Intense Hadron Beams

D. W. Posthuma de Boer

Contributions from:
J. Appleby, J. Flowerdew, C. Jolly, T-J. Kuo, A. Oeftiger,
S. Preston, N. Steerenberg
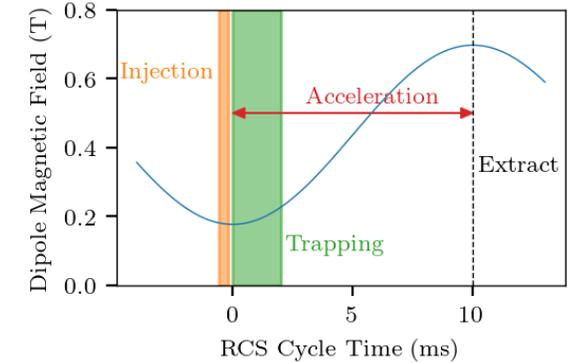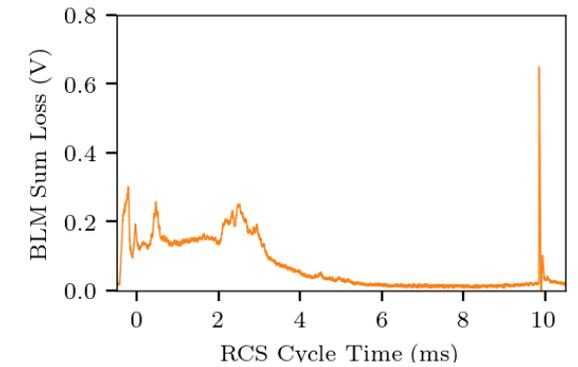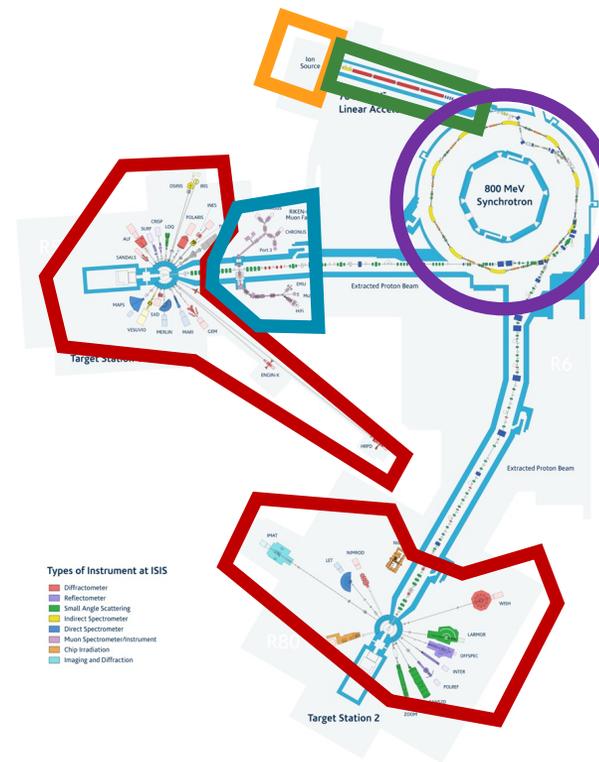
JAI Advisory Board Meeting

2025-04-24

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- Intensity Limits at ISIS
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  - Process Optimisation

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Intensity Limits at ISIS

The ISIS Neutron and Muon Source

- ISIS is the Neutron and Muon source at the Rutherford Appleton Lab.

- The primary constituents are:
  - Penning H- ion source and RFQ
  - 70 MeV H- drift-tube linac
  - 800 MeV, 50 Hz rapid cycling proton synchrotron
  - One graphite and two tungsten fixed targets + instruments

- Beam loss is concentrated towards the beginning of the 10ms acceleration cycle and mainly associated with:
  - Injection
  - Longitudinal trapping
  - Space-charge effects
  - Coherent vertical instability

- Intensity is beam-loss limited.
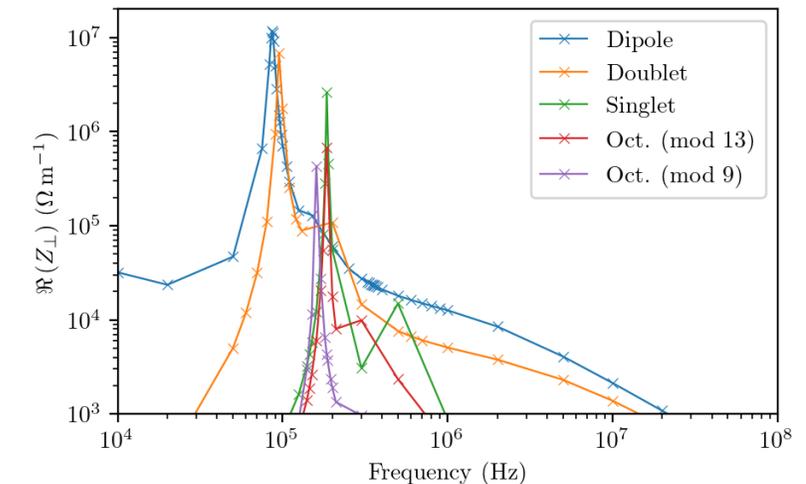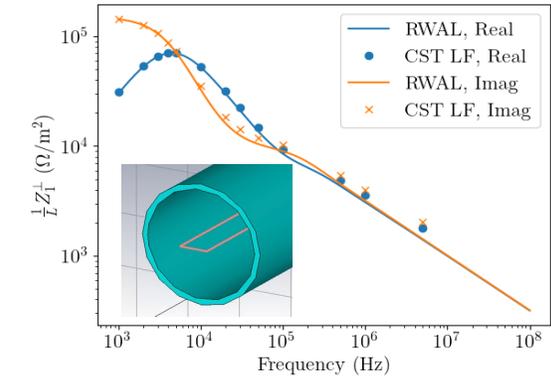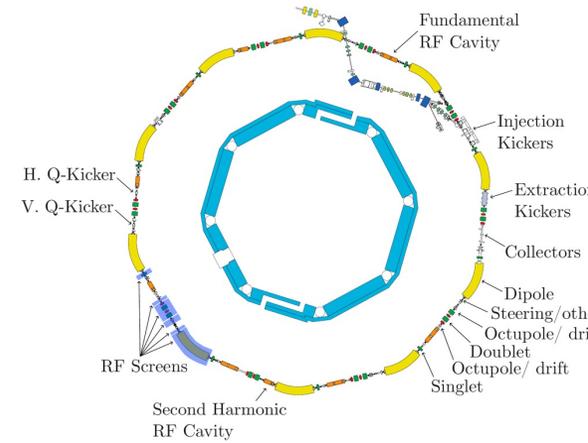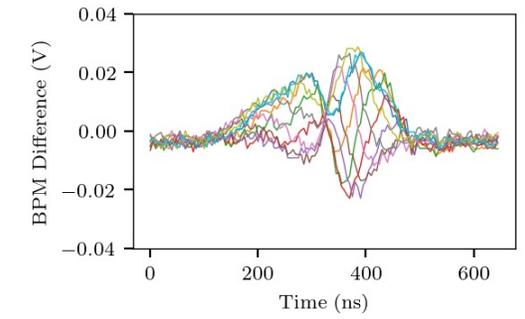 - Solutions identified on ISIS will impact future high-intensity machines.

