High-Intensity Studies on the ISIS RCS and their Impact on the Design of ISIS-II

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ISIS Accelerator Physics Group

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UKRI Science and Technology Facilities Council

ISIS Neutron and Muon Source

Contents

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- ISIS-II: next generation MW source
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- Head-tail instability on the ISIS synchrotron
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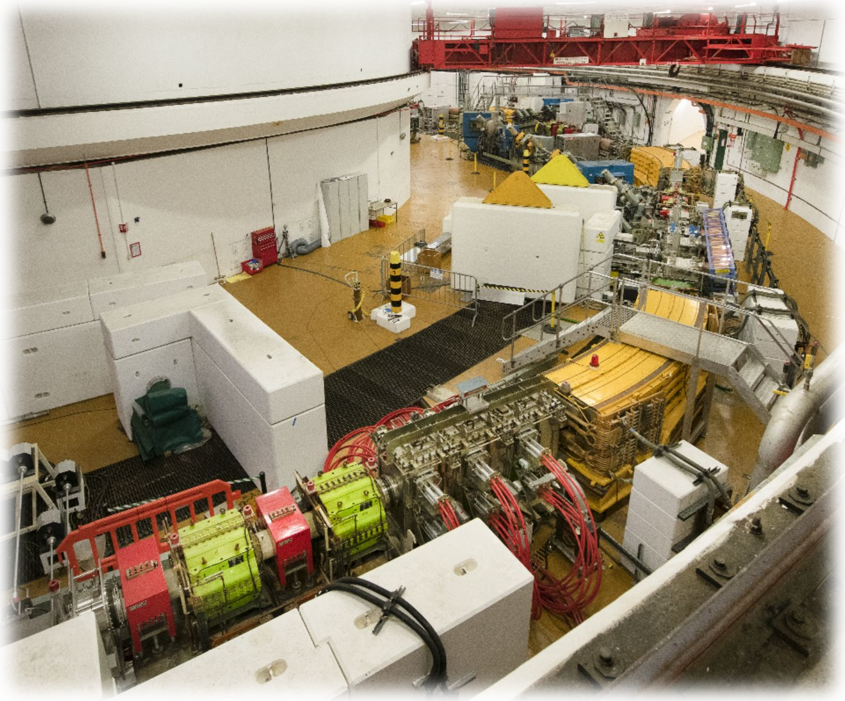

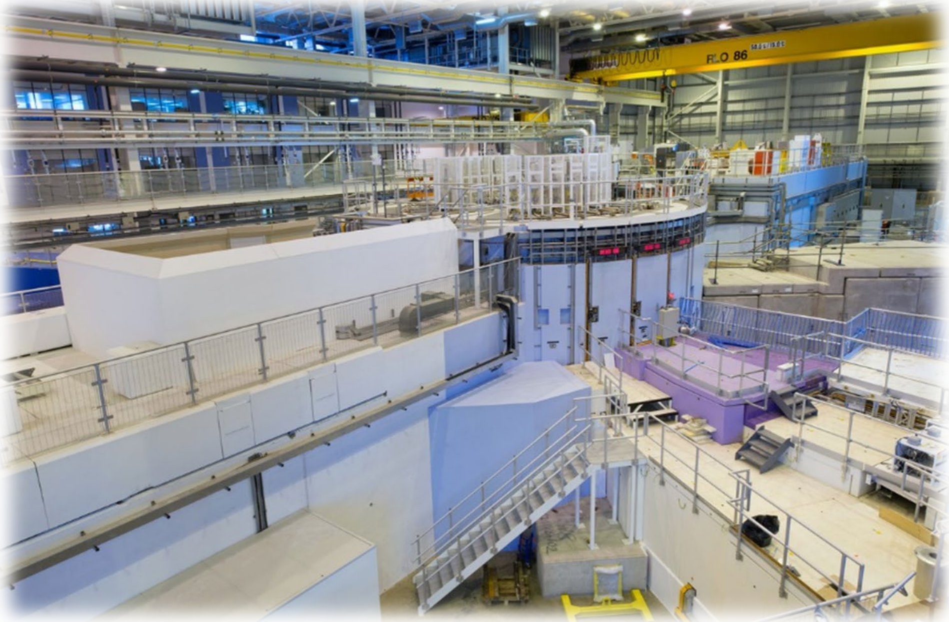

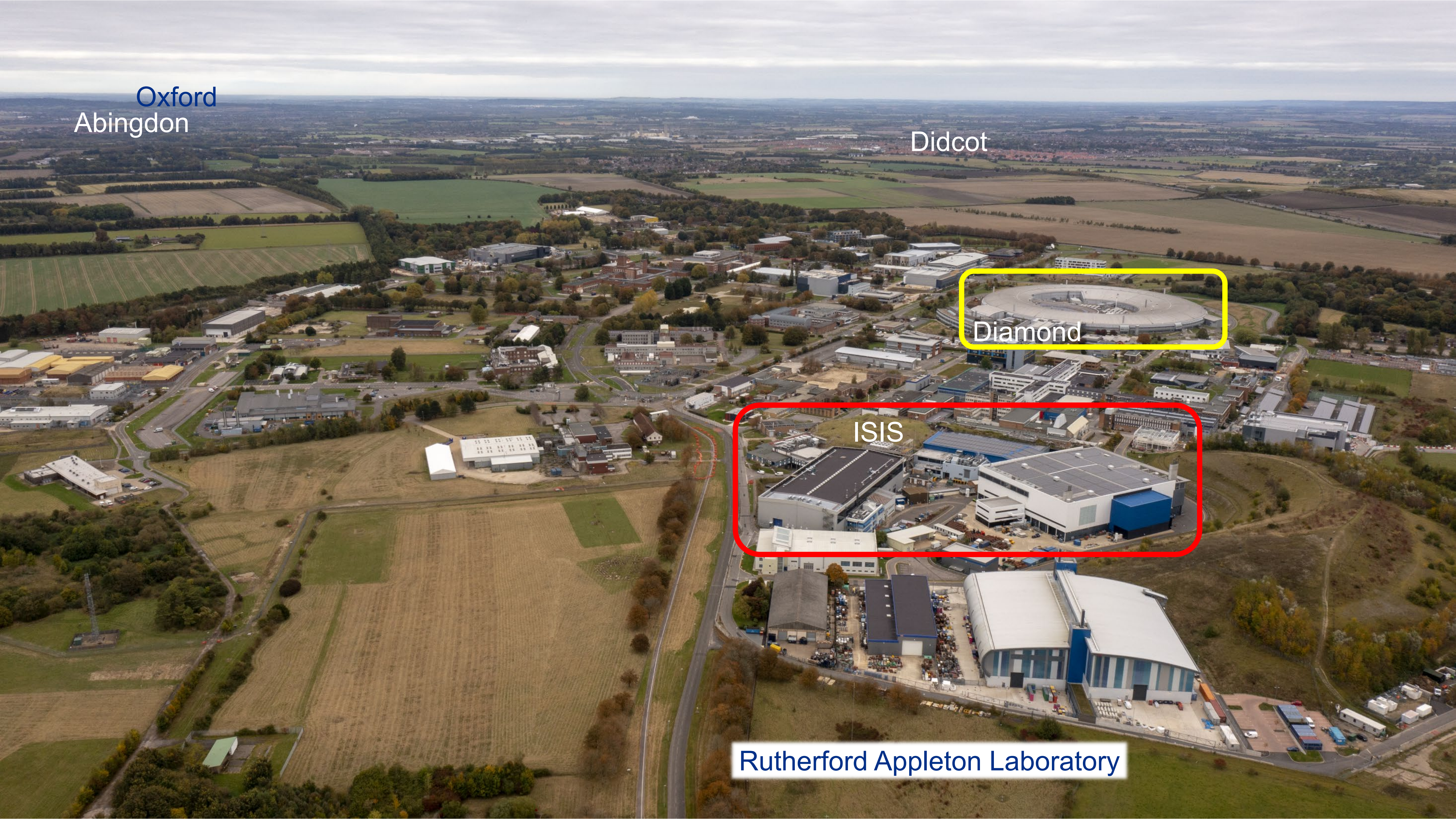
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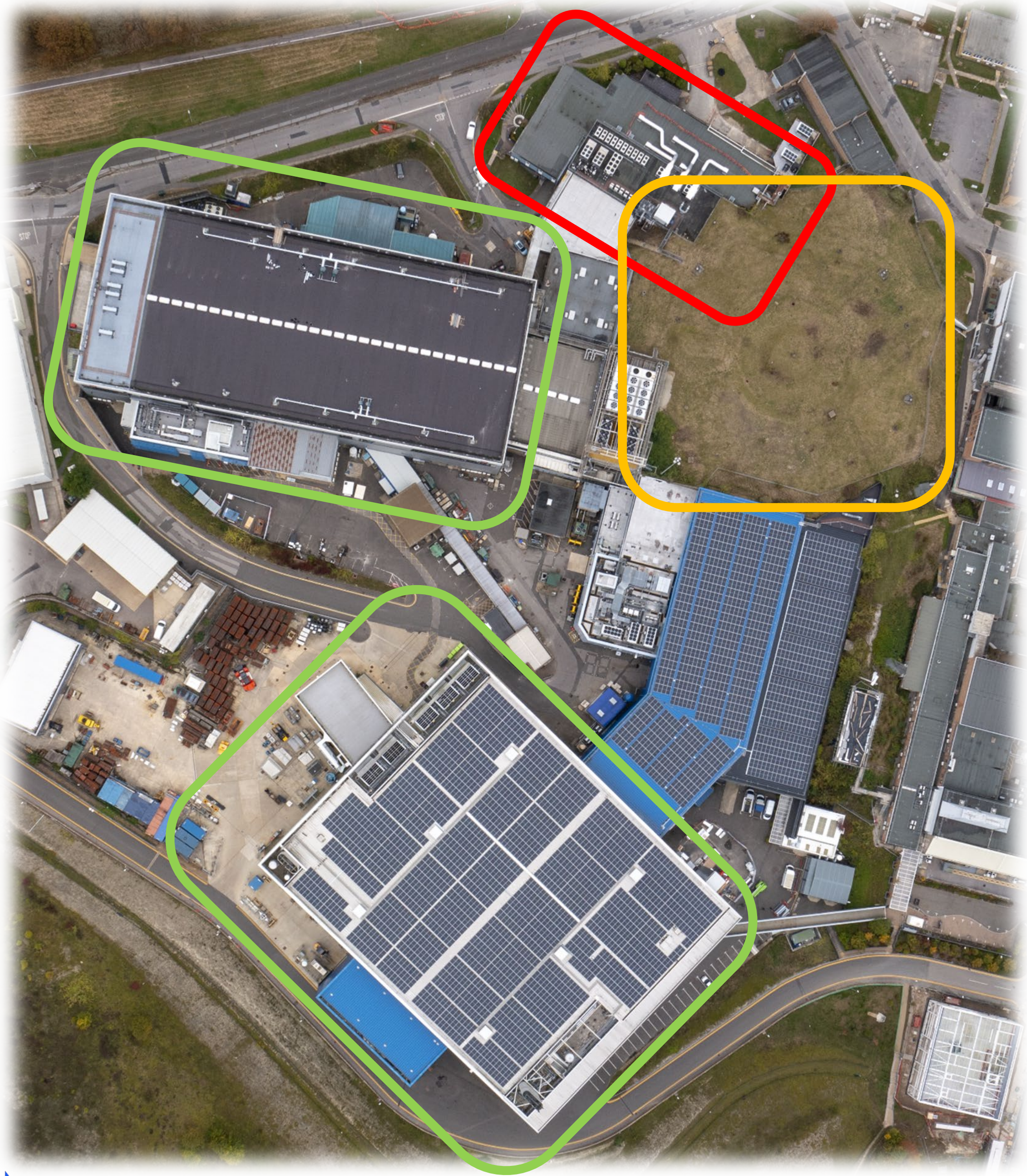

