Integrated modelling of sawtooth cycles and fishbones in tokamak plasmas

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ABSTRACT

MHD instabilities play a significant role in tokamak confinement

1. Sawtooth cycles can decrease core performance and seed neoclassical tearing modes (NTMs) that can lead to disruptions
2. Fishbone bursts, often observed between sawtooth crashes, redistribute fast ions and drive a radial electric field which can affect turbulence

Goal: develop and implement reduced models of both effects in ASTRA8[1] transport modeling framework

SAWTOOTH MODEL

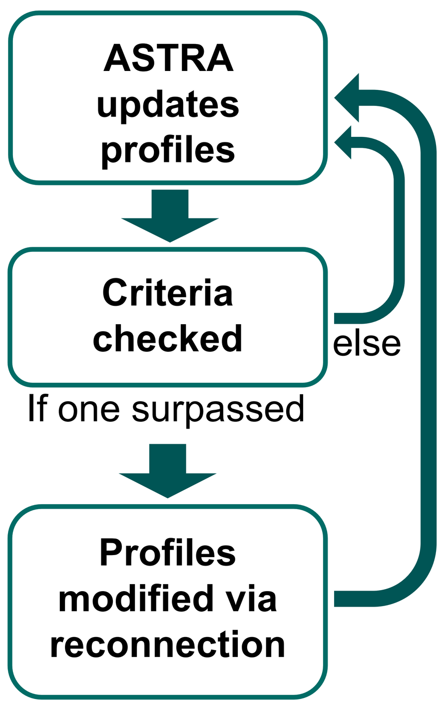
ONSET: PORCELLI CRITERIA[2]

Three possibilities to trigger a sawtooth crash:

1. **Ideal kink unstable**, no free parameter
2. **Destabilization from fast ions,** 1 free parameter
3. **Resistive kink unstable,** 2 free parameters

