

Recent Progress in Loss Control for the ISIS High-Intensity RCS: Geodetic Modelling, Tune Control, and Optimisation

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HB23 @ CERN

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HB 2023



ISIS Neutron and
Muon Source

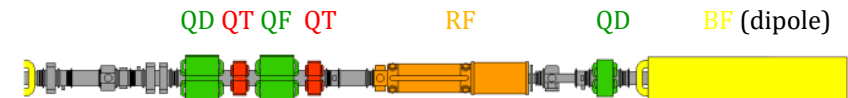
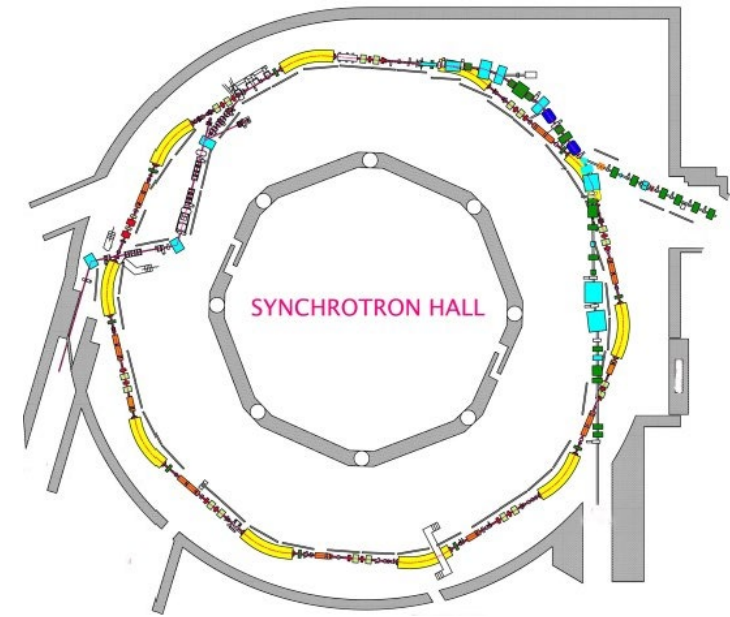
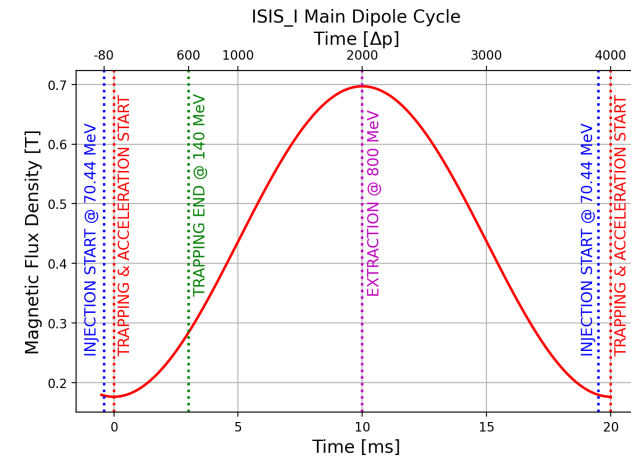
Contents

- ISIS Rapid Cycling Synchrotron
- Performance: Pre & Post Long Shutdown
- Orbit Control
- Tune Control
- Beam Loss Data Optimisation



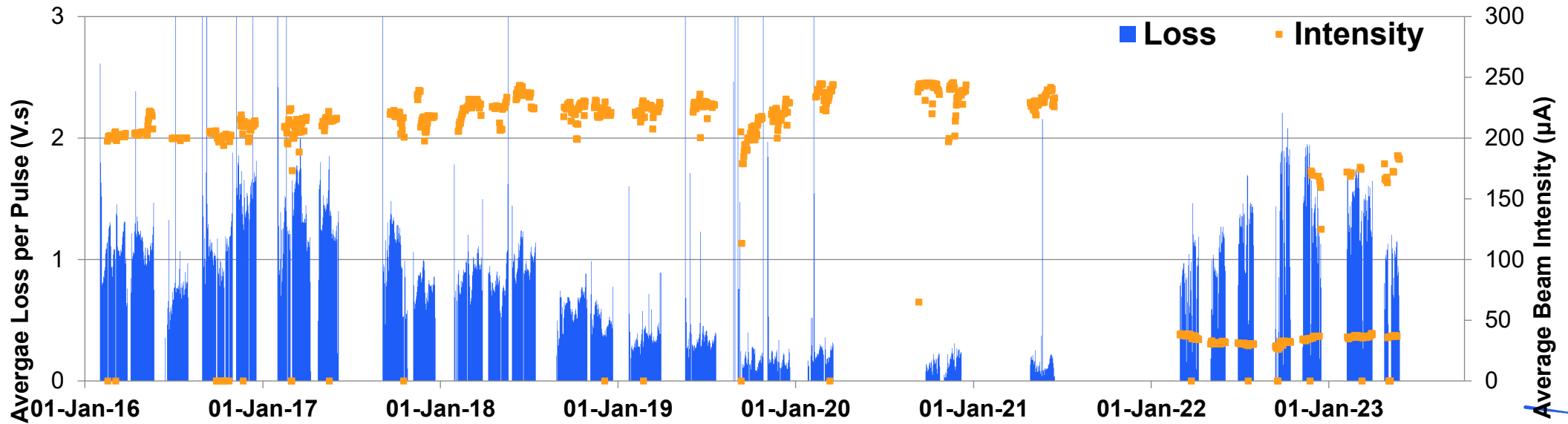
ISIS Rapid Cycling Synchrotron

- **Circumference:** 163 m
- **Energy:** 70–800 MeV
- **Repetition Rate:** 50 Hz
- **Intensity:** $\sim 3 \times 10^{13}$ ppp
- **Power:** ~ 190 kW
- **Injection:** 220 μ s, 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



ISIS RCS super period layout

A Journey in Loss Control



- General trend 2016 - 2021:

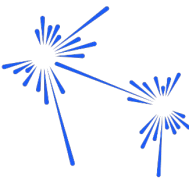
- Reduction in beam loss / Increase in beam intensity (to target)

- 2021 Long Shutdown (LS):