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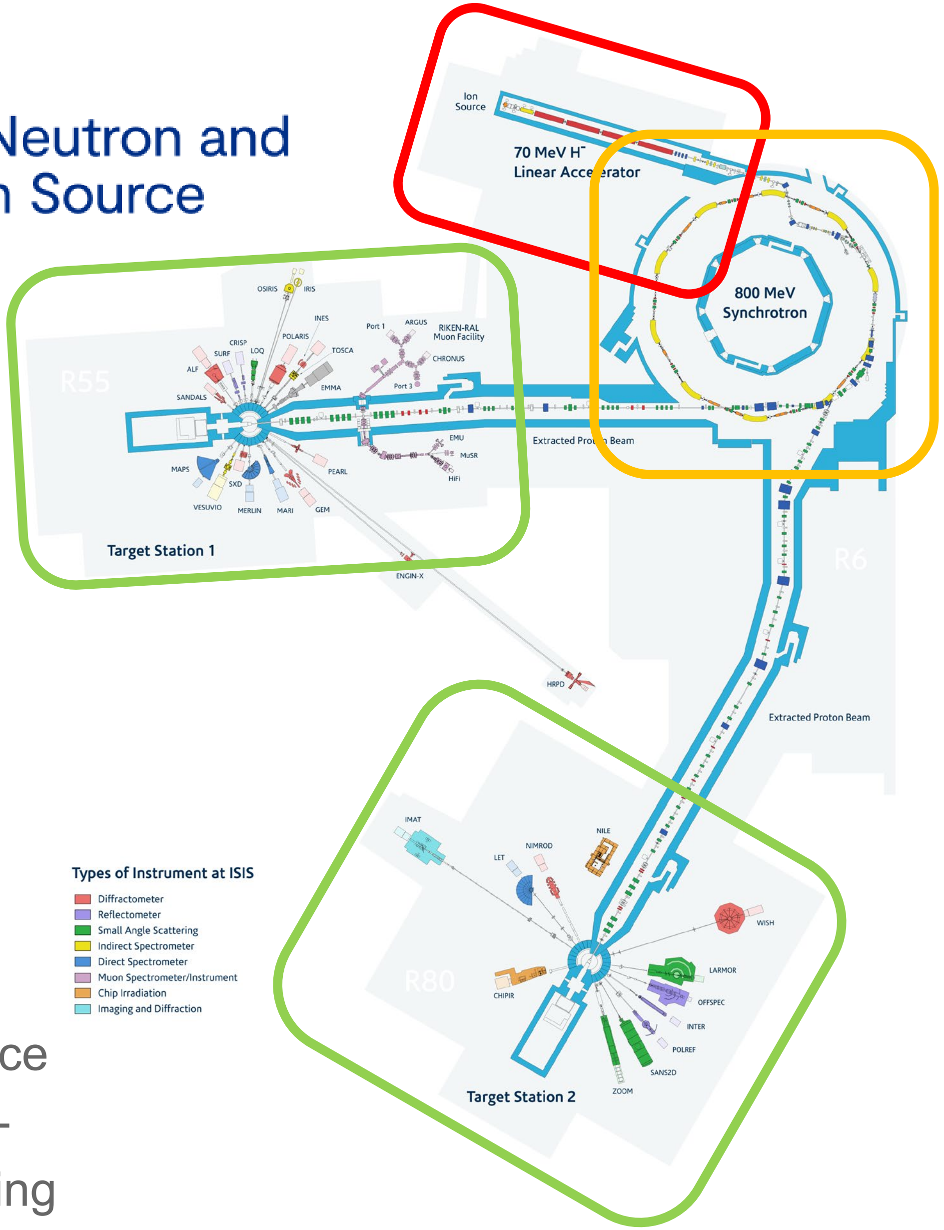


- H- Ion source RFQ & DTL
- Rapid Cycling Synchrotron
- Target Stations

ISIS Synchrotron

Circumference: 163 m

Energy: 70–800 MeV

Repetition Rate: 50 Hz

Intensity: ~3×10^{13} ppp

Power: ~190 kW

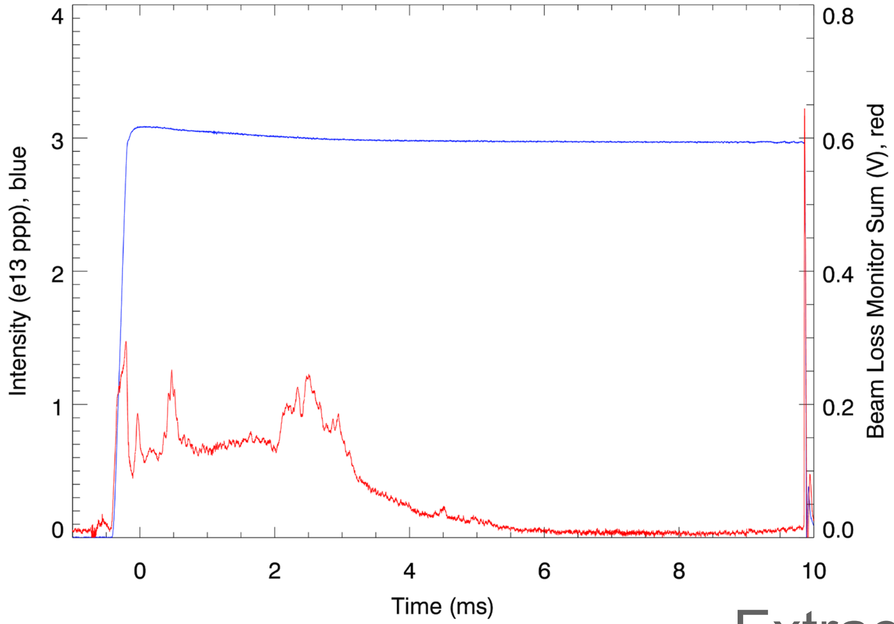
Injection: 220 µs, 130 turn, charge exchange

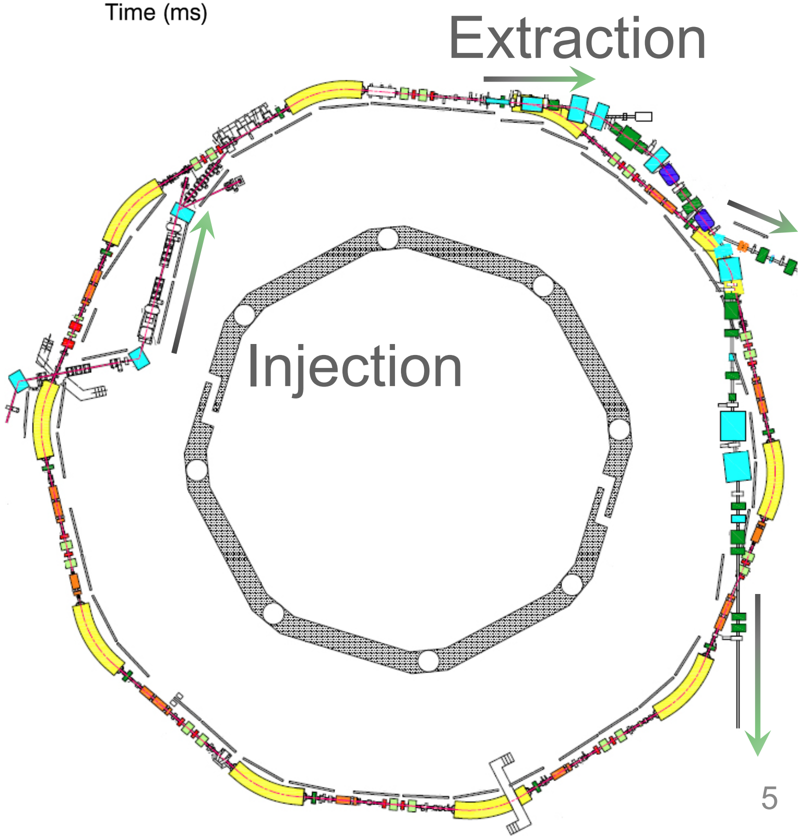
Extraction: single turn, vertical

Betatron Tunes: $(Q_x, Q_y) = (4.31, 3.83)$, programmable

Beam Losses: Injection: 2%, Trapping: <3%, Acceleration/Extraction: <0.5%

RF system: h=2, 1.3-3.1 MHz, 160 kV/turn
h=4, 2.6-6.2 MHz, 80 KV/turn





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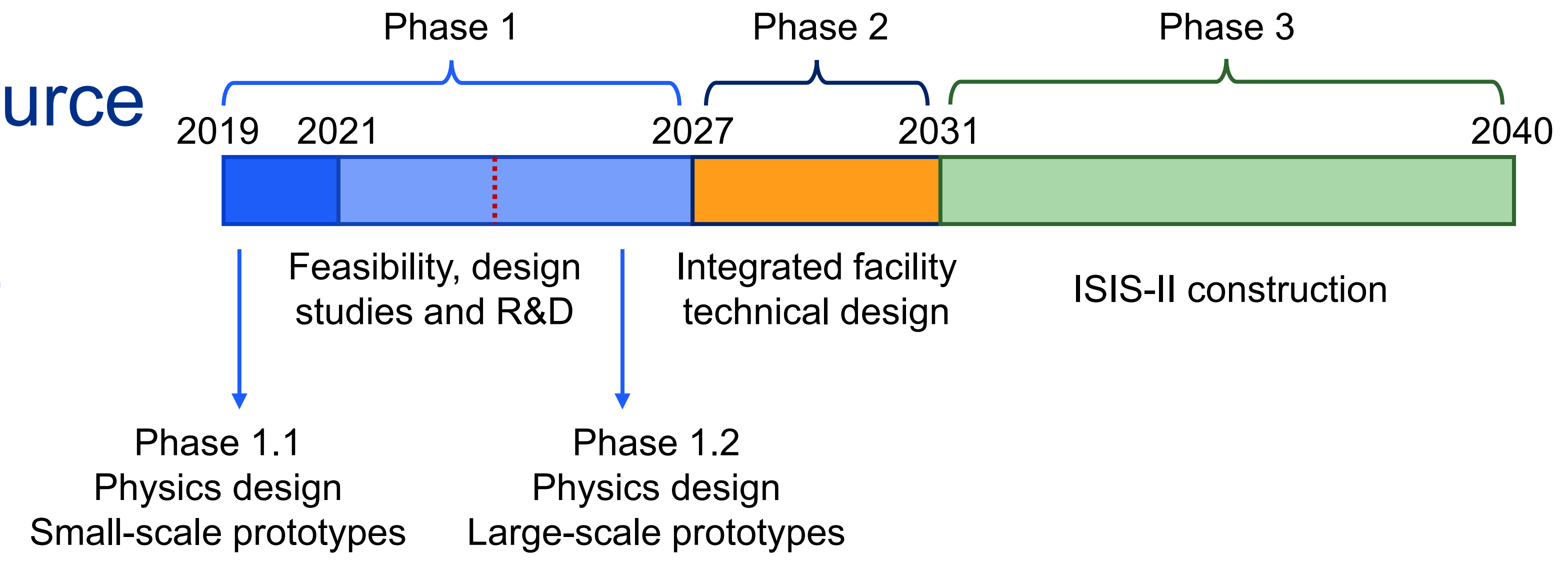
ISIS-II: Short-Pulse, MW Source

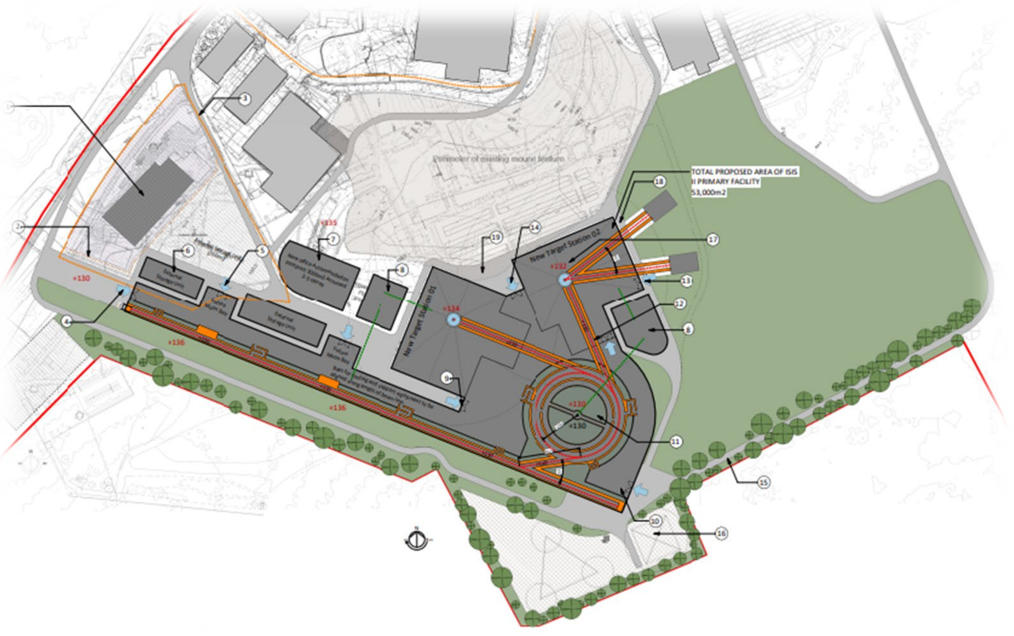
- Eventual closure of ILL will significantly reduce the number of “instrument-days”
- Address the gap in “instrument-day” capacity in Europe
- **ISIS-II** will be a **MW class,** short-pulsed neutron source
- Optimised for **impactful science**
- **Reliable**, **sustainable** source with supporting instrumentation, computing and infrastructure



