M3D-C1 modelling of tokamak vertical displacement events

D. Pfefferlé[1], N. Ferraro[1], S.C. Jardin[1], C. Myers[1], A. Bhattacharjee[1]

[1]*Princeton Plasma Physics Laboratory (PPPL), Princeton 08540 NJ, USA*

dpfeffer@pppl.gov

1. Synopsis

What are we doing ?

- full 3D modelling of an NSTX Vertical Displacement Event (VDE)
- assessment of halo/wall currents and wall forces
- investigation of key physics and dynamics of these disruptions

Why ?

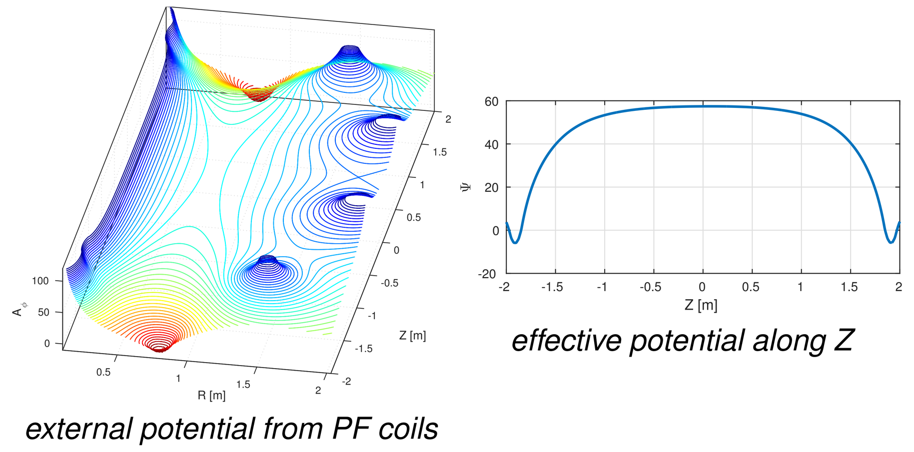
- forces during VDEs lead to **structural damage** to Plasma Facing Components (PFC)
- worst case VDE on ITER can result in machine shut-down

How ?

- numerical simulations using extended MHD code `M3D-C1`
  - finite-thickness axisymmetric resistive wall as a part of the computational domain
  - **anisotropic** unstructured mesh providing C1 weak solution on 48 planes
  - cubic spline in toroidal direction for 3D effects
  - **implicit** time-stepping

