FFAG diagnostics and challenges

Beam Dynamics meets Diagnostics Workshop
Florence, Italy, 4-6th November 2015

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& STFC/ASTeC Intense Beams Group

Overview

What is an FFAG?

What is special about FFAGs?

FFAG examples of diagnostics & measurements

- KURRI-FFAG (protons)
- EMMA (electrons)
- Other FFAGs

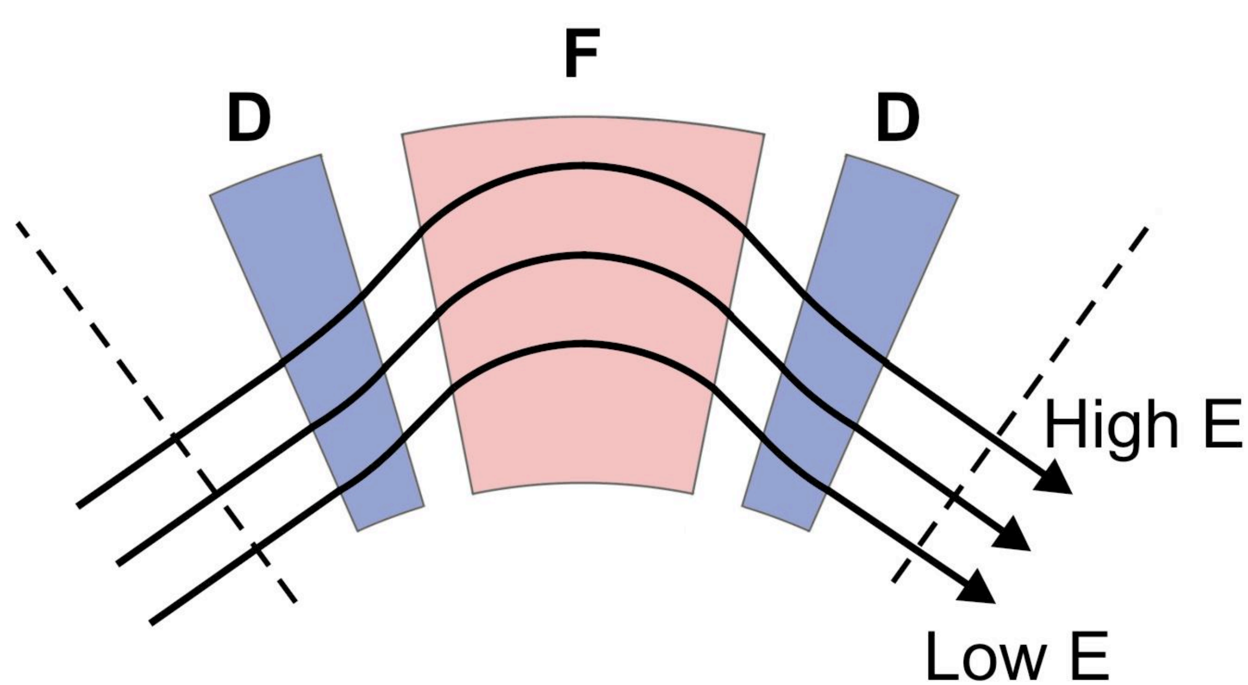
Future challenges & opportunities

What is an FFAG?

- Fixed Field Alternating Gradient accelerator

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

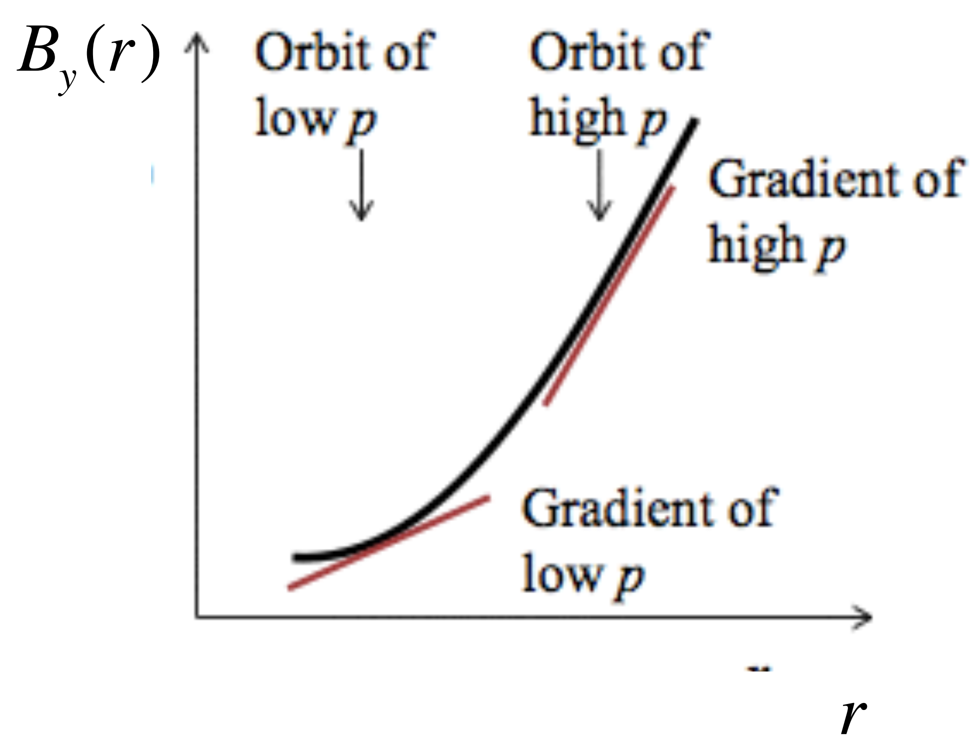
- Strong focusing
- 'Scalloped' orbits



Types of FFAG

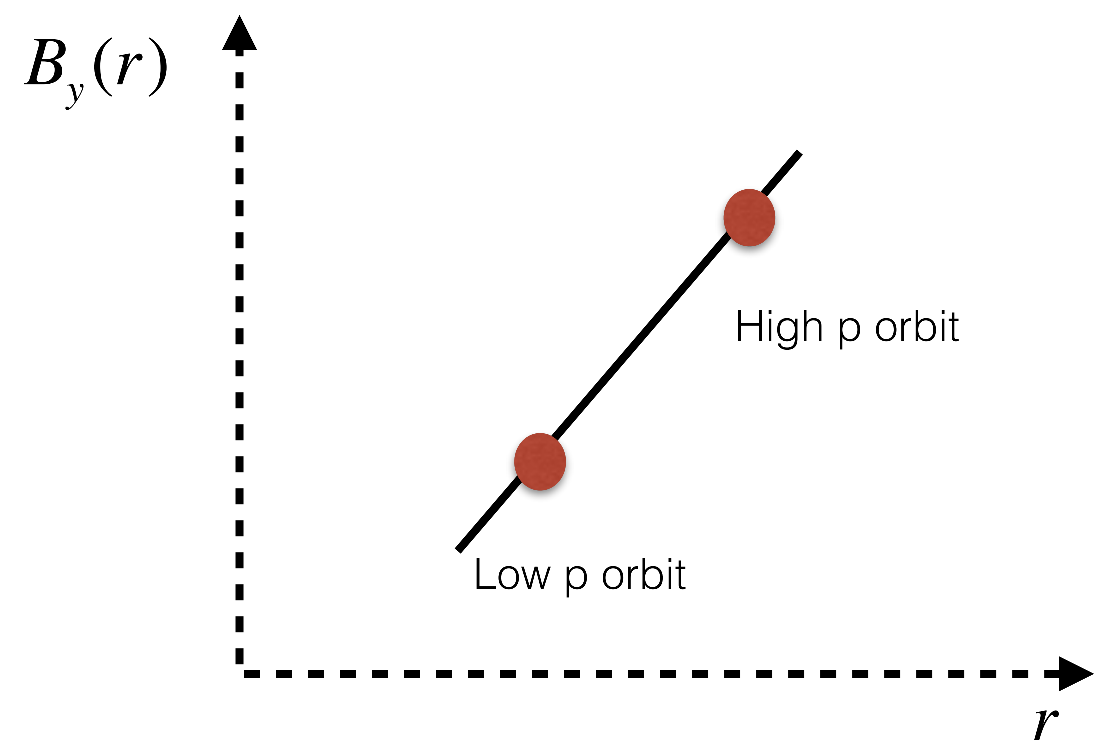
Scaling FFAG

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

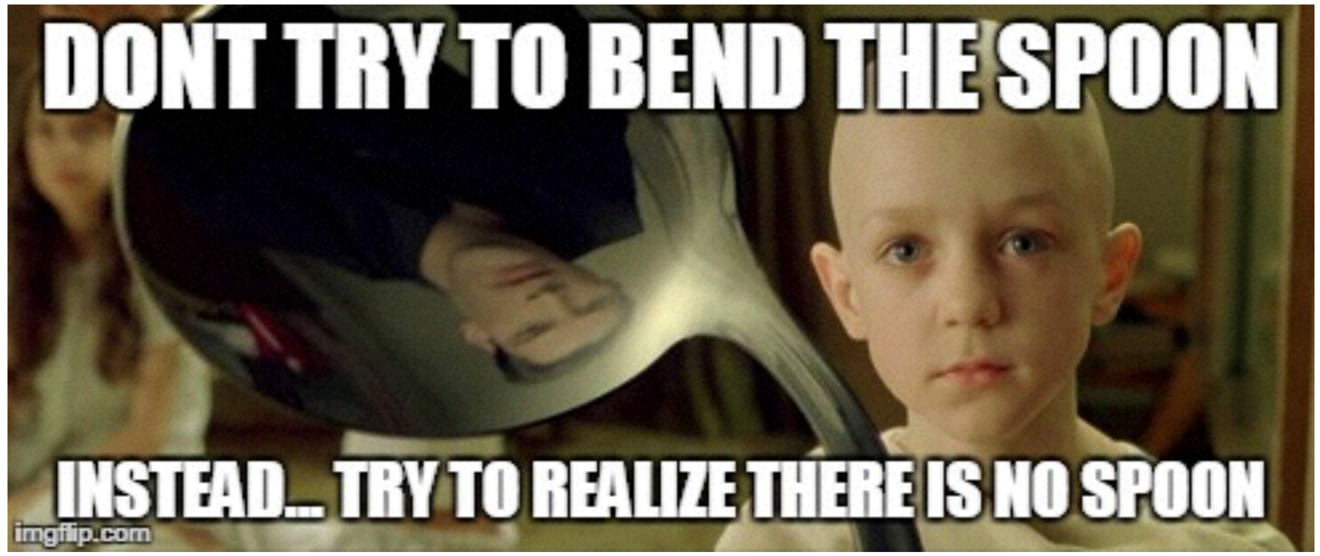


Non-scaling FFAG (linear)

$$B_y = B_1 r + B_0$$



What is special about FFAGs? (1)



1. THERE IS NO REFERENCE ORBIT

   Where is the beam supposed to be?

   Where do we have to ‘correct’ to?

BUT we know it moves with RF frequency…

What is special about FFAGs? (2)

Repetition rate:

Demonstrated at 100Hz, could go up to 1kHz or more.

Can support multiple bunches simultaneously with superimposed RF patterns

… other than that, they are just ordinary accelerators.

For the purposes of this talk, think about them like a synchrotron where the orbit moves.

