MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Wendelstein 7-X

Low frequency modes – From intermittent bursts to harmonic oscillations

D. Cipciar, C.Killer, C. Brandt, A. Koenies, A. Stechow, O.Grulke

EUROfusion

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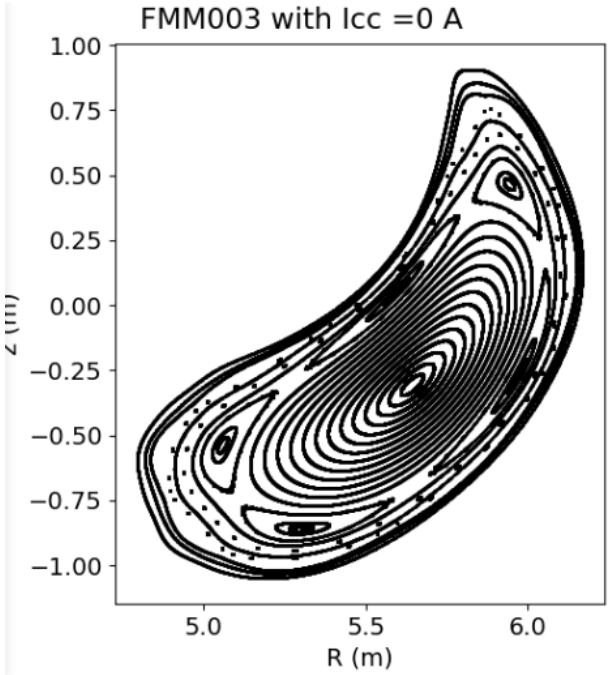
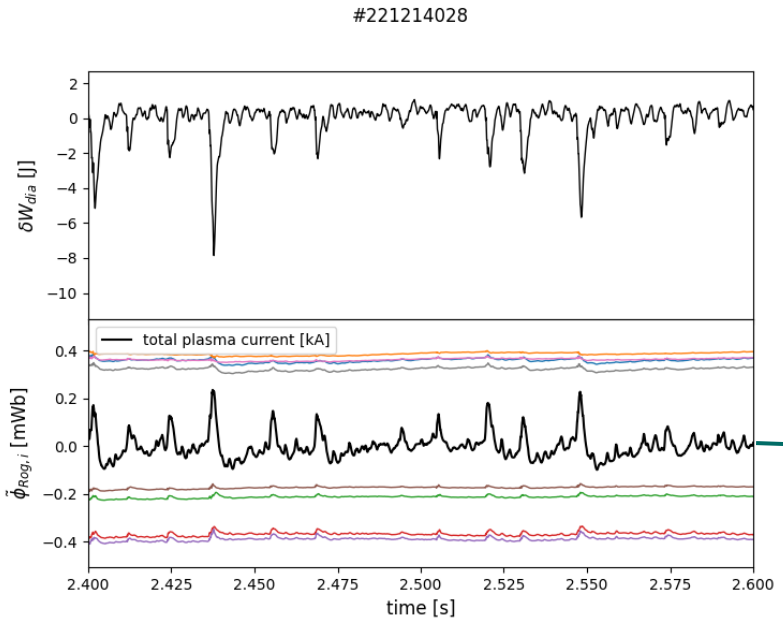
Roadmap

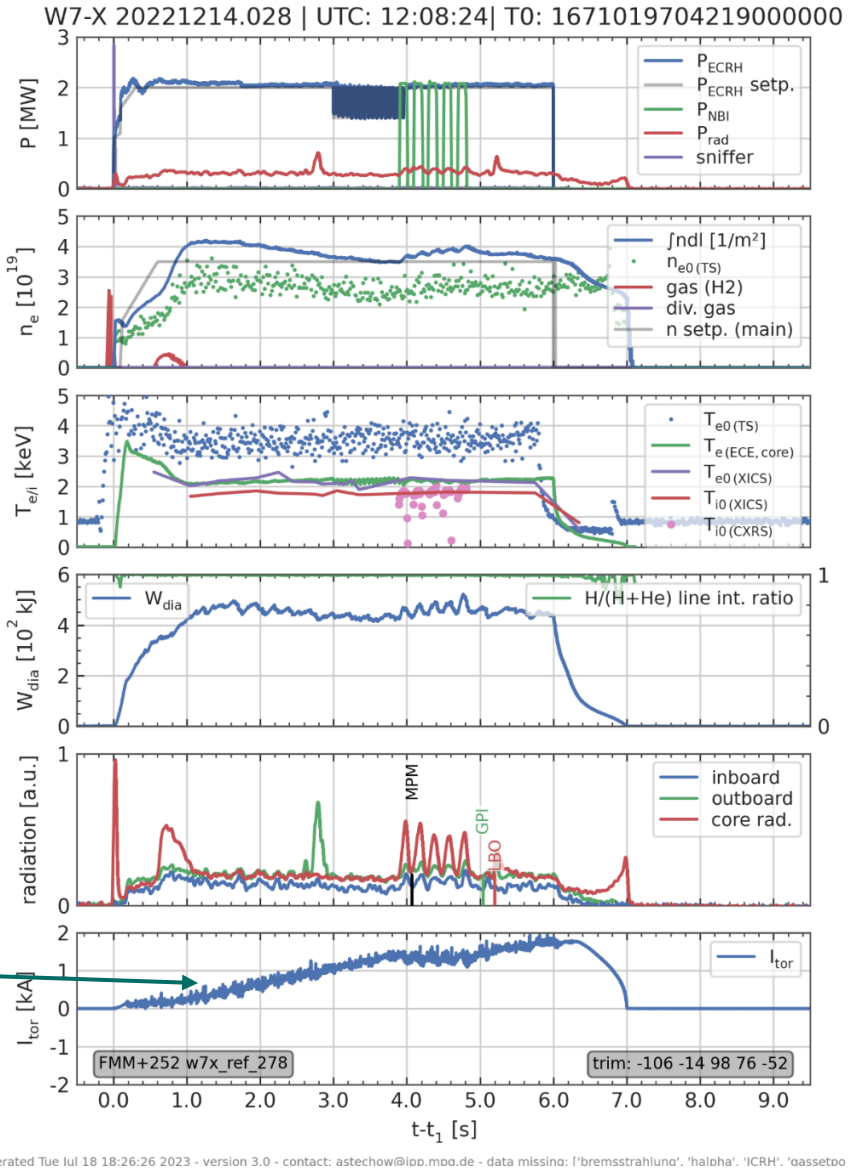
- **Are Low frequency modes Island Localized ?**
  - **FMM (island inside LCFS) case**
    - Overview,
    - ECE measurements,
    - Soft X-ray tomography
  - **EJM (island outside the LCFS) case**
    - Overview,
    - The influence of an island's "o-point",
    - Scaling of the observed frequency ,
    - Soft X-ray tomography
    - ECE radiation temperature cross-correlation
- **Implications for confinement?**
- **Other Low frequency modes**
- **Summary**

Are Low frequency modes Island localized – FMM?

- Intermittent (repetition rate 40Hz – 100 Hz) electromagnetic activity
- Causing broadband “crashes” in e.g. Rogowski coil spectrograms
- observable on virtually all diagnostics.
- In FMM activity is observable with “naked-eye” on Plasma current as spikes or drops, since some events are quite powerful (5% Wdia)

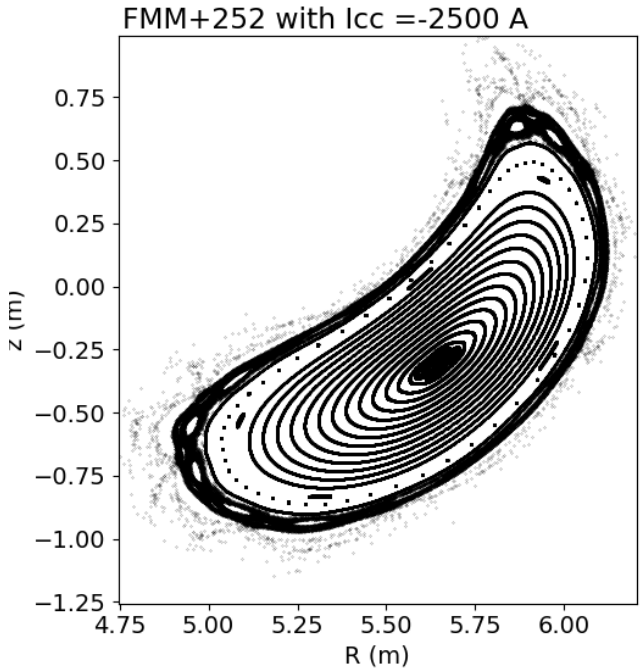


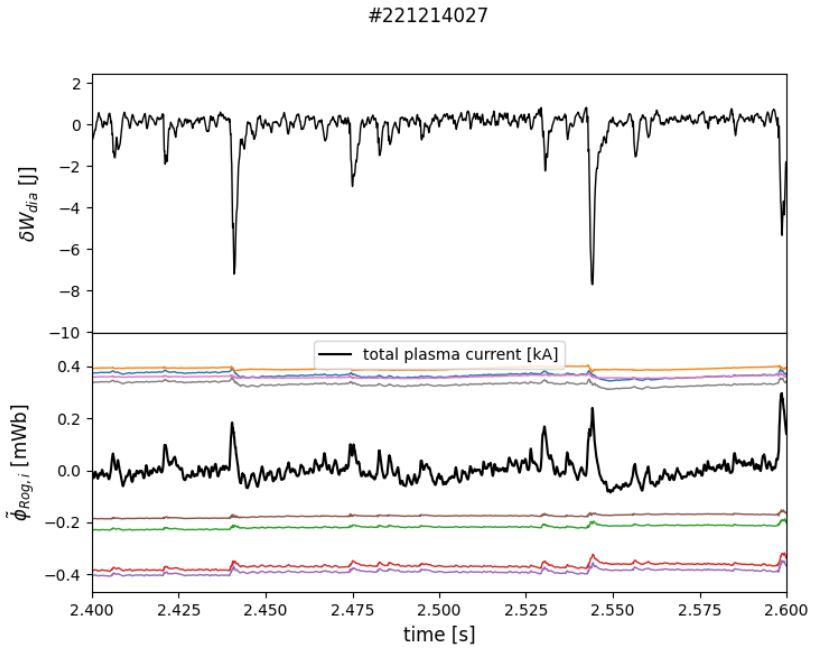


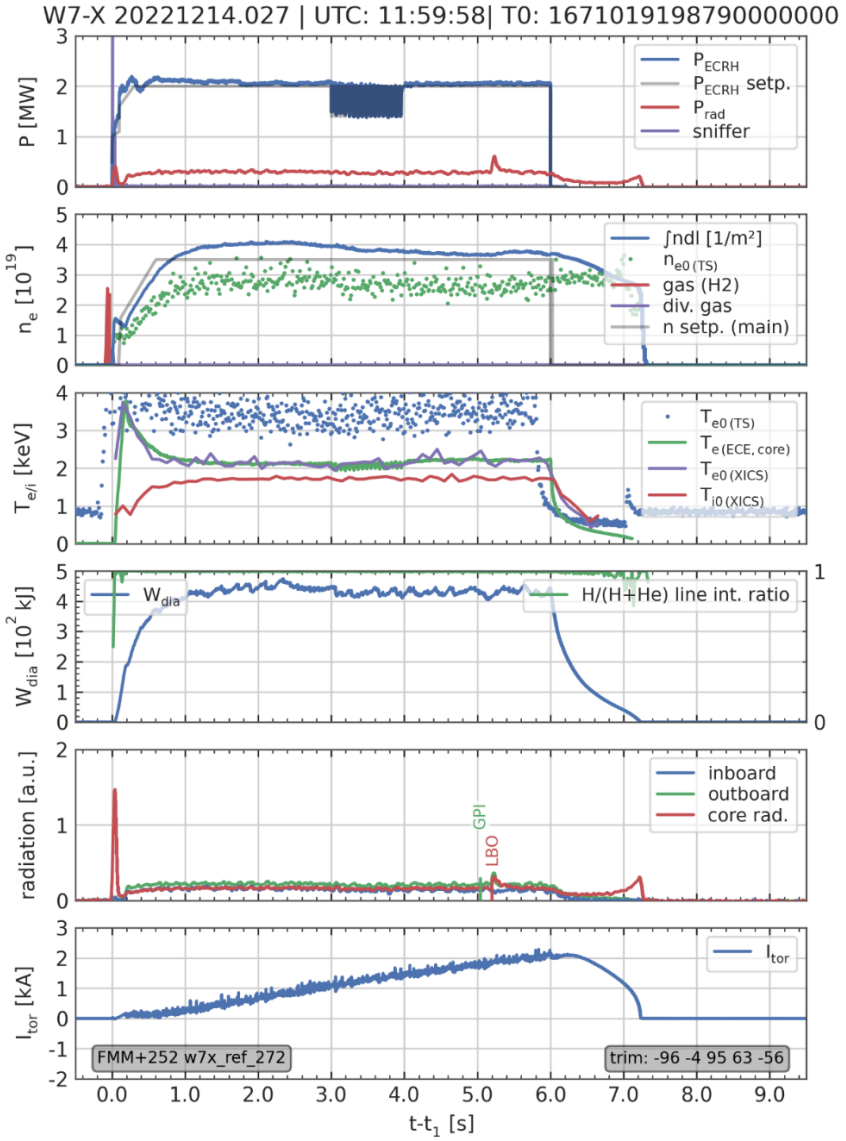


Are Low frequency modes Island localized – FMM?

- Control coils were used to supress the islands, however the activity **remaines the same** even with the same W_{dia} $loss$ of 8 kJ
- $W_{dia} \approx 450\ kJ$ **remains the same**
- This questions whether “ILMs” are **island localized**







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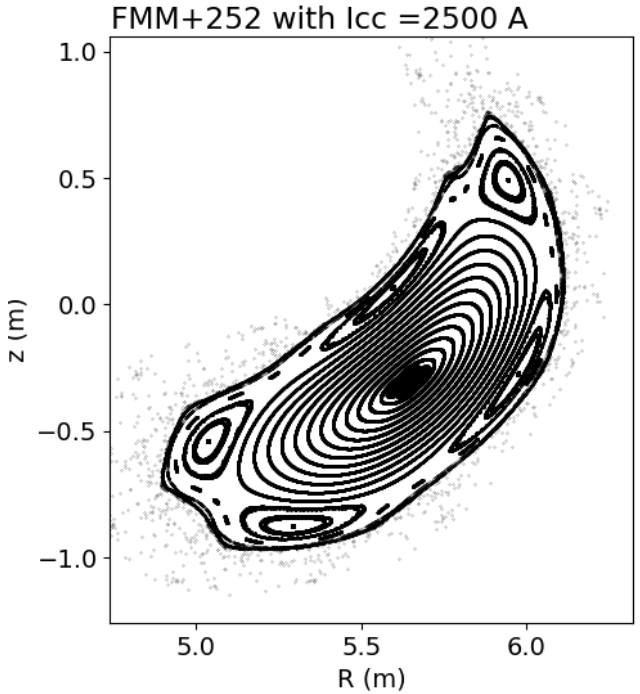
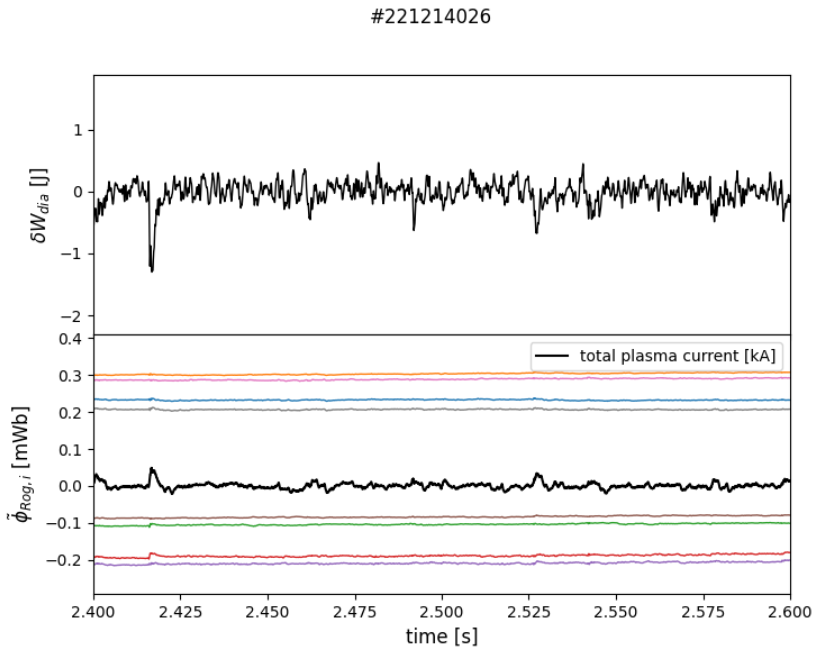
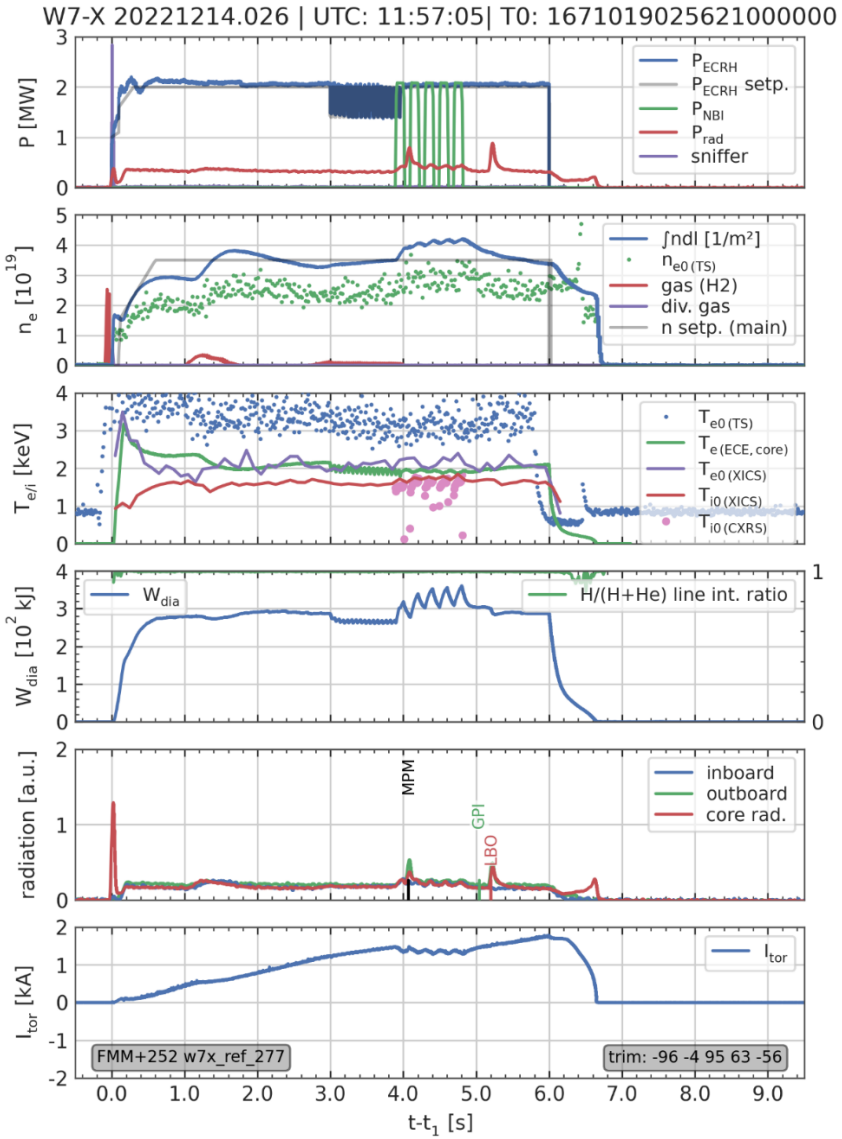
Are Low frequency modes Island localized – FMM?

