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0 0 Transient processes in fusion plasmas – 0 0 Non-linear MHD modelling with JOREK

Matthias Hoelzl for the JOREK community (see references on the slides).





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Interesting multi-physics processes





Precursors Explosive onset Filament formation Magnetic reconnection Potentially harmful energy release Described by magneto-hydrodynamics Challenging multi-scale problem Solar eruptions

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Critical for a fusion power plant



Large scale violent plasma instabilities constitute a serious risk for large fusion devices

Edge localized modes

 Periodically expell heat and particles from the boundary of the plasma and can reduce the lifetime of wall components

Major disruptions

 Complete loss of the plasma confinement causing strong heat loads and mechanical forces onto the machine

Aim to control and mitigate



LOSS OF RELATIVISTIC ELECTRONS TO MATERIAL SURFACES VIDEO FROM ALCATOR C-MOD; R. GRANETZ, PRIVATE COMMUNICATION

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Extended and hybrid MHD



Magneto-hydrodynamics (MHD) describes the plasma as a fluid by evolution equations for

- Density
- Temperature
- Velocity
- Current
- Magnetic field
- Electric field

Extended and hybrid MHD



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- Electric field

+ Kinetic effects captured by a powerful particle in cell module

Extended and hybrid MHD





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The JOREK non-linear MHD code

- 3D non-linear extended MHD
- 2D finite elements, realistic geometry
- Toroidal Fourier expansion
- Implicit time stepping
- Large HPC systems
- Strong international community lead by EUROfusion project TSVV 8 on MHD transients

[https://www.jorek.eu]

[M Hoelzl, GTA Huijsmans, SJP Pamela, M Becoulet, E Nardon E, FJ Artola, B Nkonga, et al. Nuclear Fusion 61, 065001 (2021)]



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Main fields of research





Pedestal physics: Type-I ELM cycles, small ELM regimes (QCE, EDA-H-mode), ELM free regimes (QH-mode), ELM control by resonant magnetic perturbations, pellet ELM pacing, vertical kick ELM triggering, advanced SOL/divertor modelling including kinetic neutrals and impurities, plasma-wall interaction, X-point radiator ...

Disruptions: Natural and mitigated disruptions, vertical displacement events, runaway electrons, wall forces and loads, massive gas injection, shattered pellet injection, ...

0.8 0.6 0.4 0.2 Ο. $0.00\,ms$

electron temperature [keV]

Further fields: Energetic particles, stellarator MHD, ITG and TEM turbulence, ...

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Impurity inclusion in full MHD + shock capturing



- JOREK has a set of **reduced and full MHD** models
- For many applications, reduced MHD is sufficient (eliminates fast magneto-sonic waves); validity is, however, limited for 1/1 internal kink modes at finite beta
- The full MHD model now includes a neutrals fluid model, diamagnetic drift effects, twotemperature effects, an impurity fluid model (free boundary extension is under development)
- Also a **shock capturing** method was implemented
- First application to impurity shattered pellet injection in the JET tokamak:

[A Bhole et al, Computers & Mathematics with Applications 142, 225 (2023)]



Accurate 3D wall models

- Eddy current coupling to the CARIDDI code was completed and verified by various benchmarks
- (Halo current coupling is future work needed for accurate horizontal forces)
- This enables accurate 3D plasma studies taking into account detailed 3D models of conducting structures
- One of the first applications is a 3D vertical displacement event in the ASDEX Upgrade tokamak (figure)

[N Isernia, N Schwarz et al, in preparation]



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Predicting the thermal quench in future devices

- Simulation of **natural disruption during a hot VDE**
- Realistic ITER parameters not easily accessible due to computational constraints (~500 ms VDE time scale)
- Rescaling of time, resistivity, diffusivity, etc. keeps the dynamics largely unmodified (tested by scan)
- ITER simulation with scaling factor 60 thermal quench triggered when q₉₅~2
- Several current spikes during TQ and CQ
- MHD burst at q_{95} ~1.3 moves q_{95} back to 2



Predicting the thermal quench in future devices

 MHD burst at q₉₅~1.3 moves q₉₅ back to 2 by transferring current into the halo region



Predicting the thermal quench in future devices

- A scan in the scaling factor shows a nearly linear dependency of the thermal quench time on the scaling factor
- This allows to obtain a prediction of the thermal quench time in ITER in the range of 30 ms



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force reduction explained by reduction of •

poloidal halo currents

New theory:

Previously:

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
- \rightarrow toroidal currents in the SOL stabilize the centroid motion and reduce forces



a)

48



Z-mag

42

The current centroid remains stationary during a mitigated disruption (simulation result)

44

time [ms]

46



-1.00

40

Mechanism of force mitigation by massive material injection ^{C EUROfusion}

Previously:

 force reduction explained by reduction of poloidal halo currents

New theory:

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Mechanism of force mitigation by massive material injection ^{C EUROfusion} – Experimental evidence from ASDEX Upgrade and JET

SPI mitigated VDEs

Shattered Pellets injected into moving plasma

- Current centroid Z_{curr} becomes stationary after injection leading to force reduction
- Widening of currents in the SOL confirmed experimentally





Mechanism of force mitigation by massive material injection Decision – JOREK simulation results