2. Phenomenology of VDEs

VDEs are inherent to diverted tokamak plasmas



effective potential along Z

external potential from PF coils

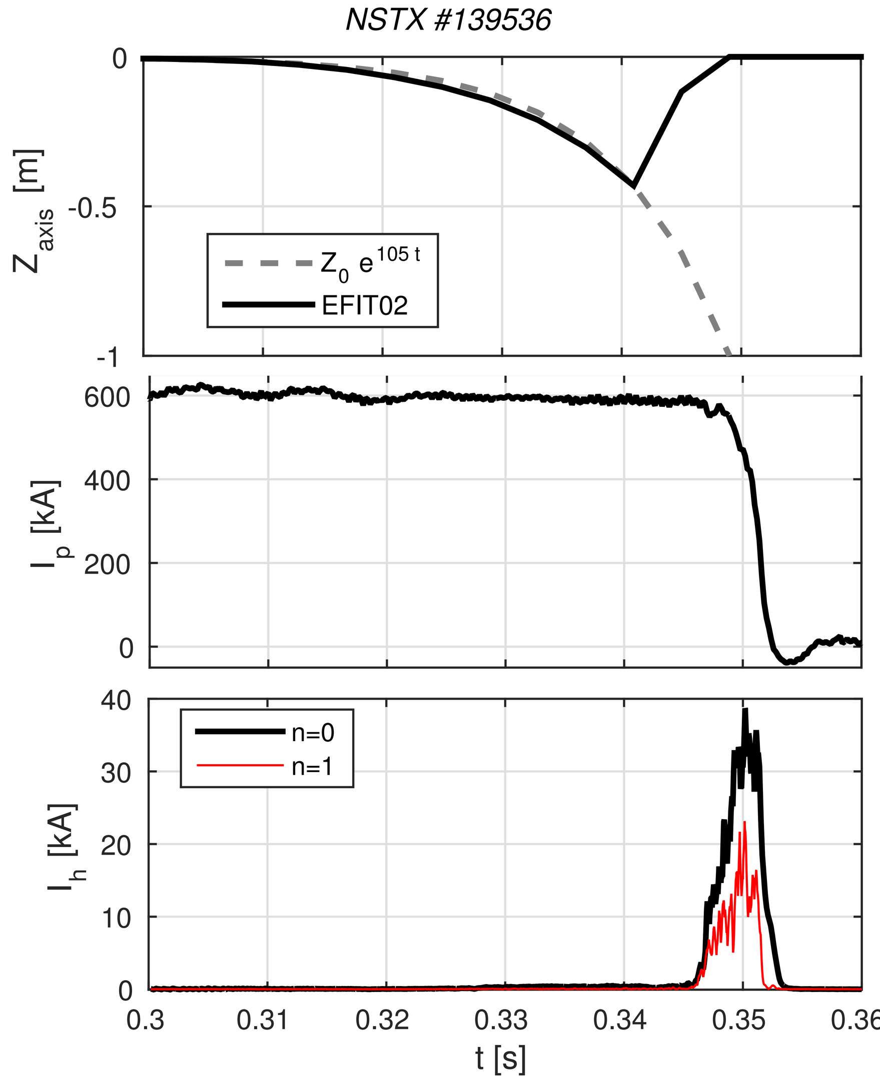
- diverted plasma sit on a saddle due to external field (PF coils) ⇒ elongation, **vertically unstable**
- conducting structures do not allow fast flux changes ⇒ **passive stabilisation** + feedback control
- loss of vertical control leads to deleterious contact with wall
  - transfer/induction of current from core → halo → wall ⇒ **forces and stresses**
  - scraping-off of $q_{edge} < 2$ ⇒ 3D instabilities (kink), toroidal peaking of forces
  - thermal collapse, impurities ⇒ breaking of flux surfaces, runaway electrons

Experimental traces serve as modelling targets

- drift phase [Pfefferlé, 2017] $t_D \sim (L_w/R_w)(I_p/I_d)(Z_d/Z_w)^2 \sim 30$ms
  - **slow** process (relaxation)
  - plasma mostly in force balance
  - advection (≈ rigid body), inductive coupling with wall ⇒ **implicit scheme**
- current quench $t_{CQ} \gtrsim L_p^*/R_p^* \sim 3ms$ [Wesley, 2006]
  - current transfer from plasma to wall
  - scrape-off of flux (advection-diffusion)
  - **time-evolving** resistivity via thermal quench
- normal wall currents $\Delta t_H \sim t_{CQ}$ [Myers, 2017]
  - shared/induced currents in resistive halo
  - counter-I_p rotation $\Omega R \sim 3$km/s $= 0.1c_s$ for max 4 turns

VDE dynamics seem to be controlled by

- wall resistivity and external PF potential
- density and temperature of open field-line region
- breaking of flux-surfaces (3D instabilities) and heat conductivity
- viscosity, diffusivity and other transport coefficients (to lesser extent)



1. **slow** vertical motion $\sim 50ms$, largely exponential
2. **rapid** $\sim 5ms$ current quench begins at wall contact
3. shunt tile measurements show $n = 0 \sim n = 1$ throughout current quench

3. Numerical simulation of hot VDEs

Strategy

1. perform **2D nonlinear** `M3D-C1` simulations (90% of physical time) until plasma reaches wall
2. linear stability analysis is performed along the way to monitor unstable modes
3. **expensive 3D nonlinear** simulations are deployed immediately when linear growth rates of instabilities (external kink) overcome $n = 0$ drift