- Control coils can be used to increase the island size. Expected behaviour would therefore be … increase of amplitude. However, quite the opposite is seen. The activity vanished.
- Notice: That Wdia is 30 - 40% lower than in the previous cases with identical heating and density.
- This questions whether “ILMs” are **island localized**, however influence of the islands is not negligible







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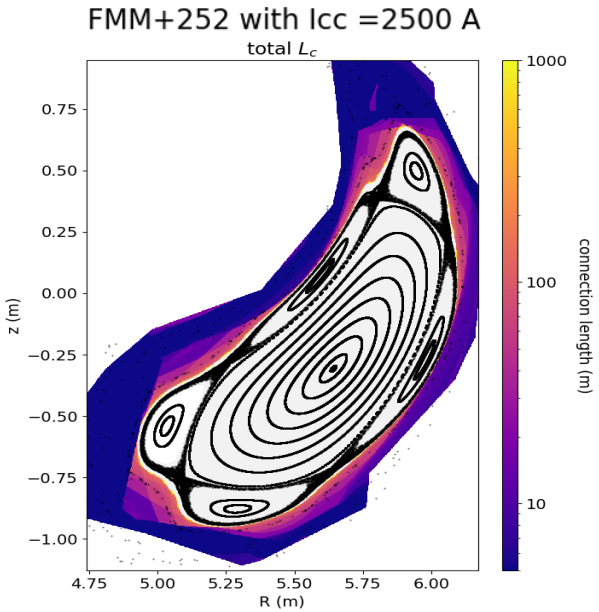

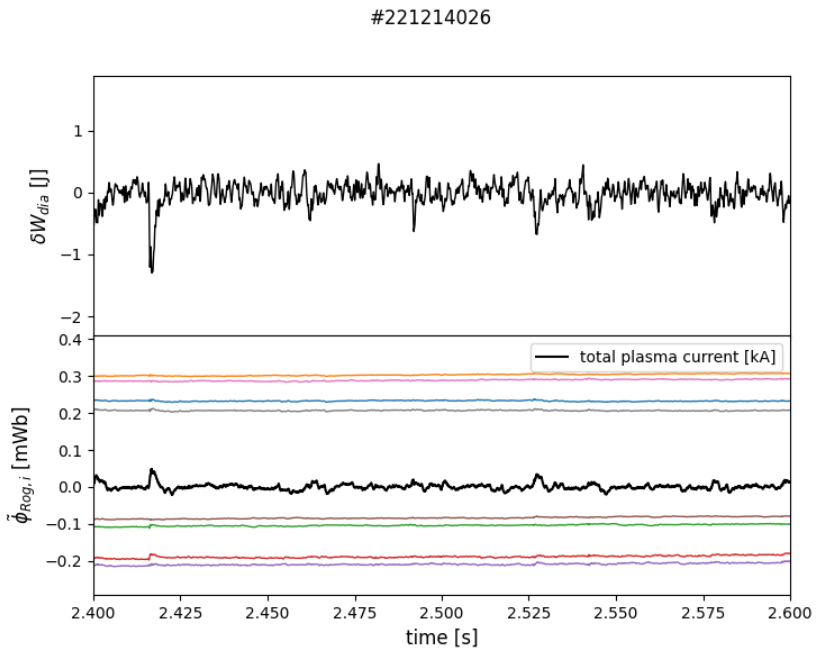

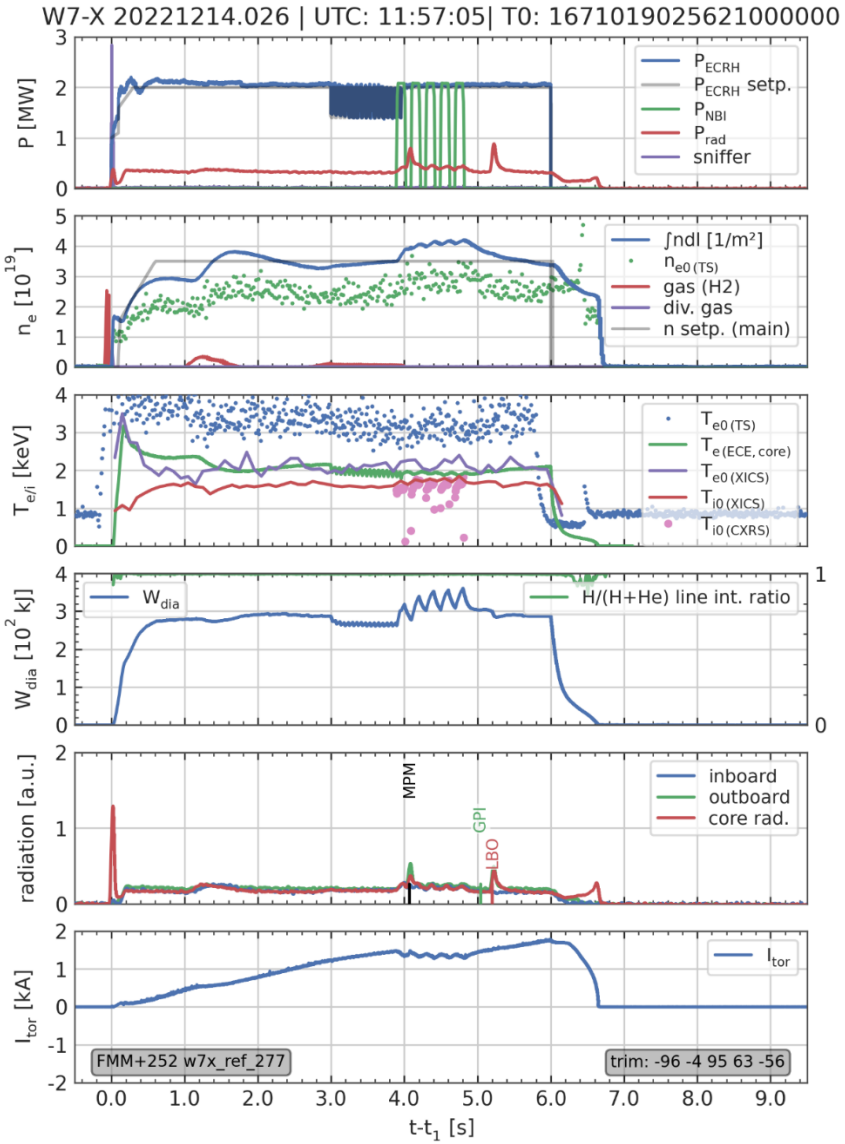

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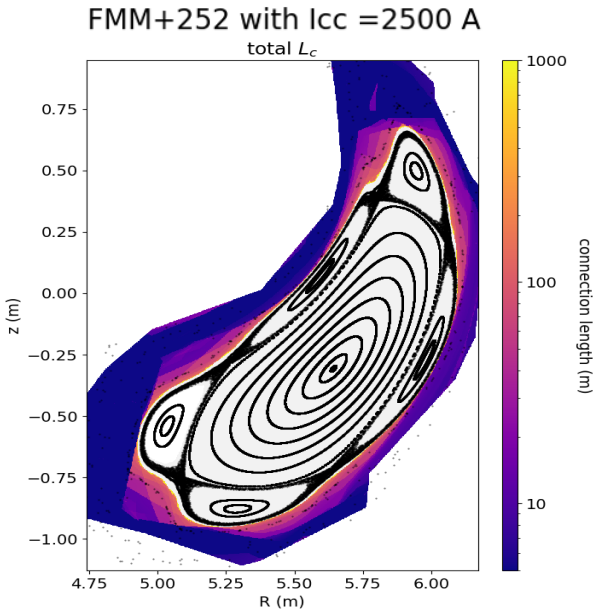
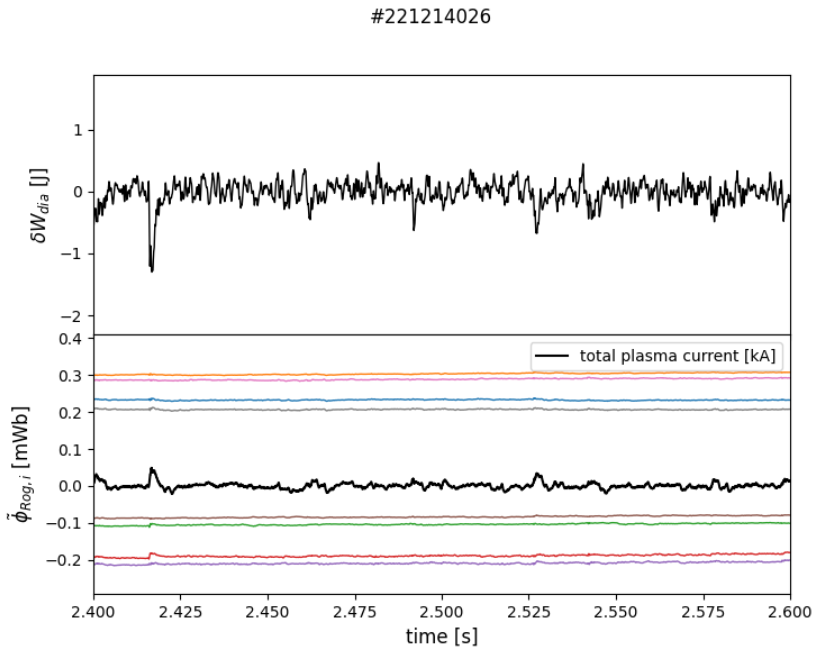
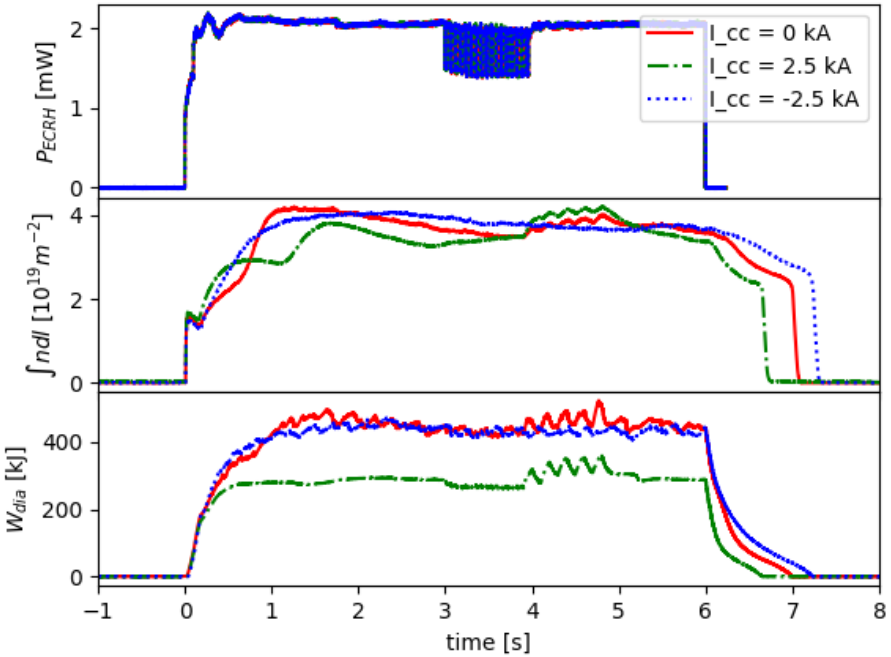


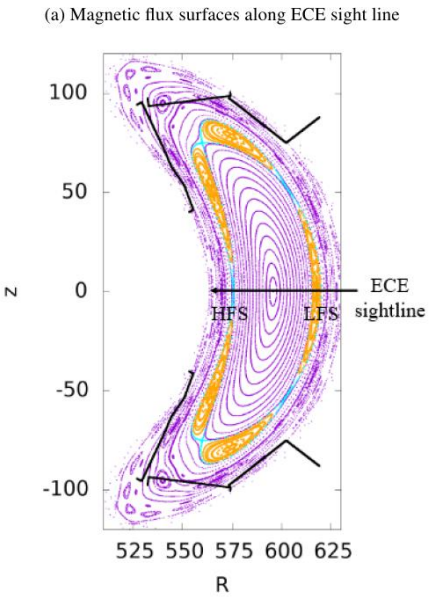


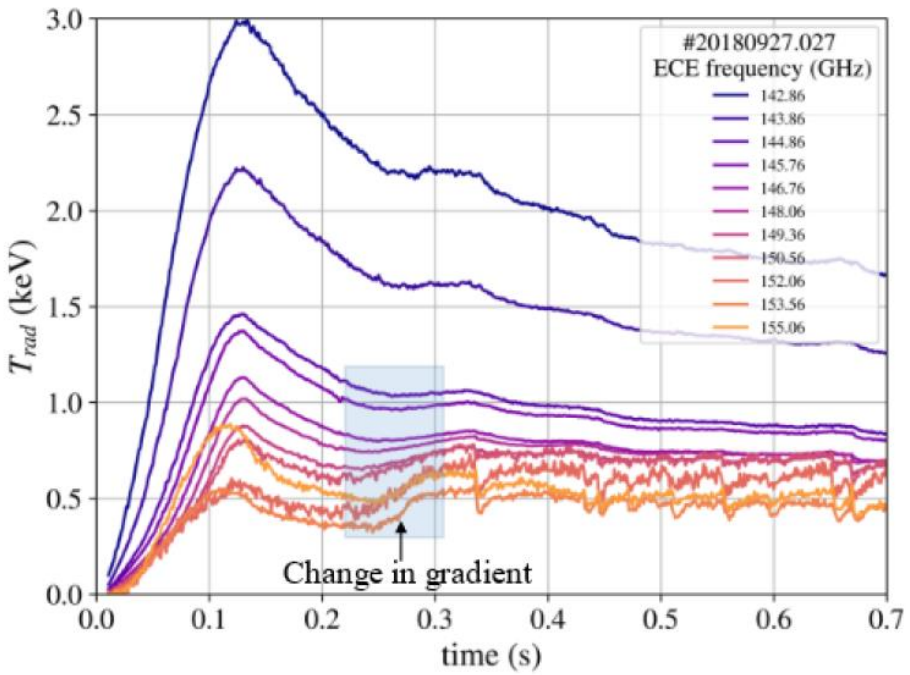
Comparison of the 3 FMM discharges

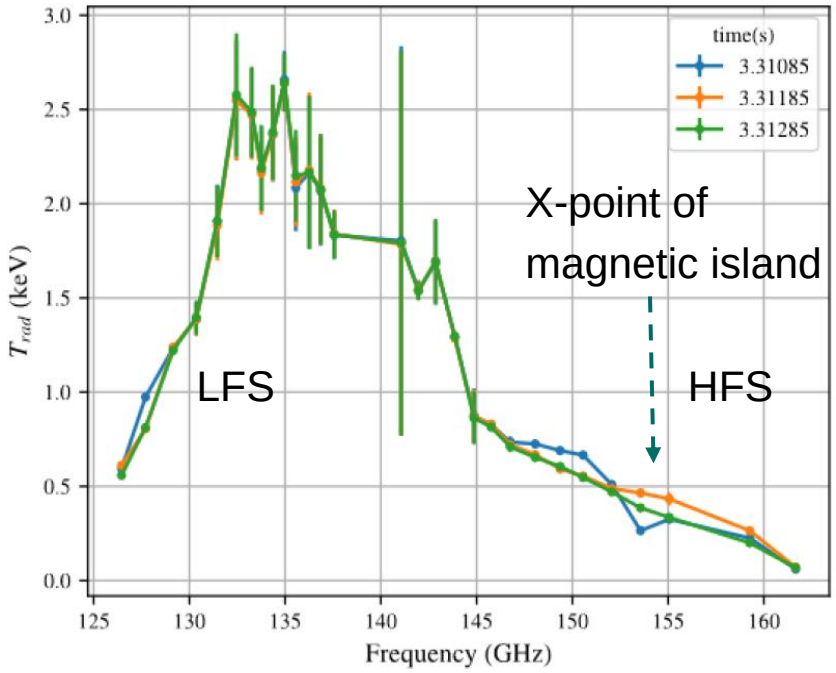


ECE measurement of a single event in FMM configuration

- ECE measures radiation emission temperature core to edge
- Observed are [1]:
  - Development of an edge electron temperature pedestal (change of gradient) at the inner side of magnetic island chain on the HFS
  - Electron temperature pedestal flattening at HFS during the crash **("ELM-like" behavior**) agrees with the Soft X-ray tomography, the change in core T_e is not clear due to high errorbars



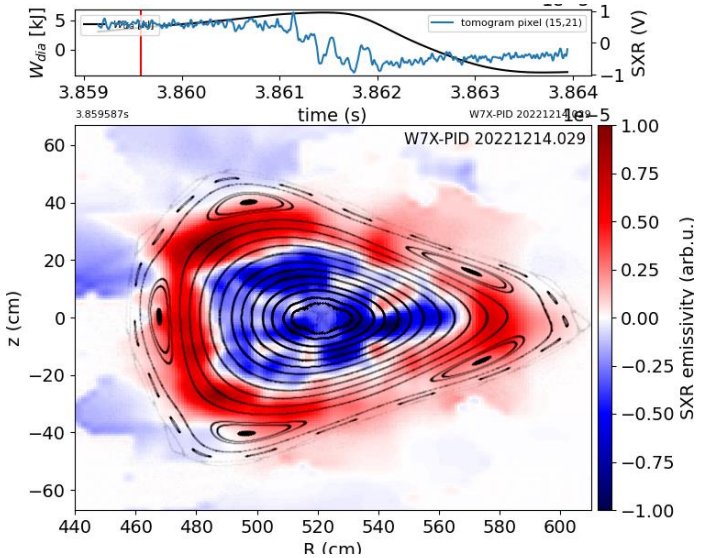




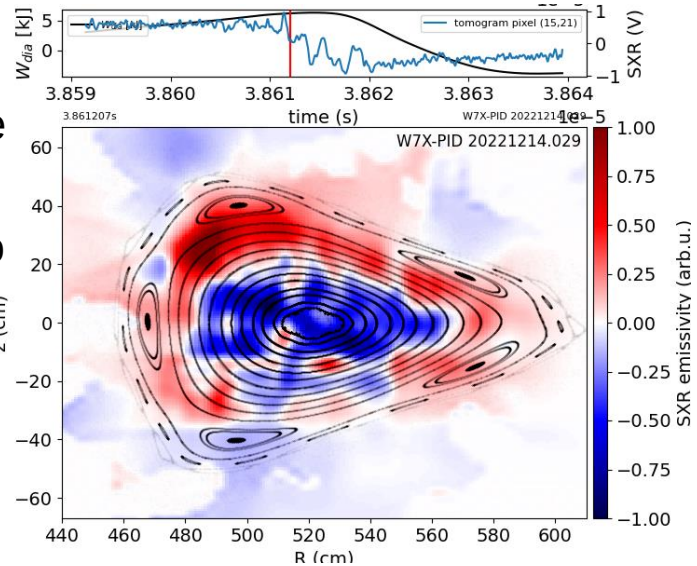
[1] N. Chaudhary et al 2023 EPJ Web of Conferences 277 03004.

