MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Mode activity observations in OP2.1 and subsequent steps towards OP2.2/2.3

Wendelstein 7-X

K. Rahbarnia on behalf of contributing colleagues

EUROfusion

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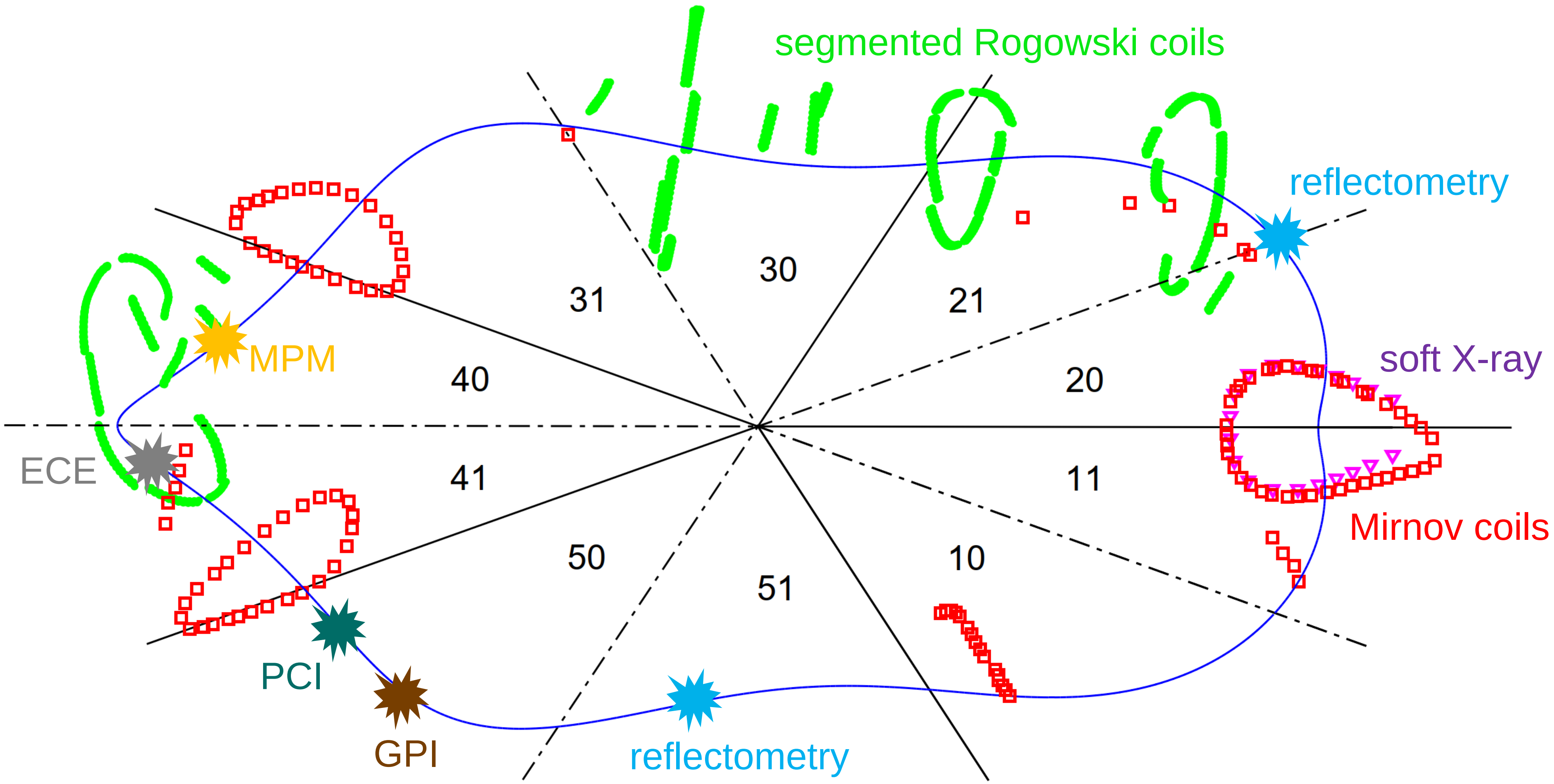
OUTLINE

- Alfvénic broad band fluctuations (~200 kHz)
- core/edge MHD modes measured with PCI (~250 kHz)
- electron temperature fluctuations in high density scenarios (≤ 200 kHz)
- TEM activity (~200 kHz core, ~800 kHz edge)
- ion driven modes (NBI ~350kHz, ICRH ~100kHz)
- low frequency (10-50 kHz) mode activity in high performance / high density scenarios (KBMs?)
- very low frequency modes (~1 kHz: ILMs, ELM-like fluctuations, zonal flows)

selected fluctuation diagnostics



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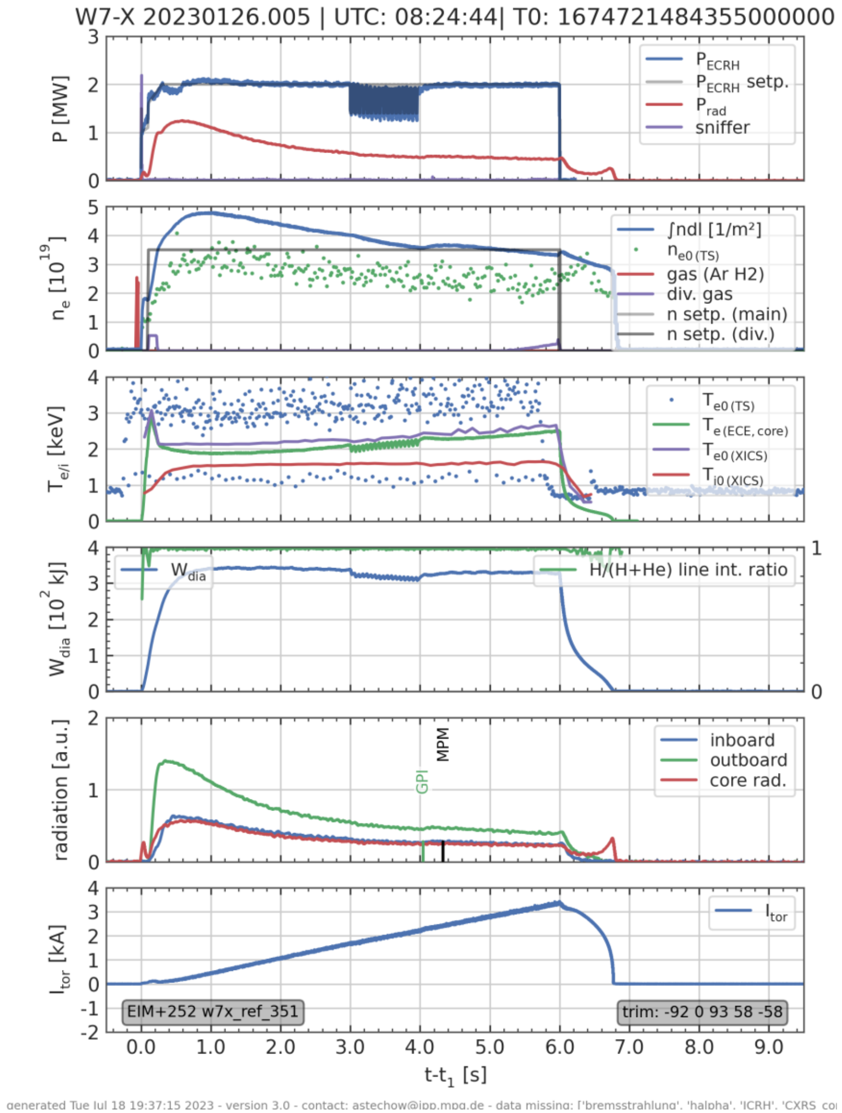
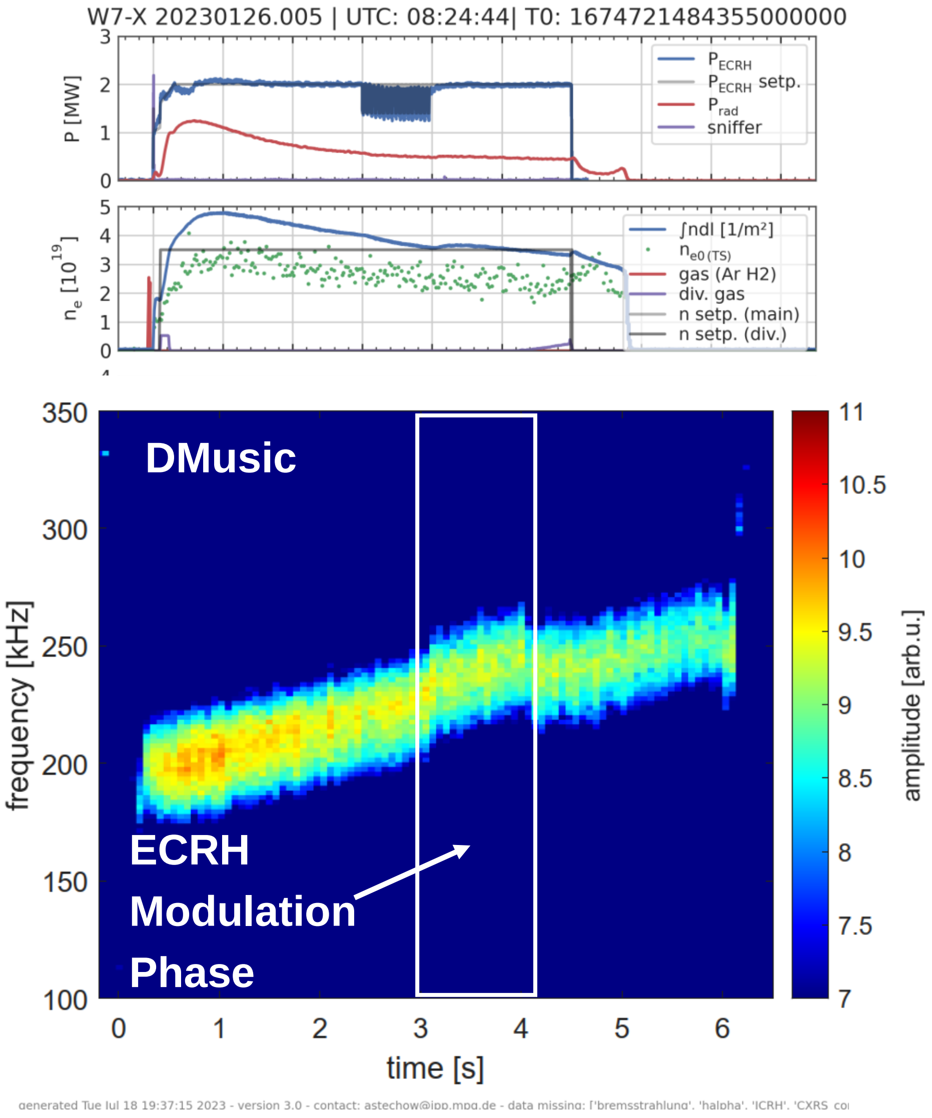
magnetic broad band fluctuations in ECRH plasmas



Alfvénic broad band fluctuations (similar to OP1)

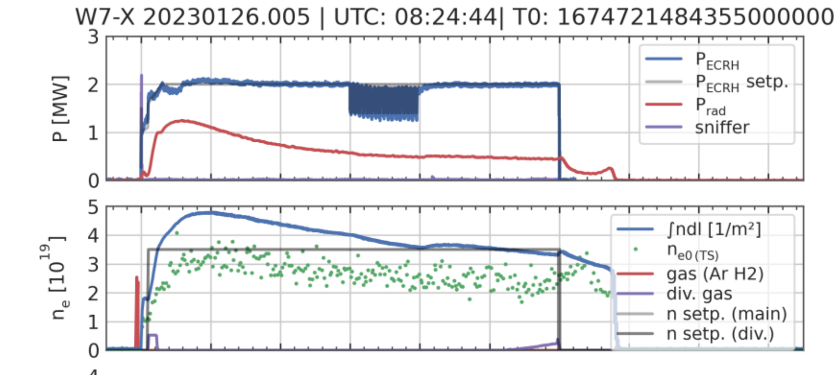
magnetic broad band fluctuations in ECRH plasmas

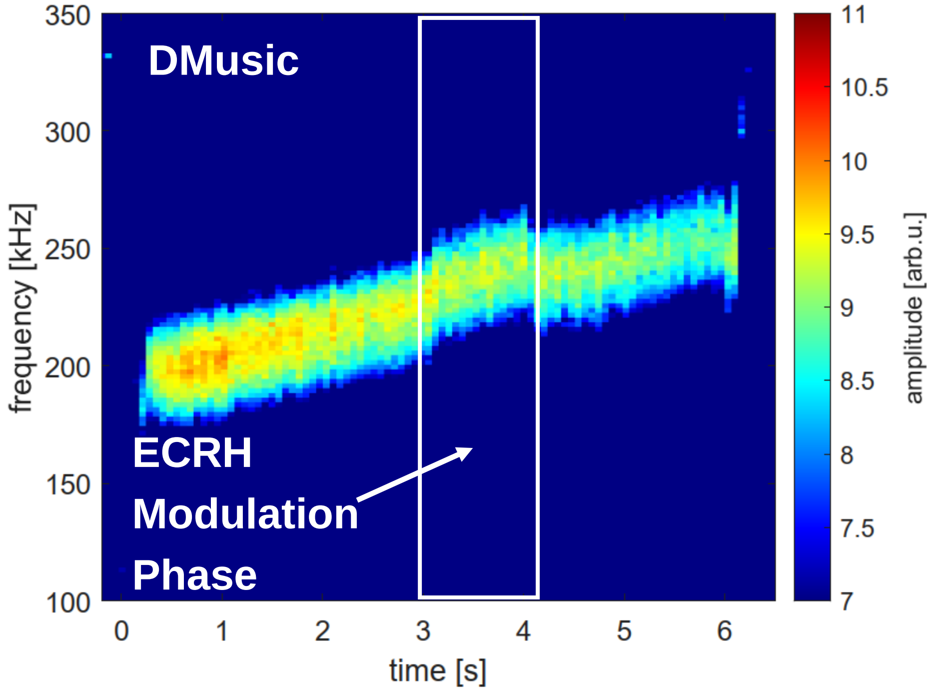


Alfvénic broad band fluctuations (similar to OP1)

- frequency **~ 200-300 kHz**

magnetic broad band fluctuations in ECRH plasmas





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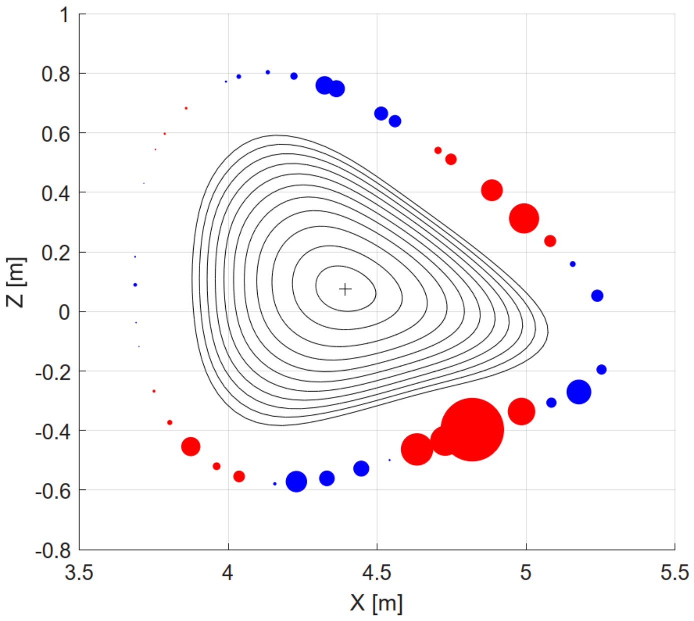
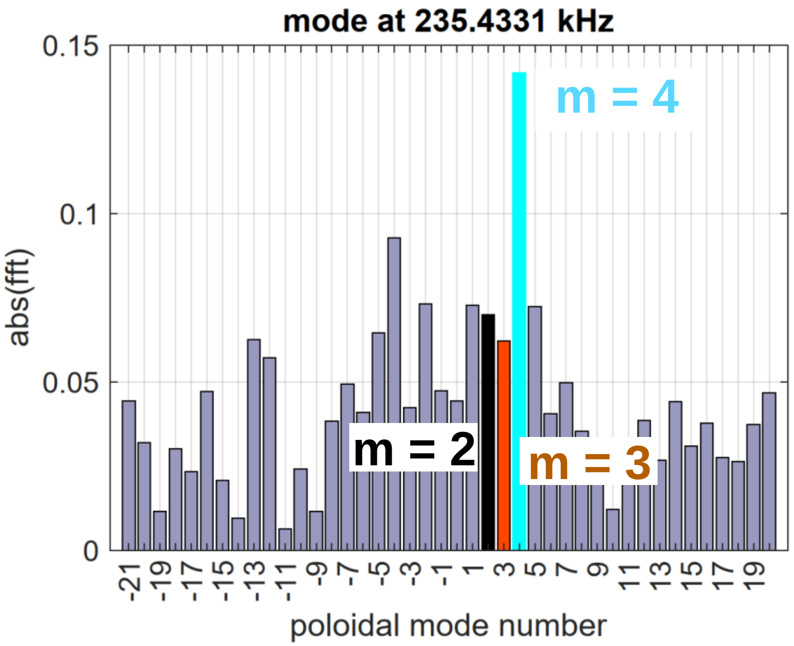
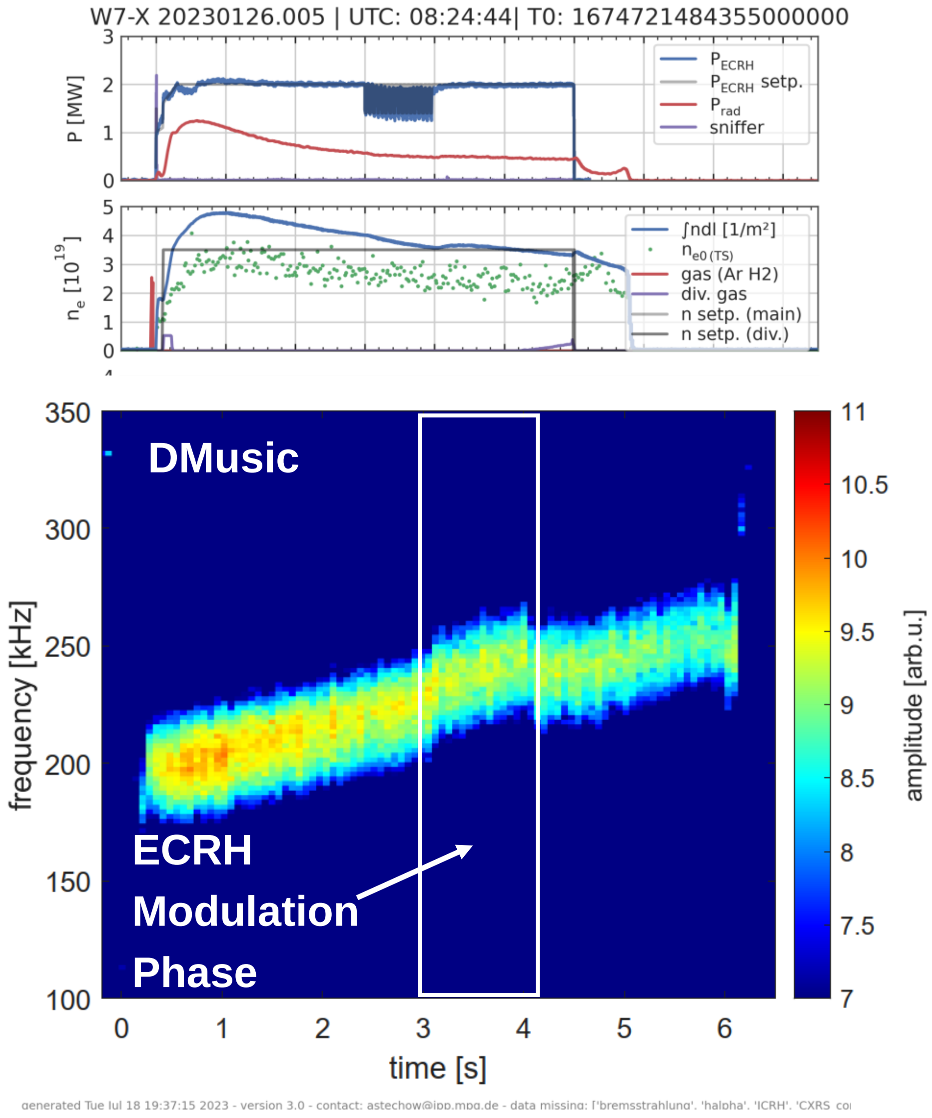
Alfvénic broad band fluctuations (similar to OP1)

