U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

NSTX Vertical Displacement Event 3D nonlinear modelling with M3D-C1

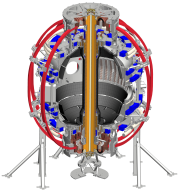
D.Pfefferlé[1]

N.Ferraro[1] **S.Jardin**[1] **C.Myers**[1] **A.Bhattacharjee**[1]

[1] *PPPL, Princeton 08540 NJ, USA*

2017 International Spherical Tokamak Workshop
19 - 22 September, Seoul, South Korea

PPPL



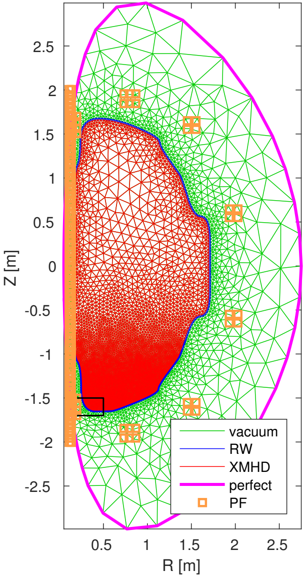
Tokamak disruptions must be tamed

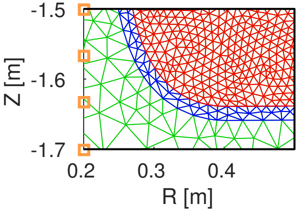
- Vertical Displacement Events (VDEs) release the largest currents in tokamak first wall
  - forces, stresses and heat loads ⇒ severe **structural damage**
  - worse if toroidal asymmetry and rotation (peaking, resonance)
- disruption databases ≡ wide range of behaviours/regimes
  - thermal and current quench **overlap**
  - transient phenomenon, case-by-case determination of chain of events
  - difficult diagnosis of plasma conditions → **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 contacts wall ($n > 0$ modes compete with $n = 0$ drift)
- investigation of key VDE dynamics in NSTX
  - driving mechanisms, chain of events, timing and scaling of various effects
  - sensitivity to parameter change
  - numerical stability/convergence
- halo/wall currents and wall forces
  - qualitative comparison with NSTX shunt tile diagnostics
  - ideal placement of shunt tiles in NSTX-U

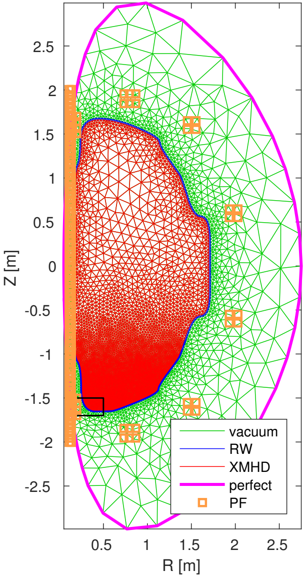
M3D-C1 has unique capabilities for modelling VDEs





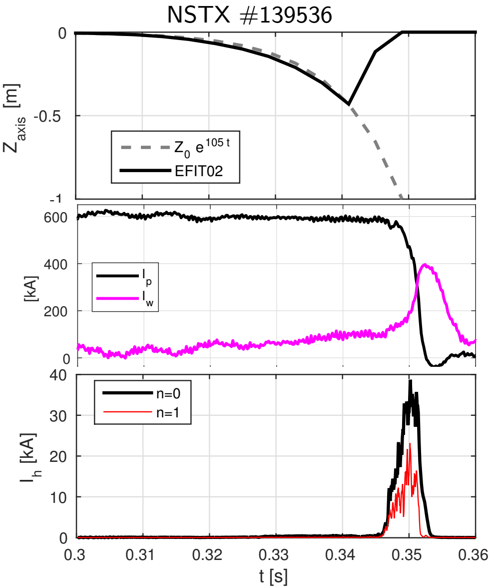
- XMDH [Breslau et al., 2009]
  - continuity, momentum, energy
  - Faraday, Ampère, Ohm
- resistive wall, $\boldsymbol{E} = \eta \boldsymbol{j}$
- vacuum, $\boldsymbol{j} = 0$
- ideal boundary (perfect conductor)
- PF coils (static)