A single “crash” as a fluctuation in soft X-ray emissivity

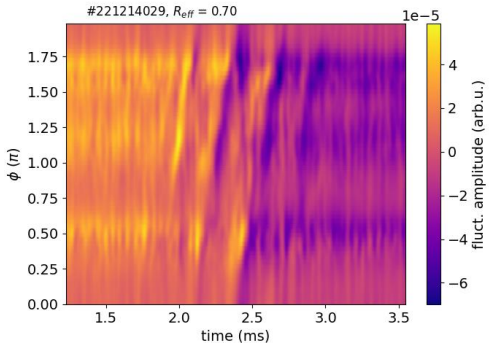
1. Initial state – before the crash the edge region X-ray emissivity is higher than core (constant over 2ms)

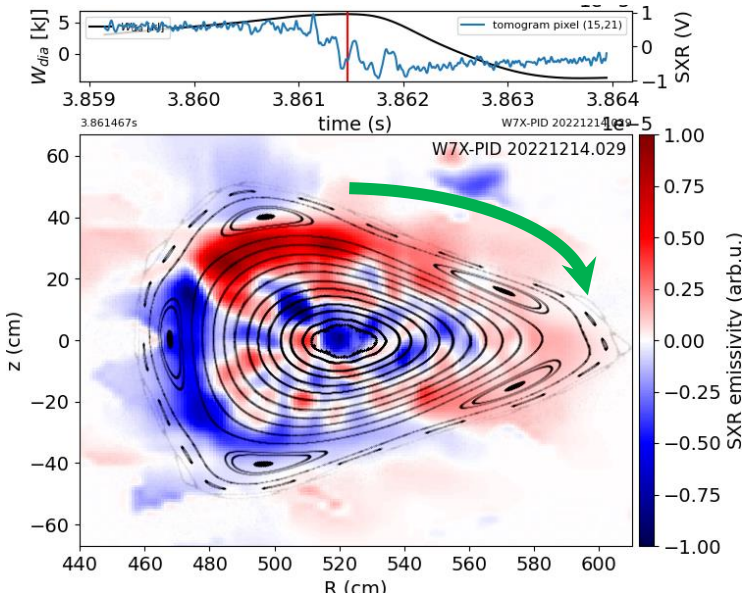


2. Evenly radiating edge gets **locally perturbed** and asymmetry starts to develop

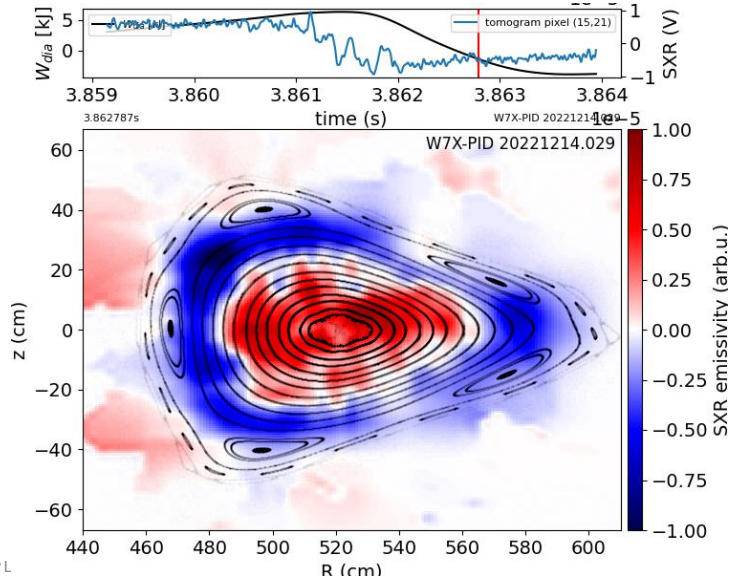


3. m = 1 structure starts rotating clock-wise (T ~ 0.25ms)





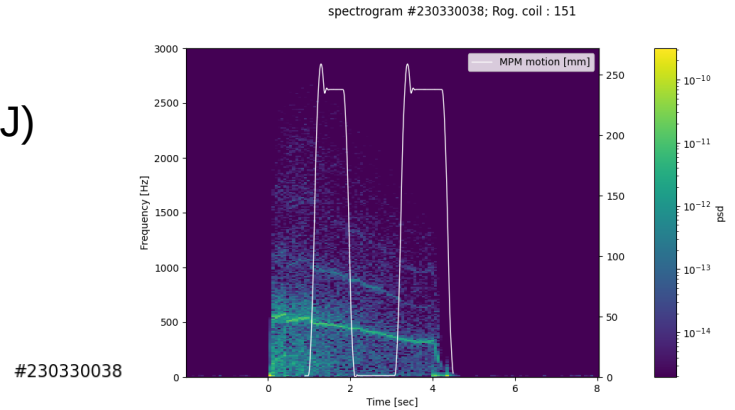
4.End state core X-ray emissivity is higher on average than edge region (constant for the remaining 2ms)



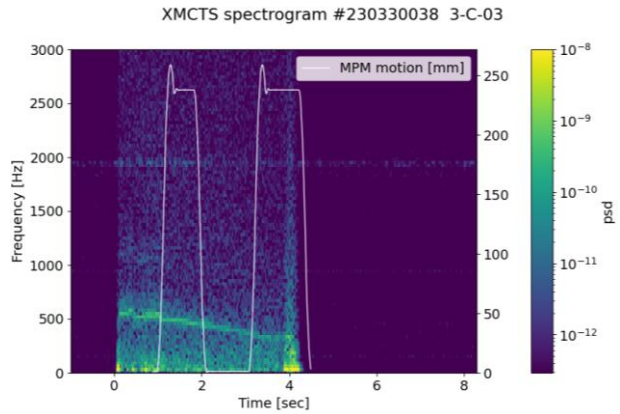
Are Low frequency modes Island Localized – EJM ?

- If we tune the iota to “island divertor” standard configuration a similar **electromagnetic**, low-frequency (100-600 Hz) activity appears
- Visible also on raw Soft X-ray (requires high T_e, n_e
- Smaller, but measurable oscillations of W_{dia} (± 1 kJ)

- Rogowski coil



- Soft X-ray sightline



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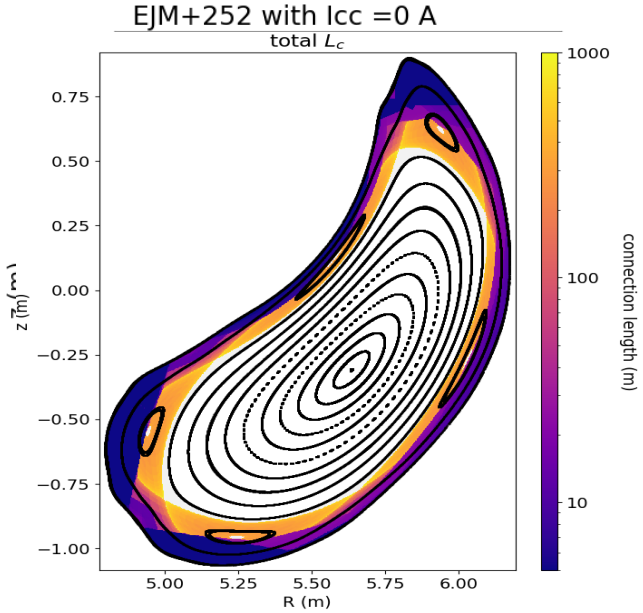

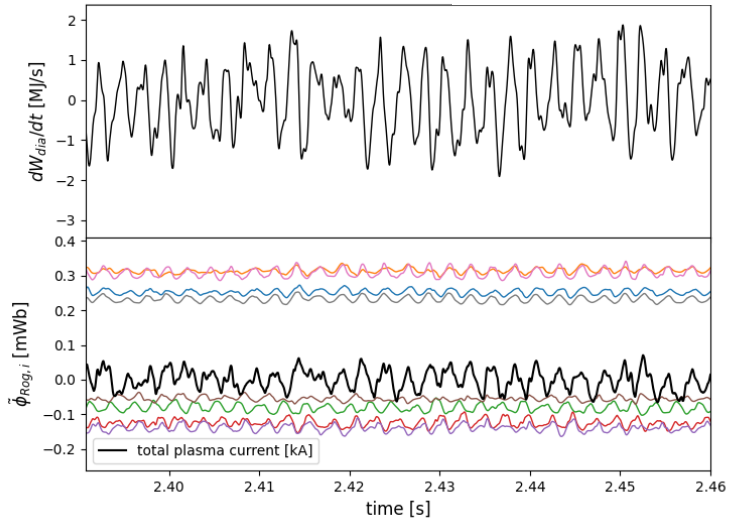

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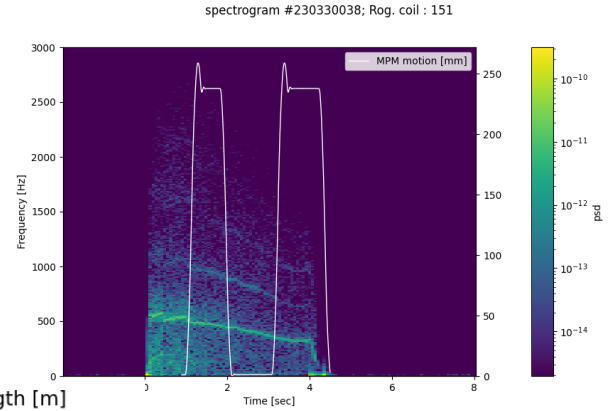
- Visible also on raw Soft X-ray (requires high T_e, n_e
- Smaller, but measurable oscillations of W_{dia} (± 1 kJ)
- In SOL signal simultaneously in $T_e, T_i, V_{Fl}, I_{sat}$

- Rogowski coil



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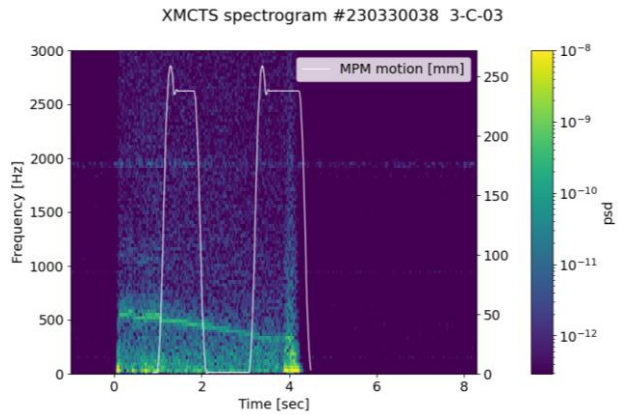
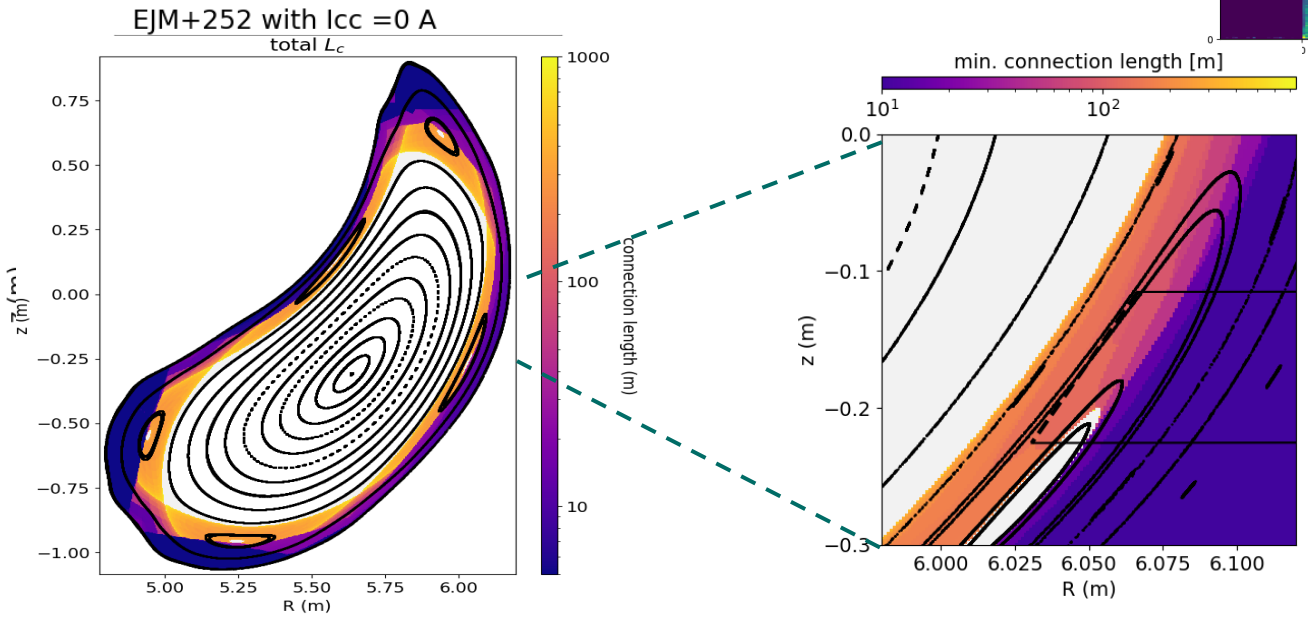
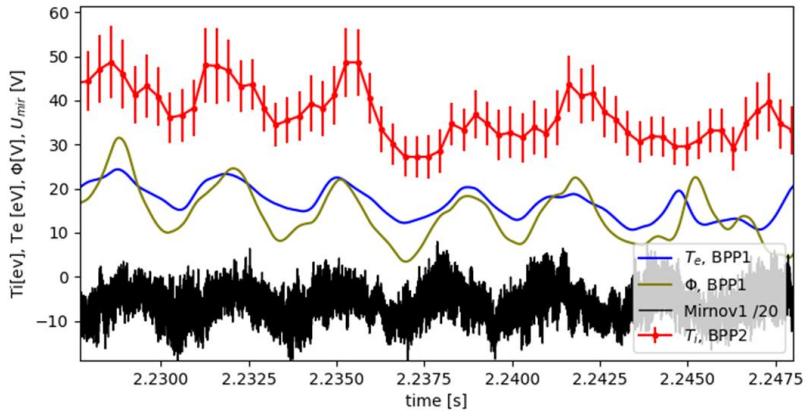
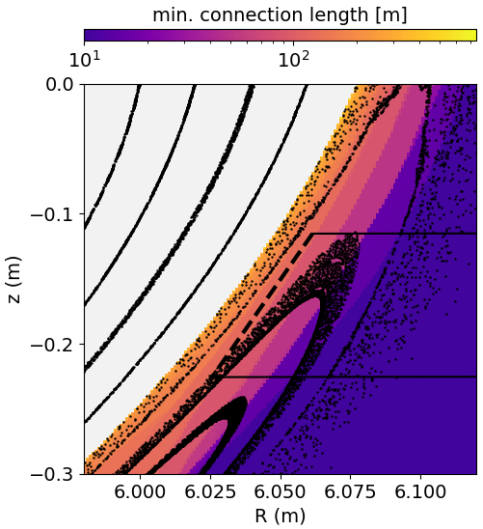




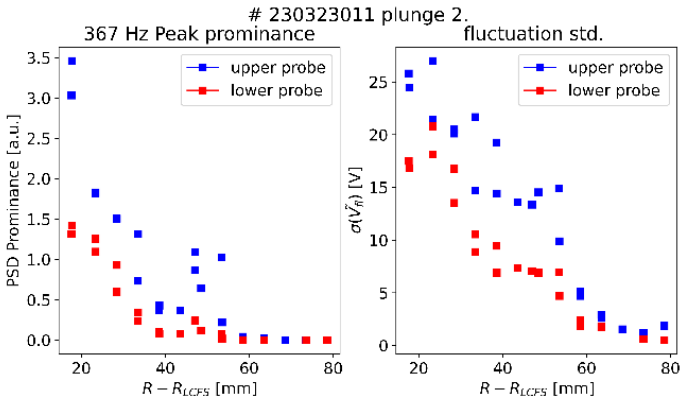
- MPM data



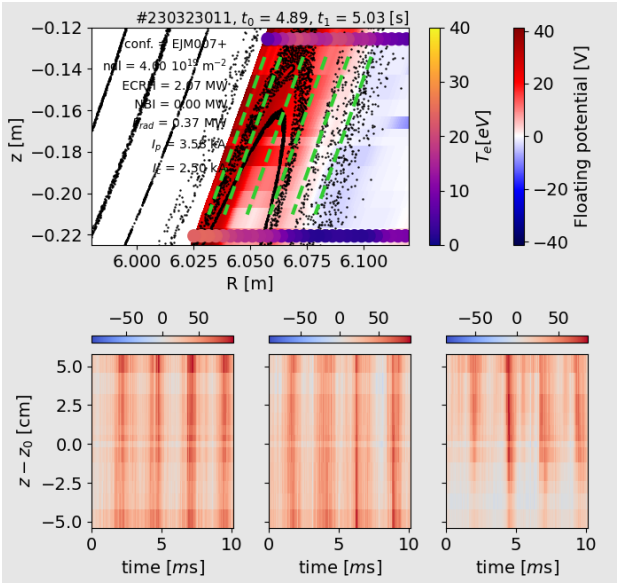
The influence of an island's "o-point" in EJM



- The fluctuation level and mode prominence increase monotonously towards LCFS regardless of poloidal position



- An example of SOL fluctuations with only finite L_c
- A "tokamak" like fluctuation attenuation



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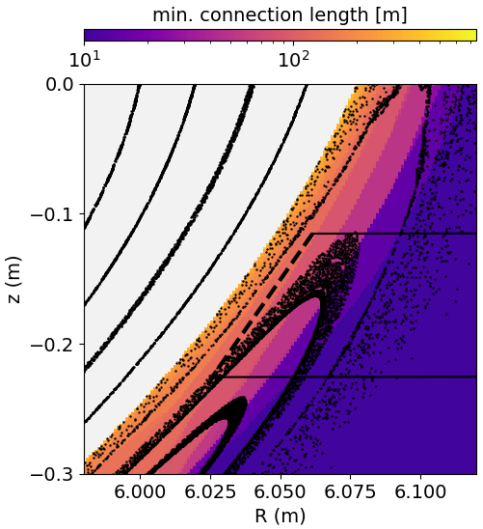

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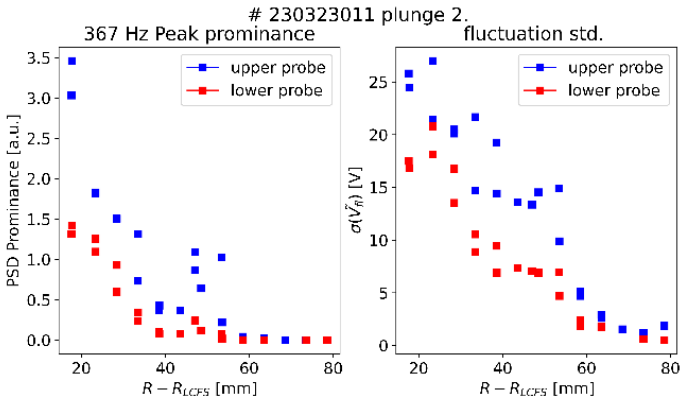

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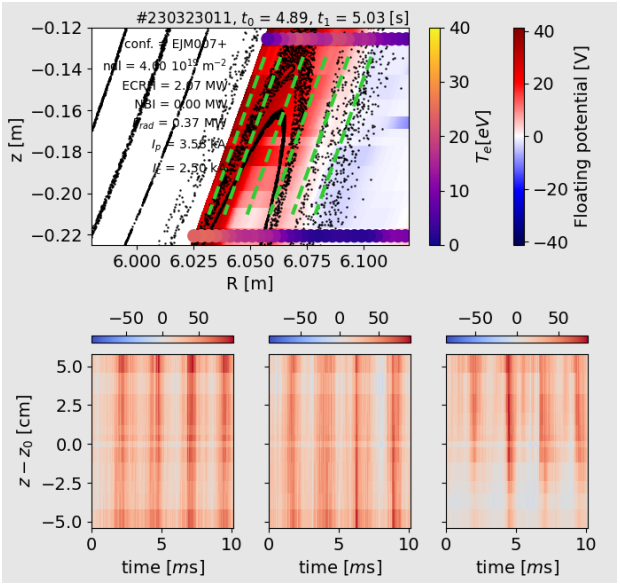
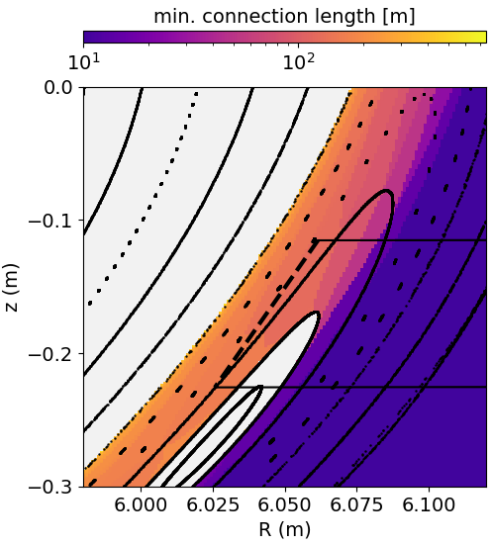
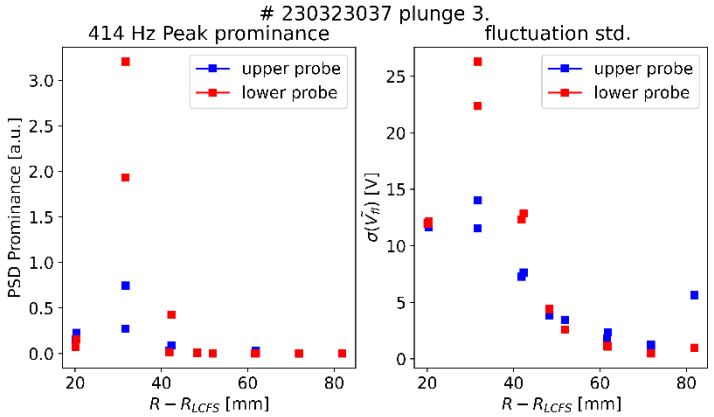
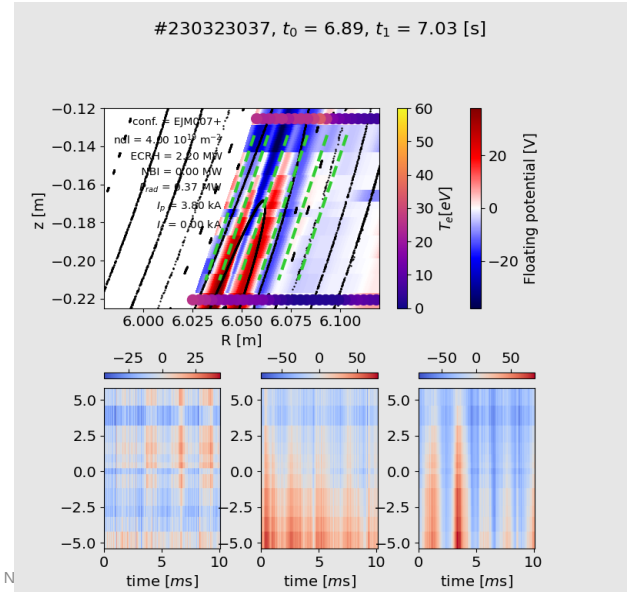




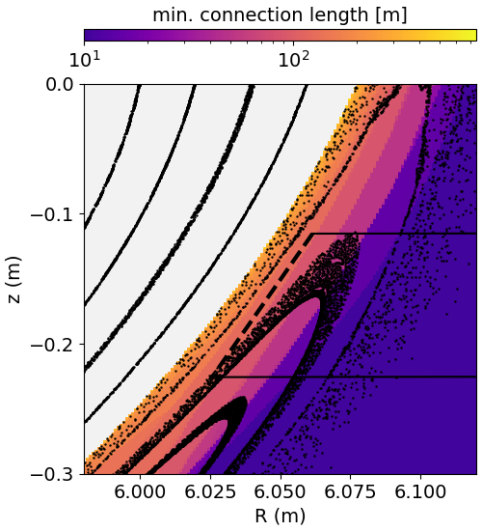
- Non-monotonic profiles and the poloidal position w/r to island confined region matters!

