3D Nonlinear Modelling of VDEs with M3D-C1

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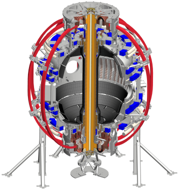


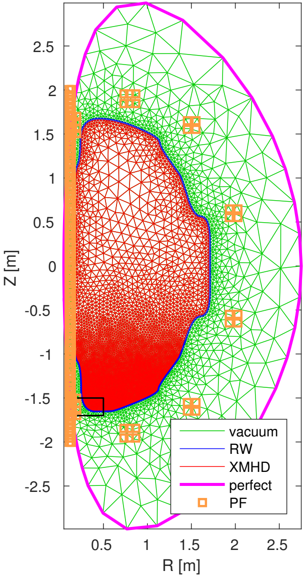
Context

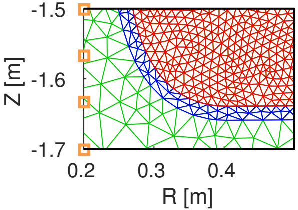
- Vertical Displacement Events (VDEs) release the largest currents in tokamak first wall
  - forces, stresses and heat loads $\Rightarrow$ severe **structural damage**
  - worse if toroidal asymmetry and rotation (peaking, resonance)
- disruption databases $\equiv$ wide range of behaviours/regimes
  - thermal and current quench **overlap**
  - transient phenomenon, case-by-case determination of chain of events
  - difficult diagnosis of plasma conditions $\rightarrow$ **uncertainty**
- steady progress from theory / numerical simulation, but
  - scans with 3D non-linear simulations **impractical**
  - realistic parameters requires robust algorithms and **costly** simulations
- **urgent** to understand VDE dynamics
  - improve avoidance (preemptive measures) and mitigation (damage control) strategies for safe ITER operation

Focus on reproducing NSTX VDE #139536 [Gerhardt et al., 2012; Breslau, 2015]

- full 3D modelling using `M3D-C1` with minimal intervention
  1. **fast** 2D nonlinear simulations for slow vertical drift (90% of physical time)
  2. linear $n > 0$ modes monitored along the way
  3. **expensive** 3D nonlinear simulations as plasma wets wall (unstable modes compete with $n = 0$ drift)
- investigation of key VDE dynamics
  - driving mechanisms, chain of events, timing of various effects
  - sensitivity to parameter change
  - numerical stability/convergence
- assessment of halo/wall currents and wall forces
  - qualitative comparison with shunt tile diagnostics
  - development of post-processing and visualisation routines (`C1Matlab`)

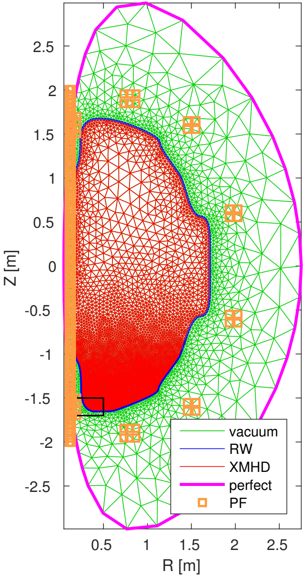
M3D-C1 has unique capabilities for modelling VDEs





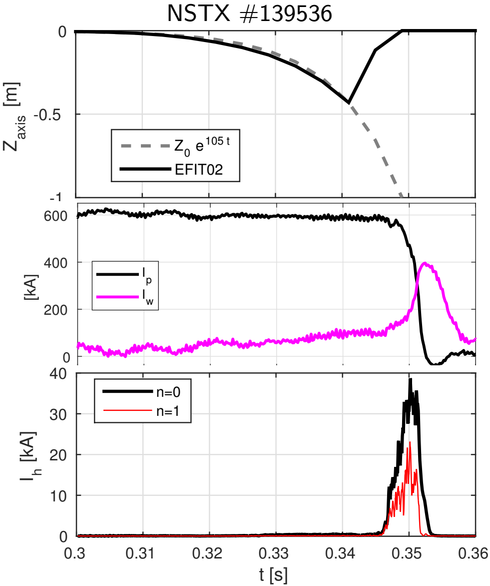
- XMDH [Breslau et al., 2009]
  - continuity, momentum, energy
  - Faraday, Ampère, Ohm
- resistive wall, $\boldsymbol{E} = \eta \boldsymbol{j}$
- vacuum, $\boldsymbol{j} = 0$
- ideal boundary (perfect conductor)
- PF coils (static)

