FIDA observations of the effects of fast-particle-driven MHD in MAST

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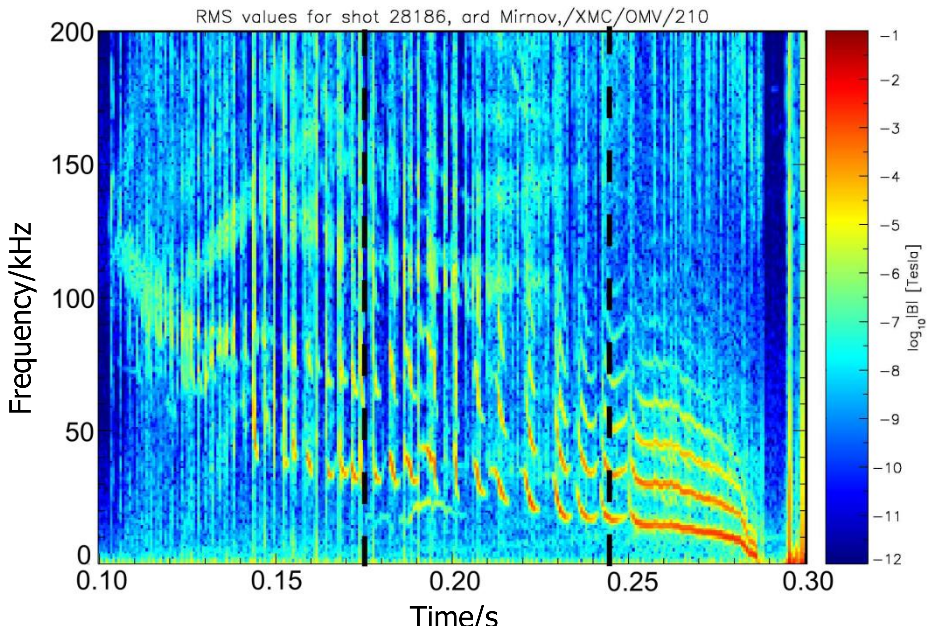
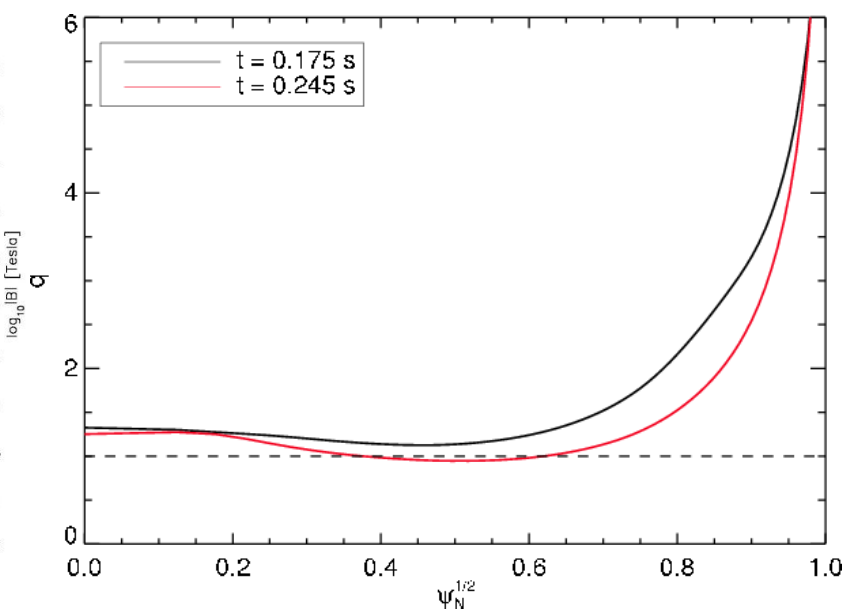
Introduction & Motivation

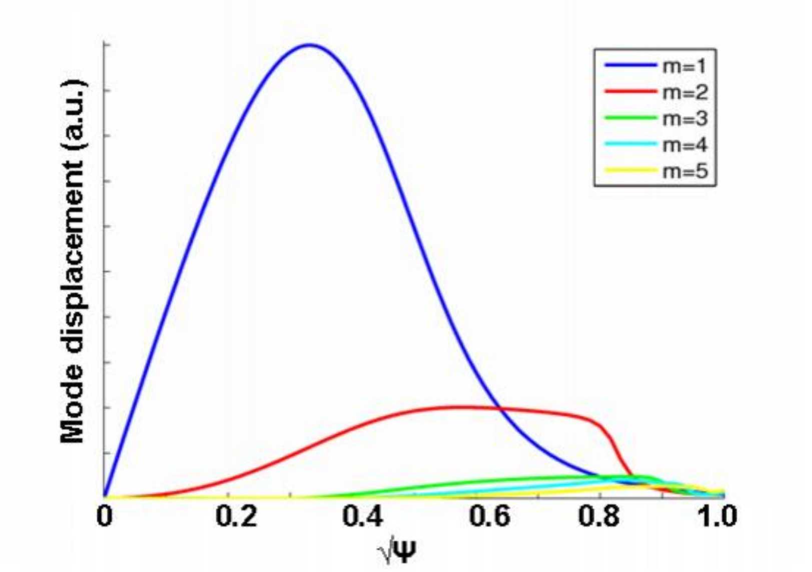
- MHD modes driven by fast ions in MAST take a variety of forms. The two which we are interested in here are the low-frequency (20 – 50 kHz) *fishbones* and *long-lived mode* (LLM).
- Both fishbones and the LLM are observed to cause strong depletion of the neutron emission from the plasma, implying losses or redistribution of fast ions[1].
- During MAST discharges with a large amount of neutral beam heating power (2 – 4 MW), these modes are ubiquitous.
- Fishbones are observed to evolve into the LLM later in the discharge…