What do we need to measure?

- Beam parameters:
  - Beam size & emittance
  - Actual beam energy & energy spread
- Beam dynamics or lattice parameters:
  - beam position at all energies
  - k value or ‘field index’
  - Dispersion
  - Beta function & other ‘Twiss’ parameters
- Operating parameters:
  - Beam loss patterns
  - Closed orbit distortion

KURRI 150 MeV ADSR-FFAG

Scaling FFAG

Injection 11 MeV,

H- charge exchange

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

Diagnostics in the ring

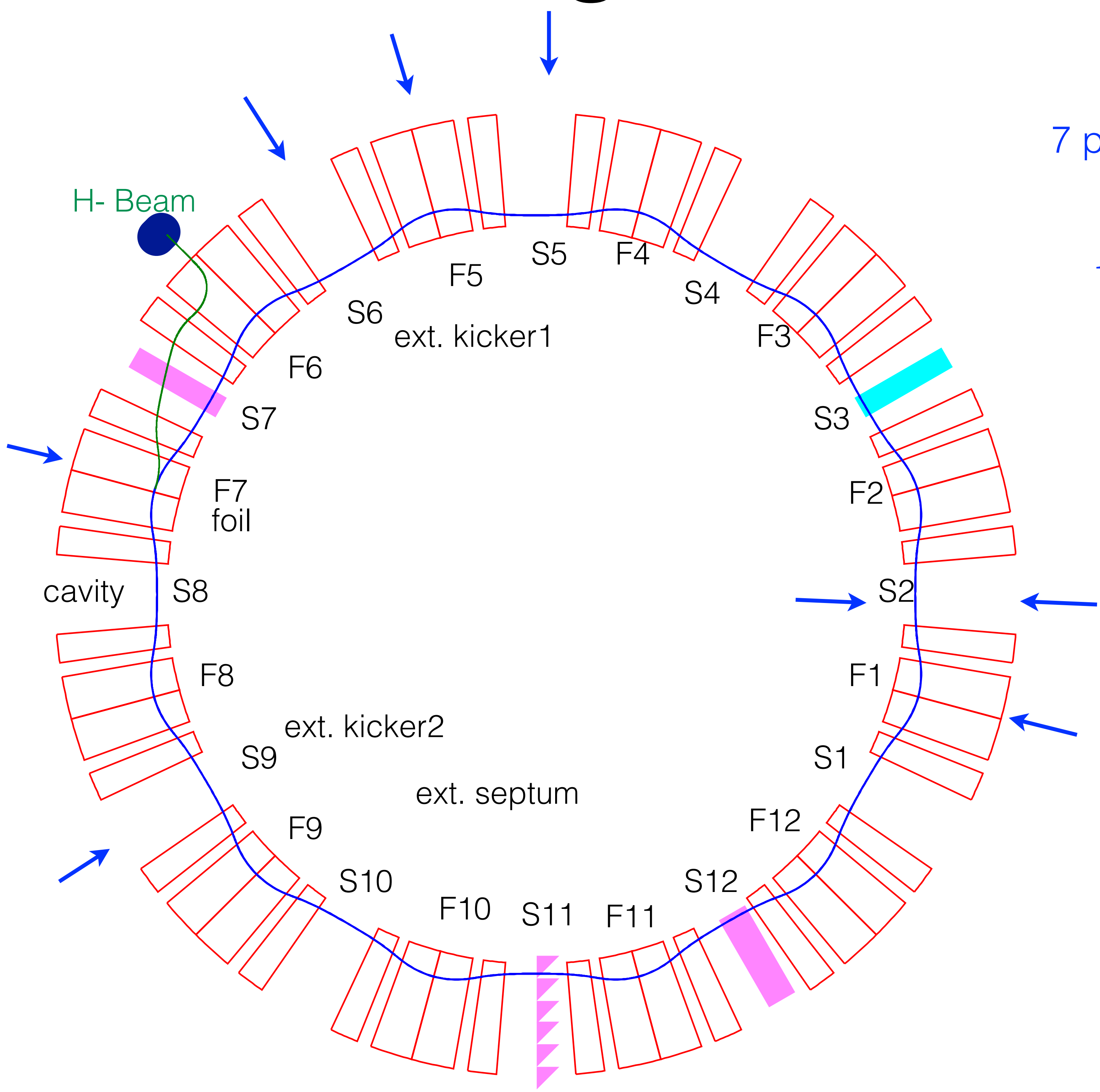


Diagram courtesy Y. Ishi

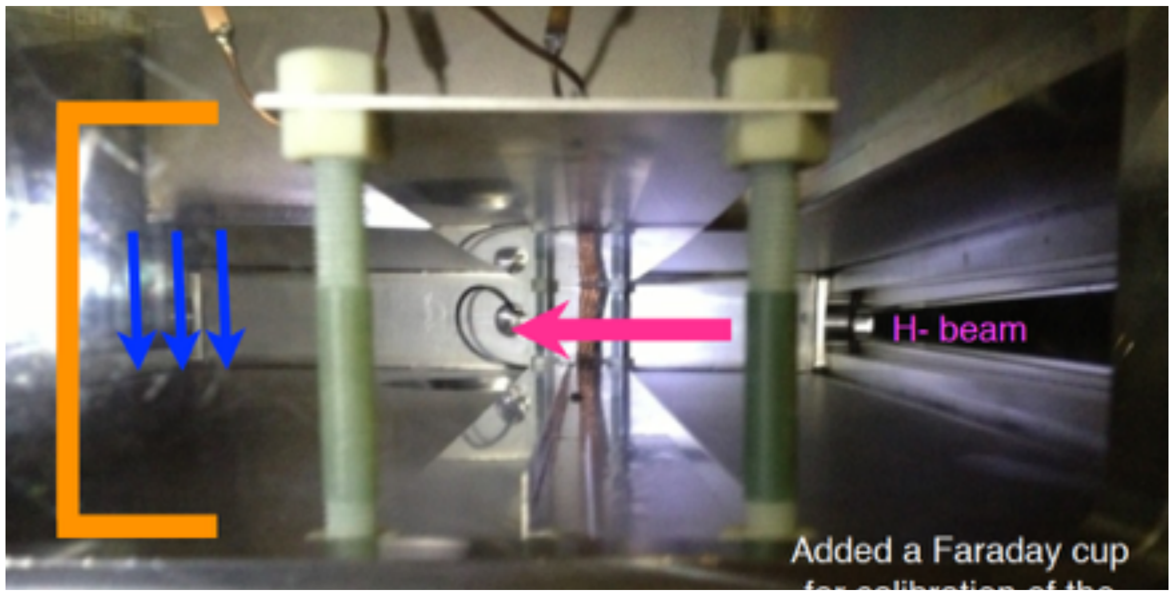
List of monitors

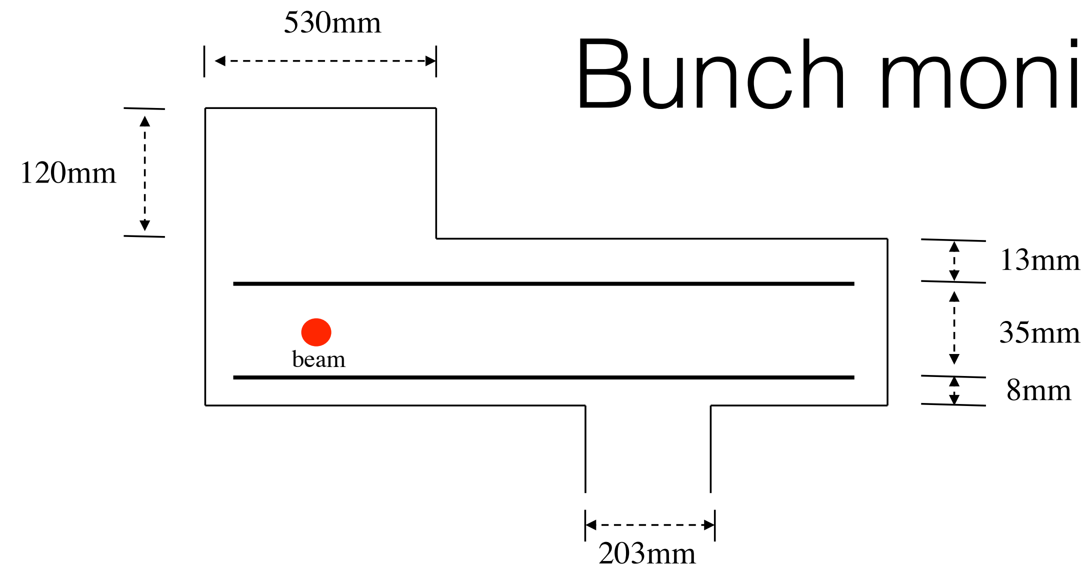
7 ports for radial probes (blue arrow, ICF70)
4 portable radial probes remote cntrl'd
2 portable radial probes manual cntrl'd
1 unportable radial probe (green arrow)
3 bunch monitors
1 faraday cup / 1 screen monitor
1 perturbator

S1	~~radial probe~~ removed
F1	radial probe
S2	radial probe / hor. perturbator
S3	vert. perturbator
S5	movable bunch mon.
F5	radial probe
S6	radial probe
(F6)	Faraday cup / screen monitor
S7	bunch monitor
F7	radial probe
S9	radial probe
S11	bunch mon.(array of triangle plates)
S12	bunch monitor

What do we want to measure? (1)

