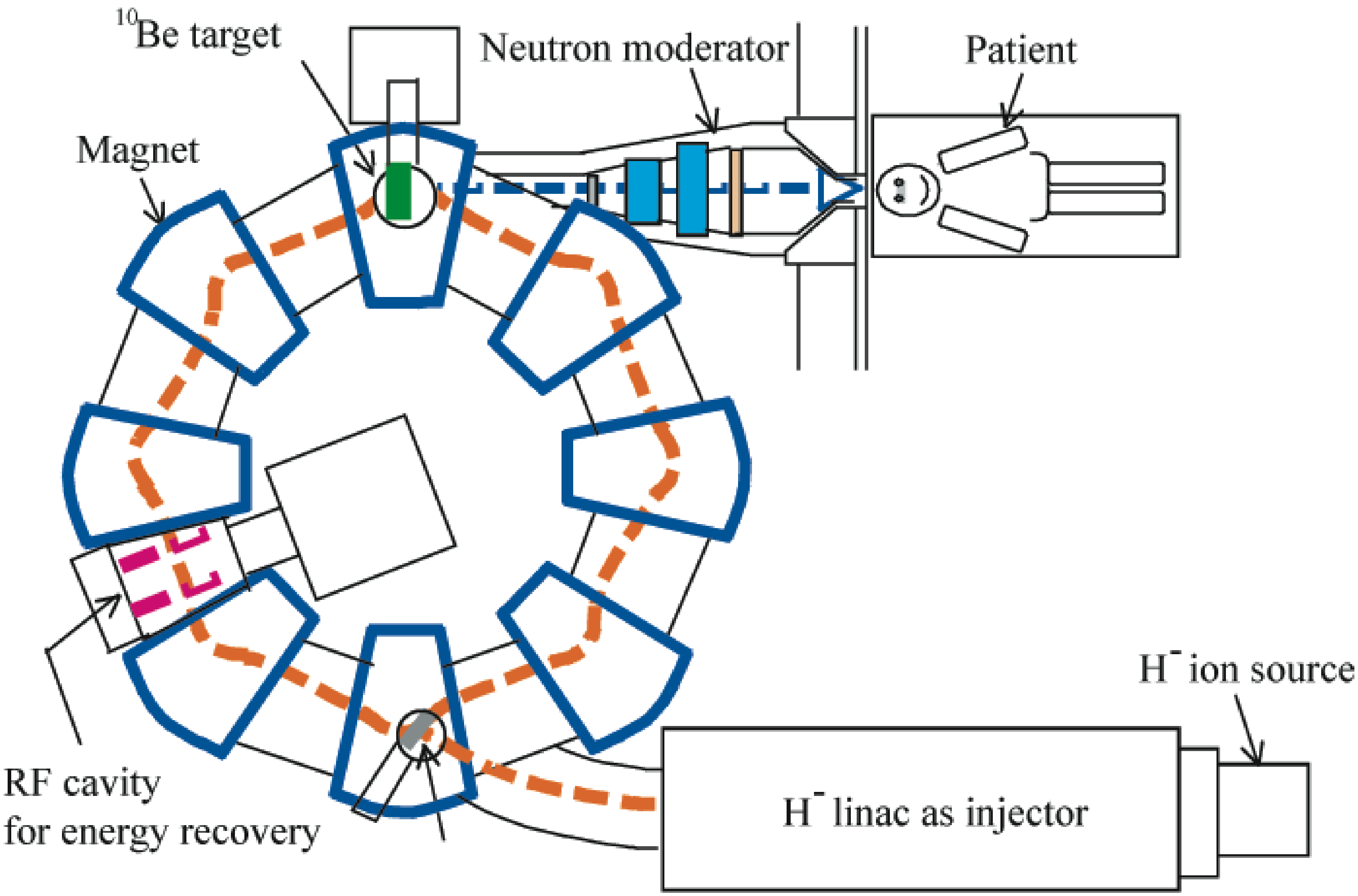
FFAG Applications
Ibaraki Proton Therapy



FFAG Applications
Energy Recovering Internal Target

- Boron Neutron Capture Therapy: Promising method for treatment of cancer
- Neutron source: need > 20 mA on target, 10 MeV
- Accelerate to recover losses in target
- Use FFAG to accomodate energy spread
- Need 10% acceptance, 1 mm transverse acceptance
- Full energy injection: 40 mA, 10 MeV
- 8 sector: needed to get 90° phase advance
- Spiral to get longer straight for target

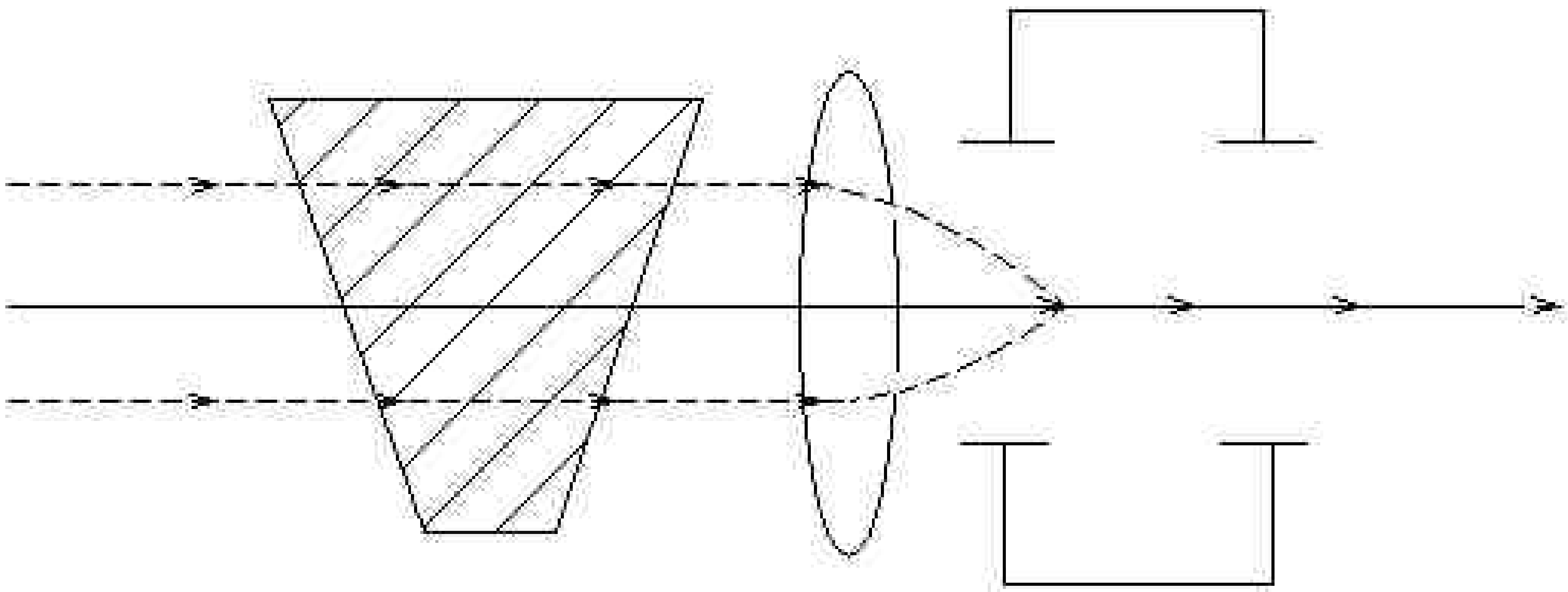
FFAG Applications
Energy Recovering Internal Target



