Status of the ISIS Upgrade: ISIS II

Chris Warsop

on behalf of the ISIS II R&D and Design Teams

4th ICFA Mini-Workshop on Space Charge 2019, CERN

4th November 2019
Contents

1. Requirements for Neutrons

2. ISIS II Plans: Working Group, Road Map, Project

3. Outline of current accelerator physics work
   3.1 FFA Rings
   3.2 Conventional AR and RCS Rings

4. Space Charge Work on Conventional Rings
   “Space Charge Issues in FFAs” covered in J-B Lagrange’s talk on Tuesday afternoon

5. Summary
What is the demand for neutrons in Europe?

ESFRI report – studied outlook
- Reduction in reactor based sources
- Longevity of ILL ...
- ... Commissioning of ESS
- Manage “gap” – avoid “neutron drought”
- A need to develop long term plans ...

UK Plans: STFC Advisory Panel, Strategic Reviews
- Need to “maintain UK’s internationally competitive ISIS facility”
- Need a detailed evaluation of UK’s neutron needs – a plan ⇒ ISIS II Working Group
2. ISIS Road Map – ISIS II

- ISIS II Working Group: look at options and establish a Road Map
  - Experts on Instruments, Neutronics, Target, Accelerator, Engineering
  - User driven: work back from “ideal instrument suite” – optimised for neutrons
  - Outline the studies to find the best facility upgrade options

- Need to evaluate options for
  - Short-pulse sources (proton pulse \(\sim 1 \mu\)s)
  - A new stand-alone facility – “green field”
  - A facility upgrade, reusing existing ISIS infrastructure
  - Study includes: Neutronics, Targets, Linacs, Rings, …

- Time outline:
  - 2017-2027 ~ Feasibility, design and R&D
  - 2027-2031 ~ Integrated facility technical design
  - 2031-2040 ~ ISIS II construction

- Here we concentrate on Rings part of Accelerator Study
  - Present emphasis is on reuse of infrastructure – more difficult (constrained)
  - Later studies address stand-alone – less demanding
2. ISIS II Accelerator Studies

The Recommended Route for ISIS II
Reuse of Existing ISIS

• Re-use of infrastructure
  • Upgrade 10 Hz TS2 for 0.25 MW
  • Build a new 40 Hz TS 3 for 1 MW
  • Phase out existing 40 Hz TS 1
  • Options for further upgrades

• New accelerator in existing synchrotron hall
  • 1.25 MW, 1.2 GeV Ring, ~ 50 Hz, R ~ 26 m
  • Consider conventional AR, RCS and FFA
  • New linac

• Accelerator options: optimal 1.2 GeV ring
  • FFA – exciting but unproven – R&D and prototype ring
  • AR/RCS – established solution – R&D for best design

• Optimise
  • Construction, operation costs
  • Performance, upgradability
  • ISIS impact, risks; environmental impact
Conventional or FFA Rings?

Why study both?
- Find optimal accelerator for the next generation ISIS II
- Compare best new vs established technology

<table>
<thead>
<tr>
<th>Ring</th>
<th>FFA</th>
<th>RCS</th>
<th>AR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet</td>
<td>DC large, complex</td>
<td>AC – fast ramp conventional</td>
<td>DC conventional</td>
</tr>
<tr>
<td>Rep rate</td>
<td>Flexible, high</td>
<td>Fixed &lt;= 50 Hz</td>
<td>Flexible, high</td>
</tr>
<tr>
<td>Linac costs</td>
<td>Lower (~0.4 GeV)</td>
<td>Lower (~0.4 GeV)</td>
<td>High (1.2 GeV)</td>
</tr>
<tr>
<td>Features</td>
<td>Large RF, Stacking</td>
<td>Large RF</td>
<td>Small RF, few turns</td>
</tr>
<tr>
<td>Will it work?</td>
<td>Need a test ring</td>
<td>Established</td>
<td>Established, simple</td>
</tr>
</tbody>
</table>

