HIGH INTENSITY AND OTHER WORLD WIDE DEVELOPMENTS IN FFAG ACCELERATORS

S. L. Sheehy,
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With thanks to many members of the FFAG community and especially the KURRI-FFAG collaboration including members from Japan, UK & US

OUTLINE

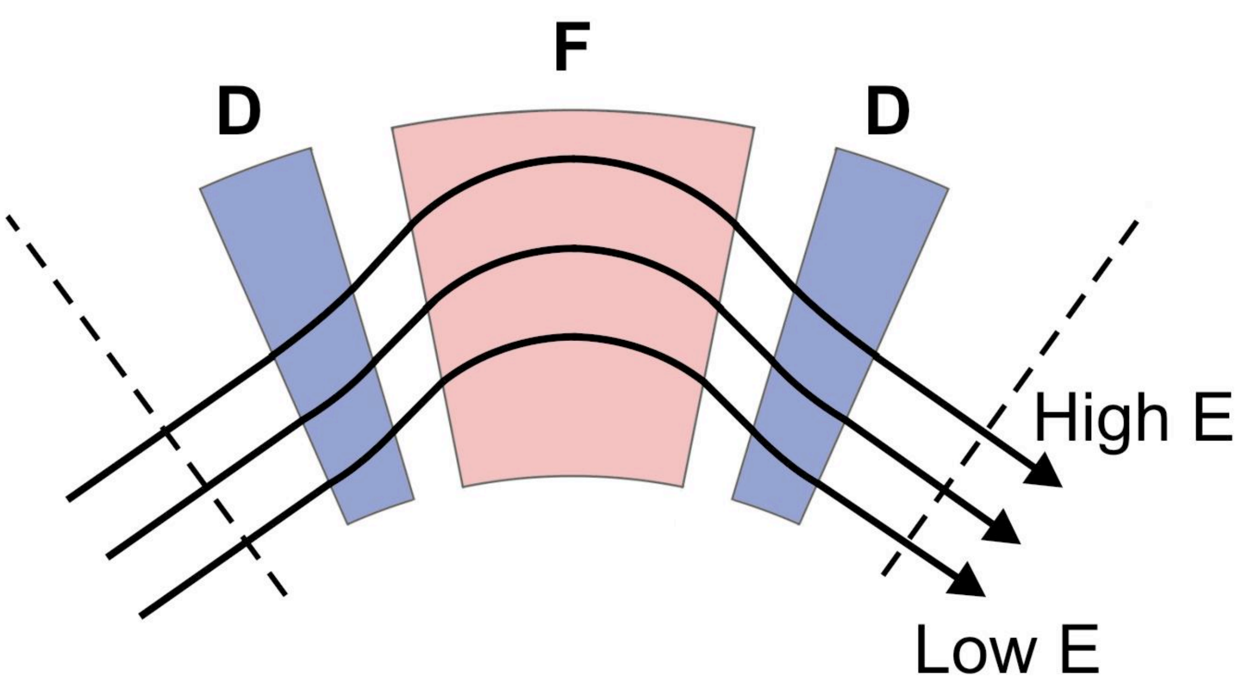
1. Intro to FFAGs
2. High power FFAGs:
    A. Experimental studies toward high power
    B. Simulation codes & studies
    C. New design studies (ADS, muons, etc…)
3. Other applications and innovations

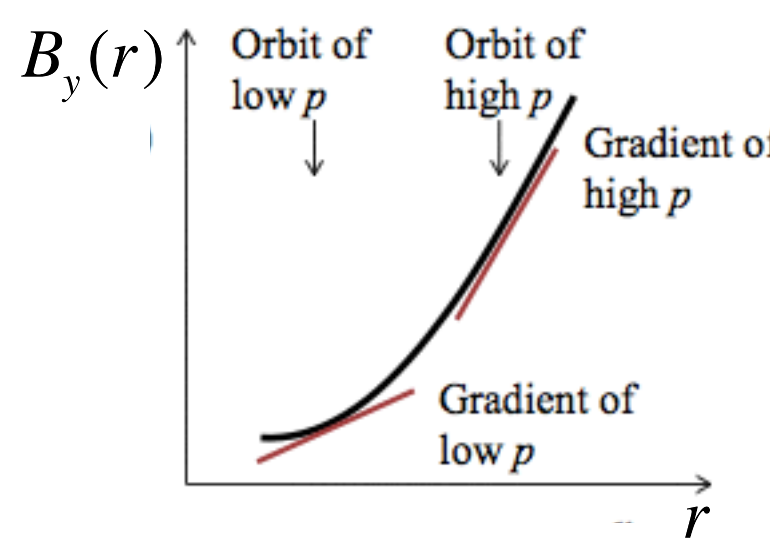
What is an FFAG?

- Fixed Field Alternating Gradient accelerator

- Field doesn't vary with time
- Orbit spirals outward with acceleration

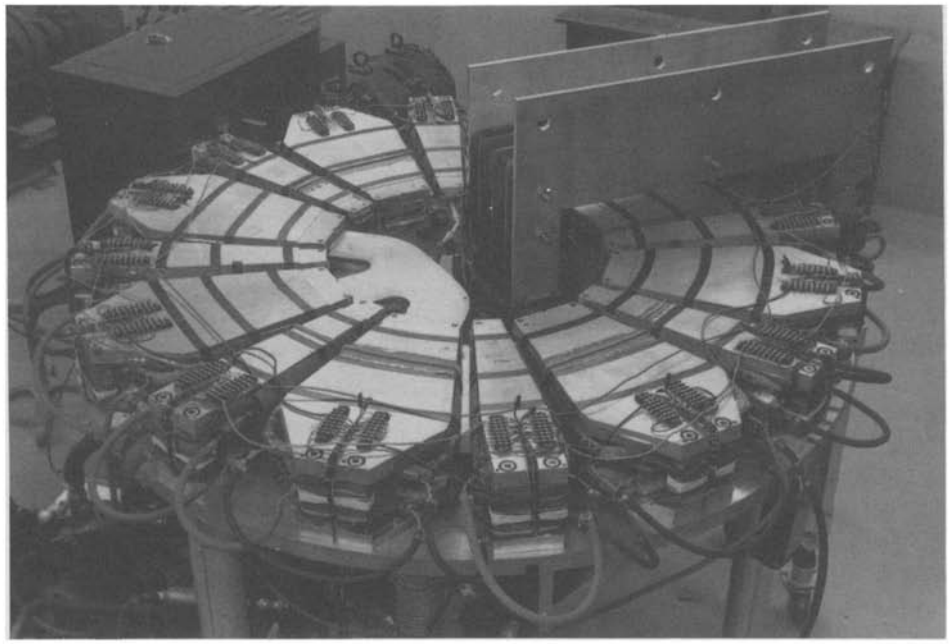
- Strong focusing
- 'Scalloped' orbits

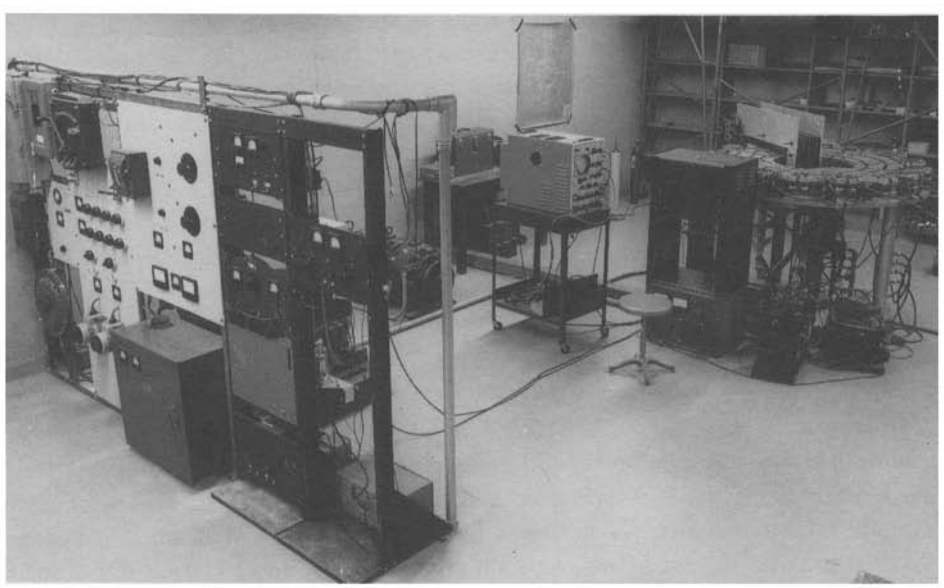


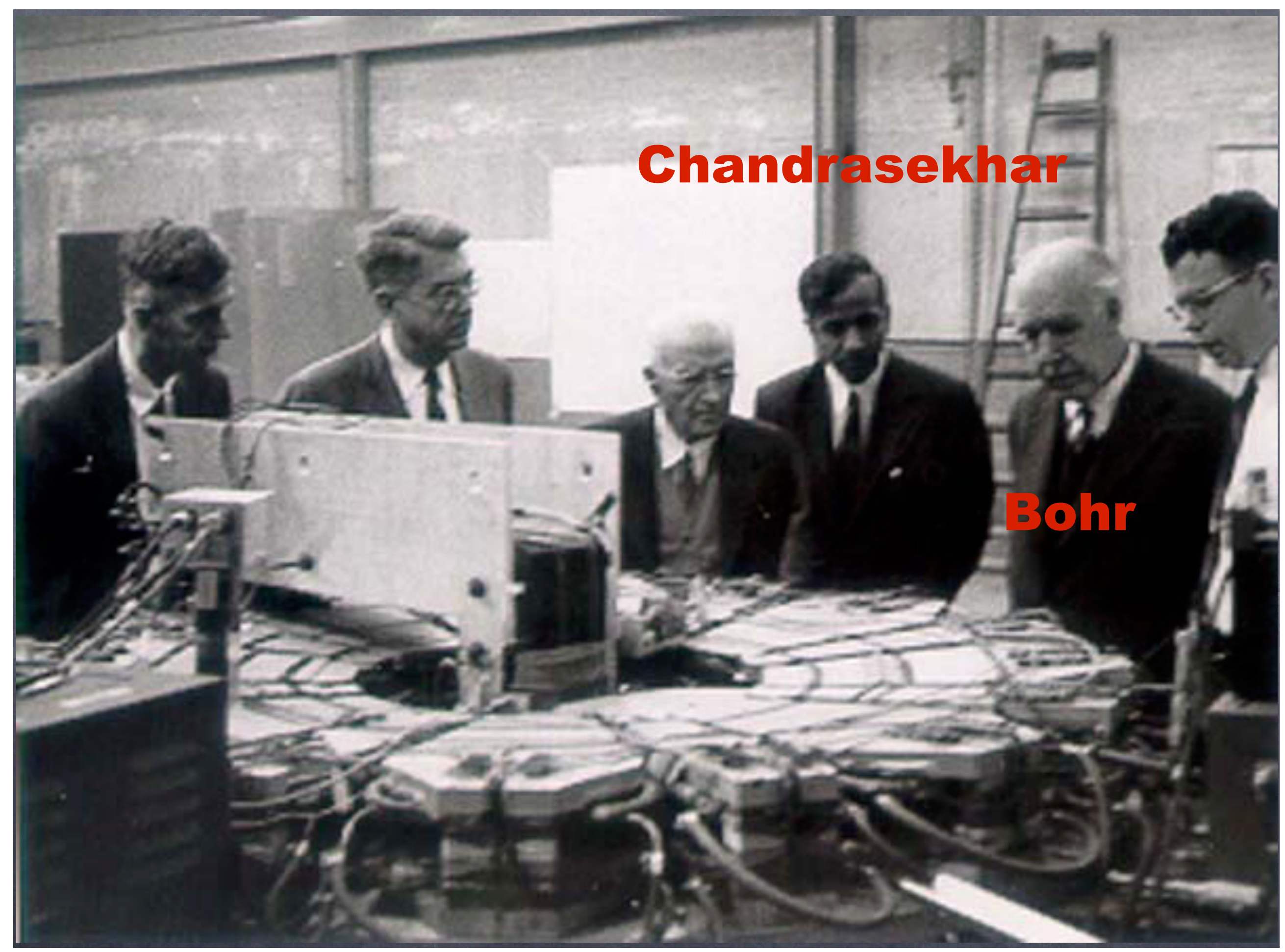


The FFAG is not so new…

1956







Since 1990's FFAGs have re-emerged

Proof of Principle machine finished in 1999 at KEK, demonstrated 1kHz rep. rate

e.g. at KURRI:

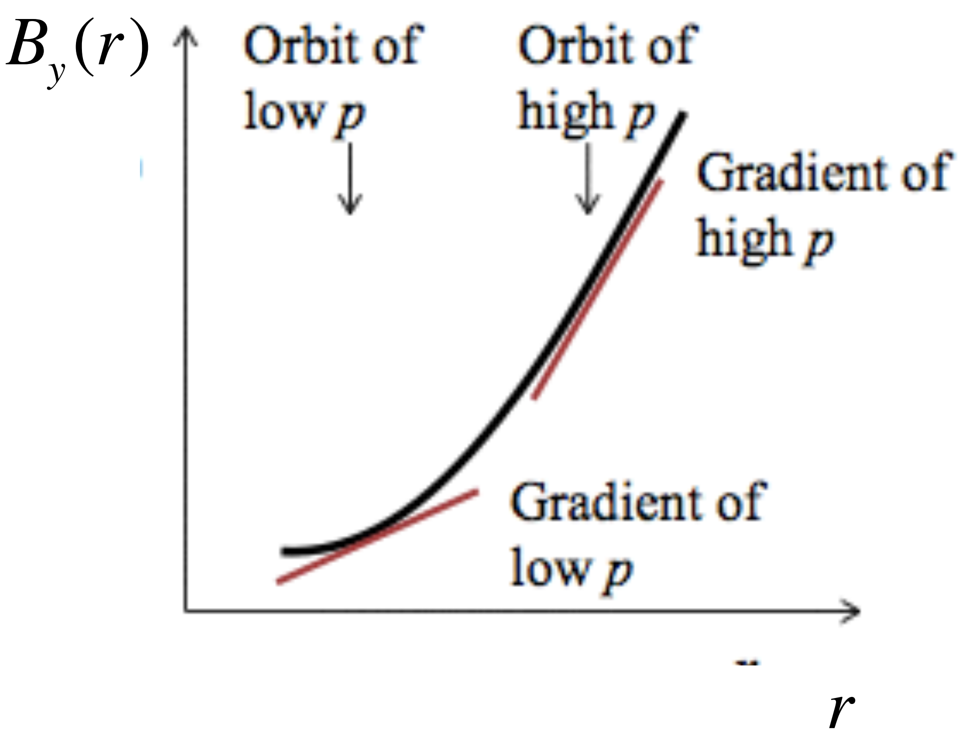
3-stage FFAG for ADSR studies
2.5 MeV spiral (ion beta) with induction cores
25 MeV radial (booster) FFAG with RF
150 MeV radial (main) FFAG with RF

+other machines too…

Types of FFAG

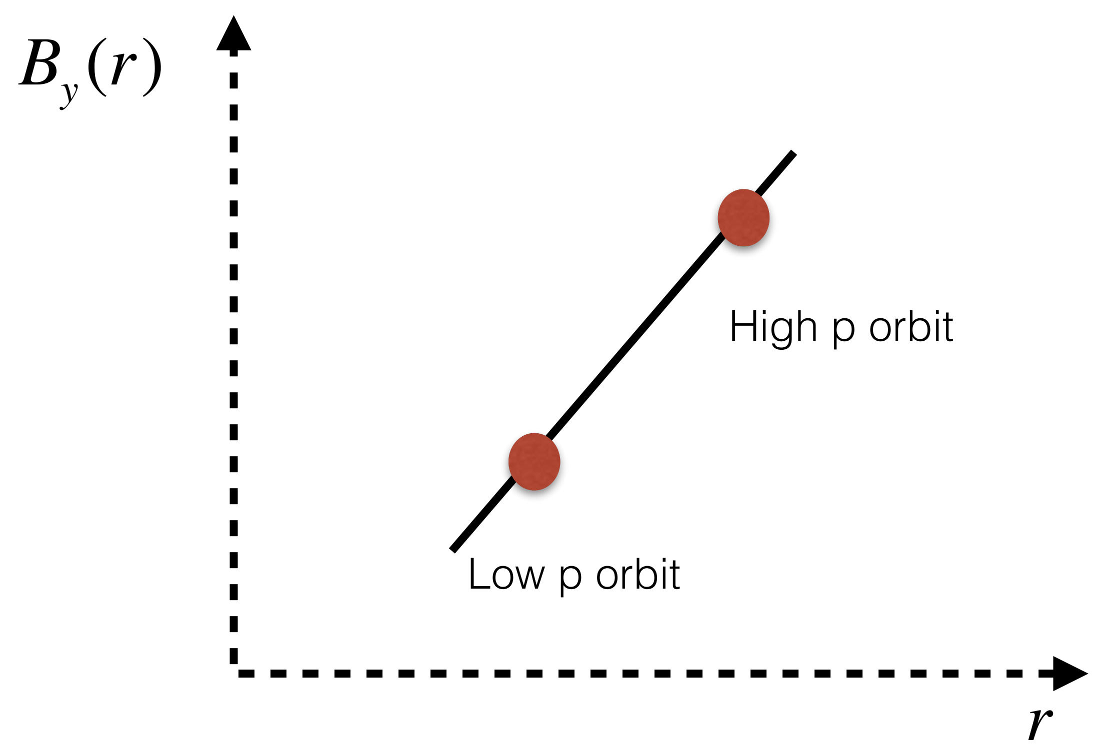
Scaling FFAG

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



Non-scaling FFAG (linear)

$$B_y = B_1 r + B_0$$



Circular Accelerators

	Cyclotron	Synchrotron	Non-scaling FFAG	Scaling FFAG
Revolution time	Constant	Variable (except relativistic)	Variable (small)	Variable
Orbit radius	Variable	Constant	Variable (small)	Variable
Transverse focusing	Variable	Constant	Variable	Constant

Types of FFAG

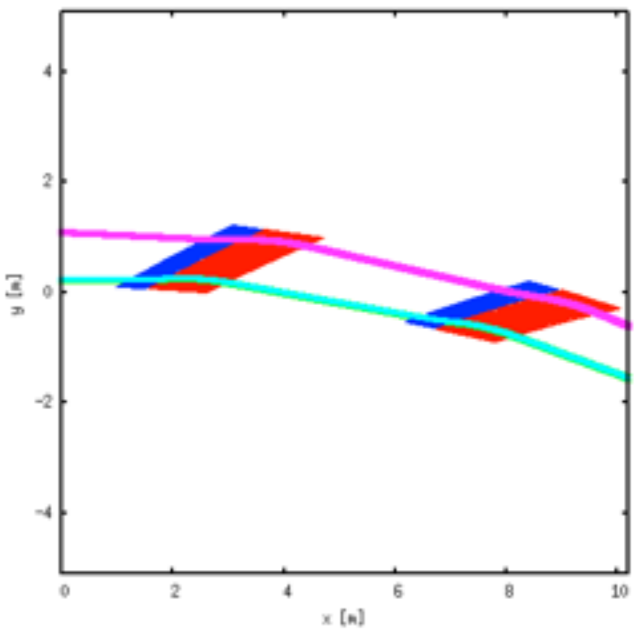
"There are other variations of these designs which preserve betatron oscillation stability, hold ν_x and ν_y constant, but do not retain the property of similar of equilibrium orbits."

