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Beam Loss Mitigation for High Intensity Operation at ISIS

Rob Williamson
Synchrotron Group

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- Head-Tail Instability
  - Mitigation
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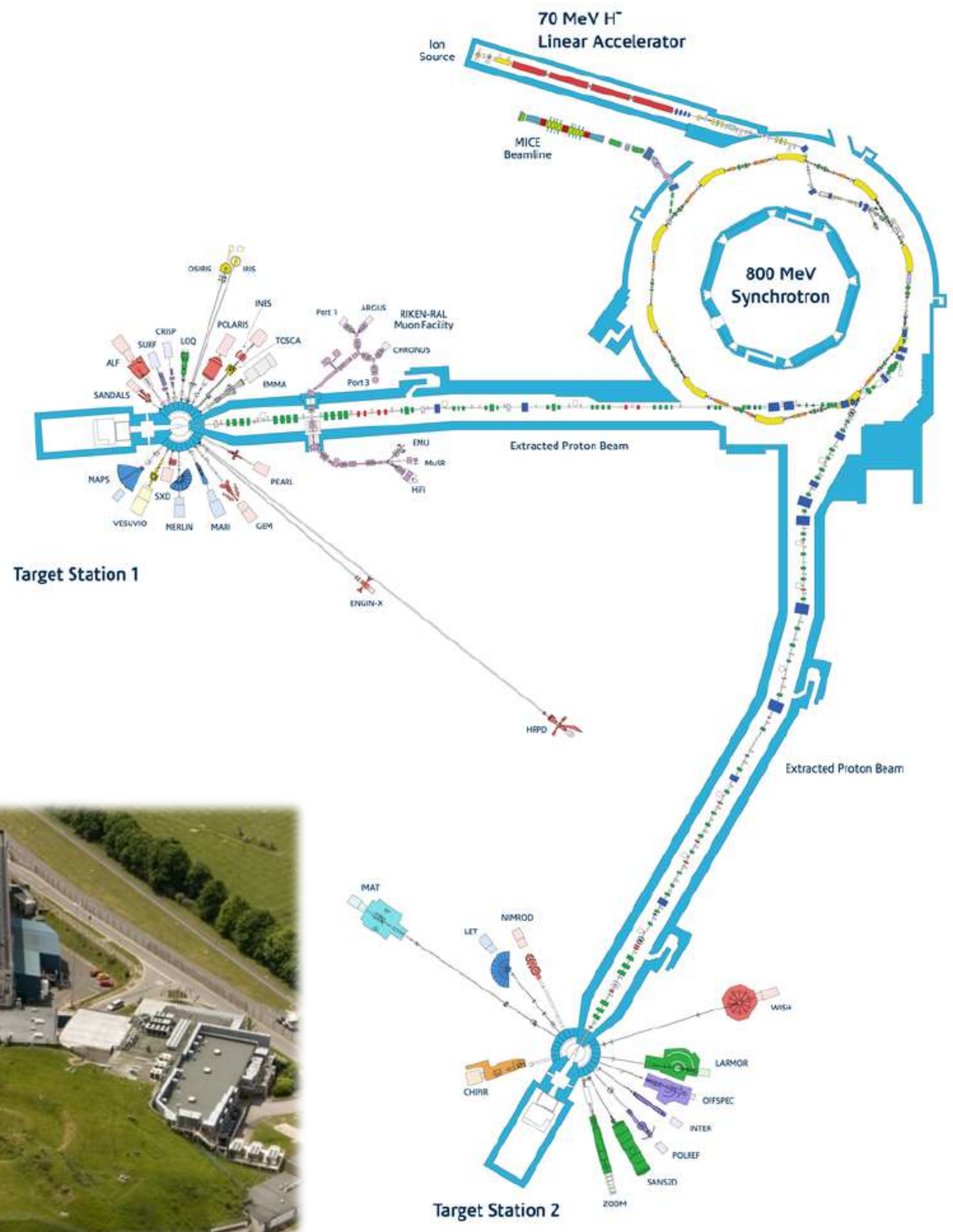
ISIS Overview

- 70 MeV H- DTL
- Charge-exchange injection
- 50 Hz, sinusoidal main magnet
- 800 MeV RCS, 10 super periods
- $3x10^{13}$ protons, 0.2 MW
- RF: 6 h=2 cavities, 4 h=4 cavities



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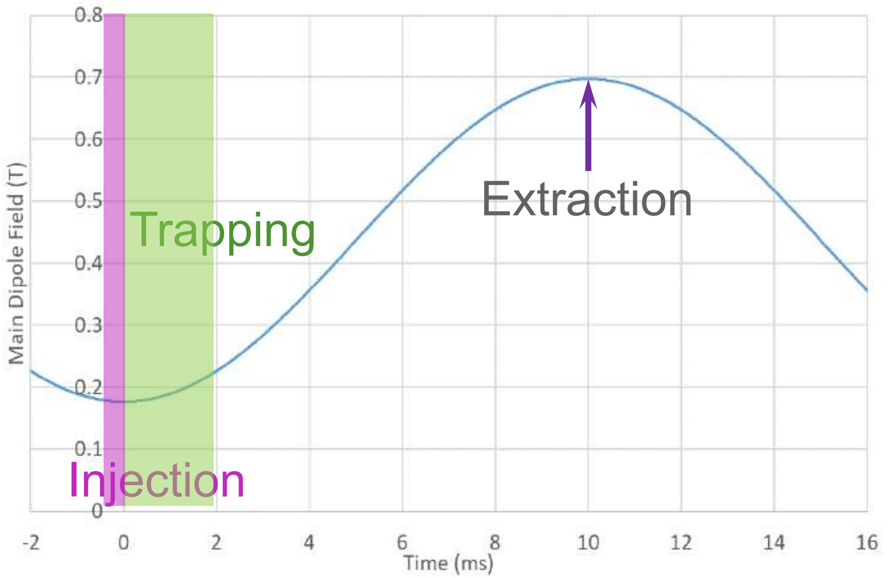
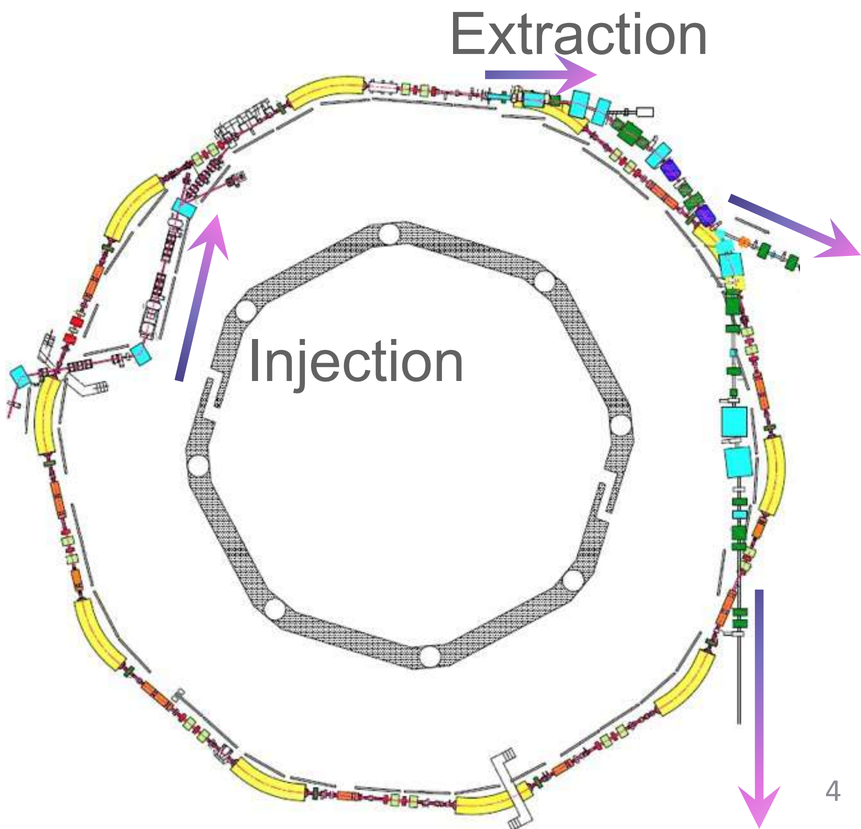
ISIS Synchrotron

Circumference	163 m
Energy Range	70 – 800 MeV
Repetition Rate	50 Hz
Intensity	~3x10^{13} ppp
Beam Power	~200 kW
RF System (2 bunches)	h=2, 1.3 – 3.1 MHz, V_{pk} ~160 kV/turn h=4, 2.6 – 6.2 MHz, V_{pk} ~80 kV/turn
Tunes	Q_x, Q_y = 4.31, 3.83 (programmable)
Extraction	Single turn, vertical
Losses	Inj: 2%, Trap: <3%, Acc/Ext < 0.5%