M3D-C1 has unique capabilities for modelling VDEs



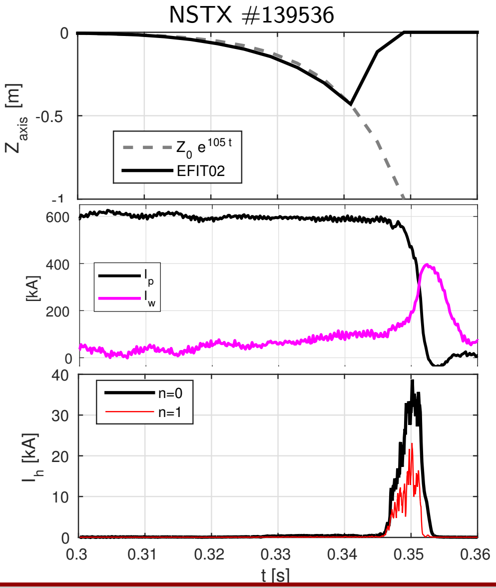
- key features
  - finite-thickness **axisymmetric** resistive wall (RW) [Ferraro et al., 2016]
  - **anisotropic** unstructured mesh as support for finite-element (week) **C1** solution
  - cubic spline on **48** planes for toroidal effects
  - **implicit** time-stepping allows simulations on RW timescales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

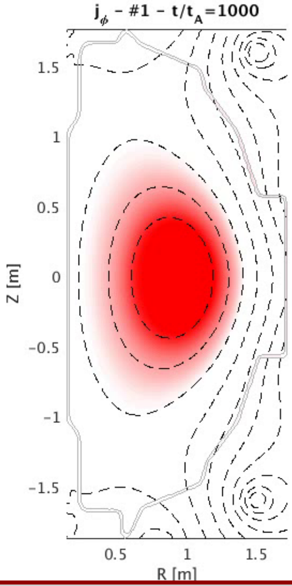
Experimental traces serve as modelling targets



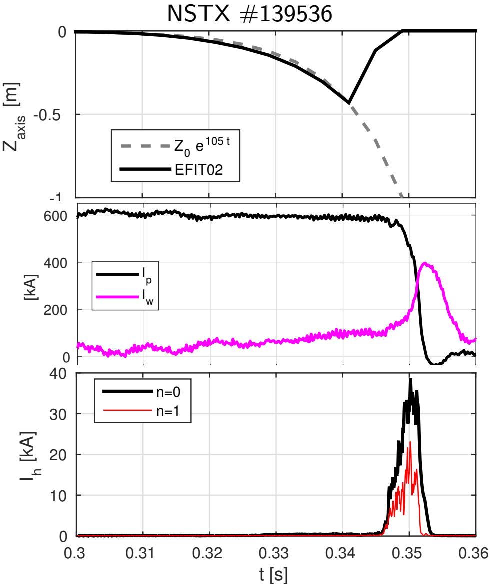
- phases and timescales
  - **slow** vertical motion $\tau_{VDE} \sim 50ms$, largely exponential
  - **rapid** $\tau_{CQ} \sim 5ms$ current quench begins at wall contact
  - relaxation of wall currents $\tau_{LR} \sim 10ms$
- $\tau_A \ll \tau_{CQ} < \tau_{LR} \ll \tau_{VDE}$
- shunt tile $n = 0 \sim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

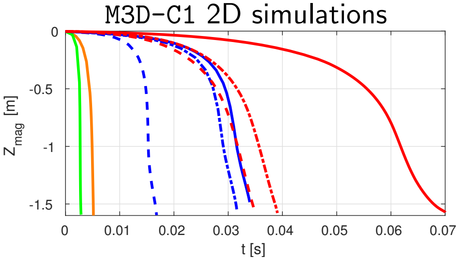
Experimental traces serve as modelling targets