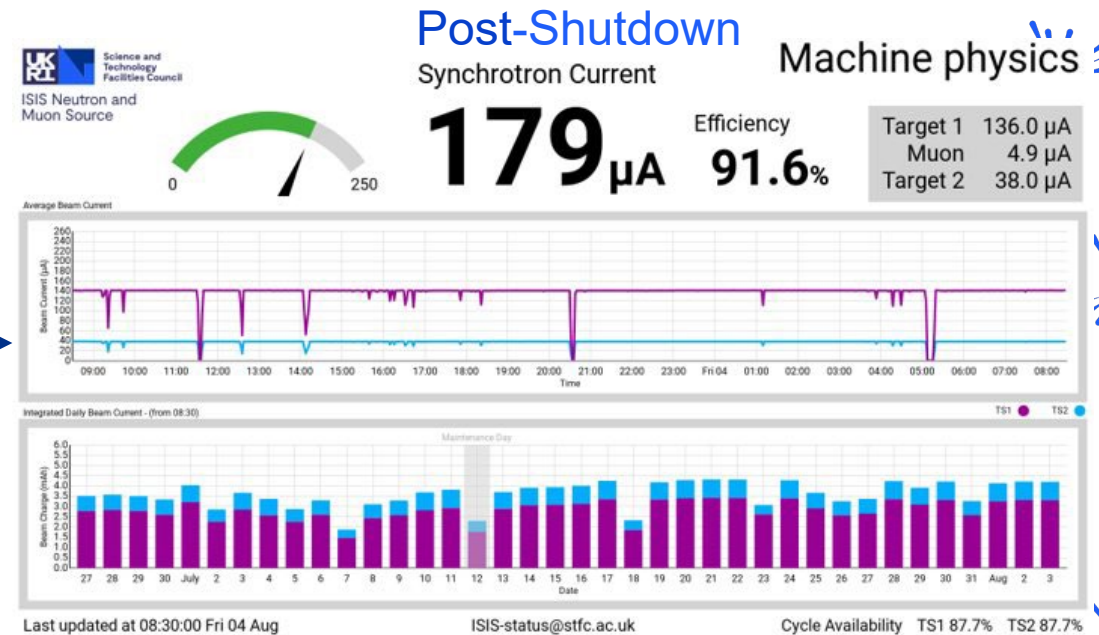
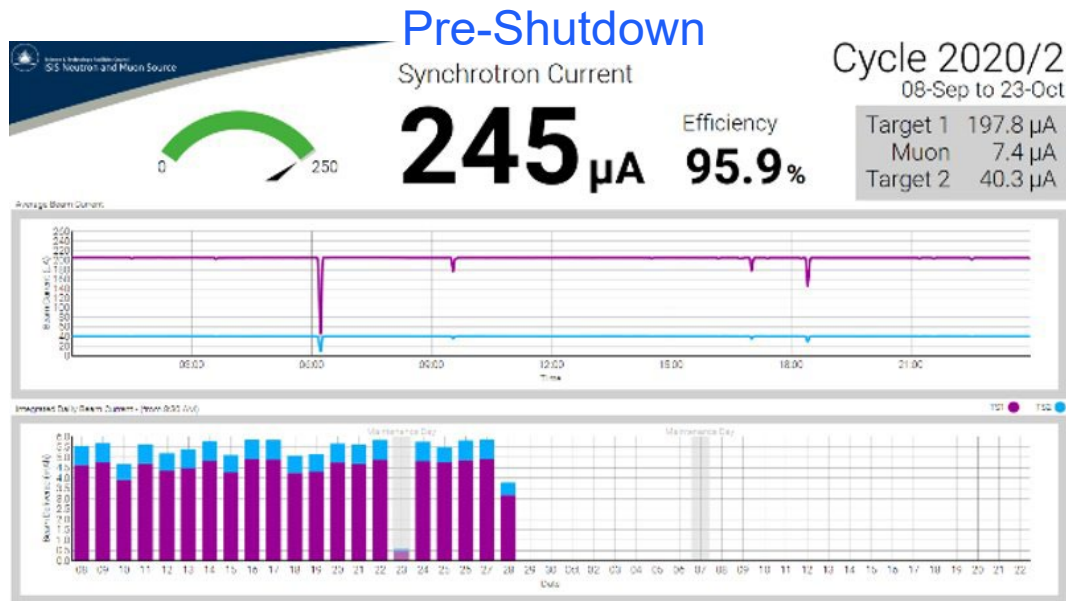
- Linac Tank 4 replacement
- Fundamental RF systems upgraded
- Multiple large projects (e.g. TS1 new target)

- 2022 Post Long Shutdown (LS):

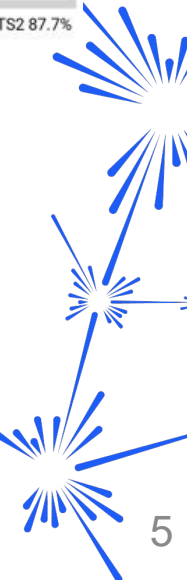
- Increase in beam loss / Reduction in beam intensity (to target)
- Operating at 10 Hz to Target Station 2 (TS2) only until late 2022



Post Long Shutdown Performance

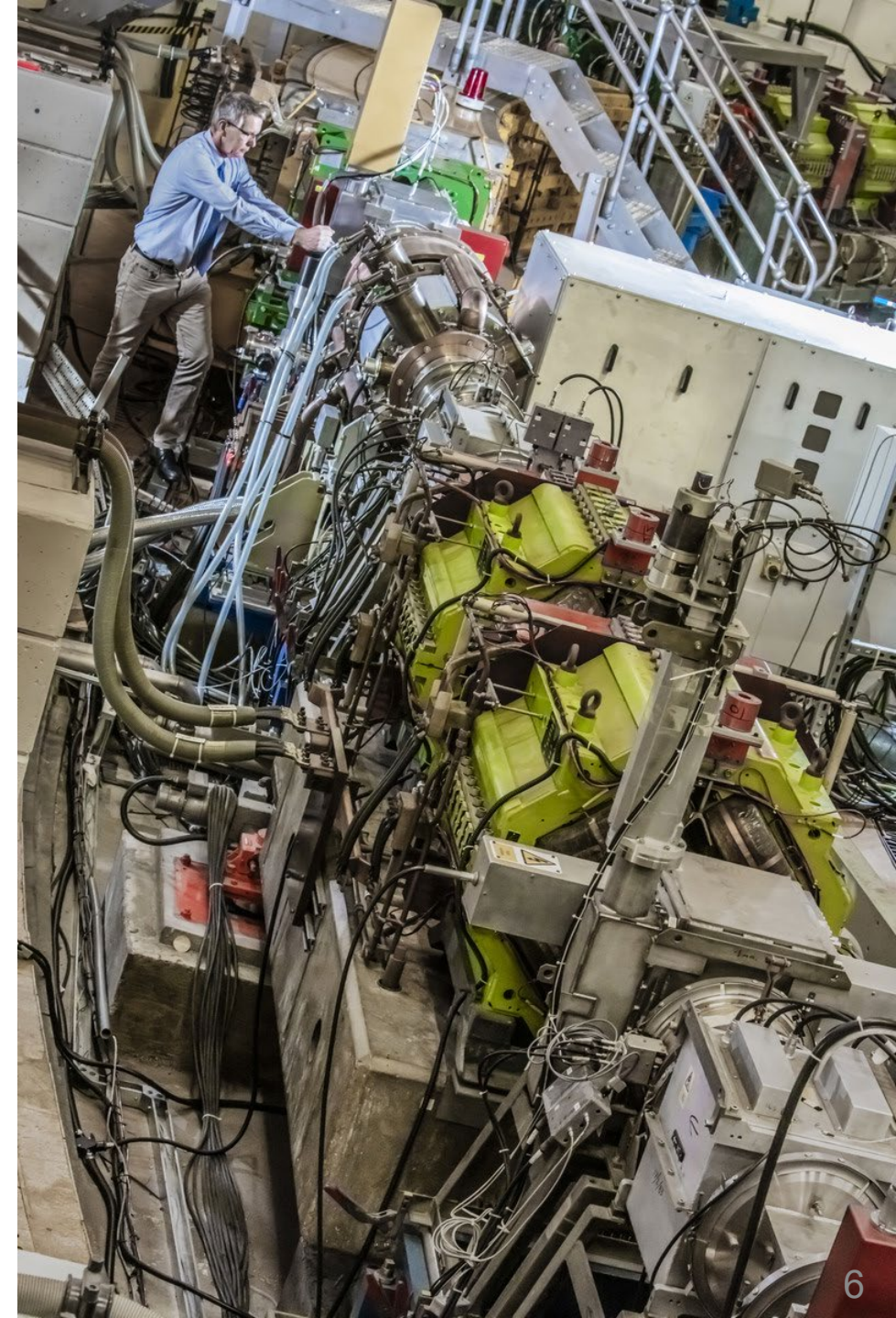


- Despite issues ISIS operating well post-LS
 - New Target 1 having teething issues – limiting RCS beam current
 - Users receiving neutrons & muons with ~ 90% availability
 - Room for improvement – aim for **200+ μA** RCS current