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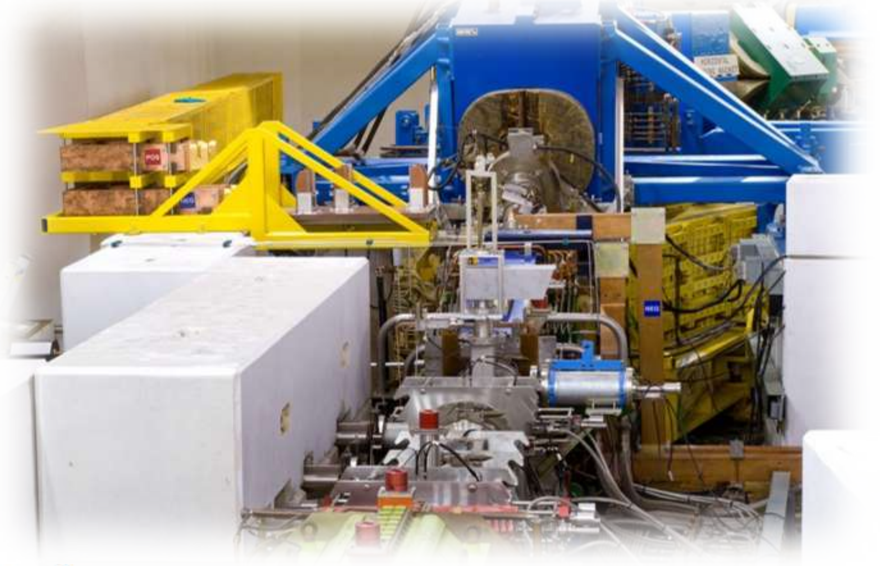
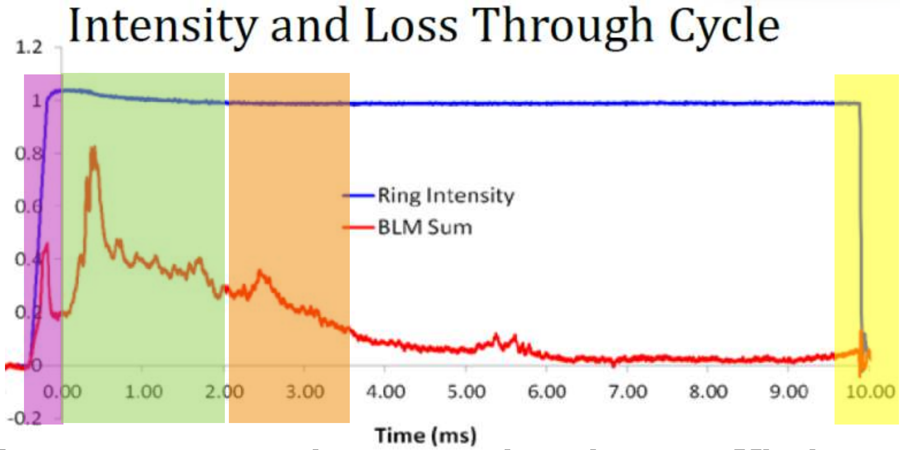
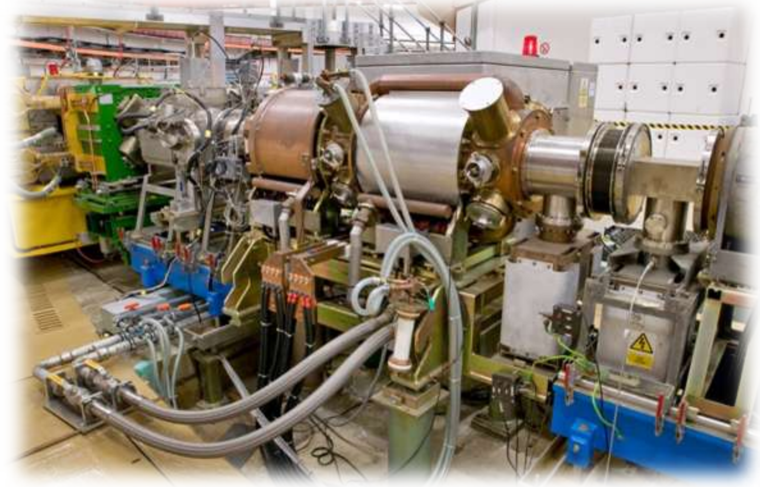
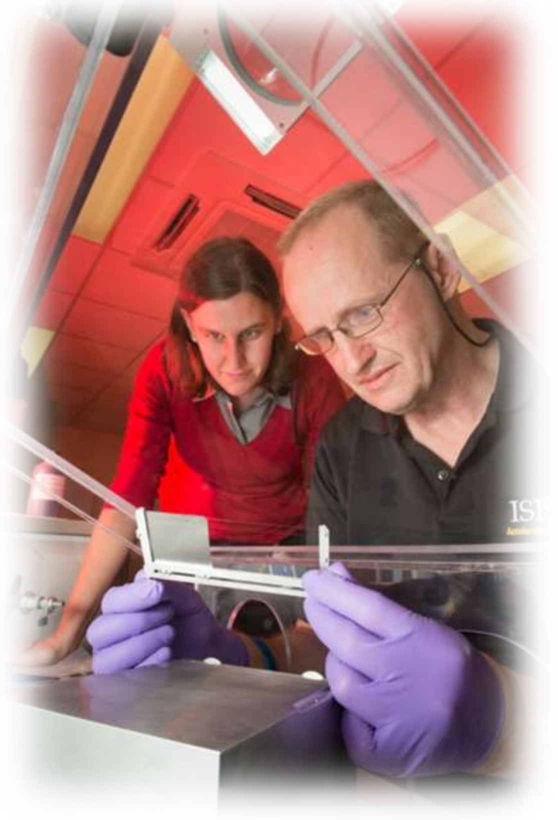
Beam Loss Control

- ISIS is loss-limited
- Beam loss → component damage, activation
- High intensity, space charge and repetition rate
- Collimation
- Minimize uncontrolled loss









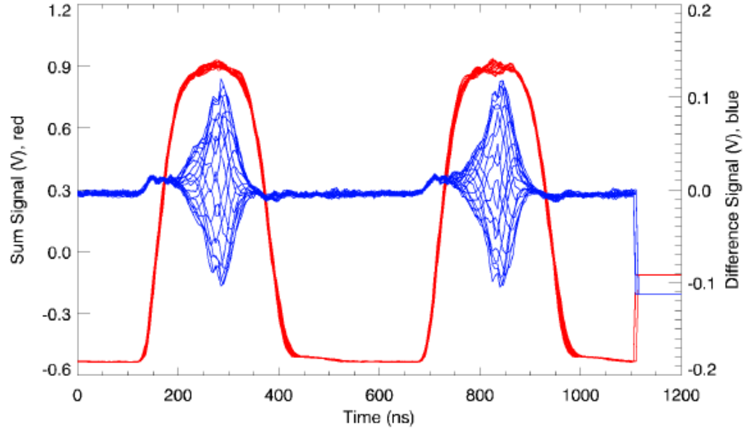
- Injection: scattering, stripping efficiency
- Trapping: un-chopped, non-adiabatic, transverse space charge
- Head-tail instability
- Extraction

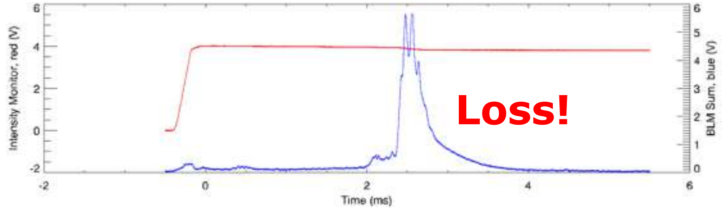
Head-Tail Instability

- High Intensity
  - Space charge $\Delta Q \sim 0.5$
- Dual harmonic operation
  - Symmetric bunches unstable
  - No longer able to cure with tune ramp
- Driven by impedances
  - Low frequency narrowband
  - Resistive wall (?)