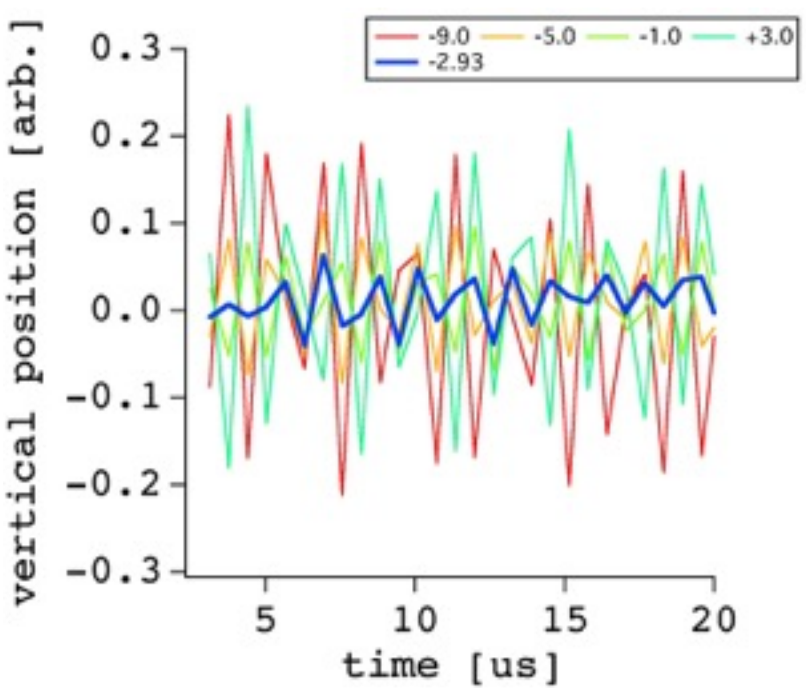
Beam orbit movement with radius





Bunch monitor

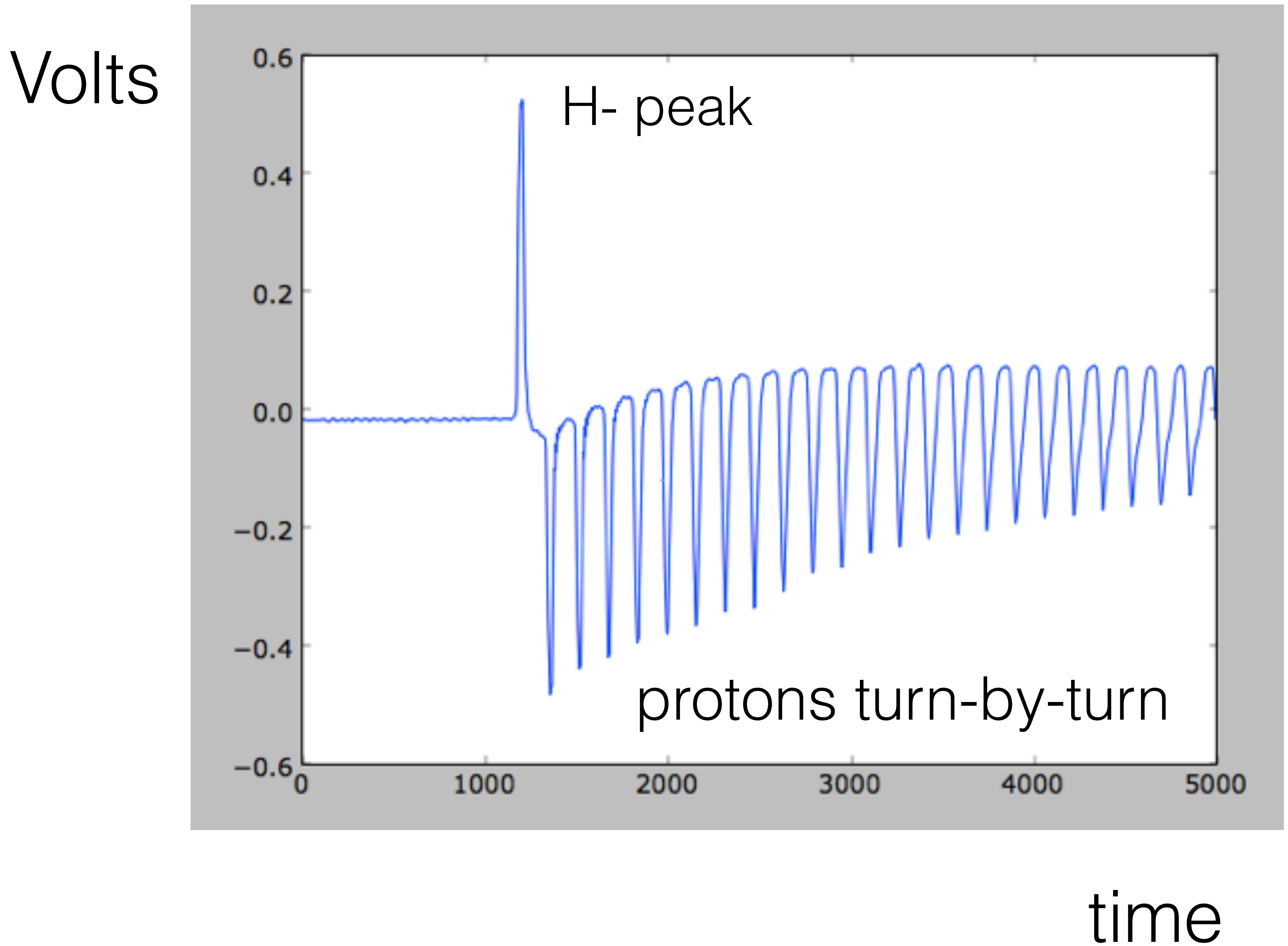
This gives vertical position (obviously?)



Bunch monitor was used to minimise vertical oscillations and optimise injection

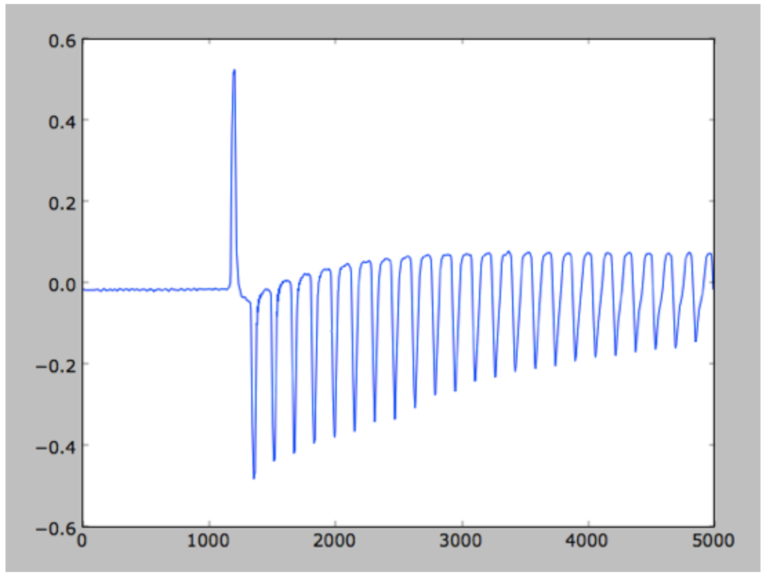
Bunch monitor signal (example)

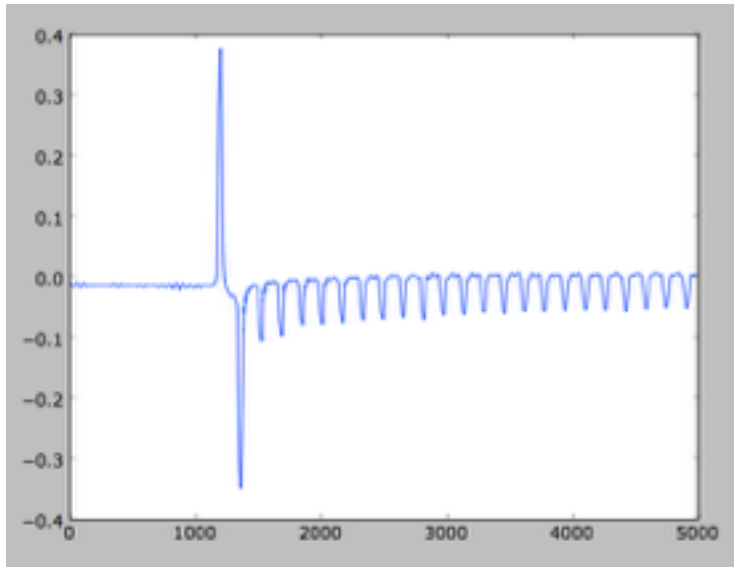
nb. coasting beam, no RF

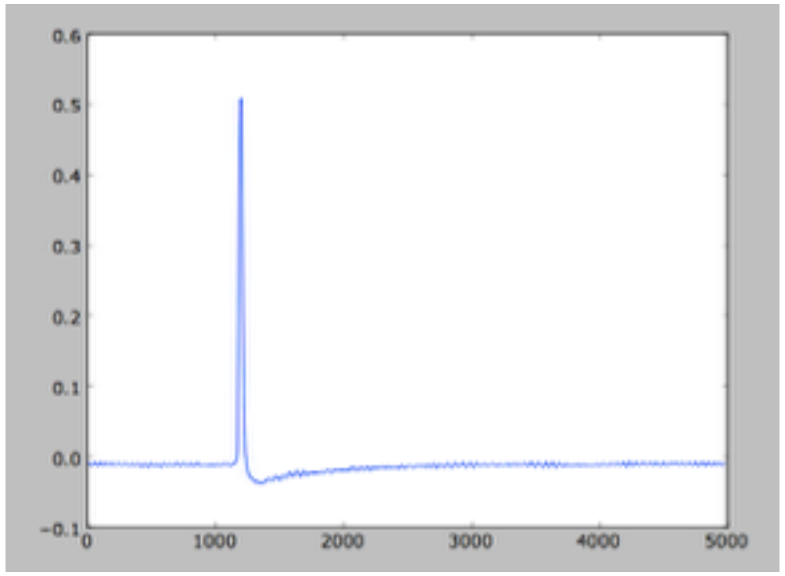


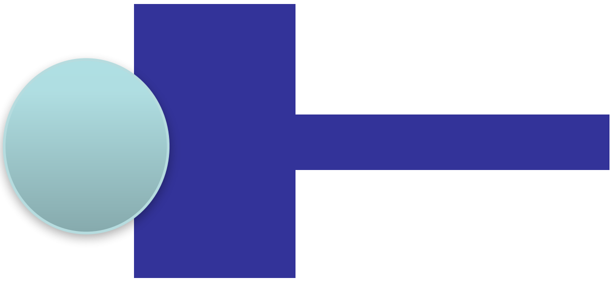
Probe intercept method

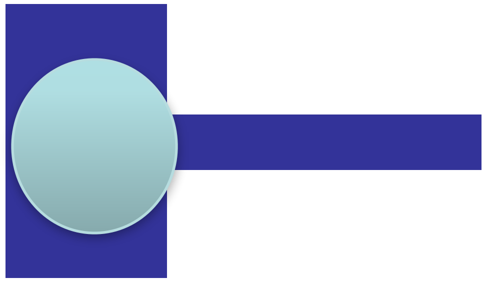
$$\text{Norm. response} = \frac{\text{peak of nth turn}}{\text{peak of 0}^{\text{th}}\text{ (H–) turn}}$$

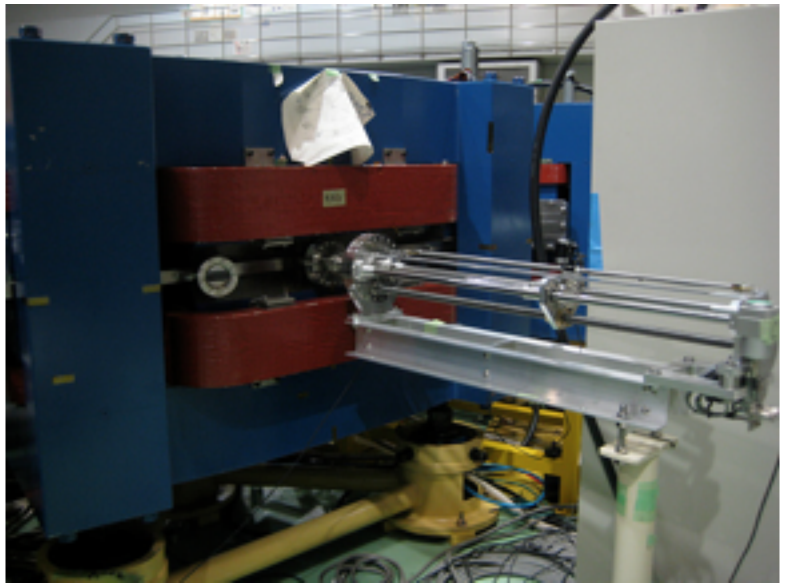












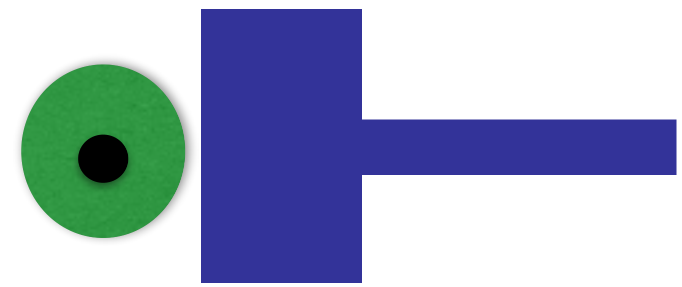
Radial probe & magnet triplet

using this (very simple) diagnostic we can build up a picture of the beam position AND beam size!

