Development of an Impedance Model for the ISIS Synchrotron and Predictions for the Head-Tail Instability

D. W. Posthuma de Boer[1], B. A. Orton, C. M. Warsop, R. E. Williamson
ISIS Neutron and Muon Source, Harwell, UK
[1] also at John Adams Institute, Oxford, UK

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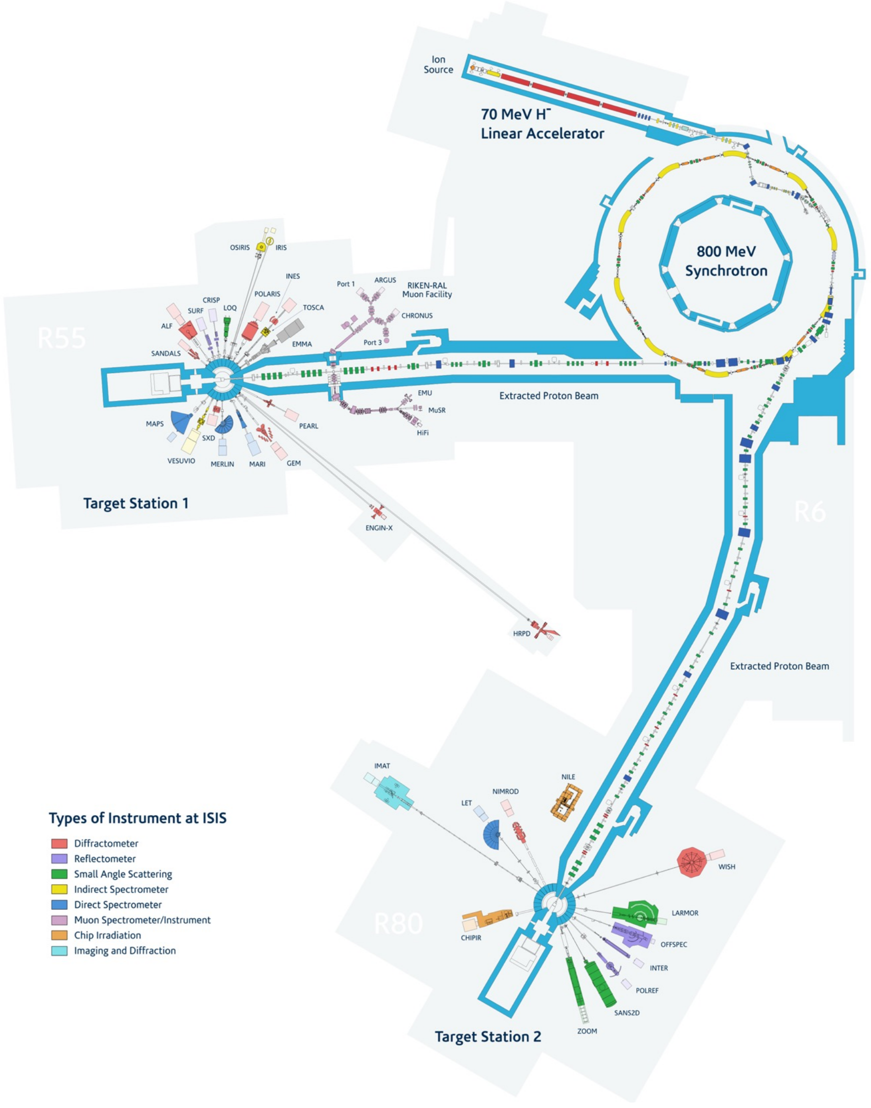
Contents

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

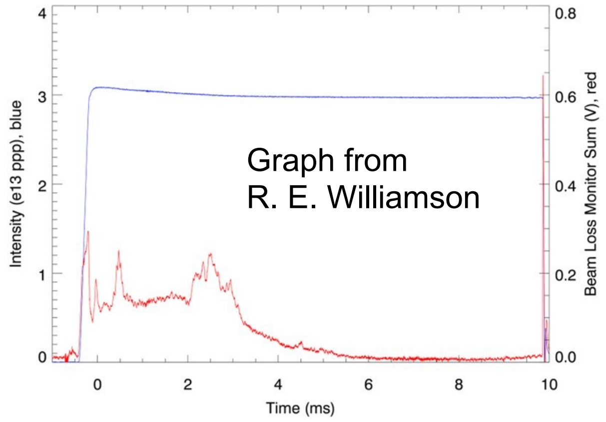
- Operational intensity is limited by loss [2].
  Its primary drivers include
  - Longitudinal trapping
  - Transverse space charge
  - **Coherent vertical instability**

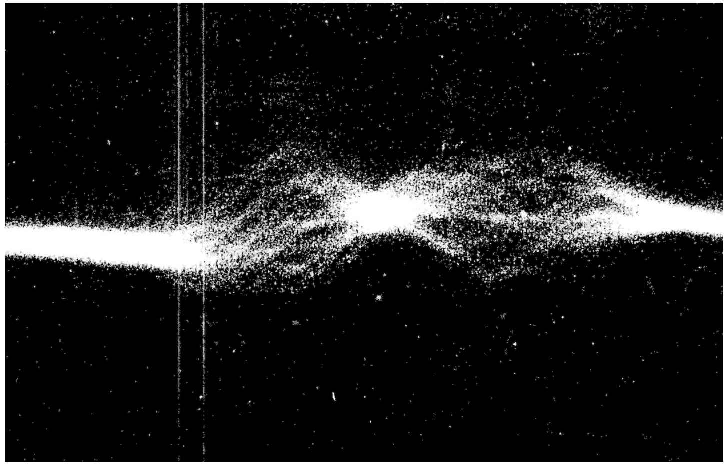
- Reports of a vertical instability at ISIS started around 1988 [3-5]. Resistive wall assumed most significant contributor.

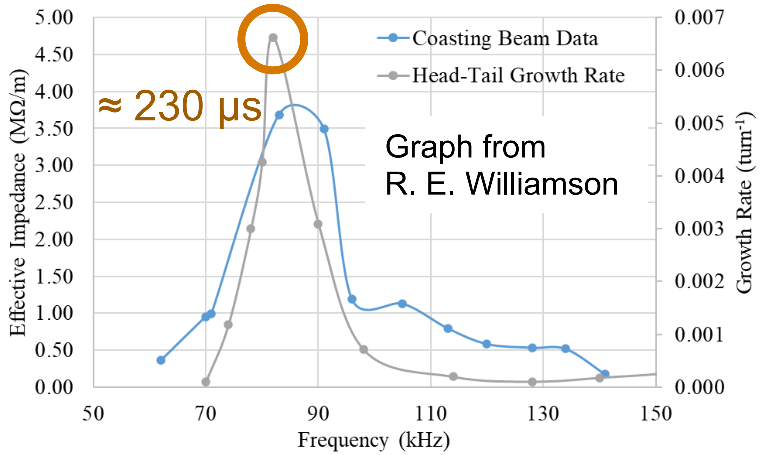
- Calculations suggest mode-2 or 3 with growth times τ≈4ms, but typically observe mode-1 with growth times on order of 100 μs.