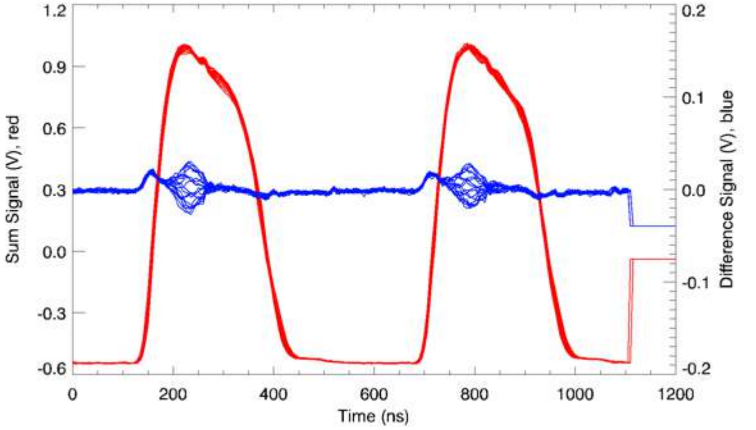
ISIS Beam Bunches at ~ 2 ms

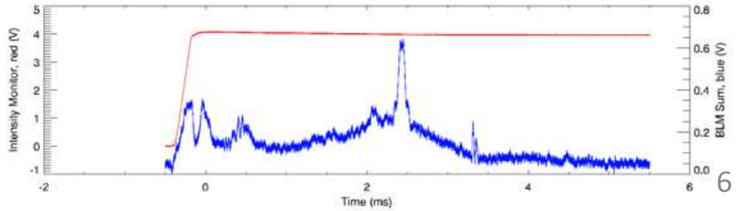
Normal beam + flat bunch
Large loss!





Normal beam + asymmetric bunch
Low loss





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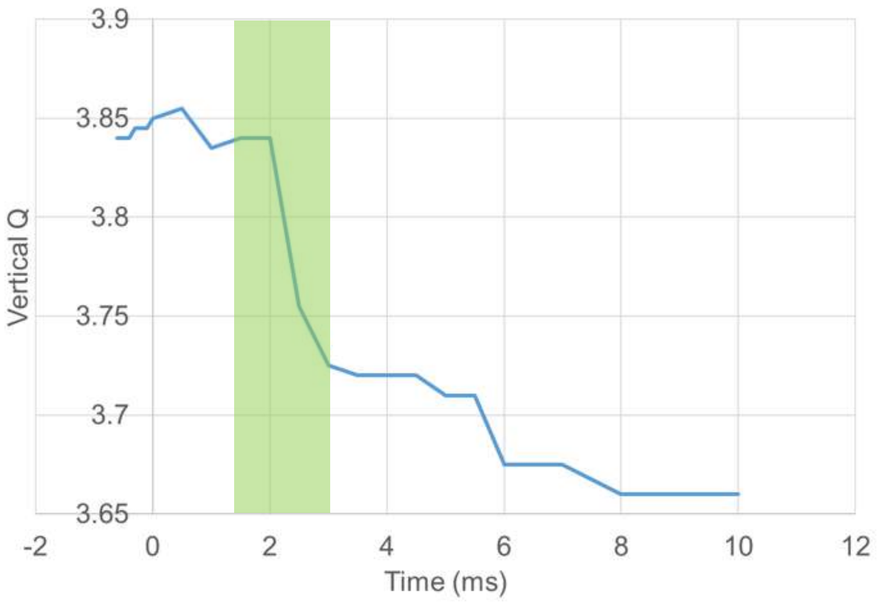
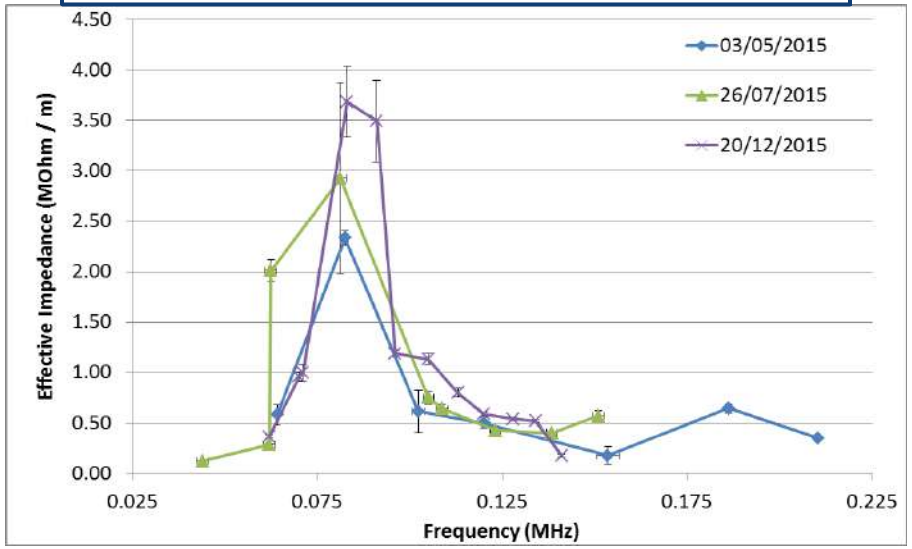
Head-Tail Mitigation



- Fast ramp in vertical tune during instability
- Longitudinal bunch asymmetry
- Injection painting: vertical and longitudinal

- Develop Impedance model
    - Beam based measurements
    - Bench measurements
    - Simulations

Effective Impedance Vs Frequency



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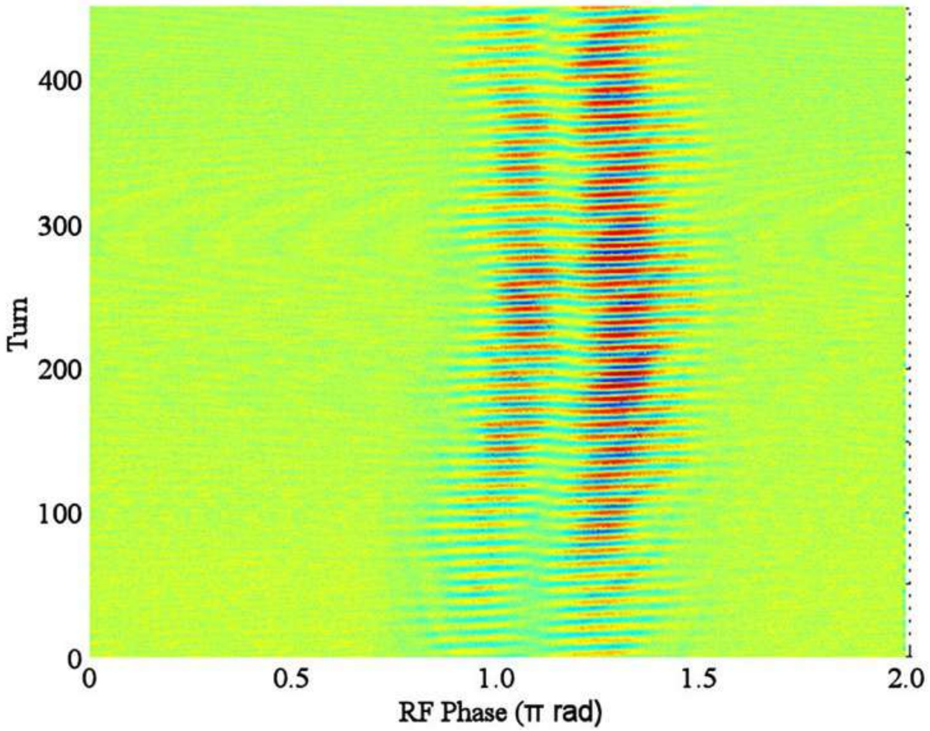
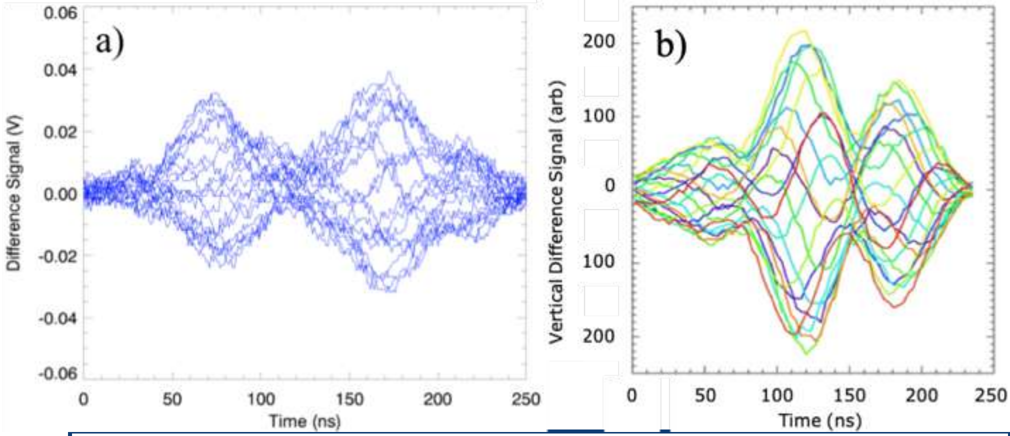
Head-Tail R&D

- Experiments
  - Simplify to single harmonic RF operation
  - Lower intensity => minimal space charge
- Theory and simulations with resistive wall predict mode number m=2 (two nodes)
- Observations show m=1 (one node)
- Less than the full bunch appears to be oscillating