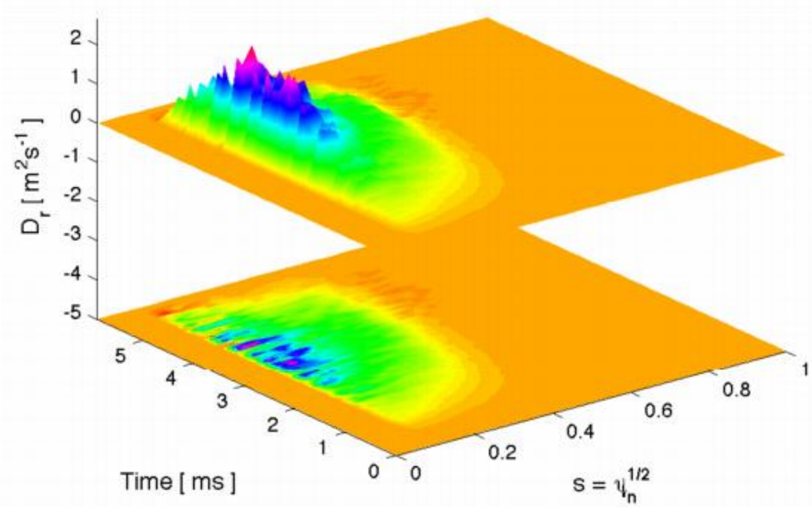




Theoretical understanding

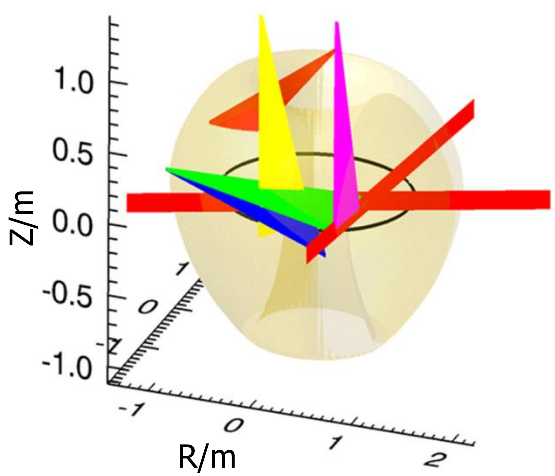
Fishbone	LLM
Energetic particle mode[2]	Ideal MHD mode[7]
Driven by bounce/ precession & transit resonances with trapped & passing fast ions[3]	Stability modified by fast particle population: becomes unstable at finite Δq[7]
'Infernal' kink-ballooning mode structure (n = 1, $m \geq 1$)[4]	Pure internal kink mode structure (n = 1, m = 1)[7]
Predicted to cause effective radial drift of fast ions, equivalent to 'anomalous' diffusion[4,5]	Effects on fast ions starting to receive theoretical attention[8]
Frequency chirp spreads impact throughout phase space[6]	Static/slowly evolving in frequency with plasma rotation[7]