"The magnet edges of focusing and defocusing sectors can be made non-radial, and the fields in positive- and negative- field magnets made different functions of radius"

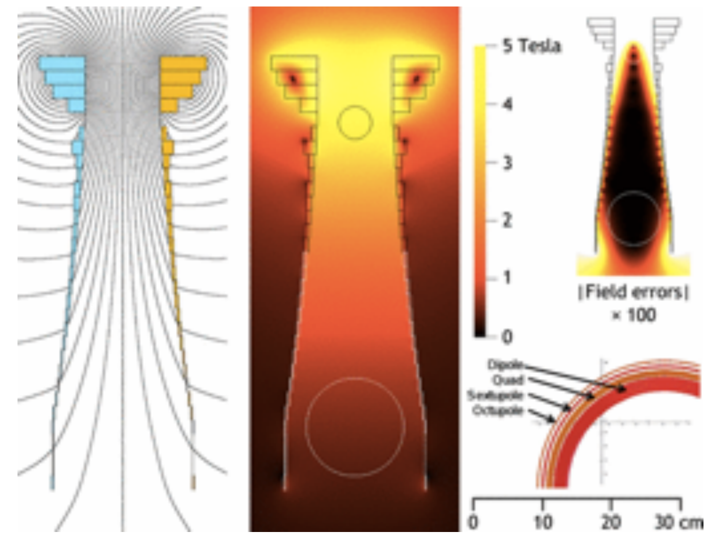
- K. Symon, D. Kerst, L. Jones, L. Laslett, and K. Terwilliger, "Fixed-Field Alternating-Gradient Particle Accelerators," Phys. Rev., vol. 103, no. 6, pp. 1837–1859, Sep. 1956.

A whole spectrum of designs have emerged in the last10 years

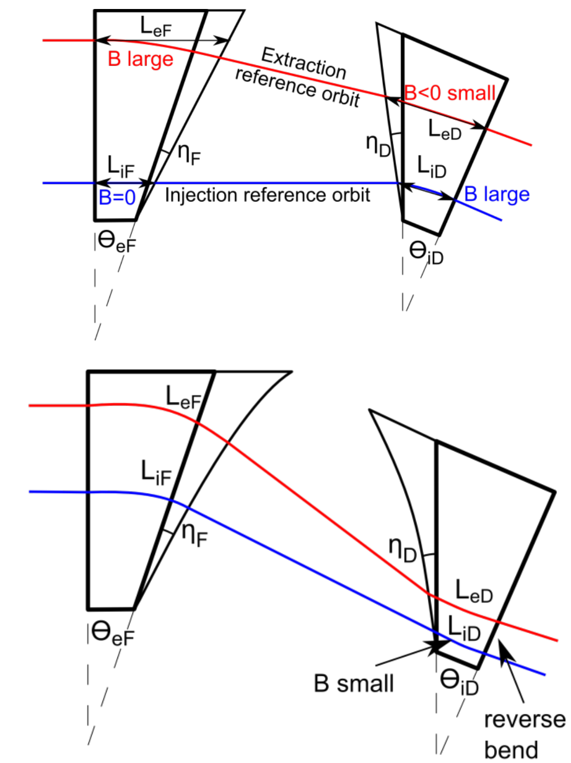
A whole spectrum of designs have emerged in the last 10 years



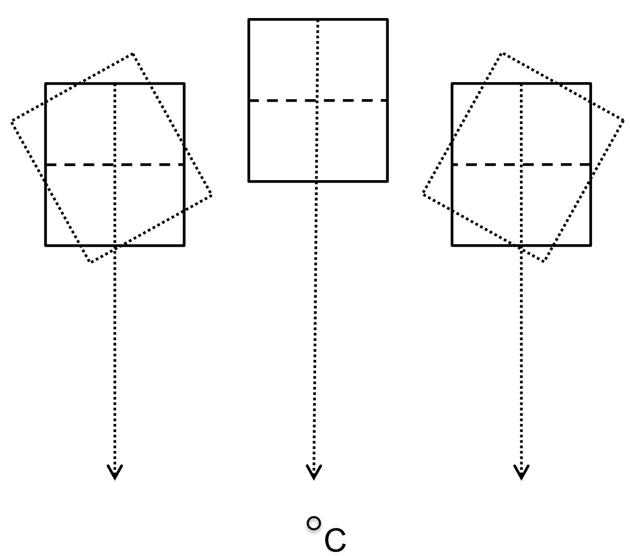
DF Spiral FFAG
- S. Machida



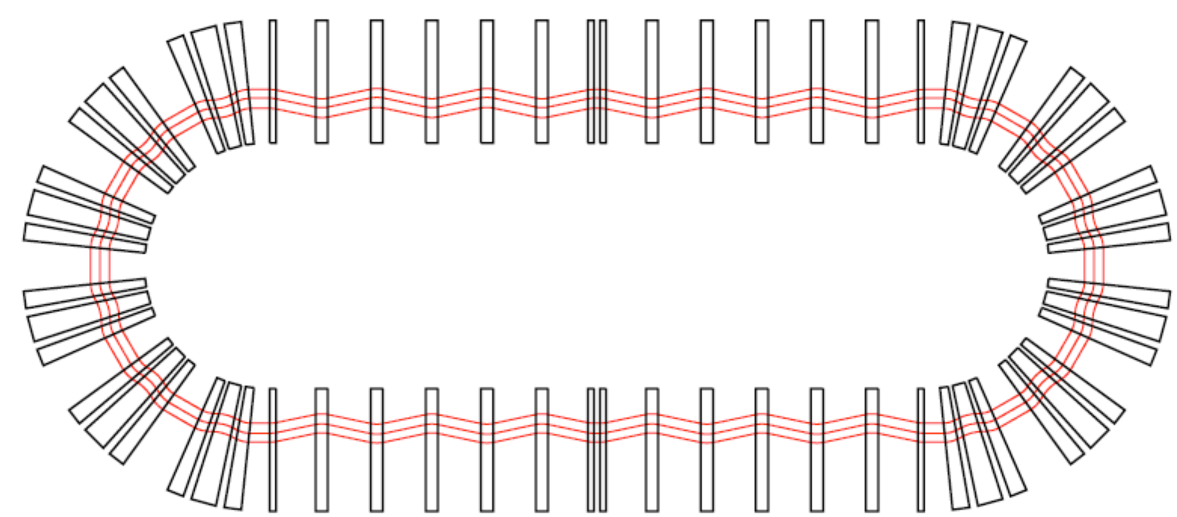
Vertical FFAG
- S. Brooks



Radial designs with edge profiles
C. Johnstone



Non-linear & Non-scaling
(S. Machida, S. Sheehy)



Insertions & racetracks
- J. B. Lagrange

FFAGs are promising for high power beams

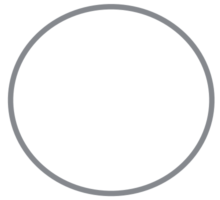
- Not limited in energy range
- Fixed B field -> rep. rate limited only by RF
- Higher rep rate = higher average current
- If we can make them CW… ultimate flexibillity

DC or 'microbunched' (due to RF) beam, $B_F \approx 1$

Average current = 10mA
Peak current = 10mA / (bunching factor)

A bunched beam in a pulsed accelerator (synchrotron/pulsed FFAG): $B_F << 1$

Average current = 10mA
Peak current = 10mA / (bunching factor)
Peak currents could be 20-30 Amps!!



synchrotron aperture

FFAG aperture

$$\Delta Q_v = -\frac{n_t r_p}{\pi \varepsilon_v (1 + \sqrt{\varepsilon_h / \varepsilon_v}) \beta^2 \gamma^3} \frac{1}{B_f}$$

larger horiz. emittance = lower tune shift

$\sqrt{\varepsilon_h / \varepsilon_v}$	25 Hz	50 Hz	100 Hz
1	1 MW	2	4
2	1.5	3	6
3	2	4	**8**

If we double injection energy, gain another factor of 3!

- from S. Machida, ASTeC/RAL

"Synchrotrons and FFAGs have some similar intrinsic features, but the repetition rate for FFAGs can be much higher (albeit without the capability for true CW operation). While promising, FFAGs have yet to demonstrate high beam-power capability."
– H. Ait Abderrahim, J. Galambos et al. (ADS White Paper, USA)

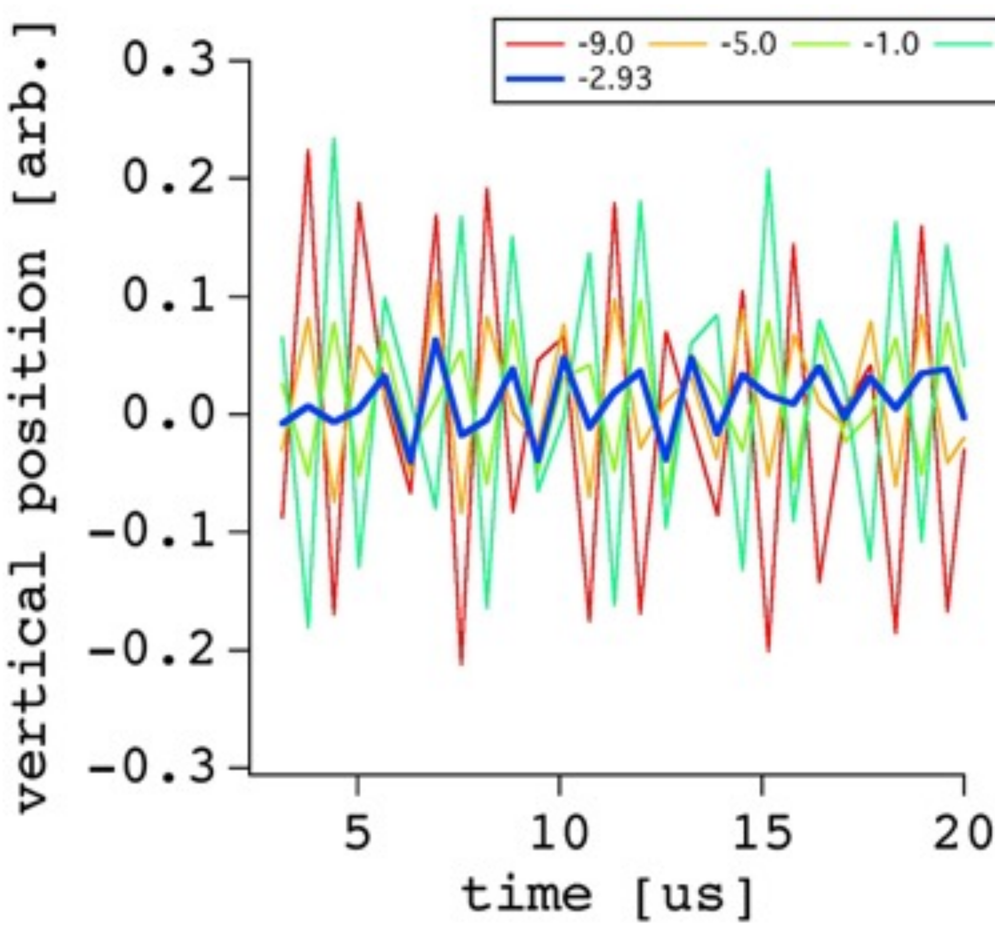
Experimental Studies towards High Power

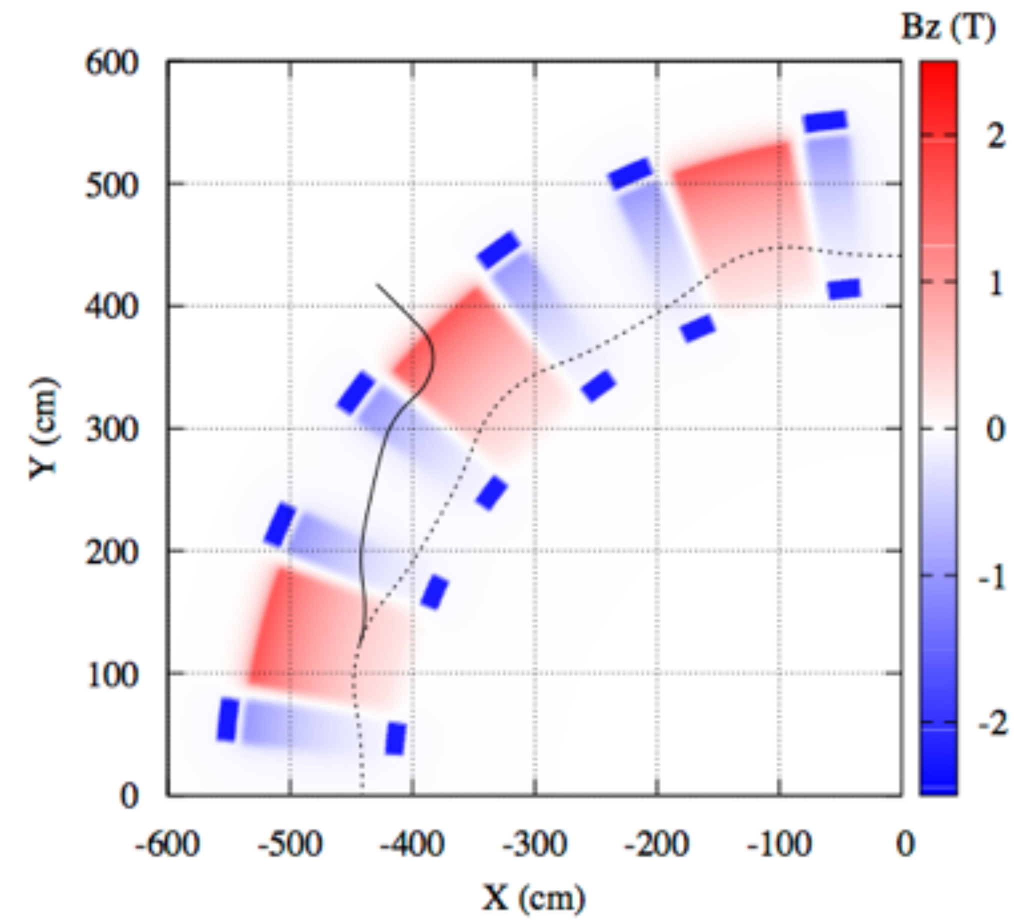
150 MeV KURRI Main Ring FFAG

Scaling FFAG
Injection 11 MeV,
H- charge exchange injection
up to 100 or 150 MeV

Parameter	Value	
R_0	4.54	m
Cell structure	DFD	
N_{cells}	12	
k, field index	7.6	
Injection Energy	11	MeV
Extraction Energy	100 or 150	MeV
f_{rf}	1.6-5.2	MHz
B_{max}	1.6	T

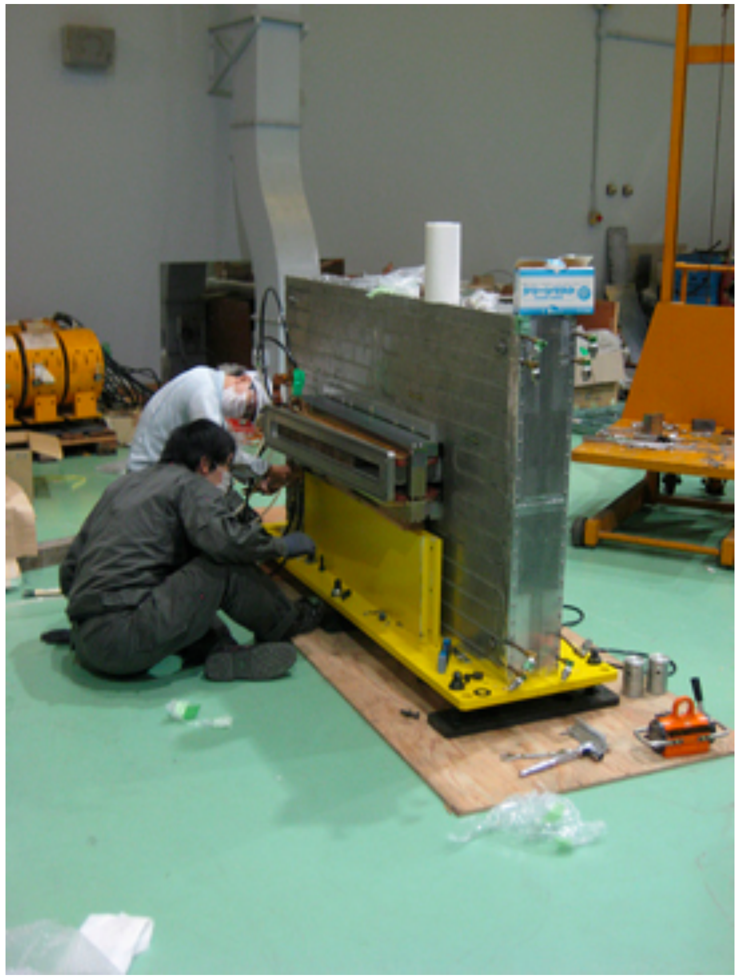
Characterisation of FFAG





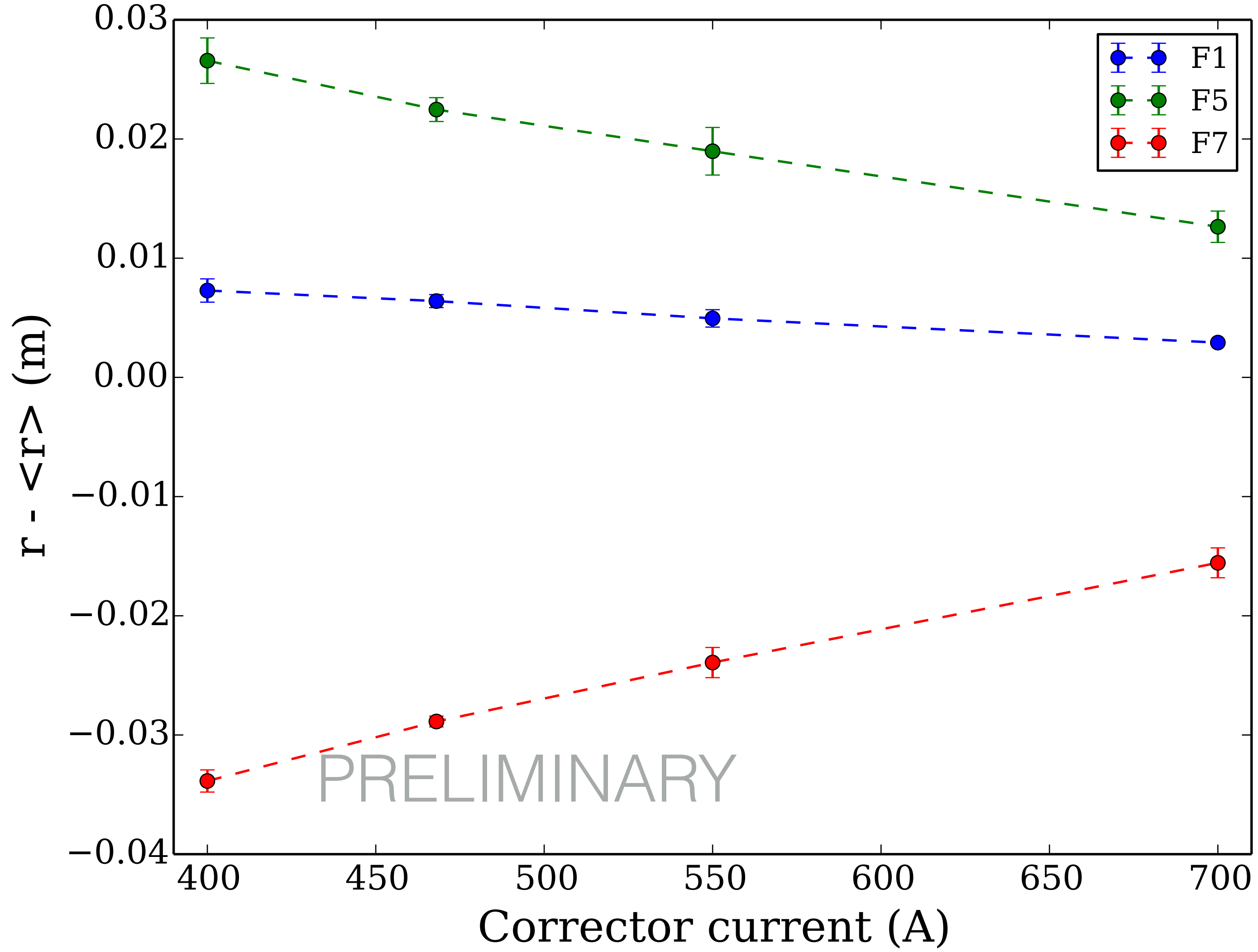
Horizontal & vertical orbit matching

Closed orbit distortion



RF cavity with 'magnetic alloy' material for tuning

Corrector poles later mounted on flanges.

