Is bigger always better?

Exploring compact fixed field accelerators for intense proton beams

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Outline

• High power proton accelerators
• FFAG accelerators
• Beam dynamics issues
• High intensity issues
• Kyoto University (KURRI) FFAG collaboration
• Paul Trap experimental collaboration
• Future plans

Thanks to:
Members of the ASTeC IB Group
The KURRI-FFAG collaboration (Japan, UK & US)
Prof. Okamoto’s group at University of Hiroshima
High power proton accelerators are useful

- Neutron spallation sources - (ie. ISIS)
- Next generation particle physics experiments
- Accelerator driven systems
- Fusion materials irradiation
- Isotope production
What is ‘high power’?

**Beam Power:**

- **Particle Energy [GeV]**
  - High E vs size
  - ×

- **Particules per beam [ppp]**
  - Spallation sources up to $10^{14}$
  - ×

- **Repetition rate [Hz]**
  - CW ideal, high rep rate better

What is ‘high power’?
Achieved beam power

Image credit: J. Wei, ‘The very high intensity future’, IPAC’14
... but they are very challenging machines

- Keep activation to ‘hands-on’ levels
- Challenging target technology
- Thermal and power management
- Space charge and instabilities
- Injection and extraction issues

450 GeV proton beam on metal target
In the future we will face additional challenges…

- **High power**: Neutrons, muons, ADS
- **Reliable**: Medical, ADS
- **Flexible**: Is industry limited by existing technology?
- **Rapid acceleration**: Muon beams
  Unstable nuclei
- **Cost**: Hadron accelerators aren’t known for being cheap
Fixed-field magnets have advantages

- Simple power supplies and no synchronisation issues
- You can accelerate very quickly (as fast as your RF allows…)
  
  (I’ll discuss machines where this means ~10 turns)

- Higher repetition rate, so higher average current.
The FFAG idea is not so new...

1956

Scaling FFAGs follow ‘cardinal conditions’

The orbits are made ‘similar’

\[
\frac{\partial}{\partial p} \left( \frac{\rho}{\rho_0} \right) \bigg|_{\theta = \text{const.}} = 0
\]

- \( \rho_0 \): Average bending radius
- \( \rho \): Local bending radius
- \( \theta \): Generalised azimuth

The ‘field index’ is constant

\[
\frac{\partial k}{\partial p} \bigg|_{\theta = \text{const.}} = 0 \quad k = \frac{r}{B} \left( \frac{\partial B}{\partial r} \right)
\]

\[
B_y(r) = B_0 \left( \frac{r}{r_0} \right)^k
\]
Scaling FFAG

• If the field profile is of this form, the ‘cardinal conditions’ are satisfied.

• We call this type of FFAG a ‘Scaling’ type.

• Alternating magnets have opposite bending fields

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

• Note that this field profile does NOT satisfy isochronicity

\[ \frac{eB}{m\gamma} \neq \text{const.} \]
The FFAG idea was re-awakened

- In the late 90’s and in 2000’s
- Particular focus on hadron FFAGs of scaling type

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

3-stage FFAG for ADSR studies

2.5 MeV spiral (ion beta) FFAG with induction cores

25 MeV radial (booster) FFAG with RF

150 MeV radial (main) FFAG with RF

+other machines built
What about high power FFAGs?

FFAGs have not yet demonstrated:

1. High bunch charge capability
2. The fundamental limitations of FFAGs with high current beams
3. High rep. rates in the kHz range (at high E) or CW beams
4. Better reliability than a synchrotron

We want to try to address (1) and (2).
• High power proton accelerators
• FFAG accelerators
• Beam dynamics issues
• High intensity issues
• Kyoto University (KURRI) FFAG collaboration
• Paul Trap experimental collaboration
• Future plans
150 MeV ADSR FFAG

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

\[ B_y = B_0 \left( \frac{r}{r_0} \right)^k \]

<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>
Beam parameters

With linac & H- injection:
10nA average current (N=3.12 E+9 ppp)
100 MeV, 20Hz rep rate
Bunch length < 100 us (injected), 0.1 us (extracted)