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

- Measurements using bunched storage-ring-mode and coasting beams revealed a low-frequency narrowband impedance [6].







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3. Vertical Impedance Model

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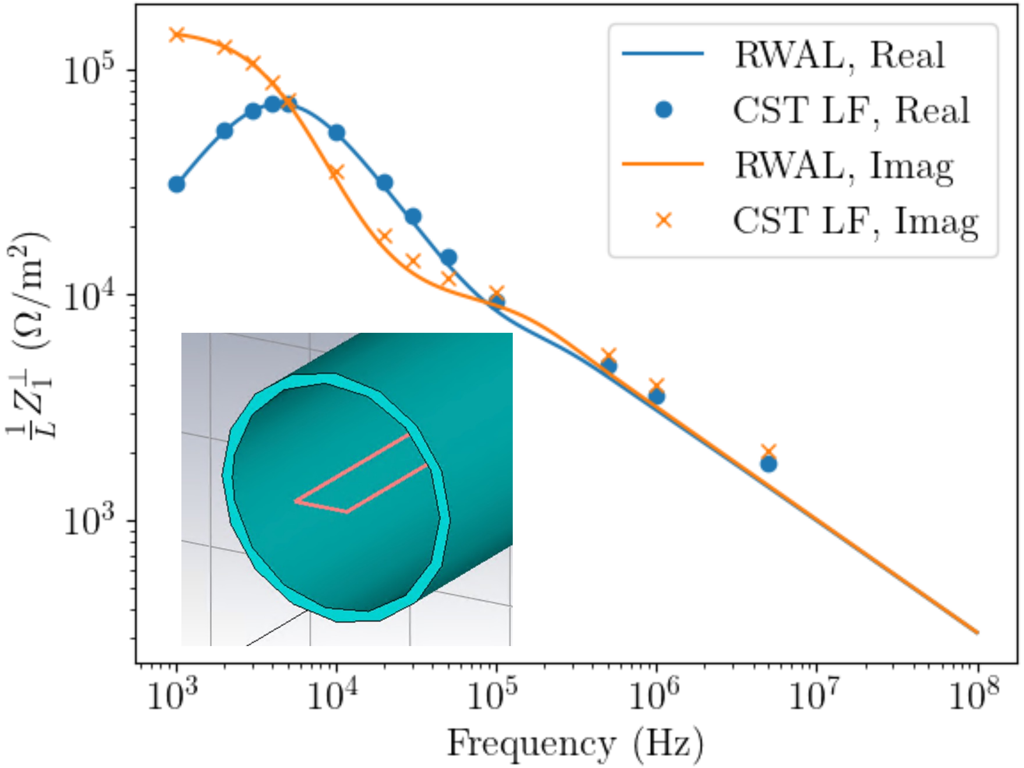
Tools for Low Frequency Impedance Computation

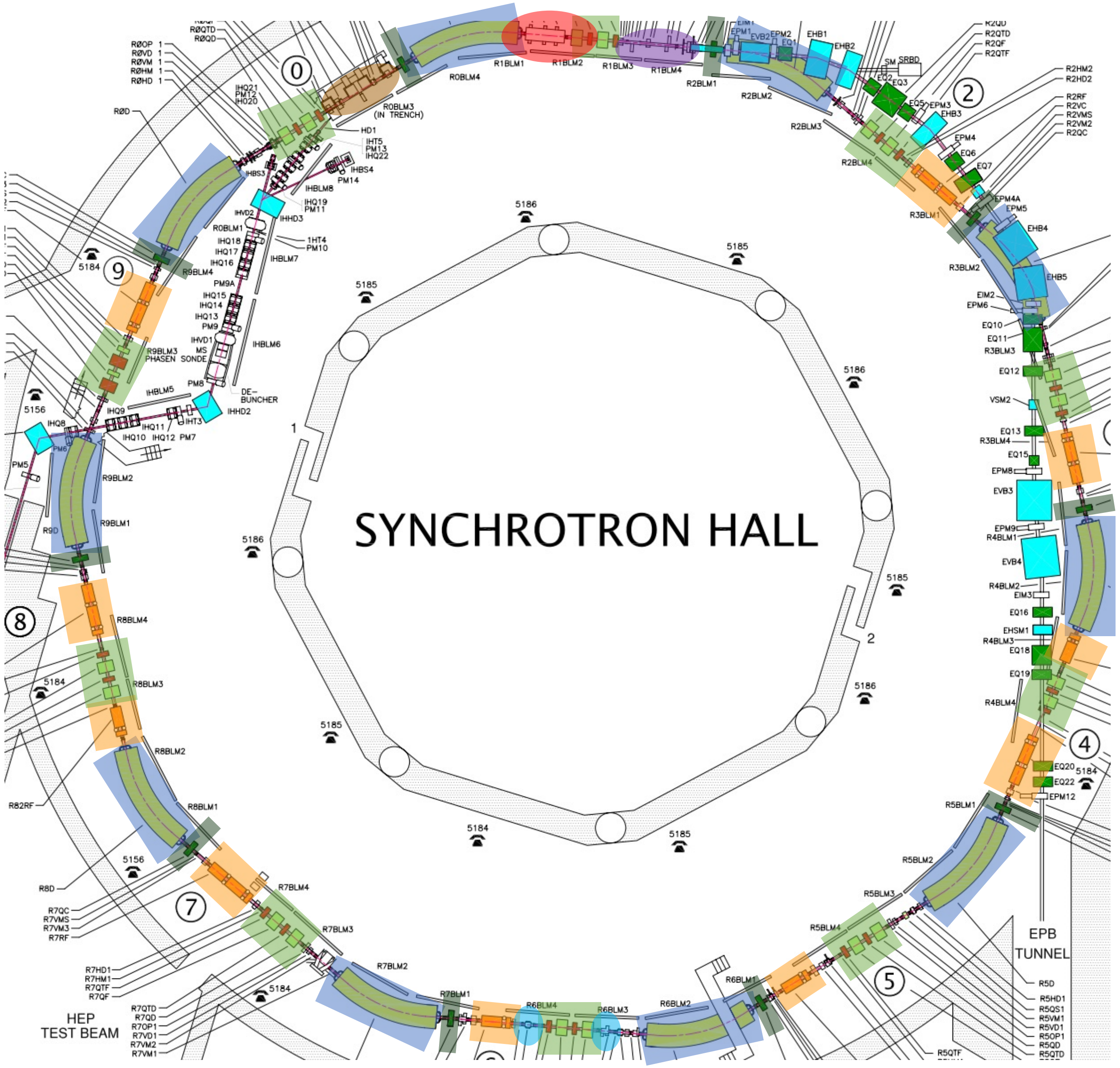
- Until now, ISIS has assumed a cylindrical stainless-steel pipe extending to infinity and neglected inductive bypass.
  - Can under-or-over estimate at low frequency.
- To improve this, developed "RWAL", based on B. Zotter and R. Gluckstern's formalisms [7-9].
  - Computes resistive wall impedance for cylindrical pipes with up to 5 material layers.
- For more complex geometries, use CST low frequency solver with a current loop excitation.
  - Mimics a low frequency bench measurement.