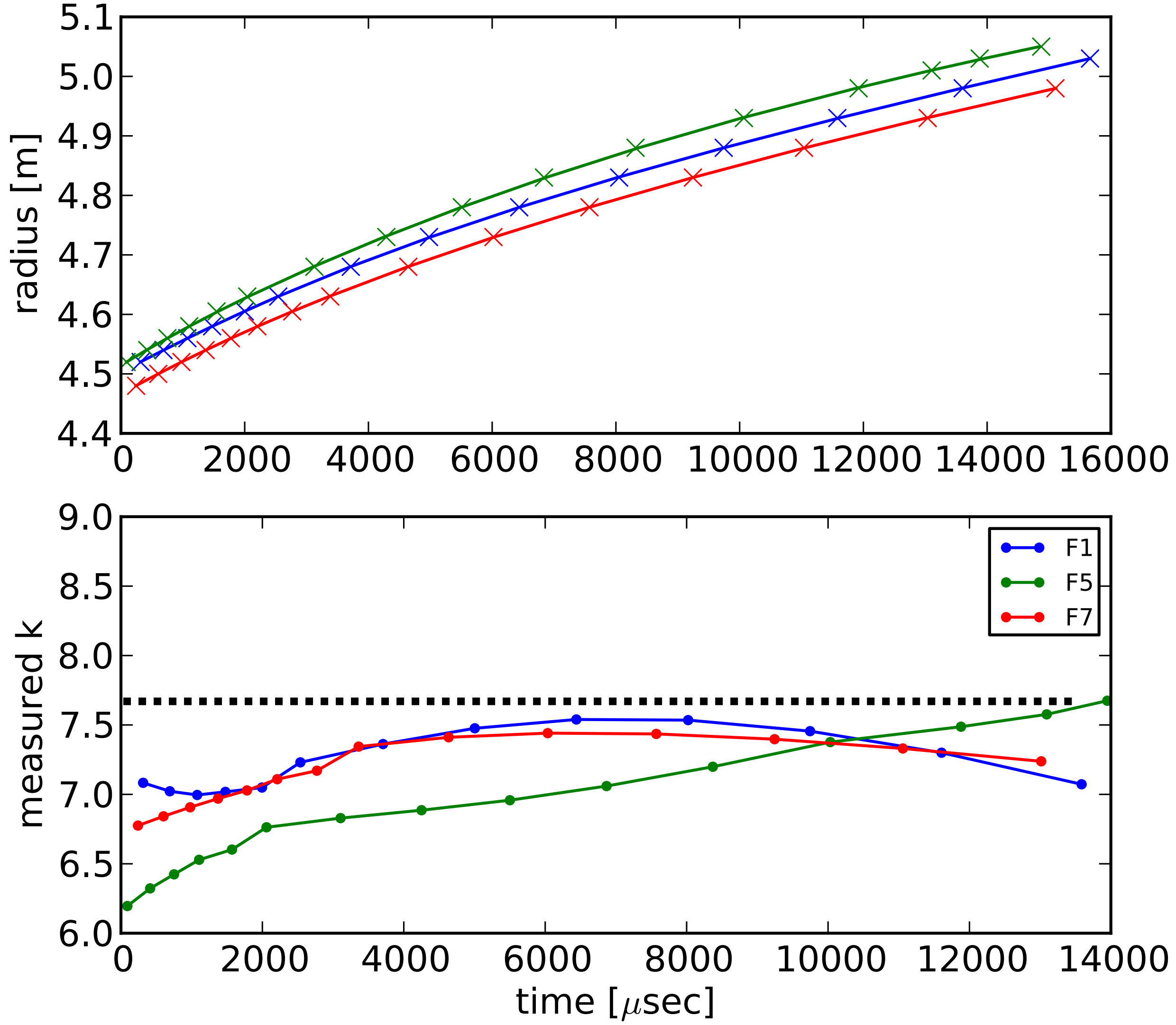


Measuring the orbit position as a function of corrector current

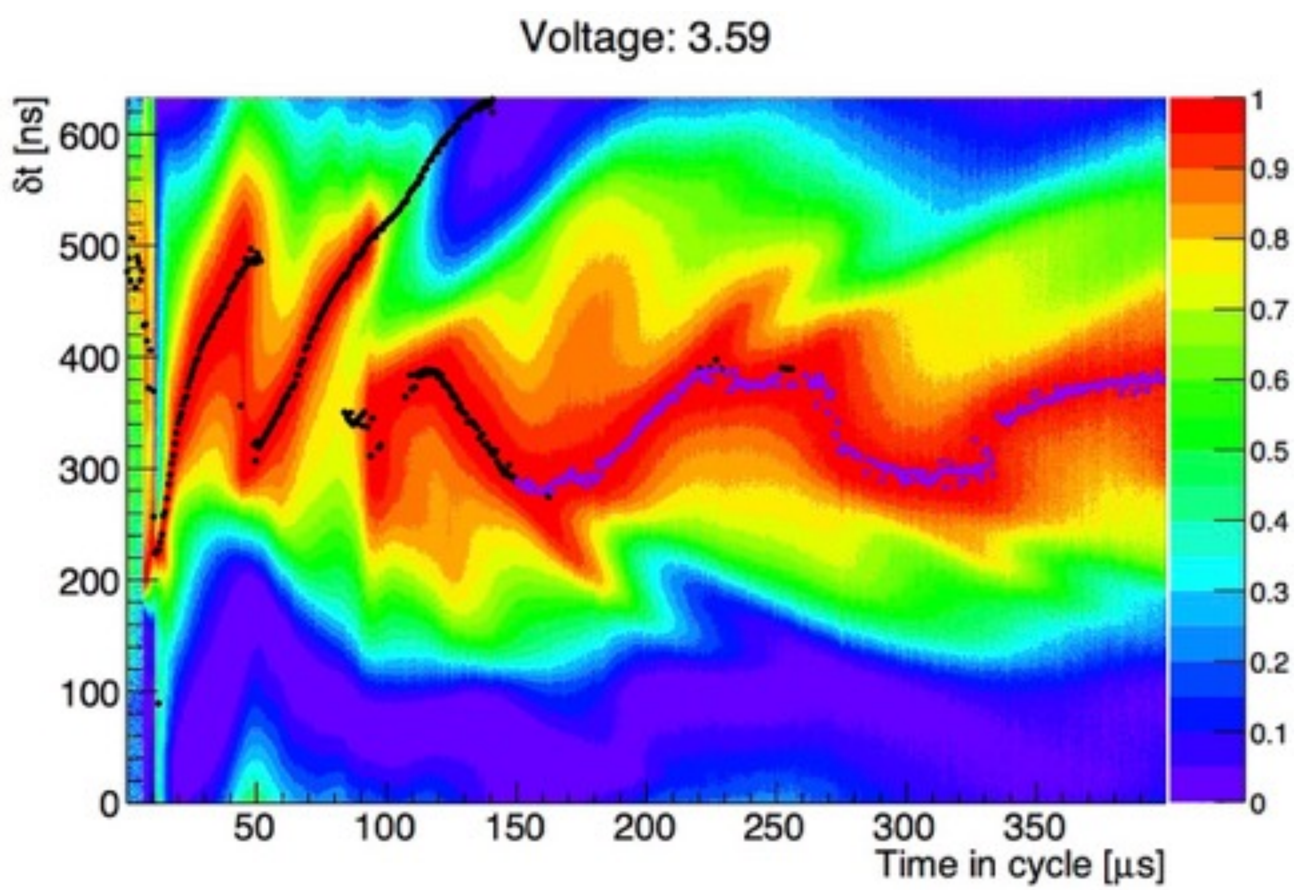
Field index measurement

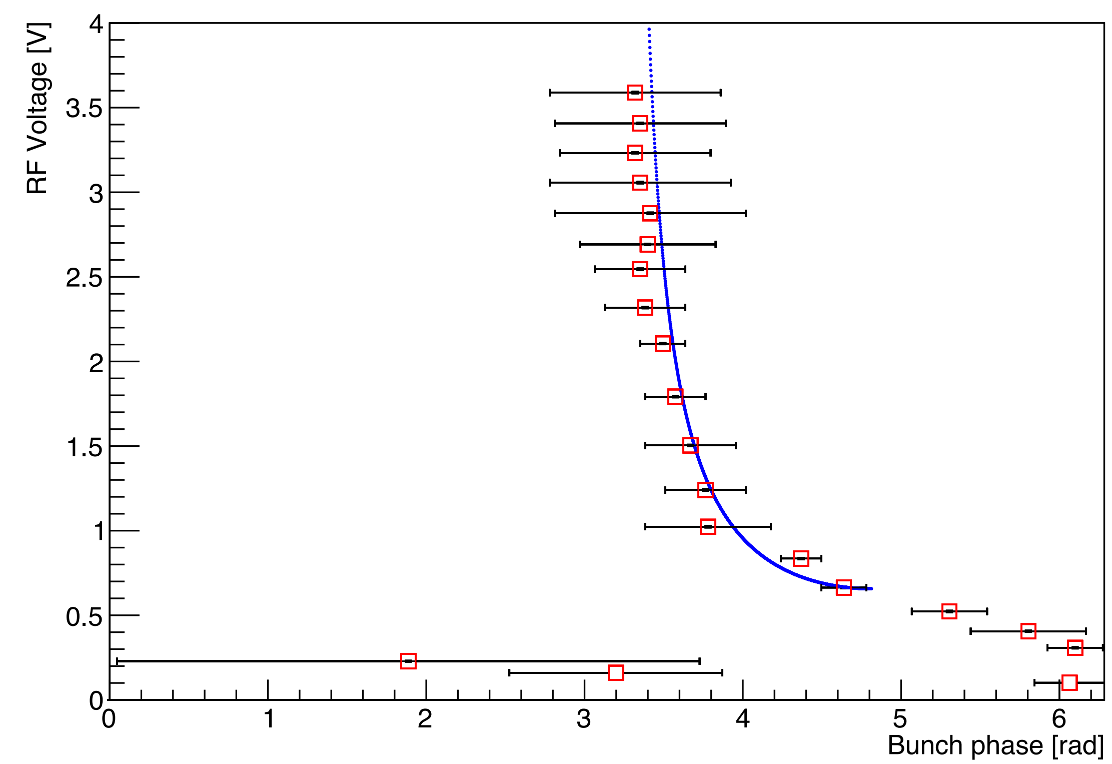
$$k = \gamma^2 \frac{df/f}{dr/r} - (1-\gamma^2)$$

df/f from RF programme
dr/r from measurement
(also assume gamma from RF)



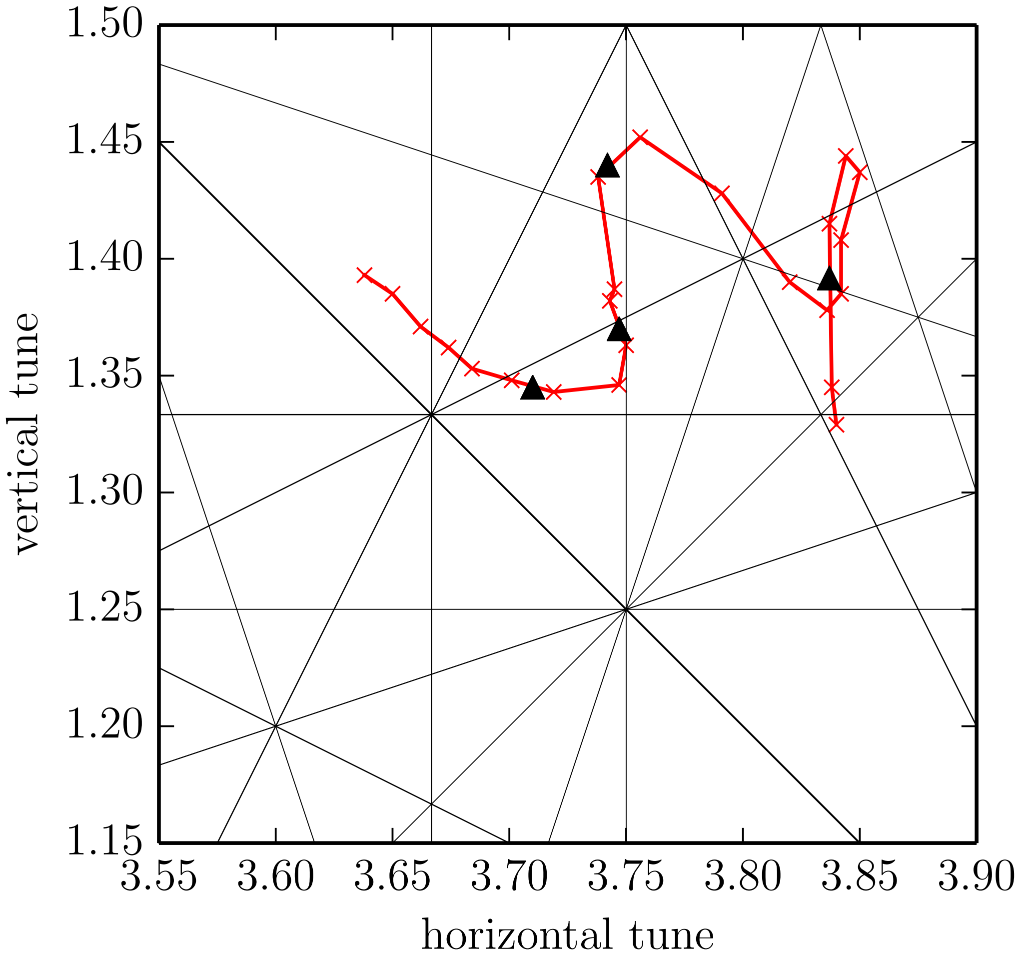
Beam-based foil energy loss & foil thickness measurement



