Studying Incomplete Sawtooth Reconnection in ASDEX Upgrade with the Nonlinear Two-fluid MHD Code M3D-C[1]

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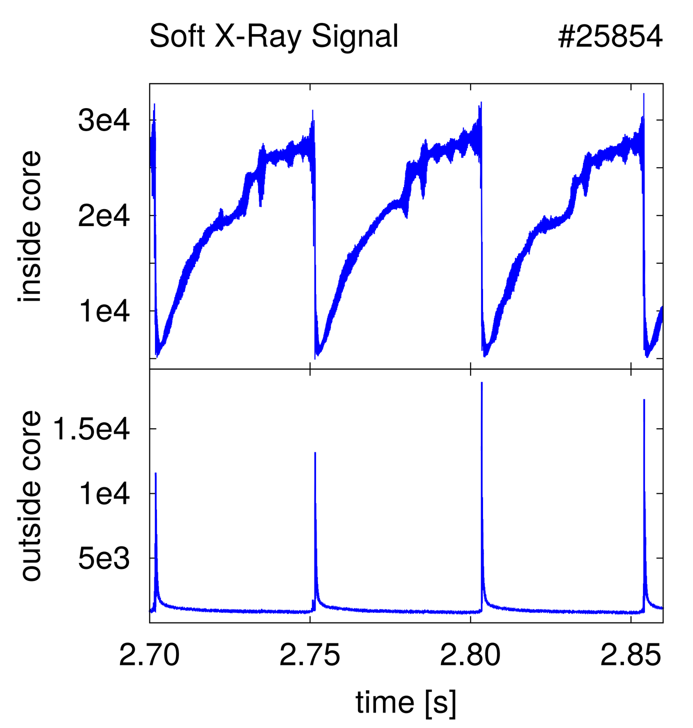
Abstract

We are investigating incomplete sawtooth reconnection in ASDEX Upgrade tokamak [1] plasmas using the 3D non-linear two-fluid MHD code M3D-C[1] [2]. Soft X-ray tomography results show that for typical sawteeth in ASDEX Upgrade the (1,1) magnetic island survives the sawtooth crash and the radial position of the q=1 surface is not significantly changed by the crash [3]. This contradicts Kadomtsev's complete reconnection model which predicts the island to entirely replace the hot plasma core so that q=1 on axis after the crash [4]. From 2D ECE Imaging measurements it can be seen that during the crash heat leaves the plasma core through a narrow poloidally localized region [3].
We want to qualitatively reproduce these two key features seen in the experiments by means of 3D non-linear two-fluid MHD simulations based on the equilibrium and parameters of such a typical sawtoothing ASDEX Upgrade discharge. This would then enable us to investigate why the (1,1) island saturates before reconnection is complete and which mechanism enables the fast transport of heat out of the core during the crash.

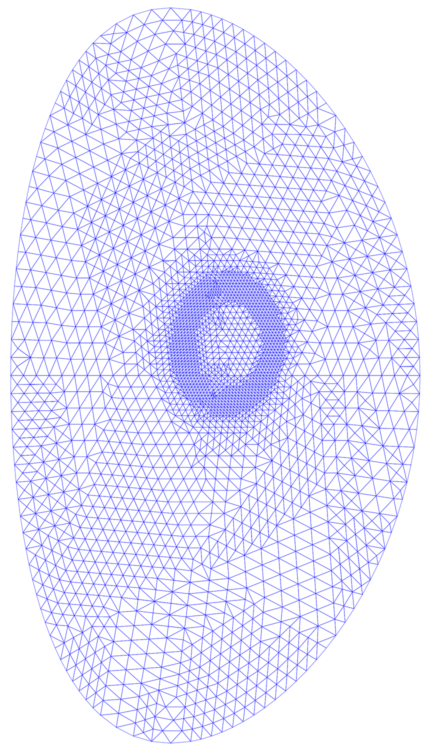


Sawtooth Instability

- core relaxation-oscillation instability in tokamak plasmas
- first observed in ST tokamak [5]

- sawtooth cycle:
  - core temperature and density increase slowly
  - (1,1) helical magnetic perturbation arises
  - core temperature and density drop suddenly

- not yet entirely explained
- reviews: e.g. [6] and [7]



