Science & Technology Facilities Council
ISIS

High Intensity Loss Mechanisms on the ISIS Rapid Cycling Synchrotron

C M Warsop,
D J Adams, B Jones, S J Payne, B G Pine, H V Smith, R E Williamson,
*V Kornilov**

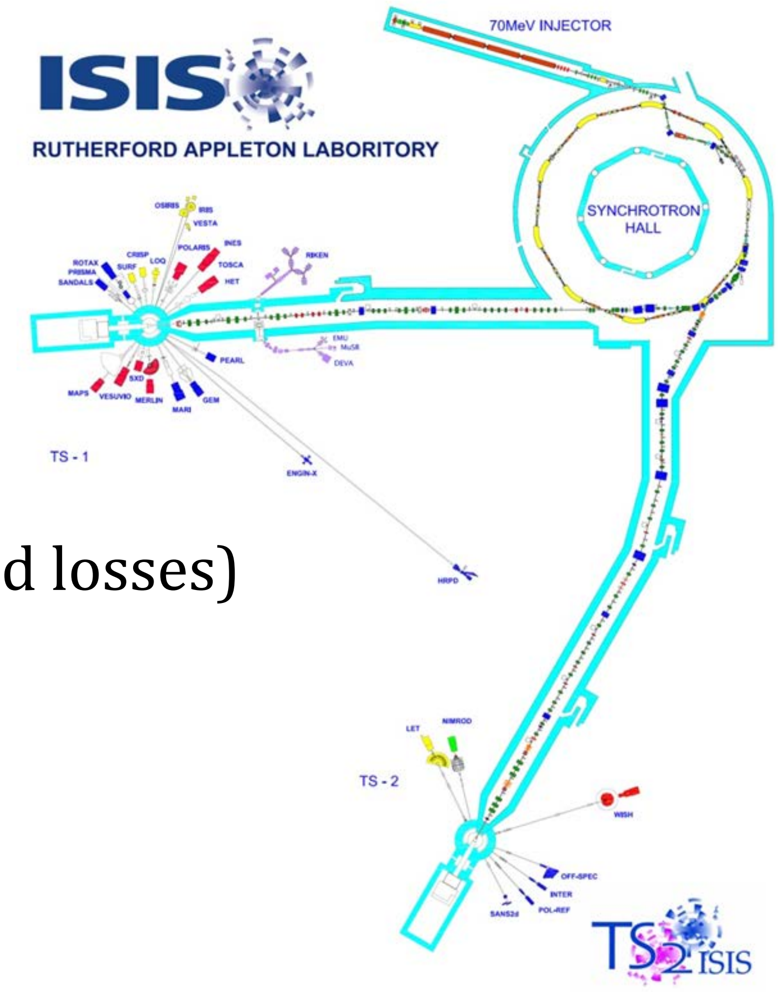
ISIS, Rutherford Appleton Laboratory, UK
*GSI, Germany

HB 2014, Michigan State University, USA, November 2014

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Contents

1. Introduction
2. The ISIS Synchrotron
3. Review of Operational Losses
4. High Intensity R&D (to understand losses)
5. Summary
6. Acknowledgements



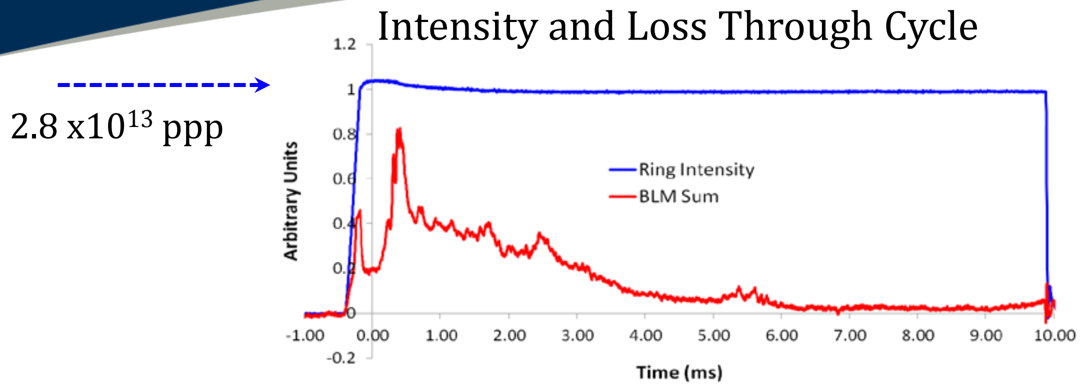
Science & Technology Facilities Council
ISIS

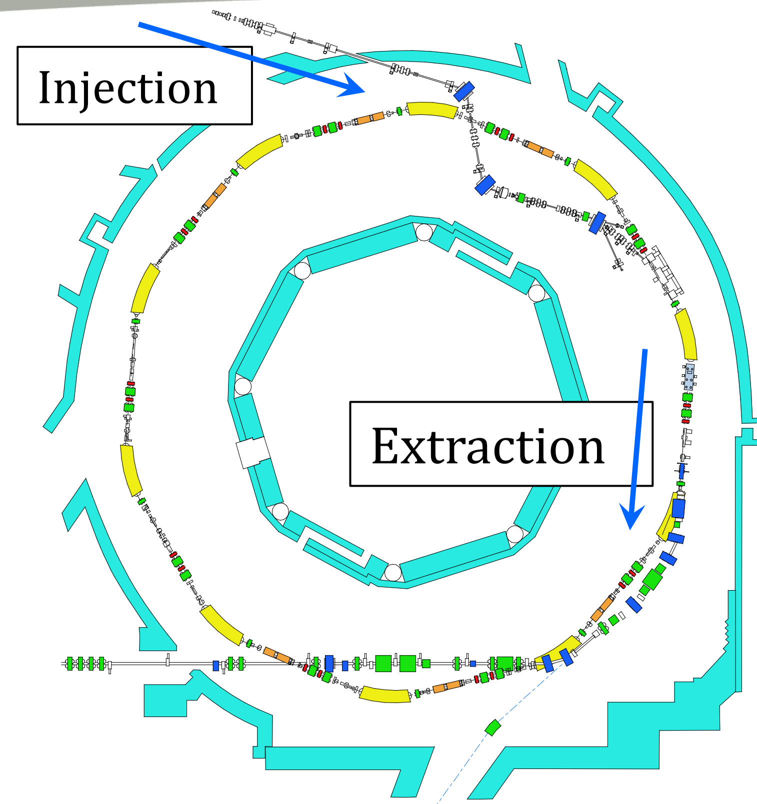
1. Introduction

Why is understanding loss on the ISIS RCS important?

