Simulations of Edge Localized Modes (ELMs) and ELM Control

Matthias Hoelzl[1], A Cathey[1], S Futatani[2], V Mitterauer[1], SK Kim[3], Q Yu[1], SQ Korving[4], SJP Pamela[5], SF Smith[5], A Fil[5], HH Wang[6], GTA Huijsmans[7,4], M Becoulet[7], FJ Artola[1], S Günter[1], JOREK Team[8], EUROfusion MST1 Team[9]

[1]Max Planck Institute for Plasma Physics, Garching, Germany [2]*Universitat Politècnica de Catalunya, Barcelona, Spain* [3]*Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ, U.S.A* [4]*Eindhoven University of Technology, Eindhoven, The Netherlands* [5]*CCFE, Culham Science Centre, Oxford, UK* [6]*Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China* [7]*CEA, IRFM, Saint-Paul-Lez-Durance, France* [8]*see M Hoelzl et al 2020 Nucl. Fusion sub, preprint: https://arxiv.org/abs/2011.09120* [9]*see B Labit et al 2019 Nucl. Fusion 59, 086020*

1. Introduction

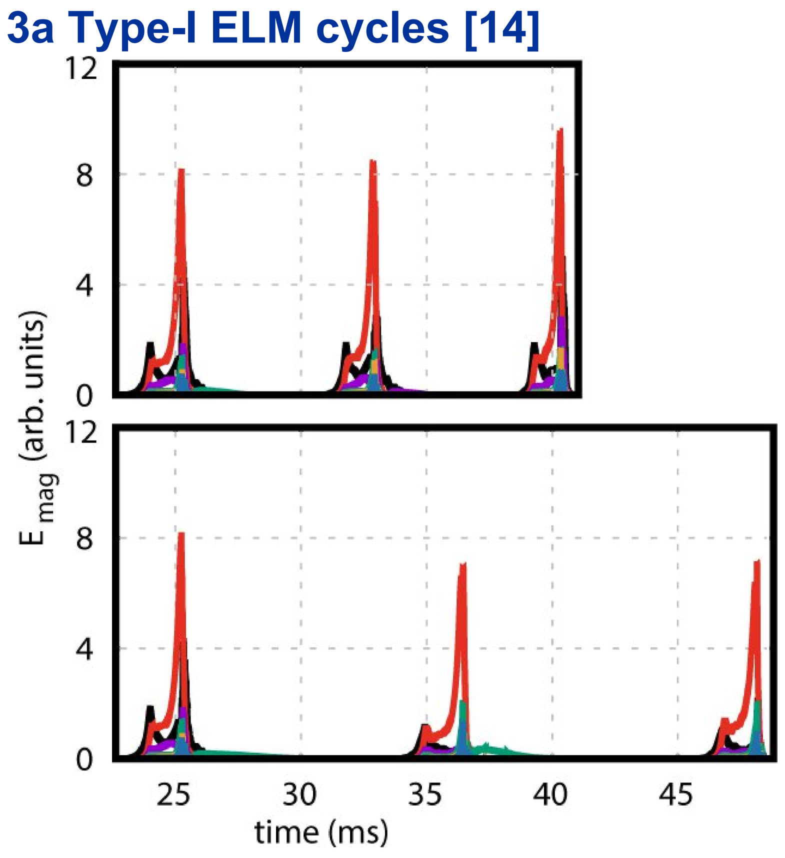
Edge localized modes (ELMs) are a concern for the ITER divertor life-time and require mitigation or suppression. We summarize developments with JOREK towards validated predictive simulation capabilities.

