EUROfusion

Update for TSVV 8 project on MHD transients

M Hoelzl for the whole project team

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

The TSVV 8 Team (at present)

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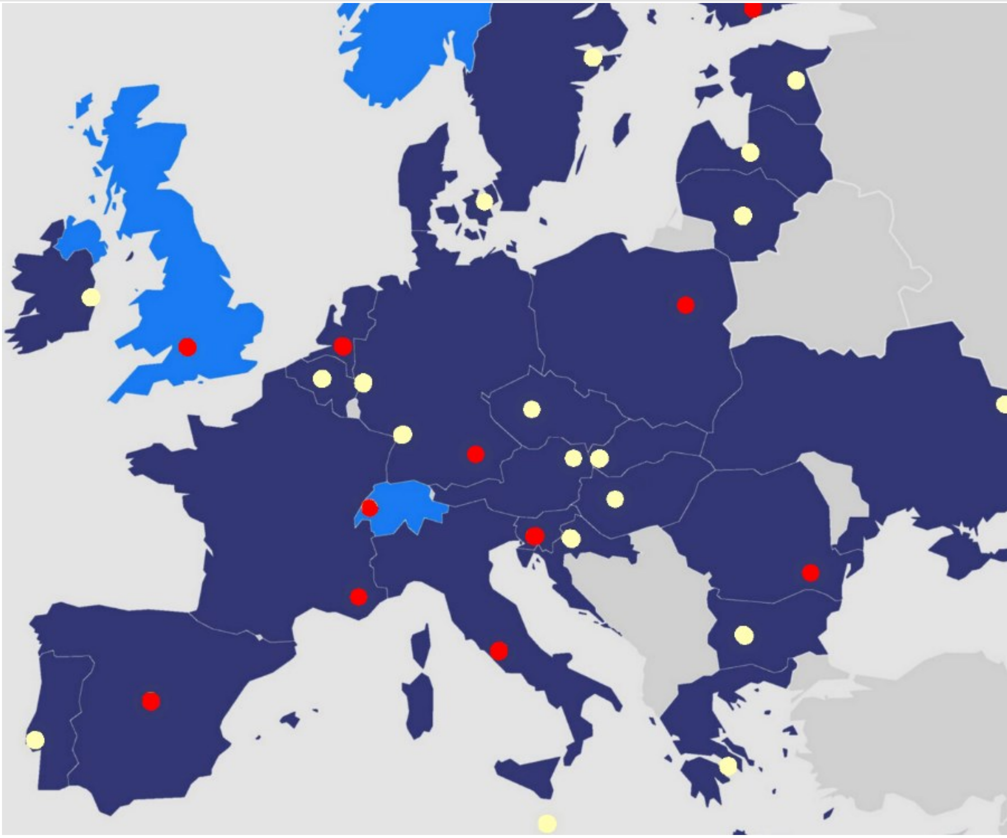

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4. ~~Huw Leggate~~

+ **Closely collaborating** with **TSVV 9, ITER,** the European and international JOREK community , WP TE, AUG, JET, SA, TSVV 10, DEMO, DTT, and various other experiments, …

Main codes developed and used

JOREK

- non-linear reduced and full MHD
- hybrid and kinetic models
- applications to SOL/divertor, pedestal, core, disruptions, turbulence
- models for neutrals, impurities, runaway electrons, energetic particles, …

STARWALL

3D thin resistive wall model

CARIDDI

3D volumetric resistive wall model

TRIMEG

- GK full-device simulations
- Developing PiC methods

Work package structure

- Models and verification

- Methods

Work package Usability

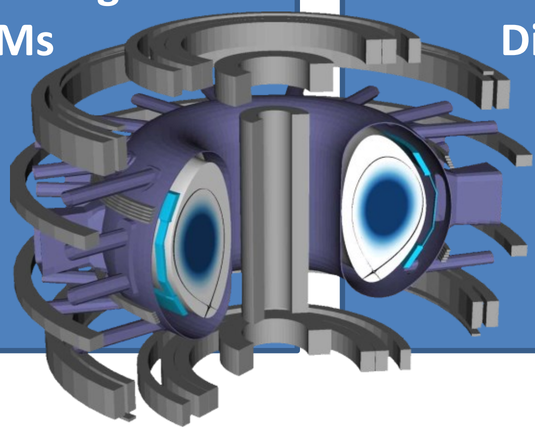
Work package Numerics

Work package Kinetics

Work package structure

Work package
ELMs

Work package
Disruptions



Other appli-cations

- Reduced models
- Predictions
- Understanding
- Experiment interpretation

↑

- Experimental validation

↑

- Models and verification

Work package
Usability

Work package
Numerics

Work package
Kinetics

↑

- Methods

Work package
Usability

Work package Usability

- Selection of papers
- **Bold** where 1st/2nd/3rd author is a project contributor
- Conferences only included if no other reference available

- **In person and remote meetings**
  - About ~50 per year
  - Last JOREK general meeting with 33 participants on site + 23 remote
- **Training** new users and students
- **Coordinating** with international community
- **Administrating** documentation wiki, mailing lists, website
- **Coordinating HPC access** and porting to new systems
- **JOREK, STARWALL & CARIDDI_J development** coordination (~150 pull requests per year)
- **Automatic regression tests** extended for optimal code stability
- **IMAS adaptations** advanced with ITER + some ACH support
- **“Model families”** for reduced & full MHD to combine extensions

- **Hoelzl M., Huijsmans G.T.A., Pamela S.J.P., Becoulet M., Nardon E., Artola F.J., Nkonga B., et al. The JOREK non-linear extended MHD code and applications to large-scale instabilities and their control in magnetically confined fusion plasmas. Nuclear Fusion 61, 065001 (2021)**
- ***(Overview of recent JOREK results foreseen as IAEA-FEC proceedings article)***
- *(Various contribution to the ITPA review articles)*

Work package
Numerics

Work package Numerics

- Re-write of solver framework
- Interfaces to new solvers
- BiCGstab as iterative solver
- Non-linear time stepping
- Grid center treatment
- **Preconditioner for highly non-linear scenarios ►**
- **Higher order FEs ►**
- **Shock capturing methods ►**

- **Holod I., Hoelzl M., Verma P.S., Huijsmans G.T.A., Nies R., JOREK Team. Enhanced preconditioner for JOREK MHD solver. Plasma Physics and Controlled Fusion 63, 114002 (2021) doi:10.1088/1361-6587/ac206b**
- **Pamela S.J.P., Huijsmans G.T.A., Hoelzl M., JOREK Team. A Generalised Formulation of G-continuous Bezier Elements Applied to Non-linear MHD Simulations. Journal of Computational Physics , 111101 (2022) doi:10.1016/j.jcp.2022.111101**
- **Bhole A., Nkonga B., Pamela S.J.P., Huijsmans G.T.A., Hoelzl M., JOREK Team. Treatment of polar grid singularities in the bi-cubic Hermite-Bézier approximations: Isoparametric finite element framework. Journal of Computational Physics 471, 111611 (2022) doi:10.1016/j.jcp.2022.111611**
- **Bhole A., Nkonga B., Costa J., Huijsmans G.T.A., Pamela S.J.P., Hoelzl M. Stabilized bi-cubic Hermite Bézier finite element method with application to gas-plasma interactions occurring during massive material injection in tokamaks. Computers & Mathematics with Applications Volume 142, 225 (2023) doi:10.1016/j.camwa.2023.04.034**

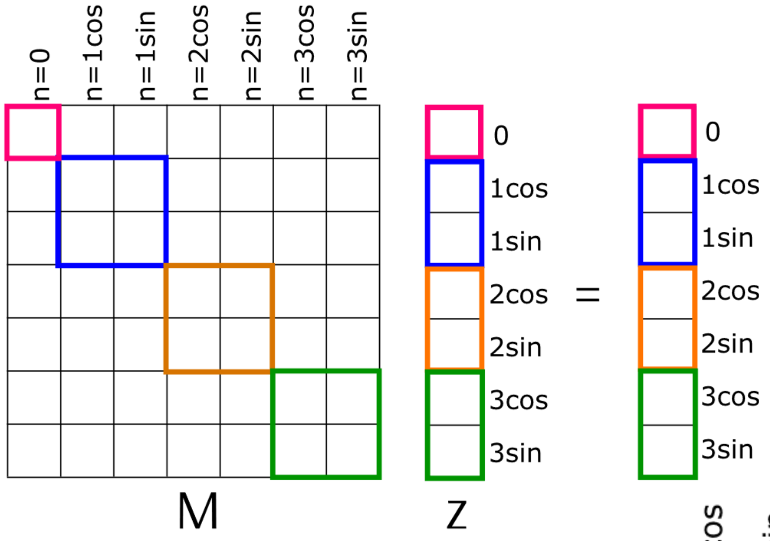
Symbols indicate that details are shown as highlight on one of the following slides

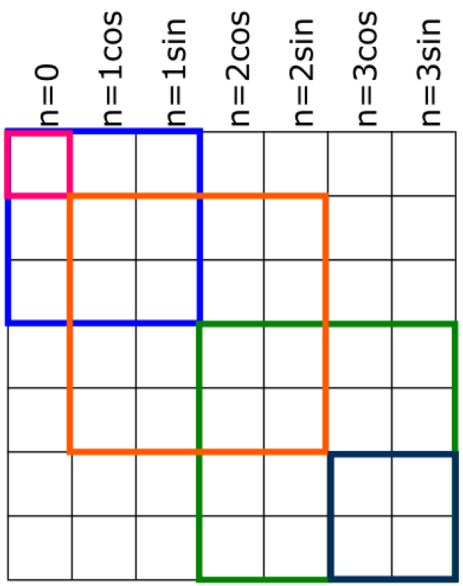
Highlight: Solver developments

Holod I., Hoelzl M., Verma P.S., Huijsmans G.T.A., Nies R., JOREK Team. Enhanced preconditioner for JOREK MHD solver. Plasma Physics and Controlled Fusion 63, 114002 (2021)
doi:10.1088/1361-6587/ac206b

- **Implicit time stepping**
- **Solve a sparse matrix system in every time step**
- Dimension ~40 million for a large problem with ~500 billion non-zero entries; matrix storage takes ~8 TB
- Solved iteratively with preconditioner

- **Preconditioner adapted to capture some of the non-linear interactions**
- **Speed-up of ~3 for some cases**

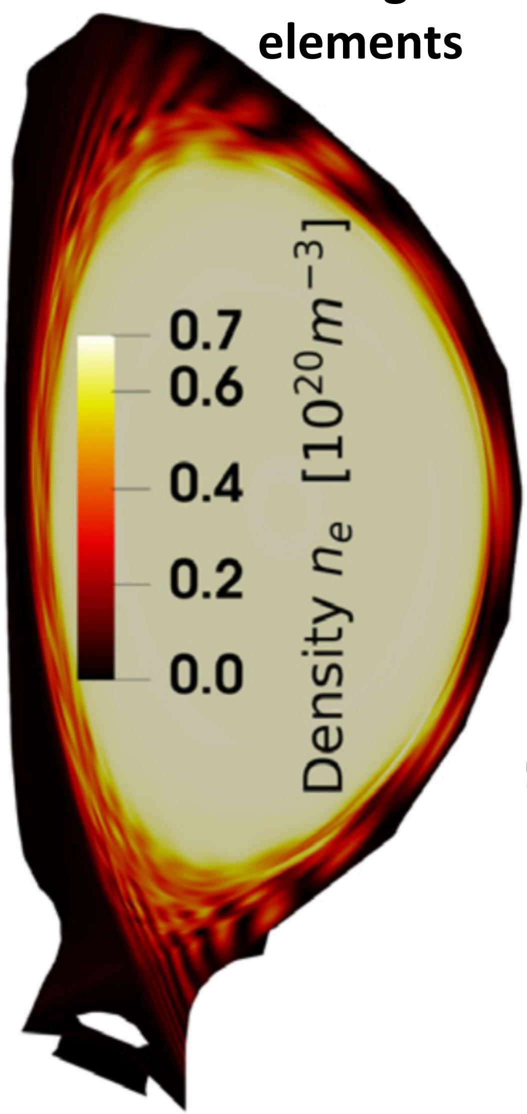


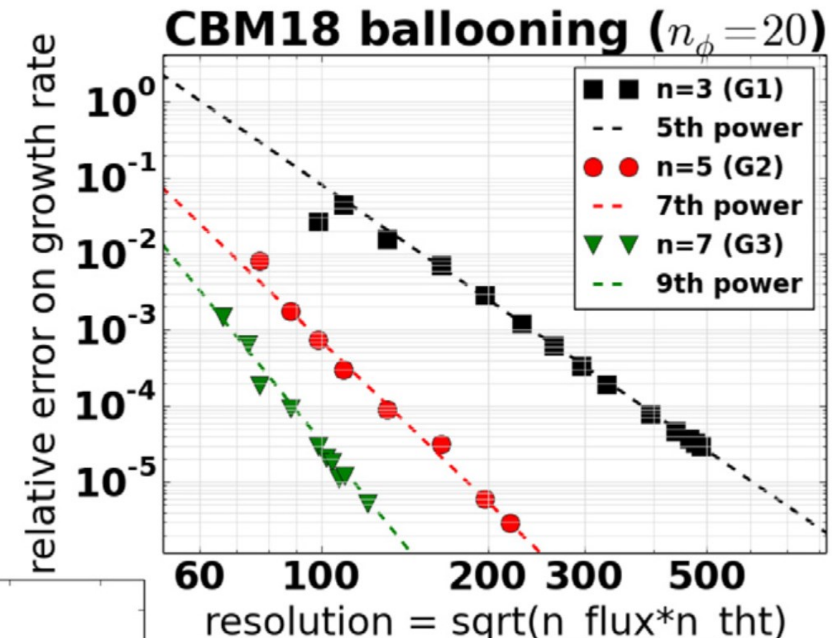


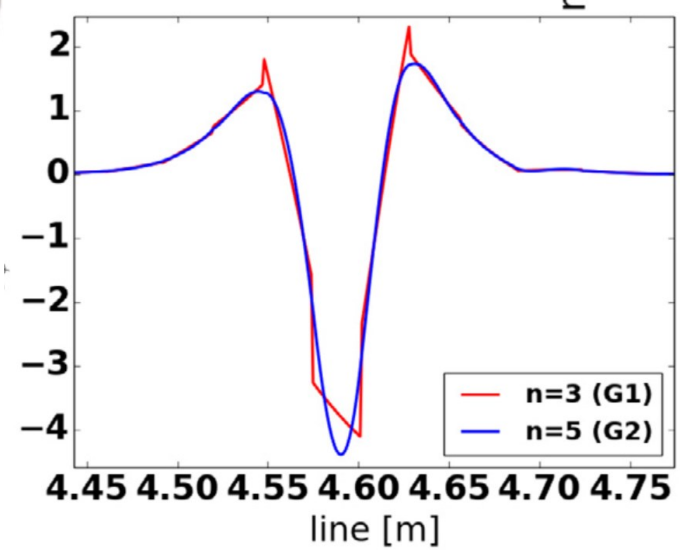
Highlight: Higher order finite elements

Pamela S.J.P., Huijsmans G.T.A., Hoelzl M., JOREK Team. A Generalised Formulation of G-continuous Bezier Elements Applied to Non-linear MHD Simulations. Journal of Computational Physics , 111101 (2022) doi:10.1016/j.jcp.2022.111101

