Disruption Mitigation: 3D MHD Simulations and Plans for Experimental Validation

S. Woodruff, J. E. Stuber, S. Schetterer
Woodruff Scientific Inc, 4000 Aurora Ave N, Seattle, WA 98103

Acknowledge conversations with: Carl Sovinec (UW), Scott Kruger (TechX), Val Izzo (UCSD), Paul Parks (GA), Eric Hollmann (UCSD), Karsten McCollam (UW), Nate Hicks (UAA), David Ennis (AU), David Rasmussen (ORNL), Larry Baylor (ORNL), Mark Lyttle (ORNL), Giovanni Cone (LANL).

American Physical Society, Division of Plasma Physics Meeting
Denver Colorado, November 11-15 (2013)

Work supported by ORNL under subcontract 4000118643 / DOE subcontract DE-AC05-00OR22725

Abstract

Two disruption scenarios are modeled numerically by use of the CORSICA 2D equilibrium and NIMROD 3D MHD codes.

The work follows the simulations of Kruger for pressure-driven modes in DIII-D and Strauss for VDEs in ITER.

The aim is to provide starting points for simulation of tokamak disruption mitigation techniques currently in the CDR phase for ITER.

- *Pressure-driven instability growth rates previously observed in simulations of DIIID are verified;*
- *Halo and Hiro currents produced during vertical displacements are observed in simulations with implementation of resistive walls for ITER*

We discuss plans to exercise new code capabilities and validation.

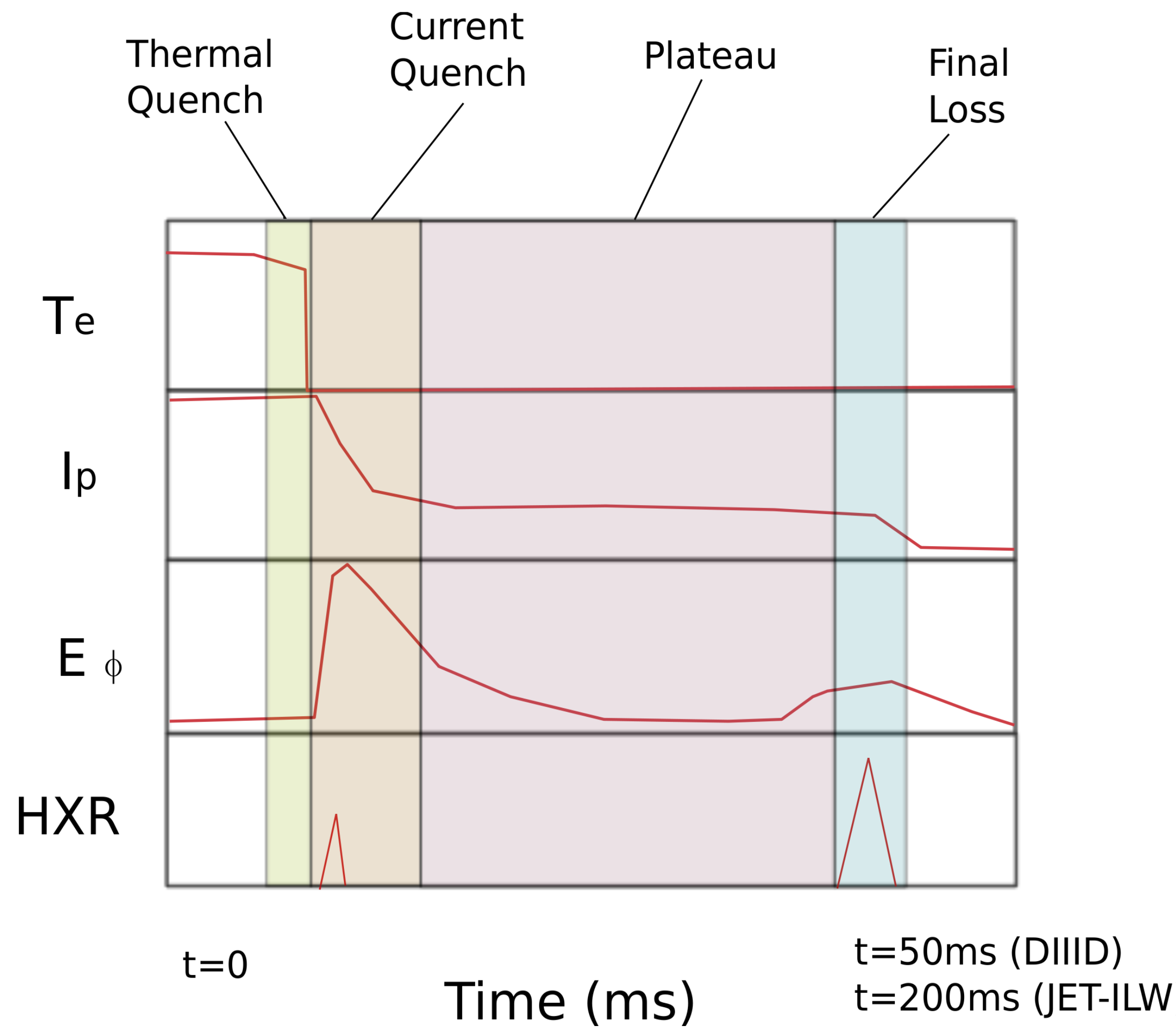
Disruptions in tokamaks

Large disruption taxonomy [1], with ~same anatomy (→ [2])