Measurement Vs HEADTAIL* Simulation: Difference Signal

** Modified CERN code*

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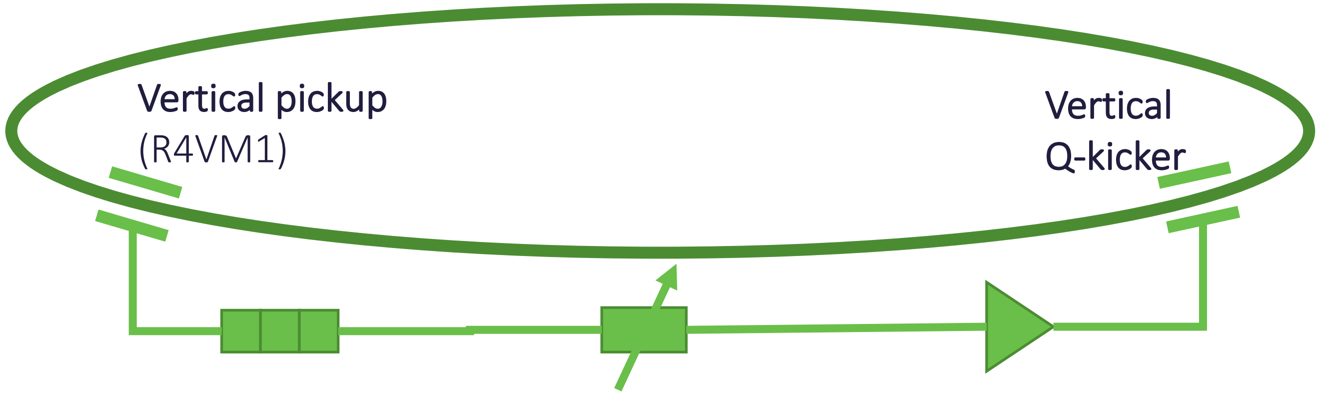
Head-Tail Damping System



- Use existing components: BPM, ferrite loaded kicker
- LLRF electronics for processing signals
- FPGA for ADC/DAC, digital filter, delays and gain
- Dynamically updated 3-tap FIR filter allows for correct phase for kick through acceleration

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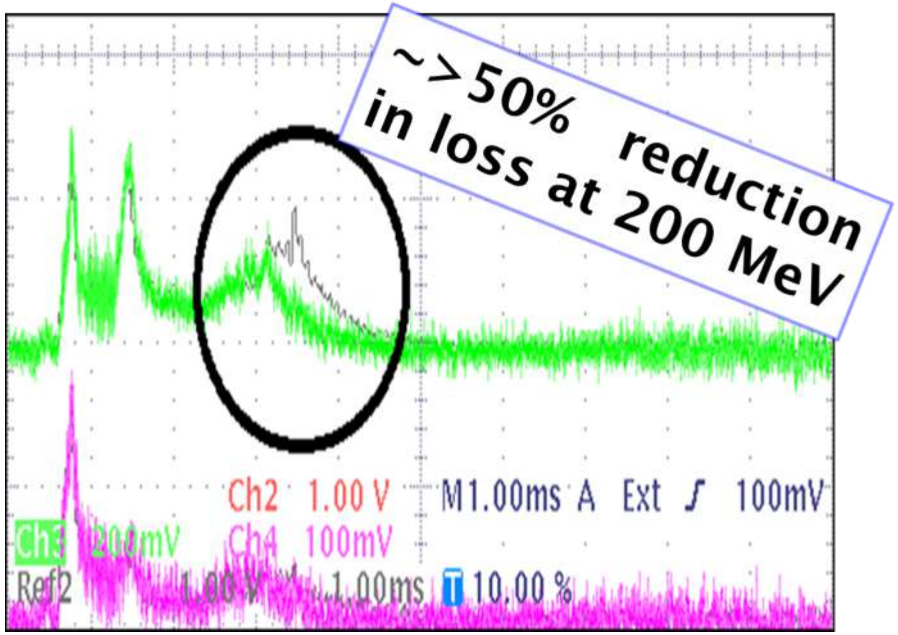
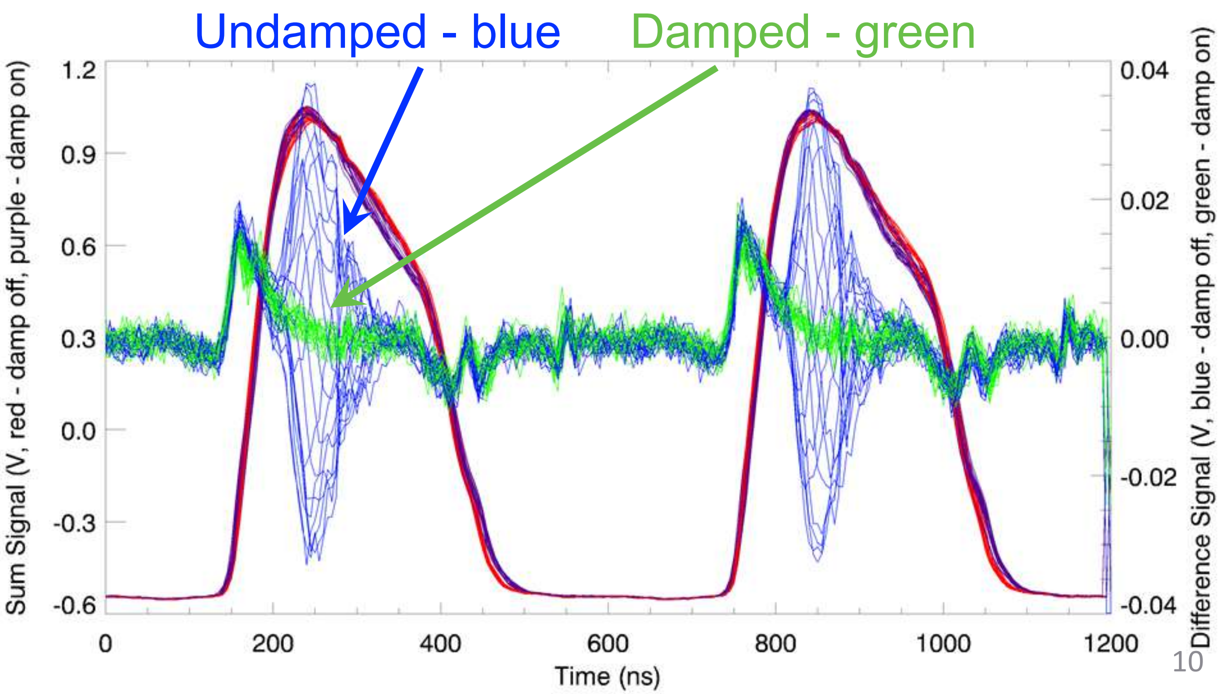
Experimental Results

- Vertical head-tail motion 1 - 2.5 ms through acceleration cycle
- Suppressed by
  - Ramping vertical tune
  - Asymmetric longitudinal distribution
  - Control of longitudinal and vertical painting
- Head-tail effectively damped and beam losses reduced
- Further commissioning required





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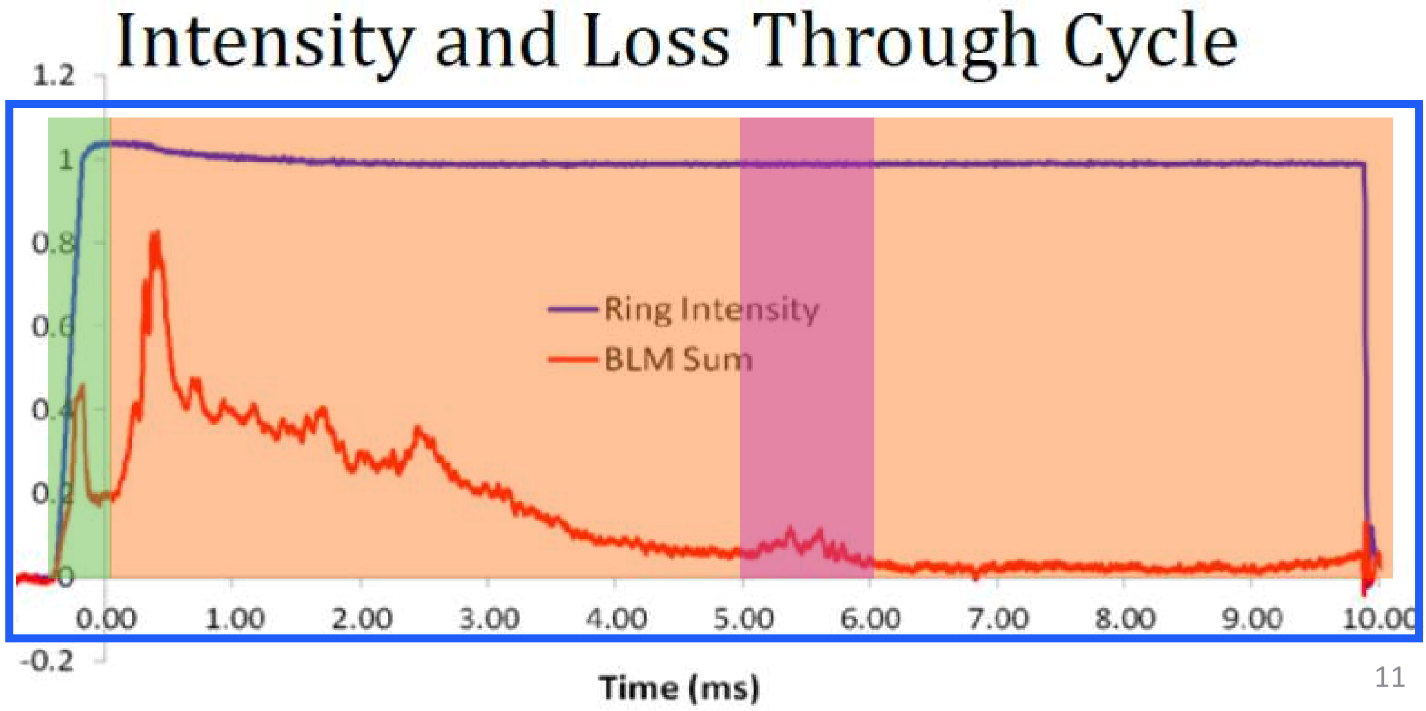
RE Williamson *et al.*, MCBI Workshop (2019)