Circumference	163 m
Energy Range	70 – 800 MeV
Intensity	~ 3e13 Protons per Pulse
Repetition rate	50 Hz
Average Power	~ 190 kW
Injection	Multi-turn, charge-exchange
Tunes (x, y)	4.31, 3.83 (programmable)
RF	6 x fundamental (h=2) 4 x 2nd harmonic (h=4)

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Coherent Instabilities

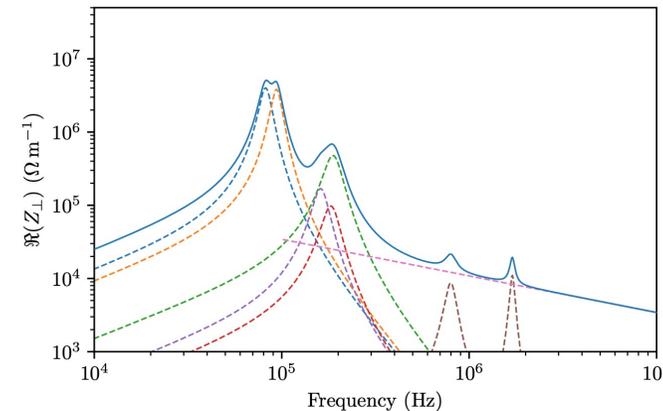# Identifying the Source of the Instability

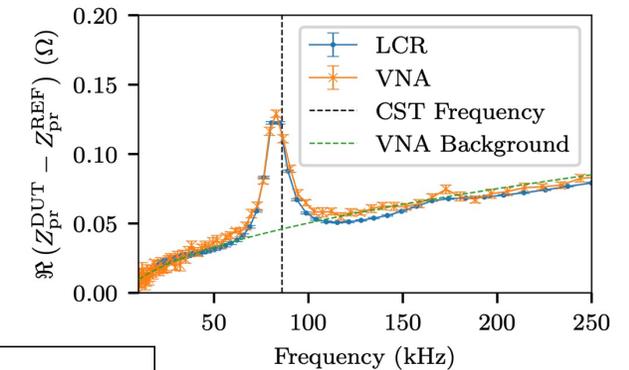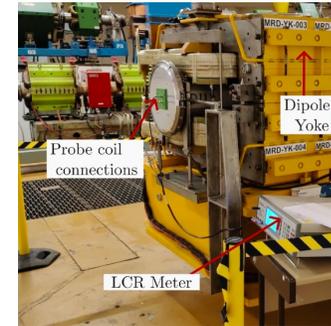D. W. Posthuma de Boer (JAI Student), B. Foster, C. M. Warsop, A. Oeftiger

- Instability was first measured on ISIS around 1988.
  - It resembled a head-tail mode-1 and has growth times on the order of 100 μs, but mode 2 or 3 was predicted with growth rates of ms.

- Work by R. E. Williamson identified resonator impedance and a dependence on transverse beam size.

- Primary impedance candidates identified and divided into resonator and broadband candidates.

- Developed tools for studying low-frequency transverse impedances:
  - RWAL (analytical resistive-wall code)
  - Low-frequency finite element method

- Using these tools identified the RF screens as presenting a large narrowband impedance.
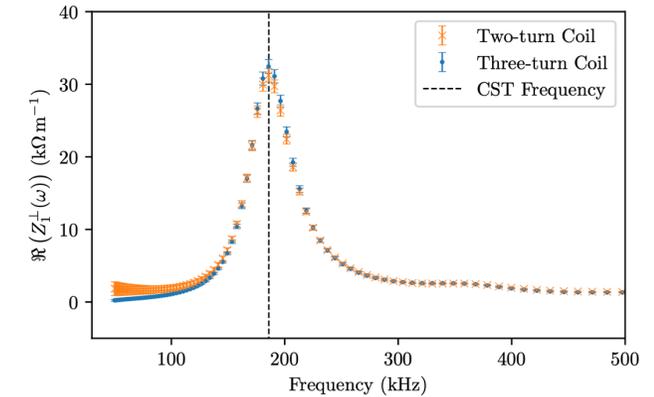
RF Screen Impedance

D. W. Posthuma de Boer (JAI Student), B. Foster, C. M. Warsop, A. Oeftiger

- Probe coil measurements on a singlet magnet completed.
  - Resonant frequency within 2% of prediction.
  - Peak magnitude and quality factor both lower than predicted.