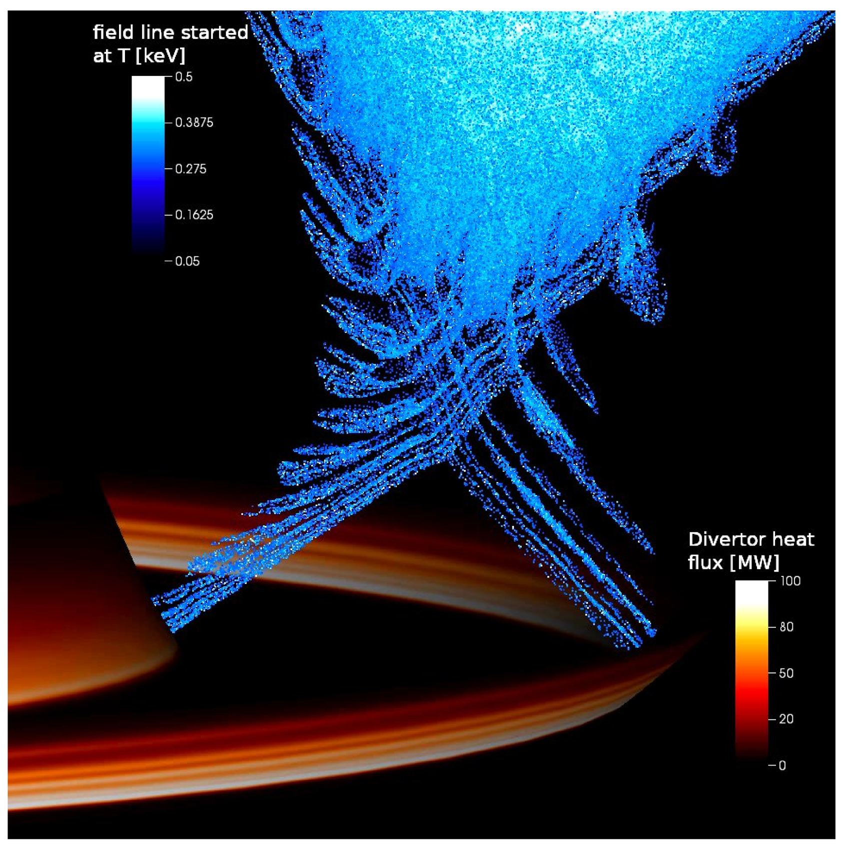
2. Methods and Code

- Non-linear extended MHD code JOREK [1,2] + free boundary [3,4]
- 2D Bezier finite elements [5] + toroidal Fourier series
- Grid aligned to flux surfaces + extension to first wall [6]
- Robust fully implicit time steps to bridge temporal scale separations
- Iterative solver + physics based preconditioner (recently optimized [7])
- Ext.: two-fluid [8], neutrals [9], impurities [10], pellets [11], kinetic particles [12,13]
- Comprehensive code review [2]