→ **three analytical formulae for stability of internal kink**

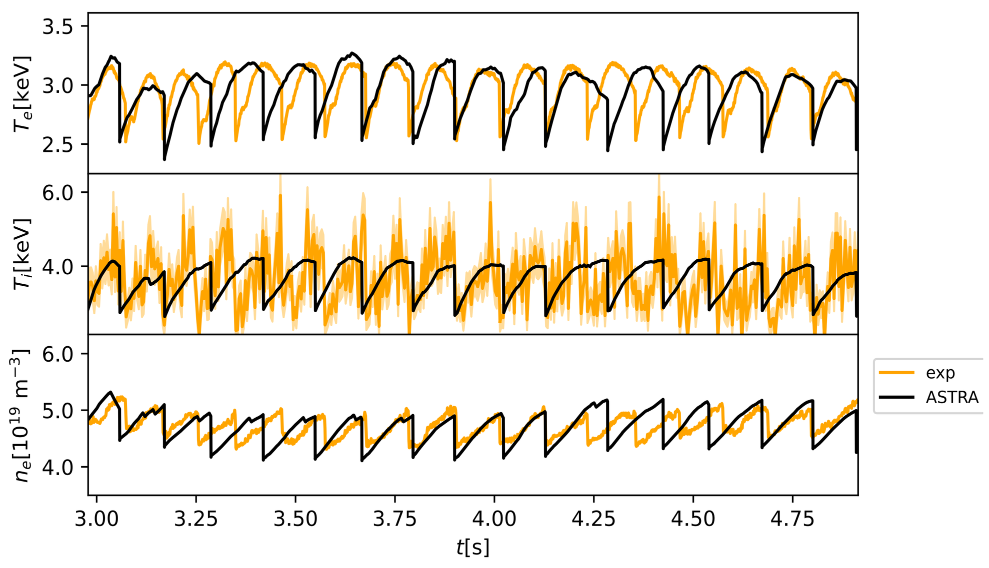
→ when one violated → sawtooth crash



#34664, NBI-only, resistive kink

$\tau_{exp} = 0.11 \pm 0.01$ s

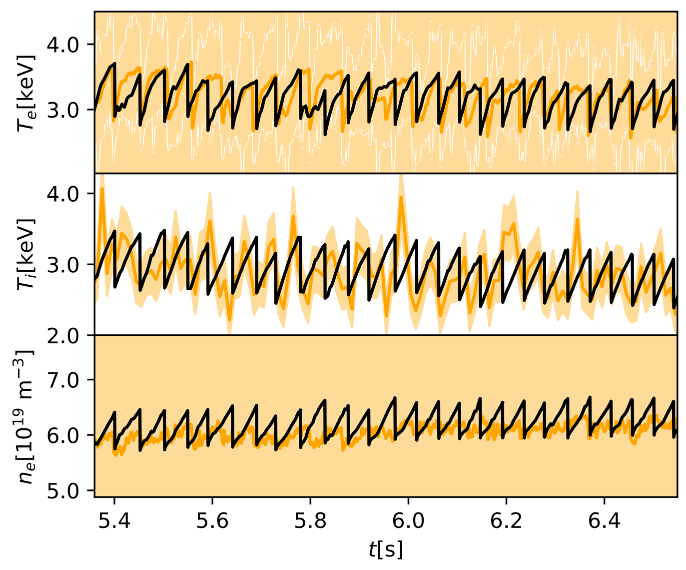
$\tau_{sim} = 0.12 \pm 0.01$ s



#34658, NBI+ECRH, ideal kink

$\tau_{exp} = 0.053 \pm 0.003$ s

$\tau_{sim} = 0.06 \pm 0.01$ s



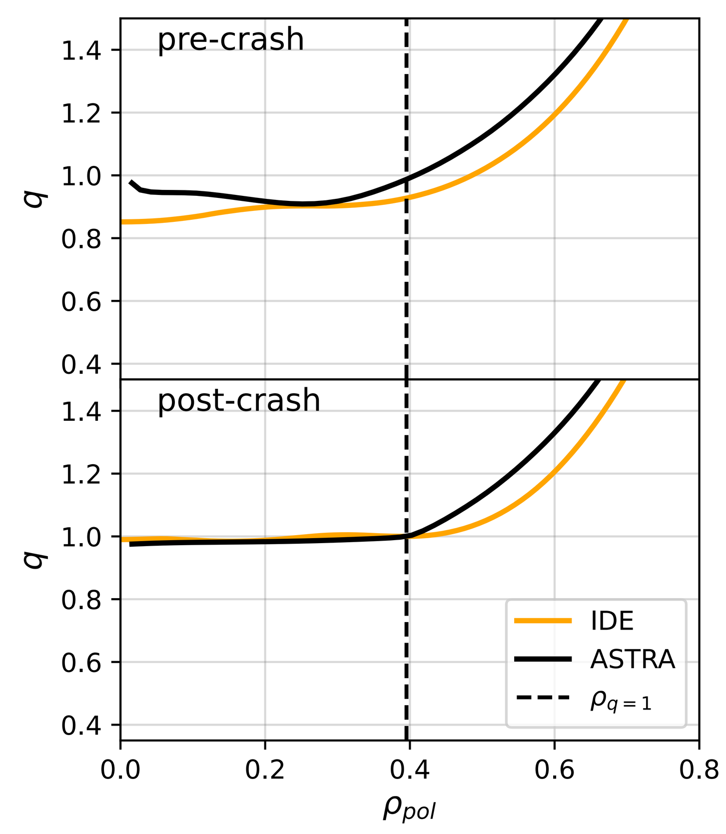
RECONNECTION: FLAT CURRENT MODEL[3]

Partial reconnection model based on:

1. Reconnection due to magnetic turbulence
2. Position of $q = 1$ surface r_1 preserved
3. Helicity $K = \int_0^{q=1} \mathbf{A}\times\mathbf{B}\, dV$ conserved

Results:

- Current density j uniform up to r_1
- $q < 1$ → partial reconnection
- No current sheet and no free parameter

