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

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HB23 @ CERN

10.10.23

HB 2023

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Contents

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

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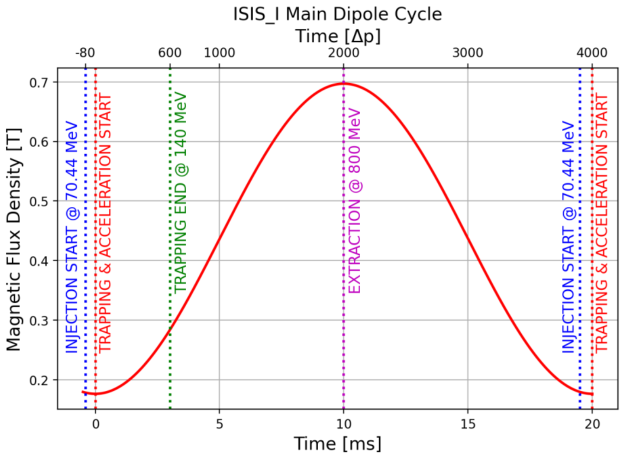
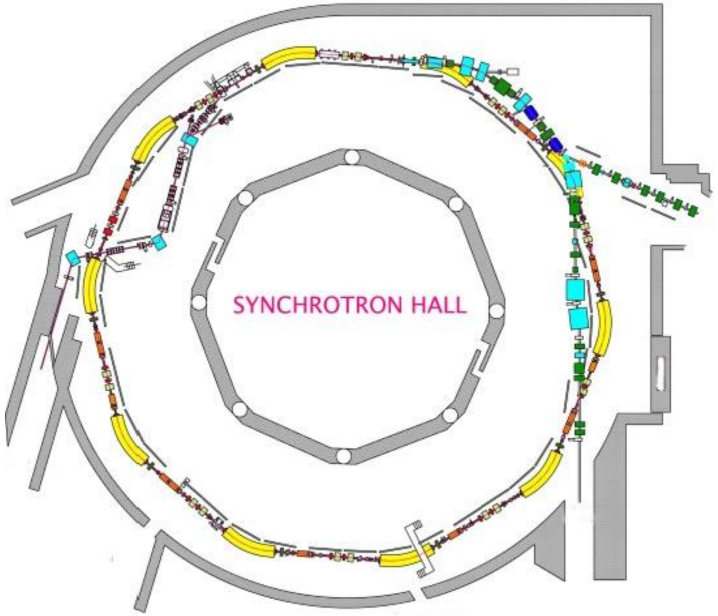
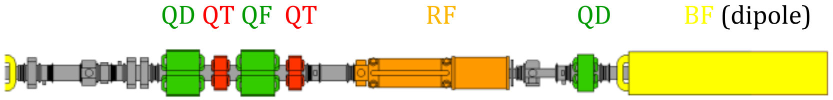
ISIS Rapid Cycling Synchrotron

- **Circumference:** 163 m
- **Energy:** 70–800 MeV
- **Repetition Rate:** 50 Hz
- **Intensity:** ~3x10^{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

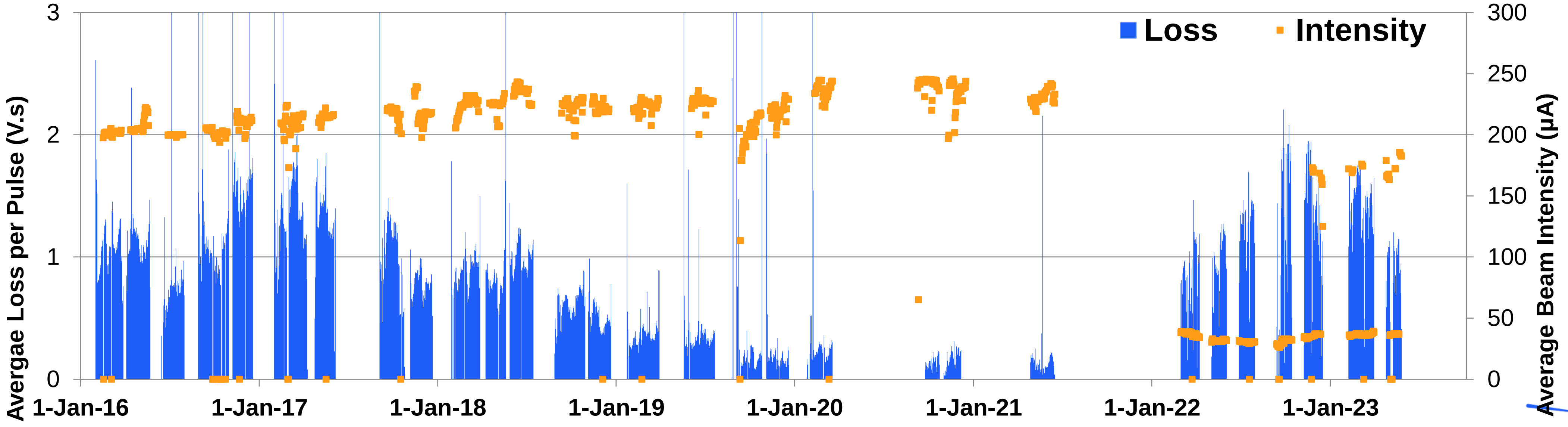






ISIS RCS super period layout

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

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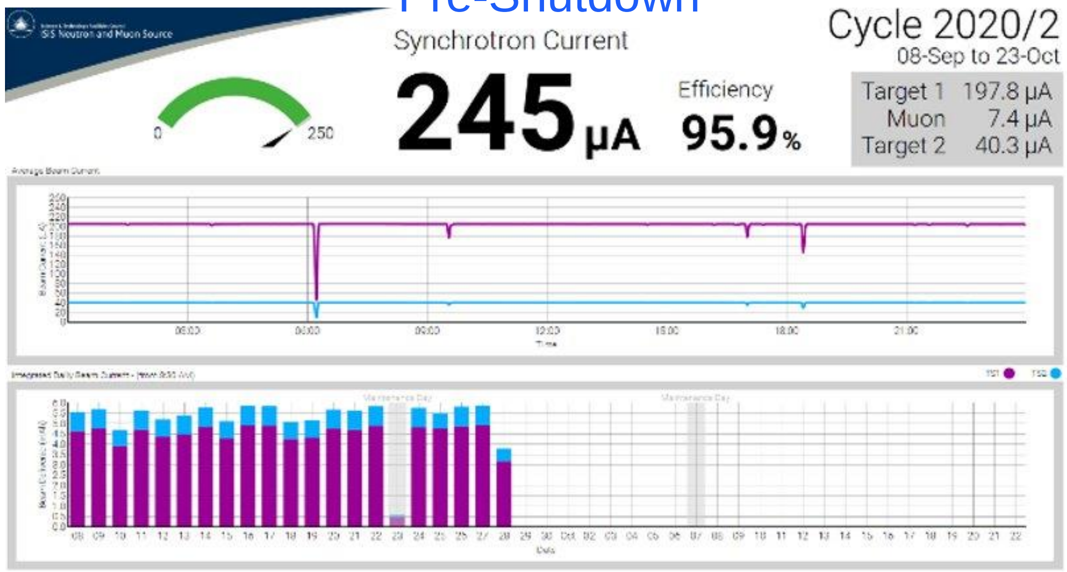
Post Long Shutdown Performance

Pre-Shutdown



Synchrotron Current

245 µA

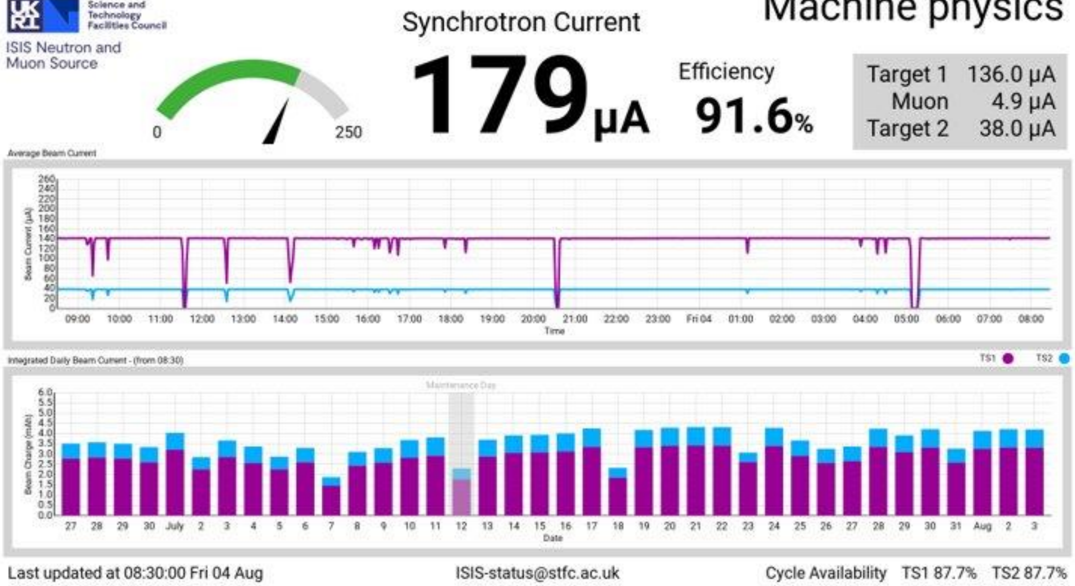
Efficiency 95.9%

Cycle 2020/2

08-Sep to 23-Oct

Target 1	197.8 µA
Muon	7.4 µA
Target 2	40.3 µA

Post-Shutdown



Synchrotron Current

179 µA

Efficiency 91.6%

Machine physics

Target 1	136.0 µA
Muon	4.9 µA
Target 2	38.0 µA

Last updated at 08:30:00 Fri 04 Aug

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Cycle Availability TS1 87.7% TS2 87.7%

- 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

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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

