Findings from a Benchmark Study of 3D Vertical Displacement with JOREK, M3D-C^1, and NIMROD

C. R. Sovinec,[1] F. J. Artola,[2,3] S. C. Jardin,[4] M. Hoelzl,[3] I. Krebs,[5] and C. Clauser[4,6]

[1]University of Wisconsin-Madison, [2]ITER Organization, [3]Max-Planck Institute for Plasma Physics, [4]Princeton Plasma Physics Laboratory, [5]Dutch Institute for Fundamental Energy Research, [6]Lehigh University

Theory and Simulation of Disruptions Workshop

Virtual Meeting July 19-23, 2021

Center for Tokamak Transient Simulation

Theme, Outline, and Acknowledgments

Our benchmark study for verifying simulations of asymmetric VDE shows strong qualitative agreement and highlights sensitivities that affect some quantitative measures.*

I. Motivation
II. Problem setup
III. Code comparison
IV. Findings
    A. General evolution
    B. Wall forces
    C. 3D Halo currents
    D. Current asymmetry
    E. Initial perturbation
    F. Resolution checks
V. Discussion and Conclusions

- Work supported by US DOE grant DE-SC0018001 and contract DE- AC02–09CH11466,
- By the ITER Monaco Fellowship Program, and
- By the EUROfusion Consortium.
    - Euratom research and training program 2014-2018 and 2019-2020 under grant agreement No 633053
    - Agreement No. WP19–20-ERG-DIFFER
    - The views and opinions expressed herein do not necessarily reflect those of the European Commission.

*F. J. Artola, *et al.*, Physics of Plasmas **28**, 052511 (2021).

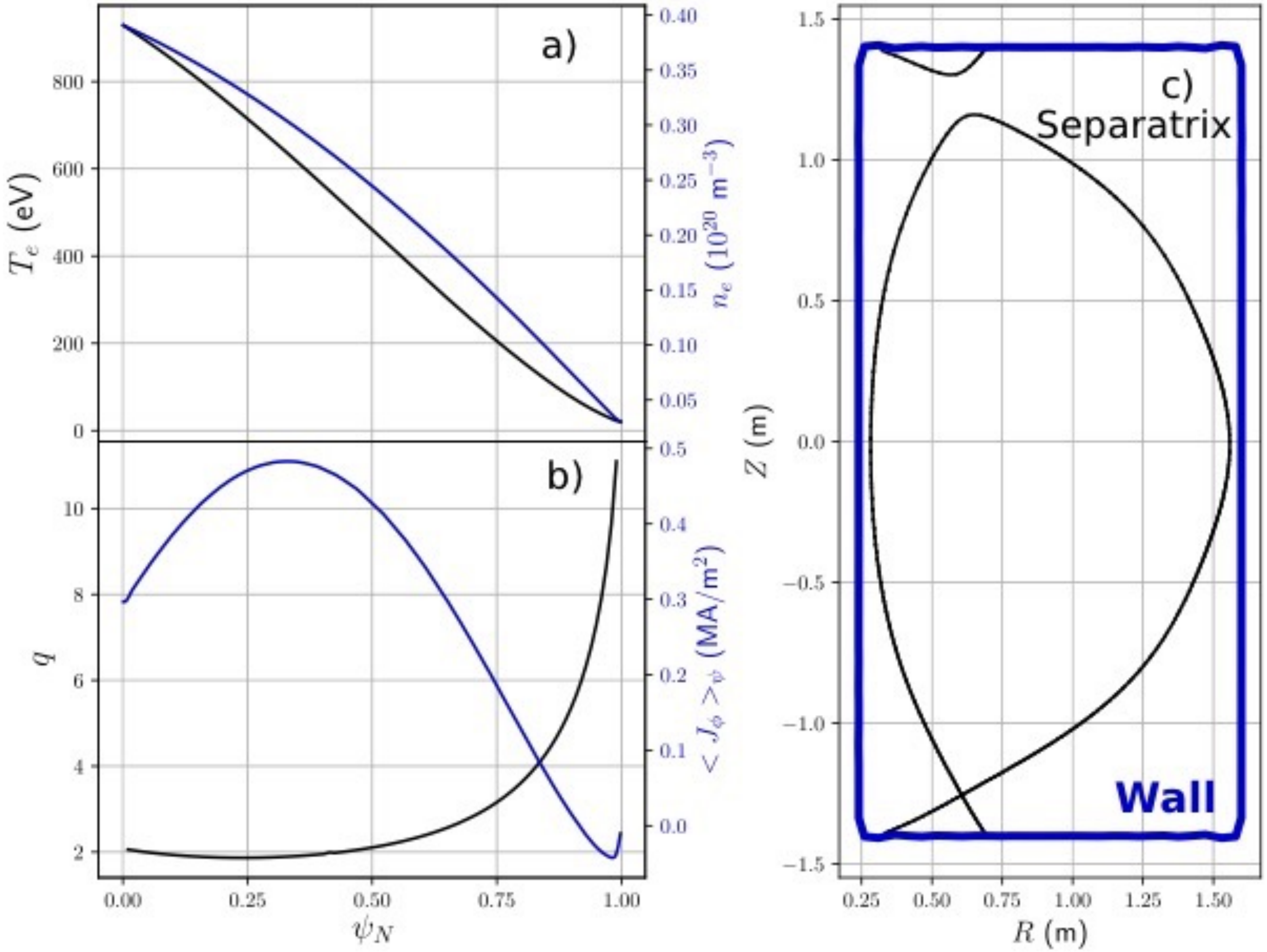
Motivation: Verification benchmarking enhances confidence when applying large simulations codes.

- JOREK,[†] M3D-C^1,[‡] and NIMROD[°] are being applied to understand and predict effects from asymmetric VDE.
- The codes have each been verified for many applications, including symmetric VDE,[*] but not specifically for asymmetric VDE.
- Comprehensive analytical solutions are not tractable, so verification relies on establishing benchmark problems and performing comparisons.

[†]M. Hoelzl, *et al.,* Nuclear Fusion **61**, 065001 (2021).
[‡]N. M. Ferraro, *et al.*, Physics of Plasmas **23**, 056114 (2016).
[°]C. R. Sovinec, *et al.*, J. Computational Physics **195**, 355 (2004).
[*]I. Krebs, *et al.*, Physics of Plasmas **27**, 022505 (2020).

Problem setup: Our computations are based on NSTX discharge 139536 at 309 ms.

- Case is representative of modeling an actual discharge.
- Feedback in the experiment was removed to allow vertical instability.
- Resistive wall shape is simplified.
- Fitted equilibrium is only used as an initial condition.