Headline Specifications

(to be confirmed)

- 1.25 – 2.5 MW beam power
- 1.2 GeV on target
- 0.1% beam loss during operation



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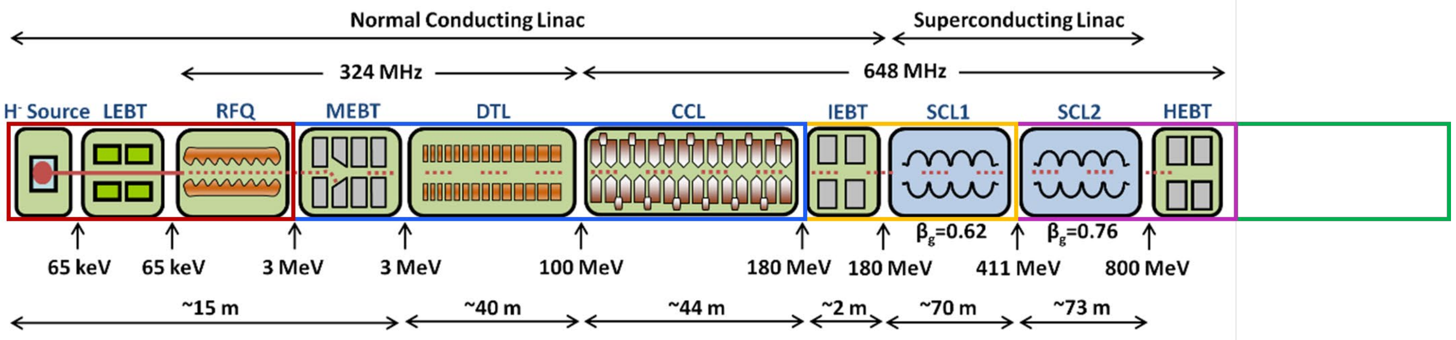
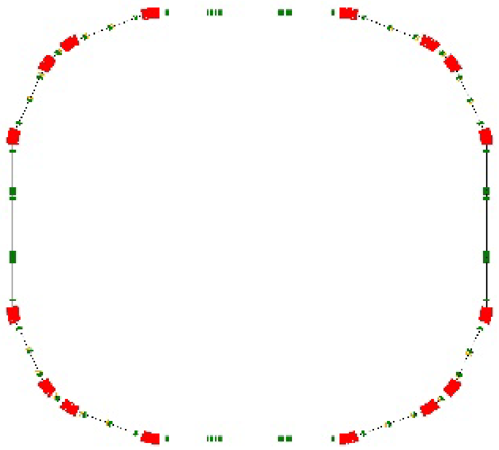
ISIS-II Options

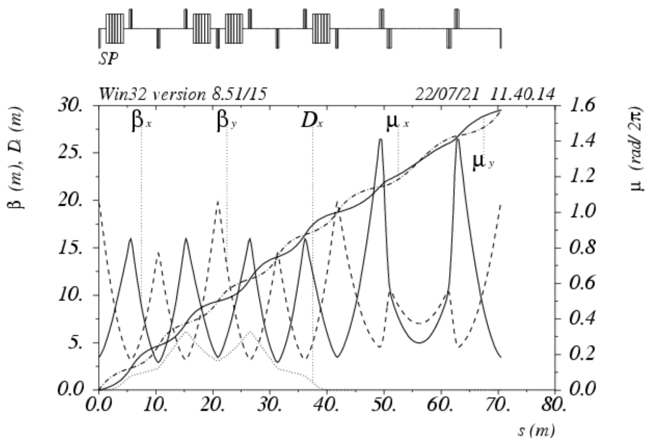


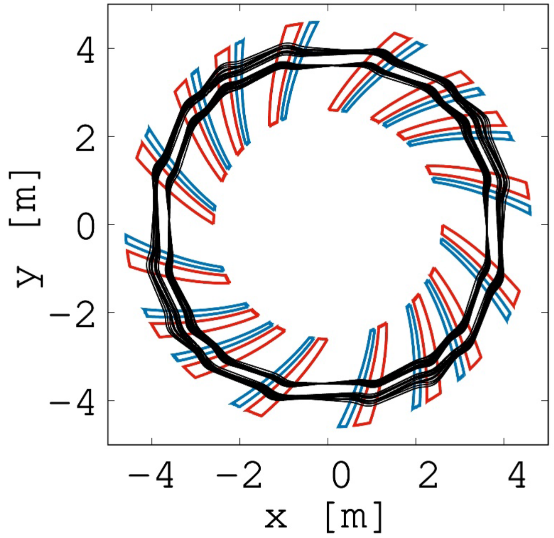
- Current studies covering machine types:
  - Rapid Cycling Synchrotrons (RCS)
  - Accumulator Rings (AR)
  - Fixed Field Alternating Gradient Accelerators (FFA)

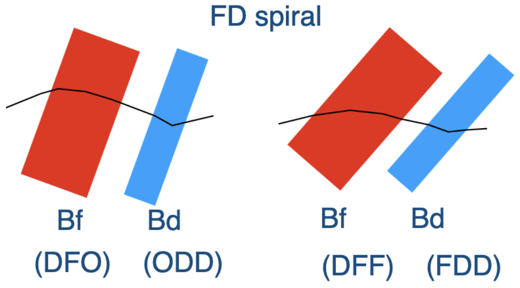
} "Conventional Rings"

- Existing RCS and AR accelerators have demonstrated similar specifications
- FFA has not yet demonstrated high-intensity operation => demonstrator
- Environmental impact will be a key consideration









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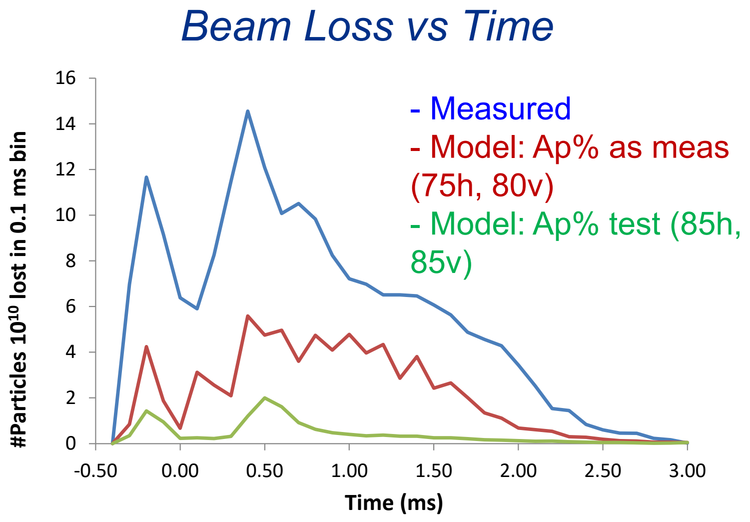
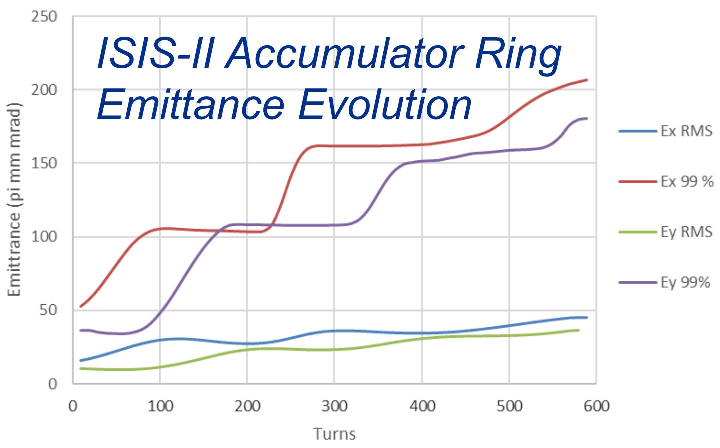
R&D on the ISIS RCS

- Detailed ORBIT model of ISIS RCS vs measurements (IPAC12)
  - 2.5D model of high-intensity operation
  - Dual-harmonic RF, 3D painting, Q variation, Apertures and Collimation
  - Linear lattice without errors
  - Qualitative agreement of beam distributions and beam-loss vs time
- ISIS-II design studies
  - Need reliable prediction/understanding beam-losses at 0.1 – 0.01% level
  - Reasons for loss observed in codes (at this level) often difficult to determine
- Revisit main aspects of models in more detail
  - Transverse, longitudinal, impedances, instabilities, etc.
  - Key loss mechanisms: targeted, regular measurements for improved models
  - Well benchmarked codes => improved ISIS operations and better ISIS-II predictions



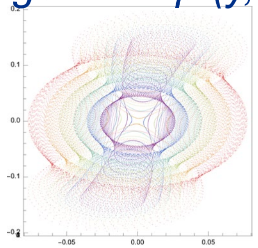


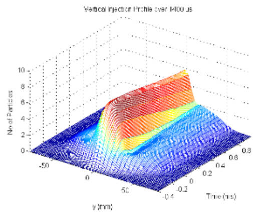
D. J. Adams et al., "Beam Loss Studies of the ISIS Synchrotron Using ORBIT", IPAC12, 2012, pp. 3942-3944

R&D on the ISIS RCS: Overview

- Transverse
  - Models vs Measurements
  - Optics
  - Non-linear magnet models
  - Resonance Crossing
- Longitudinal
  - Optimising injection/bunching
  - Bunch compression
  - Tomography
- Instability
  - Impedances
  - Head-tail measurements
  - PyHEADTAIL simulations
  - Effect of Space Charge

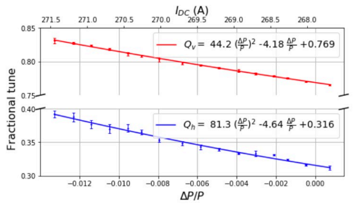
Adiabatic Half Integer Ramp (y, y')



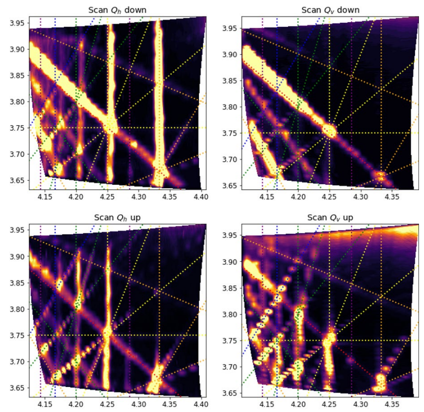


Experimental Result
Ramp through 2Qv=7

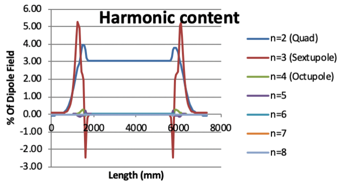
Chromaticity

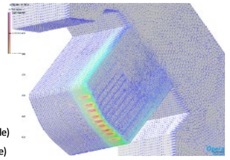


ISIS Tune Plane Measurements

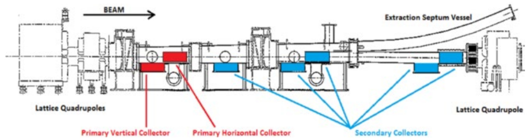


Better use of magnet measurements, models

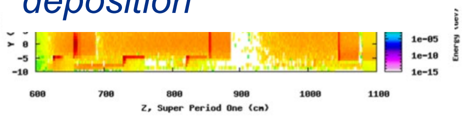




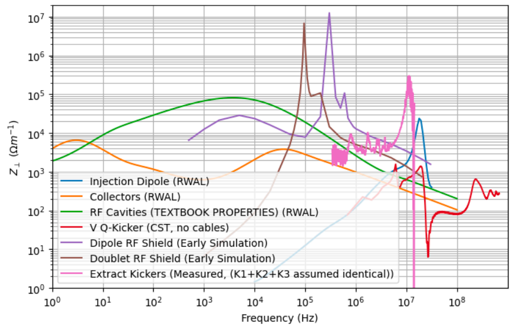
ISIS collimator straight



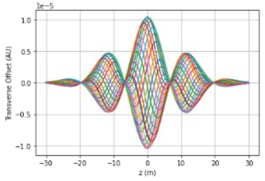
FLUKA energy deposition



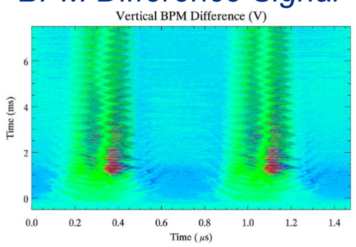
Impedance Estimates for ISIS



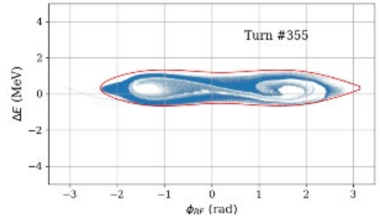
Fastest mode
(General-Gauss)