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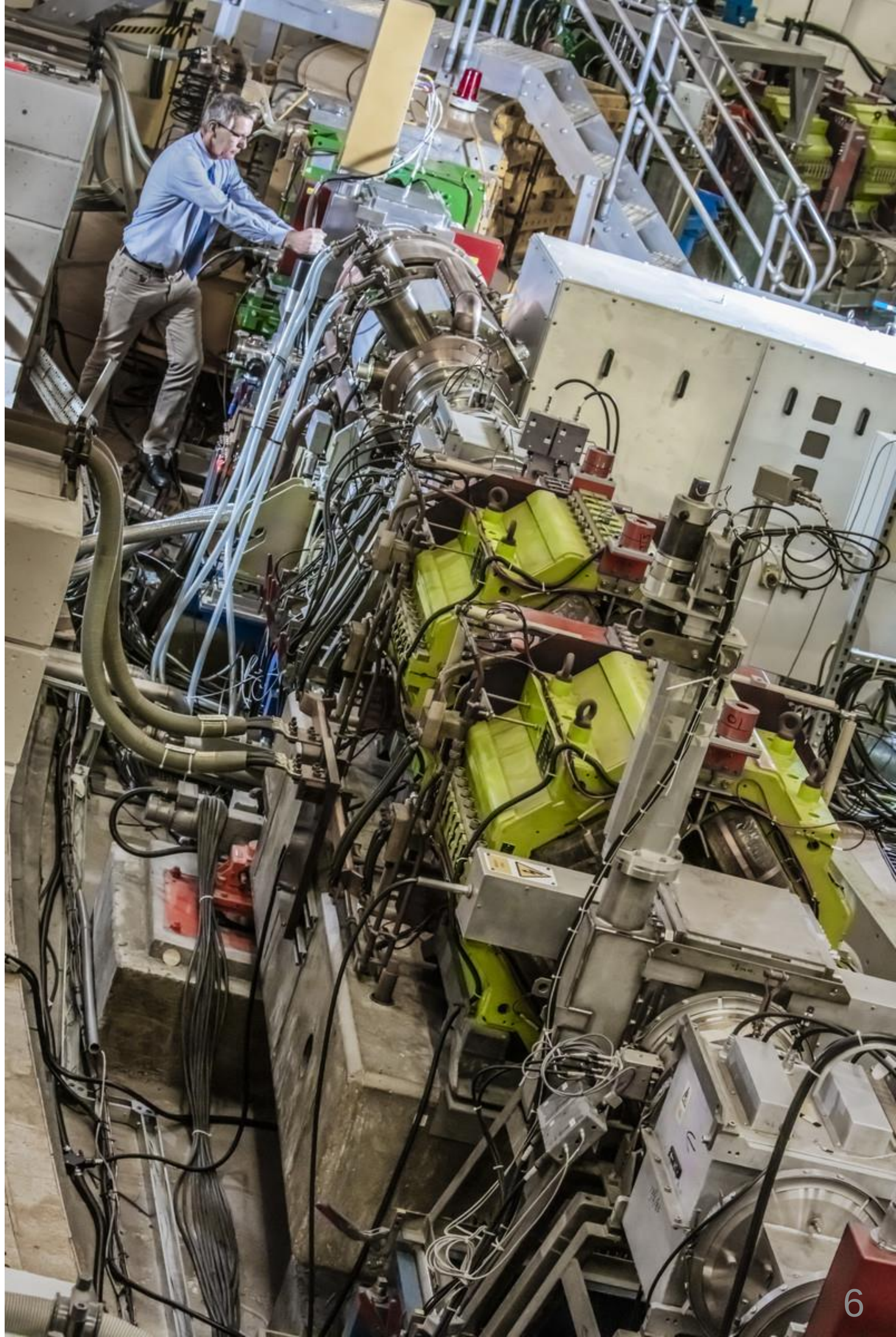

Orbit Control

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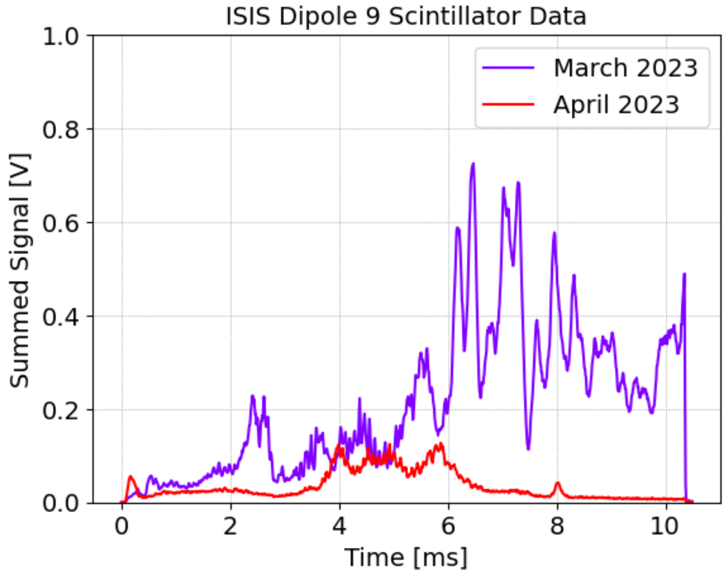
Orbit Control

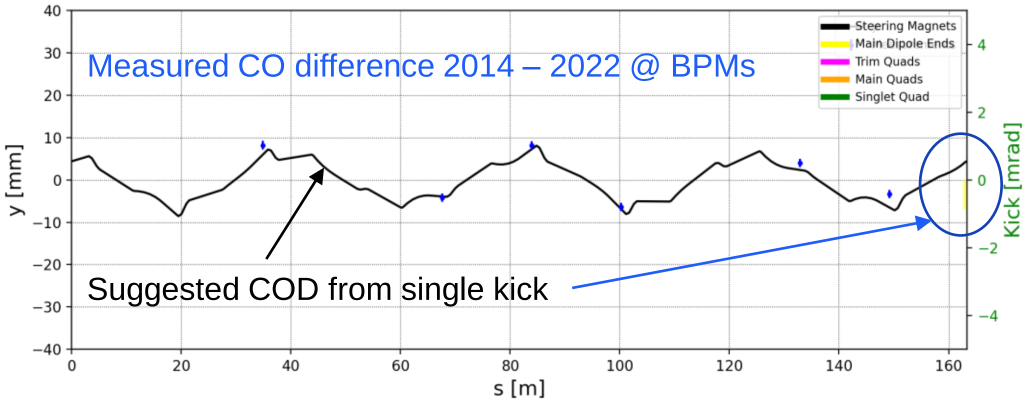
- Post – LS:
  - Larger than expected loss observed in SP8/9
  - Closed orbit distortion traced to Dipole 9 misalignment
  - Dipole 9 was swapped in LS for maintenance
  - Based on investigation Dipole 9 realigned between March / April

- 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 CO difference 2014 – 2022 @ BPMs

Suggested COD from single kick

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

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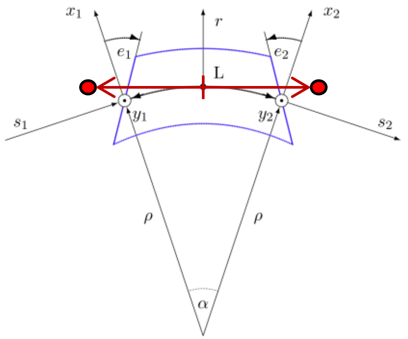
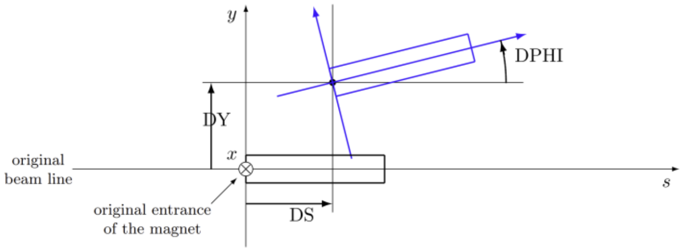
Utilising Geodetic Survey Data

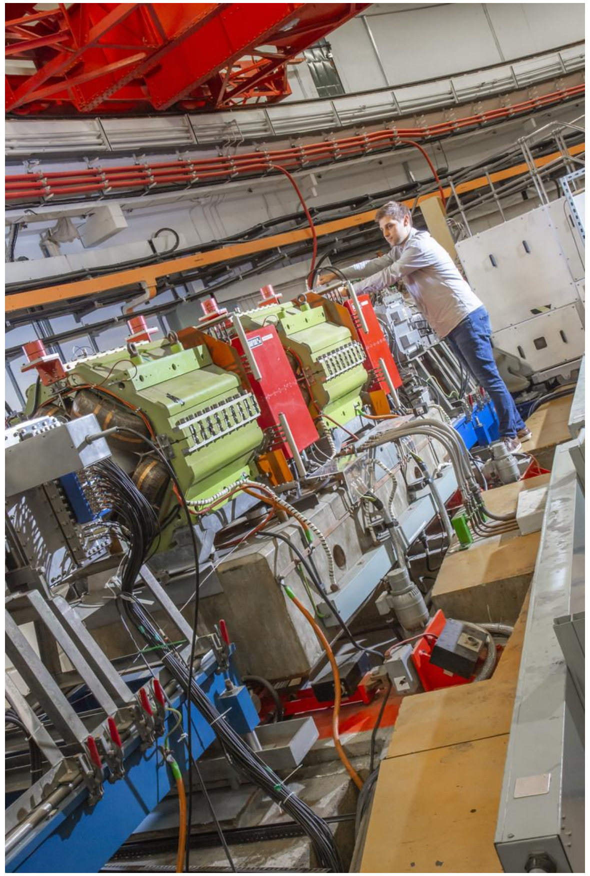
- Background:
  - Main Dipoles and Doublet Quadrupoles surveyed regularly
  - Original schematic data (40+ years old) valid but partly incomplete
- Develop tools to translate survey data to misalignment model
  - Infer bare closed orbit at time of survey
  - Suggest realignment in situ
- Implementation
  - 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!