Further Progress in Loss Mitigation

- Foil Developments
- Digital Low Level RF
- Trim Quad Power Supply Filters
- Diagnostic Developments



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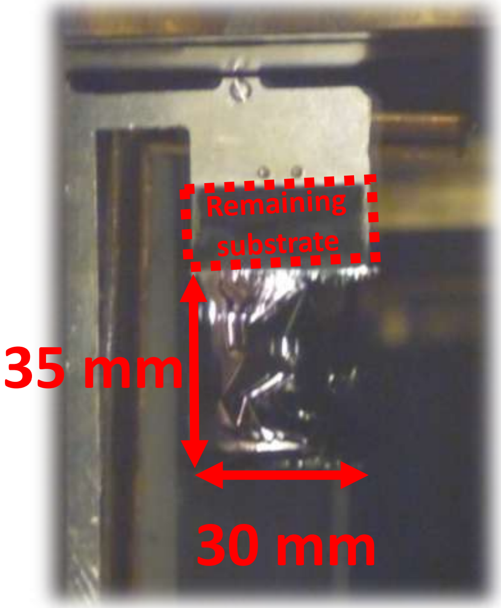
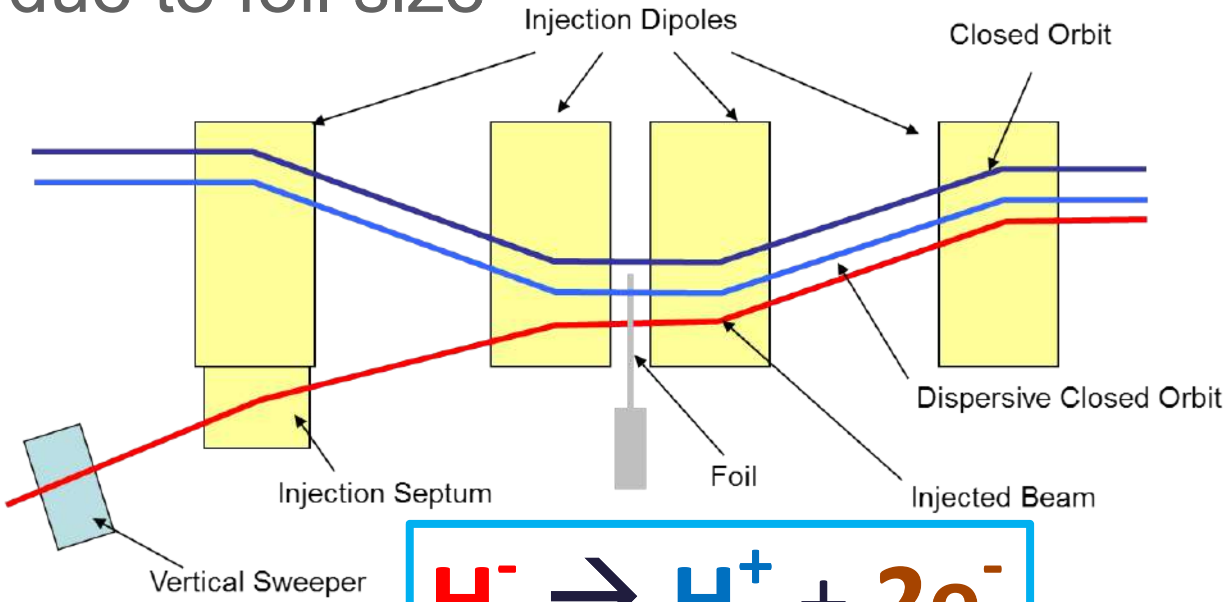
Foil Developments

B Jones & HV Cavanagh, IPAC18
10.18429/JACoW-IPAC2018-TUPAL055



- Injecting H- and strip electrons with a thin foil
- Proposed ISIS upgrades required new foil material
- Trials of carbon based foils
- Improvements in foil change time
- Beam loss reduction due to foil size
- Currently operating with large size nano-crystalline corrugated diamond foil from SNS



$H^{-} \rightarrow H^{+} + 2e^{-}$

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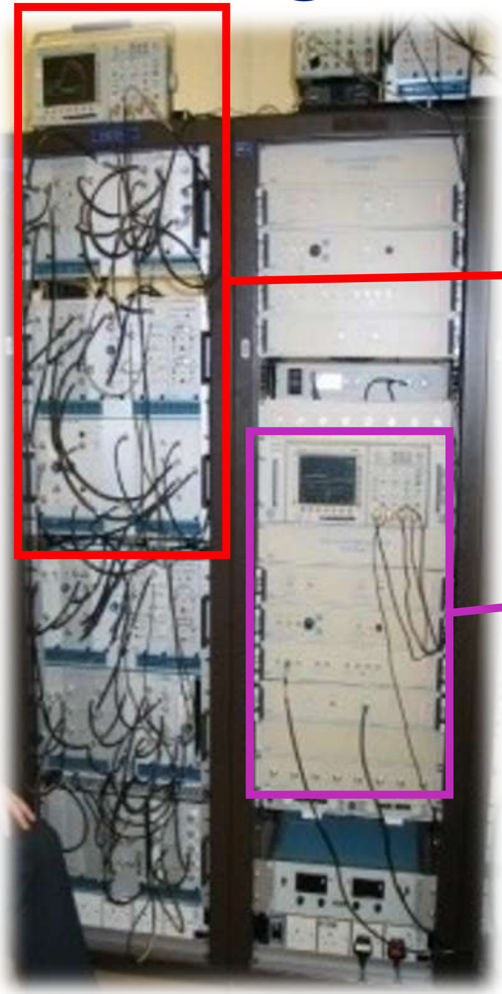
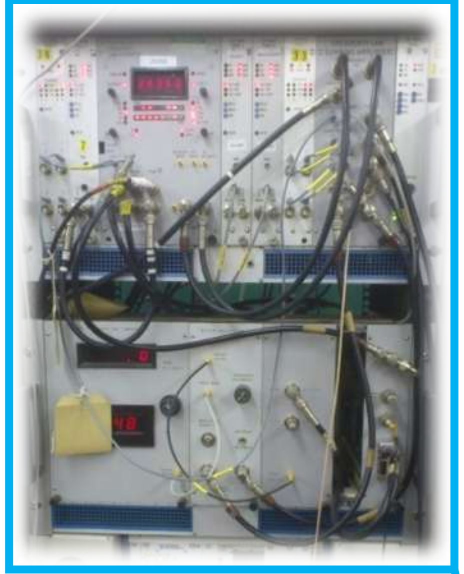
Digital Low Level RF