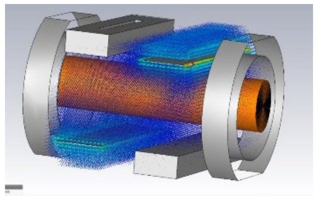
Instability Meas.
BPM Difference Signal

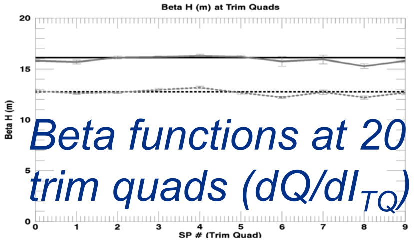


Long'l Injection Study



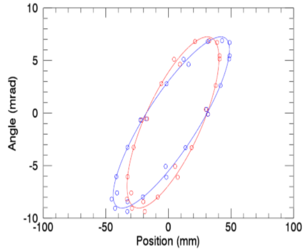
CST Model of RGI Monitor





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

Optics meas.



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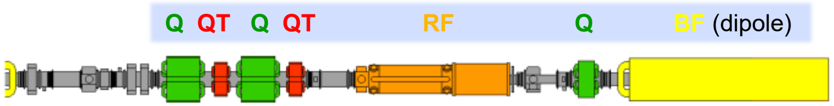
Transverse Modelling: Magnets

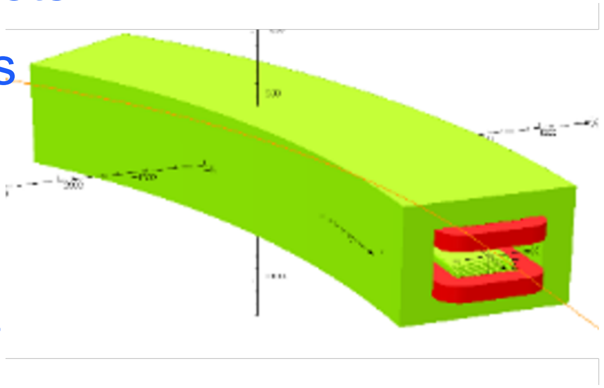


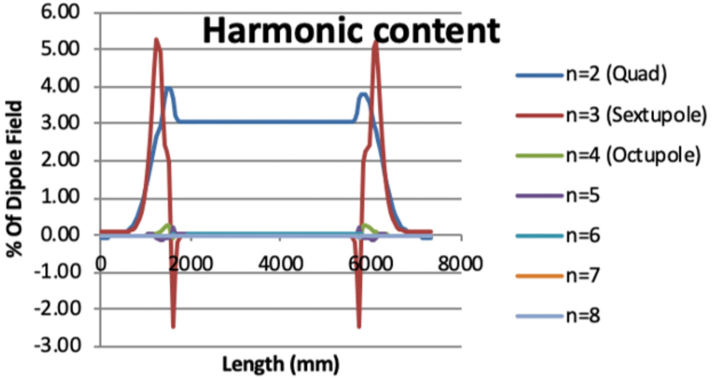
One of 10 ISIS Super periods

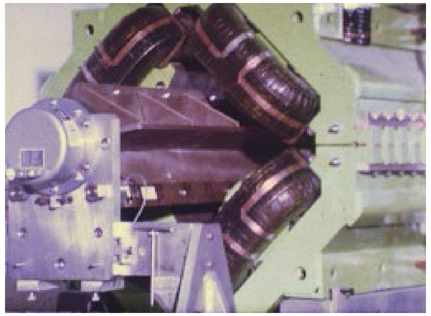
- Limited measurements available for ring magnets
- Matched OPERA simulations to measurements
- Produced models of each magnet type

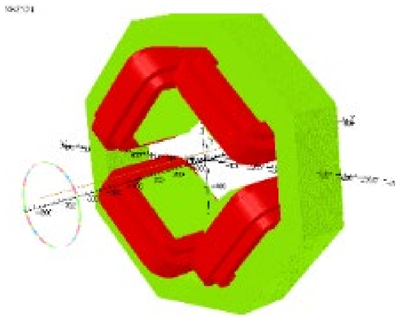
- Incorporating non-linear multipole components into simulations, including fringe fields
  - Better TEAPOT/PTC PyORBIT models

ISIS Combined Function Dipole

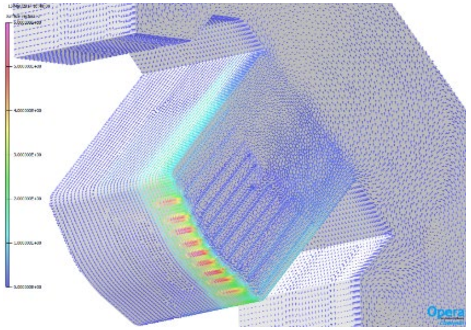


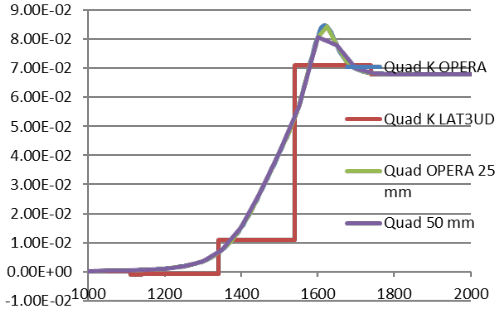






ISIS Quadrupole





Improved fringe fields

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Dean Adams, Iker Rodriguez, Steve Jago et al.

Transverse Modelling: Tune Plane

- Important experimental tool: beam-loss vs tune
  - Low-intensity, coasting beams in SRM
  - Use programmable trim quads to scan tunes
  - Identification of main resonances & strengths
- Improvements to lattice models
  - Study low-intensity tune setting
  - Improve simple, linear approx. for better tune setting and control
  - Q vs main magnet current => chromaticity
  - Survey data being incorporated => dipole errors and orbit correction
  - Non-linear terms from magnet models

Large scanned aperture

2nd order

$Q_h + Q_v = 8$

3rd order

$3Q_h = 13$
$-Q_h + 2Qv = 3$
$2Q_h - Q_v = 5$
$Q_h + 2Q_v = 12$
$2Q_h + Q_v = 12$

4th order

$4Q_h = 17$
$4Q_v = 15$
$3Q_h - Q_v = 9$
$2Q_h - 2Q_v = 1$

5th order

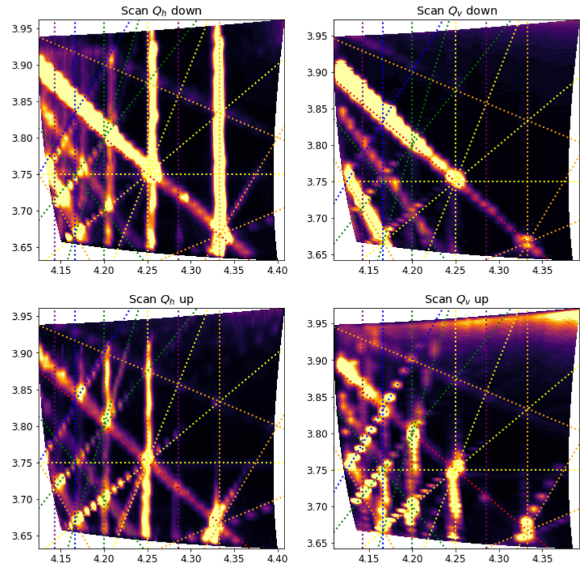
$5Q_h = 21$
$4Q_h - Q_v = 13$
$3Q_h - 2Q_v = 5$
$3Q_h + 2Q_v = 20$

6th order

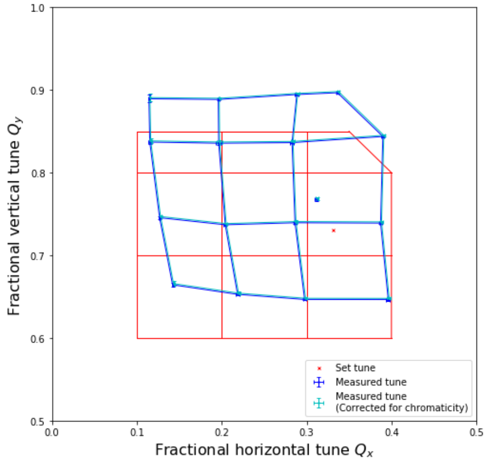
$6Q_h = 25$
$4Q_h - 2Q_v = 9$

7th order

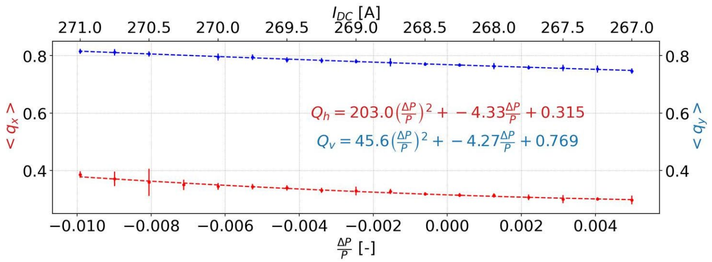
$7Q_h = 29$
$7Q_h = 30$



Linear tune calc. & actual tune



Chromaticity



Haroon Rafique's talk on
"Recent Progress in Loss Control for the ISIS High Intensity RCS: Geodetic Modelling, Tune Control, and Optimisation"

