Neoclassical Island Control with Stiff Temperature Model

F. Widmer[1], P. Maget[1], O. Février[2], H. Lütjens[3], X. Garbet[1], A. Marx[3]

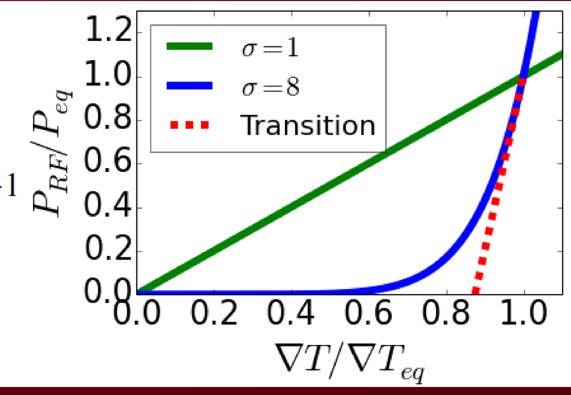
[1] CEA, IRFM, F-13108 Saint Paul-lez-Durance, France. [2] Swiss Plasma Center, Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center, Station 13, CH-1015 Lausanne, Switzerland. [3] Centre de Physique Théorique, Ecole Polytechnique, CNRS, 91128 Palaiseau, France.

Summary

- **A one-parameter critical gradient model is considered for island stabilization by localized heating**
- **It is characterized by profile stiffness, expected to be about 8 in ITER [5]**
- **Investigation of a critical temperature gradient model on ECRH/ECCD RF-efficiency**
  - **Derivation of a modified Rutherford Equation adding RF-Power contribution**
  - **Stabilization efficiency by RF-current and –power on an ITER-like equilibrium**
- **Driving a (3/2) NTM magnetic island to saturation for an ITER-like plasma**
- **Island control by ECRH and ECCD XTOR-2F full MHD code [2,4]**
- **The NTM drive is affected by the ECRH and has to be taken into account while yet it is neglected in the model**

Stiffness Model

- Turbulent transport has thresholds due to critical temperature gradient [1,3]
- Heat flux $q_\perp = -N\chi_\perp \nabla T$
- Diffusion coefficient $\chi_\perp$ modeled as $\chi_\perp = \chi_\perp^0 \left|\frac{\nabla T}{\nabla T_{eq}}\right|^{\sigma-1}$
- **1 parameter model:** stiffness σ



Modified Rutherford Equation (MRE) With RF-Current (I_{RF}) and -Power (P_{RF}) Driven by ECCD

- MRE taking into account the Ohmic contribution $a\Delta'_\Omega$

$$0.82 S_0 \frac{\mathrm{d}W}{\mathrm{d}t} = a\Delta' + a\Delta'_\Omega + C_{bs}J_{bs}W - C_{RF}I_{RF}\frac{\eta_{RF}}{W^2}$$

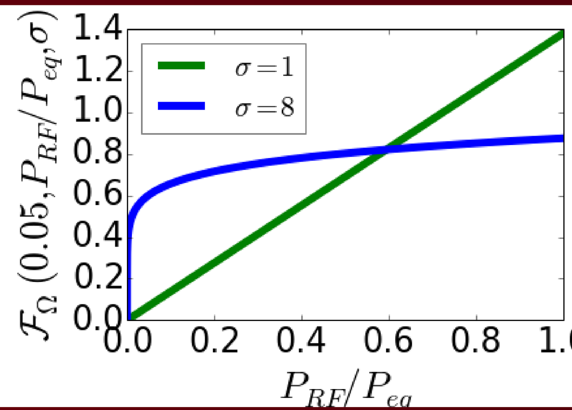
- Effect of P_{RF} while J_{RF} acts as
- No P_{RF} effects on the bootstrap current due to symmetry