3. Spontaneous ELMs

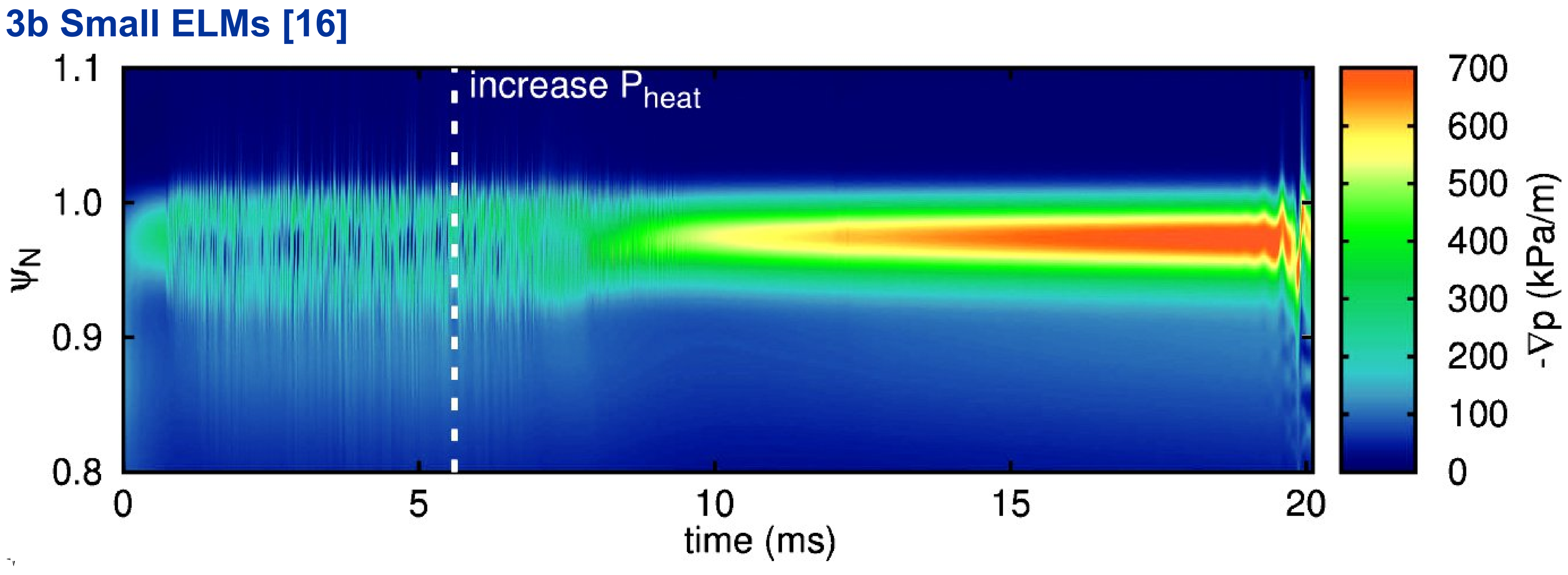
3a Type-I ELM cycles [14]





- ASDEX Upgrade (AUG) H-mode case
- Pedestal build-up via sources and ad-hoc diffusion profiles
- Self-consistent ExB and diamagnetic flows + bootstrap current
- Realistic resistivity and parallel heat conductivity
- Plasma remains quiet for several ms due to flow stabilization
- Precursor modes develop
- Explosive crash as a result of self-amplifying processes:
  1) Precursor affects n_e and T asymmetrically => stabilizing terms (sheared plasma flows) reduced more than destabilizing terms (pressure gradient, current density)
  2) Precursor induced 3D perturbations locally increase the pressure gradient destabilizing ballooning modes (comparable to Ref. [15])
- Each crash expels ~7% of total plasma thermal energy within 0.5—1 ms
- When reducing SOL density or decreasing heating power, ELM frequency drops

3b Small ELMs [16]



- When reducing the heating power further, type-I ELMs are replaced by continuous peeling-ballooning turbulence
- Outer midplane pedestal pressure gradient locked to ~250 kPa/m
- Strong similarities to small-ELM regime [17]
- Outlook: configurations where experiments show better confinement like quasi-continuous exhaust (QCE) regime [18]