Primary Impedance Candidates

- Vertical resistive wall type:
  - Dipole RF Screens
  - Doublet quadrupole RF Screens
  - Octupoles & gap RF Screens
  - Singlet quadrupoles RF Screens
  - RF cavities
  - Injection dipoles (H-kickers)
  - Collectors (collimators)

- Vertical resonator type
  - Extract kickers
  - Betatron exciters
  - Equipment with lumped components (e.g., RF screens in all magnets)



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3.1 - Resistive Wall Impedances

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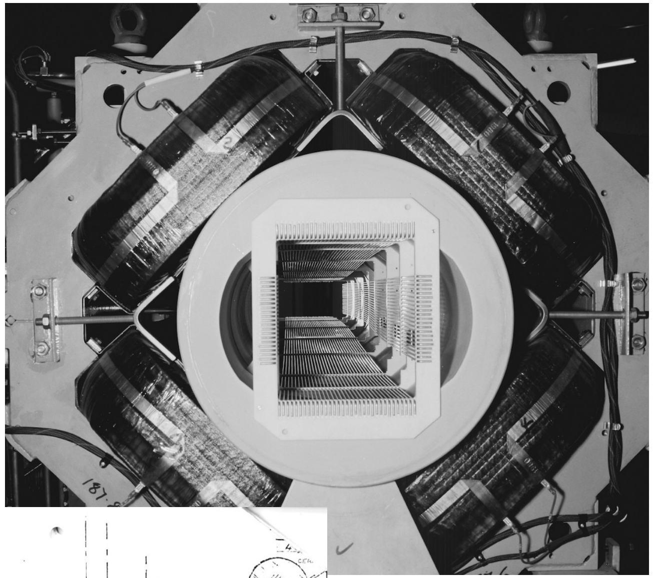
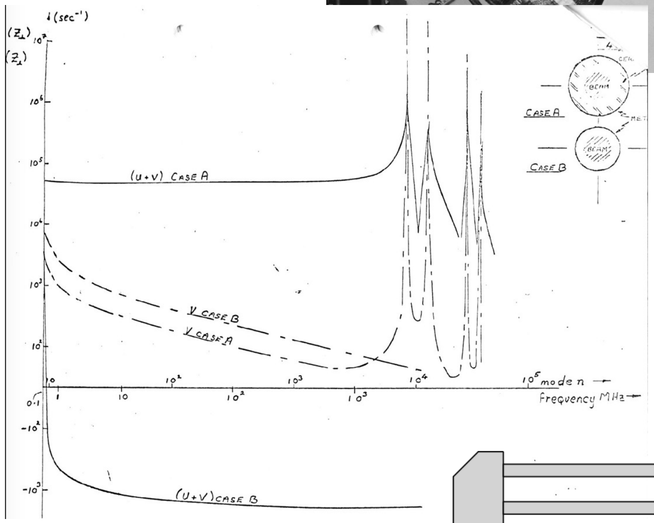
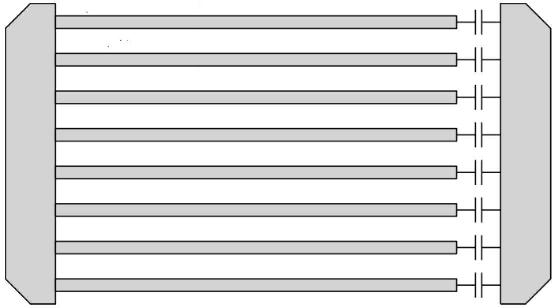
RF Screen - Geometry

- Vacuum chambers inside the AC magnets of an RCS cannot be made from solid conductors due to eddy currents effects [10].
  - 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.