Goals

- Within the context of our R&D goals (See REW Talk "High-Intensity Studies on the ISIS RCS and their Impact on the Design of ISIS-II" on Thursday):
 - **Improving lattice models**
 - **Measurement based setup**
- How can we:
 - **Optimise** use of **existing** diagnostics and data
 - Build on existing tools to **better identify** and **further protect** from issues
- Focus on three areas:
 1. **Orbit Control**
 2. **Tune Control**
 3. **Beam Loss** data optimisation

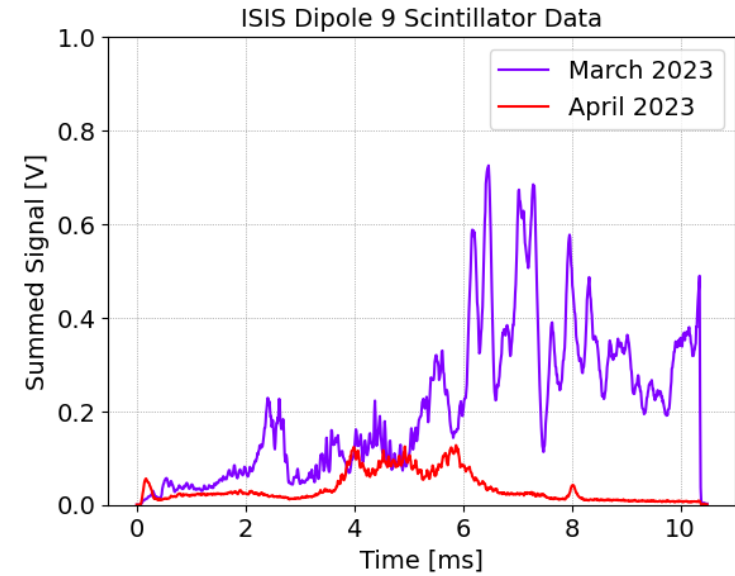


Orbit Control

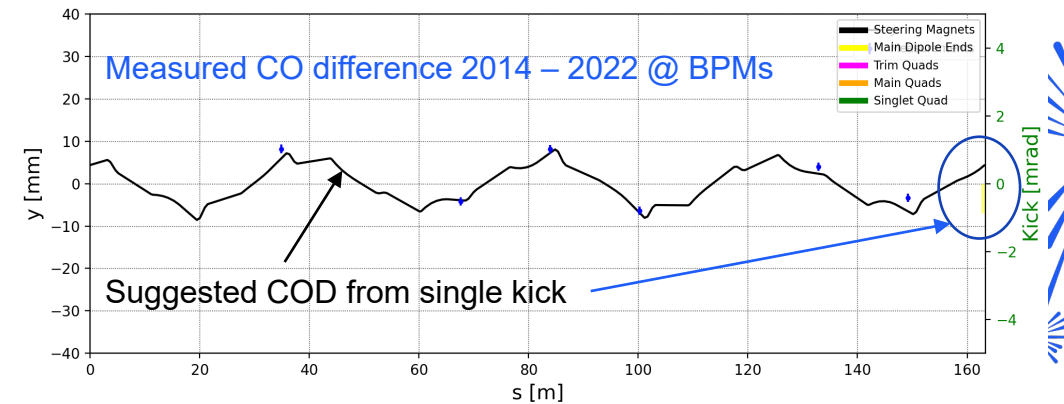


Orbit Control

- **Post – LS:**
 - Larger than expected loss observed in SP8/9
 - Closed orbit distortion traced to Dipole 9 misalignment
 - Dipole 9 was swapped in LS for maintenance
 - Based on investigation Dipole 9 realigned between **March / April**
- **Identification**
 - Operational investigation of orbit / loss with correctors, BPMs, BLMs
 - Use of historical data: 2014 – 2022 bare orbit difference – good agreement!
- **Lesson:**
 - Make better use of bare closed orbit / magnet survey data
 - Use measurements to develop working lattice models to represent post-LS machine



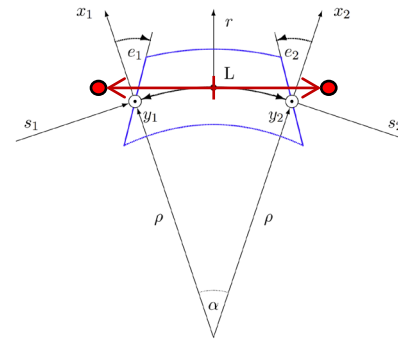
Dipole 9 internal scintillators showing post long-shutdown loss **before** and **after** Dipole 9 realignment



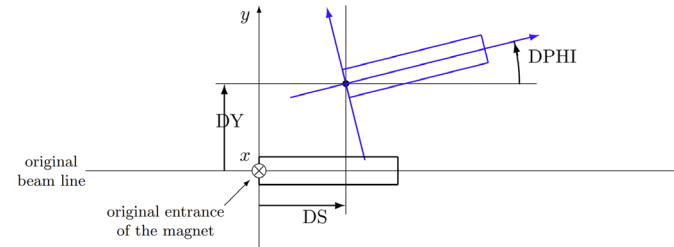
Measured bare lattice difference between 2014 – 2022 with algorithm suggested single dipole kick in dipole 9 and subsequent closed orbit

Utilising Geodetic Survey Data

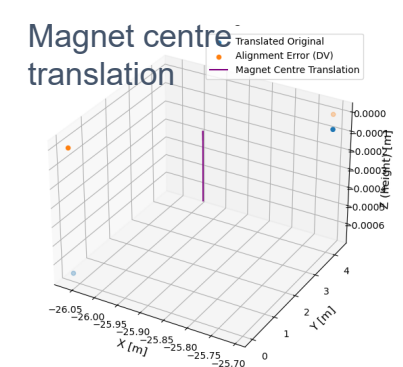
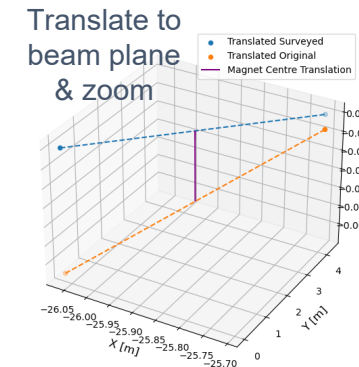
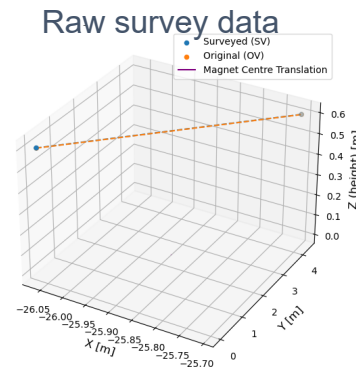
- **Background:**
 - Main Dipoles and Doublet Quadrupoles surveyed regularly
 - Original schematic data (40+ years old) valid but partly incomplete
- **Develop tools to translate survey data to misalignment model**
 - Infer bare closed orbit at time of survey
 - Suggest realignment in situ
- **Implementation**
 - Survey: non-trivial to define relation between alignment vector and MAD model, numerous assumptions to be tested. Filter required to identify systematic survey errors.
 - First approach: align centre of alignment vector with centre of MAD magnet – relative alignment error
 - Translate alignment vector to MAD EALIGN alignment error
 - Dedicated measurement campaign planned
 - Interested in relevant experience from other labs!