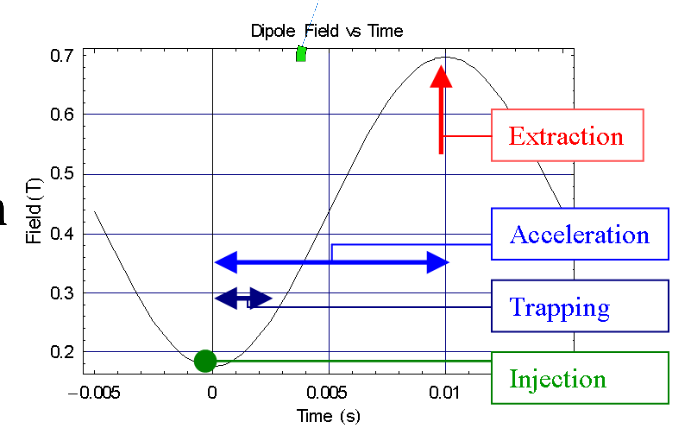
- Improve ISIS operations
  - Increase running levels from ~ 210 μA to consistent 240 μA
  - Minimise loss and activation for sustainable, reliable running
- Basis of optimal ring developments and upgrades
  - Upgrades to the existing machine, including 0.5 MW options …
- Benchmark codes and theory for major upgrade designs
  - Including stand alone "*ISIS II*" upgrade scenarios …
- Understand losses and limitations for future machines
  - Contribute to understanding of some key loss mechanisms

2. The ISIS Synchrotron





Circumference: 163 m
Energy Range: 70-800 MeV
Rep Rate: 50 Hz
Intensity: 2.5-3.0 x10^{13} ppp
Beam Power: 160-200 kW
Losses: Inj: 2%, Trap: <3%, Acc/Ext <0.5%
Injection: 130 turn, H^- charge-exchange
Acceptances: Collimated ~350 π mm mr
RF System: h=2, f_2=1.3-3.1 MHz, V_2 ~160kV/turn
(2 bunches) h=4, f_4=2.6-6.2 MHz, V_4 ~80 kV/turn
Extraction: Single turn, vertical
Tunes: (Q_x, Q_y)=(4.31, 3.83) (*programmable*)



3. Losses in the ISIS RCS

(I) Overview of beam losses

- **Beam power 160-200 kW**
  Loss limited : control activation

- **Most loss at lower energy**

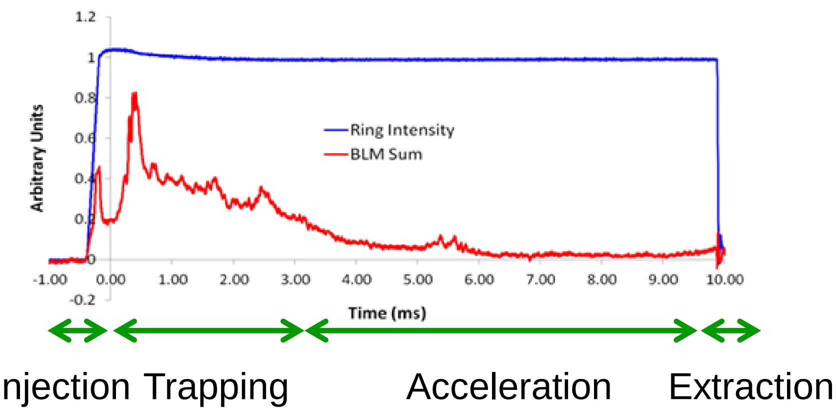
Injection	70 MeV	<2%
Trapping	70-140 MeV	<3%
Acceleration	140-800 MeV	<0.5%
Extraction	800 MeV	~0.01%

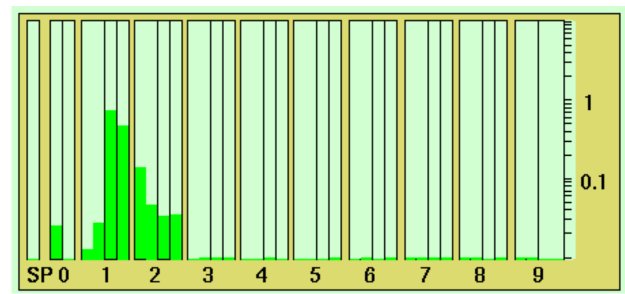
- **Loss controlled on collimator system**
  Localised in 3 of 10 superperiods

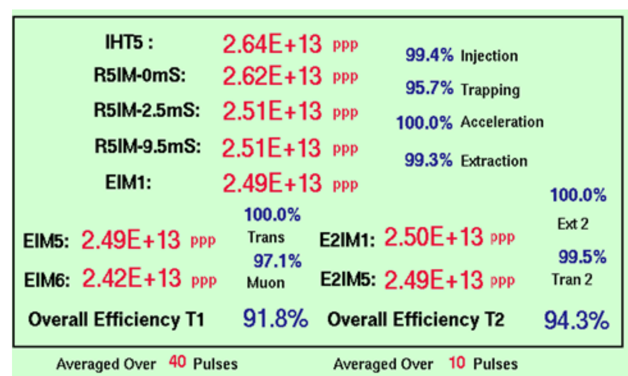
- **Protection: fast trip system**
  Ionisation monitors, toroids, scintillators

- **Activation**
  Most of machine 10-100 μSv/hr at 1 m

Losses at nominal intensity (2.8E13 ppp)





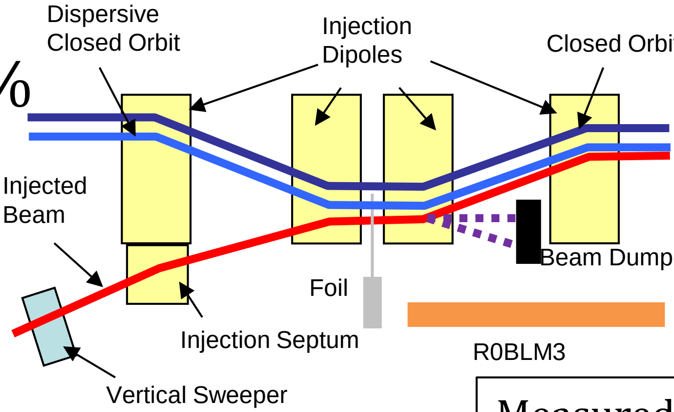


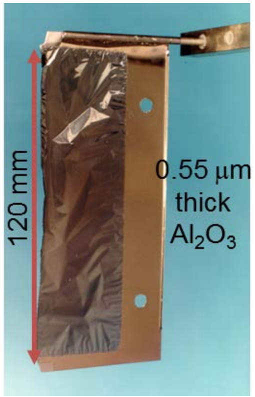
3. Losses in the ISIS RCS

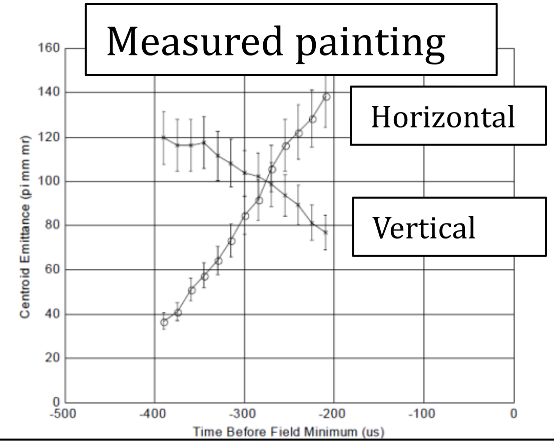
(II) Injection loss -0.4–0.0 ms <2%

- Foil related loss
  - 3×10^{13} ppp in 130 turns
  - 120×40 mm Al_2O_3 foil
  - ~30 foil re-circulations per proton
- Transverse painting process
  - Horizontal: dispersive orbit
  - Vertical: injection steer
- Optimal painted distributions
  - Space charge affects distributions & later loss
  - Experience shows large, hollow beams best
- Experimental and simulation studies
  - Agree; beam insensitive to anti/correlated
  - Optimising distributions is a topic for R&D