- **Derivation and implementation of higher order Bezier finite elements**



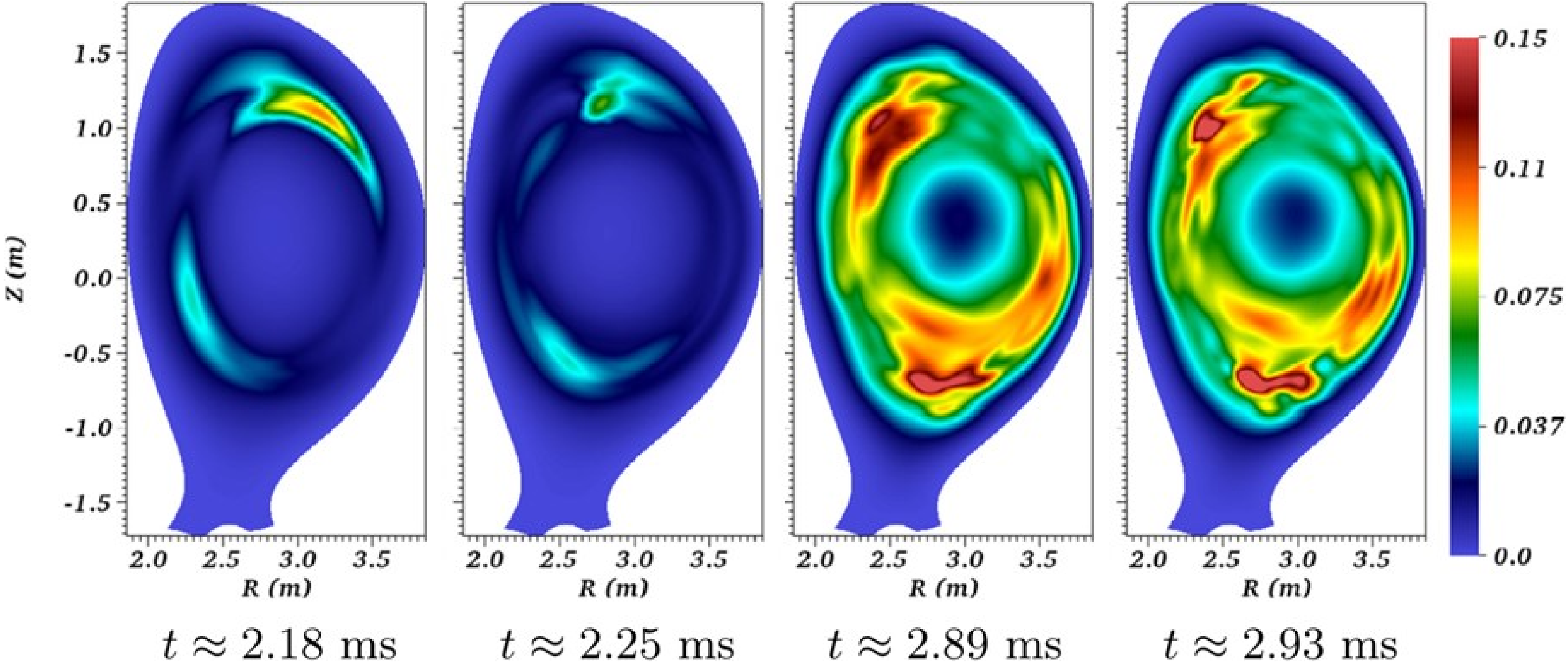




Highlight: Full MHD disruptions

Bhole A., Nkonga B., Costa J., Huijsmans G.T.A., Pamela S.J.P., Hoelzl M. Stabilized bi-cubic Hermite Bézier finite element method with application to gas-plasma interactions occurring during massive material injection in tokamaks. Computers & Mathematics with Applications Volume 142, 225 (2023) doi:10.1016/j.camwa.2023.04.034

- **Strongly improved full MHD model** for production simulations and included **neutrals and impurities**
- Implemented **shock capturing** scheme for highly non-linear mitigated disruption cases



Work package
Kinetics

Work package Kinetics

- Kinetic neutrals and impurities (see working group ELMs)
- **GK EM methods in TRIMEG ►**
- **Electrostatic ITG and TEM ►**
- **Energetic particle models ►**

- *Strien KA. Particle Model for Impurities in Magnetohydrodynamics Simulations of Shattered Pellet Injection. Master Thesis (2022).* *https://pure.tue.nl/ws/portalfiles/portal/210104346/0968579_Strien_K._MSc_thesis_report_MAP.pdf*
- *Bogaarts TJ. Hybrid MHD-kinetic simulations of energetic particle driven instabilities in JOREK: development and applications. Master Thesis (2022).* *https://research.tue.nl/files/217976833/1000549_Bogaarts_T.J._MSc_thesis_Thesis_NF.pdf*

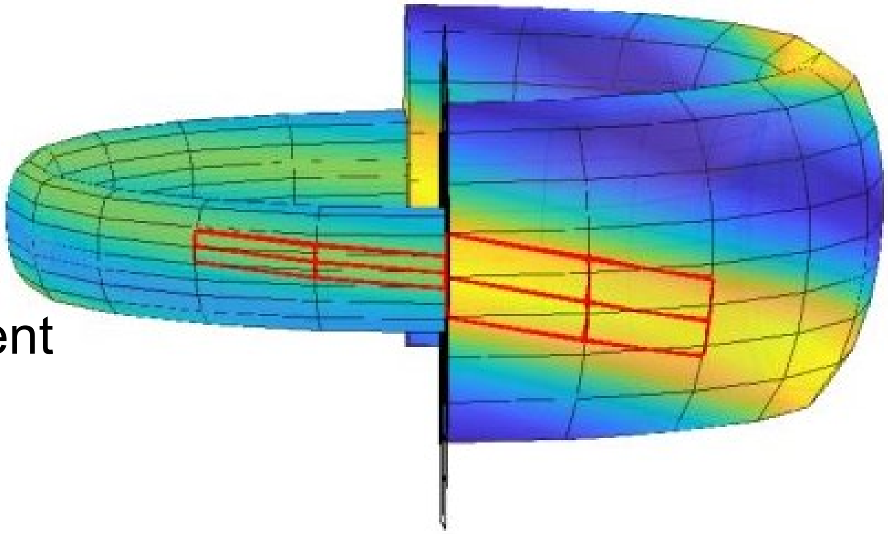
- **Lu ZX., Meng G., Hoelzl M., Lauber Ph.The development of an implicit full f method for electromagnetic particle simulations of Alfven waves and energetic particles. Journal of Computational Physics 440, 110384 (2021)**
- **Rosen M., Lu ZX., Hoelzl M. An E&B Gyrokinetic Simulation Model for Kinetic Alfven Waves in Tokamak Plasmas. Physics of Plasmas 29, 022502 (2022)**
- **Bogaarts T.J., Hoelzl M., Huijsmans G.T.A., Wang X., JOREK Team. Development and application of a hybrid MHD-kinetic model in JOREK. Physics of Plasmas 29, 122501 (2022) doi:10.1063/5.0119435**
- **Lu ZX, Meng G, Hatzky R, Hoelzl M, Lauber Ph. Full f and deltaf gyrokinetic particle simulations of Alfven waves and energetic particle physics. Plasma Physics and Controlled Fusion 65, 034004 (2023)**
- **Rekhviashvili L., Lu ZX., Hoelzl M., Bergmann A., Lauber P. Gyrokinetic simulations of neoclassical electron transport and bootstrap current generation in tokamak plasmas in the TRIMEG code. Physics of Plasmas (accepted)**
- **Huijsmans GTA, Becoulet M, Lu ZX, JOREK Team. Comparing linear stability of electrostatic kinetic and gyro-kinetic ITG modes. EPS 2023**
- **Becoulet M, Huijsmans GTA, Garbet X, Donnel P, Wang L, et al, Non-linear gyro-kinetic ITG and TEM turbulence modelling in X-point geometry with RMPs. EPS 2023**

Highlight: GK PiC methods

[1] Lu ZX, Meng G, Hoelzl M, Lauber Ph, Journal Comput. Phys. 440 (2021) 110384
[2] Rosen M, Lu ZX, Hoelzl M, Phys. Plasmas, 022502 (2022)
[3] Lu ZX, Meng G, Hatzky R, Hoelzl M, Lauber Ph, PPCF (2023)
[4] Rekhviashvili L., Lu ZX., Hoelzl M., Bergmann A., Lauber P. Gyrokinetic simulations of neoclassical electron transport and bootstrap current generation in tokamak plasmas in the TRIMEG code. Physics of Plasmas (accepted)

Testing schemes in the TRIMEG code:

- Electromagnetic **implicit full-f PiC** method demonstrated [1]
- **GK-E&B model in torus** derived and demonstrated for challenging realistic plasma parameters (in 2D with drift electrons, in 3D fluid electrons) [2]
- Formulation and implementation of **pullback-mixed variable scheme** for δf and full f GK electromagnetic simulations [3]
- **Lorentz collisions** in realistic geometry for neoclassical electron transport and bootstrap current [4]
- **Ongoing:** Field aligned FEs; nonlinear collisions; aiming at efficient multi-n nonlinear simulations



Highlight: ITG and TEM turbulence (1)

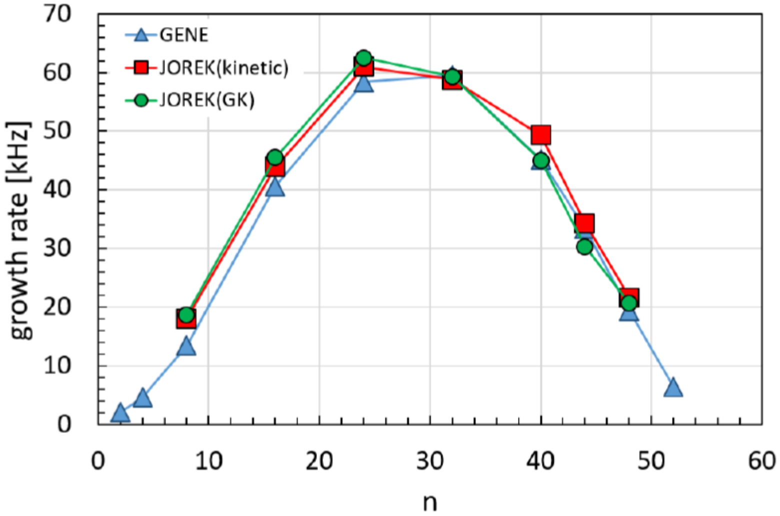
Huijsmans GTA, Becoulet M, Lu ZX, JOREK Team. Comparing linear stability of electrostatic kinetic and gyro-kinetic ITG modes. EPS 2023

Becoulet M, Huijsmans GTA, Garbet X, Donnel P, Wang L, et al, Non-linear gyro-kinetic ITG and TEM turbulence modelling in X-point geometry with RMPs. EPS 2023

$$\frac{d\vec{x}}{dt} = \frac{\vec{B}^*}{B_\parallel^*}u - \frac{\vec{b}\times\vec{E}^*}{\vec{b}\cdot\vec{B}^*} \qquad u = \vec{b}\cdot\frac{d\vec{x}}{dt}$$

$$\frac{du}{dt} = \frac{\vec{B}^*\cdot\vec{E}^*}{B_\parallel^*} \qquad \vec{B}^* = \nabla\times\vec{A}^* = \nabla\times\left(\vec{A}+u\vec{b}\right) \qquad \vec{E}^* = \langle\vec{E}\rangle - \mu\nabla B$$

Poisson equation: $n_i = n_e$



Adiabatic electrons =>ITGs only, no zonal in the model

$$\nabla\cdot\frac{m_i n_0}{q_i B^2}\nabla_\perp\phi - \frac{e n_0}{T_e}(\phi - \langle\phi\rangle) = n_i$$

$$\int -\nabla\left(\frac{T_e}{e n_0}v^*(\vec{x})\right)\cdot\frac{m_i n_0}{q_i B^2}\nabla_\perp\phi - v^*(\phi-\langle\phi\rangle)dV = \int\frac{T_e}{e n_0}v^*(\vec{x})\sum_{i=1}^{N} w_i\delta(\vec{x}-\vec{x}_i)\,dV$$

Adding kinetic electrons =>ITGs/TEMs, zonal flows

(Heavy electrons: m_i/m_e=100)

$$\int -\nabla\left(\frac{T_e}{e n_0}v^*(\vec{x})\right)\cdot\frac{m_i n_0}{q_i B^2}\nabla_\perp\phi - v^*\phi dV = \int\frac{T_e}{e n_0}v^*(\vec{x})\sum_{i=1}^{2N}\frac{q_i}{e}w_i\delta(\vec{x}-\vec{x}_i)\,dV$$