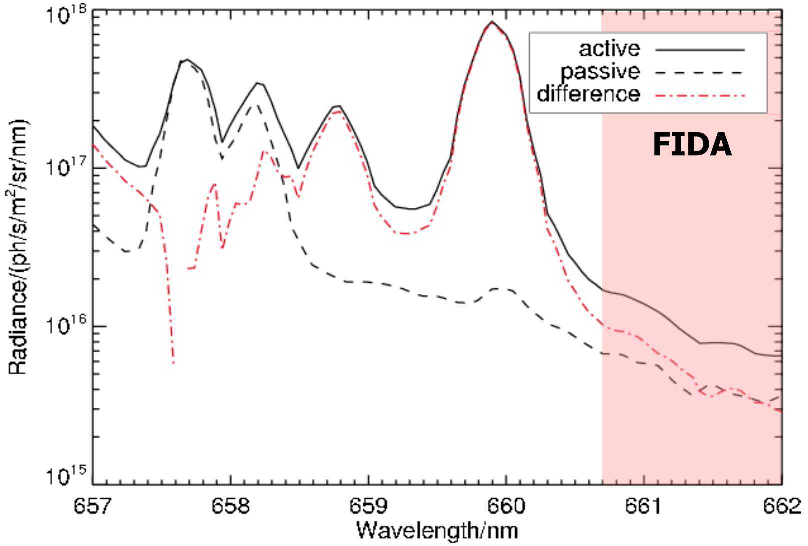




FIDA diagnostic

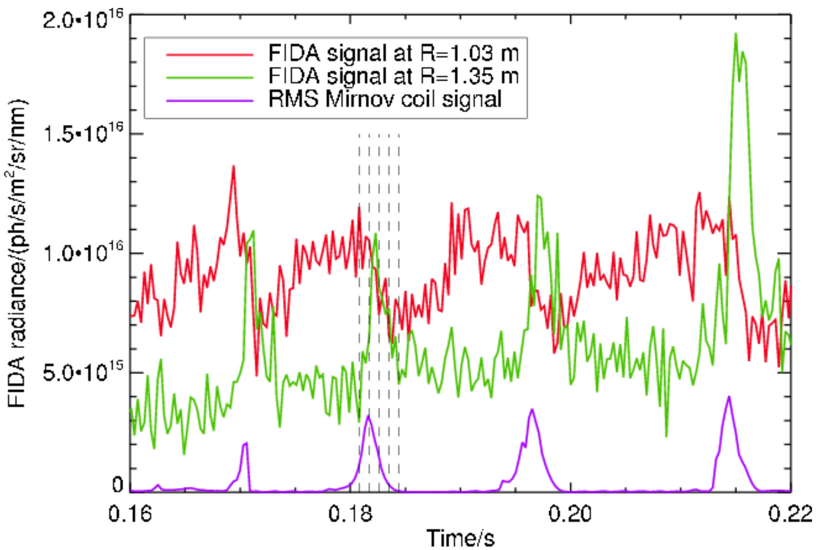
- Fast-Ion Deuterium Alpha spectrometer installed on MAST in 2010, operational throughout M8 experimental campaign[9].
- Based on charge exchange between fast ions and beam neutrals; the Doppler shift of D_α emission from 656.1 nm gives the velocity of the re-neutralised fast ion along the line of sight.