Average beam power = $10^{-9}$ [A] * $100*10^6$ [eV] = 1 W

Duty cycle factor: 0.1 us @ 20Hz = $1/(0.1E-6*20) = 5E+5$
Instantaneous beam power = 500 kW
Tune shift due to space charge effects

\[ \Delta \nu_{y, \text{inc}} = -\frac{N r_0 R}{\pi \nu_{y, \beta^2 \gamma}} \left( \frac{\beta^2 \varepsilon_1}{\hbar^2} + \frac{\beta^2 \varepsilon_2}{g^2} + \frac{F/B}{\gamma^2 b (a + b)} \right) \]
\[ = -2.25 \times 10^{-5} \text{ m}^{-2} \times (4. \text{ m}^2 + 3. \text{ m}^2 + 14004. \text{ m}^2) \]
\[ = -0.315 \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N)</td>
<td>(3.12 \times 10^{11})</td>
</tr>
<tr>
<td>(r_0)</td>
<td>(1.53 \times 10^{-18}) proton</td>
</tr>
<tr>
<td>(R_0)</td>
<td>4.54 m</td>
</tr>
<tr>
<td>(\beta, \gamma)</td>
<td>0.147, 1.011 11 MeV</td>
</tr>
<tr>
<td>(\nu_x, \nu_y)</td>
<td>(3.7, 1.4)</td>
</tr>
<tr>
<td>((a, b))</td>
<td>(20, 15) mm</td>
</tr>
<tr>
<td>(B_f)</td>
<td>1/5</td>
</tr>
<tr>
<td>(F)</td>
<td>1.5</td>
</tr>
<tr>
<td>(h)</td>
<td>32.5 mm</td>
</tr>
<tr>
<td>(g)</td>
<td>37.9 mm</td>
</tr>
</tbody>
</table>

Rep. rate: 100 ~ 200 Hz
Average current: 5uA

Y. Ishi, FFAG’14
upgrade schedule

- Reduce beam losses due to:
  - multiple scattering with the foil (fast acceleration / bump)
  - spill out of rf capture (optimization of the rf pattern)
  - betatron resonances (COD correction, fast acceleration)
    \[ \rightarrow \times 10 \]
- Raise the repetition rate from 20 Hz to 100 Hz
  - install 2nd cavity (now ready to install)
    \[ \rightarrow \times 5 \]
- Increase the ion source current
  \[ \rightarrow \times 2 \]

Aim for 1uA by the end of FY 2015

Y. Ishi, FFAG’14
Diagnostics in the ring

List of monitors

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

<table>
<thead>
<tr>
<th>Monitors</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>(F6)</td>
<td>Faraday cup / screen monitor</td>
</tr>
<tr>
<td>S7</td>
<td>bunch monitor</td>
</tr>
<tr>
<td>F7</td>
<td>radial probe</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
Examples of diagnostics
Orbit Matching

- The beam follows a complicated trajectory from the injection line through to the stripping foil.
- The horizontal orbit is currently optimised ‘by hand’ to ensure the largest transmission…
- Centre of foil is not necessarily optimal…!

Vertical matching:

Match the vertical orbit using 3 steerers in injection line, using vertical double plate BPM to minimise vertical coherent oscillation

Showed existing empirical optimisation was fairly successful.

Figure from S. Machida, 24/3/14
Closed Orbit Distortion (no RF)

Norm. response = \frac{\text{peak height of } n\text{th turn}}{\text{peak height of } 0^{th} \text{ (H−) turn}}
Closed orbit distortion

Cavity 50 mrad kick

From Y. Ishi 1/11/2013
Closed Orbit Distortion with RF

- Study effects of corrector with RF cavity in place
- Closed orbit measurement with acceleration

Beam spirals outward as it is accelerated

$t=0$, Probe doesn't stop beam

$t=\text{time to loss}$, Probe will fully stop beam after a few turns

$t=\text{time to loss}$, Probe fully stops beam
COD Correction

Correction methods tried:

1) Main corrector pole

   We achieve some correction, but it is not perfect, even with highest possible current

2) Additional coils on main magnet

   Not successful at present - complex excitation of magnets
Main losses appear to correspond to various resonances

Example of beam loss (measured total bunch charge) during acceleration cycle
Tune measurement

Acceleration + flat top
Radially movable ‘perturbator’
Radially movable BPM
RT Spectrum analyser

![Graph showing Qx vs Qy with data points for July 2014 and October 2014.]
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)
Dispersion

We have measured the dispersion:

- in the main ring
- at the position of the foil
- at a ‘slit’ before injection

All have different methods!

\[ D \approx 0.6 \]

Three probes give slightly different results

\[ D = \frac{dr}{dp/p} \]
Dispersion at the foil
“Equivalent momentum method”

- Tune and profile at foil with different magnetic strength

Set D such that tune is the same

no ‘flat top’
tells us beam bigger than foil!