What do we want to measure? (2)

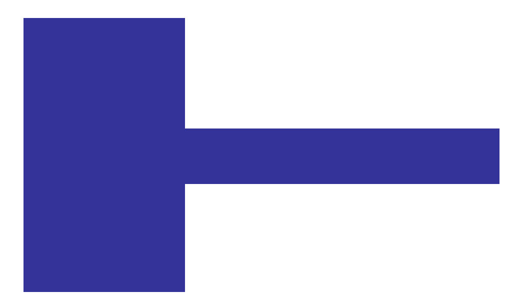
Beam orbit movement with radius

- closed orbit
- ‘smeared out’ betatron oscillations

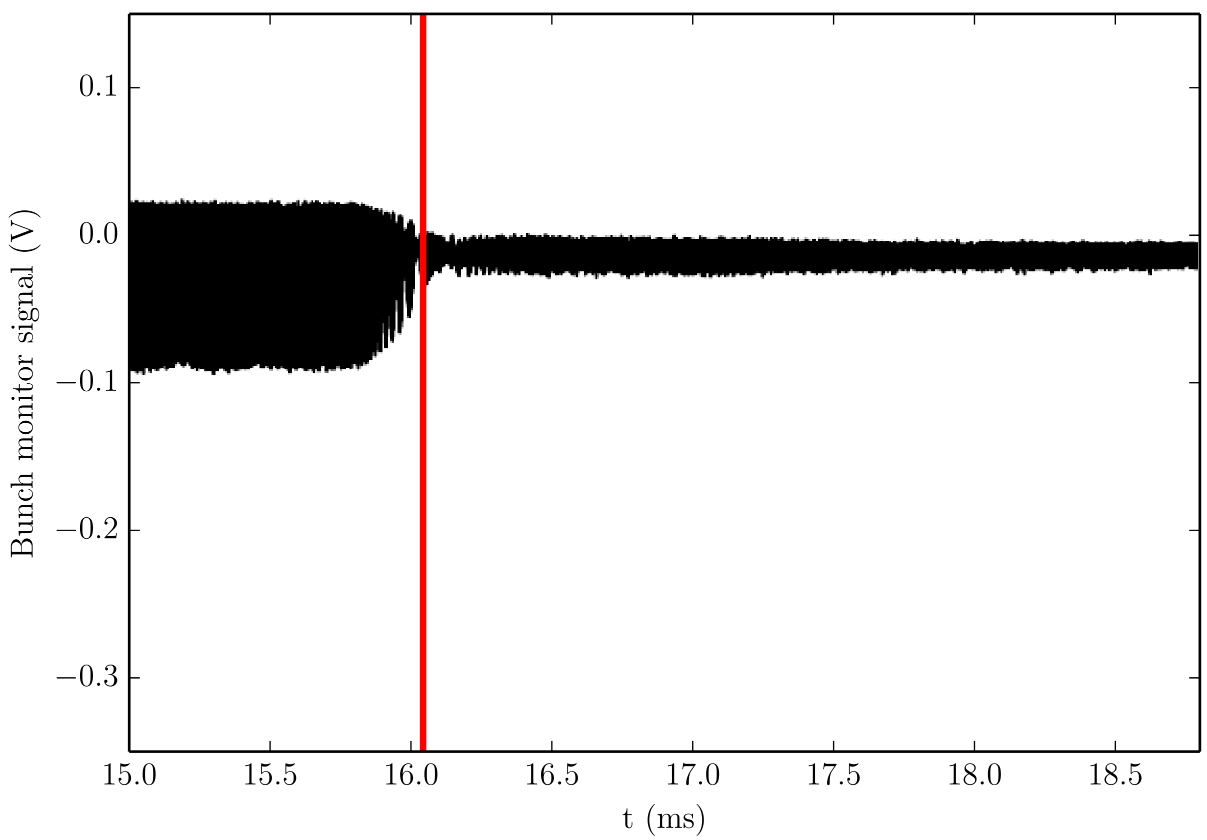


t=0, Probe doesn’t stop beam

t=time to loss, Probe will fully stop beam after a few turns



t>time to loss, all beam lost



“time-to-loss” measurement

WITH acceleration

Beam orbit movement with radius

$$k = \frac{r}{B}\left(\frac{\partial B}{\partial r}\right)$$

+ field index "for free"

"beam dynamics helps diagnostics"

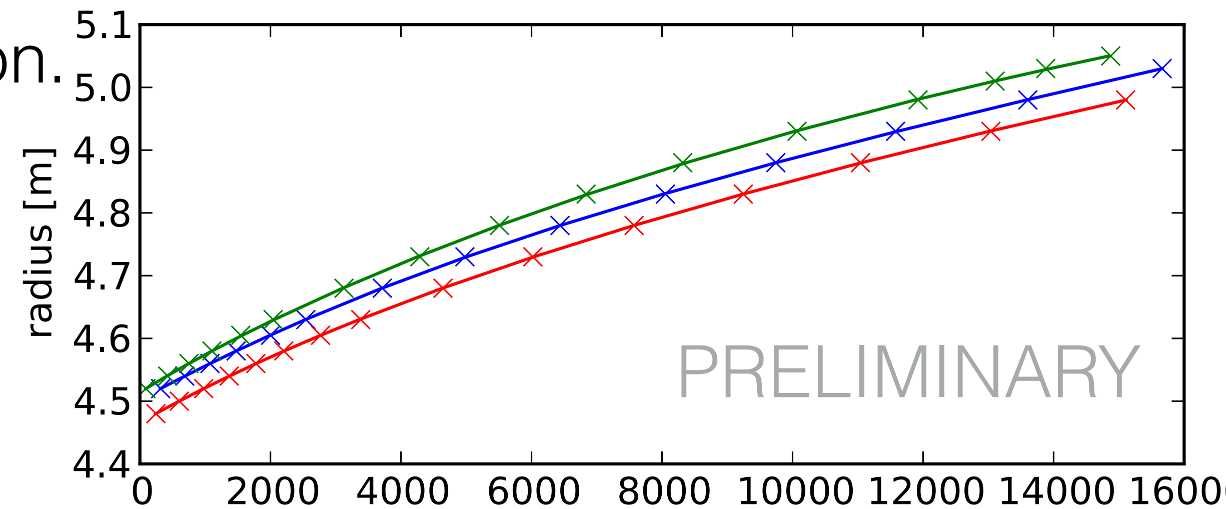
k is the 'field index' and should be constant.
It is also a measure of momentum compaction.

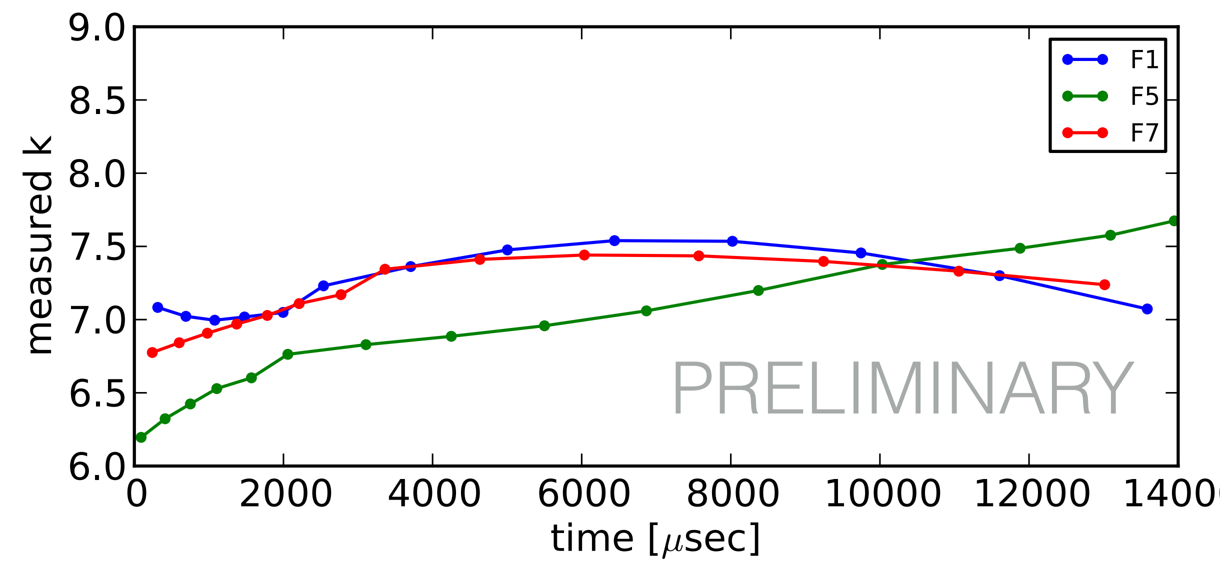
$$k = \gamma^2 \frac{df / f}{dr / r} - (1 - \gamma^2)$$

df/f from RF programme

dr/r from measurement

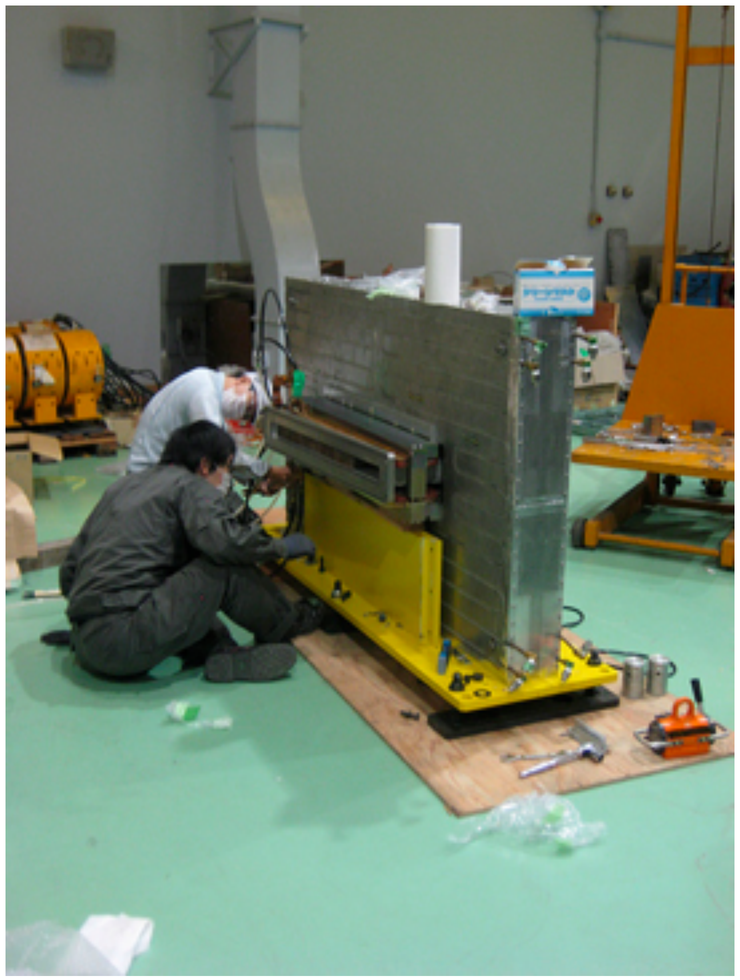
(also assume gamma from RF)