- ➢ frequency **~ 200-300 kHz**
- ➢ poloidal mode number **|m|<5**



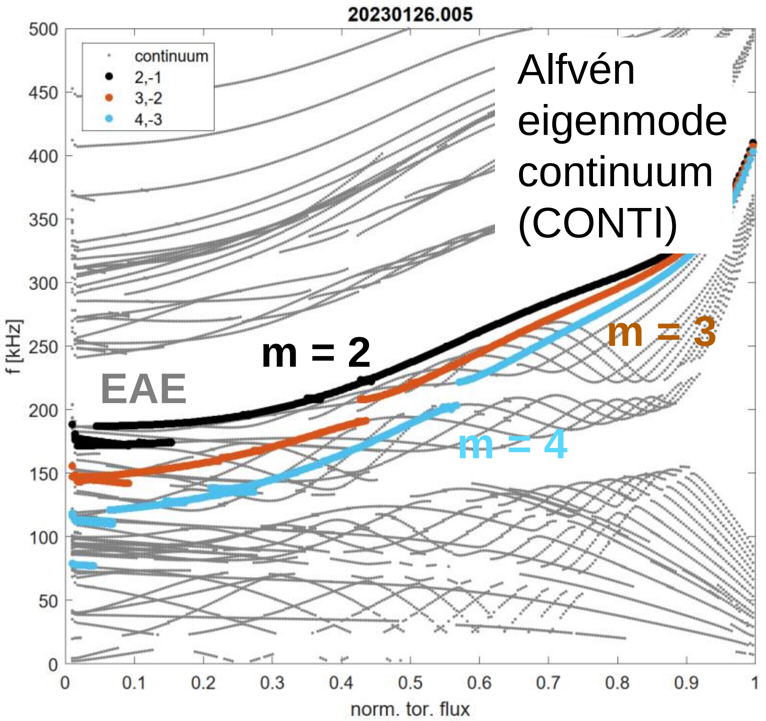


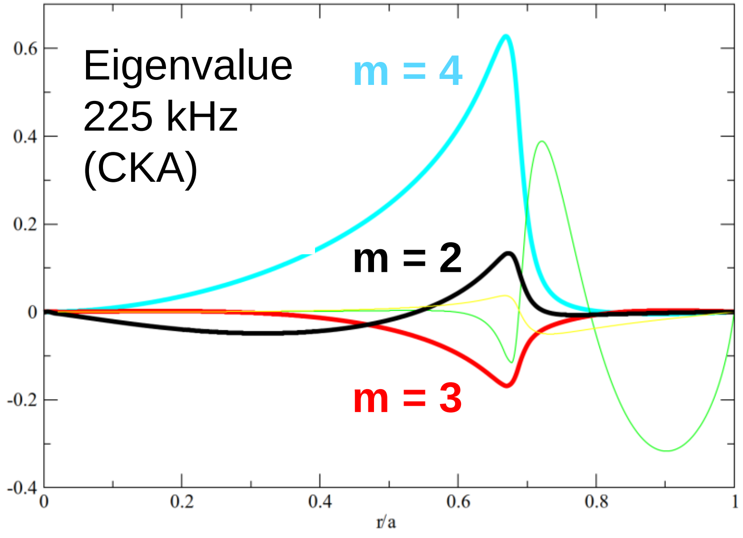
magnetic broad band fluctuations in ECRH plasmas



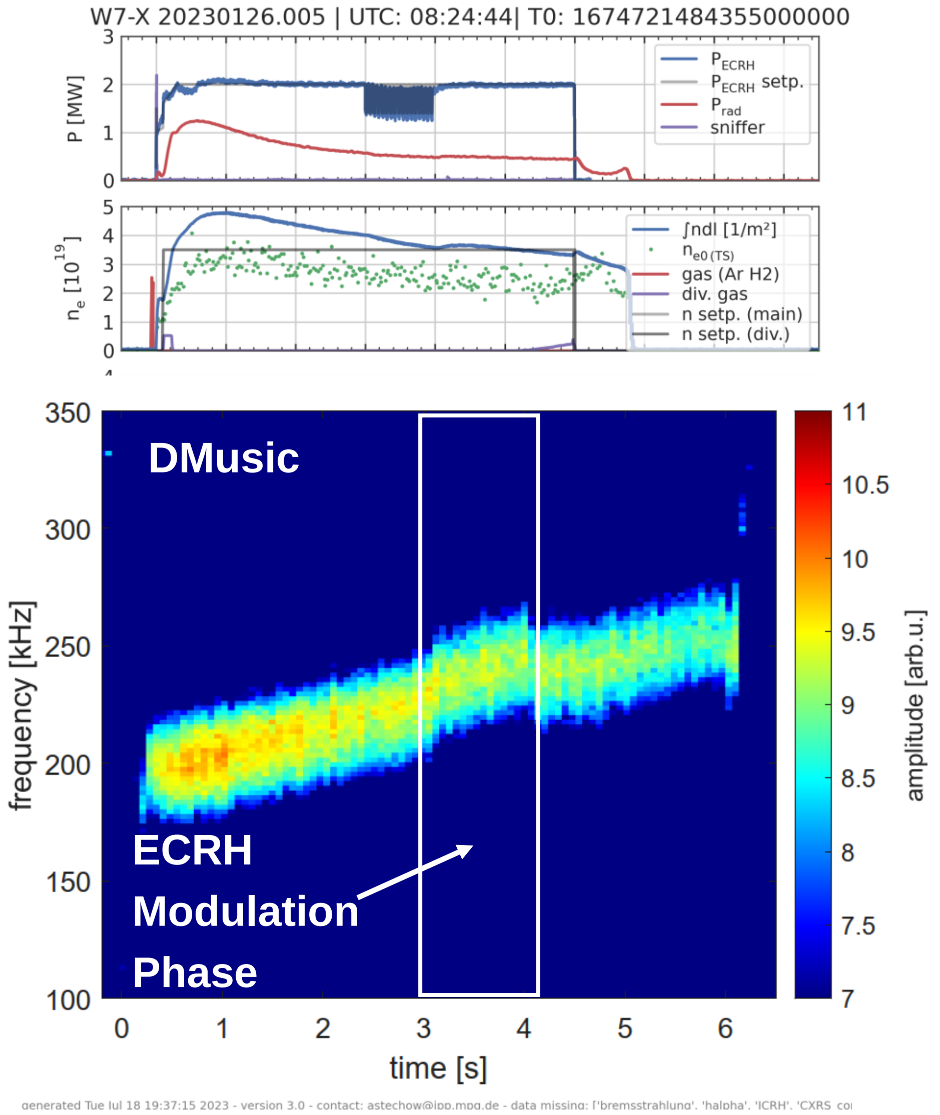
Alfvénic broad band fluctuations (similar to OP1)

- frequency ~ **200-300 kHz**
- poloidal mode number **|m|<5**
- experimental observations confirm theoretical calculations





magnetic broad band fluctuations in ECRH plasmas



Alfvénic broad band fluctuations (similar to OP1)

- frequency **~ 200-300 kHz**
- poloidal mode number **|m|<5**
- experimental observations confirm theoretical calculations
- EUTERPE simulations suggest **ITG-driven**

Next steps:

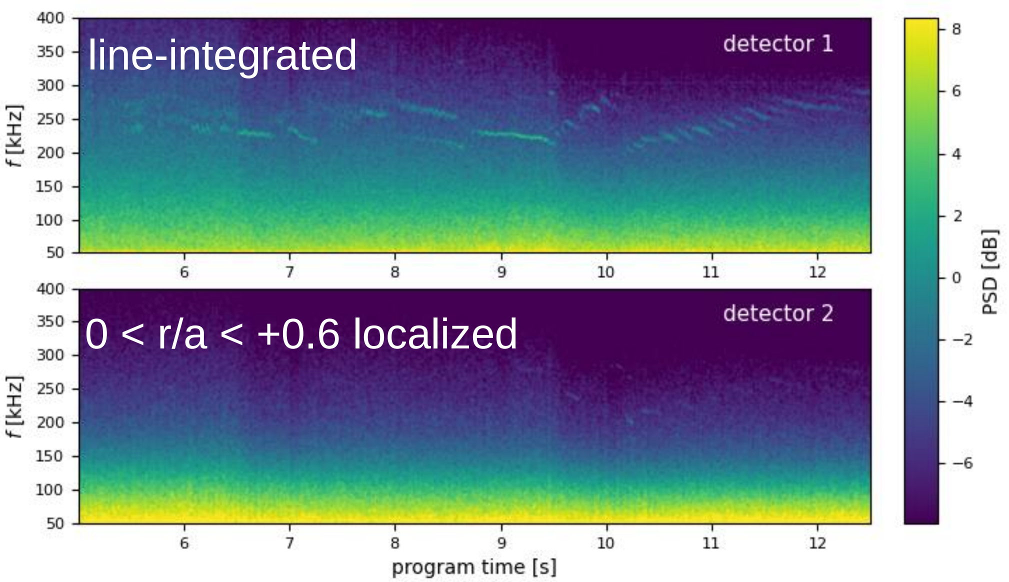
- investigate on/offset and character in different heating scenarios (high power NBI + ECRH)
- study correlation to ITG turbulence driving terms
- incorporate newly developed synthetic Mirnov diagnostic (also compare with synthetic diagnostic developed at TJ-II)

References:

C. Slaby et al 2020 Nucl. Fusion 60 112004
K. Rahbarnia et al 2021 Plasma Phys. Control. Fusion 63 015005
S. Vaz Mendes et al 2023 Nucl. Fusion 63 096008
Ch. Büschel et al, *Synthetic Mirnov diagnostic*, to be submitted
PHD-thesis, Sara v Mendes, 2023
Master thesis, Charlotte Büschel, 2023

MHD mode localization with PCI

- PCI measures line-integrated density fluctuations with poloidal wavenumber resolution
- Variable **radial localization** with spatial filter mask
  - here: **coherent modes not present in core**
- Synthetic PCI (SPCI) provides modelling and direct comparison to global simulations or simplified models



MHD mode localization with PCI

- PCI measures line-integrated density fluctuations with poloidal wavenumber resolution
- Variable **radial localization** with spatial filter mask
  - here: **coherent modes not present in core**
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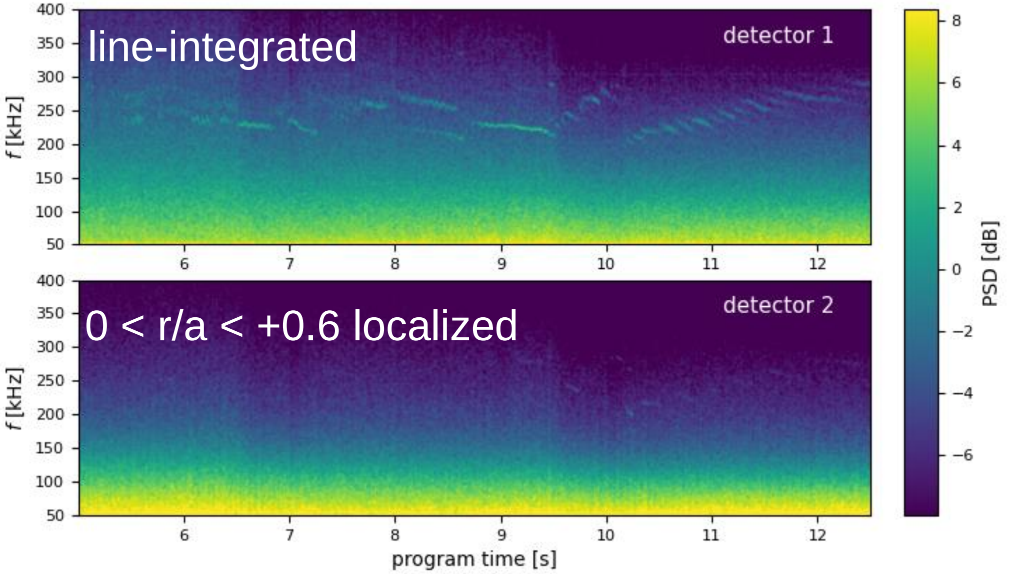
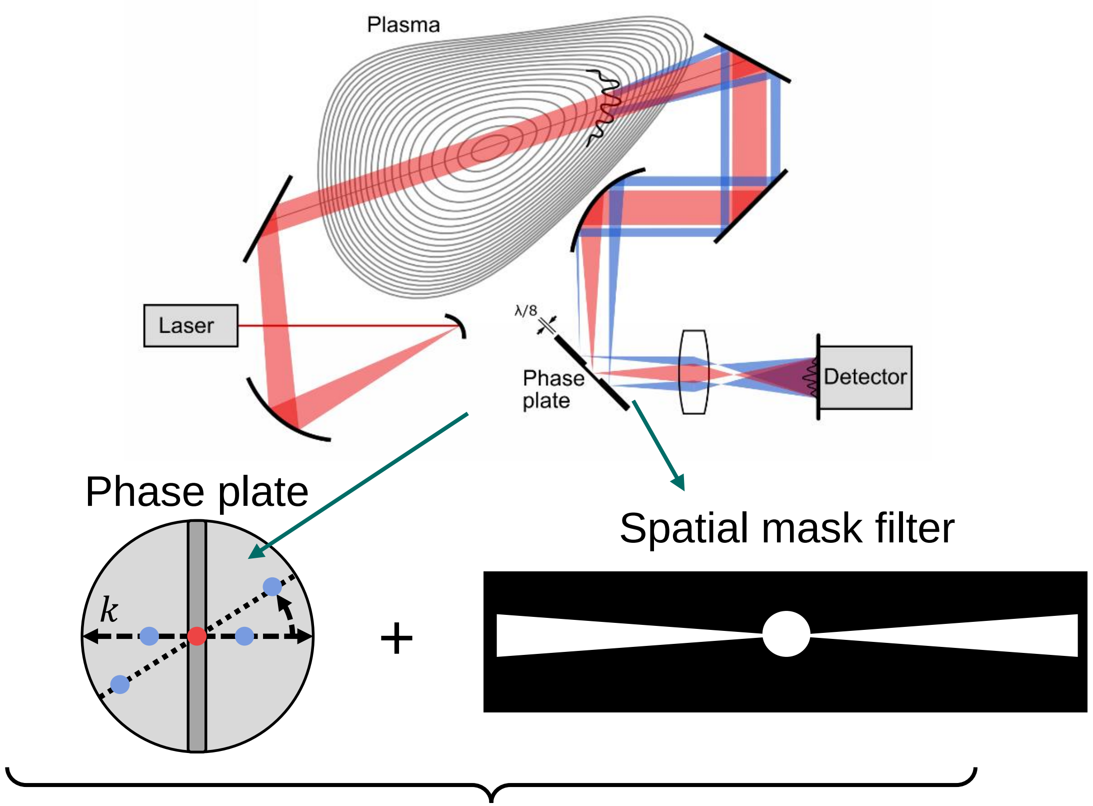
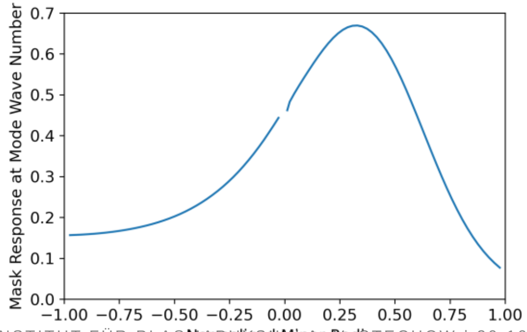
Next steps: rotate mask to get radial mode profile

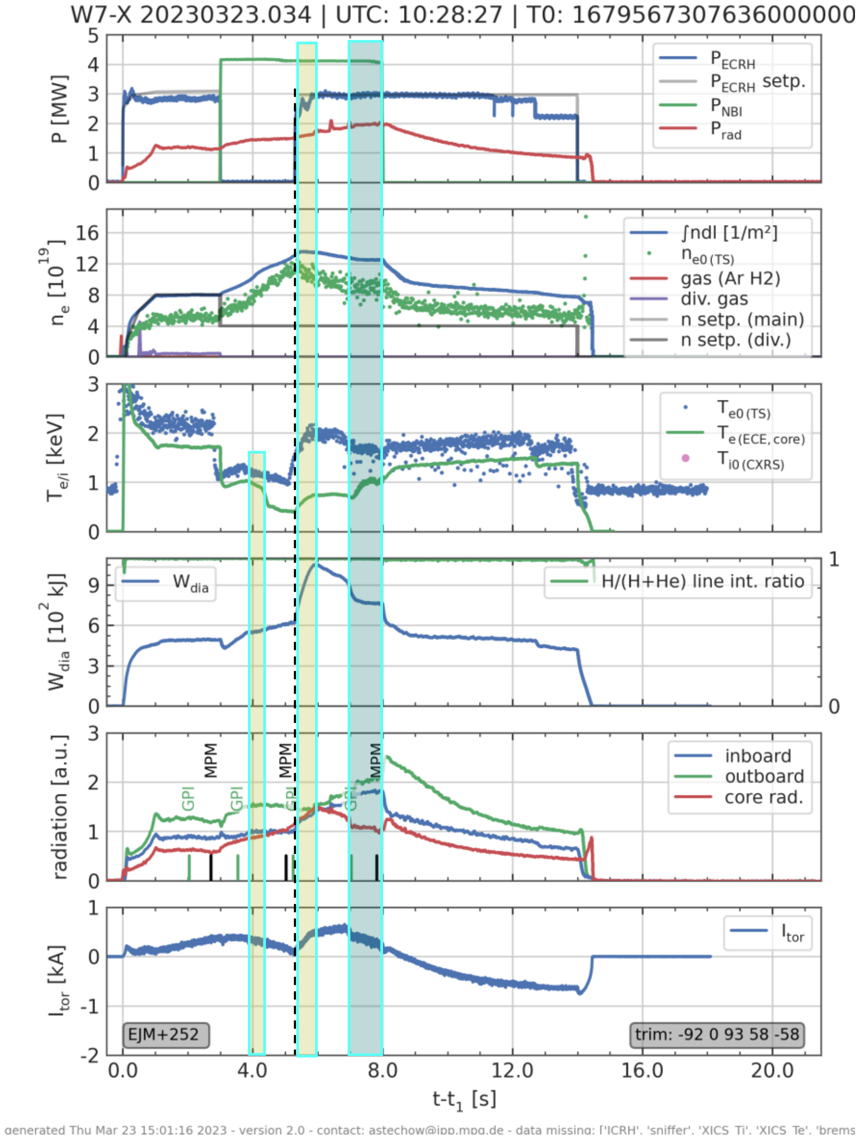




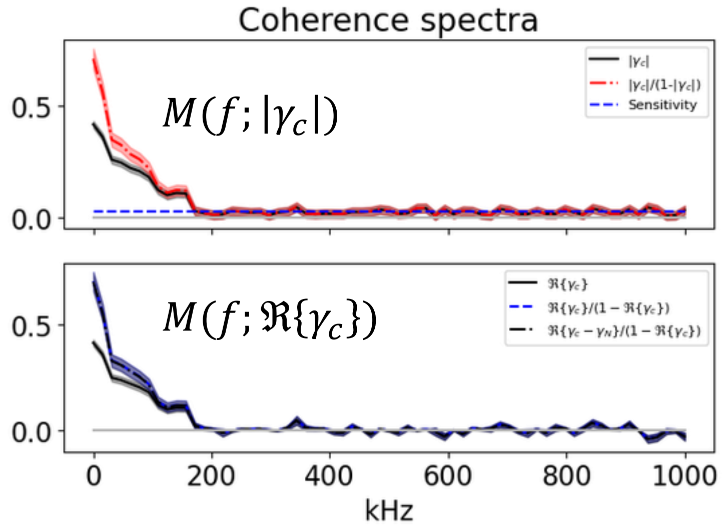
Radially selective response



T_e-fluctuations in the push to high-density operation

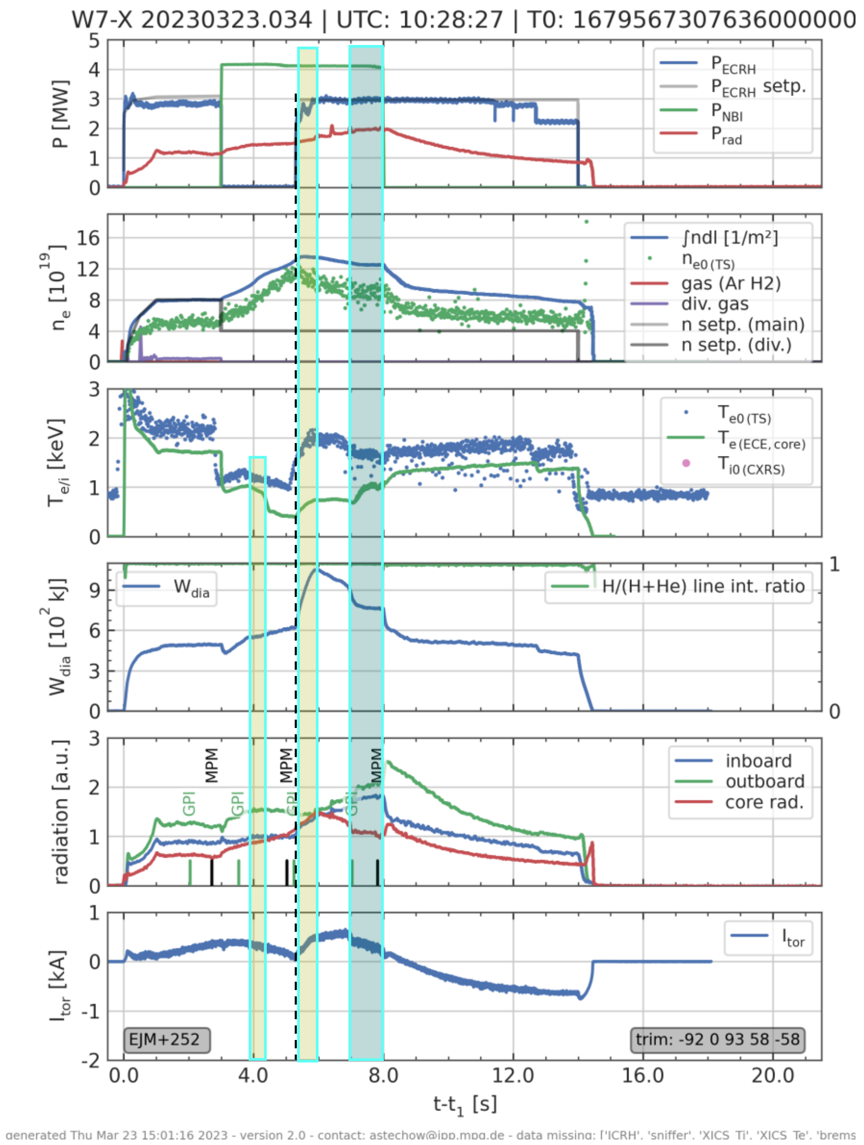


Radial correlation ECE measures relative T_e-fluctuation levels:



