EUROfusion

Experiments on Energetic Particle-driven Instabilities in AUG and TCV plasmas with ECRH and ECCD

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**TCV team: See author list of S. Coda et al 2019 Nucl. Fusion 59 112023
***MST1 team: See author list of B. Labit et al 2019 Nucl. Fusion 59 086020

CCFE IPP ASDEX Upgrade EPFL PSFT KIPT Barcelona Supercomputing Center Aalto University School of Science DIII-D

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S.E.Sharapov et al., 16th IAEA EPPI TCM, Shizuoka, Japan, 5th September 2019

INTRODUCTION

- **Strong effects of ECRH on energetic particle-driven Alfvén Eigenmodes (AEs) were first noted on DIII-D in 2007**
- **Exploration of such effects is ITER relevant since ITER will have ECRH/ ECCD and some ITER scenarios may be prone to AE instabilities driven by fusion alphas and beams**
- **ITPA EP TG established a Joint Experiment on control techniques for AEs in ITER, with ECRH/ ECCD being a major contributor**
- **Involved: DIII-D, AUG, LHD, KSTAR, TJ-II… European Labs are involved through the EUROfusion MST1 activities**

ECRH SUPPRESSES REVERSED SHEAR ALFVÉN EIGENMODES (AEs) on DIII-D AND ASDEX-UPGRADE (AUG)

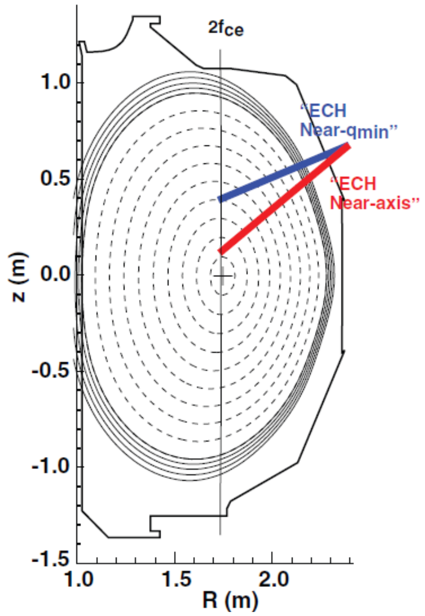
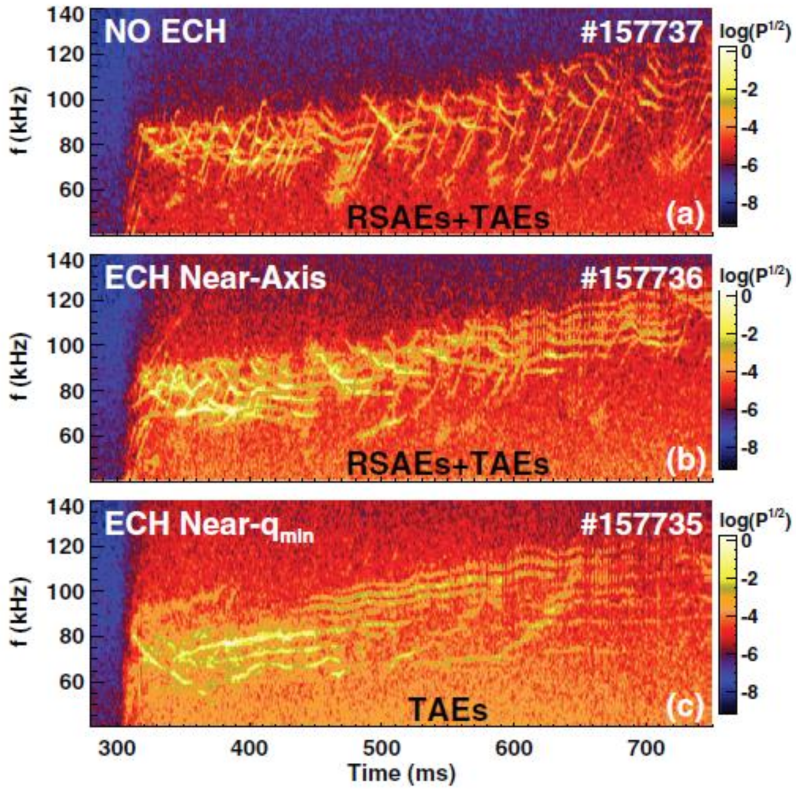


Figure 1. Representative equilibrium reconstruction with ECH steering trajectories overlaid. Dashed lines indicate equally spaced contours of normalized toroidal flux from 0.1–1.0. Actual EFIT is for discharge 157736, $t = 431$ ms.



M.A.Van Zeeland et al., Nucl. Fusion 56 (2016) 112007.

ECRH FACILITATES TAEs IN PLASMAS WITH MONOTONIC q-PROFILE:

- **Off-axis ECRH increases τ_{SD} of fast ions and facilitates TAEs (AUG):**

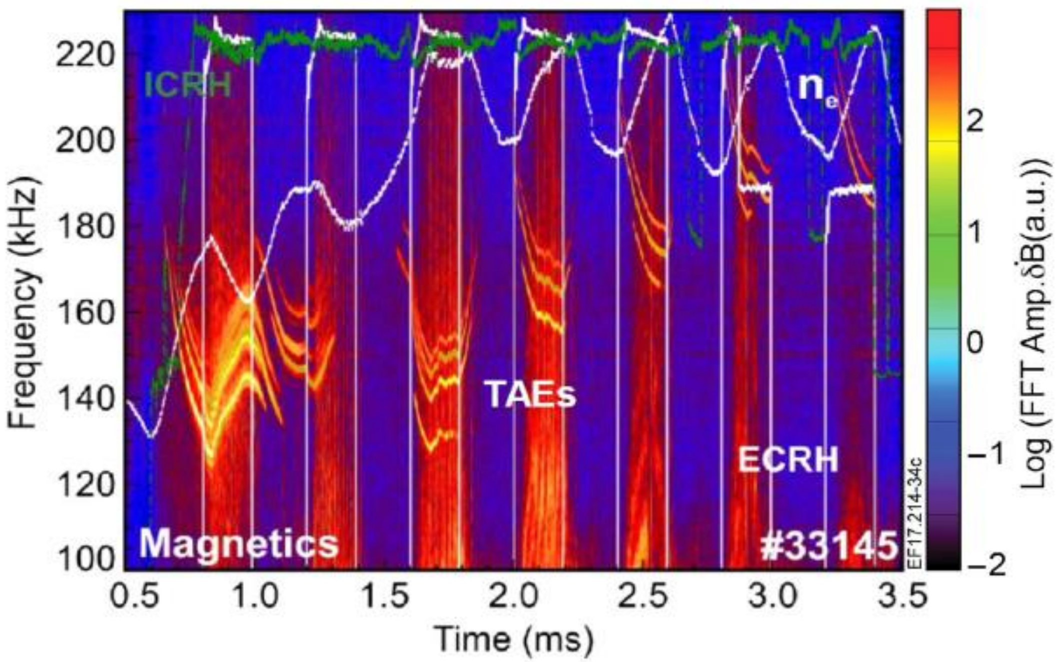


Figure 7. Zoom showing fine time scales for TAE excitation/disappearance with ECRH.

S.E.Sharapov et al., PPCF 60 (2018) 014026

TAE CONTROL WITH ECCD ON AUG

FROM ECRH TO ECCD ON AUG:

Aim: modify local magnetic shear S to suppress TAE

- TAEs cease to exist if plasma pressure gradient exceeds critical value determined by the magnetic shear, aspect ratio, and Shafranov shift [1-3]:

$$\alpha \equiv -R_0 q^2 \frac{d\beta}{dr} > \alpha_{crit} = (\varepsilon + 2\Delta') + S^2$$

- For TAE at half-radius, $\rho_t \approx 0.5$, in our AUG discharge #33145 @ 2s we had $\alpha \approx 0.224$, $\varepsilon + 2\Delta' \approx -0.231$, $S \approx 1.14$, so we had $\alpha < \alpha_{crit} \approx 1.06$.

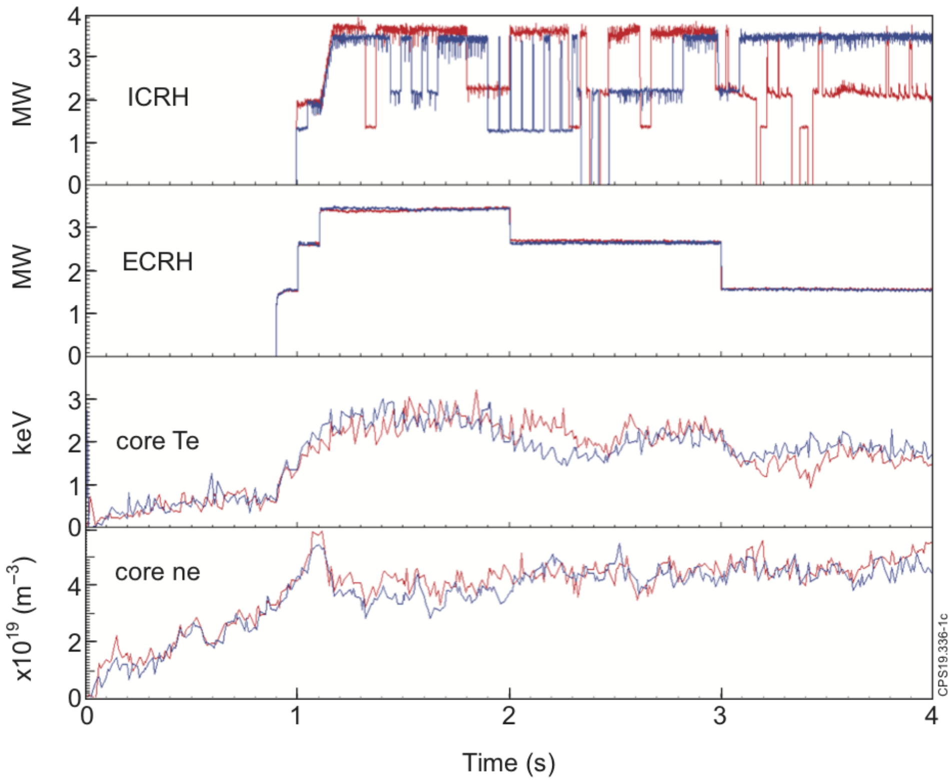
- If we could decrease magnetic shear S at the position of TAE from S≈1 down to S≈0.6 by using ECCD, we would suppress TAE by pushing frequency of the mode into Alfvén continuum

- The effect is not about the balance between TAE drive and TAE kinetic damping. The effect is about TAE existence within the gap in Alfvén continuum.

- A local increase in plasma pressure due to ECH effect could also be beneficial.

