Head-Tail Instability Predictions for the ISIS Synchrotron

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John Adams Institute for Accelerator Science

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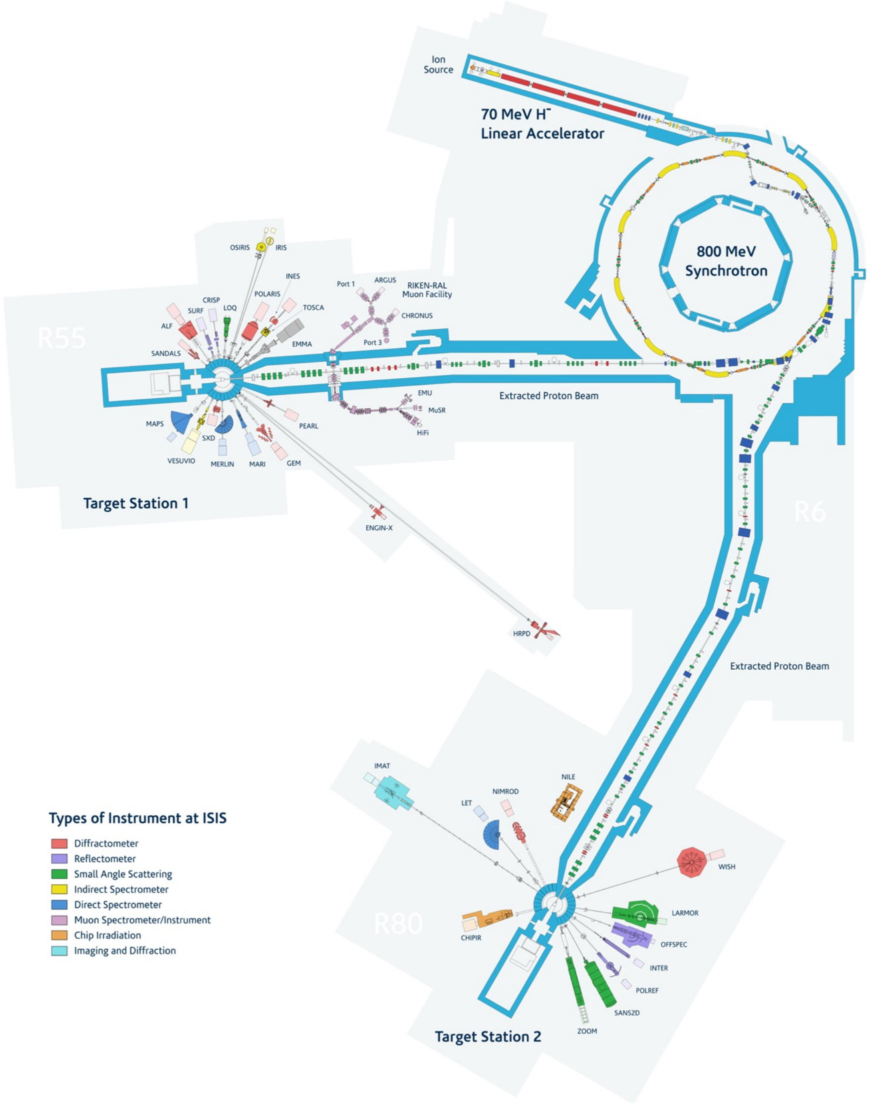
Contents

1. ISIS Neutron and Muon Source

- ISIS is the pulsed Neutron and Muon source, at the Rutherford Appleton Laboratory in the UK [1].
- Facility is centred around a high intensity, Rapid Cycling proton Synchrotron (RCS).

Parameter	Value
Circumference	163 m
Energy Range	70 – 800 MeV
Repetition Rate	50 Hz
Charge	2.5 – 3.0e13 protons-per-pulse
Extraction	Single-turn, vertical
RF System	h=2, f=1.3 – 3.1 MHz (~160 kV/turn) h=4, f=2.6– 6.2 MHz (~80 kV/turn)
Tunes (x, y)	4.31, 3.83 (programmable)