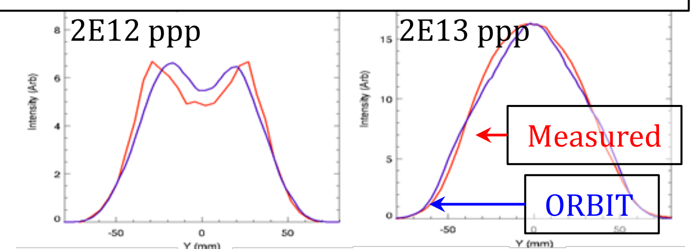
H^- charge exchange injection







Painted transverse profiles (vertical)

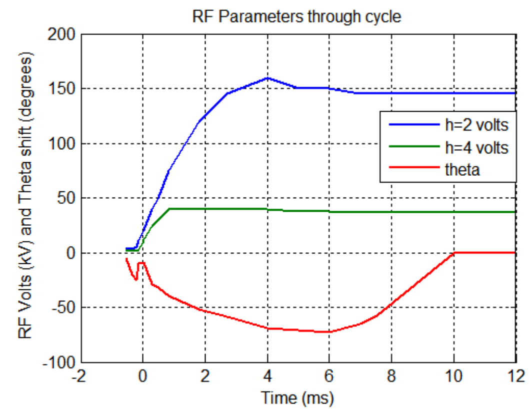


D J Adams, B Jones, H V Smith, et al

3. Losses in the ISIS RCS

Science & Technology Facilities Council ISIS

$$V = V_{h=2}\sin\varphi - V_{h=4}\sin(2\varphi + \theta)$$



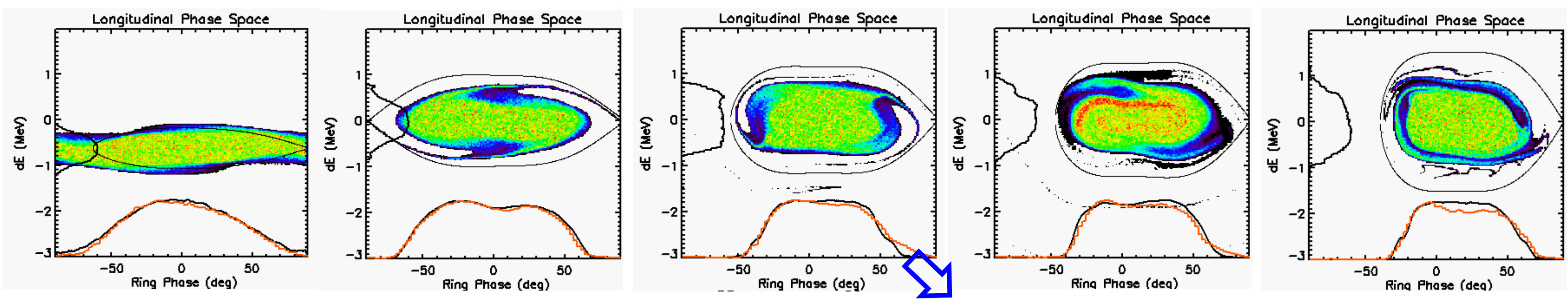
(III-a) Longitudinal trapping loss 0.0-2.5 ms

- Trapping loss <3%

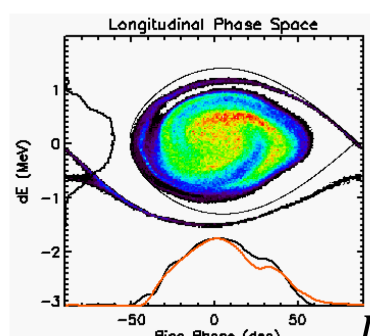
  Capture of unchopped beam, dual harmonic RF

  Improved bunching factor and acceptance

- ORBIT model: (dE, φ) at -0.2, 0.0, 0.2, 0.5, 1.0 ms, measurement in orange



(*at 2.8x10*^{13} *ppp*)



Equivalent single harmonic result

- Hardware developments

  Now allowing further optimisation

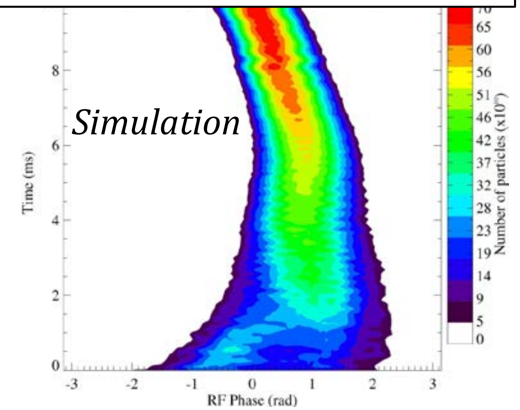
D J Adams, R E Williamson, et al

3. Losses in the ISIS RCS

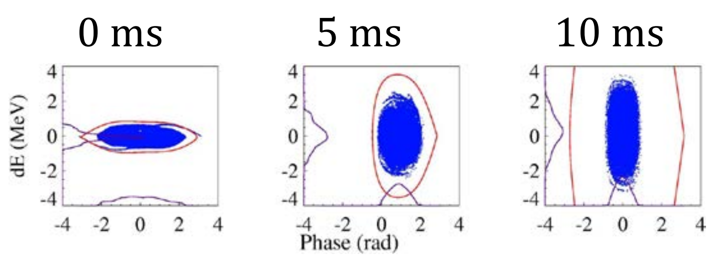
(III-b) Longitudinal trapping loss

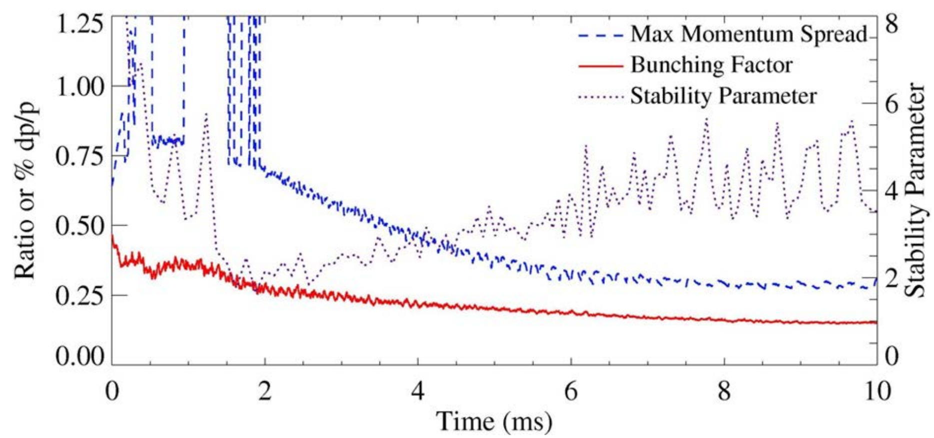
- Beam loading and cavity control
  - Key factors: control of *h*=2, *h*=4 phase, beam loading
  - Now operating all 4 dual harmonic cavities
- Longitudinal stability and space charge
  - Recent study with in-house 1D code
  - Exceed KSB on ISIS: not a problem!