M3D-C[1] Code

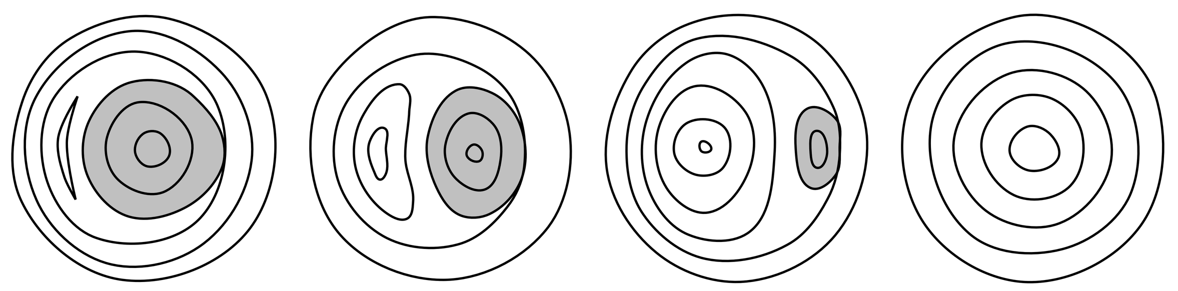
- non-linear 3D two-fluid MHD code
- developed by S.C. Jardin and N. Ferraro [2]

- high-order finite elements:
  - poloidal plane: reduced quintic
  - toroidal direction: hermite cubic
- fully implicit time stepping
- mesh can be locally refined

- highly versatile, options for:
  - 3D linear, 2D non-linear & 3D non-linear
  - straight cylinder & toroidal geometry
  - various MHD models, from reduced resistive to full two-fluid MHD

Sawtooth Reconnection

Complete Sawtooth Reconnection Model



- developed by B.B. Kadomtsev [4]

- sawtooth cycle:
  - temperature rises slowly
  - safety factor on axis drops below unity
  - (1,1) internal kink is destabilized
  - (1,1) magnetic island develops on q=1 surface
  - surfaces of equal helical magnetic flux reconnect until the island has replaced the core
  - as island O-point becomes new magnetic axis, the safety factor on axis becomes unity
  - configuration becomes stable

- central temperature drop is explained by hot core being expelled and replaced by colder island

Incomplete Sawtooth Reconnection

- observations of sawteeth in various tokamaks contradict Kadomtsev's model
  - (1,1) mode survives the crash [8,3]
  - safety factor on axis remains below unity [9-11]

- incomplete sawtooth reconnection model needs to account for:
  - saturation of island before reconnection is complete
  - mechanism for heat release

- possible explanation:
  - mode coupling causes field lines to ergodize, starting at island X-point
  - ergodization enhances heat transport
  - flattening of temperature profiles reduces drive of instability

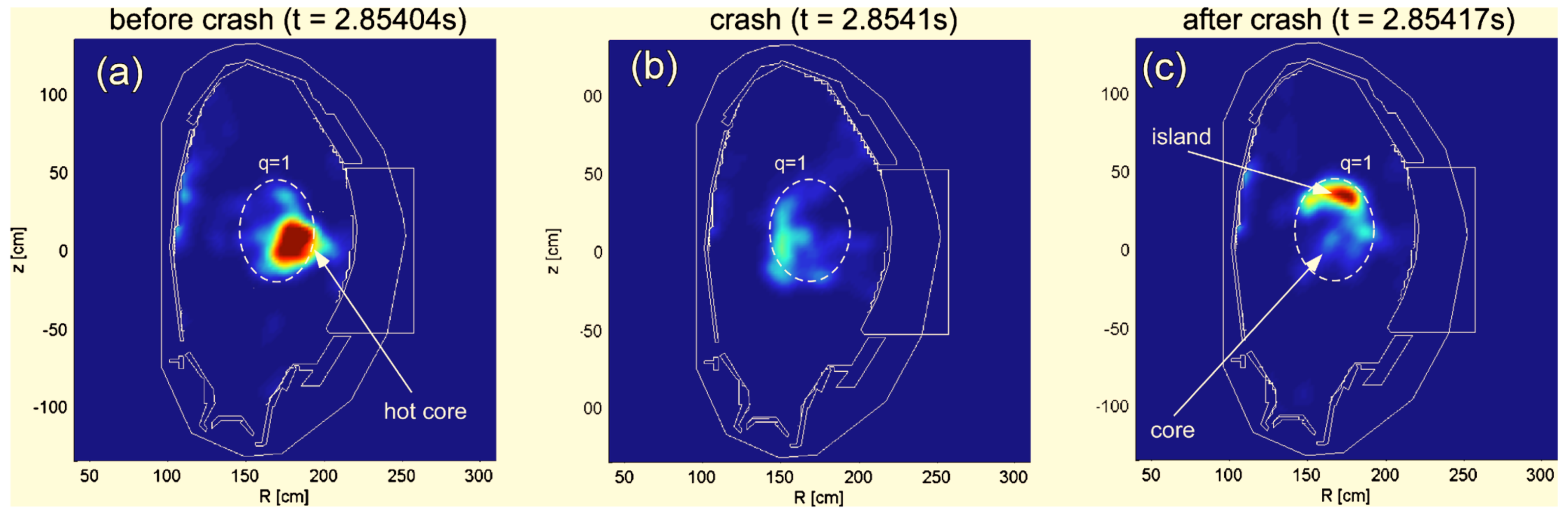
Acknowledgements
N. Ferraro (General Atomics), E. Fable (IPP), M. Dunne (IPP), M. Maraschek (IPP)

