Understanding the High Intensity Behaviour of the ISIS RCS and the Lessons for ISIS II Designs

Chris Warsop

on behalf of

Dean Adams, Hayley Cavanagh, Billy Kyle, David Posthuma de Boer, Haroon Rafique, Rob Williamson (ex-RAL: Peter Hicks, Bryan Jones, Ben Pine)

5th ICFA Workshop on Space Charge
October 24-26, 2022,
Knoxville, TN, USA

Science and Technology Facilities Council
Rutherford Appleton Laboratory

Science and Technology Facilities Council
ISIS Neutron and Muon Source

Introduction

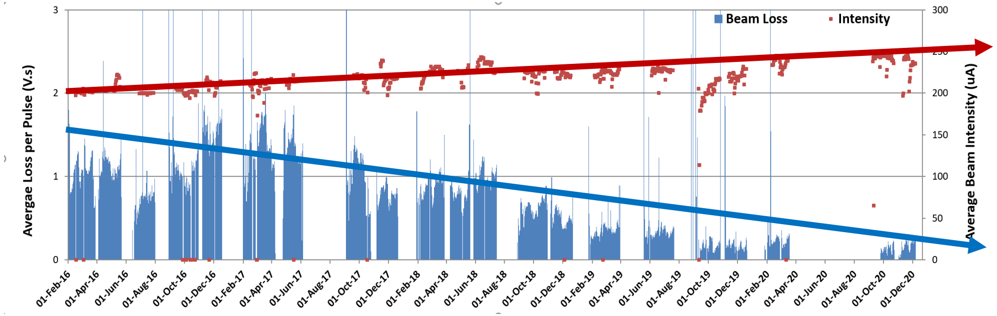
- ISIS RCS running for ~40 years, what's new?
    - Still much we don't understand ~ can't explain, model all losses
    - If we can: improve machine and optimise upgrade designs for ISIS II
- Talk outline
    1. Reminder of ISIS, recent developments
    2. Outline of the ring, its performance and limitations
    3. Recent and current work improving machine models (lattice etc.)
    4. Head-tail instability and impedances
    5. Relevance for ISIS II
    6. Summary

ISIS Facility & Recent Developments

- Spallation Neutron Source at RAL in UK
  >2000 strong user community, 644 publications in 2021

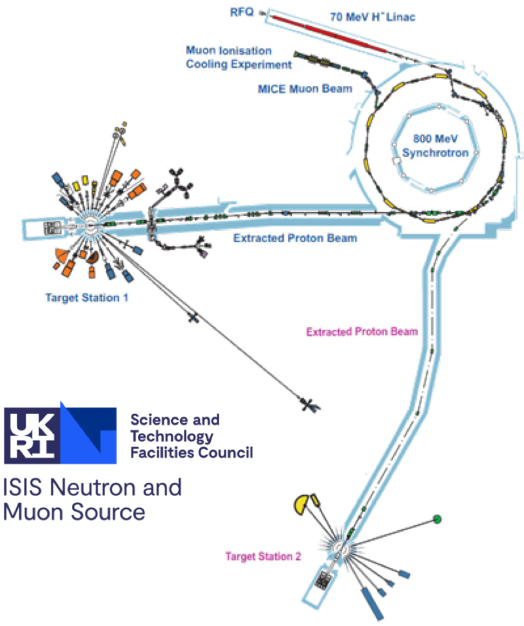
- Record operations in 2020: 245 μA running

Intensity
Beam Loss



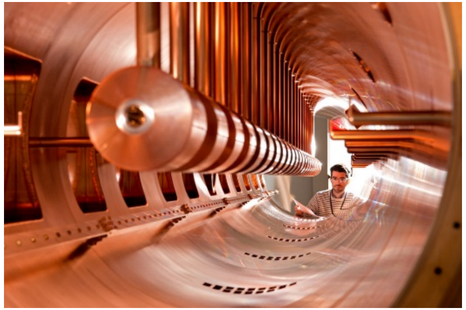
- Long shutdown last year 2021
  Linac tank 4 replacement; Target station 1 upgrade

- Have re-established TS2, 10 Hz beam during 2022
  Now tuning intensity back up ready for TS1, 50 Hz (November)



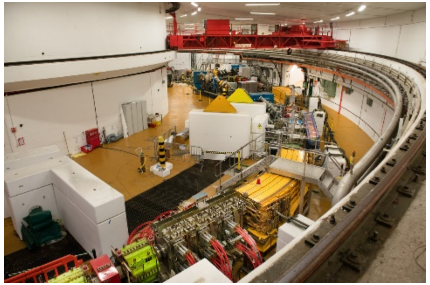
Science and Technology Facilities Council
ISIS Neutron and Muon Source

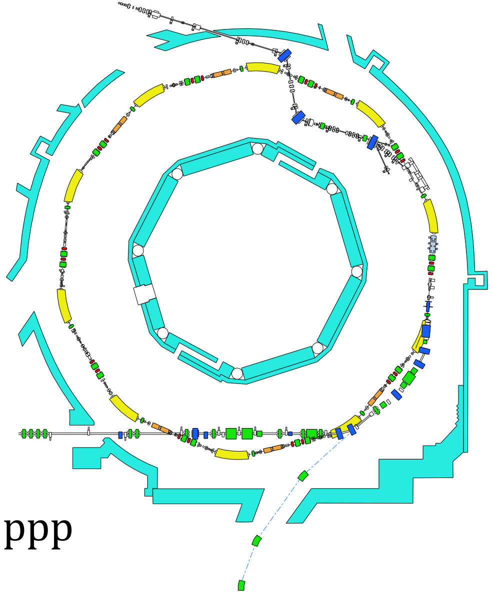
New Linac Tank 4



The ISIS RCS: Main Parameters

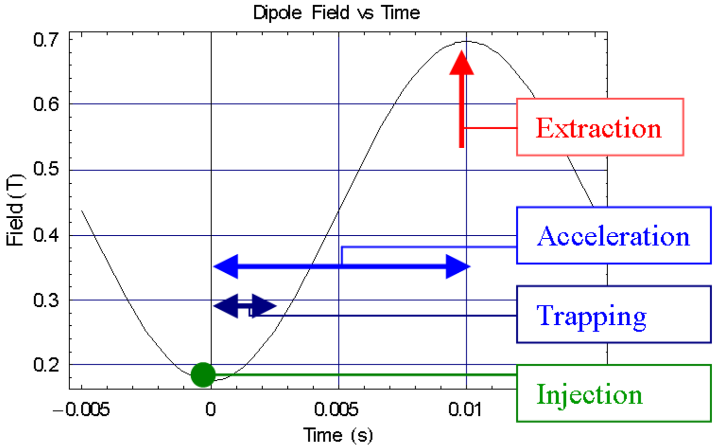
Science and Technology Facilities Council
ISIS Neutron and Muon Source