- Probe coil measurements on a dipole also completed.
  - Resonant frequency within 5% of prediction.
  - Quality factor also lower than predicted.

- Approximate solution developed for lower quality factors made and a new impedance model developed.
  - **Low frequency impedance dominated by RF screen resonator impedances.**

- Preliminary results presented at HB 2023.
  Similar impedances now identified on RF screens at CSNS.

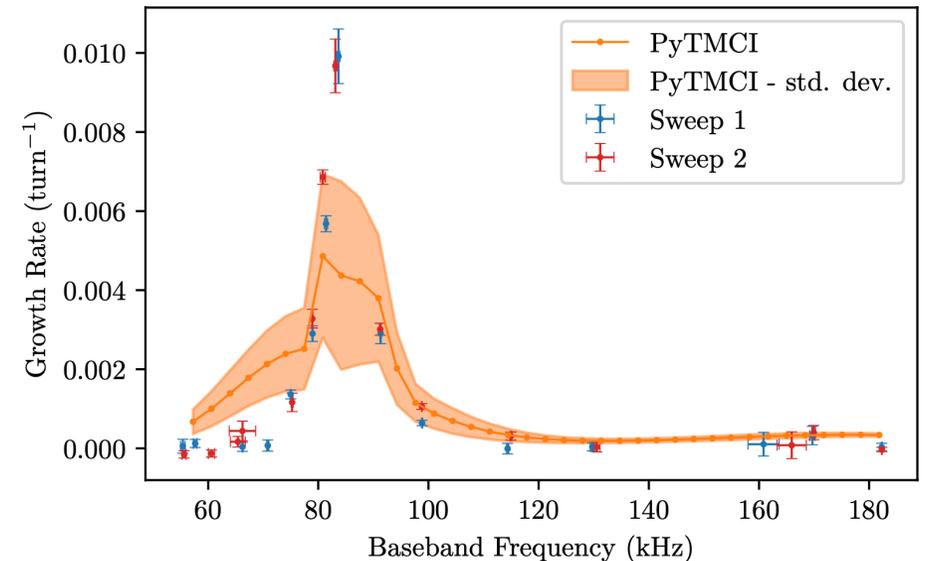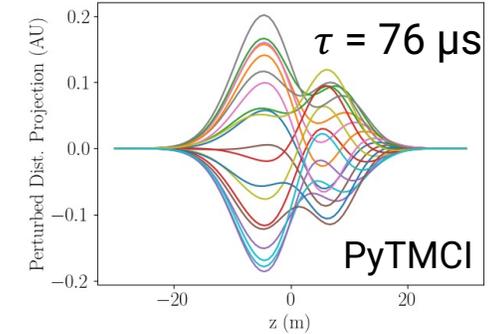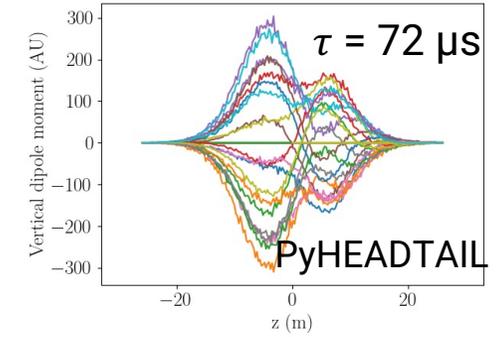https://doi.org/10.18429/JACoW-HB2023-TUC4I2

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Instability Predictions

D. W. Posthuma de Boer (JAI Student), B. Foster, C. M. Warsop, A. Oeftiger

- Formulas based on simplified instability models do not provide the most accurate analytical predictions available.

- Implemented new head-tail Vlasov solver, PyTMCI.
  - https://github.com/stfc/PyTMCI

- One benchmark is shown against PyHEADTAIL

- Using the updated impedance model and a number of simplifying assumptions
  - **PyTMCI predicts correct order-of-magnitude growth rate in tune range observed experimentally (Sweep 1/ 2)**

  - **PyTMCI predicts observed order-of-magnitude growth rate early into the RCS cycle.**
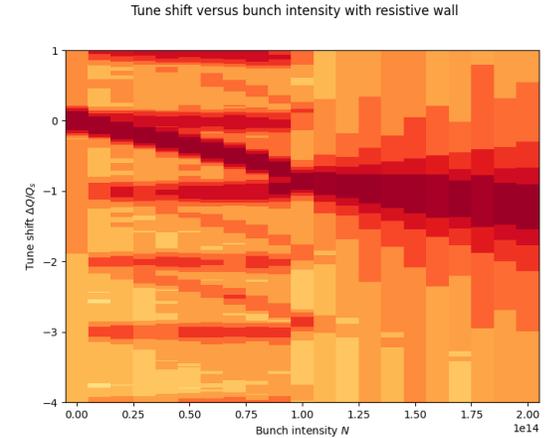
Calc. ISIS Params	Value
β	0.45
Q_y	3.83
Q_s	0.015
Chromaticity	-0.5
Num Bunches	1
Long. Model	Gaussian
σ_z	6.5 m
Impedance Model	2.4 MHz Resonator