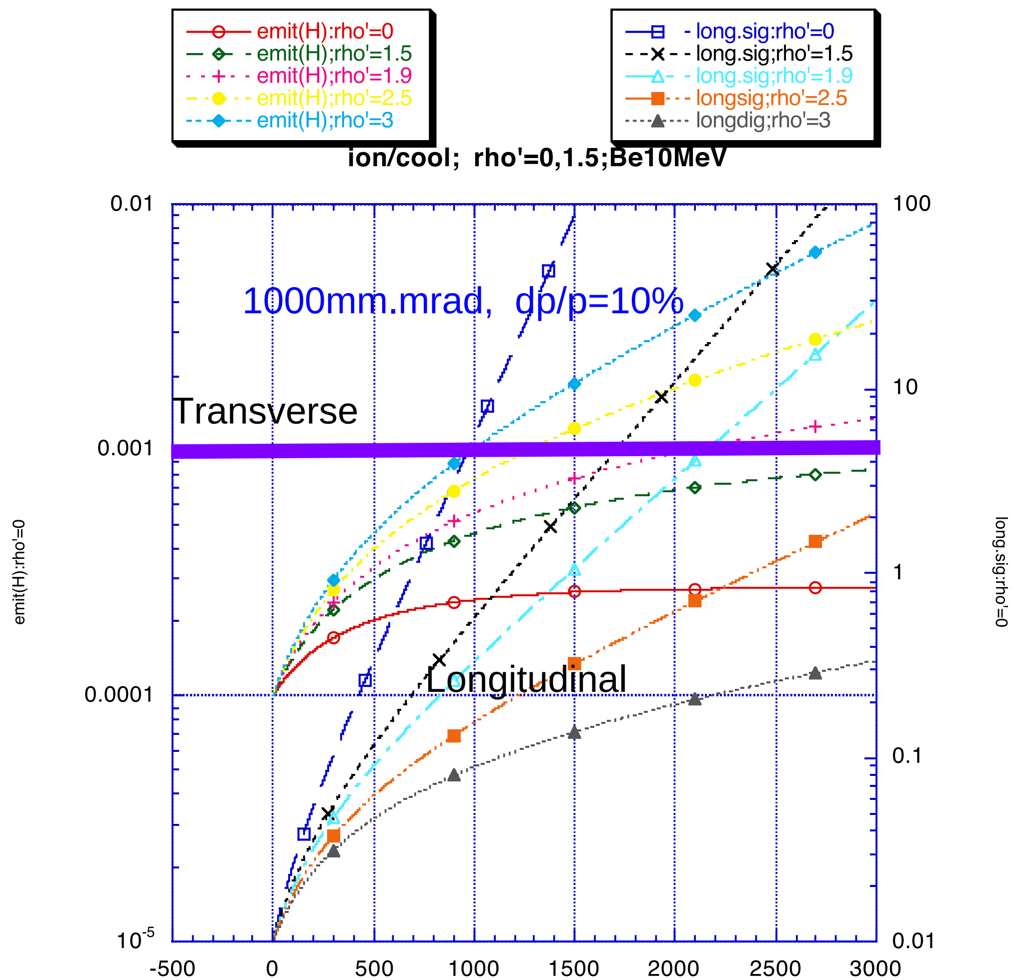
FFAG Applications
ERIT Ionization Cooling

- Energy straggling increases energy spread infinitely
- Multipole scattering increases transverse emittance, but reaches equilibrium
- Use wedge-shaped target to couple longitudinal to horizontal
- Longitudinal doesn't increase as fast, transverse growth acceptable
- If could couple vertical as well, could do even better
  - Net cooling from sum of partition numbers 0.4
  - Reach equilibrium
  - Coupling to vertical may break scaling
- Discussion of whether electron cooling might be better: more well-tested

