Investigations on Sawtooth Reconnection in ASDEX Upgrade Tokamak Discharges Using the 3D Non-linear Two-fluid MHD Code M3D-C[1]

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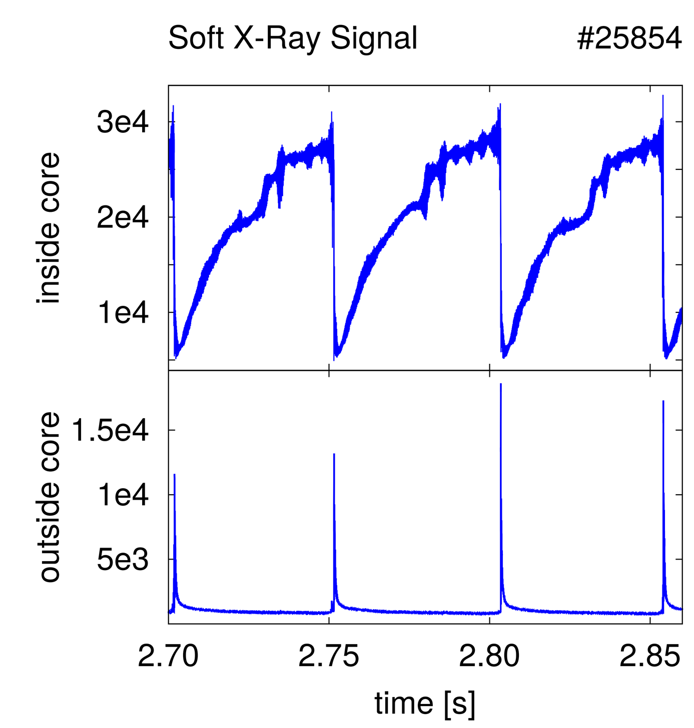
Abstract

We use the nonlinear 3D 2-fluid finite element code M3D-C[1] [1] to carry out simulations of sawtooth instabilities based on ASDEX Upgrade tokamak [2] discharges. Our aim is to perform detailed comparisons of the numerical results with experimental observations focusing on two distinct phenomena. First, the phenomenon of incomplete sawtooth reconnection is studied. It has been observed that in many cases an (m=1, n=1) perturbation survives sawtooth crashes in ASDEX Upgrade suggesting that sawtooth reconnection does not recuperate an entirely axisymmetric state after the crash [3]. We want to see if this can be reproduced in numerical simulations. The second phenomenon we want to study is the Improved H-mode (or Hybrid scenario), a stationary sawtooth-free operational regime that has been reached in many tokamaks [e.g. 4]. It has good edge as well as core confinement properties and is characterized by a flat central safety factor profile (q≳1) and (m=1,n=1) MHD activity in the core. Such helically perturbed stationary states have been found before in nonlinear M3D-C[1] simulations [5]. They are generated after sawtooth crashes if the resulting low magnetic shear in the core destabilizes an (m=1, n=1) ideal interchange instability which keeps the central temperature flat preventing a new sawtooth from occuring. A further aim would be to reproduce the natural evolution into such a stationary state without the preceeding sawtooth crash.
First preliminary results of a simplified 1-fluid 3D nonlinear simulation based on an ASDEX Upgrade discharge are shown. The plasma exhibits a single sawtooth featuring complete Kadomtsev reconnection which is followed by an ideal (m=1, n=1) interchange instability.

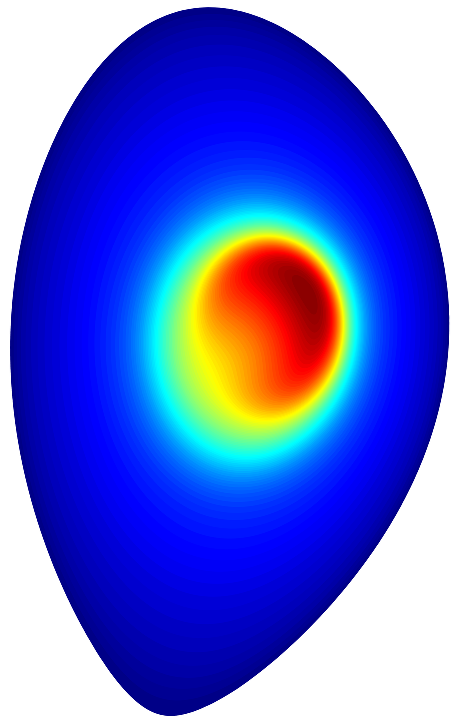


Sawtooth Instability

- core relaxation-oscillation instability in tokamak plasmas
- first observed in ST tokamak [6]