τ = 72 µs — PyHEADTAIL

τ = 76 µs — PyTMCI

UK RI — Science and Technology Facilities Council — ISIS Neutron and Muon Source

JAi — John Adams Institute for Accelerator Science
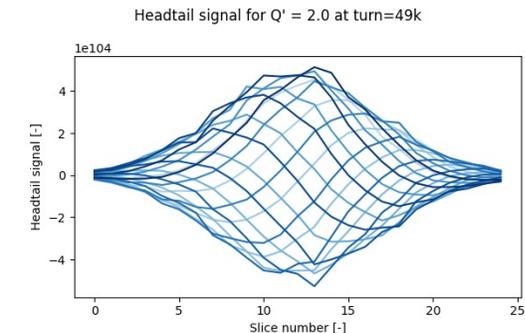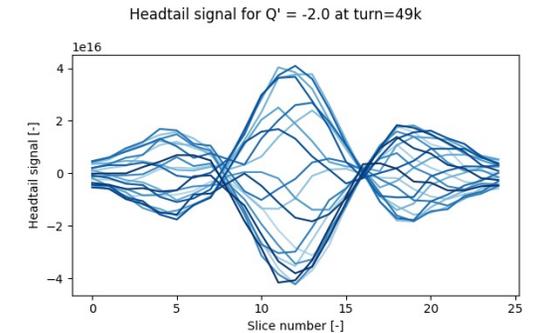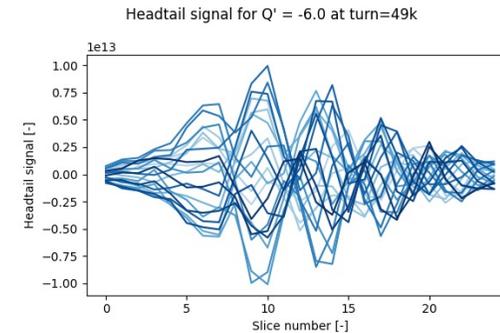
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Transverse Stability at ISIS

N. Steerenberg (JAI Visiting Masters Student), A. Oeftiger

- Goals:
  - Modelling full ISIS cycle with RCS ramp
  - Investigate impact of space-charge on head-tail instabilities
  - Include more accurate impedance model

- Update models from previous studies using Xsuite/Xwakes simulation software.

- Initial benchmarking of new model now under way.
  - Implementation of two wake models
    - Resistive wall wake
    - Resonator wake
  - Preliminary investigation to find TMCI threshold
  - Optimisation of numerical parameters to resolve vertical instability at negative chromaticities
  - Vertical tune scans: $Q_y = 3.8 - 3.9$

Intrabunch motion example for resistive wall wake

Coherent Instabilities – Future Work

- Mitigation of the identified impedances has started, but more work do.
  - Aiming to increase ISIS beam intensity.

- Detailed study of the interaction between space-charge and the coherent instability.
  - Assisted by the updated Xsuite and impedance models.

- Further development of the ISIS impedance model to improve predictions.
  - For example, longitudinal impedance, detuning impedance, conformal vacuum vessels etc.

- Visiting masters student (N. Steerenberg) has started and new DPhil student joining in October 2025 (F. Straniero).

Process Optimisation

Process Optimisation at ISIS
S. Preston (JAI Student), P. Burrows, I. Martin

- Currently optimising Linac-to-Booster injection at the Diamond Light Source using Bayesian optimisation, with the goal of automating injection over the entire complex (see I. Martin's presentation).

- Processes such as injection from the linac into the RCS, steering and focusing etc can be optimised to reduce beam losses.
  - In some cases correcting of beam losses and machine set-up after a trip requires manual intervention.

- Objective: **Reduce downtime at ISIS by using ML to automate beam steering while minimising losses and ensuring safe operation.**

- The goal is to transfer the experience gained to ISIS, but with key differences:
  - Must use **multiple objectives** (MOGP), such as maximising injection efficiency, while reducing halo losses within safe operating parameters.
  - Investigate whether combing the optimiser being investigated at Diamond with deep learning methods can yield further improvements.
  - Reinforcement learning is a very popular topic currently (ICFA 2025) and could help to achieve objectives.

UK RI Science and Technology Facilities Council

ISIS Neutron and Muon Source

JAI John Adams Institute for Accelerator Science

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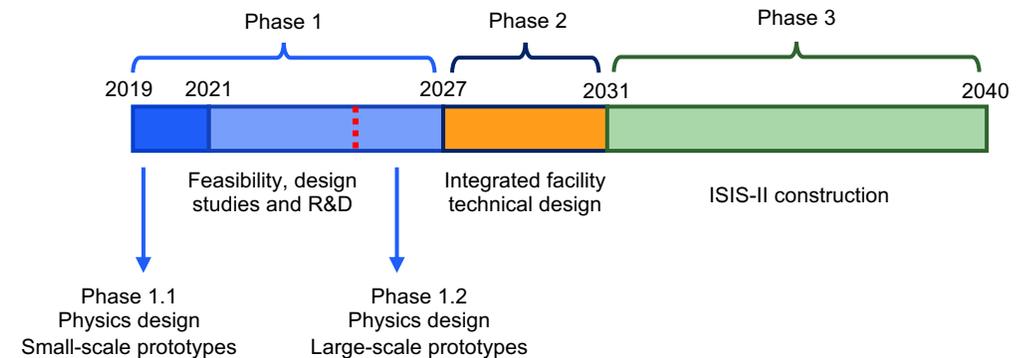
ISIS-II Development

ISIS-II Megawatt Upgrade

- ISIS-II is a proposed MW-class short pulse neutron facility.

- It is vital to maintain European competitiveness with Japanese (J-PARC) and American (SNS) short-pulse neutron sources

- Currently investigating three accelerator drivers
  - Rapid Cycling Synchrotron (RCS)
  - Accumulator Ring (AR)
  - Fixed-Field Alternating Gradient (FFA)

- Special focus on sustainability and health of the neutron user community.

ESFRI Neutron Scattering Facilities in Europe Report (2016)

"…*by far the most* **cost effective** *solution would therefore be to build a* **MW-class short pulse** *facility at* **ISIS**, **reusing** *existing* **infrastructure and facilities** *as well as drawing upon on-site* **competences**. *The current facility could operate until the new facility is operational with its initial suite of instruments.*"

Sentiment echoed in UKRI Infrastructure Opportunity Report (2023)

Phase 1 | Phase 2 | Phase 3

2019 2021 2027 2031 2040

Feasibility, design studies and R&D | Integrated facility technical design | ISIS-II construction

Phase 1.1 Physics design Small-scale prototypes

Phase 1.2 Physics design Large-scale prototypes

ISIS-II Accelerator Options

- Machines configurations being considered
  - Rapid Cycling Synchrotron (RCS)
  - Accumulator Ring (AR) } "Conventional Rings"
  - Fixed Field Alternating Gradient Acc. (FFA)

- RCS and AR facilities have demonstrated MW capability at JParc and SNS.