2. Loss Mechanisms on ISIS

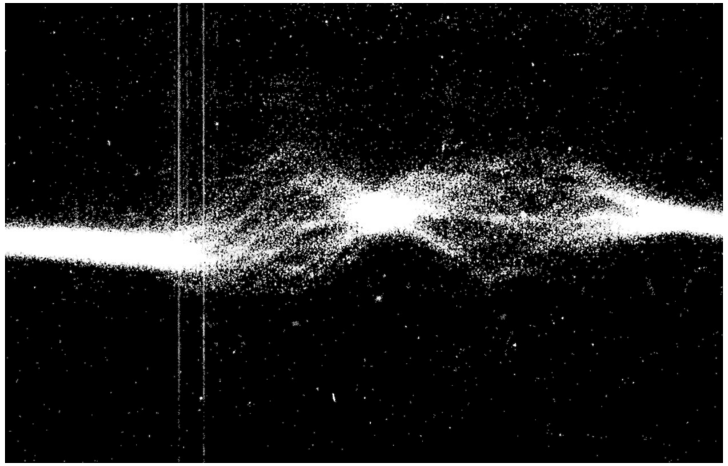
- Operational intensity is limited by loss [2].

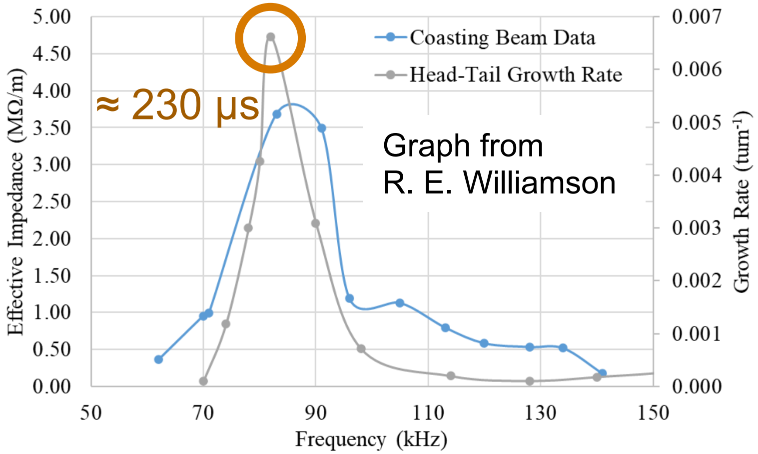
- Vertical head-tail instability is a significant loss contributor. Reports of this instability at ISIS started around 1988 [3-5].

- Resistive wall was assumed to be most significant driver.
  - Calculations suggest mode-2 or 3 with growth times $\tau\approx$4ms.
  - Typically observed mode-1 with growth times of order 100 μs.

- Contradictions motivated study of impedances, an in-depth review of theory and an extensive measurement campaign.

- More recent measurements have revealed a low-frequency narrowband impedance [6].