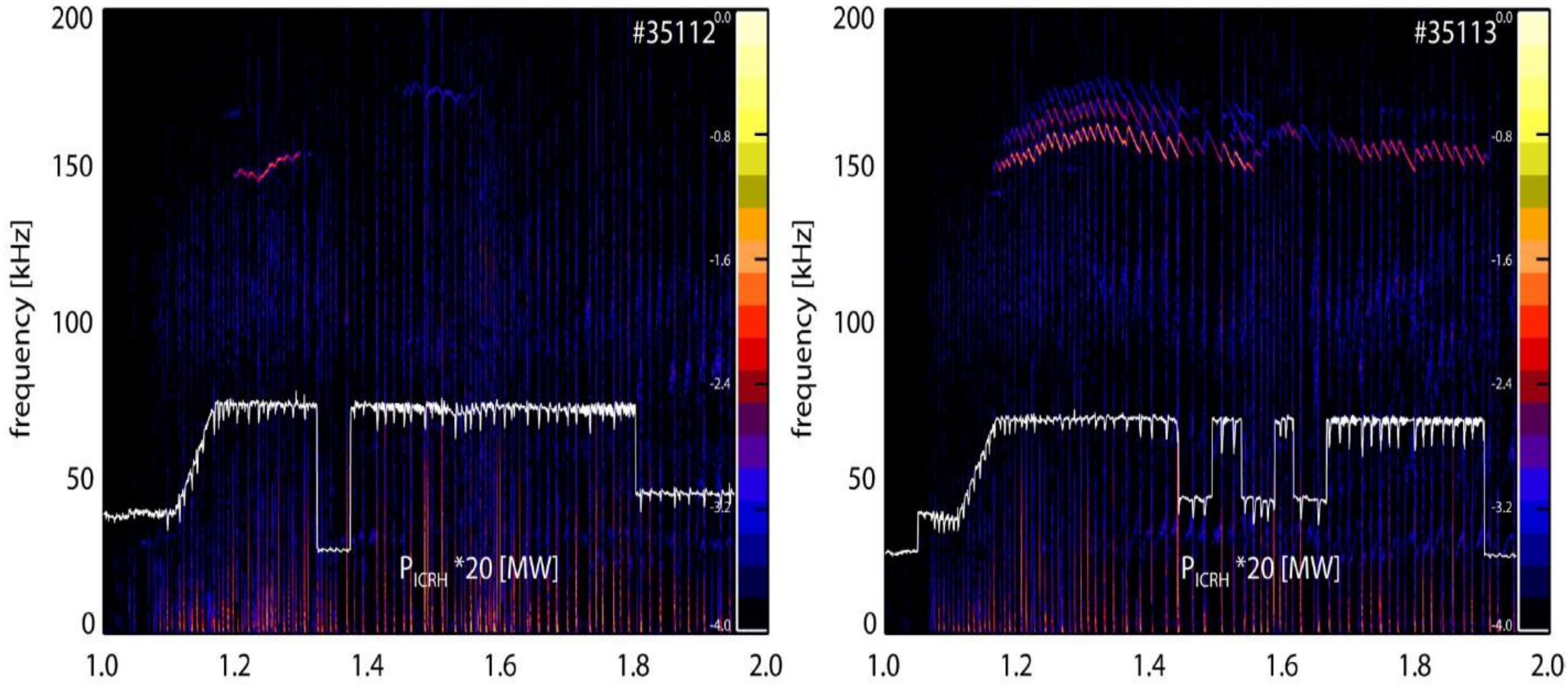
[1] G.Y.Fu, PoP 2 (1995) 1029; [2] H.L.Berk et al., PoP 2 (1995) 3401 ; [3] S.E.Sharapov et al., Nucl. Fusion 39 (1999) 373.

OFF-AXIS COUNTER- ECCD AT HIGHEST POWER (6 GYROTRONS) ON AUG:

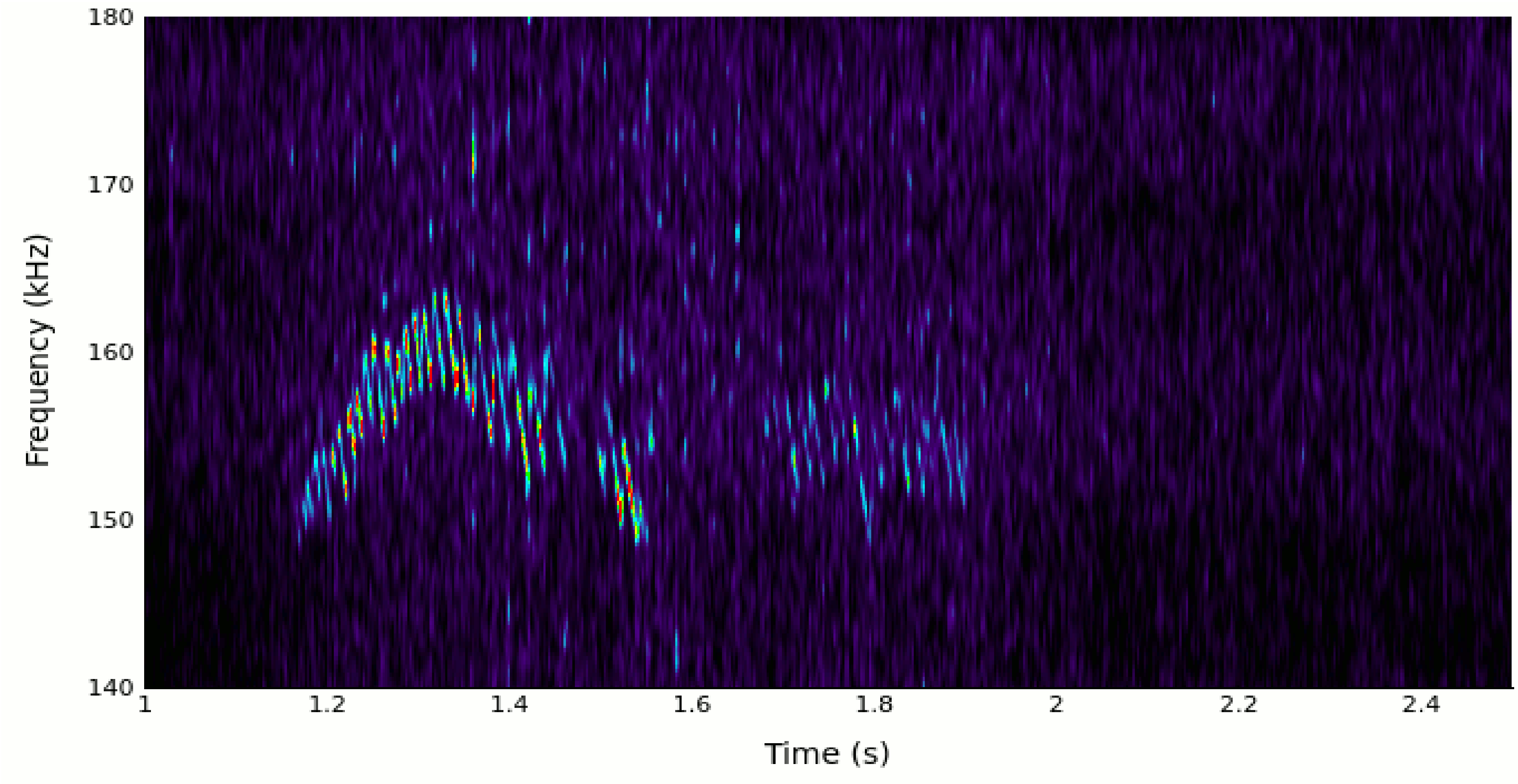


- **Pair of discharges, I_P=700 kA, B_T=2.5 T, ICRH drives TAEs unstable;**
- **#35112 counter-ECCD at ρ≈0.5; #35113 ECRH at ρ≈0.5;**
- **Similar electron density and temperature!**

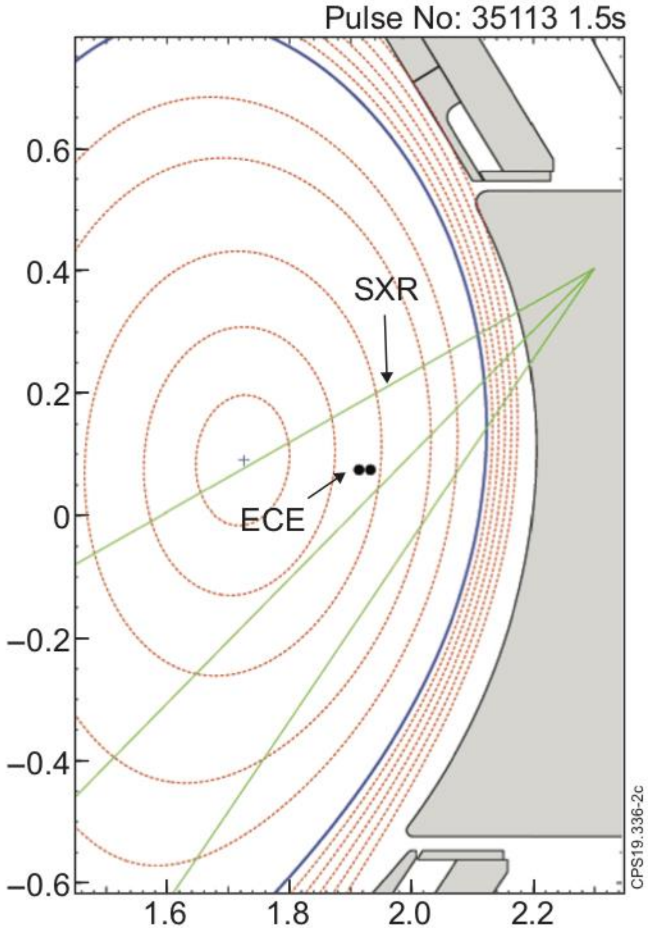
TAE ACTIVITY IS MUCH WEAKER IN ECCD PULSE #35112 (Left) THAN IN ECRH REFERENCE PULSE #35113 (Right)



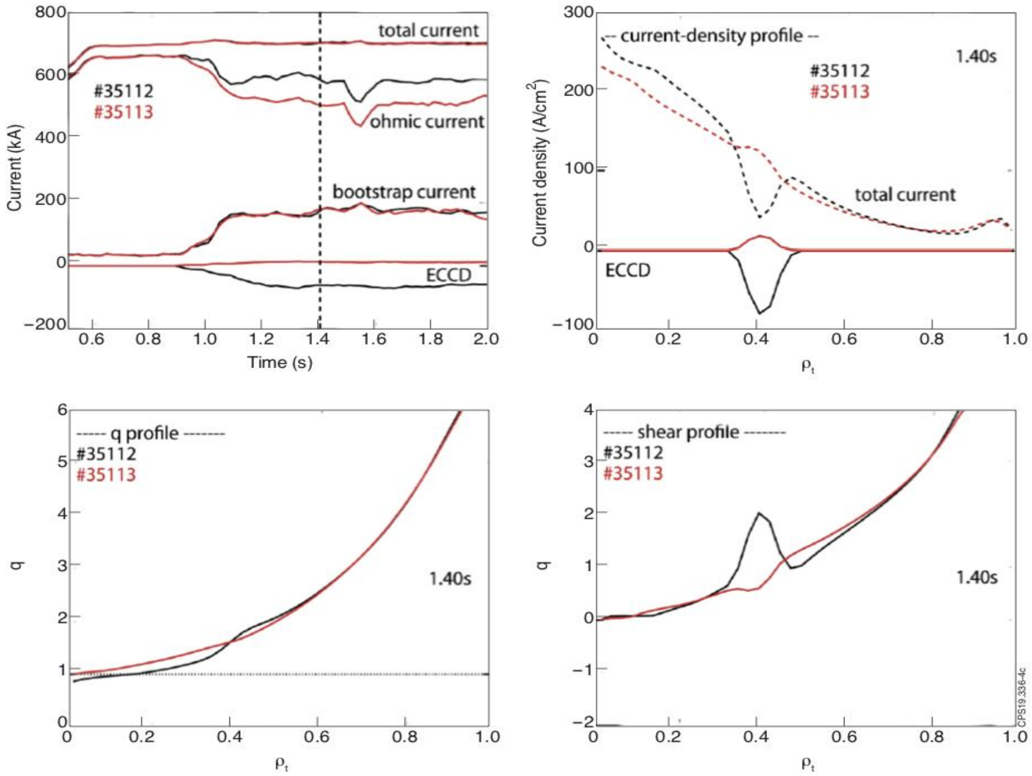
TAEs IN #35113 ARE SEEN IN SXR (BELOW) AND WEAKLY - IN ECE



SXR AND ECE SHOW TAE LOCALISATION AT r/a ~ 0.5- 0.7



TRANSP analysis for #33112 (ECCD) and #33113 (Reference ECRH)



