The IBEX Paul Trap: Studying accelerator physics without the accelerator

JAI Introducing Seminar
21/5/2015

Dr. Suzie Sheehy
John Adams Institute for Accelerator Science
& STFC/ASTeC Intense Beams Group
Oct 2007 - Oct 2010

**DPhil, Oxford**
Design of a non-scaling fixed field alternating gradient accelerator for charged particle therapy

Nov 2010 – Nov 2013:

**Research Fellowship (Brunel Fellow)**
“Novel high power proton accelerators” based at RAL
Focus on simulations of novel high power accelerators
http://www.royalcommission1851.org.uk/
Collaborating with FNAL, PSI + others

Nov 2013 – March 2015:

**Senior Accelerator Physicist**, ASTeC Intense Beams Group, RAL
Collaborating with Kyoto University, University of Hiroshima, CERN

April 2015 - present

**Researcher**, Joint Appointment
JAI/University of Oxford and STFC/RAL/ASTeC Intense Beams Group
Topic: High intensity hadron beams
Challenges in accelerator simulation
Challenges in accelerator simulation

Every particle feels coulomb force…
… from every other particle
Challenges in accelerator simulation

And are moving

...more forces & calculations
Challenges in accelerator simulation

There’s a beam pipe as well… which interacts with the beam
Challenges in accelerator simulation

It’s not always easy to include imperfections, can’t always simplify…
\[ H_{\text{beam}} = \frac{p_x^2 + p_y^2}{2} + \frac{1}{2} K(s)(x^2 - y^2) + \frac{q}{p_0 \beta_0 c \gamma_0^2} \phi \]
S-POD: Simulator of Particle Orbit Dynamics at Hiroshima University
Paul Trap

Wolfgang Paul
Nobel Prize 1989 (shared)
\[ H_{\text{beam}} = \frac{p_x^2 + p_y^2}{2} + \frac{1}{2} K(s)(x^2 - y^2) + \frac{q}{p_0 \beta_0 c \gamma_0} \phi \]

Hamiltonian for transverse beam motion

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

Hamiltonian for Paul trap
Argon gas ionised by e- gun
Lattice Structures

- FDF
- FODO
- FDDDF

Quadrupole mode
Beam losses in SIS18 from tune scans


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

\[ n = 8 \]

Dipole perturbation

\[ +V_D \quad 0 \quad -V_D \]

(a) Sinusoidal 42 periods

Quadrupole

Dipole

(b) harmonic number \( n = 8 \)

Quadrupole

Dipole
**Motion with dipole perturbation**

**COD equation of motion in circular accelerator**

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

**Equation of motion in S-POD with dipole perturbation field**

\[
\frac{d^2 x}{d\tau^2} + K_f(\tau)x = -\frac{q}{mc^2r_0} V_D(\tau)
\]
Ion losses on resonance

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

$\text{nb: each image is axially integrated distribution}$
Establishing integer stopbands with dipole perturbation

3rd order due to trap misalignment

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

Theory = Gaussian distribution
integrated over COD trajectory

tune = 8.1, varying perturbation strength

We wanted to confirm amplitude growth when OFF RESONANCE as well
Single resonance crossing

crossing speed, \( u = \frac{\delta v_{cell}}{n_{rf}} \)

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

Oscillatory behaviour for high perturbation strength... why?

- Single crossing for comparison (black)
Phase dependent effects
Vary phase of 8th harmonic, cross 9th & 8th

- Fixed perturbation
  - Varying crossing speed

- Fixed crossing speed
  - Varying perturbation
Non-linear fields play a role too…

Many interesting phenomena occur in accelerators which could be studied if the non-linear components are controlled.

IBEX
Intense Beam Experiment

• Construction of a linear Paul Trap apparatus at RAL with funding from ASTeC (£77,000)

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

• Lots of interest from accelerator community already - FNAL (IOTA, S. Ngaitsev), CERN PS (M. Giovanozzi), ISIS (C. Warsop)
e-gun to ionize Ar

Slide courtesy H. Okamoto’s group, University of Hiroshima
Non-linear Paul trap

Future 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.”

• Combination of 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)

• **Integrable optics idea with FNAL**

• More general non-linear beam dynamics (with ISIS & CERN)
“Integrable Optics”

How to make the Hamiltonian time-independent?

\[
H_N = \frac{p_{x N}^2 + p_{y N}^2}{2} + \frac{x_N^2 + y_N^2}{2} + \beta(s)V(x_N \sqrt{\beta(s)}, y_N \sqrt{\beta(s)}, s) \\
V(x, y, s) = \frac{q}{\beta(s)^2}(x^2 - y^2) \\
U(x_N, y_N) = q(x_N^2 - y_N^2)
\]

Integrable but still linear…

Tunes:
\[
\nu_x^2 = \nu_0^2(1 + 2q) \\
\nu_y^2 = \nu_0^2(1 - 2q)
\]

Tune spread: zero
From IOTA Profile, A. Valishev, April 1, 2015
<table>
<thead>
<tr>
<th>Proposed Experiment</th>
<th>Trap Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-integer studies of ISIS and other rings.</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>Long-term stability studies at various intensities.</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>Benchmarking codes to simulate high intensity rings.</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>Halo production driven by space charge.</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>Comparison of different lattice types.</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>Resonance crossing studies in the presence of lattice non-linearities.</td>
<td>Quad-Octupole</td>
</tr>
<tr>
<td>Quasi-integrable optics.</td>
<td>Quad-Octupole</td>
</tr>
<tr>
<td>Space charge effects in scaling FFAGs.</td>
<td>Higher order trap</td>
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<td>Integrable optics (IOTA).</td>
<td>Higher order trap</td>
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</tbody>
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Interested in getting involved? Please get in touch!

Opportunities:
2 MPhys projects offered for 2015/2016:

1. A new electron gun for the Intense Beam Experiment (IBEX)

2. Design and simulation of a new multipole plasma trap for the Intense Beam Experiment (IBEX)