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Simulation of RF Current Condensation on ASDEX Upgrade

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Abstract

Large, locked islands precede 95% of the disruptions occurring in JET with an ITER-like wall [1]. Electron cyclotron current drive can stabilize large islands and is planned for stabilization of tearing modes on ITER. The theory of current condensation [2] predicts a nonlinear amplification of power deposition due to the temperature sensitivity of ECCD, which improves stabilization efficiency by self-focusing power deposition at island O-points. Alternatively, premature nonlinear damping can occur at the island periphery, "shadowing" island center and reducing stabilization efficiency. The effect can be significant when large ECCD (~20MW for ITER) power is available. We present a numerical code OCCAMI (Of Current Condensation Amid Magnetic Islands) [3] and preliminary simulation results for possible experiments on ASDEX Upgrade (AUG) verifying the theory of current condensation.

Introduction

The change in local EC power deposition produced by temperature perturbation, $\tilde{T}$, is

$$P_{rf} \propto \exp(-w^2) = \exp\left(-\mathrm{w}_{eff}^2\right) \exp\left(\frac{w_{eff}^2 \tilde{T}}{T}\right)$$

Where w_{eff} determines the temperature sensitivity of the power deposition. For ECCD, deposition can be sensitive to small $\frac{\tilde{\mathrm{T}}}{\mathrm{T}}$. This produces a nonlinear feedback (current condensation) that can improve island stabilization efficiency by self-focusing power deposition to island o-points. For X2 mode, the sensitivity is approximately

$$-w_{eff}^2 = \mu\left(1 - \frac{2\Omega/\omega}{1 - N_{||}^2}\right) + \frac{\xi_2 I_{3/2}(\xi_2)}{I_{5/2}(\xi_2)} - \frac{5}{2}$$

where

$$\xi_2 = \frac{N_{||} R_2 \mu}{1 - N_{||}^2}, \quad R_2 = \sqrt{\left(\frac{2\Omega}{\omega}\right)^2 - 1 + N_{||}^2}$$

and $I_\nu(\xi)$ is the ν-th modified Bessel function of the first kind.

The effectiveness of current condensation in island stabilization is sensitive to various geometric effects. w_{eff}^2 is dependent on $N_{||}$ magnetic field and ray trajectory. Relativistic resonance condition $\frac{n\Omega}{\omega} \geq \sqrt{1 - N_{||}^2}$ prohibits damping in a LFS region, bounded by “pinch points” where the equality holds.

Methods

Candidate scenarios are chosen for AUG, a medium-sized D-shaped tokamak. 8 outboard EC wave launchers provide ~0.7MW each at 140GHz in X2 mode. [5] EC beams are directed by fast steerable mirrors, and each has range of motion covering the full poloidal plane and ±25° in the toroidal plane. [6]

We selected 2 candidate scenarios with q=2/1 and 3/2 rotating NTM. (Fig. 1a, b) EFIT Equilibrium and island T_e, density profiles are taken from 5.4s and 3.4s in shot 35350. Rotating islands are treated as annuli to reduce run time. In more realistic calculations, P_{dep} will be averaged over multiple runs with different island phases.