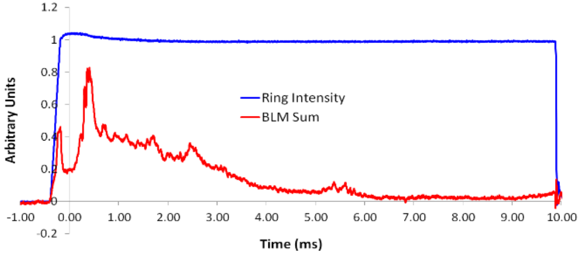


Circumference:	163 m
Energy Range:	70-800 MeV
Rep Rate:	50 Hz
Intensity:	2.5-3.0 x10^{13} ppp
Beam Power:	160-200 kW
Losses:	Inj: 2%, Trap: <3%, Acc/Ext <0.5%
Injection:	130 turn, H^- charge-exchange
Acceptances:	Collimated ~350 π mm mr
RF System:	h=2, f_2=1.3-3.1 MHz, V_2 ~160kV/turn
(*2 bunches*)	h=4,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

Main Magnet Field & Machine Cycle



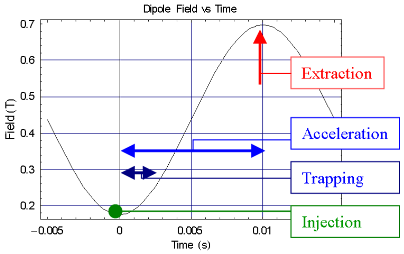
Intensity and Loss Through Cycle

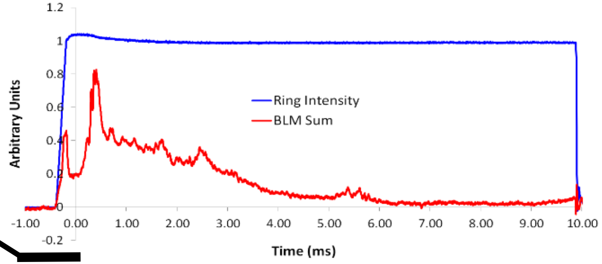


ISIS RCS Beam Losses and High Intensity Limits

UKRI Science and Technology Facilities Council
ISIS Neutron and Muon Source

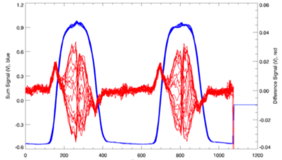
What are our losses ~ what don't we understand?





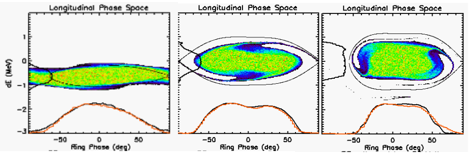
Injection
(-0.4-0.2 ms)
Stripping~2%
Foil re-circulations
Optimal painting

Head-tail instability
(~ 1.5-2.5 ms) m=0,1



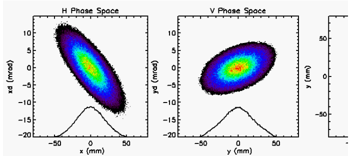
Vertical loss: ramp Q_v

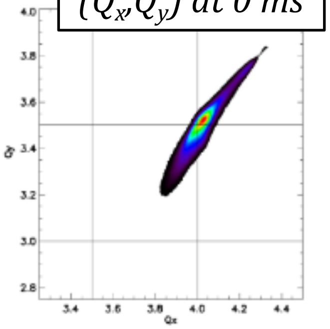
Longitudinal trapping
(-0.4-0.5 ms)



Non-adiabatic capture
Un-chopped beam
Dual harmonic RF

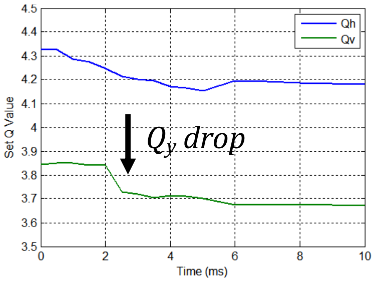
Transverse space charge
(-0.4-2.0 ms)





ΔQ_{incoh} peaks with bunching 70-100 MeV

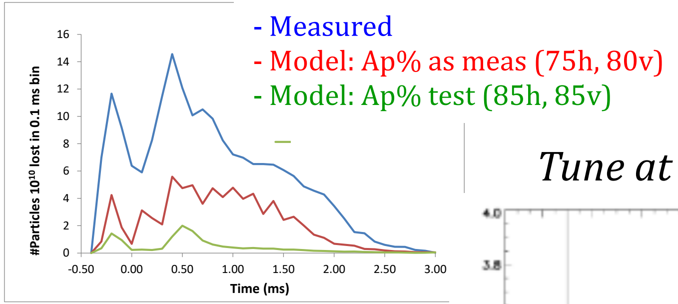
ISIS Q values through cycle



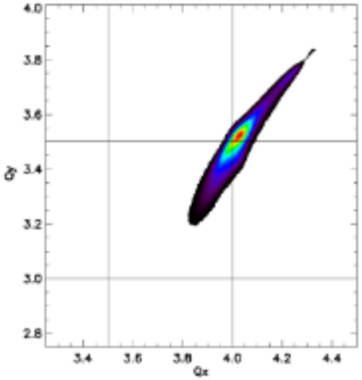
Detailed comparison RCS ORBIT model vs measurements (IPAC 2012)

- ISIS RCS 2.5D Model: 2.8E13 ppp operations
  - Dual Harmonic RF, 3D injection painting
  - Q variation, real apertures and collimators
  - Linear lattice without errors
- Basic comparison
  - Longl., transv. disns. ~ agree measurements
  - Time dependence loss = good agreement
  - Absolute loss = sensitive to collimation (~ 5mm)
- Add grad errors to model
  - $2Q_h=4$, $2Q_v=7$; $\Delta\beta/\beta \sim 10\%$
  - Aperture% 85h,85v
  - Total loss ~ same 1%
  - Small effect @ $\Delta Q \sim 0.5$
  - Real?

