Modeling of the ECCD injection effect on the Heliotron J and LHD plasma stability

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ABSTRACT

The aim of the study is to analyze the stability of the Energetic Particle Modes (EPM) and Alfven Eigenmodes (AE) in Helitron J and LHD plasma if the electron cyclotron current drive (ECCD) is applied. The analysis is performed using the code FAR3d [1] that solves the reduced MHD equations describing the linear evolution of the poloidal flux and the toroidal component of the vorticity in a full 3D system, coupled with equations of density and parallel velocity moments for the energetic particle (EP) species, including the effect of the acoustic modes. The Landau damping and resonant destabilization effects are added via the closure relation. The simulations results show that the n=1 EPM and n=2 Global AE (GAE) in Heliotron J plasma can be stabilized if the magnetic shear is enhanced, increasing (co-ECCD injection) or decreasing (ctr-ECCD injection) the rotational transform at the magnetic axis (ι0). In the ctr-ECCD simulations, the EPM/AE growth rate decreases only below a given ι0, corresponding to a ECCD intensity threshold also observed in the experiments. In addition, ctr-ECCD simulations show an enhancement of the continuum damping. The simulations of the LHD discharges with ctr-ECCD injection indicate the stabilization of the n=1 EPM and n=2 Toroidal AE (TAE), caused by an enhancement of the continuum damping in the inner plasma and increasing the EP β threshold with respect to the co- and no-ECCD simulations.

INTRODUCTION

- The external injection of electron cyclotron waves (ECW) is used to modify the iota profile of nuclear fusion devices by the generation of non inductive currents in the plasma.
- The electron cyclotron current drive (ECCD) can improve the stability of the pressure and current gradient driven modes as well as the Alfven Eigenmodes (AE).
- Helitron J discharge 61484 (no ECCD) shows unstable n=1 EPM and n=2 GAE. LHD discharge 138675 (co-ECCD) shows unstable n=1 EPM and n=2 TAE.
- Ctr-ECCD injection in LHD attains the stabilization of Toroidal and global Alfven eigenmodes (TAE / GAE) [2]. The same way, ctr-ECCD injection in Heliotron J leads to the stabilization of AEs [3].

NUMERICAL MODEL: FAR3D gyro-fluid code

Numerical model equations:

Thermal plasma

$$\frac{\partial \tilde{\psi}}{\partial t} = \sqrt{g} B \nabla_{\parallel} \Phi + \frac{\eta}{S} \tilde{J}^{\zeta}$$

$$\frac{\partial \tilde{U}}{\partial t} = -v_{eq}^{\zeta} \frac{\partial \tilde{U}}{\partial \zeta} + \sqrt{g} B \nabla_{\parallel} \tilde{J}^{\zeta} - \frac{1}{\rho}\left(\frac{\partial J_{eq}}{\partial \rho} \frac{\partial \tilde{\psi}}{\partial \theta} - \frac{\partial J_{eq}}{\partial \theta} \frac{\partial \tilde{\psi}}{\partial \rho} \right) - \frac{\beta_{tot}}{2\varepsilon^2} \sqrt{g} \left(\nabla \sqrt{g} \wedge \nabla \tilde{p} \right)^{\zeta} - \frac{\beta_f}{2\varepsilon^2} \sqrt{g} \left(\nabla \sqrt{g} \wedge \nabla \tilde{n}_f \right)^{\zeta}$$

$$\frac{\partial \tilde{p}}{\partial t} = -v_{eq}^{\zeta} \frac{\partial \tilde{p}}{\partial \zeta} + \frac{dp_{tot}}{d\rho} \frac{1}{\rho} \frac{\partial \tilde{\Phi}}{\partial \theta} - \Gamma p_{tot} \left(\nabla \sqrt{g} \wedge \nabla \tilde{\Phi} \right)^{\zeta} - \Gamma p_{tot} \nabla_{\parallel} \tilde{v}_{\parallel,th}$$

$$\frac{\partial \tilde{v}_{\parallel,th}}{\partial t} = -v_{eq}^{\zeta} \frac{\partial \tilde{v}_{\parallel,th}}{\partial \zeta} - \frac{\beta_{tot}}{2n_e} \nabla_{\parallel} p$$