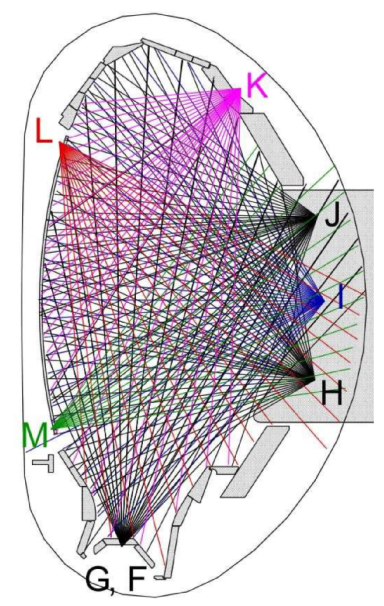
Table of Figures
- Complete reconnection sketch: J. Wesson, Proceedings of the Workshop on Theory of Fusion Plasmas, Varenna, Italy (1987) [modified]
- Soft X-ray lines of sight: V. Igochine, A. Gude, M. Maraschek, et al, IPP-Report 1/338 (2010) [modified]
- 2D ECEI set-up: I.G.J. Classen, J.E. Boom, W. Suttrop, et al, Rev. Sci. Instrum. 81 (2010)
- Soft X-ray tomography & 2D ECEI measurements: Reproduced with permission from V. Igochine, J. Boom, I. Classen, et al, Phys. Plasmas 17 (2010).

Experiment

Typical sawtoothing ASDEX Upgrade discharge (#25854)
- well diagnosed, analyzed in [3], used as basis for simulations
- 2.6 MW neutral beam heating, 4.4 MW on-axis ICRH & 0.8 MW on-axis ECRH
- H-mode discharge, $S = 1.6 \cdot 10^8$, B = 2.47 T

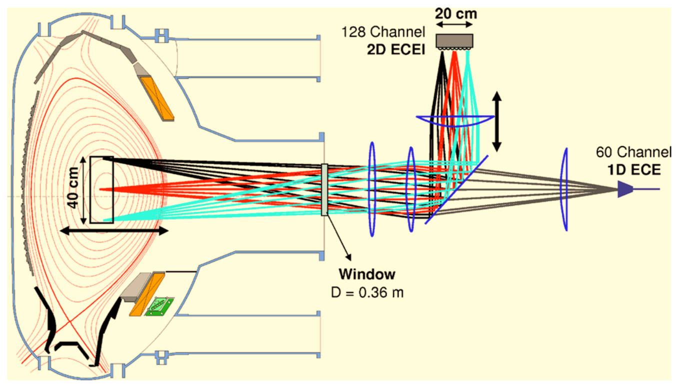
Soft X-Ray Tomography
- measures soft X-ray emission from hot impurities
- standard diagnostic to visualize core MHD processes
- 8 cameras, 208 lines of sight, 2 MHz acquisition frequency [12]