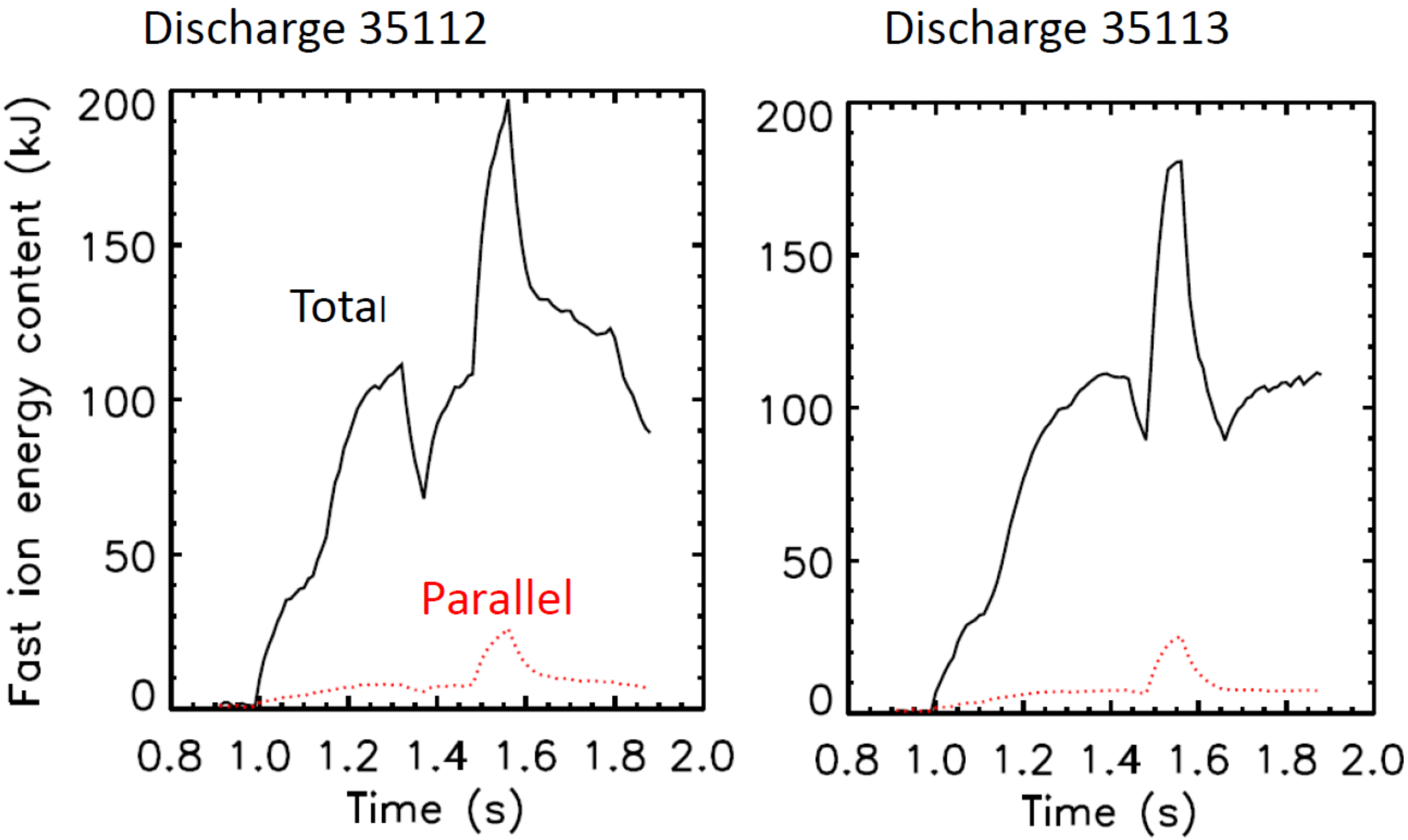
- **Similar bootstrap currents;**
- **Current density affected strongly by counter-ECCD;**
- **Clear effect on q-profile and magnetic shear!**

COULD THE SUPRESSION OF TAEs IN ECCD PULSE #35112 BE ATTRIBUTED TO A DIFFERENCE IN FAST ION DRIVE FROM ICRH?

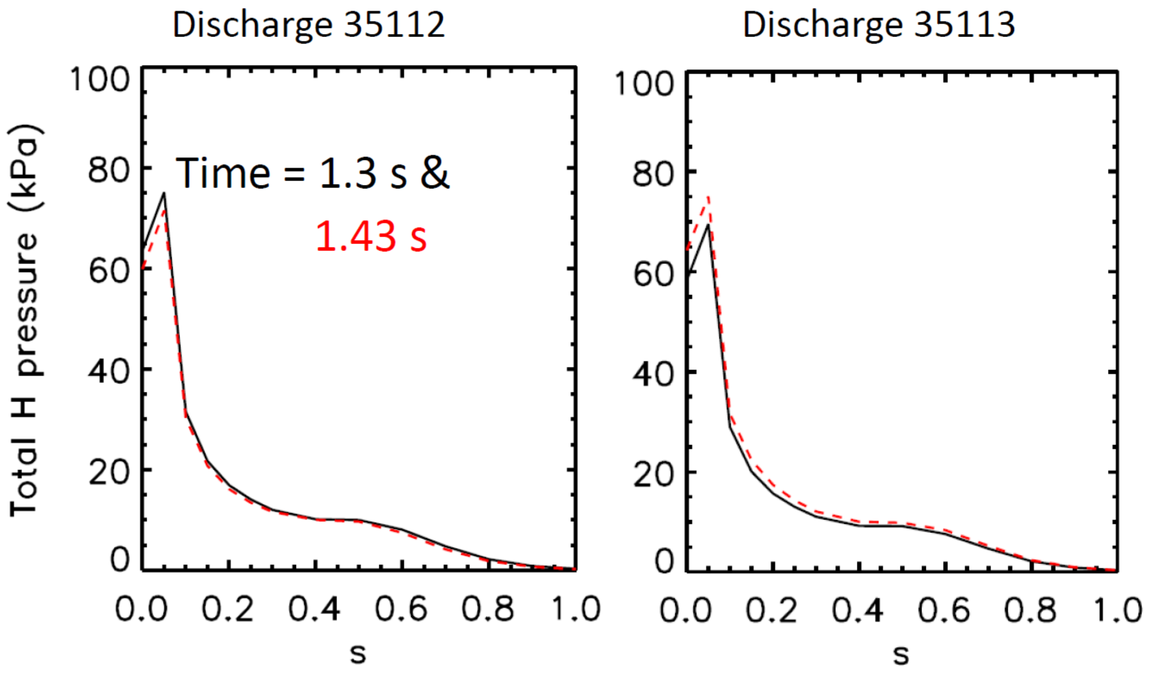
PION Modelling of ICRH ions in ##35112, 35113

- $n_H/n_e = 5\%$
- $Z_{eff} = 1.5$
- D beam source as calculated by TRANSP
- Full ICRF antenna toroidal mode number spectrum
- On-axis H minority resonance

TIME EVOLUTION OF FAST ION ENERGY CONTENTS



FAST H ION PRESSURE PROFILES IN THE TWO COMPARISON DISCHARGES



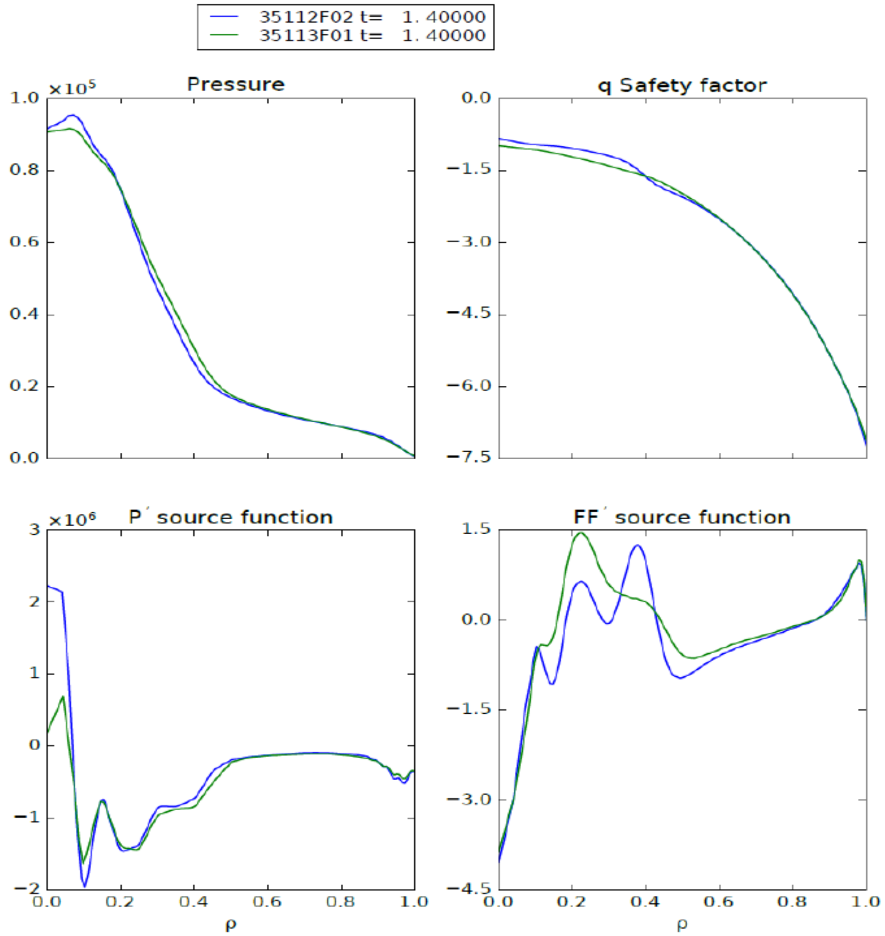
$T_{fast,perp}$ = 200 keV & $T_{fast, parallel}$ = 15 keV in the center of the plasma

Conclusion: Modelling with the PION code found no difference in fast ion populations of these two discharges → the difference in TAE could be only explained via TAE suppression and/ or TAE damping effects

SUITE OF MHD CODES USED FOR TAE MODELLING

- **The equilibria for time slices of interest are reconstructed with TEQ+MSE; with ECCD effects on the q-profile computed with the TRANSP code;**
- **HELENA code is used for a straight field line coordinate system then;**
- **Alfvén continuum structure is computed for the relevant toroidal mode numbers, and the frequency range of TAEs is identified;**
- **Spectral MHD codes CASTOR/ MISHKA are used then to compute TAEs.**

