

Mitigation of Proton Beam Instabilities under Strong Space Charge

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Contents

Background

Coherent Instability – Impedance Model

Experimental Results

Mitigation

Conclusion

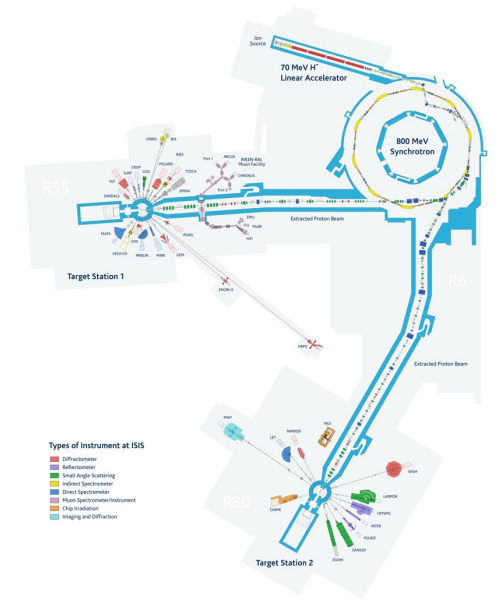


ISIS is the UK's Spallation Neutron and Muon Source

Delivers research across many disciplines (batteries, archeology, healthcare...)

Driven by a Rapid Cycling Synchrotron with a dual-harmonic RF system, which delivers up to 3×10^{13} protons to its fixed targets at 50 Hz [1]

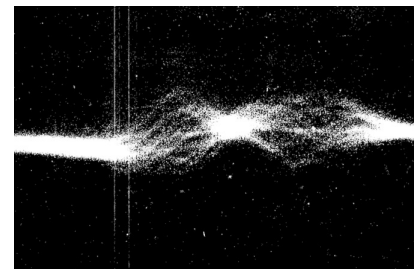
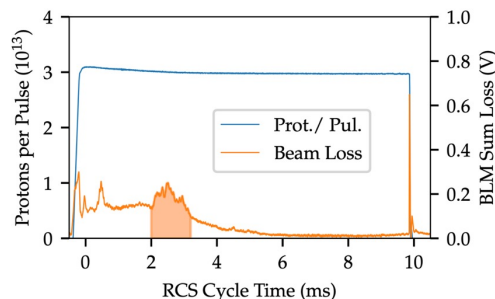
Typical space-charge parameters in operation are $\sim 30 - 50$ (strong) [3]



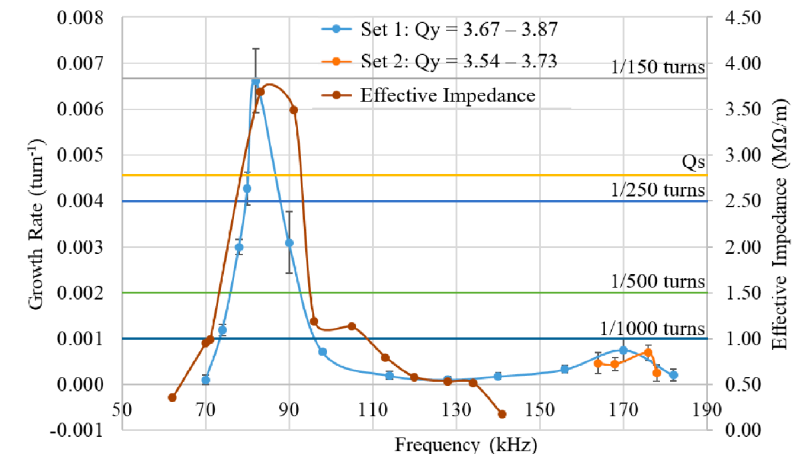
ISIS Facility [2]

Primary causes of loss include:

- Direct Transverse Space Charge
 - C. M. Warsop (Weds), E. Ahmadi (Fri), J. Appleby (Weds)
- Longitudinal Trapping
 - B. Kyle (Thurs)
- Coherent Vertical Instability
 - D. W. Posthuma de Boer (now), F. Straniero (poster)



BPM difference plot [4]



ISIS SRM and BSRM instability results [3]

The Vertical Impedance Model

Impedance model is targeted at identifying the driver of the 2 ms head-tail instability [5].