- The contribution of the power has stabilizing effect when modulated at the 'O'-point [6,7]
- A contribution to the MRE is derived for the stiffness parameter

$$a\Delta'_\Omega = -\mathcal{F}_\Omega\left(\mu_c, \frac{P_{RF}^{tot}}{P_{eq}}, \sigma\right)\frac{a}{\mathcal{J}}\frac{q}{s}\frac{\mu_0 R J_\Omega}{B_z}\frac{P_{eq}}{N\chi_\perp^0 T_s}$$

- Here μ_c corresponds to the RF-power deposition location within the magnetic island

As long as $\nabla T < \nabla T_{eq}$ for $P_{RF}/P_{eq} < 1$, $\chi_\perp$ remains low inside the island. As a consequence, the RF-power stabilization is enhanced for perfect 'O'-point heating (modulation)



ITER-like equilibrium

As an application for our model, we take an ITER-like equilibrium

- Scenario Q=10, plasma current I_p = 15 MA
- RF-current injection for control I_{RF} =0.8% I_p
- RF-power for island control P_{RF} = 13MW

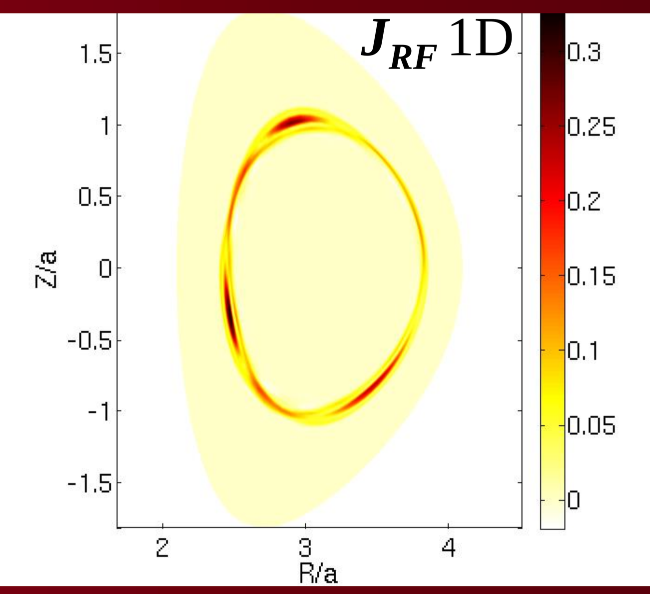
Numerical aspects, ECCD/ECRH Governing Equations

- The XTOR-2F contains an RF-current and –power source [2,4]
- Propagation of RF-current along field lines through parallel diffusion are verified [2]

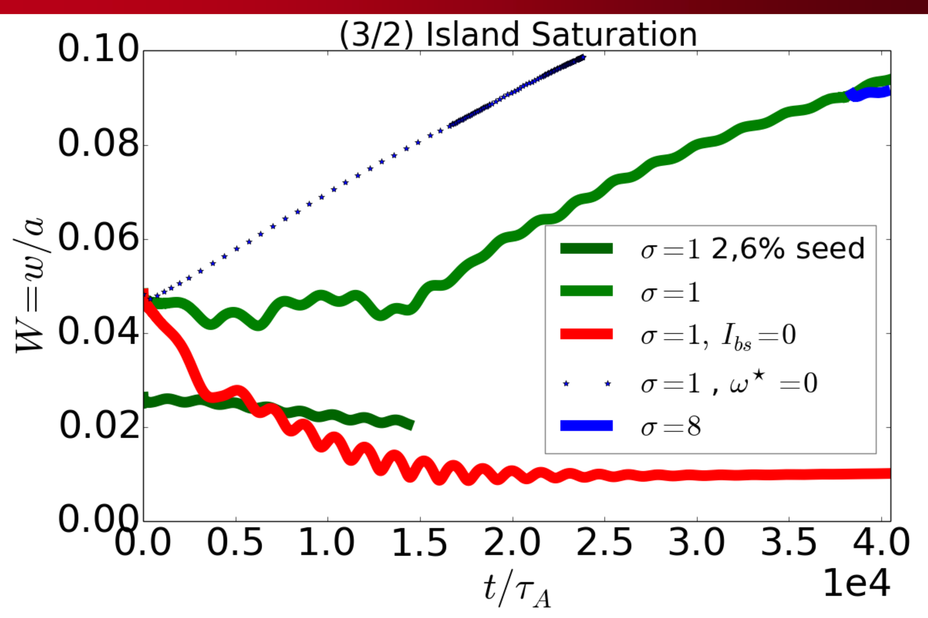
$$\frac{\partial J_{RF}}{\partial t} = \nu_f(J_s - J_{RF}) + \chi_\perp^{RF}\nabla^2 J_{RF} + \chi_\parallel^{RF}\nabla_\parallel^2 J_{RF}$$