Energetic particles

$$\frac{\partial \tilde{n}_f}{\partial t} = -v_{eq}^{\zeta} \frac{\partial \tilde{n}_f}{\partial t} - \frac{v_{th,f}^2}{\varepsilon^2 \Omega_{cy}} \Omega_d \left(\tilde{n}_f \right) - n_f \nabla_{\parallel} v_{\parallel f} - n_f \Omega_d \left(\tilde{\Phi} \right) + n_f \Omega_* \left(\tilde{\Phi} \right)$$

$$\frac{\partial \tilde{v}_{\parallel f}}{\partial t} = -v_{eq}^{\zeta} \frac{\partial \tilde{v}_{\parallel f}}{\partial \zeta} - \frac{v_{th,f}^2}{\varepsilon^2 \Omega_{cy}} \Omega_d \left(\tilde{v}_{\parallel f} \right) - 2a_0 \frac{v_{th,f}^2}{n_f} \nabla_{\parallel} n_{\parallel f} + v_{th,f}^2 \Omega_* (\tilde{\psi}) - \sqrt{2} a_1 v_{th,f} \left| \nabla_{\parallel} \tilde{v}_{\parallel f} \right|$$

The plasma velocity and perturbation of the magnetic field are defined as:

$$\vec{v} = \sqrt{g} R_0 \vec{\nabla} \zeta \wedge \vec{\nabla} \tilde{\Phi} \qquad \vec{B} = \sqrt{g} R_0 \vec{\nabla} \zeta \wedge \vec{\nabla} \tilde{\psi}$$

where: $\tilde{\Phi} \equiv$ stream function of the electrostatic potential
$\tilde{\psi} \equiv$ Poloidal flux

The model uses the next vorticity definition: $\vec{U} = \sqrt{g} \left[\vec{\nabla} \wedge \left(\rho_m \sqrt{g} \vec{v} \right) \right]^{\zeta} \vec{e}_{\zeta}$

The perturbation of the next thermal plasma variable are evolved in time:

a) Poloidal flux: $\tilde{\psi}$

b) Vorticity toroidal component: $\tilde{U}$

c) Pressure: $\tilde{p}$

d) Thermal plasma parallel velocity (acoustic modes coupling): $\tilde{v}_{\parallel,th}$

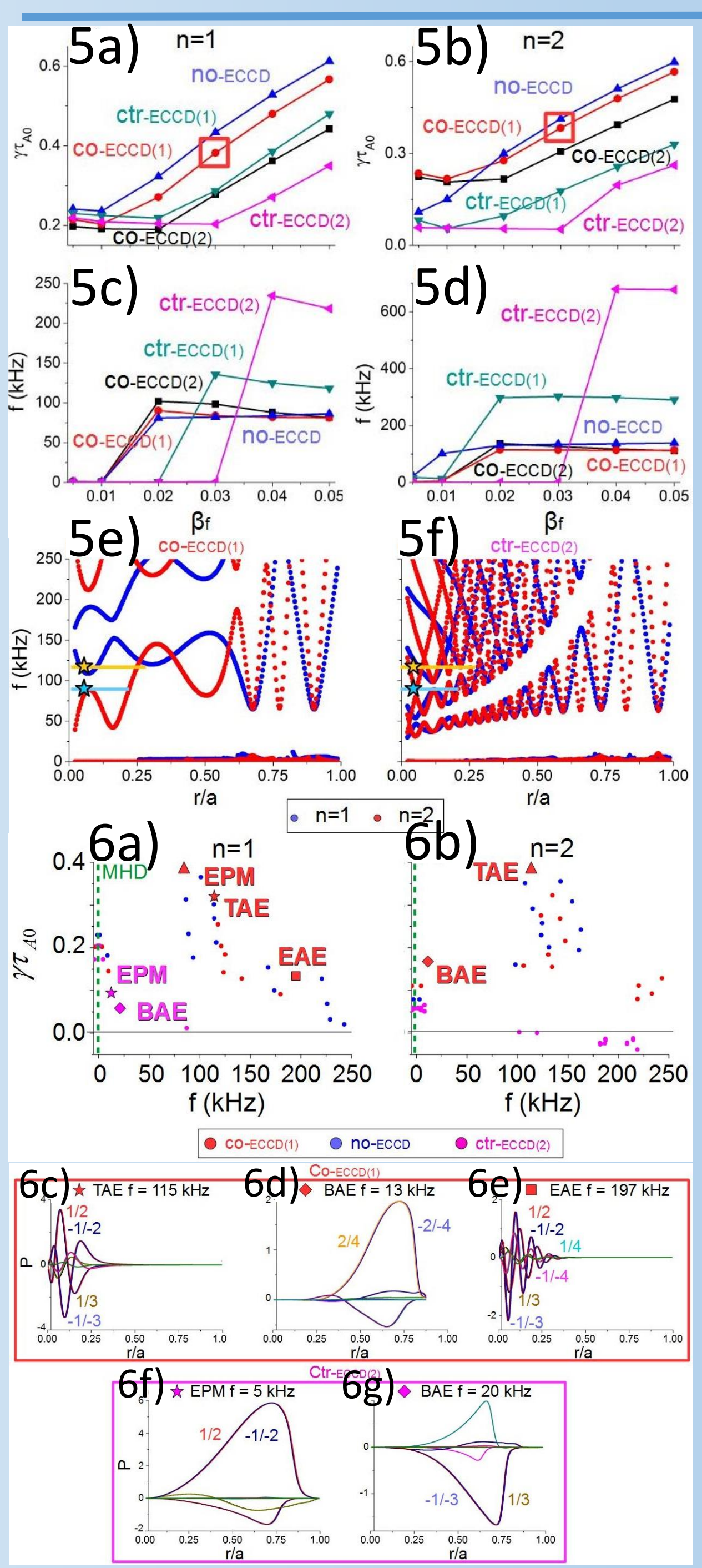
The perturbation of the next EP variable are evolved in time:

e) EP density: $\tilde{n}_f$

f) EP parallel velocity: $\tilde{v}_{\parallel,f}$

The numerical model uses an averaged Mawellian distribution for the EP fitted to the slowing-down distribution. The set of input equilibria is used in the simulations taking the fixed boundary results from the VMEC equilibrium code calculated for the LHD discharge 138675 and the Heliotron J discharge 61484 (reference cases).

EPM/TAE STABILIZATION IN LHD



-Continuum damping of the ctr-ECCD case is stronger compared to the co-ECCD case (5 e and f), in the inner-middle plasma region and in the frequency ranges of the 1/2 EPM and 2/3-2/4 TAE.

- EP β threshold of the EPM/TAE in the ctr-ECCD case is higher compared to the co-ECCD and no-ECCD cases, 0.04 versus 0.02 (5 a to d).

- The EPM/TAE growth rate is lower in the ctr-ECCD cases with respect the co- and no-ECCD cases.

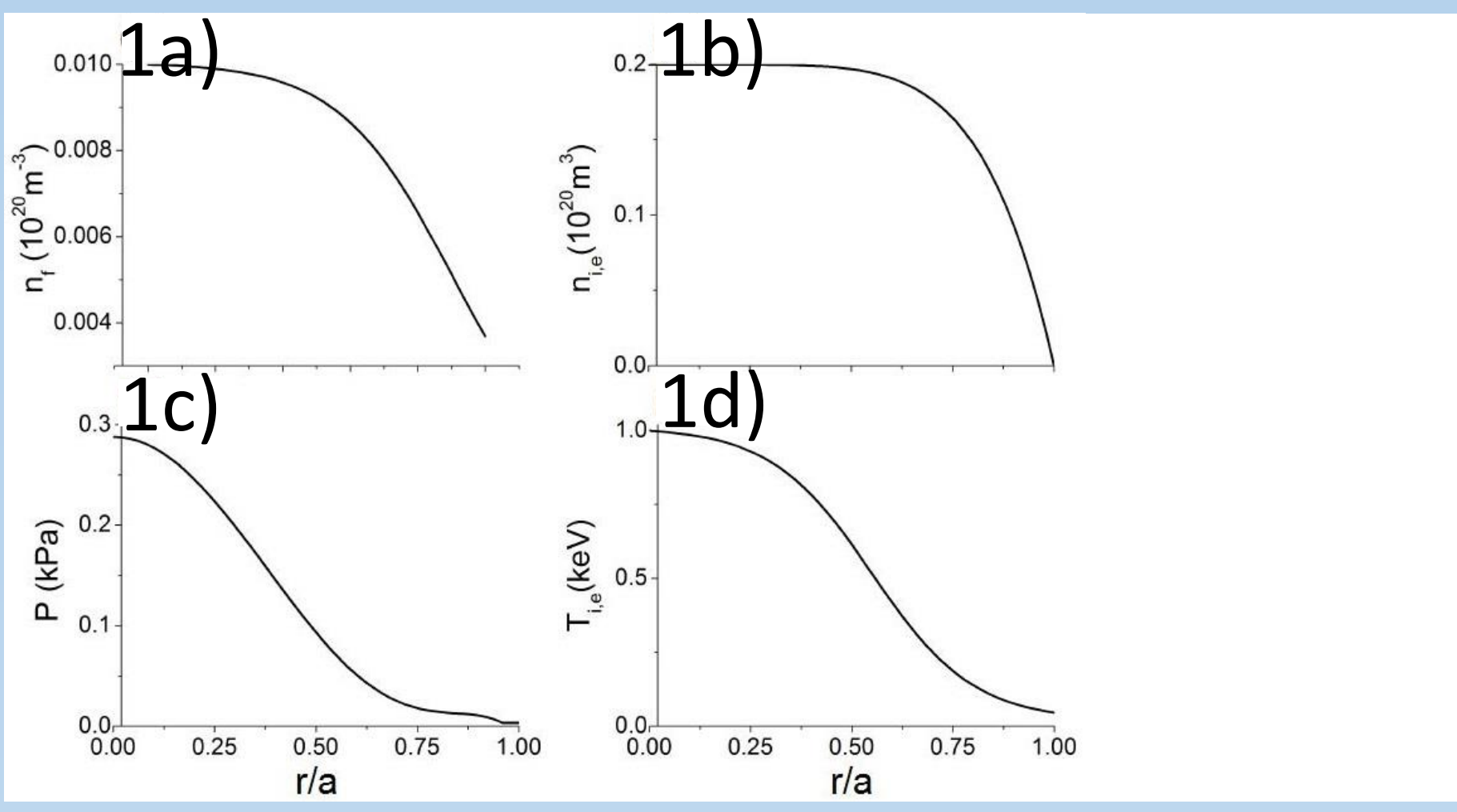
-Sub-dominant modes calculated for the co-ECCD(1), no-ECCD and ctr-ECCD(2) cases if EP β = 0.03 (6 a and b).

-Sub-dominant modes in the co-ECCD and no-ECCD cases: 2/4 BAE with f=13 kHz (6d), 1/2-1/3 TAE with f = 115 kHz (6c) and a 1/2/-1/4 EAE with f = 197 kHz (6e). Similar instabilities observed in the experiment (4a)