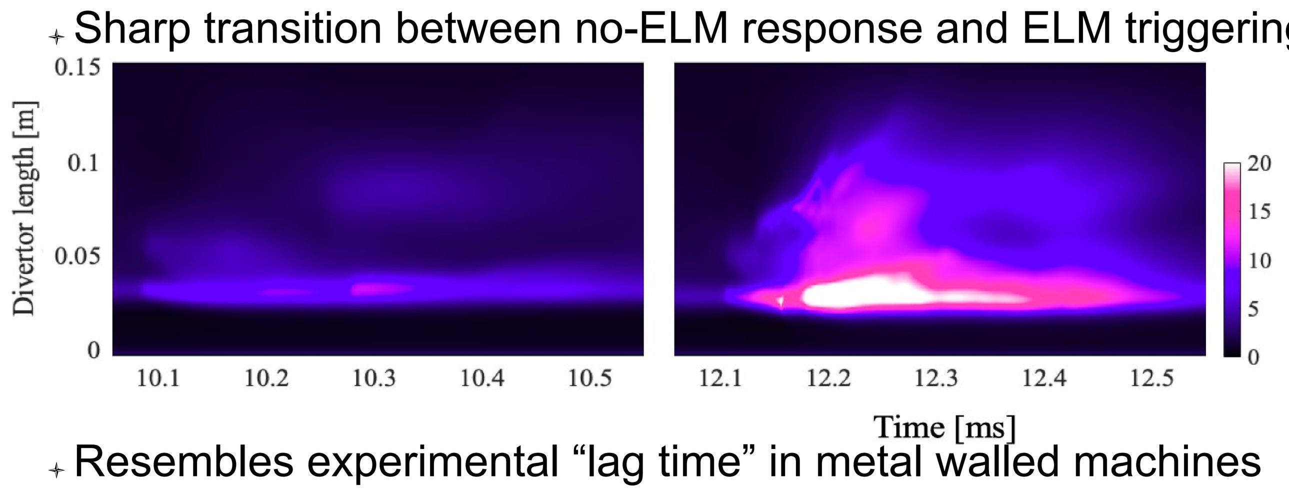
3c Further results

- Experiment comparisons of mode spectrum during ELM + q_{95} dependency [19-21]
- Comparison of ELM induced cold-front penetration [22]
- Tungsten transport in SOL/pedestal during ELM [23]
- MAST-Upgrade ELMs including super-X divertor and burn-through [24]
- Reduce/full MHD comparison: Excellent agreement for ELMs [25]

4. ELM triggering / pacing

4a Pellet injection during pedestal build-up [26,27]

- Sharp transition between no-ELM response and ELM triggering



- Resembles experimental "lag time" in metal walled machines
- Losses of triggered ELM crashes are smaller than spontaneous ELMs, but triggered ELMs have a smaller wetted area
- JET study reproduces experimental heat loads + finds toroidal asymmetry [28]

4b Magnetic kicks [29]

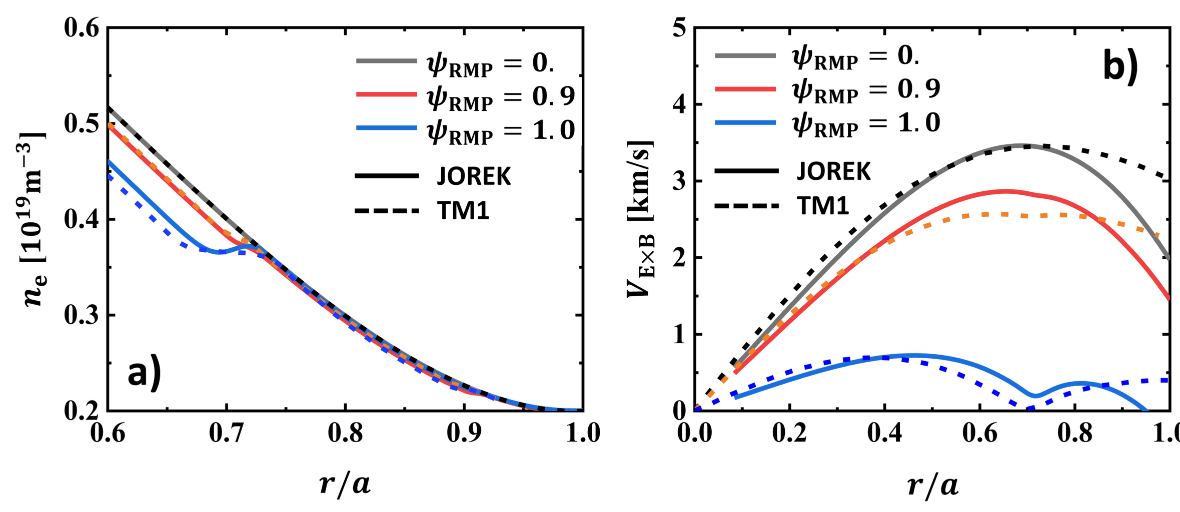
- Alternative approach for pacing studied in an ITER plasma
- ELM triggering occurs only during downward plasma motion
- Confirms that modified edge current density destabilizes the plasma
- Application in the ITER 7.5 MA/2.65 T operation seems possible