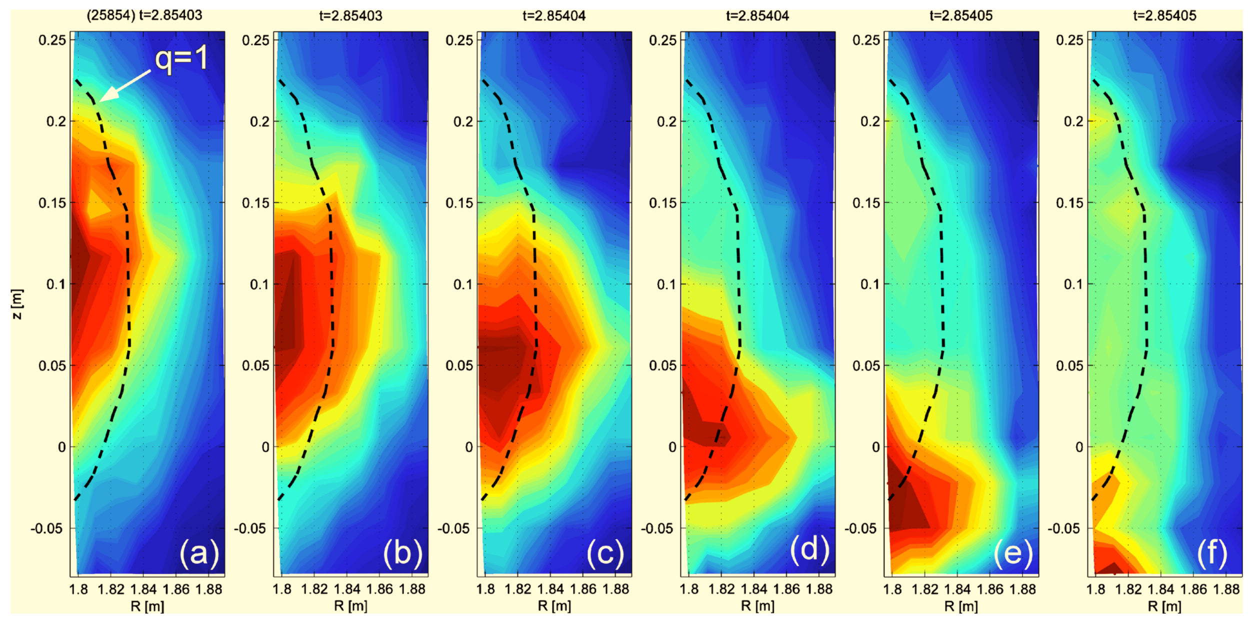




- color scheme is different for each time slice
- impurity accumulation visualizes magnetic topology
- before crash: displaced core shows as rotating hot spot
- after crash: emission from the (1,1) island is slightly stronger than that from the core as the island confines plasma from inside the inversion radius
- radial position of q=1 surface is maintained

2D ECE Imaging
- provides 2D electron temperature evolution by measuring electron cyclotron radiation along multiple lines of sight
- 12X40 cm area, 128 channels [13]





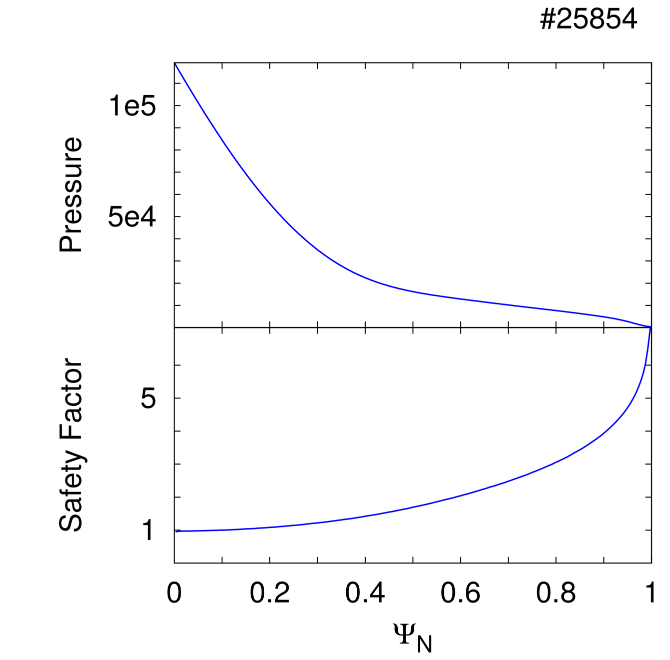
- localized heat flux through island X-point during crash

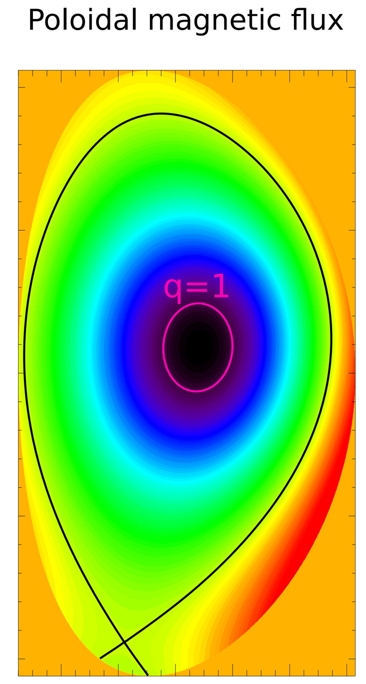
Ongoing Simulations

Aim of Simulations
- Qualitatively reproduce
  - saturating (1,1) island which maintains radial position
  - temperature crash & localized heat flow

Setup
- full 3D two-fluid model & toroidal geometry
- based on equilibrium reconstruction of ASDEX Upgrade discharge (#25854)
- ASDEX Upgrade parameters
- enhanced resistivity for computational reasons

Steps
- Set up equilibrium from CLISTE equilibrium reconstruction [14]
- obtain transport model from transport code ASTRA [15]
- 2D simulations to adjust transport model
- 3D linear simulations
- mesh refinement
- 3D nonlinear simulations





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