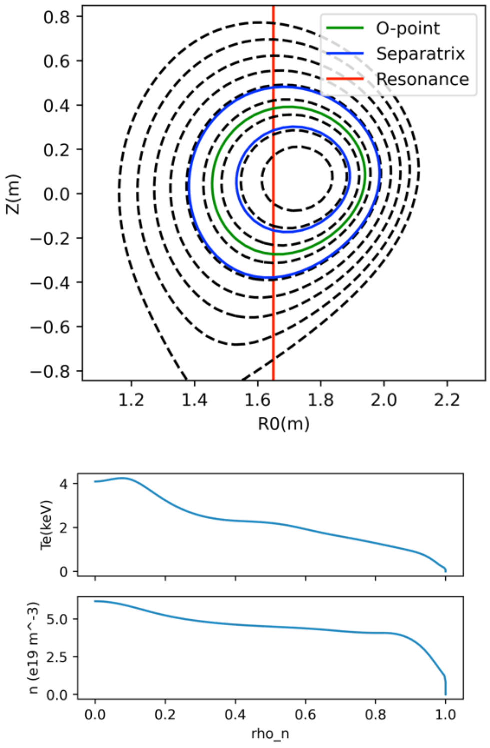

Fig. 1a: equilibrium and profile at t=5.4s, q=2/1

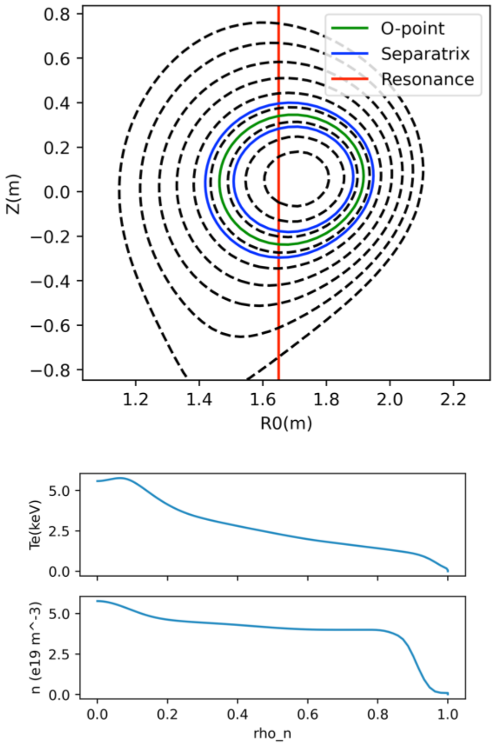

Fig. 1b: equilibrium and profile at t=3.4s, q=3/2

Our numerical code OCCAMI (Of Current Condensation Amid Magnetic Islands) iterates between Genray, a geometric ray-tracer [4], for propagation and power deposition, and a heat diffusion equation solver for island temperature profile. Island thermal conductivity (κ) is assumed constant. Heat diffusion equation is:

$$\frac{\partial u}{\partial \sigma} = -\frac{P_{dep}}{n\chi_{\perp}T_s}\frac{\sigma}{E(\sigma)-(1-\sigma^2)K(\sigma)}\frac{WM}{32\pi r_r R_0}$$

where $u = (T - T_s)/T_s$ is the normalized island temperature; T_s is temperature at separatrix; σ is island flux coordinate, and takes 0 at o-point and 1 at separatrix; $E(\sigma),\ K(\sigma)$ are complete elliptical integrals of the first and second kind; W is island width in normalized radius; R_0 is major radius; M is island mode number. We assume constant diffusion coefficient $\chi_{\perp} \approx 0.1 m^2/s$. Strength of non-linear effect is benchmarked using amplification of u between the first and last iteration.

Results

During simulation, non-linear amplification is observed for all launchers in both scenarios. w_{eff}^2 is maximized at high $N_{||}$ for all launchers and tends to be high away from the resonance plane, while power deposition tends to be higher close to the resonance plane. (Fig. 2) There is trade-off between the two effects. Amplification is maximized when launching at maximum allowed toroidal angle. Additional direct heating at island o-point can produce a nonlinear shift in the location of maximum deposition from outside the island to inside the island. This is a promising scenario for validating the theory.

Recent results in AUG and W7X find that when heating power increase, χ_{ion} substantially increases, while χ_e remains approximately constant.[7] A two-fluid diffusion equation will be developed for future calculations.