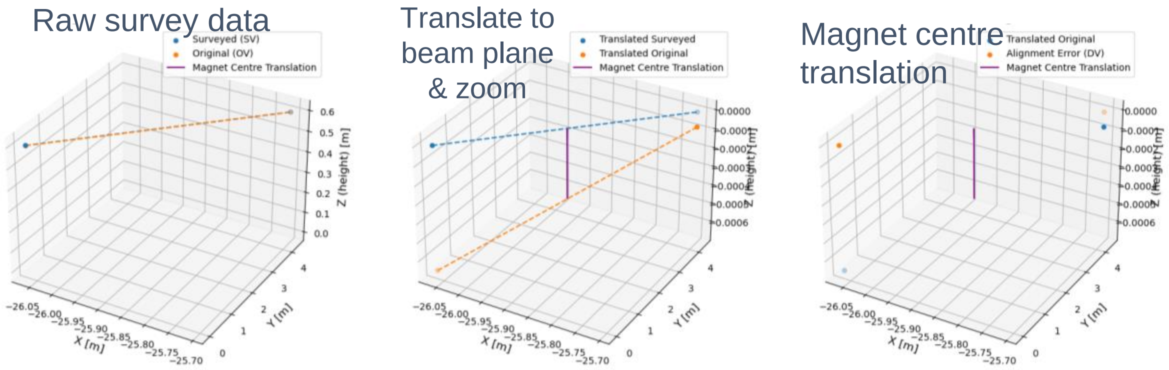


MAD-X SBEND reference system (from MAD Manual) with survey vector overlayed



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





Raw survey data

Translate to beam plane & zoom

Magnet centre translation

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

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Tune Control

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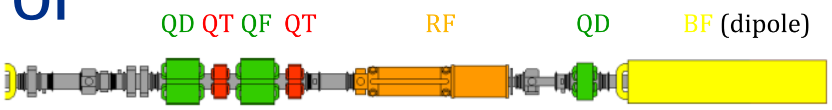
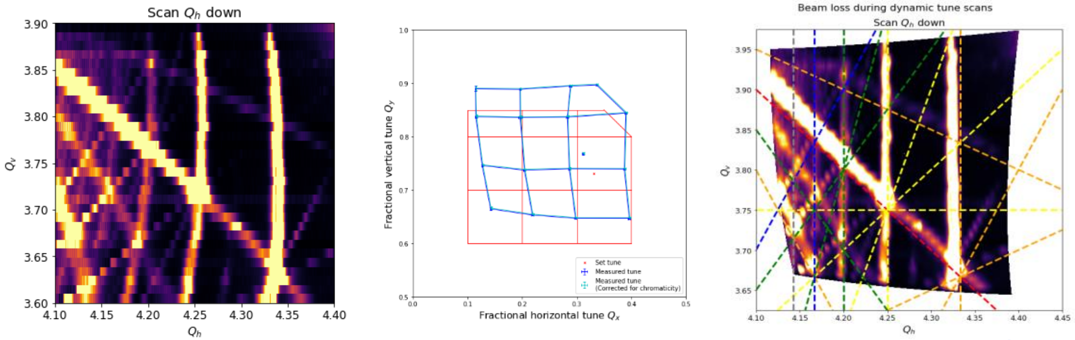
RCS Tune Control

P. T. Griffin Hicks



ISIS RCS super period layout

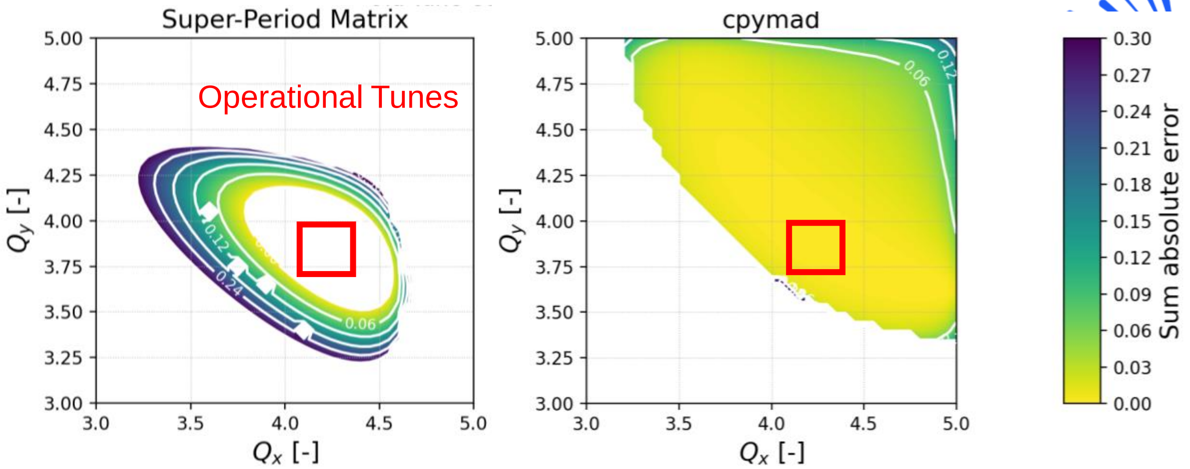
- Resonance Studies (R&D to improve models)
  - Resonances observed with dynamic tune scans
  - Limitation in tune setting observed – curvature of resonance lines
  - Q control uses 2 trim quads per super-period at QD and QF
  - Q control limited far from operational working point – first order analytical – 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



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

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

Tune control functions derived using Q change from quadrupole error



Predicted error in set tune for old and new Q control

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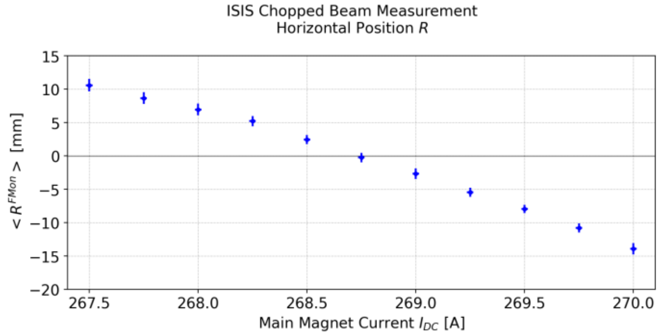
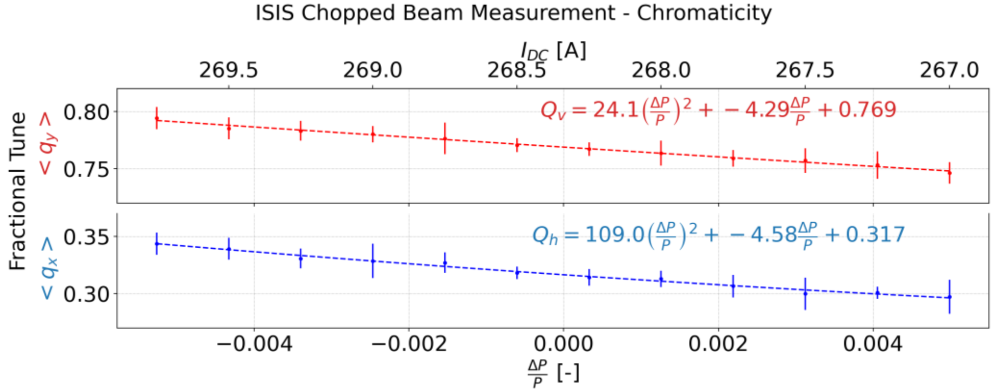
RCS Lattice Measurements

- 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

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

Chopped beam measurement fit and function





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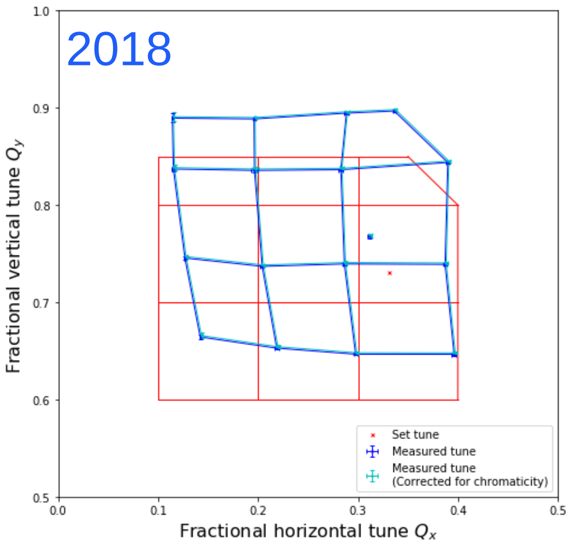
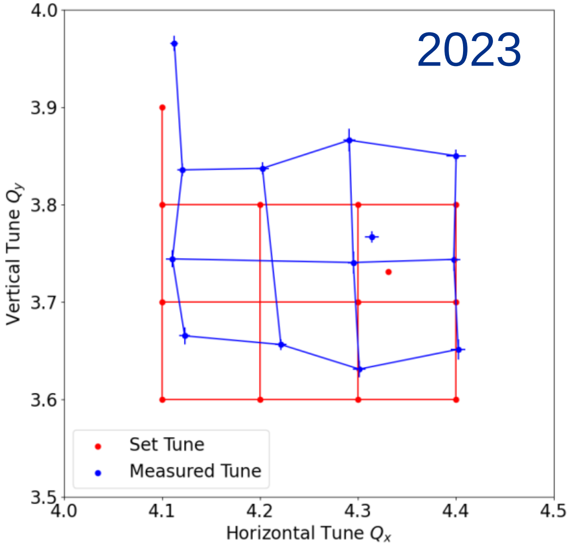
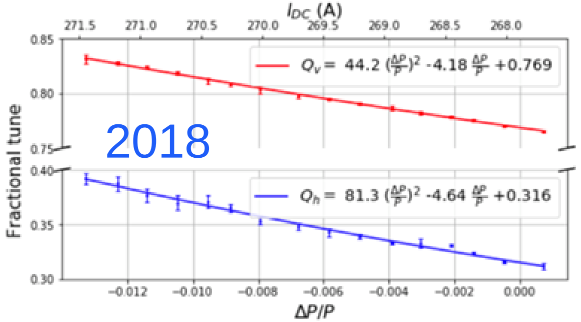
RCS Lattice Measurements