$$\frac{\partial P_{RF}}{\partial t} = \nu_f(P_s - P_{RF}) + \chi_\perp^{RF}\nabla^2 P_{RF} + \chi_\parallel^{RF}\nabla_\parallel^2 P_{RF}$$

- Index s stands for source which is implemented as a 1D or 3D one
- Note that the sources used in simulations are 1D except for modulation which are 3D



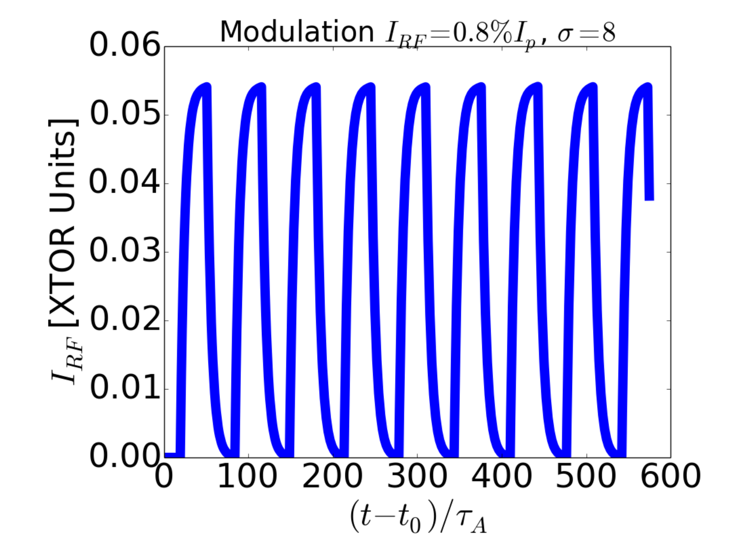