PLASMA EQUILIBRIA IN AUG DISCHARGES ##35112, 35113



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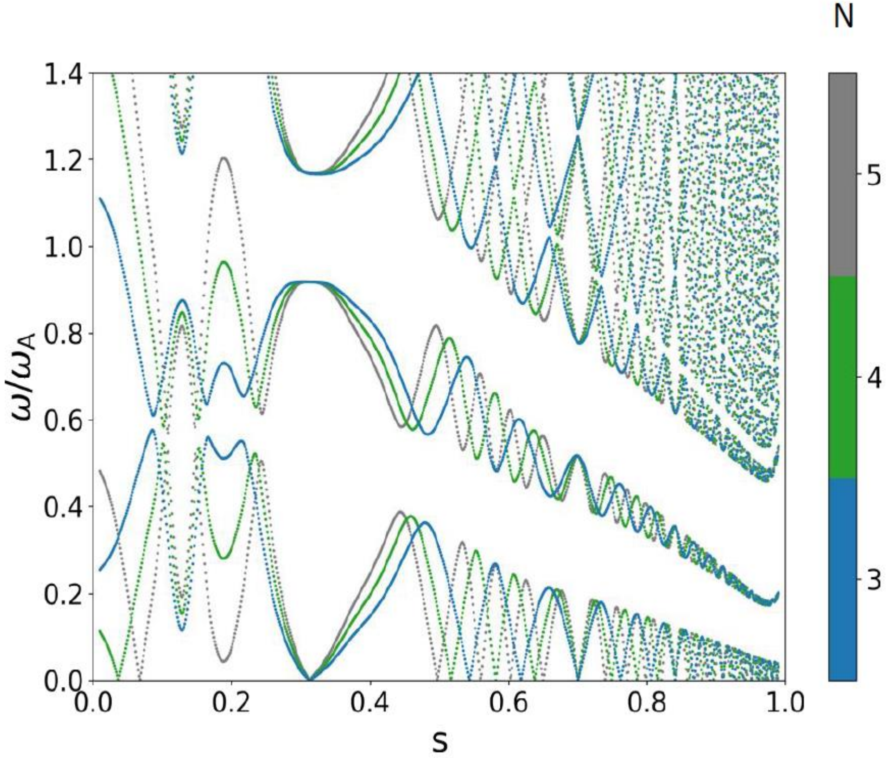
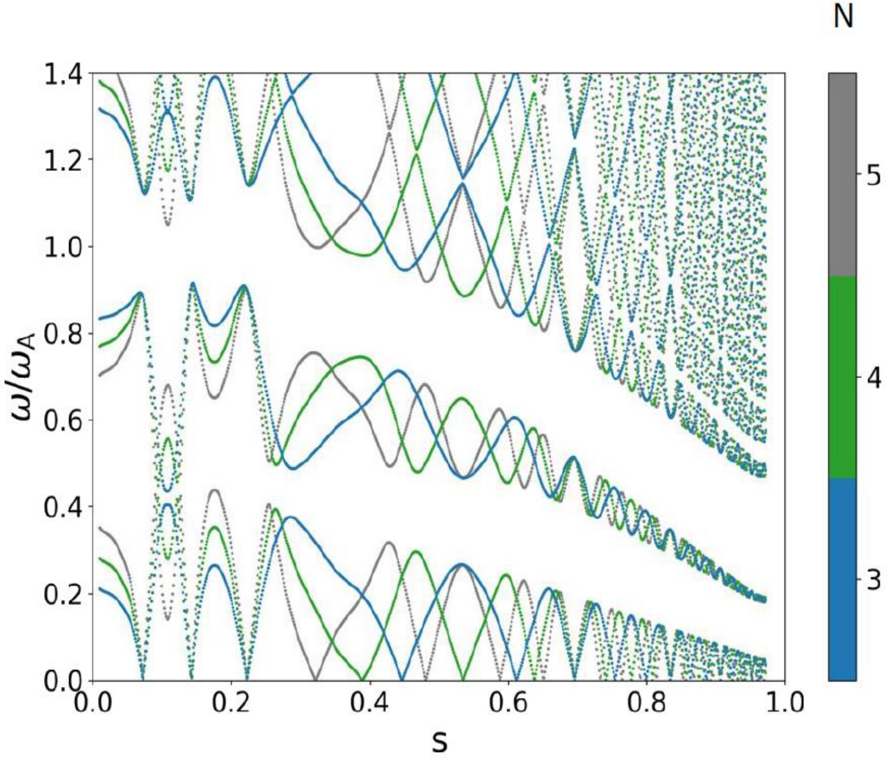
STRUCTURE OF ALFVÉN CONTINUUM FOR n= 3, 4, 5 IN ##35112, 35113

Alfvén continuum

#35112F02 @ 1.4s



#35113F01 @ 1.4s



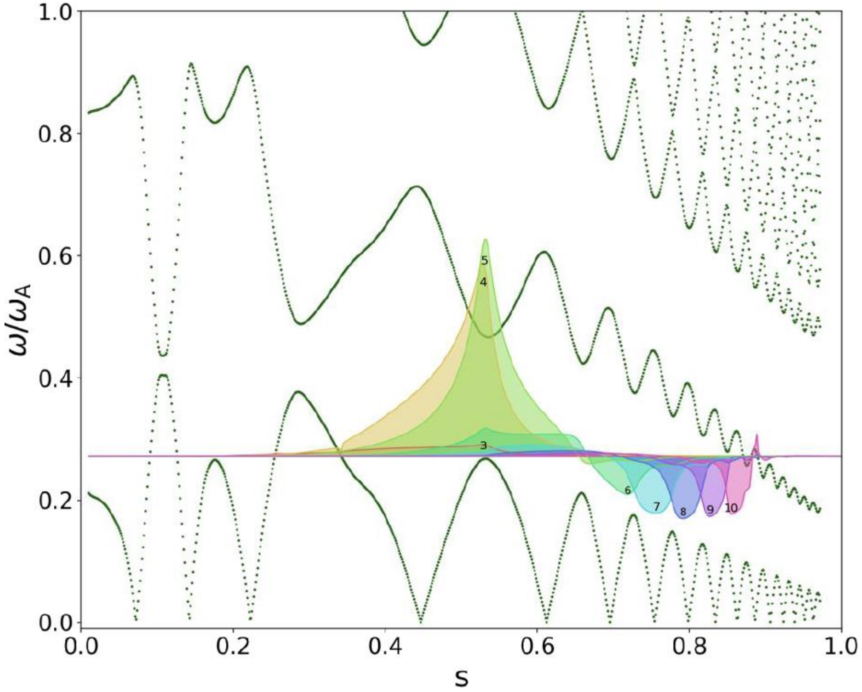
TAE COMPUTED ARE CONSISTENT WITH TAE OBSERVED

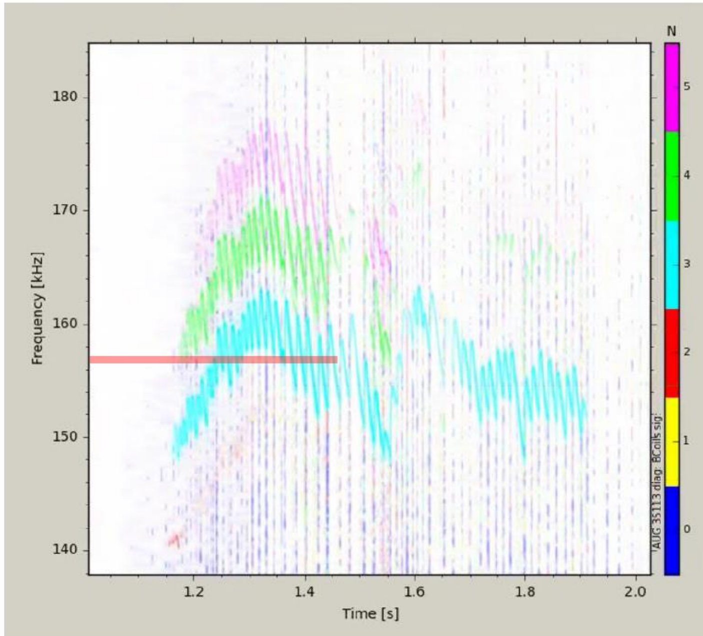
Structure of poloidal harmonics m (left) and TAE frequency computed (right).

#35113F01 @ 1.4s

n = 3

Alfvén freq. ~ 526 kHz
mode freq. ~ 143 ± tbd kHz (f/fA ~ 0.2722)
exp freq. ~ 157 ± 5 kHz
rotational freq. ~ 4 kHz?





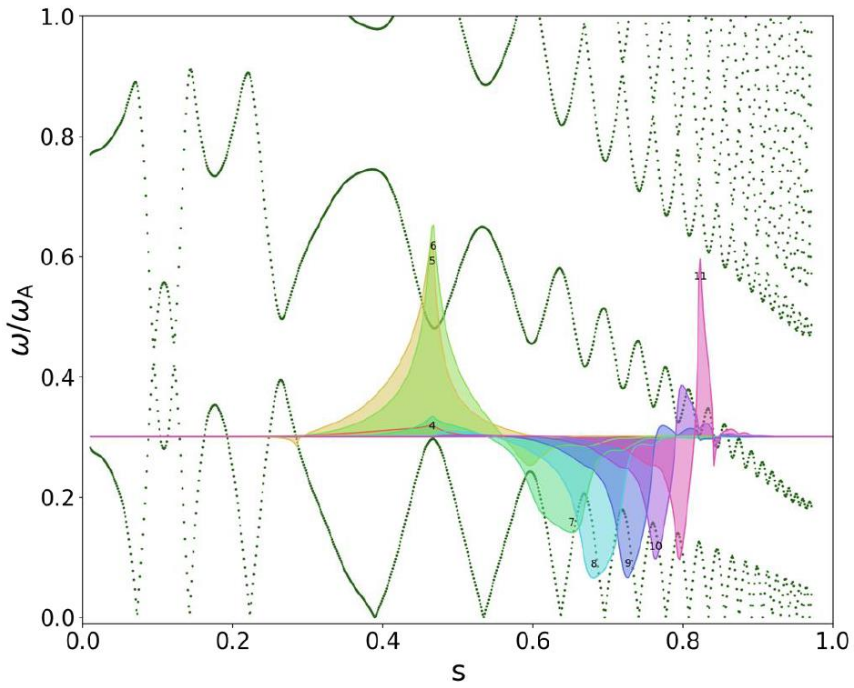
TAE COMPUTED ARE CONSISTENT WITH TAE OBSERVED

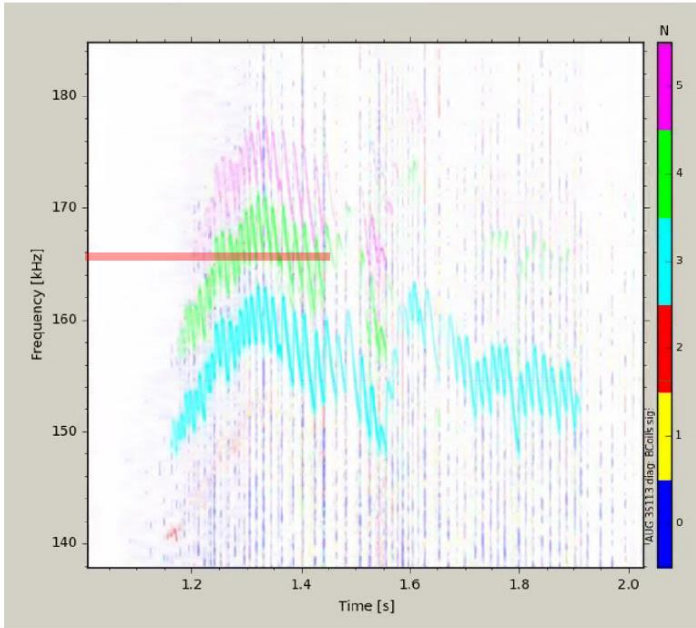
Structure of poloidal harmonics m (left) and TAE frequency computed (right).

#35113F01 @ 1.4s

n = 4

Alfvén freq. ~ 526 kHz
mode freq. ~ 158 ± tbd kHz (f/fA ~ 0.301)
exp freq. ~ 166 ± 5 kHz
rotational freq. ~ 2 kHz?





NO TAEs ARE FOUND WITH MHD CODES ECCD CASE OF AUG #35112 @ 1.4 s.

