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Study of TAE Effects on the Global **Confinement in TCV L-mode Plasmas**

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This work is under review in *Frontiers in Physics* for the Special Issue Impact of highly energetic ions on magnetically confined plasmas

[kJ]

 W_{MHD}

Motivations & Background

• TAEs expected to be destabilized in ITER [Pinches2016] \rightarrow What the effect on plasma confinement?

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C22

- Stabilization of Ion-Temperature-Gradient (ITG) turbulent transport due to Fast-Ion-triggered complex mechanism involving TAEs and enhanced zonal flows [Citrin2013, Garcia2015, DiSiena2019, Garcia2022, Citrin2023]
- Extended the beneficial mechanism to unstable Toroidal Alfven Eigenmodes (TAEs) in JET L-mode plasmas with MeV-range fast ions [Mazzi2022]

TAE Impact on Global Plasma Confinement

#76179

#76180

#7636.

- Various plasma parameters cross-analyzed during TAE phase (vertical dashed lines):
 - Increase of plasma energy content (W_{MHD}) up to the saturation (correlated with plasma elongation control failure)

Open question: Is this complex and beneficial mechanism *universal* (devices / turbulent regimes)?

■ Observed TAEs destabilized in TCV L-mode plasma [Vallar2023] dominated by Trapped Electron Mode instability → Suitable test-bed case!

Observation of Fast-Ion-Driven Instabilities in TCV





- Busy magnetic spectrogram: various high-frequency instabilities observed in counter-current NBI-heated TCV scenario
 - Possible nonlinear three-wave coupling occurring:
 - \succ $f_a + f_b = f_c$ > $2f_b = f_d$ → Zonal flow coupling?
 - Global gyrokinetic (ORB5 [Lanti2020]) studies ongoing

TCV #76361



- \succ Despite P_{NBI} increase, total energy confinement time τ_{tot} is stable
- > H89 P factor is increased during TAE phase and then saturates/decreases
- \succ Plasma density n_e increases due to unavoidable NBI fueling
- \succ Central ion temperature $T_{i,0}$ increases
- The ion temperature gradient R/L_{T_i} is enhanced in the radial region of TAEs



The global plasma confinement is improved in conditions of unstable TAEs \rightarrow Similar to what observed in the past

[DiSiena2019, Mazzi2022]

- Other fast-ion-driven instabilities observed:
 - > n = -1 @ ~15 kHz $> n = 0 \& m = 1 @ \sim 50 \text{ kHz}$ (EGAM? [Geiger2020]) $> n = 2 \text{ EAE } @ \sim 180 \text{ kHz}$
 - > Other modes triggered by nonlinear coupling
- Unveiling P_{NBI} (or E_{FI}) thresholds \rightarrow Different NBI power waveforms been adopted
- Step-like waveform (TCV #76361): defining quasi-steady phases for characterizing TAE impact on plasma properties & confinement



TCV #76180

Reflectometer Study of Fast-Ion-Driven Instabilities



- Short-Pulse Reflectometer [Molina2019] allows mode localization:
 - > TAE @ $\rho_{\psi} \approx [0.55 0.65]$
- Difficulties due to continuous density increase \rightarrow Cut-off position moving

Local Gyrokinetic Studies

• Realistic local (flux-tube) gyrokinetic modelling: GENE [Jenko2000] of TCV #73461 @ $\rho_{\psi} = 0.65$ (TAE radial region)

W/O Fast lons



- lon-scale region dominated by Trapped Electron Modes (TEMs)
- Ubiquitous modes unstable [Coppi1990] for $k_{v}\rho_{s} \sim 5-10$
- Electron Temperature Gradient (ETG) unstable in the electron-scale
- Nonlinear simulations \rightarrow Retaining only ion-scale region ($k_{\nu}\rho_s < 1.45$) and without carbon impurities
 - \succ Carbon stabilizes TEMs \rightarrow Overestimation of fluxes without impurities [Merlo2015]
- Effects of Zonal Flows on ion-scale TEM-driven turbulence \rightarrow When turned off, large increase (\times 3.5) of heat & particle fluxes
 - > In this parameter range $(T_e/T_i > 1)$ great effect of ZFs on TEMs [Lang2008]
 - \succ If JET fast-ion beneficial effects holds \rightarrow Possible reduction of turbulence and improvement of

confinement



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- Preliminary analyses on electron density fluctuations $\tilde{n}_e \rightarrow \ln$ the presence of TAE, \tilde{n}_e amplitude does not increase
- To be confirmed by more in-depth studies and gyrokinetic modelling:
 - \blacktriangleright Using method in [Krutkin2023] \rightarrow Need for accurate electron density gradient values
 - > ORB5 gyrokinetic global modelling addressing interplay between TAEs and micro-turbulence

	[Citrin 2012] : Citrin at al. Dhua Day Latt 111 (2012)	[lonko2000]: E. lonko of al. Phys. Plasmas 7 (2000)	[I]	$\phi(x)$	$,y)$ \blacksquare	2000 -1000	0 1	1000 200	$[T_e]$	$ ho_s/e]$	 Nonlinear flux-tube simulations with fast-ion modes unstable: 		
	[Citrin2013] : J. Citrin et al., Phys. Rev. Lett. 111 (2013) [Citrin2023] : J. Citrin et al., Plasma Phys. Control. Fusion 65 (2023) [Conpi1990] : B. Conpi et al., Phys. Fluid, B 2 (1990)	[Krutkin2023] : O. Krutkin <i>et al.</i> , <i>Nucl. Fusion</i> (2023) [Lang2008] : J. Lang <i>et al.</i> , <i>Phys. Plasmas</i> 15 (2008) [Lanti2020] : F. Lanti <i>et al.</i> , <i>Comp. Phys. Comm.</i> 251 (2020)	rection <i>y</i>								Passing-through (streamer-like) structures appear even with box radial domain > TCV size		
References	ViSiena2019] : A. Di Siena <i>et al.</i> , <i>Nucl Fusion</i> 59 (2019) Sarcia2015] : J. Garcia <i>et al.</i> , <i>Nucl. Fusion</i> 55 (2015) Sarcia2022] : J. Garcia <i>et al.</i> , <i>Plasma Phys. Control Fusion</i> 64	[Mazzi2022] : S. Mazzi et al., Nat. Phys. 18 (2022) [Merlo2015] : G. Merlo et al., Plasma Phys. Control. Fusion 57 (2015) [Molina2019] : P. Molina et al. Rev. Sci. Instr. 90 (2019)	0 Di 1.0-	0.3	0.2	0.1	0	0.1	0.2	0.3	 Need for global gyrokinetic modelling → 		
	[Geiger2020] : B. Geiger <i>et al.</i> , <i>Plasma Phys. Control. Fusion</i> 62 (2020)	[Pinches2016] : S. Pinches <i>et al.</i> , <i>Phys. Plasmas</i> 22 (2016) [Vallar2023] : M. Vallar <i>et al.</i> , <i>Nucl. Fusion</i> 63 (2023)	Bi	-0.5	Radial	Radial D	irectio	n x [m]	0.2	0.3	ORB5 simulations ongoing		

The simulations were performed on CSCS Piz Daint HPC system, in the framework of the projects s1097, s1100 and s1180.

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600 800 1000 1200 1400 400 Time $t [a/c_s]$

With NBI Fast lons

In linear spectra, fast-ion-driven modes unstable for n = [1,2,3], but frequency @ ~150-200 kHz