Bunch Evolution Over 10 ms



(at 2.8x10^13 ppp)





Keil-Schnell-Boussard

$$\frac{Z_{sc} e \beta^2}{F|\eta| E} \frac{I(\varphi)}{(\Delta E(\varphi)/E)^2} \leq 1$$

- R&D planned to investigate KS, KSB criteria
  - Coasting and non-accelerated bunched beams …

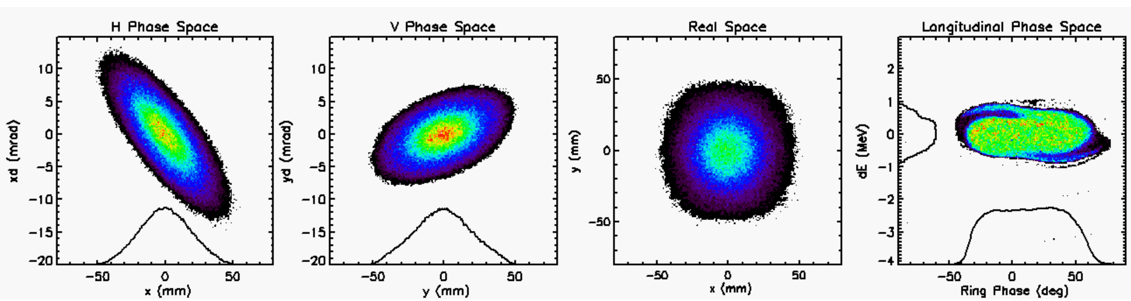
I S K Gardner, R J Mathieson, A Seville, R E Williamson, et al

3. Losses in the ISIS RCS

(IV-a) Transverse space charge

- *Q* shifts peak ≥ -0.5 over 0.0-0.5 ms
  Beam bunches at low energy (~80 MeV)
  Fill transverse apertures (beam ~300 π mm mr)

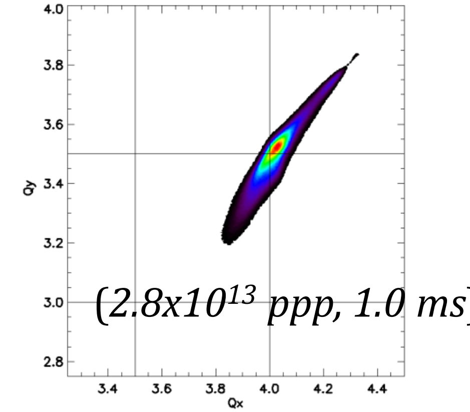
- ORBIT model (x, x') $(y, y')$$(x, y)$,$(dE, \varphi)$ at 0.5 ms



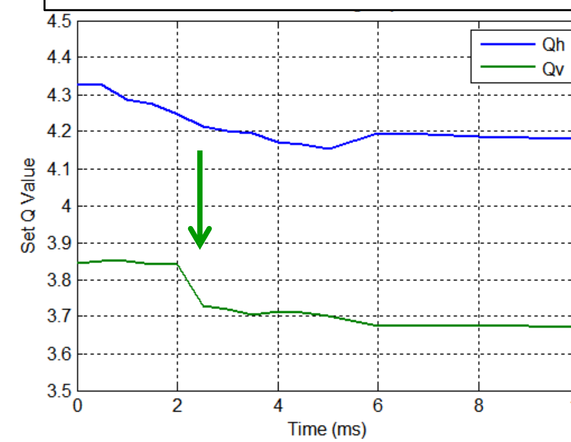
- Variable *Q* ramp with trim quadrupoles
  Push Q_y down to minimise head-tail motion ~2 ms

- Half integer limit: push on to half integer?
  What is mechanism: coherent, incoherent, 2D, 3D?
  No coherent motion measured; some evidence in 3D simulations

Incoherent tunes from ORBIT



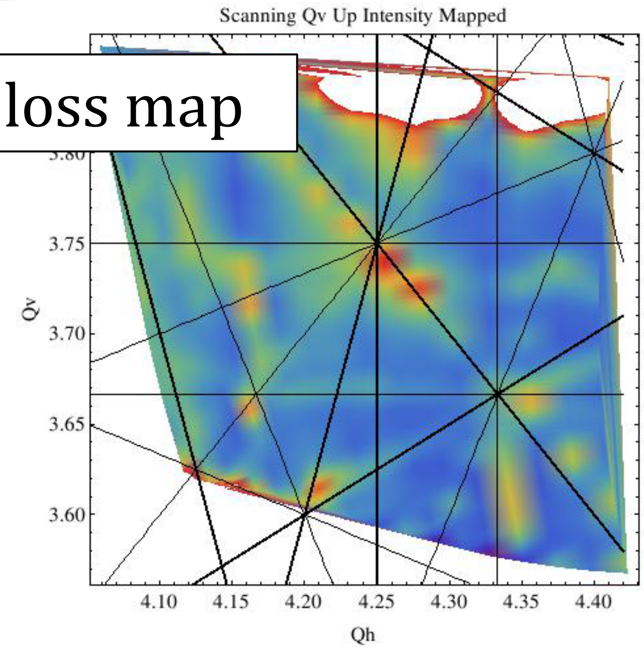
ISIS *Q* values through cycle



D J Adams, B G Pine, C M Warsop, et al

3. Losses in the ISIS RCS

Q vs loss map

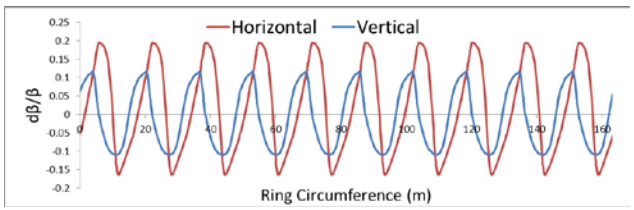


(IV-b) Transverse space charge

- Non-linear lattice driving terms
  Q vs loss measurements show non-linear lines
  Study for source (magnet models) and effects

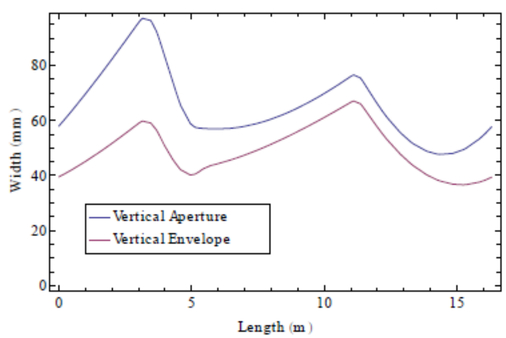
- Loss from space charge image effects
  Driving terms in rectangular vessels (later slide)

Beta Beat

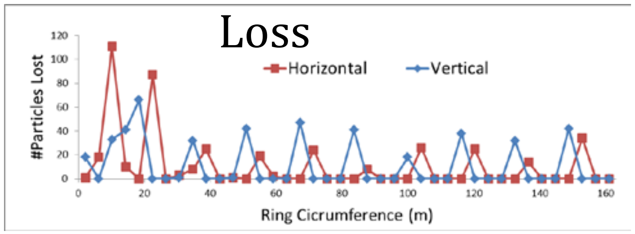


- *Q* ramp effects in conformal vacuum vessel
  Beam envelope varies with *Q*: reduces acceptance

Upgrade studies show is a key effect



3D ORBIT simulations show correlated loss



- Real machine uses empirical optimisation
  Time dependent optimisation: orbits, *Q*, envelopes, ...