MAD-X SBEND reference system (from MAD Manual) with survey vector overlaid



MAD-X EALIGN errors DS DY DPHI (from MAD Manual)



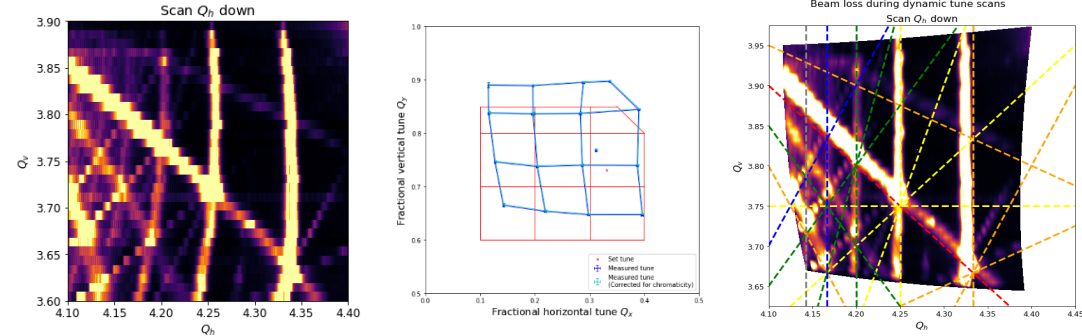
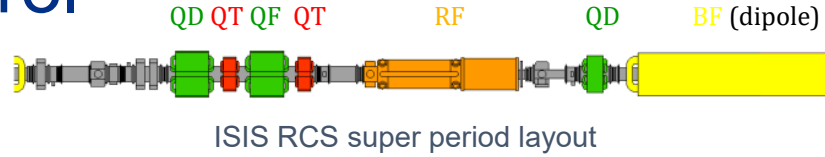
Error vector at magnet centre translation. Difference between design position and surveyed position for Dipole 9 at time of misalignment.

Tune Control



RCS Tune Control

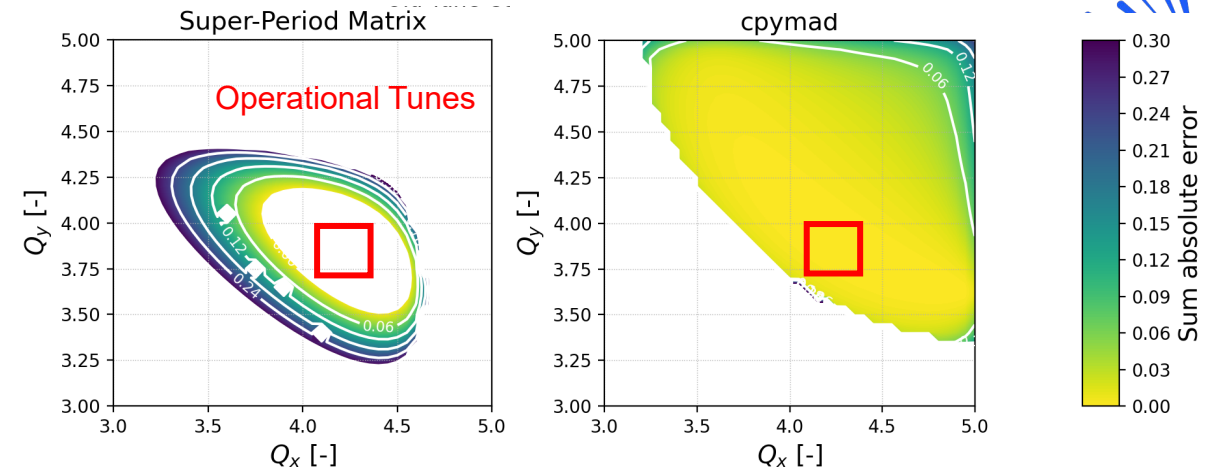
P. T. Griffin Hicks



Dynamic Q scan (vs loss) data taken 22.12.19. Raw data (left) and corrected (right). Centre plot shows measured Q grid pre-LS.

$$\Delta Q = \frac{1}{4\pi} \int \beta[s] \cdot k[s] \cdot ds \quad k_1 = \frac{2 \cdot \pi (\beta_{v2} \cdot \Delta Q_h + \beta_{h2} \cdot \Delta Q_v)}{5 \cdot L_1 \cdot (\beta_{h1} \cdot \beta_{v2} - \beta_{h2} \cdot \beta_{v1})}$$

Tune control functions derived using Q change from quadrupole error



Predicted error in set tune for old and new Q control

Resonance Studies (R&D to improve models)

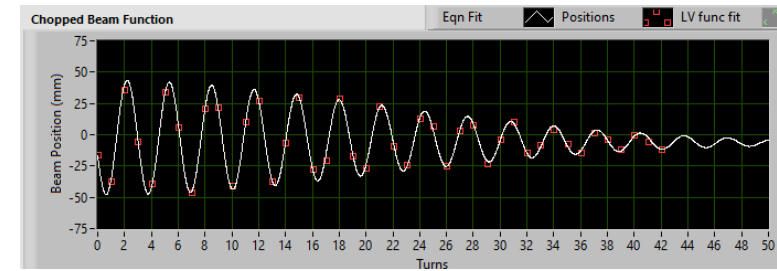
- Resonances observed with dynamic tune scans
- Limitation in tune setting observed – curvature of resonance lines
- Q control uses 2 trim quads per super-period at QD and QF
- Q control limited far from operational working point – first order analytical – not an issue operationally as ΔQ small
- Corrected resonance maps using known issue
- Developed improved model dependent Q control – includes variation of optics with Q

New Q control developed

- Use super-period lattice model with thin trim quads
- Predicted error reduced
- Development and implementation underway