- 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. [7] and [8]



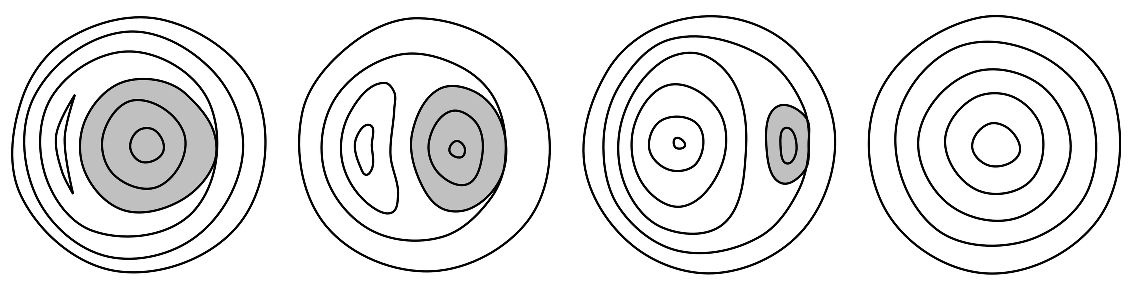
M3D-C[1] Code

- non-linear 3D two-fluid MHD code
- developed by S.C. Jardin and N. Ferraro [1]

- 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

Kadomtsev Sawtooth Reconnection



- developed by B.B. Kadomtsev [9]

- 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 (central temperature drop)
  - as island O-point becomes new magnetic axis, q_0 becomes 1
  - configuration becomes stable

ASDEX Upgrade Experimental Observations

Incomplete sawtooth reconnection
- observations in several tokamaks suggest that sawtooth reconnection in some cases does not recuperate a completely axisymmetric state after the crash

  - (m=1, n=1) mode survives the crash [10,3]
  - q_0<1 after crash [11-13]

Sawtooth-free Improved H-mode (Hybrid scenario)
- stationary operational regime with good confinement
- reached by generating flat central current density profile during ramp-up phase
- flat safety factor profile (q≳1) in the core stabilizes sawteeth
- (m=1, n=1) MHD modes in the core are observed

- has been found in various tokamaks (e.g. AUG [14], DIII-D [15], JET [16], TFTR [17])

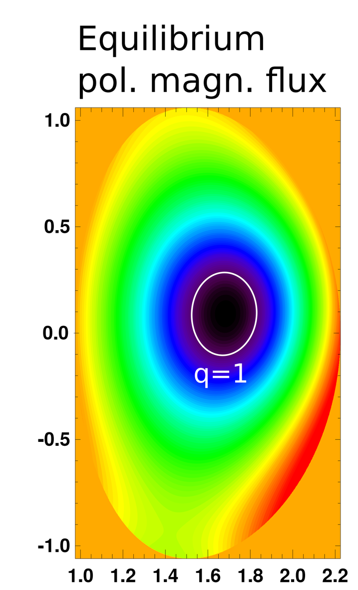
First Nonlinear Simulations

Set-up
- 3D nonlinear 1- and 2-fluid model
- toroidal geometry

- based on ASDEX Upgrade equilibrium and parameters
- enhanced transport coefficients for computational reasons
  - Lundquist number $S = 8\cdot 10^{6}$
  - heat diffusion anisotropy $\kappa_{\parallel}/\kappa_{\perp} = 3\cdot 10^{5}$