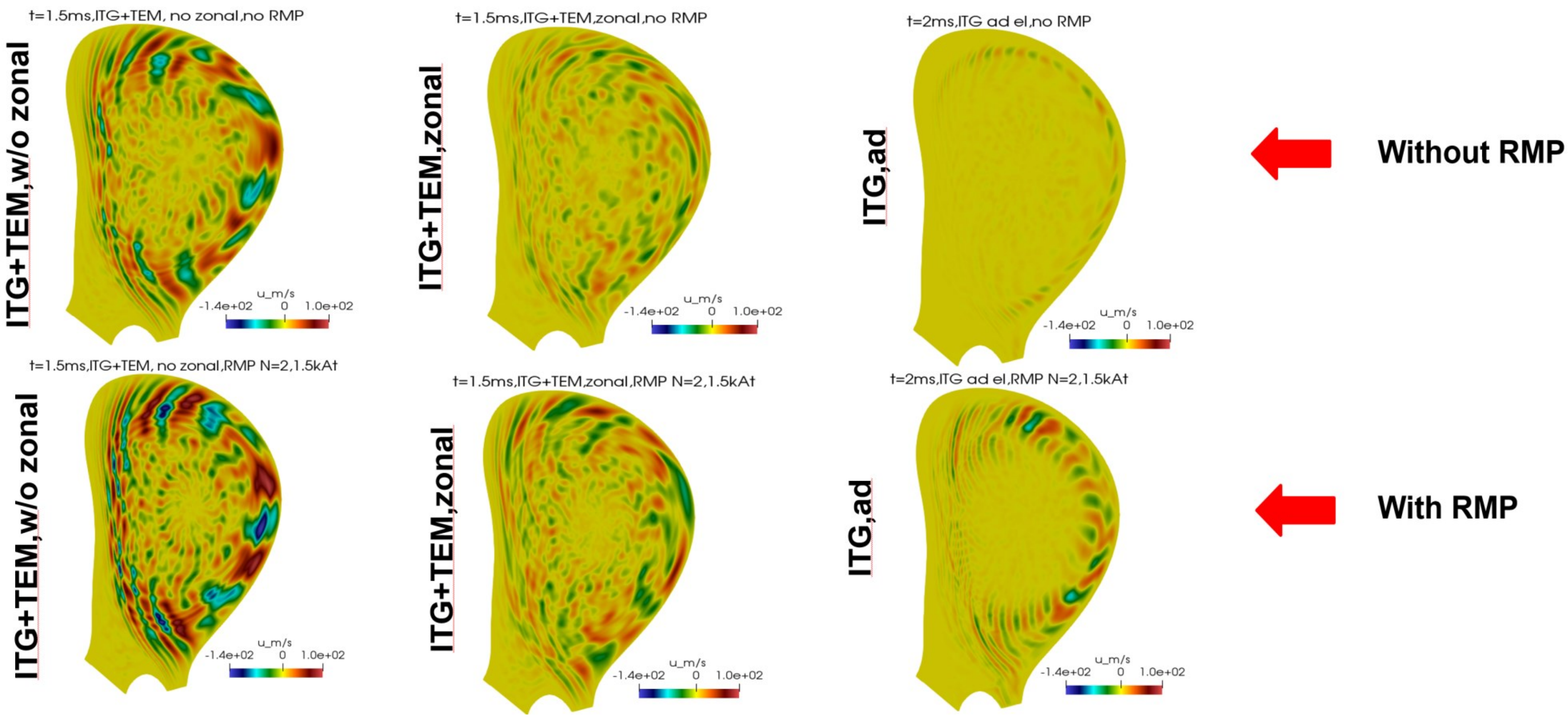
Highlight: ITG and TEM turbulence (2)

Huijsmans GTA, Becoulet M, Lu ZX, JOREK Team. Comparing linear stability of electrostatic kinetic and gyro-kinetic ITG modes. EPS 2023

Becoulet M, Huijsmans GTA, Garbet X, Donnel P, Wang L, et al, Non-linear gyro-kinetic ITG and TEM turbulence modelling in X-point geometry with RMPs. EPS 2023

COMPASS L-mode:

- **Larger turbulence in presence of RMP fields**
- **TEM+ITG turbulence stronger than ITG only**



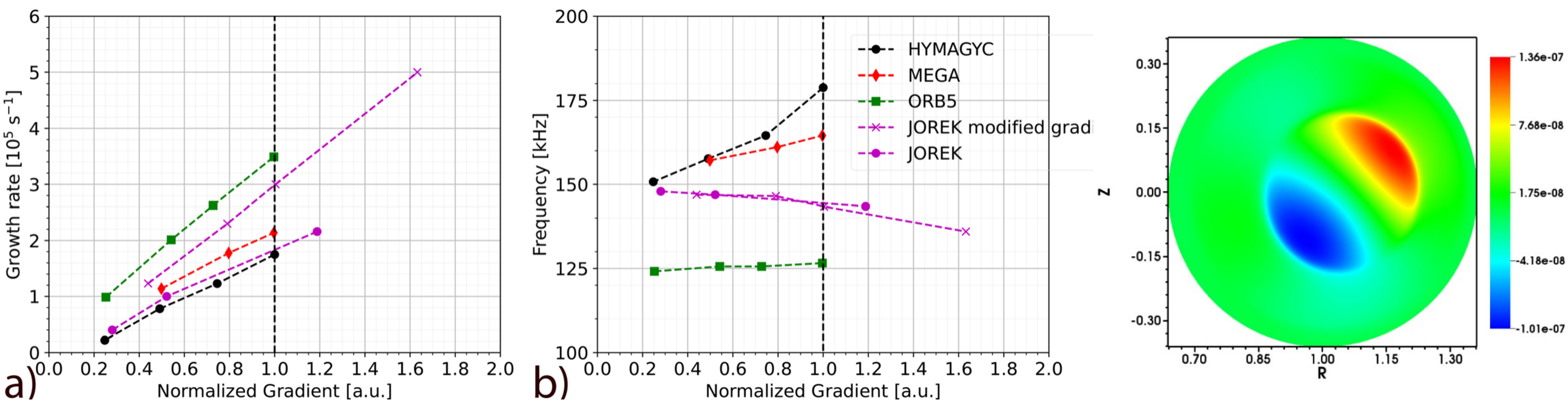
Highlight: Energetic particle model

Bogaarts T.J., Hoelzl M., Huijsmans G.T.A., Wang X., JOREK Team. Development and application of a hybrid MHD-kinetic model in JOREK. Physics of Plasmas 29, 122501 (2022) doi:10.1063/5.0119435

Antlitz F et al, in progress

- **Full-f PiC energetic particle model** with anisotropic pressure coupling to reduced and full MHD
- Benchmarked for TAEs (ITPA case)
- Comprehensive phase-space diagnostics
- AUG interpretative simulations for NLED case

- **Non-linear fishbone** simulations on the way
  + New model with kinetic thermal ions in development



Work package ELMs

Work package ELMs

- RMP ELM suppression in ITER
- RMP pump-out by electron polarization drift
- ITG & TEM turbulence with RMPs (see WP kinetics)
- ELM electron acceleration
- **Advanced SOL/divertor model ►**
- **Pellet-ELM triggering studies►**
- **Free boundary RMP model ►**
- **Island at pedestal top w/ RMP ►**
- **Small ELMs►**
- **QH-mode ►**

- ***Cathey A. Non-linear magnetohydrodynamic simulations of edge localised modes (ELMs). PhD Thesis (2021).*** ***https://pure.mpg.de/rest/items/item_3344034_3/component/file_3344037/content***
- ***Mitterauer V. Non-linear simulations of the penetration of error fields into tokamak plasmas. master Thesis (2021).*** ***https://pure.mpg.de/rest/items/item_3347751_2/component/file_3347752/content***
- *Meier L. Numerical simulations of the access to QH-Mode in ASDEX Upgrade. master Thesis (2022).* *https://pure.tue.nl/ws/portalfiles/portal/268417590/1498509_Meier_L.D._MSc_thesis_report_NF.pdf*

- **Futatani S, Cathey A, Hoelzl M, et al. Transition from no-ELM response to pellet ELM triggering during pedestal build-up - insights from extended MHD simulations.. Nuclear Fusion 61, 046043 (2021) doi:10.1088/1741-4326/abdfb4**
- **Cathey A., Hoelzl M., Futatani S., Lang P.T., Lackner K., et al. Comparing spontaneous and pellet-triggered ELMs via non-linear extended MHD simulations. PPCF 63, 075016 (2021) doi:10.1088/1361-6587/abf80b**
- **Becoulet M., Huijsmans G.T.A., Passeron C., Liu Y.Q., Evans T.E., et al. Non-linear MHD modelling of edge localized modes suppression by resonant magnetic perturbations in ITER. Nuclear Fusion 62, 066022 (2022) doi:10.1088/1741-4326/ac47af**
- **Cathey A., Hoelzl M., Harrer G., Wolfrum E., Lackner K., et al. MHD simulations of small ELMs at low triangularity in ASDEX Upgrade. Plasma Physics and Controlled Fusion 64, 054011 (2022) doi:10.1088/1361-6587/ac5b4b**
- **Kim S.K., Pamela S., Logan N.C., Na Y.-S., Lee C.Y., et al. Nonlinear MHD modeling of n = 1 RMP-induced pedestal transport and mode coupling effects on ELM suppression in KSTAR. Nuclear Fusion 62, 106021 (2022) doi:10.1088/1741-4326/ac84ef**
- **Isliker H, Cathey A, Hoelzl M, Pamela SJP, Vlahos L. Filamentary plasma eruptions and the heating and acceleration of electrons. Physics of Plasmas 29, 112306 (2022) doi:10.1063/5.0115754**
- **Mitterauer V., Hoelzl M., Schwarz N., Artola J., Willensdorfer M., et al. Non-linear free boundary simulations of the plasma response to resonant magnetic perturbations in ASDEX Upgrade plasmas. Journal of Physics: Conference Series 2397, 012008 (2022) doi:10.1088/1742-6596/2397/1/012008**
- **Korving S.Q., Huijsmans G.T.A., Park J.-S., Loarte A., JOREK Team. Development of the neutral model in the nonlinear MHD code JOREK: Application to ExB drifts in ITER PFPO-1 plasmas. Physics of Plasmas 30, 042509 (2023) doi:10.1063/5.0135318**
- **Cathey A, Hoelzl M, Gil L, Dunne MG, Harrer GF, et al, EUROfusion MST1 Team. Probing non-linear MHD stability of the EDA H-mode in ASDEX Upgrade. Nuclear Fusion 63, 062001 (2023) doi:10.1088/1741-4326/acc818**
- **Meier L, Hoelzl M, Cathey A, Huijsmans GTA, Viezzer E, et al. MHD simulations of formation, sustainment and loss of Quiescent H-mode in the all-tungsten ASDEX Upgrade. Nuclear Fusion (accepted)**
- **Willensdorfer M, Mitterauer V, Hoelzl M, Suttrop W, et al. Magnetic islands in 3D tokamak plasmas during suppression of edge localised modes. Nature Physics (in preparation)**

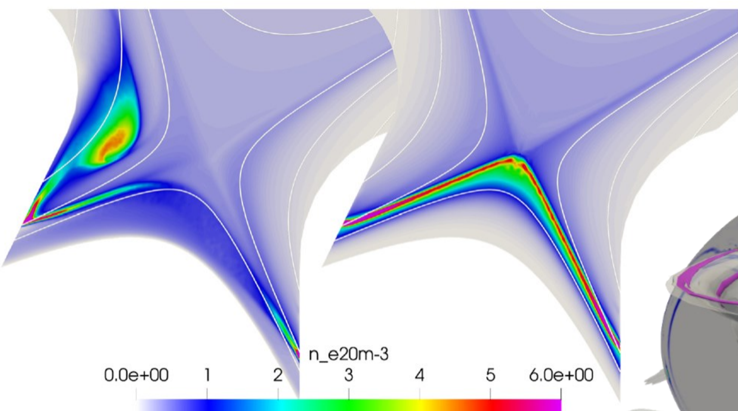
Highlight: SOL & divertor modeling

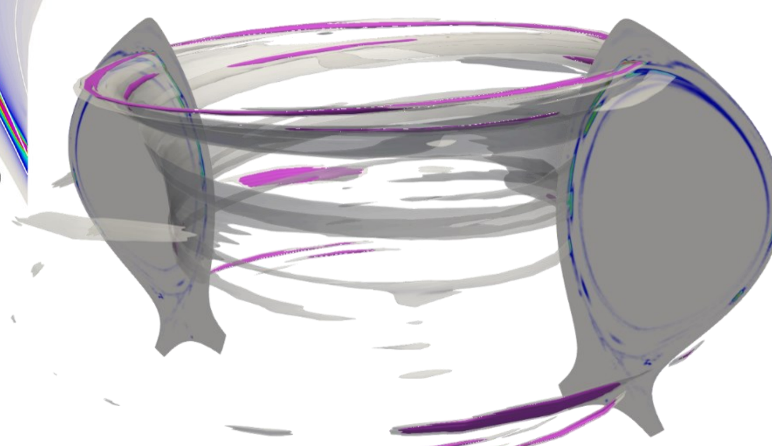
Korving S.Q., Huijsmans G.T.A., Park J.-S., Loarte A., JOREK Team. Development of the neutral model in the nonlinear MHD code JOREK: Application to ExB drifts in ITER PFPO-1 plasmas. Physics of Plasmas 30, 042509 (2023) doi:10.1063/5.0135318

Koving SQ, Huijsmans GTA, Mitterauer V, Loarte A et al. Simulation of neoclassical heavy impurity transport in AUG with applied 3D magnetic fields with the nonlinear MHD code JOREK. EPS 2023

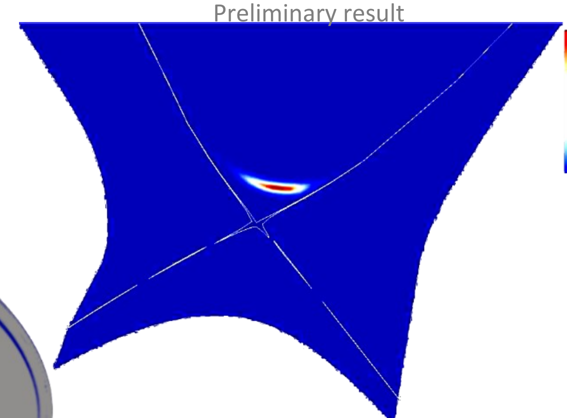
van Tongeren J et al, in preparation

- **Kinetic neutrals and impurities** implemented incl. neoclassical collisions; molecular physics extension on the way
- Extensively benchmarked to SOLPS-ITER
- Applications: HFSHD formation in ITER, tungsten transport w/ RMPs in AUG, X-point radiator in AUG, …