Translate current to field strength

S. Machida

T. Uesugi
Dispersion control: Dispersion at the slit before injection

1. Setup transfer line with calculated magnet settings
2. Adjust BM2, Q6, BM3, Q7, Q8 by ratio (-2%, -1%, 0%, +1%, +2%)
   - Move slit after Q8 and record bunch monitor signals on M1 & M2 for each slit position
   - ‘Peak ratio’ = P2(H- peak)/P1
Experimental data

Setup 1
(usual)

Setup 2
30/06/14
nb. lower transmission.
Dispersion results

Setup 1
\[ D = \frac{dx}{(dp/p)} = -0.18 \text{m} \]
\[ dI \sim dB \sim -1.0 \times dp \]
cf. From inj. line model
\[ D(sl) = -0.431 \]

Setup 2
\[ D = \frac{dx}{(dp/p)} = -0.36 \text{m} \]
cf. From inj. line model
\[ D(sl) = -0.981 \]

We found that the measured dispersion is not that predicted by the model - by more than a factor of two.
Why is the dispersion not as predicted?

- In high D’ region, D can easily vary with small errors in magnet field setting.

It is very important to understand the real field of injection line magnets!
Foil energy loss

Simulation performed by C. Rogers in Geant 4 for varying target thicknesses to see energy loss and distribution

- turn 0
- turn 30
- turn 70

20 ug/cm² foil
Foil energy loss

Method: synchronous phase measurement as a function of RF voltage

1. check set RF frequency by circulating a bunch with RF off
2. set RF voltage & inject beam, find peaks in bunch monitor signal vs those in RF signal to determine phase offset
3. fit phase vs RF voltage to determine energy change per turn

\[ dW = V_0 r_c \sin(\phi_s + \phi_c) \]

Preliminary data had some issues
We have re-done the experiment
Still analysing…
Foil scattering

- Need to establish emittance growth from foil vs emittance growth from space charge

- Look at effect of foil on beam emittance
  - No RF
  - Inject 8 micron geometric emittance
  - Lose 50% of beam in first 200 turns
  - Injection cycle is ~ 160 - 1200 turns

C. Rogers

Lower emittance growth for 10 μg/cm² foil
Current status of experiments

- Optics matching (in progress with new fluorescent monitor system)
- Full analysis of foil energy loss data
- Detailed simulation work planned including space charge
- Develop methods for emittance growth measurement (wire scanner)
- New RF cavity being installed in early 2015
- Longitudinal studies in early 2015 in planning stages
• FFAG accelerators
• Beam dynamics issues
• High intensity issues
• Kyoto University (KURRI) FFAG collaboration
• Paul Trap experimental collaboration
• Future plans
...the non-scaling FFAG has been realised

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
Non-scaling FFAGs cross betatron resonances

\[ n\nu_x + m\nu_y = 0, 1, 2, \ldots \]

- There are many resonance lines in tune space
- Normally, particles would be lost on resonance, but if the resonance is weak and the crossing is fast the beam can survive.
- The strongest are integer resonances, which are crossed in EMMA…
Results from EMMA

Orbit and tune shift with momentum

No beam ‘blowup’ despite resonance crossing

Can a chromatic proton FFAG work?

- Lattice 1 (blue) crosses 12 integers
- Lattice 2 (pink) crosses 3 integers
- Lattice 3 (green) doesn't cross any

How can we study resonance crossing?

*Resonance crossing*, particularly of integers is a *key concern* in the FFAG community, particularly with the development of non-scaling FFAGs.