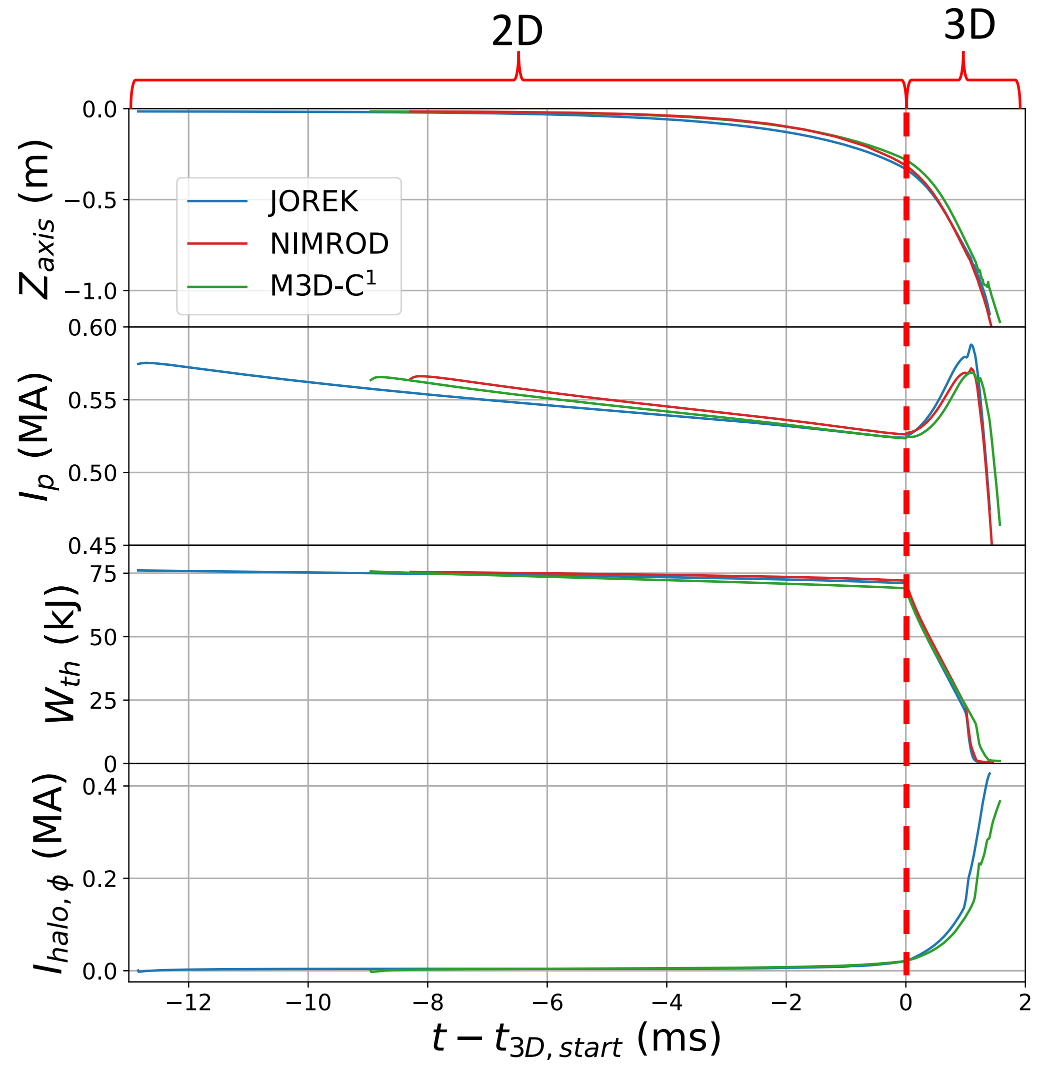
I_p	$= 5.74 \times 10^5$ A	W_{mag}	$= 1.12 \times 10^5$ J	W_{thm}	$= 7.61 \times 10^4$ J
β_N	$= 3.83$ %	β_p	$= 5.32 \times 10^{-1}$	$l_i(3)$	$= 6.98 \times 10^{-1}$
q_0	$= 2.04$	q_{95}	$= 7.32$	V_p	$= 1.19 \times 10^1$ m^3
R_{xpoint}	$= 6.06 \times 10^{-1}$ m	Z_{xpoint}	$= -1.26$ m	ψ_{xpoint}	$= 1.19 \times 10^{-2}$ Wb/rad
R_{axis}	$= 1.07$ m	Z_{axis}	$= -1.52 \times 10^{-2}$ m	ψ_{axis}	$= -4.73 \times 10^{-2}$ Wb/rad

d)

Heavy blue "Wall" line indicates the resistive wall used in the computations. [Figure from Artola, *et al.*, PoP **28**, 052511.]

The computations are run in two phases: 2D until LCFS contact, then 3D.

- The toroidally symmetric 2D computations are similar to those in Krebs, PoP **27**, 022505.
  - Transport coefficients are larger, making VDE displacement time closer to NSTX.
  - Linear stability to $n > 0$ is tested over displacement intervals of ¼.
- 3D computations are started from 2D results when the LCSF contacts the lower surface.
  - Thermal conductivities are increased by 150 to start a thermal quench (TQ).
  - Particle diffusivity is increased by 26.
  - Small asymmetric perturbations are applied.



Computed traces of magnetic axis position, plasma current, thermal energy, and net halo current. [From Artola, *et al.*, PoP **28**, 052511.]

Modeling is visco-resistive MHD with anisotropic thermal conduction.

- The anisotropic thermal conduction, $\kappa_{||} = 10^5 \kappa_\perp$, is with respect to the evolving 3D magnetic field.
- Resistivity depends on local, evolving temperature, $\eta(T) = \eta_0 (T_0/T)^{3/2}$.

$$\frac{\partial}{\partial t} n + \nabla \cdot (n\mathbf{V}) = \nabla \cdot (D \nabla n)$$

$$\rho \left(\frac{\partial}{\partial t} \mathbf{V} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \cdot \mathbf{\Pi}$$

$$\frac{3}{2} n \left(\frac{\partial}{\partial t} T + \mathbf{V} \cdot \nabla T \right) = -\frac{p}{2} \nabla \cdot \mathbf{V} + \nabla \cdot \left[\left(\kappa_{||} - \kappa_\perp \right) \hat{\mathbf{b}} \hat{\mathbf{b}} + \kappa_\perp \mathbf{I} \right] \cdot \nabla T + Q - T \nabla \cdot (D \nabla n)$$

$$\frac{\partial}{\partial t} \mathbf{B} = \nabla \times (\mathbf{V} \times \mathbf{B} - \eta \mathbf{J})$$