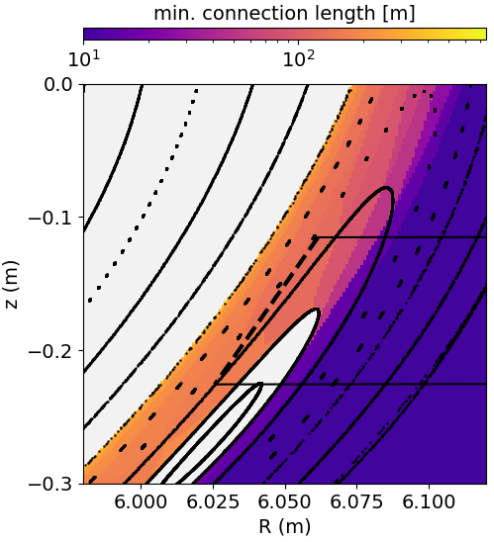


- An example of SOL fluctuations with an island containing a confined region.
- The fluctuations on average result in a strange background profile.

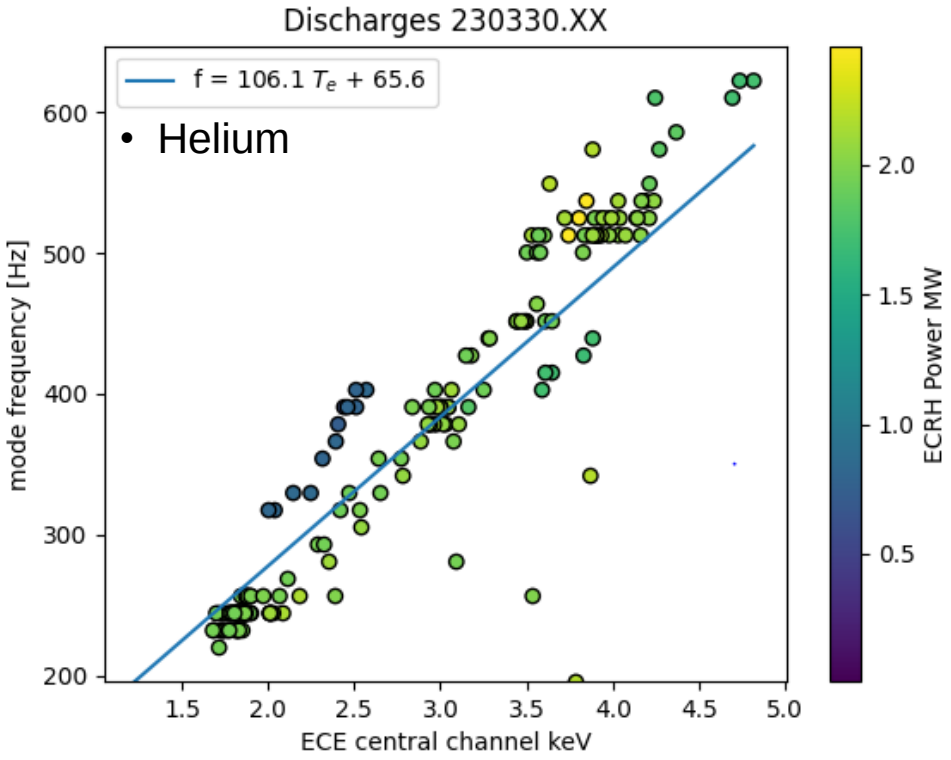


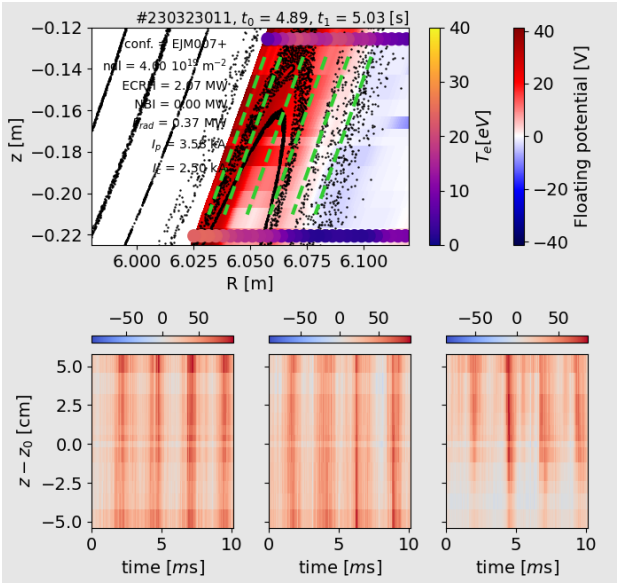
Scaling of the observed frequency

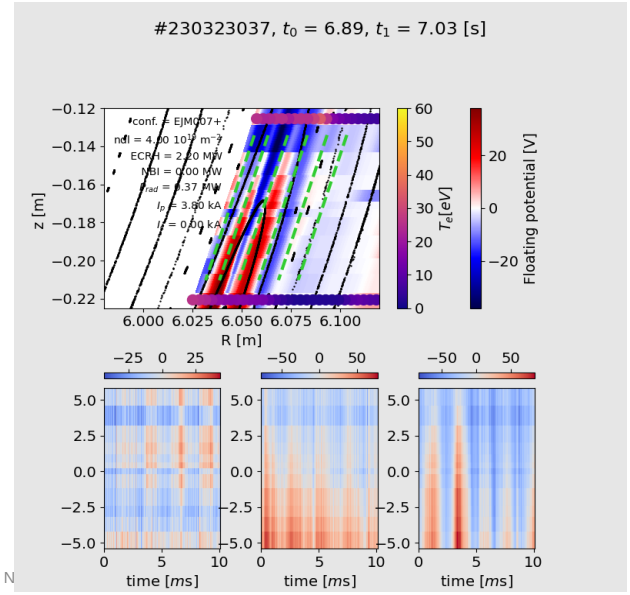




- In both cases (intersected or confined island) a common scaling of the frequency can be found with core parameters
- **The SOL connection length does not matter!**







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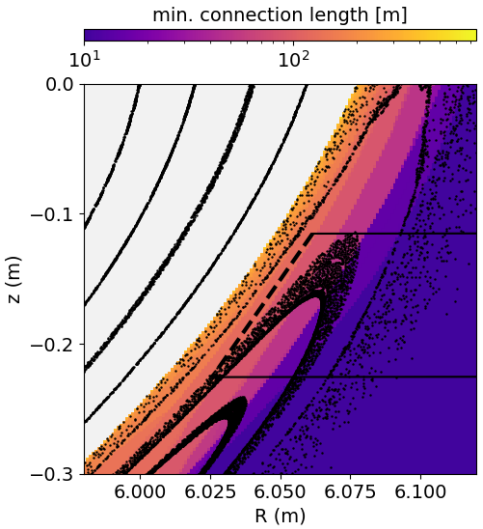
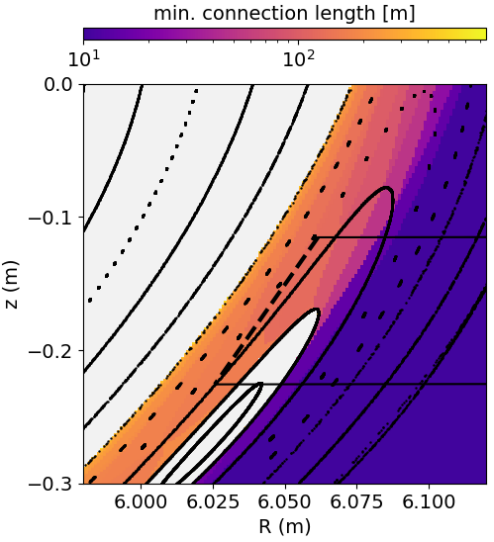
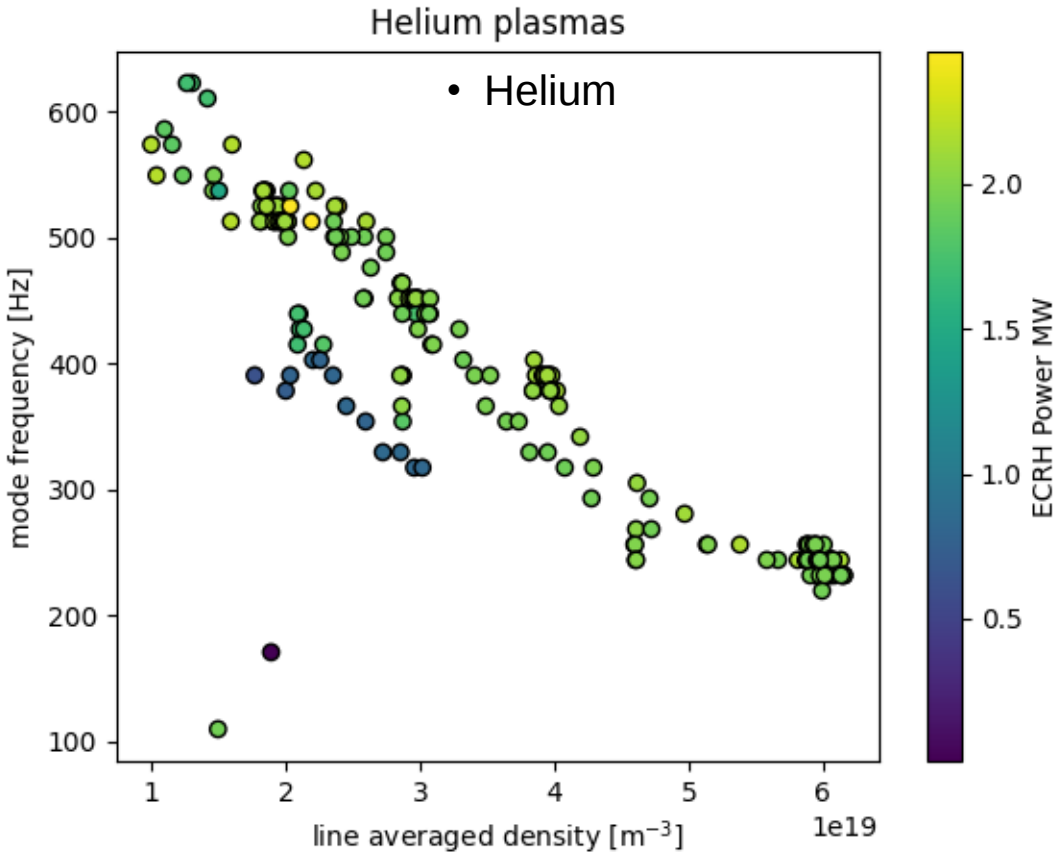
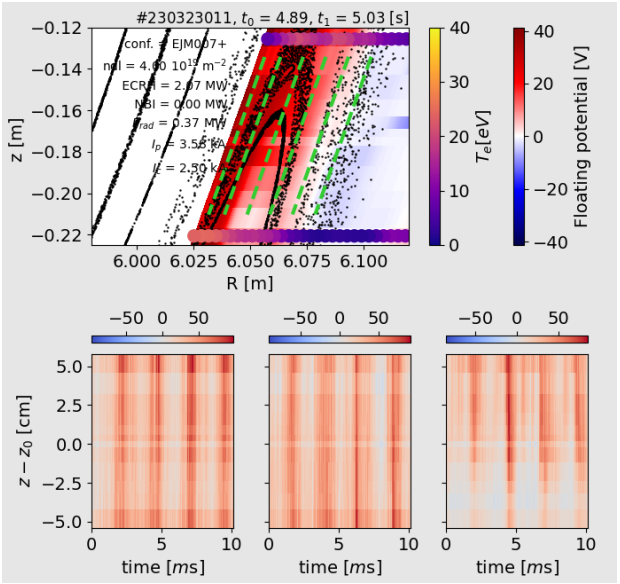
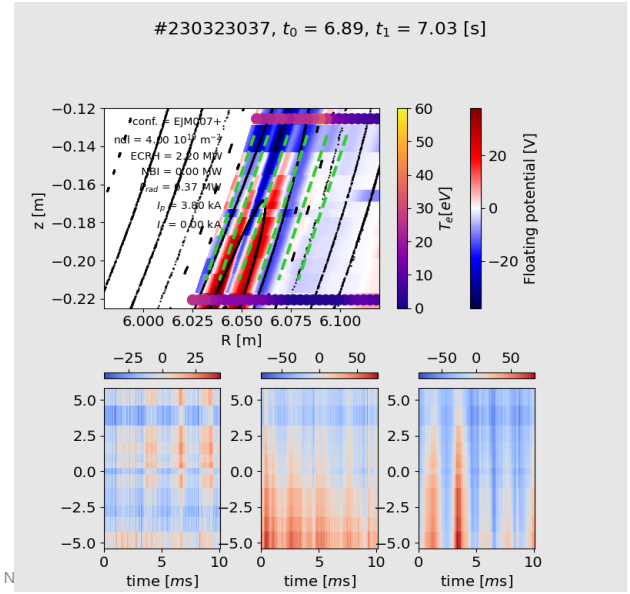




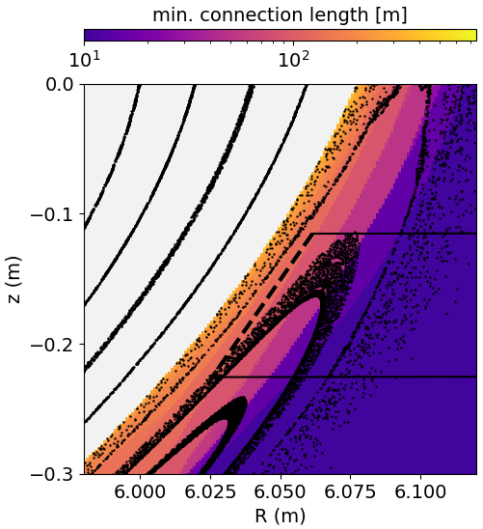
- Frequency is scaling with line averaged density as $f \approx \frac{1}{n}$ **ruling out Alfvenic activity**

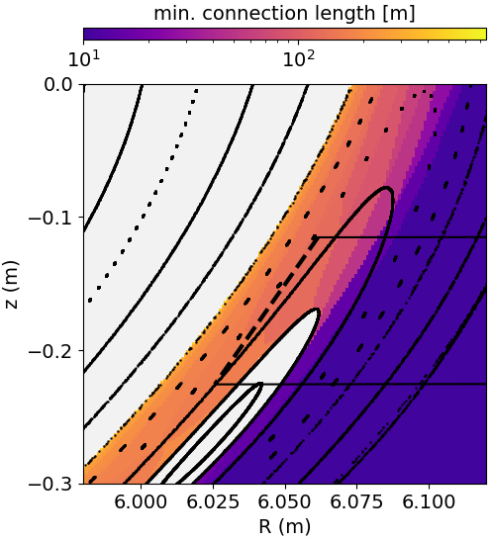




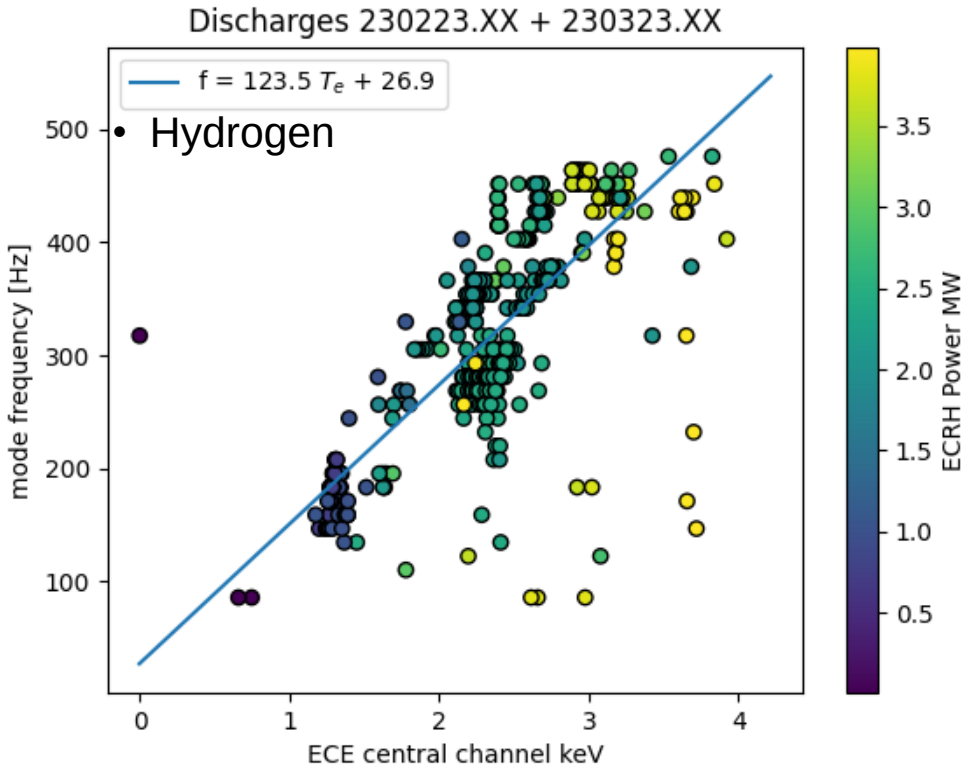


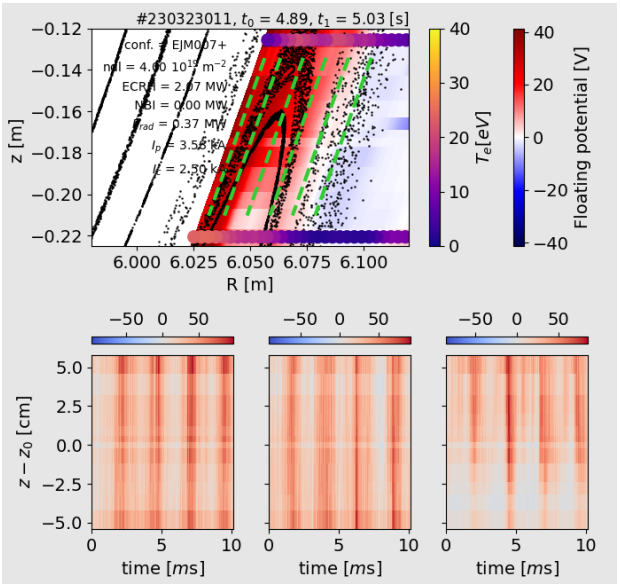
Scaling of the observed frequency

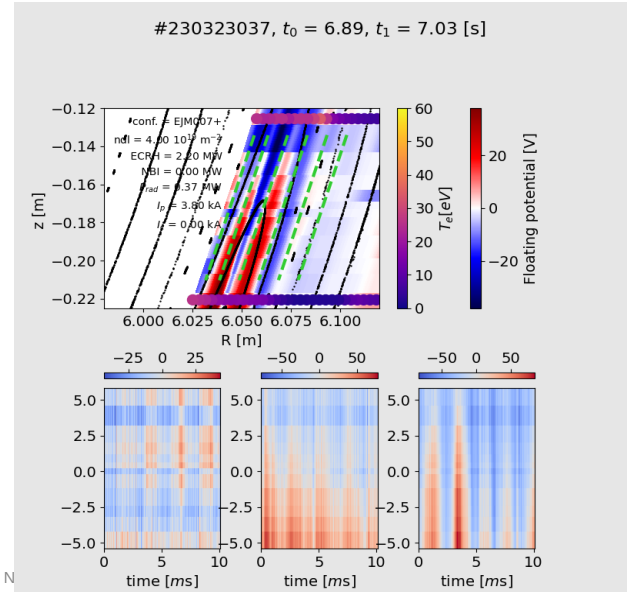




- In both cases (intersected or confined island) a common scaling of the frequency can be found with core parameters
- **The SOL connection length does not matter!**