Beam Loss vs Time



Tune at 0 ms

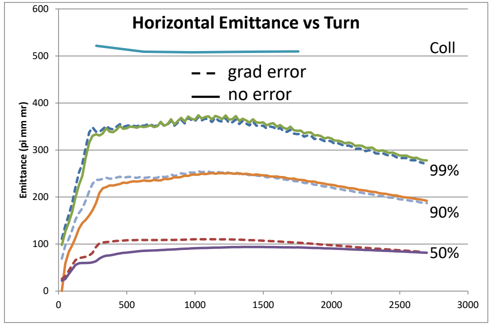


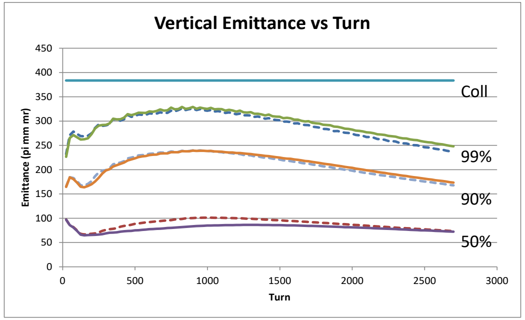
Acceleration efficiency

Measured	Model
93.0%	97.3%

Comparisons with/without grad errors

Horizontal and vertical emittances





D J Adams, et al

Beam measurements to improve models on ISIS

Science and Technology Facilities Council
ISIS Neutron and Muon Source

- Reconfigure machine for studies

  RCS — *Rapid cycling synchrotron* – Magnet & RF ramps (70-800 MeV)
  BSRM — *Bunched storage ring mode* – DC magnets, RF fixed freq (70 MeV)
  SRM — *Storage ring mode* – DC magnets, no RF ("2D" coasting) (70 MeV)

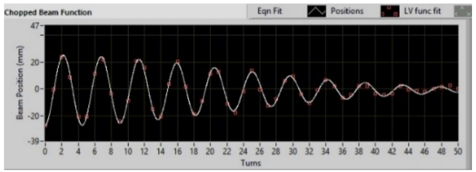
- Low intensity measurement of lattice parameters

  Optics, beta functions (gradient errors & correction)

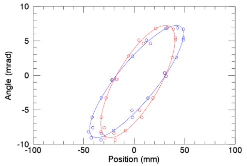
One of 10 ISIS Super periods

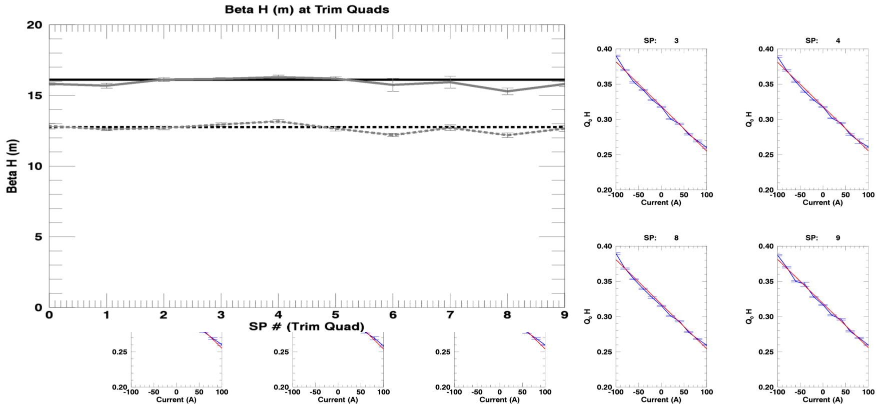
Beta functions at 20 trim quads (dQ/dI_{TQ})

Turn by turn positions



Optics meas



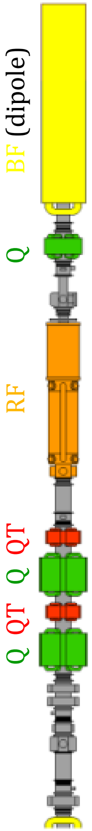


- *i.e. better linear models!*

H V Cavanagh, et al

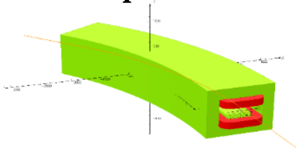
Transverse Dynamics 1: Improving Magnet Models

- Limited measurement data available for ring magnets
  - Have matched simulation models to measurements available – good agreement
  - Now adding non-linear multipole components to models
  - Have OPERA model of each lattice type – *not every magnet*

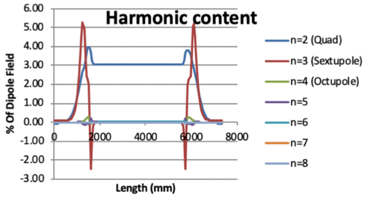


One of 10 ISIS Super periods

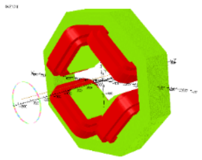
Dipoles



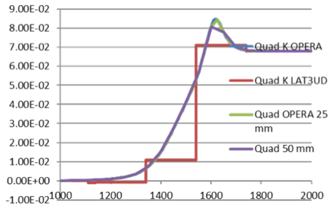
OPERA Results for Dipoles



Quads

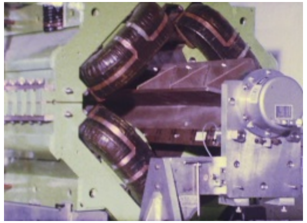


Improved fringe fields

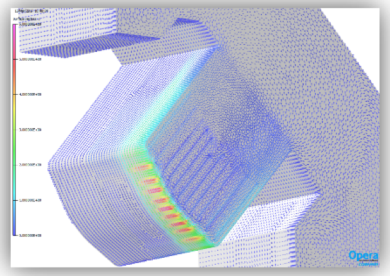


OPERA models

Measurements



OPERA Quad Model



Use increased detail from OPERA

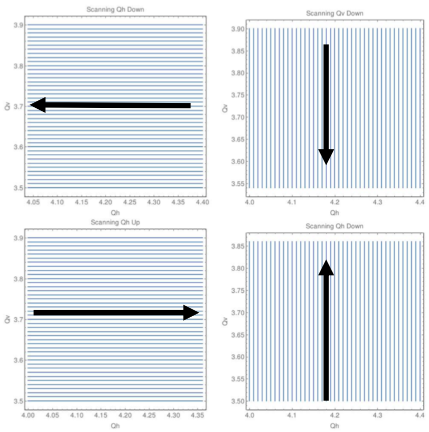
- Build better TEAPOT/PTC PyORBIT models
- With fringe fields and non-linear terms

