FFAG diagnostics and challenges

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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

![Diagram of FFAG with focusing and '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
Scaling FFAG
Injection 11 MeV,
H- charge exchange
up to 100 or 150 MeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_0$</td>
<td>4.54 m</td>
</tr>
<tr>
<td>Cell structure</td>
<td>DFD</td>
</tr>
<tr>
<td>$N_{cells}$</td>
<td>12</td>
</tr>
<tr>
<td>k, field index</td>
<td>7.6</td>
</tr>
<tr>
<td>Injection Energy</td>
<td>11 MeV</td>
</tr>
<tr>
<td>Extraction Energy</td>
<td>100 or 150 MeV</td>
</tr>
<tr>
<td>$f_{rf}$</td>
<td>1.6-5.2 MHz</td>
</tr>
<tr>
<td>$B_{max}$</td>
<td>1.6 T</td>
</tr>
</tbody>
</table>
Diagnostics in the ring

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

<table>
<thead>
<tr>
<th>Port</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>radial probe removed</td>
</tr>
<tr>
<td>F1</td>
<td>radial probe</td>
</tr>
<tr>
<td>S2</td>
<td>radial probe / hor. perturbator</td>
</tr>
<tr>
<td>S3</td>
<td>vert. perturbator</td>
</tr>
<tr>
<td>S5</td>
<td>movable bunch mon.</td>
</tr>
<tr>
<td>F5</td>
<td>radial probe</td>
</tr>
<tr>
<td>S6</td>
<td>radial probe</td>
</tr>
<tr>
<td>S7</td>
<td>bunch monitor</td>
</tr>
<tr>
<td>S8</td>
<td>radial probe</td>
</tr>
<tr>
<td>F7</td>
<td>Faraday cup / screen monitor</td>
</tr>
<tr>
<td>S9</td>
<td>radial probe</td>
</tr>
<tr>
<td>S11</td>
<td>bunch mon. (array of triangle plates)</td>
</tr>
<tr>
<td>S12</td>
<td>bunch monitor</td>
</tr>
</tbody>
</table>

Diagram courtesy Y. Ishi
What do we want to measure? (1)
Beam orbit movement with radius

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

Volts

H- peak

protons turn-by-turn

time
Probe intercept method

Norm. response = peak of \( n \)th turn
peak of 0\(^{th} \) (H−) turn

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

Radial probe & magnet triplet
What do we want to measure? (2)

Beam orbit movement with radius

- closed orbit
- ‘smeared out’ betatron oscillations

![Graph showing "time-to-loss" measurement with acceleration]

"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.

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

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

betatron tunes

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

Table 1: EMMA Diagnostic implementation

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

Figure 1: A typical EMMA BPM pickup and Installation.

“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

**eRHIC: Low** *(left)* **and High** *(right)* **Energy FFAG Orbits**

Simulated in Muon1 tracking code
Orbits exaggerated transversely 100x

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