Nonlinear 3D runs reveal complex dynamics *(see figures on the right)*

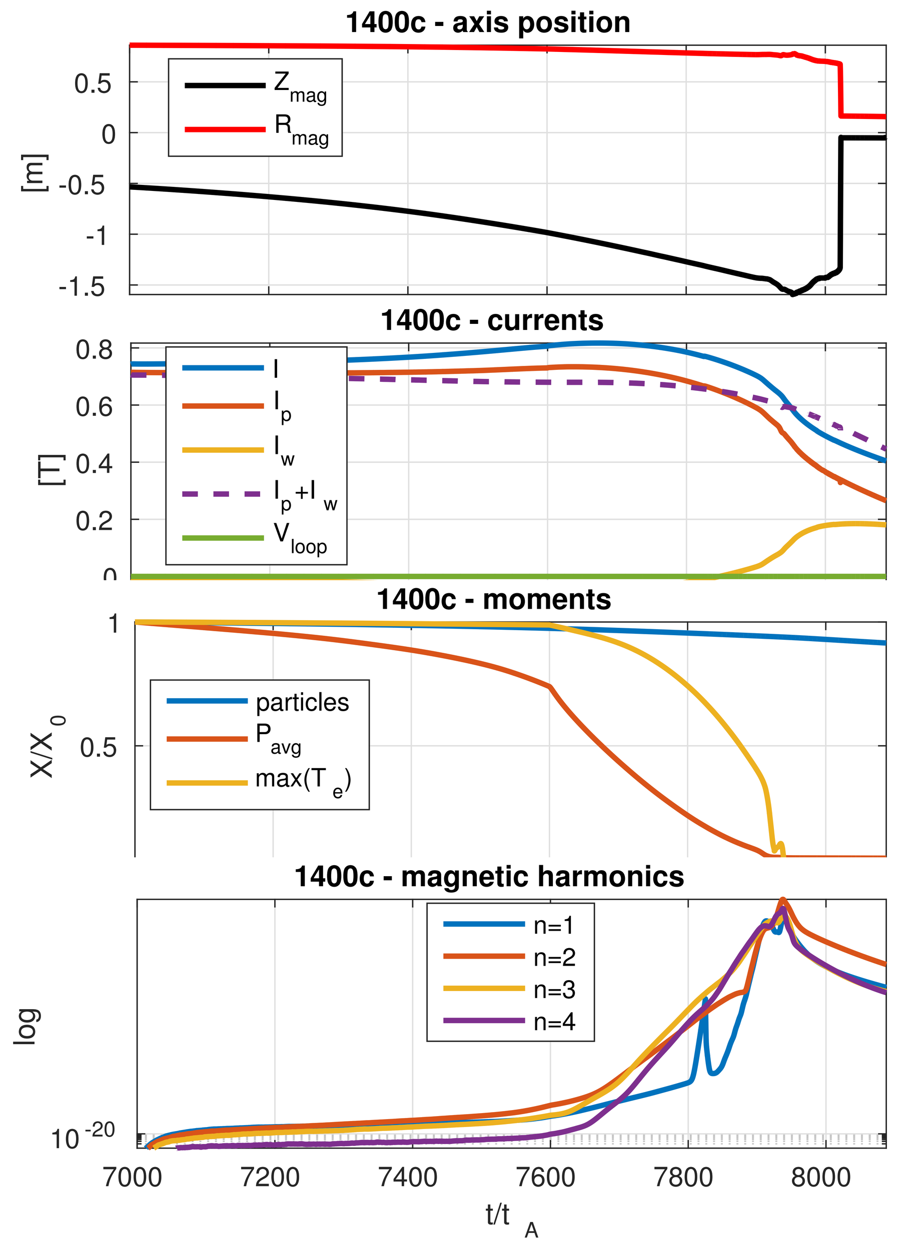
p.1 Harmless drifting of plasma (in 3D)

p.2 Vertical motion stalls via induced $n = 0$ wall currents
- scrape-off of LCFS but $q_e > 2$ stable
- thermal quench initiated by wetting with cold wall

p.3 edge surface currents develop as $q_e < 2$
- stabilise external kink

p.4 rapid growth of all m, n modes
- edge modes penetrate and merge into massive $1, 1$
- violent termination as $q_e < 1$