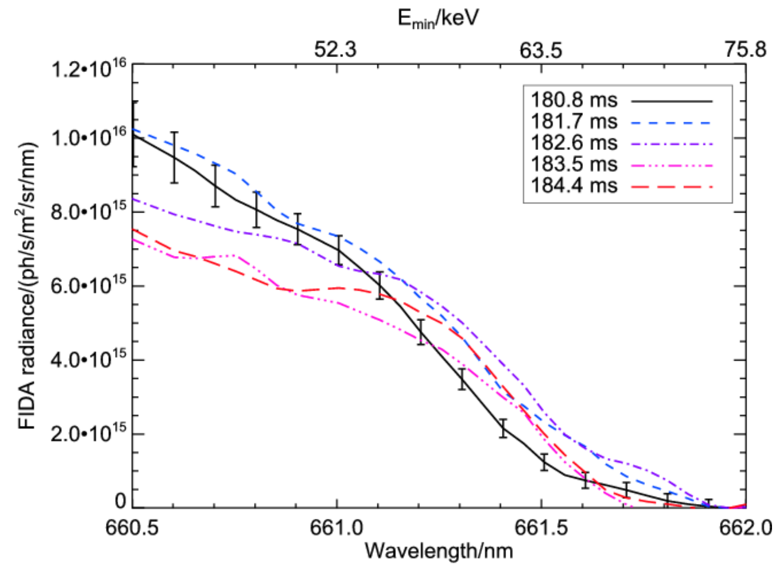


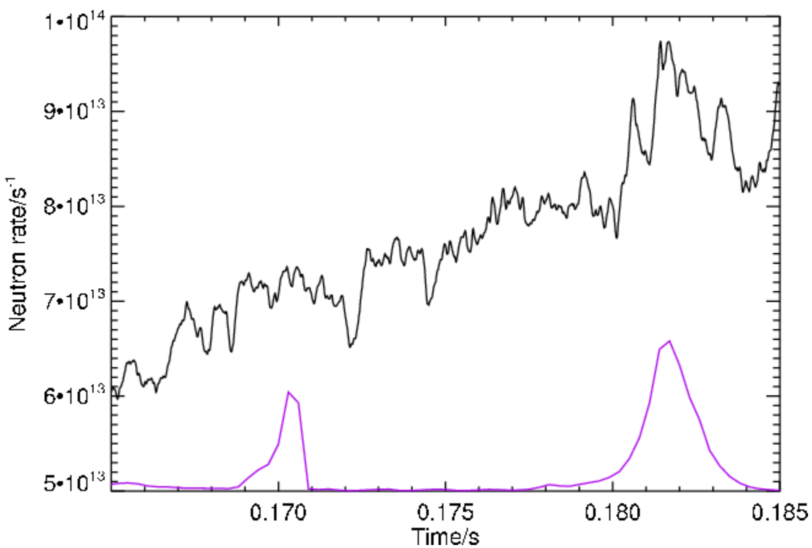


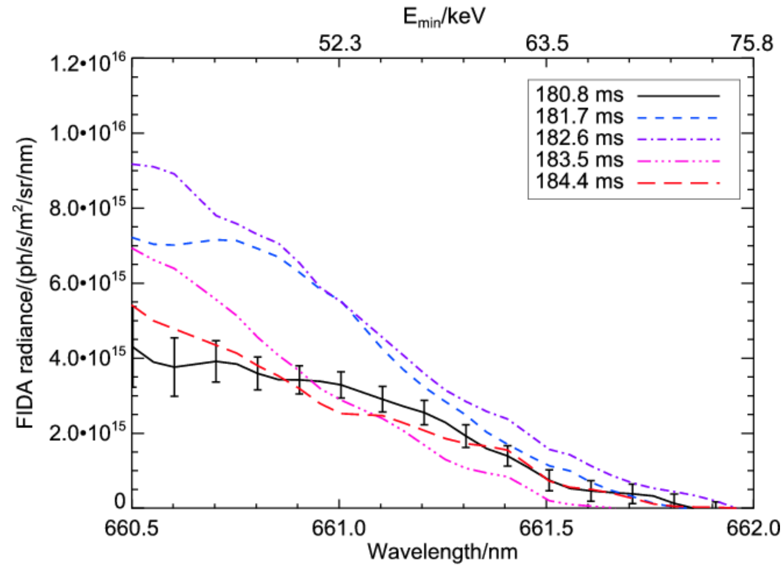
- Signal to noise ratio limits practical temporal resolution to 0.3 ms.
- Spectral resolution 0.3 – 0.6 nm (depending on slits used).
- Spatial resolution parallel to line of sight set by extent of beam and halo neutrals (~20 cm). Perpendicular resolution set by re-neutral velocity and decay time of D_α transition (~2 cm).