- fluctuations occur at relatively **high plasma density ($\geq 8 \times 10^{19}$ m^{-3})** with introduction of O2 ECRH and NBI
- fluctuations appear across the plasma mid-radius/core region (**approximately 0.3<r/a<0.6**)
- broadband T_e-fluctuations **respond to changes in heating / core fueling** during O2 ECRH re-introduction experiments
- fluctuations **coincide with electromagnetic fluctuations** measured by Mirnov coils

T_e-fluctuations in the push to high-density operation



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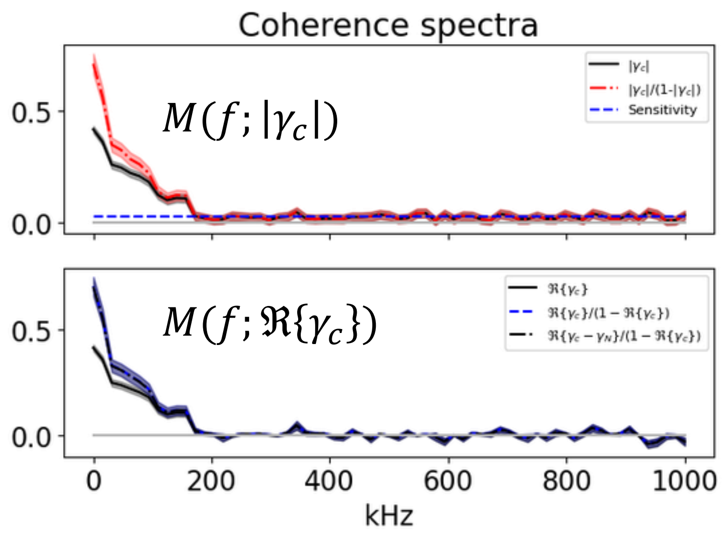

Next steps:

- ➢ investigate the effect of profile gradient changes
- ➢ study transition from low to high plasma pressure
- ➢ investigate the role of these modes with respect to plasma transport

- ➢ fluctuations occur at relatively **high plasma-density (≥ 8×10^{19} m^{-3})** with introduction of O2 ECRH and NBI
- ➢ fluctuations appear across the plasma mid-radius/core region (**approximately 0.3<r/a<0.6**)
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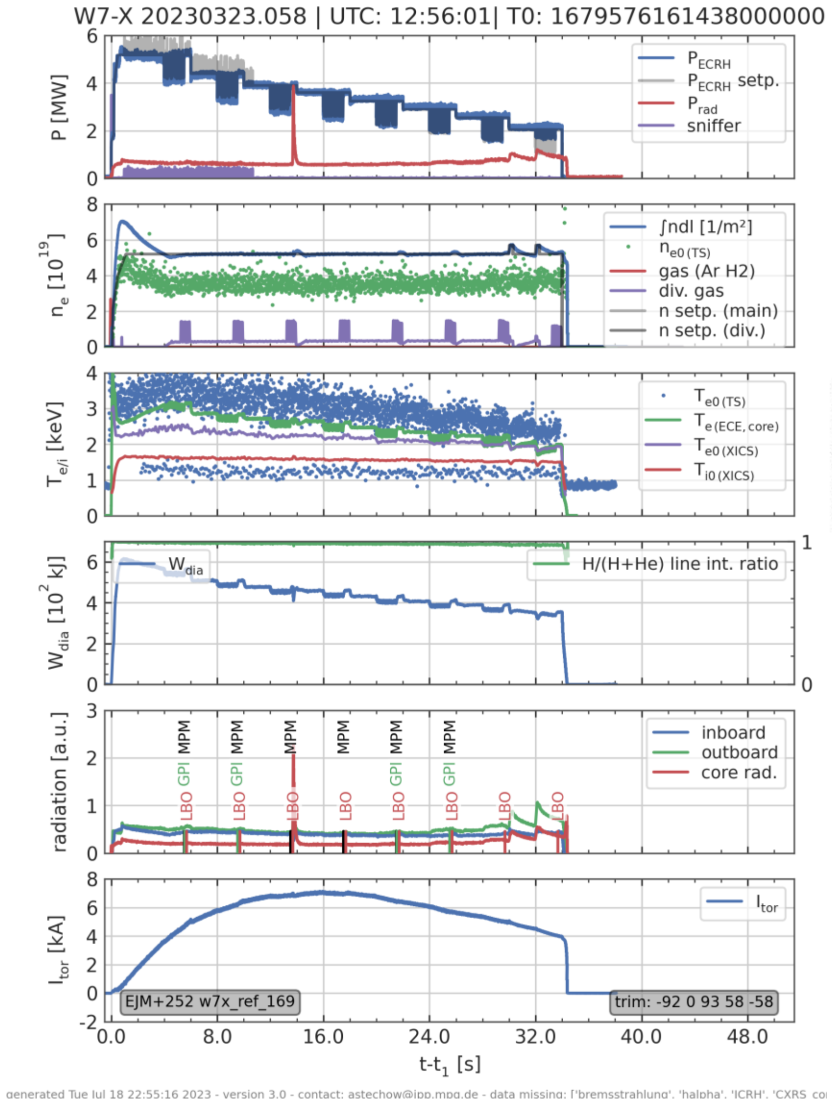
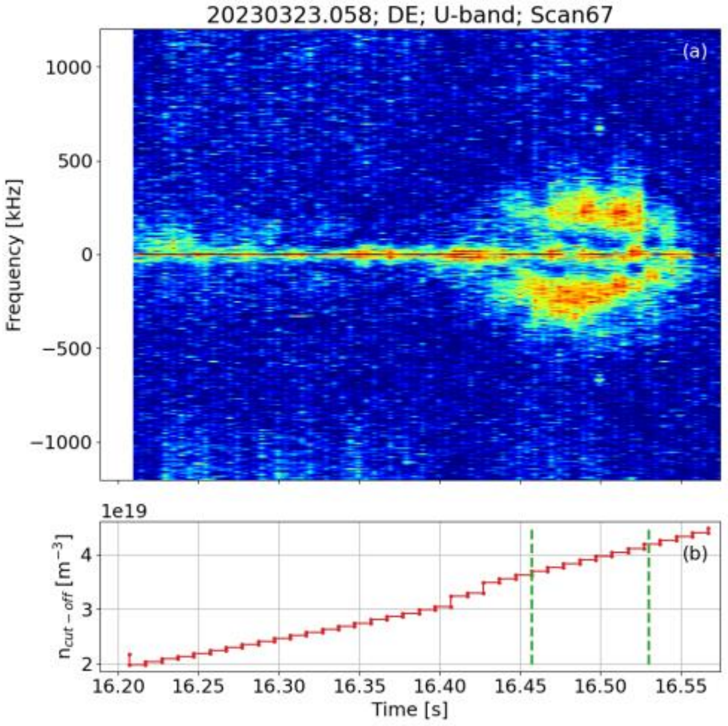
Trapped Electron modes in W7-X



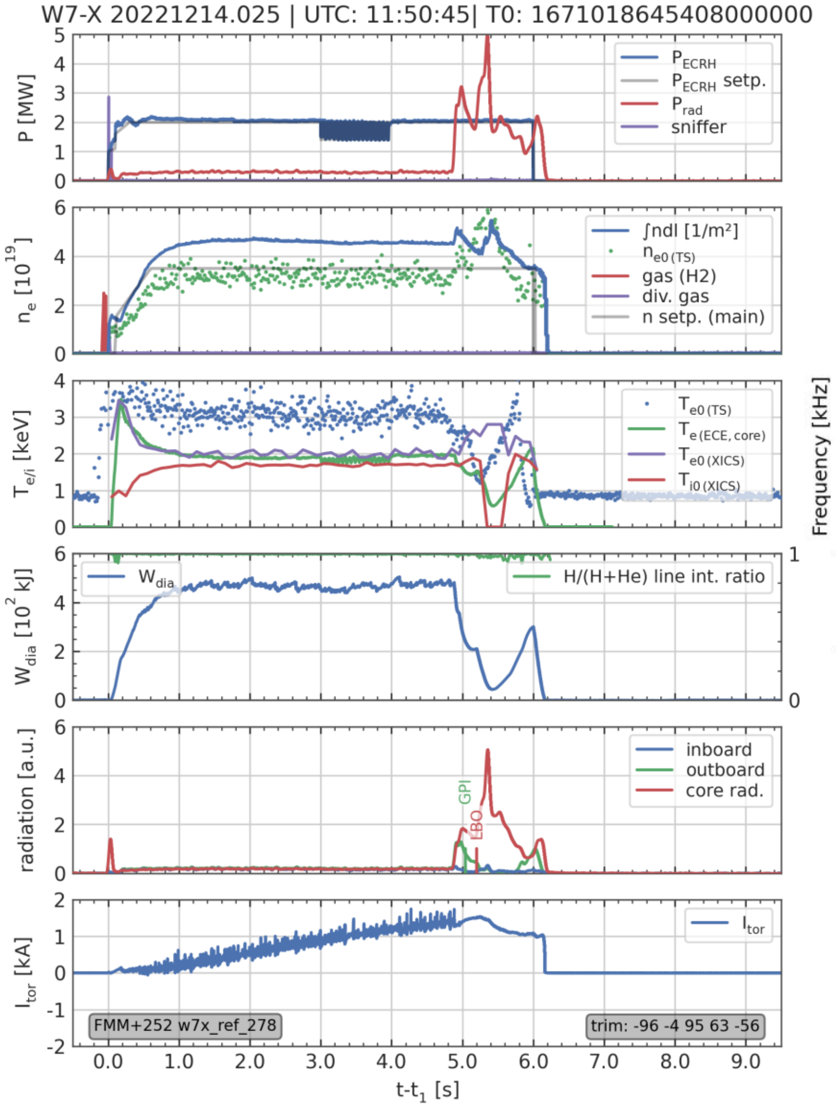
Poloidal correlation reflectometry

coherence spectrogram



- Plasma **core shows strong mode activity**
- **Strong in EIM and AIM** configurations and **weaker in DBM and FTM, KKM** show **no mode** so far
- Mode **depends on ∇T_e**
- Small poloidal scale, **$L_\perp$ ≈20 mm**
- Rotation in **e^--diamagnetic drift direction**
- **$k_\perp \rho^* \geq 1$** is estimated
- **Gyrokinetic calculations support TEMs**

Trapped Electron modes in W7-X



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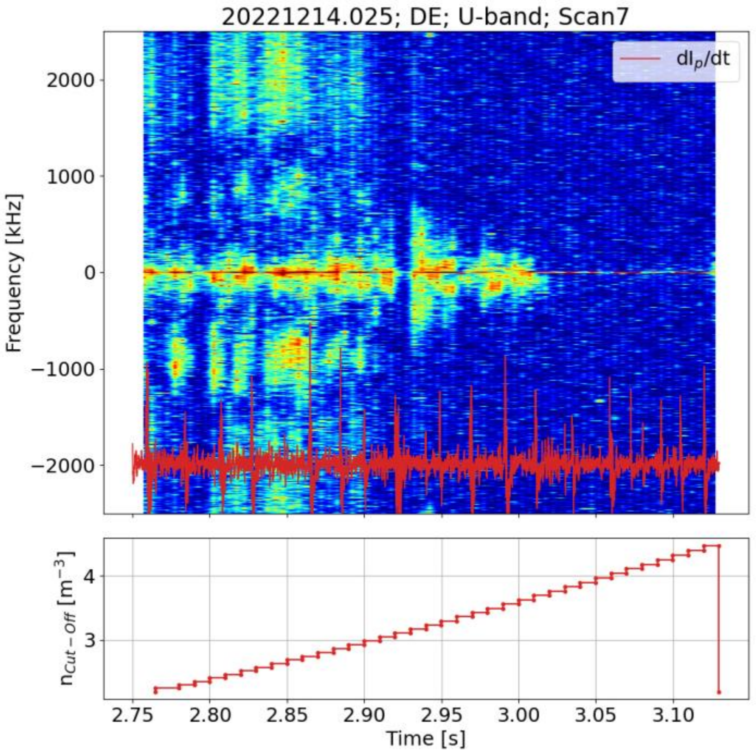
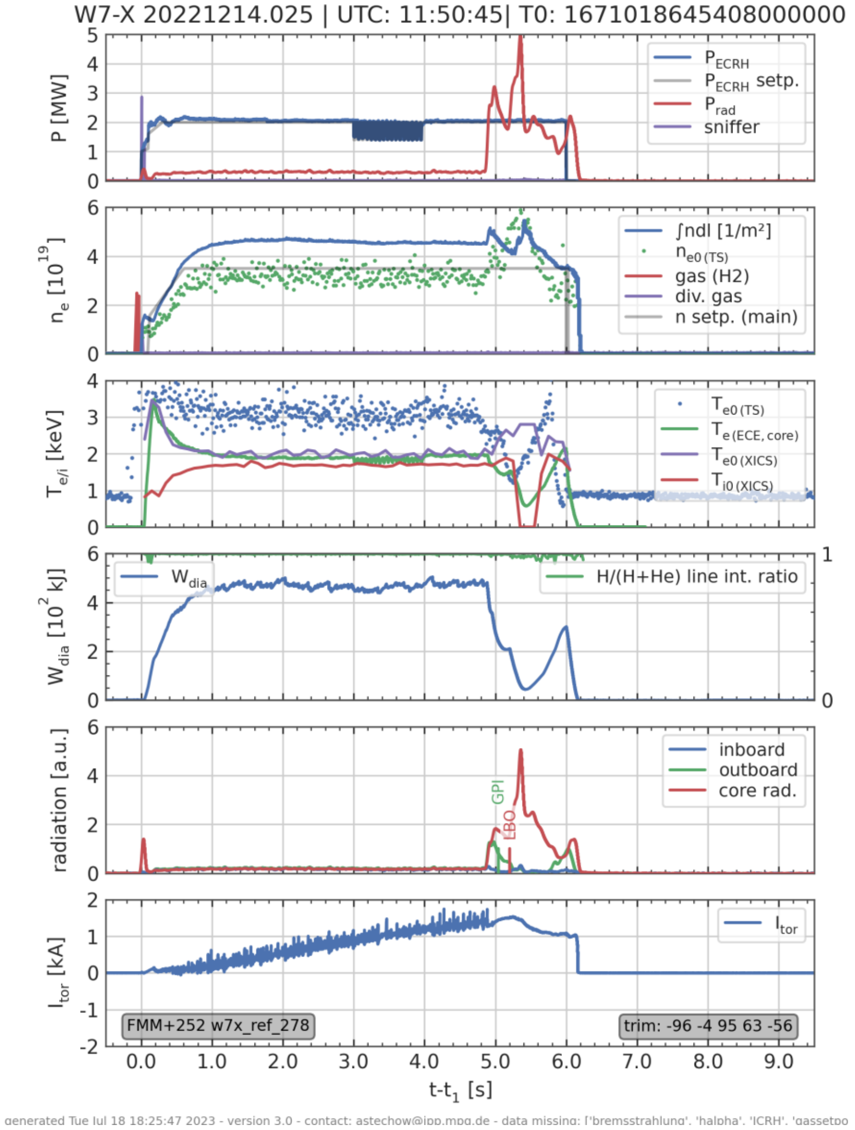
Poloidal correlation reflectometry

coherence spectrogram



- ➢ Modes in **FMM configuration**
- ➢ Located **inside the edge**
- ➢ Frequency: **800 kHz to 1000 kHz**
- ➢ Terminated by I_p-crash
- ➢ Correlates with increase in W_{dia}
- ➢ Mode number **m ≈ 170**
- ➢ Poloidal scale length **$L_\perp$ ≈ 20 mm**
- ➢ Rotation in **e⁻-diamagnetic drift direction**
- ➢ Mode **driven by ∇n_e**