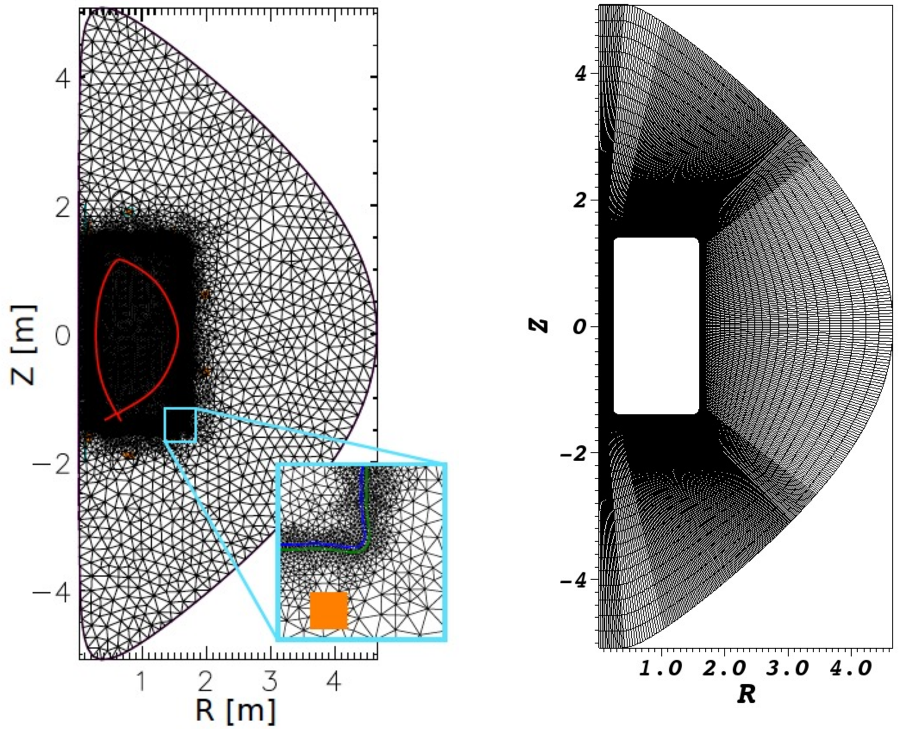
Note:

- Loop voltage and Ohmic heating are not applied.
- Runaway electrons and radiation effects are not modeled.
- The JOREK modeling here uses reduced MHD, unlike M3D-C^1 and NIMROD.

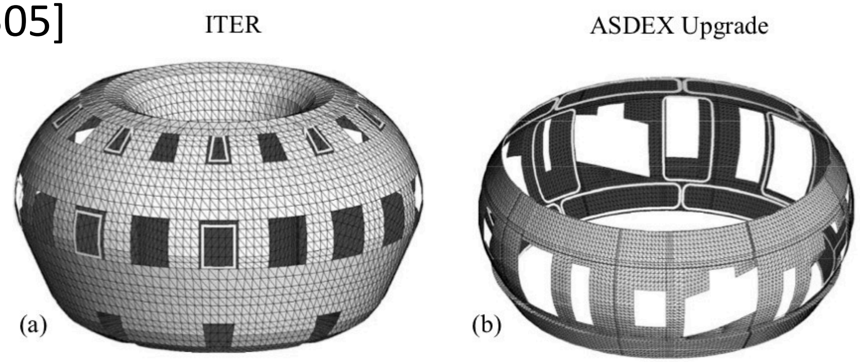
Boundary conditions allow flow and magnetic field to decouple at the resistive wall.

- Dirichlet conditions on n, T, and $\mathbf{V}$ are applied at the resistive wall.
  - Fixing $T_w = 15\ eV = 0.015\ T_0$ maintains cold-wall conditions that allow field and flow to decouple.
  - Evolution is insensitive to $\mathbf{V}_w$.*
- Resistive wall/vacuum magnetic models differ among the codes.
  - Thin wall (JOREK, NIMROD) vs. thick (M3D-C[1])
  - Boundary element vs. meshed vacuum

*Bunkers and Sovinec, PoP **27**, 112505 (2020).



M3D-C[1] (left) and NIMROD (right) evolve vacuum-**B** over meshed external regions. [Krebs, *et al.*, PoP **27**, 022505]



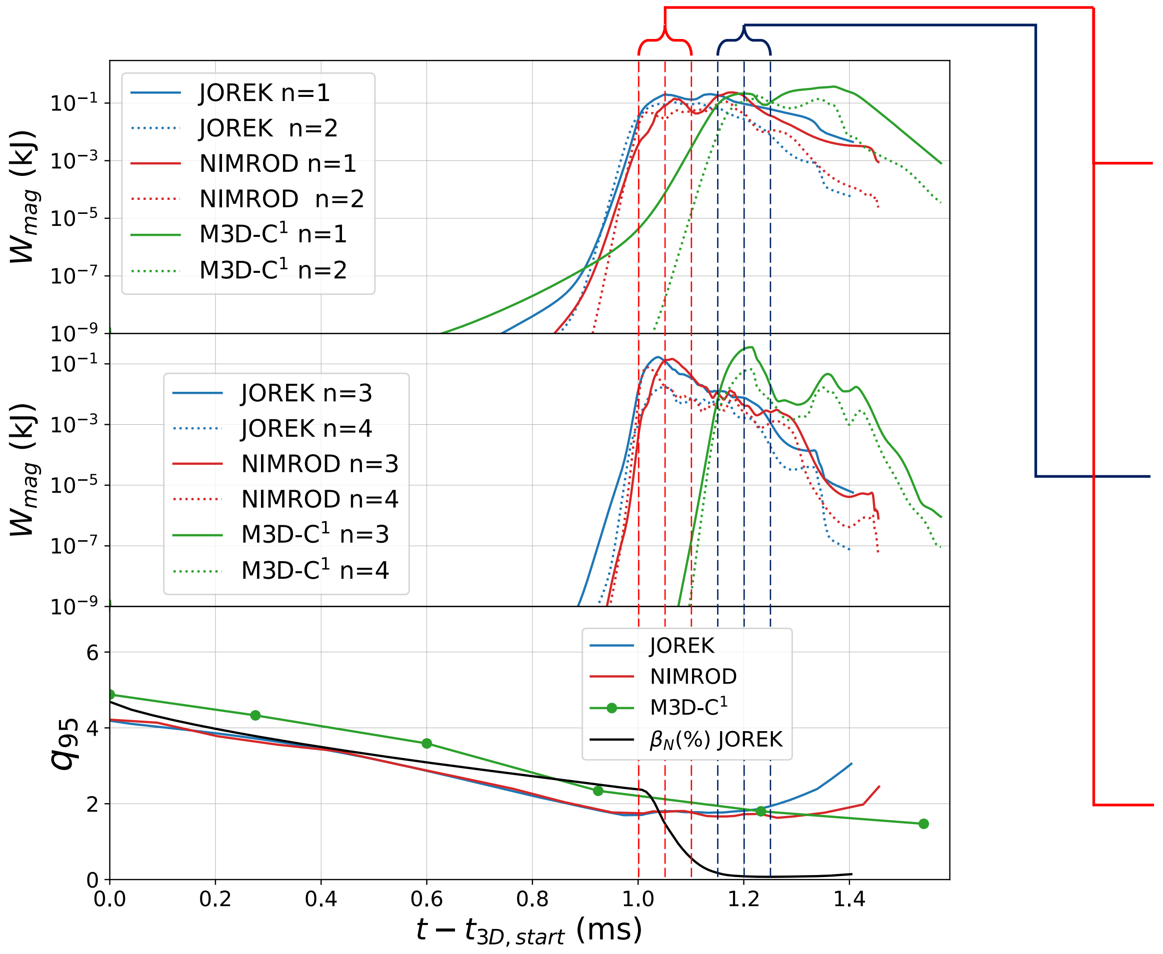
JOREK is coupled to the boundary-element STARWALL code that can represent complex 2D shapes. [Strumberger, *et al.*, PoP. **15**, 056110]