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3. Vertical Impedance Model

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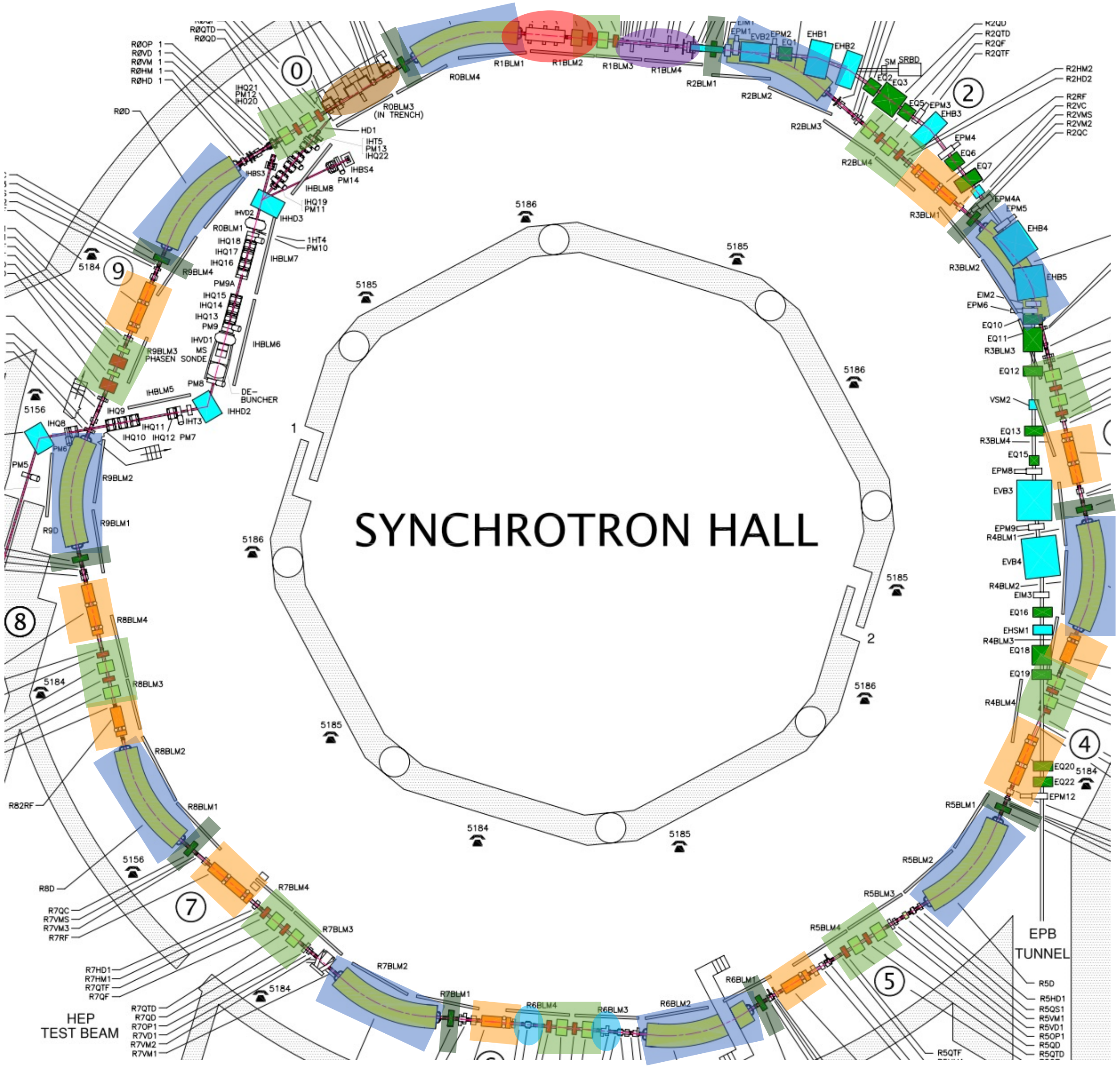
Primary Impedance Candidates

- ISIS has previously used a vertical driving impedance model based a resistive pipe extending to infinity and neglected inductive bypass.

- Improved estimates made for
  - Dipole RF Screens
  - Doublet quadrupole RF Screens