FFA Study
- Build an $R \sim 4$ m demonstrator ring, use FETS as injector (3 MeV)
- Verify key aspects of operation for high intensity
## 2. ISIS II Accelerator Studies
### Outline Ring R&D

<table>
<thead>
<tr>
<th>Dates</th>
<th>AR/RCS Ring Study</th>
<th>FFA Ring Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>Ref 1 designs:</td>
<td>Prototype ring design</td>
</tr>
<tr>
<td></td>
<td>RCS &amp; AR for ISIS Hall</td>
<td>Beam dynamics studies</td>
</tr>
<tr>
<td></td>
<td>RCS &amp; AR Green Field</td>
<td>Prototype hardware: magnets, ...</td>
</tr>
<tr>
<td>2021</td>
<td>Working designs done</td>
<td>Decide to build</td>
</tr>
<tr>
<td>2022</td>
<td>Ref 2 designs:</td>
<td>Construct test ring</td>
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<tr>
<td></td>
<td>R&amp;D, Optimise, HI limits</td>
<td>Experimental program: verify</td>
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<tr>
<td>2023</td>
<td>Finalise designs</td>
<td>Finalize designs</td>
</tr>
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<td></td>
<td>ISIS Hall, Green Field</td>
<td>ISIS Hall, Green Field</td>
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<tr>
<td>2025</td>
<td>Designs Complete -&gt; Design Costings</td>
<td>Decide AR/RCS or FFA</td>
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<tr>
<td>2026</td>
<td>Finalise chosen physics designs for accelerator type</td>
<td></td>
</tr>
<tr>
<td>2026-2027</td>
<td>Design Costings</td>
<td>Decide ISIS Hall or Stand Alone</td>
</tr>
<tr>
<td>2027-2031</td>
<td>Facility technical design</td>
<td></td>
</tr>
<tr>
<td>2031-2040</td>
<td>ISIS II construction</td>
<td></td>
</tr>
</tbody>
</table>
### 2. ISIS II Accelerator Studies

#### Outline Ring R&D

<table>
<thead>
<tr>
<th>Dates</th>
<th>Project Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td><strong>AR/RCS Ring Study</strong> (ISIS-II R&amp;D) Ref 1 designs: RCS &amp; AR for ISIS Hall</td>
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<tr>
<td></td>
<td>Working designs done: Prototype ring design, Beam dynamics studies</td>
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<tr>
<td>2020</td>
<td><strong>ISIS-II R&amp;D Phase 1</strong></td>
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<tr>
<td></td>
<td>Ref 2 designs: R&amp;D, Optimisation, Faraday limits</td>
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<tr>
<td></td>
<td>Finalise designs: ISIS Hall, Green Field</td>
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<tr>
<td>2021</td>
<td><strong>ISIS-II R&amp;D Phase 2</strong></td>
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<td>Finalise designs: ISIS Hall, Green Field</td>
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<td>2022</td>
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<tr>
<td>2023</td>
<td>Finalise chosen physics designs for accelerator type</td>
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<tr>
<td>2024</td>
<td>Finalise chosen physics designs for accelerator type</td>
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<td>2025</td>
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<tr>
<td>2031-2040</td>
<td>Finalise chosen physics designs for accelerator type</td>
</tr>
</tbody>
</table>

*G Aymar, J W G Thomason et al*
• Basic Requirements for Upgrade Rings

<table>
<thead>
<tr>
<th>Power</th>
<th>TS1</th>
<th>TS2</th>
<th>Machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (MW)</td>
<td>1.0</td>
<td>0.25</td>
<td>1.25</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>40</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Energy (GeV)</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
</tbody>
</table>

• Potential for further upgrades, higher performance (~2.5 MW)
  • FFA (AR)
    ~ Higher rep rates; stacking for flexible pulse structure
  • RCS (AR)
    ~ Stack two rings