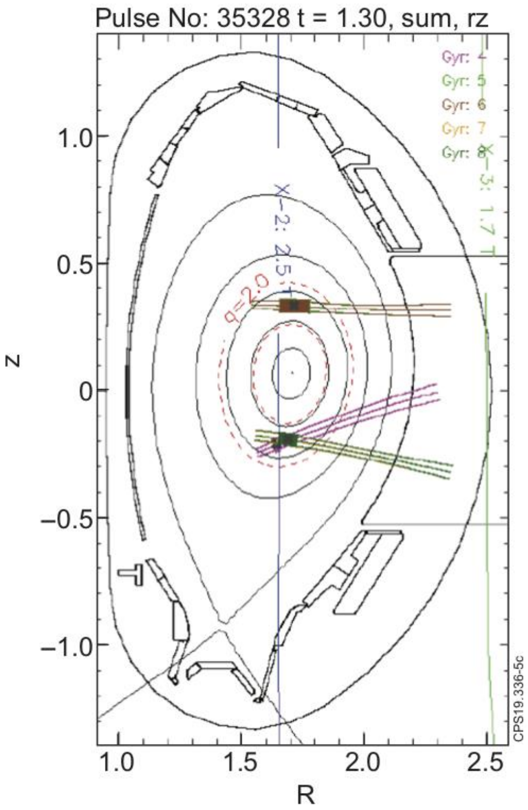
This is compatible with the pressure suppression effect:

	ρ	S	Δ'	ε	α_{crit}	α
#35112 t=1.4 s	0.498	0.9272	-0.26	0.149	0.489	≈0.42
#35113 t=1.4 s	0.498	1.0960	-0.2522	0.148	0.8448	≈0.42

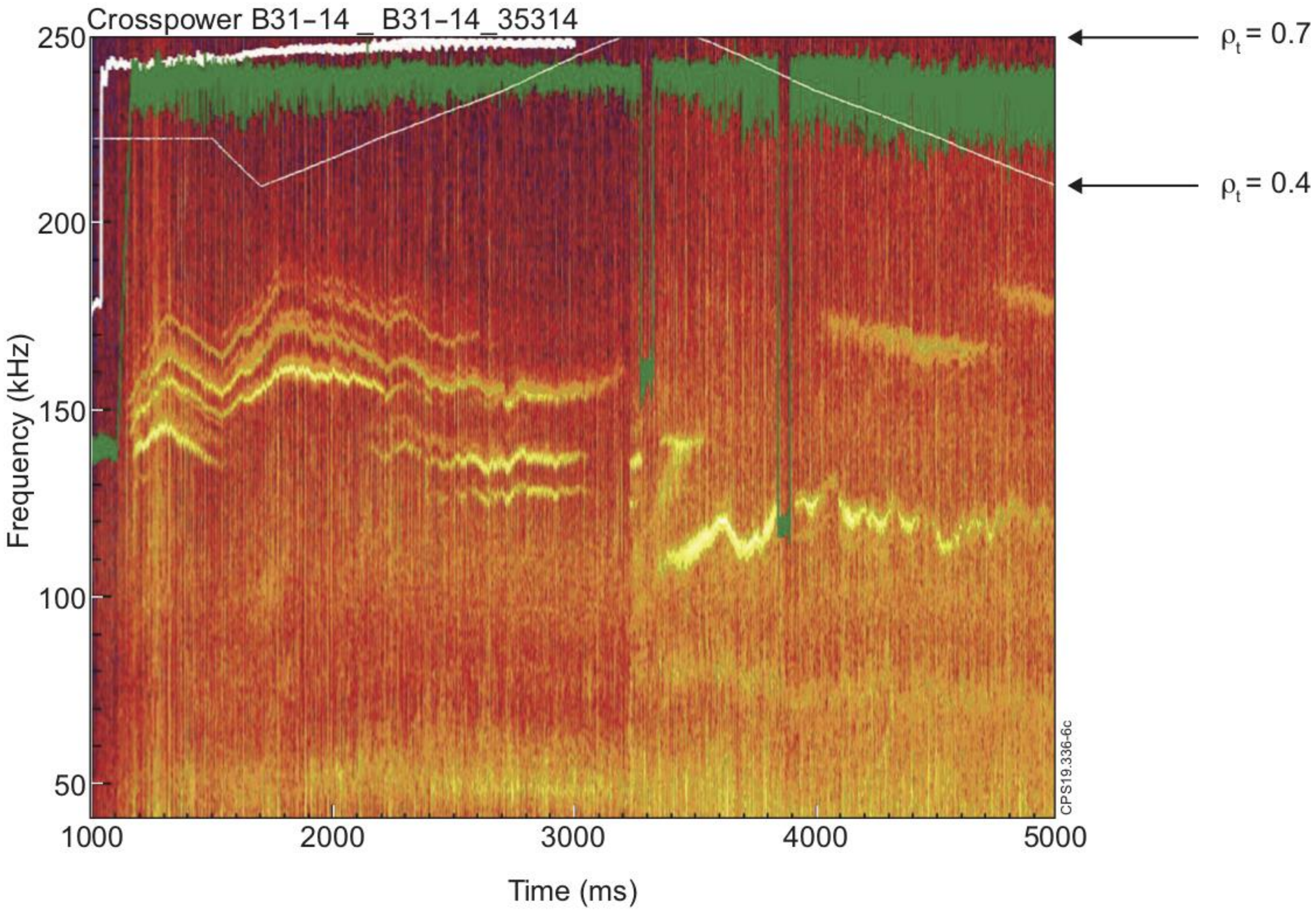
- Magnetic shear S at $\rho \approx 0.5$ was smaller in #35112 (ECCD) thus making the critical pressure gradient significantly lower than in #35113 (ECRH)

MORE SOPHISTICATED ECCD MIRROR SCAN EXPERIMENT STARTED:

- **Two gyrotrons were kept at fixed positions;**
- **Mirrors for other 2x2 gyrotrons moved ECCD power deposition across TAE:**



SIGNIFICANT CHANGES IN TAEs SEEN AS ECCD SWEEPS ACROSS



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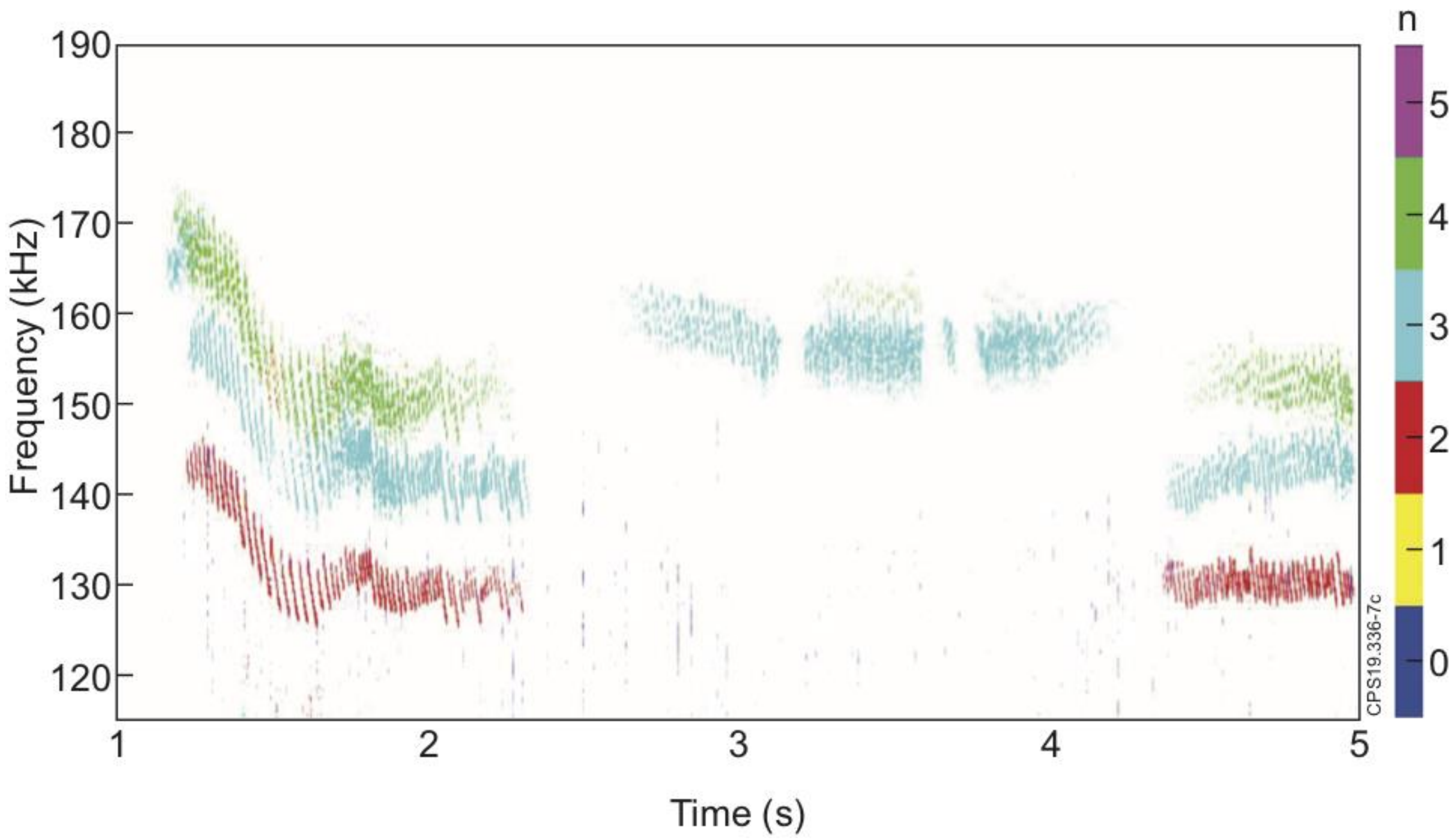
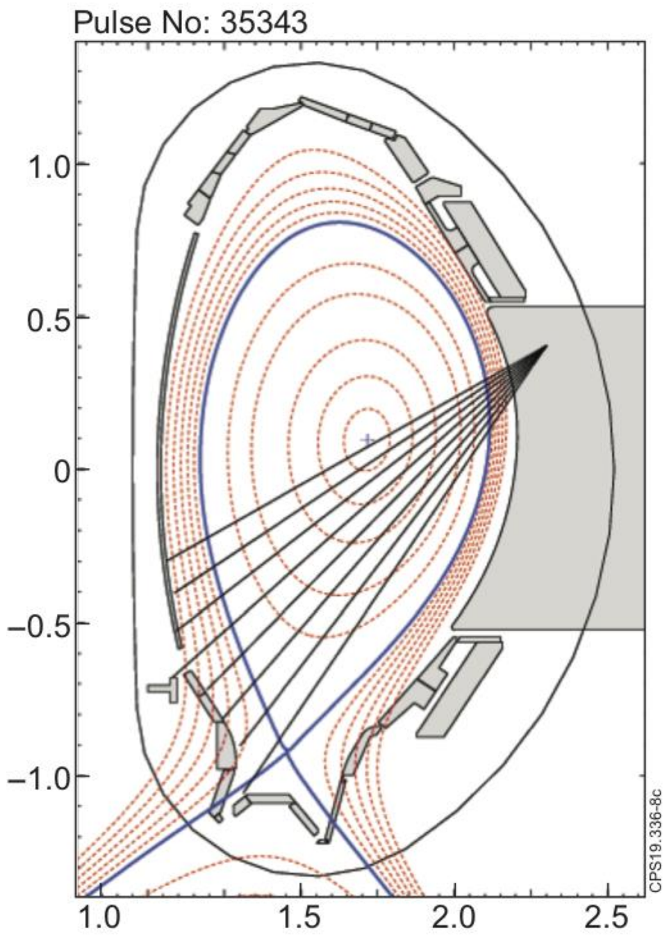
SOME TAEs DISAPPEAR, SOME APPEAR. TIMES EXIST WITH “NO TAE”.