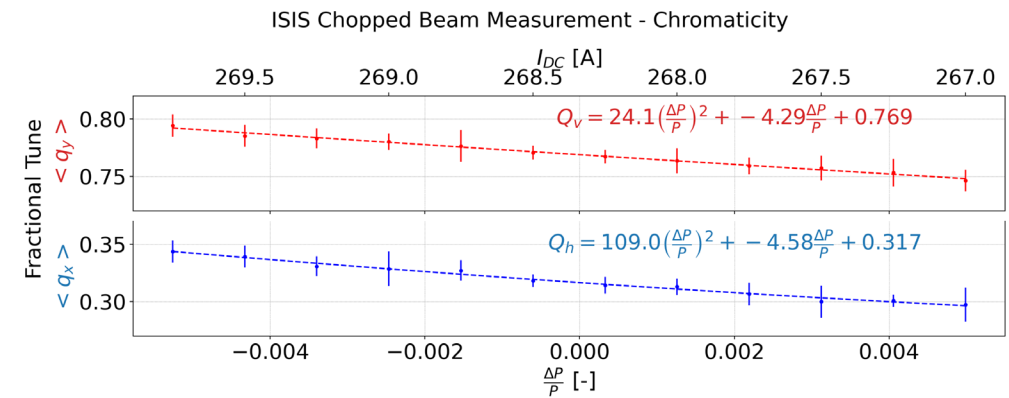
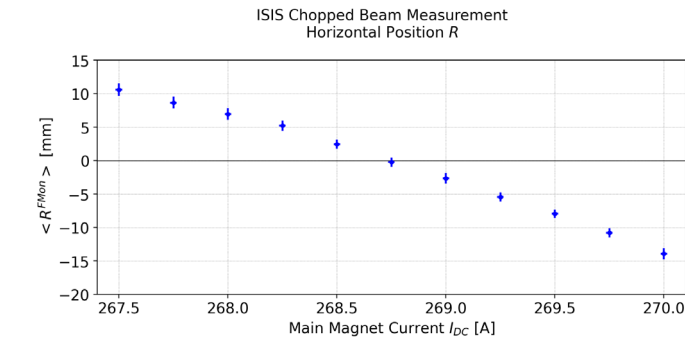
RCS Lattice Measurements

- Rely on the chopped beam measurement
 - Provides much information
 - Low intensity chopped beam (<1% operational beam)
 - Only DC main magnet power, RF off, no extraction
 - Small transverse emittance 600 ns pulse behaves like a single particle
 - Use BPMs in high gain to observe beam position over ~ 50 turns
 - Fit natural oscillation
- Chromaticity
 - Vary MMPS DC – scan in $\left(\frac{\Delta B}{B}\right)_{P_{const}} \equiv \left(\frac{\Delta P}{P}\right)_{B_{const}}$
 - Plot $\langle x \rangle = \langle r_0 \rangle$ against I_{DC} to identify central orbit $r_0 = 0$
 - Plot $\langle q_{x,y} \rangle$ against $\frac{\Delta P}{P}$ to define chromaticity and bare lattice tunes
 - Pre-LS 2018: $(q_x, q_y)_{bare} = (0.316, 0.769) \pm 0.004$
 - Post-LS 2022: $(q_x, q_y)_{bare} = (0.316, 0.765) \pm 0.004$
 - Post-LS 2023: $(q_x, q_y)_{bare} = (0.317, 0.769) \pm 0.004$
- Machine Checks
 - Zero crossing current (I_{DC} where beam is horizontally centred in the aperture)
 - Chromaticity, bare lattice tune
 - Dispersion at BPMs
 - Trim quad functionality
 - State of the injector



$$Y(n) = \eta + n\delta\eta + Ae^{-\frac{(\Delta v/n)^2}{2}} \cos\left(2\pi n\left(\nu_0 + n\left(\frac{\delta\nu}{2}\right) + \phi\right)\right)$$

Chopped beam measurement fit and function



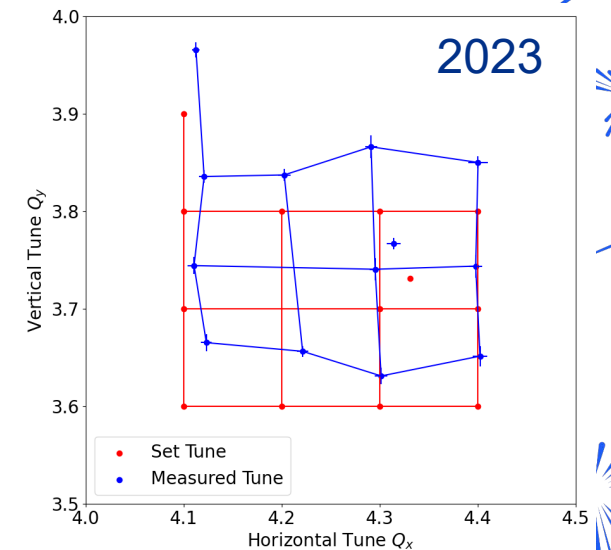
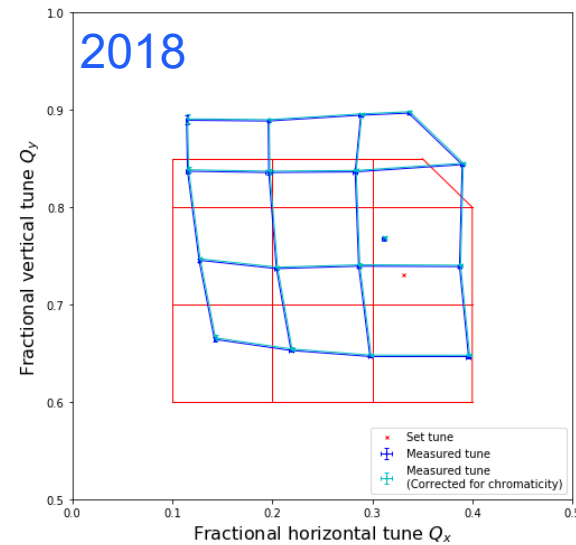
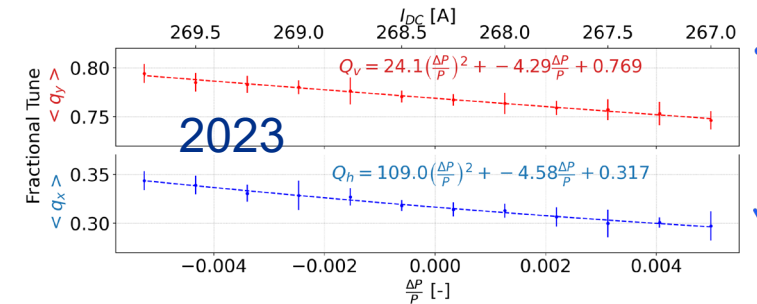
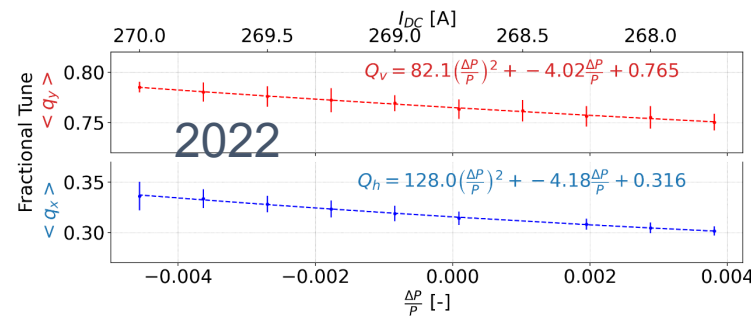
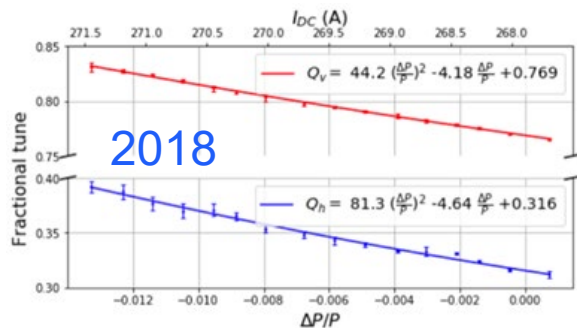
RCS Lattice Measurements