D J Adams, B G Pine, et al

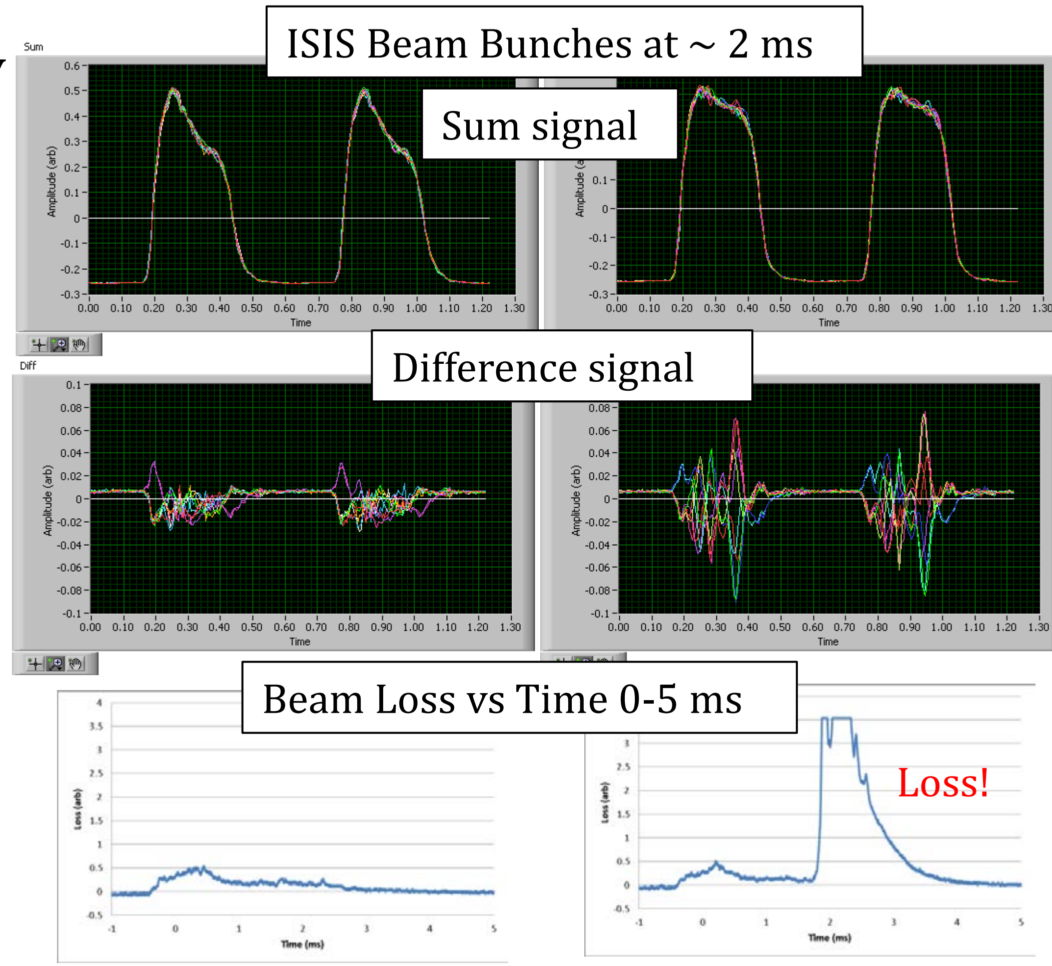
3. Losses in the ISIS RCS

Science & Technology Facilities Council ISIS

(V) Head-tail instability 2-4 ms

- Limits operational intensity
  - With dual harmonic RF upgrade
  - Previously cured with Q_y ramp
  - Driven by *resistive-wall*
- Operational observations
  - Symmetric bunches unstable
  - Plots show effect of θ variation
- Damper in development
- R&D under way
  - See below

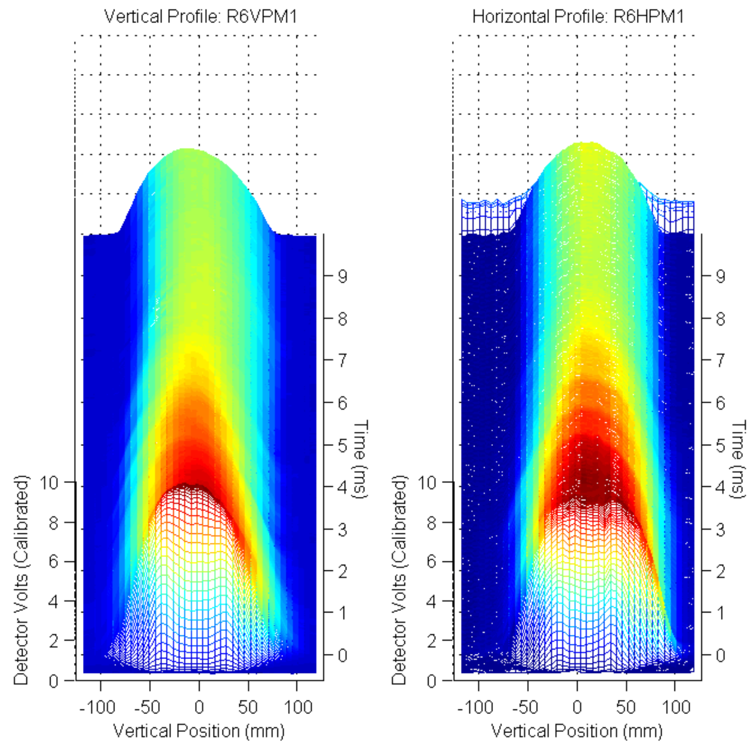
Normal beam	Normal beam + Θ shift
Low loss	Large loss!
1RF = 108 kV, 2RF = 52.8 kV	1RF = 108 kV, 2RF = 52.8 kV
$\Delta = 0.489$, $\delta\Theta = 0^{o}$	$\Delta = 0.489$, $\delta\Theta = -10^{o}$