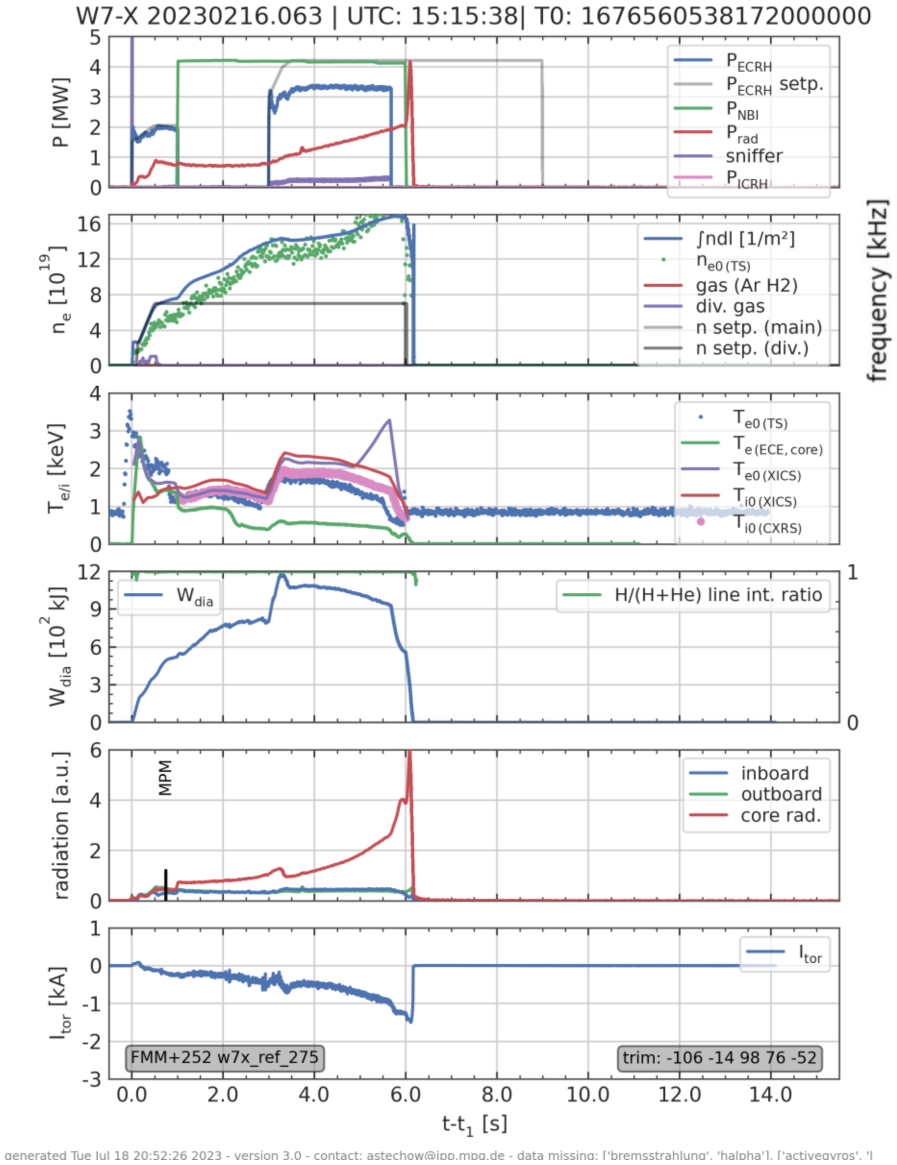
Trapped Electron modes in W7-X

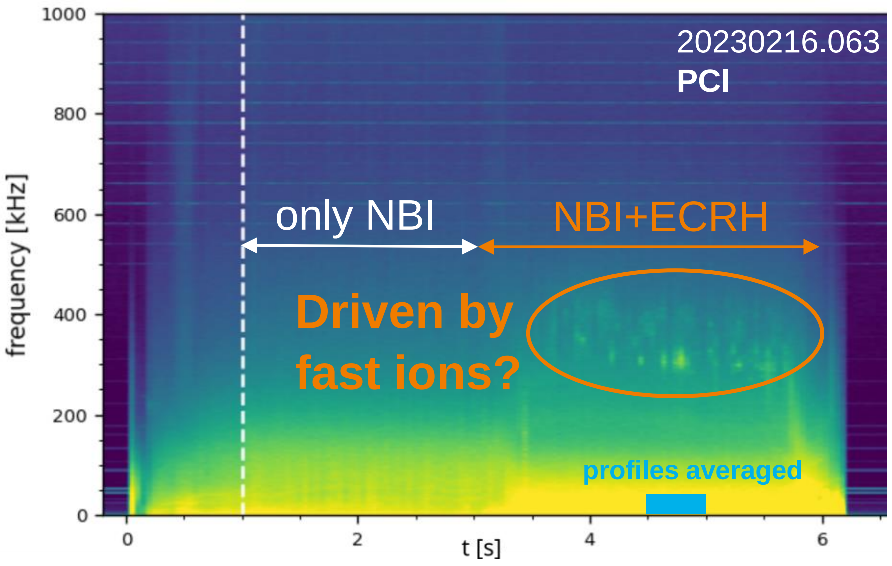


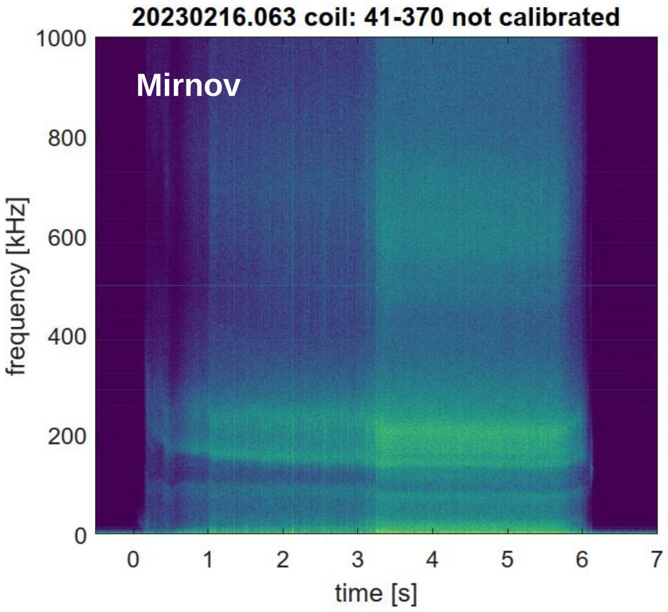
Next steps::

- Mirror Scan for ∇T_e driven TEMs in OP2.2
- Understand absence of modes in some configurations
- Investigate particle transport with TEMs
- Investigation on interaction TEMs and low frequency turbulence
- Detailed gyrokinetic calculations to validate TEM nature of modes
    1. For ∇T_e driven TEMs in the core
    2. For ∇n_e driven TEMs in the plasma edge
- Verify the ∇n_e dependence in FMM plasmas → needs better profile data
- Investigation of ∇n_e-TEMs in relation with transition to higher confinement

Mode activity in discharges with fast ions



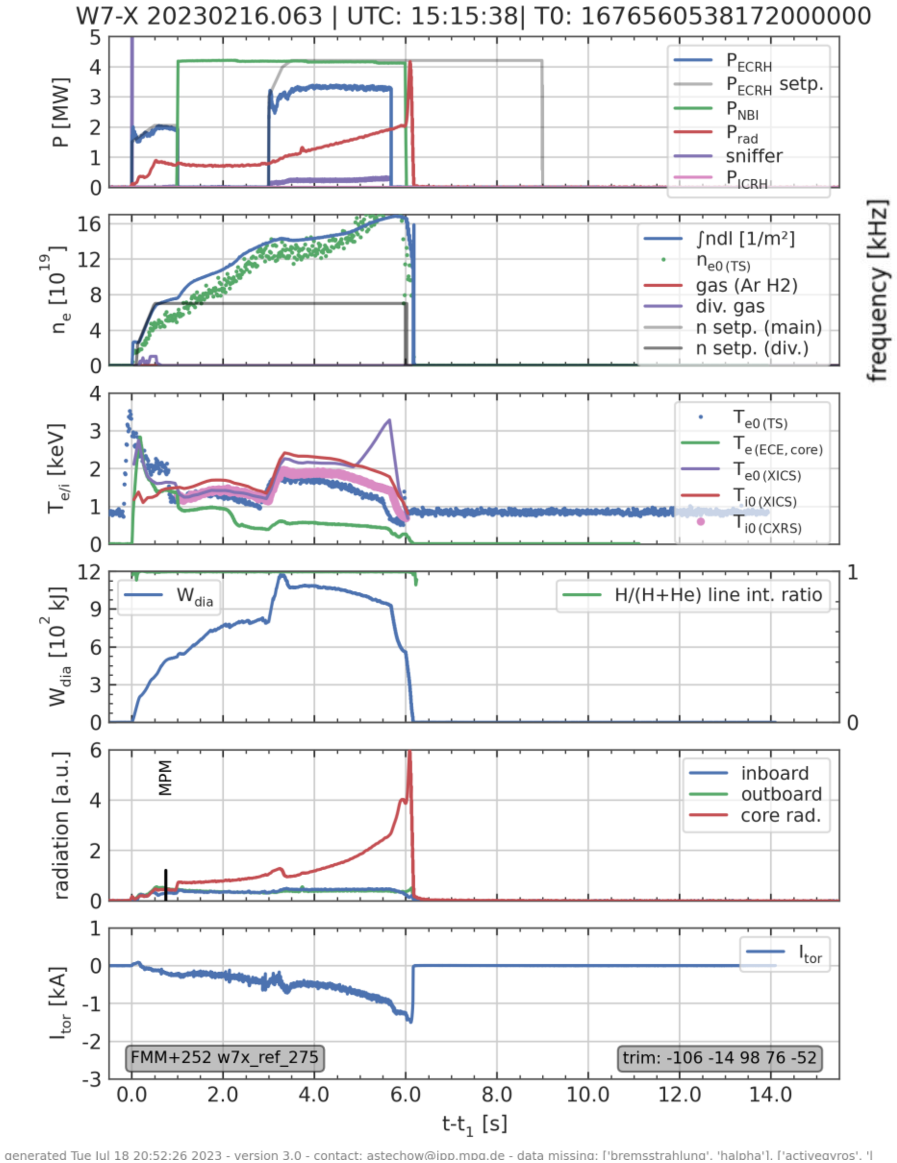


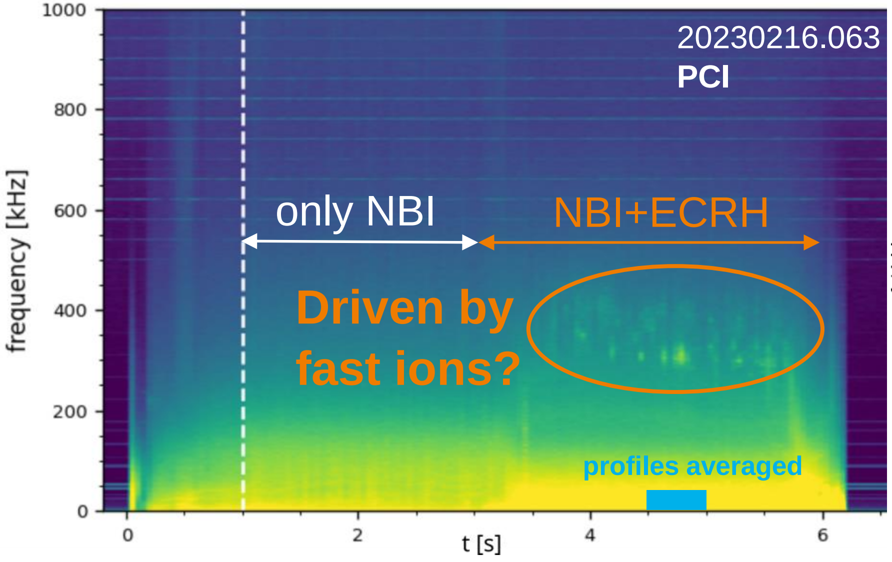


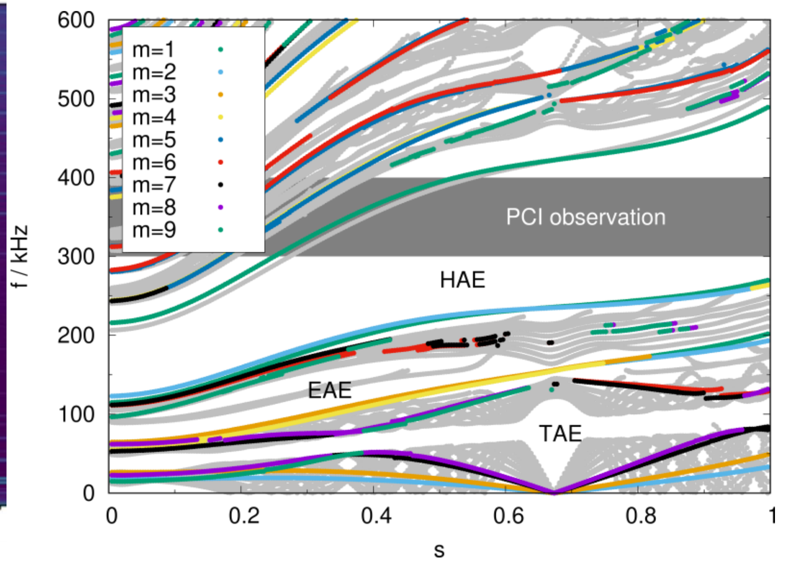
Mode activity observed in discharge combining ECRH and NBI

➢ **visible with PCI** (350-400kHz) but **not with Mirnov coils**

Mode activity in discharges with fast ions



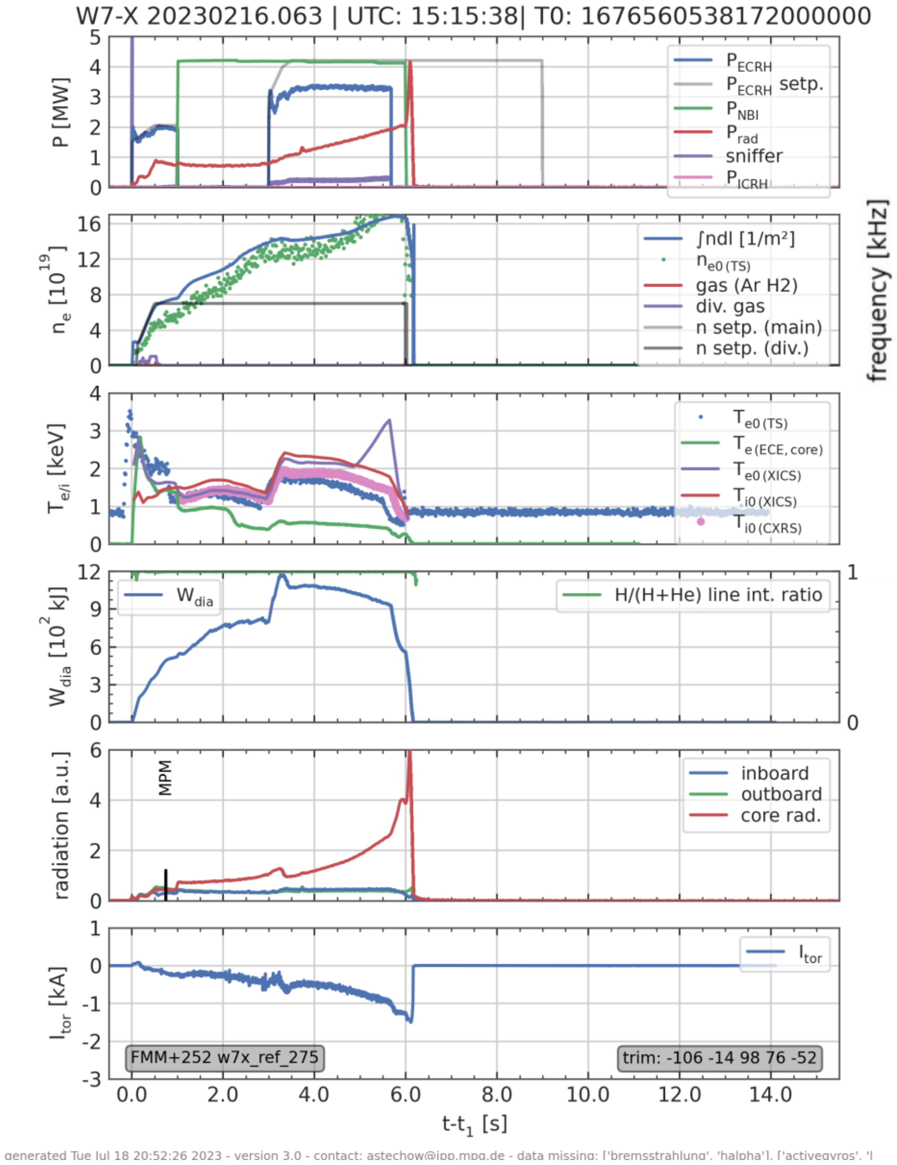


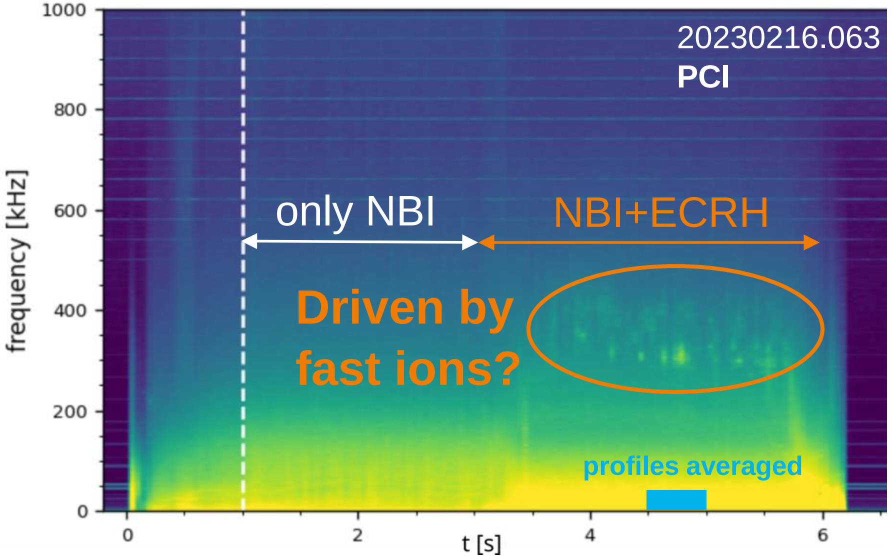


Mode activity observed in discharge combining ECRH and NBI

- **visible with PCI** (350-400 kHz) but **not with Mirnov coils**
- preliminary profile data used for the calculation of the shear Alfvén continuum (averaging profiles between t=4.5 and t=5.0 seconds)
  → **observation fits well into broad HAE$_{2,-1}$ gap** (assuming the mode is not core-localized)
- Mode **frequencies seem high** given the high density in the NBI phase (note that $\omega \sim vA \sim 1/\sqrt{n_e}$)

Mode activity in discharges with fast ions





Next steps:

- ➢ determine mode numbers
- ➢ calculate the fast-ion distribution function
- ➢ assess the resulting drive
- ➢ increase NBI power

Mode activity observed in discharge combining ECRH and NBI

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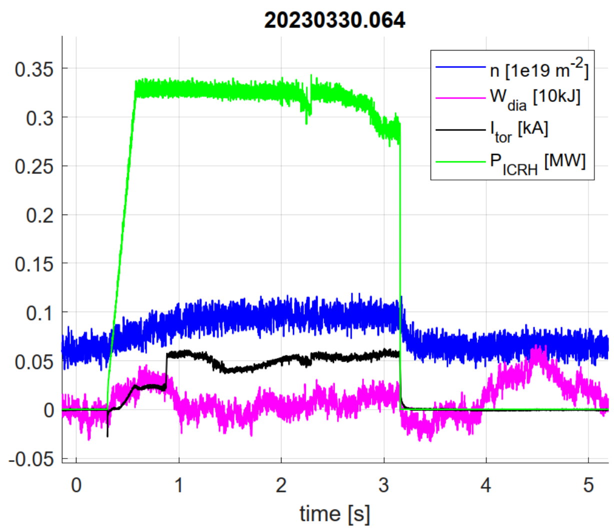
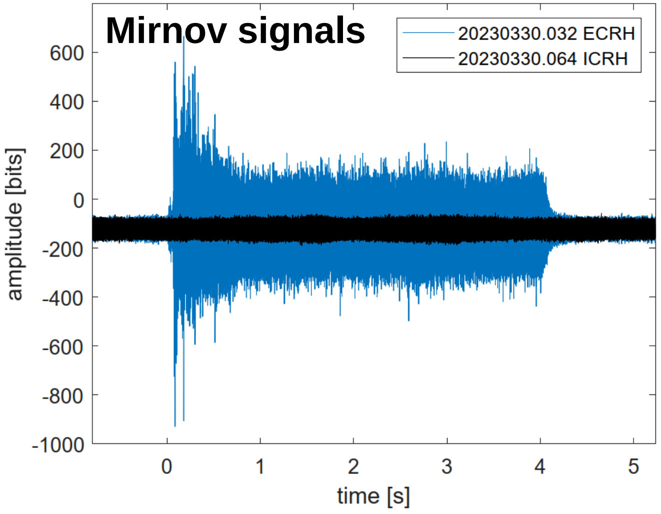
magnetic narrow band fluctuations in ICRH plasmas