In EMMA and other accelerators, it can be difficult to do slow resonance crossing studies due to:

- Limited parameter range (RF)
- Coupling to longitudinal plane
- Lack of range of control for driving terms
- Time consuming experiments

![Graph showing resonance crossing](image-source)

Slow resonance crossing in EMMA, all particles lost for tune crossing rate 0.01 to 0.1/turn (ring tune)

Image source: J. Garland.
There are many questions to address…

- Can we mitigate resonance crossing effects in FFAGs?
- How do nonlinear effects come into play?
- Does space charge make a difference?
S-POD: Simulator of Particle Orbit Dynamics

at Hiroshima University

S-POD is a tabletop sized linear Paul trap device which can simulate a linear focusing channel in an accelerator (including space charge)
Why is S-POD suitable for our studies?

- Hamiltonians in the two systems have correspondence

\[ H_{\text{beam}} = \frac{p_x^2 + p_y^2}{2} + \frac{1}{2} K(s)(x^2 - y^2) + \frac{q}{p_0\beta_0 c\gamma_0^2} \phi \]

Hamiltonian for transverse beam motion

\[ H_{\text{S-POD}} = \frac{p_x^2 + p_y^2}{2} + \frac{1}{2} K_p(\tau)(x^2 - y^2) + \frac{q}{m c^2} \phi_{sc} \]

Hamiltonian for Paul trap
How does S-POD work?

Linear Paul traps are ‘standard’ devices for confinement of non-neutral plasmas

- Ar+ gas ionised by e- gun
- Trapped longitudinally in a potential well
- 1 MHz confinement wave applied to quadrupole rods
- Add a perturbation wave
S-POD Collaboration so far

Prof. Hiromi Okamoto’s group in Hiroshima

Preliminary results shown in IPAC’13 and IPAC’14 papers

First PRSTAB paper currently going through peer review
Method of S-POD Experiments

In many cases, it is faster to carry out the S-POD experiment than to run the equivalent simulation.

Control the tune by varying voltage of RF wave.

In an accelerator focusing varies with s. In S-POD we vary focusing with time.

We can (in principle) have any lattice structure we like - FODO, FDF, FDDF etc...

Wait some period (accumulation time), then extract remaining plasma onto MCP.

Measure remaining ions and/or time-integrated distribution.
Motion with dipole perturbation

Quadrupole focusing

\[ \frac{d^2 x_{\text{COD}}}{ds^2} + K_x(s)x_{\text{COD}} = -\frac{\Delta B}{B\rho} \]

COD equation of motion in circular accelerator

Dipole perturbation

\[ \frac{d^2 x}{d\tau^2} + K_{rf}(\tau)x = -\frac{q}{mc^2r_0}V_D(\tau) \]

Equation of motion in S-POD with dipole perturbation field
Establishing integer stopbands with dipole perturbation

- On resonance, we clearly see large ion losses
- Can also see a clear widening in the distribution

Note that we can excite each integer individually by expanding dipole field into fourier harmonics:

\[
\frac{\Delta B}{B \rho} = \sum_{n} b_n \cos(n\theta + \phi)
\]
Amplitude growth with error

We wanted to confirm amplitude growth when OFF RESONANCE as well

Theory = Gaussian distribution integrated over COD trajectory

\[ \text{tune} = 8.1, \text{ varying perturbation strength} \]

\[ w_8 [V] \]

\[ \text{FWHM [mm]} \]
Single resonance crossing

crossing speed, \[ u = \frac{\delta v_{\text{cell}}}{n_{\text{rf}}} \]

In EMMA, for 10 turn extraction \( u \) is roughly \( 5 \times 10^{-4} \) if the tune per cell decreases by 0.2 during acceleration
Amplitude growth vs. crossing speed

Critical perturbation voltage at which the maximum transverse shift of the plasma centroid reaches 5 mm (the LPT aperture) after single resonance crossing at $v_0 = 8$

nb. we use the non-smooth formula to find g coefficient for amplitude growth

$$\Delta A_n = g_n \frac{w_n}{\sqrt{u}}$$
Double resonance crossing

- Single crossing for comparison (black)
- Oscillatory behaviour for high perturbation strength... why?
Phase dependent effects

Vary phase of 8th harmonic, cross 9th & 8th

Fixed perturbation
Varying crossing speed

Fixed crossing speed
Varying perturbation
Nonlinear effects

- If purely linear, ion survival would always go to zero eventually...
- ‘Plateau’ effect observed and studied
- With amplitude dependent tune shift, particles shift off-resonance