(3/2) Neoclassical Island



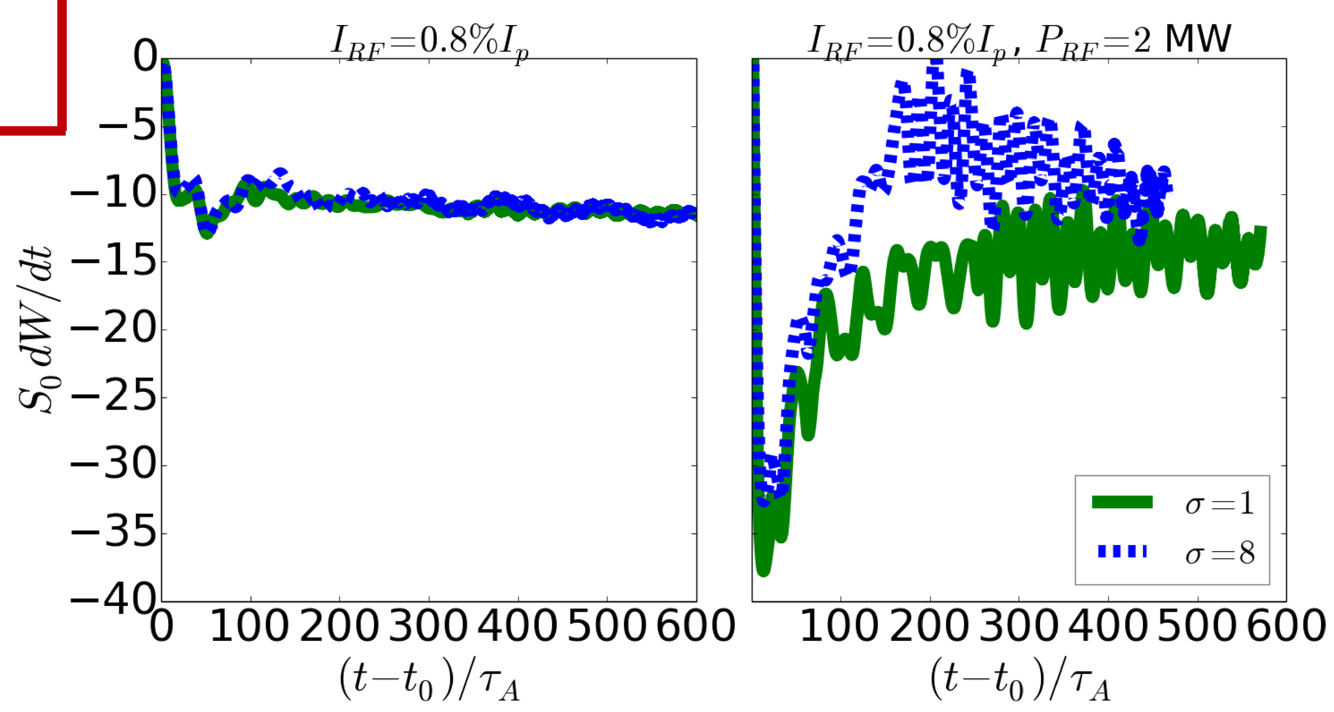
1. The bootstrap current (I_{bs}) is the drive that made the island growth
2. A threshold exist under which the magnetic island is stable
3. The $\omega^\star$ effects are stabilizing

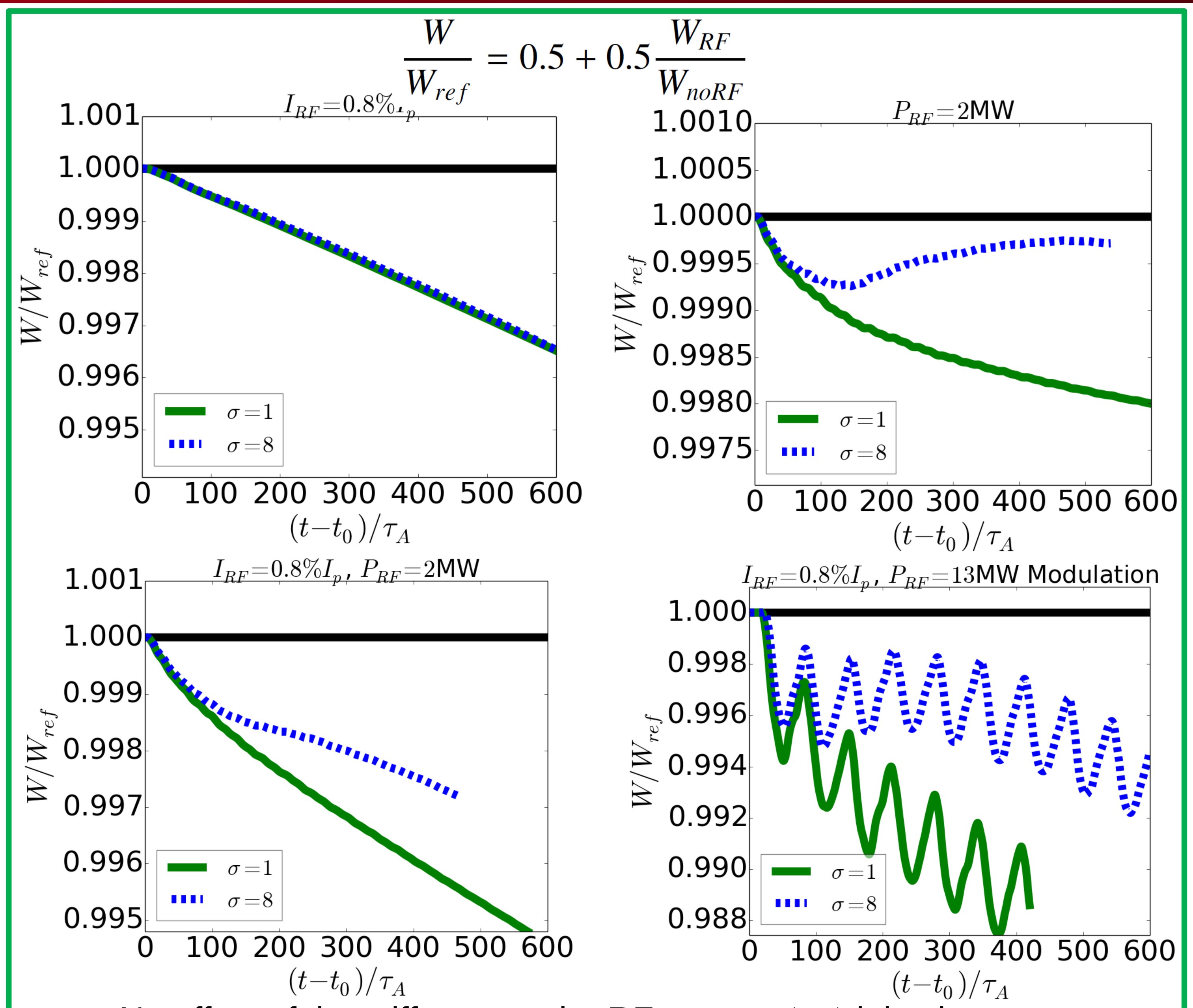
(3/2) Neoclassical Tearing Mode Control driving RF-Current and Power