D J Adams, I Rodriguez, S J Jago, et al

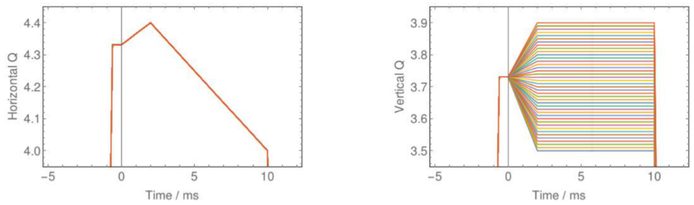
Transverse Dynamics 2: Tune vs Loss Measurements

- Experimental method developed for ISIS ring
  - Storage ring mode, low intensity, 70 MeV (not RCS, high intensity)
  - Use programmable TQ to scan tunes – automated
  - Use R5IM (toroid), BLMs, scintillators, ~ 8 ms Q ramp

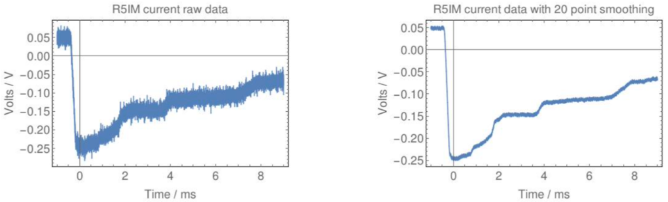
Q scans in Q plane



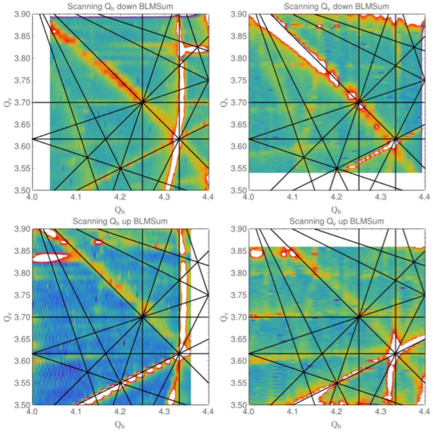
Q_x and Q_y programme



Loss on toroid & BLM



Loss vs Q_x, Q_y



B G Pine, P T Hicks, et al ...

UKRI Science and Technology Facilities Council
ISIS Neutron and Muon Source

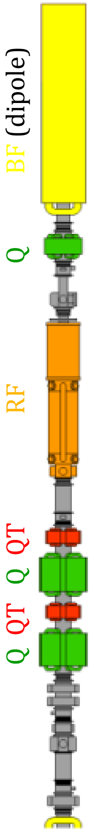
Transverse Dynamics 3: Tune vs Loss Measurements

- Distortions in Q vs loss exposed errors in Q setting & lattice model

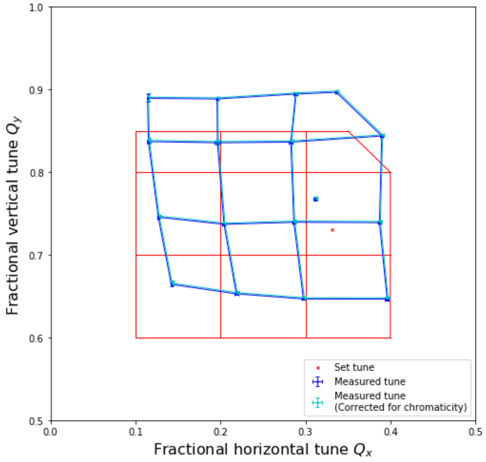
  Detailed study of low intensity tune setting (trim quads)

  Better Q control & lattice model (base Q, set *ΔQ*, chromaticity)

  Improved/corrected Q scan

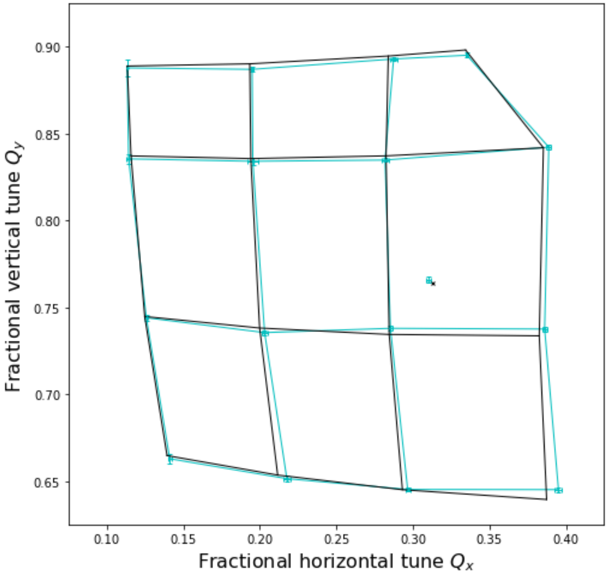


Linear tune calc & actual tune

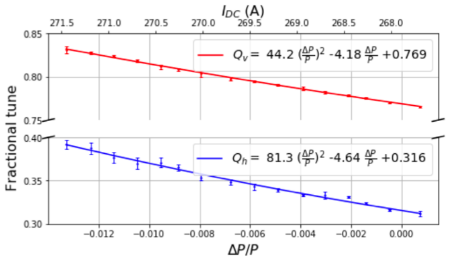


$$\Delta Q = \frac{1}{4\pi}\oint \Delta k(s)\beta(s)ds$$

New set and actual tune



Chromaticity



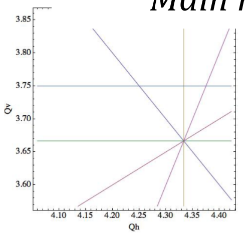
P T Hicks, H Rafique, et al

Science and Technology Facilities Council

ISIS Neutron and Muon Source

Transverse Dynamics 4: Tune vs Loss Measurements

Main resonances

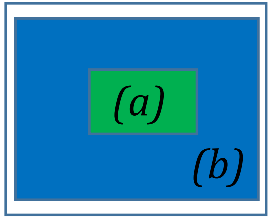


Order	Resonance
Sextupole	$3Q_h = 13$
Sextupole	$3Q_v = 11$
Octupole	$4Q_v = 15$
2^{nd} order	$Q_h + Q_v = 8$
3^{rd} order	$Q_h - 2Q_v = -3$
3^{rd} order	$2Q_h - Q_v = 5$