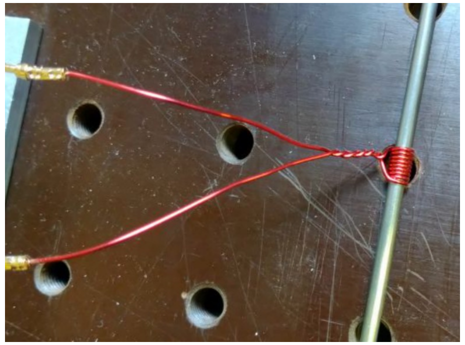


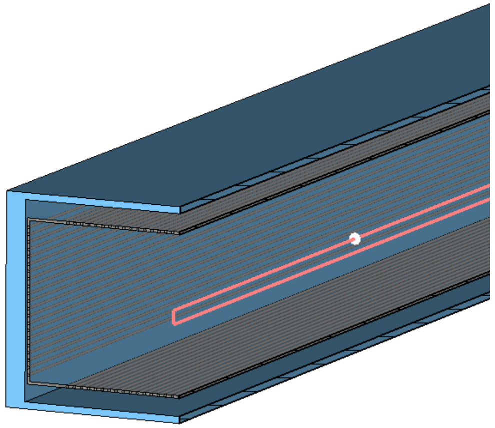
RF Screen – Resistive Wall Impedance

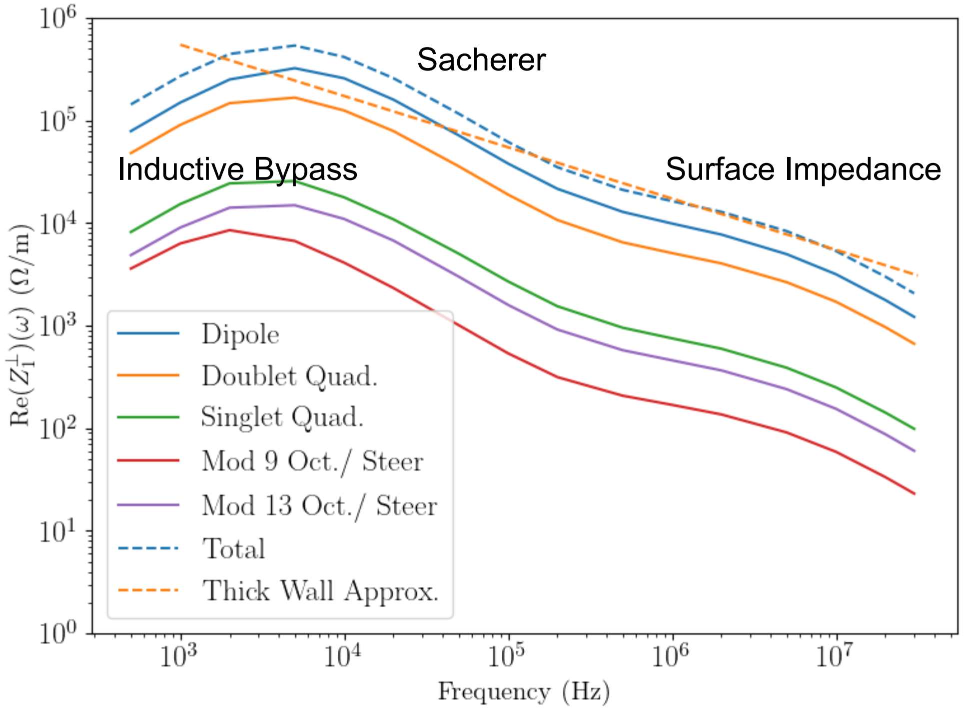
- Measured wire conductivity using eddy current probe technique [11].
  - Wrap coil around screen wire, measure resistance.
  - Subtract resistance of coil in free space.
  - Use root finder to estimate conductivity.

- 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.







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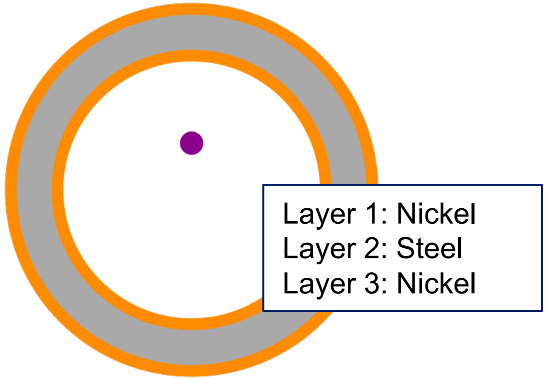
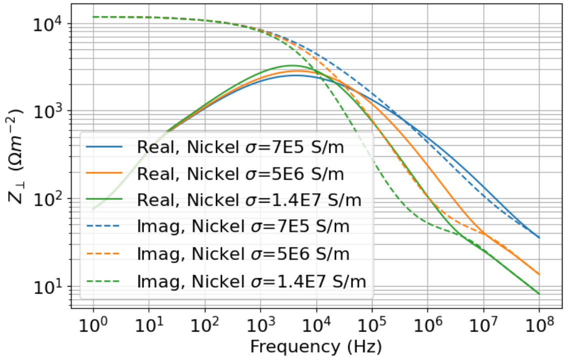
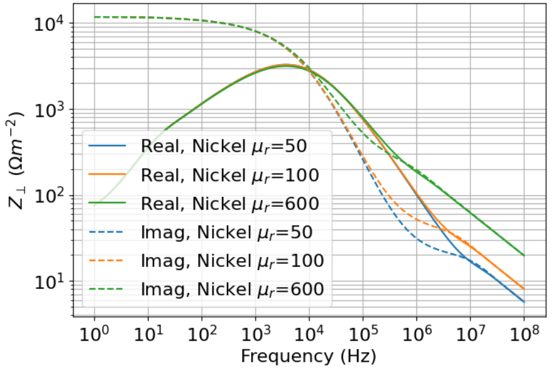
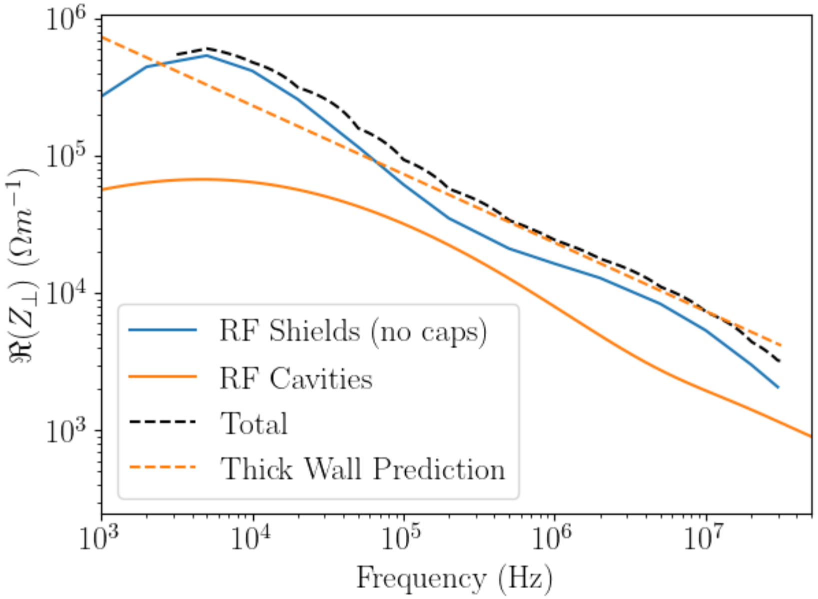
RF Cavity Resistive Wall

- ISIS uses ferrite-loaded fundamental and second-harmonic cavities.
  - Vacuum vessel is nickel plated, mild steel, which is used for magnetic shielding [12].
- Detailed properties about the nickel coating are unknown, and published properties vary widely.
  - Methods such as the eddy current probe are not necessarily applicable, because of nickels nonlinearity.
  - Use RWAL to investigate a range of parameters
- Use the “worst case scenario” for the impedance.
  - Took the result which maximise difference in impedance between baseband and first harmonic.