Preliminary result

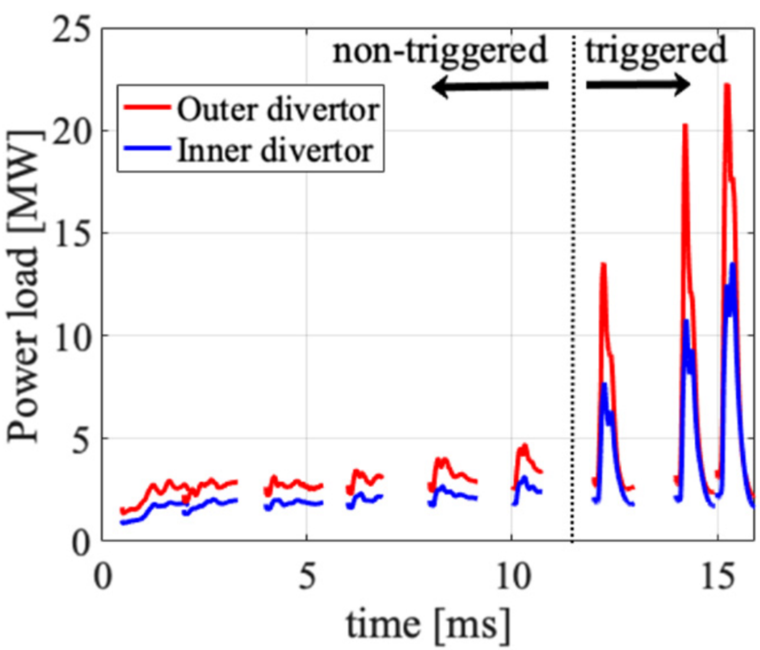


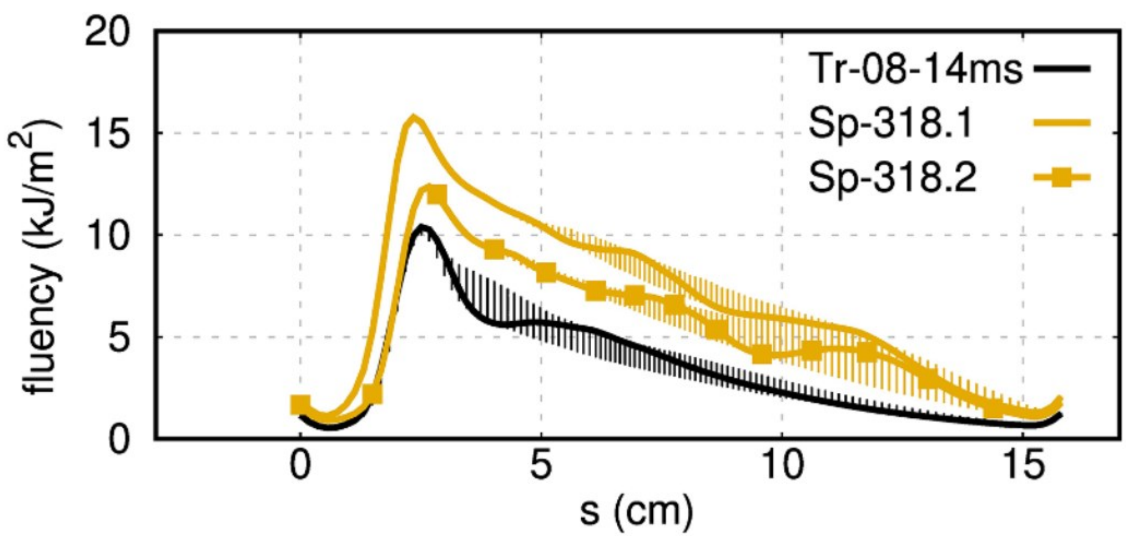
Highlight: Pellet ELM triggering

Futatani S, Cathey A, Hoelzl M, et al. Transition from no-ELM response to pellet ELM triggering during pedestal build-up - insights from extended MHD simulations.. Nuclear Fusion 61, 046043 (2021) doi:10.1088/1741-4326/abdfb4

Cathey A., Hoelzl M., Futatani S., Lang P.T., Lackner K., Huijsmans G.T.A., Pamela S.J.P., Günter S., JOREK Team, ASDEX Upgrade Team, EUROfusion MST1 Team. Comparing spontaneous and pellet-triggered ELMs via non-linear extended MHD simulations. PPCF 63, 075016 (2021) doi:10.1088/1361-6587/abf80b

- AUG pellet simulations with realistic parameters and plasma flows **reproduce experimental lag-time** during which ELM triggering is not possible
- Pellet reduces ELM size, but also narrows deposition

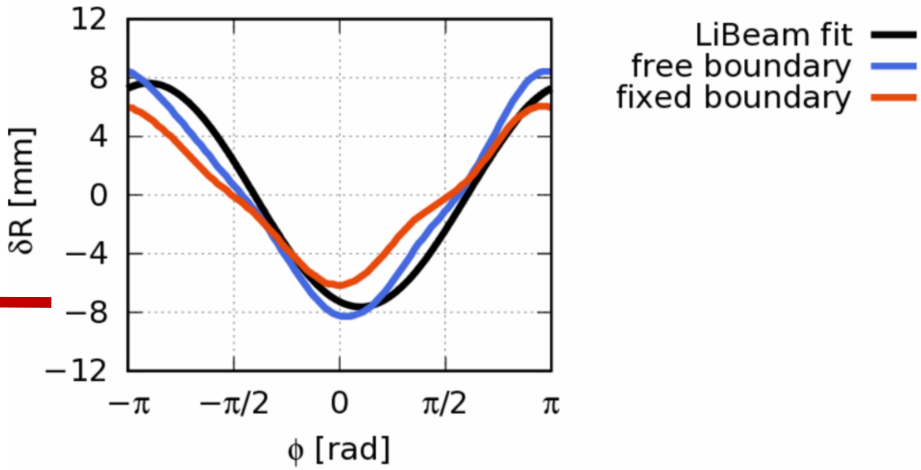


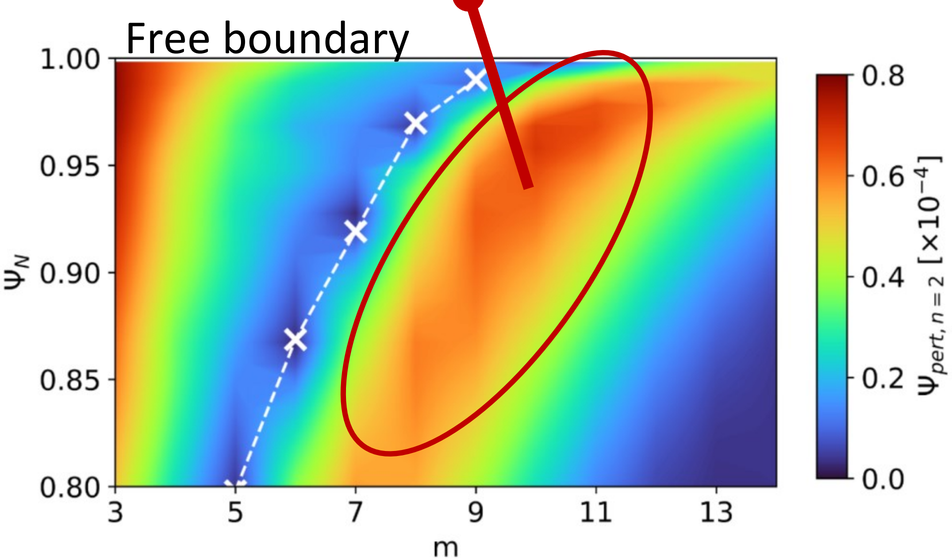


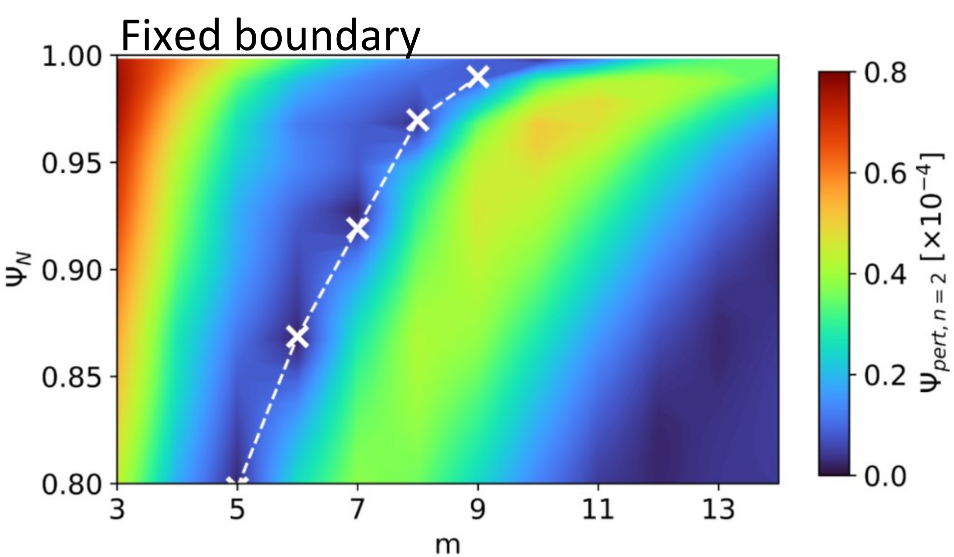
Highlight: Free boundary RMPs

Mitterauer V., Hoelzl M., Schwarz N., Artola J., Willensdorfer M., Dunne M., JOREK Team, ASDEX Upgrade Team, EUROfusion MST1 Team. Non-linear free boundary simulations of the plasma response to resonant magnetic perturbations in ASDEX Upgrade plasmas. Journal of Physics: Conference Series 2397, 012008 (2022) doi:10.1088/1742-6596/2397/1/012008

- Self-consistent modelling of RMPs includes the plasma response up to the boundary of the simulation domain
- **Validated against AUG**
- **Allows to capture external kink response accurately**



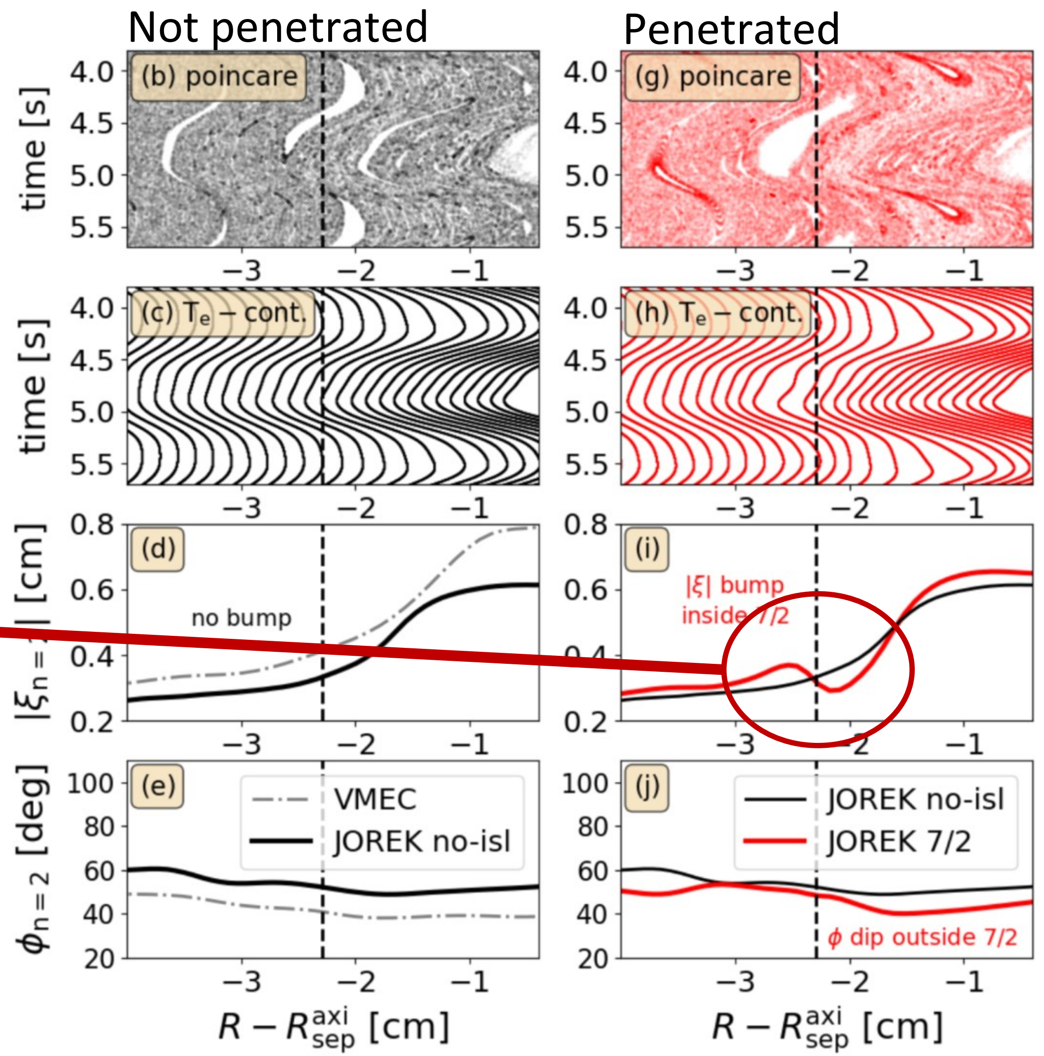




Highlight: Pedestal Island w/ RMPs

- **First of a kind evidence for a 7/2 island at the pedestal top in RMP ELM suppression at AUG**
- JOREK simulations reproduce the corresponding "bump" in the displacement for penetrated islands

Willensdorfer M, Mitterauer V, Hoelzl M, Suttrop W, et al. Magnetic islands in 3D tokamak plasmas during suppression of edge localised modes. Nature Physics (in preparation)