Fishbones in detail



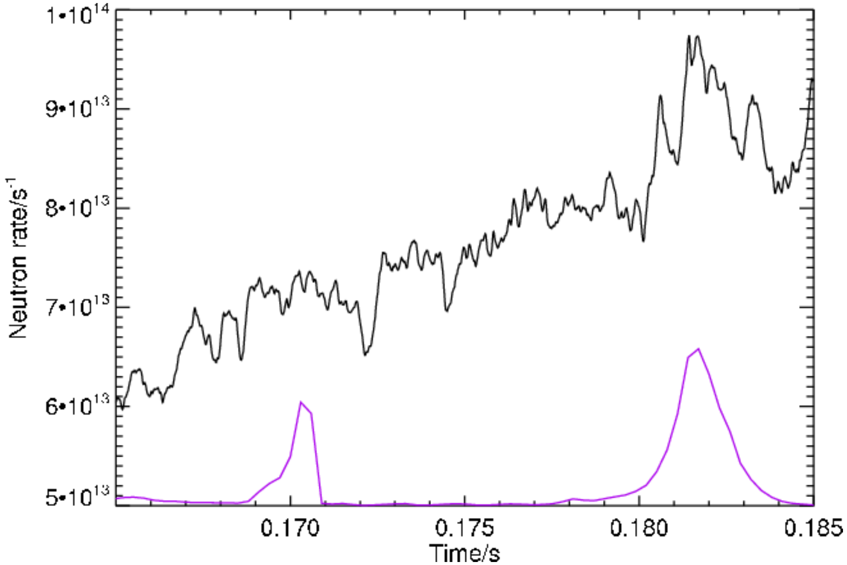


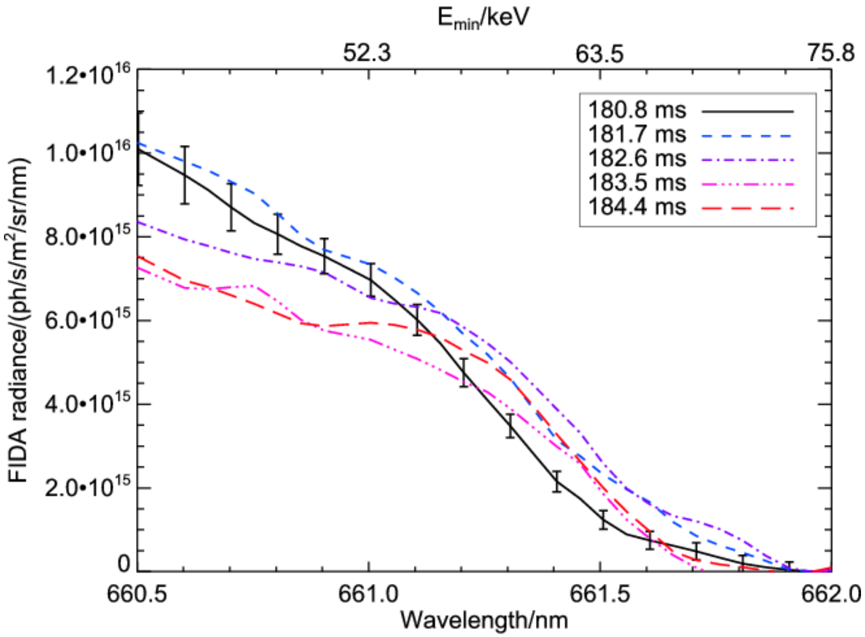


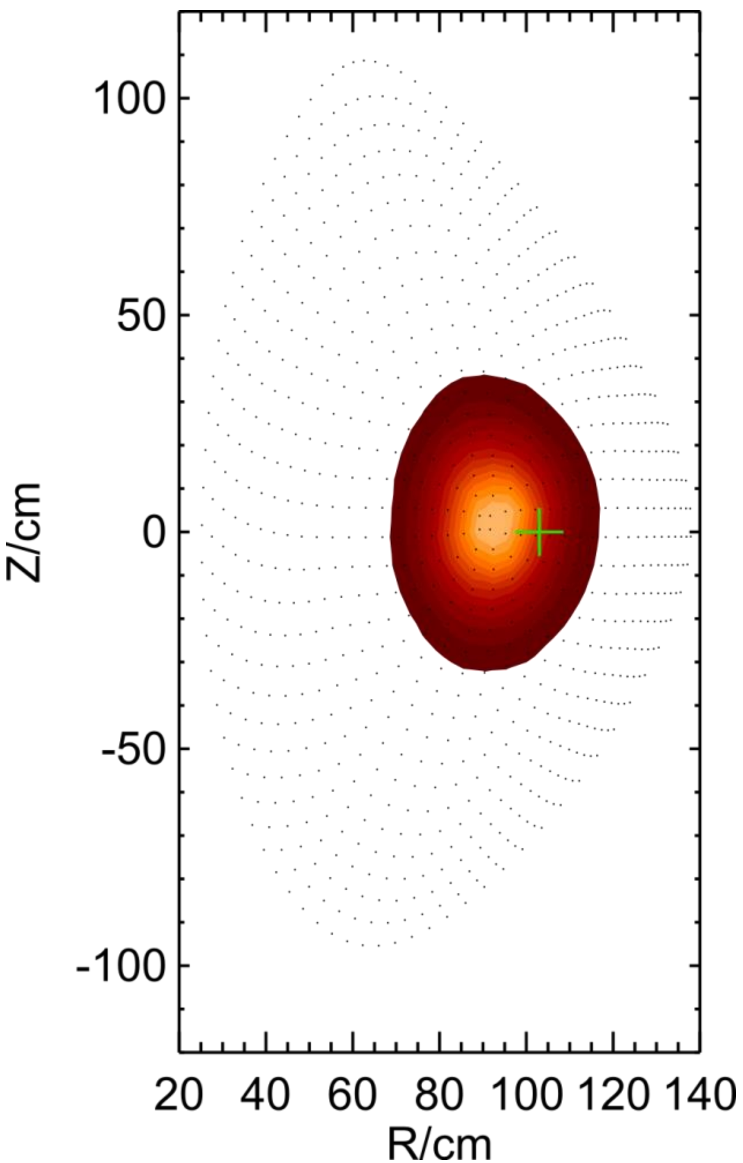


- Data at edge affected by incorrect background subtraction of passive FIDA.

Fishbones in detail

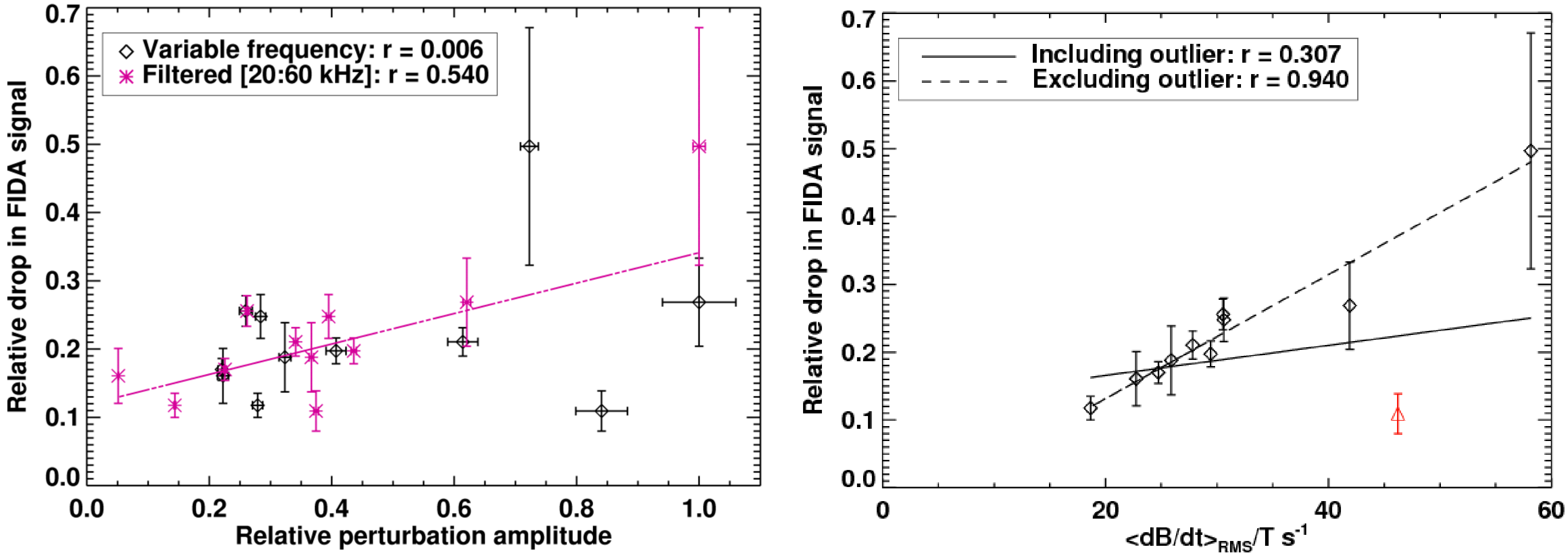






Magnitude of the change in FIDA signal

- Correlation with amplitude of magnetic perturbation is weak.
- Under certain conditions, the relative drop in FIDA signal is seen to be strongly correlated with the RMS amplitude of the Mirnov coil signal, i.e. with $<\partial B_\theta/\partial t>_{RMS}$.