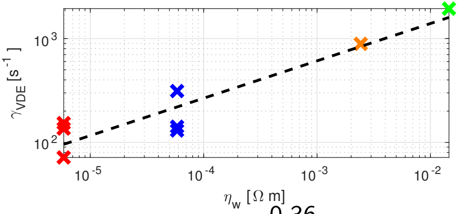


Experimental traces serve as modelling targets



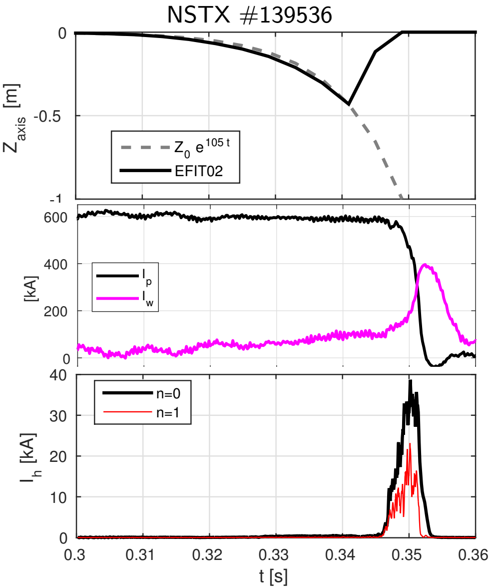


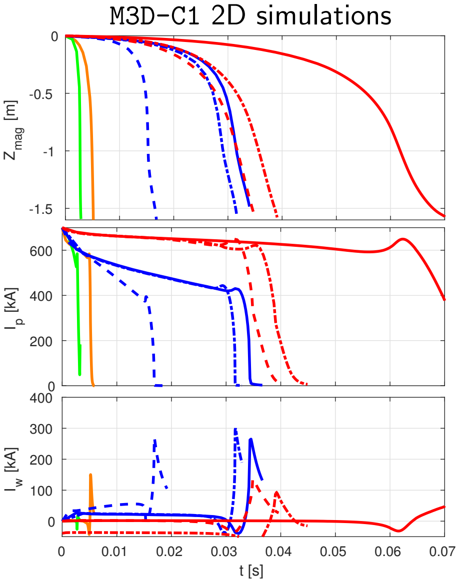
$\eta_w = 1.4 \times 10^{-3}$, 2.4×10^{-3}
5.8×10^{-5}, 5.8×10^{-6} Ω m



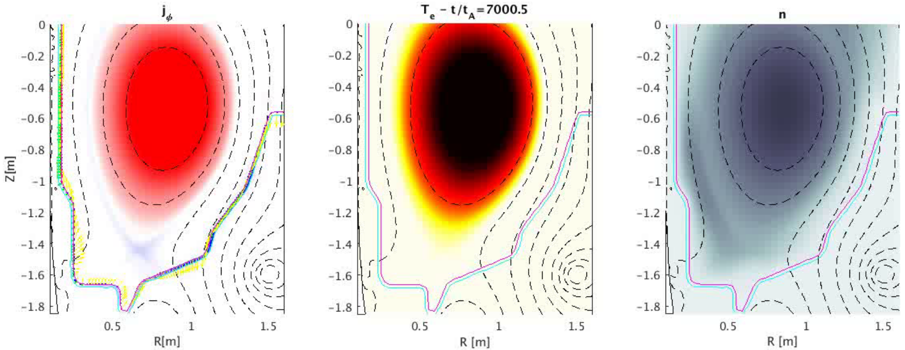
$$\gamma_{VDE} \propto \eta_w^{0.36}$$

Experimental traces serve as modelling targets



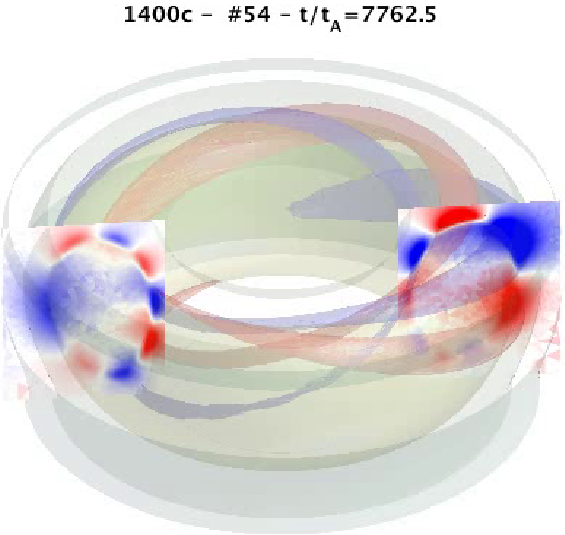


3D nonlinear simulations capture richer physics



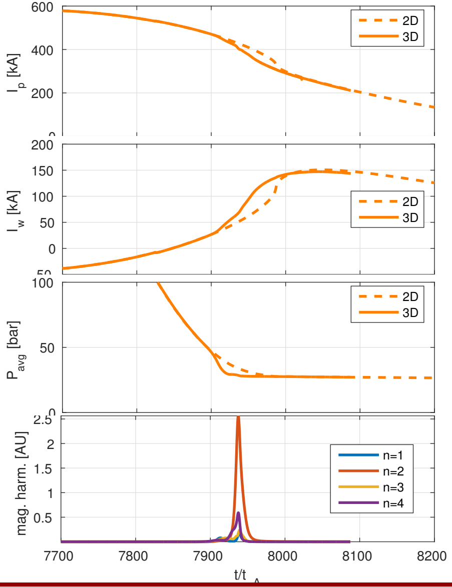
- orange case
  - $\eta_W = 2.4 \times 10^{-3}$ Ωm, short τ_{VDE}
  - high $T_h = 25$ eV