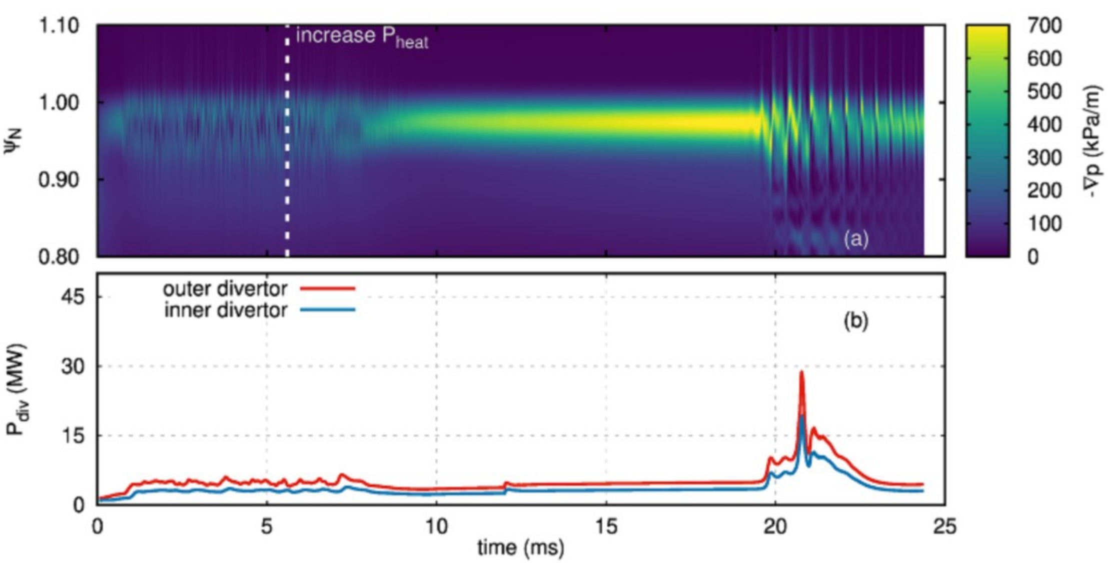


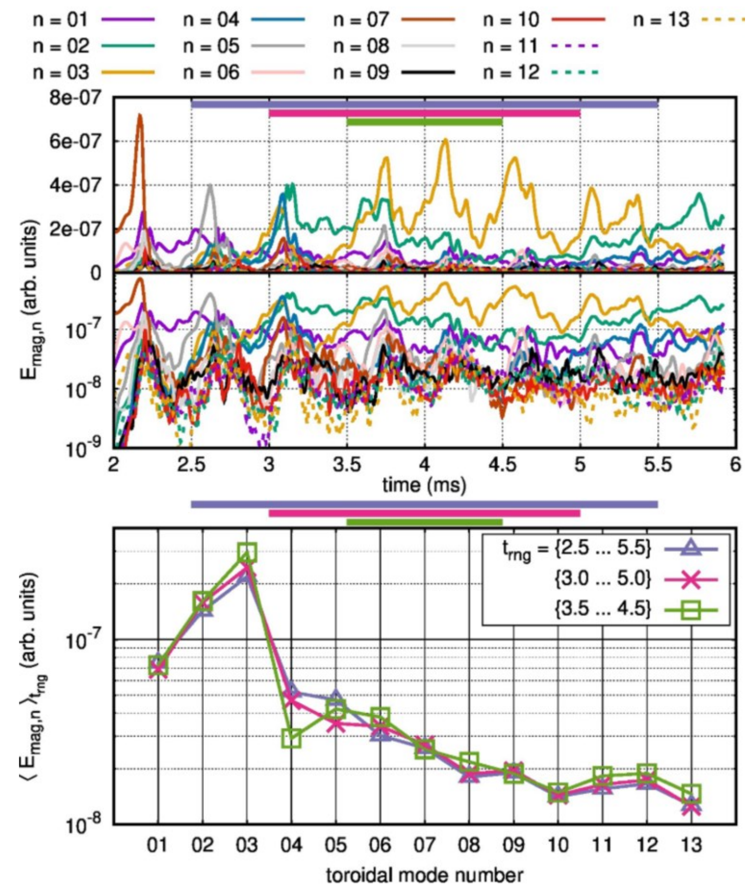
Highlight: Small-ELM regimes

Cathey A., Hoelzl M., Harrer G., Wolfrum E., Lackner K., et al. MHD simulations of small ELMs at low triangularity in AUG. Plasma Physics and Controlled Fusion 64, 054011 (2022) doi:10.1088/1361-6587/ac5b4b

Cathey A, Hoelzl M, Gil L, Dunne MG, Harrer GF,. Probing non-linear MHD stability of the EDA H-mode in ASDEX Upgrade. Nuclear Fusion 63, 062001 (2023) doi:10.1088/1741-4326/acc818

- **QCE in AUG:** peeling-ballooning turbulence stops pedestal build-up towards ELMs; transition small to large ELMs at higher heating power or lower density (bottom)
- **EDA H-mode in AUG:** Resistive ballooning modes; structure and rotation comparable to experiment (right)



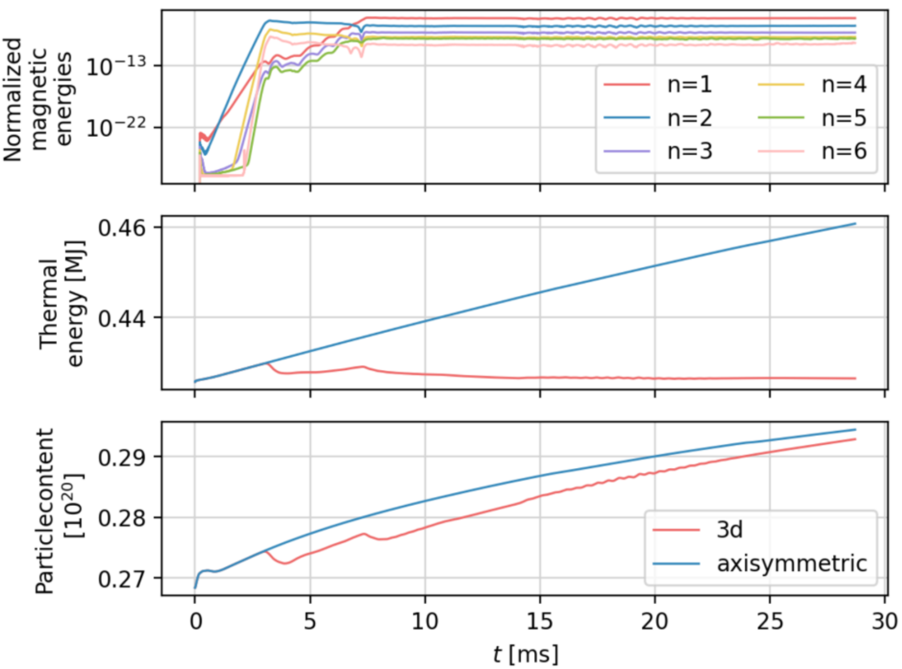


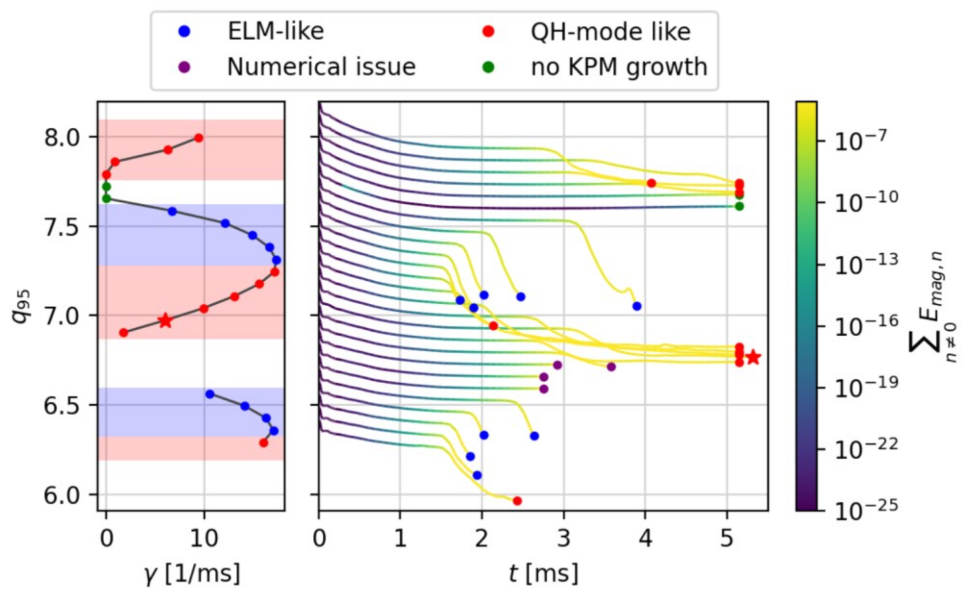
Highlight: ELM free QH-mode

Meier L, Hoelzl M, Cathey A, Huijsmans GTA, Viezzer E, Dunne M, van Dijk J. et al. MHD simulations of formation, sustainment and loss of Quiescent H-mode in the all-tungsten ASDEX Upgrade. Nuclear Fusion (accepted)

AUG simulations for QH-mode with tungsten walls reproduce experimental observations and provide insights into mechanisms

- Saturated n=1 external kink mode at plasma boundary
- Edge harmonic oscillation in the density obtained
- q95 windows // non-linear q95 evolution contributes to saturation
- Transition to ELMs at increased density, limit cycle oscillations





Work package Disruptions

Work package Disruptions

- 3D CQ in ITER + Trapped REs
- **Enhanced impurity model ►**
- **SPI in JET, ITER & AUG ►**
- **Ion saturation current limit ►**
- **Hot VDEs in AUG ►**
- **Vertical force mitigation ►**
- **JOREK-CARIDDI coupling ►**
- **Benign RE termination ►**
- **3D ITER RE termination ►**

- ***Wieschollek F. Non-linear Simulations of Natural and Mitigated Disruptions. PhD Thesis (subm.)***
- **Hu D, Nardon E, Hoelzl M, Wieschollek F, Lehnen M,et al. Radiation asymmetry and MHD destabilization during the thermal quench after impurity shattered pellet injection. Nuclear Fusion 61, 026015 (2021) doi:10.1088/1741-4326/abcbcb**
- **Bandaru V, Hoelzl M, Reux C, Ficker O, Silburn S, et al. Magnetohydrodynamic simulations of runaway electron beam termination in JET. Plasma Physics and Controlled Fusion 63, 035024 (2021) doi:10.1088/1361-6587/abdbcf**
- Reux C, Paz-Soldan C, Aleynikov P, Bandaru V, Ficker O, et al. Demonstration of Safe Termination of Megaampere Relativistic Electron Beams in Tokamaks. PRL 126, 175001 (2021) doi:10.1103/PhysRevLett.126.175001
- **Artola F.J., Loarte A., Matveeva E., Havlicek J., Markovic T., et al. Simulations of COMPASS vertical displacement events with a self-consistent model for halo currents including neutrals and sheath boundary conditions. PPCF 63, 064004 (2021) doi:10.1088/1361-6587/abf620**
- **Artola F.J.,Sovinec C.R., Jardin S.C., Hoelzl M., Krebs I., Clauser C. 3D simulations of vertical displacement events in tokamaks: A benchmark of M3D-C1, NIMROD, and JOREK. PoP 28, 052511 (2021) doi:10.1063/5.0037115**
- **Nardon E., Hu D., Artola F.J., Bonfiglio D., Hoelzl M., et al. Thermal quench and current profile relaxation dynamics in massive-material-injection-triggered tokamak disruptions. Plasma Physics and Controlled Fusion 63, 115006 (2021) doi:10.1088/1361-6587/ac234b**
- **Hu D., Huijsmans G.T.A., Nardon E., Hoelzl M., Lehnen M., et al. Collisional-radiative non-equilibrium impurity treatment for JOREK simulations. Plasma Physics and Controlled Fusion 63, 125003 (2021) doi:10.1088/1361-6587/ac2afb**
- **Wieschollek F., Hoelzl M., Nardon E., JOREK Team, ASDEX Upgrade Team, EUROfusion MST1 Team. On the role of preexisting MHD activity for the plasma response to massive deuterium injection. Physics of Plasmas 29, 032509 (2022) doi:10.1063/5.0075473**
- **Artola F.J., Loarte A., Hoelzl M., Lehnen M., Schwarz N., JOREK Team. Non-axisymmetric MHD simulations of the current quench phase of ITER mitigated disruptions. Nuclear Fusion 62, 056023 (2022) doi:10.1088/1741-4326/ac55ba**
- **Särkimäki K., Artola F.J., Hoelzl M. Confinement of passing and trapped runaway electrons in simulation of ITER current quench. Nuclear Fusion 62, 086033 (2022) doi:10.1088/1741-4326/ac75fd**
- **Schwarz N, Artola FJ, Hoelzl M, Bernert M, Brida D, et al. Experiments and non-linear MHD simulations of hot vertical displacement events in ASDEX-Upgrade. Plasma Physics and Controlled Fusion 65, 054003 (2023) doi:10.1088/1361-6587/acc358**
- **Nardon E., Särkimäki K., Artola F.J., Sadouni S.,et al. On the origin of the plasma current spike during a tokamak disruption and its relation with magnetic stochasticity. Nuclear Fusion 63, 056011 (2023) doi:10.1088/1741-4326/acc417**
- **Hu D., Nardon E., Artola F.J., Lehnen M., Bonfiglio D., et al. Collisional-radiative simulation of impurity assimilation, radiative collapse and MHD dynamics after ITER Shattered Pellet Injection. Nuclear Fusion 63, 066008 (2023) doi:10.1088/1741-4326/acc8e9**
- **Schwarz N, Artola FJ, Vannini F, Hoelzl M, Bernert M, et al. The mechanism of the global vertical force reduction in disruptions mitigated by massive material injection. Nuclear Fusion (submitted)**
- **Nardon E., Bandaru V., Hoelzl M., Artola F.J., the JOREK team, JET contributors. Non-linear dynamics of the double tearing mode. Physics of Plasmas (submitted)**
- **Nardon E., Särkimäki K., Artola F.J., Sadouni S., JOREK Team, JET contributors. On the origin of the plasma current spike during a tokamak disruption and its relation with magnetic stochasticity. Physics of Plasmas (submitted)**
- **Isernia N, Schwarz N, Artola FJ, Ventre S, Hoelzl M, Rubinacci G, Villone F. Self-consistent coupling of JOREK and CARIDDI: On the electromagnetic interaction of 3D tokamak plasmas with 3D volumetric conductors. Physics of Plasmas (on the pinboard)**
- **Kong M, Nardon E, Hoelzl M, Bonfiglio D, Hu D et al, Interpretative 3D MHD modelling of deuterium shattered pellet injection into a JET H-mode plasma. In preparation**
- **Bandaru V, Hoelzl M, Bergstroem H, Artola FJ, Särkimäki K, Lehnen M. Assessment of runaway electron beam termination and impact in ITER. Nuclear Fusion (in preparation)**
- **Tang W, et al, 3D non-linear simulations of shattered pellet injection in the ASDEX Upgrade tokamak. In preparation**
- **Bonfiglio D et al, 3D non-linear simulations of Neon and mixed SPI in JET. In preparation**