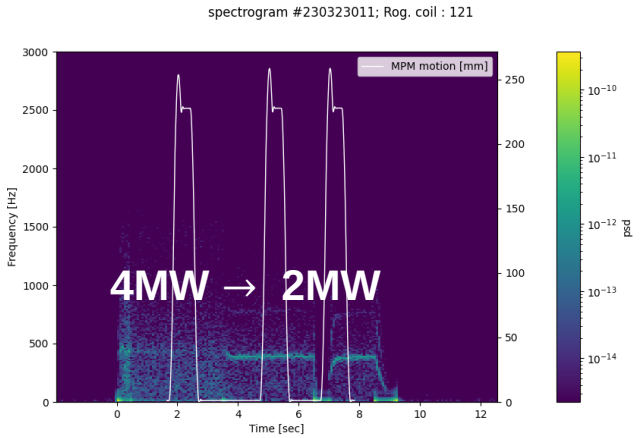




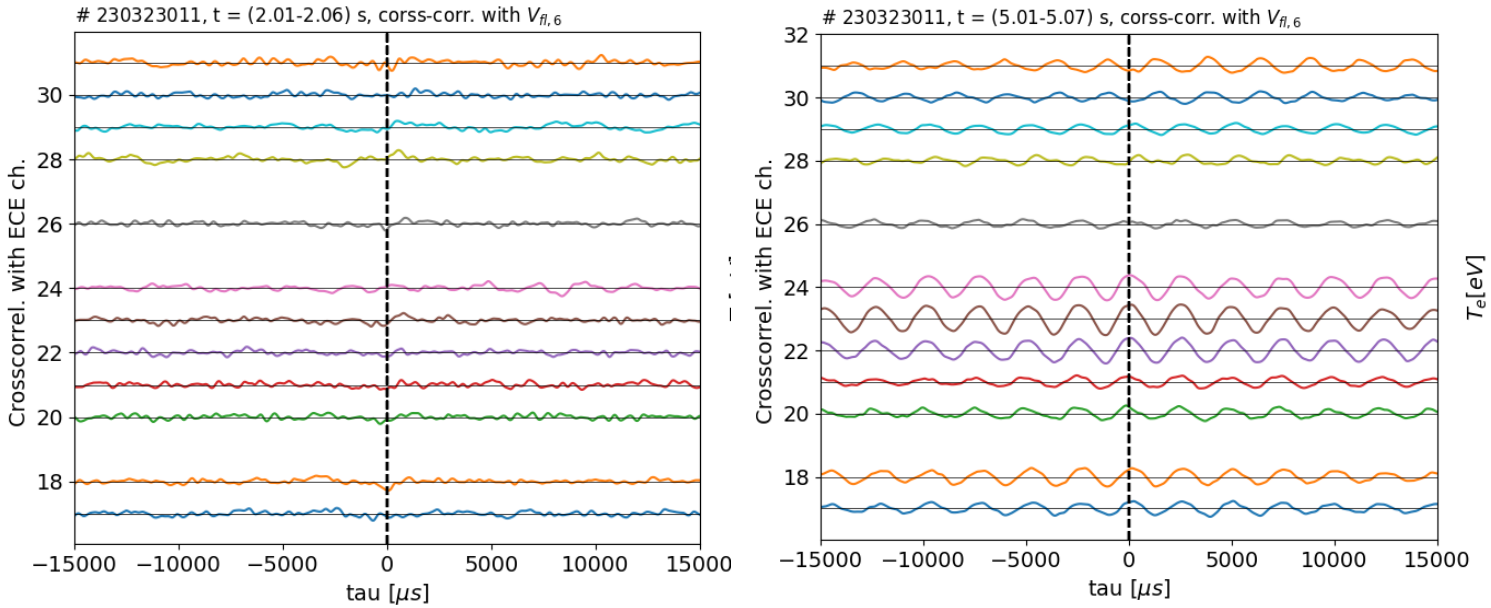


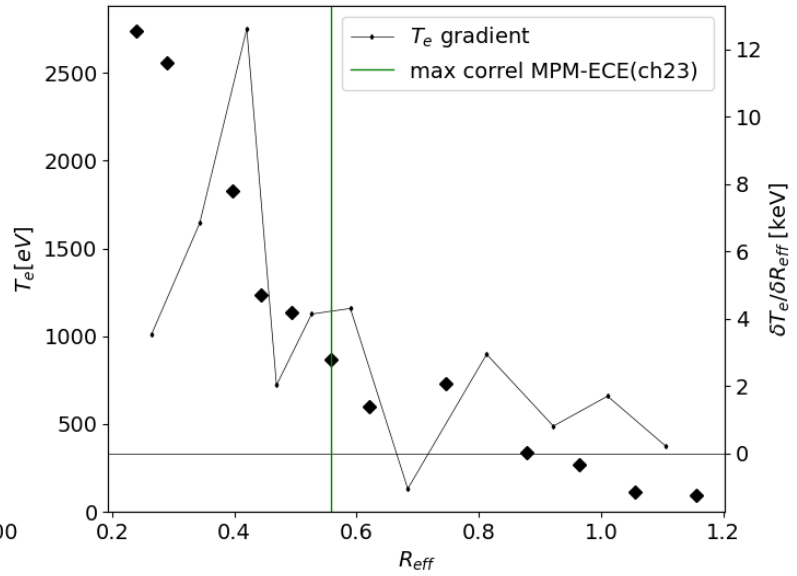
Can we pin-point R_{eff} of the mode in EJM?

- If it is not SOL parameters that determine the frequency where does the frequency originate?
- In cases when the mode is present a surprisingly significant (0.5) correlation can be found between MPM and ECE
- Highest cross-correlation around the channel 23, $R_{eff} = 0.5$



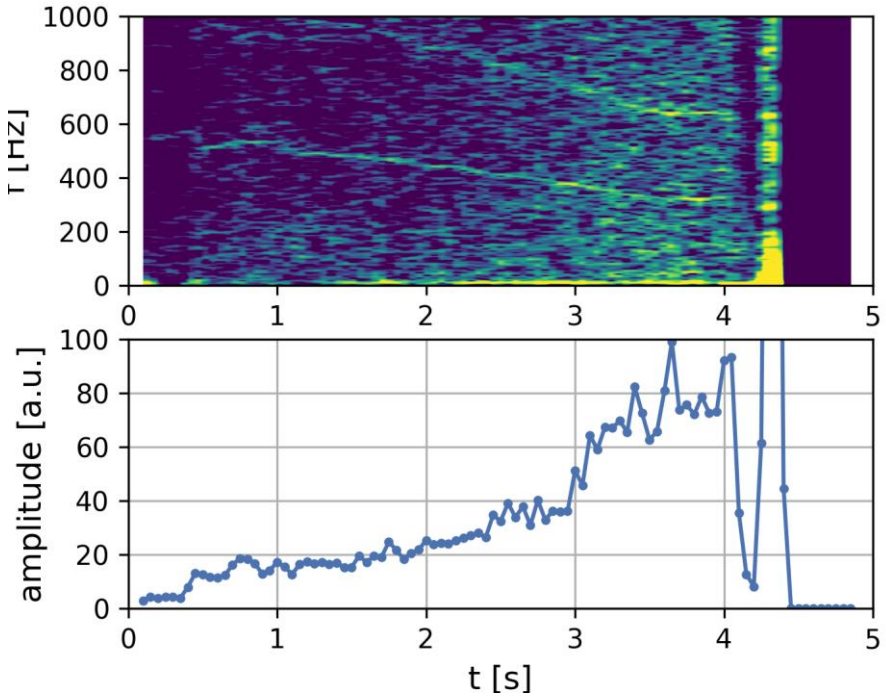
4 MW → 2 MW



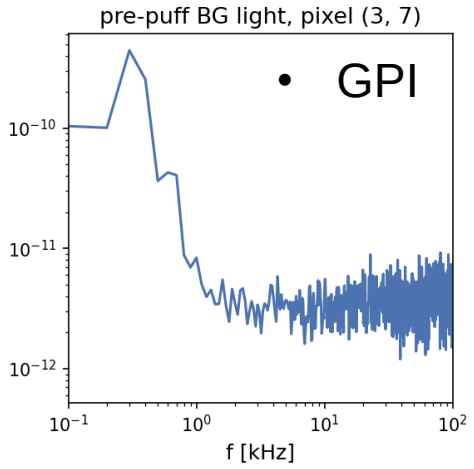


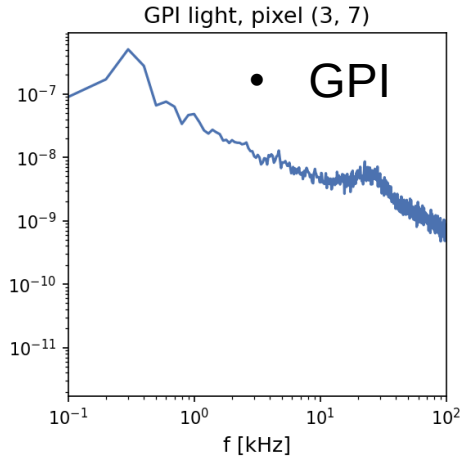
PCI: spectrum of fluctuation amplitude [2]

Phase Contrast Imaging (**PCI**)
"spectrogram of spectrogram"



- Spectral analysis of integrated **fluctuation amplitude of line-integrated density** clearly shows mode + harmonic
- Extremely narrowband, especially compared to dropouts + spikes
- Depending on pixel, mode is clearly visible in both pre-puff background light and active puff light of GPI

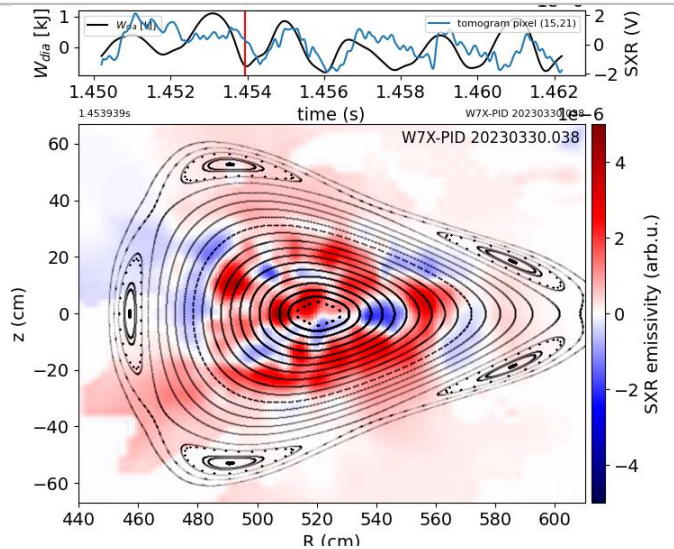




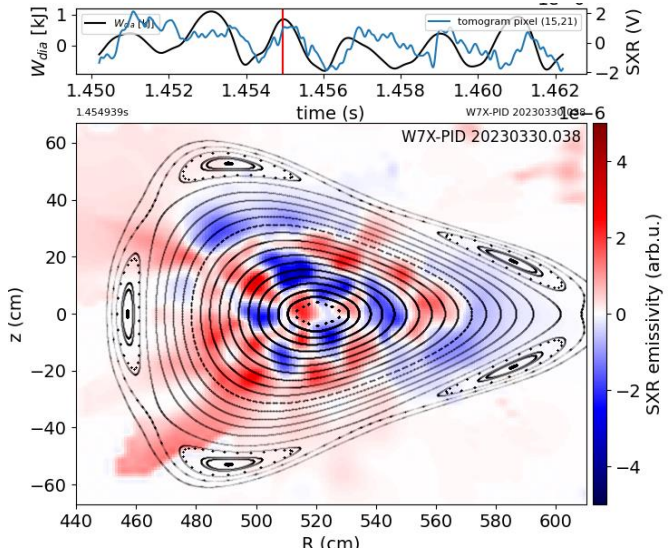
[2] Courtesy of Adrian Von Stechow

EJM harmonic oscillations an Soft X-ray overview

- **1. unstable** local W_{dia} minimum
- no consistent, stationary structure

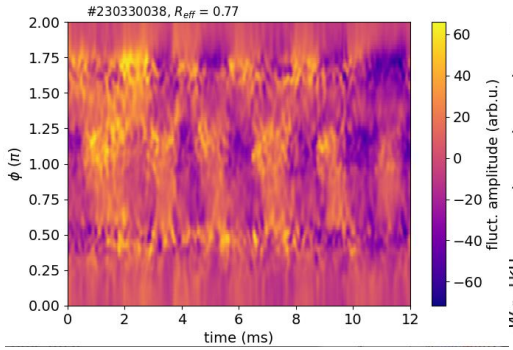


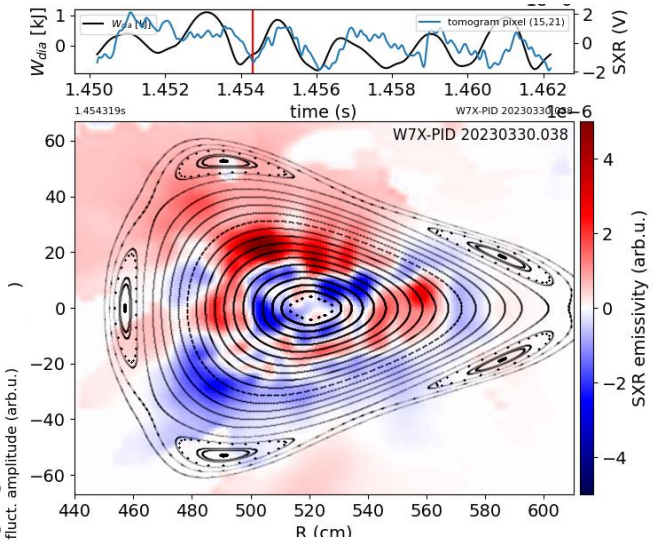
- **3. unstable** local W_{dia} maximum
- no consistent, stationary structure



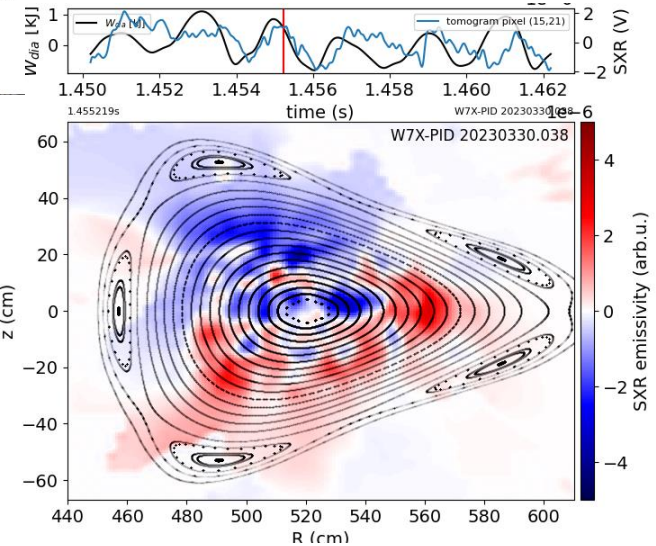
- **Continuously repeating m = 1 structure**

- **2. transient m=1** structure consistently repeating at each W_{dia} increase every 2ms





- **4. transient m=1** structure consistently repeating at each W_{dia} decrease every 2ms



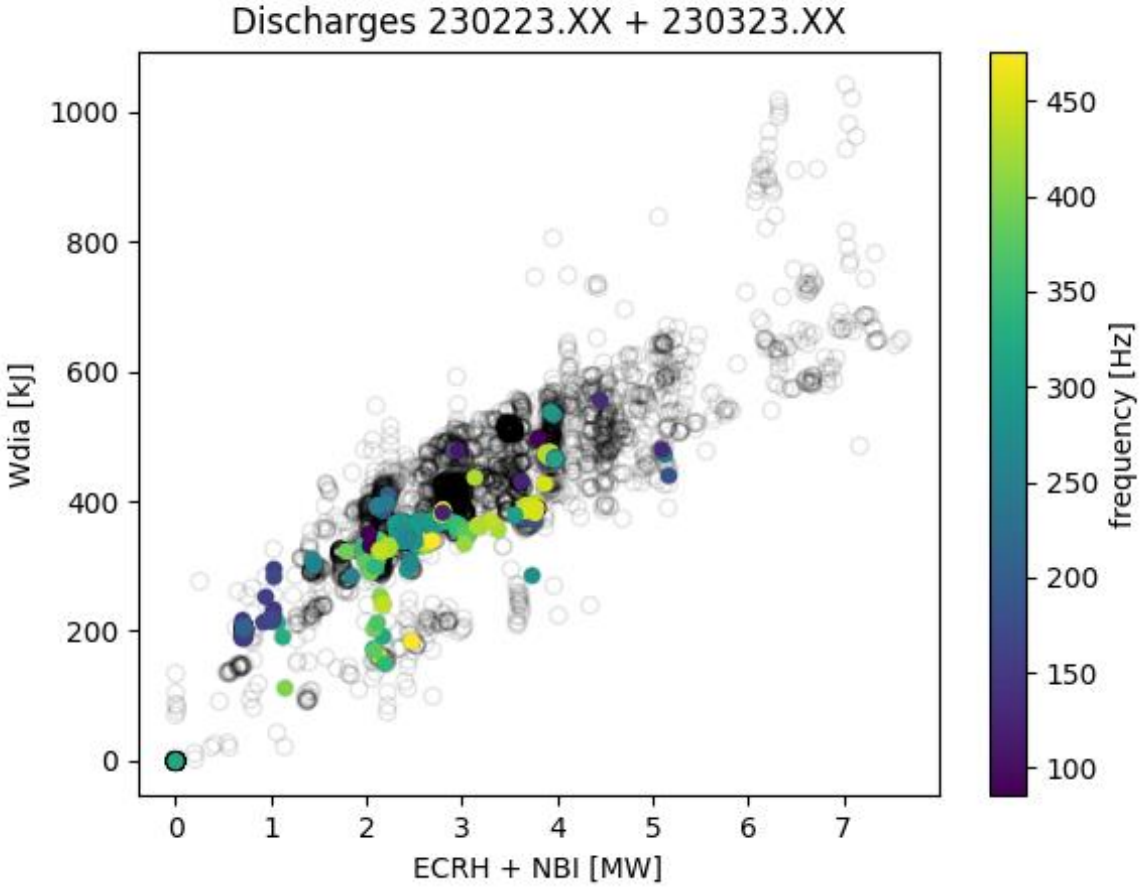
Implications for confinement?

Empty circles = database scanned

Full circles = mode is present with some frequency

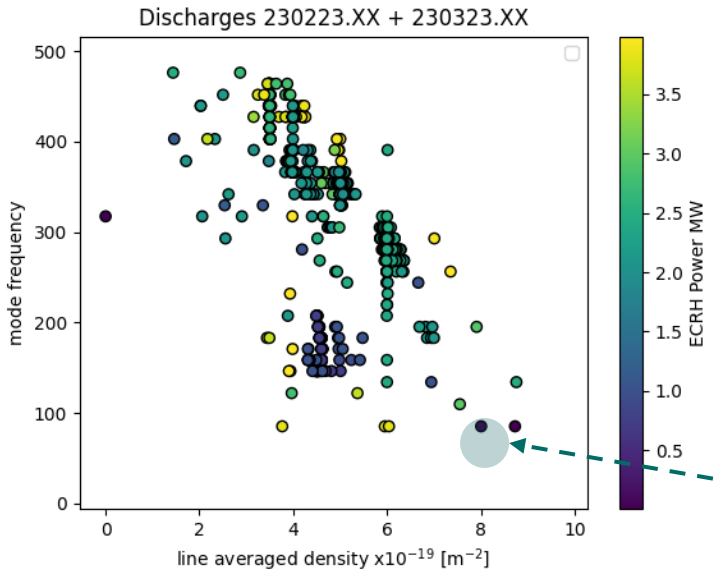
Remarks:

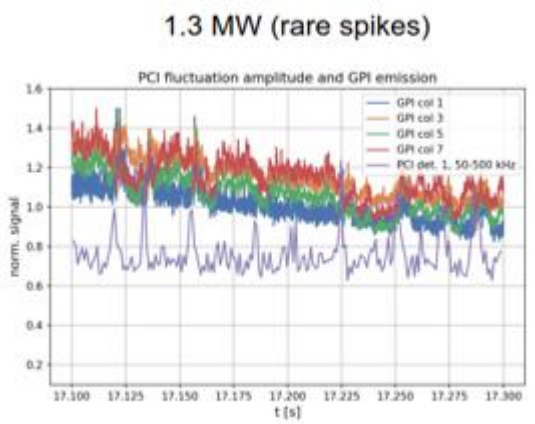
- The mode tends to “live” on the low side of W_{dia}
- Therefore, a likely explanation is that the continuous m = 1 mode does not improve confinement

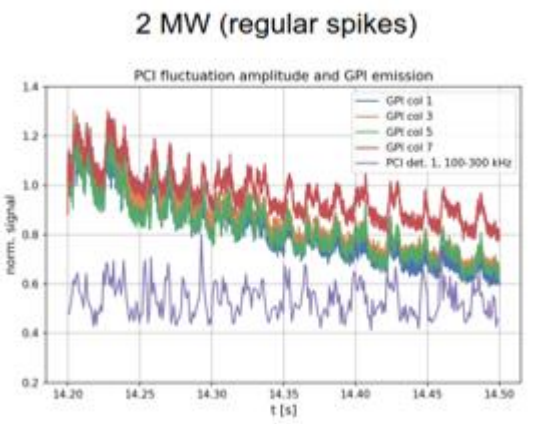


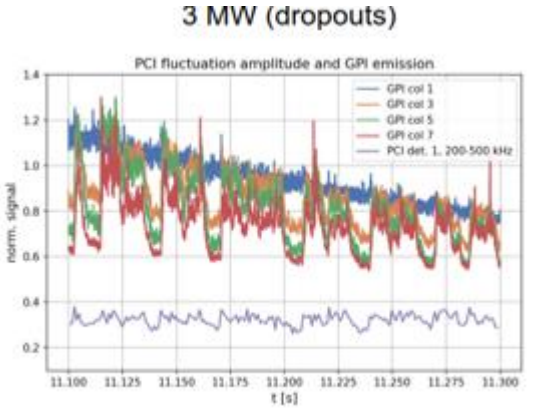
From EJM harmonic oscillations to EJM bursts?