FFAG Applications
ERIT Ionization Cooling



FFAG Applications
ERIT Ionization Cooling

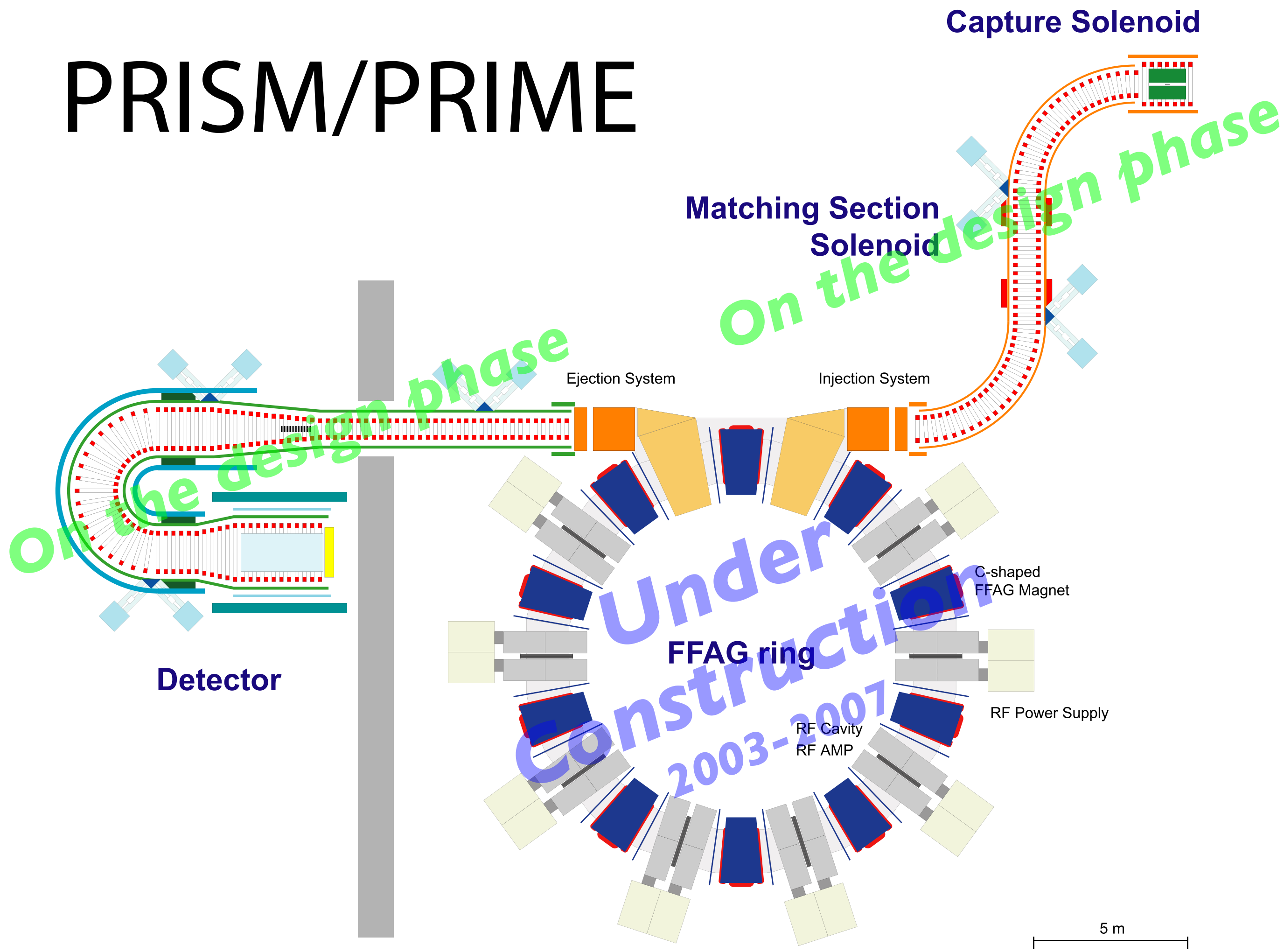


FFAG Applications
PRISM

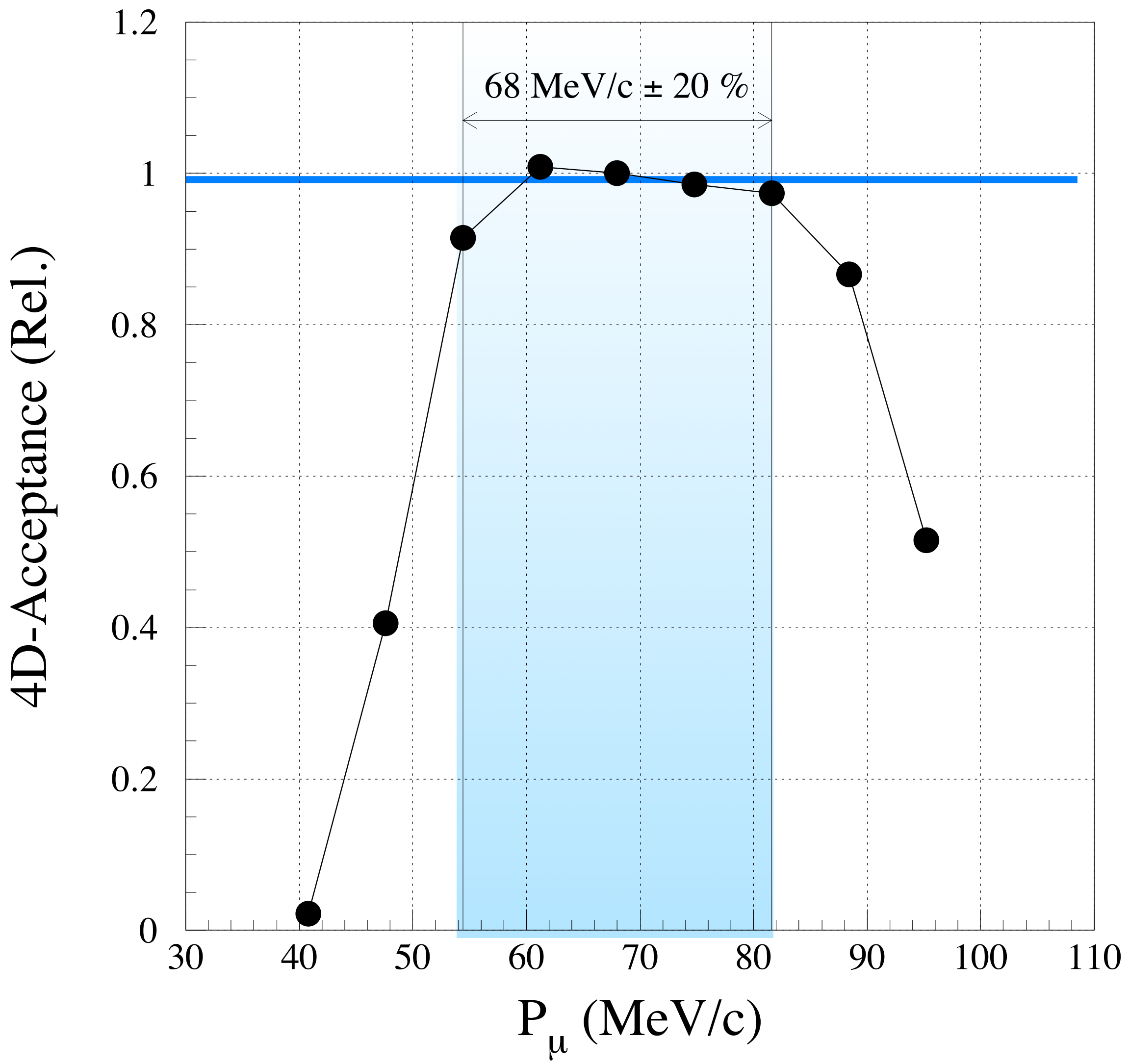
- Beam optics and magnet design done
  - Tracking studies done and continuing
  - Effects of magnet errors studied
- Prototype magnets are being constructed
- RF system: 5 MHz, 200 kV/m, mag alloy core
  - Only money for 1 RF gap per straight; eventually want 5
  - Sinusoidal vs. sawtooth waveform studied
- Injection/extraction studied and designed: vertical
- Diagnostics studied
- Commissioning in 2007

FFAG Applications
PRISM

PRISM/PRIME



FFAG Applications
PRISM Acceptance



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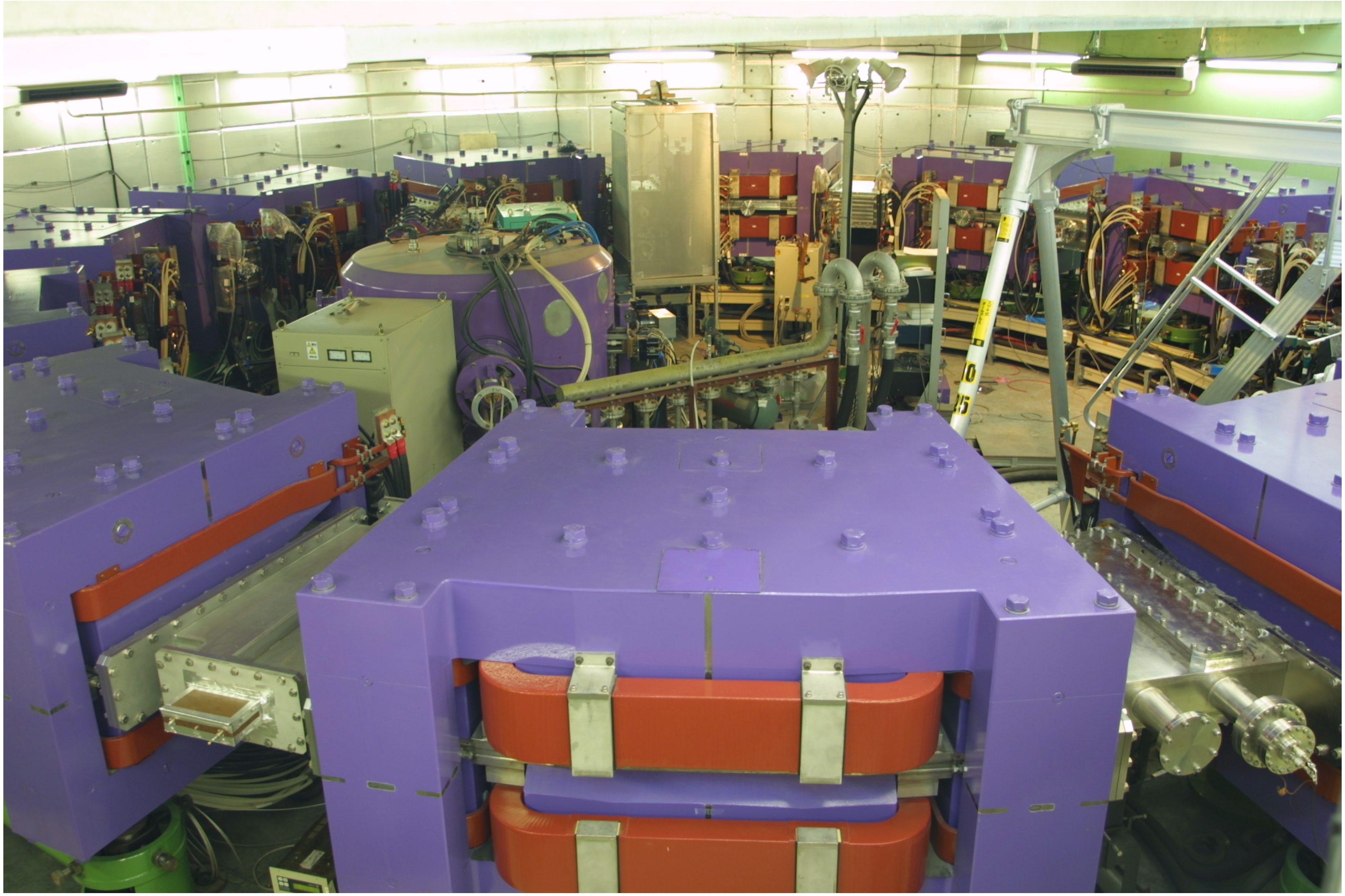
FFAG Applications
150 MeV FFAG