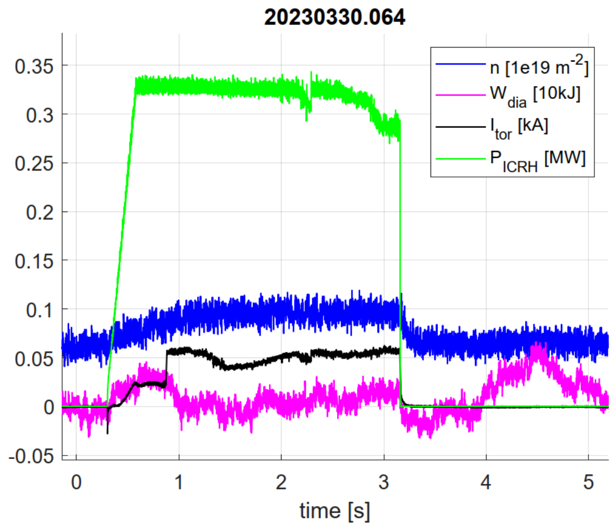


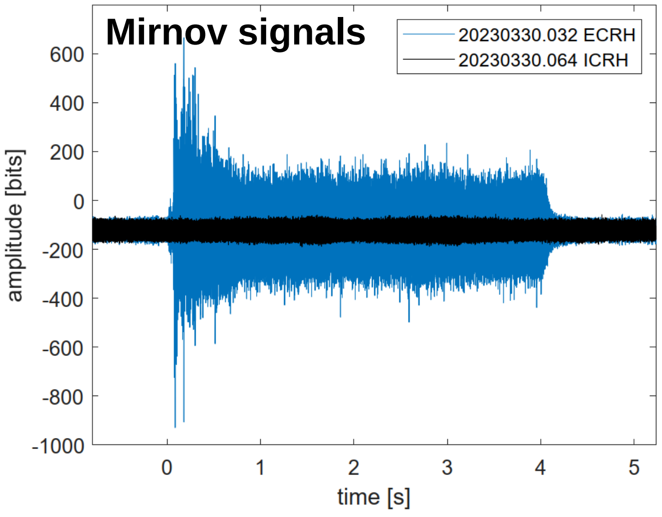


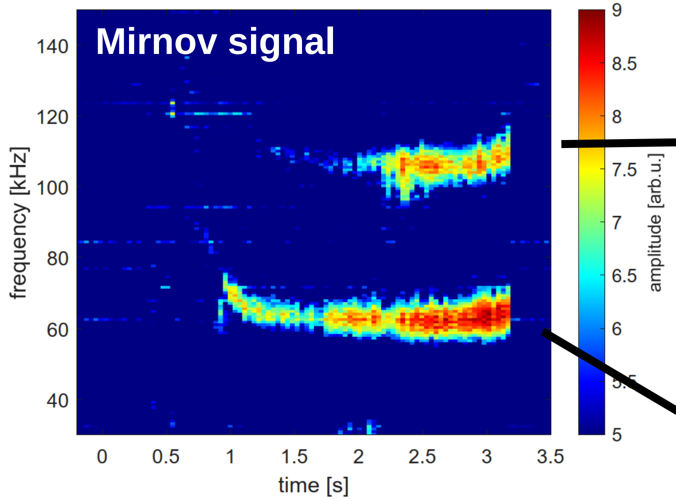
ICRH plasmas at **very low power**

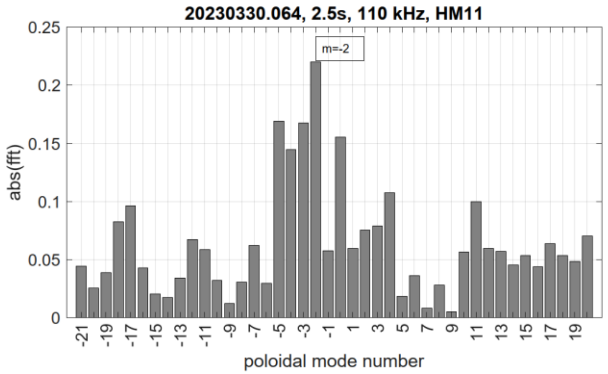
- ➢ weak signal in Mirnov coils

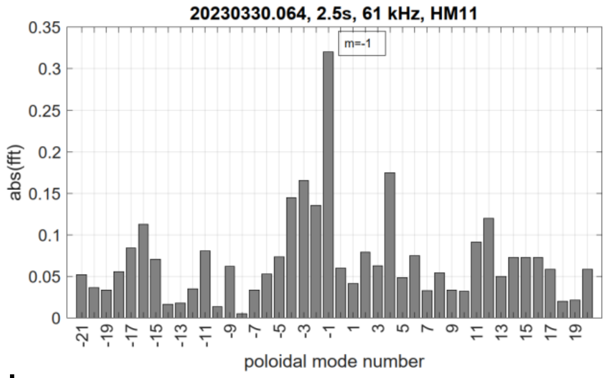
magnetic narrow band fluctuations in ICRH plasmas











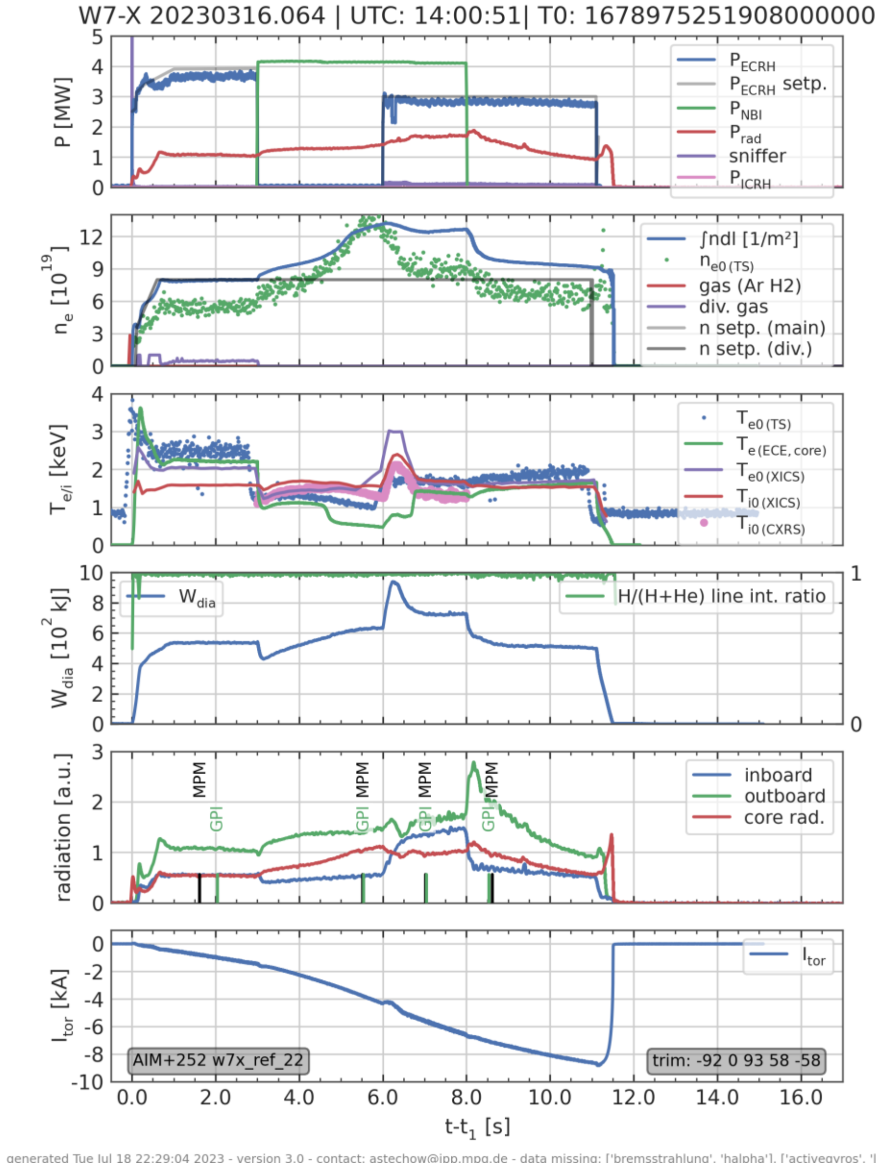
ICRH plasmas at **very low power**

- ➢ weak signal in Mirnov coils
- ➢ **narrow band fluctuations** detected
- ➢ f ~ 60-110kHz, m = -1,-2

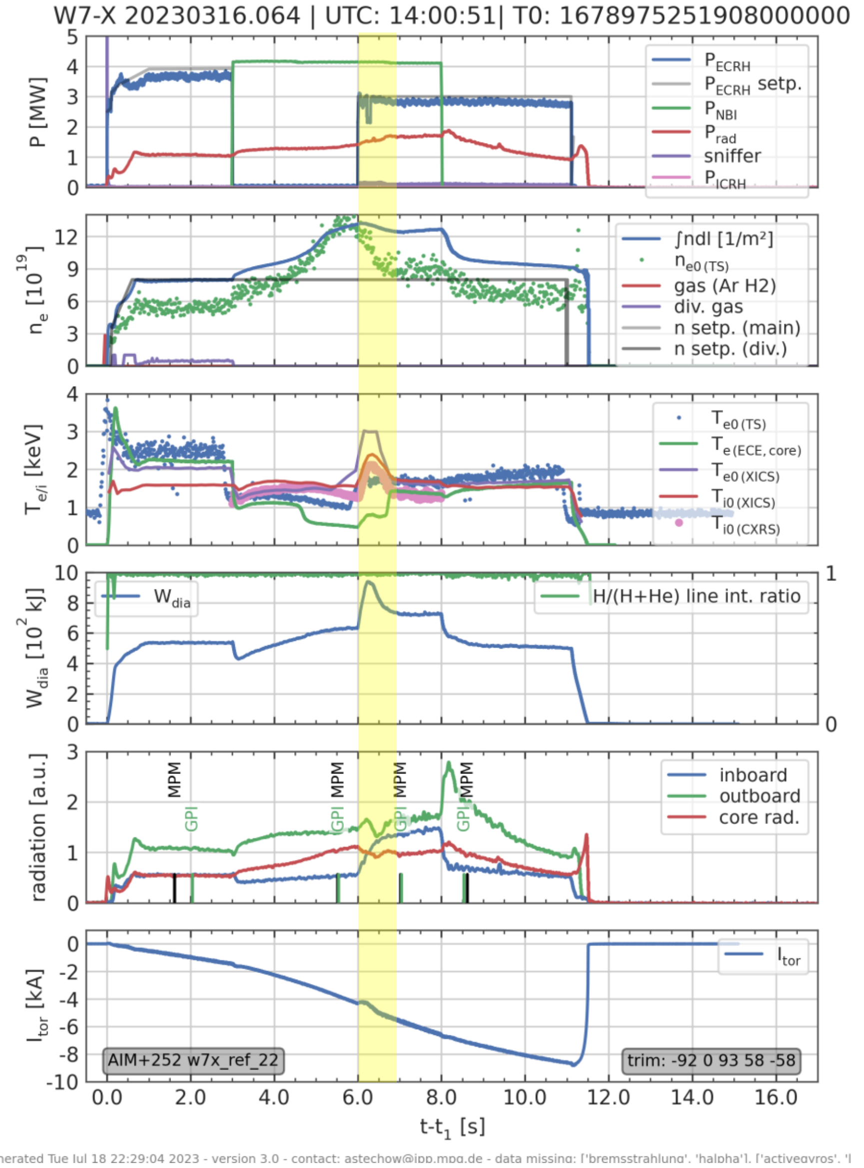
Next steps:

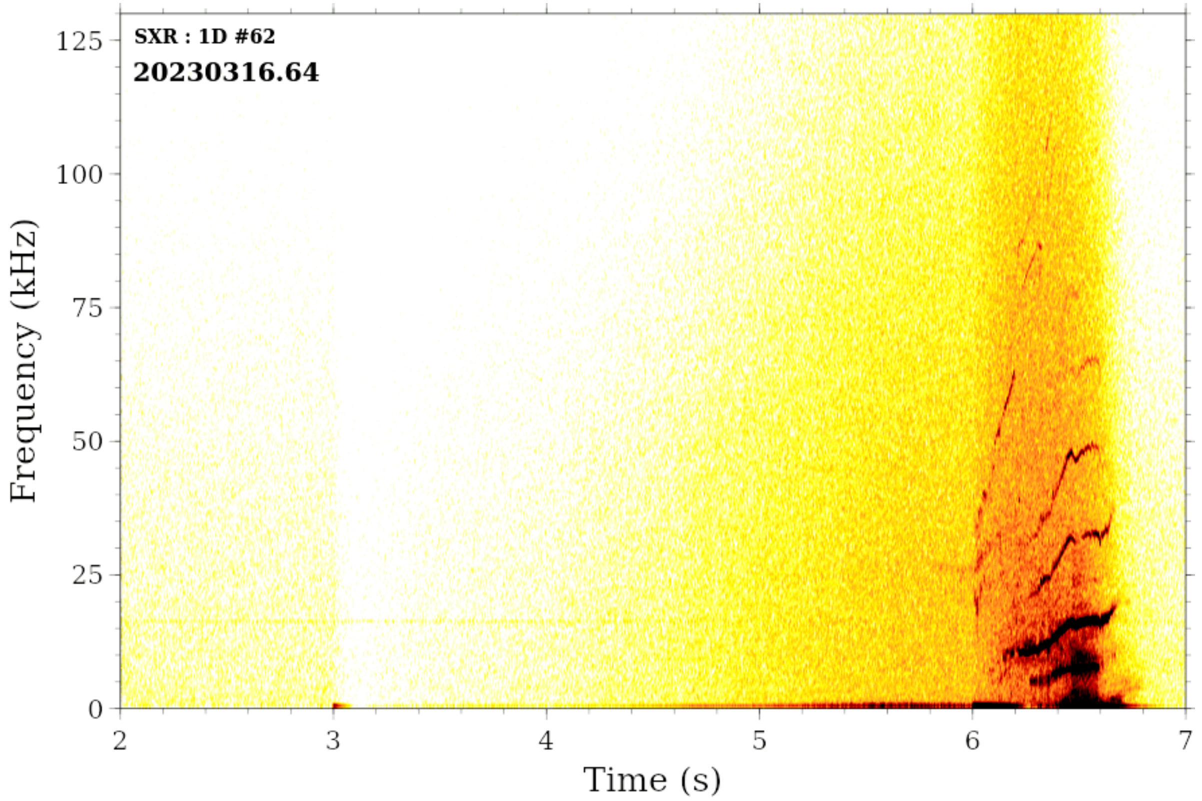
- ➢ investigate modes at high power ICRH