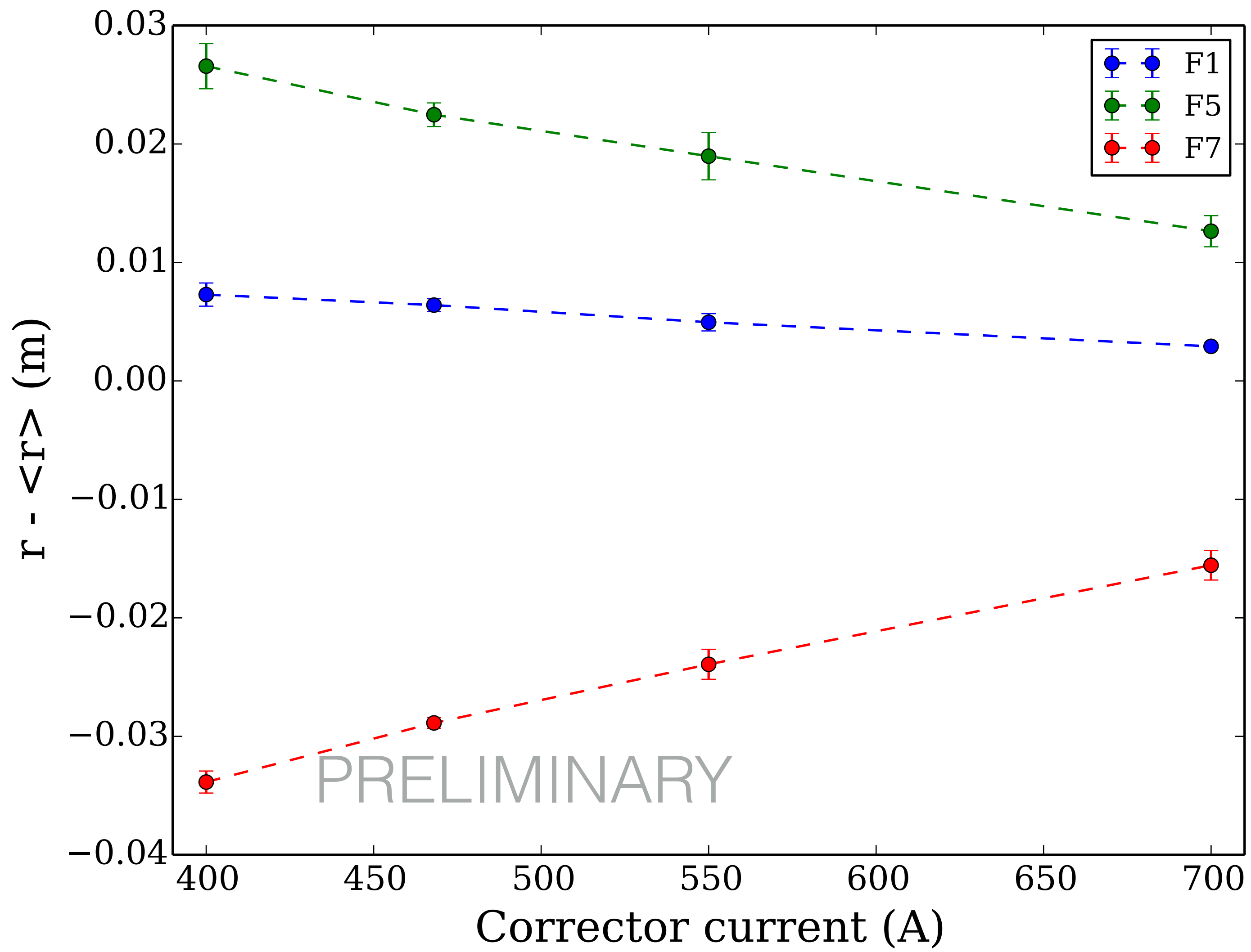
S. L. Sheehy et al., Characterization techniques for fixed-field alternating gradient accelerators and beam studies using the KURRI 150 MeV proton FFAG.
http://arxiv.org/abs/1510.07459

Closed orbit distortion



RF cavity with 'magnetic alloy' material for tuning

Corrector poles later mounted on flanges.



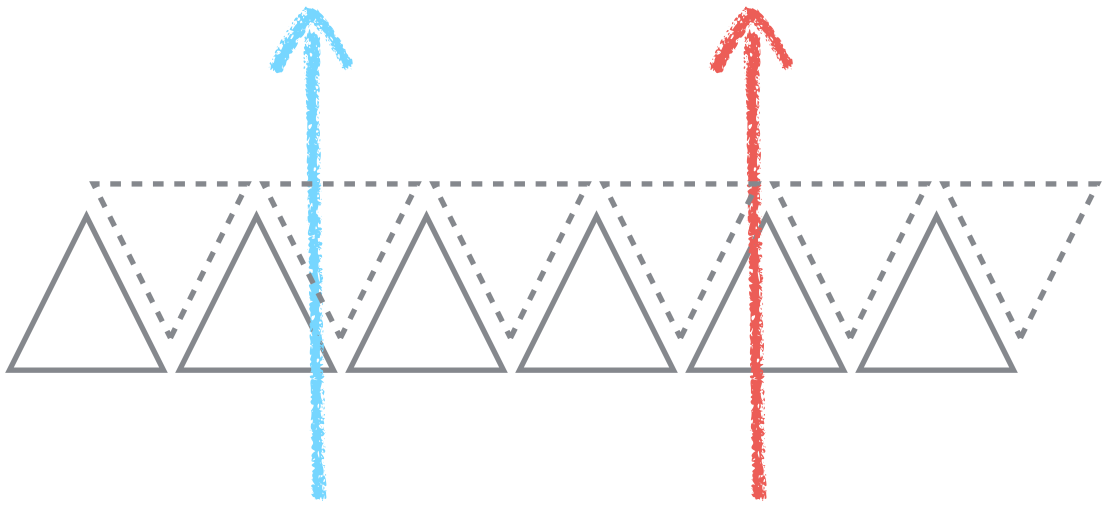
Measuring the orbit position as a function of corrector current

Additional Diagnostics

Triangle-plate bunch monitor

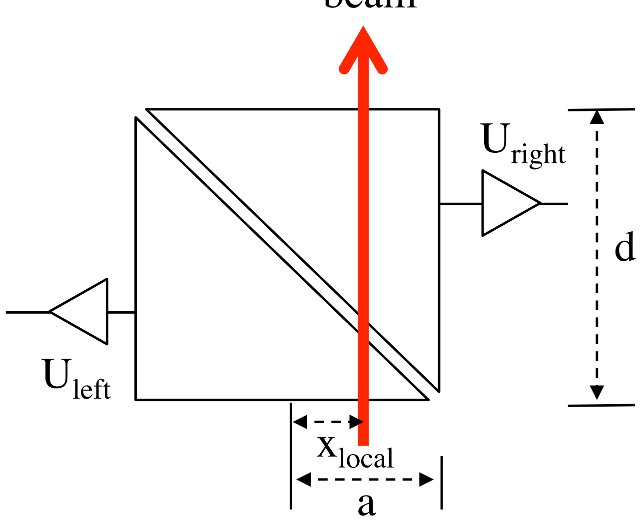
At KURRI no ‘second plate’ to normalise position, but this is still used for tune measurements.

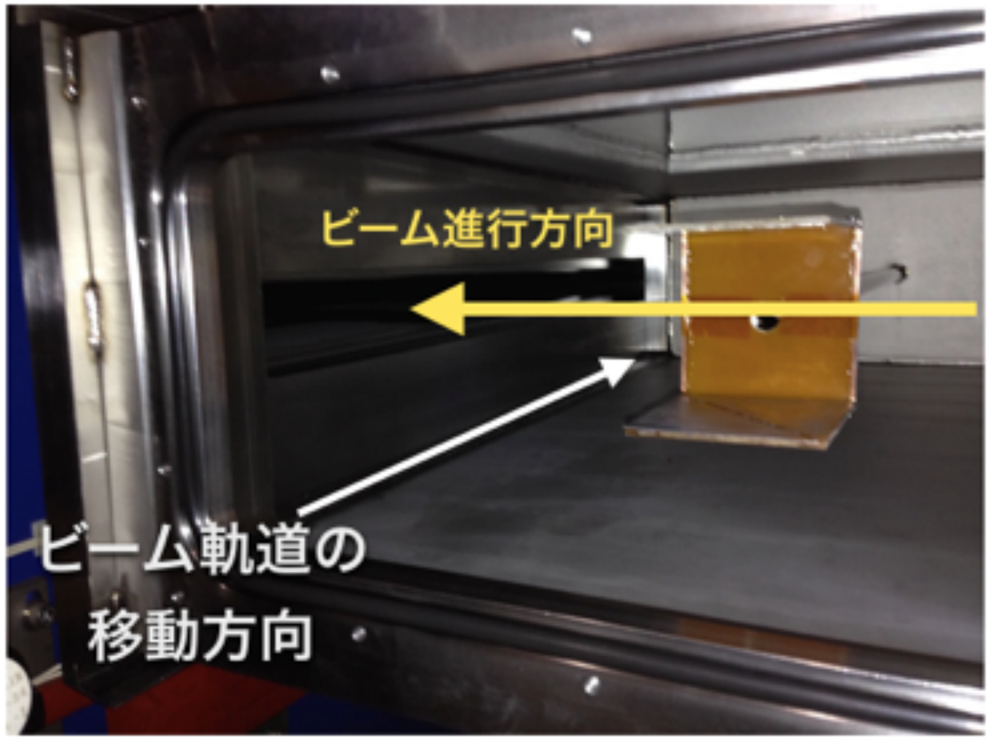
At Kyushu, they have the full double-plate system installed.