Highlight: Impurity model

Hu D, Huijsmans GTA, Nardon E, Hoelzl M et al. Collisional-radiative non-equilibrium impurity treatment for JOREK simulations. Plasma Physics and Controlled Fusion 63, 125003 (2021) doi:10.1088/1361-6587/ac2afb

Hu D, Nardon E, Artola FJ, Lehnen M et al. Collisional-radiative simulation of impurity assimilation, radiative collapse and MHD dynamics after ITER Shattered Pellet Injection. Nuclear Fusion 63, 066008 (2023) doi:10.1088/1741-4326/acc8e9

- Based on the PiC module, an **impurity treatment without the coronal equilibrium assumption** has been implemented and successfully benchmarked against other codes
- In production applications to ITER and other devices, this can capture dynamics more accurately than possible before (e.g. early radiation)

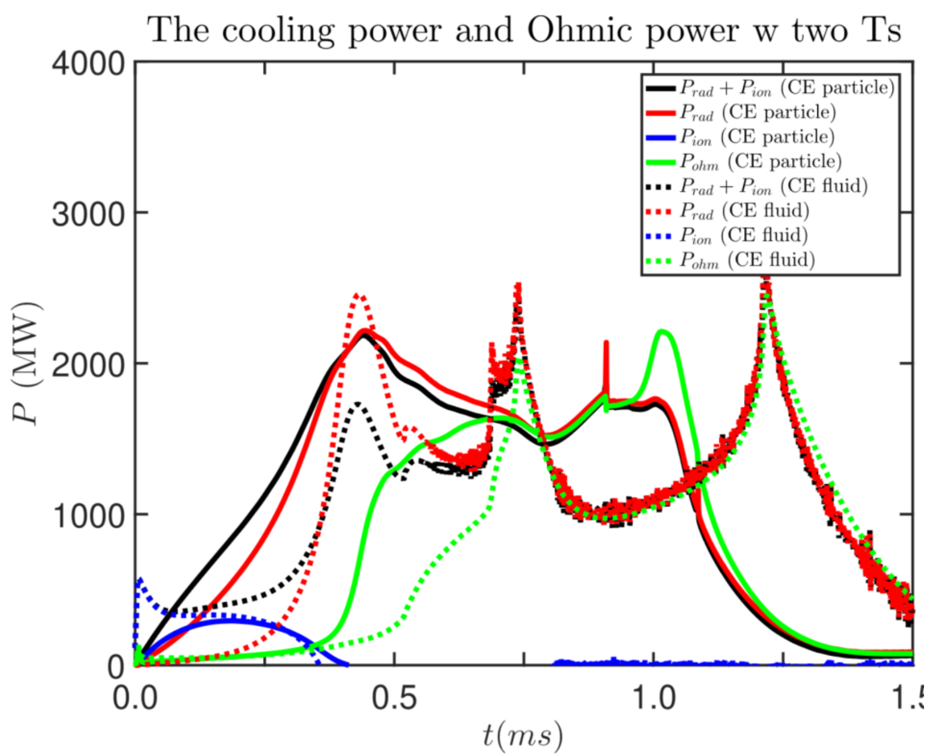
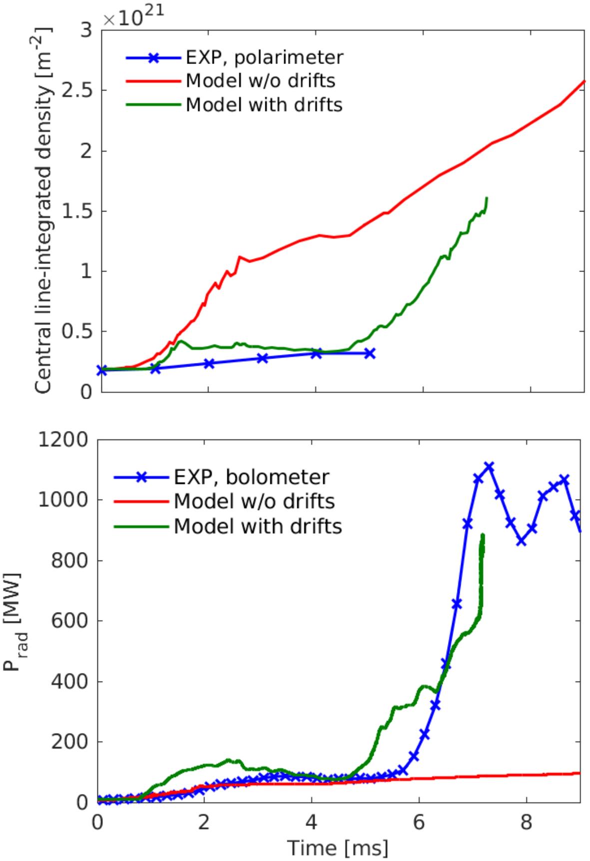


Figure 3. The radiation power (red), ionization power (blue) and Ohmic power (green) for the particle model (solid lines) and the CE model (dotted lines) with two temperature treatment. The black solid and dotted lines are the combined radiation and ionization power for the particle model and the CE model respectively.

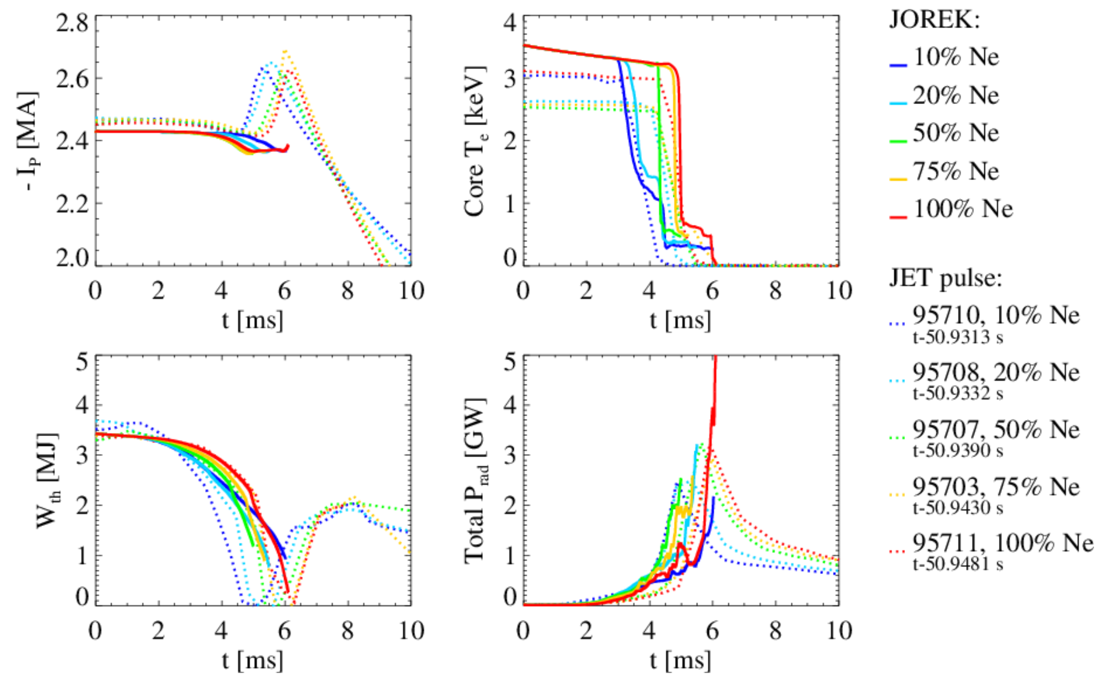
Highlight: SPI in JET

Kong M, Nardon E, Hoelzl M, Bonfiglio D, Hu D et al, Interpretative 3D MHD modelling of deuterium shattered pellet injection into a JET H-mode plasma. In preparation

Bonfiglio D et al, 3D non-linear simulations of Neon and mixed SPI in JET. In preparation



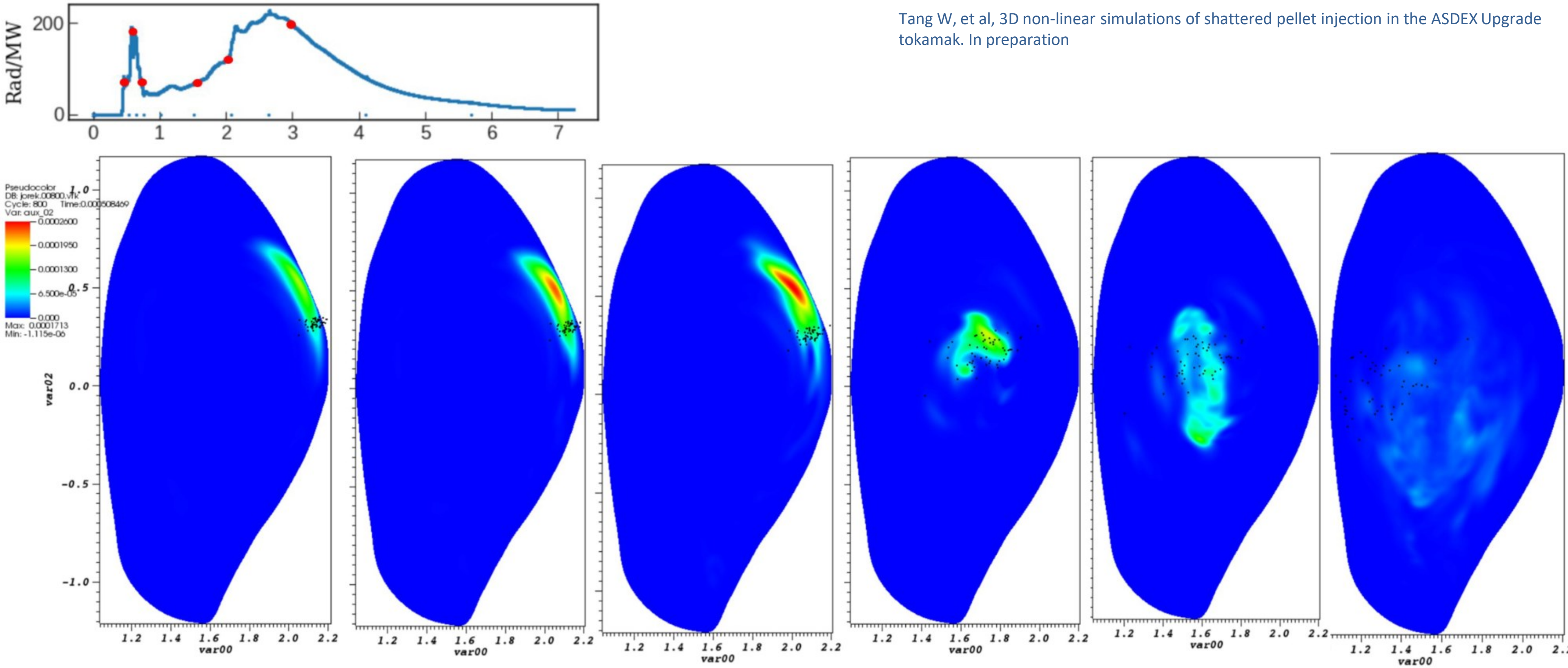
- **Pure D-SPI:** the plasmoid drift is essential to reproduce experimental material assimilation and radiation



- **Neon and mixed SPI:** simulations agree well with experiments (Ip spike is not yet realistic)

Highlight: SPI in AUG

Tang W, et al, 3D non-linear simulations of shattered pellet injection in the ASDEX Upgrade tokamak. In preparation

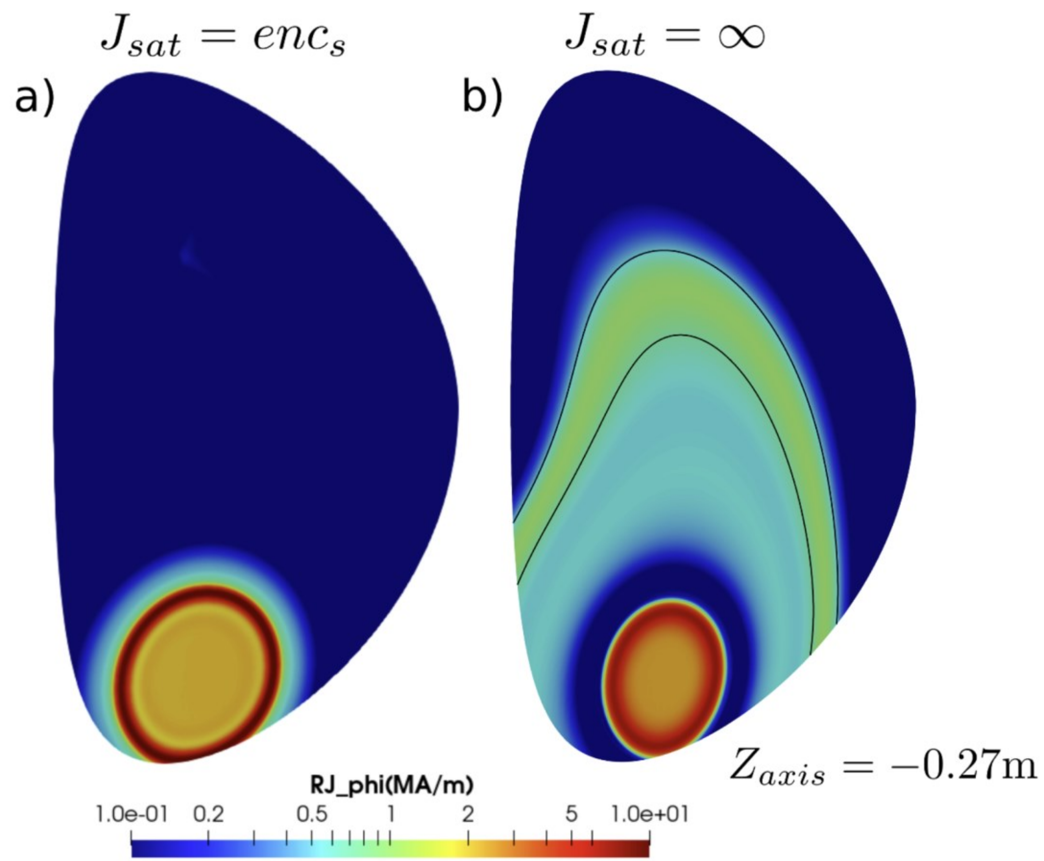


- **Injections with low Neon content show a double radiation peak** like in experiment with the first one originating from the edge (injection location) and the second one from the core
- Detailed comparisons for different injection parameters are on the way