Q Grid

- Define grid of set tunes, measure using chopped beam to observe tune control limitations
- Pre-LS: small errors, clear shift in Q plane
- Post-LS: large errors, jitter in Q due to ion source dominates measurement – still investigating
- Observe similar Q plane shift

Chromaticity

- Pre-LS 2018:
 - $(q_x, q_y)_{bare} = (0.316, 0.769) \pm 0.004$ $\xi_x = -1.075 \pm 0.15$, $\xi_y = -1.109 \pm 0.15$
- Post-LS 2022:
 - $(q_x, q_y)_{bare} = (0.316, 0.765) \pm 0.004$ $\xi_x = -0.97 \pm 0.184$, $\xi_y = -1.067 \pm 0.14$
- Post-LS 2023:
 - $(q_x, q_y)_{bare} = (0.317, 0.769) \pm 0.004$ $\xi_x = -1.061 \pm 0.1$, $\xi_y = -1.138 \pm 0.11$



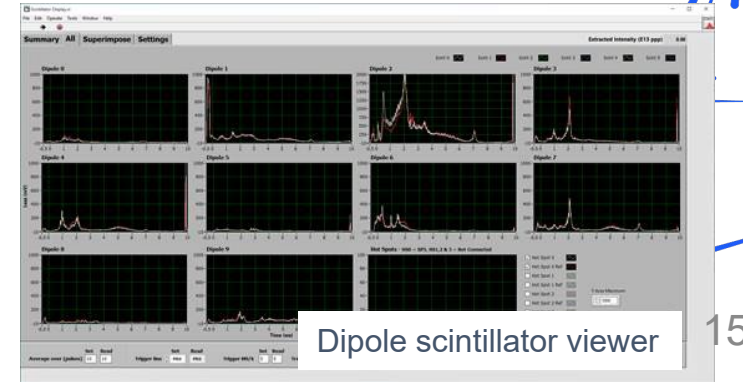
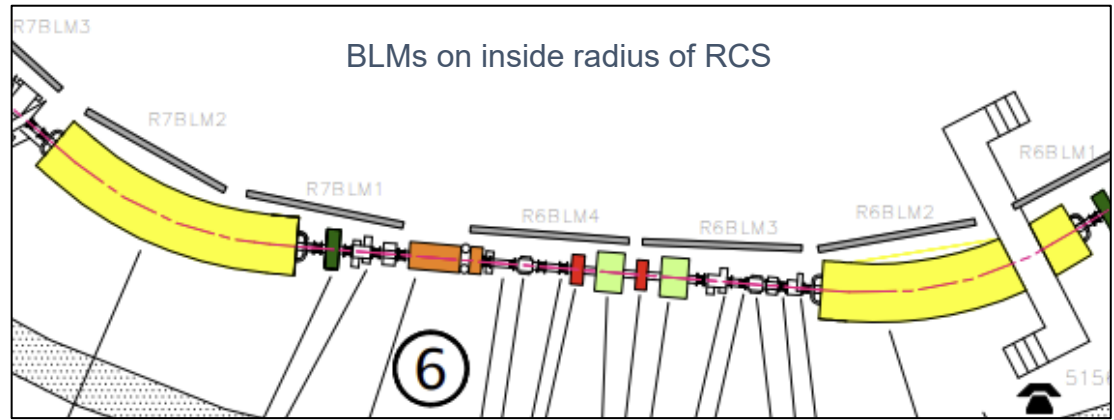
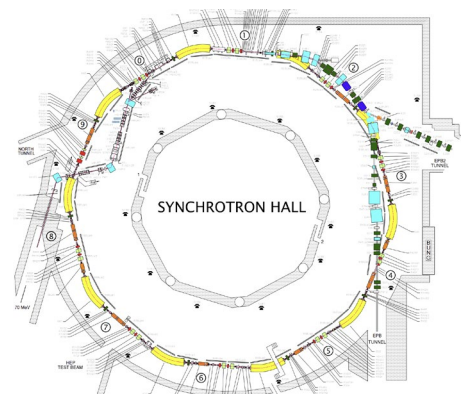
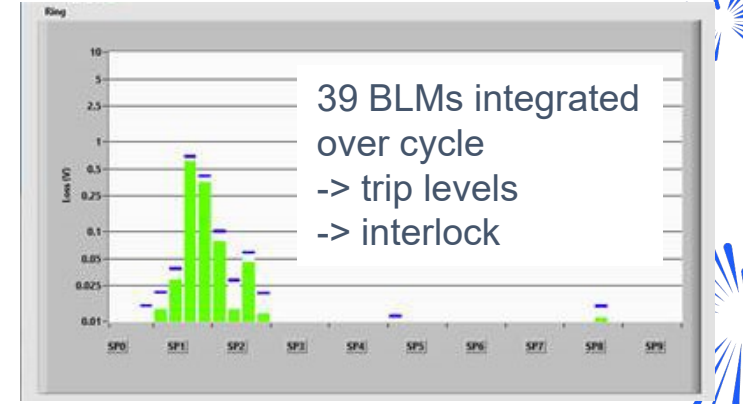
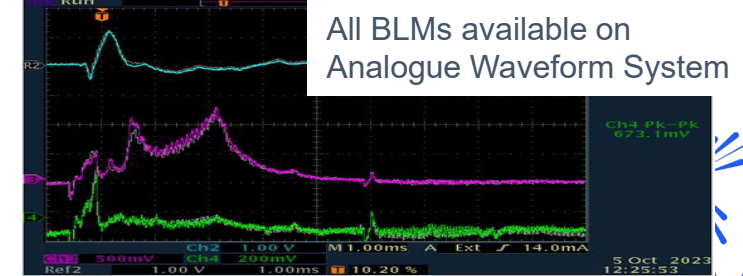
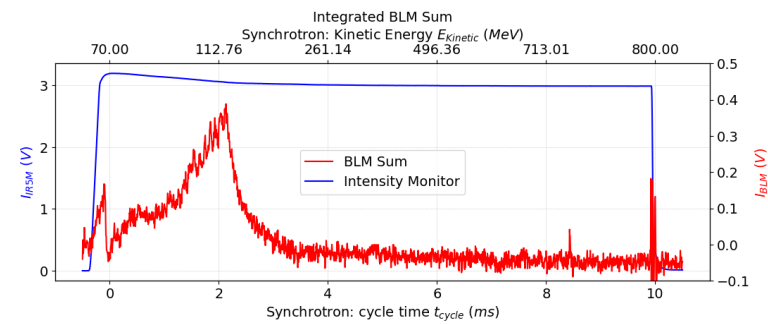
Plans:

- New Q control implementation & testing ongoing
- Validation with Chromaticity & Q Grid chopped beam measurements
- Repeat dynamic Q scans to show resonance lines
- Aim to regularly perform lattice measurements to feedback into model & control

Optimisation of Loss Data

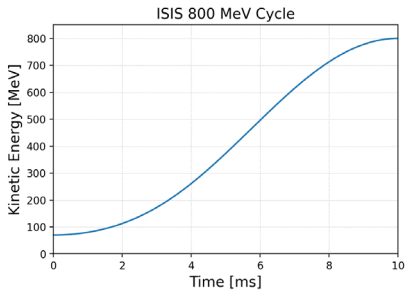
Beam Loss Monitoring

- ISIS is loss limited due to activation; loss levels define RCS operational intensity
 - 39 RCS Beam Loss Monitors (BLMs), multiple Intensity Monitors (IMs)
 - Ar ionisation chamber BLMs detect isotropically emitted evaporation neutrons
 - 10 sets of internal dipole scintillators (6 per dipole) – large iron yoke shields BLMs
- 10 ms machine cycle (at 50 Hz) split roughly into Injection / Trapping / Acceleration / Extraction
 - Intensity Monitors: loss vs time -> feed into protection interlocks
 - Each RCS BLM integrated over individual machine cycle -> histogram with trip levels based on activation
 - Use BLM Sum vs time as key diagnostic for tuning out loss, select individual BLMs where necessary
 - Too much data to monitor whilst tuning!
- Robust system based on much operational experience. How can we condense and organise all this data to best optimise the machine to reduce beam loss??

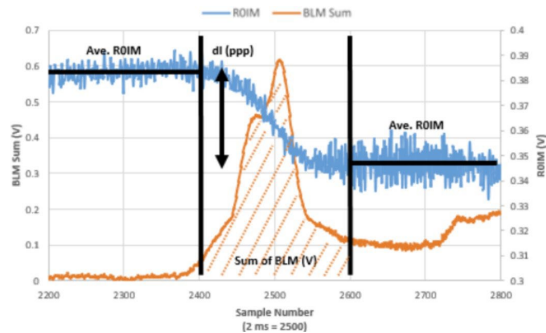


BLM Calibration

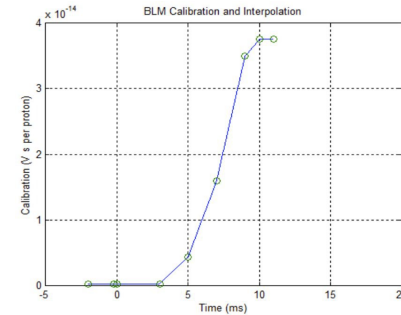
- Intensity monitor is calibrated to protons, but limited sensitivity $\sim 0.1\%$
- Beam loss monitors highly sensitive (10^{-8}) but not well calibrated
- High energy losses at end of cycle cause more activation
- Campaigns in 1993, 2003, 2016 to ascertain energy loss calibrations for RCS BLMs



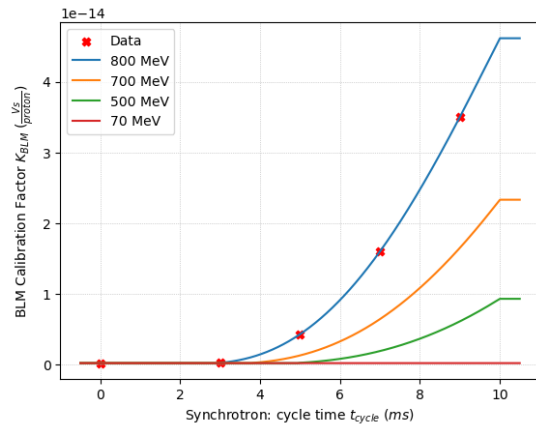
ISIS energy ramp



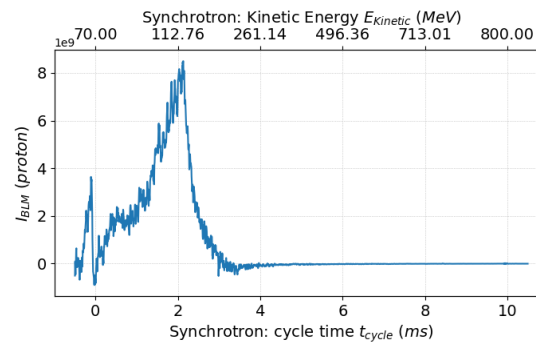
1. Drive beam loss at a selected time in the 10ms RCS cycle



2. For each time point calculate calibration factor



3. Functionalise calibration curve for arbitrary extraction energy



4. Convert BLM Sum from Volt seconds to Protons

***** Loss Data from R5IM *****
 Data Taken on : 03/12/2003 1605
 Integrated over 0.5 ms intervals (end time shown)

| Time (ms) | R5IM LOSS (1E12) {+/- 0.1E12} | Energy Loss (J) {+/- 1} | R5IM CIRC (1E13) {+/- 0.01E13} |
|-----------|----------------------------------|----------------------------|-----------------------------------|
| 0.0 | 25.8 | 289 | 0.00 |
| 0.5 | -1.0 | -14 | 2.58 |
| 1.0 | -0.7 | -6 | 2.47 |
| 1.5 | -0.5 | -7 | 2.41 |
| 2.0 | -0.2 | -3 | 2.35 |
| 2.5 | -0.2 | -3 | 2.34 |
| 3.0 | 0.0 | 0 | 2.32 |
| 3.5 | 0.0 | 0 | 2.32 |
| 4.0 | 0.0 | 0 | 2.32 |
| 4.5 | 0.0 | 0 | 2.32 |
| 5.0 | 0.0 | 0 | 2.32 |
| 5.5 | 0.0 | 0 | 2.32 |
| 6.0 | 0.0 | 0 | 2.32 |
| 6.5 | 0.0 | 0 | 2.32 |
| 7.0 | 0.0 | 0 | 2.32 |
| 7.5 | 0.0 | 0 | 2.32 |
| 8.0 | 0.0 | 0 | 2.32 |
| 8.5 | 0.0 | 0 | 2.32 |
| 9.0 | 0.0 | 0 | 2.32 |
| 9.5 | 0.0 | 0 | 2.32 |
| 10.0 | -22.2 | -2885 | 2.32 |

Total Lost Power per pulse = 33 W (+/-3 W) [0.0-9.5 ms]
 Mean Lost Power @ 50 Hz = 1650 W (+/-150 W) [0.0-9.5 ms]
 Injected Power @ 50 Hz = 14450 W (+/-150 W)
 Extracted Power @ 50 Hz = 144250 W (+/-1500 W)
 Lost Power/Extr Power eff = 1 %
 Error R5IM +/- 1.3E11 ppp