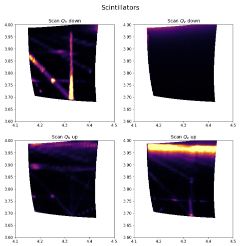
- Application
  - Identified main resonances: what is their strength?
  - Next: estimate via comparison with simulations …

- Dependence on aperture explored

Schematic of scanned aperture (x-y)



(a) Small aperture



(b) Larger aperture

2^{nd} order
$Q_h + Q_v = 8$

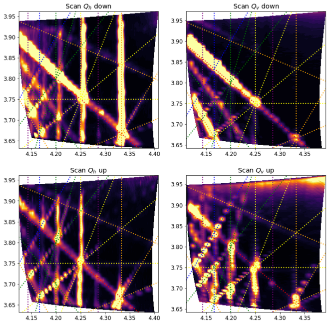
3^{rd} order
$3Q_h = 13$
$-Q_h + 2Qv = 3$
$2Q_h - Q_v = 5$
$Q_h + 2Q_v = 12$
$2Q_h + Q_v = 12$

4^{th} order
$4Q_h = 17$
$4Q_v = 15$
$3Q_h - Q_v = 9$
$2Q_h - 2Q_v = 1$

5^{th} order
$5Q_h = 21$
$4Q_h - Q_v = 13$
$3Q_h - 2Q_v = 5$
$3Q_h + 2Q_v = 20$

6^{th} order
$6Q_h = 25$
$4Q_h - 2Q_v = 9$

7^{th} order
$7Q_h = 29$
$7Q_h = 30$



- Developments
  - Can vary painting and explore resonance dependence on $(\varepsilon_x, \varepsilon_y)$
  - Use of spatially distributed loss monitors: azimuthal disn gives h ($n\,Q_y = h$)

P T Hicks, H Rafique…

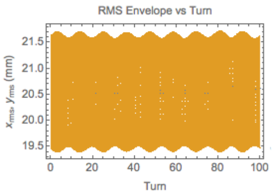
Science and Technology Facilities Council
ISIS Neutron and Muon Source

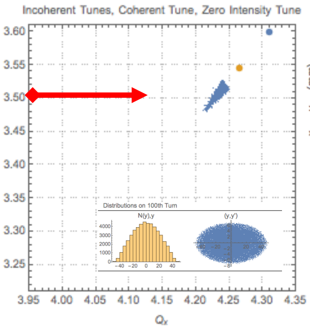
Transverse Dynamics 5: Half integer resonance

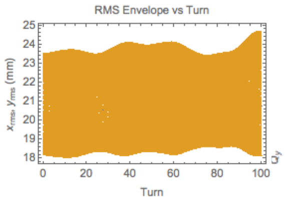
Science and Technology Facilities Council
ISIS Neutron and Muon Source

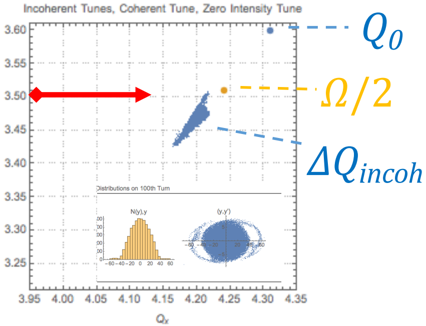
- Unclear how important on operational machine: 3D RCS
- Continue experiments/simulations: coasting 2D beam to help understand
  - Constant $(\varepsilon_x, \varepsilon_y)$, Q's, grad error $(2Q_v=7)$
  - Increase intensity to approach coherent resonance: What happens?
- Observations suggest
  - 2D static sims

Off coh. resonance is OK … behaviour of single particle in averaged coh. field → predict halo?



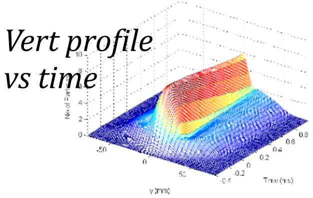




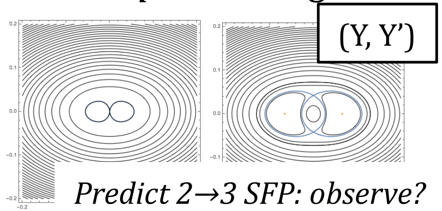


- 2D experiments seem to confirm
  - Working on tying up time evolution
- 3D Effect in a bunch with Q_s
  - Variable coh/incoh effect along bunch
  - Next: study with BSRM: *High intensity limit?*