- Driving RF-current in addition with RF-power results in a large decrease of the island size for a short time period
- Large stiffness is apparently less favorable

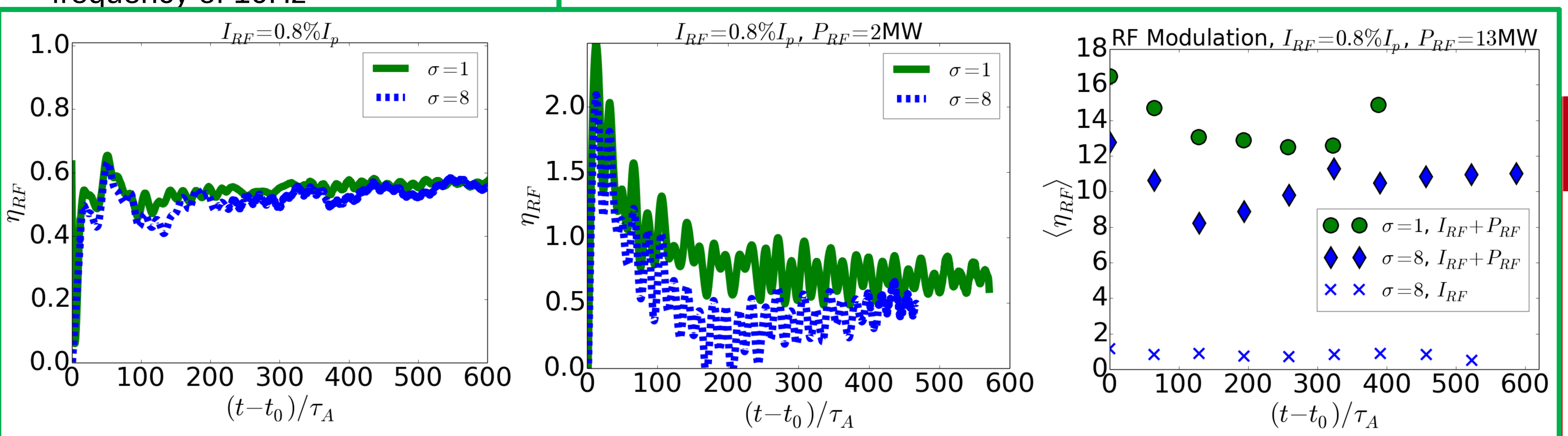


Modulation cycle for modulated driven RF-current (I_{RF}) at a frequency of 10Hz





- No effect of the stiffness on the RF-current (I_{RF}) injection
- Injection of RF-power (P_{RF}) seems to be efficient only during about 200 τ_A for the case $\sigma=8$