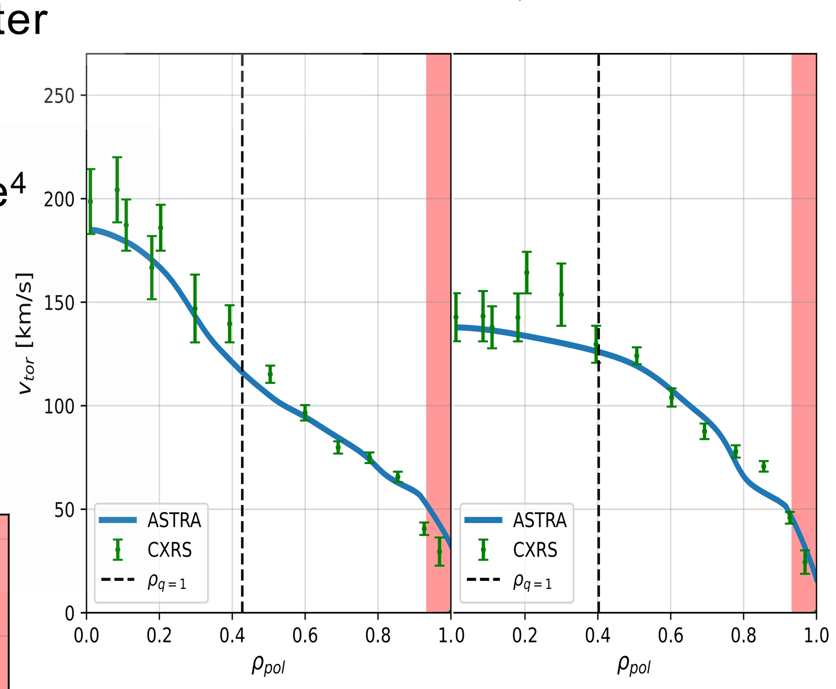


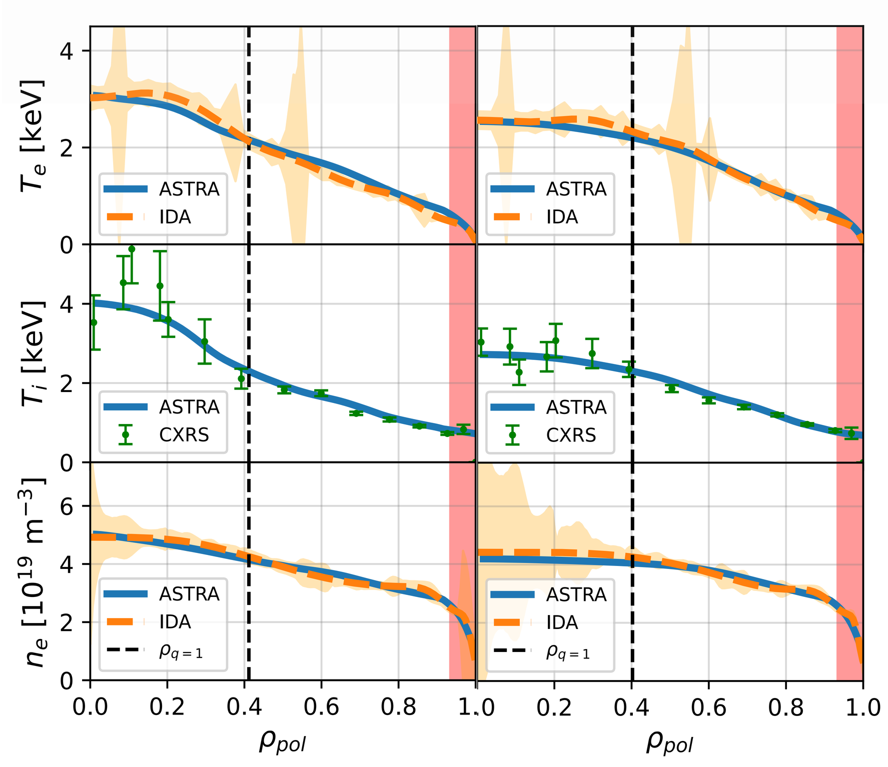
CRASH OF KINETIC PROFILES

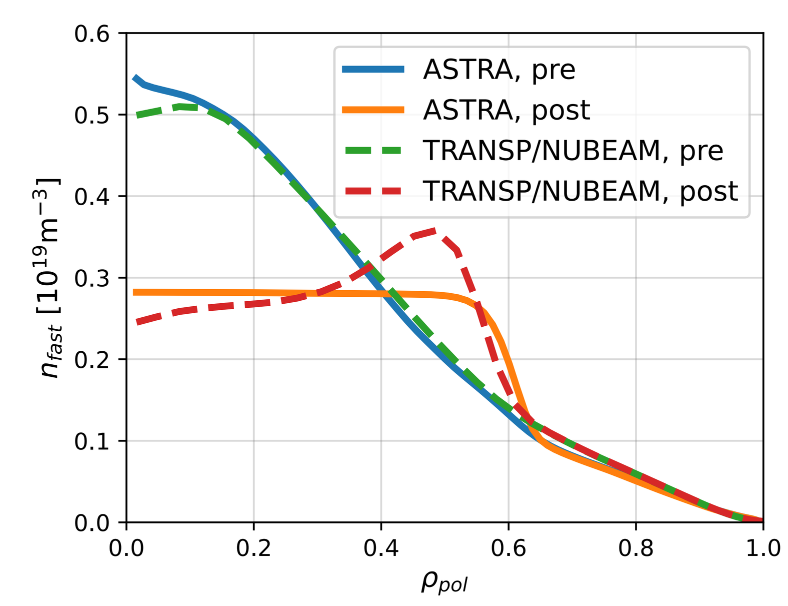
Anomalous transport up to $q = 1$ surface[4]

$$\chi_{i,e}, D_{e,fast} \sim \frac{r_1^2}{\tau_{crash}}$$

+ extended to fast particles and rotation







RECOVERY PHASE:

Turbulent transport: TGLF-SAT2[5], neoclassical transport: NCLASS[6]

CONCLUSION & OUTLOOK

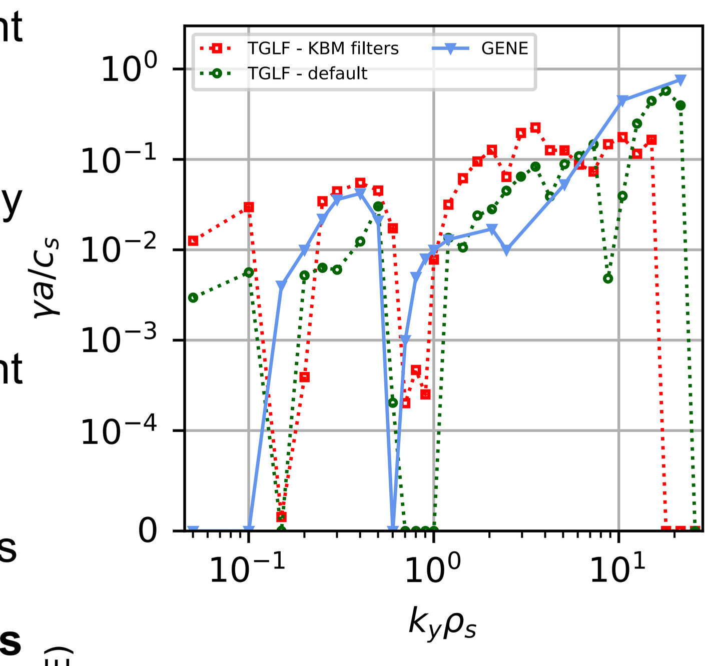
1. **Developed integrated model for sawtooth cycles and fishbones and implemented in ASTRA, including effects on fast ions and rotation**
2. **Validated on AUG discharges**
3. **Excellent agreement with experimental data for both sawtooth and fishbone**
4. **Good interaction between sawtooth model and TGLF-SAT2 with default settings**
   But results with KBM settings hint at missing turbulent stabilization mechanism