Measurement



Frozen space charge halo

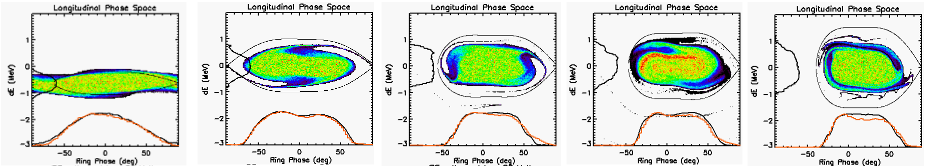


C M Warsop, et al

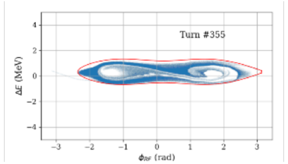
Longitudinal Dynamics

Science and Technology Facilities Council
ISIS Neutron and Muon Source

- Generally good agreement measurement and models

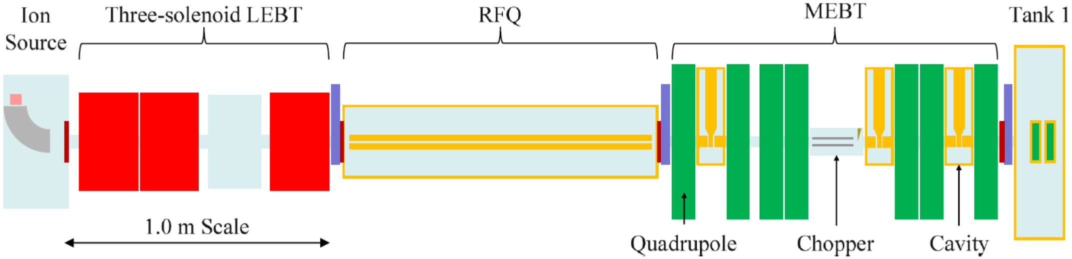


Latest trapping study

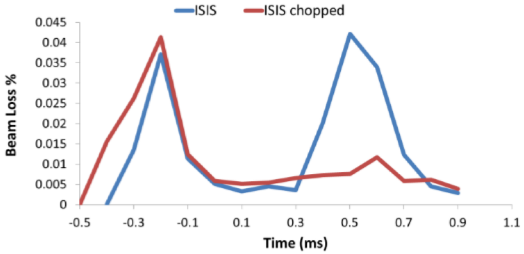


- Potential for improvements, more detailed study
  - RF hardware upgrades – now have better control – more optimisation
  - Details of complicated non-adiabatic, dual-harmonic trapping worth study

- New MEBT with fast chopper to be installed



Losses reduced with chopper



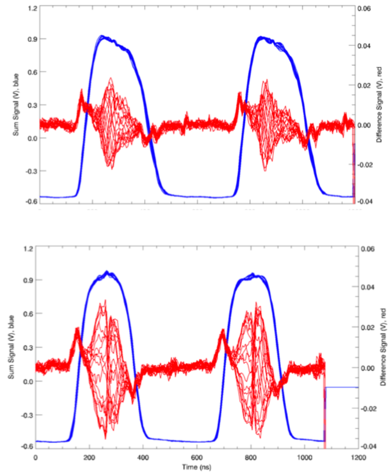
D J Adams, R E Williamson, B Kyle, members of RF group, Low Energy Beam Group, et al

Vertical head-tail instability

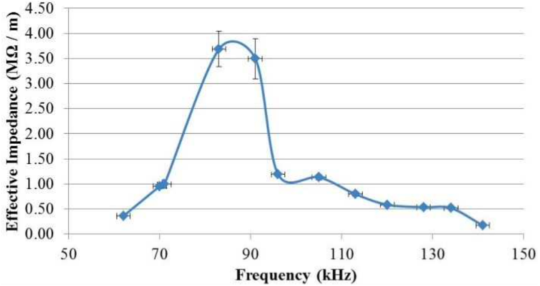
Science and Technology Facilities Council
ISIS Neutron and Muon Source

- Causes loss in high intensity operations
  - Dual Harmonic RF (m=0, 1), stabilise: Q_v, paint, bunch shape
  - Single Harmonic RF (m=1, Sacherer predicts m=2)
  - Damping system being developed
  - *Complicated by fast RCS ramp and high space charge*
- Dedicated experimental campaign: remove complications
  - Remove energy and RF frequency ramp – BSRM
  - Lower intensity (and space charge): 1.5E12 ppb
  - Measurements as function of Q_y and beam size ε_y
  - Compare with PyHEADTAIL 2.5D PIC simulations
- Driving impedance presently unknown (see later)
  - Effective Z from coasting beam growth rate meas.
  - Gives narrow band model for simulations

Head-tail modes during ops



Effective Impedance Measurements



R E Williamson

Head tail study

Measurements

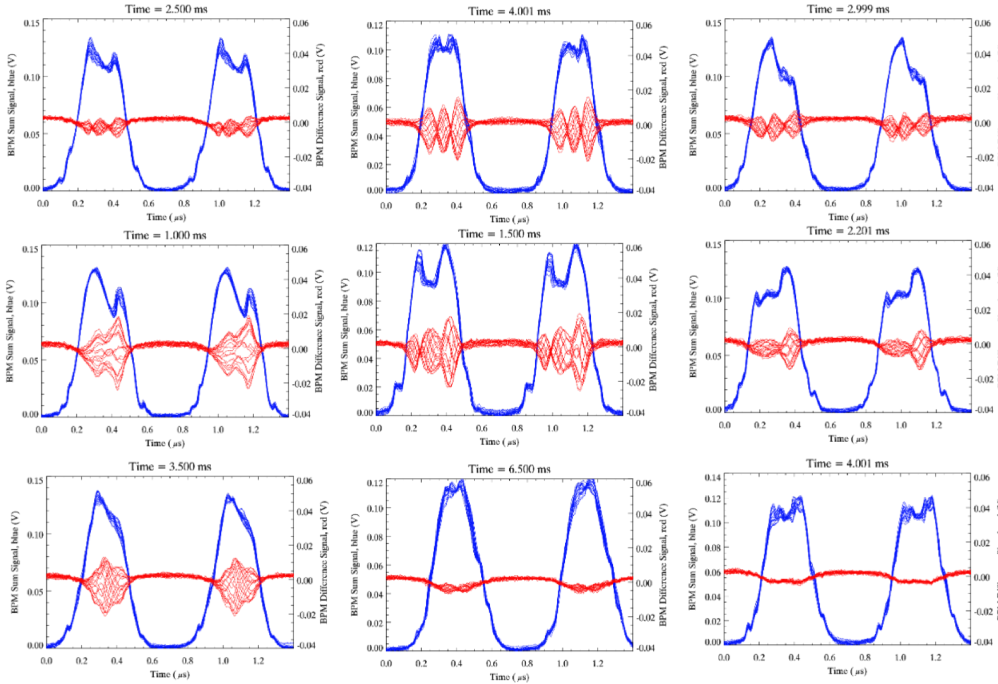
- BSRM, 10% normal intensity (~1.5E12 ppb)
- Vertical head-tail vs (Q_y, ε_y)

Results

- Mode change with Q_y and ε_y
- Growth rate ↑ as ε_y ↓ (space charge?)