Low frequency mode activity



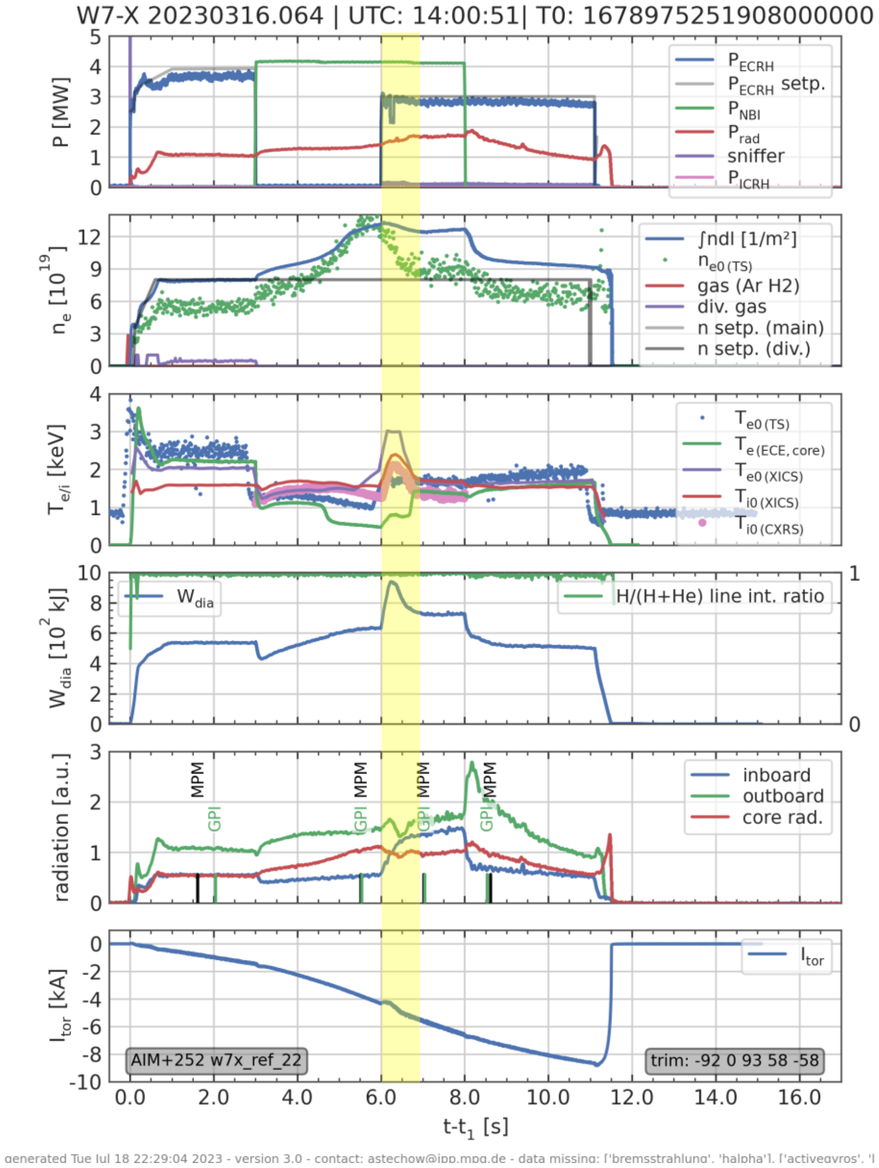
Low frequency mode activity

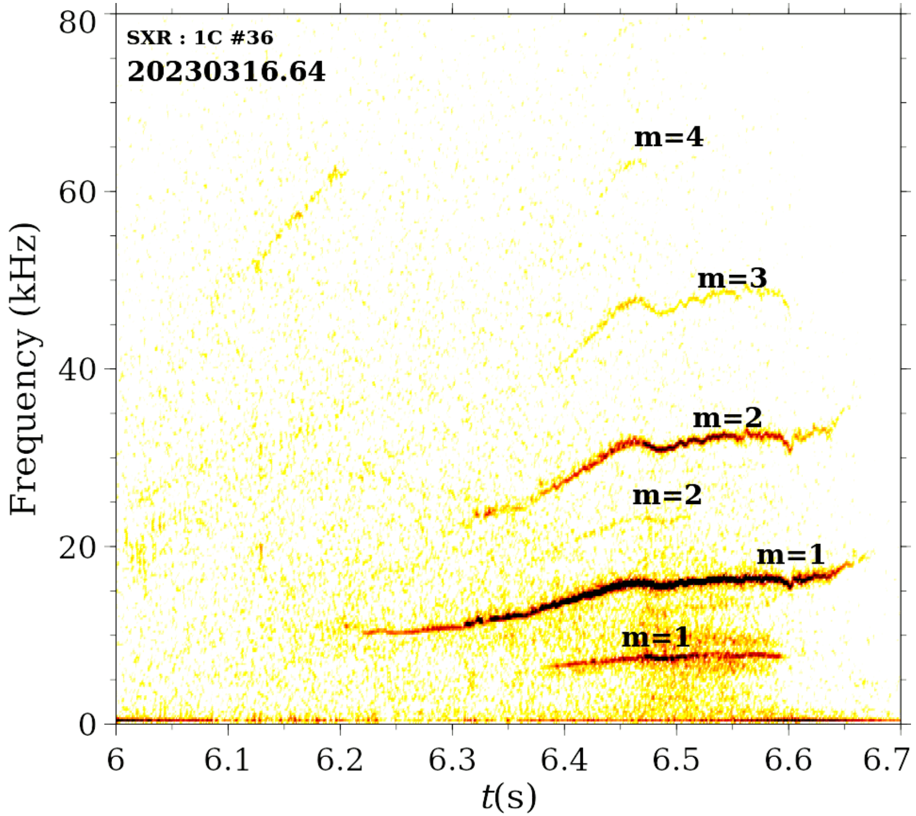




➢ **low frequency** mode activity in complex heating scenarios

Low frequency mode activity



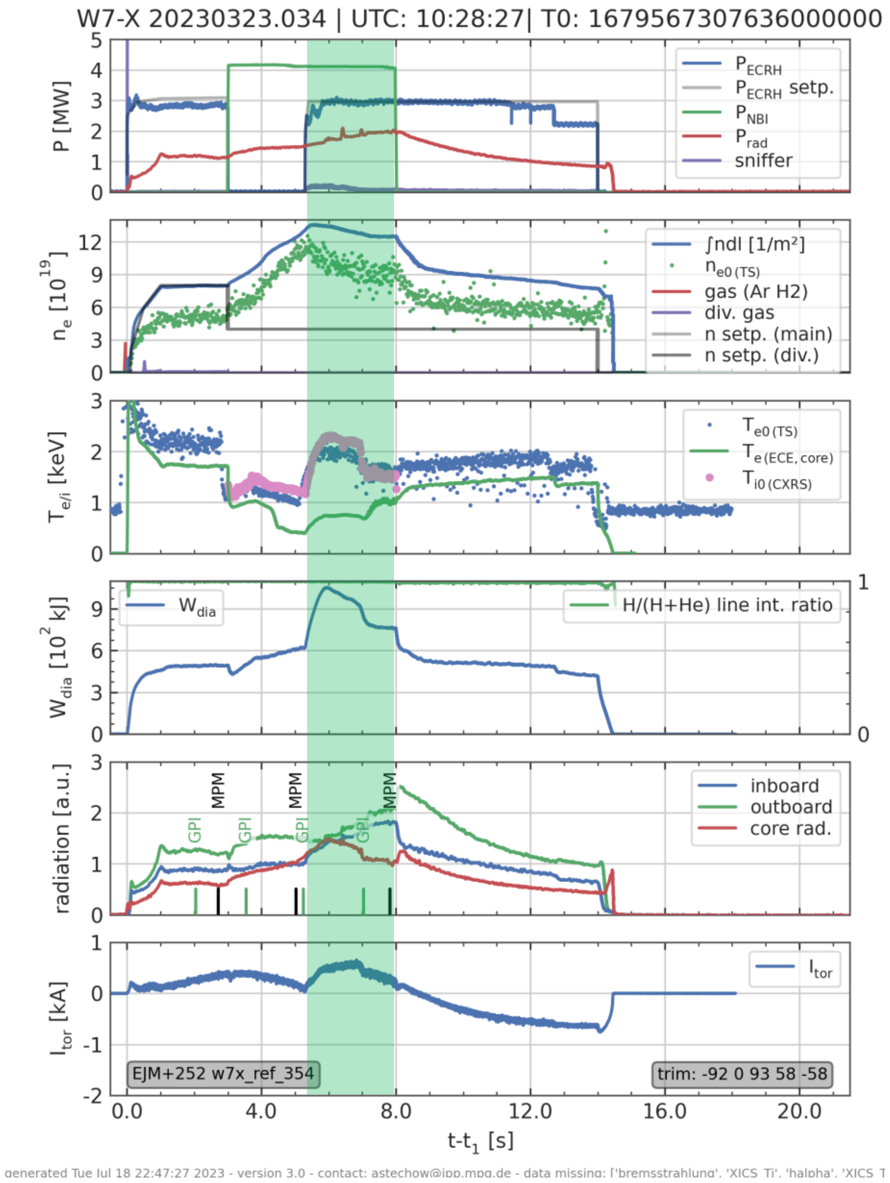


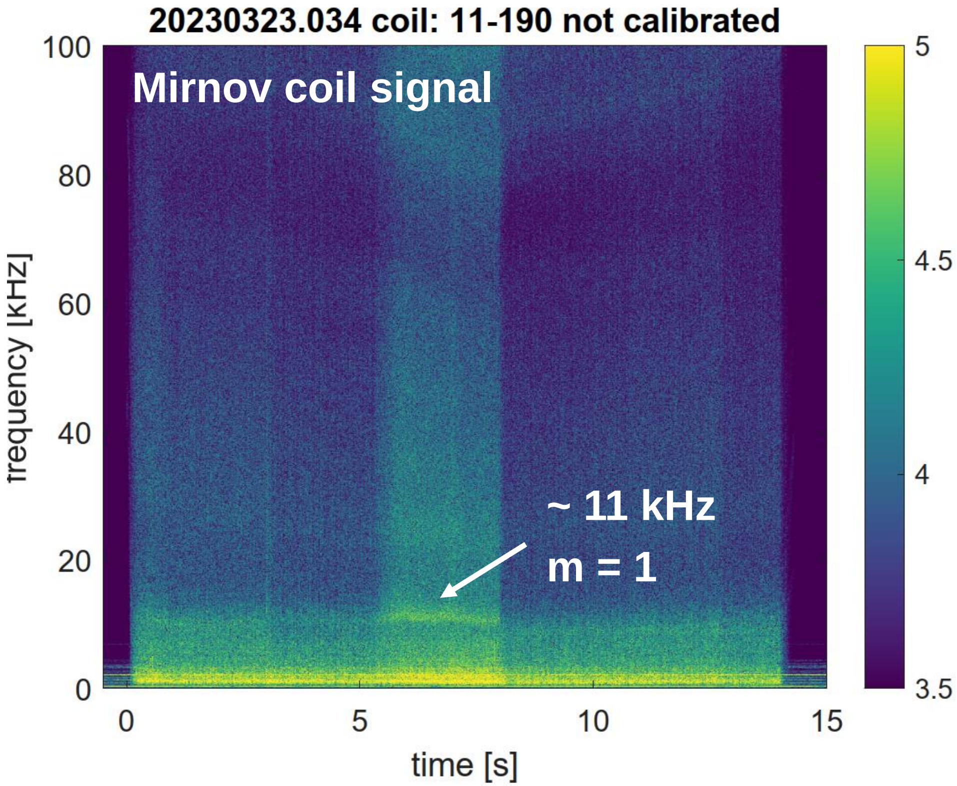
- **low frequency** mode activity in complex heating scenarios
- soft x-ray measurements reveal **low mode numbers**

References:

Dreval M B *et al* 2023 Plasma Phys. Control. Fusion **65** 035001
Dreval M B *et al* 2021 Plasma Phys. Control. Fusion **63** 065006

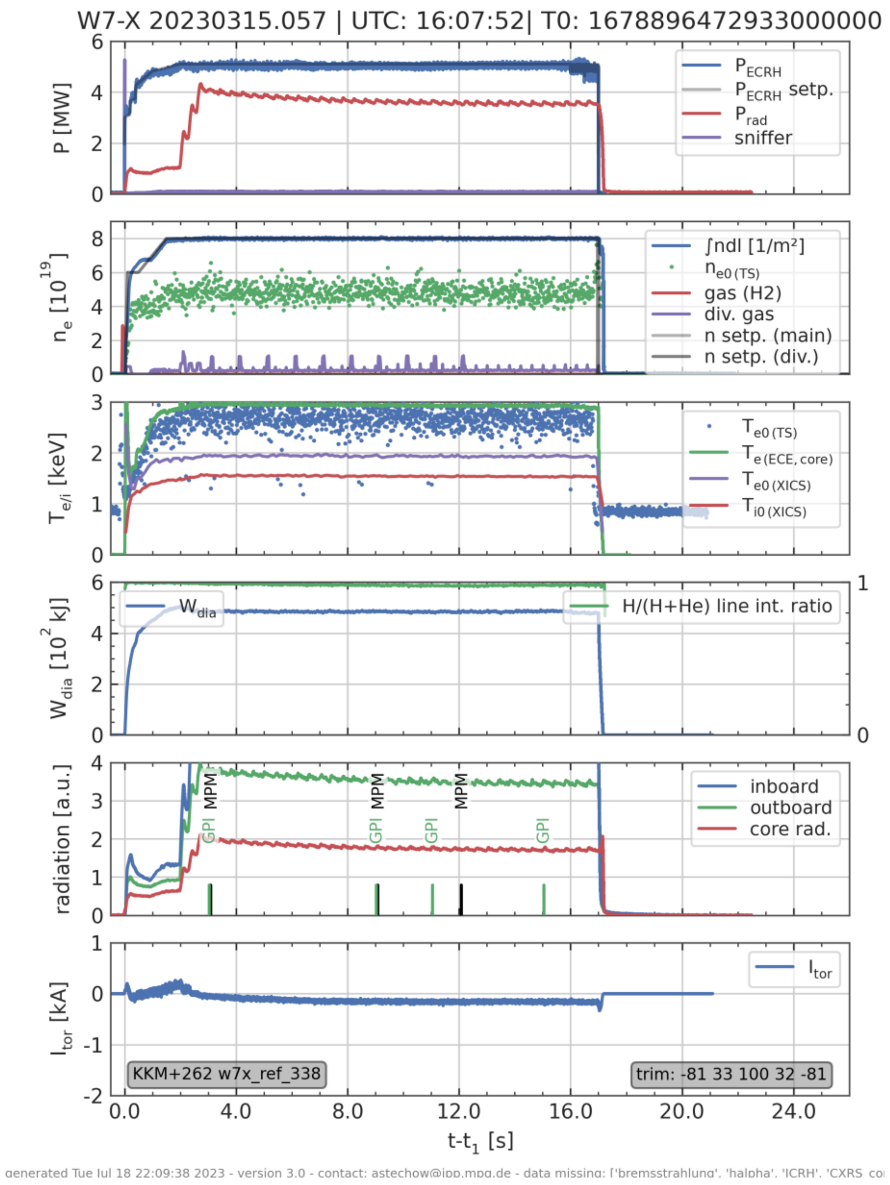
Low frequency mode activity

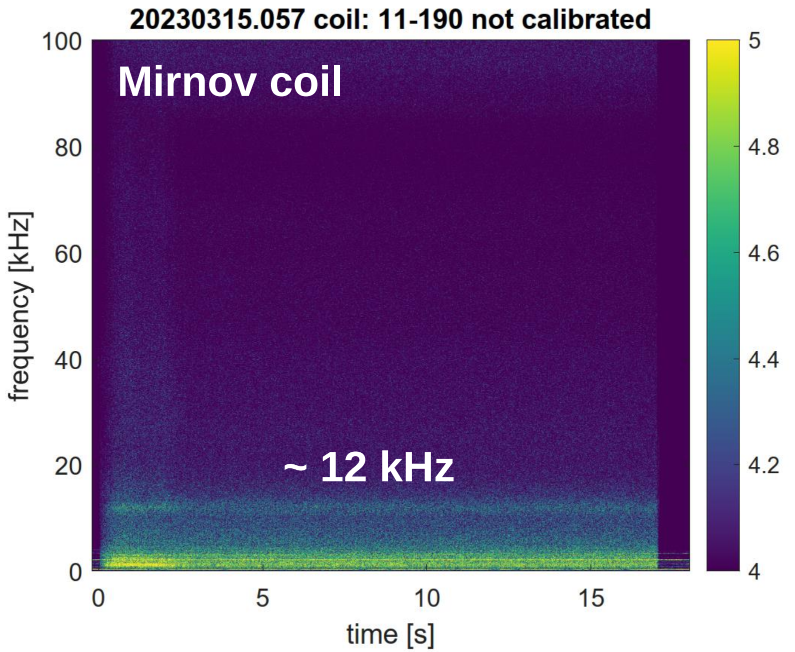




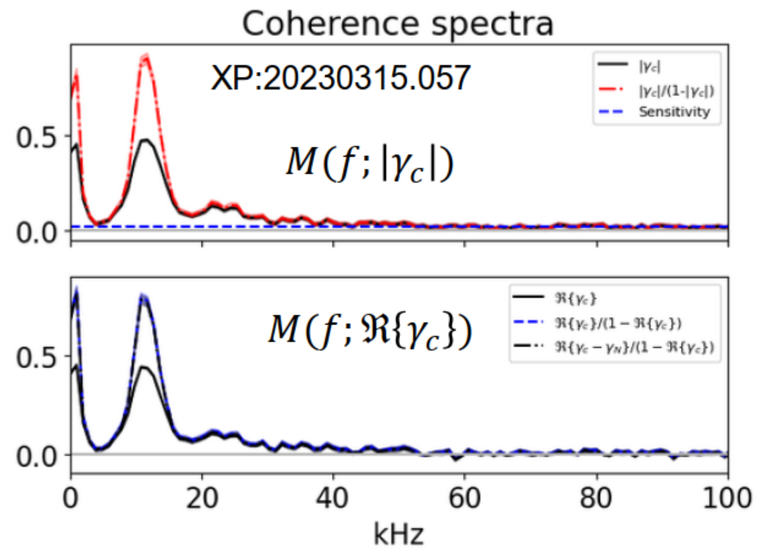
- **low frequency** mode activity in complex heating scenarios
- soft x-ray measurements reveal **low mode numbers**
- **magnetic signature** at high density (also observed without NBI)

Low frequency mode activity



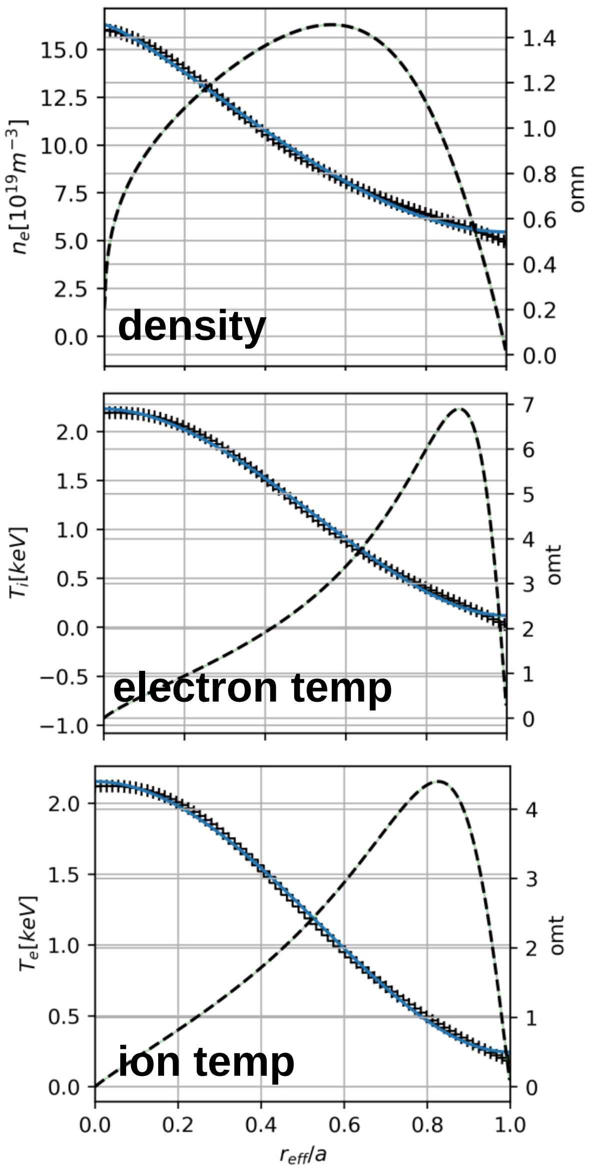


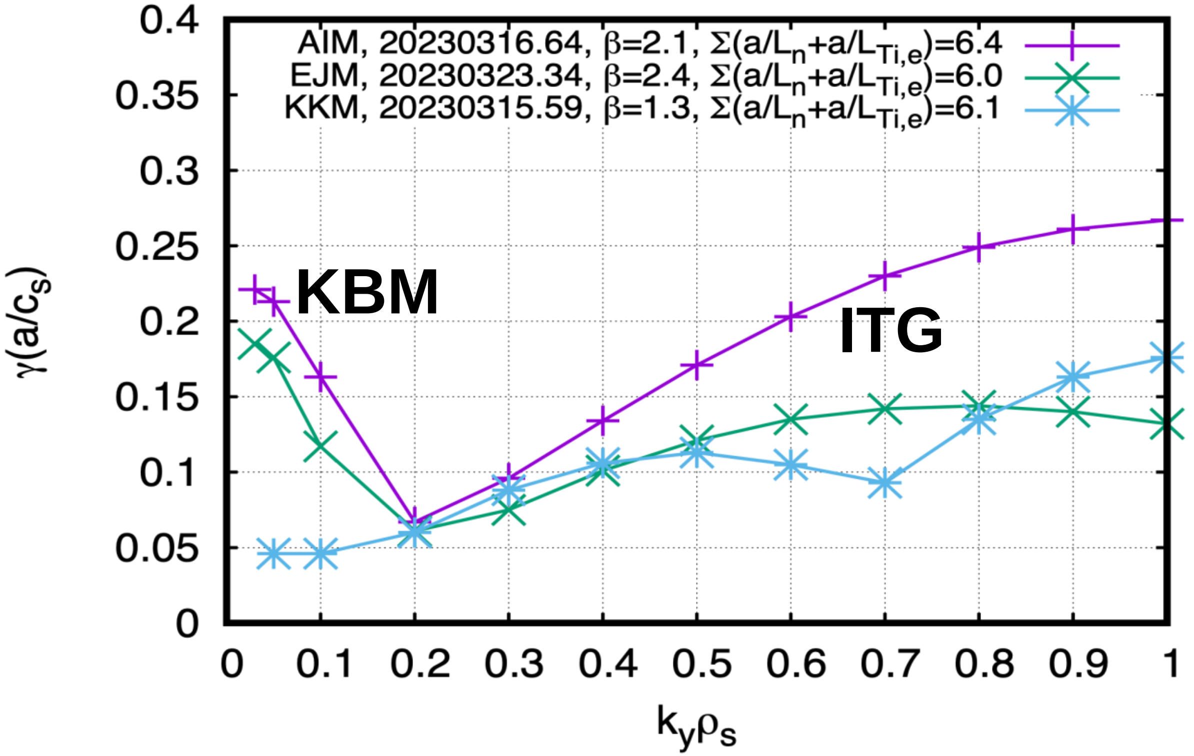
correlation radiometry



- **low frequency** mode activity in complex heating scenarios
- soft x-ray measurements reveal **low mode numbers**
- **magnetic signature** at high density (also observed without NBI)
- **radial correlation ECE** also sees ~10 kHz mode at high density

Low frequency mode activity – theoretical predictions (KBMs)





GENE simulations

Experimental parameter range:

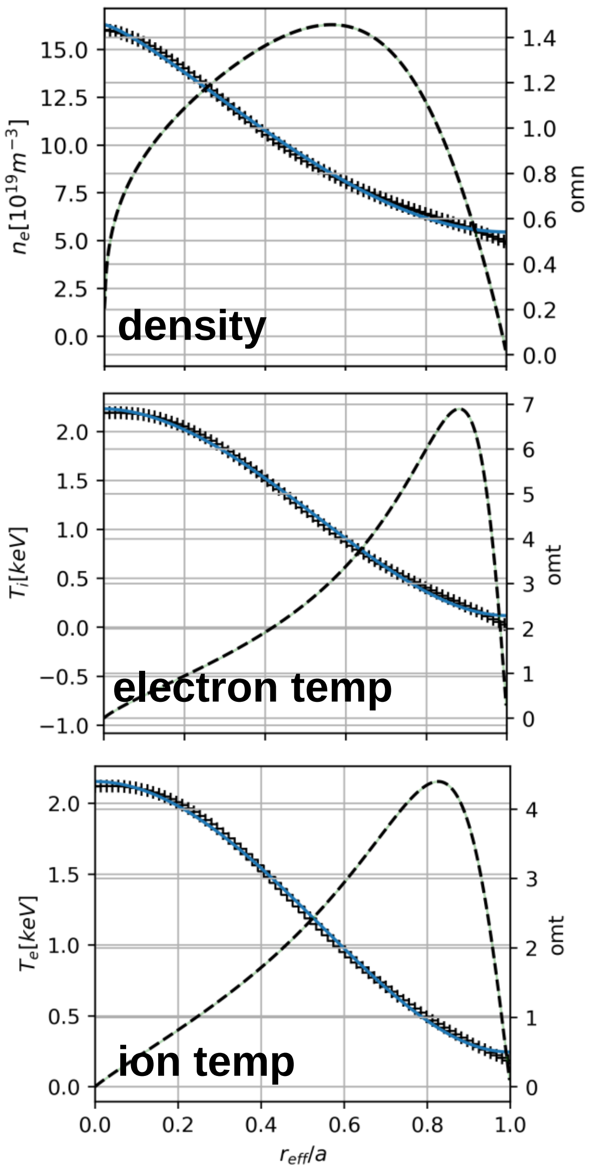
$a/L_n=1.4$, $a/L_{Ti}=2.0$, $a/L_{Te}=1.8$, local β = 2.1% at $s = (r_{eff}/a)^2 = 0.16$

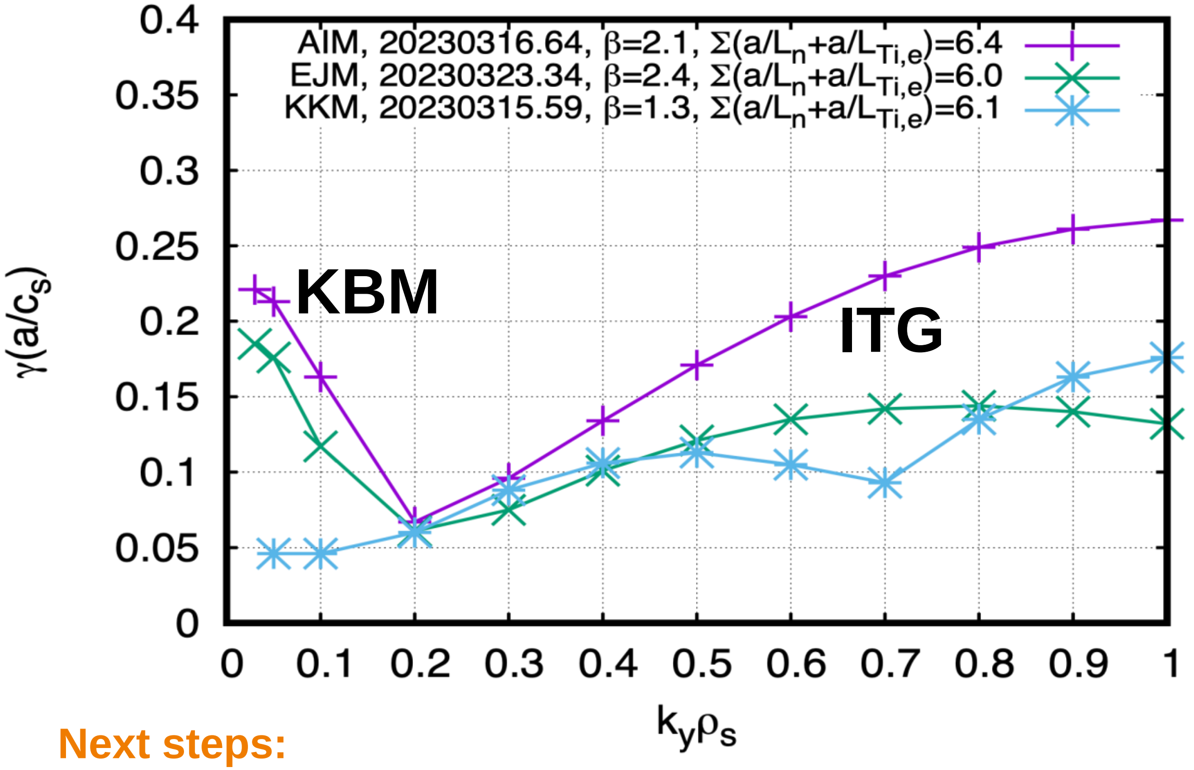
predicted frequency and mode numbers (#64, #34):
f = 26 – 44 kHz
m = 7-12
(for $k_y\rho_s$ = 0.03, 0.05)

- The comparison of **GENE results** for two shots with energy setbacks and one with a stable plasma **aligns with the concept that KBMs are restricting performance.**
- Despite plasma parameters being relatively low and KBMs exhibiting greater stability (compared OP1.2b, 20180911.033), and while ITG displays a comparable growth rate, **it was demonstrated that KBMs govern the transport in similar cases** [1,2].