- FFAG prototype, rapid cycling, extraction
- Ion source improved
  - before, 200 μ pulse from cyclotron, but only 10 μs kicker pulse
  - Now ion source has 10 μs pulse
  - Peak current increased by factor of 3-4
- Increased RF voltage
- Drive mechanisms on injection/extraction hw: optimize without breaking vacuum
- Extracted beam at 100 MeV
- Tested 100 Hz operation
- 0.2 nA at 20 Hz
- Tested resonance crossing

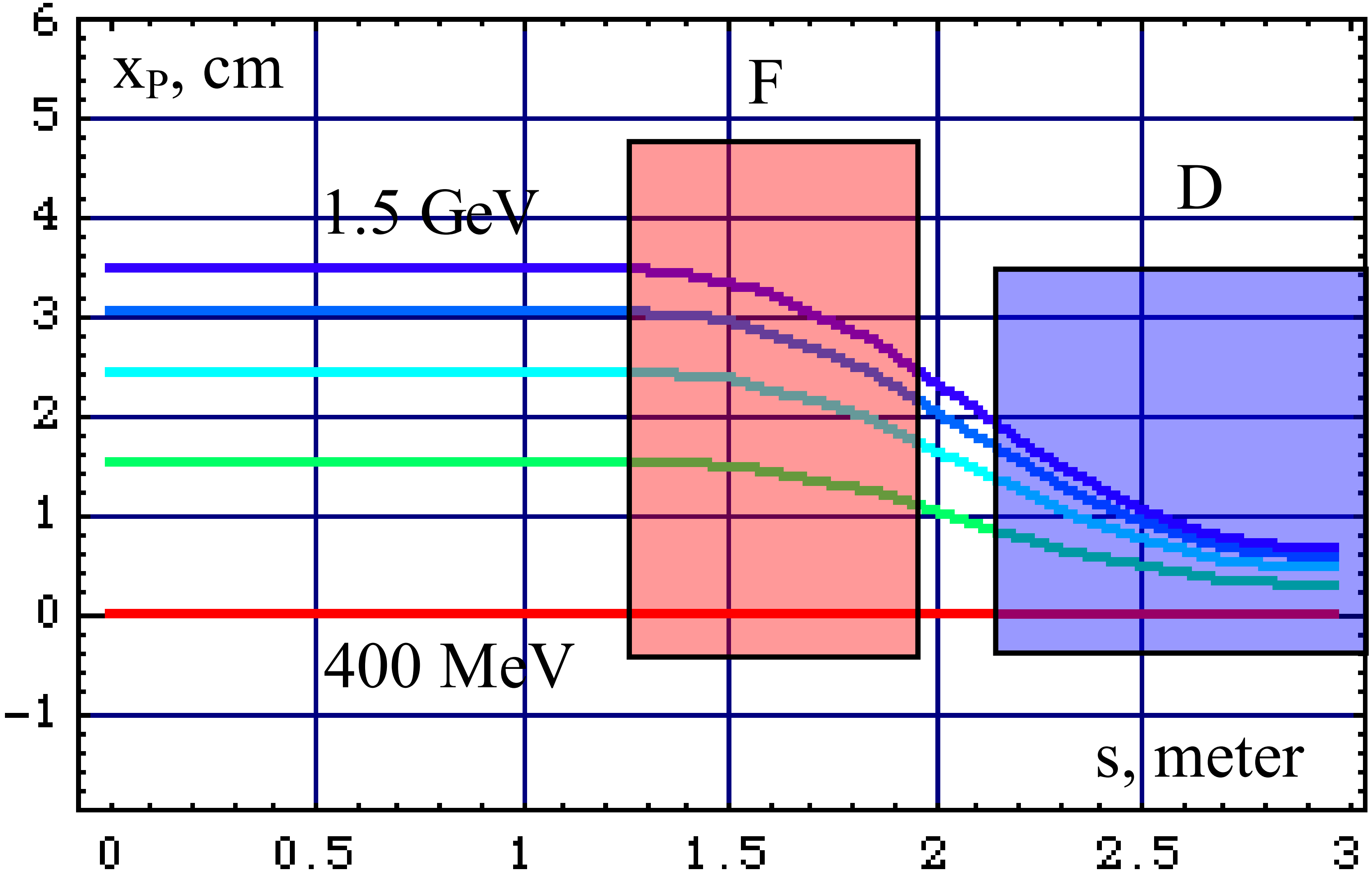
FFAG Applications
150 MeV FFAG



FFAG Applications
Non-Scaling Proton FFAGs

- FDF triplet designs
- Several machines designed from simple scaling laws
- Gave up on "adjusted field profile" machines due to tune shift with amplitude problems
- Variable frequency or harmonic number jump: latter allows CW
- Machines
  - Injector to AGS
  - 1 GeV, 10 MW proton driver
  - Higher energy proton driver (11.6 GeV) for neutrino factory
  - Electron model to simulate these

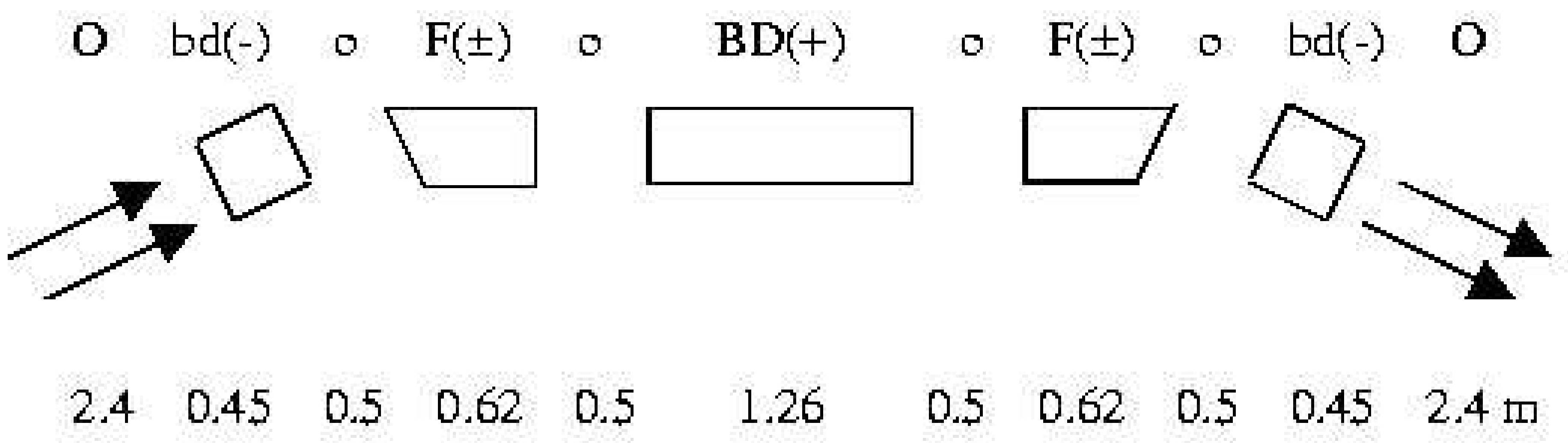
FFAG Applications
Non-Scaling Proton FFAGs