Highlight: Ion saturation current

Artola F.J., Loarte A., Matveeva E., Havlicek J., Markovic T., et al. Simulations of COMPASS vertical displacement events with a self-consistent model for halo currents including neutrals and sheath boundary conditions. PPCF 63, 064004 (2021) doi:10.1088/1361-6587/abf620

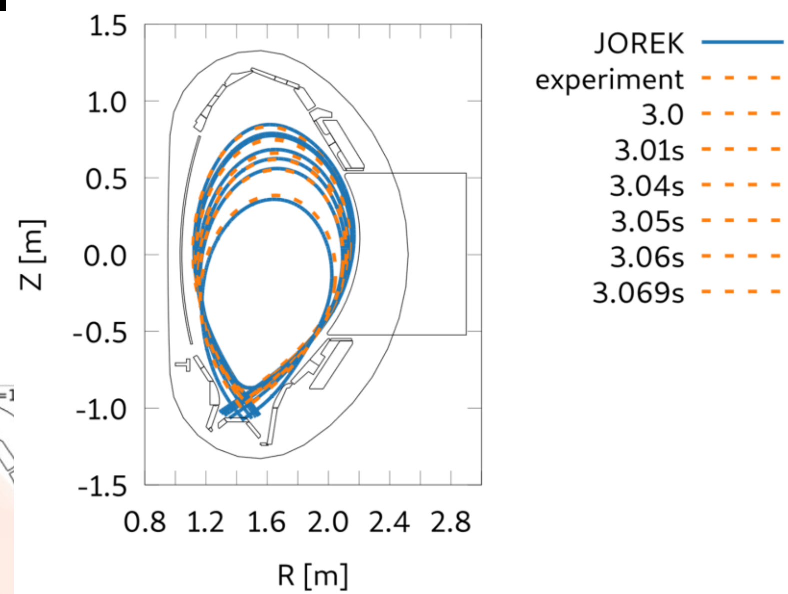
- Dedicated COMPASS studies show that the **ion saturation current is important to capture the halo current distribution** (besides realistic anisotropic heat diffusion, impurities, neutrals etc.)
- Simulations taking the limit into account demonstrate this effect and agree well with experiments

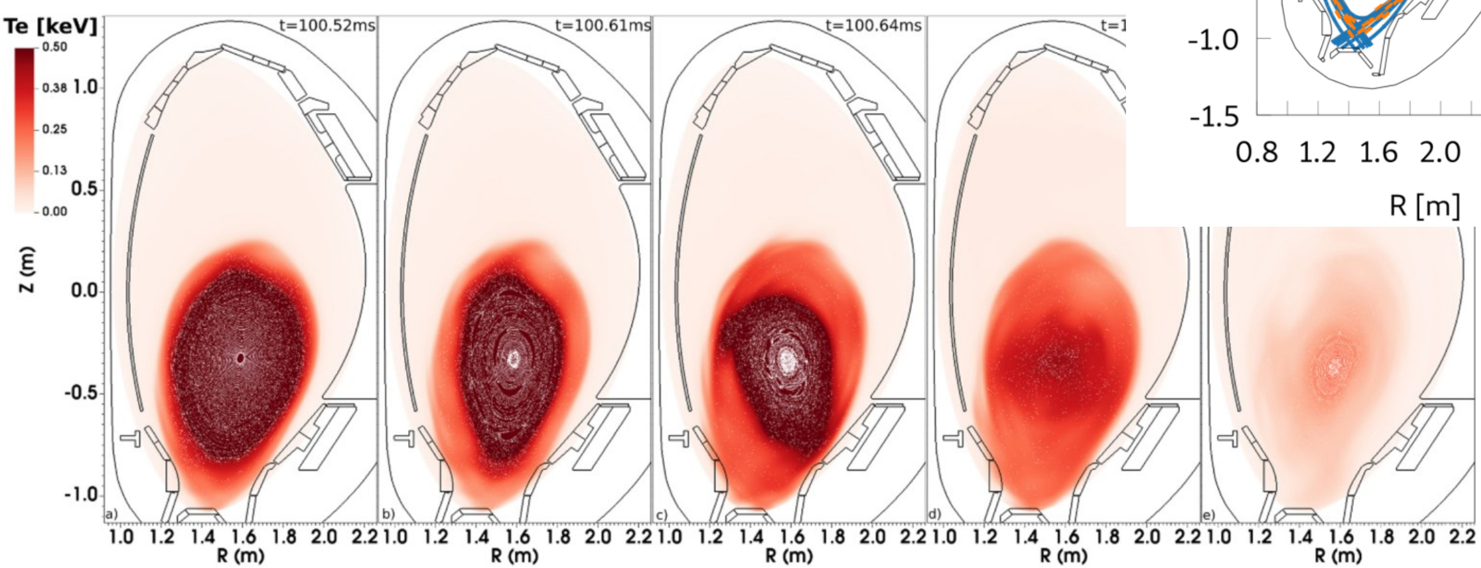


Highlight: Unmitigated VDEs in AUG

Schwarz N, Artola FJ, Hoelzl M, Bernert M, et al. Experiments and non-linear MHD simulations of hot vertical displacement events in ASDEX-Upgrade. Plasma Physics and Controlled Fusion 65, 054003 (2023) doi:10.1088/1361-6587/acc358

- Dedicated AUG experiments of unmitigated VDEs
- **Simulations reproduce vertical plasma motion, magnitude of halo currents, magnitude of vertical force, TQ onset point**





Highlight: Force mitigation

Schwarz N, Artola FJ, Vannini F, Hoelzl M, et al. The mechanism of the global vertical force reduction in disruptions mitigated by massive material injection. Nuclear Fusion (submitted)

Previously:

- force reduction explained by reduction of poloidal halo currents

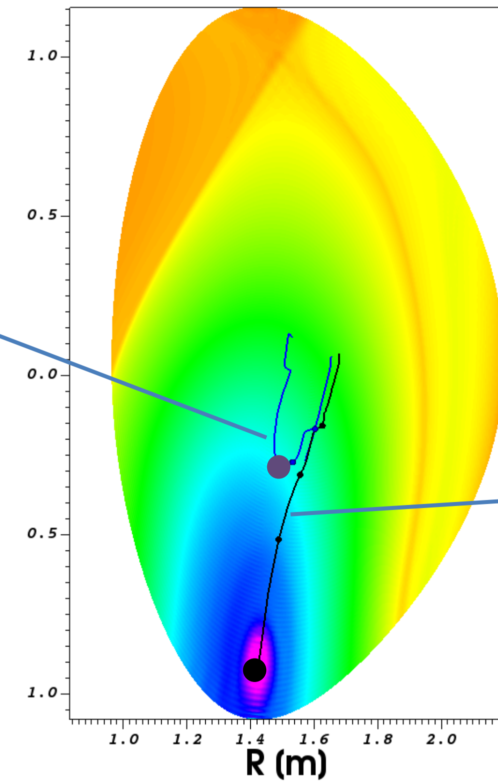
New theory:

- **The vertical force is connected to the current centroid**

$$F_z \propto I_p \Delta z_{curr}$$

- **Impurity injection leads to a flattening of the current profile beyond the separatrix**

□ **toroidal SOL currents stabilize centroid motion and reduce forces**



Late during VDE:

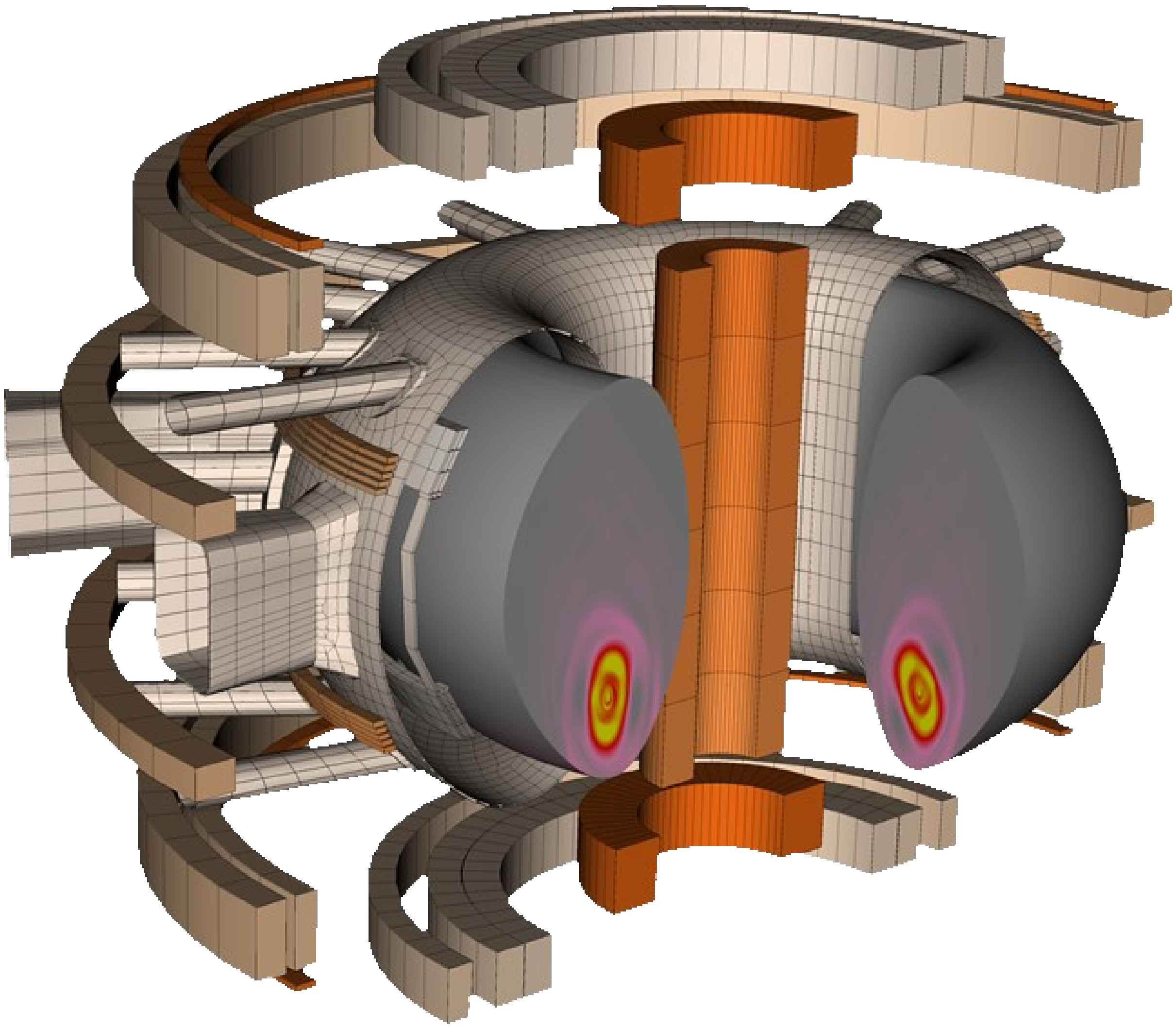
Axis reaches the wall, i.e., separatrix vanishes

Current centroid remains close to the midplane

Highlight: JOREK-CARIDDI coupling

Isernia N, Schwarz N, Artola FJ, Ventre S, Hoelzl M, Rubinacci G, Villone F. Self-consistent coupling of JOREK and CARIDDI: On the electromagnetic interaction of 3D tokamak plasmas with 3D volumetric conductors. Physics of Plasmas (on the pinboard)

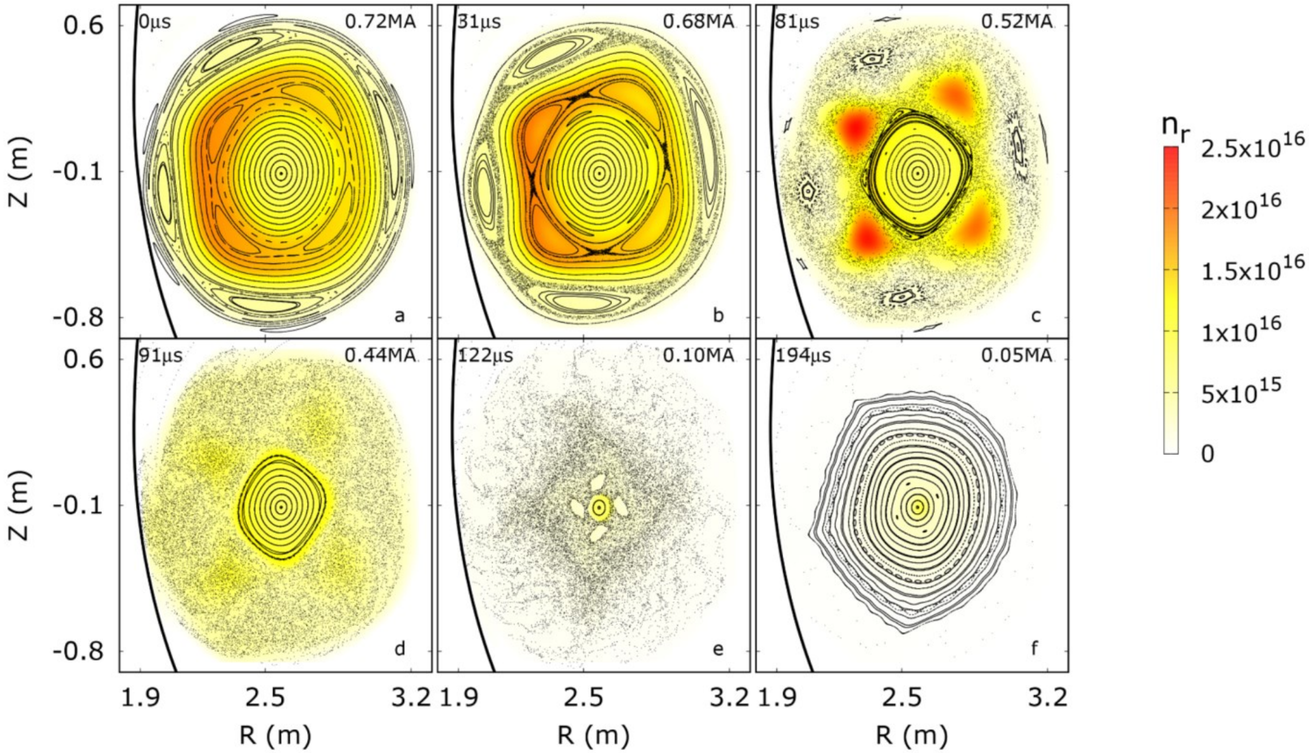
- **JOREK-CARIDDI eddy current coupling completed and tested**
- Halo current coupling is future work
- Enables accurate 3D plasma 3D wall studies
- One of the first applications: 3D VDE in AUG