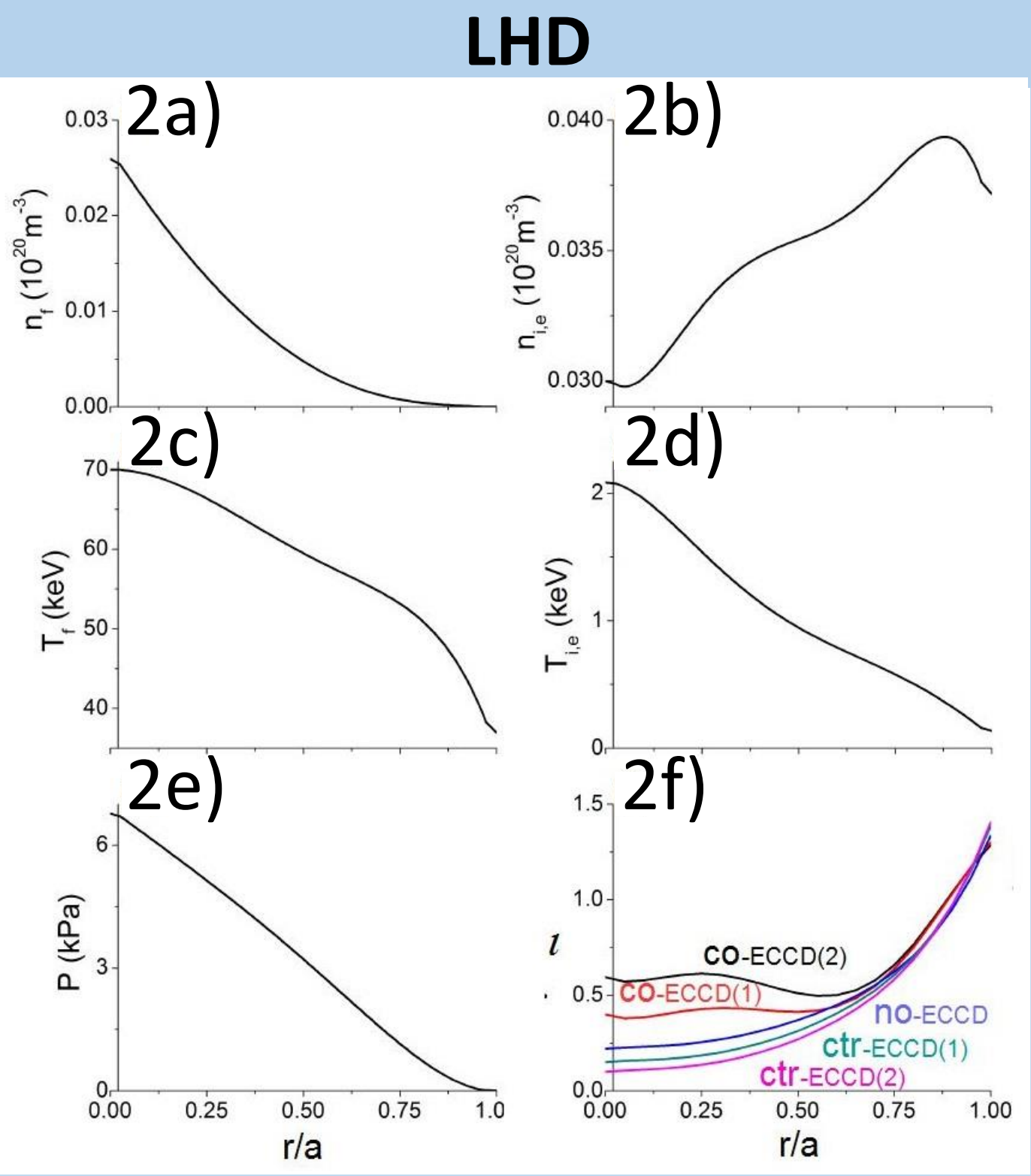
-Ctr-ECCD case: 1/2 EPM with f=5 kHz (6f) and 1/3 BAE with f=20 kHz (6g), consistent with the experiment (no data shown).