Radially movable BPM

Mounted on a radial mover
Cut-type BPM
For horizontal beam measurements

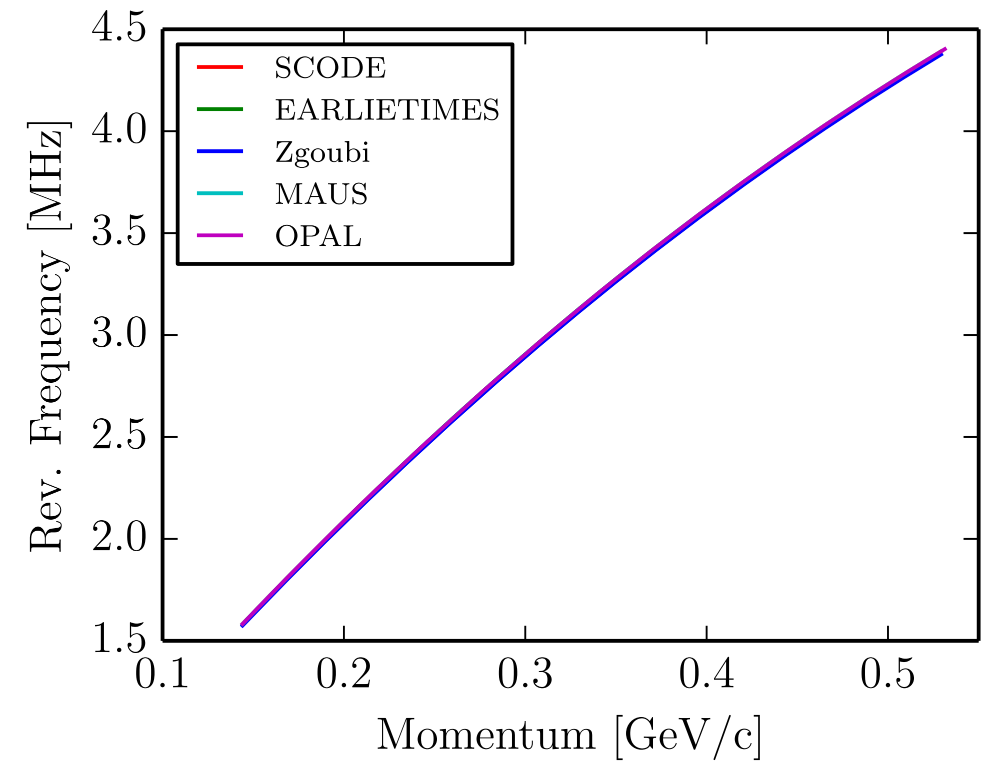


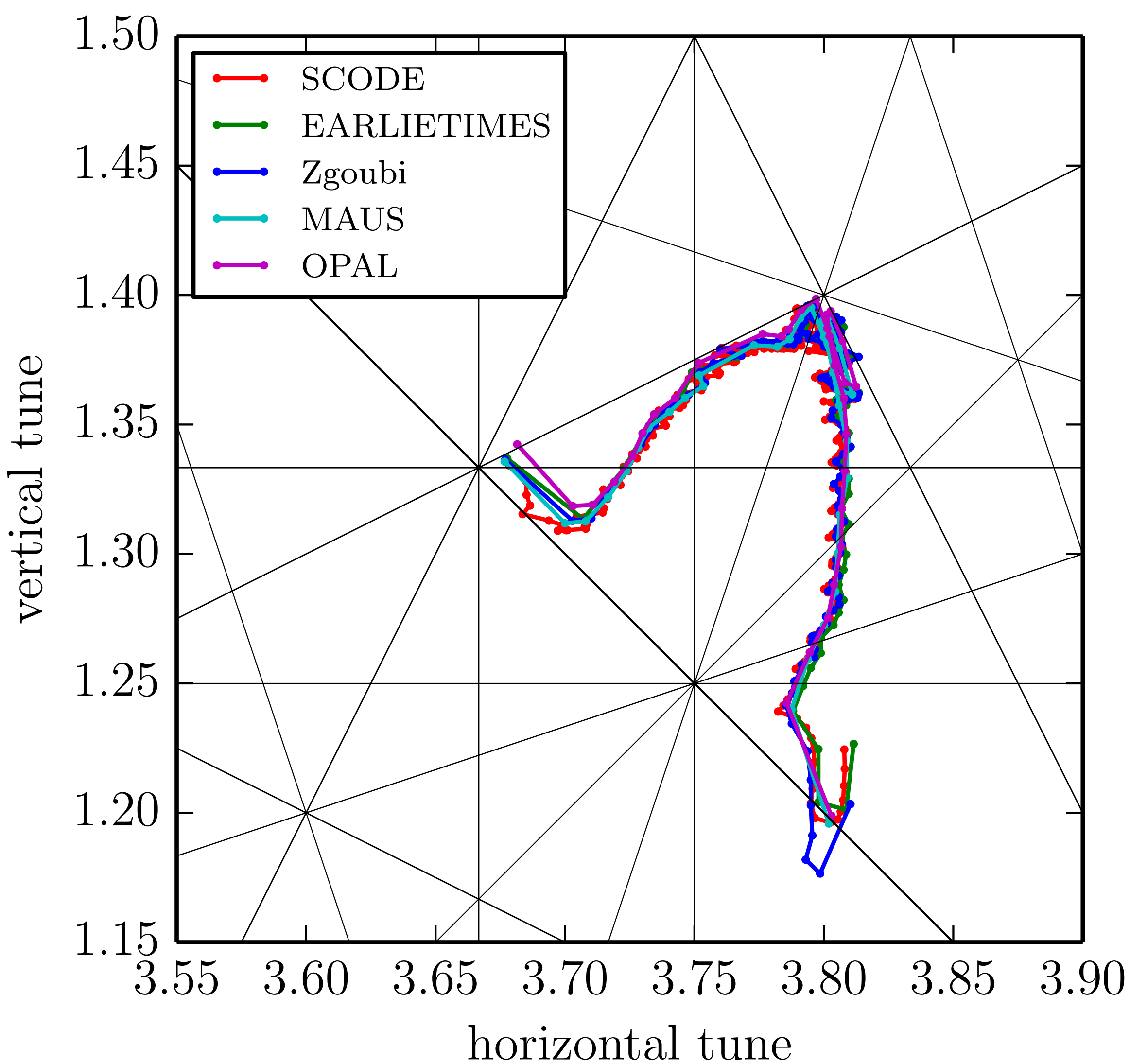


M. Sakamoto, KURRI

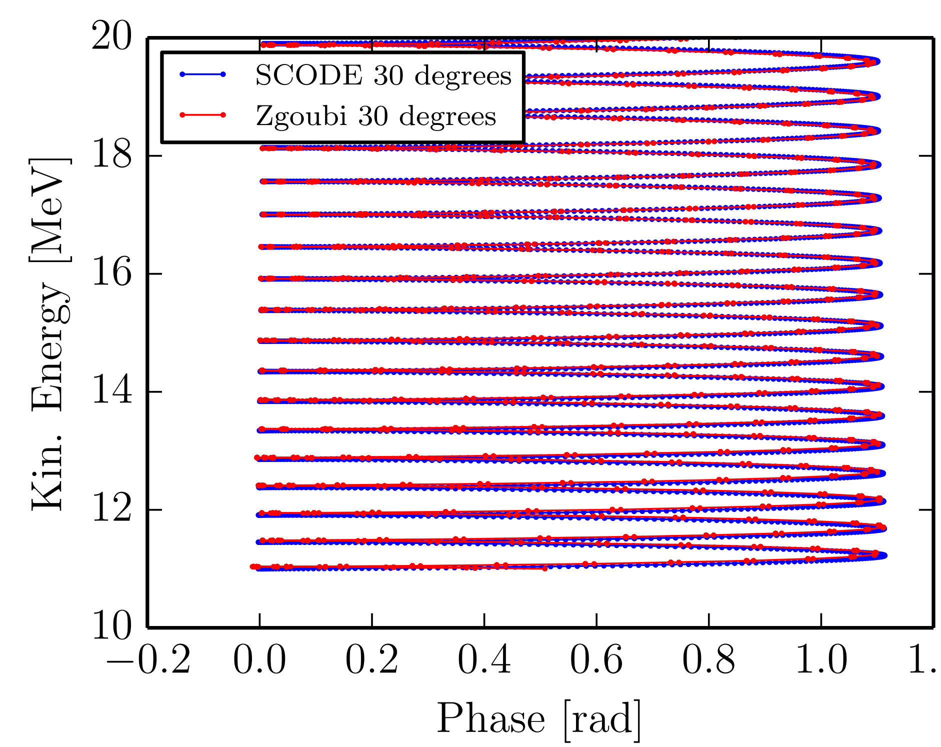
Simultaneous simulation benchmarking exercise