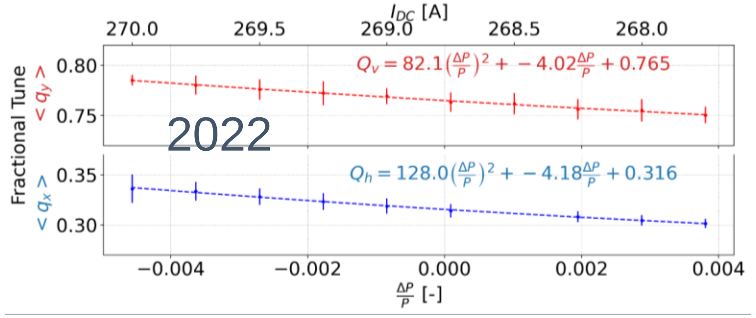
- Q Grid
  - Define grid of set tunes, measure using chopped beam to observe tune control limitations
  - Pre-LS: small errors, clear shift in Q plane
  - Post-LS: large errors, jitter in Q due to ion source dominates measurement – still investigating
  - Observe similar Q plane shift

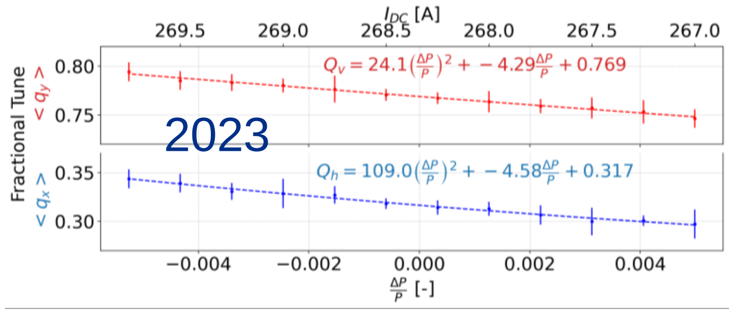




- Chromaticity
  - Pre-LS 2018:
    - $\left(q_x, q_y\right)_{bare} = (0.316, 0.769) \pm 0.004 \quad \xi_x = -1.075 \pm 0.15, \ \xi_y = -1.109 \pm 0.15$
  - Post-LS 2022:
    - $\left(q_x, q_y\right)_{bare} = (0.316, 0.765) \pm 0.004 \ \xi_x = -0.97 \pm 0.184, \ \xi_y = -1.067 \pm 0.14$
  - Post-LS 2023: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







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

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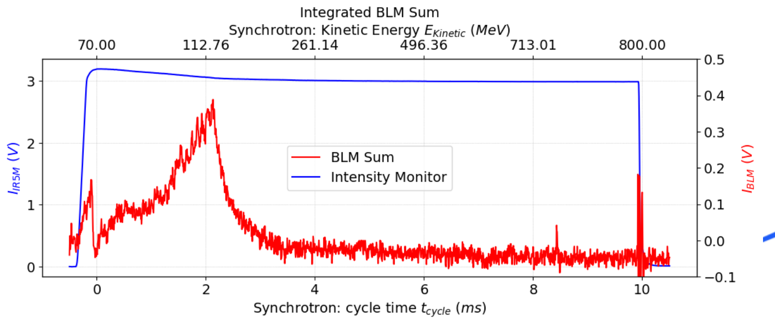
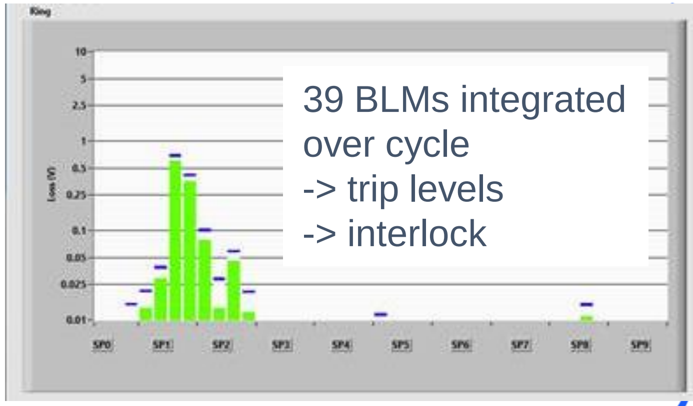
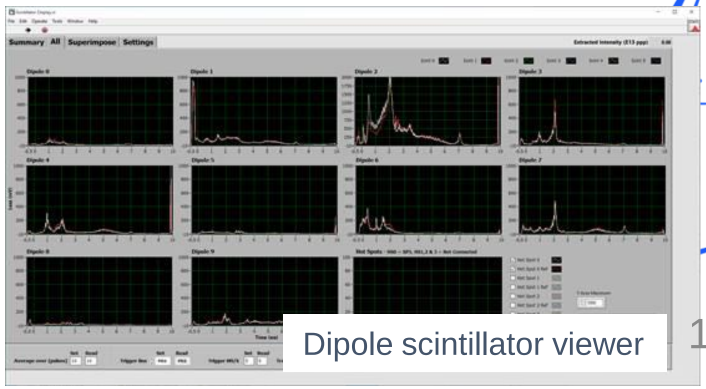
Beam Loss Monitoring

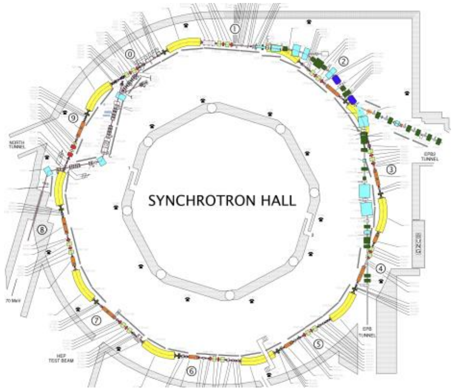
- ISIS is loss limited due to activation; loss levels define RCS operational intensity
    - 39 RCS Beam Loss Monitors (BLMs), multiple Intensity Monitors (IMs)
    - Ar ionisation chamber BLMs detect isotropically emitted evaporation neutrons
    - 10 sets of internal dipole scintillators (6 per dipole) – 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??

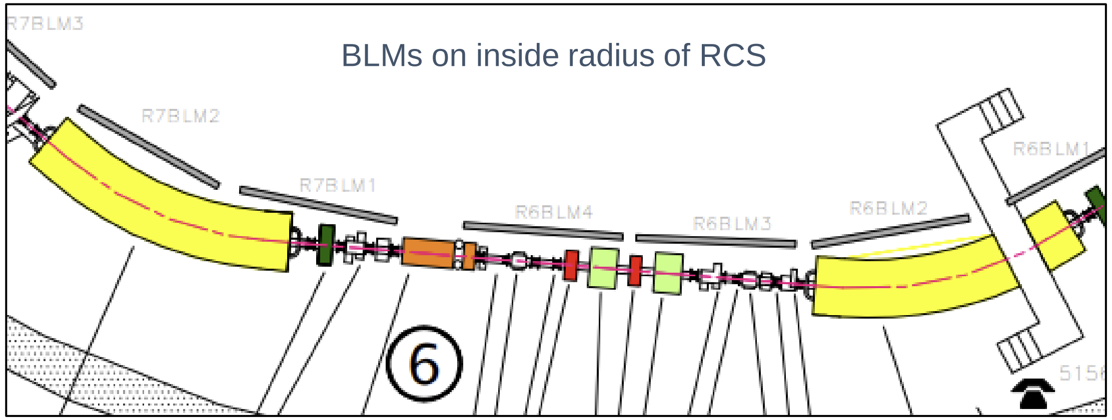



All BLMs available on Analogue Waveform System


39 BLMs integrated over cycle
-> trip levels
-> interlock


Dipole scintillator viewer




BLMs on inside radius of RCS

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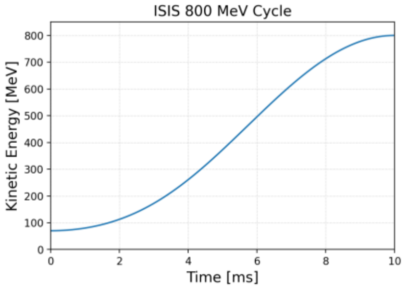
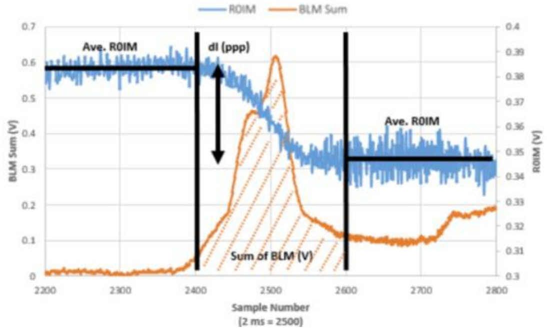
BLM Calibration

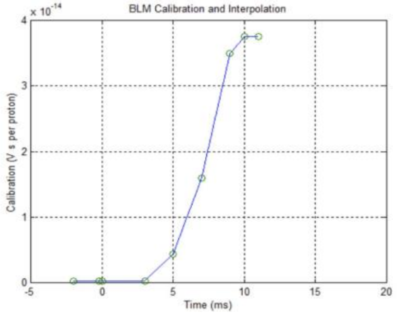
- Intensity monitor is calibrated to protons, but limited sensitivity ~ 0.1%
- Beam loss monitors highly sensitive (10^{-8}) but not well calibrated
- High energy losses at end of cycle cause more activation
- Campaigns in 1993, 2003, 2016 to ascertain energy loss calibrations for RCS BLMs