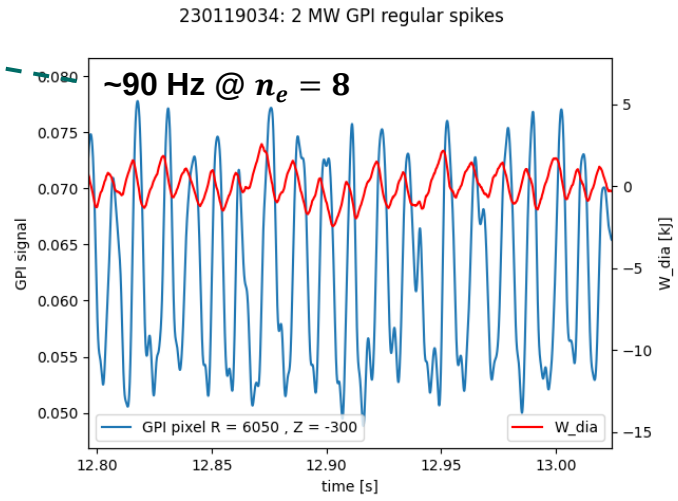
- GPI and PCI report “dropouts” and “spikes” in high density ($9\text{x}10^{19}m^{-2}$) plasma

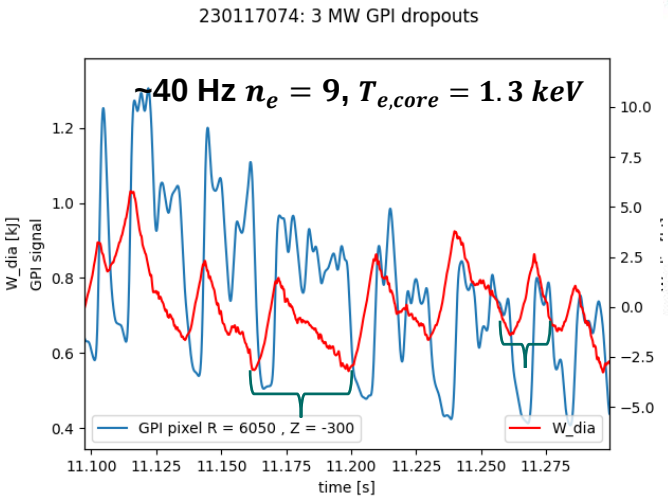


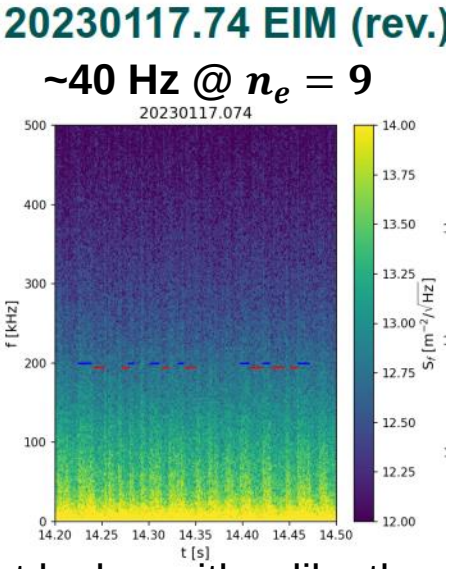












- Frequencies < 100 Hz are not possible to observe using the same PSD peak search technique as used to create this graph
- The GPI “spikes” fit with the scaling.
- “dropouts” do not scale with core Te, and have different behaviour
- Expected W_{dia} oscillation is observed

- Intermittency starts to show, but looks neither like the harmonic oscillations or the bursts

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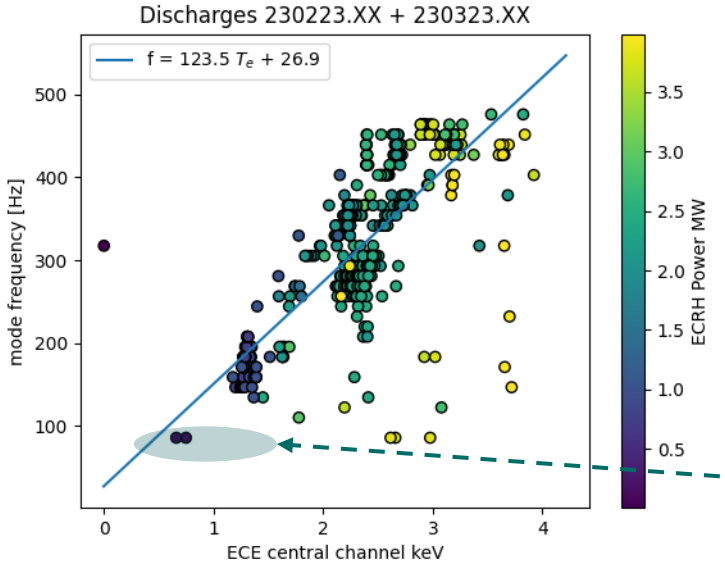

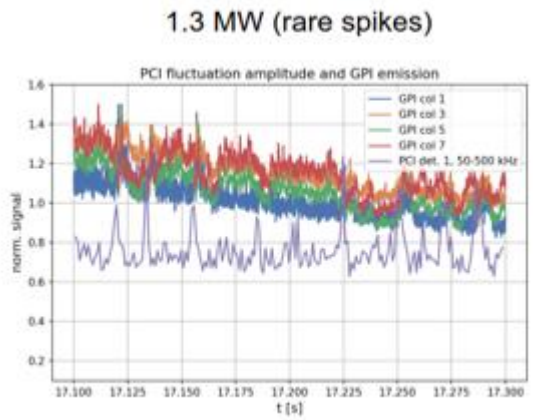

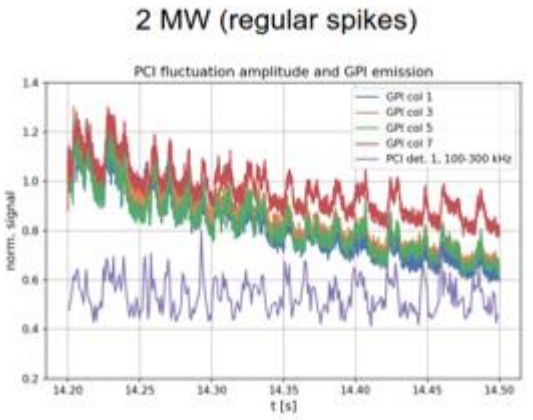

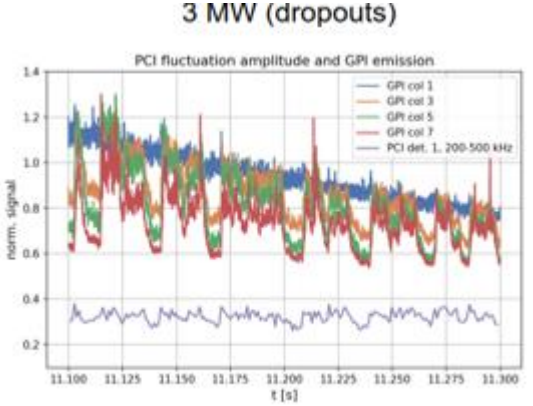

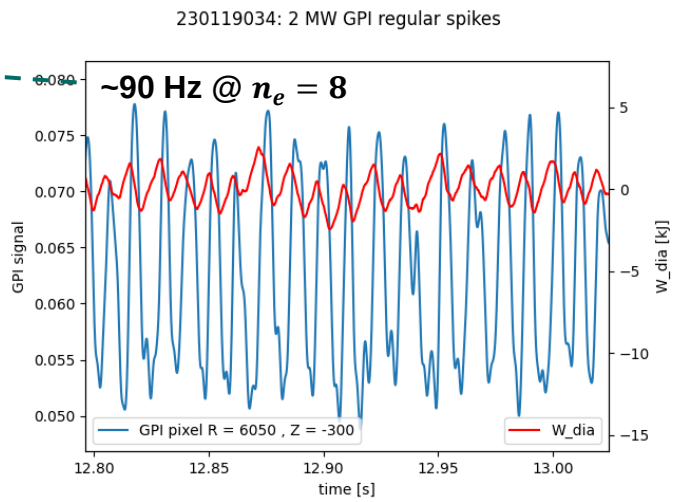

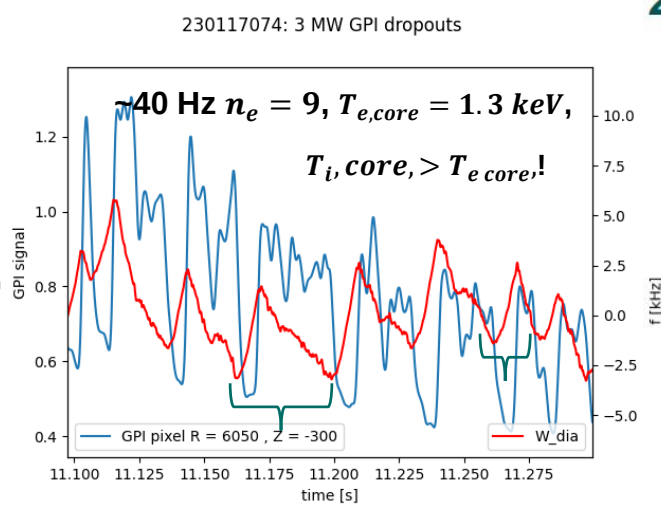

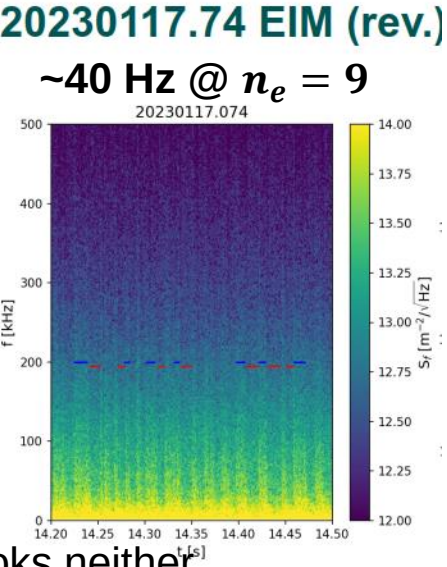

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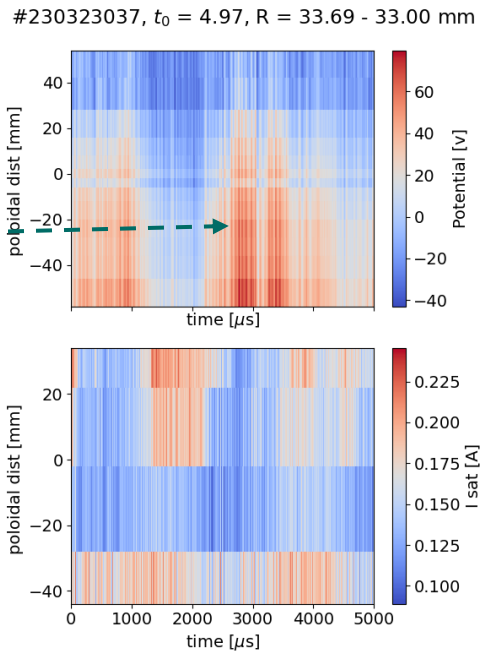
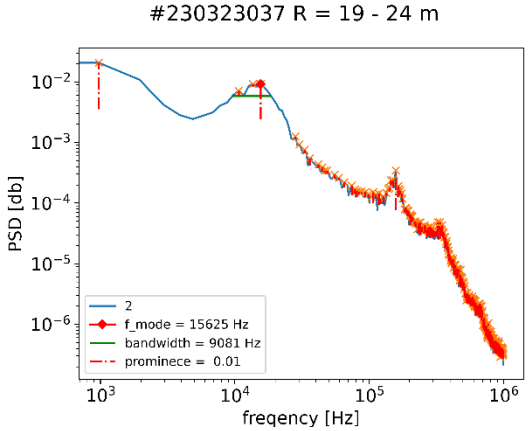
Relation to other low frequency activity: 10kHz QCM

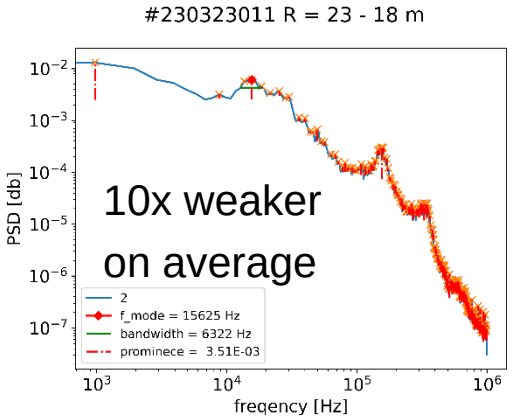
- MPM can see the $QCM \approx 10 - 25\ kHz$ [3]
- QCM is seen to be modulated by the 500 Hz mode in the “O-point” region
- Frequency might scale with $\sqrt{n_e}$
- However, on MPM data there is still a trace of 10 kHz mode without “o-point”



- “O-point” in sight



- Fully intersected island



[3] X. Han et al 2020 Nucl. Fusion 60 016011, [4] S Zoletnik *et al* 2020 *Plasma Phys. Control. Fusion* **62** 014017

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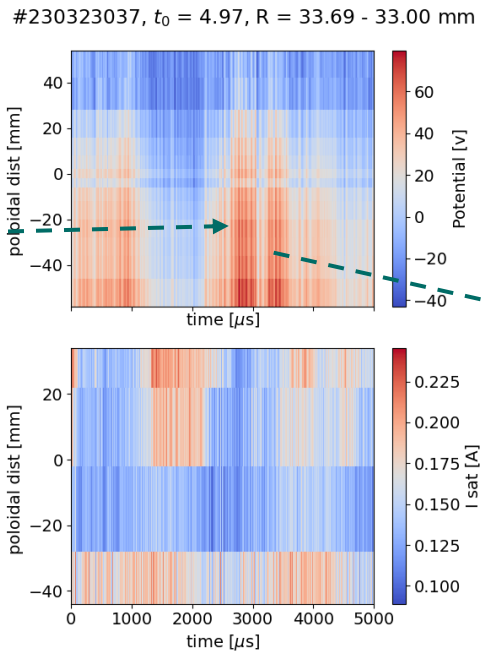
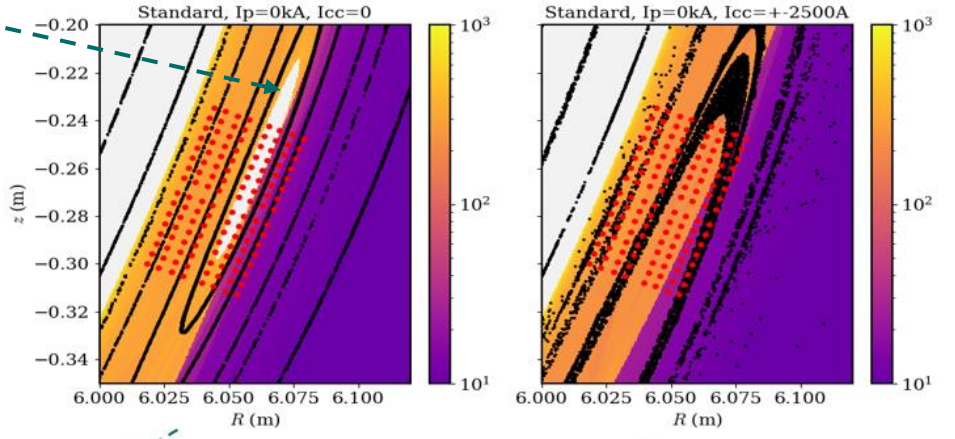


- GPI can associate the “QCM” to O-point region
- However Correlation reflectometry [4] gives conflicting information



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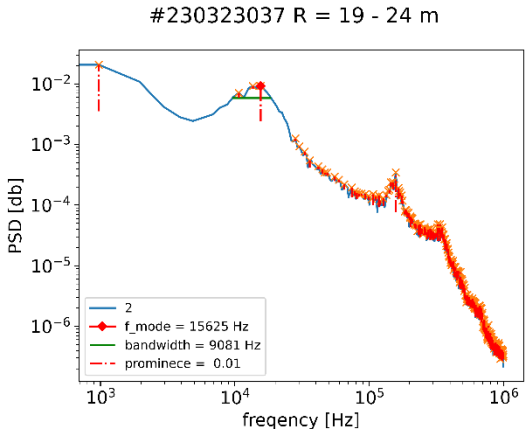

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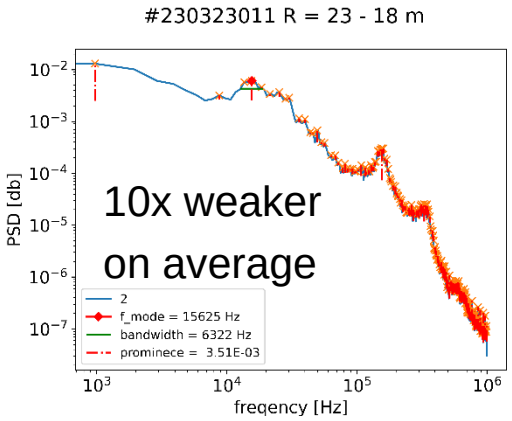
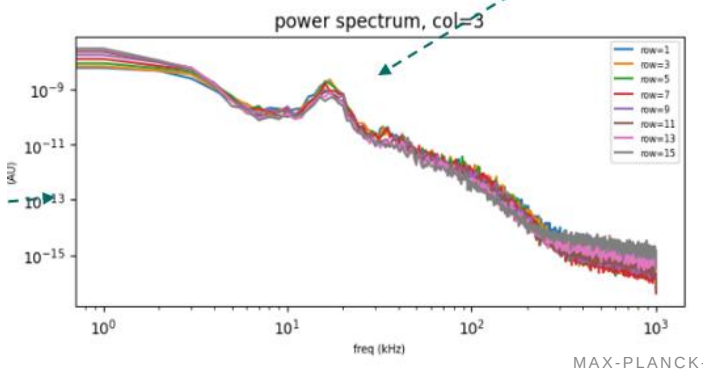
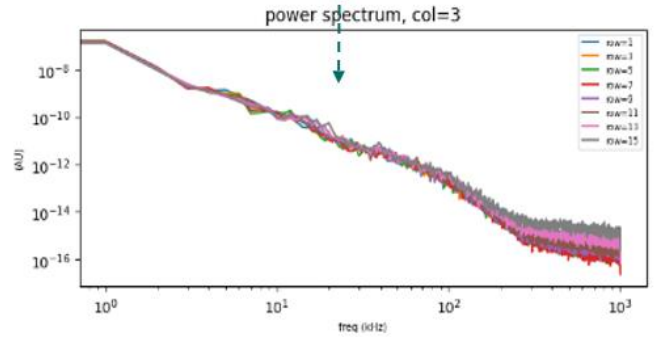