FFAG Applications
5-Magnet Nonlinear FFAGs

- Can meet several conditions
  - Isochronous
  - Constant (approximately) tunes
  - Ability to add insertions
- Several applications
  - Proton driver
  - Muon acceleration
  - Ionization cooling of muons

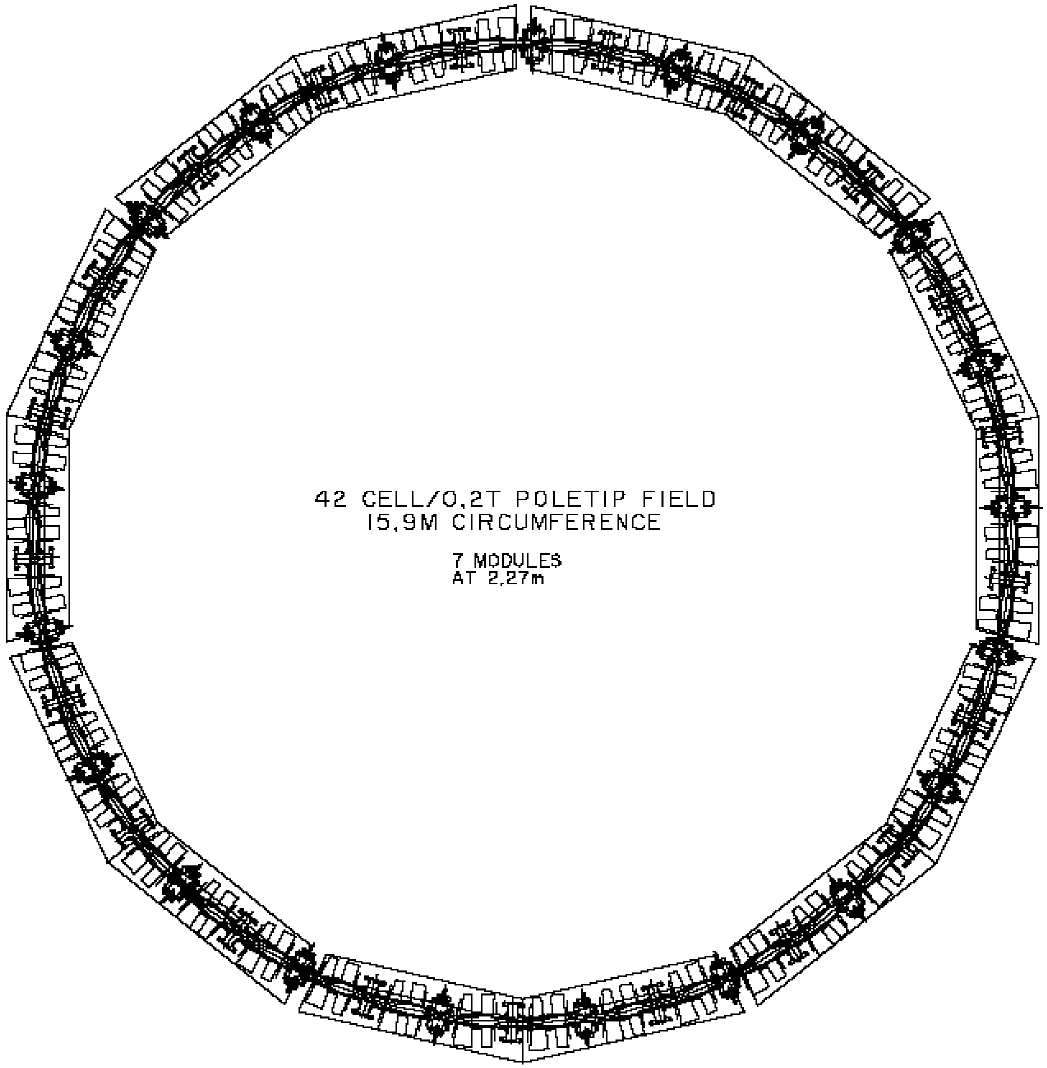
FFAG Applications
5-Magnet Nonlinear FFAGs



FFAG Applications
Linear Non-Scaling Model FFAGs

- Electron model based on muon acceleration parameters (EMMA)
  - Test “gutter acceleration” and resonance crossing
  - 1.3 GHz RF, 42 cells, 10–20 MeV
- Proton machine
  - Irradiate mice for studies
  - Study feasibility of linear non-scaling FFAGs
  - 40–100 MeV final energy, size constraint
  - Good chance of funding

FFAG Applications
Linear Non-Scaling Electron FFAG Model



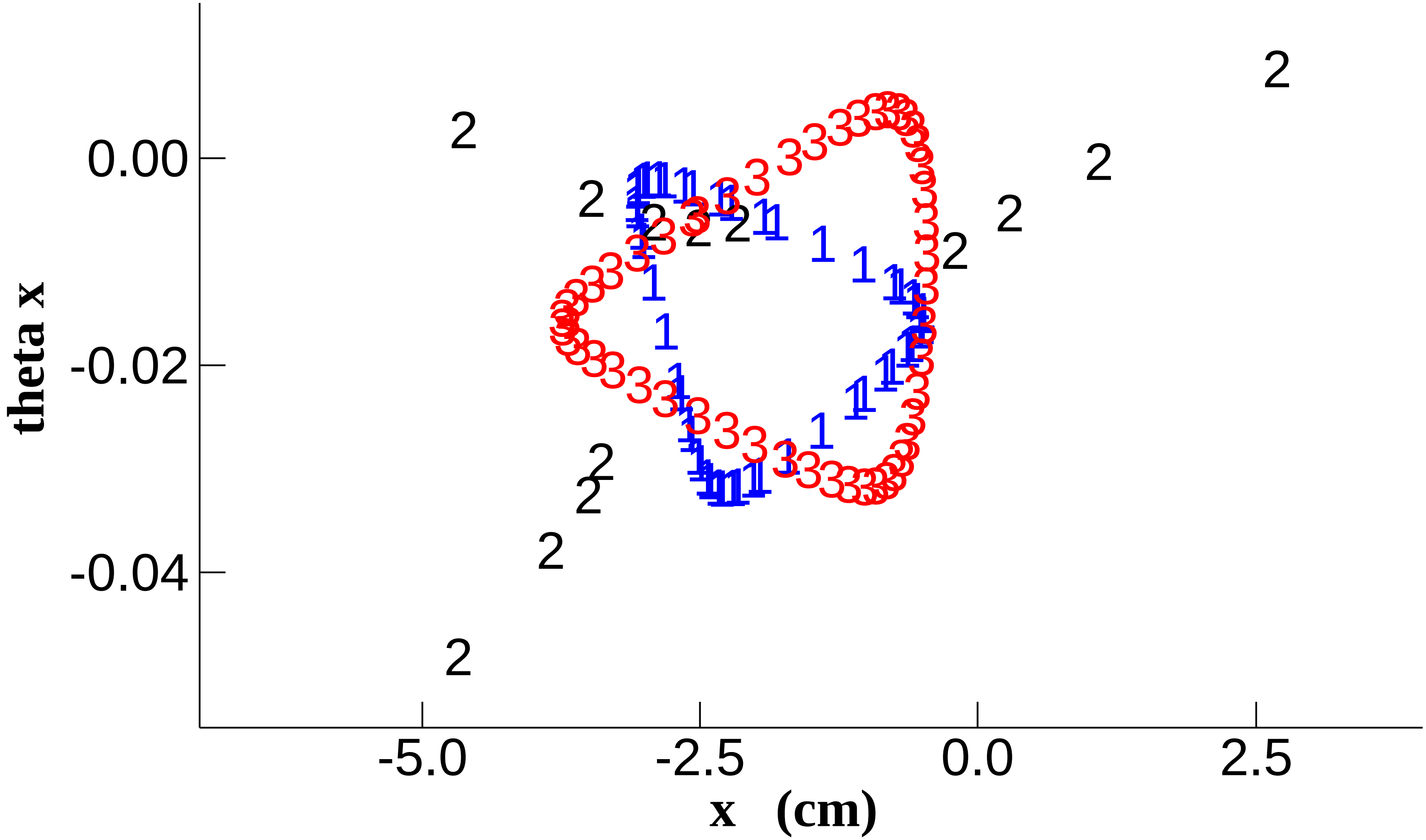
FFAG Applications
Broader Interest

- Success with FFAGs has bred interest
- More projects keep coming in Japan
- Beijing: spallation neutron source
- France, UK, others: medical applications (real money on the table)