$\varepsilon_{rmsy} = 10\ \pi$ mm mr $30\ \pi$ mm mr $50\ \pi$ mm mr

Q_y ↓



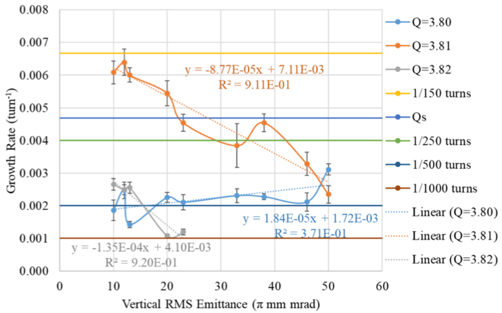
Q_y=3.87

Q_y=3.88

Q_y=3.89

ε_y (RMS) ⟶

Growth rate vs ε_y



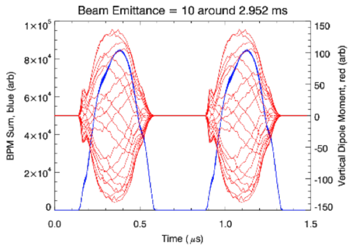
R E Williamson

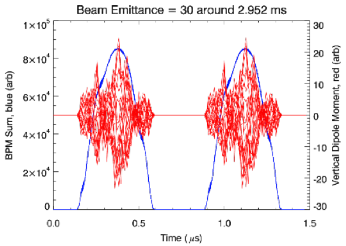
Science and Technology Facilities Council

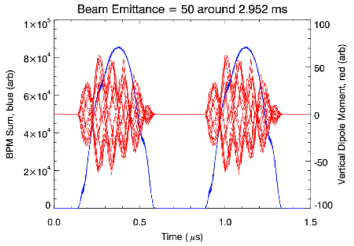
ISIS Neutron and Muon Source

Head tail study

$\varepsilon_{rmsy} = 10\ \pi$ mm mr　　30 π mm mr　　50 π mm mr







$Q_y = 3.87$

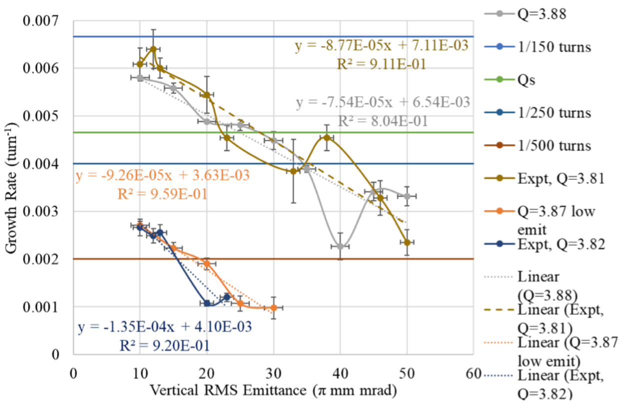
Simulations

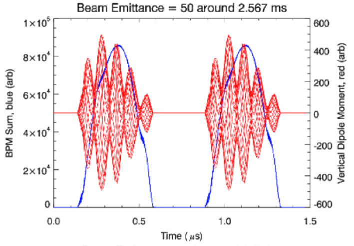
- PyHEADTAIL ISIS Model
- Low freq narrowband Z
- 2.5D space charge PIC

Results

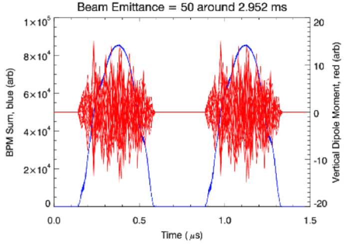
- Mode change with Q_y and ε_y
- Growth rate ↑ as ε_y ↓

- Different modes from meas.
- Gradient of growth vs emittance similar to meas.





$Q_y = 3.88$



$Q_y = 3.89$

Much to disentangle!

Results should help us understand:

- Role of space charge …
- Intra-bunch structure, multiple modes …?

R E Williamson

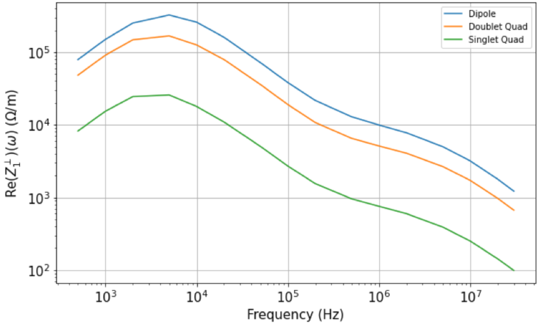
UKRI Science and Technology Facilities Council
ISIS Neutron and Muon Source

Beam Impedances on the ISIS RCS

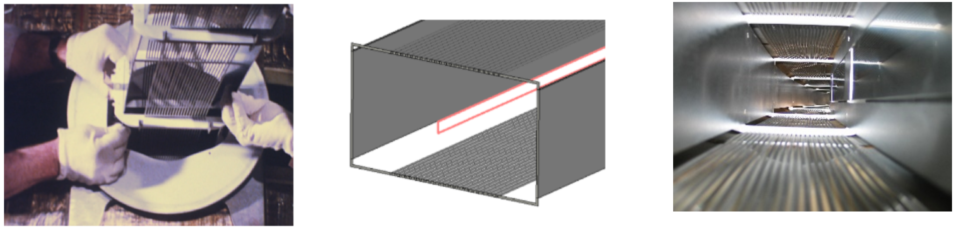
Science and Technology Facilities Council
ISIS Neutron and Muon Source

- New work assessing low frequency transverse impedances
- Expect contribution from RCS magnets (~45% of ring)
  - Laminated poles, ceramic vessels, RF shields
  - Studies indicate main LF part is from RF shield
  - RWAL code: analytical soln. for cylindrical multilayers
  - Confirmed comparisons CST: calcs of Z contribution

Z from Main Magnets

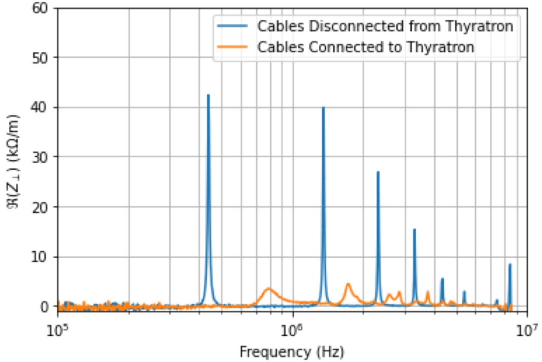


ISIS RF shield



- Extract kickers (likely contribution)
  - Vertical plane, long cables, terminated at thyratron end
  - Single-turn loop measurements on spare kicker
  - Indicate impedance OK with suitable terminations

Extraction kicker meas.