D J Adams, B Jones, V Kornilov, R E Williamson, C M Warsop, et al

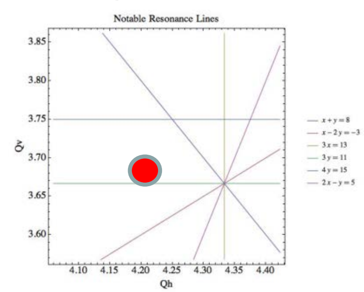
3. Losses in the ISIS RCS

Transverse Profiles -0.5-10.0 ms

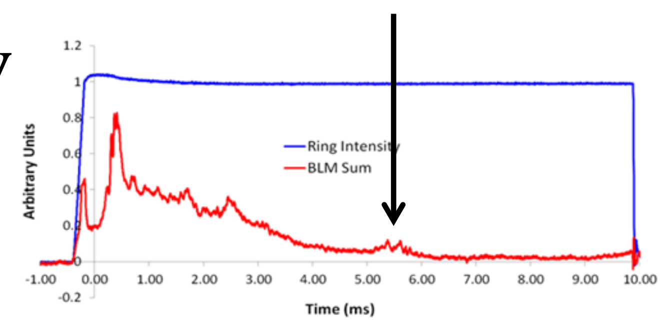


(VI) Acceleration and extraction 4-10 ms

- Rest of cycle generally easier
  Space charge reduces, emittances damp
- Must avoid halo at extraction (0.01%)
  Extraction system acceptance 280 π mm mr
  Orbit bump moves beam into edge fields
  Q ramp avoids resonances



- Problem with new magnet power supply
  Trim quads switch mode f=112 kHz
  Sweeps through Q_x side bands: loss at 5.5 ms
  Hope to exploit as quad exciter!

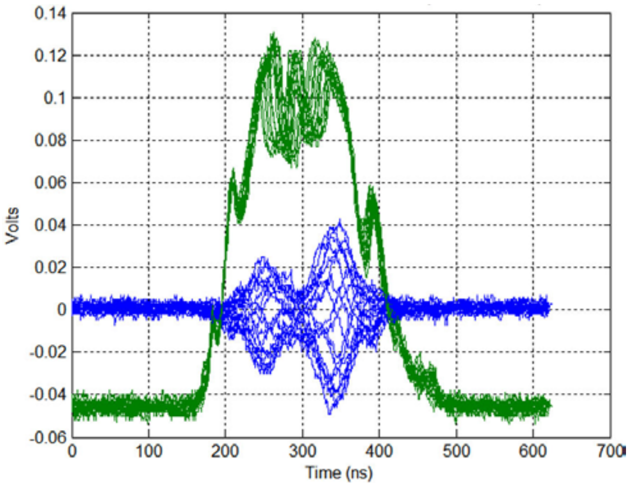


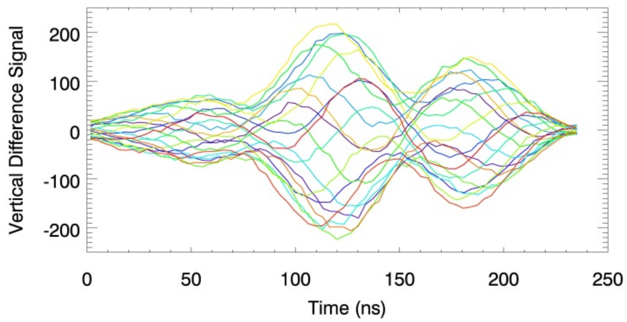
D J Adams, B Jones, et al

4. High Intensity R&D on ISIS

(I) Head tail studies

- Results presented by V Kornilov
  Collaboration on ISIS head-tail motion
- Study single harmonic RF, low intensity
  Simpler case, compare simulations & theory
  Experiments: mode m=1; code and theory m=2
  Measured growth rates faster than theory …
  Much interesting work to do!
- Plans
  Assess beam impedances (measure)
  Build up more representative simulations
  Explore limits of Sacherer theory …
  Build damper system





V Kornilov: Talk

R E Williamson: Poster

V Kornilov, R E Williamson, D J Adams, B Jones, C M Warsop, et al

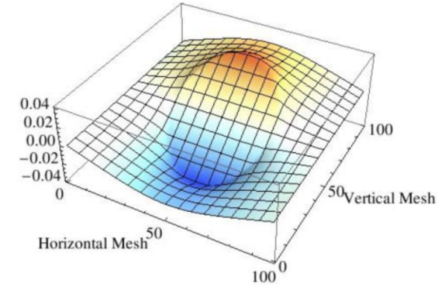
4. High Intensity R&D on ISIS

(II) Space charge image studies

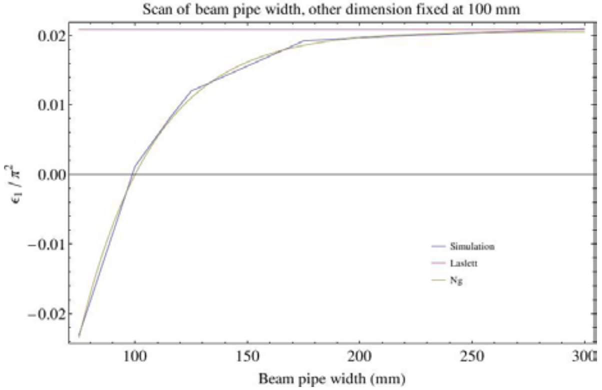
- Effects of images in vacuum vessels
  - ISIS vessels are rectangular and conformal
  - May provide additional driving terms for loss
  - Explain strong dependence of loss on orbit errors?
- Developing Set code to model effects
  - Suitable boundary conditions for images
- Recent work — B G Pine: Poster
  - Check field solvers, identify driving terms
  - Range of validity of theoretical models
    - Incoherent Laslett coefficients for centred beam
    - *Parallel plates (Laslett)* $\epsilon_1 = \frac{\pi^2}{48}$
    - *Rectangular Geometry (Ng)* $\epsilon_1 = \frac{K^2(k)}{12}(1 - 6k + k^2)$
- Use to explain leading terms in simulations
  - Investigate coherent, incoherent image effects …

ISIS vacuum vessels

Electric field for KV beam



Laslett coefficient ε_1 *dependence on aspect ratio*



B G Pine

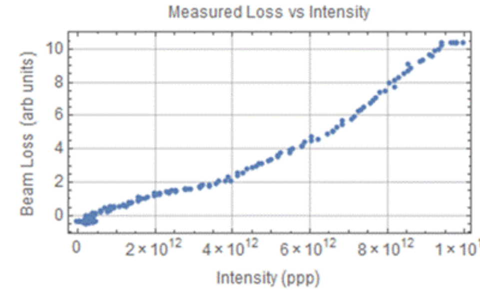
4. High Intensity R&D on ISIS

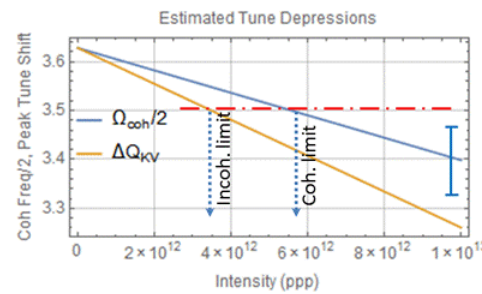
Science & Technology Facilities Council ISIS

(III) Half integer studies - key loss mechanism

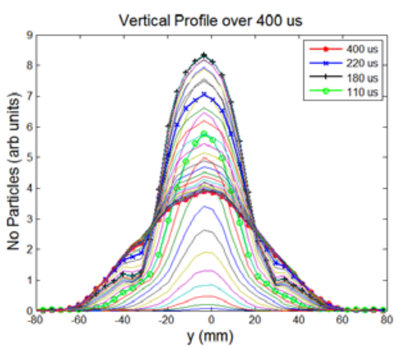
- Study experimentally in "2D" coasting beams
  RF off, DC field, small beam, $2Q_y$=7 driving term
  Constant Q_y, ramp intensity onto single resonance
- Study profile evolution; variation with Q, etc.
  Observations agree reasonably with ORBIT models
  Show formation of core and lobes: model?