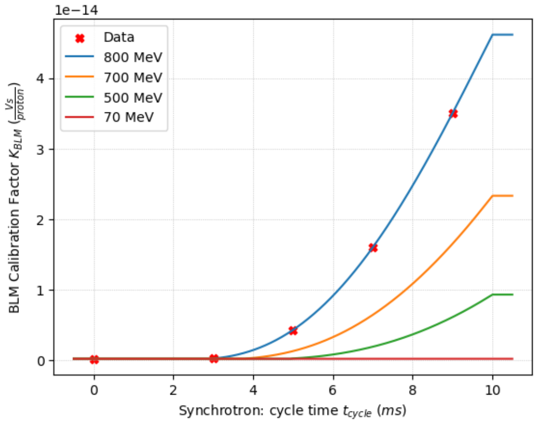
ISIS energy ramp



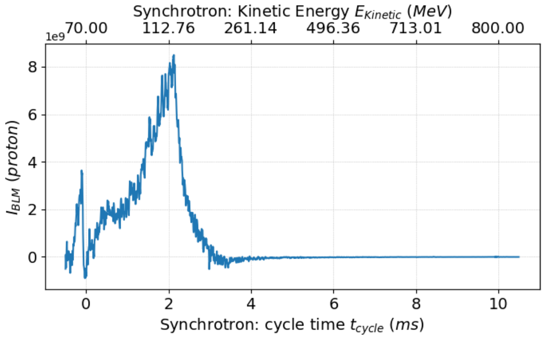
1. Drive beam loss at a selected time in the 10ms RCS cycle



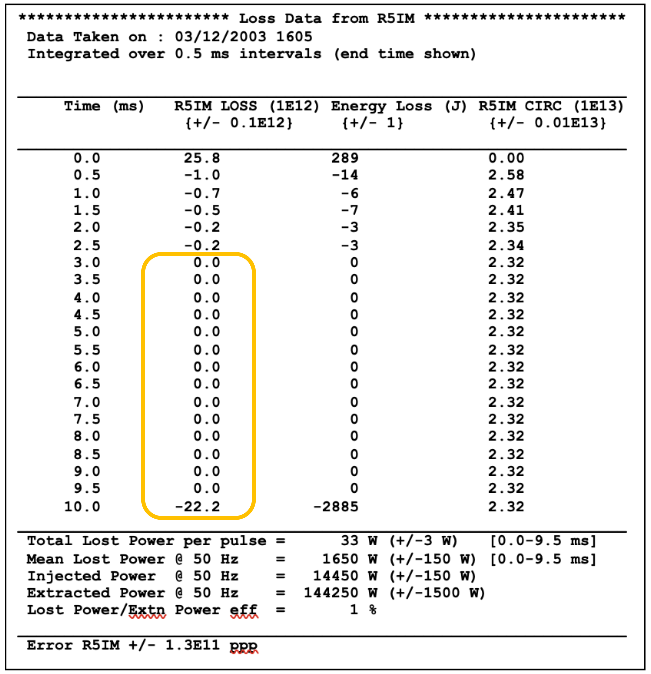
2. For each time point calculate calibration factor



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) Energy Loss (J) R5IM CIRC (1E13)
                   {+/- 0.1E12}      {+/- 1}         {+/- 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/Extn Power eff  =       1 %

 Error R5IM +/- 1.3E11 ppp
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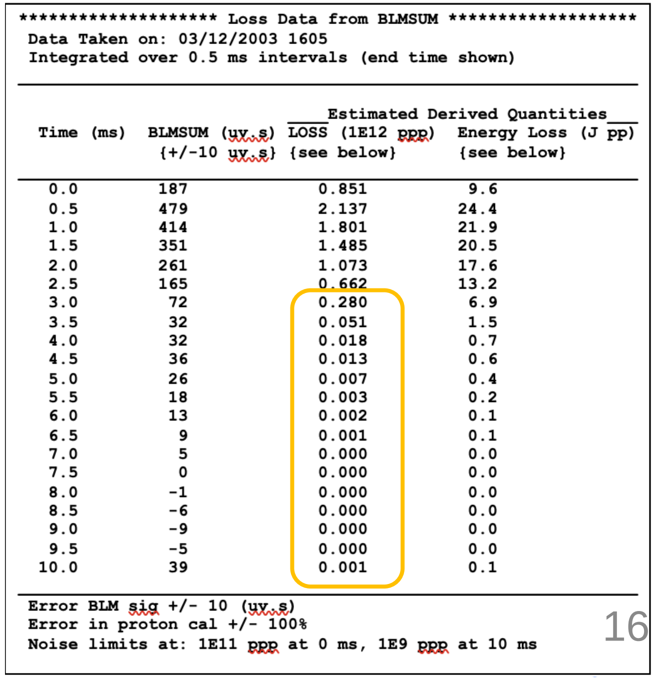

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******************** Loss Data from BLMSUM ********************
 Data Taken on: 03/12/2003 1605
 Integrated over 0.5 ms intervals (end time shown)