MAIN MODEL PROFILES

Heliotron J



LHD

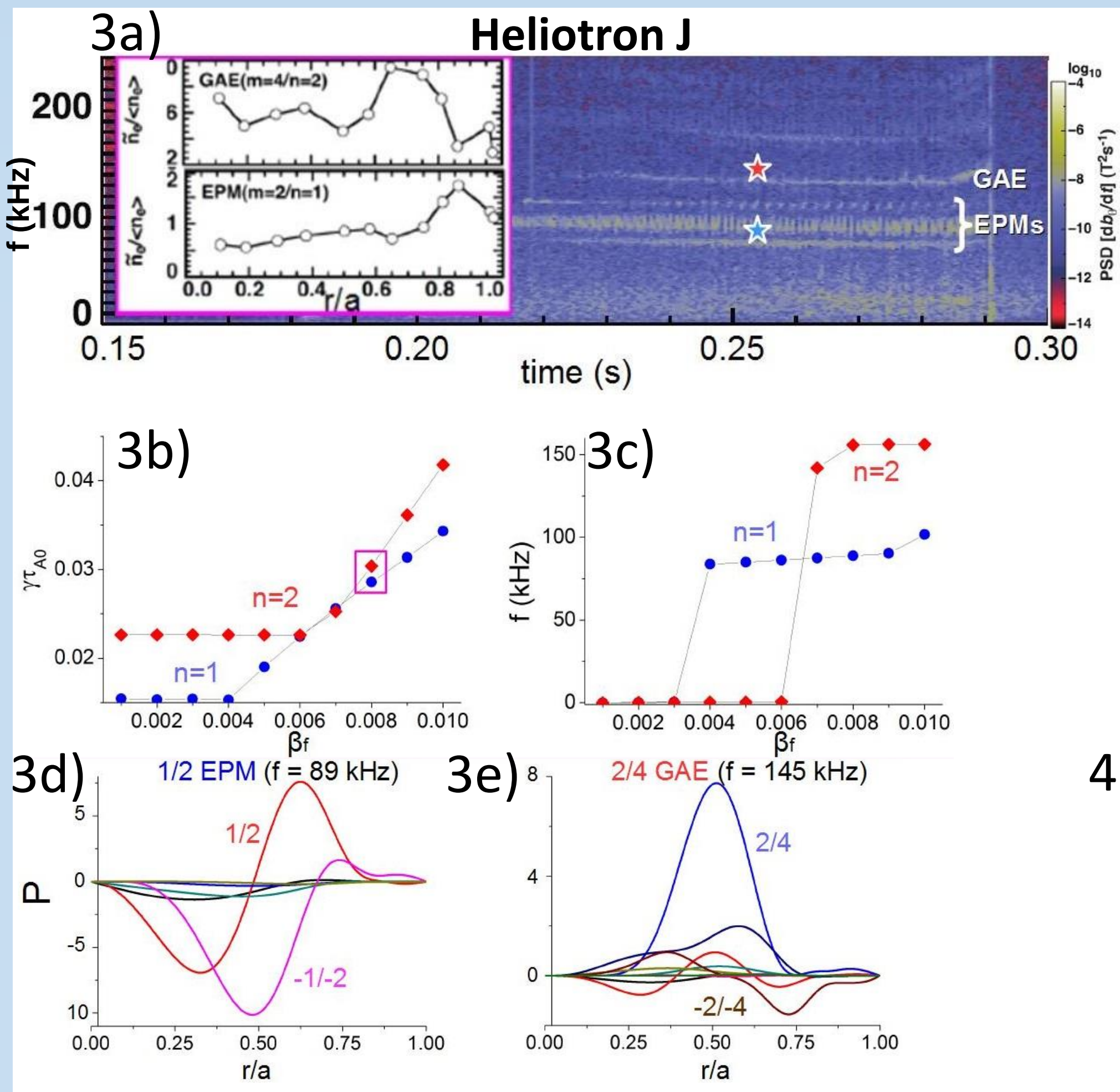


EP energy in the Heliotron J simulations no radial dependency is assumed, fixed to 25 keV.

Mode selection:

n	m (Heliotron J)	m (LHD)
0	[0,14]	[0,10]
1	[1,3]	[1,5]
2	[2,6]	[2,10]