M3D-C1 has unique capabilities for modelling VDEs



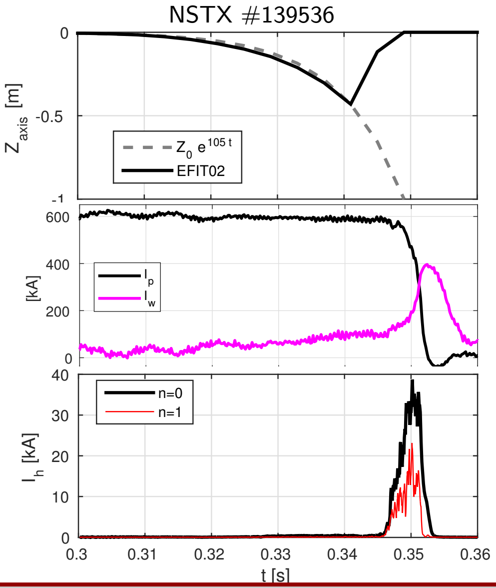
- key features
  - finite-thickness **axisymmetric** resistive wall (RW) [Ferraro et al., 2016]
  - **anisotropic** unstructured mesh as support for finite-element (week) **C1** solution
  - cubic spline on **48** planes for toroidal effects
  - **implicit** time-stepping allows simulations on RW timescales ~ 10 ms $\gg t_A$
- limiting assumptions
  - "halo" is a cold, low density, resistive plasma $\rightarrow$ dissipation, diffusion
  - static external fields, no feedback, no loop-voltage, no sources
  - no-slip boundary conditions (no sheath physics)
  - turned-off effects: two-fluid, impurity radiation

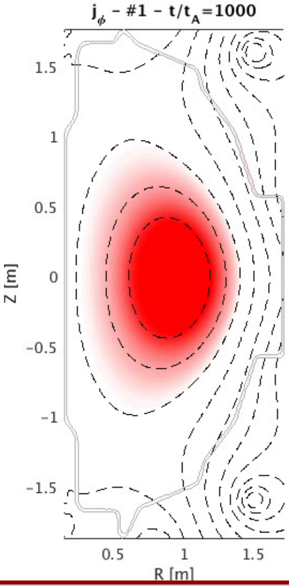
Experimental traces serve as modelling targets



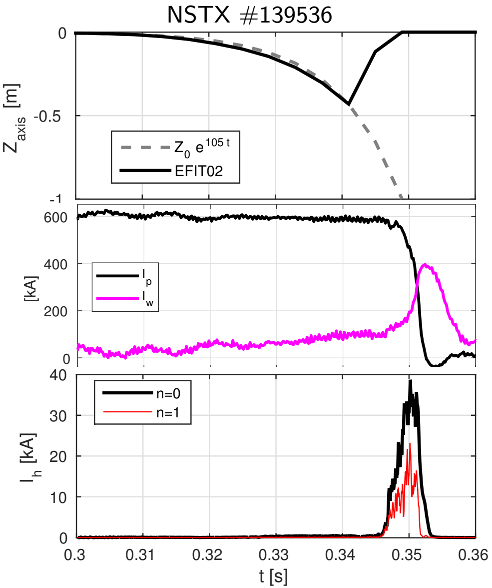
- phases and timescales
  - **slow** vertical motion $\tau_{VDE} \sim 50ms$, largely exponential
  - **rapid** $\tau_{CQ} \sim 5ms$ current quench begins at wall contact
  - relaxation of wall currents $\tau_{LR} \sim 10ms$
- $\tau_A \ll \tau_{CQ} < \tau_{LR} \ll \tau_{VDE}$
- shunt tile $n = 0 \sim n = 1$ throughout current quench

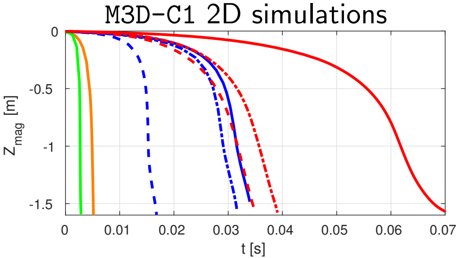
Experimental traces serve as modelling targets