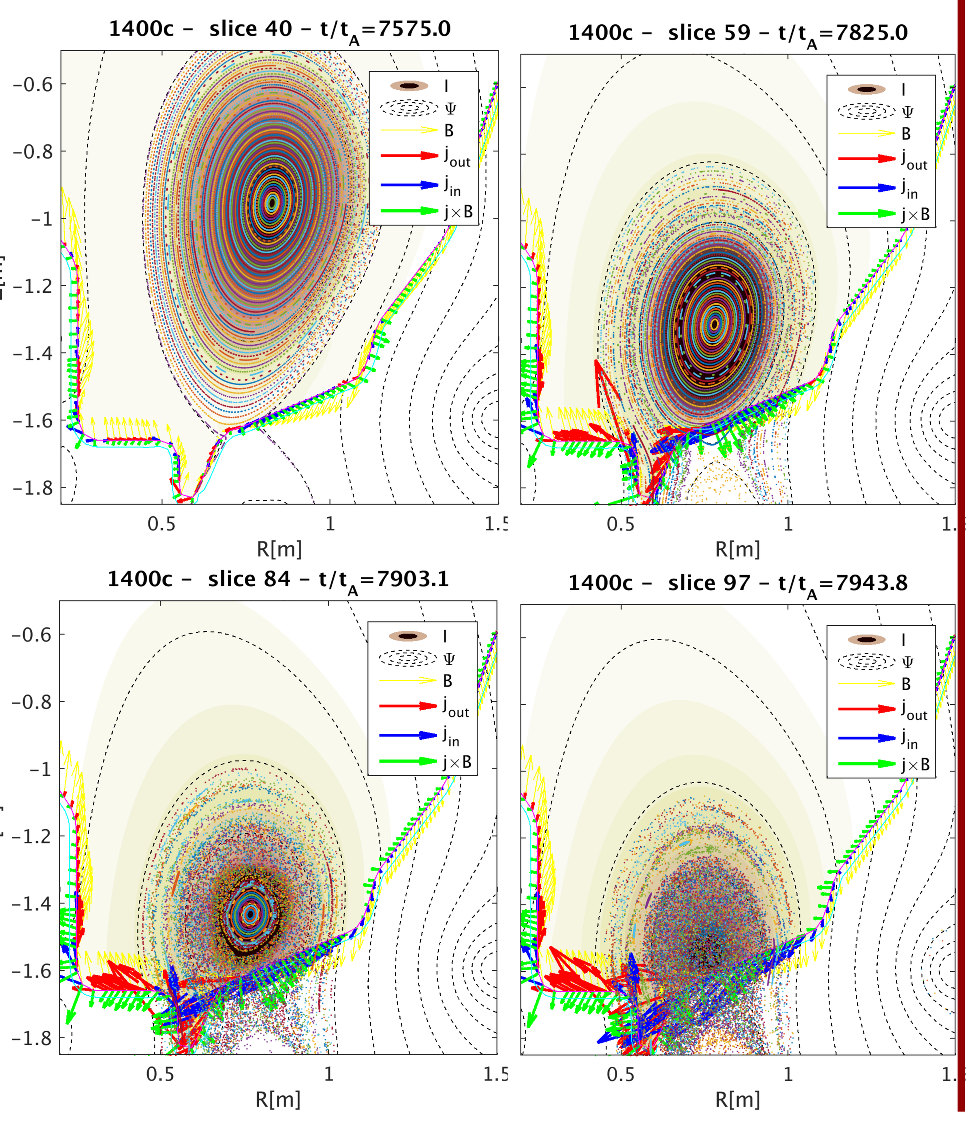
p.5 current decays in residual cold plasma and resistive wall