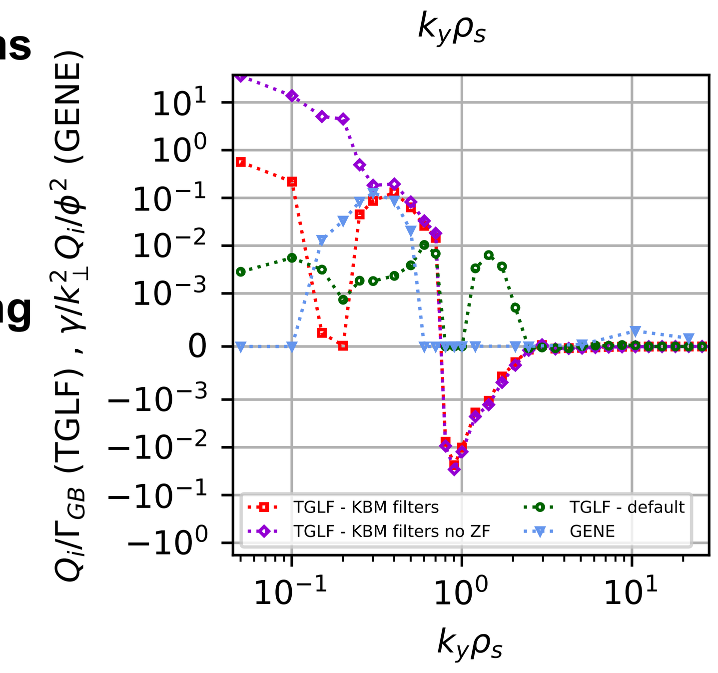
Next: validate on further machines and predict performance of future machines

VALIDATION OF TGLF-SAT2 AT $q = 1$ SURFACE

- TGLF-SAT2 with default settings yields excellent agreement with experiments
- But TGLF predicts much more transport with newly developed settings[7] to better capture KBMs
- Comparison with GENE[8] linear shows good agreement between TGLF-KBM and GENE for $k_y\rho_s > 0.1$
- Default TGLF predicts modes with much lower growth rates
- **Main hypothesis: turbulence stabilization mechanisms missing → compensated by low γ of default TGLF**
- **Possible candidates:**

1. **Fast ion dilution on zonal flow from self-interacting turbulent modes[9] at $q = 1$**
2. **MHD activity between sawtooth crashes**
   - **Can drive additional E_r (TAEs, fishbones)**
   - **Can break axisymmetry → 3D helical structures**





FISHBONE MODEL

- Onset criterion on $\langle \partial\beta_{fast}/\partial r\rangle$: Miyamoto model[10]

$$\left(-\langle \partial\beta_{fast}/\partial r\rangle - \frac{3}{4R}\langle\beta_{fast}\rangle\right) r_1 \geq \frac{r_1}{R}\left(\frac{\omega^m_{prec}}{\omega_A}\frac{1}{\pi^2}\frac{K_b^2}{K_2^2}\right)$$

$\omega_{prec} \propto \frac{E_{fast}}{BRr_1}$, $\omega_A \propto (\tau_A s)^{-1}$, K_b, K_2 bounce integrals

- Fast-ion redistribution: radial flow $J(r)$ drives poloidal flow v_θ

$$a\frac{\partial v_\theta}{\partial t} = -\nu v_\theta + fJ(r) \rightarrow v_\theta \sim v_0 e^{-\nu(t-t_0)} \quad (1)$$

- From Liu's model[11] estimate $v_0 \propto D$ fast ion deposition rate
- Model $J(r)$ as $J(r) = J_0\frac{r}{r_1}\Theta(r-r_1)$ soft-step function
- Invert Eq. (1) to estimate J_0