Loss vs time (Intensity)

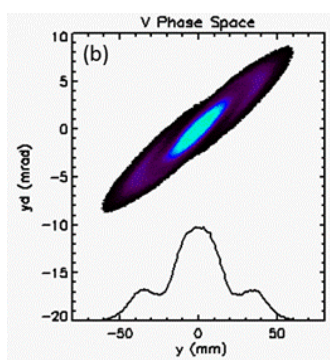


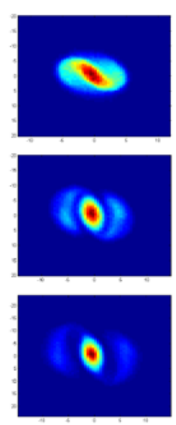


Transverse profile
Measured over 400 μs



ORBIT results





Single particle model ?

$$H(J,\varphi) = \delta J + G_2 J\ \cos(2\varphi) + G_4 J^2$$

C M Warsop: Poster

- Interesting recent experiments: "stable halo" lasts 500 turns

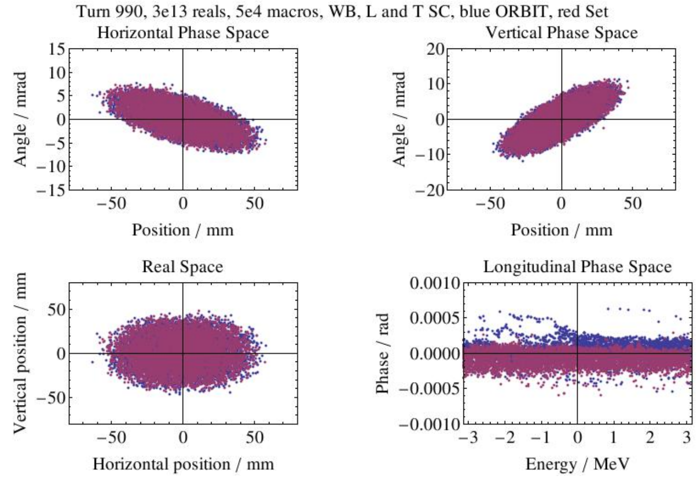
C M Warsop, D J Adams, B Jones, B G Pine, H V Smith, C Wilcox, R E Williamson, et al

4. High Intensity R&D on ISIS

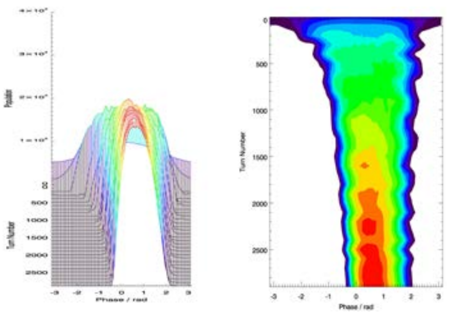
(IV) Development of ISIS code: Set 3Di

- 3D space charge code
  Transverse and longitudinal PIC code
  Injection, bumps, foil, orbits, AG, SF
  Images, coherent, incoherent tunes, …
- Tests and benchmarking
  Comparison with ORBIT and ISIS
- Applications
  Upgrades
  Images
  2D, 3D resonances
  Develop for instabilities?
  …

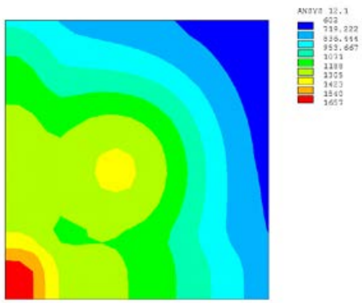
Benchmarking with ORBIT



Longitudinal profiles



Foil temperatures



B G Pine, H V Smith, R E Williamson

Science & Technology Facilities Council ISIS

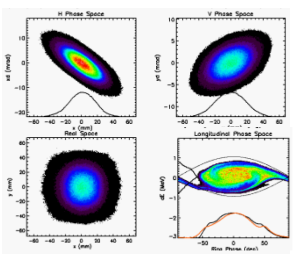
4. High Intensity R&D on ISIS

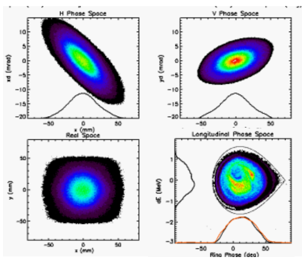
(V) Beam modelling and upgrade studies

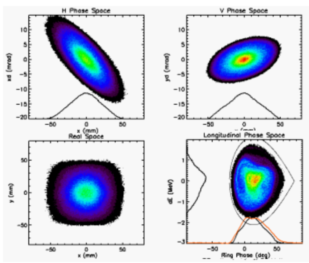
- ORBIT models of ISIS operations

  ISIS single harmonic RF: agreement on loss

  ((x, x'),(y, y');(x, y),(dE, φ)) through trapping



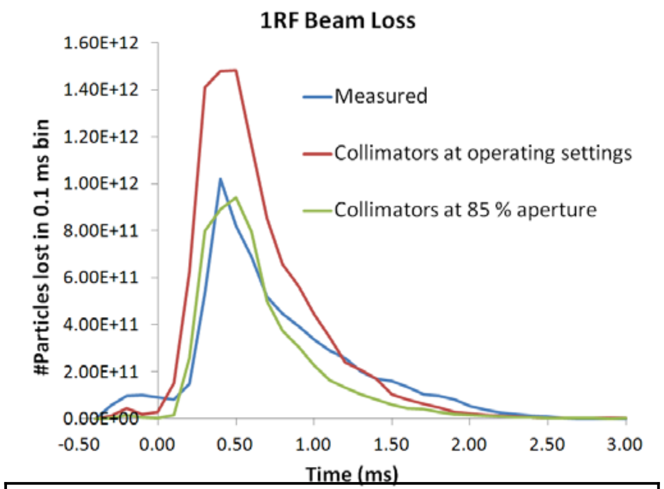




- Models being used for upgrade designs

  Injection upgrade 0.5 MW, new 1+ MW rings

  ISIS Set 3Di code now being benchmarked ....