revolution frequency





betatron tunes



acceleration

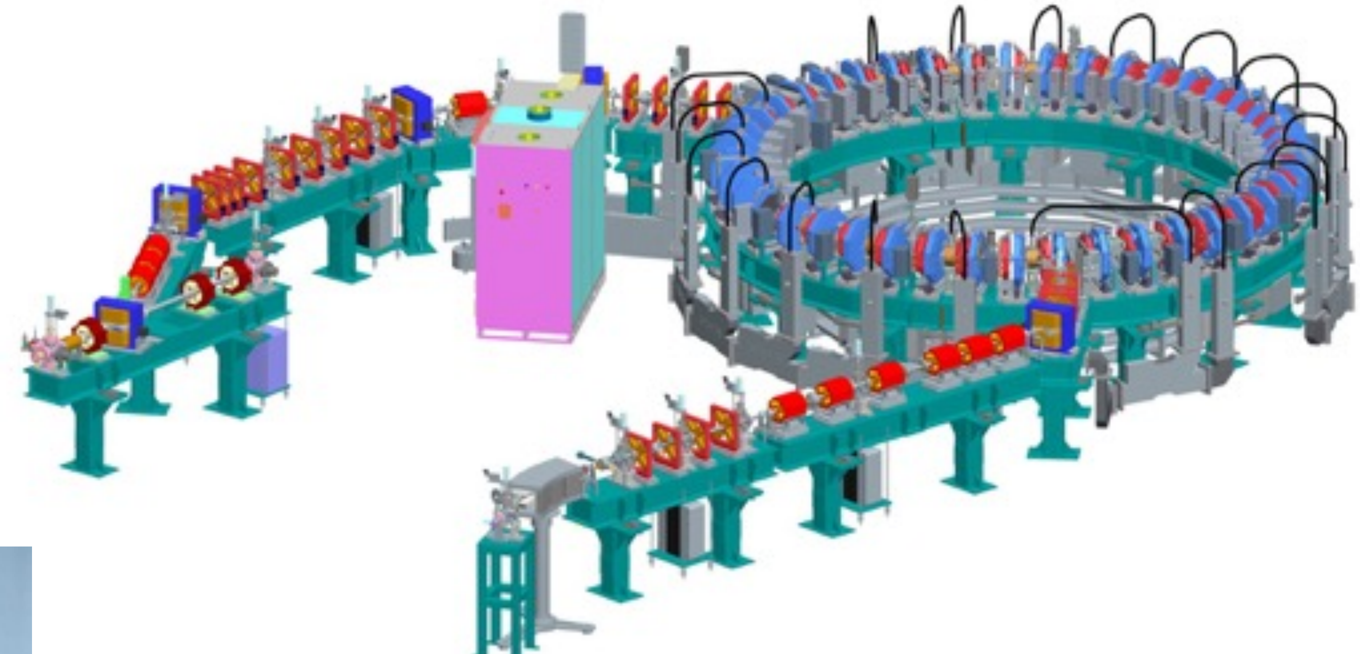
S. Sheehy et al, MOPJE077 at IPAC'15

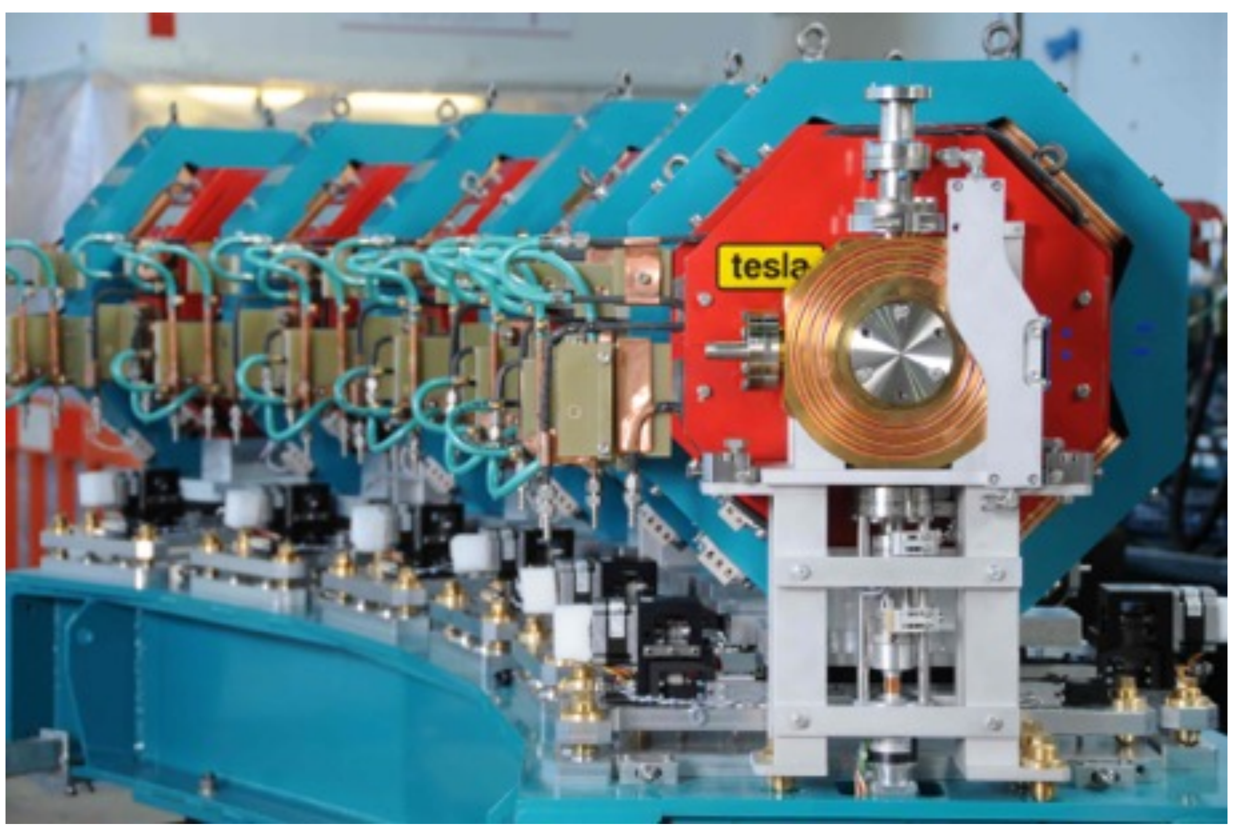
The ‘EMMA’ accelerator

42 Quadrupole doublets

10-20 MeV e-

Demonstrates **‘non-scaling’ FFAG**



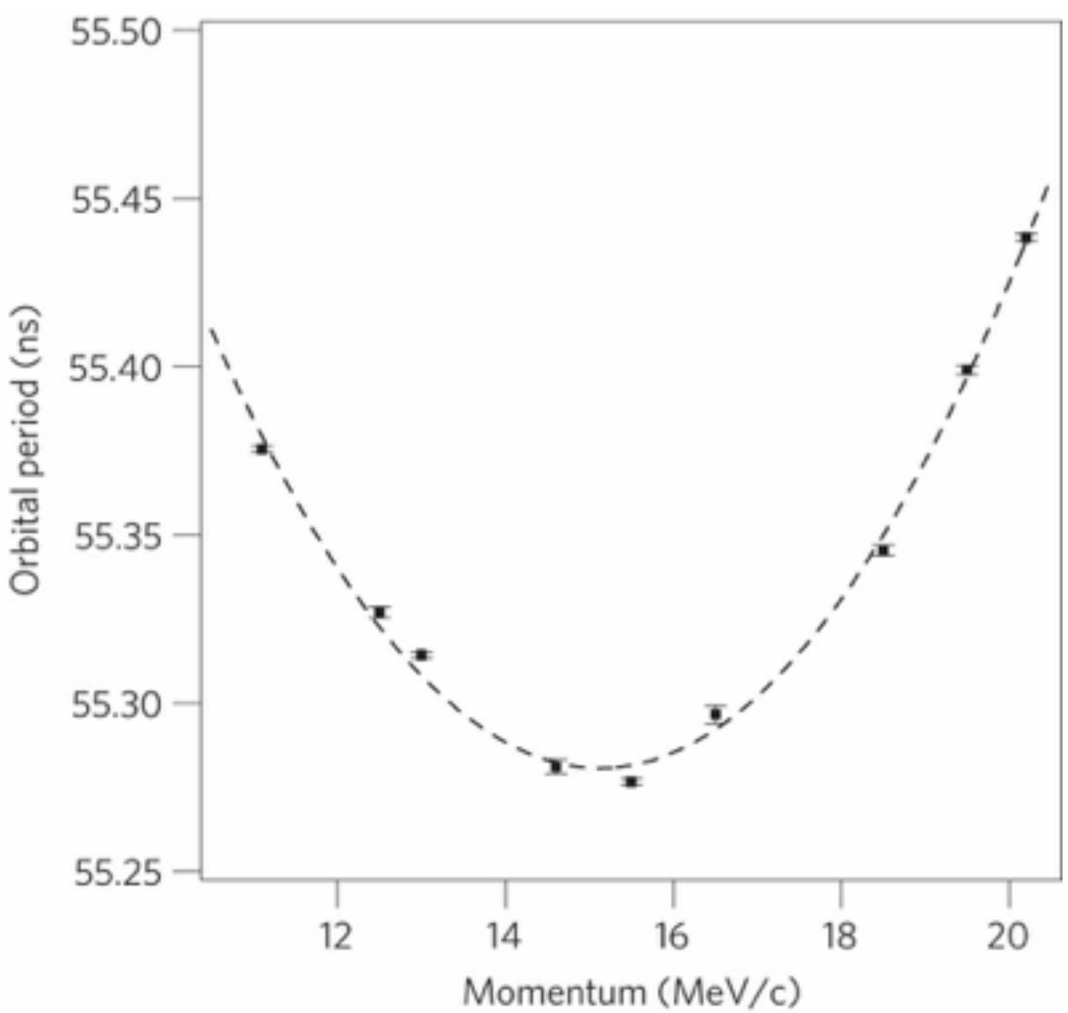


‘Electron Model for Many Applications’
= EMMA

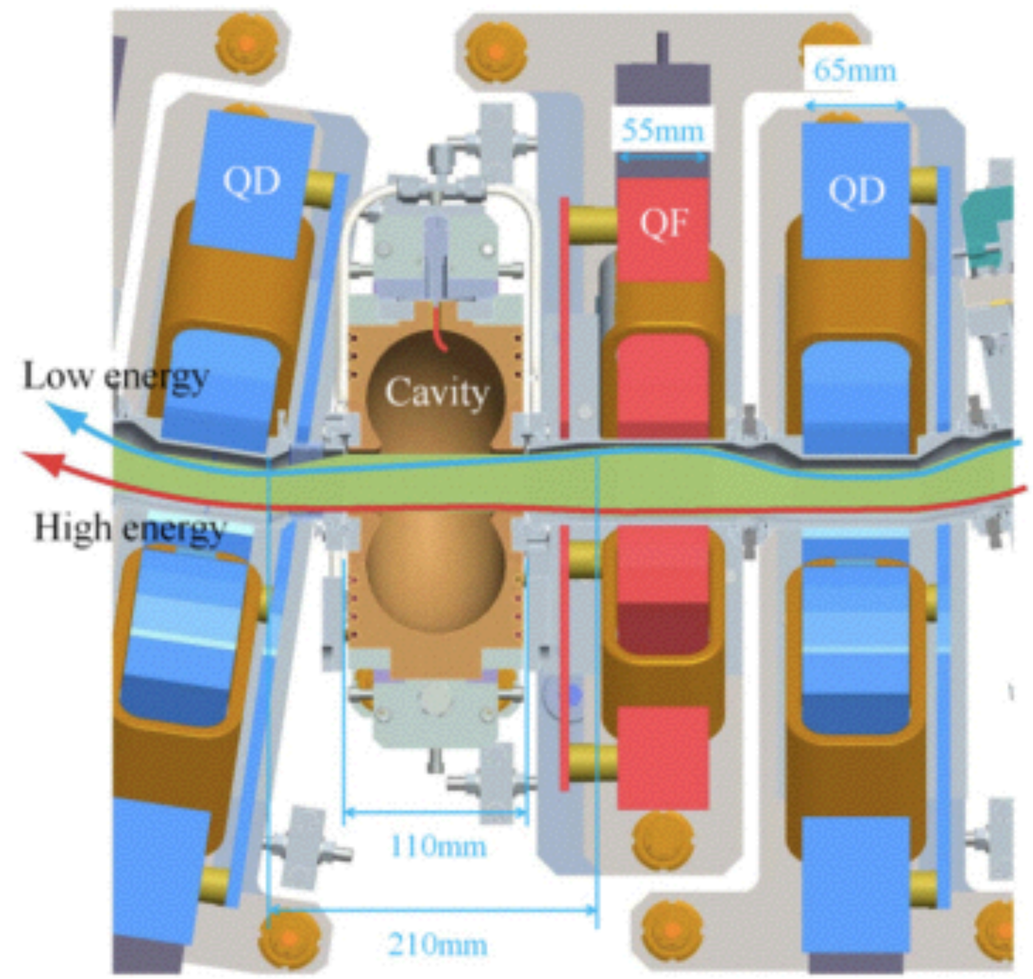
Built and commissioned at STFC
Daresbury Laboratory, UK

The ‘EMMA’ accelerator

Revolution time varies (a little)