[1] Mulholland, P., K. Aleynikova, B. J. Faber, et al, 2023, Physical Review Letters 131, no. 18: 185101.
[2] McKinney, I.J., Pueschel, M.J., Faber, et al, 2021, Plasma Physics, 87(3), p.905870311.

Low frequency mode activity – theoretical predictions (KBMs)





GENE simulations

Experimental parameter range:

a/L_n=1.4, a/L_{Ti}=2.0, a/L_{Te}=1.8,
local β = 2.1% at
s = $(r_{eff}/a)^2$ = 0.16

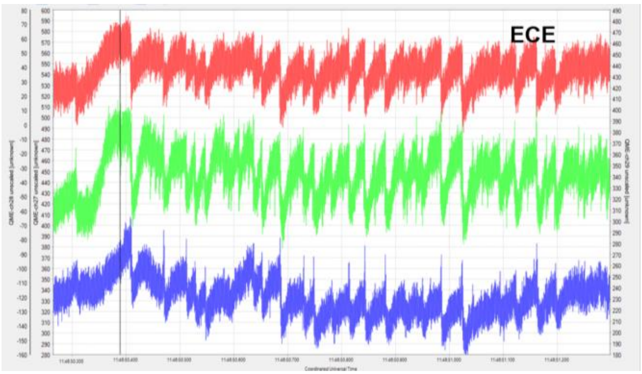
predicted frequency and mode numbers (#64, #34):
f = 26 – 44 kHz
m = 7-12
(for $k_y\rho_s$ = 0.03, 0.05)

Next steps:

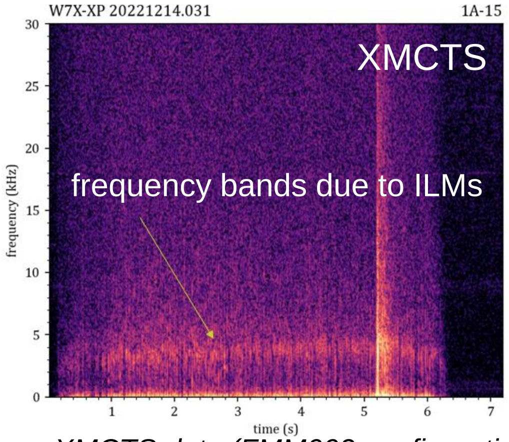
- investigate modes in high performance experiments with pellets (and higher β)
- KBMs are more stable in configurations with higher mirror ratio and high iota on axis [3]
  → new configuration, KTM
- systematic comparison of different configurations (AIM, EJM, KTM, …)

[3] Aleynikova, K., A. Zocco, and J. Geiger, JPP 88, 4, 905880411 (2022)

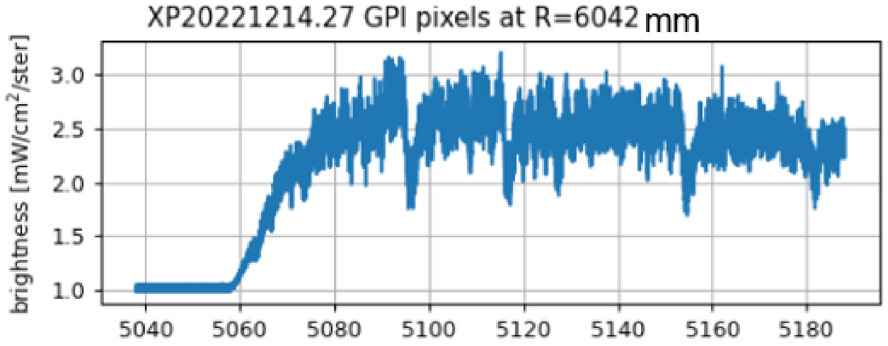
ILM / ELM-like observations



ECE traces from three neighbor channels near the edge (red - more inside, blue - more outside)



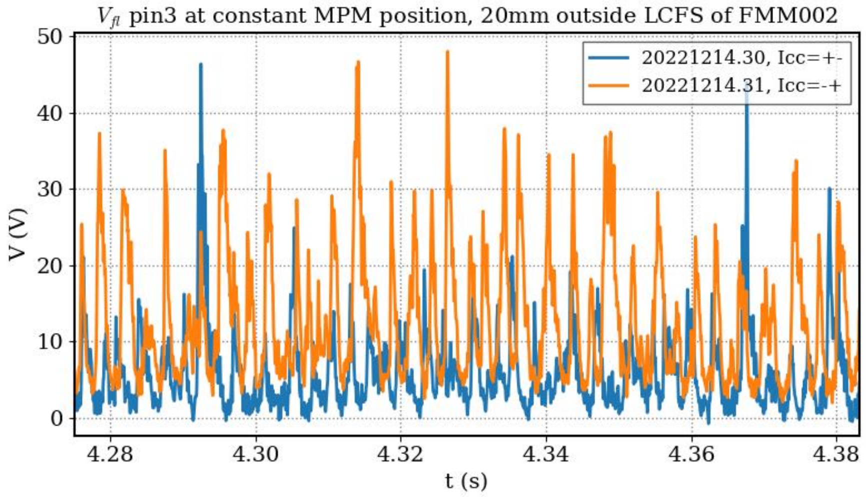
XMCTS data (FMM002 configuration)

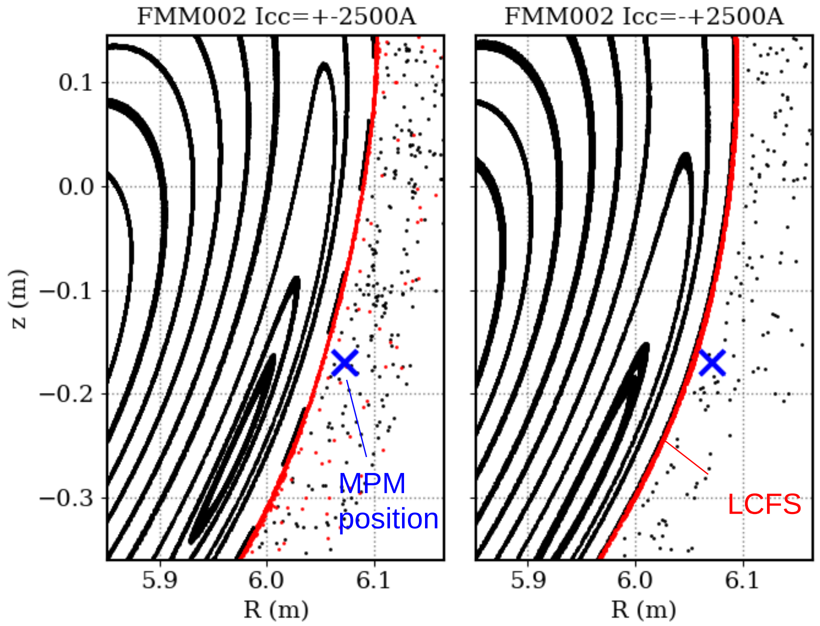


GPI time traces (FMM003 configuration)

- **low frequency bursts** (a few kHz or less) located near islands
- observed during **iota scans**
- OP2.1 observations **partly contradicted OP1.2b** observations:
  - similar discharges showed different mode amplitude
  - island size variation in OP2.1 showed the opposite influence on the mode activity as in OP1.2b
  - different iota scans showed different ILM activities (Standard-High iota scan vs. Standard-Low iota scan)

ILM / ELM-like observations





difference between configurations

- 5/5 islands slightly poloidally rotated
- LCFS more stochastic in +- case

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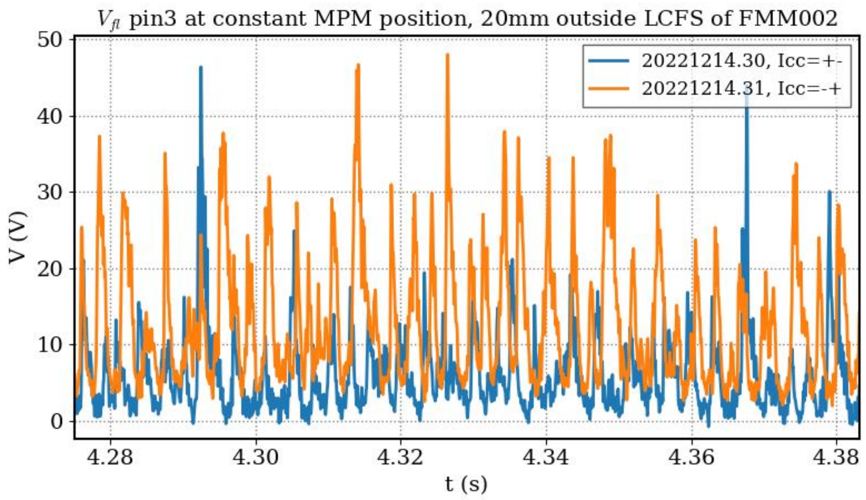
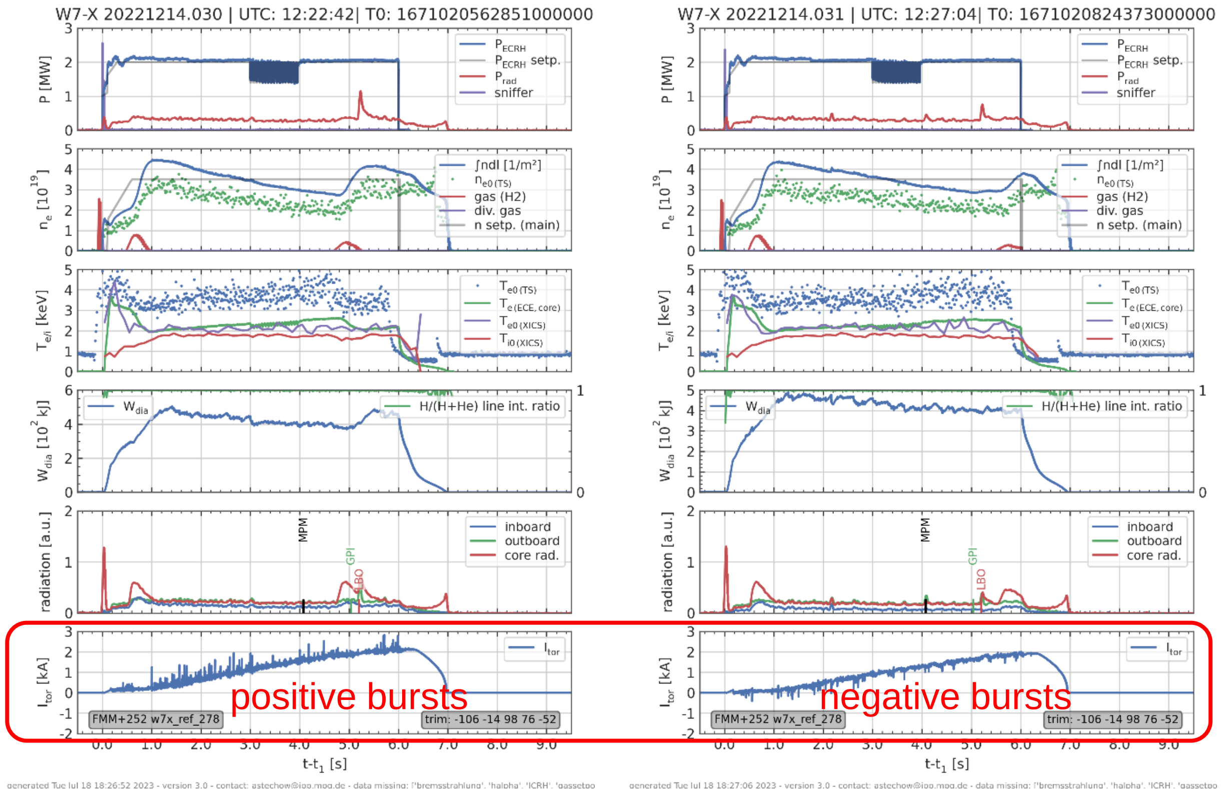
  - no major obvious differences in magnetic structure

ILM / ELM-like observations





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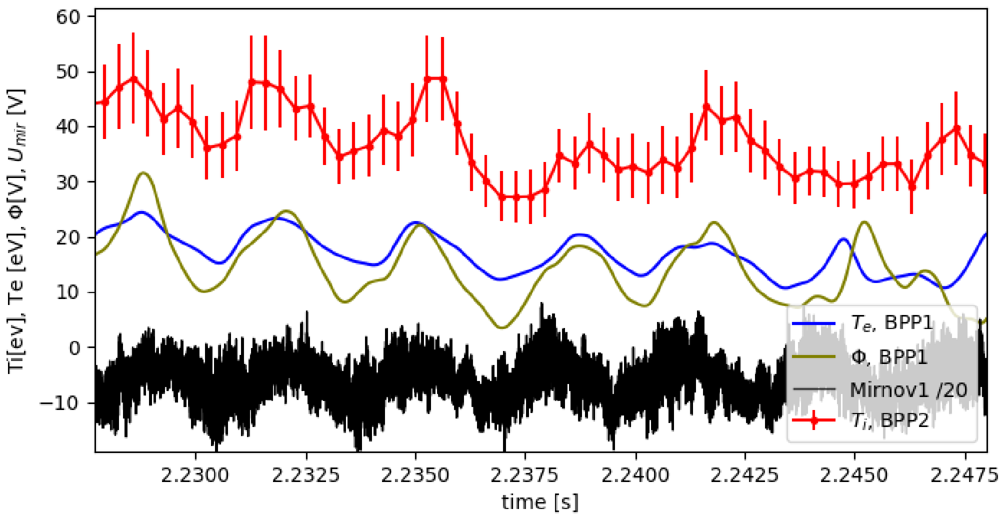
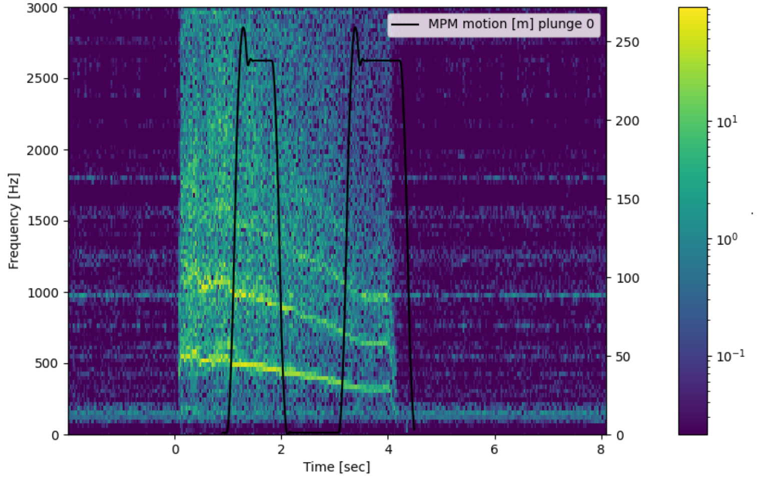
- OP2.1 observations **partly contradicted OP1.2b** observations
- much **stronger fluctuations activity in Icc "+-"** mode compared to "-+" mode
  - no major obvious differences in magnetic structure
  - very similar plasma scenarios

ILM / ELM-like observations

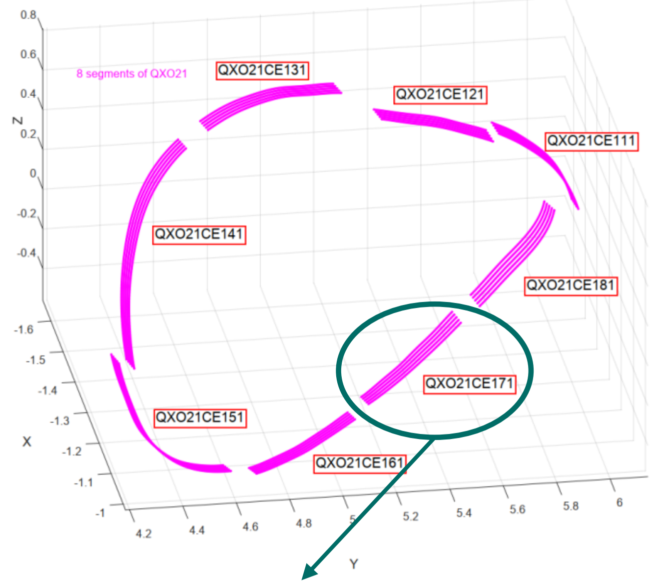
#230330037 MPM



spectrogram Mirnov coil



segmented Rogowski coils in HM21



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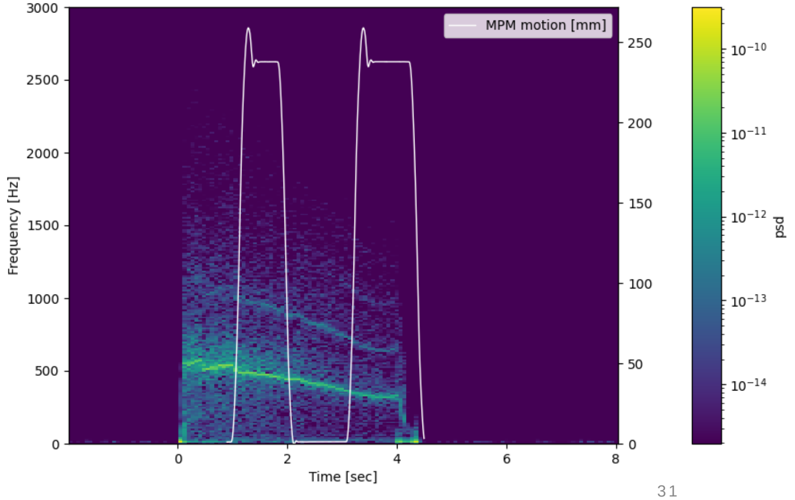
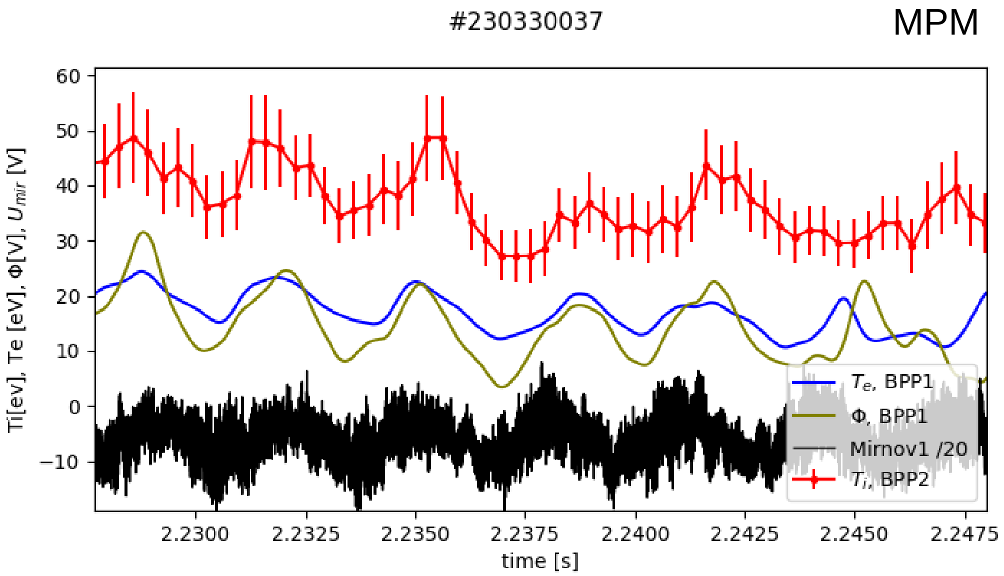
- much **stronger fluctuations activity in Icc “+-”** mode compared to “-+” mode
- 500 Hz signal **simultaneously in T_e, T_i, ϕ**
  - MPM profile indicates mode **related to magnetic island**