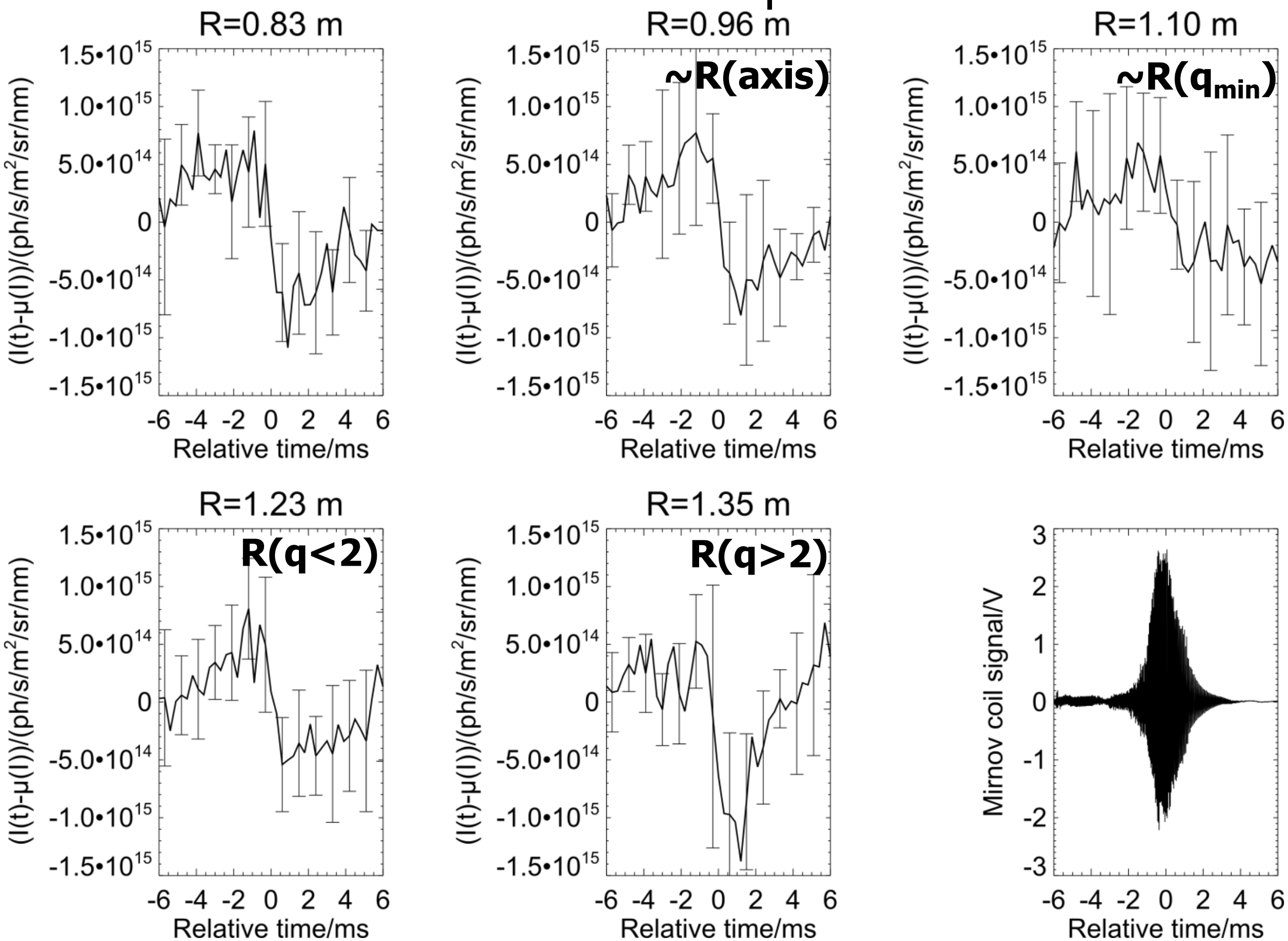


- Gradient of line of best fit and strength of correlation vary depending on the plasma scenario.

0.540 for df=9 is significant at 10% level. Removing the same point ('outlier') in integrated amplitude plot changes r to 0.682; significant at 5% level for df=8.