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3.2 - Resonator Impedances

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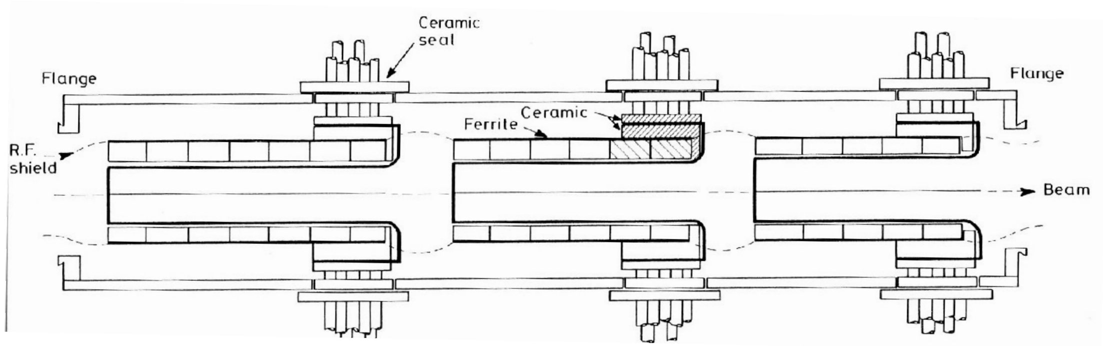
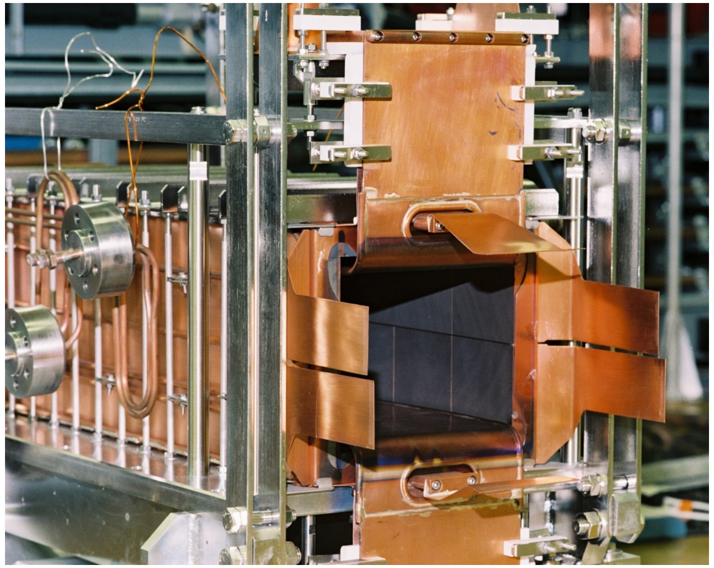
Extract Kickers

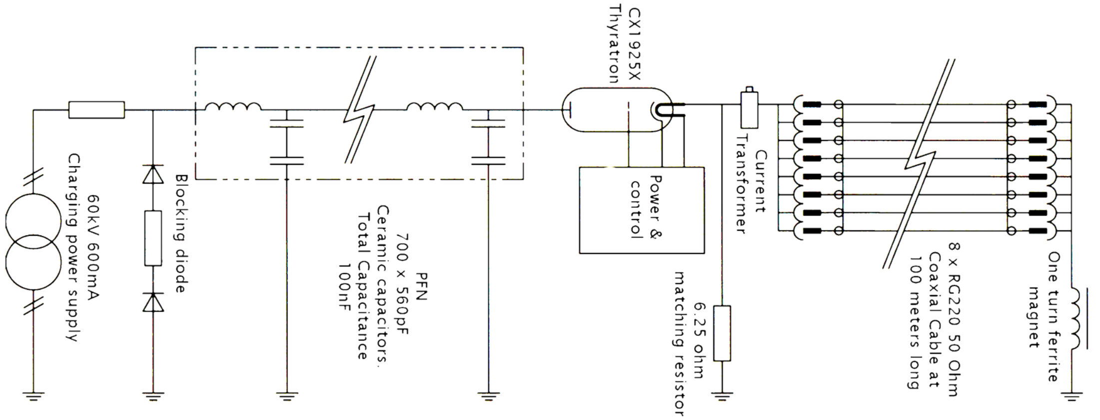
- Kicker magnets are a common cause of low-frequency, narrowband transverse impedances in the plane that they kick [13, 14].

- ISIS has three vertical extraction kickers.
  - Lengths differ, but are otherwise similar
  - Kickers all have window-frame ferrite (8C11)
  - Opposing plates driven with opposite polarity by 8x 50Ω, ≈100 m long, RG220 cables.
  - Plates shorted on upstream side.

- They were designed with 6.25Ω terminating resistors.







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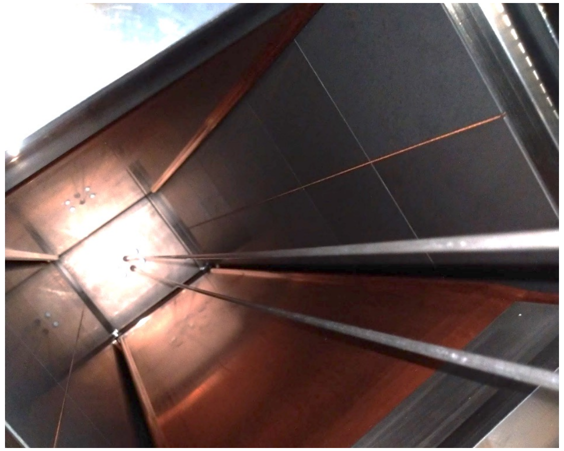
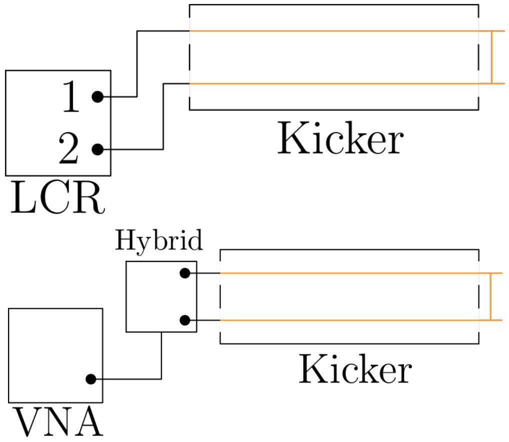
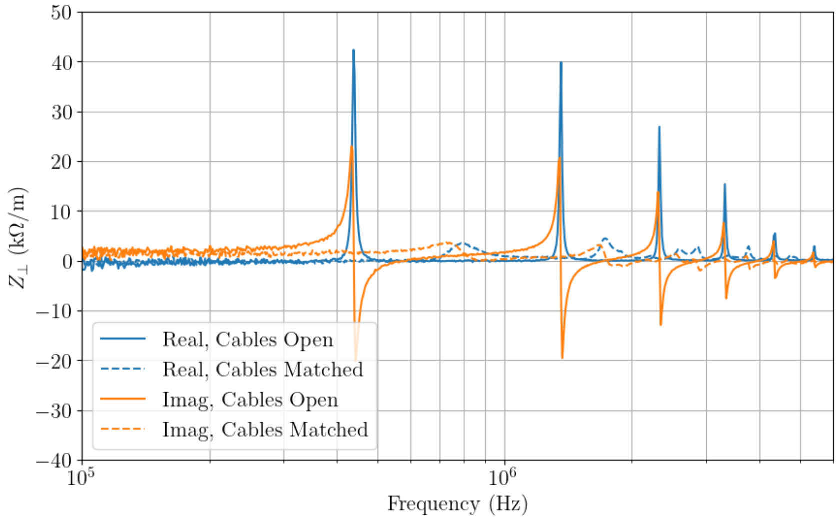
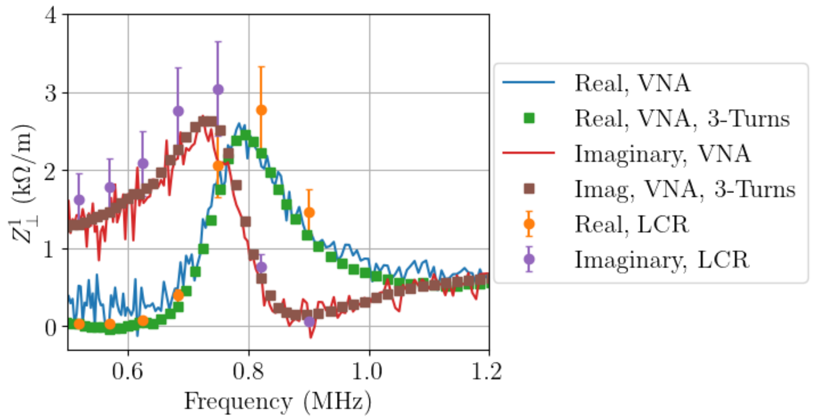
Extract Kickers