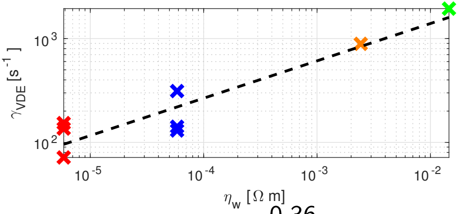


Experimental traces serve as modelling targets



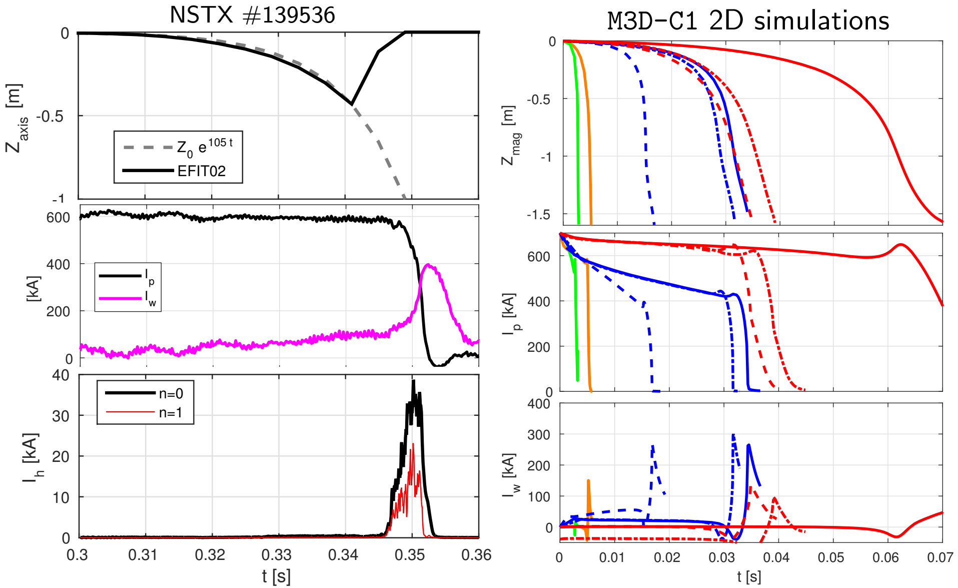


$\eta_w = 1.4 \times 10^{-3}, 2.4 \times 10^{-3}$
$5.8 \times 10^{-5}, 5.8 \times 10^{-6}$ Ω m