0.0

-0.5

Simulations for JET, AUG and ITER

- Relevant experimental features reproduced (CQ time, force reduction, Z_{curr} behaviour)
- Force proportional to $I_p \Delta Z_{curr}$



no VDE

#40955

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Electrostatic turbulence: PiC modelling of ITGs and TEMs in X-point plasmas with applied magnetic perturbations



- Various hybrid and kinetic models have been established in JOREK for neutrals, impurities, energetic particles, runaway electrons
- The following is about the electrostatic ITG and TEM turbulence model with gyro-kinetic ions and adiabatic or kinetic electrons
- (electromagnetic model with kinetic thermal ions is on the way)





[M Becoulet, GTA Huijsmans et al, in preparation]

Electrostatic turbulence: PiC modelling of ITGs and TEMs in X-point plasmas with applied magnetic perturbations





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MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK | MATTHIAS HOELZL | MAY $22^{ND} 2023$

Stellarator model in JOREK

Starting from the viscoresistive MHD equations, using the ansatz:

$$\mathbf{B} = \nabla \chi + \nabla \psi \times \nabla \chi \tag{1}$$

$$\mathbf{v} = rac{
abla \Phi imes
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m v}^2} + v_{\parallel} \mathbf{B}$$
 (2)

Where $\nabla \chi$ is the vacuum field generated by external coils, and defining the auxiliary equations:

$$j = \Delta^* \psi$$
 (3)

$$\omega = \Delta^{\perp} \Phi \tag{4}$$

The following equations are derived:

$$\frac{\partial \rho}{\partial t} = -B_{V} \left[\frac{\rho}{B_{V}^{2}}, \Phi \right] + \nabla \cdot \left(D_{\perp} \nabla_{\perp} \rho + D_{\parallel} \nabla_{\parallel} \rho \right) + S_{\rho}$$
(5)

$$\nabla \cdot \left(\frac{\rho}{B_{\nu}^{2}} \nabla^{\perp} \frac{\partial \Phi}{\partial t}\right) = \frac{B_{\nu}}{2} \left[\frac{\rho}{B_{\nu}^{2}}, \frac{(\Phi, \Phi)}{B_{\nu}^{2}}\right] + B_{\nu} \left[\frac{\rho\omega}{B_{\nu}^{4}}, \Phi\right] - \nabla \cdot \left(\frac{P}{B_{\nu}^{2}} \nabla^{\perp} \Phi\right) + \nabla \cdot (j\mathbf{B}) + B_{\nu} \left[\frac{1}{B_{\nu}^{2}}, \rho\right] + \nabla \cdot (\mu_{\perp} \nabla^{\perp} \omega) - \Delta^{\perp} (\mu_{num} \Delta^{\perp} \omega)$$

$$(6)$$

$$\rho \frac{\partial T}{\partial t} = -\frac{1}{B_{v}} \left[\rho T, \Phi\right] - \gamma \rho T B_{v} \left[\frac{1}{B_{v}^{2}}, \Phi\right] + \nabla \cdot \left[\kappa_{\perp} \nabla_{\perp} T + \kappa_{\parallel} \nabla_{\parallel} \nabla_{\parallel} T + \frac{\rho T D_{\perp}}{\rho} \nabla_{\perp} \rho + \frac{\rho T D_{\parallel}}{\rho} \nabla_{\parallel} \rho\right] + \left(S_{e} + \eta_{Ohm} B_{v}^{2} j^{2}\right) - T \frac{\partial \rho}{\partial t}$$

$$(7)$$

$$\frac{\partial \psi}{\partial t} = \frac{\partial^{*} \Phi - [\psi, \Phi]}{B_{v}} - \eta \left(j - j_{source} \right) + \nabla \cdot \left(\eta_{num} \nabla^{\downarrow} j \right)$$
(8)

[Nikulsin N., Ramasamy R., Hoelzl M., et al. Physics of Plasmas 29, 063901 (2022)]





(4, 1) external kink simulation shows the nonlinear triggering of a (7, 2) internal mode in an I=2 stellarator



Figure 1: q profile of the simulated $N_{\rho} = 5$ case.

The radial extent of the (7, 2) mode is larger than in a tokamak with the same edge safety factor.



Figure 2: Pseudocolour plots of ρ and u in $\phi = 0$ plane.

[Ramasamy R. et al, Physics of Plasmas (submitted)]

Ongoing verification for optimised stellarator studies



Figure 3: q profile of the W7-AS test case.



Figure 4: Flux surfaces of W7-AS from initial VMEC equilibrium.

[Ramasamy R. et al, in preparation]

The expected (2, 1) tearing mode is observed, but requires further verification of the linear mode structure.

The MHD JFRS-1 project has enabled high toroidal resolution scans, necessary in the verification of this test case.

(Simulations of double tearing mode instabilities on the way for W7-A and for advanced stellarators [K Aleynikova et al])



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Summary

- MHD transients like edge localized modes or disruptions are critical for fusion reactors
- The non-linear MHD code JOREK aims to predict physics and control of such phenomena
 - Many fluid and kinetic extensions beyond basic MHD
 - Implicit time stepping, G¹ continuous 2D Bezier FEs + toroidal Fourier
- Major recent extensions
 - Inclusion of impurities in full MHD and shock capturing
 - Coupling to CARIDDI for 3D walls
- Recent highlights
 - **Disruption mitigation:** Mechanism of force mitigation
 - Predicting the thermal quench in future devices
 - Electrostatic turbulence in perturbed plasmas
 - Stellarator MHD is undergoing validation