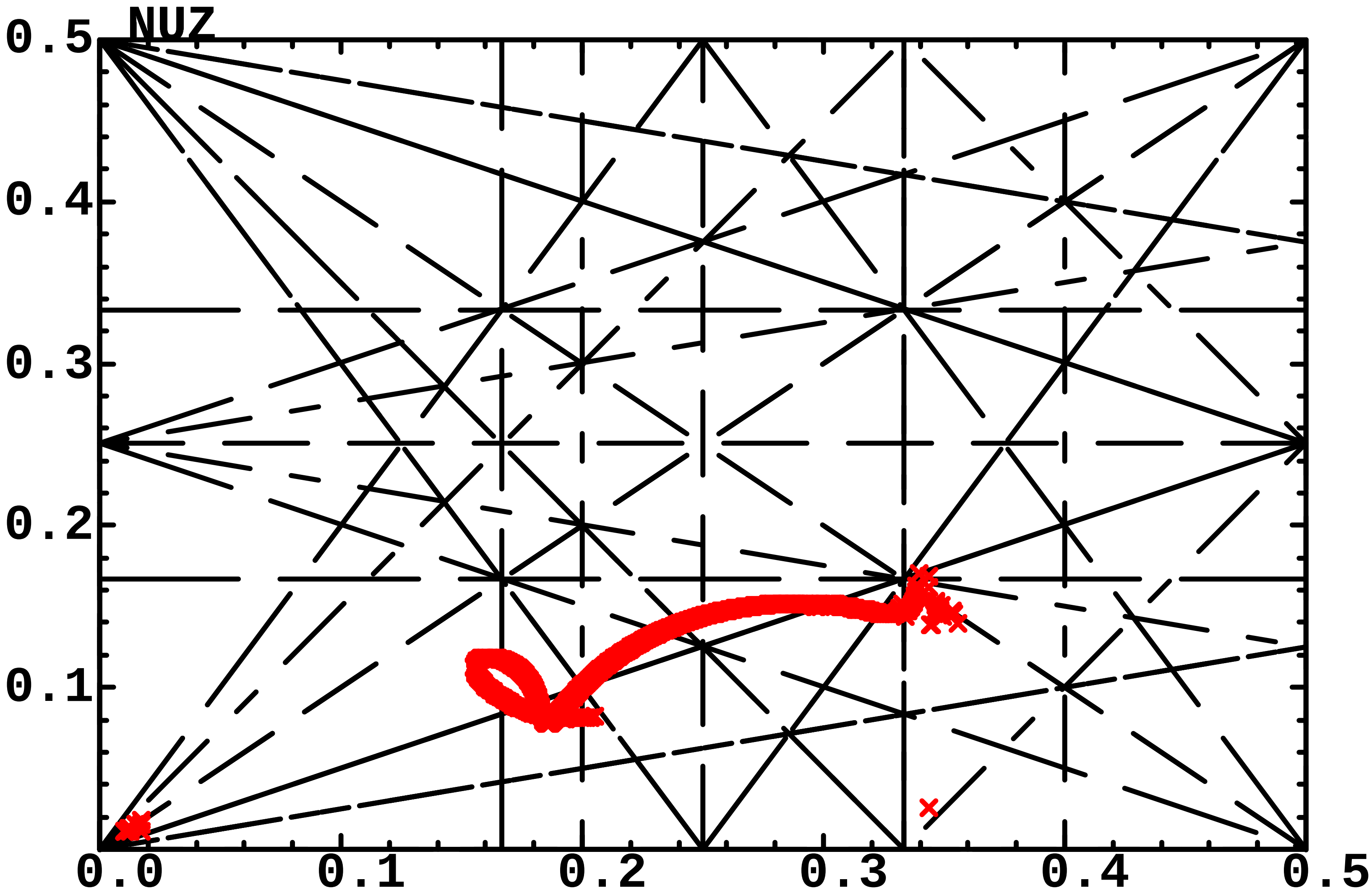
Tracking Studies

- Heard about three codes: ZGOUBI (Méot and Lemuet), Machida-code, and ICOOL, as well as general comments on tracking codes
- Tracking studies of scaling, linear non-scaling muon FFAGs, EMMA, isochronous FFAG lattices
- Introduction of end sextupoles in linear non-scaling FFAGs causes problems: probably correctable
- Isochronous FFAG lattices
  - Electron model was OK
  - Muon FFAG had poor transmission: hit a resonance at 17 GeV; will adjust parameters

Tracking Studies
Sextupole End Fields



Tracking Studies
Isochronous Non-Scaling FFAG



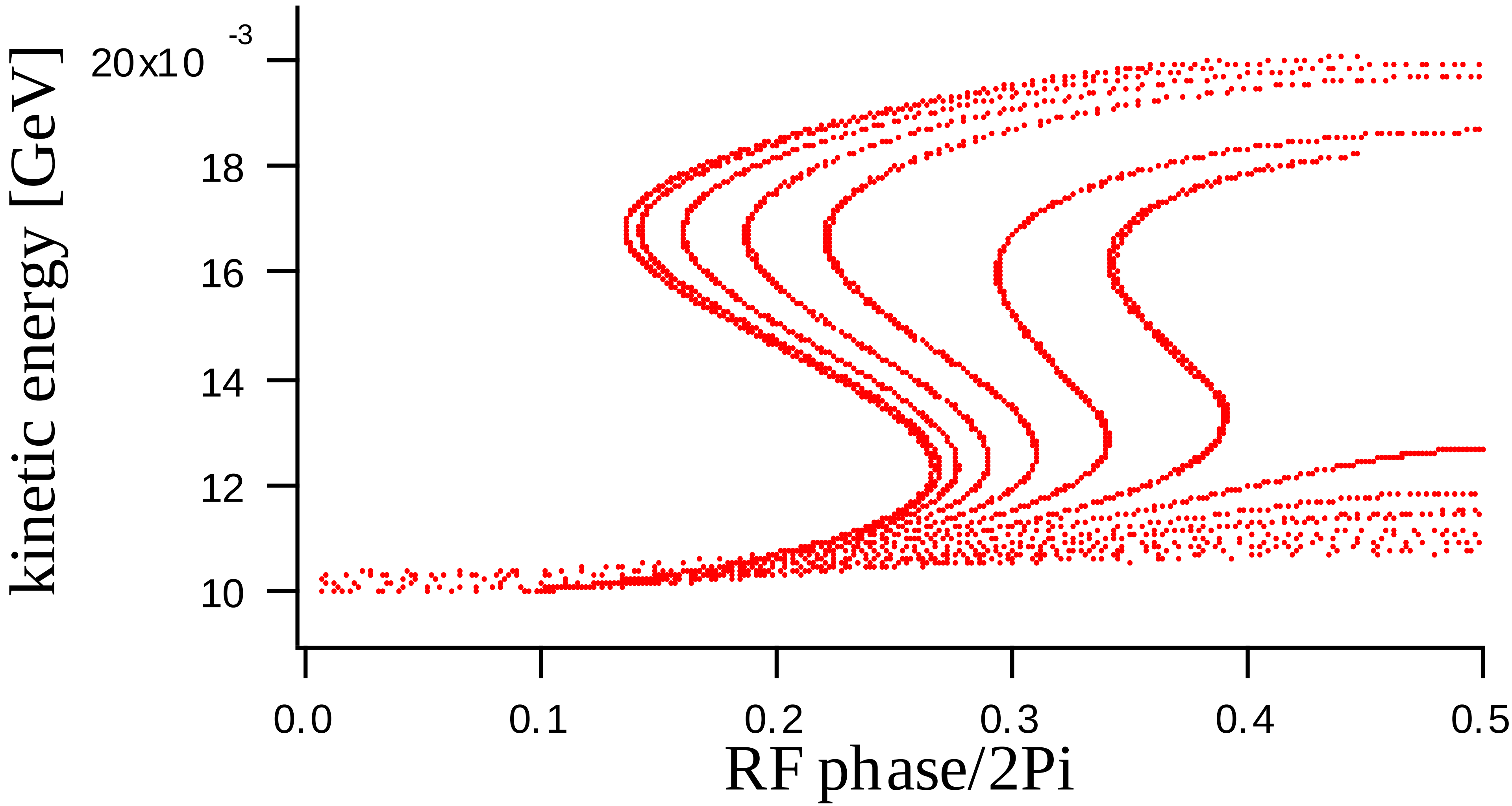
Tracking Studies
Transverse Amplitude and Longitudinal Motion