- High-intensity FFA has not been demonstrated, so the FETS-FFA is a proposed proof-of-principle.
  - Low energy but with large space-charge tune shift.
  - Study injection, painting, orbit correction, resonances, stacking etc.
  - CDR to be published soon.

Conventional Rings

1. Lattice Design (D. J. Adams)
2. Longitudinal Dynamics (R. E. Williamson)
3. Transverse Dynamics (C. M. Warsop, et al.)
4. 3D Beam Dynamics Design (D. J. Adams, et al.)
5. Injection Straight Design and Foils (H. V. Cavanagh, B. Kyle, et al.)
6. Correction Systems (H. Rafique)
7. Collimation, Extraction (H. V. Cavanagh, H. Rafique, et al.)
8. Instabilities (R. E. Williamson, D. W. Posthuma de Boer)

FFA

1. Optics and Dynamics (S. Machida, D. Kelliher, et al.)
2. Analytical Approach (M. Topp-Mugglestone)
3. Injection & Extraction (C. Rogers, J. Pasternak)
4. Longitudinal Dynamics (D. Kelliher, C. Jolly)
5. Collective Effects (D. Kelliher)
6. Magnet Physics Design (J. B. Lagrange, T-J. Kuo)
7. Magnet Engineering (I. Rodriguez, et al.)
8. Collimation & Diagnostics (E. Yamakawa, D. W. Posthuma de Boer, S. Sapkota)
9. RF Hardware (B. Kirk, I. S. K. Gardner)

Energy Range	3 -12 MeV
Intensity	3e11 ppp
Repetition Rate	100 Hz
Mean Power (equiv.)	60 W
Mean Orbit Radius	3.6 – 4.2 m

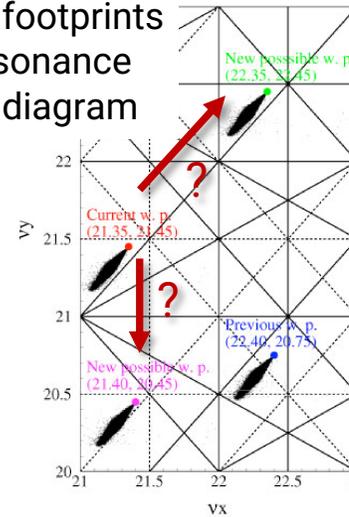# Sustainability – See Talk by H. M. Wakeling

Working Point

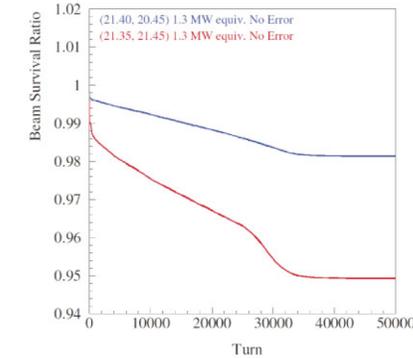# Working Points and Space Charge Limit

J. Appleby (JAI Student), A. Oeftiger

- Space charge limit =
  Maximum achievable beam intensity in
  space-charge-dominated accelerators
  - Resonance stopbands increase with intensity
  - Depends on betatron tune / working point

- JPARC Main Ring and FAIR SIS100:
  ongoing studies on identifying optimal working points
  at space charge limit

- Challenge: computationally very expensive simulations,
  complex beam dynamics

- Can we produce higher-intensity hadron beams via split
  integer tunes / beam shaping? If so, why?

- Collaboration project started with ISIS and JPARC to
  draw conclusions for ISIS-II designs

Space charge
tune footprints
in resonance
tune diagram

JPARC MR: towards 1.3MW beam power

Lower beam loss at
new working point
(PIC simulations)

FAIR SIS100

Beam loss simulations
across tune quadrants
show **better** working points
than FAIR SIS100 design!
(3.5 CPU-years / quadrant)

FETS-FFA – Magnets

FETS-FFA Magnet Physics
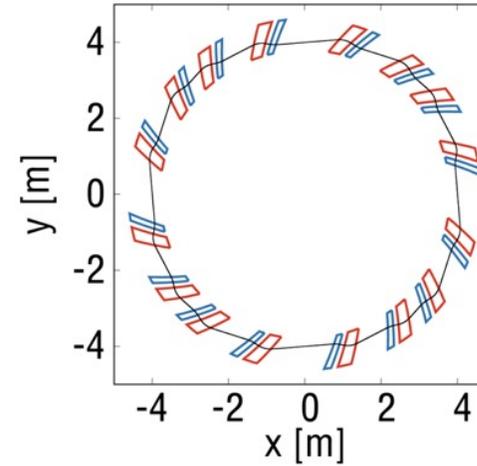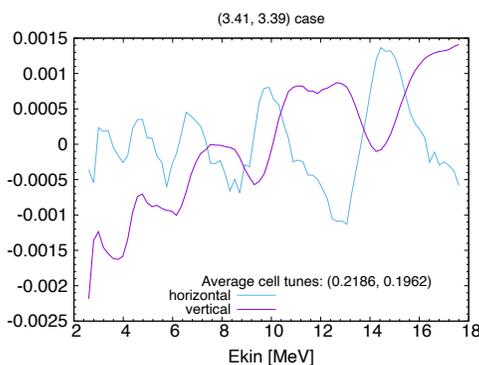
T-J. Kuo (JAI Student), J. Pasternak

- Demonstrator for FFA for ISIS-II

- Doublet spiral design

- Zero chromaticity if fields increase with radius following scaling law:

$$BL = BL_0 \left(\frac{r}{r_0}\right)^{k+1}$$

- Field index k defined by integral of field:

$$k = \frac{r}{\int B \, d\theta} \frac{\partial}{\partial r} \int B \, d\theta - 1$$