• Possible update of facility design parameters: not “set in stone”
  • “Watching brief” on science performance of SNS, JPARC, ESS, etc.
  • “Facility Parameters Review Group” (users) to monitor, update spec. if required
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   “Space Charge Issues in FFAs” covered in J-B Lagrange’s talk on Tuesday pm
5. Summary

AR - Accumulator Ring
RCS - Rapid Cycling Synchrotron
FFA - Fixed Field AG Synchrotron
3.1 Accelerator work: FFA Rings
3.1.1 Vertical Excursion FFA: Prototype

- Vertical FFA selected, *not* Horizontal
  - Smaller, simpler magnets
  - Flexible scaling law
  - Suitable for SC magnets

- vFFA ~ would be a world first
  - Orbit moves vertically with acceleration
  - Coupled focusing fields
  - Intrinsic non-linearity

Baseline design
*FETS-FFA parameters*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic energy</td>
<td>3 - 12 (17) MeV</td>
</tr>
<tr>
<td>Number of cell</td>
<td>10</td>
</tr>
<tr>
<td>Cell length</td>
<td>2.5 m (=1.25 m + 1.25 m)</td>
</tr>
<tr>
<td>Num er of Bd segment</td>
<td>2</td>
</tr>
<tr>
<td>Length of Bd segment</td>
<td>0.2 m</td>
</tr>
<tr>
<td>Space between Bd segment</td>
<td>0.1 m</td>
</tr>
<tr>
<td>Angle between Bd segment</td>
<td>-8 deg</td>
</tr>
<tr>
<td>Number of Bf segment</td>
<td>2</td>
</tr>
<tr>
<td>Length of Bf segment</td>
<td>0.2 m</td>
</tr>
<tr>
<td>Space between Bf segment</td>
<td>0.1 m</td>
</tr>
<tr>
<td>Angle between Bf segment</td>
<td>+16 deg</td>
</tr>
<tr>
<td>Relative displacement btw Bd and Bf</td>
<td>+/- 0.154 m</td>
</tr>
<tr>
<td>Length of straight section</td>
<td>0.75 m</td>
</tr>
<tr>
<td>Fringe length L (Tanh x/L)</td>
<td>0.125 m</td>
</tr>
<tr>
<td>Bd/Bf</td>
<td>0.44</td>
</tr>
<tr>
<td>Field index m</td>
<td>1.58 m^-1</td>
</tr>
</tbody>
</table>

Magnet field required

\[ B_z (z, x, y) = B_0 \exp (m z) \sum_{i=0}^{\infty} b_{z_i} (x) y^i \]
\[ B_x (z, x, y) = B_0 \exp (m z) \sum_{i=0}^{\infty} b_{x_i} (x) y^i \]
\[ B_y (z, x, y) = B_0 \exp (m z) \sum_{i=0}^{\infty} b_{y_i} (x) y^i \]

- \( b_{x0} (x) = g (x) \)
- \( b_{y0} (x) = 0 \)

Field expanded as polynomial in y about mid plane
Designing prototype ring to demonstrate the technology

- **Vertical FFA with FETS injector**
  - $^1$H$^-$ (proton) beam
  - Inject, Extract, RF, Diagnostics
  - High intensity, space charge

- **Physics design objectives**
  - Show vFFA design works
  - Benchmark simulation
  - Beam dynamics study
  - High intensity effects

- **Hardware R&D objectives**
  - Wide aperture components
  - Optimise designs
  - Develop in-house skills

---

Magnet design loop

Initial proposal

After refinement

Analytical model

Coil configuration

Engineering feasibility

Solve Biot-Savart law inversely to find coil shape

Magnet field required

\[
B_z (z, x, y) = B_0 \exp (mz) \sum_{i=0}^{\infty} b_{zi} (x) y^i
\]

\[
B_x (z, x, y) = B_0 \exp (mz) \sum_{i=0}^{\infty} b_{xi} (x) y^i
\]

\[
B_y (z, x, y) = B_0 \exp (mz) \sum_{i=0}^{\infty} b_{yi} (x) y^i
\]

\[
b_{z0} (x) = g' (x)
\]

\[
b_{z0} (x) = \frac{1}{m} \frac{dg}{dx}, \quad b_{y0} (x) = 0
\]