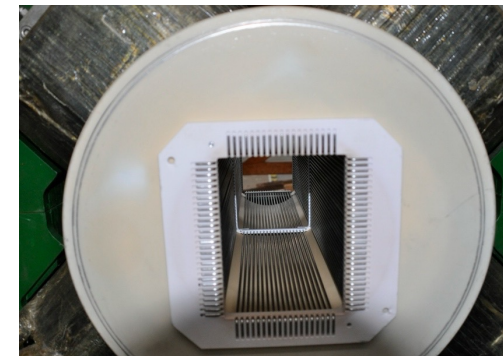
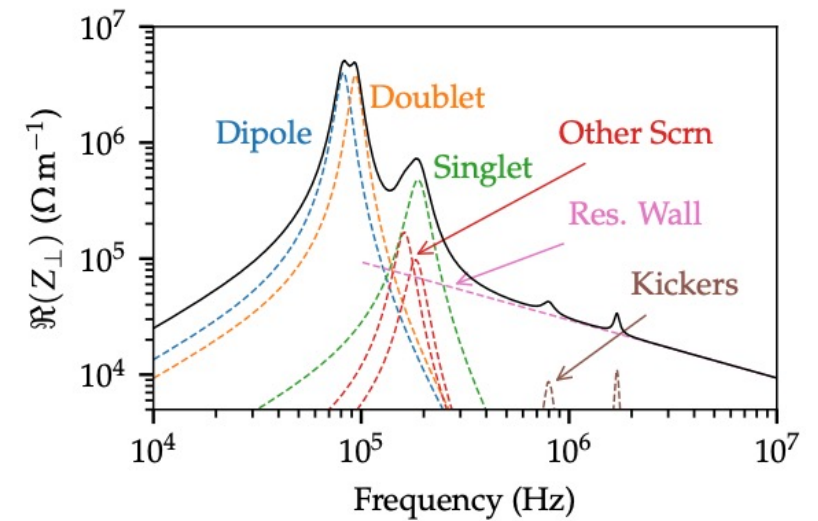
- Low-frequency, vertical, driving resonator impedances

Includes:

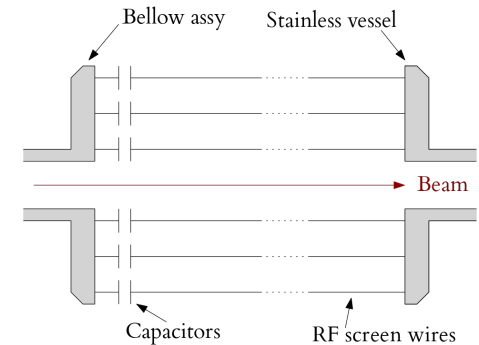
- Resonator from capacitively coupled RF screens
- Thick resistive-wall
- Terminated kicker magnets
- Indirect space-charge

Lowest frequency sideband in early part of acceleration (~100-200 kHz), overlaps with RF screen resonators.

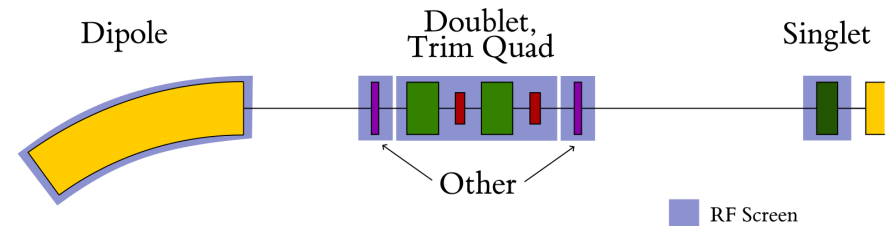
- Dominated by RF screens



Photograph of an RF screen and ceramic vessel.



Schematic of RF screen wire connections.