5. Resonant magnetic perturbations (RMPs)

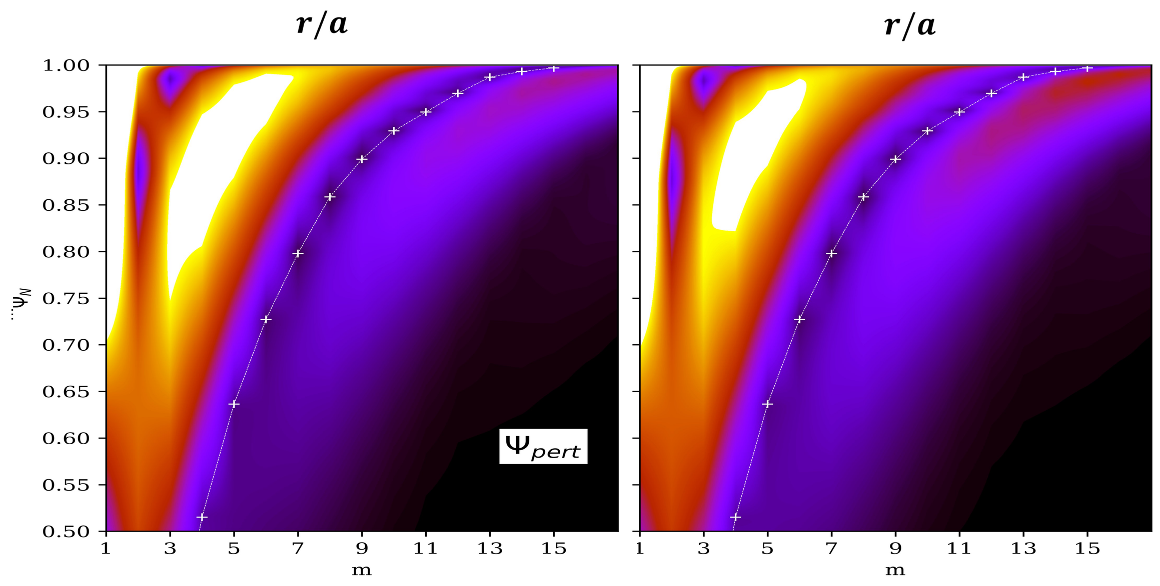
- AUG: transition at increasing amplitude ELM → mitigation → suppression [32]; mode coupling essential; locked modes in suppressed state.
- KSTAR: RMPs show suppression due to increased energy exchange between harmonics (non-linear coupling); density pump-out under-predicted
- EAST: n=1 RMPs mitigate pedestal instability by one order of magnitude [36]
- ITER: Suppression beyond coil currents of 45 to 60kAt (within engineering limit of 90 kAt). Divertor footprints exhibit splitting.

5b New developments

- Neoclassical toroidal viscosity (NTV) contributes to density pump-out [37]
- Polarization drift contributes to density pump-out; good agreement of JOREK and TM1 in simple geometry [39]; Shaping + toroidal effects are investigated



- Free boundary RMP simulations [41] show differences in the penetrated state



6. Scrape-Off Layer (SOL), Divertor And Impurity modelling [42]

- Fluid neutral model agrees well with SOLPS-ITER [43]
- Realistic divertor conditions from a attached to almost completely detached divertor
- Poloidal flows cause outer-inner target asymmetries in line with [44]
- Kinetic neutrals + impurities => 3D simulations + state of the art SOL/divertor model