Initial RF cavity design

Initial BPM design

Preliminary design of the FFA BPM, modelled in CST

3.1 Accelerator work: FFA Rings
3.1.4 vFFA Beam Dynamics

- Dynamic aperture verification for baseline design
  - Strongly coupled traverse motion
  - Non-linearity of all orders
  - DA for 1000 turns: >30 π mm mr (nor.)

Coupled space (y - z)

Decoupled space (u - v)
3.1 Accelerator work: FFA Rings
3.1.5 vFFA Beam Dynamics

- Adjustability for baseline design: tuning knobs
  1. Field index (gradient) $m$
  2. Ratio of $B_d/B_f$
  3. Radial distance between $B_d$ and $B_f$

- $m=1.60$
  - stable $>10$ mm

- $m=2.00$
  - stable $>10$ mm
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5. Summary

AR - Accumulator Ring
RCS - Rapid Cycling Synchrotron
FFA - Fixed Field AG Synchrotron
3.2 Accelerator work: Conventional Rings

3.2.1 Lattice Designs

- Lattice and optics requirements for RCS
  - Circumference, apertures, long straights, magnets
  - Injection, extraction, collimation, RF, correction
  - Beam dynamics, stability, foil, loss ~0.2%

- A number of “working designs” for RCS
  - Optics: BF-D & triplet; FODO & doublet
  - Long achromatic straights
  - Satisfy essential “first order” requirements ...

### Nominal RCS Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>0.4 – 1.2 GeV</td>
</tr>
<tr>
<td>Intensity</td>
<td>1.3×10^{14} ppp</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Mean Power</td>
<td>1.25 MW</td>
</tr>
<tr>
<td>Circumference (mean R)</td>
<td>163 m (26 m)</td>
</tr>
<tr>
<td>No. Super-periods</td>
<td>3</td>
</tr>
<tr>
<td>Nominal Tunes ((Q_x, Q_y))</td>
<td>(4.40, 4.36)</td>
</tr>
<tr>
<td>Magnet Excitation</td>
<td>Sinusoidal</td>
</tr>
<tr>
<td>Dipole Fields</td>
<td>0.49 – 0.99 T</td>
</tr>
<tr>
<td>Gamma Transition</td>
<td>3.78</td>
</tr>
<tr>
<td>Peak RF ((h = 2))</td>
<td>(240, 120) kV/turn</td>
</tr>
<tr>
<td>RF Frequency ((h = 2))</td>
<td>2.62 – 3.30 MHz</td>
</tr>
<tr>
<td>Number of Bunches</td>
<td>2</td>
</tr>
</tbody>
</table>

**REF 1 Study Ring (EPAC 18)**

**REF 2 Study Ring**

*D J Adams, C M Warsop, R E Williamson et al*
3.2 Accelerator work: Conventional Rings
3.2.2 Injection Designs

Examples from 180 MeV Injection Upgrade

- Injection straight requirements
  - Foil, geometry and mounting
  - Stripping product control: H*, e-
  - Painting and bump magnets
  - Physical space and optics

- Beam dynamics requirements
  - Paint stable beam distributions
  - Minimise foil re-circulations: temperature, loss
  - Optimise at high intensity: simulations – see later

- Working design parameters
  - Solutions for 400 MeV injection into RCS
  - Foil: 300 μg/cm² carbon
  - Foil re-circulations ~2 (simulation)
  - Foil temps ~1700 K

D J Adams, H V Cavanagh, B Jones, et al
3.2 Accelerator work: Conventional Rings
3.2.3 Injection Designs

- RCS Injection system designs under study
  - Lattice optics: zero dispersion, dual waist
  - Horizontal injection bump (chicane)
  - Horizontal and vertical painting bumps
  - Flexible, independent painting vs time

- Key optimisation: bump program
  - Collapse bump, move away from foil
  - Key challenge ⇒ low foil re-circulations
  - Minimise emittance growth ...