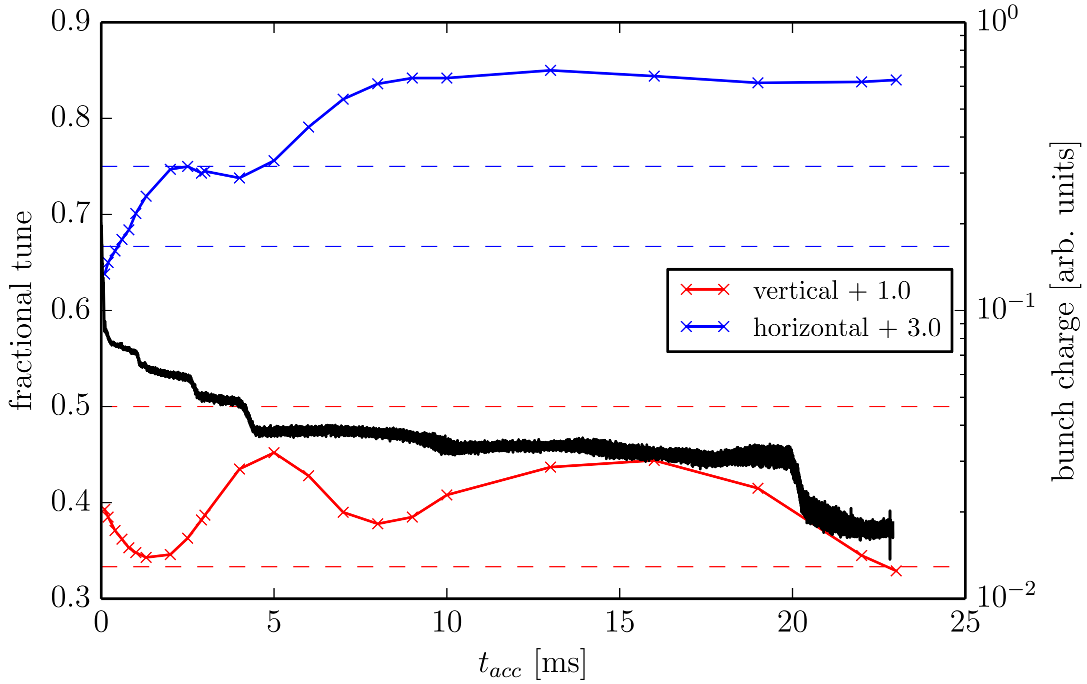


S. L. Sheehy, et al., Prog. Theor. Exp. Phys. 7, 073G01, July 2016.

Betatron tune measurement



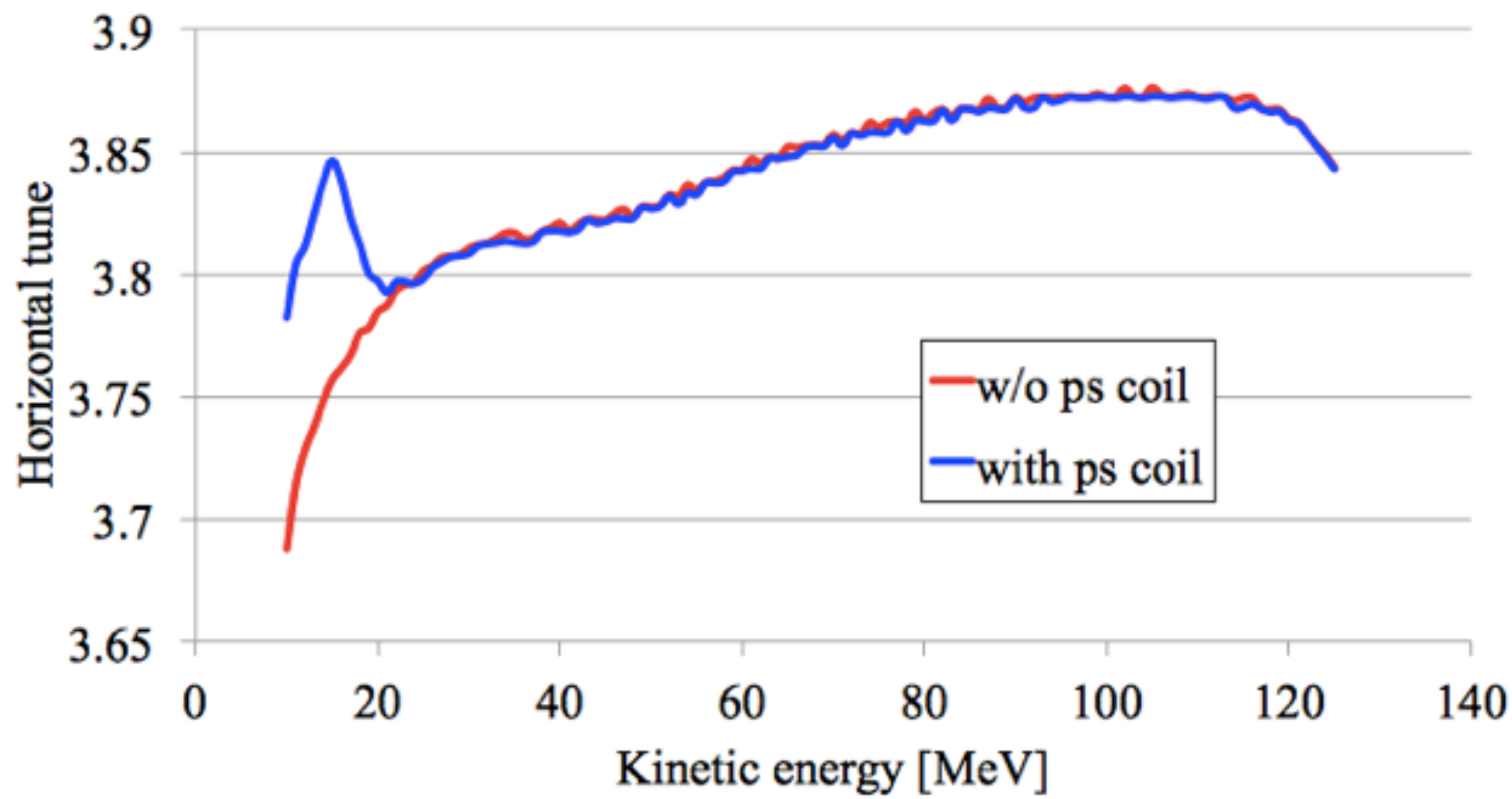
Beam loss



S. L. Sheehy, et al., Prog. Theor. Exp. Phys. 7, 073G01, July 2016.

How to optimise tunes?

- 3D field map calculation
- Previously: 'patch' pieces added to magnet poles

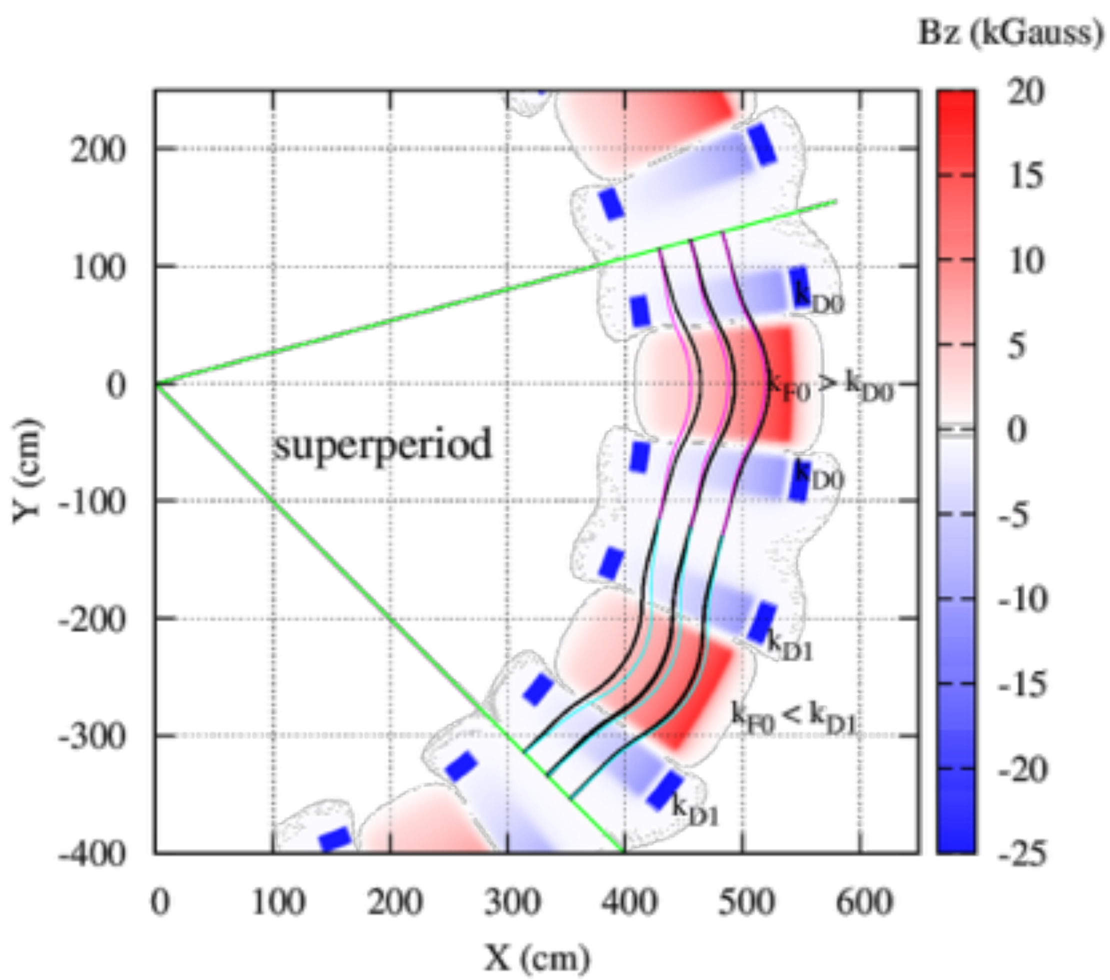


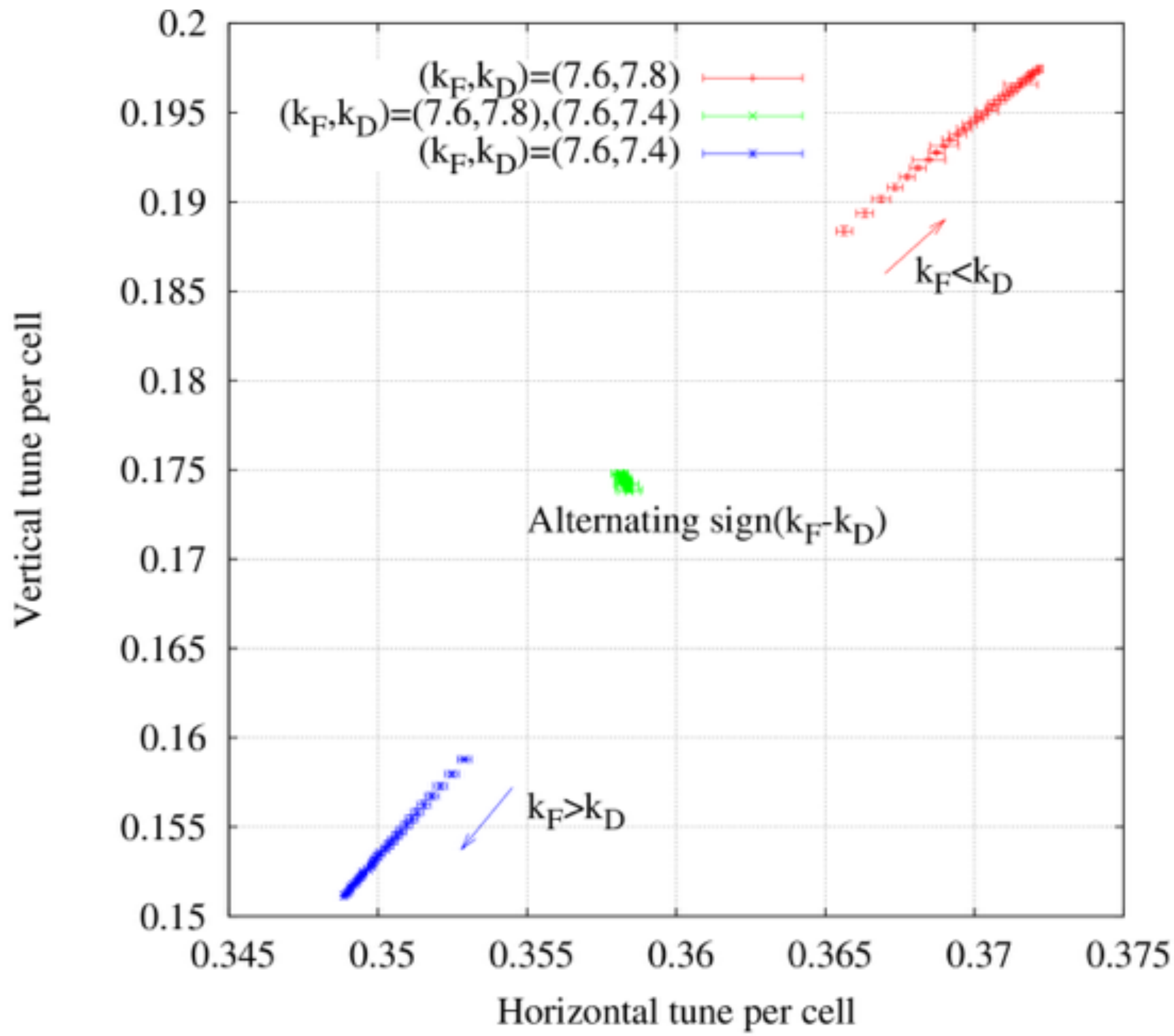
$\Delta\nu_H = 0.185 \Longrightarrow \Delta\nu_H = 0.091$

- Kyushu University study of pole surface coils
- Achieved control over betatron tunes

Introduce superperiods

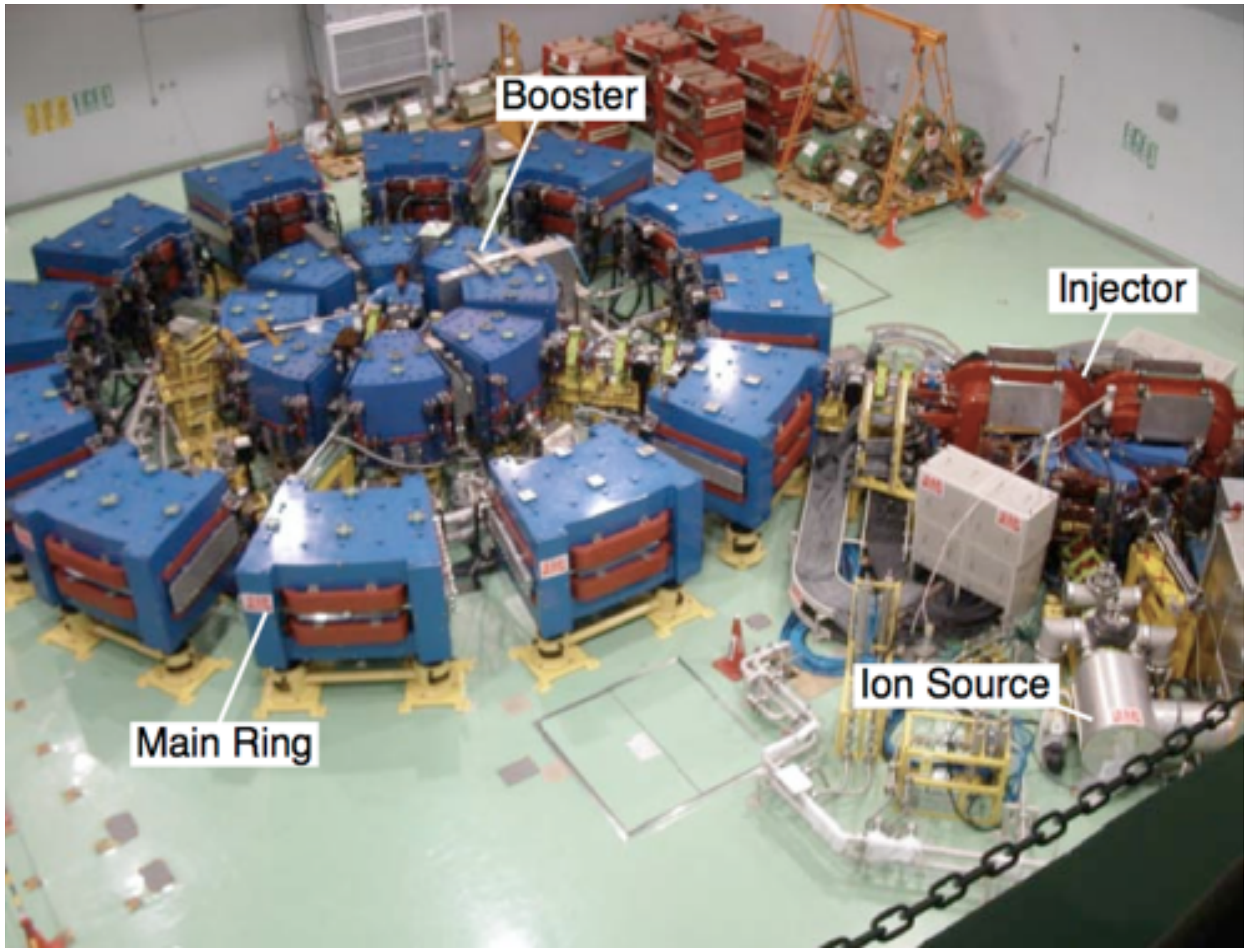
Alternating κ allows to alternate the phase advance so that the tune becomes constant.





M. Tahar, FFAG'16 workshop

Future Experimental Studies



Next studies:
Dynamic aperture scans
Longitudinal optimisation

- Operation toward space charge limit.
- Operation with asymmetric emittance.
- Stacking at the end and re-shaping time structure.
- Tunability study with additional trim coils.

Simulation - Progress

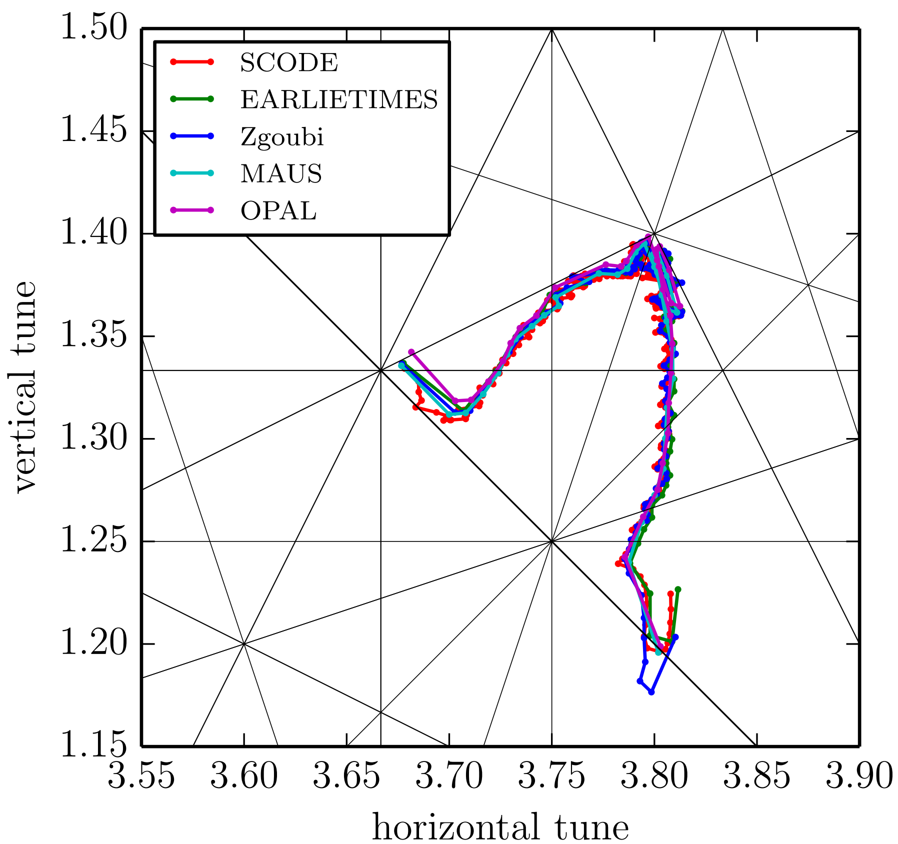
- OPAL (PSI code) has been updated to have variable rf frequency & geometry modules that will help with FFAG work (C. Rogers)
- With KURRI-FFAG collaboration experiments, there is a good opportunity to benchmark against real machine

Github for results/progress:

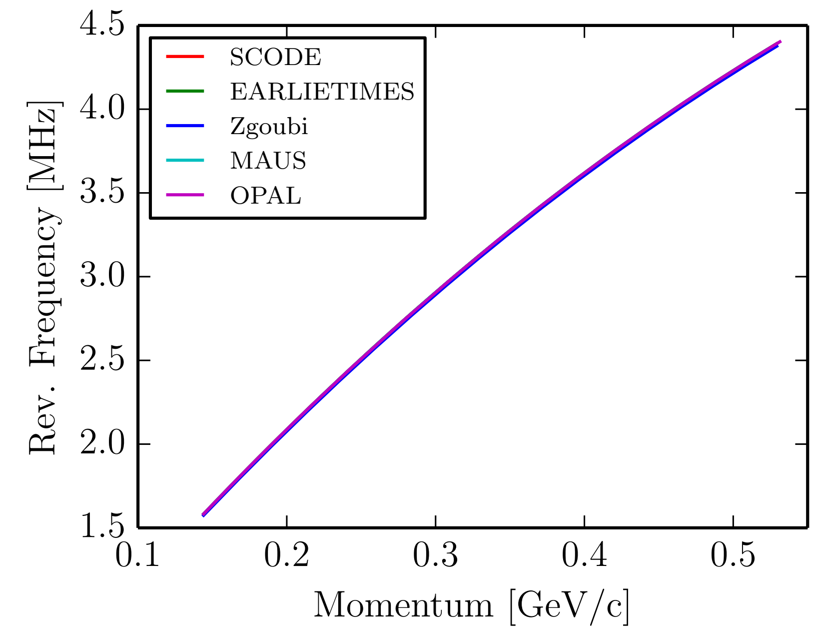
https://github.com/fixed-field-accelerator-simulation

Simulation - Code Benchmarking

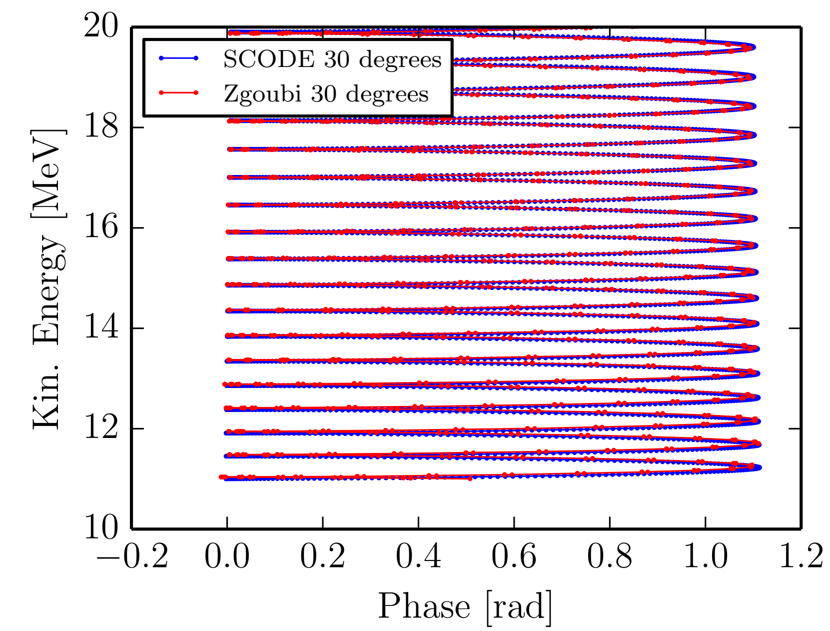
Low intensity benchmarking
(from IPAC'15)



betatron tunes



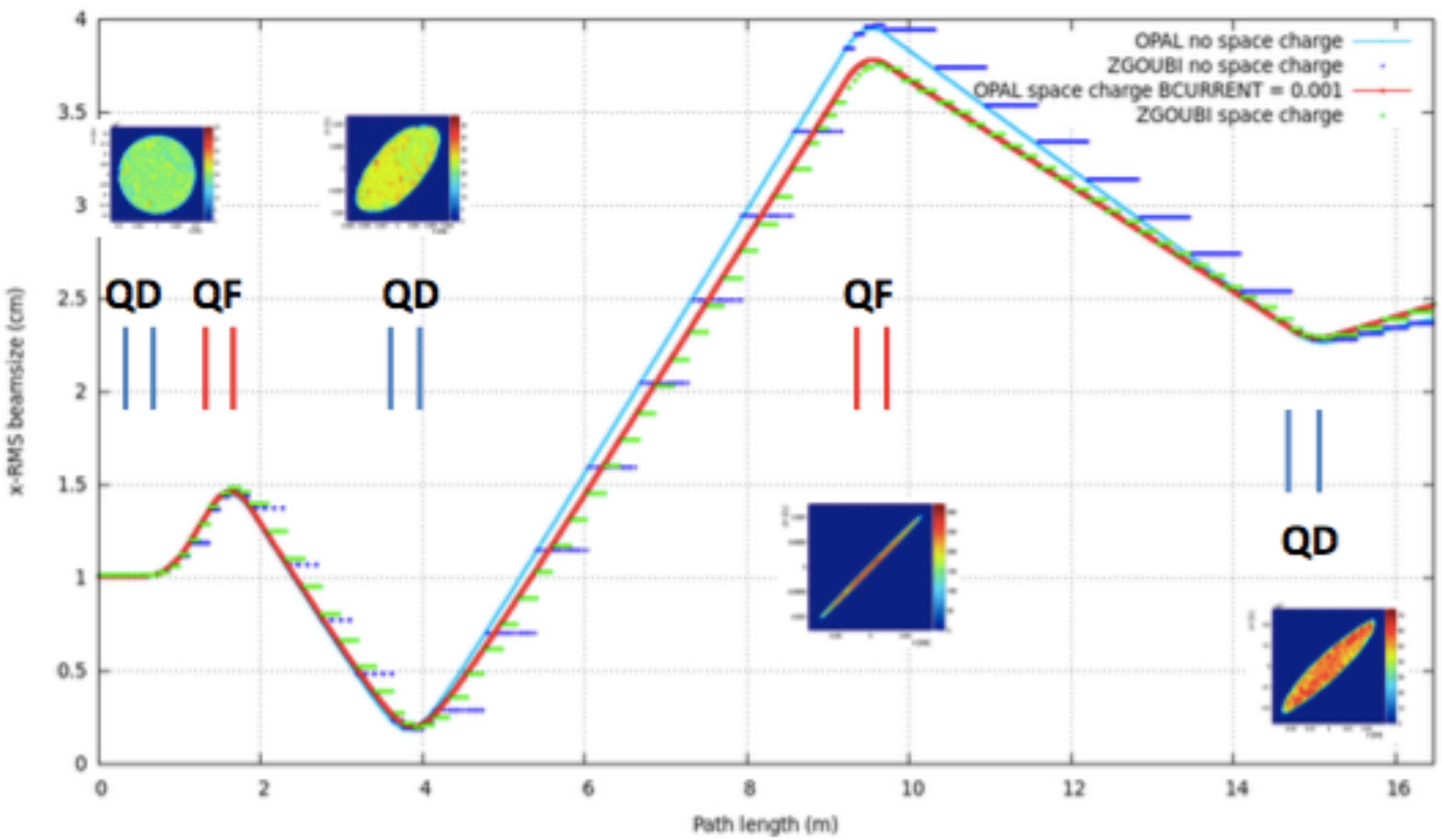
revolution frequency

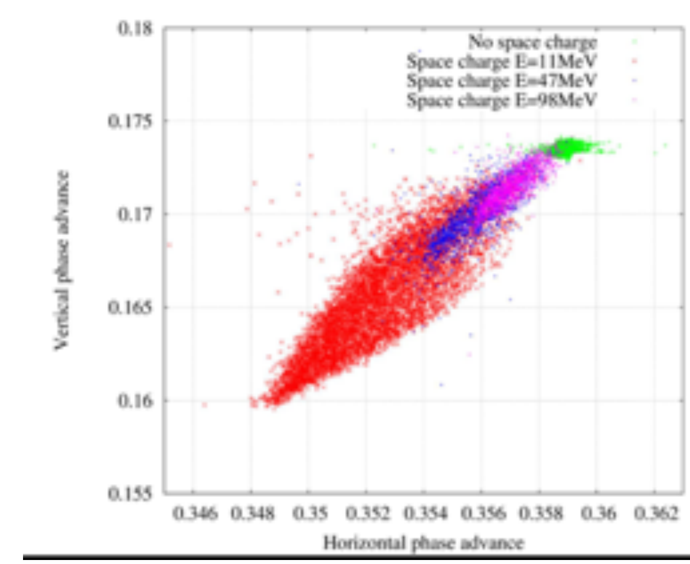


acceleration

S. Sheehy et al, MOPJE077 at IPAC'15, www.jacow.org

Space Charge in ZGOUBI





Space charge introduces a coupling between the longitudinal and transverse phase spaces: this translates into a change of the linear charge density in the model.

9

$$\Delta x'_{sc} = -\frac{q}{m\gamma_b^3\beta_b^2c^2}\frac{\partial\phi}{\partial x}\Delta s = \frac{2\pi\epsilon_0 Q_{perv}}{\lambda}\left(-\frac{\partial\phi}{\partial x}\right)\Delta s$$

$$\Delta y'_{sc} = -\frac{q}{m\gamma_b^3\beta_b^2c^2}\frac{\partial\phi}{\partial y}\Delta s = \frac{2\pi\epsilon_0 Q_{perv}}{\lambda}\left(-\frac{\partial\phi}{\partial y}\right)\Delta s$$

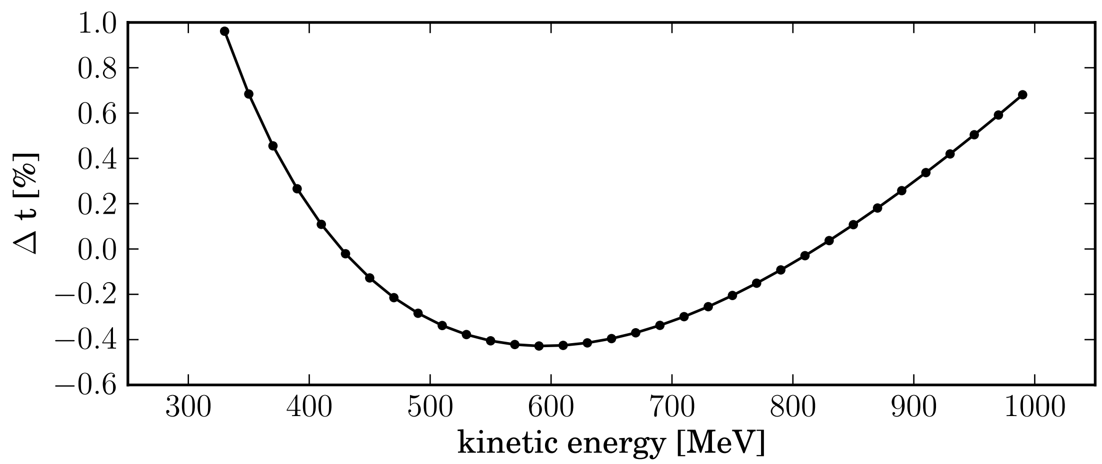
- M. Haj Tahar, F. Meot (BNL)

A few design studies:

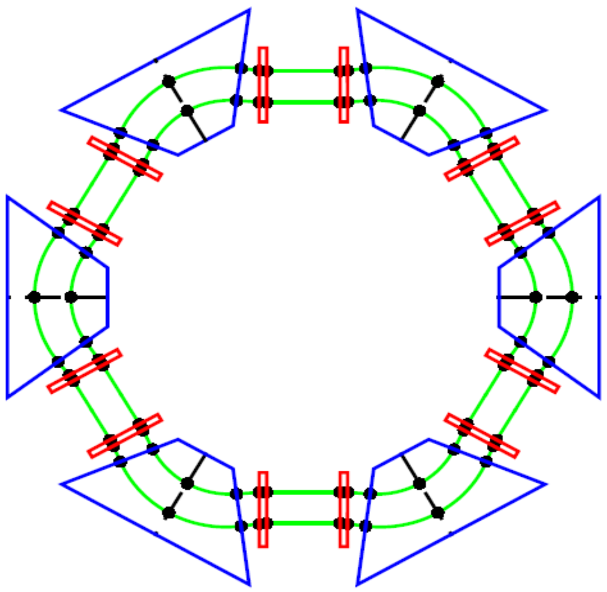
- ADS 1 GeV Design
- Muon transmutation FFAG
- Pulsed High Power FFAG

ADS: 1 GeV near-isochronous FFAG

- Initial designs only ±1% isochronous (C. Johnstone)
- Further optimisation required
- Racetrack configurations now possible
- Initial simulations with space charge promising, but need iteration (code is now ready)



Time of flight variation

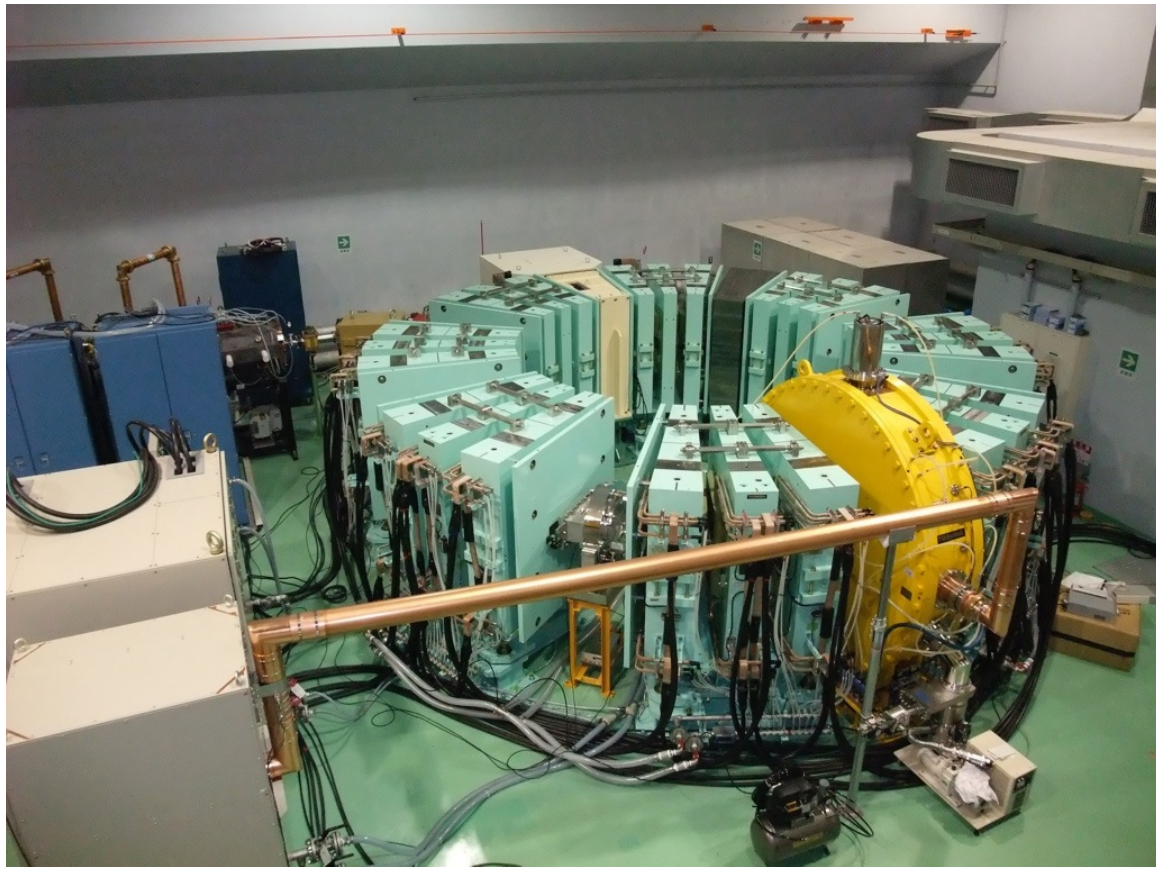


Initial 1 GeV design
2m straight sections

See S. L. Sheehy, AccApp13, Bruges.

Muon transmutation of LLFP

- Novel design - energy recovery with an internal target
- Could produce 10^{16} negative muons from a 2.5 mA proton beam
- Fixed frequency radio-frequency system for re-acceleration
- Muons are produced through interactions with an internal target.



Builds on the successful demonstration machine ERIT (Energy Recovery Internal Target) [21] at KURRI, Japan

Y.Mori : Nucl. Instr. Meth., PRS, A563(2006) 591-595.
Y.Mori : FFAG workshop (FFAG'16), Imperial College, London, 2016.