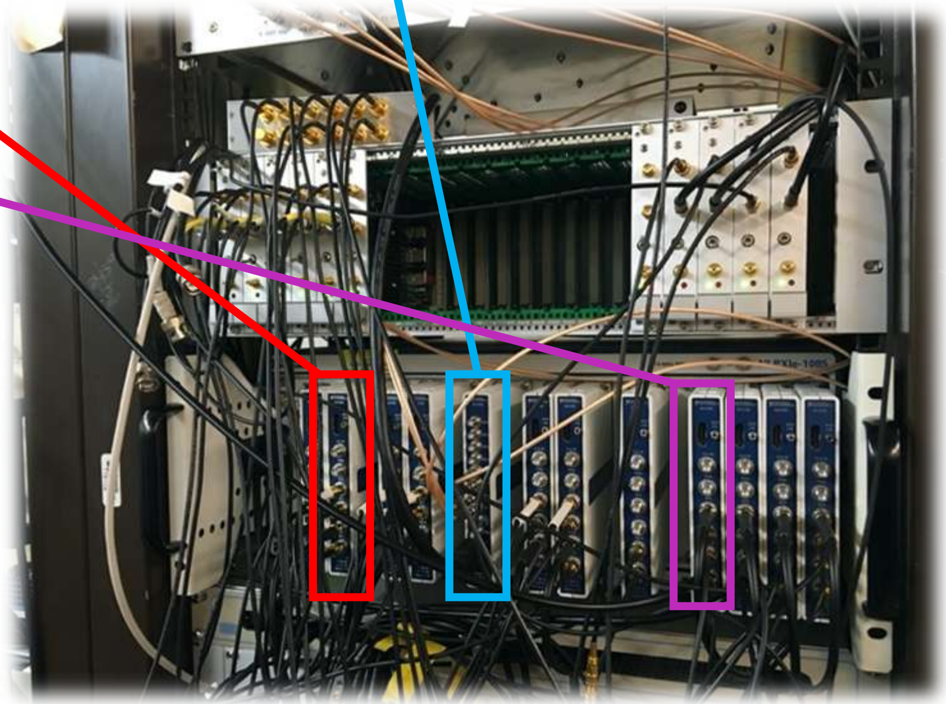


- Original 1RF Analogue LPRF controls (c.1982)
- Loops to control cavity voltage amplitude and phase + tuning

- 2RF Analogue LPRF controls (c. late 90s)



Original (c. 1982) Frequency Law Generator / Master Oscillator



- Ageing components more likely to fail
- Replacements harder to source

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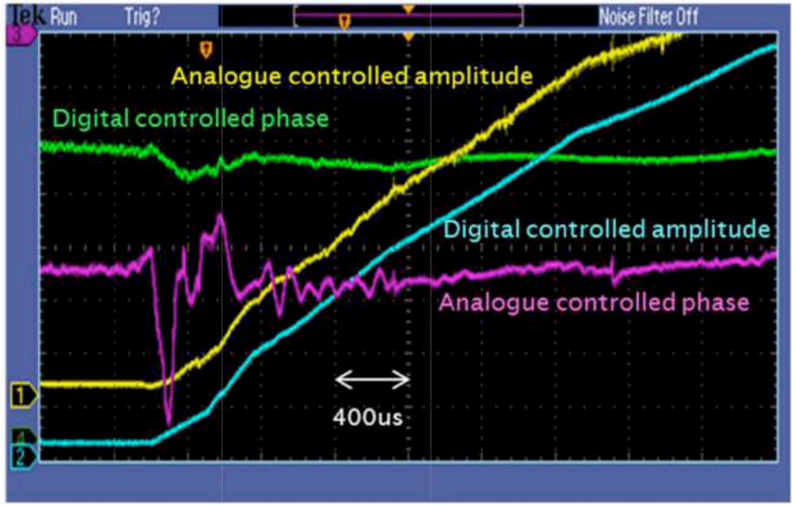
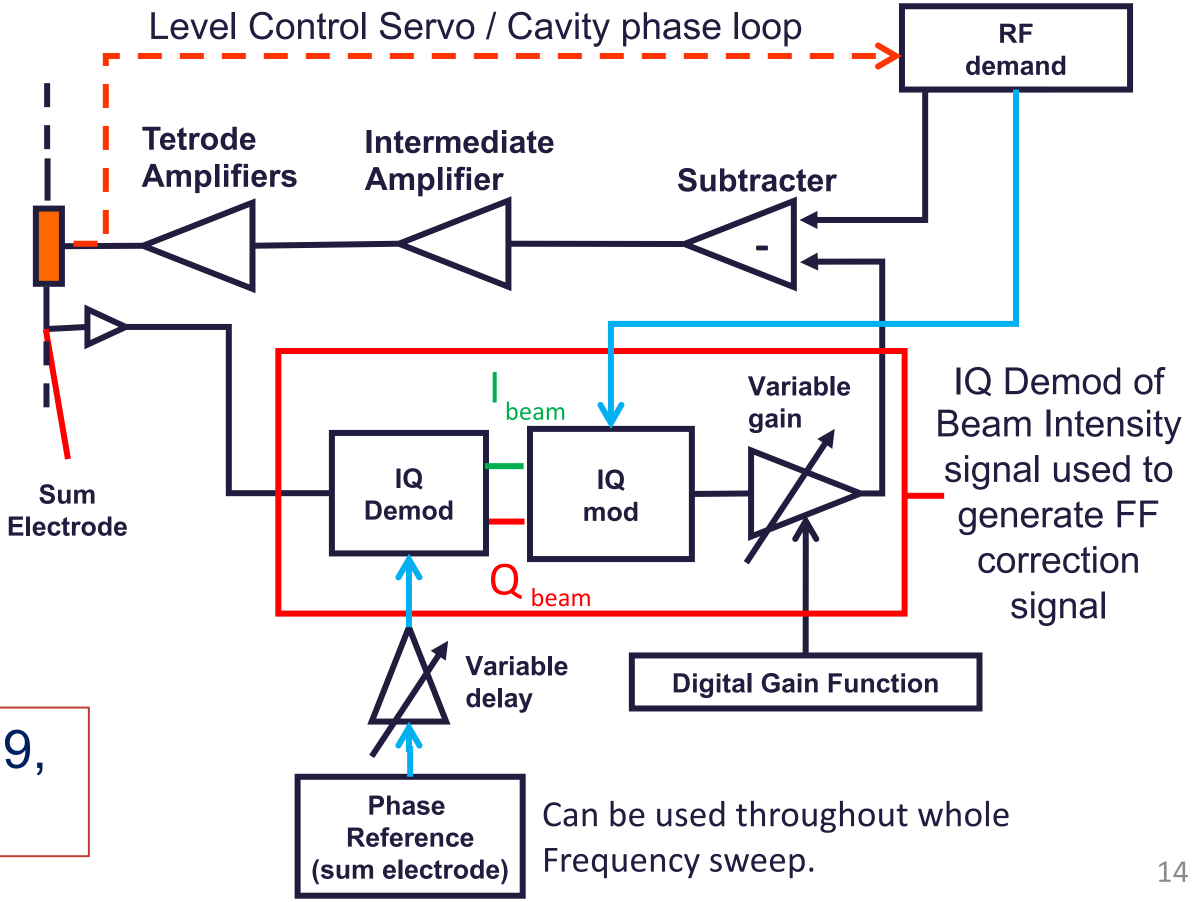
Digital Low Level RF

- NI FlexRIO based system previously used to provide the frequency
- Upgraded to include an IQ PID loop around each system
- Controls amplitude and phase of the cavity voltage
- Digital feed-forward beam compensation now throughout cycle
- Digital reference for tuning loop
- UPS driven filament power supplies





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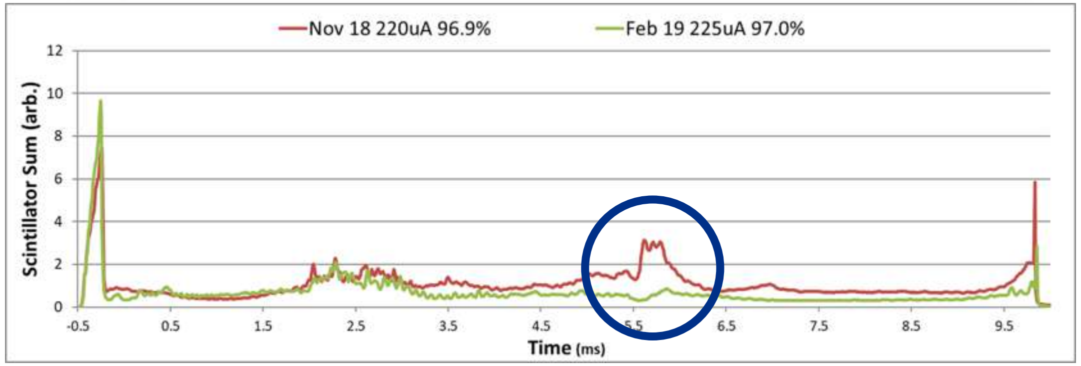
A Seville *et al.*, LLRF2019, arXiv:1910.07302