10x weaker on average





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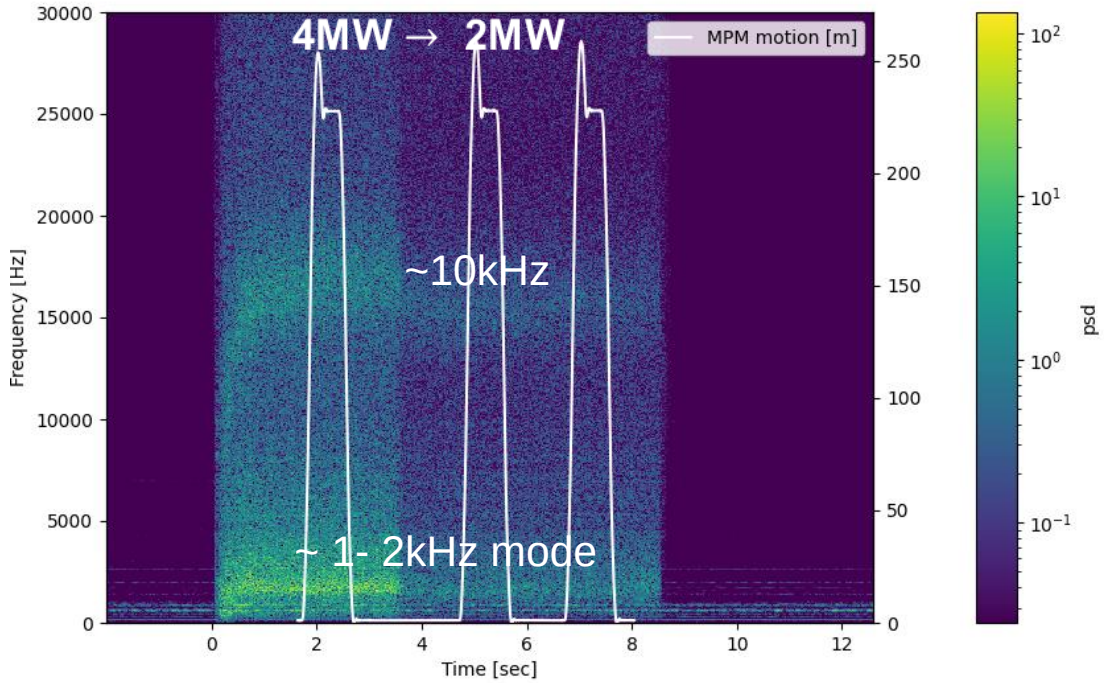
Relation to other low frequency activity: 1-2kHz mode

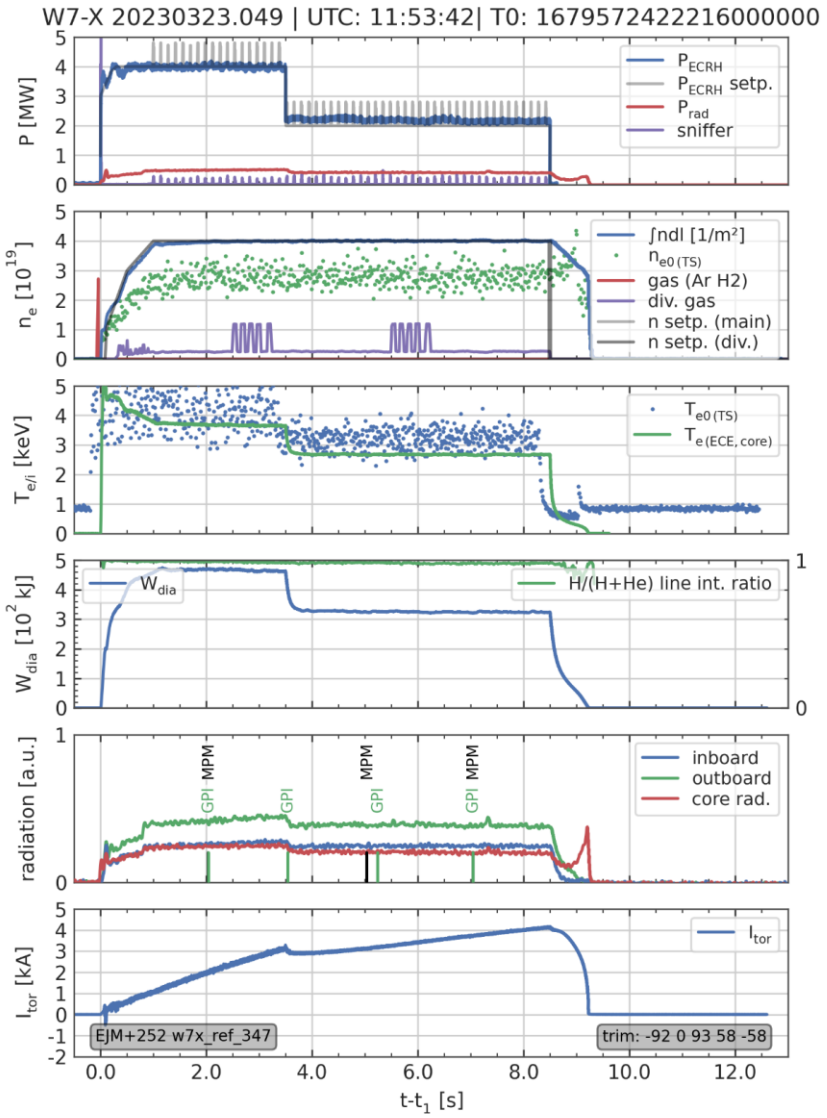
1-2kHz electromagnetic mode [5]:

- More broadband than 500Hz modes
- Appears in rather higher power plasmas > 4MW
- The fluctuation appears to rotate poloidally in the E×B direction between 1 and 10 km/s.

- It does not follow the same scaling with core Te
- Both can be present in High performance discharges

spectrogram #230323049; Mirnov coil 70





[5] S.B. Ballinger et al. Nuclear Materials and Energy 27 (2021) 100967

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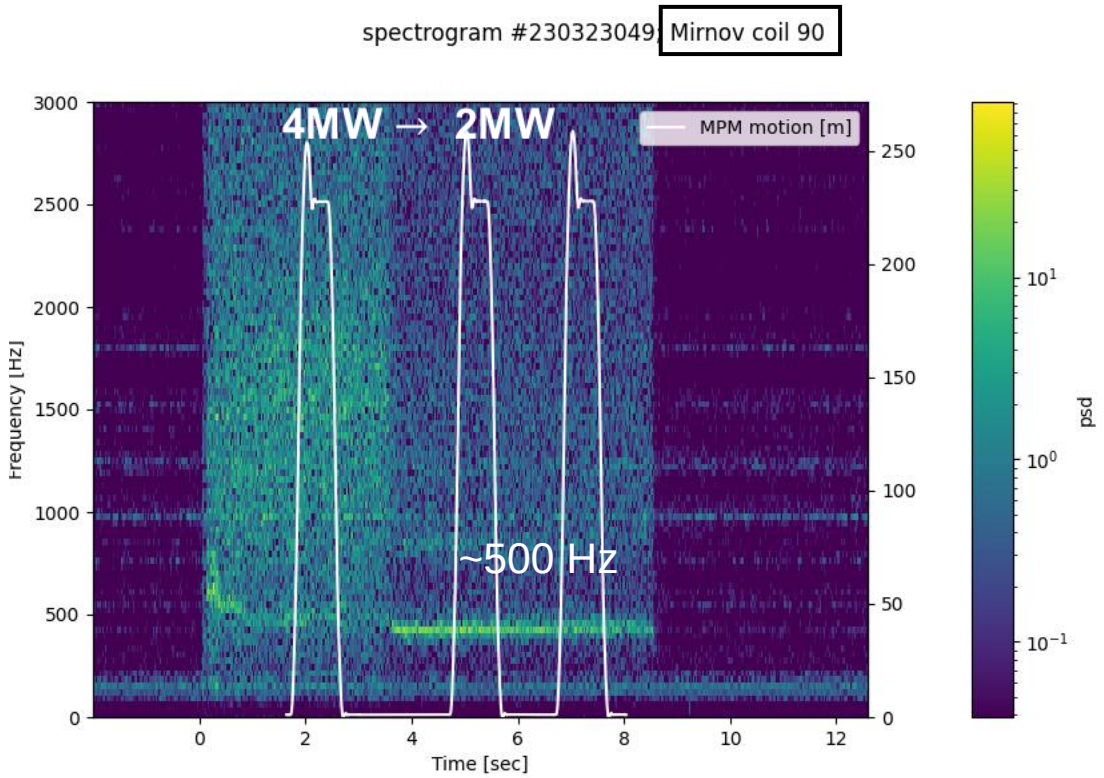
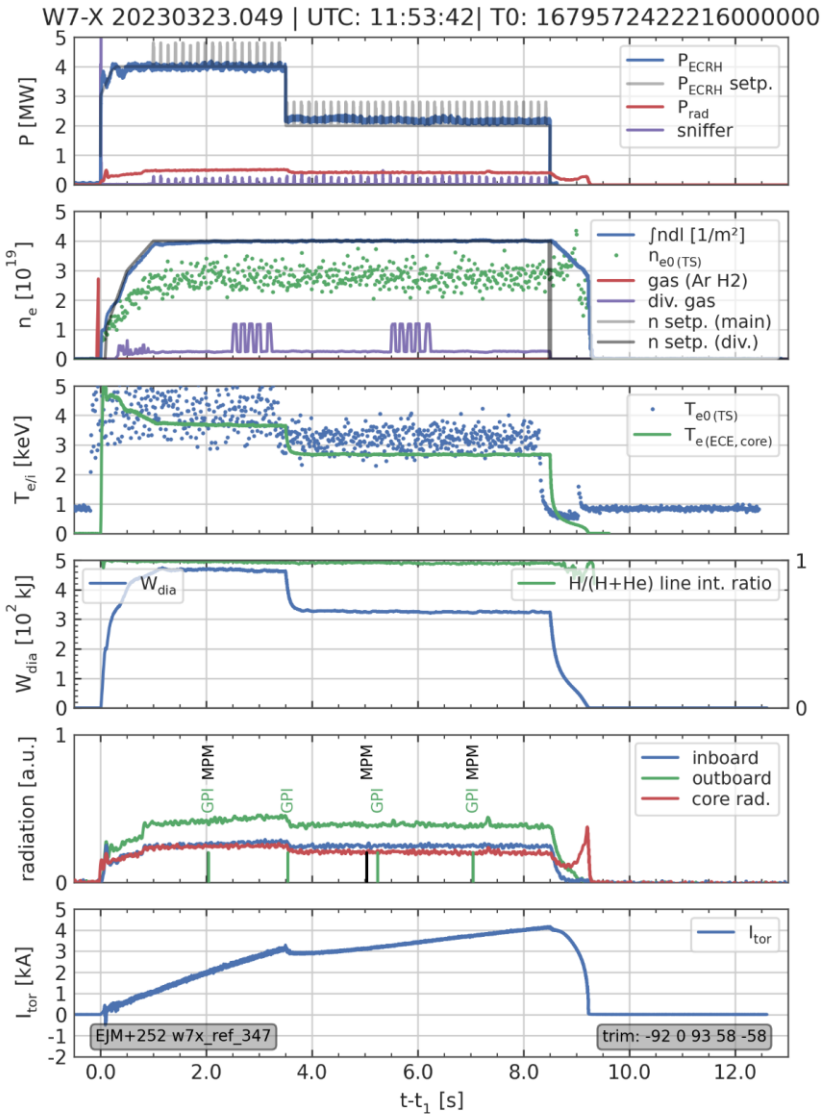




[5] S.B. Ballinger et al. Nuclear Materials and Energy 27 (2021) 100967

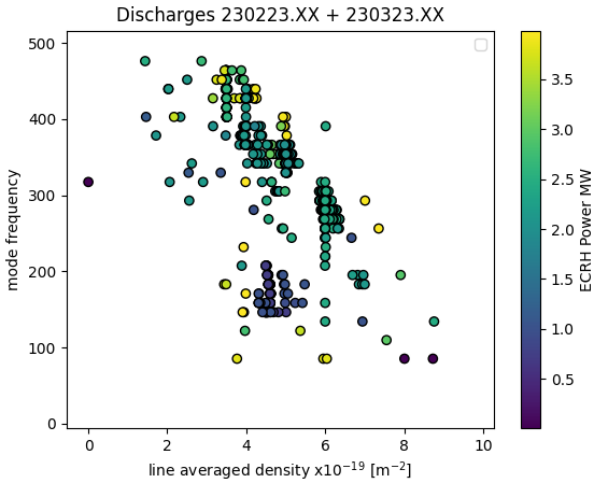
Summary

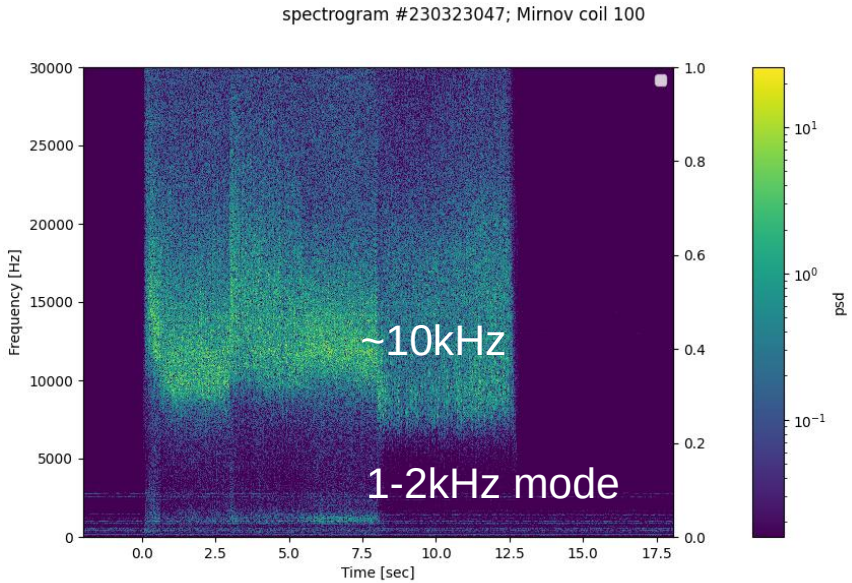
	“crash” (*ELM-like event*)	“periodic mode”
occurrence	• in configurations with 5/5 islands just inside the LCFS	• in island divertor configurations (inner island separatrix=LCFS)
appearance	• intermittent, quasi-frequency ~50-100Hz(?), seen by most (all?) diagnostics • broadband activity in spectra • m=1 core mode in XMCTS, different soft-X emission pre/post crash	• periodic, ~50-500Hz seen by many diagnostics • sharp narrow-band mode in spectra, clear harmonics • frequency correlates with core T_e (or $1/n_{dl}$) • continuous m=1 core mode in XMCTS (weaker than “crashes”) • mode exists more clearly in Helium than Hydrogen (also OP1)
role on confinement	• W_{dia} loss of up to some % per crash (some kJ to 10kJ) • possibly relaxation of edge gradient pedestal (ECE)	• smaller but significant W_{dia} modulation, some kJ
role of magnetic islands	• 5/5 islands have to be close to the LCFS for crash formation • island manipulation with control coils significantly affects crashes / confinement, but in a non-trivial manner→ potentially the effect of islands on the gradient shapes is the critical effect	• mode propagation seems to be spatially modulated by SOL magnetic islands (i.e. stronger in O point), but this is probably an island transport effect, not a source of the mode • in island center, the mode modulates a 10-20kHz QCM

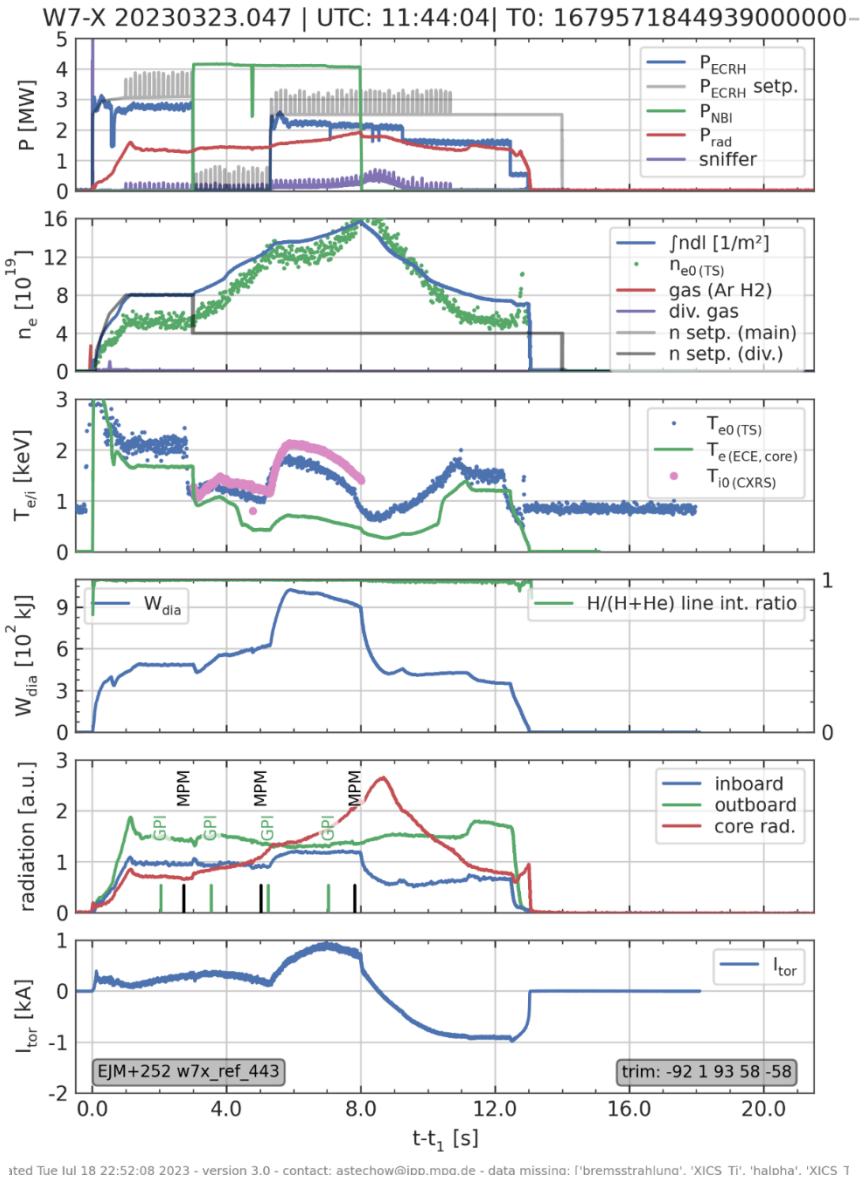
Backup

What about high-performance?

- No obvious 500Hz activity, but rather a faint 1-2 kHz and a 10 kHz QCM mode.
- P_{ECRH} was low enough for 500Hz mode, but n_e too high
- Are there ANY GPI/PCI dropouts?
  - We know that mode exists despite NBI, if P_{ECRH} is low enough. Why not here? ne?