  - Octupoles & gap RF Screens
  - Singlet quadrupoles RF Screens
  - RF cavities
  - Injection dipoles (H-kickers)
  - Collectors (collimators)
  - Extract kickers
  - Betatron exciters



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3.1 – RF Screens

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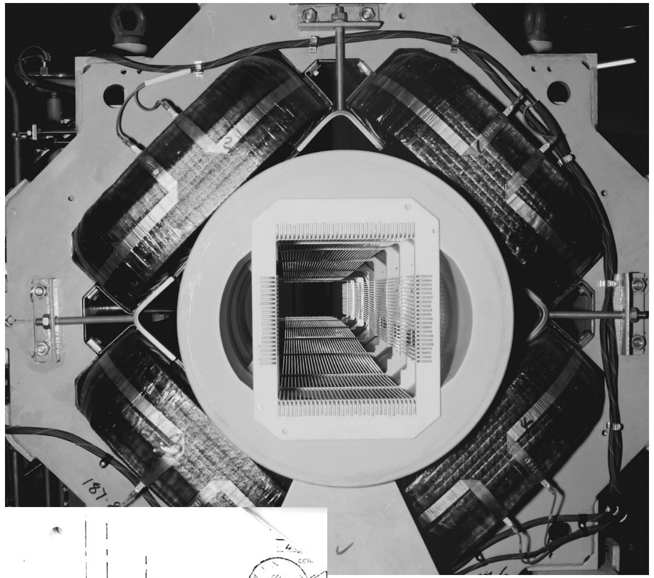
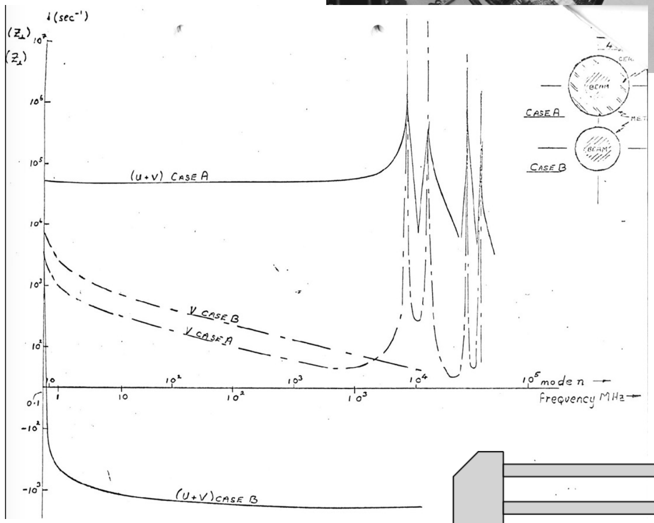
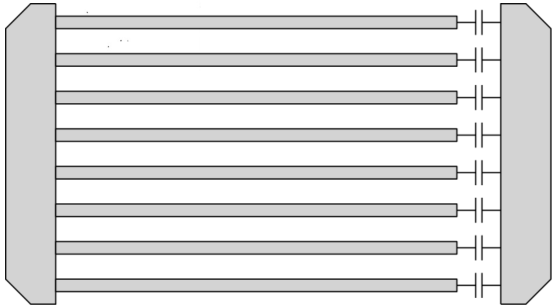
RF Screens - Background