- ESS AR Study, R=26 m at 1.25 MW
  - Unusual dispersive injection system
  - Reworked dynamics: detailed simulation
  - Foil temperatures OK, losses ~0.1%

- Outline of RCS injection
  - Real space at Foil
  - Injection painting, bumps
  - Foil
  - Inj. Beam
  - Closed Orbit
3.2 Accelerator work: Conventional Rings
3.2.4 Transverse 2D Dynamics and Errors

- Assessment of working points
  - Study near equal tunes \((Q_x, Q_y) \sim (4.40, 4.36)\)
  - Basic resonances, systematics ...

- Simple 2D PIC study* with Space Charge
  - Checks of high intensity behaviour

- Error studies: correction; tune-ability
  - Closed orbit prediction, corrections
  - Tune range and options in lattice

- Non-linear correction and optimisation
  - Non-linear errors (non-space charge)
  - Sextupole, octupole families, dynamic aperture

* Using in-house PIC code

D J Adams, P T Hicks, B G Pine, C M Warsop, et al
3.2 Accelerator work: Conventional Rings
3.2.5 Longitudinal and 3D Dynamics

- Longitudinal dynamics design* (1D)
  - Optimised bunch capture, control
  - Lattice space for \( h=2, 4 \) RF systems
  - Volts/turn for 0.4-1.2 GeV in 10 ms
  - Chop at revolution frequency
  - 58 mA injector beam, 60%, 780 turns
  - Optimise painting for distribution
  - Capture, stability, halo, bunching factor
  - Free gap for extraction

- 3D Design and Simulation Model
  - Longitudinal and transverse dynamics
  - ORBIT 3D PIC, AG lattice, ...
  - Injection painting, foil, collimation, ...
  - 1.5E6 macro particles 128x128x64 bins
  - Linear and TEAPOT lattices

- Extraction, Collimation
  - Designs include suitable optics and space

* Using in-house PIC code
R E Williamson, D J Adams, et al
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5. Summary

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FFA - Fixed Field AG Synchrotron
High intensity check on RCS lattice

2D simulation study: Set* PIC code
RCS AG lattice, quadrupole errors
4D Waterbag distribution (~matched)
\( \varepsilon_{x\text{rms}} = \varepsilon_{y\text{rms}} = 50 \pi \text{ mm mr} \)

\( Q = (4.44, 4.40) \), 100 turn track

Analyse with increasing intensity
Check for loss, emittance growth
Coherent and incoherent frequencies

Result: OK at RCS design intensity
Beam OK at equiv. \( \sim 1.3 \times 10^4 \) ppp

Much to understand in detail
Coupling \( Q_x \approx Q_y \); \( 2Q_x - 2Q_y = 0 \)

\( 4Q_x = 17 \) driven by coherent moment
Next level: painted distributions, 6D, ...

*in-house PIC code
4. Space Charge on Conventional Rings

4.2 Injection Optimisation: Search Codes

- Key challenge: control distributions
  - Foil hits ⇒ temperature, loss (small R ring)
  - Emittance growth ⇒ aperture occupied

- Working on numerical optimisation codes
  - "Brute force hill search" on foil hits, with time
    $\left( \varepsilon_h, \varepsilon_v \right)$ vs time (i.e. bumps); also $(Q_h, Q_v)$, $(\beta_h, \beta_v)$

- Levels of approximation and speed
  - Analytical, no space charge
  - Smooth Focusing, 2D PIC space charge*
  - AG 3D PIC in ORBIT

- Typical search: optimise 2D paint bump
  - Step through injection process
  - Test foil hits/loss for surrounding points
  - Adjust to minimise: generate time dependent bumps

- Challenges
  - Select constraints: optimisation metrics (loss, $\Delta Q$, ...)
  - Confidence in results?