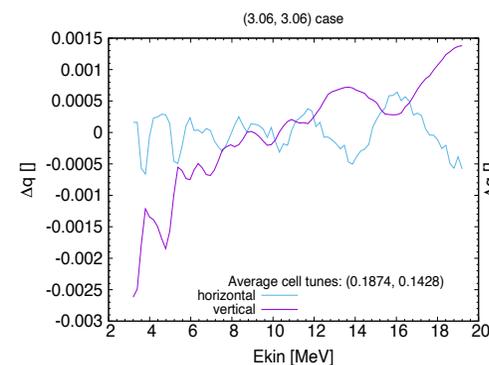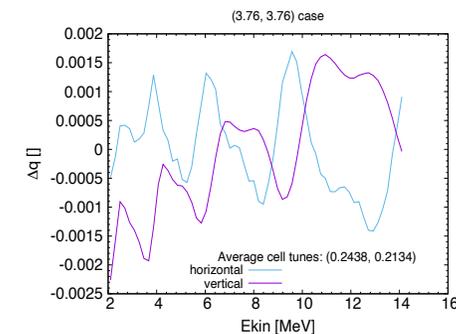- B field produced by distributed conductors each with a different current setting

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FETS-FFA Magnet Physics

T-J. Kuo (JAI Student), J. Pasternak

Flexibility in operating tune point to test dynamics for high beam intensity, target is to achieve cell tune variation: +/- 0.000625 for all the working points

Smaller prototype magnet has been delivered

- Measure magnet with different configurations and compare with Opera model

- Create Jacobian matrix for change in field for each coil.

- Investigate local correction scheme (k value and COD).

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FFA – Dynamics (Beam Stacking)

Beam stacking in FFAs

C. Jolly (JAI Student), P. Burrows, C. Rogers, A. Oeftiger

- Beam stacking is one of the primary advantages of FFA for high intensity applications.
    - Allows you to use the full aperture at extraction.
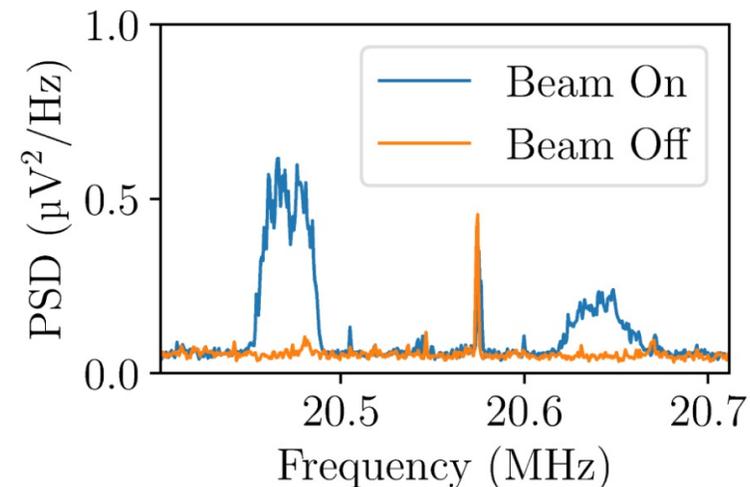   - Freedom with the repetition rate.
    - The benefits of an Accumulator Ring without needing a full energy linac.

- In 2023 we conducted an experiment to systematically study beam stacking the KURNS FFA.

- Results published early 2025 and chosen as PRAB "Editors' Suggestion".

Longitudinal phase space after beam stacking

https://doi.org/10.1103/PhysRevAccelBeams.28.012803
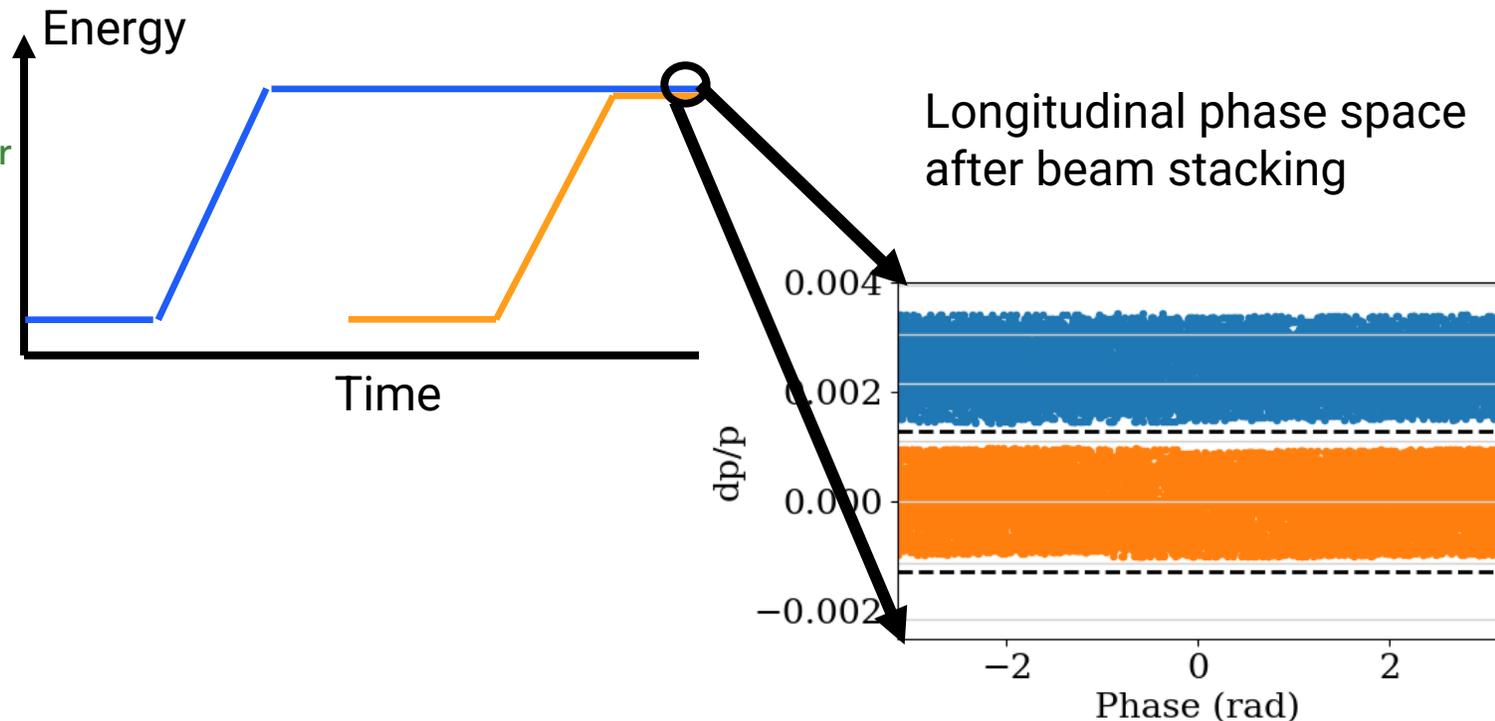
Beam stacking in FFAs