- Vacuum chambers inside the AC magnets of an RCS cannot be made from solid conductors due to eddy currents effects [7].
    - Ceramic vessels are used instead, but to prevent a longitudinal interrupt of the conducting vessel, RF screens are inserted [5].
- In designing these screens, there were two main options: put the screens inside the vacuum or outside.
    - Two-layer impedance calculations identified resonances in the lossy ceramic for the case with the screens outside and a larger imaginary impedance.
    - Because of this, and other practical considerations the screens were placed inside.
    - Nearly fifty years later, this is the geometry we use today.
- The screens are made from stainless steel wire, which would also carry eddy currents were it not for a coupling capacitor.
    - The capacitors present a high impedance to 50 Hz Eddy currents and low impedance to beam-induced currents.







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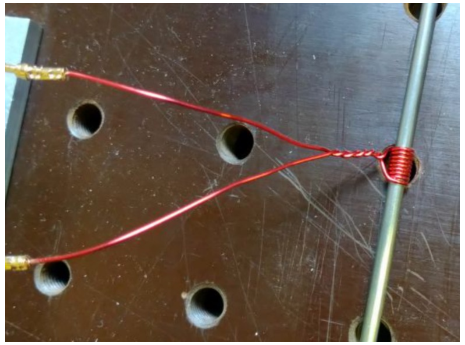
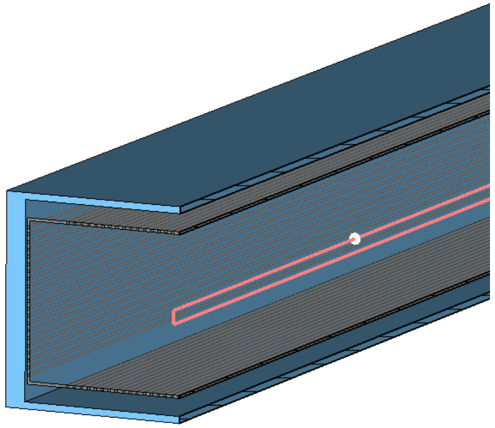
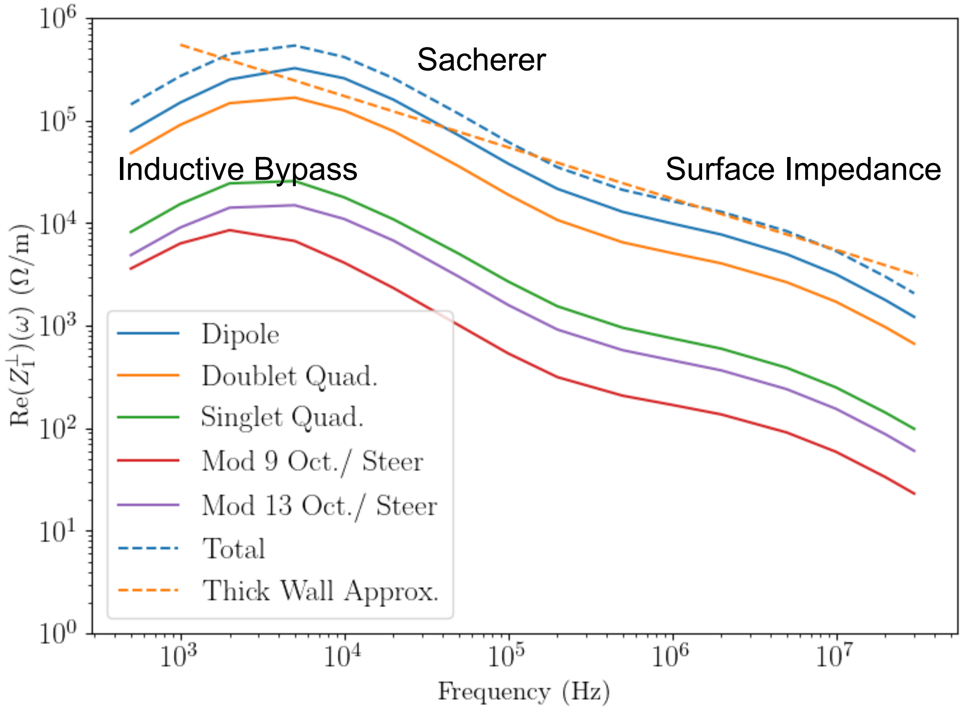
RF Screens – Resistive Wall Impedance