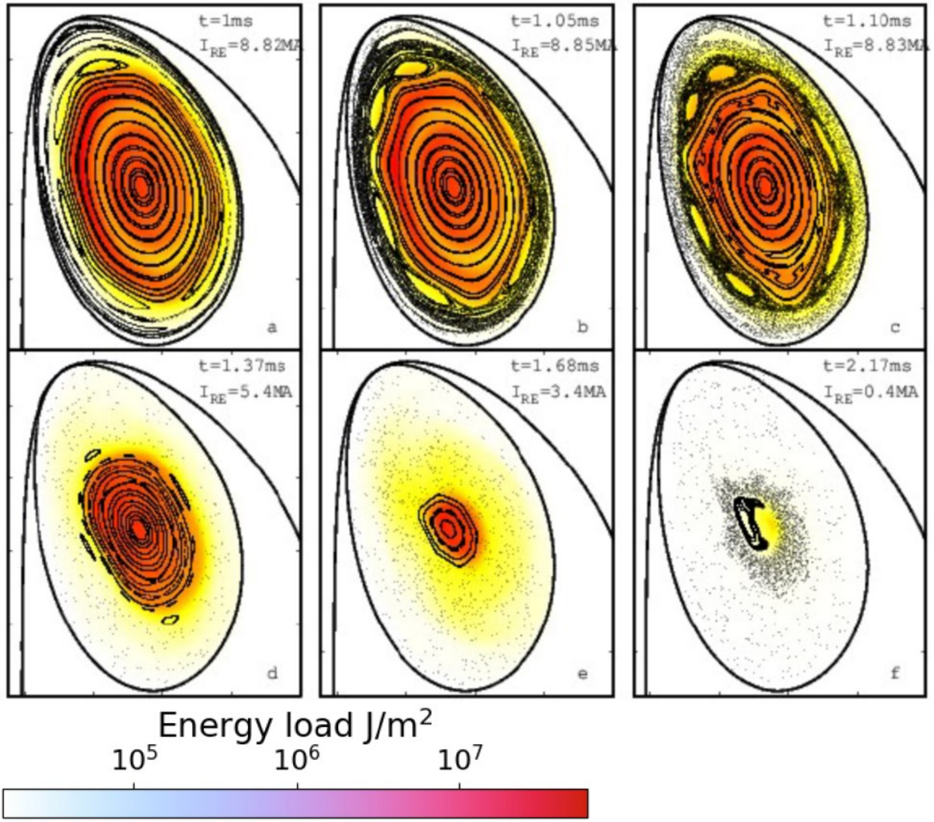
Highlight: Benign RE termination

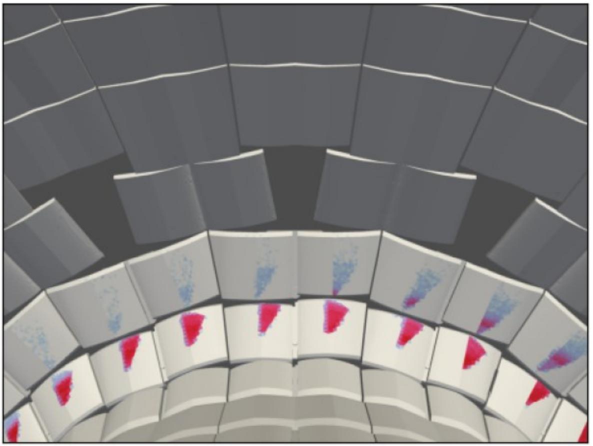
Bandaru V, Hoelzl M, Reux C, Ficker O, Silburn S, et al. Magnetohydrodynamic simulations of runaway electron beam termination in JET. Plasma Physics and Controlled Fusion 63, 035024 (2021) doi:10.1088/1361-6587/abdbcf

- **Double TM instability after secondary D-SPI proposed to explain benign termination**
- Important role of stochastization front moving inwards from the edge



Highlight: ITER 3D RE studies





Bandaru V, Hoelzl M, Bergstroem H, Artola FJ, Särkimäki K, Lehnen M. Assessment of runaway electron beam termination and impact in ITER. Nuclear Fusion (in preparation)

Bergstroem H, Saerkimaeki K, et al, in preparation

- **3D ITER simulations of RE termination**
- Also re-formation observed
- **Load to 3D walls**: 0.1 to 1 m^2 exposed to a load beyond the tungsten / beryllium melting threshold
- Role of resistivity and density

- DEMO studies started

Further activities

Further Activities

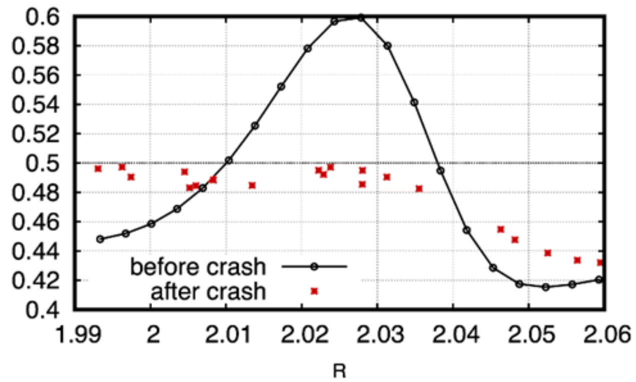
- **Supporting development of a stellarators extension ►**

- *Nikulsin N. Models and methods for nonlinear magnetohydrodynamic simulations of stellarators. PhD Thesis (2021). https://pure.mpg.de/rest/items/item_3359934_3/component/file_3359935/content*
- *Ramasamy R. Equilibrium and initial value problem simulation studies of nonlinear magnetohydrodynamics in stellarators. PhD Thesis (2022). https://hdl.handle.net/21.11116/0000-000B-FD50-E*

- **Nikulsin N., Hoelzl M., Zocco A., Lackner K., Günter S., JOREK Team. Testing of the new JOREK stellarator-capable model in the tokamak limit. JPP 87, 855870301 (2021) doi:10.1017/S0022377821000477**
- **Ramasamy R., Hoelzl M., Strumberger E., Lackner K., Günter S.. Nonlinear MHD simulations of external kinks in quasi-axisymmetric stellarators using an axisymmetric external rotational transform approximation. Nuclear Fusion 61, 076017 (2021) doi:10.1088/1741-4326/abffdf**
- **Nikulsin N., Ramasamy R., Hoelzl M., Hindenlang F., Strumberger E., et al. JOREK3D: An extension of the JOREK nonlinear MHD code to stellarators. Physics of Plasmas 29, 063901 (2022) doi:https://doi.org/10.1063/5.0087104**
- **Ramasamy R., Bustos Ramirez G., Hoelzl M., Graves J., Suarez Lopez G., et al. Modeling of saturated external MHD instabilities in tokamaks: A comparison of 3D free boundary equilibria and nonlinear stability calculations. Physics of Plasmas 29, 072303 (2022) doi:10.1063/5.0090008**
- **Ramasamy R., Hoelzl M., Henneberg S., Strumberger E., Lackner K., Guenter S. How well can VMEC predict the initial saturation of external kink modes in near circular tokamaks and l=2 stellarators? Physics of Plasmas 30, 062506 (2023)**
- Aleynikova K, Ramasamy R, Nikulsin N, Hindenlang F, Hoelzl M. Nonlinear tearing mode evolution and sawtooth crashes in a stellarators. EPS 2023
- Ramasamy R, et al, in preparation

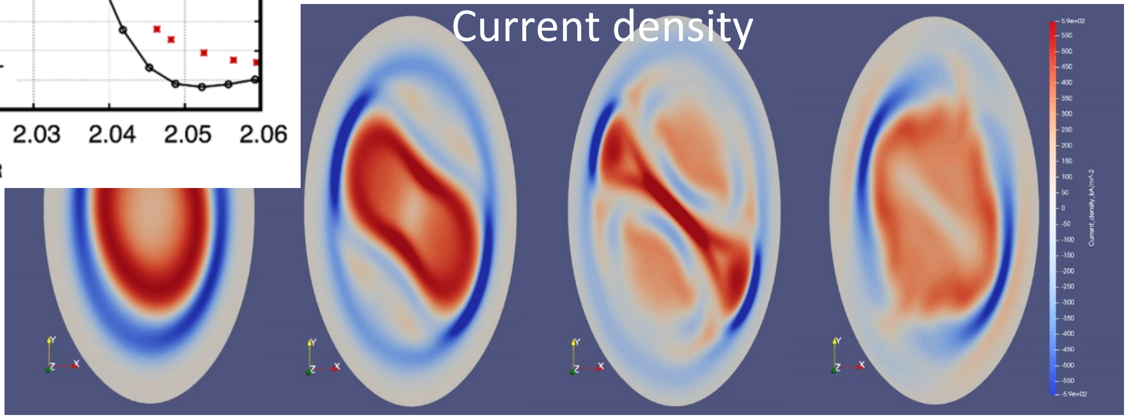
Highlight: First stellarator simulations

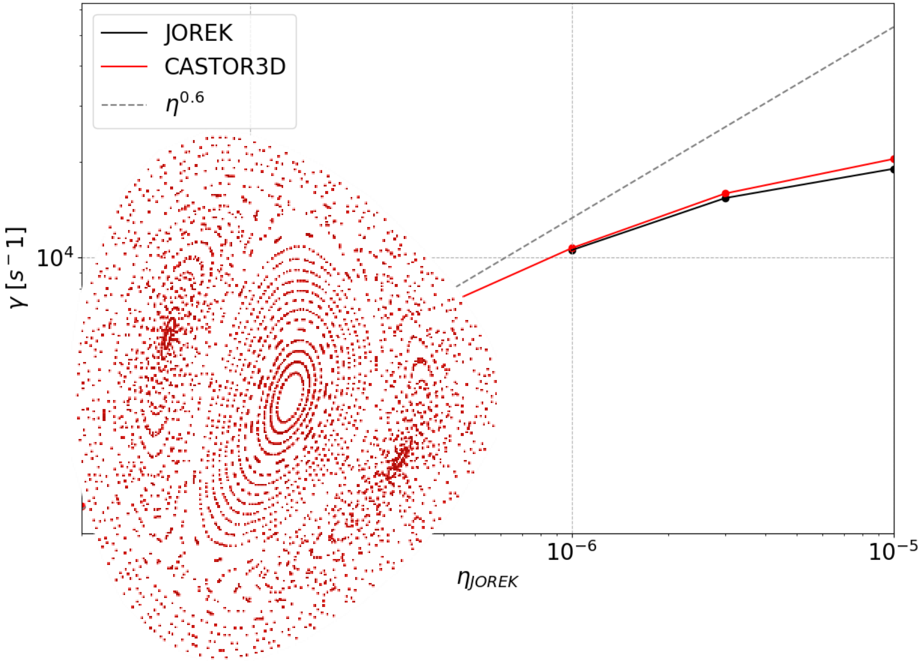
- **Non-linear dynamics of double TM** instability in W7-A



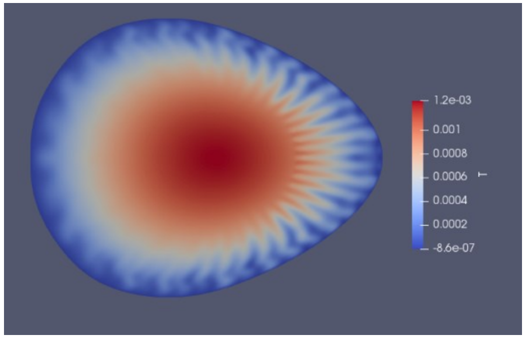
Aleynikova K, Ramasamy R, Nikulsin N, Hindenlang F, Hoelzl M. Nonlinear tearing mode evolution and sawtooth crashes in a stellarators. EPS 2023

Ramasamy R et al, in preparation





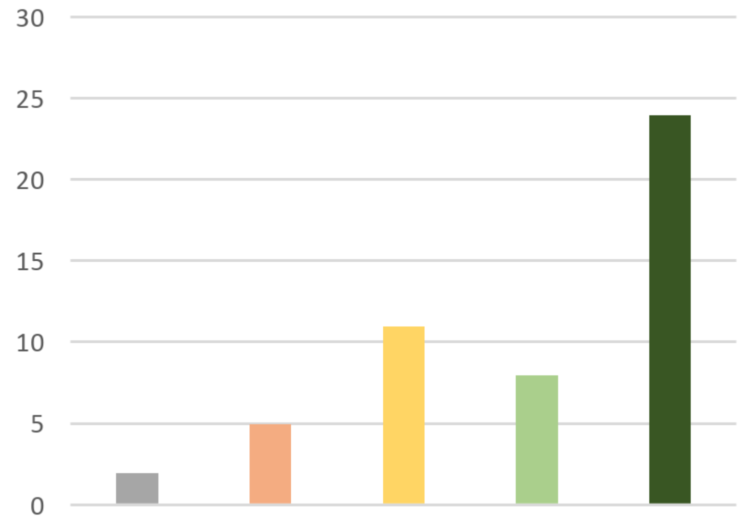
- **Successful benchmark for TM in W7-AS geometry + ballooning mode tests** (first applications to advanced stellarators)



Conclusions

- **Good progress in all work packages**
- **More than 45 refereed publications** where the 1st/2nd/3rd author is a project contributor + many more in preparation

- **Milestones:**
  - **48% completed**
  - **16% almost complete**
  - 22% half way
  - 10% started
  - 4% not started



- More details regarding milest
  discussed in the midterm review presentation