- sheared toroidal rotation included

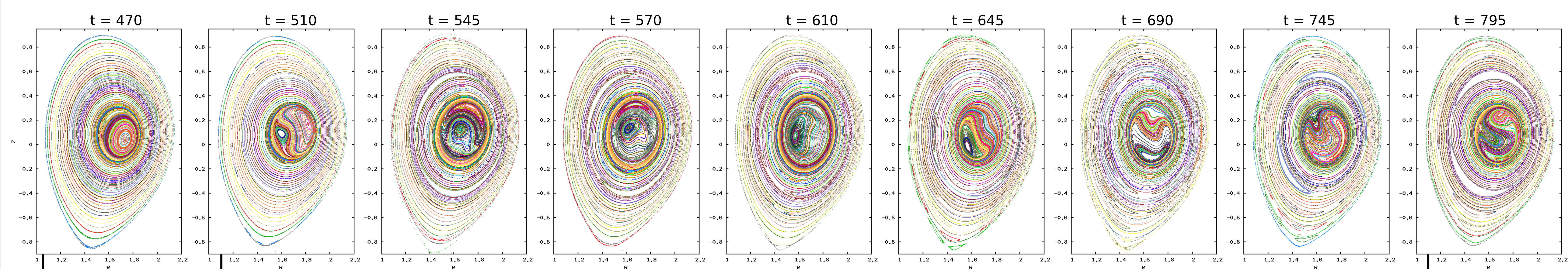
- poloidally and radially refined mesh around q=1 surface
- 8 toroidal planes

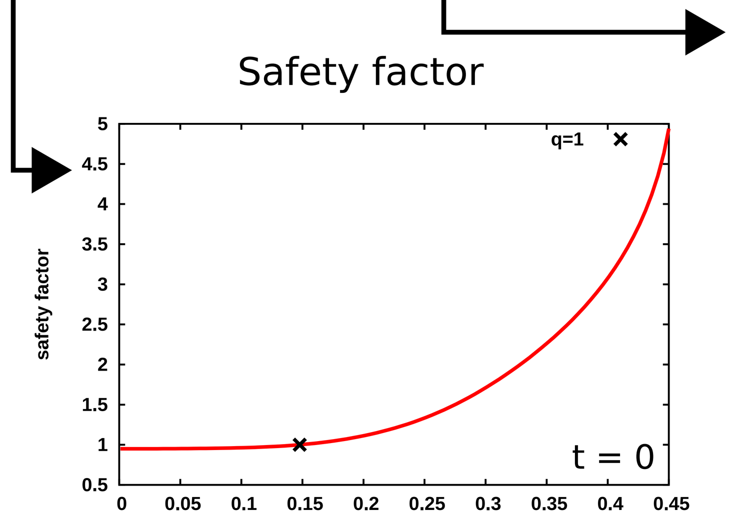


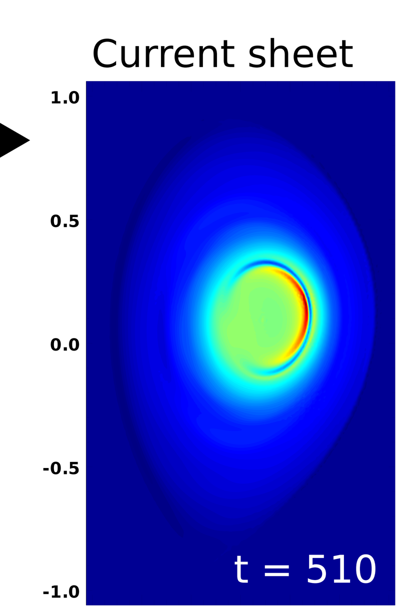
Preliminary results of a first single-fluid 3D nonlinear simulation
- resistive internal kink develops as initially q_0<1
- complete Kadomtsev reconnection takes place, central temperature crashes

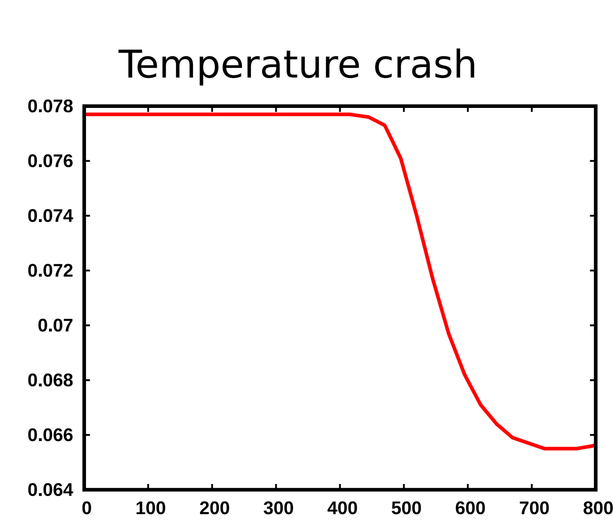
[$t_{SI} = t \cdot 0.5$ μs, $T_{SI} = T \cdot 50$ keV]