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



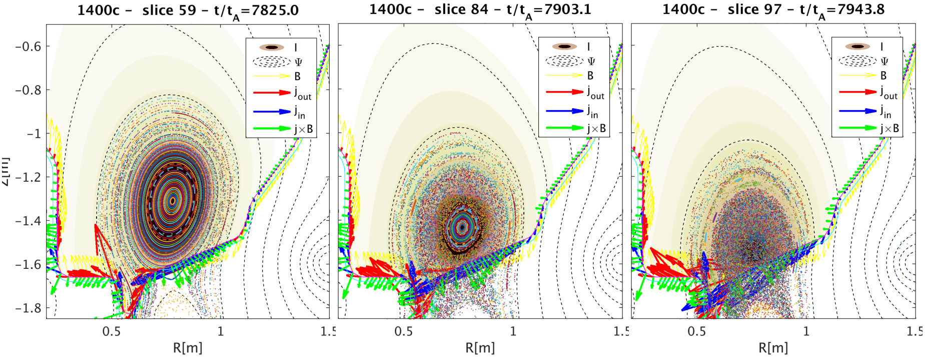
- orange case
  - $\eta_W = 2.4 \times 10^{-3}$ Ωm
  - high $T_h = 25$ eV
- LCFS scrape-off
  - shrinking of iso-tubes
  - spaghettification
- $n = 3 \rightarrow n = 1$
- figure caption
  - poloidal cuts at $\phi = 0, \pi$
  - isocontours at $\pm\tilde{\Psi}_{p,max}/2$
  - transparency scales with mode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

Onset of 3D modes causes evolution to differ



- orange case
  - $\eta_W = 2.4 \times 10^{-3}$ Ωm, 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 ↘

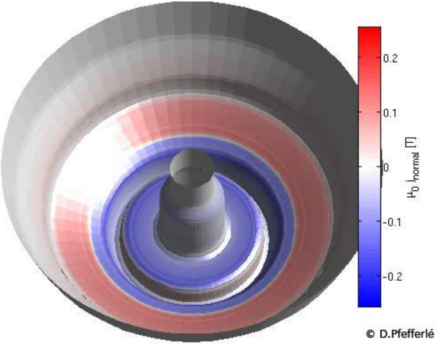
Penetrating edge modes precipitate current quench

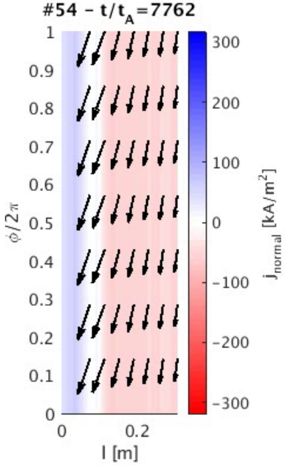


- stochastic field-lines ⇒ efficient heat transport via $\kappa_{||}$
- rapid cooling (cold wall) → increase in Ohmic dissipation
- only from 3D (effective 2D model?)

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

normal currents on wall (total)





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

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

Conclusions

- 3D nonlinear modelling of NSTX VDEs using `M3D-C1`
  - match realistic τ_{VDE}, τ_{CQ} and τ_{LR} timescales with 2D nonlinear simulations
  - **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

S. Gerhardt, J. Menard, S. Sabbagh, and F. Scotti, Nuclear Fusion **52**, 063005 (2012), URL http://stacks.iop.org/0029-5515/52/i=6/a=063005.

J. Breslau, TSDW 15 (2015).

J. Breslau, N. Ferraro, and S. Jardin, Physics of Plasmas **16**, 092503 (2009).

N. M. Ferraro, S. C. Jardin, L. L. Lao, M. S. Shephard, and F. Zhang, Physics of Plasmas **23**, 056114 (2016).