Flexible Operation Mode For Neutron Users

25 Hz pulse to 4 target stations.

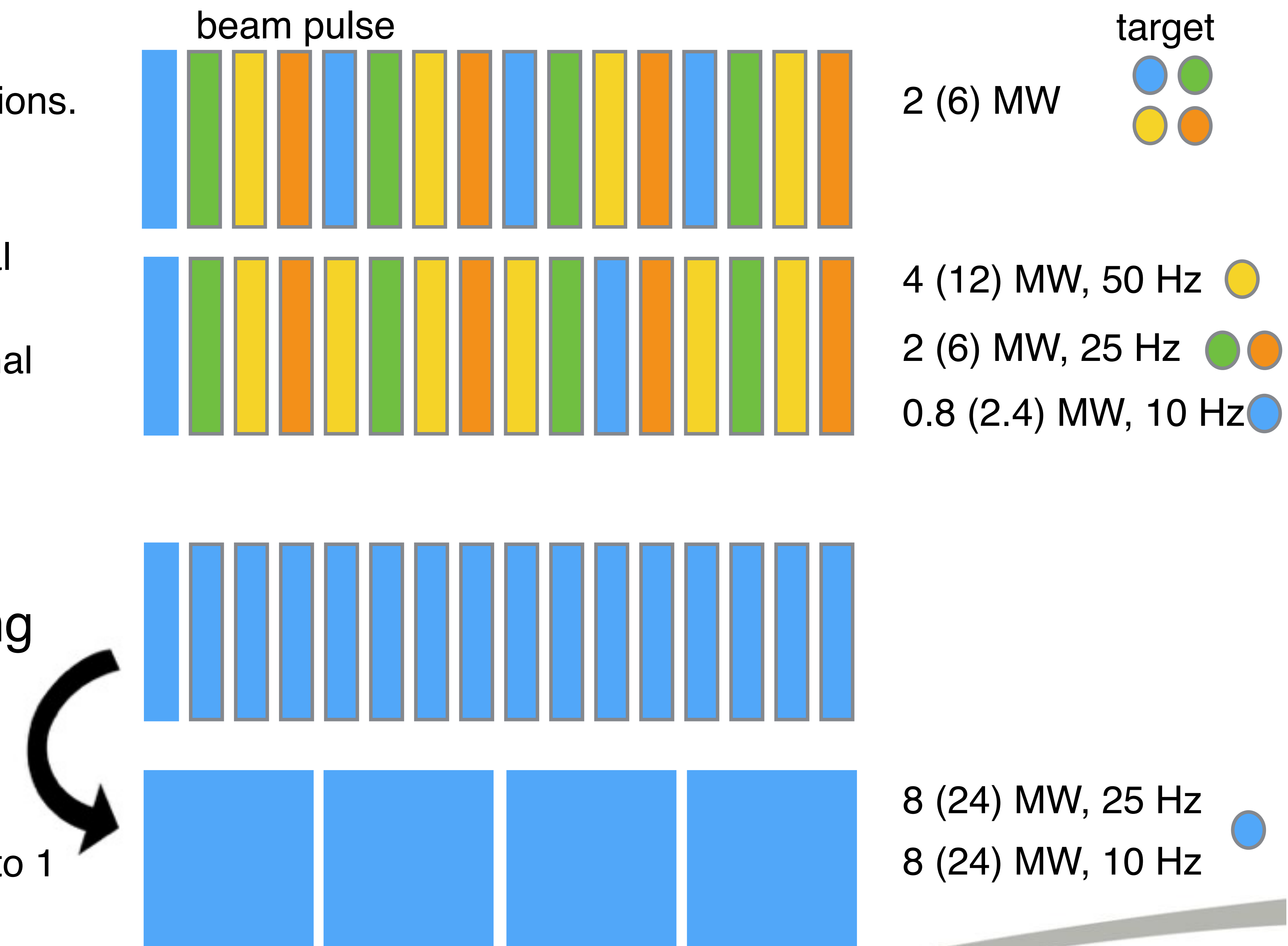
50 Hz pulse with occasional missing pulse

Two of 25 Hz with occasional missing pulse

10 Hz pulse

beam stacking inside FFAG

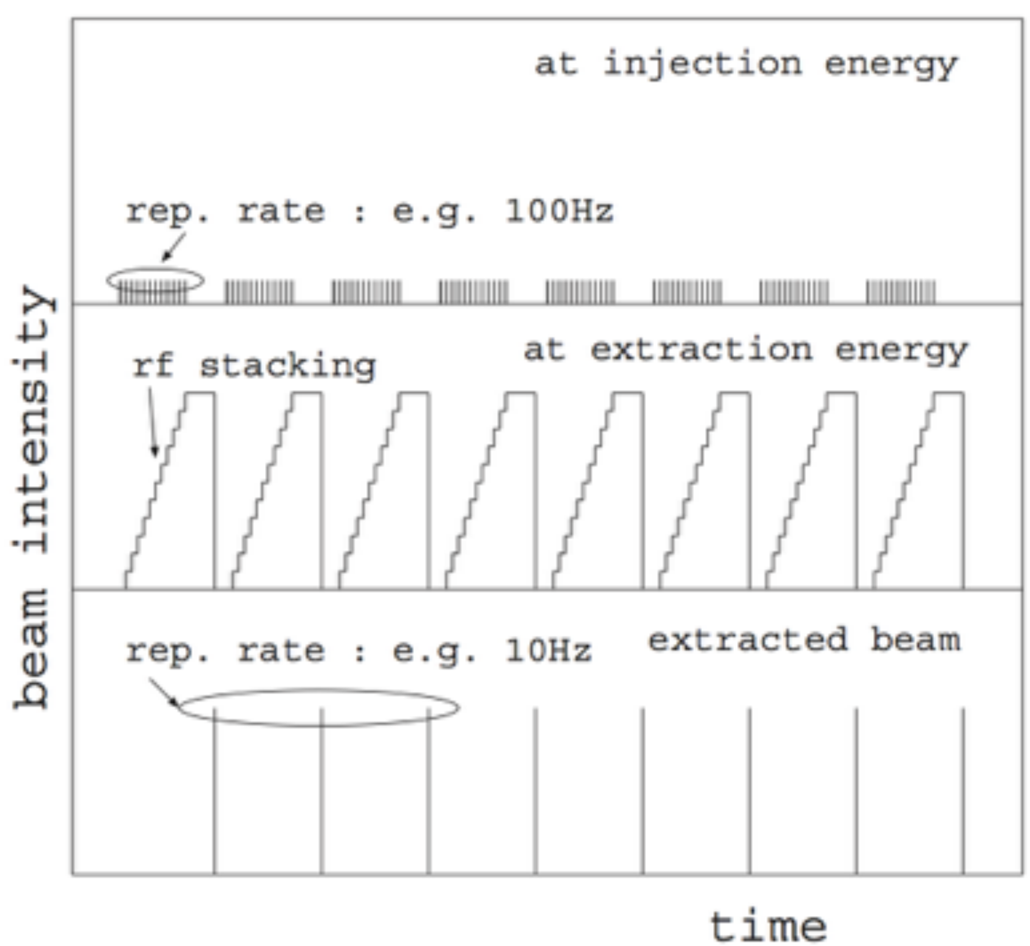
Single 25 (or 10) Hz pulse to 1 target station with 4 (or 10) times higher power.



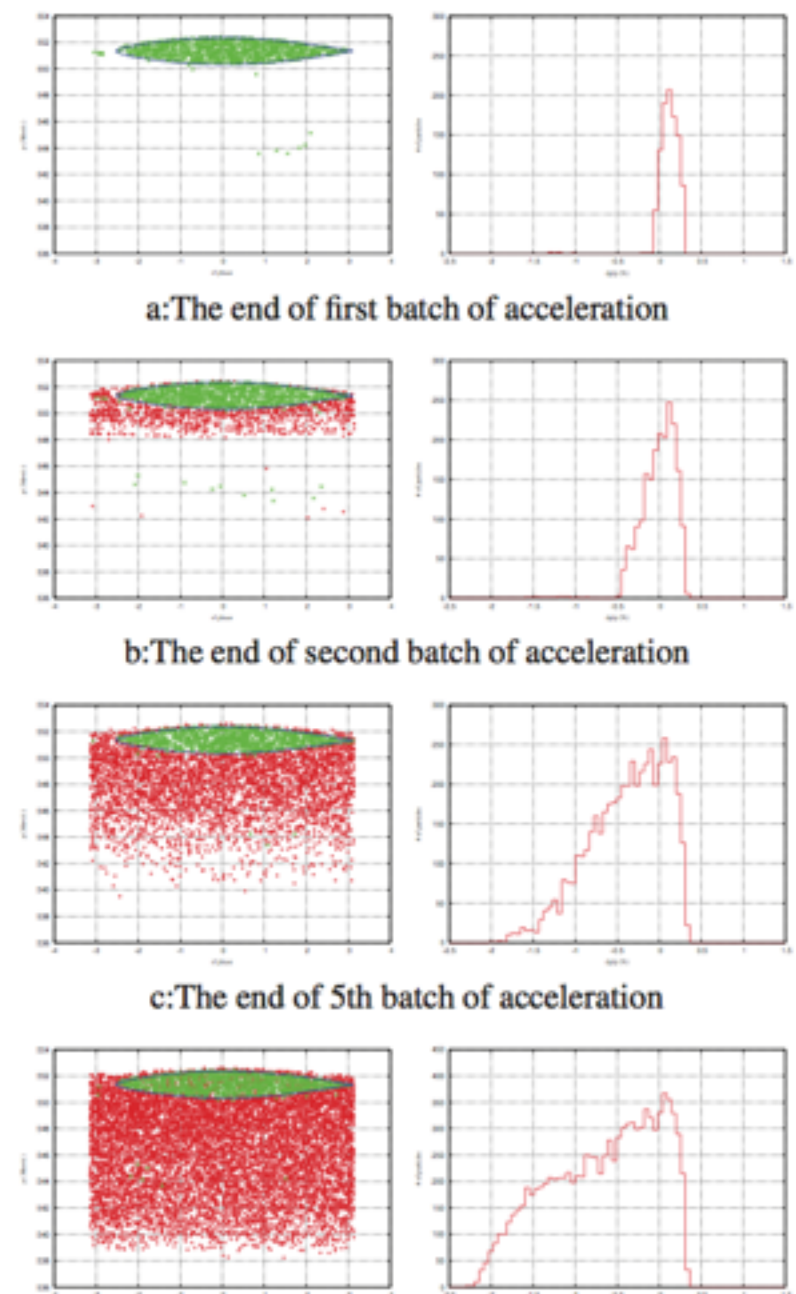
Beam Stacking at High Energy

Because of DC magnets, beams at top energy can stay in the ring while other beams are accelerated.

FFAG = synchrotron + storage ring
Momentum spread becomes larger.



Ishi, *et al*
HB2012



a:The end of first batch of acceleration

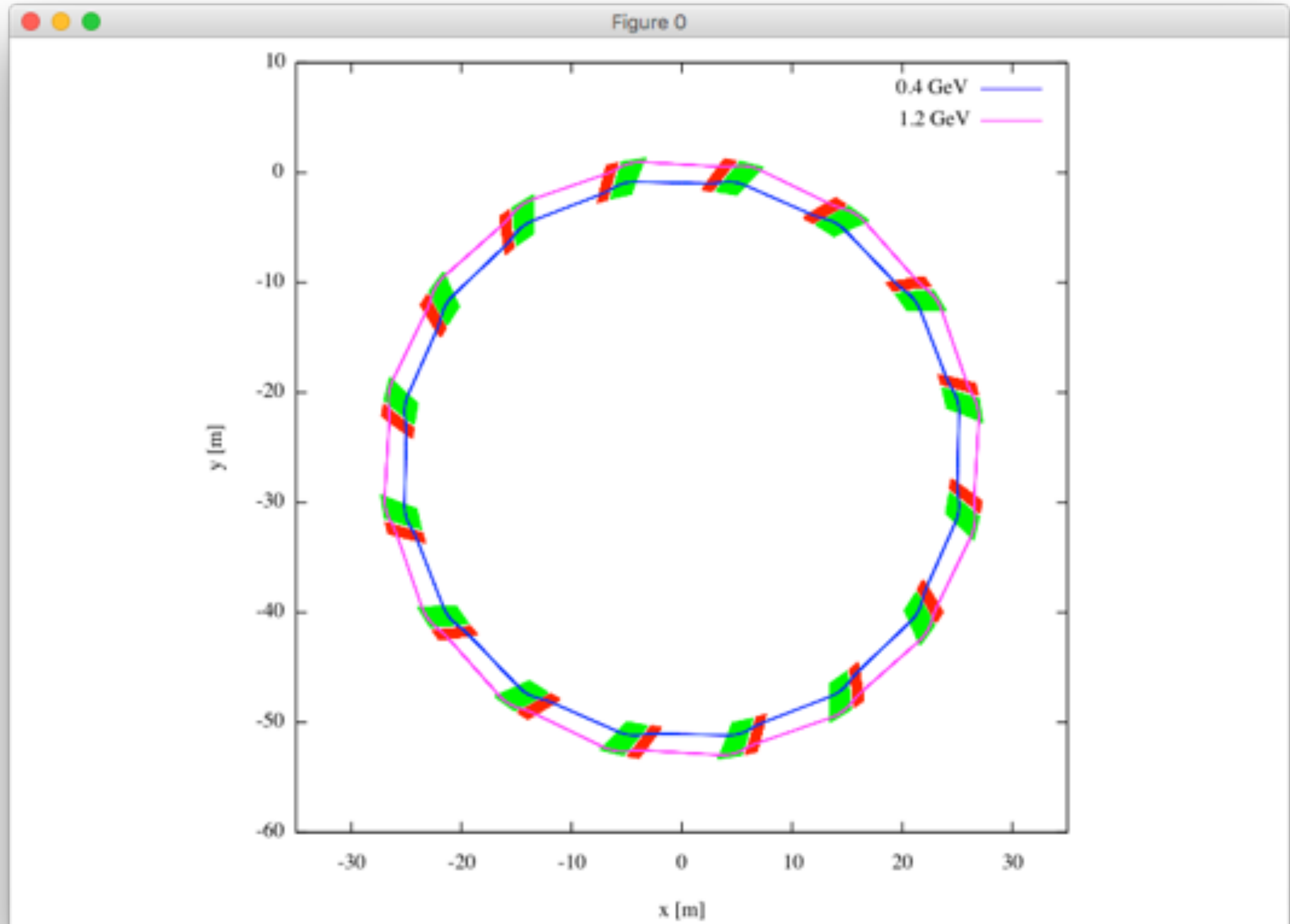
b:The end of second batch of acceleration

c:The end of 5th batch of acceleration

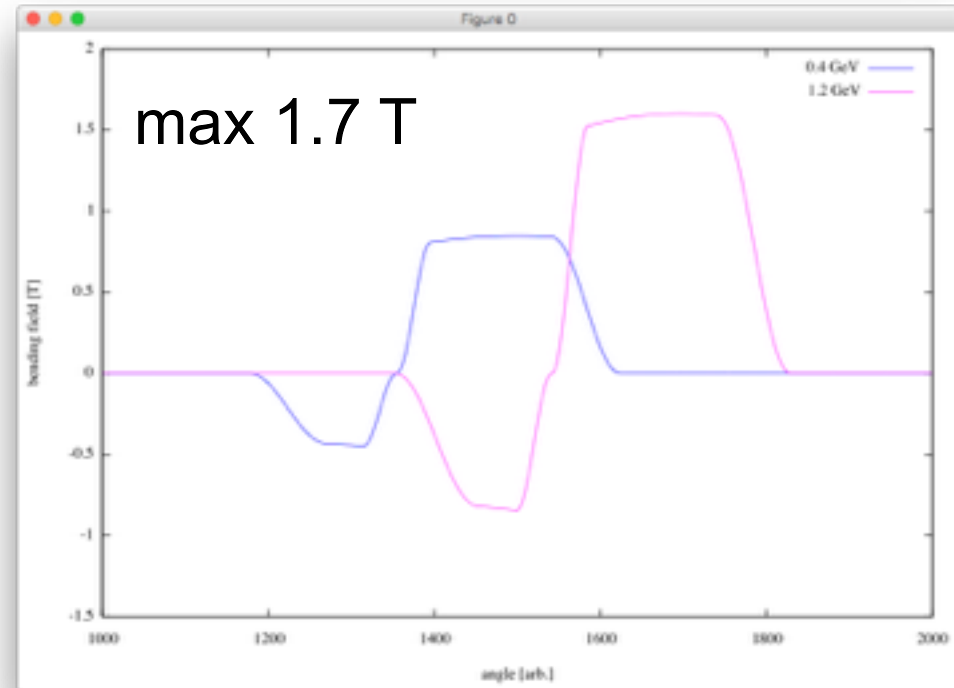
d:The end of 10th batch of acceleration

New Concept: DF Spiral FFAG

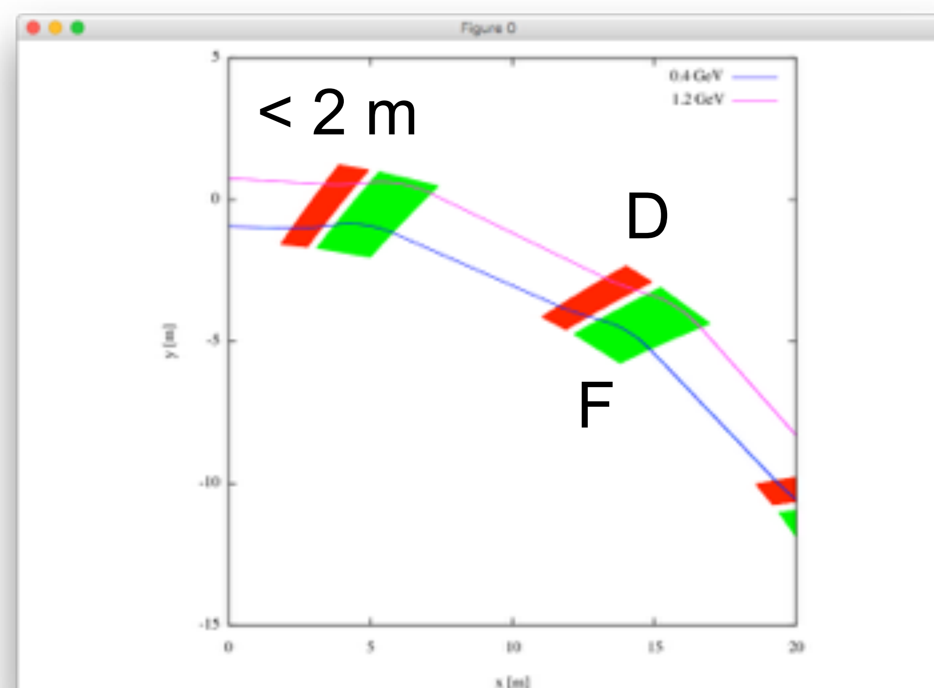
R = 26 m



bending field



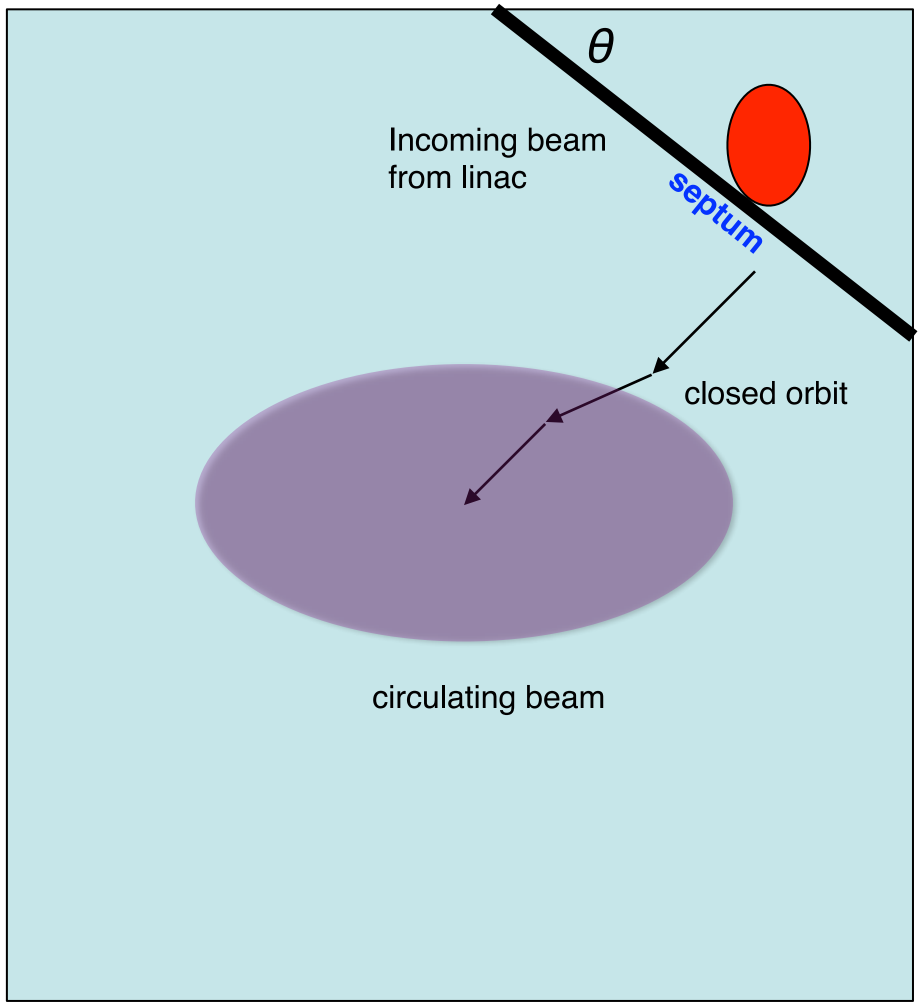
orbits excursion



0.4-1.2 GeV
100 Hz operation
Up to 3.8 MW

Multiturn Injection of Protons

- Liouvillean injection using a tilted electrostatic septum
- Simple injection chicane
- Injection simultaneously into 4D transverse phase space
- Optimise h and v closed orbit bumps to minimise beam loss
- Requires careful choice of septum angle θ and ring optics (tunes, β-functions at injection point).