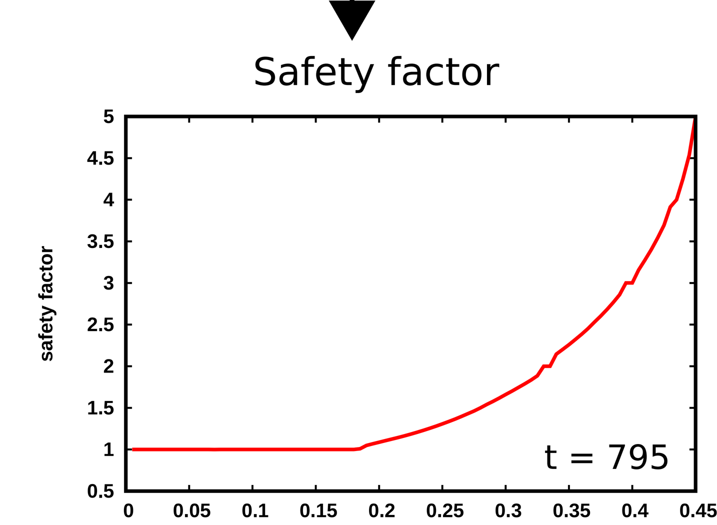
- after crash: q=1 inside entire core
- flat central q-profile destabilizes ideal (m=1, n=1) interchange instability
- plasma flows develop and prevent central temperature from peaking

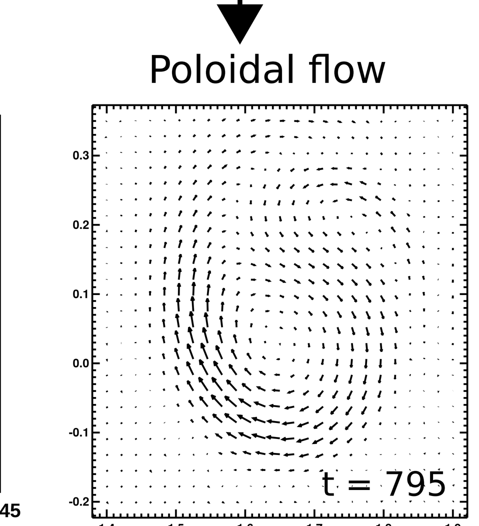


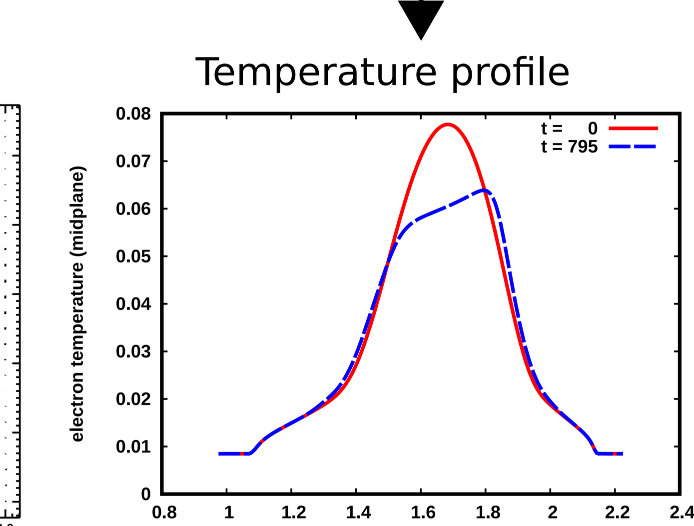












Outlook

- increase toroidal resolution
- more realistic transport coefficients
- study 2-fluid effects and influence of toroidal rotation

⟶ theory-experiment comparisons (ASDEX Upgrade)
  - see if incomplete sawtooth reconnection can be reproduced in simulations
  - reproduce natural evolution into Hybrid scenario without preceeding sawtooth crash

References:
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Table of Figures: Complete reconnection sketch: J. Wesson, Proceedings of the Workshop on Theory of Fusion Plasmas, Varenna, Italy (1987) [modified] **Acknowledgments:** N. Ferraro, E.Fable, M. Dunne, M. Maraschek, D. Vezinet

⟶ in earlier M3D-C[1] simulations of single sawtooth crashes it has been found that an ideal (m=1, n=1) interchange instability following the crash may lead to a sawtooth-free helically perturbed stationary state similar to the Hybrid scenario [BP8.00024]