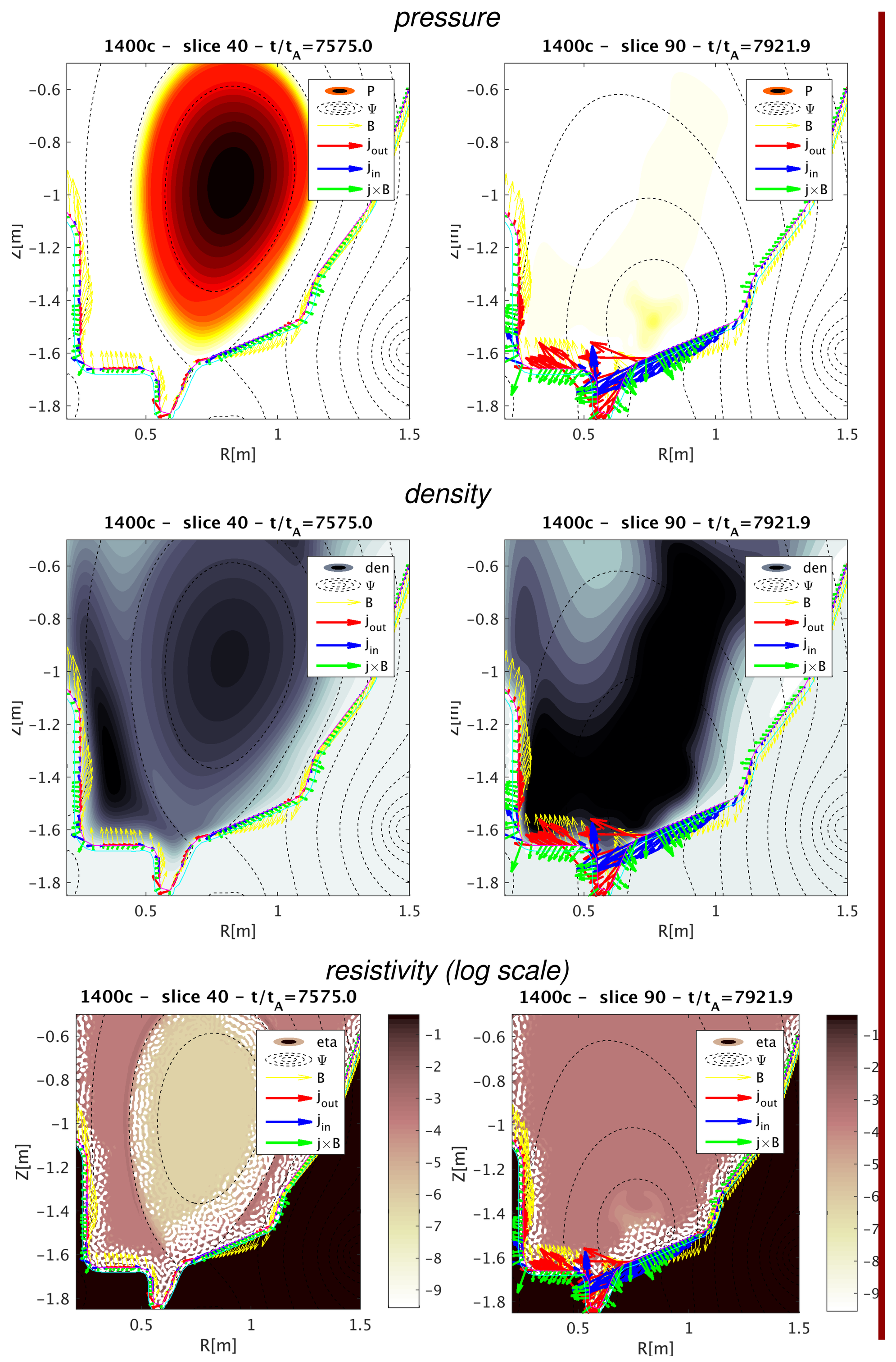


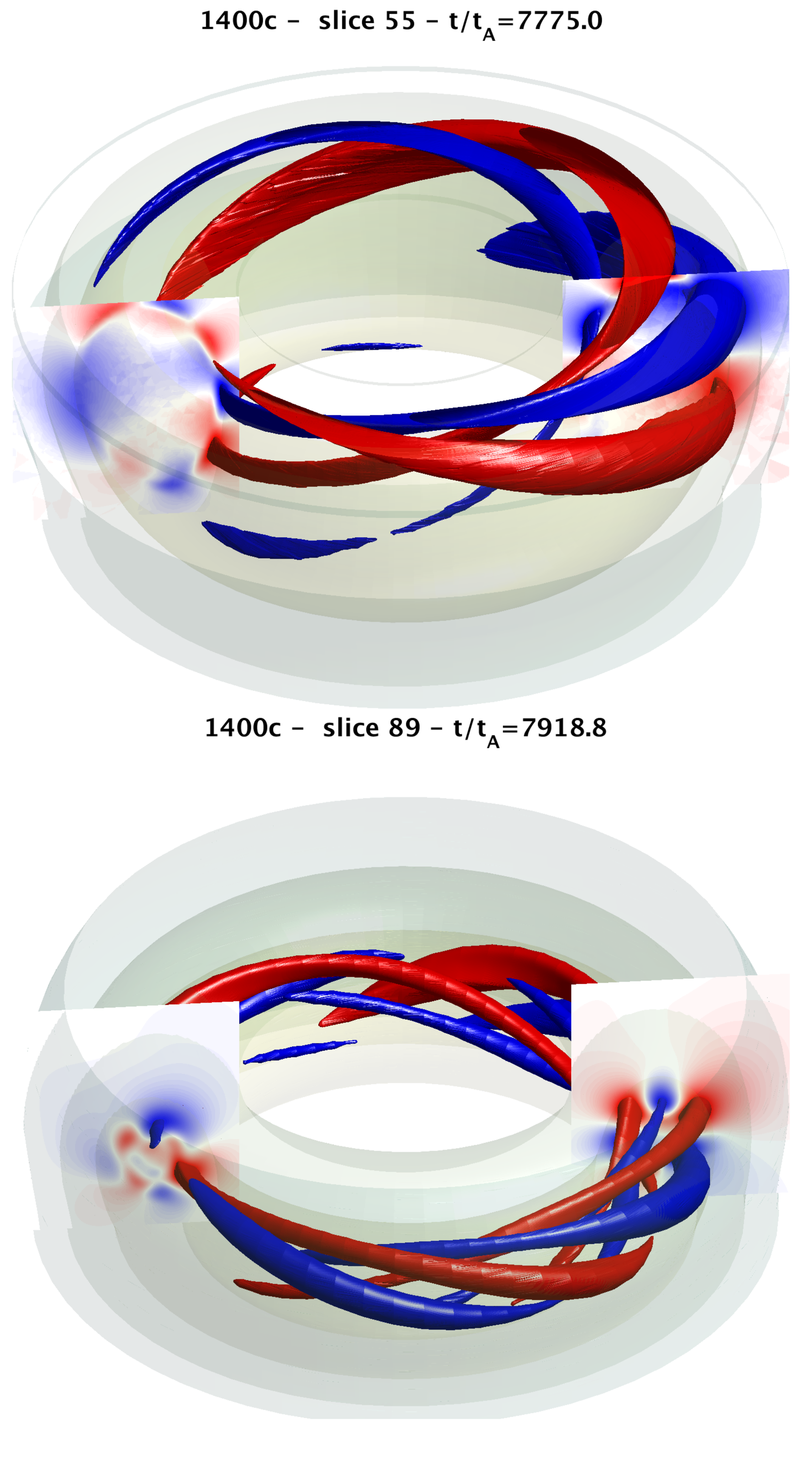