Acceleration efficiency single harmonic RF	
Measured	74%
3D Simulation (coll h75 v80)	64%
3D Simulation (coll h85 v85)	79%

(*at 2.8x10^{13} ppp*)

D J Adams: Talk

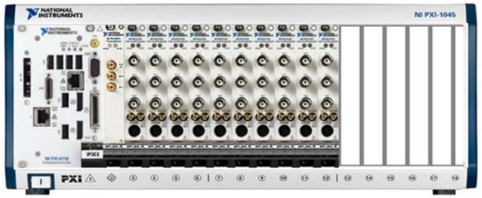
D J Adams, R E Williamson, et al

4. High Intensity R&D on ISIS

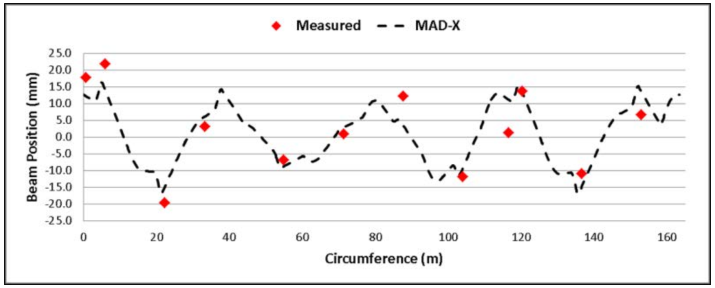
(VI) Machine measurements and diagnostics

- Better beam measurement, control
  - Updating DAQ, hardware, magnet systems
  - Better alignment, profiles, lattice optics, ….
- Diagnostics (for high intensity study)
  - Ring profile monitors, loss monitors, …
  - Beam kickers, damper systems

PXI System

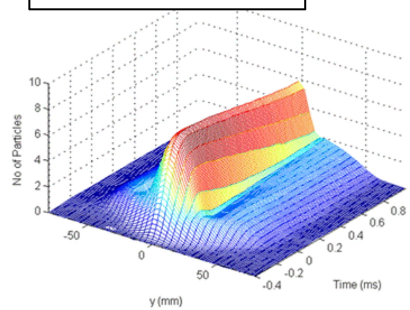


Measurements indicating magnet errors



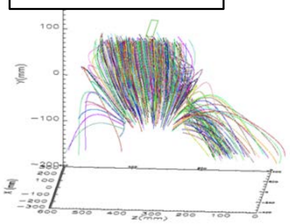
Simulations of profile monitors for halo measurements

Measured Halo

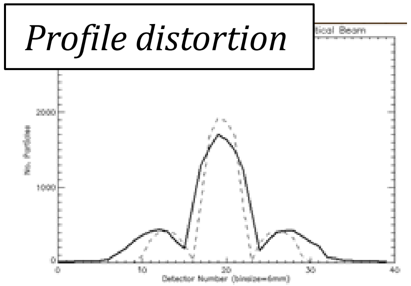


Ion track monitor simulation

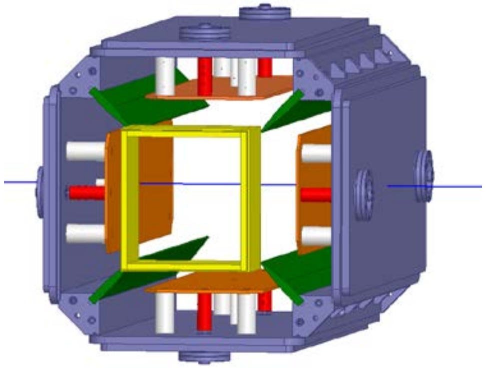
Ion tracks



Profile distortion



New strip-line kicker



B Jones, H V Smith, S J Payne, A Pertica, C Wilcox, R E Williamson, et al

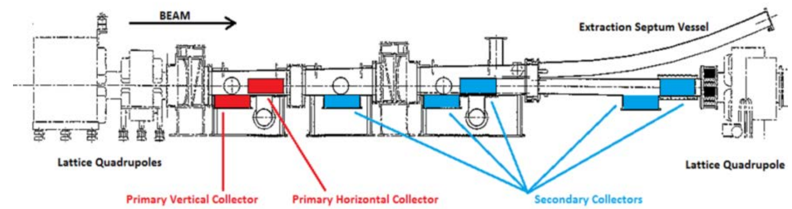
4. High Intensity R&D on ISIS

Science & Technology Facilities Council ISIS

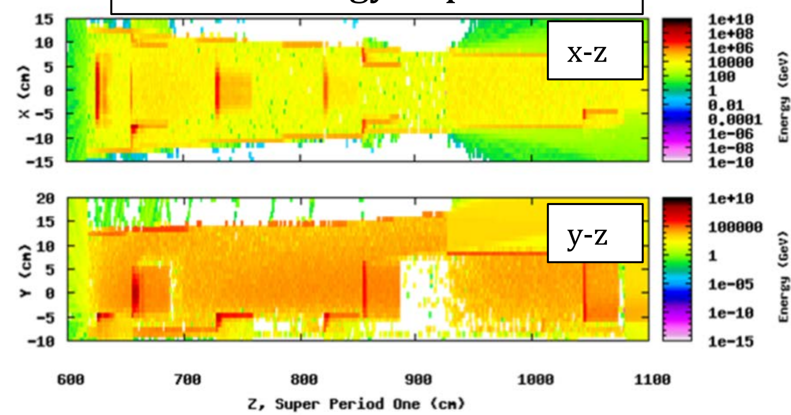
(VII) ISIS ring collimator simulation

- New detailed FLUKA simulations
  - Key information on loss control
  - Flux particles escaping – prevent damage
  - Activation calculations – predictions

ISIS collimator straight



FLUKA energy deposition

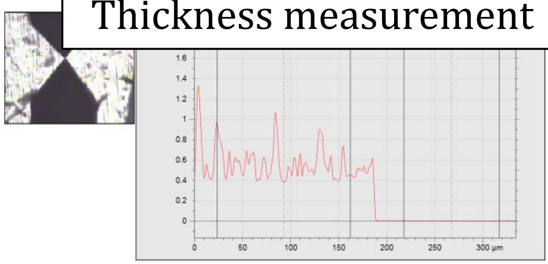


(VIII) Foil studies R&D

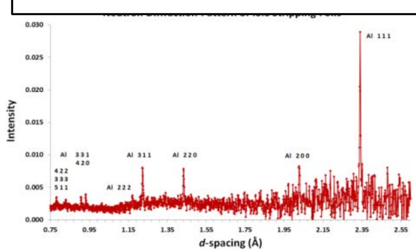
H V Smith: Poster

- New measurements of Al_2O_3 foil
  - Thickness, uniformity (AFM, SEM)
  - Structure (neutron diffraction)
  - Composition (spectroscopy)
  - Findings: thickness 0.55 μm
  - *(more than the expected 0.25 μm)*
- Re-evaluating injection losses
  - Relative effects: stripping, scattering, space charge

Thickness measurement



Neutron diffraction



H V Smith, B Jones, et al

5. Summary and Plans

- The ISIS RCS runs with low and well controlled losses
  - Particularly for high levels of transverse space charge
  - Need to improve beam control for higher intensity running
- We are improving the machine and our understanding of it
  - Better measurements, diagnostics …
  - On going experimental studies …
- Building simulation models and codes
  - Benchmarking against theory and ISIS …
- Studying key topics
  - Resonances and images with space charge, instabilities, foils, activation, …
- Design of a next generation short pulse neutron source
  - ISIS II …

Science & Technology Facilities Council
ISIS

Acknowledgements

Many thanks to …

ISIS Diagnostics Section
ISIS RF Section
ISIS Operations
ASTeC Intense Beams Group