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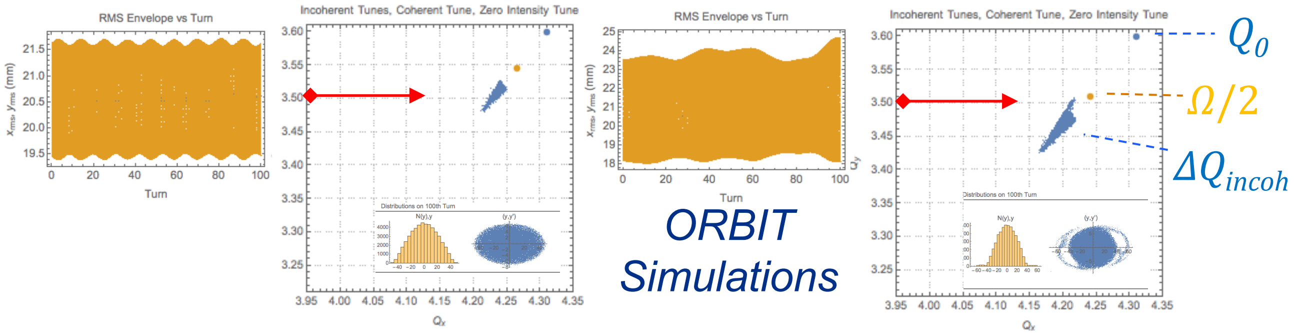
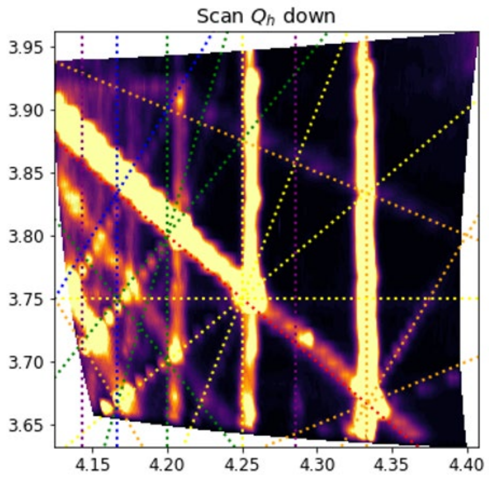
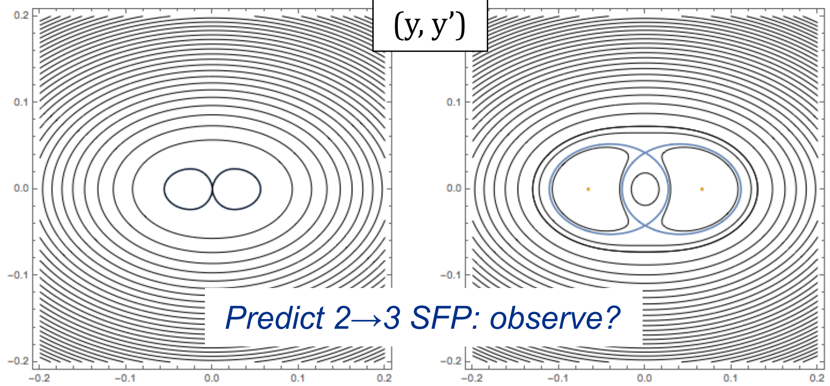
Transverse Modelling: Resonances & Space Charge

- Better lattice models => more detailed resonance R&D
  - Explore low-intensity behaviour
  - Focus on $2Q_y=7$, $3Q_x=13$ and $4Q_y=15$
- Half-integer resonance
  - Low-intensity, coasting beams in SRM
  - Tune & driving term control with trim quads
  - Crossing during accumulation => ORBIT sims and measurements compare well
  - Now focused on adiabatic crossing => predictions of particle trajectories
  - Early meas. consistent with expectations
- Once understood => higher intensities and bunched beams

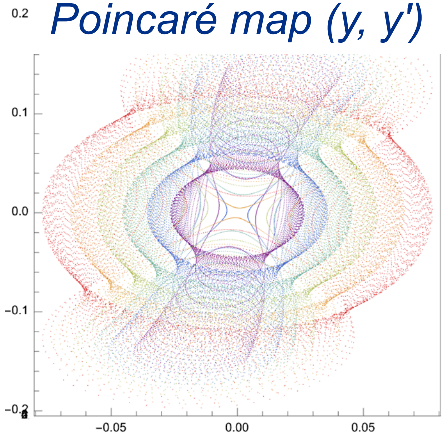


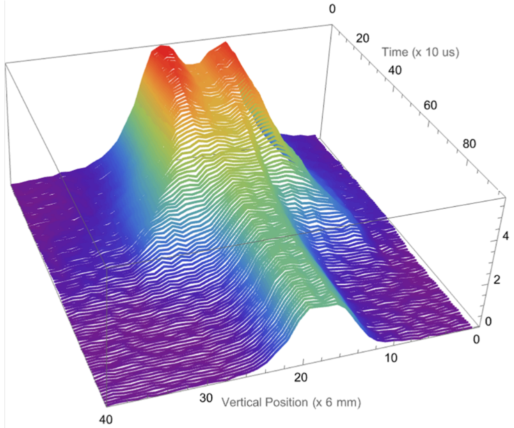


Frozen space charge, halo



Poincaré map (y, y')





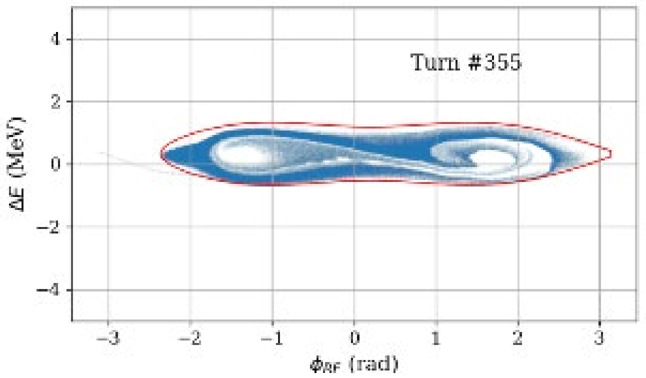
Measured Vertical Profiles

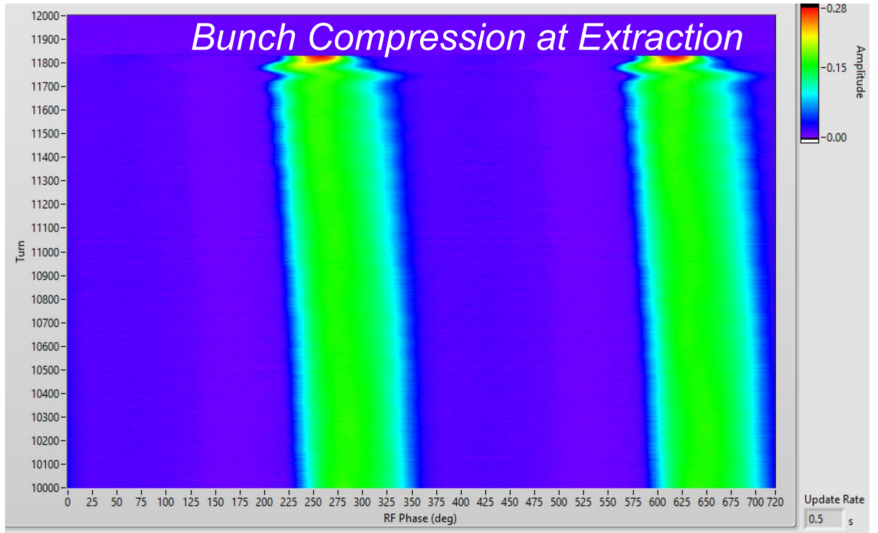
Chris Warsop et al.

Longitudinal Modelling

- Good agreement between tracking and measurements (IPAC12)
- Recent upgrades to RF hardware and control => renewed benchmark
- Injection/trapping process
  - Complex, non-adiabatic capture
  - Dual-harmonic RF
  - Improved operations efficiency
  - New MEBT incl. chopper to be installed ~2025
- Bunch compression techniques
  - Provides increased range of muon experiments
  - Explore best option for efficient and sustainable compression

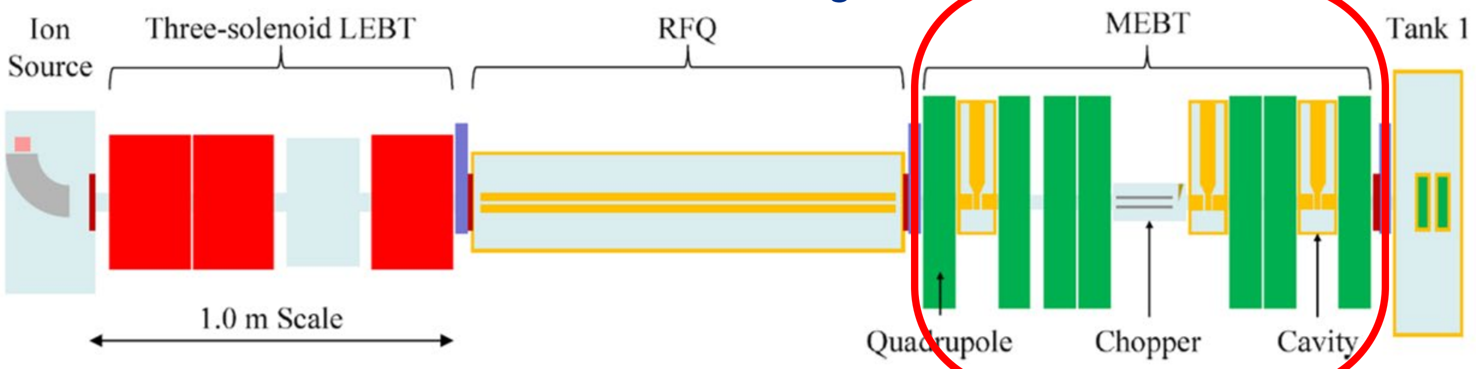
Longitudinal Injection Study





Billy Kyle's poster on "Tomographic Longitudinal Phase Space Reconstruction of Bunch Compression at ISIS"

MEBT Design



Sasan Ahmadiannamin's talk on "Beam Physics Simulation Studies of 70 MeV ISIS Injector Linac"

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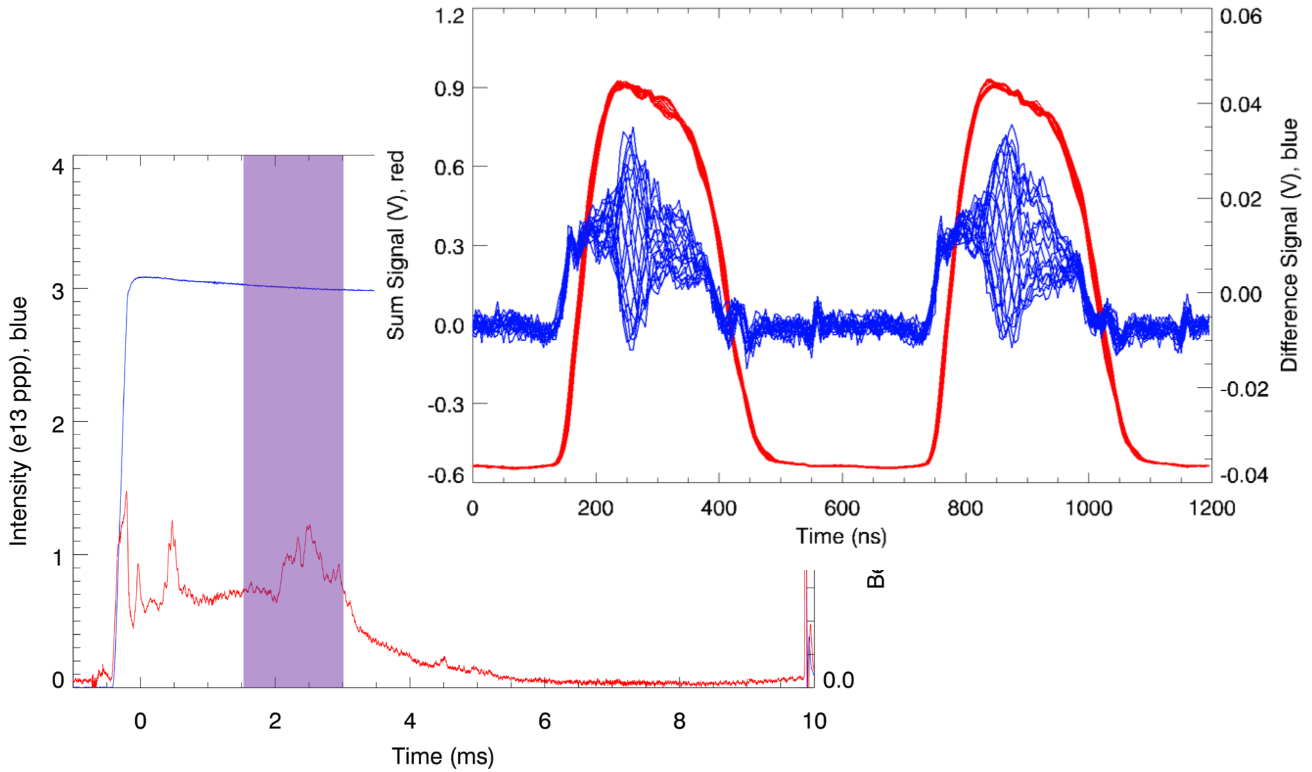
Head-Tail Instability: Operations

- Coherent vertical instability observed
- Key intensity limit due to beam-loss
- Instability mitigation
  - Ramp in Q_y
  - Asymmetric longitudinal bunch shape
  - Vertical painting
- Prototype damping system successfully tested
  - Planned commissioning for user operations



R&D Aims

- Identify source of driving impedance
- Measure, simulate and understand head-tail instability mechanism
  - Dual-harmonic RF, space charge, etc.
  - Investigate unexpected features
- Possible further mitigation methods