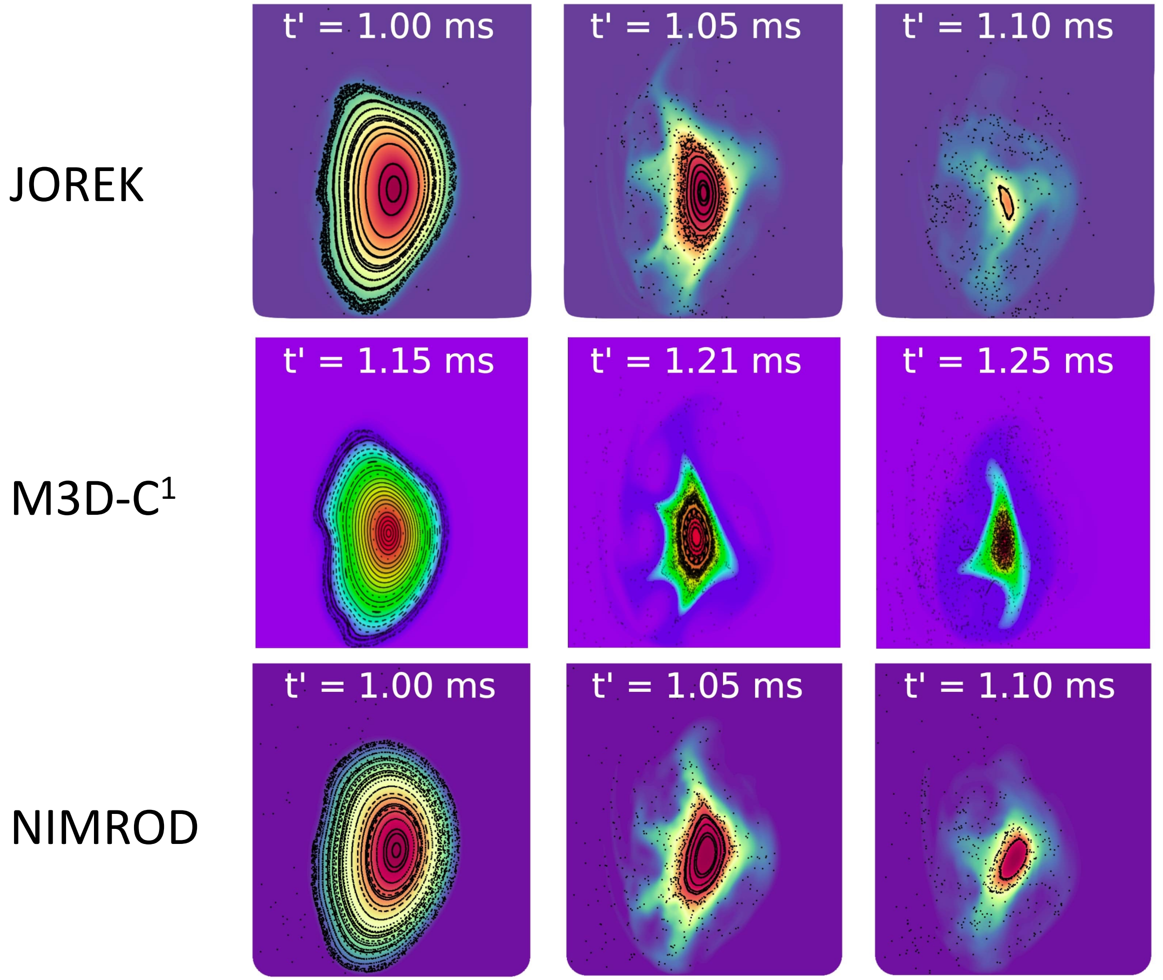
Code comparison: Models and numerical methods differ among the three codes.

	NIMROD	M3D-C1	JOREK
MHD model	full	full	reduced used here
Variables	*n*, *T*, **V**, **B**	*n*, *T*, scalar potentials for **V** and **A**	*n*, *p*, scalar potentials for **V** and **A**
Poloidal representation	39k bicubic or biquadratic elements	reduced quintics, 17.5k nodes	22k Bézier cubics
Toroidal representation	Fourier, $N_{max} = 10, 21$	16 Hermite cubics	Fourier, $N_{max} = 10, 20$
Temporal advance	implicit leapfrog	split implicit	implicit
Resistive wall / vacuum field	thin wall, direct representation	thick wall, direct representation	thin wall, Green's function

- The unique aspects of each makes this benchmarking a substantial numerical test.

Findings: The three codes reproduce strong asymmetric destabilization from wall contact.