- Linear non-scaling lattices: find problem with large transverse amplitude particles not being accelerated
- Caused by time-of-flight dependence on amplitude
- Explanation provided: time variation with transverse amplitude related to tune variation with energy

$$\frac{dT}{dJ} = -2\pi p \frac{d\nu}{dE}$$

- Correctly predicted time of flight difference with amplitude
- There was great discussion regarding this explanation (angles)
- Attempts to symmetrize high amplitude parabola by changing dipole field didn't work very well
- Reduction of low-amplitude tune should help: $d\nu/dE$ reduced

Tracking Studies
Transverse Amplitude and Longitudinal Motion



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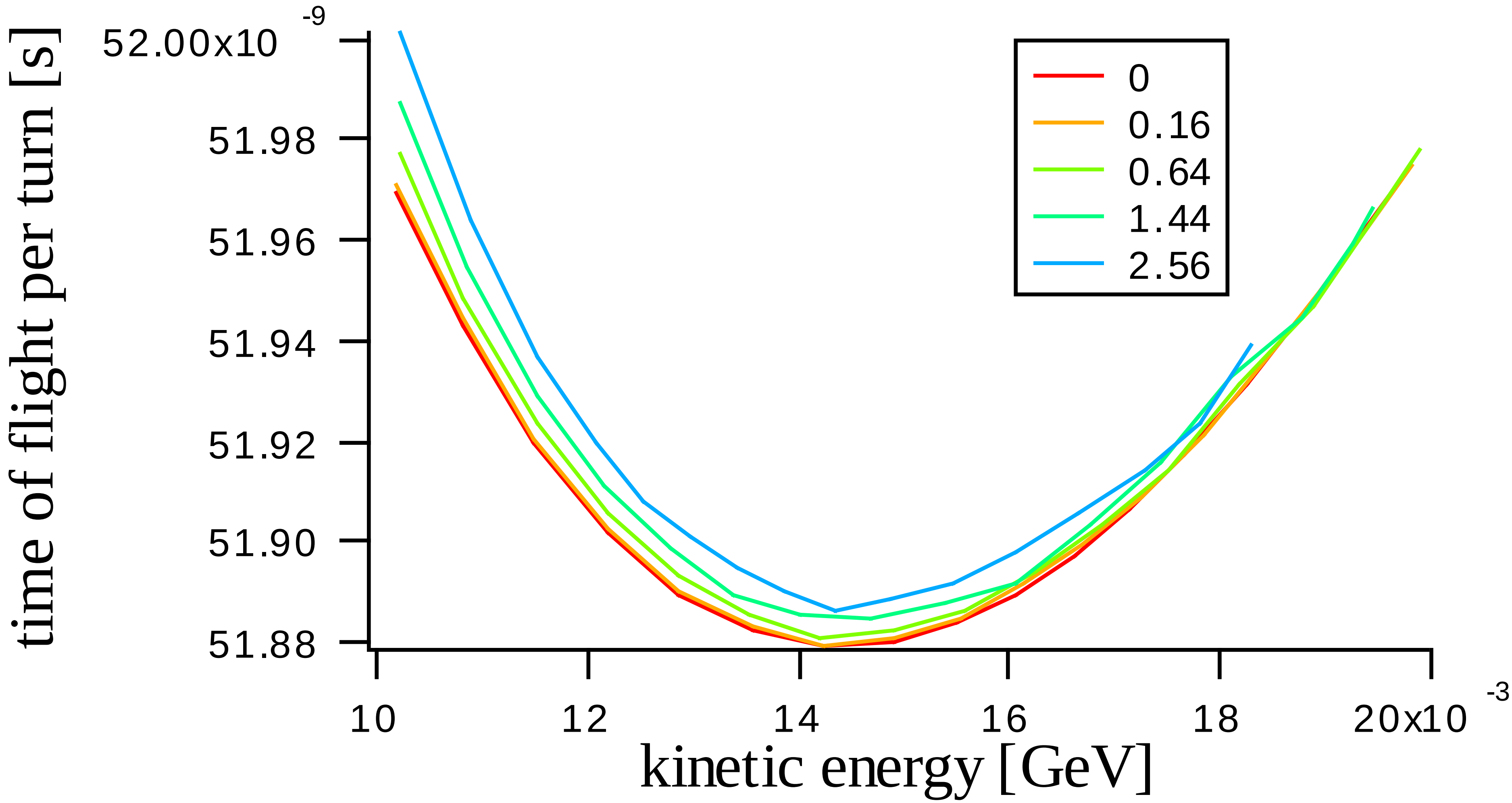
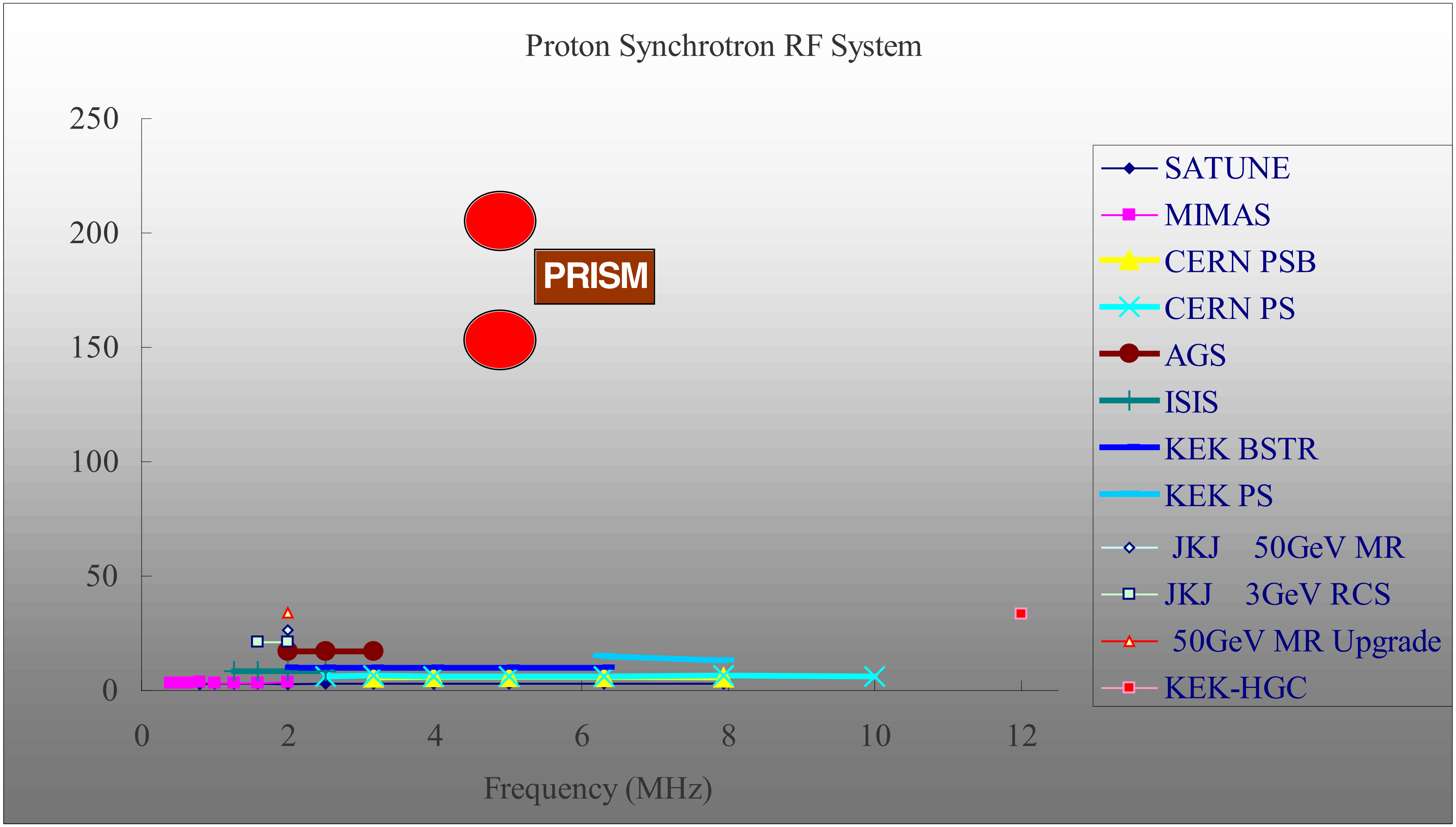
Tracking Studies
Transverse Amplitude and Longitudinal Motion