AUG pulse #35334. TAEs with n= 2, 3, 4 change as ECCD sweeps across:

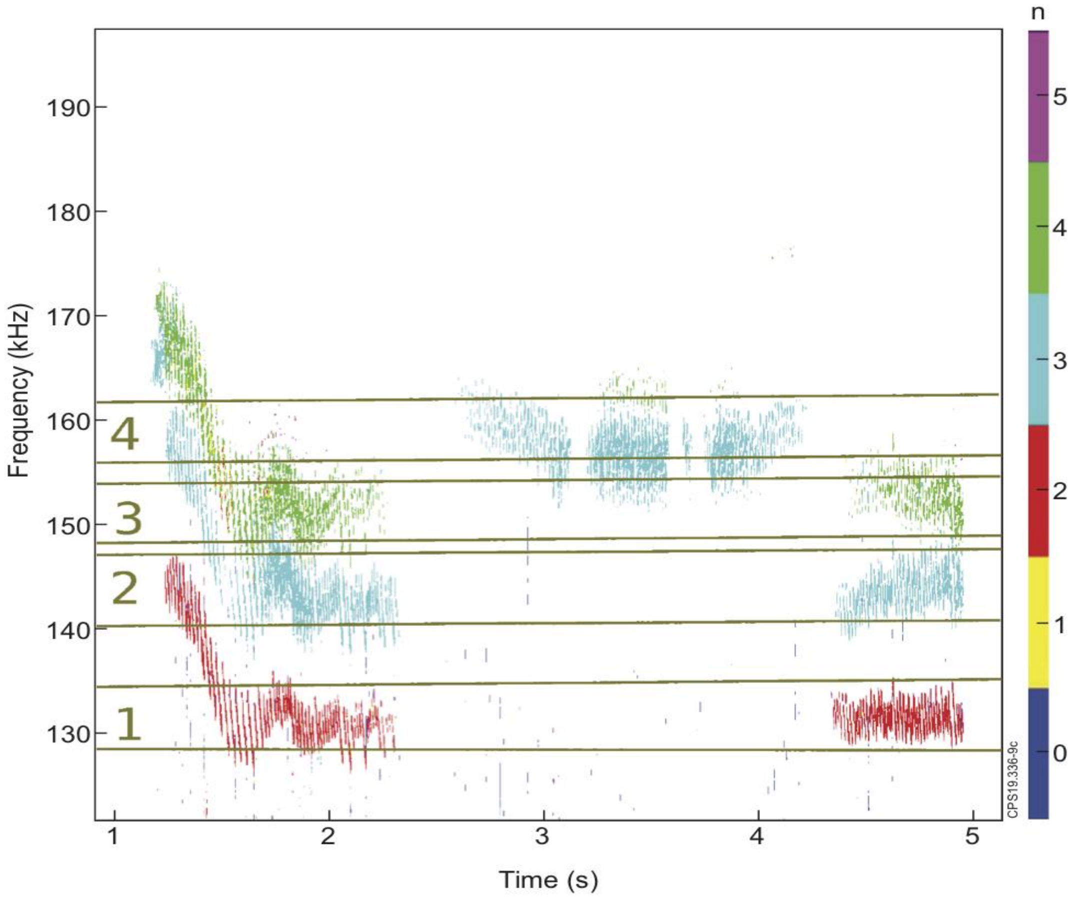


INTERNAL SXR DIAGNOSTICS:



INTERNAL SXR DIAGNOSTICS (cont'd):

AUG pulse #35334



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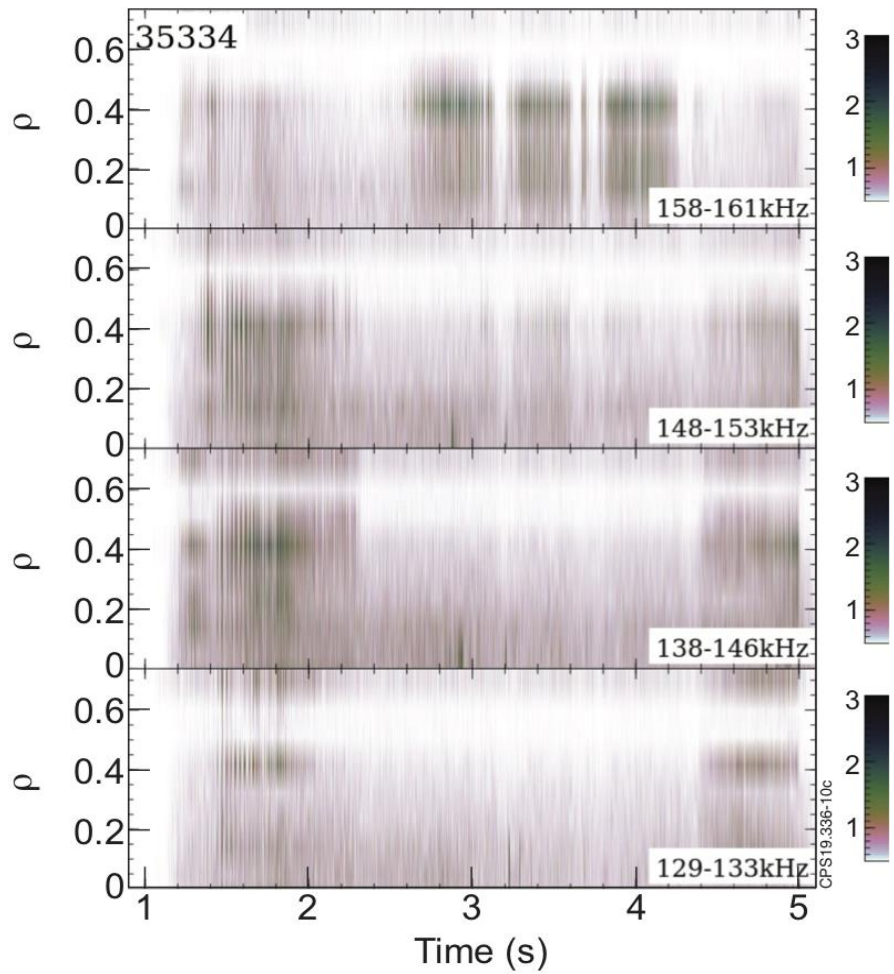
INTERNAL SXR DIAGNOSTICS (cont'd):



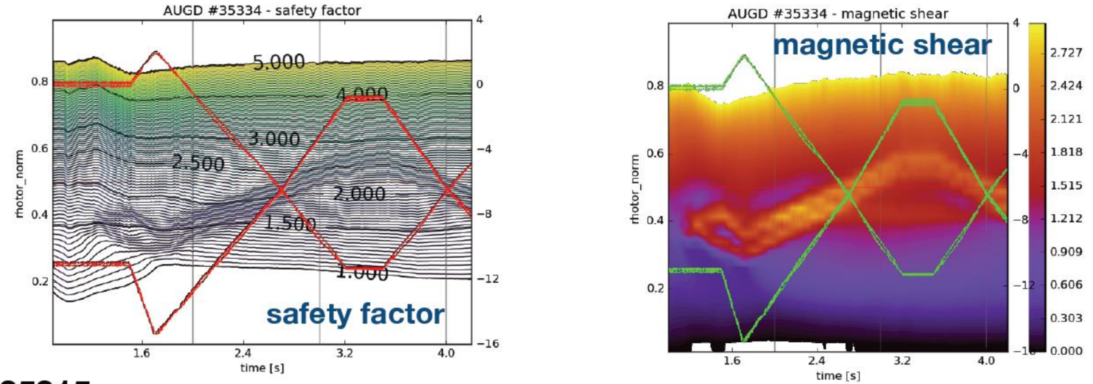
SUMMARY ON TAE LOCALISATION:

- **Low-frequency TAEs seen during 1.4 s – 2.4 s are rather global with the mode structure extending to ρ≈ 0.65;**
- **Higher-frequency TAEs seen at 3-4 s are core-localised at ρ≈ 0.3;**
- **The core-localised TAEs are well seen by SXR, but not all of them are seen well by magnetics;**
- **Clear TAE-suppression phase at 2.5 s is seen by all diagnostics.**

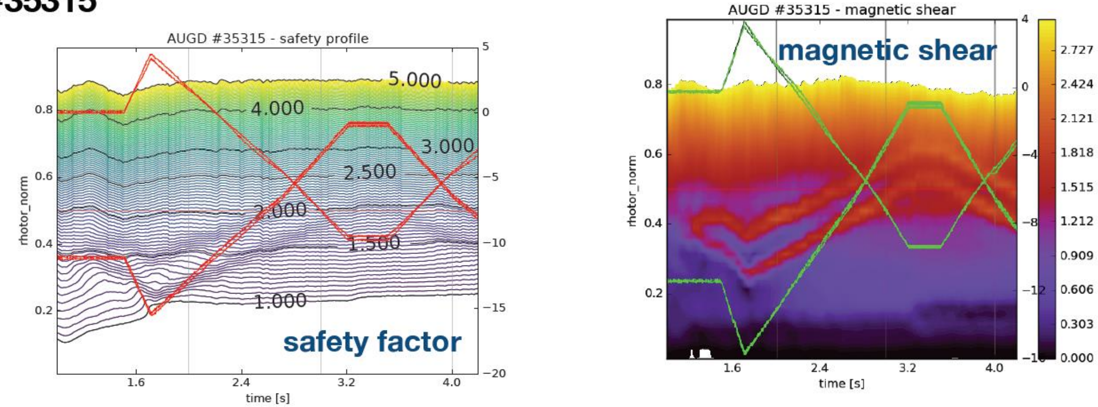
TRANSP MODELLING FOR ECCD WITH MOVING MIRRORS

Preliminary TRANSP runs - EC counter drive current

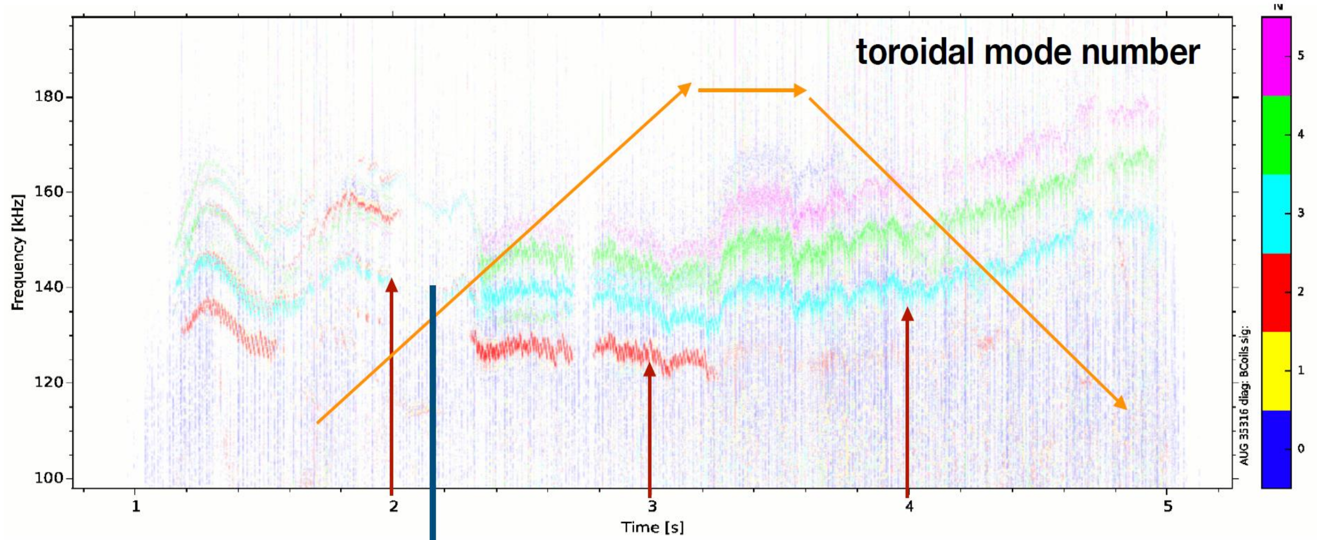
- **#35334** - ECCD effect on q and shear (better EC alignment)