![Graph showing ion survival fraction versus time with different warp voltages.](image)

- Warp simulation
- 0.5% 4th order nonlinear field
- $w_8 = 0.05$ [V]
- $w_8 = 0.1$ [V]
- $w_8 = 0.5$ [V]
- $w_8 = 1$ [V]
- $w_8 = 2$ [V]
Future collaborative research topics

This technique has wide-ranging applications and will allow us to establish understanding in beam dynamics topics which are vital for the design of future high power proton or ion accelerators.

Completed:

- Integer resonance crossing:
  - Single & double crossing, phase-dependent effects, nonlinear effects

Current:

- Effects of coupling, detuning effects due to nonlinearities, long term effects

Future:

- Combination of the resonance crossing with intense beams is a natural extension
- Lattice variants and higher order stability regions
- Systematic study and control of non-linear effects (possible CERN PS topics)
- More general non-linear beam dynamics (with ISIS & CERN)
S-POD at RAL

• We are building an S-POD “Simulator of Particle Orbit Dynamics” ion trap apparatus at RAL.

• Complementary to the existing setup at Hiroshima and built in close collaboration.

• We hope to control non-linear component

• Study non-linear phenomena and space charge effects.

• Lots of interest from accelerator community already!

So where are we now?

- Working to understand the real potential of FFAG accelerators
- Hope we can build confidence in idea of a high power compact FFAG

Issue of integer resonance crossing studied in detail

Potential to use Paul traps to look at many topics of interest to community —> Building a new Paul trap system at RAL

Continuing experimental work with the KURRI FFAGs

Simulation progressing in parallel with experiments
Thanks for your attention

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Thanks to:
Members of the ASTeC IB Group
The KURRI-FFAG collaboration (Japan, UK & US)
Prof. Okamoto’s group at University of Hiroshima
• extra slides...
Dispersion distortion

D. Kelliher

- What is effect of dipole kick on dispersion? Calculate the off-momentum COD in Zgoubi with the dipole kick and find $D_{\text{kick}}$.
- The dispersion distortion is defined as $D_{\text{kick}} - D_{\text{ideal}}$.
- The distortion in dispersion looks similar to the COD itself, though with the opposite sign.

nb. COD measurement
Dispersion at the foil

- Measured dispersion function at foil after B calibration.
  \[ \frac{dr}{-dB/B} = -0.59 \pm 0.07 \]

- Good agreement with Malek’s calculation.
  \[ \frac{dr}{dp/p} = -0.57 \]

nb. definition of dispersion in a transport line

\[
\begin{pmatrix}
D_f \\
D'_f
\end{pmatrix}
= \begin{pmatrix}
m_{11} & m_{12} \\
m_{21} & m_{22}
\end{pmatrix}
\begin{pmatrix}
D_i \\
D'_i
\end{pmatrix}
+ \begin{pmatrix}
D_p \\
D'_p
\end{pmatrix}
= \begin{pmatrix}
0.52 \\
-0.033
\end{pmatrix}
\]

S.Y. Lee ‘Accelerator Physics’ pp. 116
‘Dispersion vector’

using transfer matrix from tracking

Is fairly consistent with 0.6 value in ring
Dispersion at the foil

“Equivalent momentum method”

- Tune and profile at foil with different magnetic strength

Set D such that tune is the same

no ‘flat top’
tells us beam bigger than foil!

Translate current to field strength

S. Machida

T. Uesugi
Dispersion and COD calculation

D. Kelliher

- Starting with field in a scaling FFAG
  \[ B_z = B_{z0} \left( \frac{r}{r_0} \right)^k \]
- Can show dispersion D is given by
  \[ D = \frac{r}{k+1} = \frac{r_0}{k+1} \left( \frac{p}{p_0} \right)^{\frac{1}{k+1}} \]
- Calculate off-momentum closed orbit in Zgoubi, compare dispersion with prediction

- A large (+/- 30 cm) COD is measured at the probes.
- We determined that the major source of COD is in the cavity region. Simulate in Zgoubi model by introducing kick in middle of single drift.