Magnetic Alloy Cavities

- Easily saturated by external magnetic fields: less than 100 Gauss
- Cooling is a big issue for high duty factor
  - Higher voltage, rep rate, duty factor: more cooling power needed
  - Schemes, order of increasing power
    - Forced air
    - Indirect cooling: no impedance reduction, run at high frequency (20 MHz)
    - Direct water cooling: high rep rate, but impedance reduction, frequency below 4 MHz

Magnetic Alloy Cavities
PRISM Requirements



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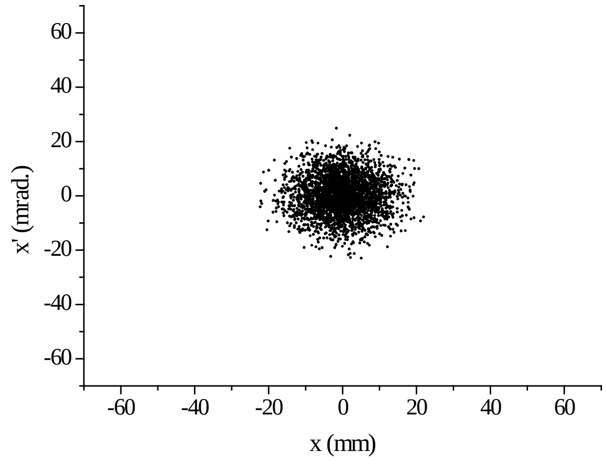
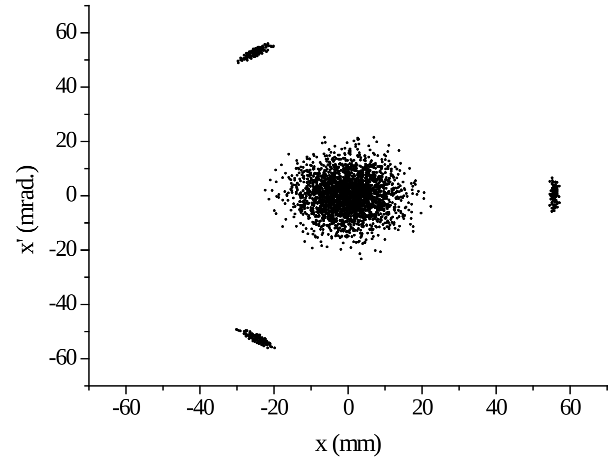
Resonance Crossing

- Resonance crossing is of broad interest in FFAGs
  - Non-scaling do it a lot
  - Scaling do it because field is not ideal
- Theoretical computation of resonance crossing
  - Precise effect depends on direction resonance is crossed
- Experimental demonstration showing crossing in 150 MeV FFAG
  - Non-structural $3\nu_x = 11$ resonance excited by closed orbit distortion (COD) feed-down
  - COD caused by cavity core
  - Dipoles to correct COD
  - Demonstrated loss at resonance crossing, and successful correction by dipoles

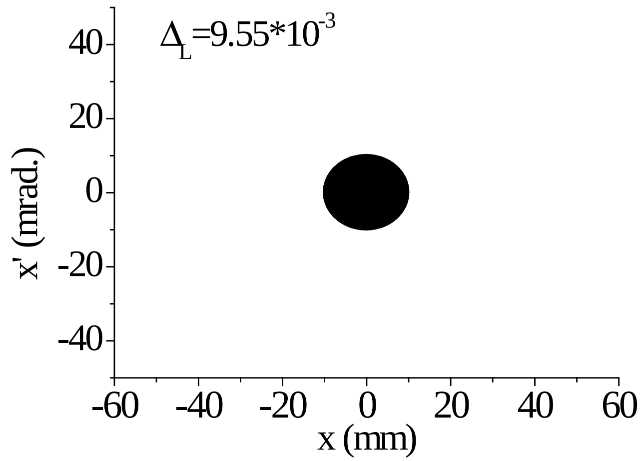
Resonance Crossing
Dependence on Crossing Direction

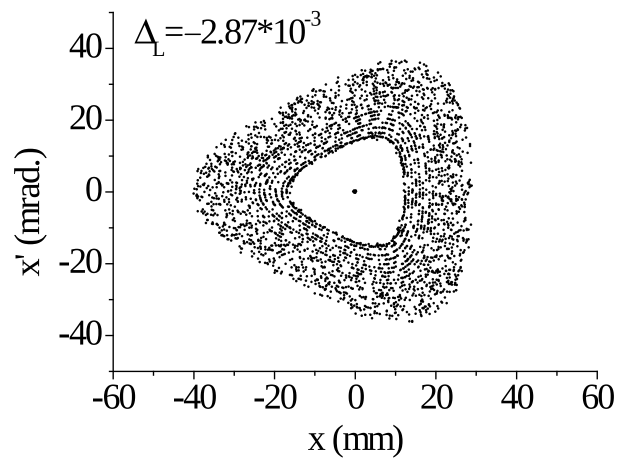
Trapping





Growth





Conclusion

- Lots of scaling FFAGs are in the process of being designed, built, and commissioned for many applications
- New ideas for better hardware to improve performance continue to be developed
- Interest in FFAGs is growing
- Much design work continues on non-scaling FFAGs
  - Extensive tracking studies
  - Finding problems, but have an understanding of them, and hope to solve them
- Work being done on the important issue of resonance crossing
- Thanks to Mori-san for organizing a great workshop!