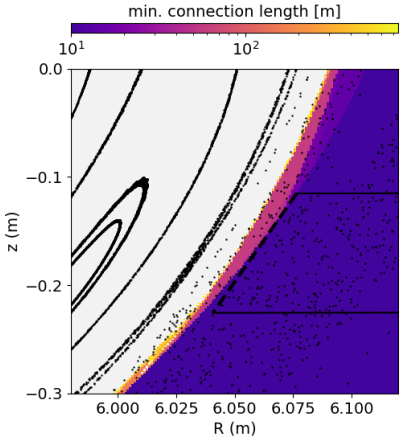




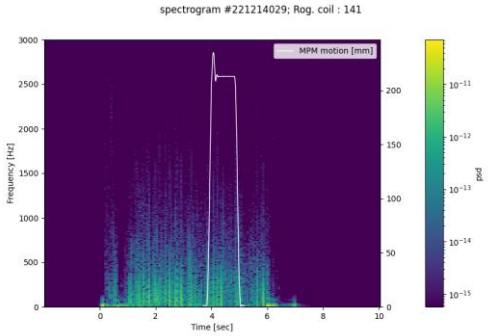


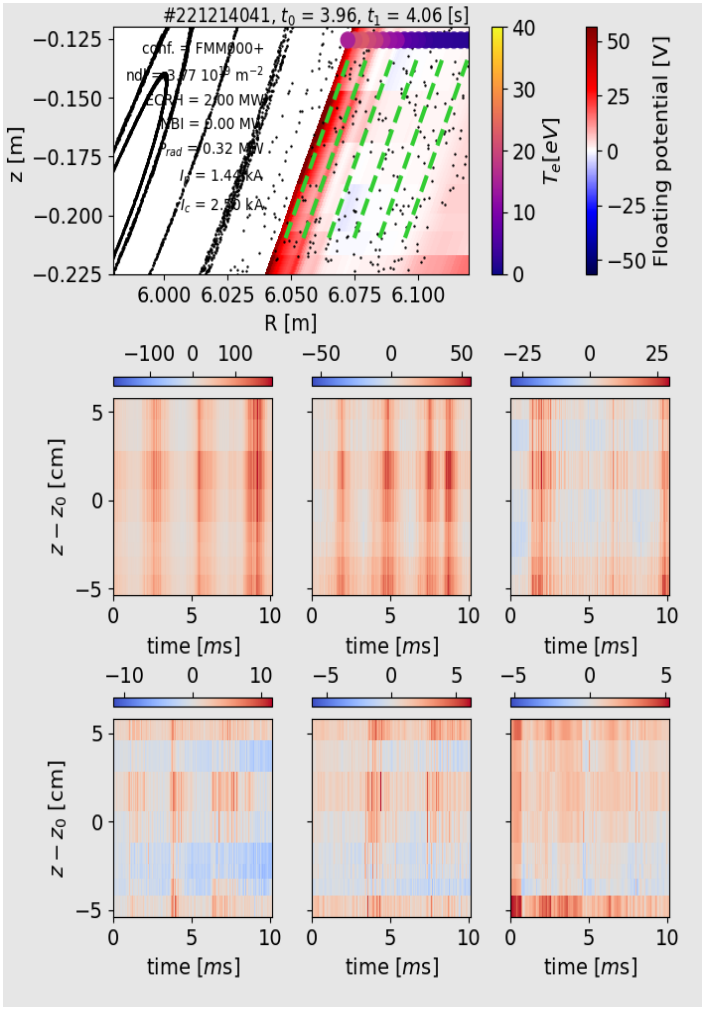
MPM in FMM bursts vs. EJM oscillations

FMM

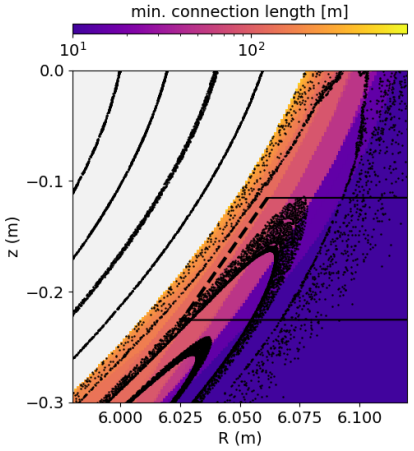


- The SOL floating probes see $\pm 50\ V$ **Intermittent oscillations** without signs of poloidal propagation throughout the poloidal extent of the probe

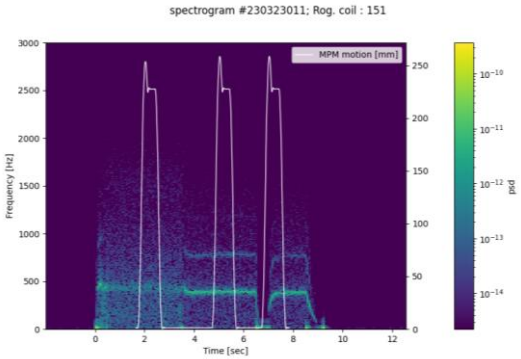


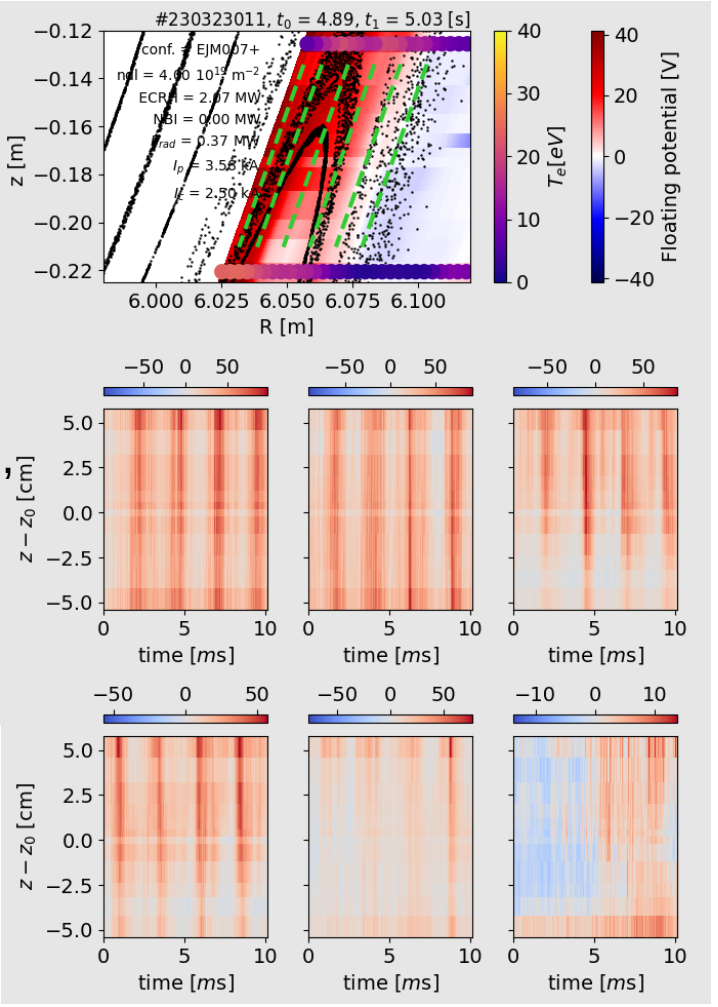


EJM



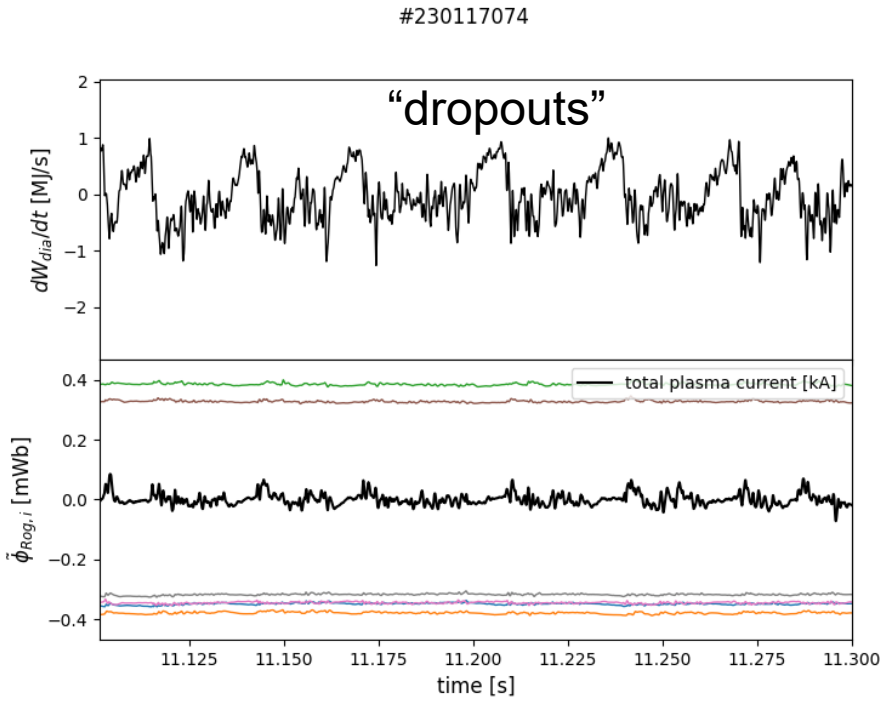
- **Coherent oscillations**, with defined frequency, which scale with core parameters!

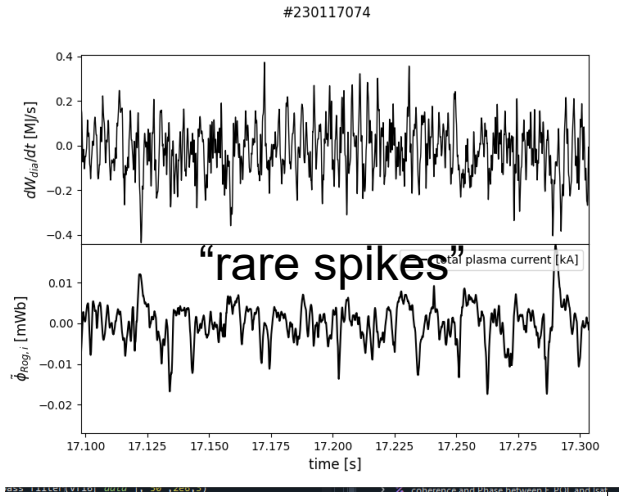


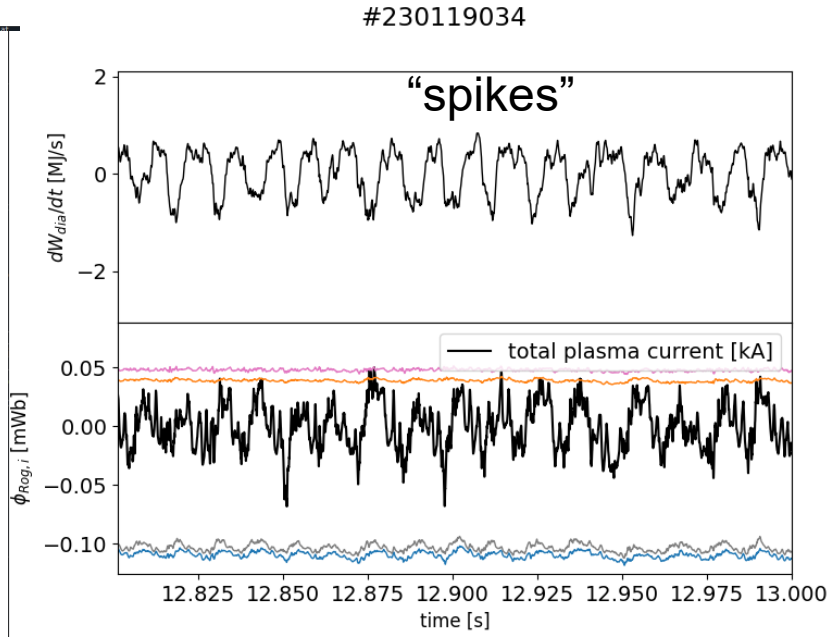


“spikes” vs. “dropouts”

- Different flavours of ELMs in EJM ?

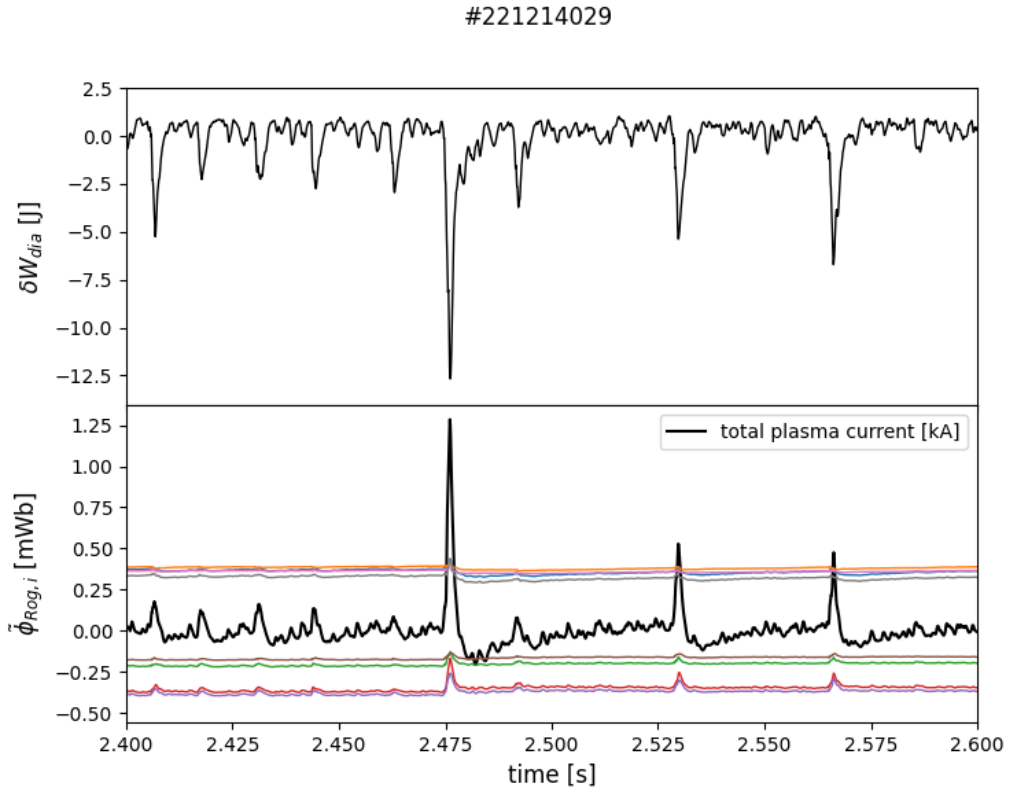


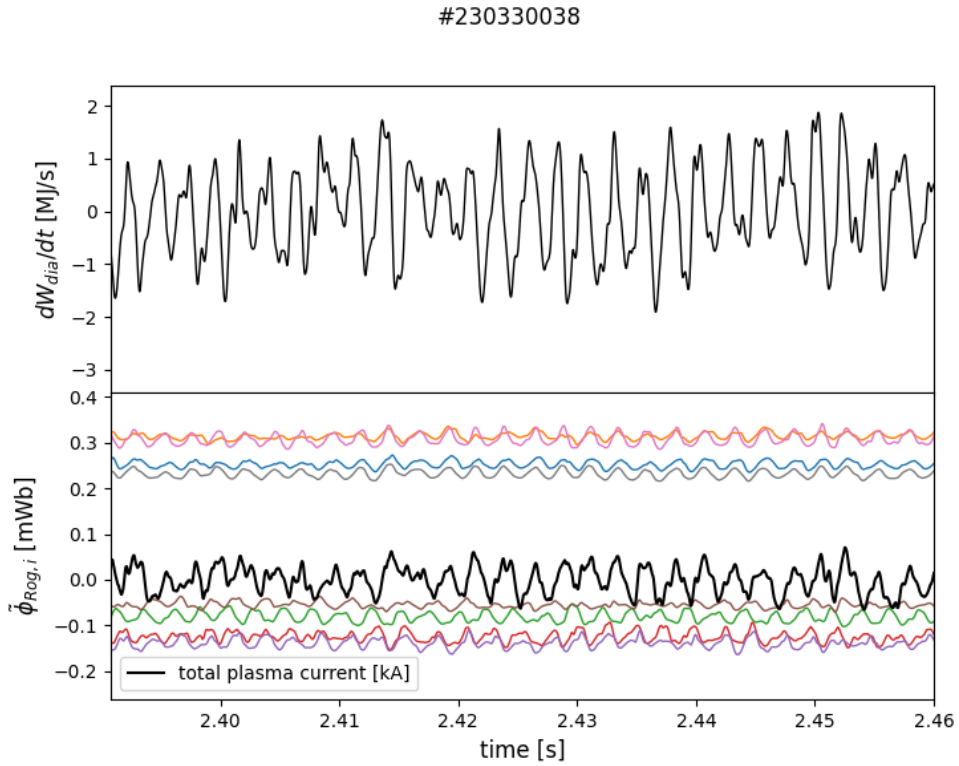




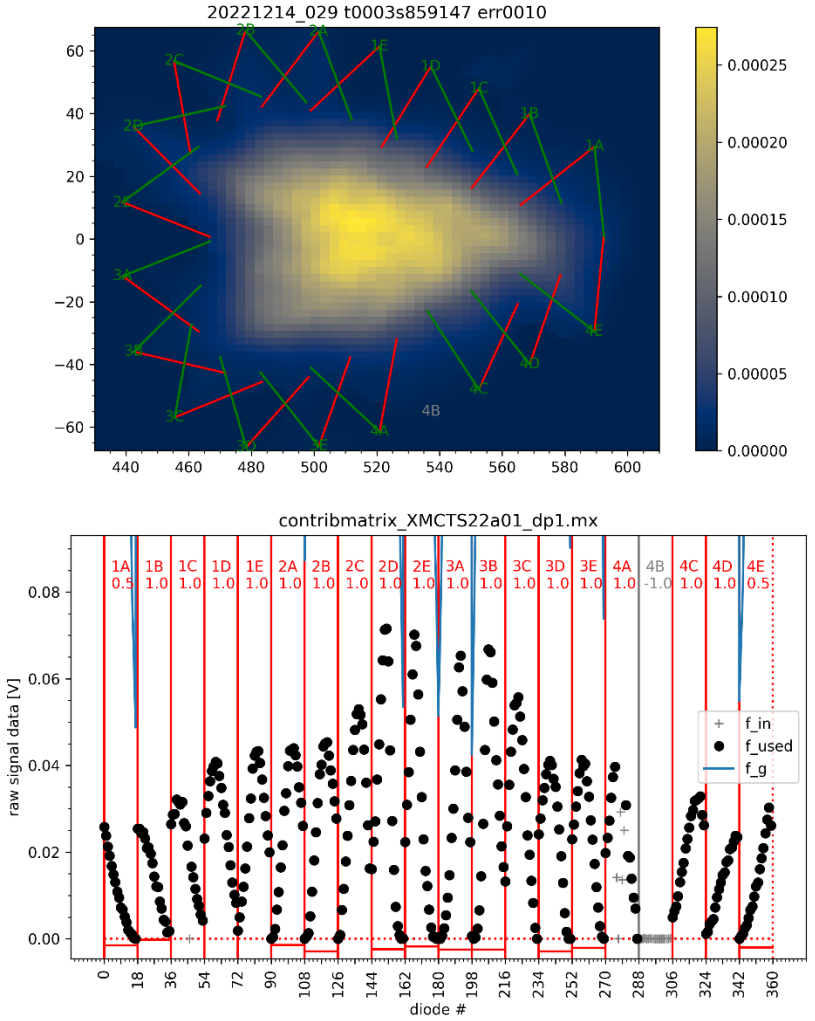
FMM bursts vs. EJM oscillations

- Hypothesis:
  - The harmonic oscillations observed throughout island divertor configuration are the same as the oscillations that occur within one ELM-like crash in island limited configuration

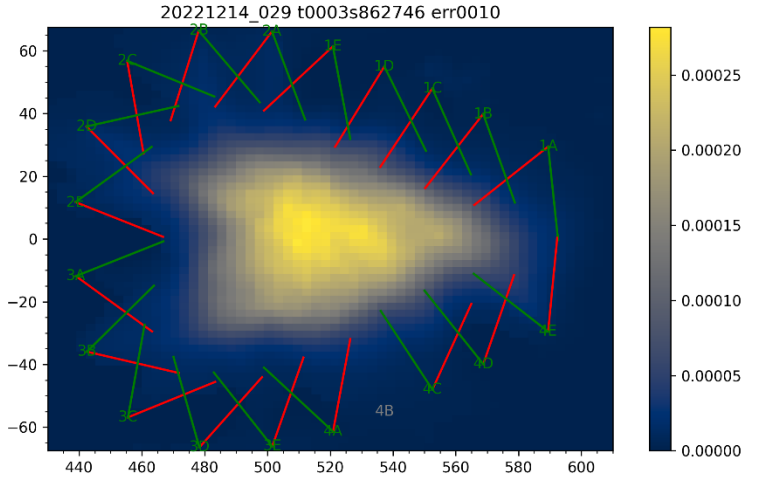


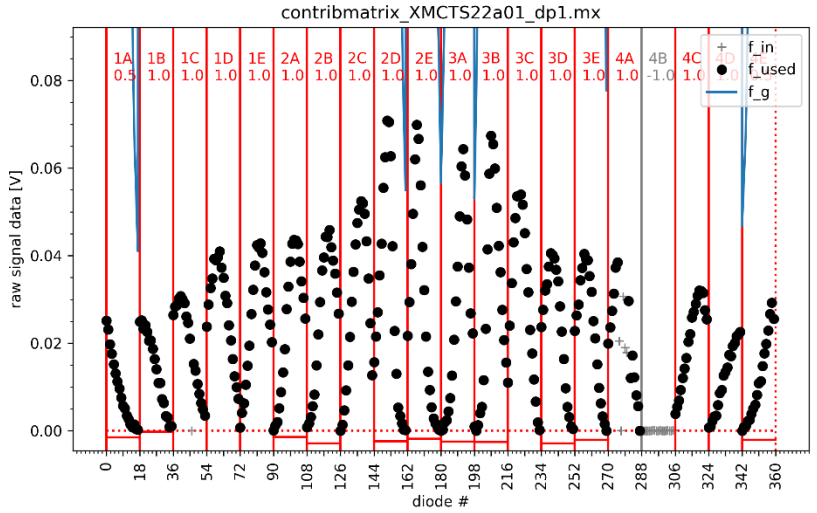


Comparison RAW tomogram before / after crash



Comparison RAW tomogram before / after crash





1-2khz -> 500Hz switch coil 90