* Using in-house PIC code

D J Adams, B G Pine, C M Warsop, et al
4. Space Charge on Conventional Rings
4.3 Injection Optimisation: Simulation Results

- Study of “optimised” injection
  - RCS ORBIT injection, 750 turns
  - Linear lattice, no errors
  - N=1.3E14 ppp, Q=(4.36,4.40)

1. Oscillating paint
   - $\varepsilon \approx 10^{-270} \pi \text{ mm mr}$
   - Foil hit 2
   - $\varepsilon 99\% \sim 600$

2. Simple paint: limited $\Delta Q_{sc} \sim -0.2$
   - $\varepsilon \approx 10^{-600} \pi \text{ mm mr}$
   - Foil hit 7
   - $\varepsilon 99\% \sim 1000$

- Work in progress ...
  How far can we optimise painting? Can we trust, understand codes?
Critical task: understand & optimise injection: ⇒ true for AR/RCS/FFA
  • Can we achieve better distribution control? Detailed, fast paint variation?
  • If paint smaller, stable beam ⇒ get cheaper ring (beam power)

Key factors
  • Geometric effects: optimise bumps, Q to miss foil, paint over halo
  • High intensity beam dynamics effects: evolution of distributions
    • Coherent, incoherent; magnet errors, space charge; 4D-6D

What are the best code beam diagnostics?
  • Coherent: moments, spectra, ...
  • Semi-coherent: moments of sub sets
  • Incoherent: particle \( \epsilon, Q, \) trajectories, growth, ...
  • As function of \( (\epsilon_h, \epsilon_v, \epsilon_l); \) injection time;

Next ...
  • Continue to study, identify key physics
  • Cross check with different codes
  • Include non-linear lattice effects

4. Space Charge on Conventional Rings
4.4 Injection Optimisation: What Next?
5. ISIS II Upgrade Project Summary

- A substantially upgraded ISIS will be required to supply the neutrons Europe needs
- A roadmap for determining the best upgrade route for ISIS has been established
- An extensive and ambitious program of accelerator physics R&D and design work is underway to determine the best accelerator solution for the optimal next generation source
- We need to study many interesting accelerator physics challenges to find the best solutions
Additional Slides
A1. ISIS II Accelerator Studies
Reuse of ISIS Infrastructure
A.2 Accelerator work: General R&D
Relevant work on and around ISIS

- Space charge studies on ISIS Ring
  - Transverse loss and resonances
  - Profile evolution on resonance
  - Profile monitor errors: performance

- Impedance, instabilities on ISIS
  - Head-tail study (space charge)
  - Impedance measurements
  - Damper system

- Also:
  - Codes, diagnostics, ...
  - Magnets, power supplies, ...
  - Ion Sources, MEBT, FETS, ...

**ISIS Loss vs Q Measurements**

<table>
<thead>
<tr>
<th>Order</th>
<th>Resonance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd</td>
<td>$Q_h + Q_v = 8$</td>
</tr>
<tr>
<td>3rd</td>
<td>$Q_h - 2Q_v = -3$</td>
</tr>
<tr>
<td>3rd</td>
<td>$2Q_h - Q_v = 5$</td>
</tr>
</tbody>
</table>

Resonances found during investigations.

**Resonance Studies**

**IBEX Paul Trap**

**Head-tail instability with space charge**

**Mode Structure**

**Y Dipole Motion in Longitudinal Plane**

Colour = vertical dipole moment, 3 turns

P T Hicks, B Jones, B G Pine, A Pertica, D Posthuma de Boer, C M Warsop, C C Wilcox, R E Williamson, L K Martin, D J Kelliher, S L Sheehy, et al