***** Loss Data from BLMSUM *****
 Data Taken on : 03/12/2003 1605
 Integrated over 0.5 ms intervals (end time shown)

| Time (ms) | BLMSUM (uv.s) {+/-10 uv.s} | Estimated Derived Quantities | |
|-----------|-------------------------------|--------------------------------|-----------------------------------|
| | | LOSS (1E12 ppp) {see below} | Energy Loss (J pp) {see below} |
| 0.0 | 187 | 0.851 | 9.6 |
| 0.5 | 479 | 2.137 | 24.4 |
| 1.0 | 414 | 1.801 | 21.9 |
| 1.5 | 351 | 1.485 | 20.5 |
| 2.0 | 261 | 1.073 | 17.6 |
| 2.5 | 165 | 0.662 | 13.2 |
| 3.0 | 72 | 0.280 | 6.9 |
| 3.5 | 32 | 0.051 | 1.5 |
| 4.0 | 32 | 0.018 | 0.7 |
| 4.5 | 36 | 0.013 | 0.6 |
| 5.0 | 26 | 0.007 | 0.4 |
| 5.5 | 18 | 0.003 | 0.2 |
| 6.0 | 13 | 0.002 | 0.1 |
| 6.5 | 9 | 0.001 | 0.1 |
| 7.0 | 5 | 0.000 | 0.0 |
| 7.5 | 0 | 0.000 | 0.0 |
| 8.0 | -1 | 0.000 | 0.0 |
| 8.5 | -6 | 0.000 | 0.0 |
| 9.0 | -9 | 0.000 | 0.0 |
| 9.5 | -5 | 0.000 | 0.0 |
| 10.0 | 39 | 0.001 | 0.1 |

Error BLM sig +/- 10 (uv.s)
 Error in proton cal +/- 100%
 Noise limits at: 1E11 ppp at 0 ms, 1E9 ppp at 10 ms



BLM Data Opportunities

Can now use lost energy vs time / space at higher sensitivity – application?

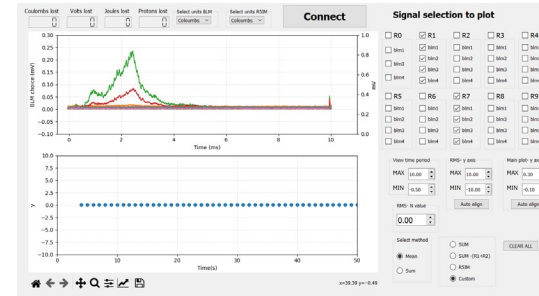
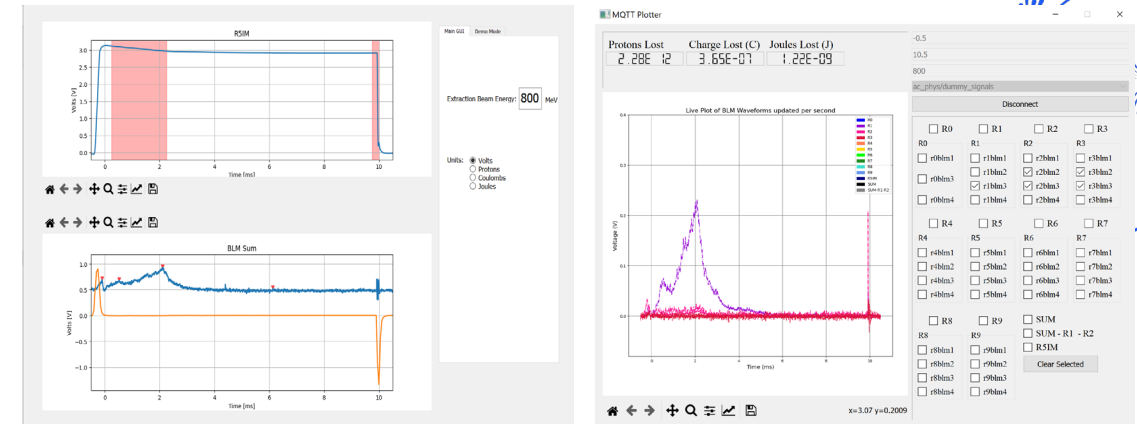
• Data Streaming:

- Digitised via PXI crate
- Sampled & streamed via MQTT
- Received with MQTT python Paho client
- GUI: PyQt5

• Opportunities:

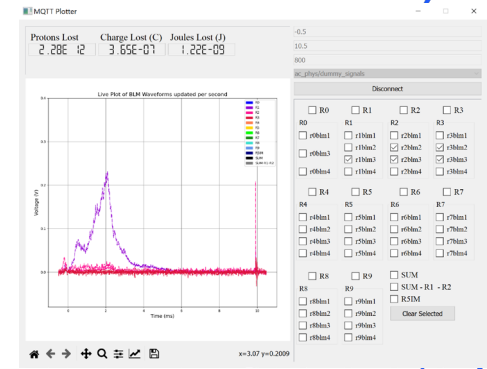
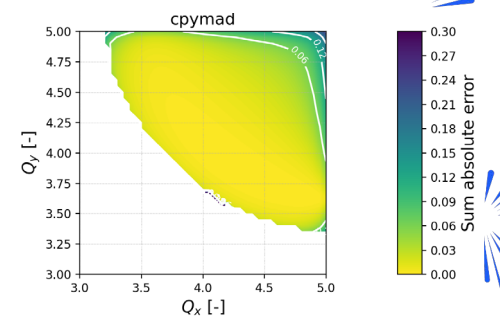
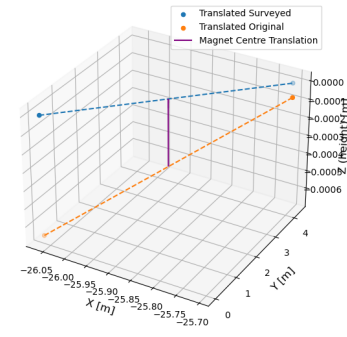
- Spatial and temporal selection
- Calibrated conversion to:
 - Protons
 - Energy (Joules)
 - Power (Watts)
- Monitoring of selected values over time
- Comparison of Intensity and Loss signals
- Loss locator

• Better defined loss status!



Summary

- Closed Orbit control critical in recovering post LS
 - Control re-established
 - Aim to leverage regular magnet surveys to predict closed orbit
- New method of tune control being implemented and tested
 - Chopped beam measurement provides much utility in lattice status checks
 - Lattice measurements improving lattice models
- Beam loss critical to operations
 - Existing diagnostics provide robust machine protection
 - Utilising data for more systematic and detailed loss control and optimisation
- Long-Term:
 - Continue to support measurement-based machine setup
 - Develop understanding of our RCS by developing more complex lattice models based on regular measurements



Acknowledgements

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- Accelerator Physics group for **fruitful input & experience**
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 - Ivan Finch, Kathryn Baker, and Gareth Howells and the Controls group **for their invaluable support**
 - Sara Karbassi for upgrading chopped beam **analysis tools**
 - The **ISIS Operations Crew** for supporting measurements and operations 24/7
 - Tony Millington and Greg Seeney from the Survey section for their diligent measurements
 - **26 work experience students** for developing 5 beam loss GUI prototypes
 - Everyone at ISIS because it takes a dedicated team of experts to operate a facility!



Chris Warsop
Synchrotron R&D Section Leader



Hayley Cavanagh
Machine Physics Operations Leader

Peter Griffin Hicks
Former ISIS Accelerator Physicist

ISIS Operational Crew



“Special diagnostic methods and beam loss control on high intensity proton synchrotrons and storage rings Circular proton accelerator“, C. M. Warsop, PhD Thesis 2002



ISIS Neutron and Muon Source



Esher Bansal
Industrial Placement Student



Thank you
Questions?