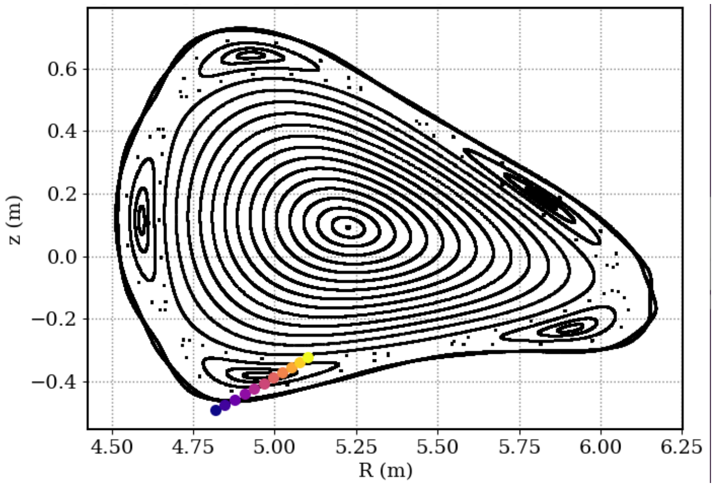
spectrogram coil #171



ILM / ELM-like observations



MPM path mapped to HM21



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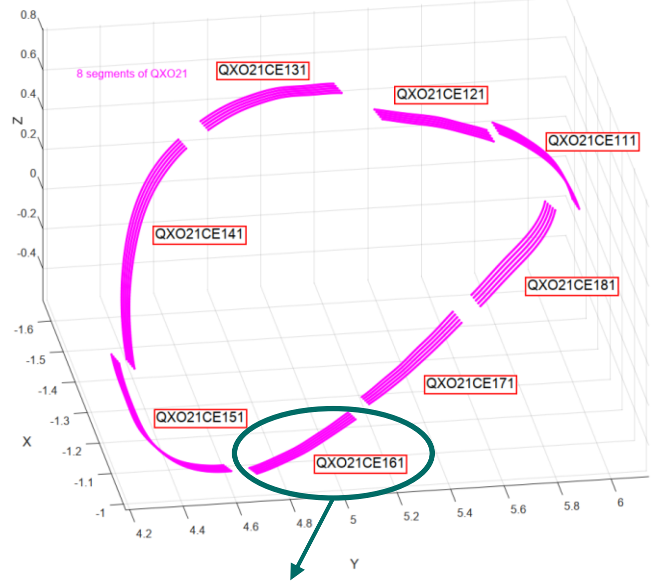
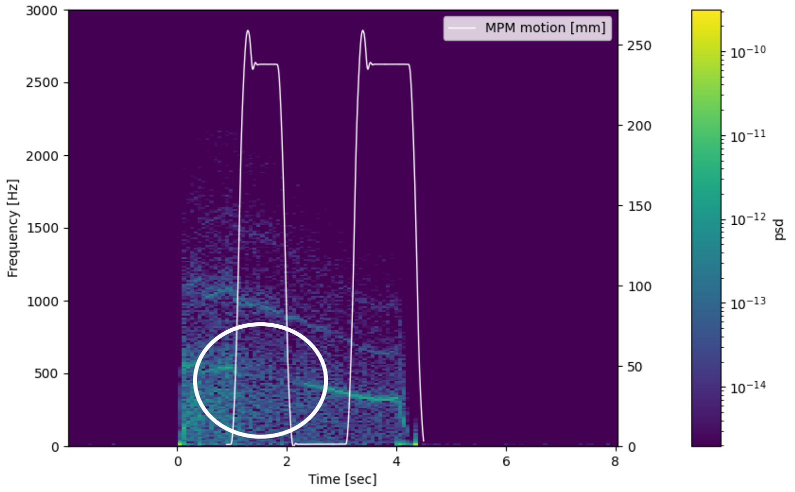


spectrogram coil #161



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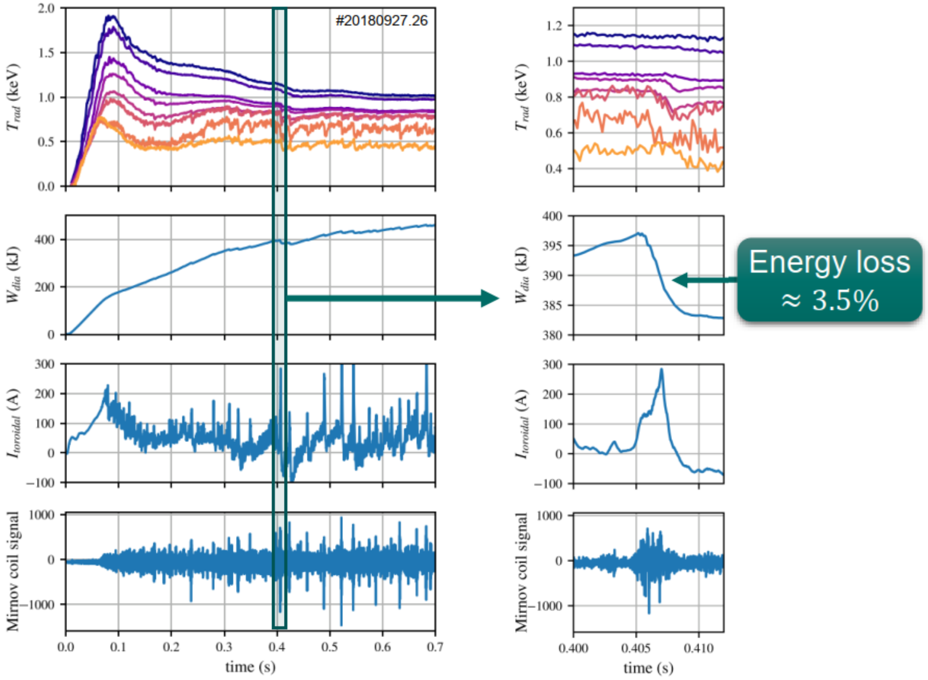
- 500 Hz signal **simultaneously in T_e, T_i, ϕ**
  - MPM profile indicates mode **related to magnetic island**
  - MPM path mapped to segmented Rogowski coil loacation → **signal only vanishes on effected coil**

ILM / ELM-like observations



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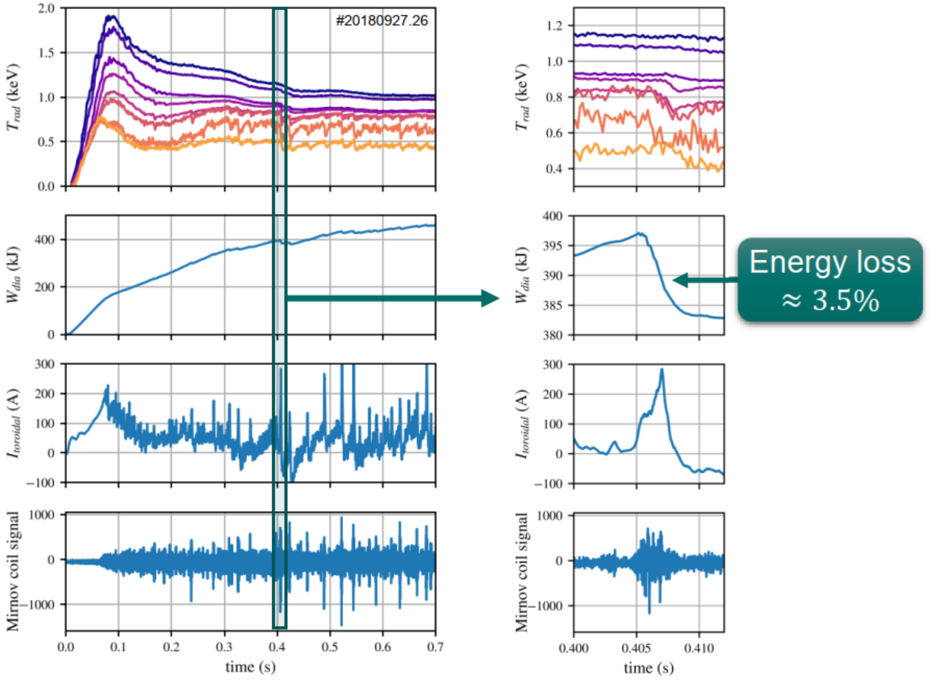
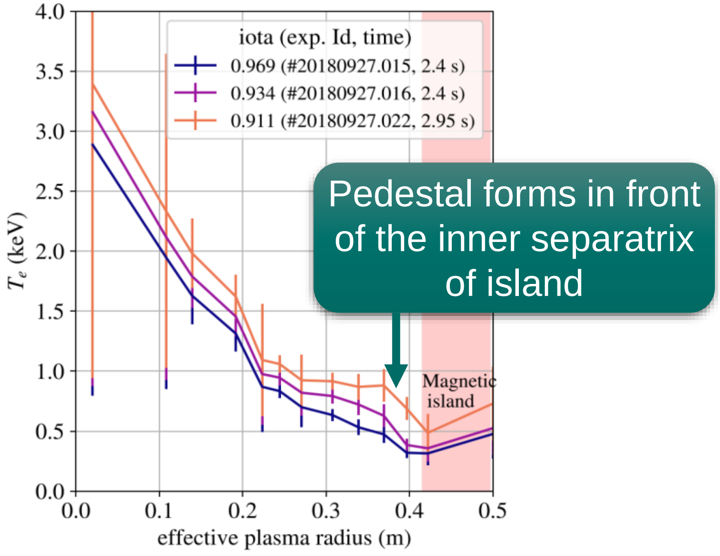
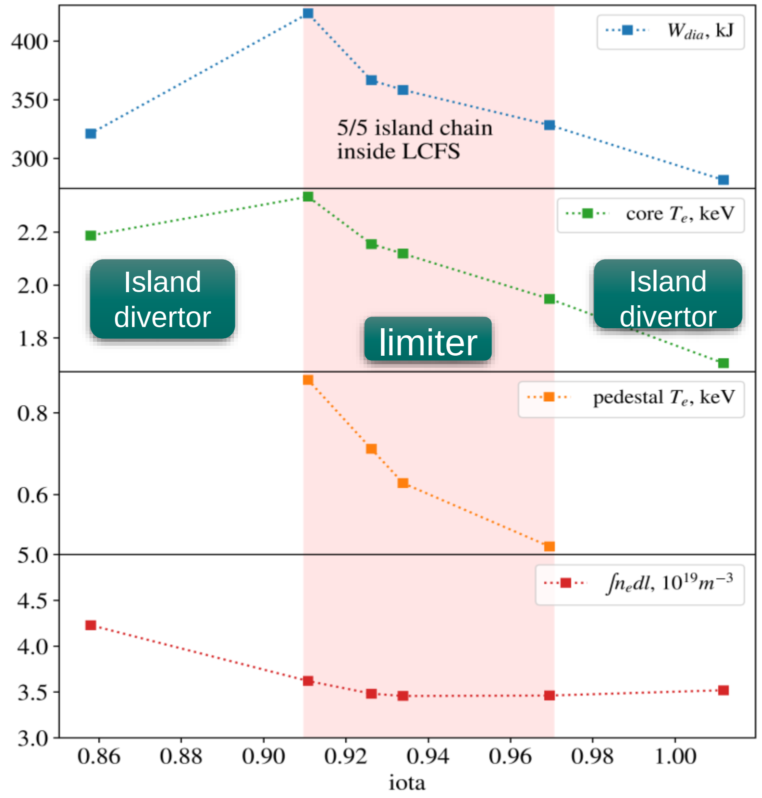
ILM / ELM-like observations







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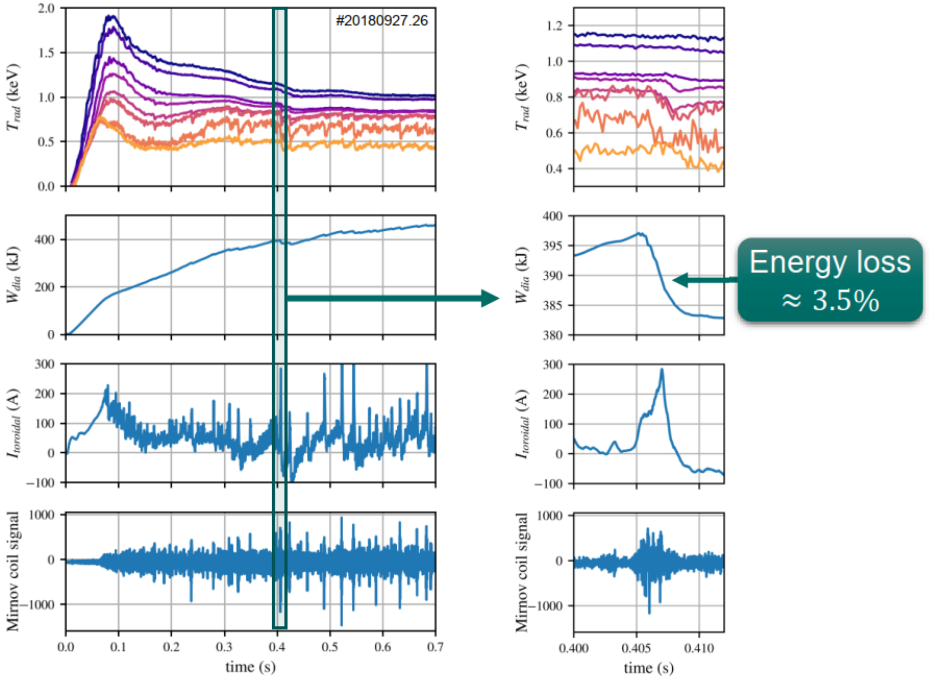

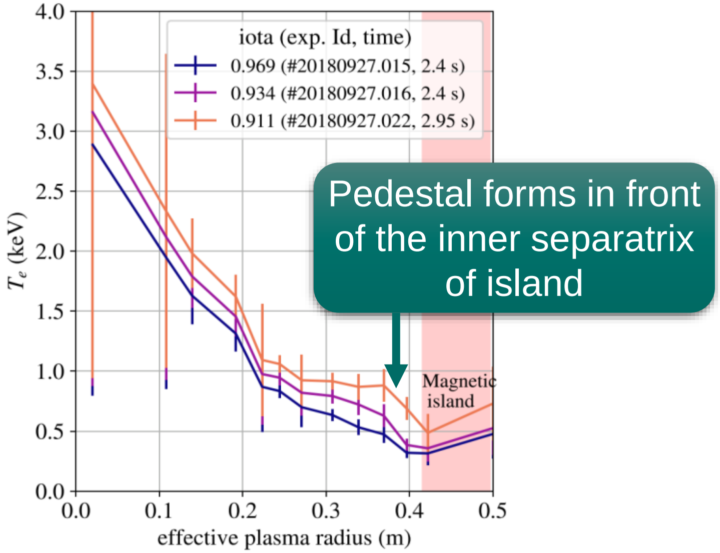

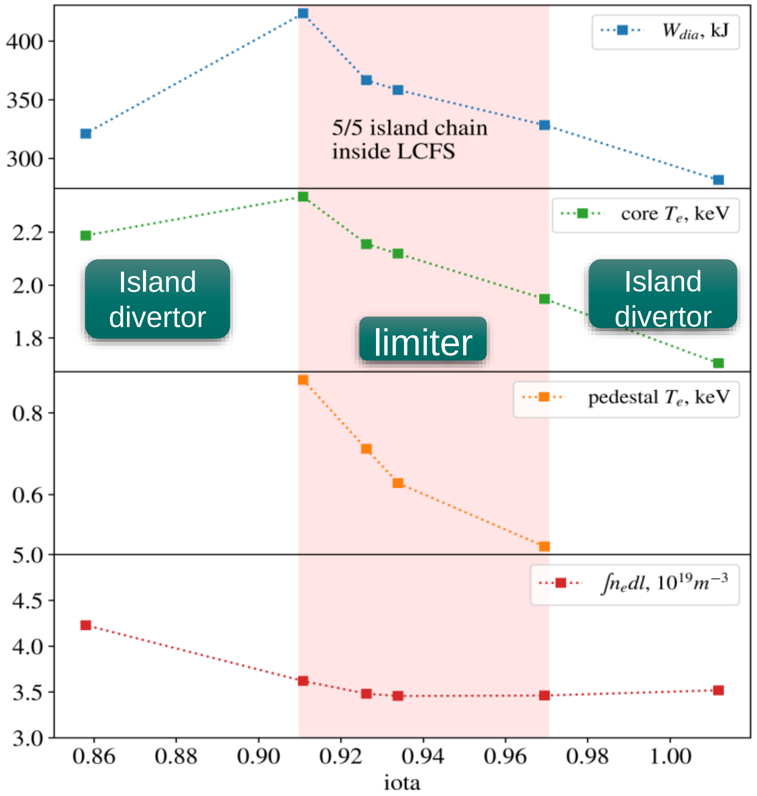

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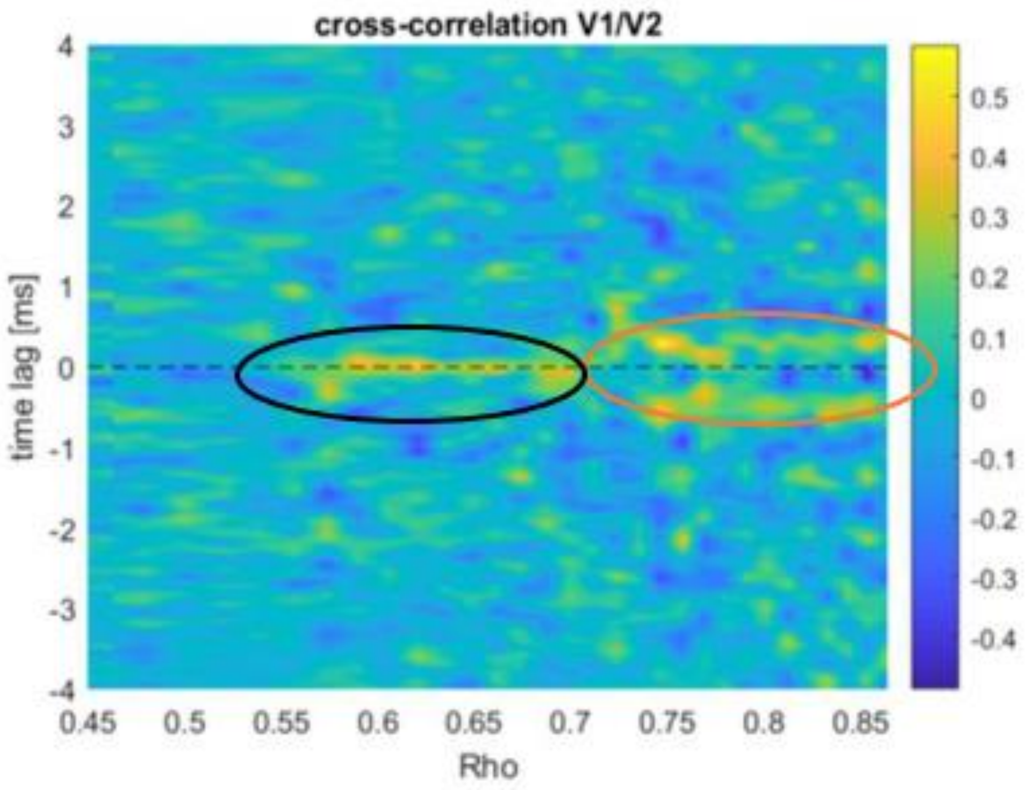
Next steps:

- improve edge diagnostics
- role of turbulence?
- ILMs in n_e, P-scans
- ILMs in detached scenarios

Zonal-flow detection

Doppler reflectometry measurements detect perpendicular plasma flows AEA21 (V1) - AEK51 (V2)

→ long range correlation between u_{perp} to measure zonal flows



- **At the edge (r > 0.75),** this correlation corresponds to a **well-known MHD coherent mode** (also detected by interferometer, Mirnov, SXR)
- Coherent mode **f ~ 1.2 kHz**, toroidal+poloidal structure.

- **At the core (r ~ 0.6)** QMRV1/QMRV2 are in phase, indicating m=0, n=0 **→ frequency band rather than coherent mode.**
- No trace in Mirnov/SXR/interferometer

- Experimental characteristics are all consistent with ZF activity **and in good agreement with ZF component in non-linear GK calculations (stella).**

Summary

- broad band fluctuations (~200 kHz)
  - If β is increased, what's their impact on transport and confinement?
  - How does the mode activity change in the presence of fast ions?

- low frequency (10-50 kHz) mode activity in high performance / high density scenarios
  - What's their role in abrupt endings of high performance?
  - Can we experimentally confirm the theoretically predicted stability threshold of KBMs?

- very low frequency modes (~1 kHz)
  - Can we theoretically predict the formation of ILMs?
  - Further explore the onset and effect of an island localized transport barrier → W7-X H-Mode?