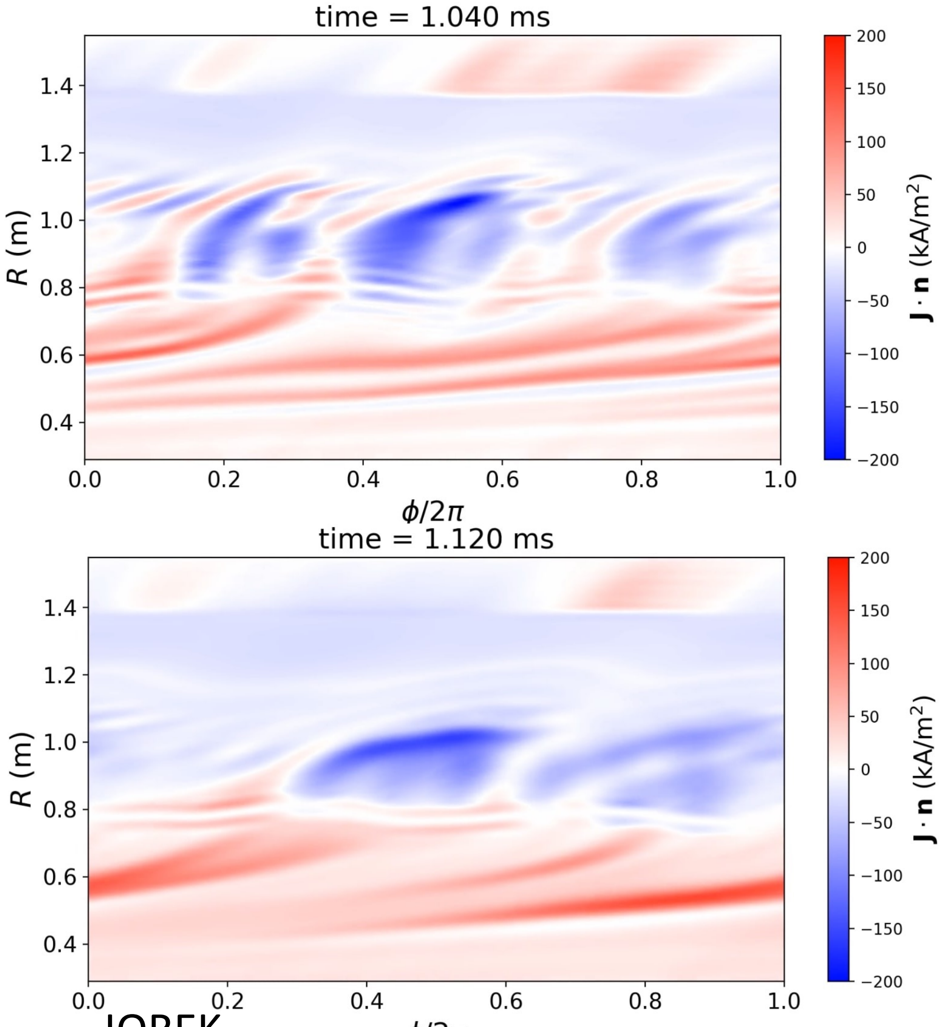




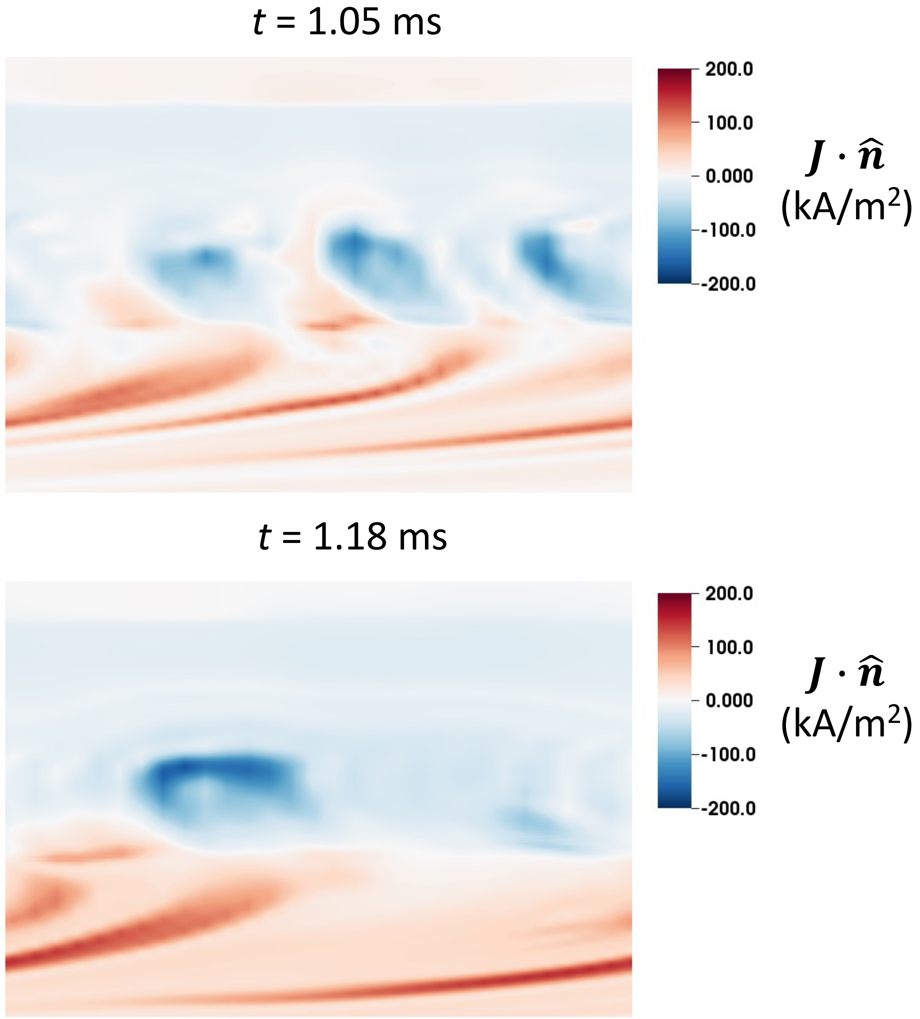
A slowly growing (m=2,n=1) is dominant until q_{95} passes 2, when other components become large. [Figures from Artola, *et al.*, PoP **28**, 052511.]

Poincaré plots (pressure contours) show similar effects on magnetic topology (thermal energy loss).

Halo asymmetry evolves with the MHD activity during the rapid quench.