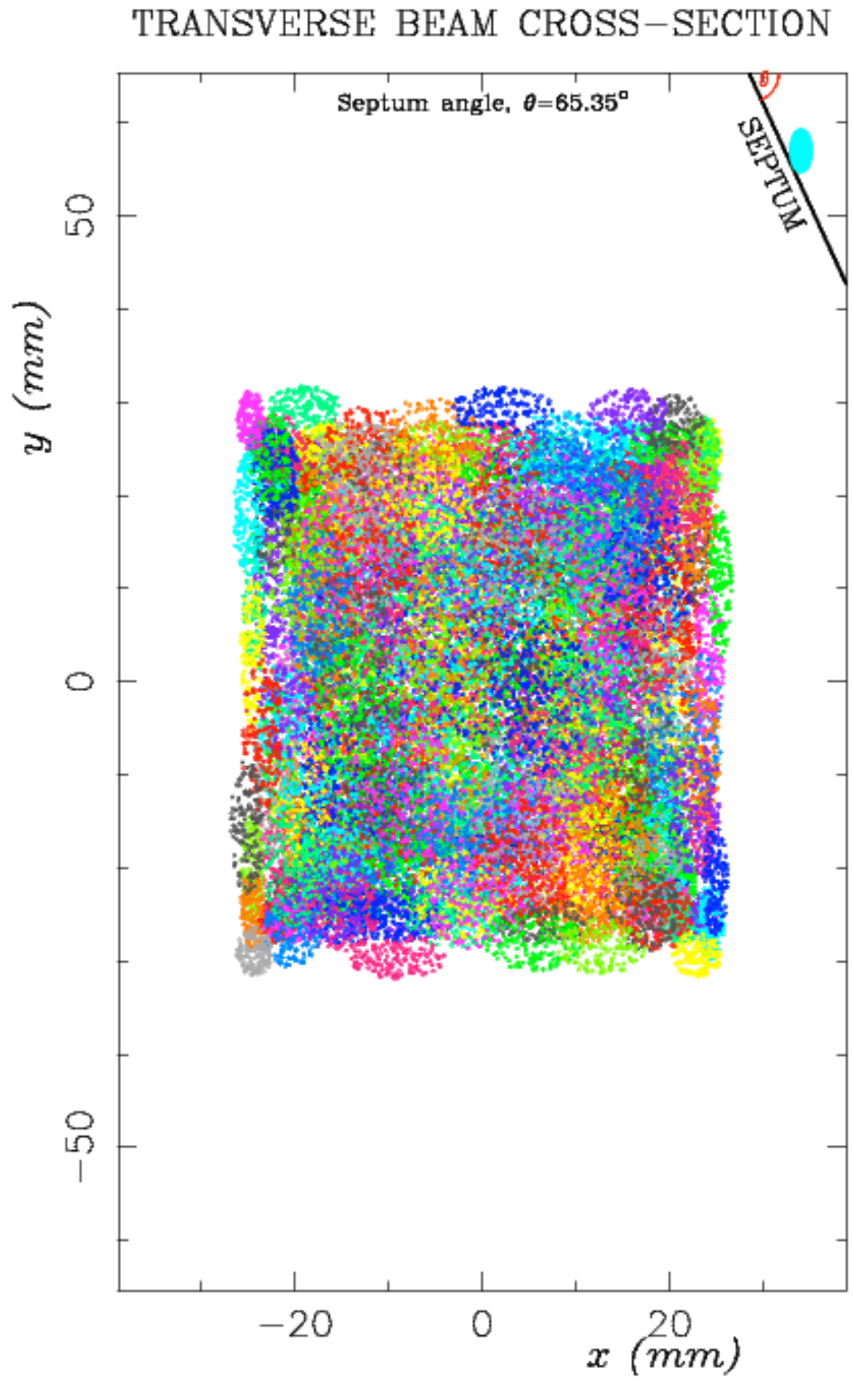


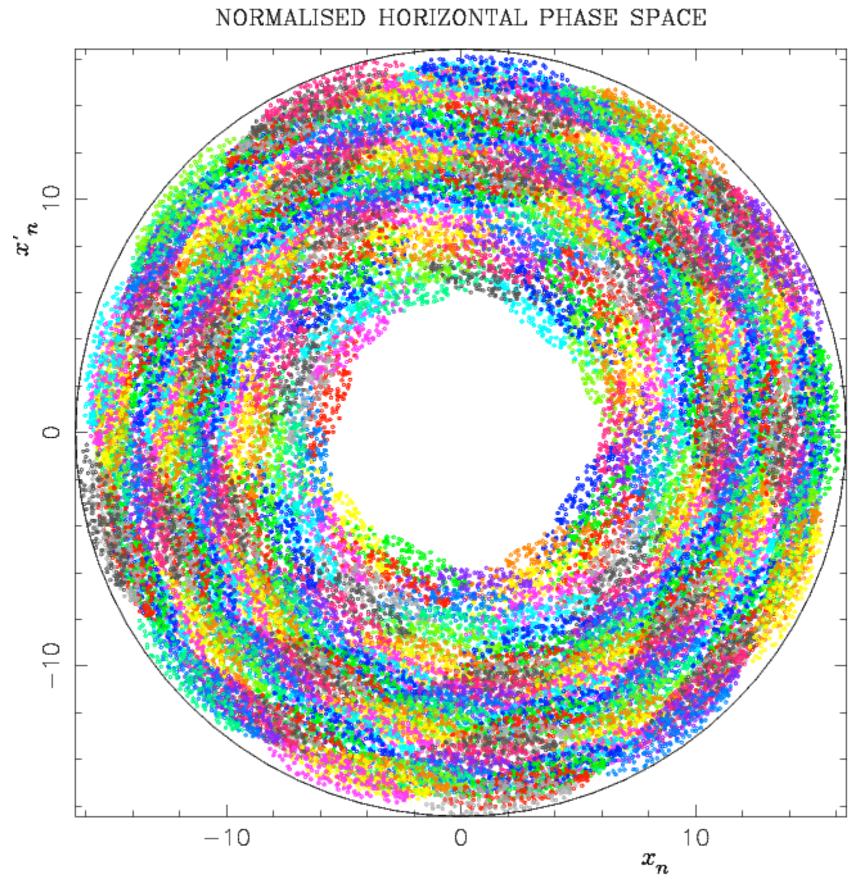
- Earlier simulations for HIDIF suggest maximum number of turns is

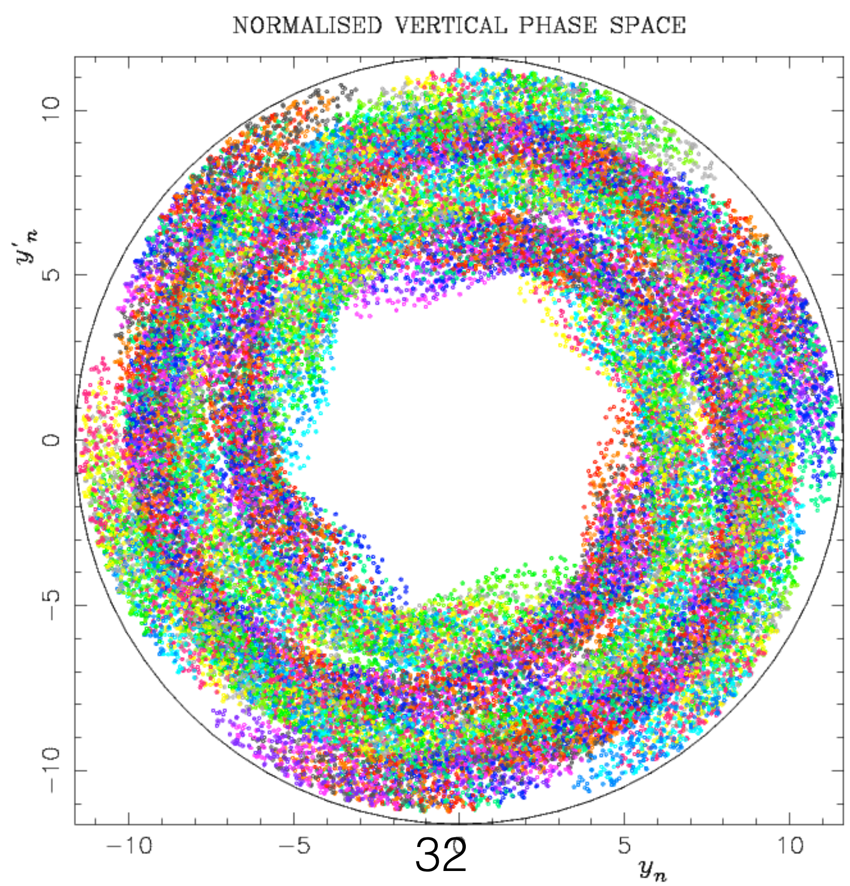
$$N_{\max} \approx \frac{1}{F} \frac{(\epsilon_h \epsilon_v)_{\text{ring}}}{(\epsilon_h \epsilon_v)_{\text{inj}}} \qquad \text{where} \qquad F \approx 20$$

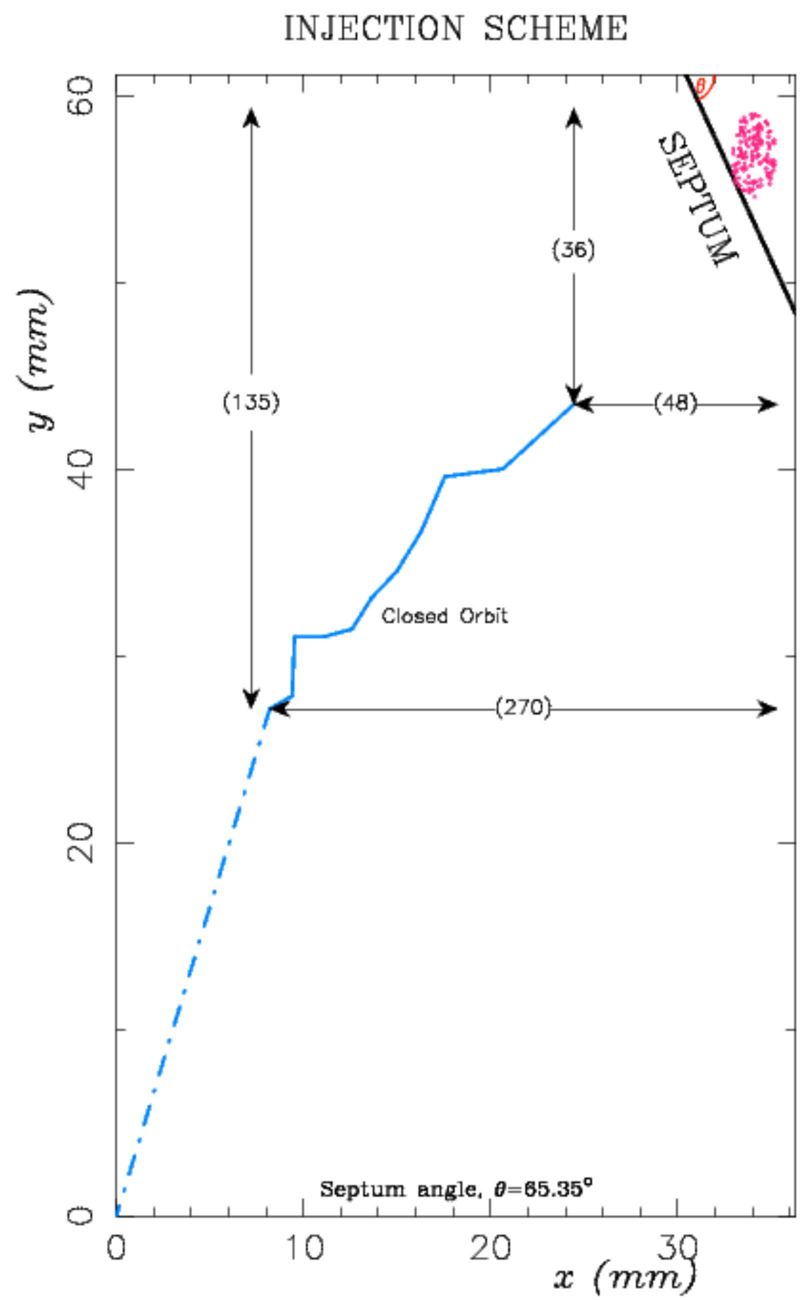
Multiturn Proton Injection - C. R. Prior

Achieve >250 turns







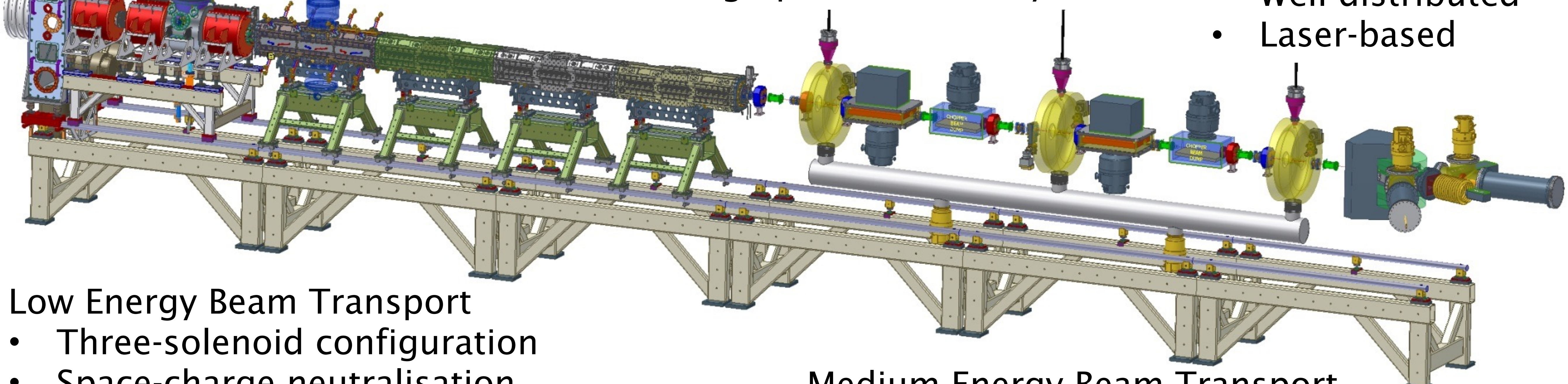


Front End Test Stand (FETS)

High brightness H^- ion source
- 4 kW peak-power arc discharge
- 60 mA, 0.25 π mm mrad beam
- 2 ms, 50 Hz pulsed operation

Radio Frequency Quadrupole
- Four-vane, 324 MHz, 3 MeV
- 4 metre bolted construction
- High power efficiency

Diagnostics
- Non-interceptive
- Well distributed
- Laser-based



Low Energy Beam Transport
- Three-solenoid configuration
- Space-charge neutralisation
- 5600 Ls^{-1} total pumping speed

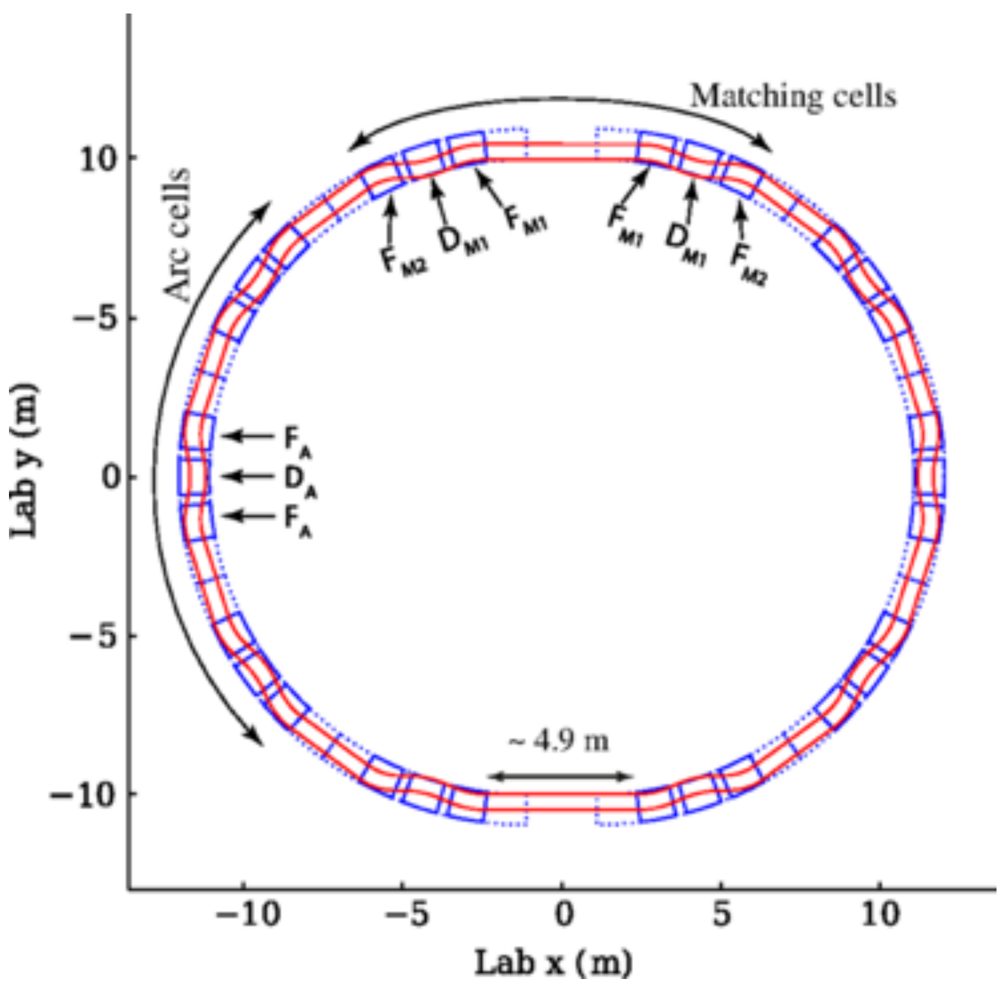
Medium Energy Beam Transport
- Re-buncher cavities and EM quads
- Novel ‘fast-slow’ perfect chopping
- Low emittance growth