A typical ISIS superperiod

Low-Intensity Experiments

Studies with operational beams challenging, so Bunched Storage Ring Mode (BSRM) used [3, 5]:

- Beam stored in stationary bucket
- Typically with lower intensity (SC-parameter of ~3-5)

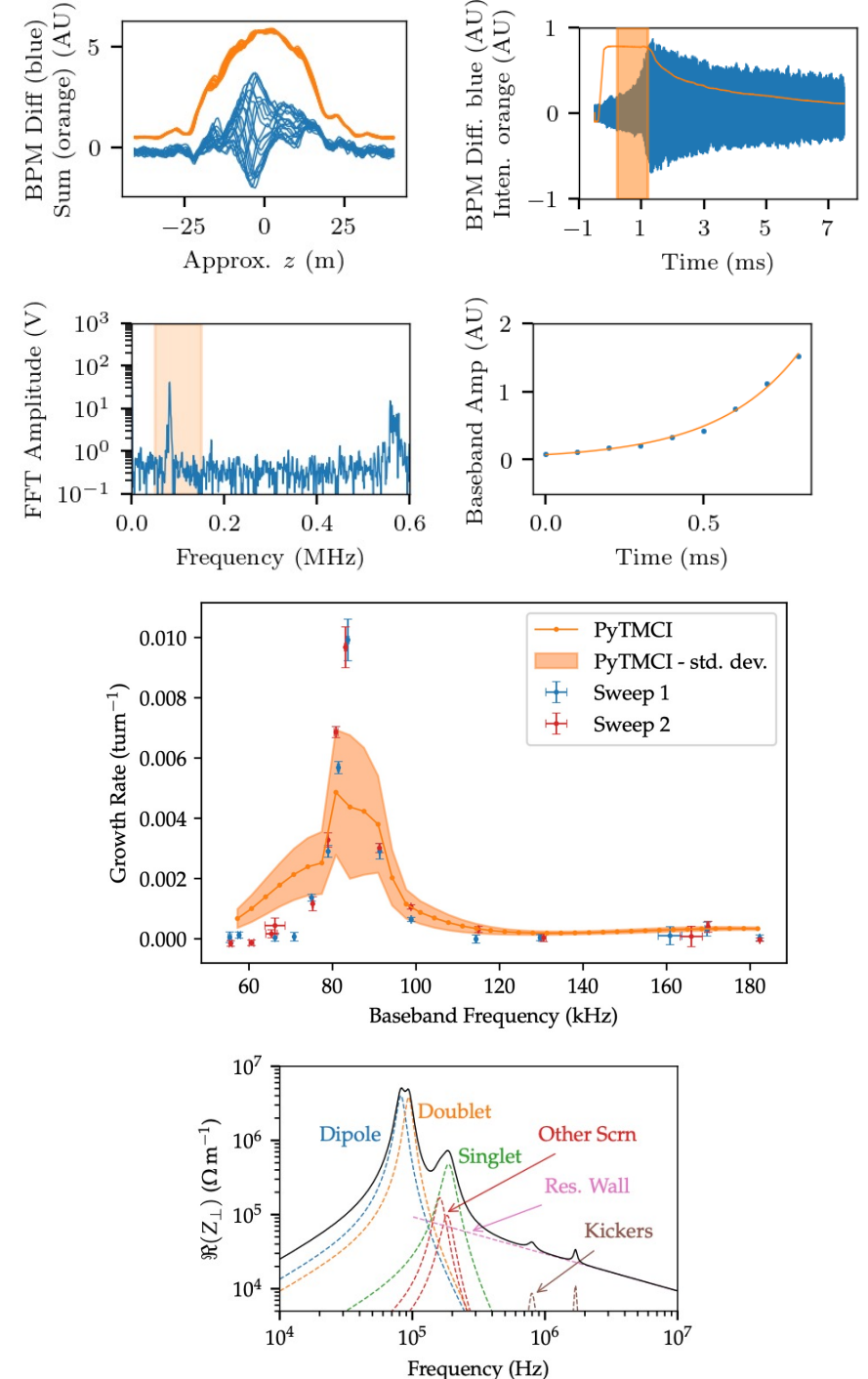
Sweep vertical tune, record instability growth rate.

Benchmark with PyTMCI [6] predictions

- Vlasov solver – no direct space charge

Order of magnitude agreement in growth rate at ~85 kHz

- Driver understood from impedance model as dipole/ doublet RF screens.



Low-Intensity Experiments – Distribution

In general, distributions not well predicted by PyTMCI, but is this because space-charge omitted?