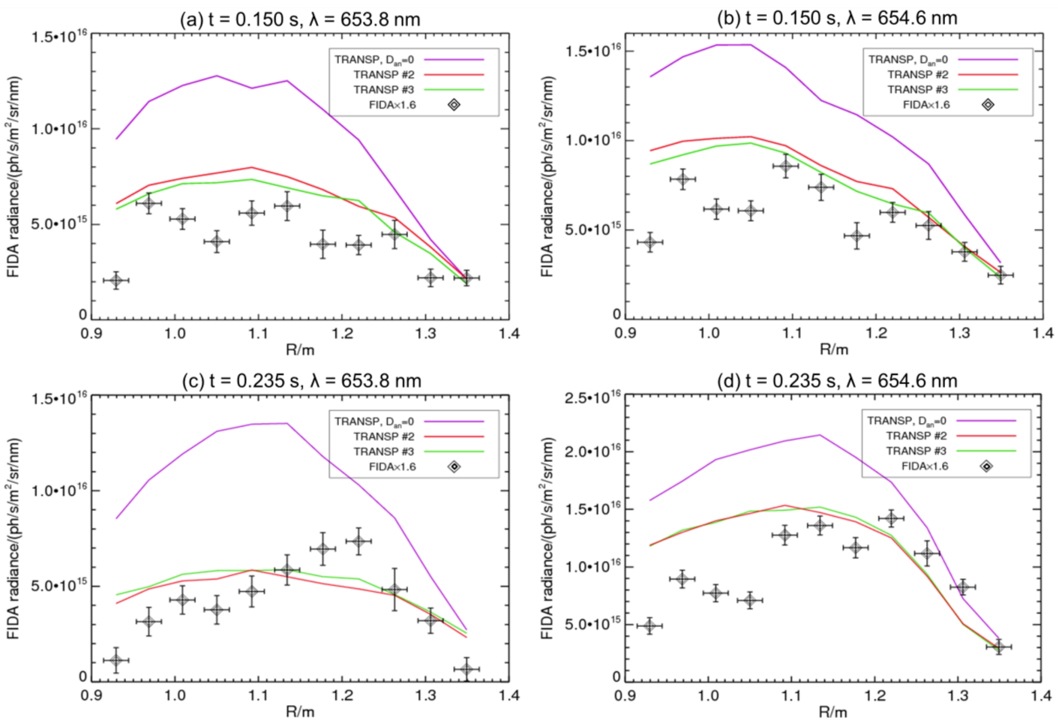
The ‘composite’ fishbone

- FIDA signal centred on five events from three nominally identical shots.
- Mean subtracted from FIDA signal in each time window, but no normalisation performed.
- Error bars from natural variation of sample.

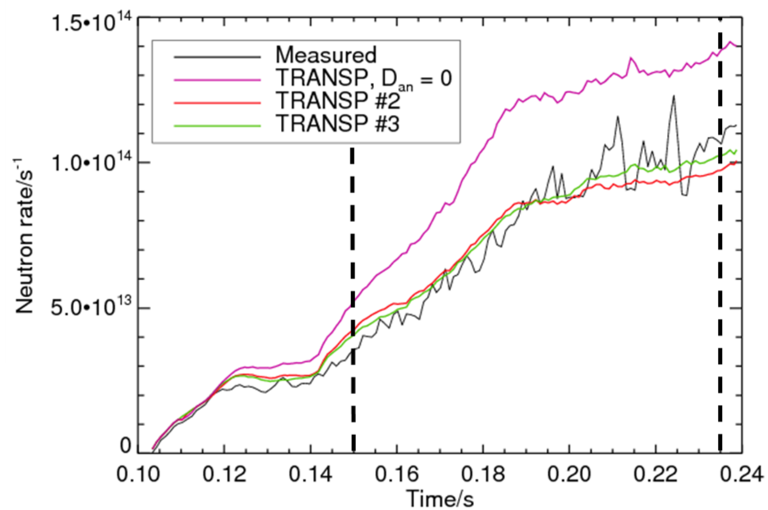


Effects of the LLM

- The LLM is observed to cause a strong depletion of the FIDA signal in the core of the plasma.
- Signal at outer radii increases, suggesting spatial redistribution.
- Effect persists for as long as the mode remains active.



Spatially-uniform anomalous diffusivity introduced into TRANSP simulations reproduces the neutron rate, but fails to account for the core-localised depletion of the FIDA signal.



	t = 0.150 s	t = 0.235 s
TRANSP #2	1.4 m^2/s	1.8 m^2/s
TRANSP #3	1.8 m^2/s	1.7 m^2/s

Conclusions

- The first systematic study with a FIDA diagnostic of fast-ion redistribution due to fishbones has been carried out on MAST[11].
- Fishbone-induced redistribution spans the range of wavelengths corresponding to LOS-projected kinetic energies from 30 keV up to 95% of the primary injection energy. Probably extends to lower energies too.
- Redistribution seen out to at least mid radii: consistent with model of mode with large m=1,2 amplitude between axis and *q*=2 surface.
- Core emissivity behaves appropriately for a *limit cycle*: fast-ion pressure gradient builds to the point where the mode is driven unstable; mode grows, causing outward radial transport of fast ions; pressure gradient is reduced and mode is stabilised; cycle repeats.
- As far as energy selectivity of DD fusion allows, behaviour of FIDA signal is seen to be consistent with that of neutron signal.
- Under at least one of the scenarios considered, relative change in FIDA signal is seen to be strongly correlated with maximum *time derivative* of magnetic perturbation.
- Core fast-ion density is depleted by the LLM, and the fast ions appear to be pushed out to larger minor radii; this redistribution persists while the mode remains active.