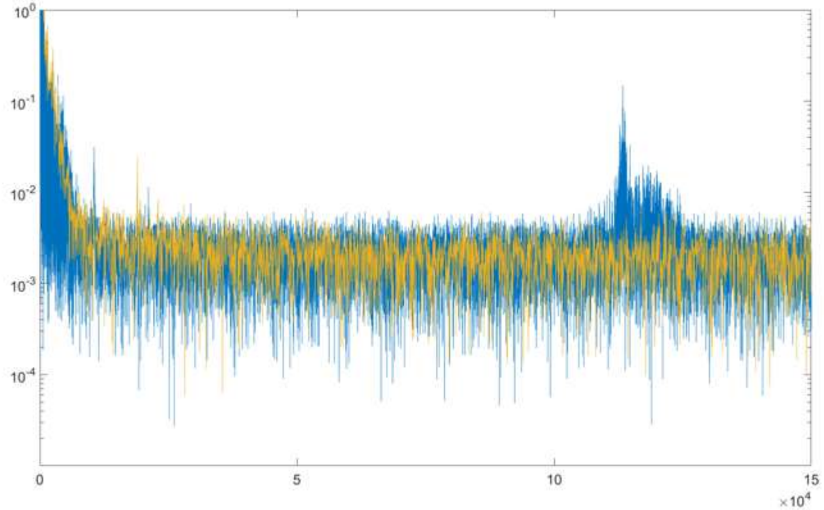
Trim Quad Power Supply Filters

- New correction magnet PS installed
- Small induced instability and loss
- Old PS – 20 kHz, New PS – 120 kHz
- Parallel low pass and notch filter installed

Beam Loss Scintillator in Dipole



Fourier Transform of Trim Quad Current



B Jones *et al.*, IPAC19, 10.18429/JACoW-IPAC2019-WEPGW091

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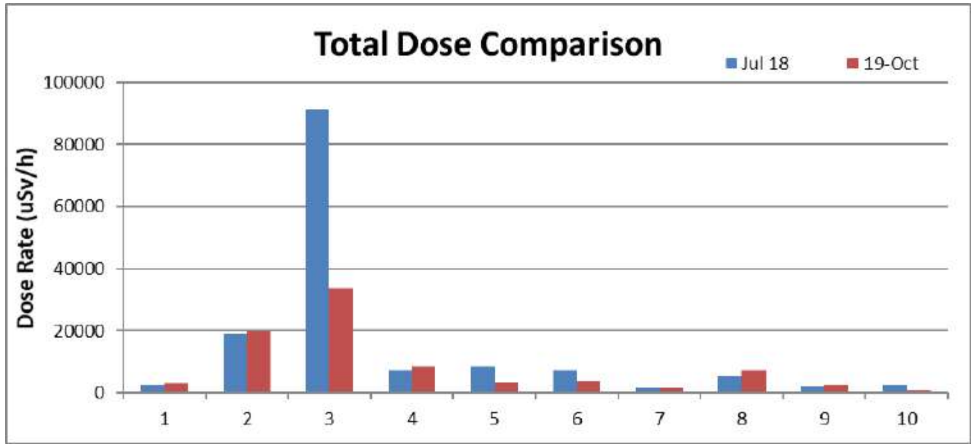
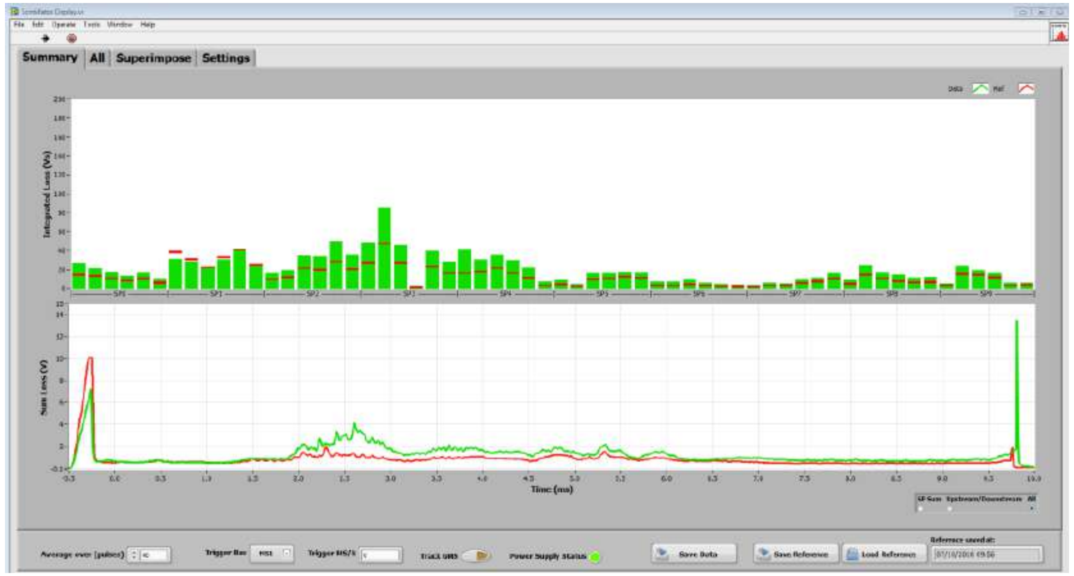
Diagnostic Developments

- New beam loss monitors installed in all main dipoles
- Investigate/cure cause of RF screen damage
- Previously unseen losses inside dipoles now measured
- Beam parameters further optimised to reduce loss/activation and protect dipoles
- 40% reduction in residual activation measured from cycle 2018-1 to 2019-2

Scintillators installed along vacuum chamber inside dipole



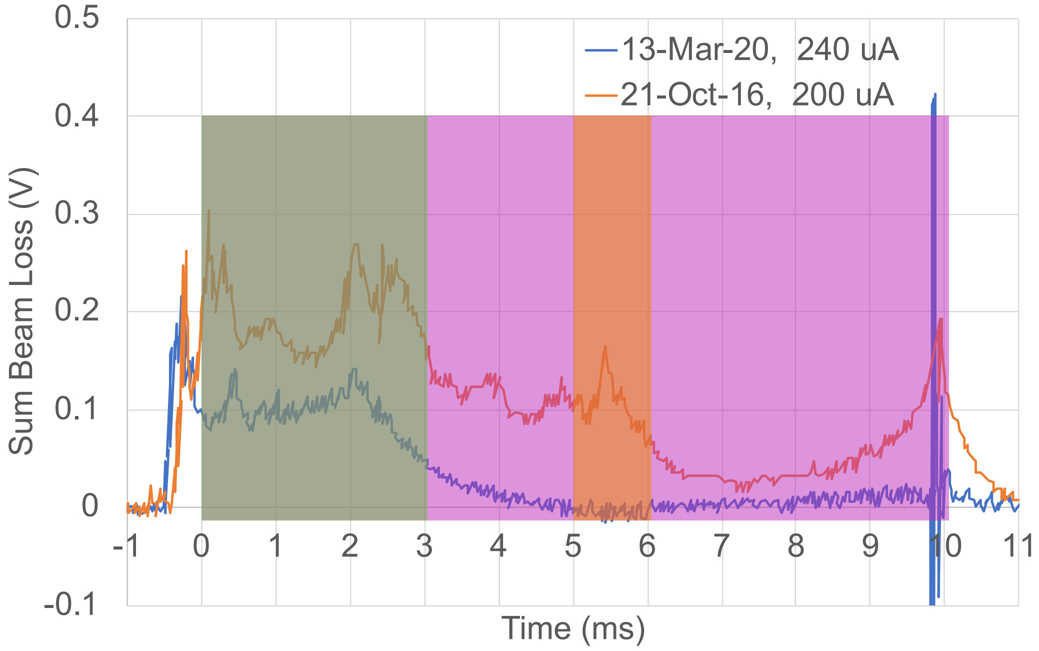
B Jones *et al.*, IPAC19, 10.18429/ JACoW-IPAC2019-WEPGW091