References: [1] Huysmans GTA, Czarny O. Nucl Fusion 47, 659 (2007) [2] Hoelzl M, Huijsmans GTA et al. Nucl Fusion (subm.). pre-print arXiv:2011.09120 [3] Hoelzl M, Merkel P, Huysmans, GTA et al. Journal of Phys: Conf Series. 401, 012010 (2012) [4] Merkel P, Strumberger E. arXiv:1508.04911 (2015) [5] Czarny O, Huysmans G. JCP 227, 7423 (2008) [6] Pamela S, Huijsmans G et al. Comp Phys Commun 243, 41 (2019) [7] Holod I, Hoelzl M et al. Plasma Phys Control Fusion (subm.); arXiv:2101.0864 [8] Orain F, Becoulet M et al. Phys Plasmas, 20, 102510 (2013) [9] Fil A, Nardon E, Hoelzl M, et al. Phys Plasmas 22, 062509 (2015) [10] Hu D, Nardon E, Hoelzl M et al. Nucl Fusion 61, 026015 (2021) [11] Futatani S, Huijsmans G et al. NF 54, 073008 (2014) [12] van Vugt DC, PhD Thesis (2019) [13] Dvornova A, PhD Thesis, 2021 [14] Cathey A, Hoelzl M et al. Nucl Fusion 60, 124007 (2020) [15] Wilson HR and Cowley SC Phys Rev Lett 92, 175006 [16] Cathey A, Hoelzl M et al. 4th AAPPS-DPP (Virtual) 2020 [17] Wolfrum E et al. Plasma Phys Control Fusion, 53, 085026, 2011 [18] Harrer G F et al. Nucl Fusion 58.11 112001 (2018) [19] Hoelzl M, Huijsmans GTA et al. Contrib Plasma Phys 58, 518 (2018) [20] Mink AF, Hoelzl M et al. Nucl Fusion 58, 026011 (2018) [21] Mink AF, Wolfrum E et al. Plasma Phys Control Fusion 60, 125011 (2018) [22] Trier E, Wolfrum E et al. Plasma Phys Control Fusion 61, 045003 (2019) [23] van Vugt DC, Huijsmans GTA, Hoelzl M et al. Phys Plasmas 26, 042508 (2019) [24] Smith SF, Pamela SJP et al. Nucl Fusion 60, 066021 (2020) [25] Pamela SJP, Huijsmans GTA et al. Phys Plasmas 27, 102510 (2020) [26] Futatani S, Cathey A, Hoelzl M et al. Nucl Fusion 61, 046043 (2021) [27] Cathey A, Hoelzl M, Futatani S et al. Plasma Phys Control Fusion (submitted). preprint at arXiv:2102.0585 [28] Futatani S, Pamela S et al. Nucl Fusion 60 026003 (2020) [29] Artola FJ, Huijsmans GTA, Hoelzl M et al. Nucl Fusion 58, 096018 (2018) [30] Nardon E, Bécoulet M et al. PoP 14, 092501 (2007) [31] Bécoulet M, Orain F, Huijsmans GTA et al. PRL 113, 115001 (2014) [32] Orain F, Hoelzl M et al. Phys Plasmas 26, 042503 (2019) [33] Becoulet M. this conf. [34] Kim SK, Pamela S et al. Nucl Fusion 60, 026009 (2020) [35] Wu S, EAST Team. Fusion Eng. Design 82, 463 (2007) [36] HH Wang, M Becoulet et al, priv. commun. (Mar 1st 2021) [37] Kim, SK et al., 62nd APS (2020, Nov.9-13), VO08 [38] Orain F, PhD Thesis (2014) [39] Kim SK, Yu Q et al, private communication (Mar 1st 2021) [40] Yu Q and Günter S. Nucl Fusion 51, 073030 (2011) [41] Mitterauer V, Hoelzl M, Schwarz N, Artola J. priv. commun. (Mar 31st 2021) [42] Korving S, Huijsmans GTA et al. priv. commun. (Mar 31st 2021) [43] Wiesen S et al. Journal of Nuclear Materials 463, 480 (2015 [44] Kevevaa E et al. Nucl Fusion 60, (2020) 04601

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.
Part of this work was carried out using the Marconi-Fusion supercomputer.