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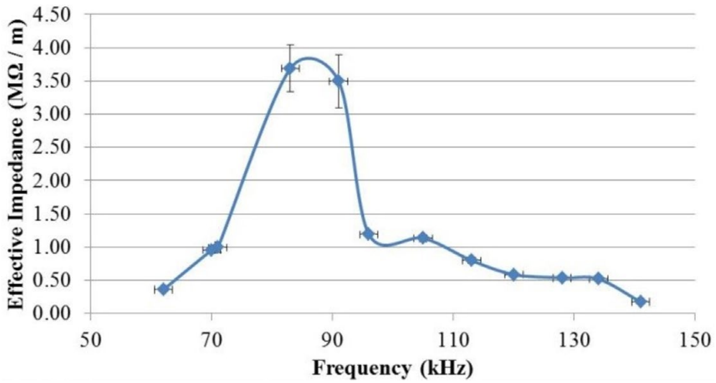
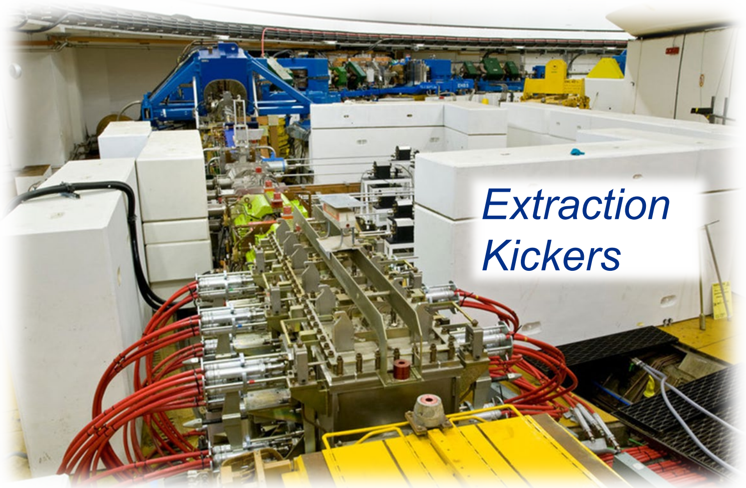
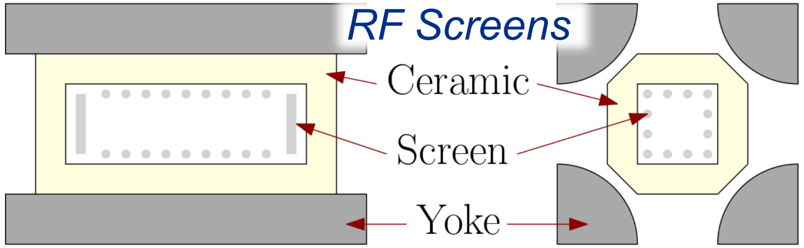
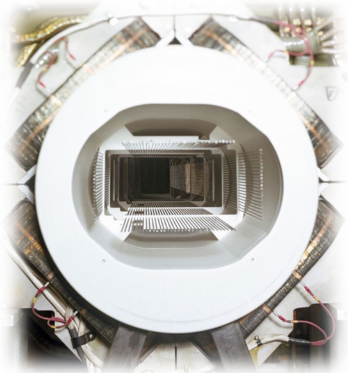
Head-Tail Instability: Impedances

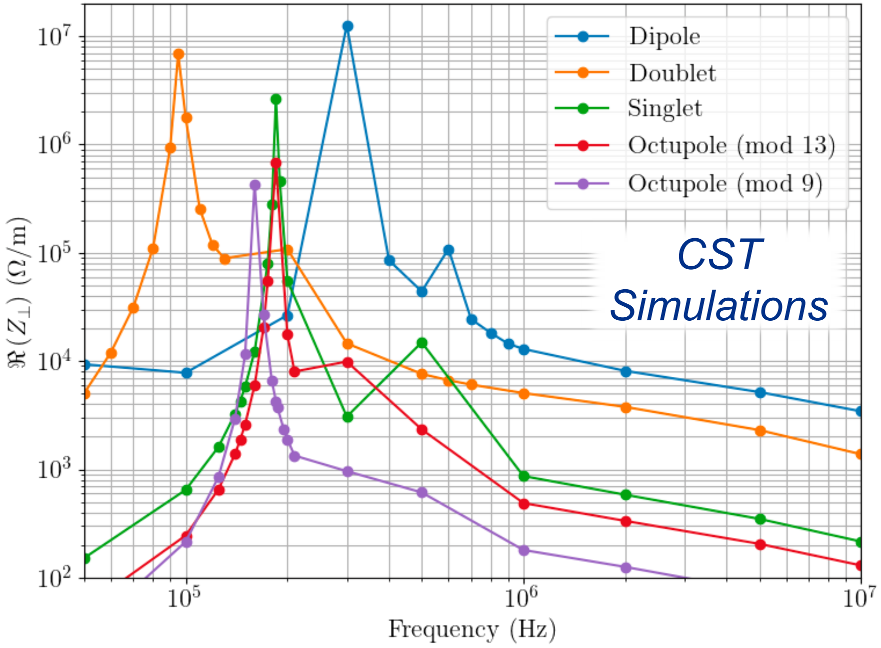
- Beam-based measurements
  - Coasting beam instability
  - Vary vertical tune
  - Low-frequency narrowband
  - Possible driver for head-tail?
- Expected vertical impedances
  - Resistive wall
  - Extraction kickers
  - Collimators
- Simulations
  - In-house multi-layer code, RWAL
  - CST Studio
  - Low-frequency narrowband from RF screens incl. capacitors
- Bench measurements underway











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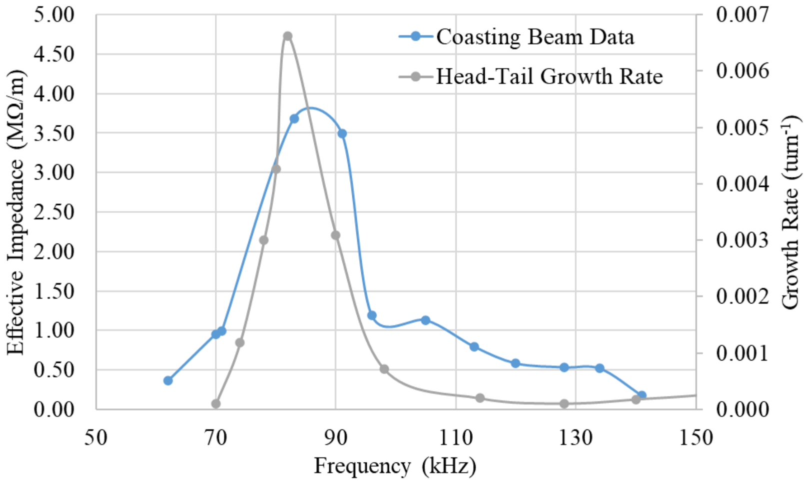
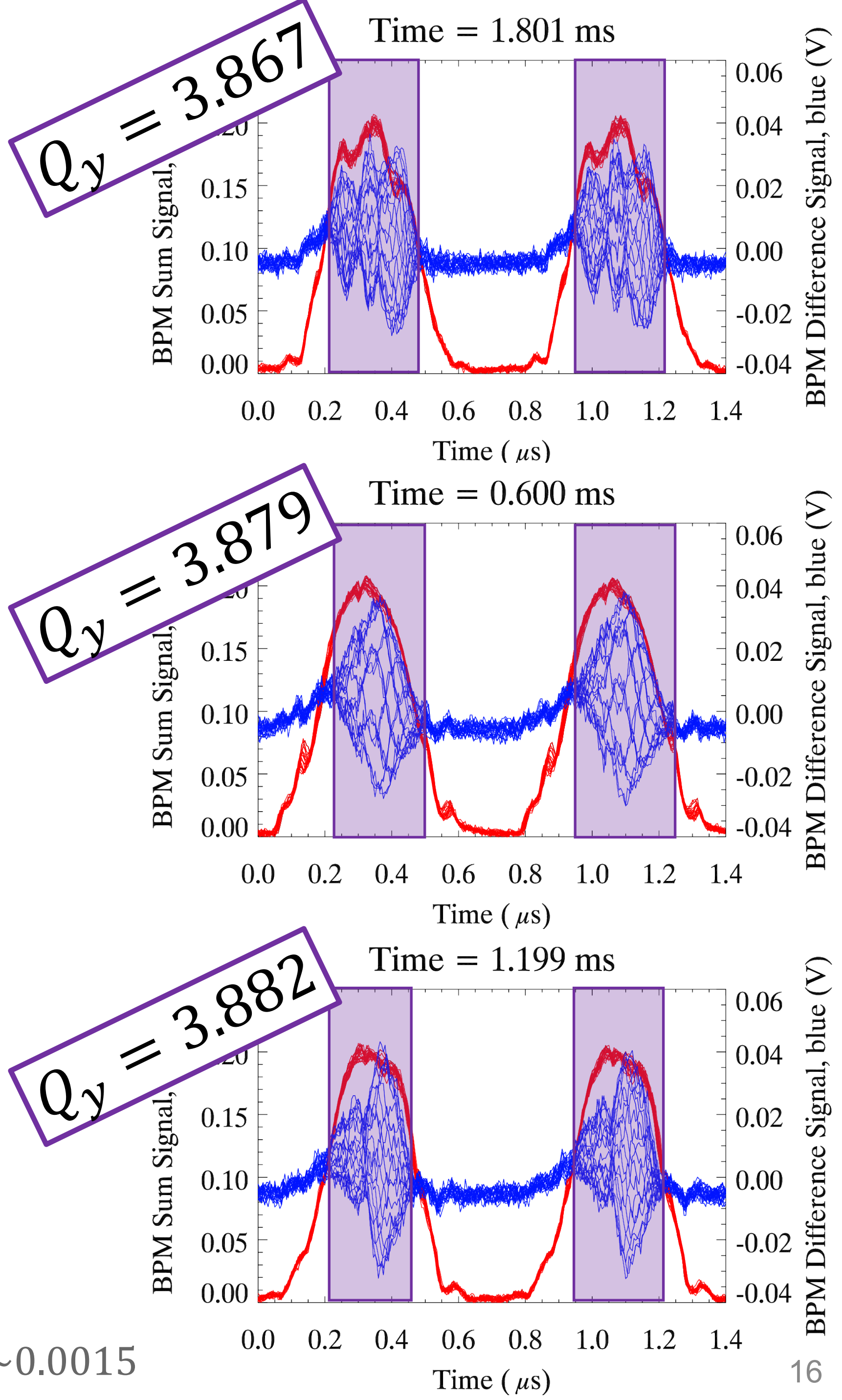
David Posthuma de Boer's Talk
"Development of an Impedance Model for the ISIS Synchrotron and Predictions for the Head-Tail Instability"

Head-Tail Instability: Measurements Vs Q_y

- Bunched storage ring mode (BSRM)
  - Main magnet fields constant at 70 MeV settings
  - 1 h=2 cavity powered, others off-tune
  - Fine control of beam/lattice parameters
  - Reduced complexity, low-intensity (~10^{12} per bunch)
- Instability characteristics vs Q_y
  - Intra-bunch head-tail mode excited
  - Growth rate vs Q_y peaks at same freq. as coasting beam
- Unexpected features
  - Mode discrepancy with theory (predicted mode m=3)
  - Mode variation with Q_y
  - Effective bunch length