DAQ system and LabVIEW software enables monitoring across ISIS network

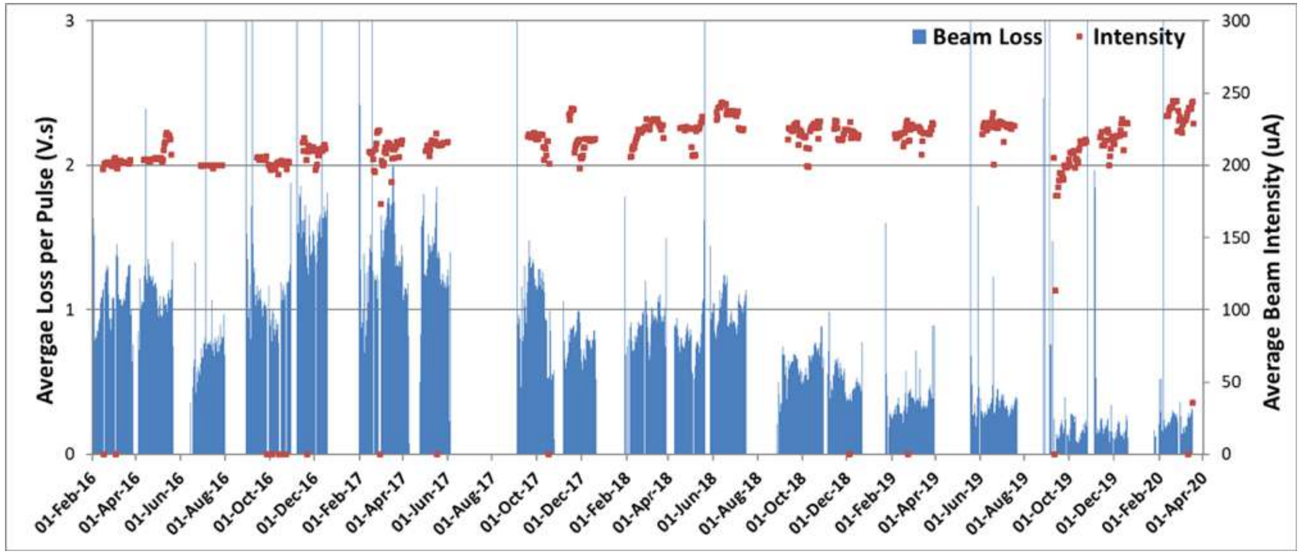
Improved Operations

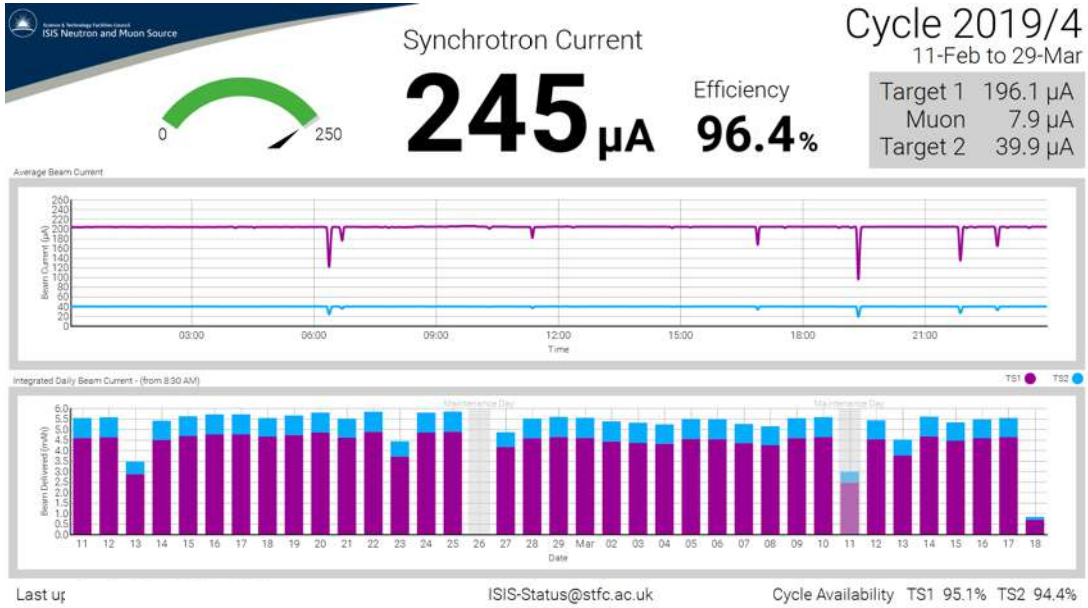
- Beam loss levels have been reduced systematically
- RF stability and re-optimized collimation
- Trapping and head-tail associated losses mitigated to half their usual value
- Trim quad PS instability removed
- Progress ongoing with increased beam intensities…



Improved Operations

- During Cycle 2019/4 (11th Feb – 27th Mar 2020)
- Beam delivery record exceeded 7 times
  - Best day was 25th February with 243.5μA and 99.6% availability
  - A total of 5.84 mAh delivered to the targets
- Overall availability was 95%, the second highest on record
- Synchrotron beam current is now the maximum required by the target stations, **no longer loss limited!**





Summary

- Need for control of beam loss
- Head-tail instability: mechanism & mitigation
- Foil developments
- RF stability
- Magnet power supply frequencies
- Diagnostic improvements
- Lower beam losses enabling higher intensities with lower activation

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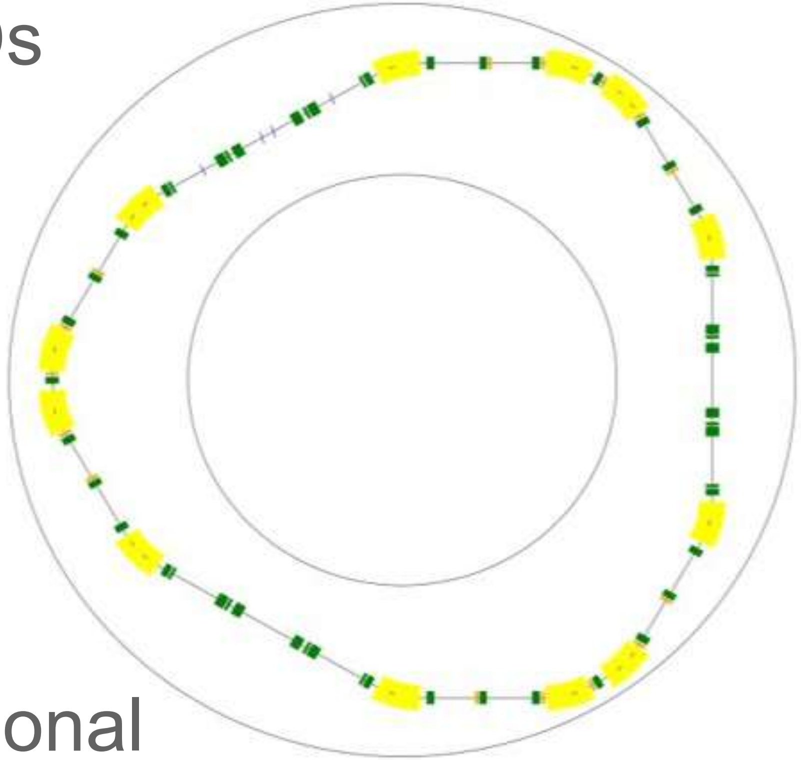
DJ Adams *et al.*, "Operational Experience and Future Plans at ISIS", HB16, 10.18429/JACoW-HB2016-TUPM3Y01

JWG Thomason *et al.*, "The ISIS Spallation Neutron and Muon Source – The First 33 Years", NIMA, 917 (2019) 61-67

Many hands make light work

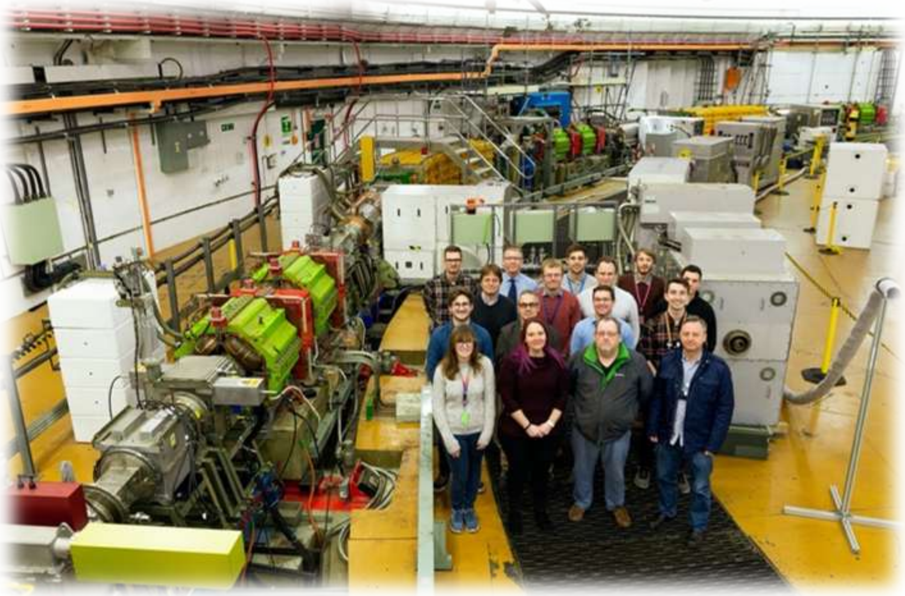
Future Work

- Work is never complete!
- High intensity beam studies
- Further commissioning and development of damper system
- More digital development alongside new HPDs
- Diagnostic upgrades
- MEBT upgrade



- ISIS-II MW upgrade
  - FFA & conventional rings
  - Detailed user consultation
- R&D on ISIS and FETS
- Discussions with the international community

Acknowledgements



- ISIS Accelerator Physics
- ISIS Diagnostics
- ISIS RF

- ISIS Electrical Engineering
- ISIS Operations Crew