JOREK



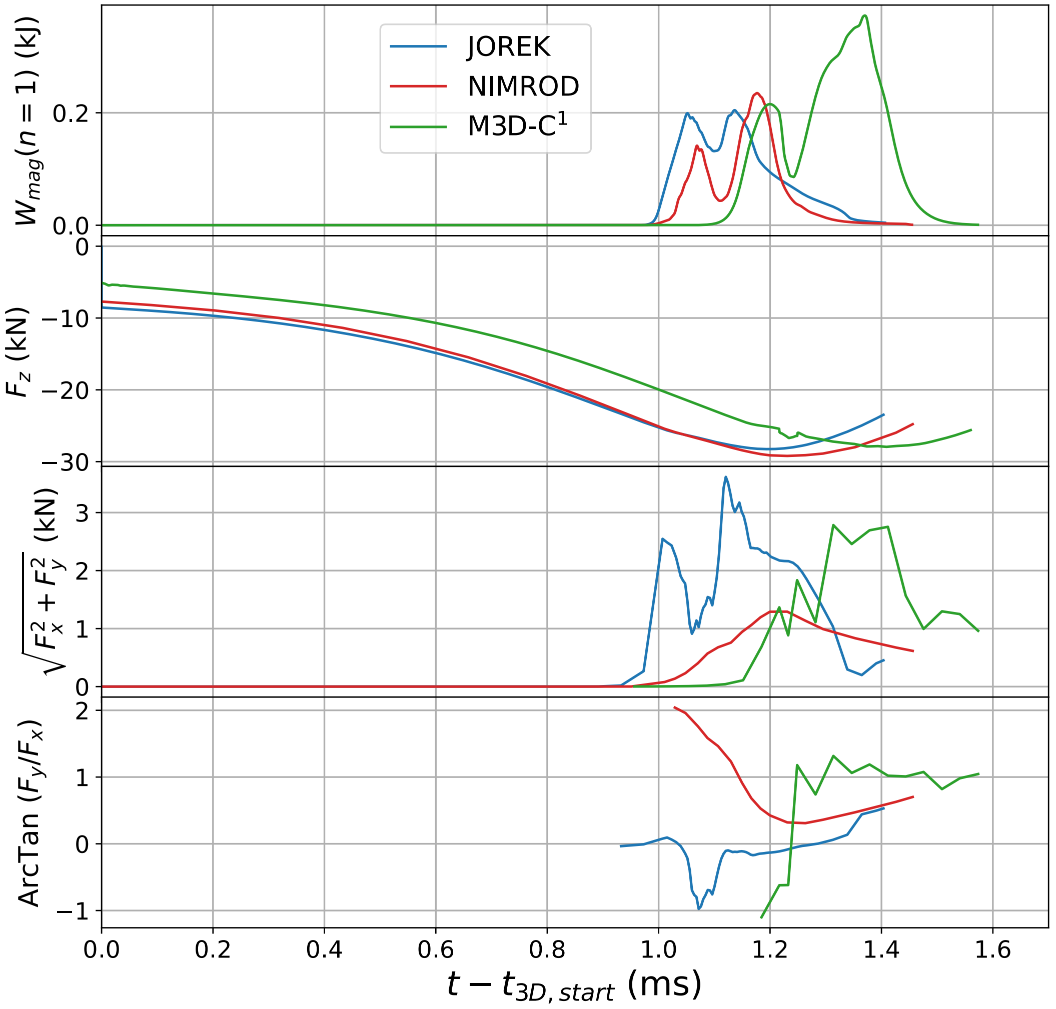
NIMROD

- Energy in n = 3 magnetic fluctuation exceeds that in n = 1 briefly during the multi-helicity saturation. [JOREK plots from Artola, *et al.,* PoP **28**, 052511.]

There are nontrivial quantitative discrepancies among some results.

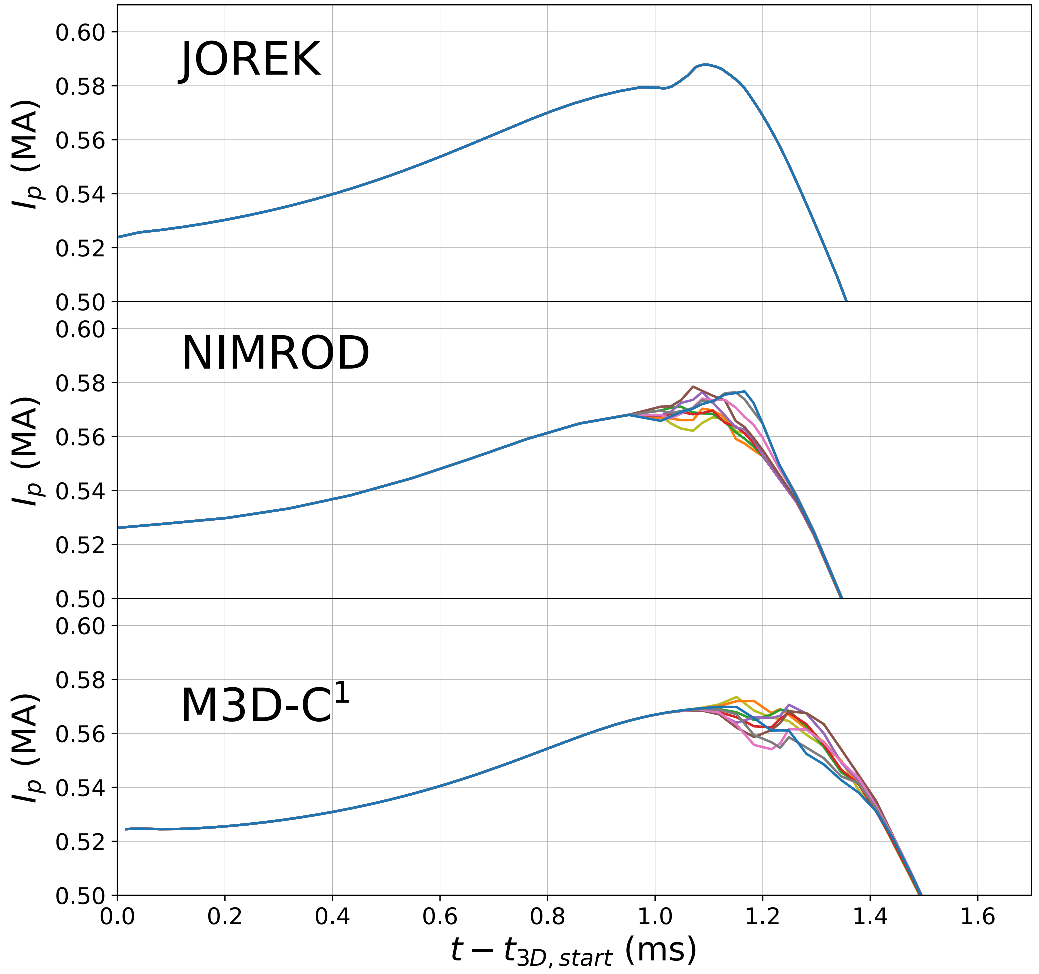
	NIMROD	M3D-C1	JOREK
max($W_{n=1}$)	0.24 kJ	0.37 kJ	0.20 kJ
max(F_{horiz})	1.3 kN	2.7 kN	3.5 kN
Final TQ duration	0.18 ms	0.24 ms	0.14 ms

- Largest discrepancy (factor of 2.7) is in the net horizontal wall force.
- Peak n=1 magnetic energy in M3D-C^1 is largest.
- Other quantitative predictions are in better agreement.



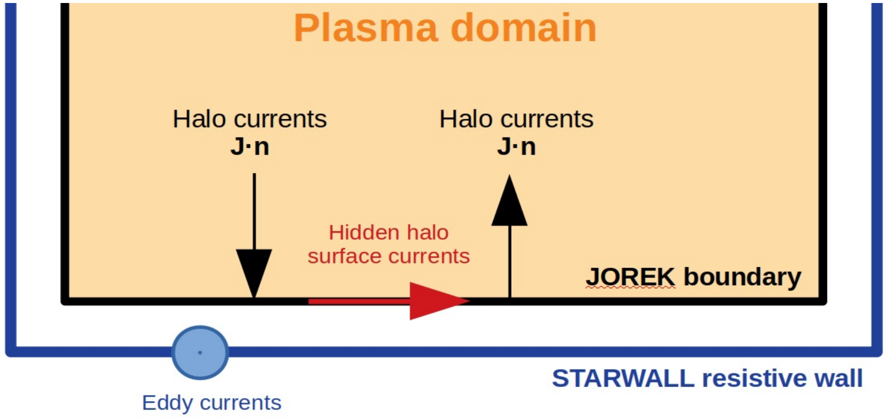
Magnetic fluctuation energy (n=1), net vertical and horizontal wall force, and force orientation. [Artola, *et al.*, PoP **28**, 052511.]

Peaking of toroidal current depends on numerical wall coupling.



Toroidal current recorded over 10 equally spaced poloidal planes. [Artola, *et al.*, PoP **28**, 052511.]