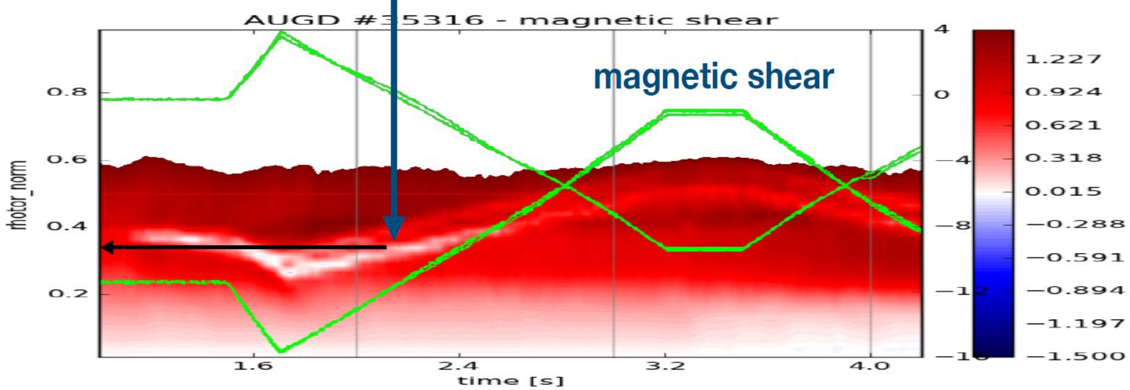


- **#35315**



ECCD CO-CURRENT CASE (AUG #35316):





MHD MODELLING IS YET TO BE FINISHED

- **The rather complex pattern of TAEs with different n's appearing/ disappearing as ECCD sweeps across, the modelling of TAEs is not finished yet.**
- **For unambiguous identification of the main ECCD effects on TAEs, the TRANSP code with moving ECCD mirrors must also now include Kadomtsev model for sawteeth (which are observed in these discharges).**

FUTURE STUDIES ON AUG:

- **Reproduce the mirror scan scenario and identify the mirror position/ time for the short time window when no TAEs are seen;**
- **Perform experiment at highest ECCD power with the mirror position identified above. Investigate the possibility of a steady-state "no TAE" scenario;**
- **Vary ECCD power to assess the "no TAE" power threshold on AUG;**

THE TCV TEAM HAS JOINED THE STUDY OF ECRH/ ECCD EFFECTS ON AEs IN 2018

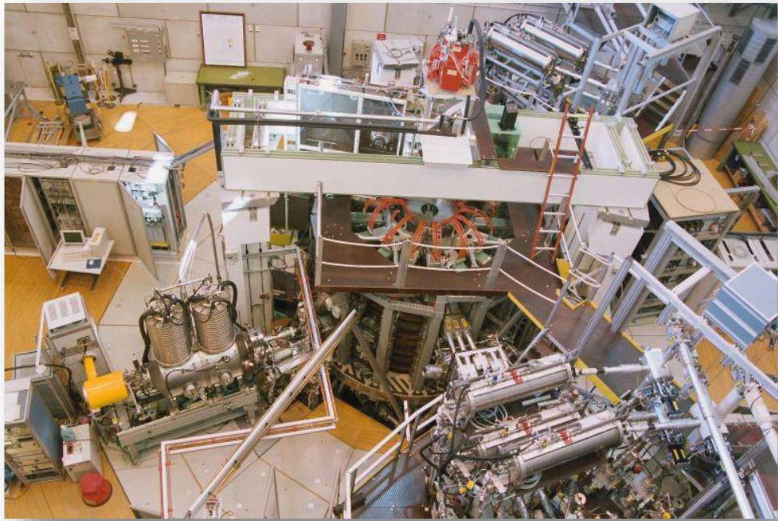
- **TCV has an excellent ECRH/ECCD system, but NBI energy of 25 keV is low to drive AEs effectively via the wave-particle resonance**

↓

- **Scenario development for beam-driven modes was the highest priority first.**

TCV: Tokamak à Configuration Variable

- R_{maj}=0.88, r_{min}= 0.25 m
- 1 m^3
- > 2 MW of ECRH
- NBI with 1 MW of neutral power at
  25 keV injection voltage
- B_t = 1.43 T



https://crppwww.epfl.ch

$$v_A = \frac{B}{\sqrt{\mu_0 n_i m_i}}$$

For m_i = 2 x $10^{19}/m^3$:

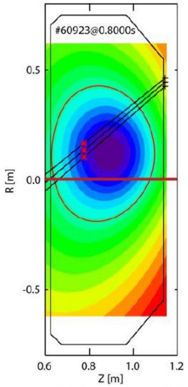
- $v_A/3$ = 5000 km/s ~28.2 keV

→ Reduced Bt to 1.3 T

- $v_A/3$= 4500 km/s ~**23.3 keV**

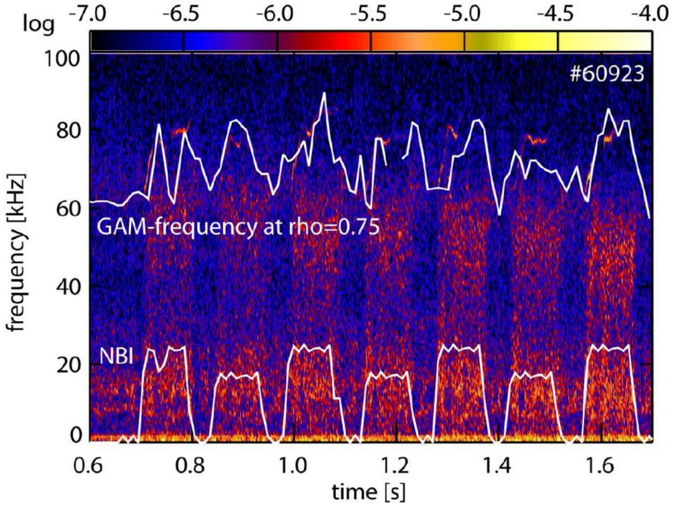
OFF-AXIS NBI+ECRH ON TCV: BEAM-DRIVENE-GAMs OBSERVED

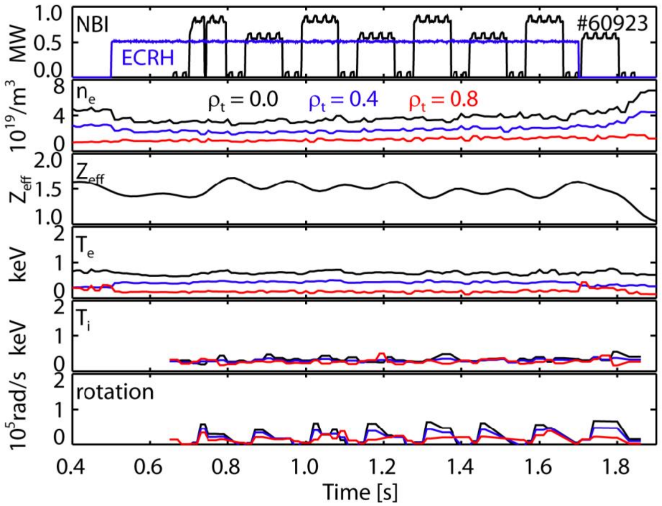
#60923: off-axis NBI configuration



- off-axis configuration (z_{mag}=+12 cm)
- 1.3 T, 120 kA
- off-axis ECRH
- n_e ~4 x10^{19}/m^3 ,T_e~ 800 eV
- 96 ms long NBI phases with 25 keV and 22 keV

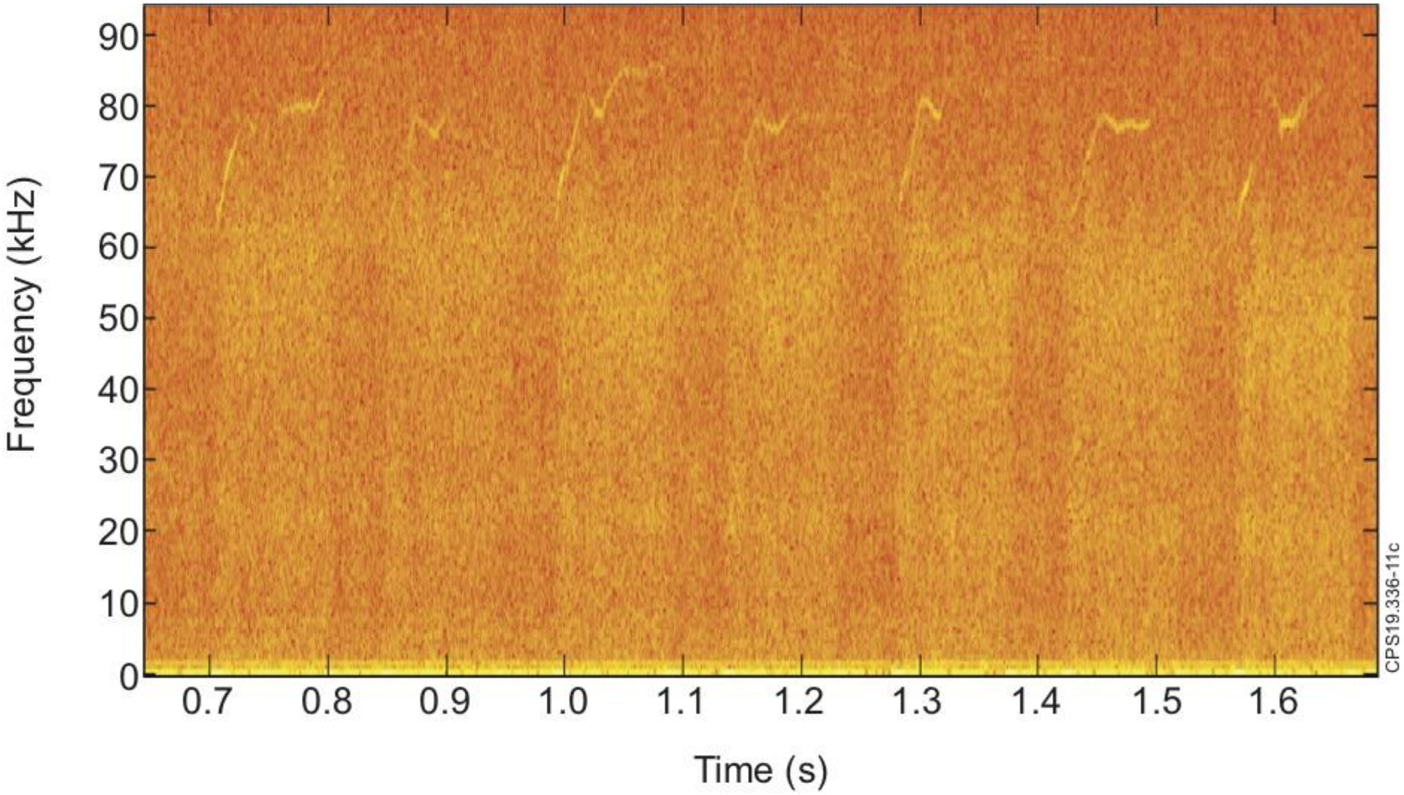
- Alfven modes at ~ 80 kHz during NBI operation (m=4,n=2)
- Identified as E-GAMs/BAEs (not TAEs)





WEAK BEAM-DRIVEN E-GAMs WERE EXCITED FIRST:

TCV pulse #60923, n=2



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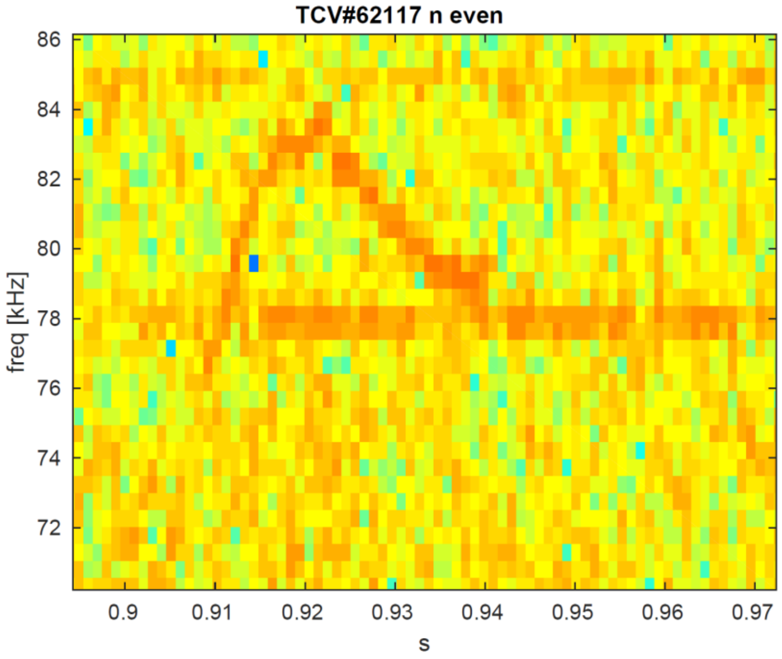
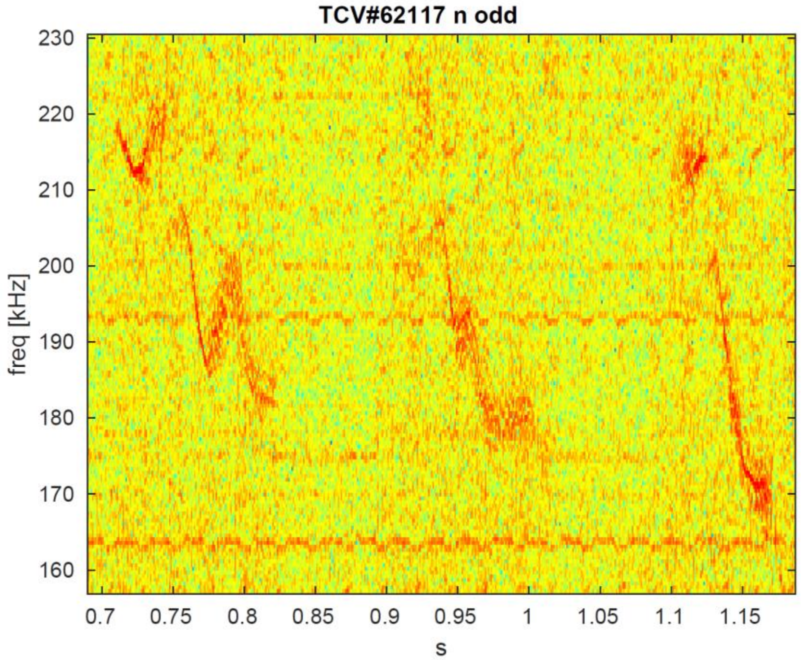
OFF-AXIS NBI+ECRH WERE ALSO DRIVING TAEs!

- **By doing NBI power scan and scan in Z_0 (off-axis position), we managed to *excite TAE* on TCV with 25 keV beam *and ECRH* off-axis!**





Beam-driven EGAMs/ BAEs	TAEs excited with the same beam

TAEs EXCITATION WAS SENSITIVE TO THE OFF-AXIS POSITION Z_0:

Overview of MST1-HLT13-TCV shots

List of useful TCV shots, October 02-03, 2018

	aim	TAEs
TCV#62111:	Zo:+11.9cm	1st, 2nd & 3rd pulses
TCV#62112:	rpt.	1st, 2nd & 3rd pulses
TCV#62113:	low density	1st TAEs, 1st & 2nd EGAMs
TCV#62114:	BT ramp-up	1st pulse (low)
TCV#62117:	rpt.	1st, 2nd & 3rd pulses
TCV#62123:	rpt.	1st, 2nd & 3rd pulses
TCV#62124:	Zo:+3.4cm	no TAEs
TCV#62125:	Zo:+7.4cm	no TAEs
TCV#62126:	Zo:+14.9cm	no TAEs
TCV#62127:	Zo:+14.8cm	no TAEs
TCV#62128:	NB high-to-low	1st pulse
TCV#62129:	NB low-to-high	no TAEs
TCV#62130:	NB 2 levels	1st pulse

Reproducible "good" shots: 62111, 62112, 62117 & 62123

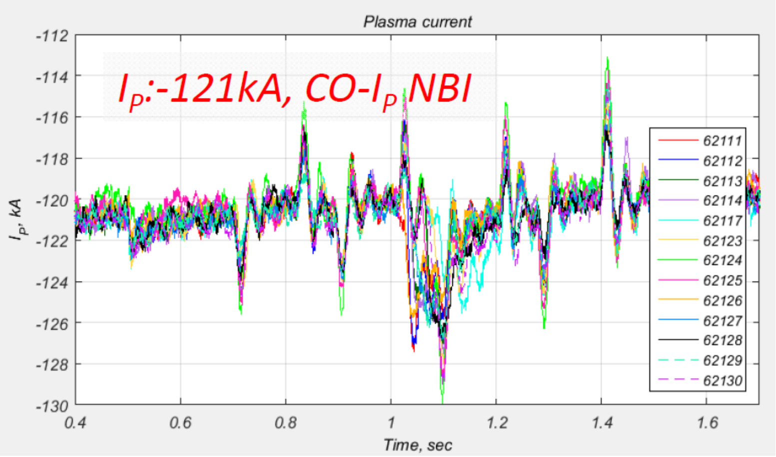
TAEs: NB 1.03MW, ECH-X2 400KW, Zo +12cm,
BT: 1.30...1.35T, $<ne_{19}>$: 2.3...2.8

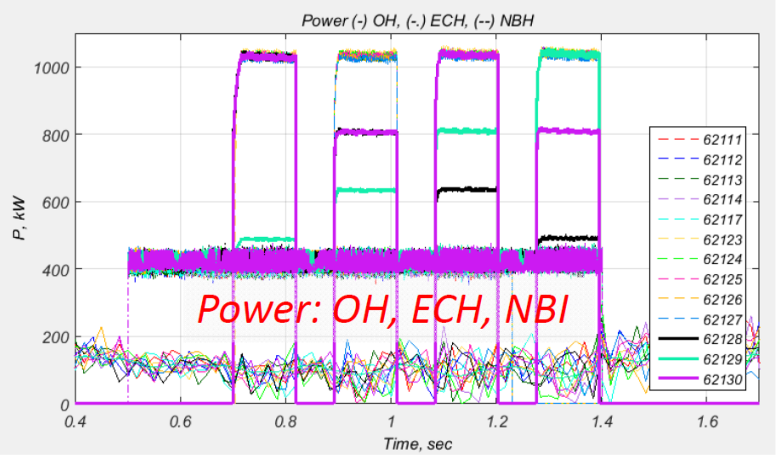
Zo scan: 62124, 62125, 62123, 62126 & 62127

NB power scan: 62128, 62129 & 62130.

TCV#60923: Zo:+12cm, OFF-axis NBI reference, May 2018

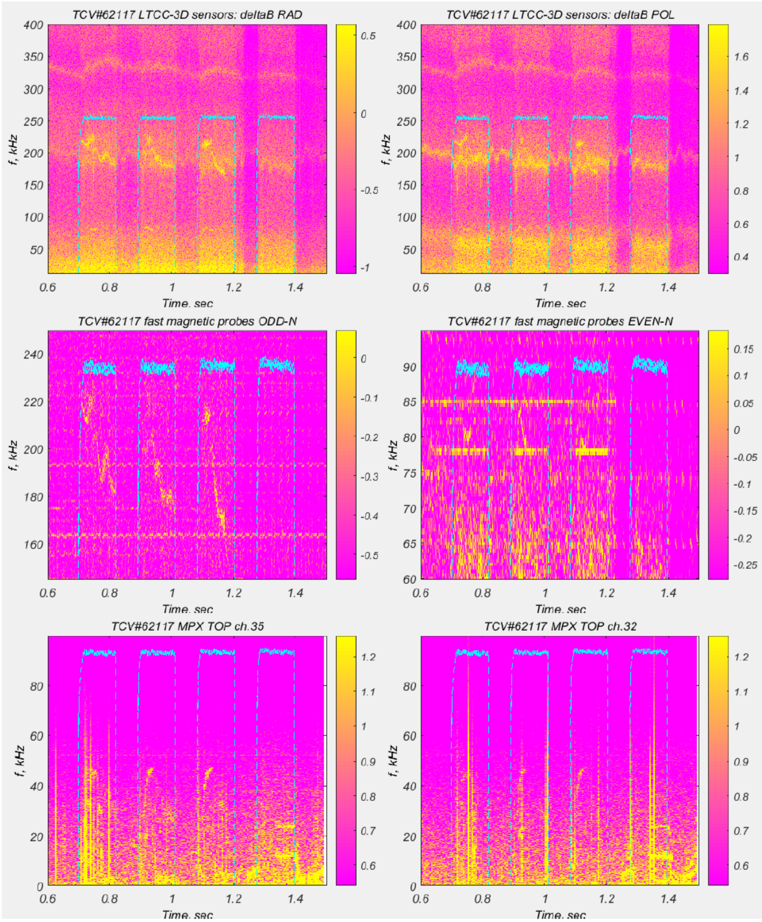
TCV#60924: Zo:-0.6cm, ON-axis NBI reference





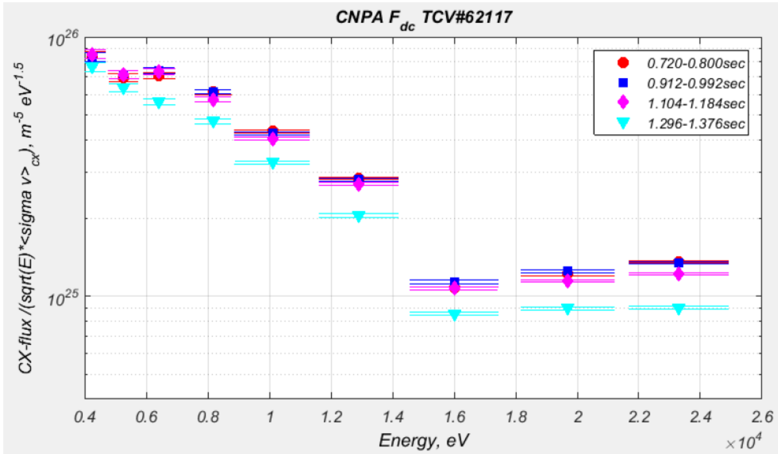
NPA SHOWS BUMP-ON-TAIL IN THE BEAM DISTRIBUTION!

Consistent with ASTRA modelling for the beam off-axis when $\tau_{CX} < \tau_{SD}$



TCV#62117: ref.#62111, I_p:-121kA; Z_0:+11.9cm;
κ_{edge}: 1.31; δ_{edge}: 0.12; q_{95}: 5.24; q_0: 1.27;
$\langle ne_{19} \rangle$: 2.37 (2.48,-5%); W_{DML}: 4.39kJ; B_{T0}: 1.304T

EAEs: 345…320kHz (full shot)
TAEs: 225→165kHz (first-third NB pulses),
EGAMs: ~80kHz (first-third pulses)
GAMs: ~45kHz (first-third pulses), 24/12kHz (forth non-ECH)



FUTURE STUDIES ON TCV:

- **Effect of plasma shape on TAEs;**
- **Scan in B for ECRH closer to the magnetic axis/ search for TAEs excited with on-axis NBI;**
- **Preparing for installation of the second beam with higher energy (≈ 50 keV);**

SUMMARY ON AUG

- Several effects of ECRH on energetic particle-driven AEs were found experimentally and identified;
- On AUG, the step from ECRH to ECCD has delivered an important message that TAEs could be controlled by the shear variation and associated pressure suppression/ TAE damping effects
- In AUG experiment with the mirror scan of ECCD across TAEs, significant changes in TAE spectrum were observed, including the no-TAE window
- Analysis of magnetics, SXR, and ECE shows a broad agreement with the modelling
- TRANSP modelling of the mirror-ECCD discharges on AUG was completed and its results are under investigation

SUMMARY ON TCV

- Scenario for EGAM and TAE instabilities driven by off-axis NBI and ECRH was developed on TCV
- A steady-state bump-on-tail beam distribution has been measured in such scenario facilitating the mode excitation
- Further experiment with NBI closer to the axis, various beam and ECRH powers etc. is currently planned