- Loop measurements performed on spare kicker.
  - Reference made by shorting the kicker connectors.
- Without termination, first resonant frequency of in $Z_\perp^1(\omega)$ expected at quarter-wavelength of cable.
- Without resistors, see resonances from 450 kHz and amplitude of ~ 42 kΩ/m
- Order of magnitude reduction with resistors.
  - First resonance amplitude is ~ 3 kΩ /m
  - Also moved to ~ 800 kHz
- Verified with three-turn-coil and LCR measurement.









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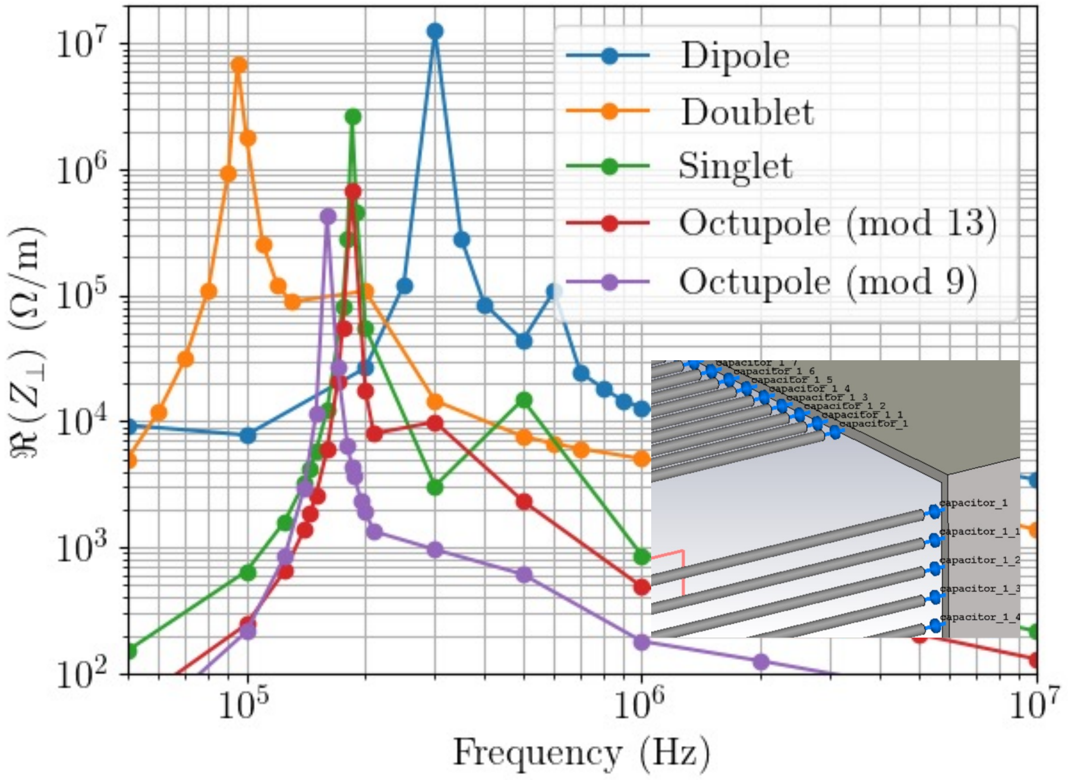
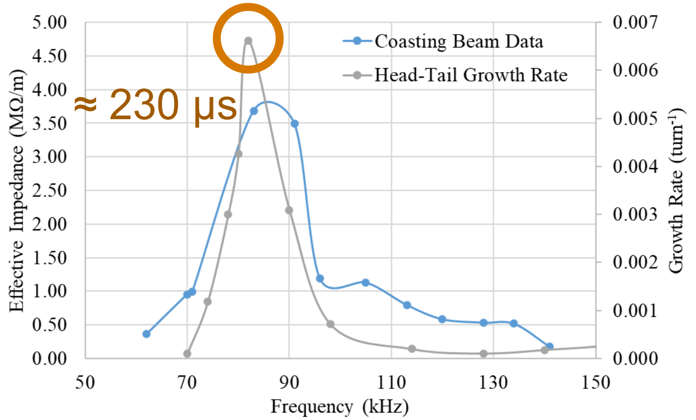
RF Shields with Capacitors