Science & Technology Facilities Council | ISIS | ASTeC | JAI John Adams Institute for Accelerator Science | CERN | Imperial College London | Royal Holloway University of London | The University of Warwick | University of Huddersfield | UCL | ESS Bilbao

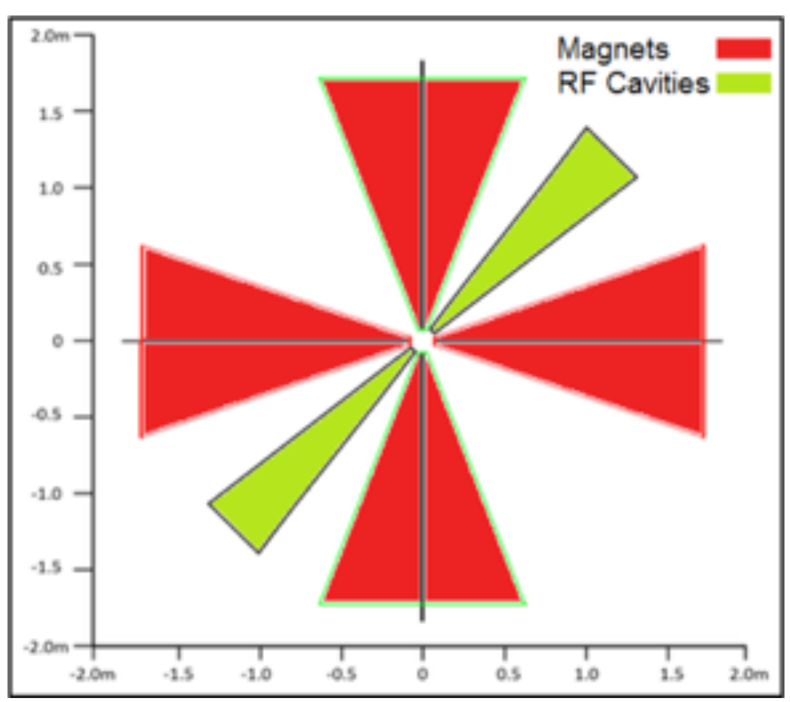
3. Other applications and innovations

Other Innovations - Medical

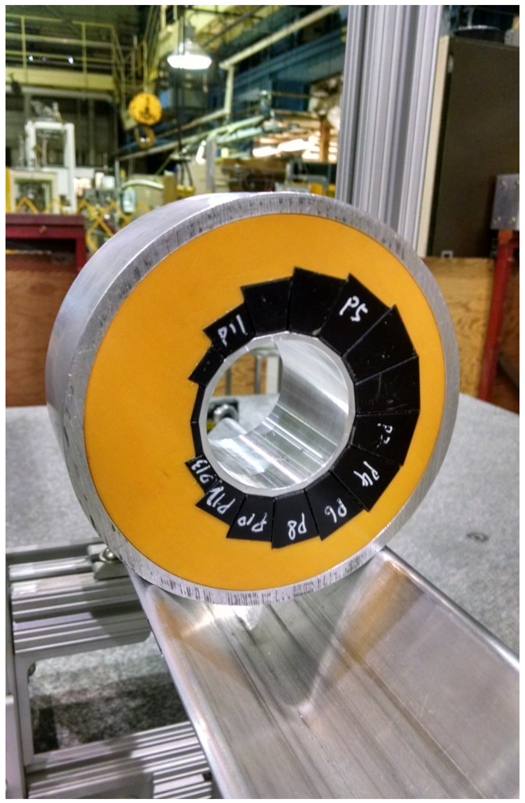
- NORMA design study - S. Tygier, J. Garland
- Gantry innovations, D. Trobjevic
- Helium ion accelerator - “HEATHER”, J. Taylor
- PIP - Protons Isotope Production, R. Barlow



NORMA racetrack 330 MeV FFAG
S. Tygier

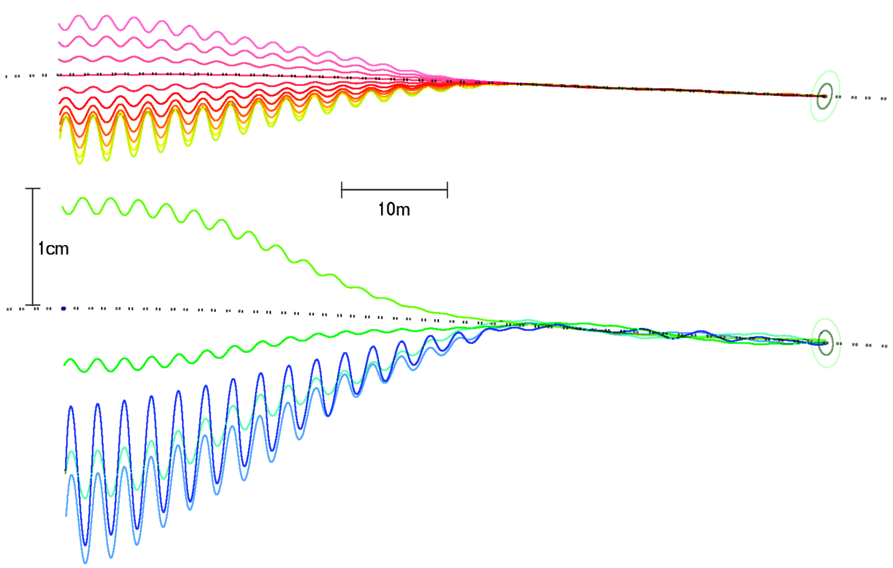


PIP Ring Layout
R. Barlow

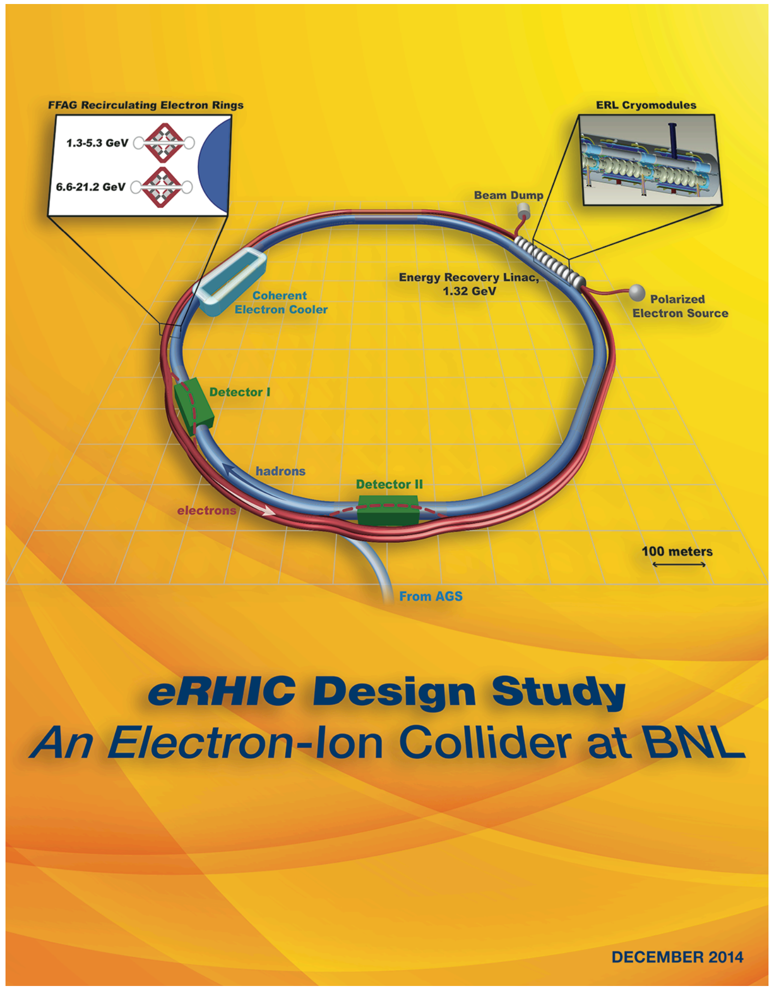


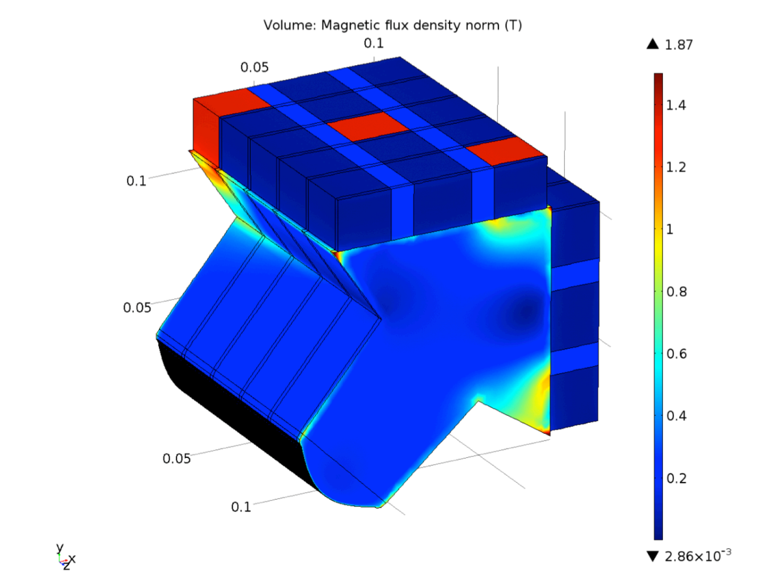
Novel Haibach Magnets
S. Brooks

eRHIC Design - many FFAG innovations



Adiabatic matching



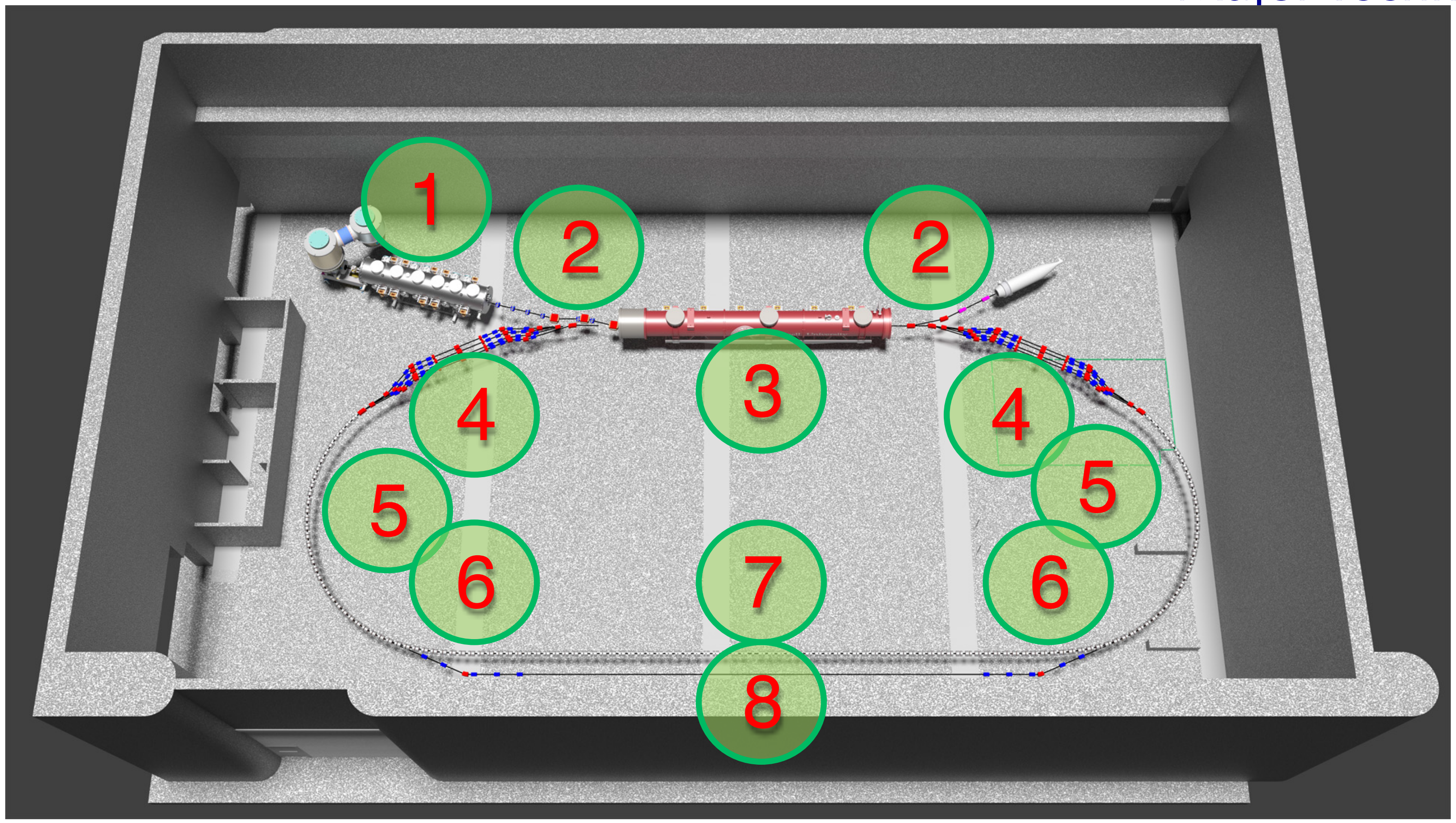


Synchrotron radiation in FFAG arcs

Permanent + iron quads

CBETA to De-Risk the FFAG ERL Concept

Technical Overview of eRHIC prototype CBETA



Major Technical Components:

① Electron Gun with Linac
② ERL mergers
③ Superconducting Linac - ERL
④ Spreaders and Combiners
⑤ NS-FFAG arcs
⑥ Merging arcs to straight section
⑦ Straight section
⑧ Extracted high energy beam

C-β eta will comprise the first ever Energy Recovery Linac (ERL) based on a Fixed Field Alternating Gradient (FFAG) lattice.

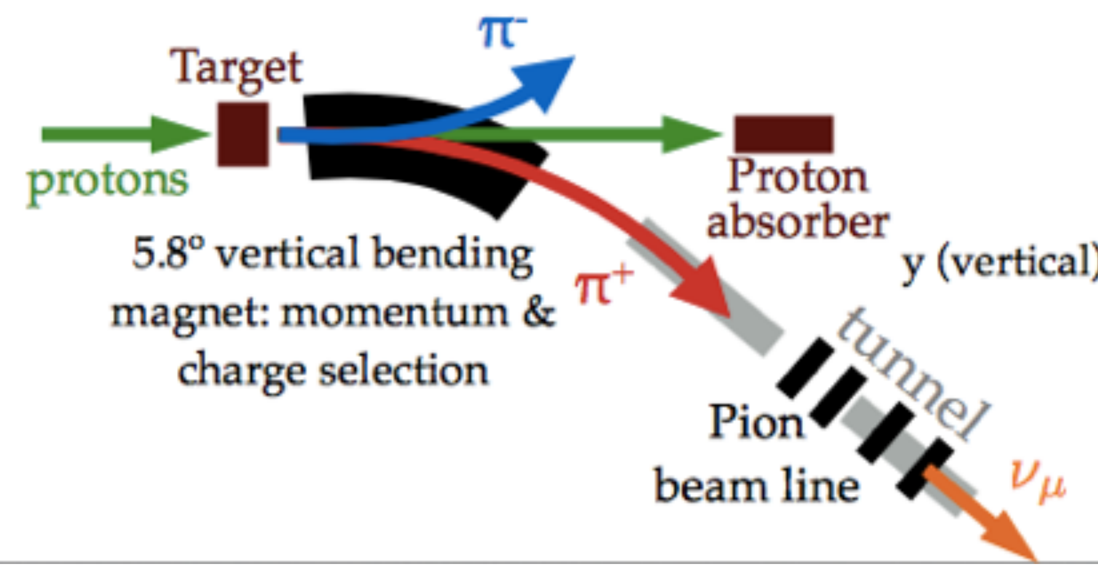
BROOKHAVEN NATIONAL LABORATORY

D. Trbojevic, FFAG'16

Other applications…

Neutrino Production:

NuPIL
(Pion decay line)



NuSTORM
(Racetrack FFAG muon decay ring
(J. B. Lagrange et al)

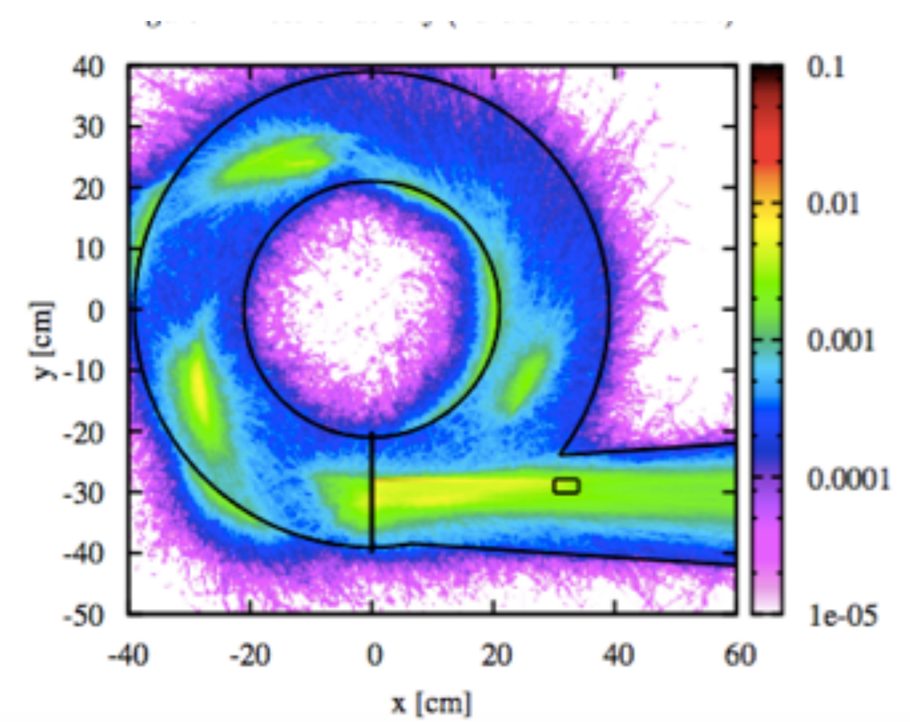


Figure 2: Photon density (from the same fluka simulation).

Electron to photon conversion (T. Planche et al)

Summary

- Simulation tools are now in place to study high intensity beams
- Experimental work is helping us benchmark and optimise
- Exciting new concepts for high power (pulsed) and almost-CW
- Many beam dynamics and lattice innovations around the world
- New magnet technologies, we are pushing the state-of-the-art

50 years later, high intensity FFAGs are in sight.

We need to work with the cyclotron community!