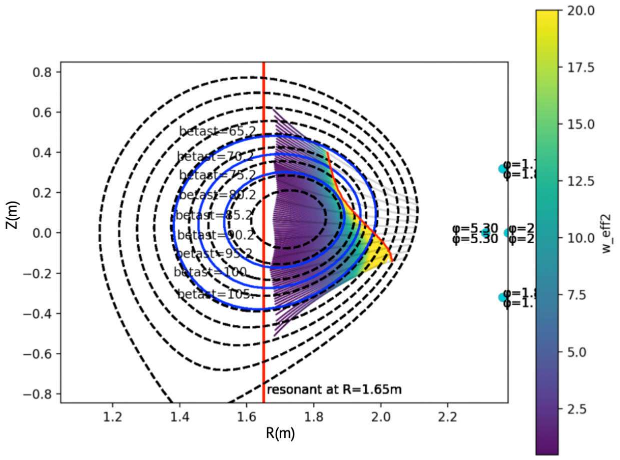

Fig. 2: Poloidal w_{eff}^2 map, launcher #0, 5.4s

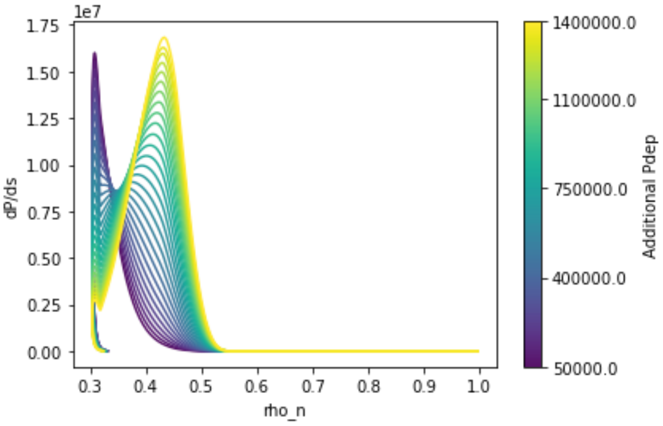

Fig. 3: Damping profiles as island heating increases, 98°pol angle, launcher #0, 5.4s

Conclusion and discussion

This project has produced a narrowed parameter range for current condensation experiments at AUG. Calculation using realistic island geometry and gaussian beams will be conducted in the range for greater accuracy. Effect of additional heating's location, width, magnitude will be investigated in greater detail, and will be reproduced using multi-launcher configurations if feasible.

References

1. Gerasimov, S. N., Abreu, P., Artaserse, G., Baruzzo, M., Buratti, P., Carvalho, I. S., Coffey, I. H., De La Luna, E., Hender, T. C., Henriques, R. B., Felton, R., Jachmich, S., Kruezi, U., Lomas, P. J., McCullen, P., Maslov, M., Matveeva, E., Moradi, S., Piron, et al. (2020). Overview of Disruptions with JET-ILW. Nuclear Fusion, 60(6), 066028.
2. Reiman, A. H., & Fisch, N. J. (2018). Suppression of Tearing Modes by Radio Frequency Current Condensation. Physical Review Letters, 121(22), 225001. https://doi.org/10.1103/PhysRevLett.121.225001.
3. Nies, R., Reiman, A. H., Rodriguez, E., Bertelli, N., & Fisch, N. J. (2020). Calculating RF Current Condensation with Consistent Ray-tracing and Island Heating. Physics of Plasmas, 27(9), 092503.
4. Smirnov , A. P., & Harvey, R. W. (2013). The GENRAY Ray-tracing Code. CompX. https://www.compxco.com/genray.html
5. Meyer, H., et al. "Overview of Physics Studies on ASDEX Upgrade." Nuclear Fusion, vol. 59, no. 11, Nov. 2019, p. 112014. DOI.org (Crossref), doi:10.1088/1741-4326/ab18b8.
6. Wagner, D., Stober, J., Leuterer, F. et al. Status, Operation, and Extension of the ECRH System at ASDEX Upgrade. J Infrared Milli Terahz Waves 37, 45–54 (2016). https://doi.org/10.1007/s10762-015-0187-z
7. Beurskens et al, IAEA FEC 2021

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