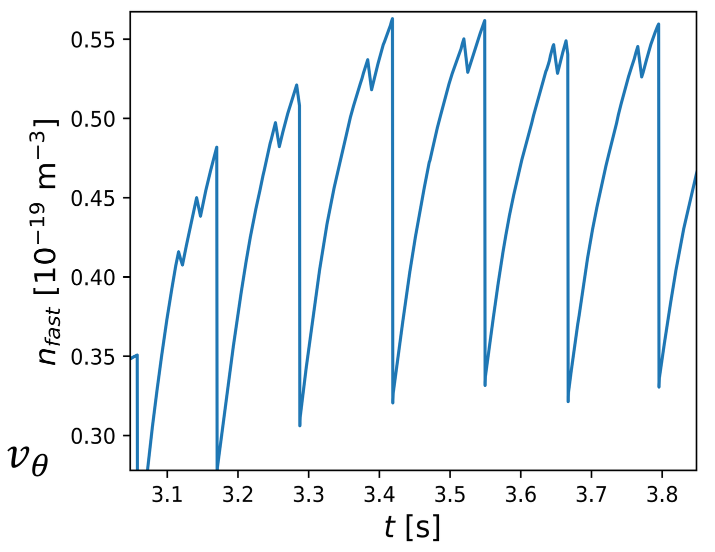
→ **In ASTRA:**

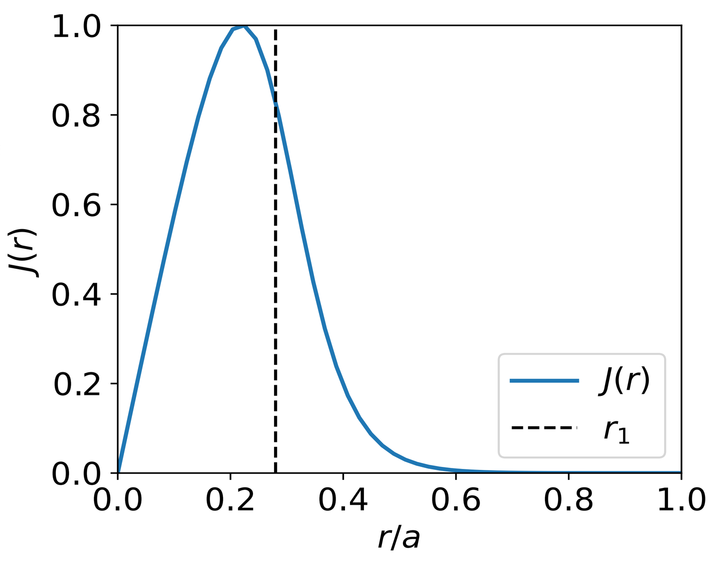
1. **redistribute fast ions with $J(r)$**
2. **add $E_r \sim v_\theta B_\phi$**
3. **Fishbones observed to redistribute also electrons**
   → $J(r)$ added also to electron transport

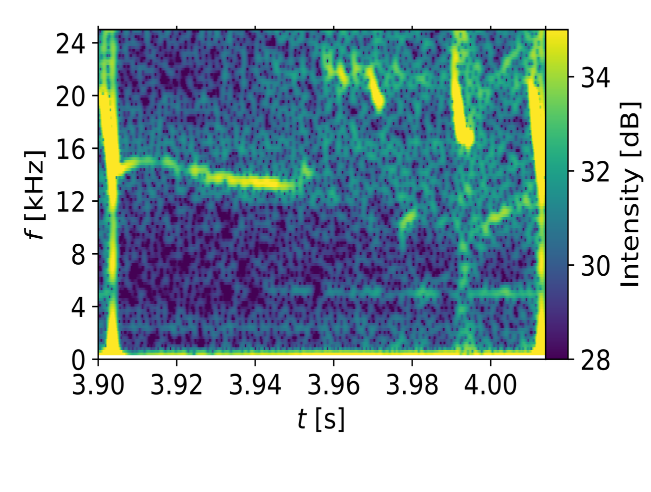
- **Model prediction: fishbones redistribute ~3% of fast ions**

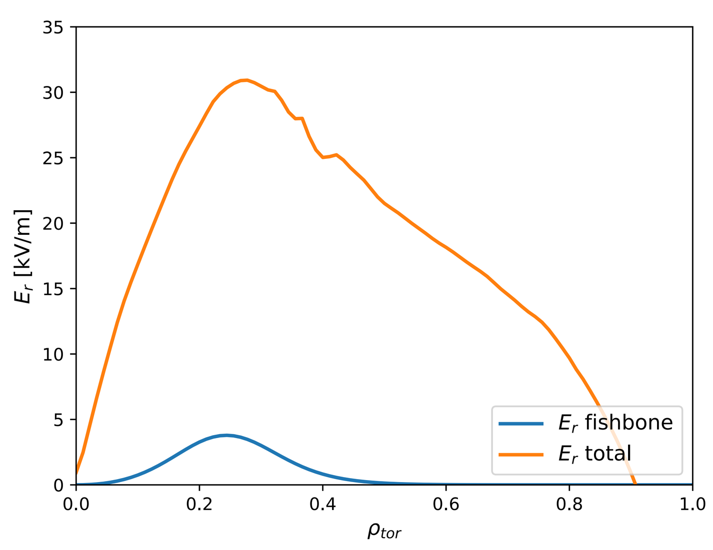
→ consistent with JET and DIII-D experimental results[12,13]