4. Analysis and visualisation

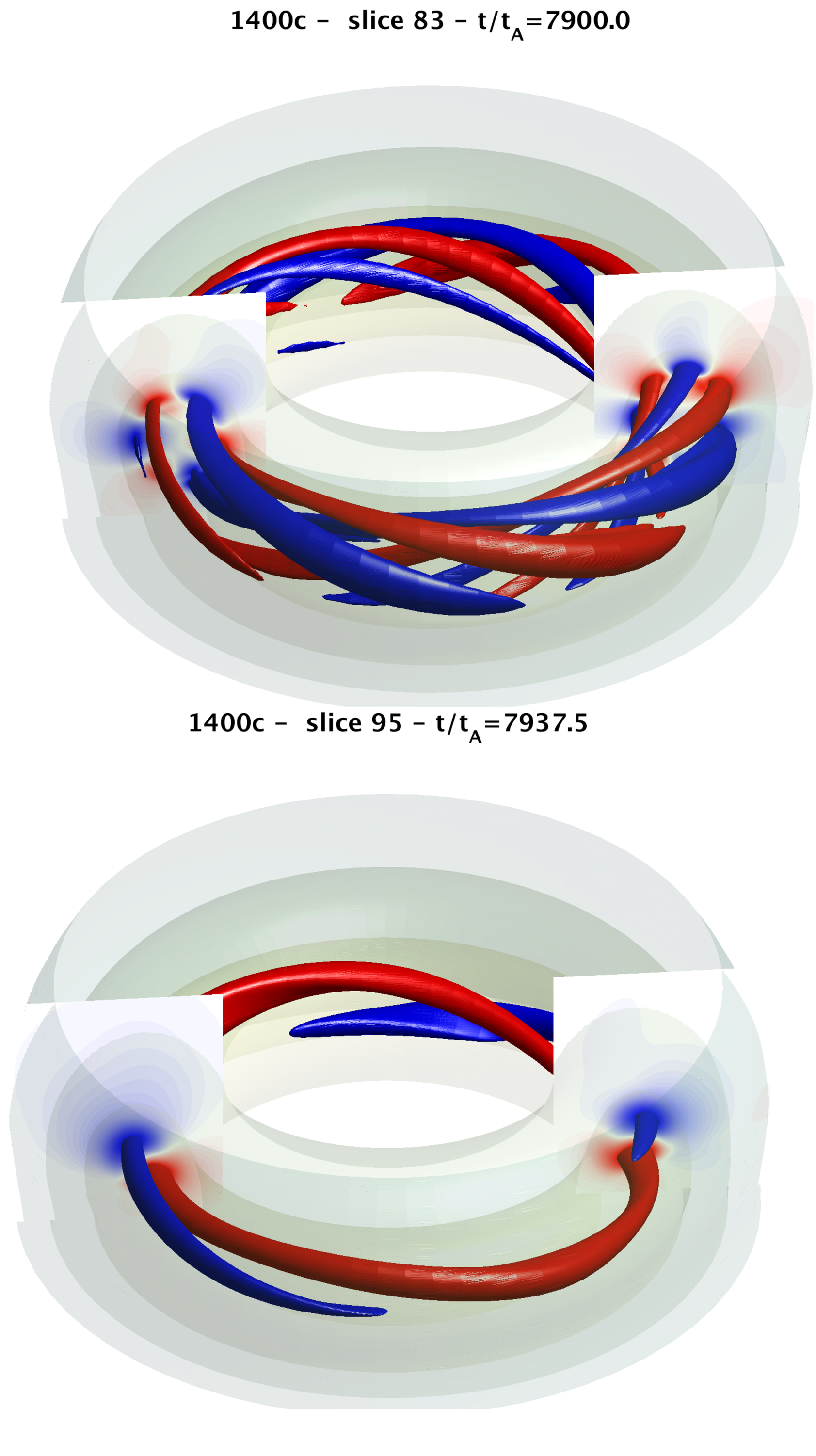
Current quench induces halo/wall currents and provokes $j \times B$ forces