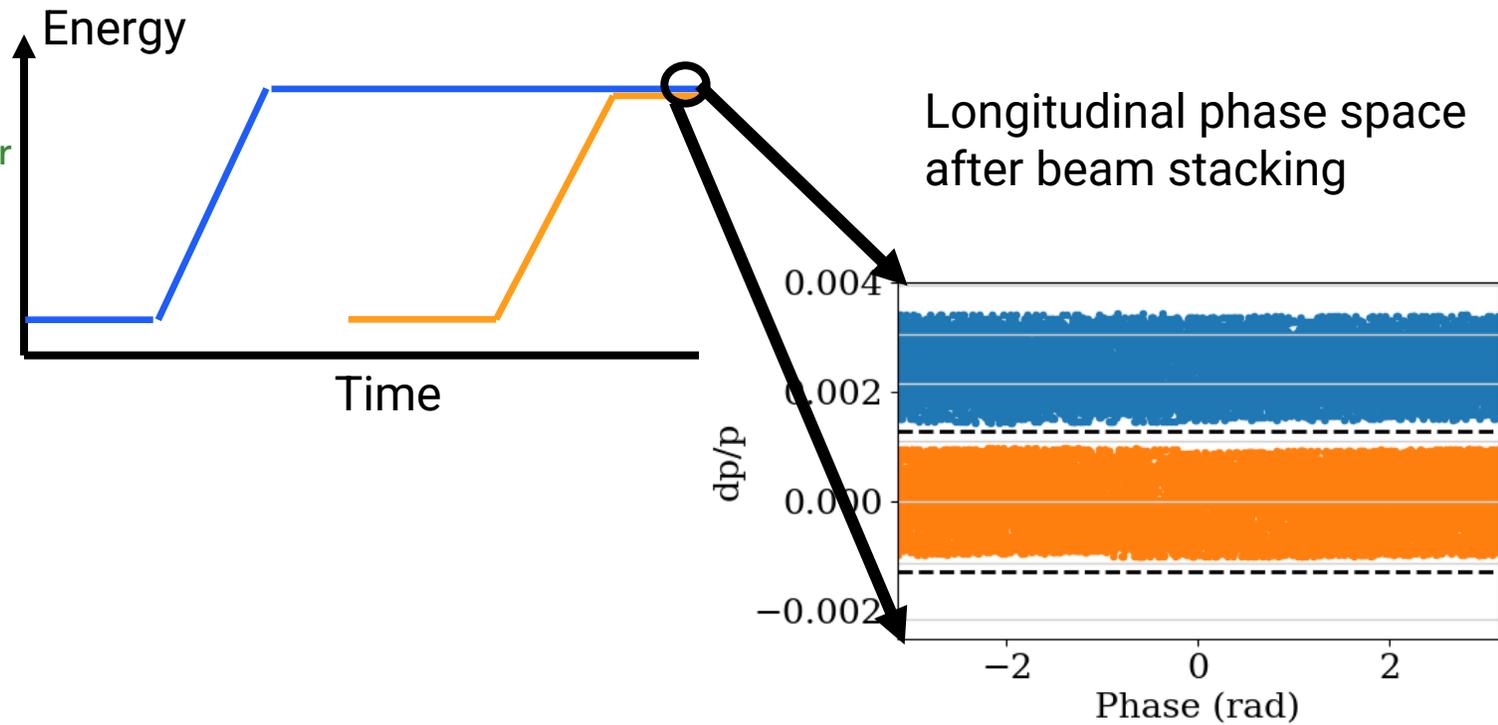C. Jolly (JAI Student), P. Burrows, C. Rogers, A. Oeftiger

- Beam stacking is one of the primary advantages of FFA for high intensity applications.
  - Allows you to use the full aperture at extraction.
  - Freedom with the repetition rate.
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- In 2023 we conducted an experiment to systematically study beam stacking the KURNS FFA.

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Longitudinal phase space after beam stacking

In 2023 we successfully stacked two beams in the KURNS FFA

But there was significant beam loss during stacking. → loss caused by **RF knockout.**

RF knockout
C. Jolly (JAI Student), P. Burrows, C. Rogers, A. Oeftiger

- The orbit in an FFA is dispersive.

- When a particle gains energy from a cavity it moves to a new closed orbit.

- → Equivalent to **a horizontal displacement** at the cavity.