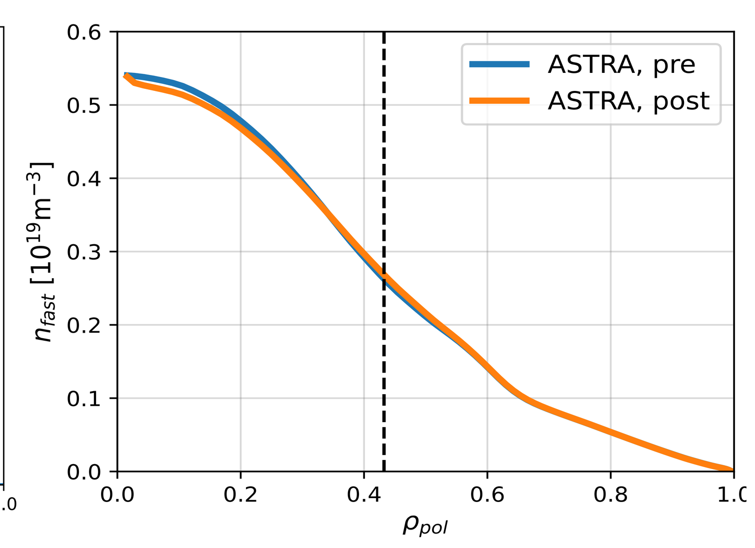
- **Predicted ω_{prec}~7 kHz → ~22 kHz in plasma frame**
- **v_θ model prediction: small contribution to total v_θ and E_r**

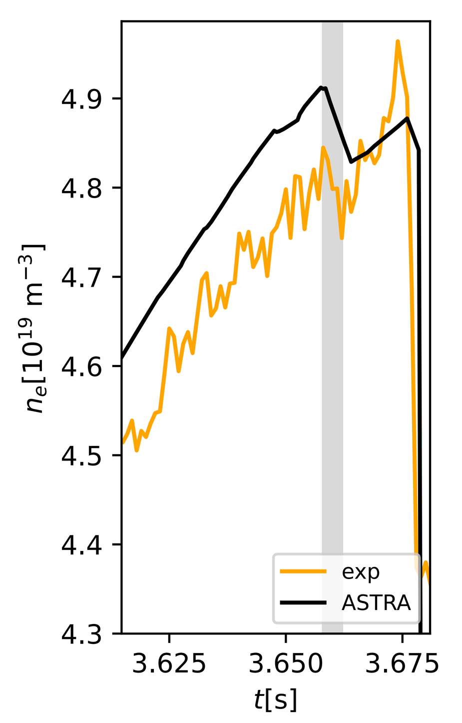












(1) G. Tardini et. al., 2026 (2) F. Porcelli, D. Boucher and M. N. Rosenbluth, 1996. (3) R. Fischer et al 2019 (4) T.C. Hender et. al. 2007 (5) Staebler G., Belli E.A., Candy J., Kinsey J.E., Dudding H. and Patel B. 2021 (6) Houlberg W.A., Shaing K.C., Hirshman S.P. and Zarnstorff M.C. 1997 (7) Najlaoui A. et al 2025 Plasma Phys. Control. Fusion (8) Görler T. et al 2011 Journal of Computational Physics 230 7053–7071 (9) Brioschi D. et al 2026 Nucl. Fusion (10) Miyamoto K. 2016 (11) Liu Z. et al 2023 (12) C. Perez von Thun et al 2012 Nucl. Fusion (13) G. Brochard et al 2025 Nucl. Fusion

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