D Posthuma de Boer

Beam Impedances on ISIS

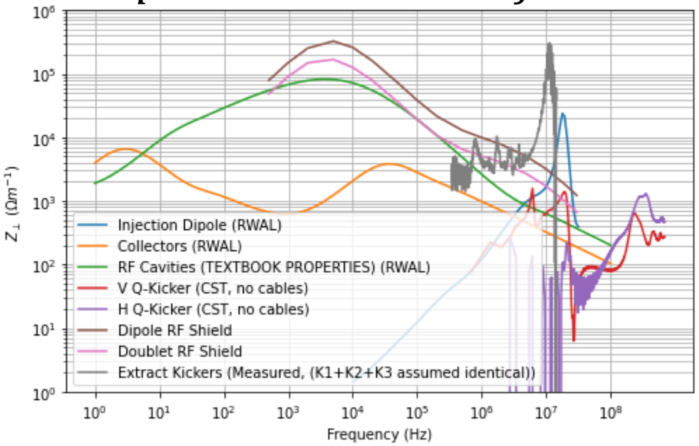
- Overall machine Z assessment
  RWAL, CST estimates for most equipment
  Building up a better picture …

- Head-tail coupled-mode Vlasov solver
  New solver implemented in Python
  Find modes frequ/GR for complicated Z
  Treats longtl disns: airbag, nested ab, arbitrary
  Benchmark vs PyHEADTAIL generally agree

- Example Calculations for ISIS (Q_y=3.87)
  Narrow band impedance etc. (as above)
  Airbag and Gaussian longtl. disn.
  Not coupled modes

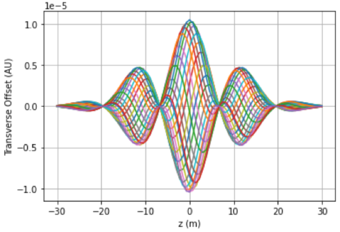
Capability to test effects of different impedances

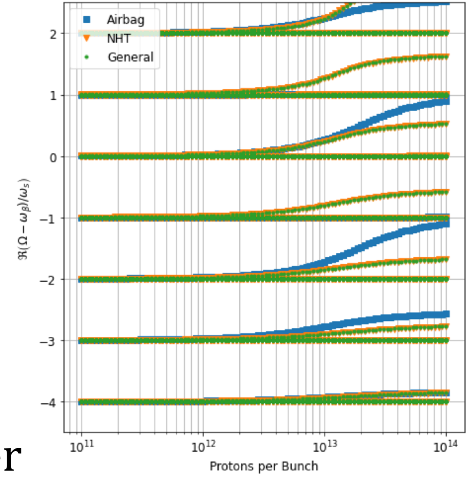
Impedance Estimates for ISIS



Predictions from Vlasov Solver

Fastest mode
(General-Gauss)

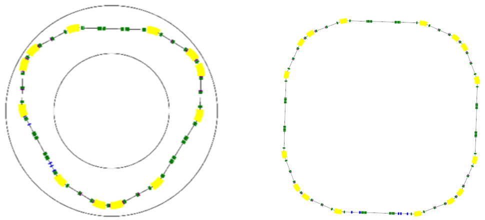




D Posthuma de Boer

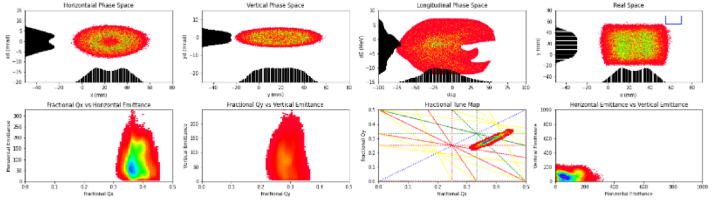
Relevance of ISIS I to ISIS II Work

1.2 GeV RCS, Accumulator Ring



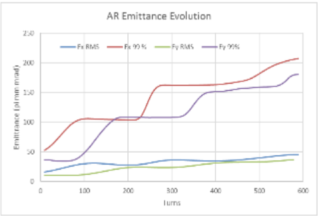
- ISIS II ~ next generation neutron source ~ under study
  - Present spec. 1.25 MW (40 and 10 Hz Targets)
  - Recently completed exploratory designs of 4 RCS/AR rings

AR 3D PyORBIT Runs



- Design studies highlighted requirements to
  - Reliably predict, understand losses: 0.1-0.01%
  - Want halo evolution: foil, loss control
  - *Reasons for loss in codes often not clear: correct?*

Emittance evolution



- Needs models benchmarked vs measurements (ISIS I)
  - Design tests for particular loss mechanisms
  - Effects of particular resonances (2D, 3D), Instabilities
  - 2D, 3D injection paint, trapping … (MEBT chopper)

Compare other machines, other codes … reliable *high intensity limit*

Science and Technology Facilities Council
ISIS Neutron and Muon Source

Summary

ISIS Neutron and Muon Source

- We continue to improve performance of the ISIS RCS
  - E.G. 275 μA equivalent at low rep rates

- We continue to learn and understand more about its losses & limits

  Working on improving our models as the basis for:
  - Development of ISIS
  - Optimal ISIS II and future designs

- Key things to understand ("*gaps in our knowledge*")
  - Achieve, reliably predict 0.1-0.01% loss with $\Delta Q_{incoh} \sim 0.2 - 0.5$ or more?
    - What is the high intensity space charge limit?
    - Can we predict head-tail motion with space charge?

- Collaboration rather than duplication?
  - If we work together on codes and experiments = less time & better results?