During beam stacking, the RF is accelerating a second beam while one beam is stored in the machine
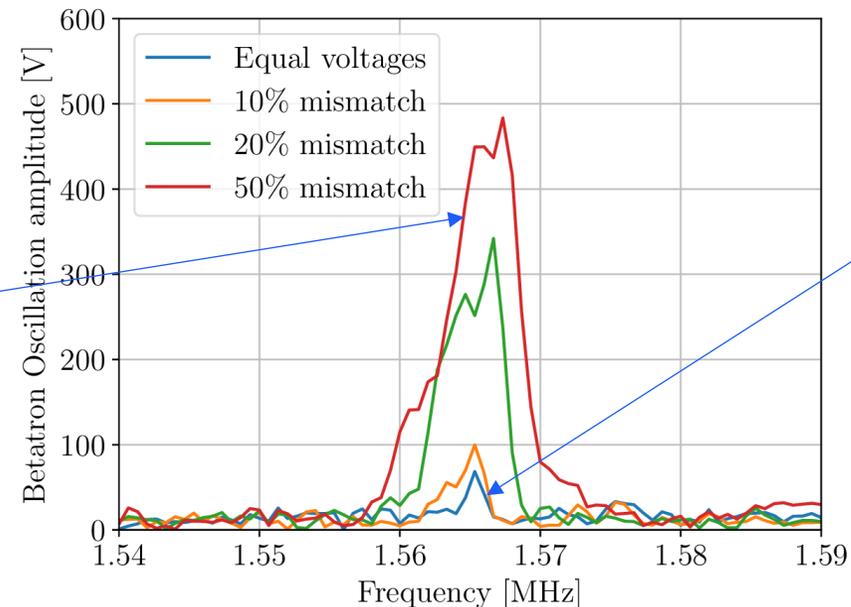
$$\delta x = \frac{D_x}{1+\gamma}\frac{\delta E}{E}$$

If the **RF frequency synchronises** with the **horizontal tune** then the displacements could build up turn-by-turn and cause **beam loss.**

Mitigating the beam loss from RF knockout
C. Jolly (JAI Student), P. Burrows, C. Rogers, A. Oeftiger

- In 2024, we used the ISIS synchrotron to characterise and test various methods for mitigating the RF knockout loss.

- The experimental results below show that by using cavities placed symmetrically around the ring the RF knockout displacements can be cancelled.

RF knockout loss returning
With mismatched voltages.

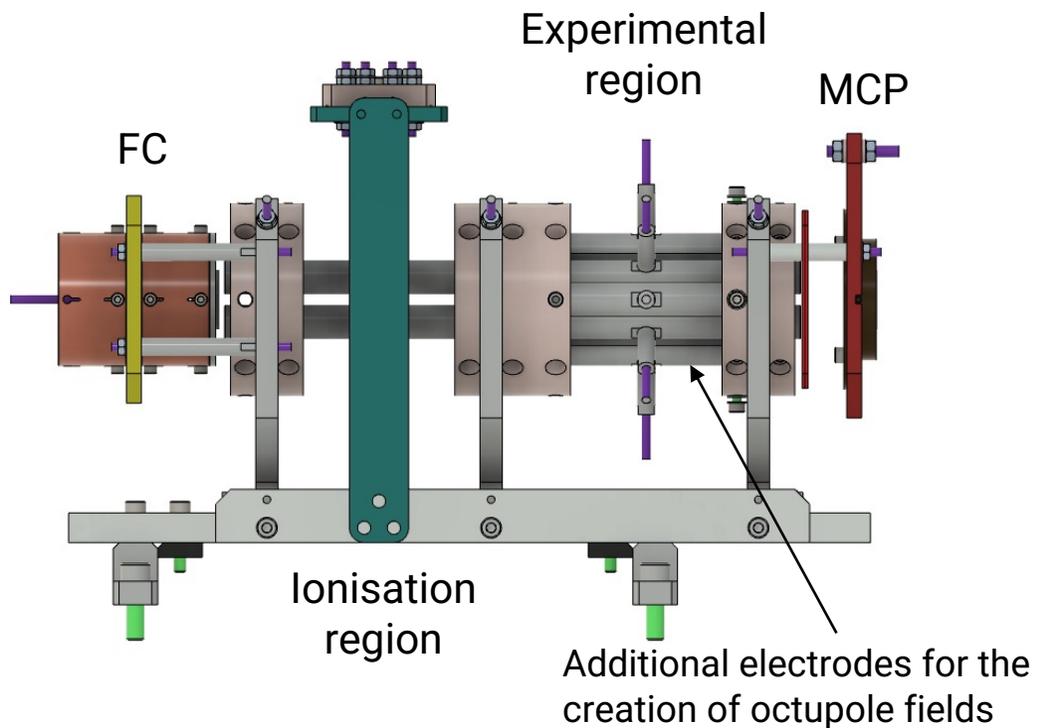RF knockout loss cancelled with equal cavity voltages.

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ISIS Neutron and Muon Source

John Adams Institute for Accelerator Science

IBEX Experimental Results

IBEX Paul Trap – Exp. Results

J. Flowerdew (Former JAI Student), A. Reichold, S. Sheehy

Nonlinear upgrade

Experimental region

MCP

FC

Ionisation region

Additional electrodes for the creation of octupole fields

J. Flowerdew: Investigating Nonlinear Integrable Optics

Reducing resonant loss with octupoles

Testing Quasi-Integrable Optics

Summary

- High intensity hadron beams are a vibrant area of research. Beams on ISIS offer unique research opportunities in the UK.
  - Research into coherent instabilities has made significant progress, and is having an <u>international impact</u>. Students are joining us to continue this research.
  - Progress on the impedance model can be seen as a starting point for future studies.
  - New areas of research being explored, such as ML for process optimisation.
  - <u>ISIS is being used as a testbed for research into future high-intensity machines, like ISIS-II.</u>

- Significant progress in many areas of ISIS-II development.
  - Working point studies have started <u>in collaboration with international labs</u>, to address a major intensity limitation in hadron machines.
  - FFA studies have yielded designs for new magnets, with a <u>prototype now delivered</u>.
  - Solutions to the RF knock-out effect have been successfully tested on ISIS.