- Used CST low-frequency solver to estimate resistive-wall impedance. Neglecting capacitors.
  - Verified linear dependence on length and independence of bounding box size.
  - Observe a surface-impedance, Sacherer and inductive bypass region, just as for a solid conducting pipe.

- Results above 100 kHz are well approximated by thick-wall circular vessel formula with 5 cm radius.

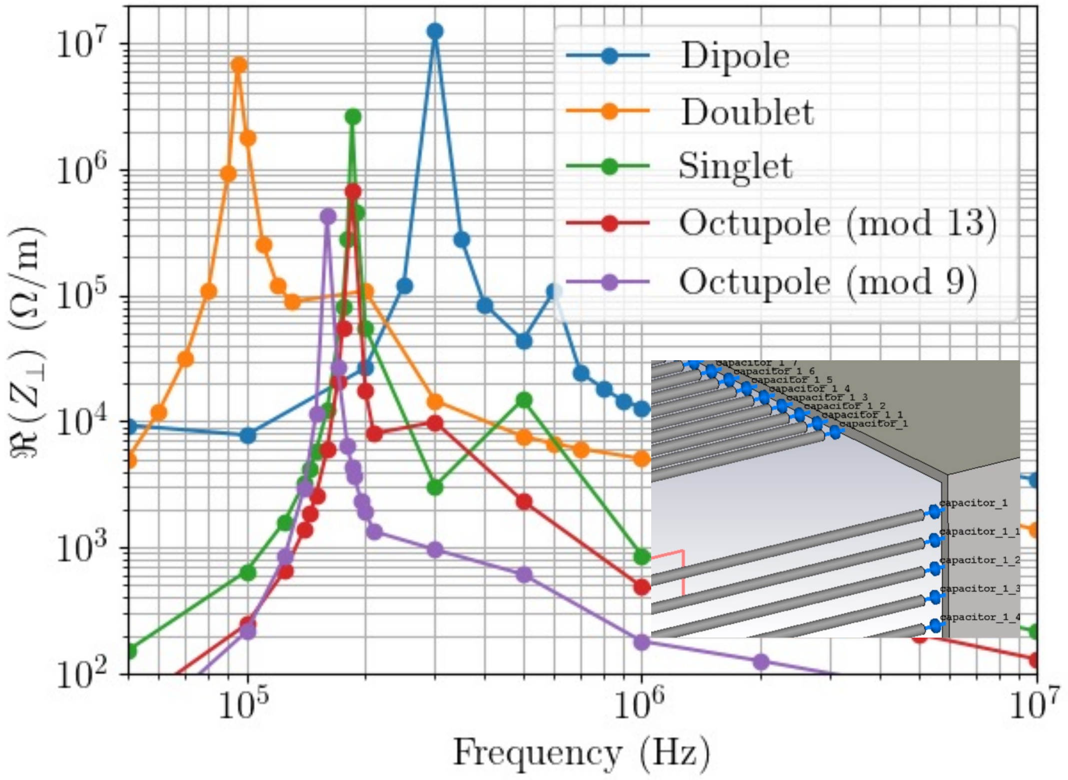






RF Screens with Capacitors

- Low frequency CST simulations of RF screen have so far neglected capacitors.
- Add capacitors by creating a 5 mm gap and using a lumped circuit element.
- <u>Observe narrowband impedances (Q≈15-30) in the 100 kHz frequency range.</u>
    - Magnitudes (0.4-10)MΩ/m for each family.
    - Less common families yet to be simulated.



RF Screen	Resonant Frequency (kHz)	$R_\perp$ (MΩ/m)	≈Q	Quantity
Dipole	300	1.3	15	10
Doublet	95	0.7	15	10
Singlet	185	0.26	30	10
Oct. a	185	0.1	30	6
Oct. b	160	0.07	30	6

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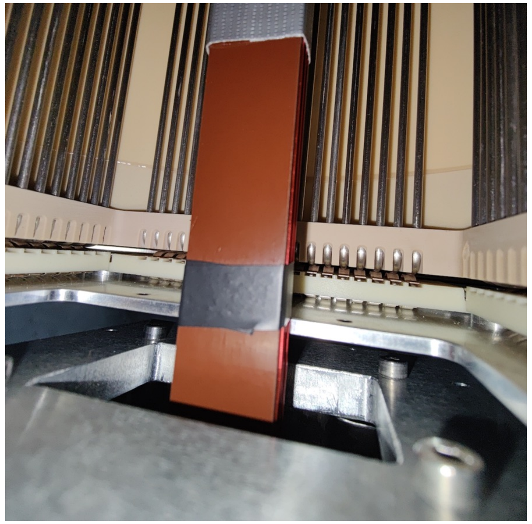
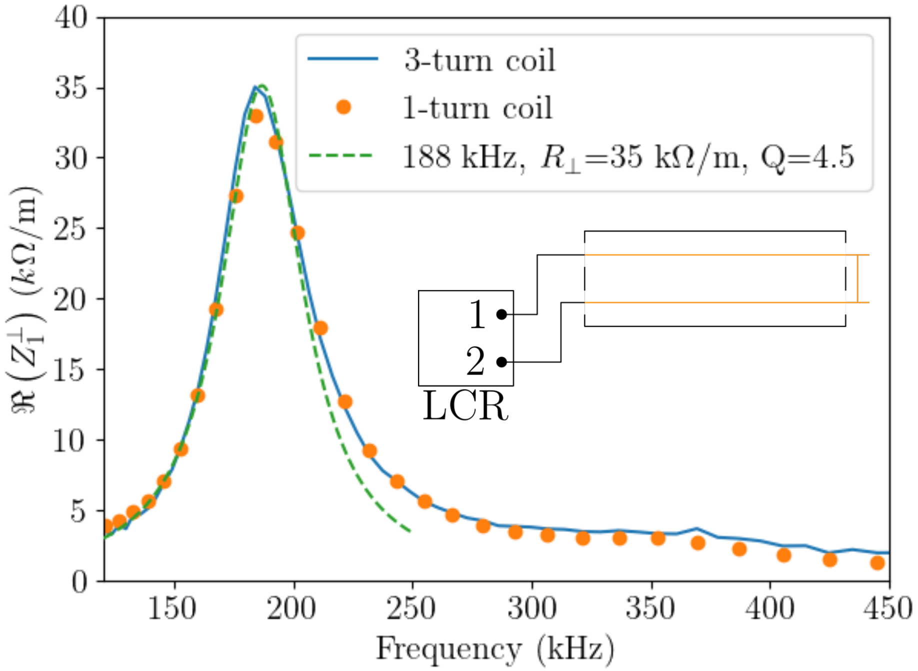
RF Screens with Capacitors – Preliminary Measurement

- Probe coil measurement using a singlet are currently being performed [8].
- **Preliminary** results taken using LCR meter, a 1-turn and a 3-turn coil.
  - Shown results are not final. Currently optimising reference measurements which have sometimes added offsets.
- Narrowband impedance at ~185 kHz, as predicted.
  - Amplitude is smaller (35 not 260 kΩ/m, 7.4x difference)
  - Peak is broader (Q≈4.5 not 30, 6.7x difference)
  - Differences likely due to idealised geometry in CST and/ or presence of coil in measurement
- Simulations can be improved, but conclusion now is **capacitors in the RF screens are causing a large, low frequency resonator-type transverse impedance.**