                                   ____Estimated Derived Quantities___
  Time (ms)   BLMSUM (uv.s) LOSS (1E12 ppp)  Energy Loss (J pp)
               {+/-10 uv.s} {see below}       {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
```

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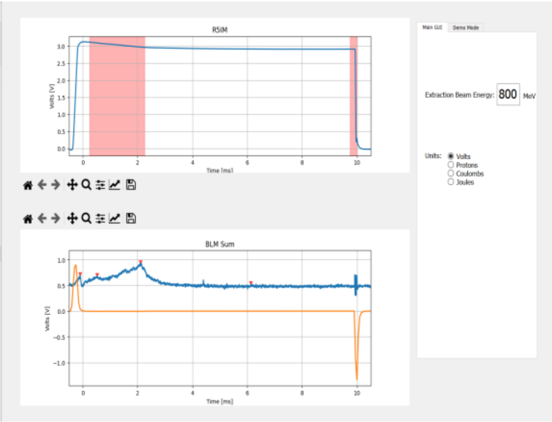
BLM Data Opportunities

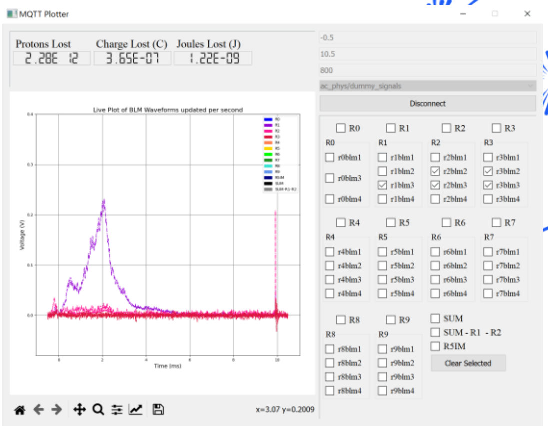
Can now use lost energy vs time / space at higher sensitivity – application?

- 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!



Extraction Beam Energy: 800 MeV

Units: ● Volts ○ Protons ○ Coulombs ○ Joules

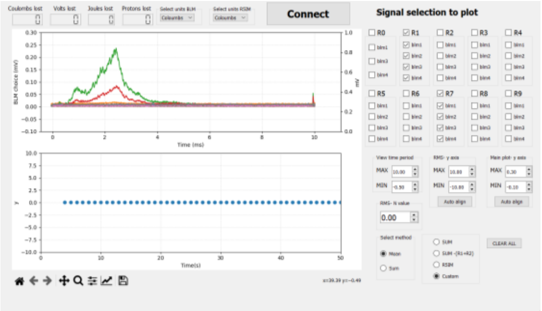


Protons Lost 2.28E 12

Charge Lost (C) 3.65E-07

Joules Lost (J) 1.22E-09

ac_phys/dummy_signals



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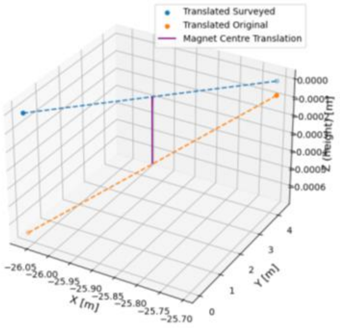
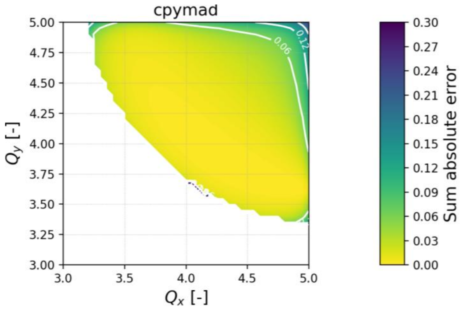
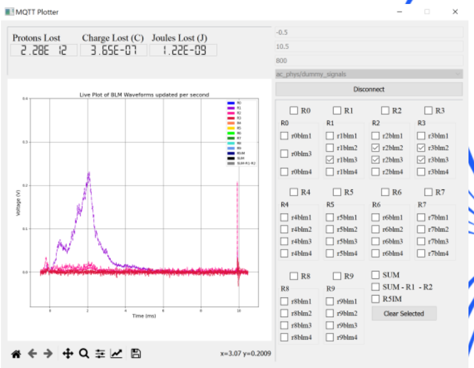
Summary



- 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





Protons Lost 2.28E 12
Charge Lost (C) 3.65E-07
Joules Lost (J) 1.22E-09

-0.5
10.5
800
ac_phys/dummy_signals

☐ R0 ☐ R1 ☐ R2 ☐ R3
R0: ☐ r0blm1 ☐ r0blm3 ☐ r0blm4
R1: ☐ r1blm1 ☐ r1blm2 ☑ r1blm3 ☐ r1blm4
R2: ☐ r2blm1 ☑ r2blm2 ☑ r2blm3 ☐ r2blm4
R3: ☐ r3blm1 ☑ r3blm2 ☑ r3blm3 ☐ r3blm4
☐ R4 ☐ R5 ☐ R6 ☐ R7
R4: ☐ r4blm1 ☐ r4blm2 ☐ r4blm3 ☐ r4blm4
R5: ☐ r5blm1 ☐ r5blm2 ☐ r5blm3 ☐ r5blm4
R6: ☐ r6blm1 ☐ r6blm2 ☐ r6blm3 ☐ r6blm4
R7: ☐ r7blm1 ☐ r7blm2 ☐ r7blm3 ☐ r7blm4
☐ R8 ☐ R9
R8: ☐ r8blm1 ☐ r8blm2 ☐ r8blm3 ☐ r8blm4
R9: ☐ r9blm1 ☐ r9blm2 ☐ r9blm3 ☐ r9blm4
☐ SUM
☐ SUM - R1 - R2
☐ R5IM

x=3.07 y=0.2009

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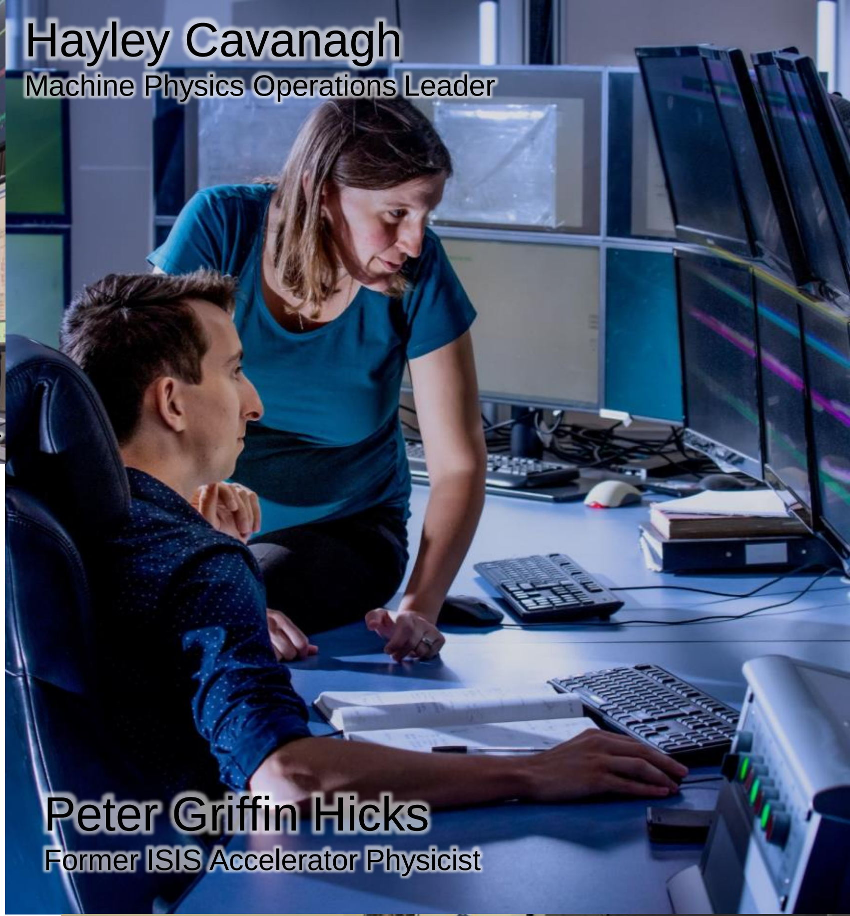
Acknowledgements

The authors are grateful to the ISIS;

- Accelerator Physics group for **fruitful input & experience**
- Diagnostics group,
- Sarah Fisher and the Diagnostics Software section,
- 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!