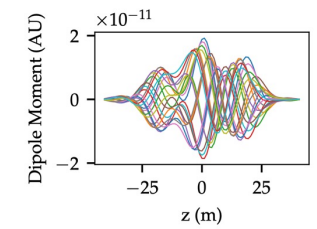
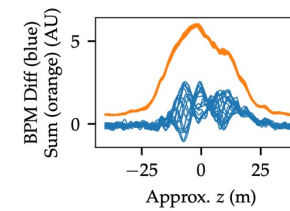
For most unstable setting (3.876), PyTMCI predicts several modes with similar growth rates.

- If we wait a long time, one will dominate
- Before that time, we'll see a sum of several modes

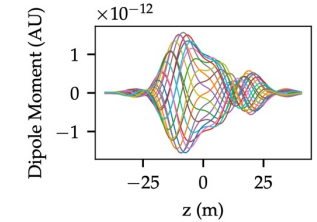
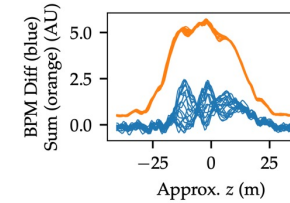
Estimate ~3 ms for dominant mode with most unstable setting, but beam loss occurs after ~0.5 ms.

Space-charge definitely important – but challenging anyway.

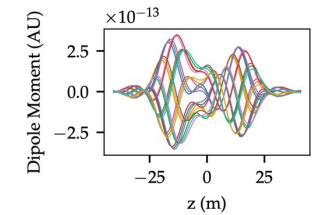
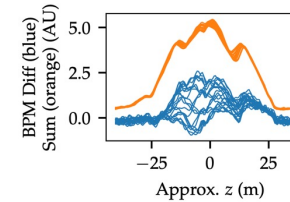
3.854



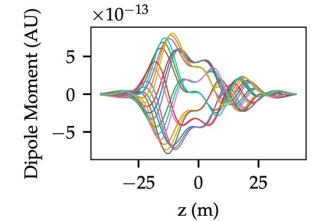
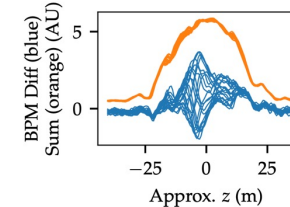
3.865



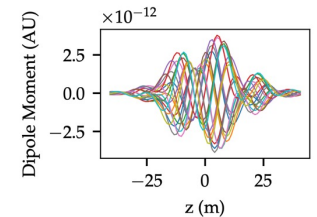
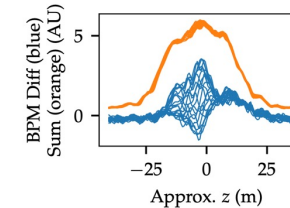
3.876



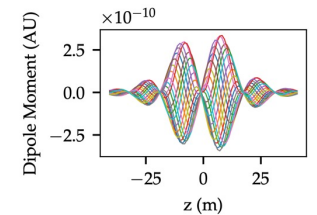
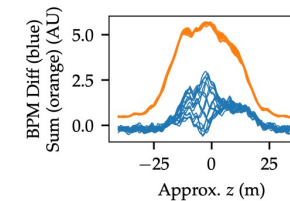
3.879



3.884



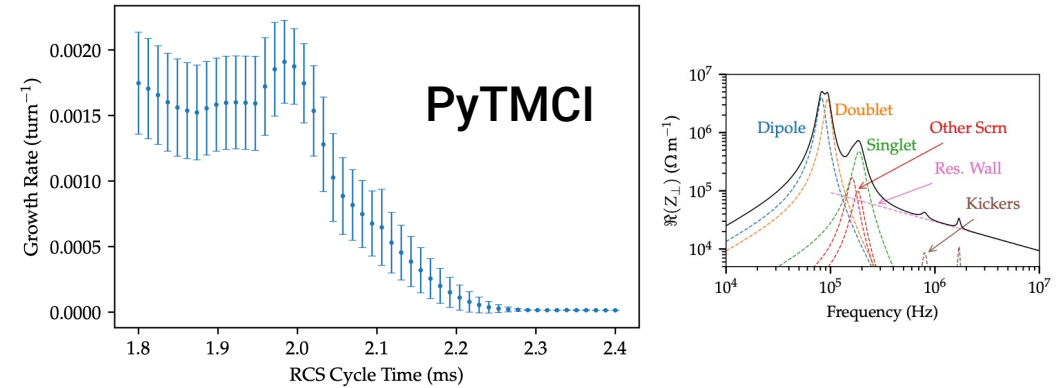
3.889



Mitigation under Strong Space-Charge

PyTMCI also predicts key elements of observed instability

- Growth rate (~ 0.4 ms predicted, ~ 0.2 – 0.6 ms observed)
- RCS cycle time when the beam will be unstable (~ 2 ms)



Impedance optimisation is still a fundamental solution.