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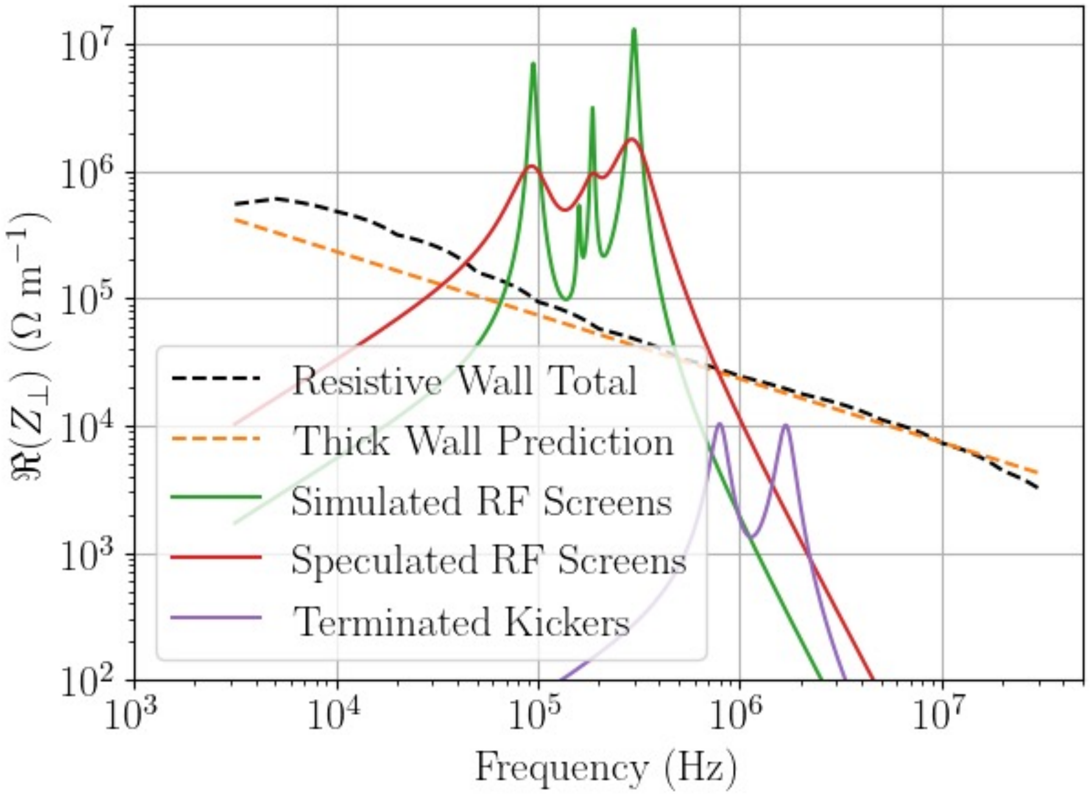
Vertical Impedance Model Summary

- **Thick resistive wall** model is reasonable approximation above ~ 500 kHz - 1 MHz.
  - Plotted is for ~70% of circumference (not just RF screens).
  - Remaining 30% assumed.

- Terminated extract kickers contribute relatively small peaks and **will be neglected**.

- Simulations & preliminary measurements suggest the **RF screens drive low frequency resonant impedance.**
  - So far, results agree that **amplitudes are order-of-magnitude larger than resistive wall**

- For now, consider two resonator models:
  - Use estimated resonator properties from CST
  - Speculate 6.7x reduction in Q and 7.5x reduction in $R_\perp$