Error on Q_y~0.0015

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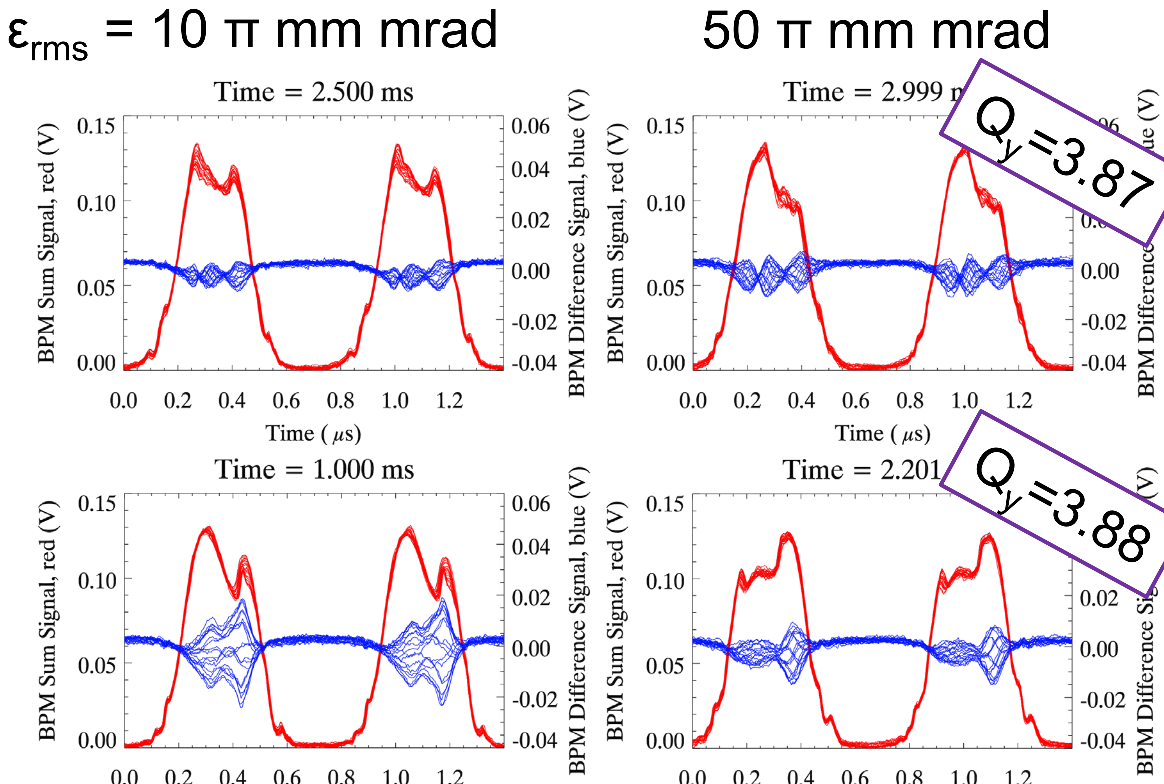
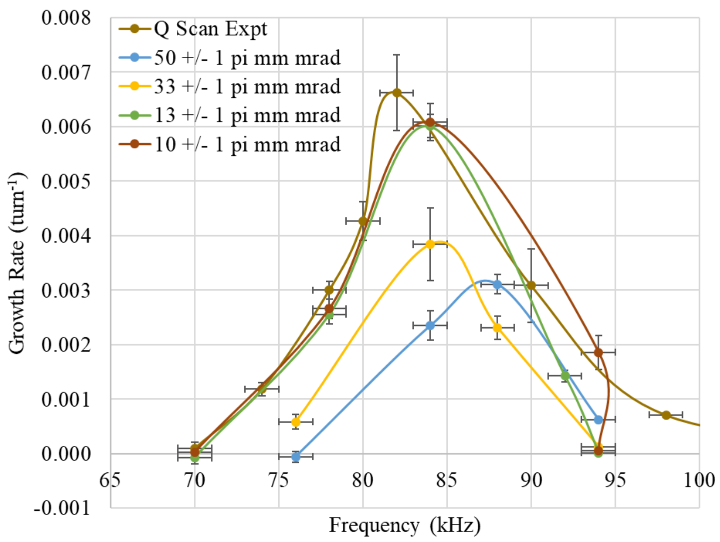
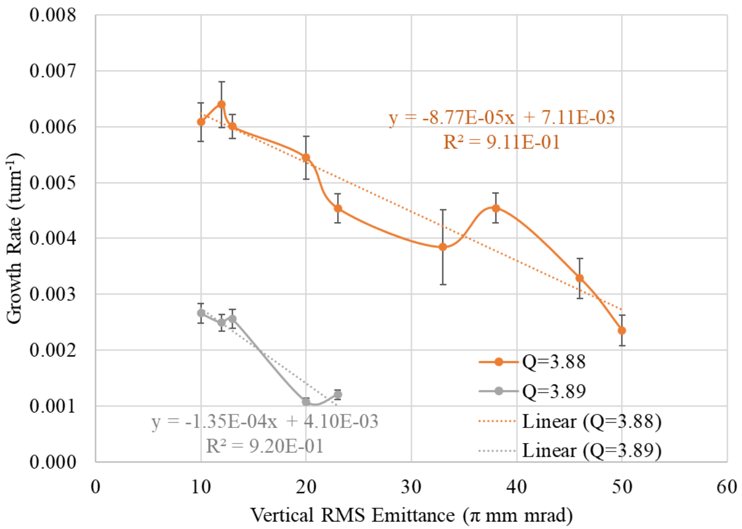
Head-Tail Instability: Measurements Vs Beam Size

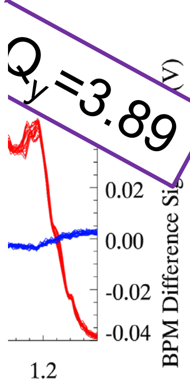
- Control vertical beam size with painting
- Measure vertical profile with ionisation profile monitors
- Expected to probe the effect of space charge
- **Assume** Z is not a function of vertical beam size => no effect on head-tail



- Observations:
  - Mode largely consistent with beam size
  - Beam size threshold at Q_y=3.89
  - **Growth rate dependent on beam size**







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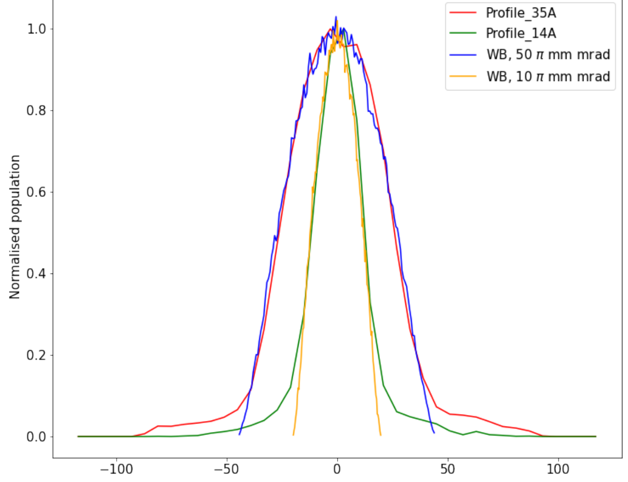
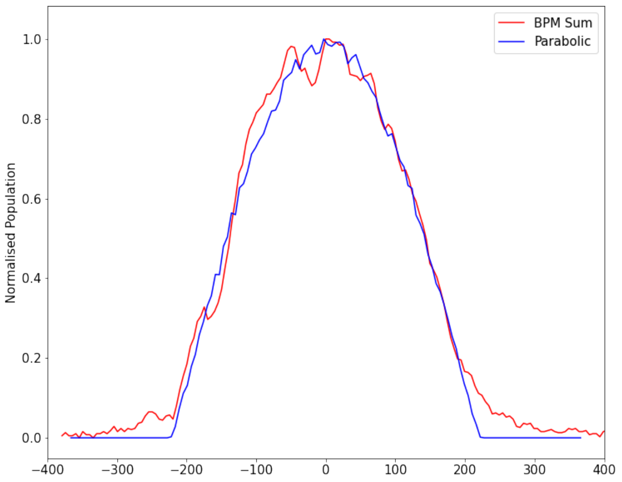
Head-Tail Instability: Simulations without Transverse Space Charge

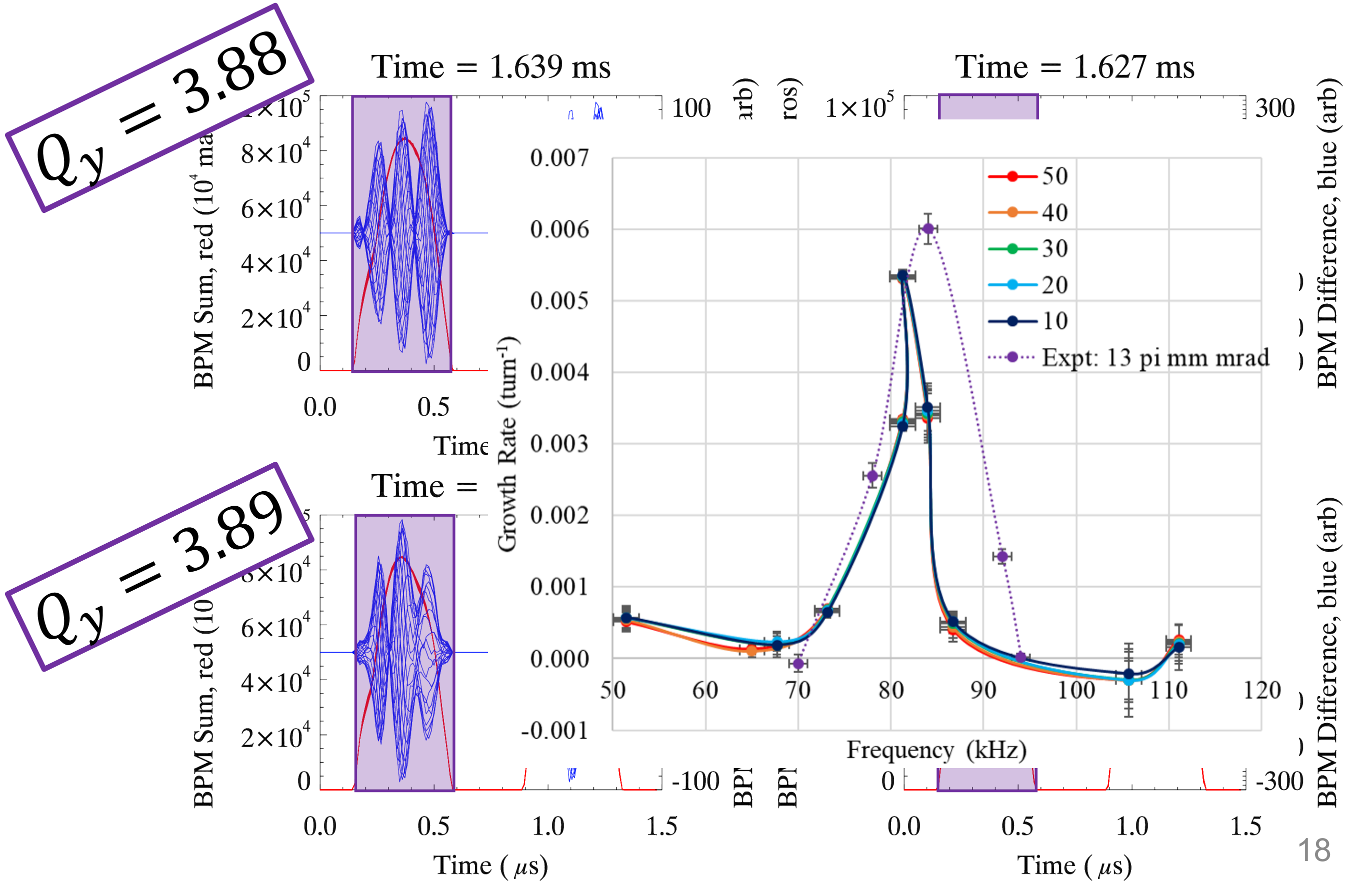
- PyHEADTAIL simulations
  - Beam/lattice parameters to match BSRM
  - Convergence tests performed
  - Transverse: smooth-focusing
  - Longitudinal: non-linear RF
- Results without transverse space charge:
  - Mode broadly matches theory (not experiment)
  - Small change in mode with Q_y extent (modes 2 & 3)
  - Oscillation along full bunch length
  - Growth rate largely consistent with predictions
  - Growth rate unaffected by beam size