- 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.
- Observe narrowband impedances (Q≈15-30) in the 100 kHz frequency range.
  - 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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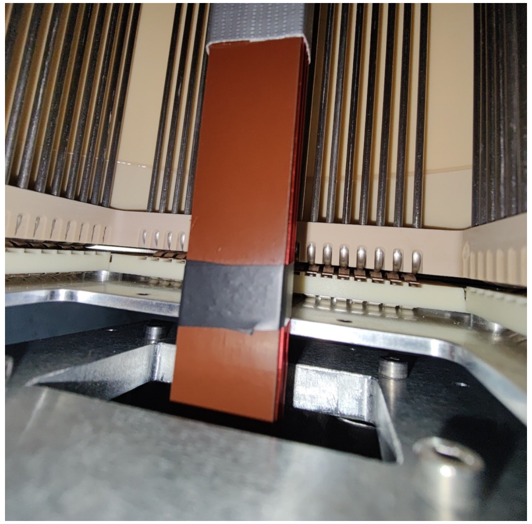
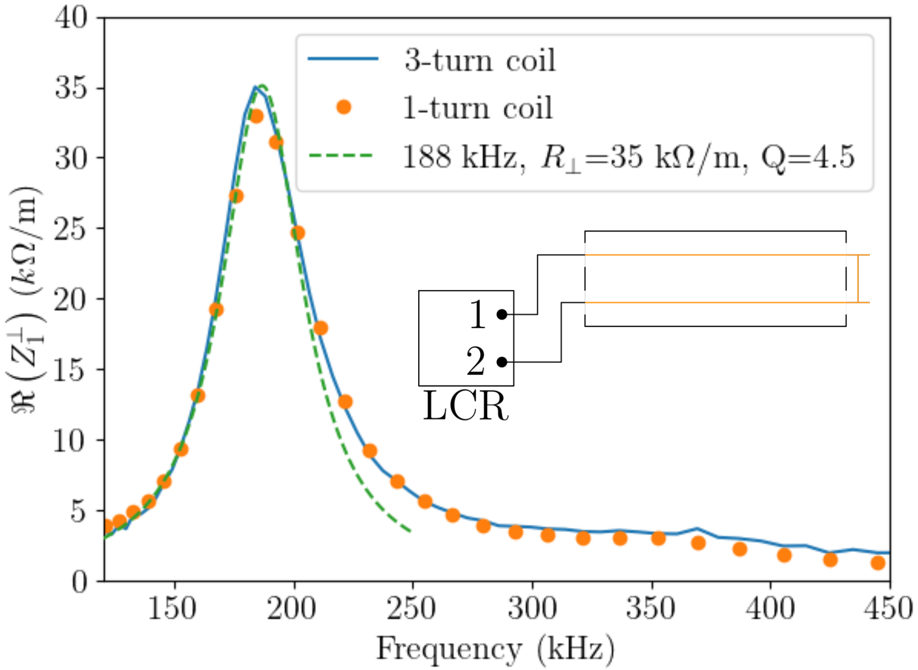
RF Shields with Capacitors – Preliminary Measurement

- Probe coil measurement using a singlet are currently being performed.
- **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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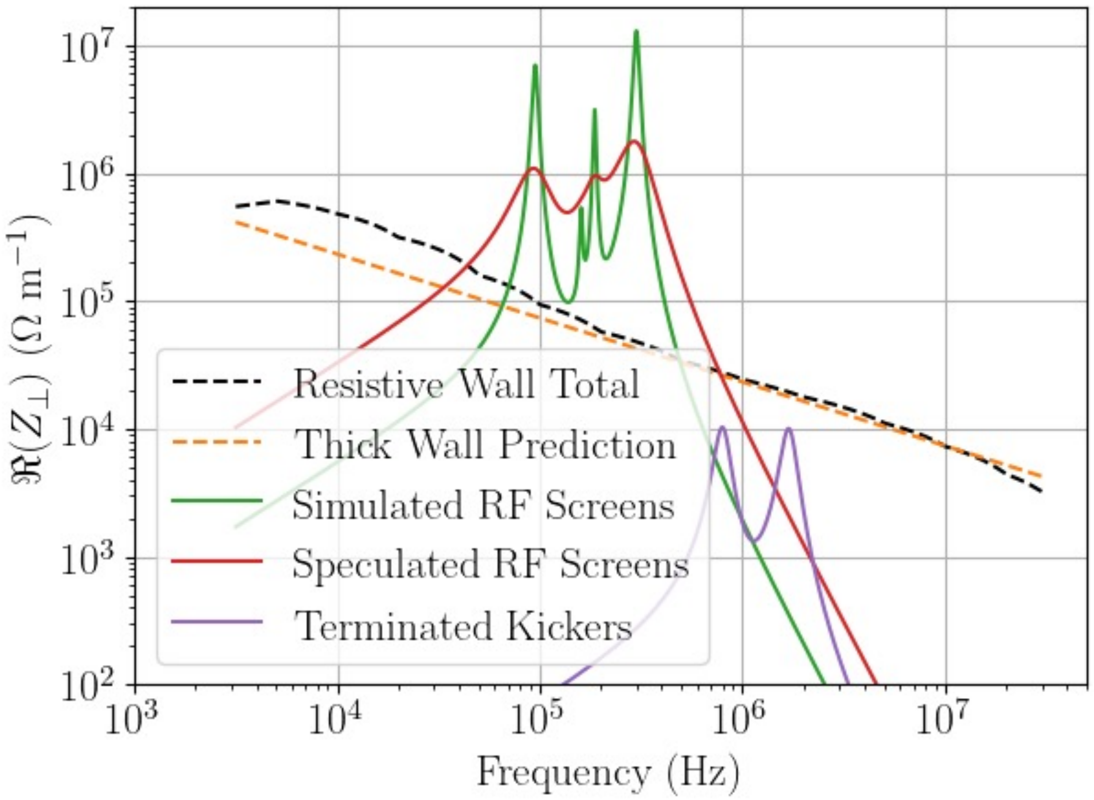
Vertical Impedance Model Summary

- **The original thick resistive wall model is reasonable approximation above ~ 500 kHz - 1 MHz.**
  - Plotted is for ~70% of circumference, remaining 30% assumed.
- Terminated extract kickers contribute relatively small peaks and **will be neglected**.
- Simulations & preliminary measurements suggest the RF screens cause low frequency resonant impedance.
  - So far results agree that **amplitudes are order-of-magnitude larger than resistive wall**
- For now, consider thick wall plus 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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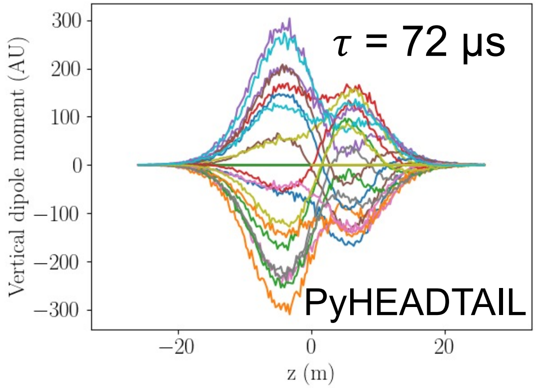
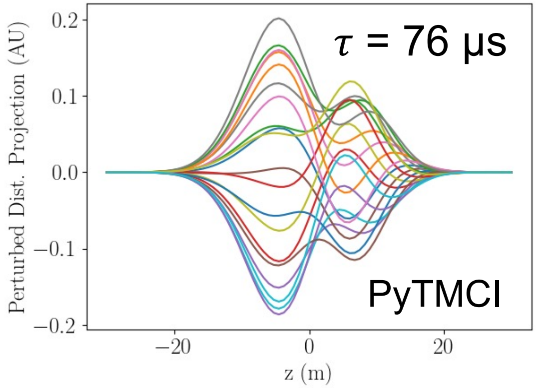
PyTMCI - Vlasov Solver