4. Head-Tail Predictions

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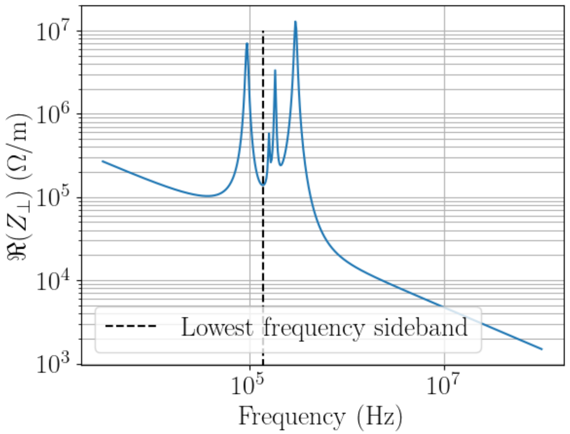
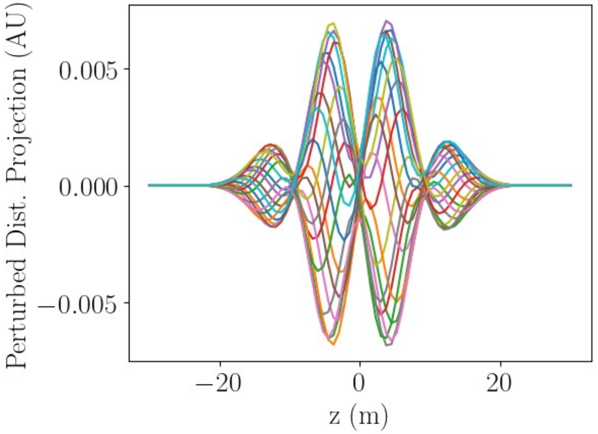
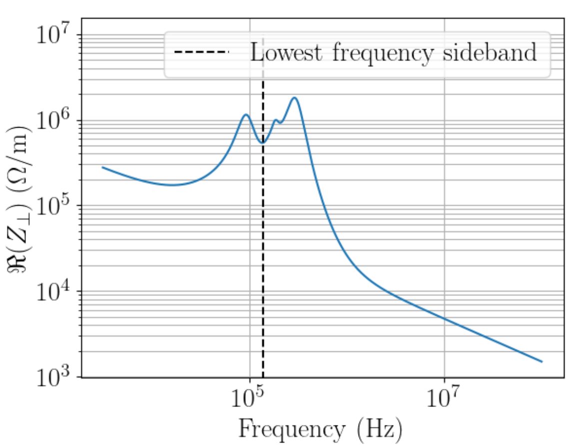
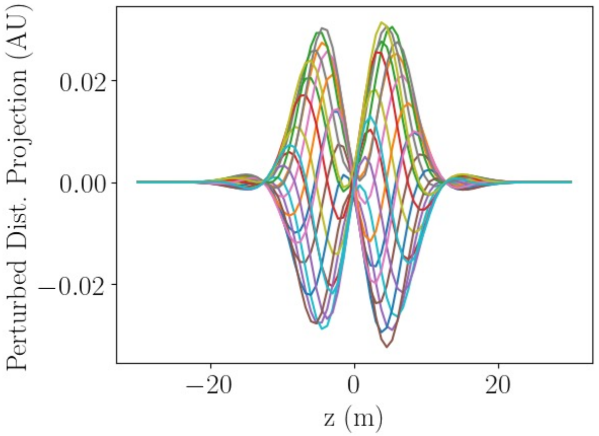
PyTMCI - Application to ISIS

- Simplified formulae do not provide the most accurate analytical predictions available.
- Developed new head-tail Vlasov solver [9-11].
  - PyTMCI
  - Open-source python package
    - https://github.com/stfc/PyTMCI
    - `pip install PyTMCIVlasov`
- Impedance model 1 – Thick resistive wall plus simulated resonators.
  - Mode -3, $\tau \approx 440$ μs
- Impedance model 2 – Thick resistive wall, plus modified resonators based on measurements,
  - 6.7x reduction in Q and 7.5x reduction in $R_\perp$
  - Mode-1, $\tau \approx 175$ μs.









5. Conclusion

- CST simulations have identified resonant impedance from RF screens + capacitors.
- Preliminary measurements on a singlet RF screen have identified a resonance at the expected frequency, but with a smaller, wider peak than predicted.
- New impedance model is a thick wall impedance plus five resonators with properties TBC.
- A new head-tail Vlasov solver, PyTMCI, has been developed and is available on pypi.
- With the new impedance model, PyTMCI predicts growth times with the same order of magnitude as observation, and distributions closer to those observed.
- Future work will focus on the following:
  - Resonator properties must be verified with improved measurements and simulation.
  - Less common RF screen families to be simulated.
  - This analysis has not included direct or indirect space-charge.

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Thank You

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