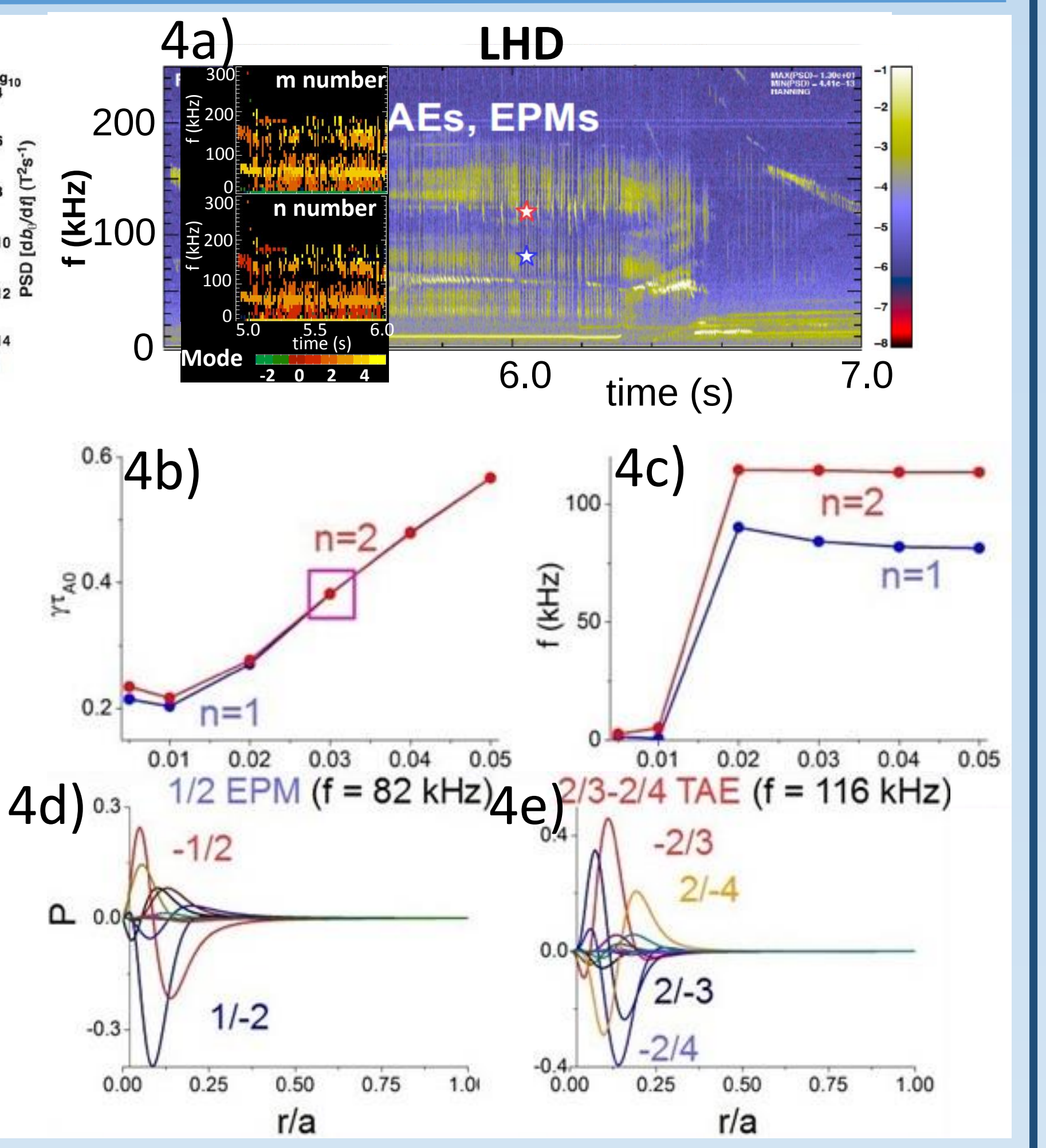
MODE IDENTIFICATION: REASONABLE AGREEMENT



-EP β threshold of the n=1 EPM is 0.004 and 0.007 for the n=2 GAE (3b and c).

-The frequency of the simulated n=1 EPM is 89 kHz and the n=2 GAE is 145 kHz, similar to the experiment (3a).

-1/2 EPM and 2/4 GAE mode structure similar to the experiment (3d and e).