- peeling of flux leads to penetration of edge modes and **stochastisation** of field-lines ⇒ **thermal quench**







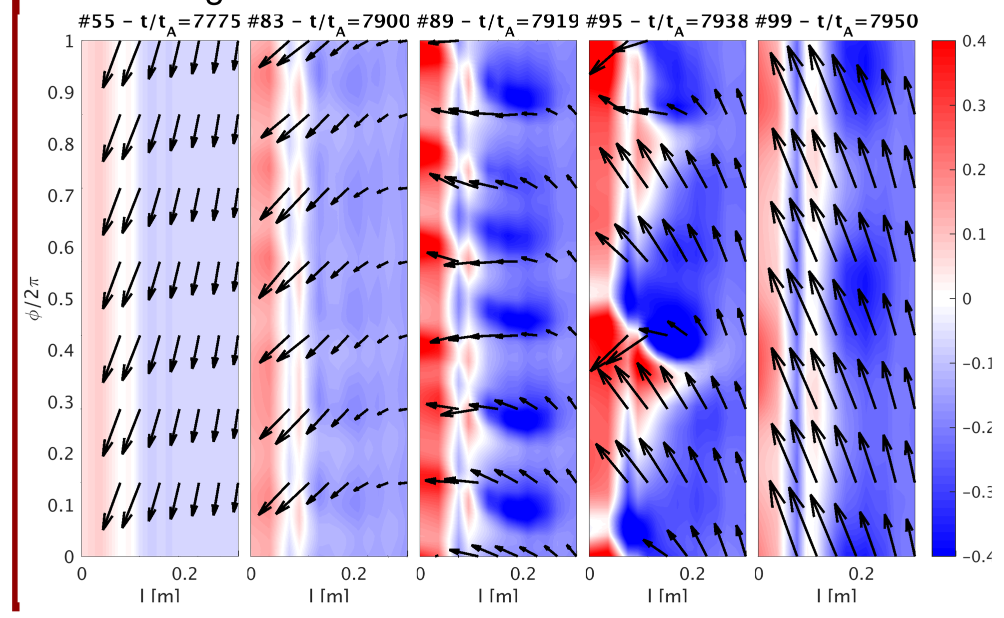


Non-axisymmetric modes form islands and current sheets near edge *(see left figures)*

- high-m and high-n mode numbers are **dominant** as $q_e > 1 - 2$ (but all modes are important)
- plasma shrinks and edge modes penetrate ⇒ core temperature ruined
- islands merge to lower m, n mode numbers
- no toroidal rotation but **shearing** of structures caused by q-values sweep

Current on divertor plate show time-evolving non-axisymmetric patterns

1. **Eddy currents** present to oppose vertical motion
2. contact line defined by in and out currents (blue/red)
3. transition period where **high-n structures** develop
4. most intense halo currents with **low-n signature**
5. wall current flows **co-I_p** as plasma shrinks into conducting wall



5. Concluding remarks

Summary

- M3D-C1 is employed to model NSTX VDEs with realistic parameters
  - **anisotropic** mesh to resolve sharp gradients at plasma/wall contact point
  - **implicit** scheme to resolve advection-diffusion stiff problem
- massive 3D nonlinear runs for evolution/saturation of non-axisymmetric structures
  - predominance of **edge high-n modes** in early stages of wall contact
  - cascade to **low-n** core modes as plasma disappears into wall
  - **stochastisation** of field-lines causing rapid cooling of plasma
- virtual diagnostics of normal wall currents qualitatively agree with experimental data

Extensions and additional effects

- non-uniform / non-axisymmetric wall resistivity
- toroidal rotation, torque, plasma/wall boundary conditions, sheath physics

References

D. Pfefferlé, to be submitted (2017).

J. Wesley and al., GA-A25410 (2006).

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Sherwood Fusion Theory Conference, May 1st-3rd, 2017 Annapolis, MD - USA