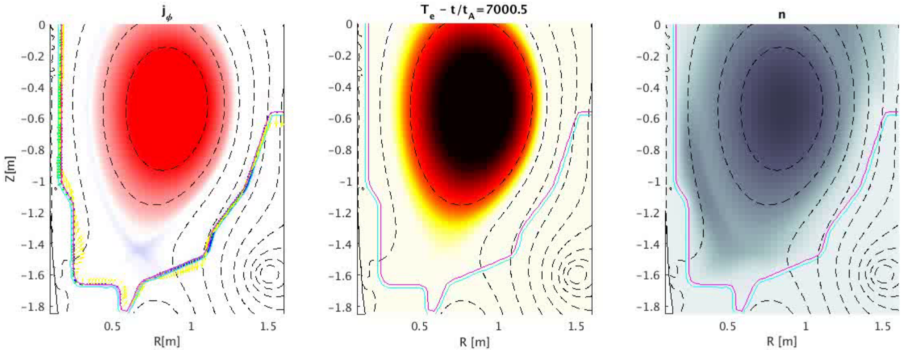


$$\gamma_{VDE} \propto \eta_w^{0.36}$$

Experimental traces serve as modelling targets

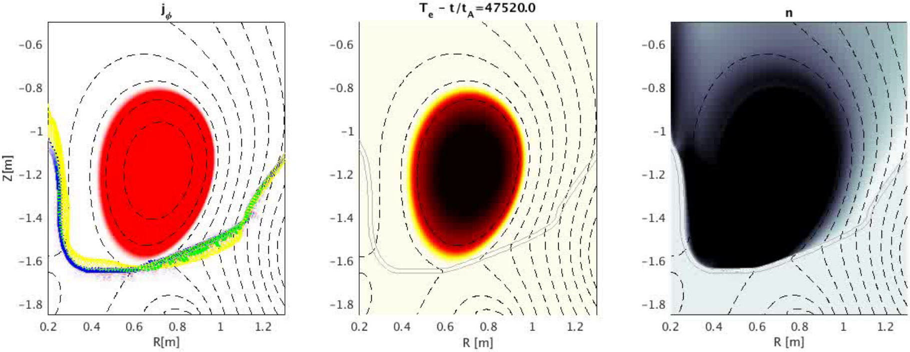


3D nonlinear simulations capture richer physics



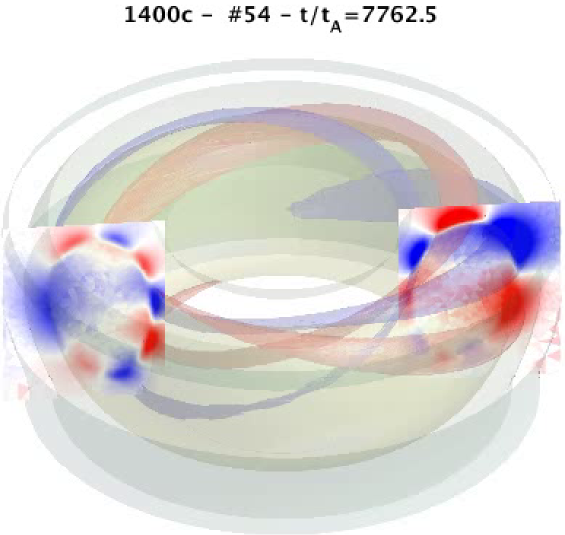
- orange case
  - $\eta_W = 2.4 \times 10^{-3}$ Ωm, short τ_{VDE}
  - high $T_h = 25$ eV

3D nonlinear simulations capture richer physics



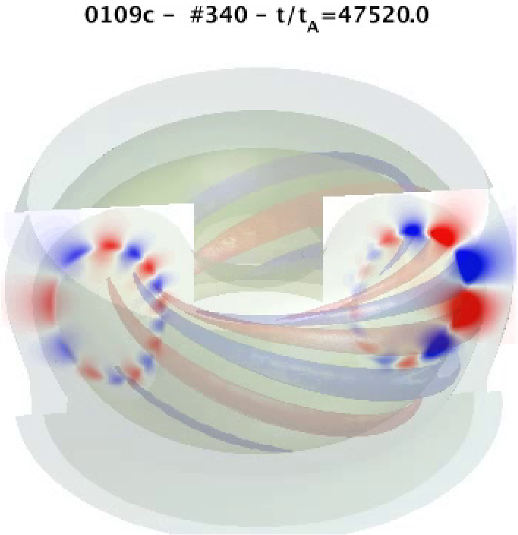
- blue case
  - $\eta_W = 5.8 \times 10^{-5}$ Ωm, long τ_{VDE}
  - low $T_h = 9$ eV

Isocontours of $\Psi_p - <\Psi_p>$ reveal toroidal modes



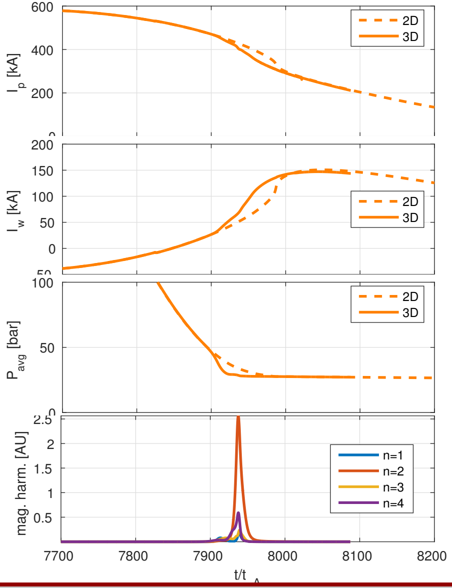
- orange case
  - $\eta_W = 2.4 \times 10^{-3}\ \Omega\text{m}$
  - high $T_h = 25$ eV
- LCFS scrape-off
  - shrinking of iso-tubes
  - spaghettification
- $n = 3 \rightarrow n = 1$
- figure caption
  - poloidal cuts at $\phi = 0, \pi$
  - isocontours at $\pm\tilde{\Psi}_{p,max}/2$
  - transparency scales with mode amplitude

Isocontours of $\Psi_p - < \Psi_p >$ reveal toroidal modes



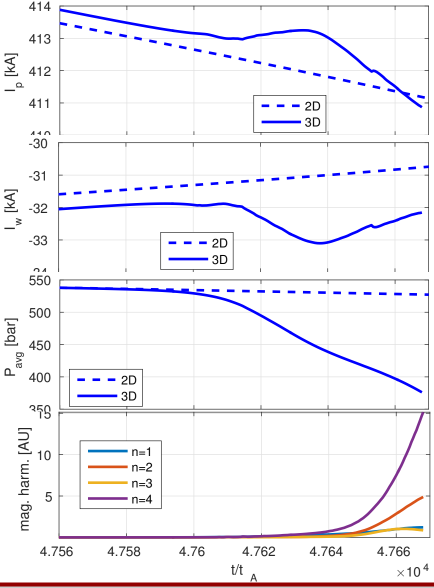
- blue case
  - $\eta_W = 5.8 \times 10^{-5}\ \Omega$m
  - low $T_h = 9$ eV
- filamentation, fingers
- $n = 6$, collapse
- figure caption
  - poloidal cuts at $\phi = 0, \pi$
  - isocontours at $\pm\tilde{\Psi}_{p,max}/2$
  - transparency scales with mode amplitude