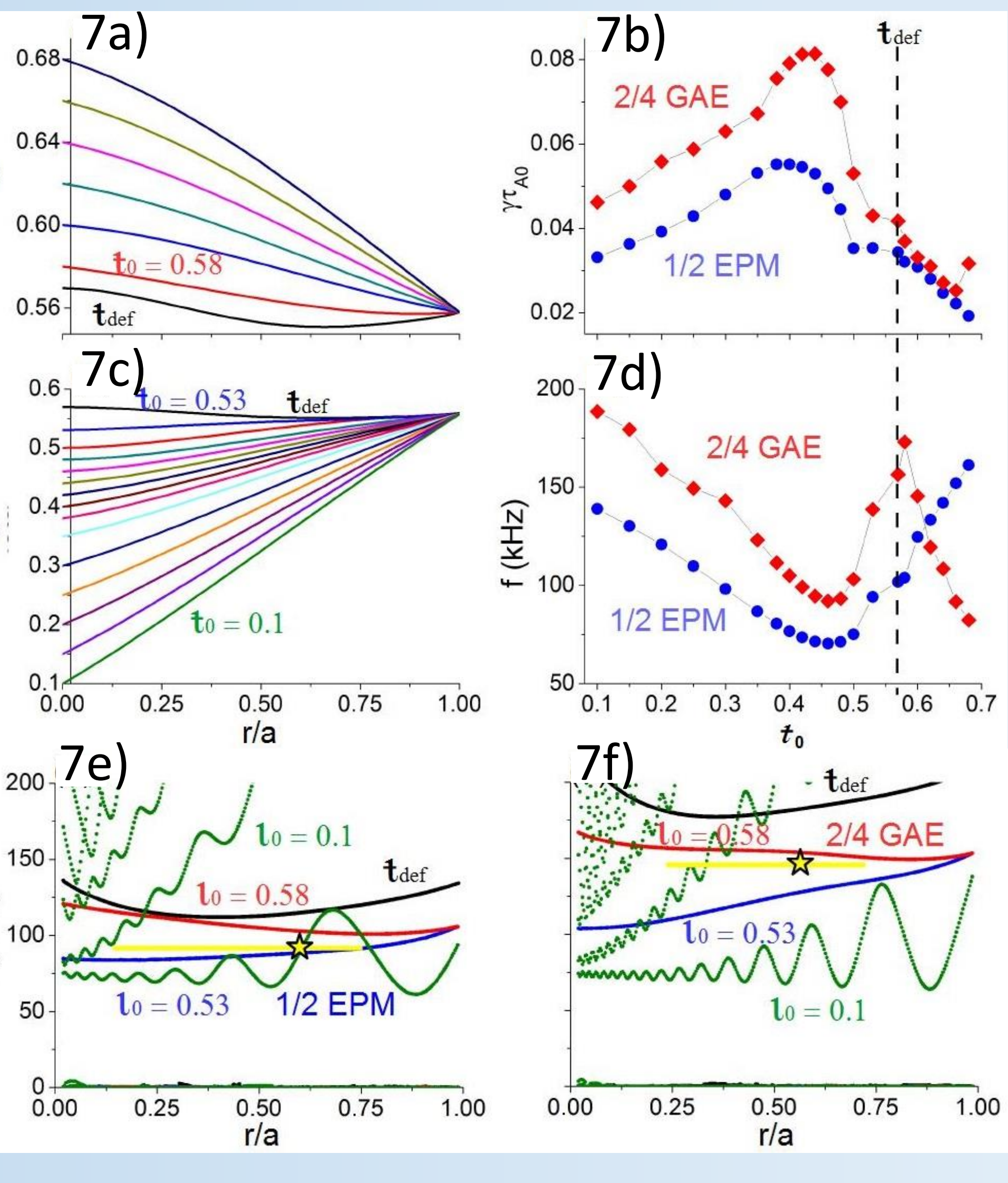


-EP β threshold of the EPM/TAE is 0.02 (4b and c).

-The frequency of the simulated n=1 EPM is 82 kHz and the n=2 TAE is 116 kHz, similar to the experiment (4a).

-1/2 EPM and 2/3-2/4 TAE mode number is consistent with the experiment (4d to e).

EPM/GAE STABILIZATION IN HELIOTRON J



-The ι profile is deformed by the ECCD injection. The EPM/GAE growth rate and freq. change (7a to d).

-A Co-ECCD increases ι0 and a ctr-ECCD decreases ι0 (7a and b).

-Co- and ctr-ECCD increase the magnetic shear in the inner -outer plasma.

-A ctr-ECCD with ι0 = [0.4 , 0.56] further destabilize the EPM/GAE, because the 1/2 rational surface enters in the plasma. If ι0 < 0.4, the 1/2 is located at the plasma periphery where the magnetic shear is stronger, so the EPM/GAE growth rate decreases.

-The continuum damping is enhanced as the ι0 decreases (7 e and f).

CONCLUSIONS

- A set of linear simulations are performed by the FAR3d code studying the effect of the ECCD injection on the Heliotron J and LHD plasma stability. The simulation results are compared with the experimental data showing a reasonable agreement.
- The simulations for Heliotron J show an improvement of the EPM/AE stability if the magnetic shear is enhanced as ι0 increases (co-ECCD injection), although only below a given threshold if ι0 decreases (ctr-ECCD injection). The ι0 threshold is linked to the destabilizing effect of the 1/2 rational surface, entering in the plasma and overcoming the stabilizing effect of the magnetic shear.
- A further decrease of the ι0 leads to a 1/2 rational surface located at the plasma periphery where the magnetic shear is strong enough to stabilize the EPM/AE. In addition, the application of ECCD also leads to an enhancement of the continuum damping.
- The simulations of LHD discharges with ECCD indicate the further destabilization of EPM/AEs in the cases with co-ECCD injection and stabilization in the cases with ctr-ECCD. The EPM and TAE observed in the experiment are destabilized in the inner plasma region where the continuum damping is enhanced as the ι0 decreases due to the ctr-ECCD.

Acknowledgments

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