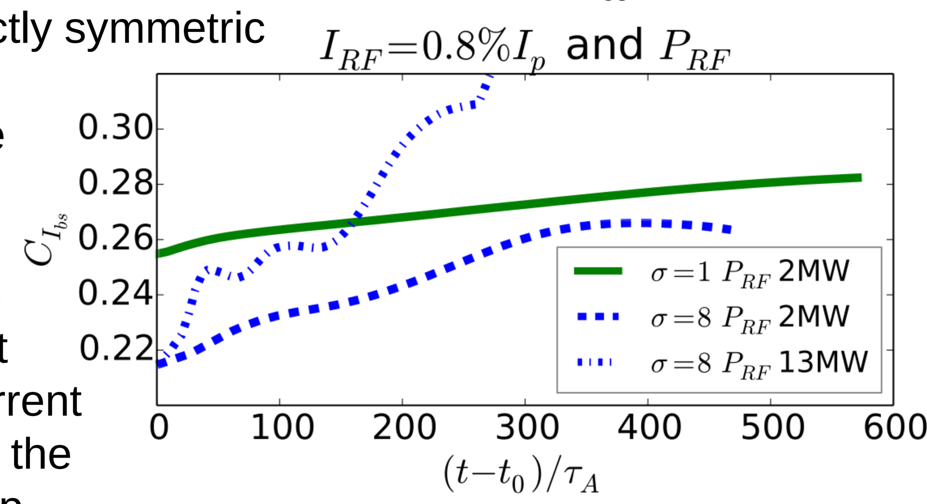


- The RF-efficiency is slightly affected by the stiffness when only RF-current (I_{RF}) is driven
- The RF-efficiency is largely enhanced driving RF-current (I_{RF}) and power (P_{RF}) inside the magnetic island
- RF-efficiency is averaged at each RF-cycles from the half-hight to the maximum.
- RF-power enhances the RF-efficiency for both a stiffness of 1 and 8

Conclusion and Outlooks

1. Adding RF-power (P_{RF}) to the RF-current (I_{RF}) enhances the RF-efficiency
2. In presence of stiffness, it seems that driving RF-power (P_{RF}) is less effective even for modulation control scheme
3. Possible explanation is the effect of the bootstrap current (I_{bs}) since the magnetic island is not perfectly symmetric

- C_{Jbs} is the contribution of the bootstrap current to the island current
  - The stiffness has an non-negligible effect on the bootstrap current and heating acts on the equilibrium bootstrap



References

[1] M. Romanelli, C. Bourdelle, and W. Dorland, Physics of Plasmas, 11, 3845 (2004)
[2] O. Février, P. Maget, H. Lütjens, et al., Plasma Physics and Controlled Fusion, 58, 045016 (2016)
[3]F. Imbeaux, F. Ryter, and X. Garbet, Plasma Physics and Controlled Fusion, 43, 1503 (2001)
[4] H. Lütjens, and J.-F. Luciani, Journal of Computational Physics 229, 8130 (2010)
[5] J.E. Kinsey, et al., Nuclear Fusion, 51, 083001 (2011)
[6] C.C. Hegna, and J. D. Callen, Physics of Plasmas, 4, 2940 (1997)
[7] D. D. Lazzari and E.Westerhof, Nuclear Fusion, 49, 075002, (2009)

Acknowledgements

Work carried out within the framework of the AMICI project funded by the Agence Nationale pour la Recherche (ANR-14-CE32-0004-01).

Numerical resources provided by GENCI (project no. 056348), Mésocentre of Aix-Marseille University (project no. b009), EUROfusion (project MaCoToP)