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

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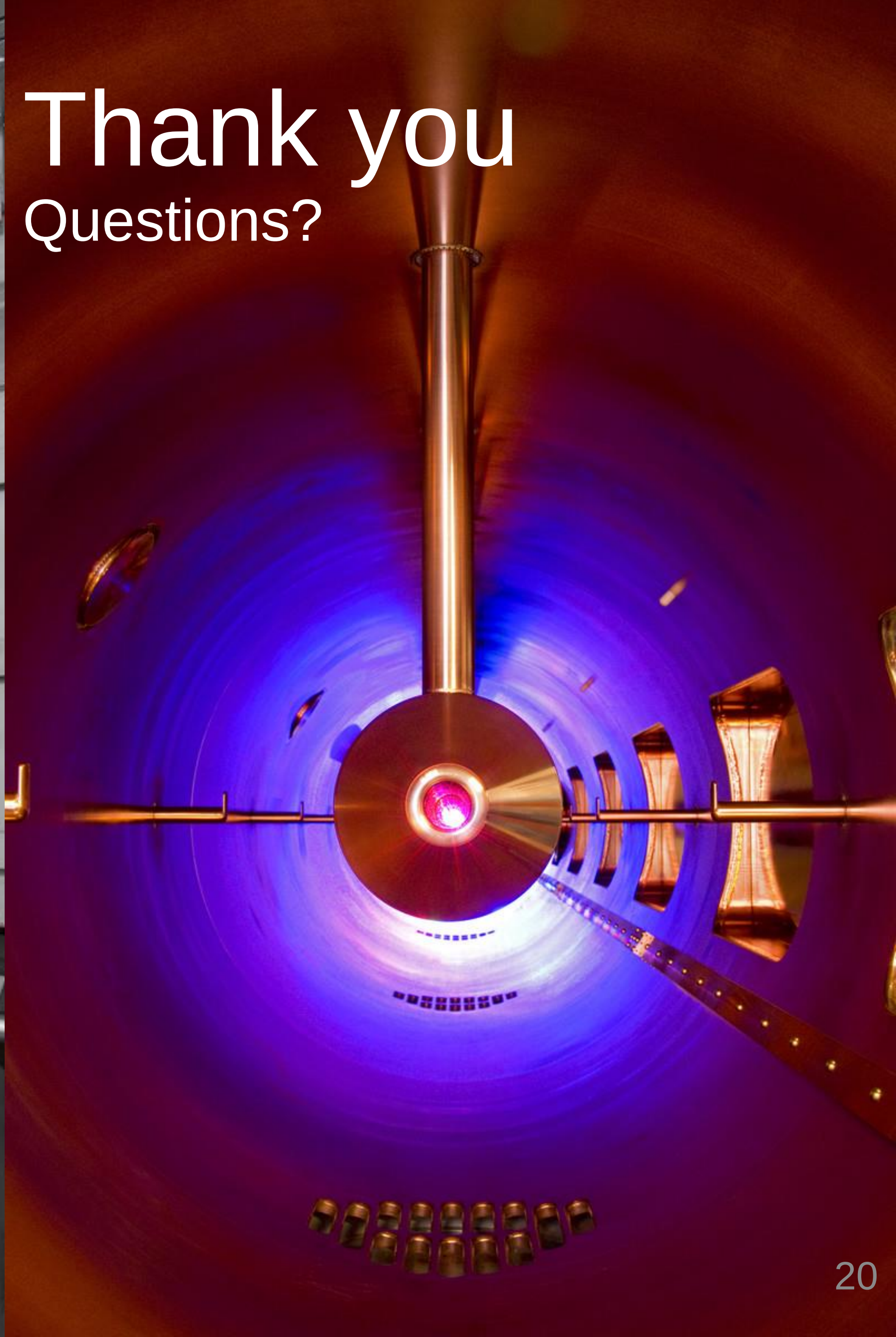


Thank you

Questions?

Backup Slides

ISIS Operation

Multiple user cycles of 5-8 weeks per year

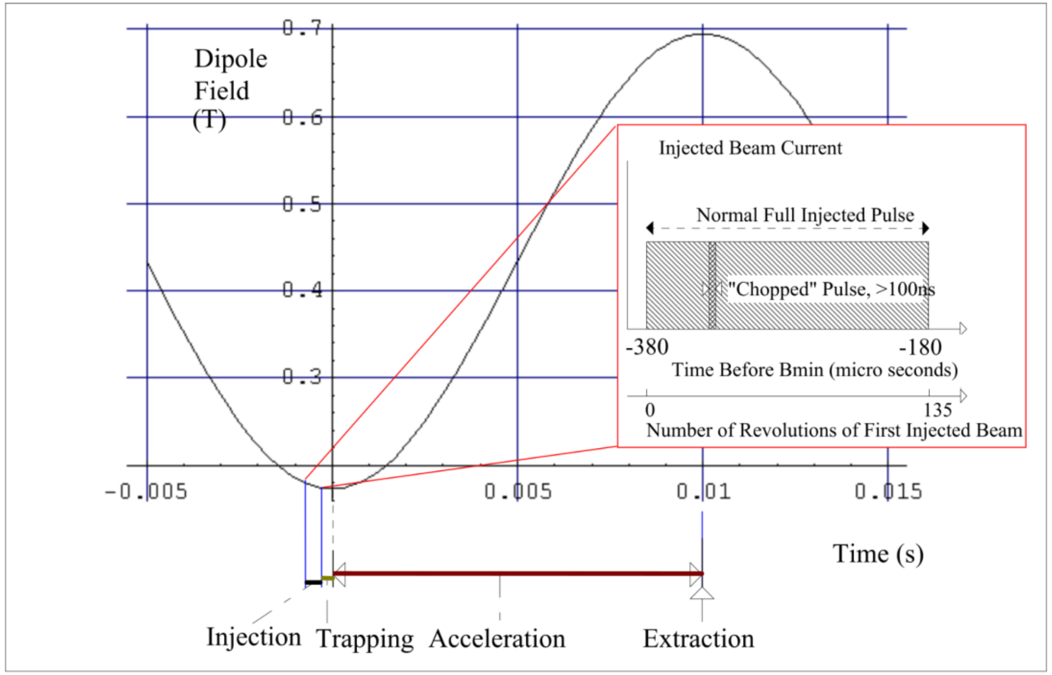
1-2 weeks startup each cycle

Tuning of loss performed using integrated BLM signal histograms and Analogue Waveforms (still remain most reliable at 50Hz)

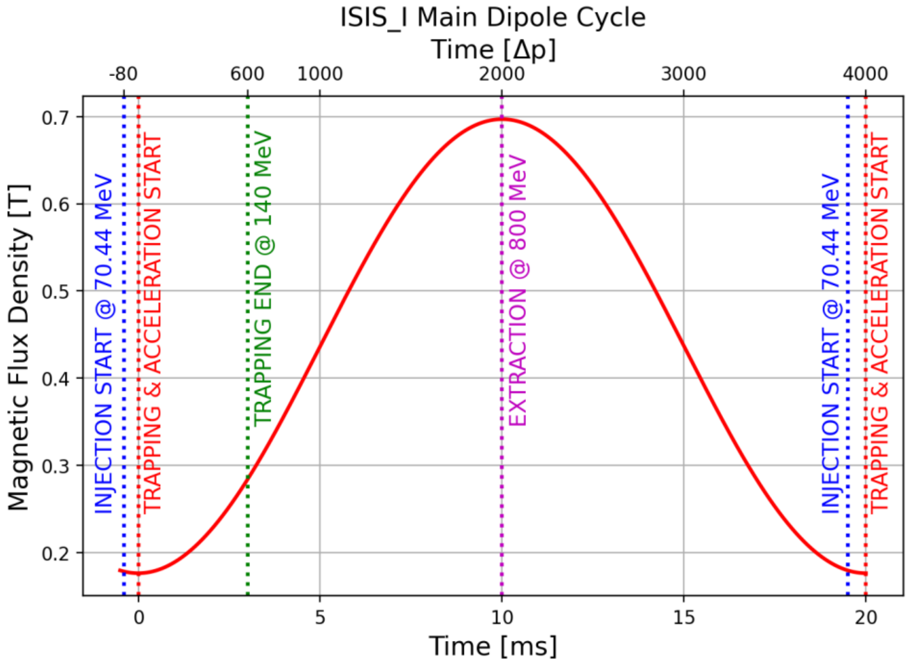
Each cycle offers new opportunities for reducing synchrotron loss ☺

ISIS Machine Cycle (50 Hz)

Figure 2.1(b)
Relation of Beam Chopping to Main Magnet Field.



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



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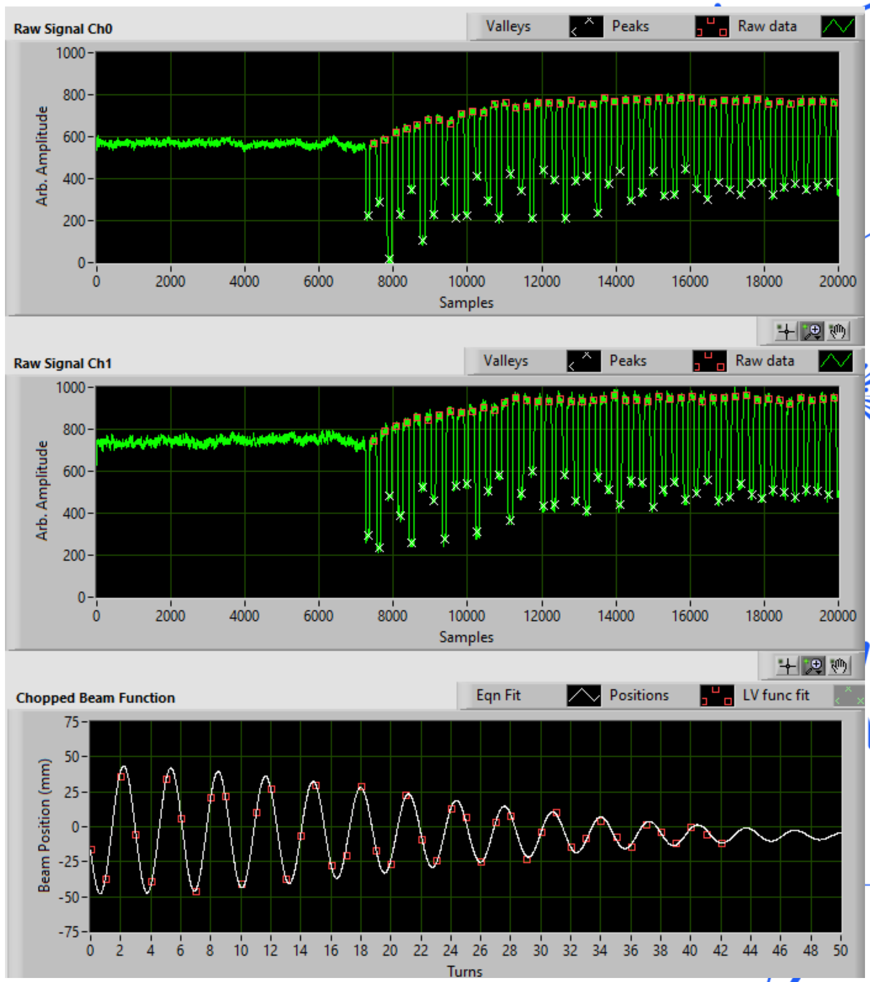
Chopped Beam Measurement

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

where:

- Y is the chopped beam transverse position in either the horizontal or vertical plane, all further quantities in the same plane
- n is the turn
- η is the position of the closed orbit about which the particle is undergoing betatron oscillations (referred to as equilibrium in [1])
- $\delta\eta$ is the change in closed orbit due to the falling magnetic field
- A is the amplitude of betatron oscillations
- ν is the betatron tune in the plane of interest
- $\delta\nu$ is the tune shift from the falling magnetic field's effect on orbit
- $\Delta\nu$ is the tune spread of a Gaussian bunch
- ϕ is the phase of betatron oscillations



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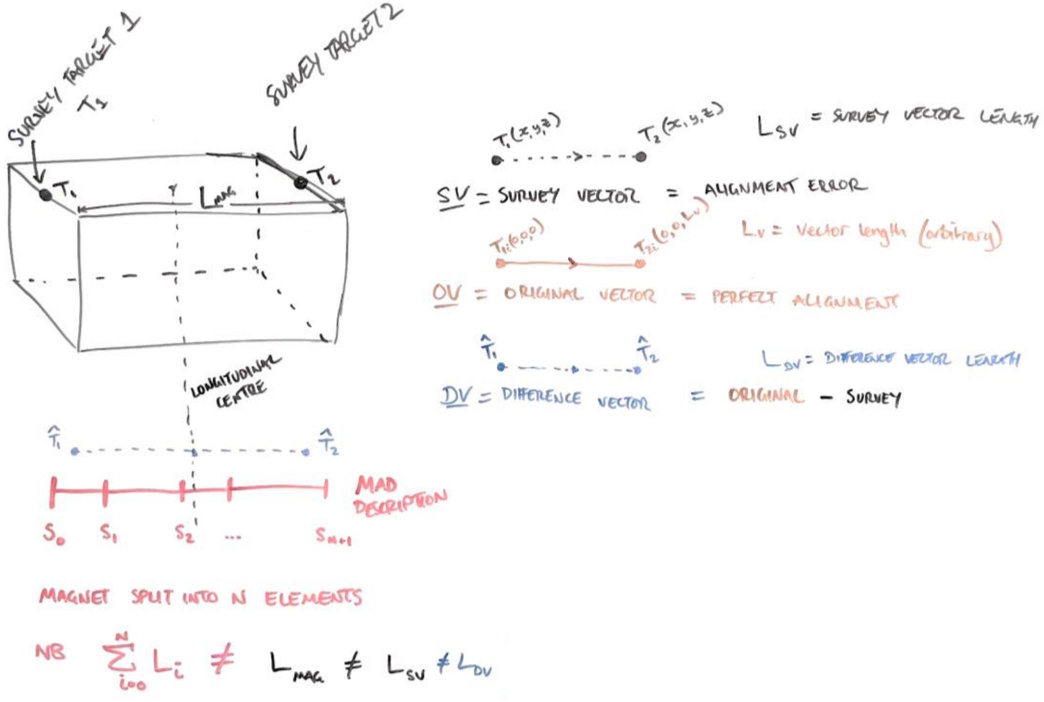
Geodetic Modelling: Survey Data

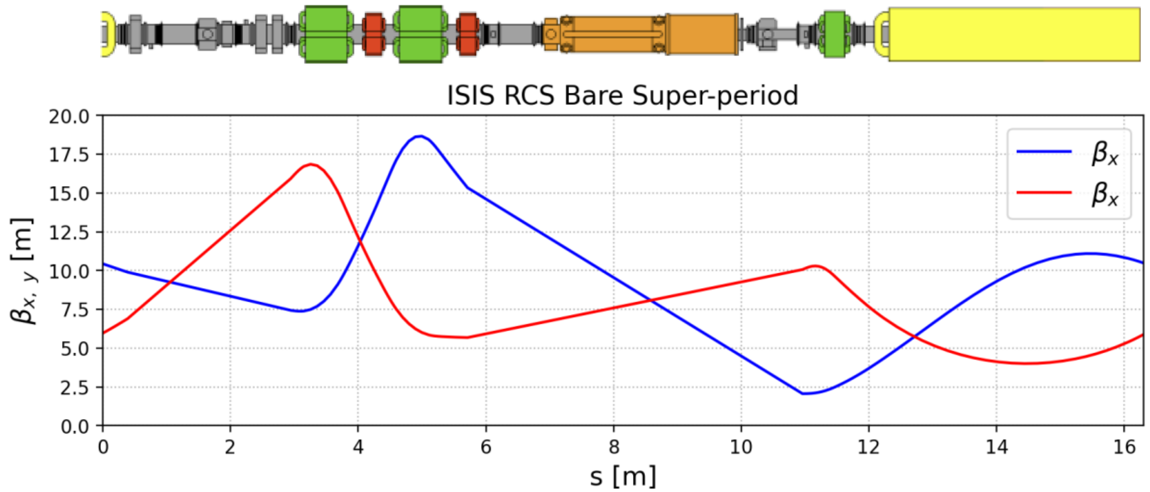
- Historical geodetic data available:
  - 2 survey sockets per main magnet, one on each end
  - Survey performed from survey pillars – some movement over ~40 years of operation
  - Position of sockets on main quads not defined – measurement requested