Conclusions and further work

- Correlation between drop in FIDA signal and peak RMS time derivative of magnetic perturbation:
  - White *et al.* (1983): "Particle loss due to mode pumping is a linear function of mode amplitude"[4].
  - Hsu *et al.* (1994): Radial convection proportional to mode amplitude and rate of frequency sweeping[6].
  - Potential applicability of 'hole-clump' model (Berk, Breizman & Petviashvili, 1997)[10] to fishbones is unexplored…

- Dedicated experiment to examine effects of fishbones, performing a controlled TF scan (10 shots, shared with neutron camera group).
- Solve existing calibration consistency problem to get absolute values, allowing comparison with TRANSP + anomalous diffusion, LOCUST etc.
- Develop forward model of diagnostic to aid tomographic inversion/ Bayesian inference approaches to reconstructing FI distribution.
- Examine shots with fishbones suppressed for further signs of anomalous diffusion. Analyse redistribution due to ELM, NTM and possibly TAE avalanches.

References

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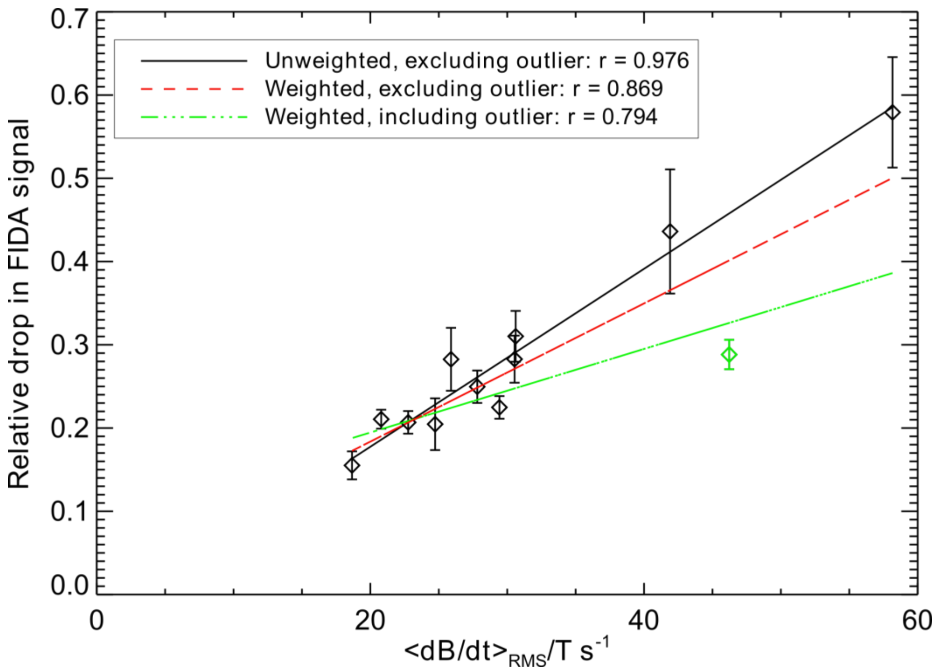
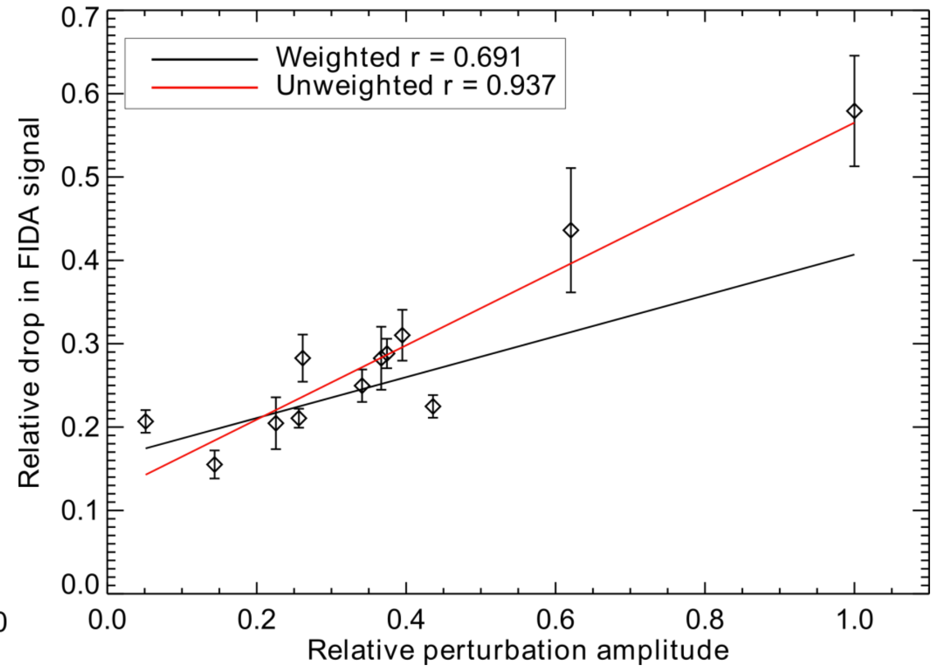
Correlations: a closer look





Analysis of FIDA data was re-done. Correlation with integrated mode amplitude over a 20 – 60 kHz bandpass filter improved, while correlation with time derivative was reduced. Nonetheless, strong correlation with time derivative remains, and is unexplained by present models…

- For time derivative, all values of r significant at 1% or lower.
- For mode amplitude, weighted r significant at 2%.