Onset of 3D modes causes evolution to differ



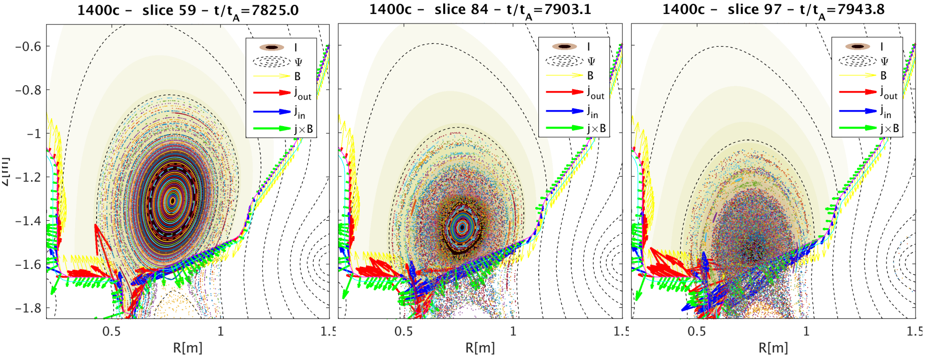
- orange case
  - $\eta_W = 2.4 \times 10^{-3}\ \Omega$m, short τ_{VDE}
  - high $T_h = 25$ eV
- 3D evolution identical to 2D until strong presence of toroidal modes
- observations
  - plasma current ↘
  - wall current ↗
  - temperature ↘

Onset of 3D modes causes evolution to differ



- blue case
  - $\eta_W = 5.8 \times 10^{-5}$ Ωm, long τ_{VDE}
  - low $T_h = 9$ eV
- 3D evolution identical to 2D until strong presence of toroidal modes
- observations
  - plasma current spikes
  - wall current ↘
  - temperature ↘

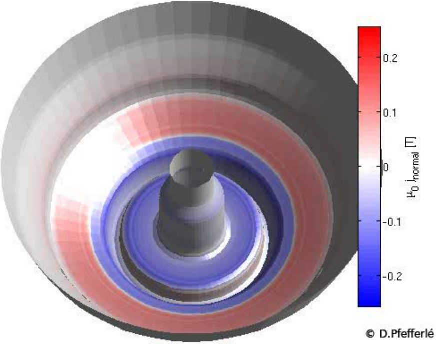
Penetrating edge modes precipitate current quench



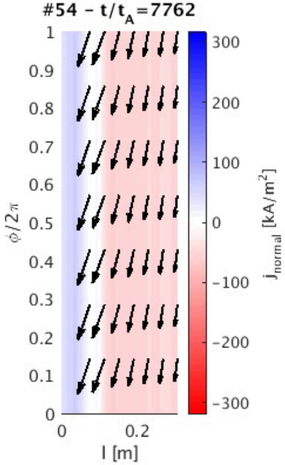
- stochastic field-lines $\Rightarrow$ efficient heat transport via $\kappa_{||}$
- rapid cooling (cold wall) $\rightarrow$ increase in Ohmic dissipation
- only from 3D (effective 2D model?)

Virtual diagnostic of 3D normal wall current to compare with shunt tile measurements

normal currents on wall (total)



- pattern rotation
  - globally zero momentum
  - sheared rotation from pealing of q
- amplitude quantitatively matches experimental shunt tile



toroidal (arrows) and normal (colour) currents on divertor

Conclusions

- report on 3D nonlinear modelling of NSTX VDEs using `M3D-C1`
  - match realistic τ_{VDE}, τ_{CQ} and τ_{LR} timescales with 2D nonlinear simulations
  - deployment of **heavy** 3D nonlinear simulations
  - post-processing and diagnostics (visualisation) for wall currents
- 3D effects and break-up of flux-surfaces
  - inward penetration of modes
  - field-line stochastisation $\Rightarrow$ rapid cooling
  - crucial for thermal quench / current quench
- wall currents
  - incomplete match with experiment on mode number, rotation and timescale (numerical constraint on halo temperature)
- routes to explore with `M3D-C1`
  - toroidal variation of wall resistivity
  - time-varying external field (drive): loop voltage, PF control feedback

Bibliography I

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