10 π mm mrad



50 π mm mrad



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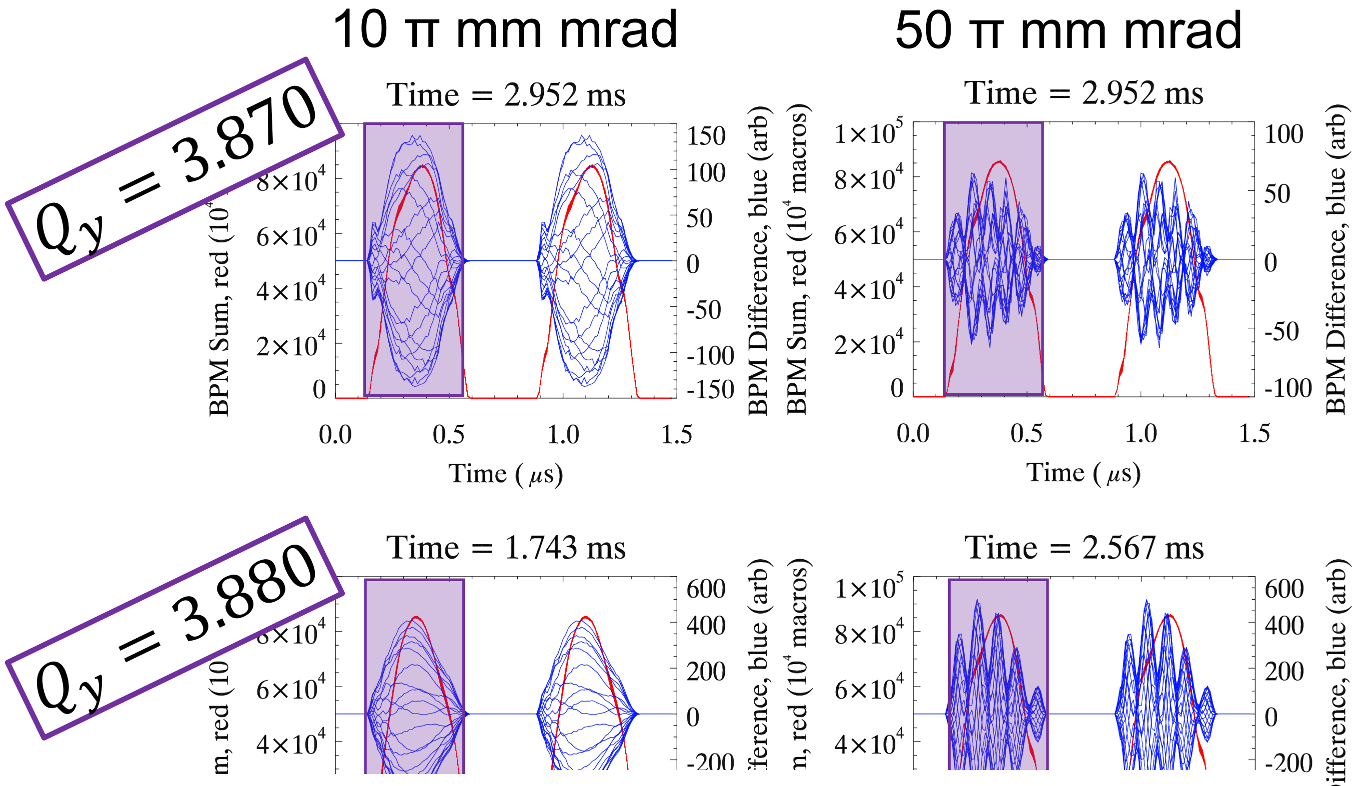
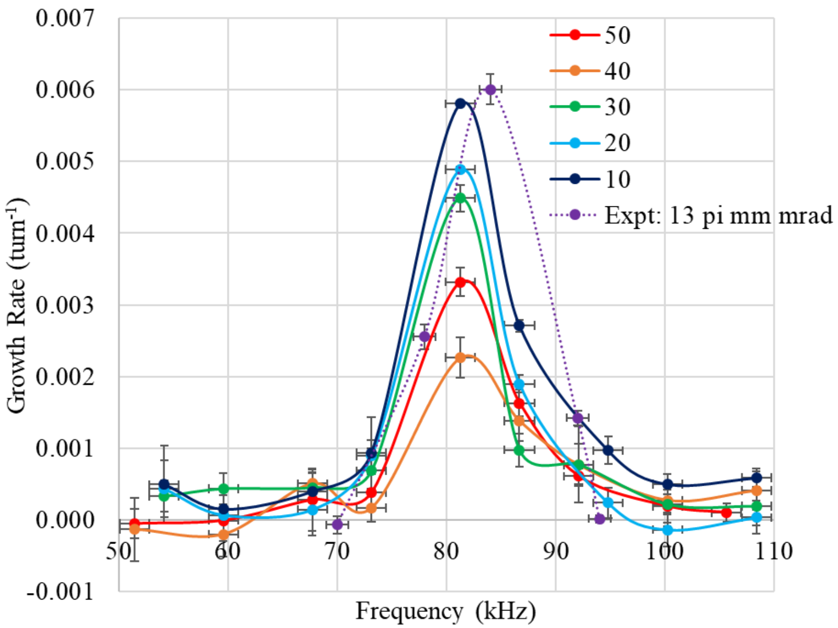
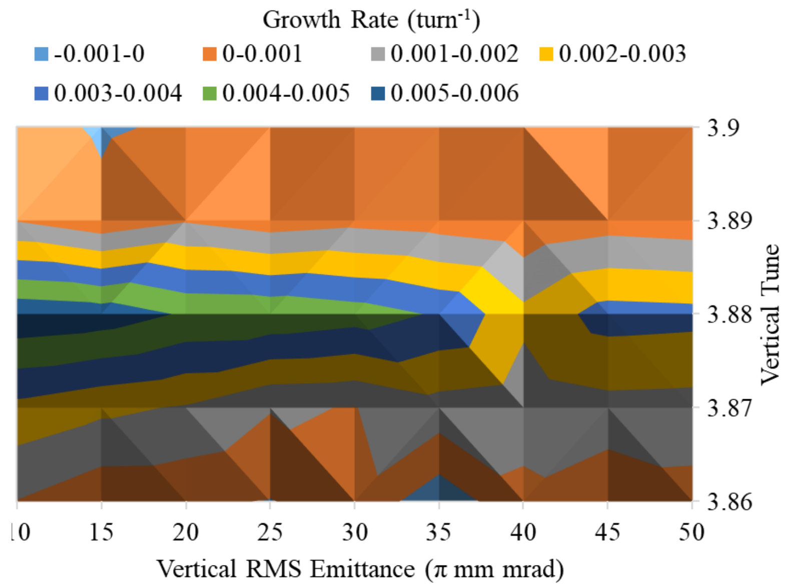
Head-Tail Instability: Simulations with Transverse Space Charge

- 2.5D GPU PIC space charge model
- Instability characteristics:
    - Mode does not match expectations
    - Mode depends on beam size and tune
    - Oscillation along full bunch length
    - Growth rate largely consistent with predictions
    - Growth rate strongly influenced by beam size







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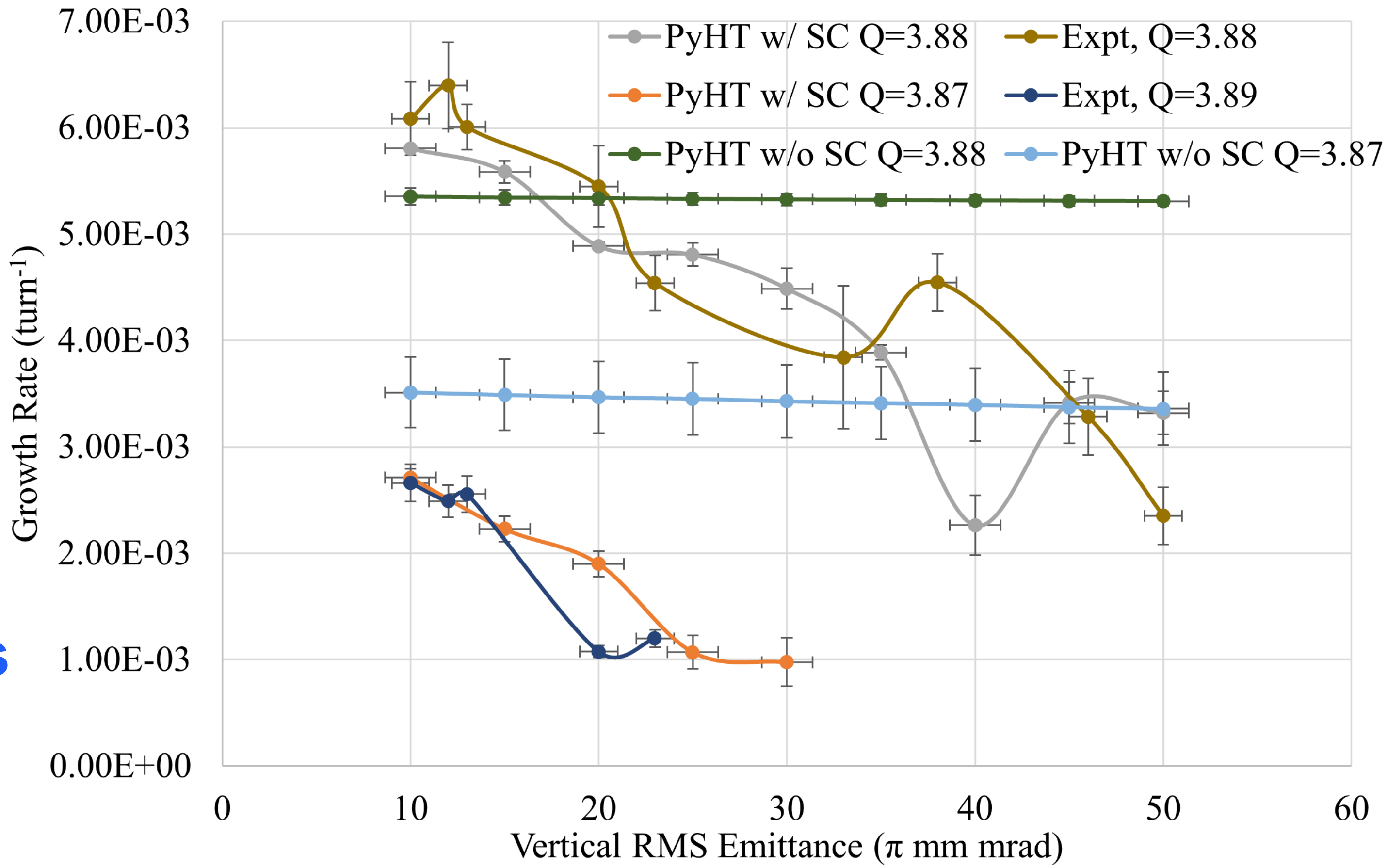
Head-Tail Instability: Effect of Space Charge

- Growth rate linear with emittance (for tunes with an instability)
- Broadly matches experiment
  - Linear dependence
  - Gradients similar
  - Beam size threshold replicated

- **Simulations appear to confirm transverse space charge causes dependence on beam size**



- Next steps:
  - Intensity & beam distribution dependence
  - Predictions using modelled impedances

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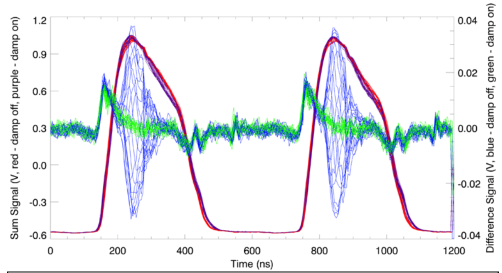
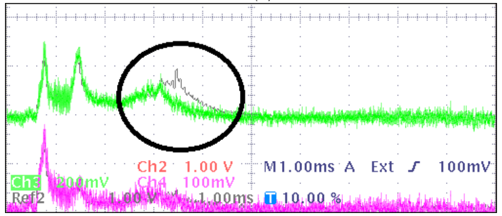
Summary

- Renewed push to benchmark models for high-intensity operation
  - Transverse dynamics: magnet modelling, tune control, resonance investigations, …
  - Longitudinal dynamics: injection optimisation, bunch compression, tomography, …
  - Impedances & instabilities: impedance measurements and modelling, …
- Extensive study of head-tail with space charge
  - Measurements in RCS and BSRM
  - PyHEADTAIL simulations with and without SC
  - Instability characteristics (mode and growth rate) vs vertical tune and emittance
- Better understanding of losses and intensity limits
  - Better predictions of ISIS beam dynamics => efficient operations,
  - Increased confidence in ISIS-II design predictions
  - Achieve, and reliably predict, losses of 0.01 – 0.1% with space charge
- Next steps:
  - Benchmarks against other high-intensity hadron accelerators and other codes: collaboration not duplication
  - Push the current state-of-the-art in terms of the high-intensity limit.





Acknowledgements

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