  - Focus on dipole effects first
- Approach
  - Dipole socket positions assumed via symmetry (assume to be centred around magnet centre)
  - Some magic performed by survey team to fit data to their models – assume provided data is representative of relative changes in position
  - Use original schematic data to define positions of geodetic markers with respect to magnet
  - To start: assume design position equates to perfect alignment, model difference from design to latest survey as misalignment
  - Define difference vector from design to survey positions = geodetic error vector

Geodetic Modelling: cpymad Model

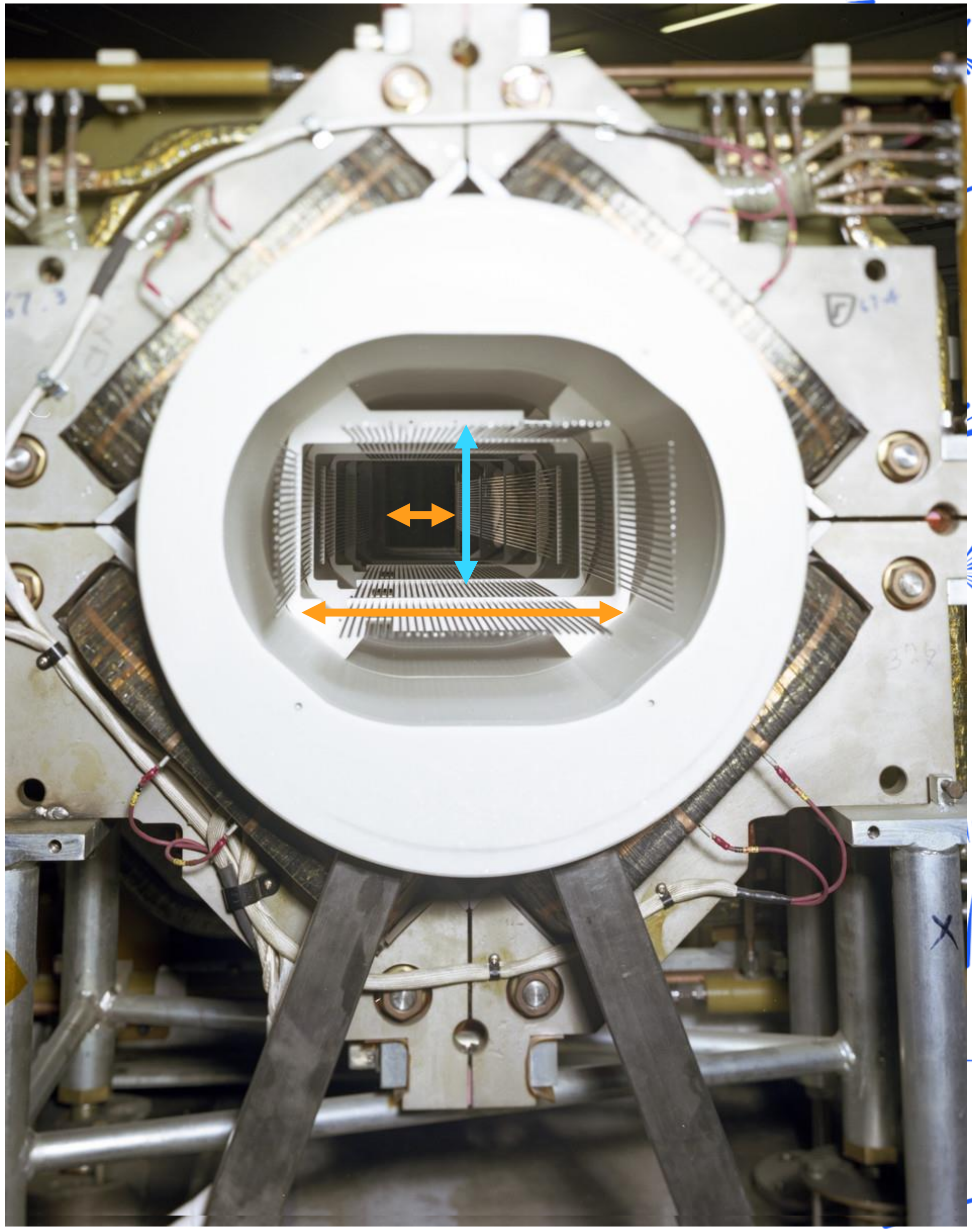


- ISIS Lattice Model
  - Main dipole modelled as 6 segments and 10 fringe segments
  - Main quadrupoles modelled as 1 segment and 8 fringe segments
- Approach
  - Translate geodetic error vector from real space to segmented EALIGN MAD variables (Δs, Δx, Δy, ΔΨ, ΔΦ, ΔΘ) in MAD s co-ordinate space
  - Define the ‘corrected’ errors at each magnet subsection entrance as the scaled magnet error
  - Apply scaled magnet error to modelled magnet (all magnet subsections) using MAD Error table
  - Predict closed orbit -> suggest realignment if necessary
  - Use benchmarked correctors to predict settings for minimised COD before beaming

ISIS Apertures



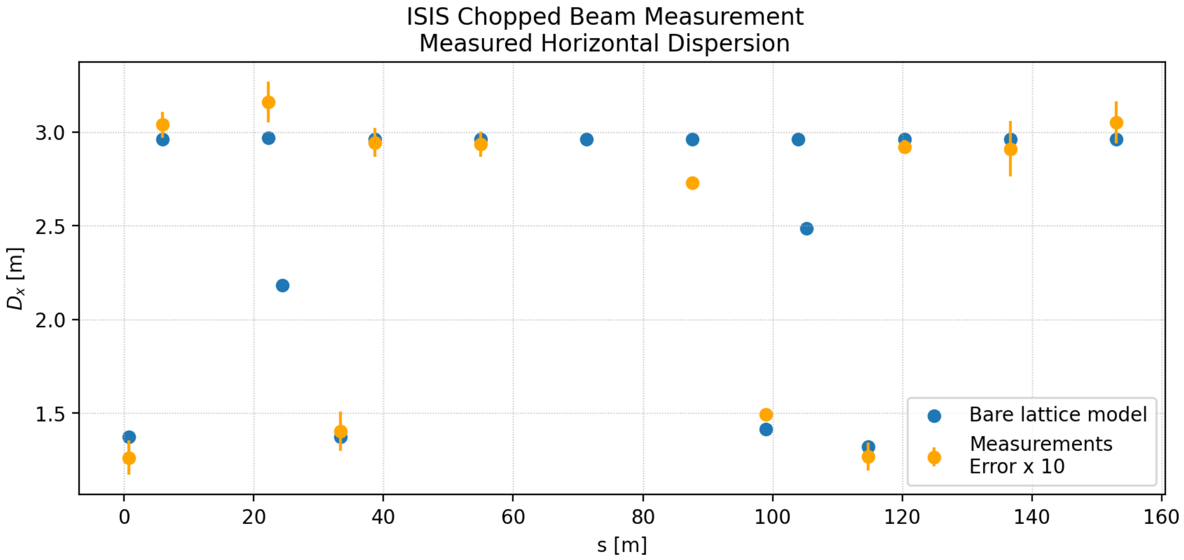
- ISIS has tapered ceramic apertures that follow design envelopes
  - Regularly employ harmonic tune variations to reduce loss
  - Accurate modelling of envelope (tune, betas, orbit etc) required to ascertain mismatch between envelope and aperture
  - Improved tune control effects collimation, space charge, and head-tail which are major loss factors



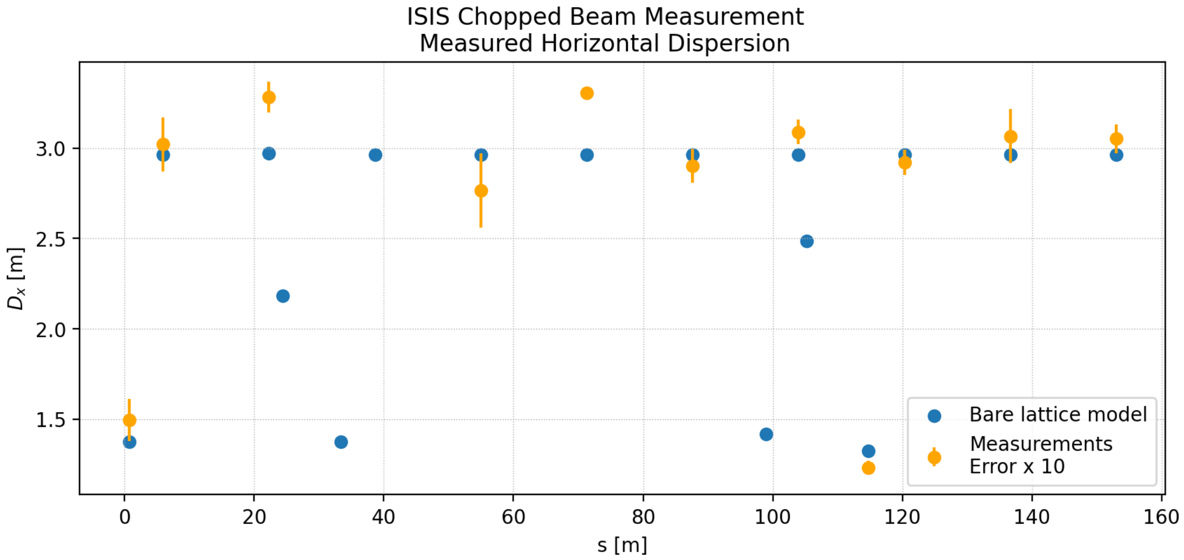
View from ISIS SP quadrupole doublet aperture end (s ~ 6 m)

Measured Dispersion

2022



2023



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