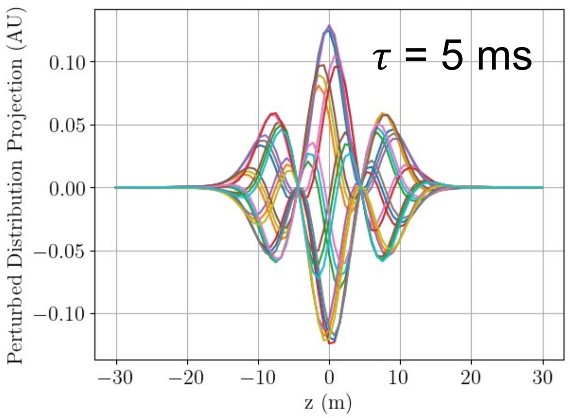
- Simplified formulae do not provide the most accurate analytical predictions available.
- Implemented new head-tail Vlasov solver, PyTMCI.
  - Open-source python package
    - https://github.com/stfc/PyTMCI
    - `pip install PyTMCIVlasov`
  - Three longitudinal models (Laguerre poly [15], NHT[16], airbag[17])
  - Multiple frequency approximation options [17]
    - perturbed frequency ($\Omega \approx \omega\beta + l\omega s$)
    - simplified perturbed frequency ($\Omega \approx \omega\beta$)
    - Broadband ($\Sigma \rightarrow \int$)
- One benchmark is shown against PyHEADTAIL
- Also recreate original ISIS calculation with a thick resistive wall impedance.

Calc. ISIS Params	Value
β	0.45
Q_y	3.83
Q_s	0.015
Chromaticity	-0.5
Num Bunches	1
Long. Model	Gaussian
σ_z	6.5 m
Impedance Model	2.4 MHz Resonator





Calc. ISIS Params	Value
β	0.45
Q_y	3.83
Q_s	0.015
Chromaticity	-1.4
Num Bunches	2
Long. Model	Gaussian
σ_z	6.5 m
Impedance Model	Thick RW



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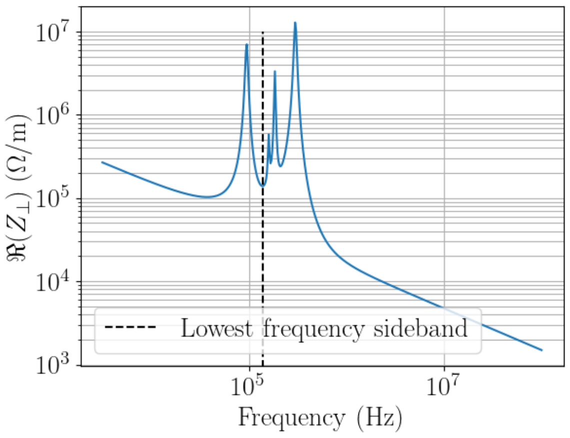
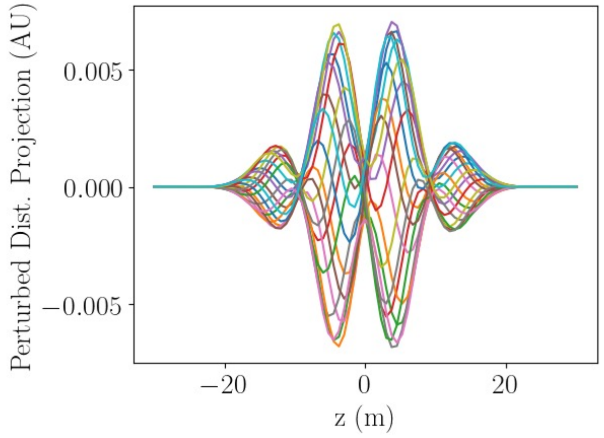
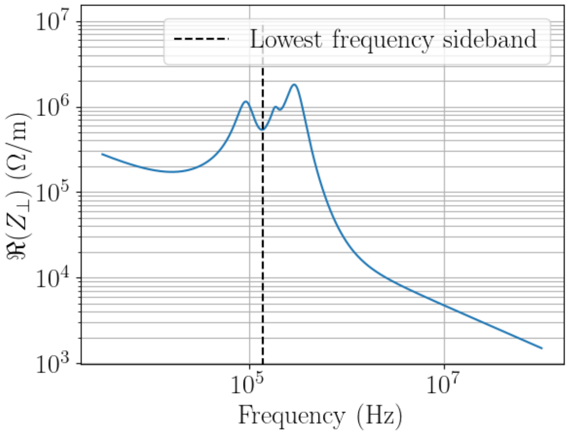
PyTMCI – Application to ISIS

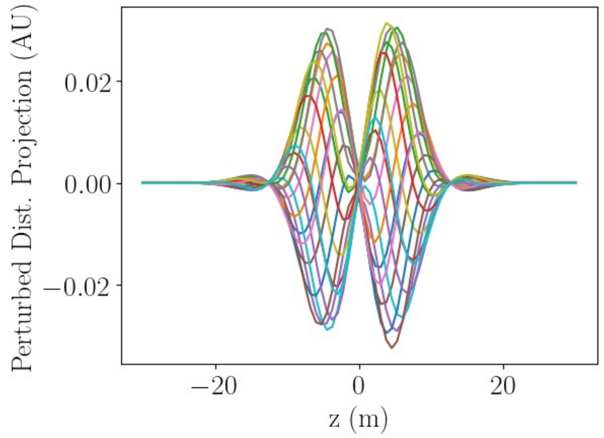
- With RF shield impedance from CST + thick resistive wall impedance.
  - Mode -3, $\tau \approx 440$ μs.
  - Centre of bunch oscillates with larger amplitude than the edges.





- Based on the singlet measurements, speculate that other magnets have 6.7x reduction in Q and 7.5x reduction in $R_\perp$.
  - PyTMCI predicts Mode-1, $\tau \approx 175$ μs.





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5. Conclusion

- A detailed resistive wall model has been developed, by itself it cannot explain observed instability.
- Measurements on spare extract kicker suggest its contribution at low frequencies is suppressed due to its terminating resistors. Extract kicker contributions have been neglected for the overall model.
- CST simulations suggest the low-frequency vertical driving impedance on ISIS is dominated resonance 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, 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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