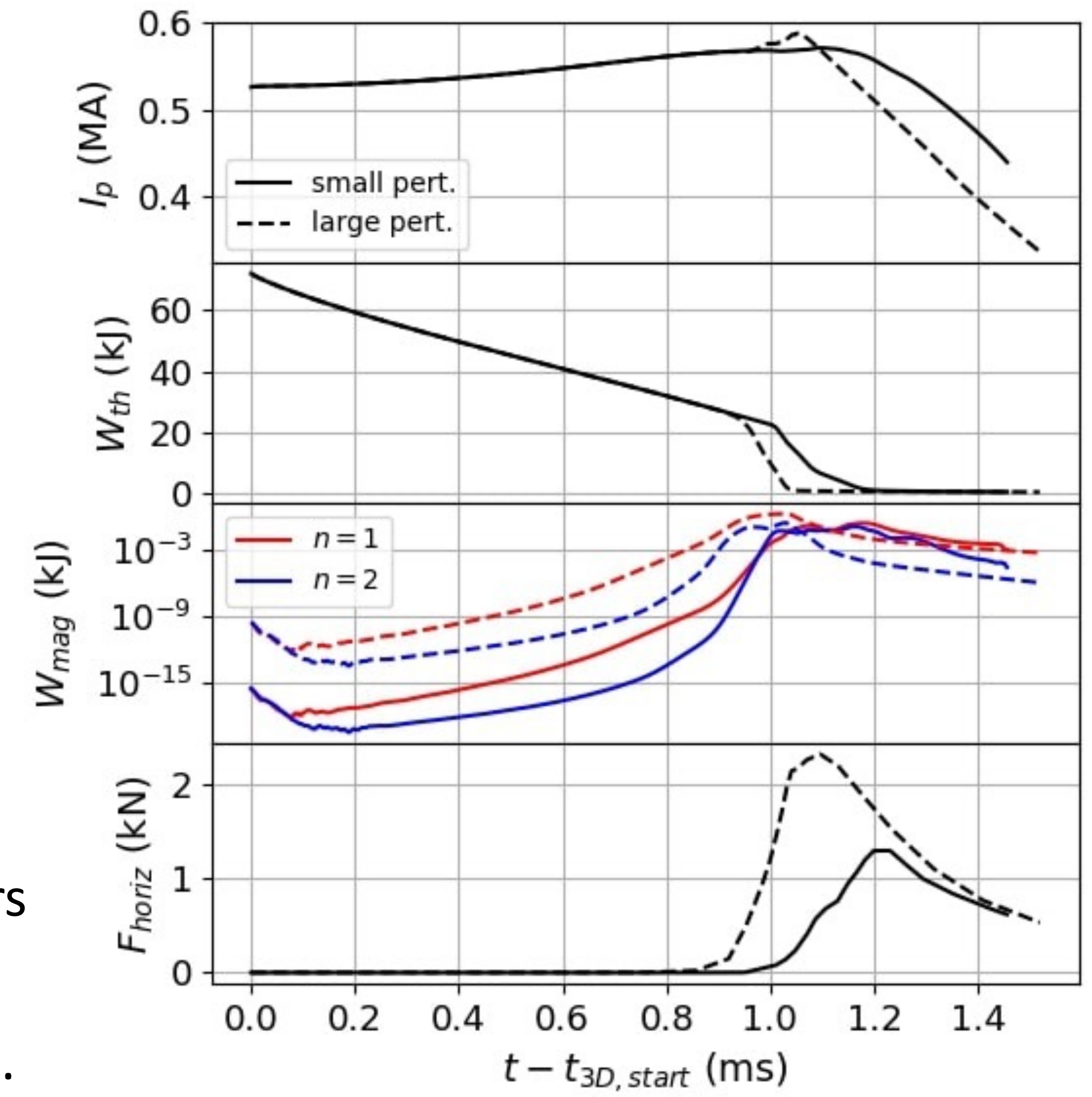
- NIMROD and M3D-C[1] produce similar levels (2%) of toroidal current asymmetry.
- JOREK analysis shows no asymmetry.
  - The STARWALL coupling does not allow halo current to flow to the wall.
  - Surface currents effectively flow without leaving the JOREK mesh.



Schematic of JOREK halo-current continuity.

The asymmetric perturbations at the start of the 3D phase affect the long-term evolution.

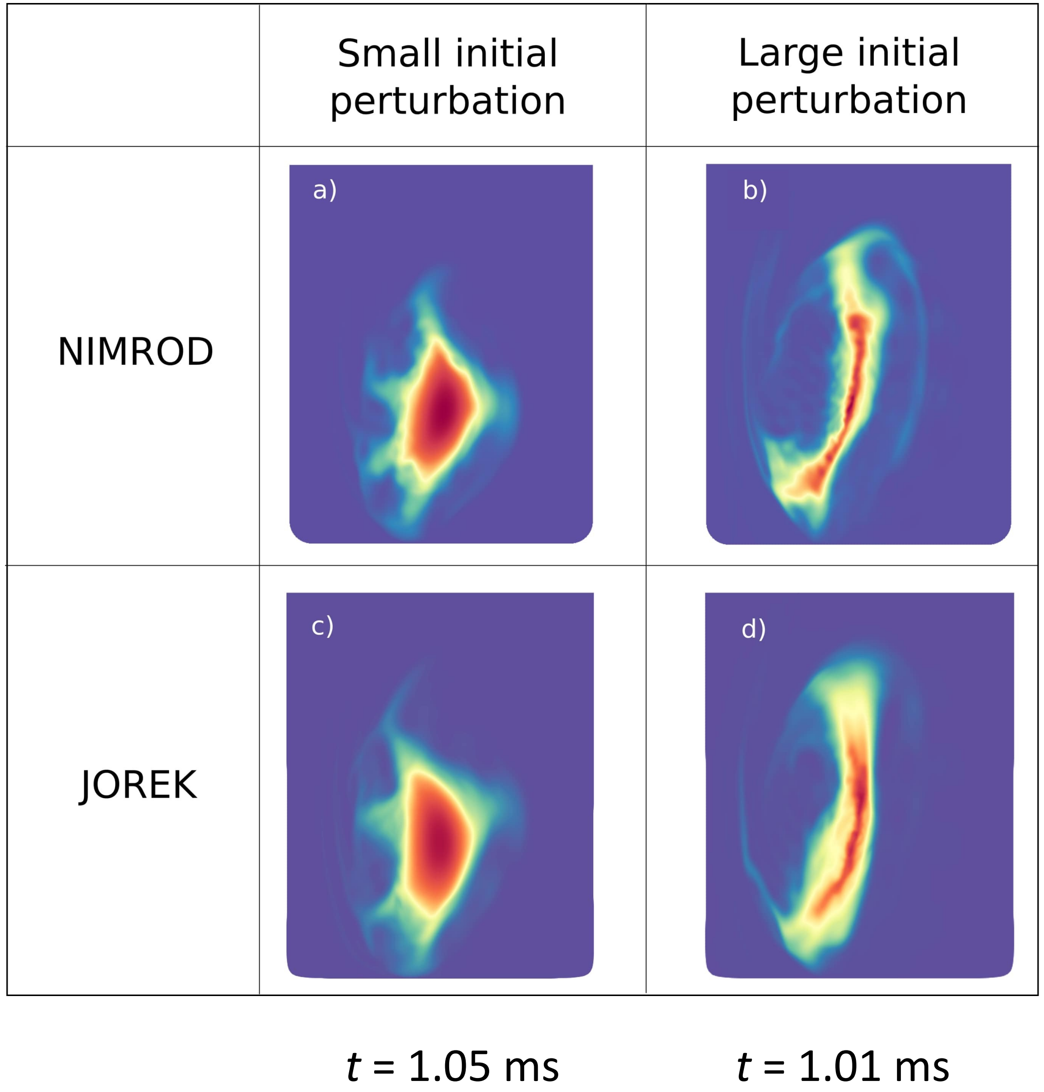
- Perturbations excite unstable asymmetric modes.
- Amplitude and spatial distribution are usually arbitrary, and they differ among the codes.
- Differing magnitudes were tested in NIMROD and JOREK.
    - All perturbations are initially in a linear phase.
    - Net growth during vertical displacement matters in this configuration.
    - Increase in F_{horiz} with larger perturbation is 80%.