Verified that resonant frequency follows $\sim 1/\sqrt{C}$ [7].

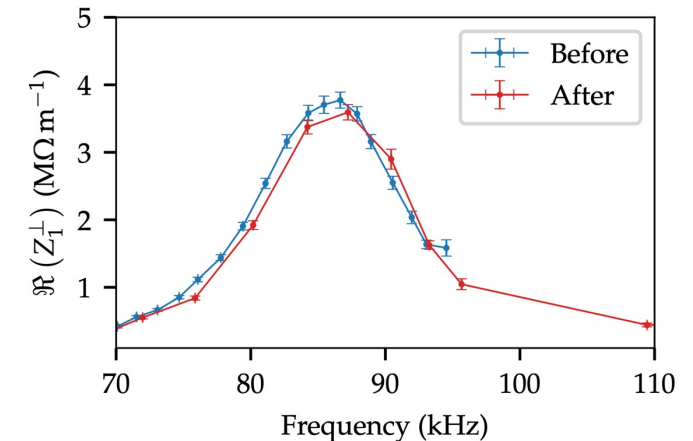
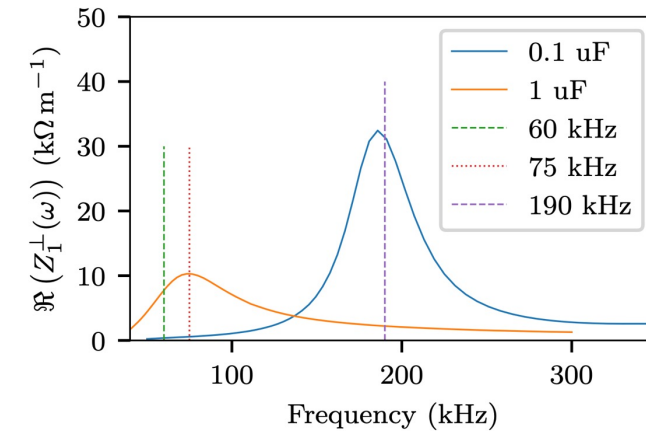
- C is the capacitance of rf-screen capacitors

Predicted growth times increase by 2+ orders of magnitude if all resonant frequencies reduced by factor of 3.

- $\sim 10x$ increase in capacitance

Trial of operational capacitor replacements ongoing –impact monitored using coasting beams.

- Initial results promising – but more data required.



Conclusions

Instability growth rates reasonably well predicted by PyTMCI without direct SC, despite experimental space-charge parameter of $\sim 3-5$.

- Driven by dipole/ doublet RF screens.

Predicting distribution could be challenging on ISIS, even without SC.

PyTMCI also reproduces key observations of an operational beam.

- Driven by RF screens.

Traditional approach to mitigation: impedance optimisation, coasting-beam experiments to monitor progress.

Francesco Straniero combining space-charge with impedance model for ISIS

References

- [1] - isis.stfc.ac.uk
- [2] - <https://doi.org/10.5281/zenodo.21157242>
- [3] – R. E. Williamson, “Studies of beam instabilities and associated beam-loss on a high-intensity proton synchrotron”, DPhil thesis, 2023.
- [4] – C. Planner, “Progress to operating at 100- μ A on ISIS”, Snowmass88, 1988.
- [5] – D. W. Posthuma de Boer, “Studies of beam impedance with related beam stability and loss effects on a high intensity proton synchrotron”, DPhil thesis, 2026.
- [6] - <https://github.com/stfc/PyTMCI>
- [7] – D. W. Posthuma de Boer et al, “Low-frequency transverse resonator impedances on the ISIS proton synchrotron”, HB2025.