Beam orbit moves
~ 5cm during acceleration



EMMA - Diagnostics

82 button BPMs

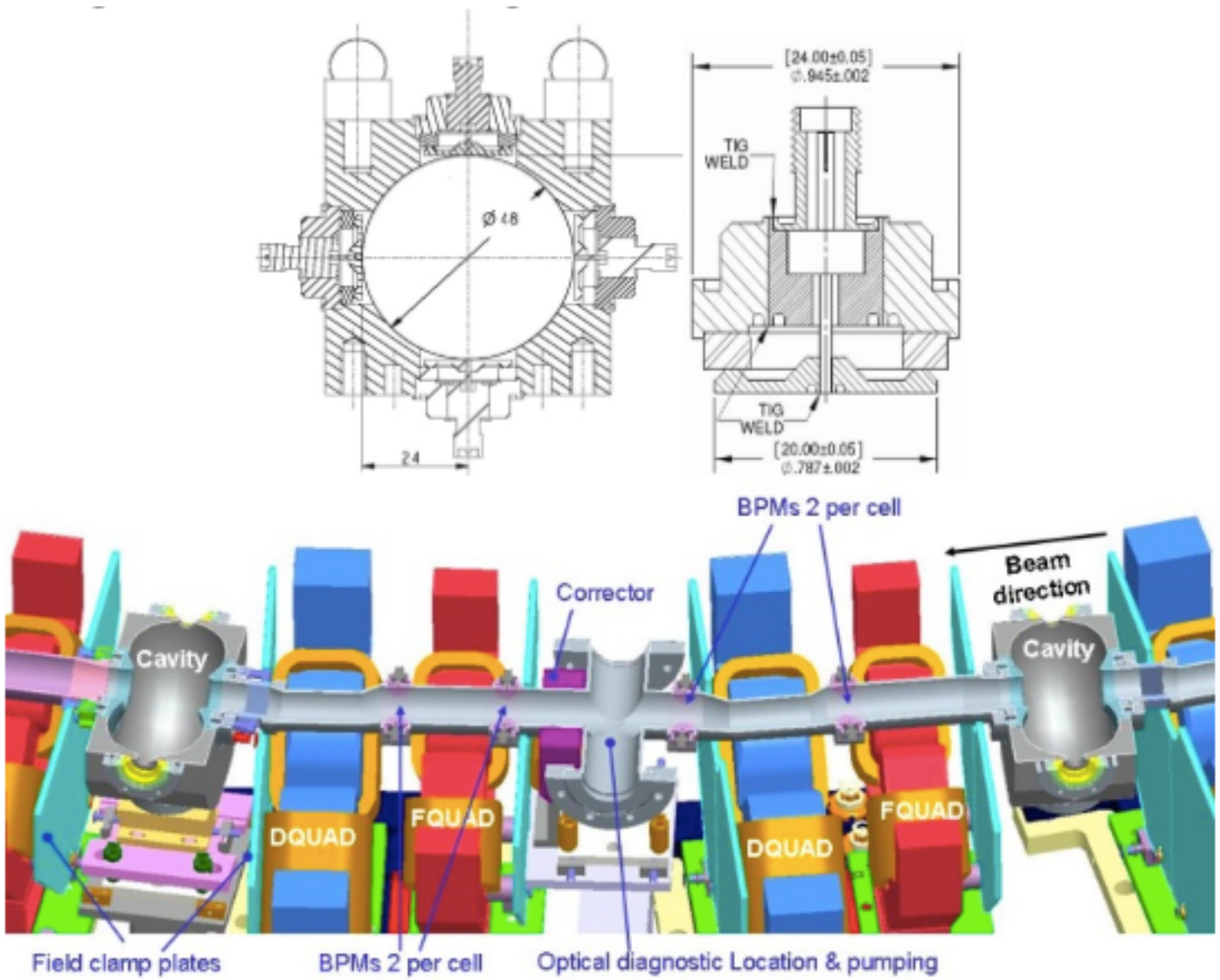


Figure 1: A typical EMMA BPM pickup and Installation.

Table 1: EMMA Diagnostic implementation

Measurement	Device	Number	Required resolution
Beam position RING	4 button BPM	82	50 um
Beam position INJECTION	4 button BPM	7	50 um
Beam position EXTRACTION	4 button BPM	5	50 um
Beam profile RING	Screens	2	100 um pixel size
Beam profile INJECTION	Screens	5	100 um pixel size
Beam profile EXTRACTION	Screens	6	100um pixel size
Beam current ALL	Wall Current Monitor (WCM)	3	5%
Transmission	WCM	As Above	5%
Transmission	Faraday Cup	2	5%
Momentum RING	BPMs and WCMs		100 keV
Momentum EXTRACTION	Spectrometer	1	1%
Emittance INJ/DIAG	Screens	3	10%
Longitudinal profile EXTRACTION	Electro Optic station	1	20 keV and 5 degrees

A. Kalinin, http://accelconf.web.cern.ch/accelconf/ipac2011/papers/wepc158.pdf

EMMA - Lessons learned

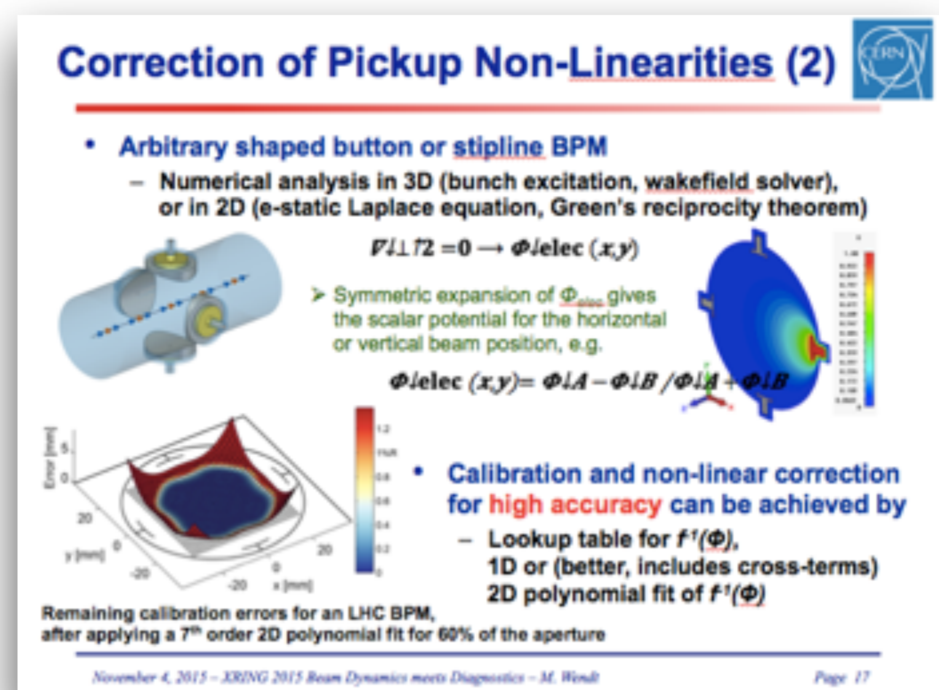
“We need a BPM which covers the beam position measurement in the **entire aperture** with good **precision**.

In synchrotrons, the beam is supposed to be near the centre and the accuracy should be guaranteed only around the centre.

In cyclotrons, the situation is similar to FFAGs, but the beam moves quite fast per turn so that it is no use to demand the similar **accuracy** of synchrotrons/FFAGs.”

- Shinji Machida, RAL.

“Beam dynamics is demanding for diagnostics”'



cf. LHC where BPM is corrected for 60% of aperture (M. Wendt)

Future Challenges

How could we do beam-based alignment in FFAGs?

It is not clear to me how we could use the beam based alignment. Again, FFAG does not have an ideal orbit. In synchrotrons, we find an 'ideal' orbit which does not move when quadrupole strength changes. Once we find it, we can calibrate BPM position. Such a technique does not work in FFAGs. I asked this at the FFAG workshop at BNL because people seem to assume it is possible. I do not think I heard a clear answer.
- S. Machida, RAL

How could we measure & control high power beams in FFAGs?

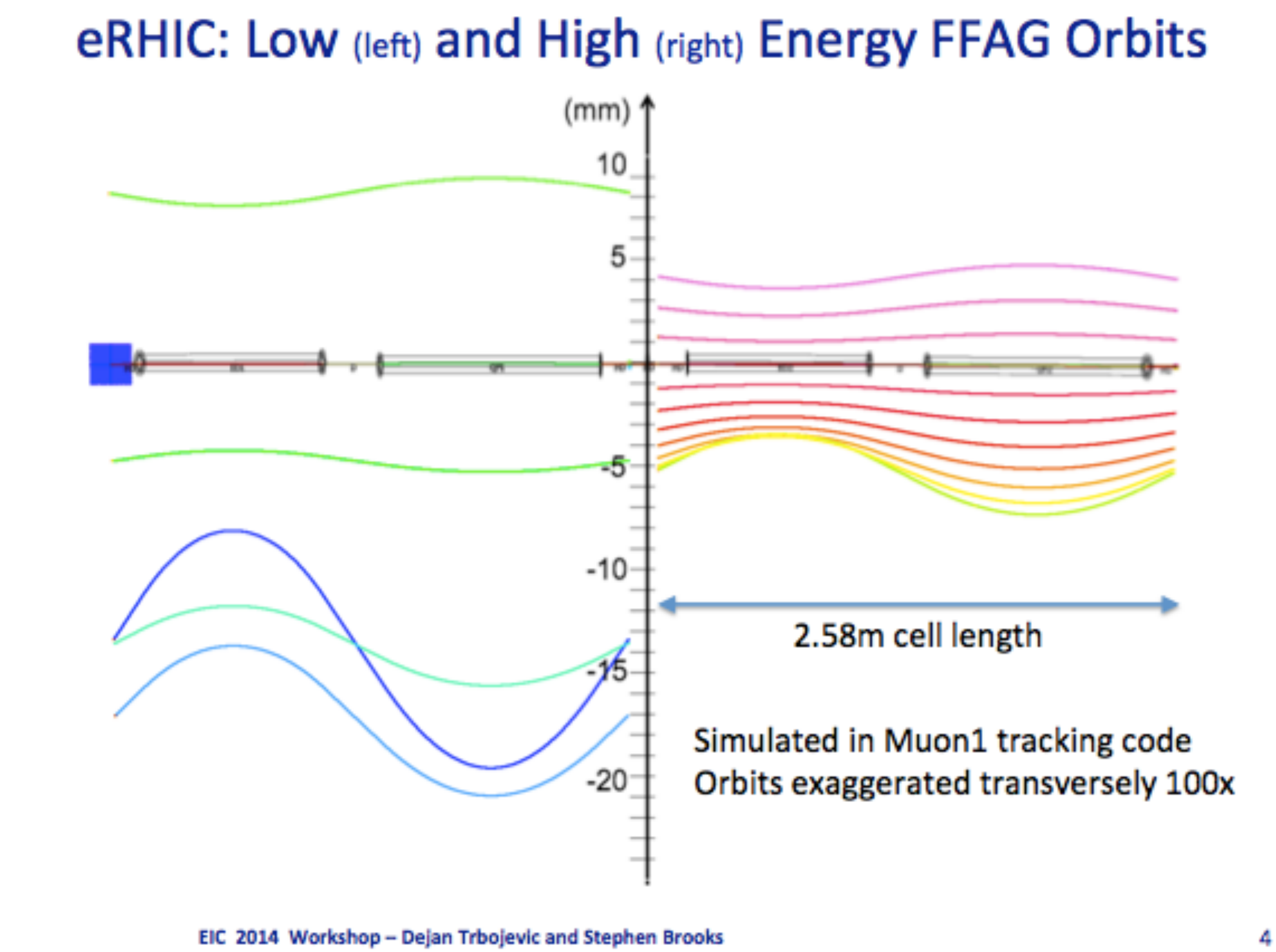
In high intensity synchrotrons, collimation to localise the beam loss is rather essential. Is it easier or harder in FFAGs? ‘

How can we measure very large beams (ie. muons) in a few turns?

Perhaps there is still a need to develop (improve) our ability to measure precisely multiple parameters of very large beams in only a few turns for muon applications (in ~6 for PRISM and ~100 for nuSTORM). - J. Pasternak, Imperial College

eRHIC challenges

Diagnostics for multiple beams in eRHIC, and related multiple orbit control.
Up to 12 beams in one of the two recirculating FFAG rings.
F. Meot, BNL



S. Brooks. EIC 2014

Summary

- FFAGs have unique beam dynamics properties
- These can sometimes make life more difficult, but can sometimes help
- Many new challenges to face
- Perhaps you already know the answers…?
- Both beam dynamics & diagnostics must work together