NIMROD results from computations with perturbations of smaller and larger amplitude. [Artola, *et al.*, PoP **28**, 052511.]

Different perturbation amplitudes lead to qualitatively different evolution.

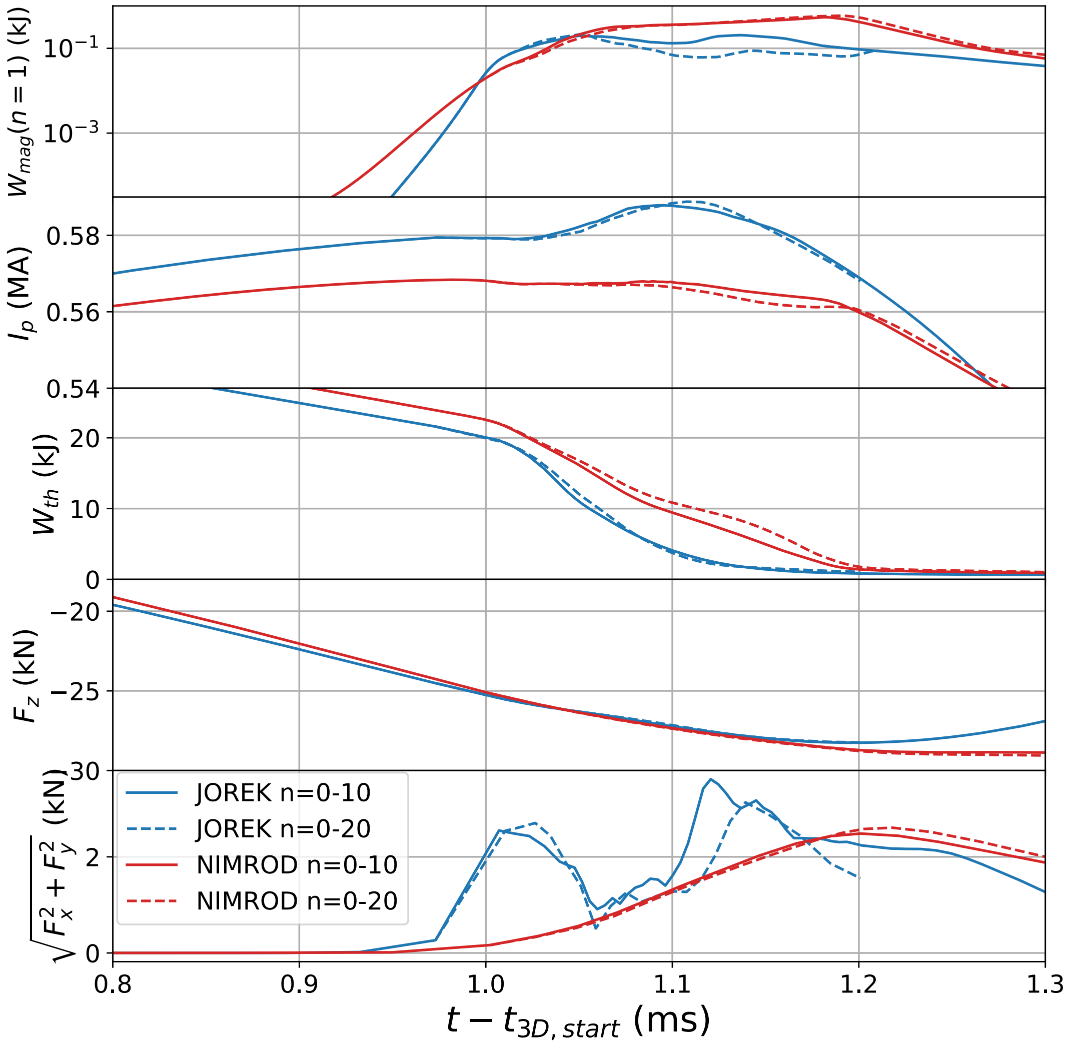
- All 3D-phase computations first show weakly growing (2,1).
- With smaller perturbations, q_{95} dropping below 2 leads to multi-helicity saturation and TQ.
- With larger perturbations, (2,1) and its harmonics saturate before other helicities are excited.
- Finding is verified with NIMROD and JOREK.



Pressure contours from NIMROD and JOREK results with perturbations of smaller and larger amplitude. [Artola, *et al.*, PoP **28**, 052511.]

Numerical resolution tests have been performed.

- Doubling the number of toroidal harmonics in JOREK and NIMROD computations only makes small quantitative effects.
  - NIMROD computations in this comparison used 2D resistivity.
- A check of poloidal resolution was most easily accomplished by switching NIMROD's elements to biquadratic.
  - Peak *n* =1 magnetic energy is 37% larger.
  - max(F_{horiz}) is only 2.2% larger.



Key results from JOREK and NIMROD with varied toroidal resolution. [Artola, *et al.*, PoP **28**, 052511.]

Discussion and Conclusions

- There is strong qualitative agreement in the evolution predicted by JOREK, M3D-C^1, and NIMROD.
  - Evolution from vertical motion and wall contact directly influences 3D stability.
  - With sufficiently small 3D perturbations, all three codes show a slowly growing (2,1) followed by multi-helicity saturation.
  - The Ansatz-based reduced MHD in JOREK works well in this application.
- Non-trivial quantitative discrepancies are found.
  - Net horizontal force predictions vary by 2.7.
  - Resolution checks have not accounted for the discrepancies.
- The evolving stability of the profile and non-repetitive behavior makes the results sensitive to initial perturbations.
  - This is unlike many other applications of nonlinear computation in MFE.