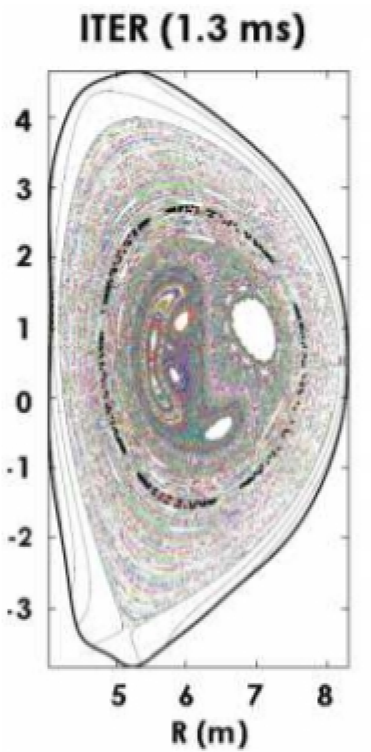
Current philosophy is to control the plasma to avoid disruptions, and mitigate if necessary.

Mitigation aims to: 1) limit impacts of CQ on in-vessel components; 2) suppress REs.

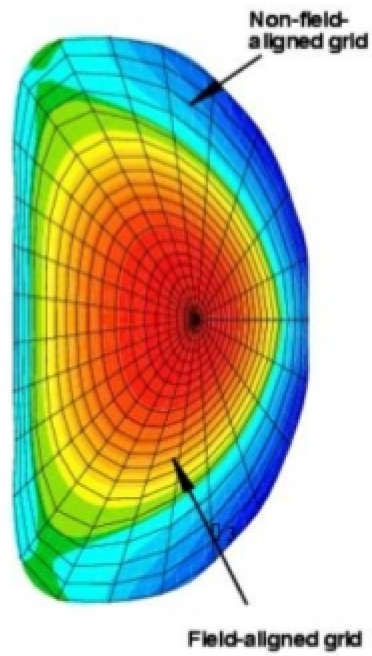
Main options right now: rapid massive pellet injection or rapid massive gas injection [3].



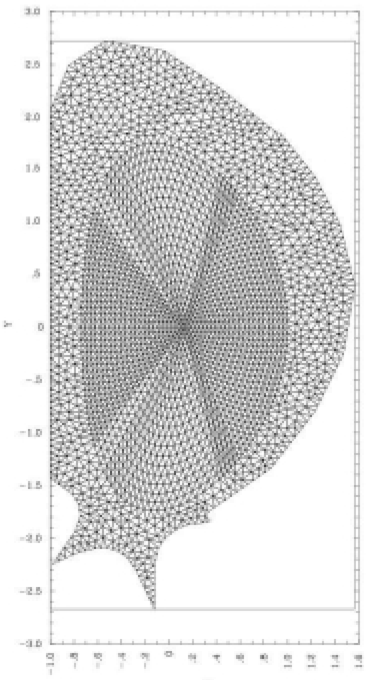
Prior disruption simulations



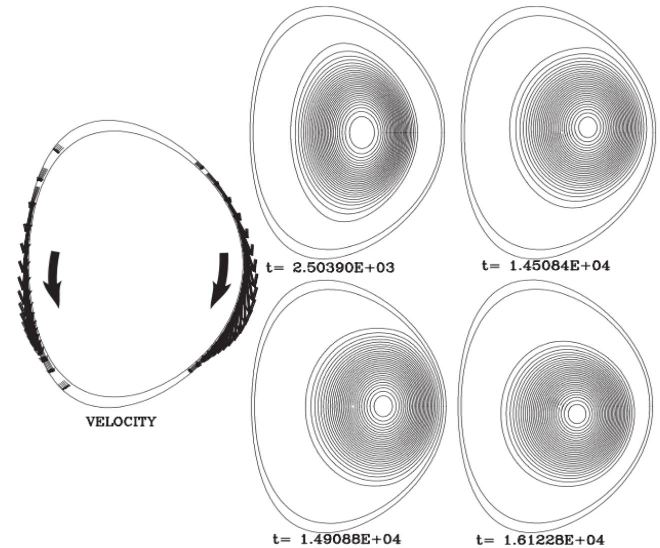
Izzo [4]



Kruger [5]



Strauss [6]



Aydemir [7]

Prior work focused on: REs, VDEs, halo / hiro current, and wall current.

We start with verification of Kruger [5] and Strauss [6], implementing NIMROD BCs like Aydemir [7].

Our tools

Initial conditions

CORSICA [8] is a 1.5D plasma simulation code, coupling equilibrium, stability and transport: used for ITER, NSTX, DIIID and other major fusion systems, which we operate under license to LLNL.

Light Tools

Ray-tracing in realistic geometries (obtained from CATIA engineering drawings) [10].

Engineering CAD

CATIA / STP compatible CAD.

3D MHD

The **NIMROD** code [9] solves non-linear initial value problems in 2 fluid MHD with the addition of the Hall term. Finite elements in the poloidal plane and fourier series in the toroidal direction. Used extensively for tokamaks, including ITER, NSTX, DIIID and for compact tori.

(2013 NERSC allocation: 200k hours)

Stability

DCON is a code for determining the MHD stability of static axisymmetric toroidal plasma. It uses an algorithm, developed by Newcomb for cylindrical plasmas and generalized by Glasser to axisymmetric plasmas [11].

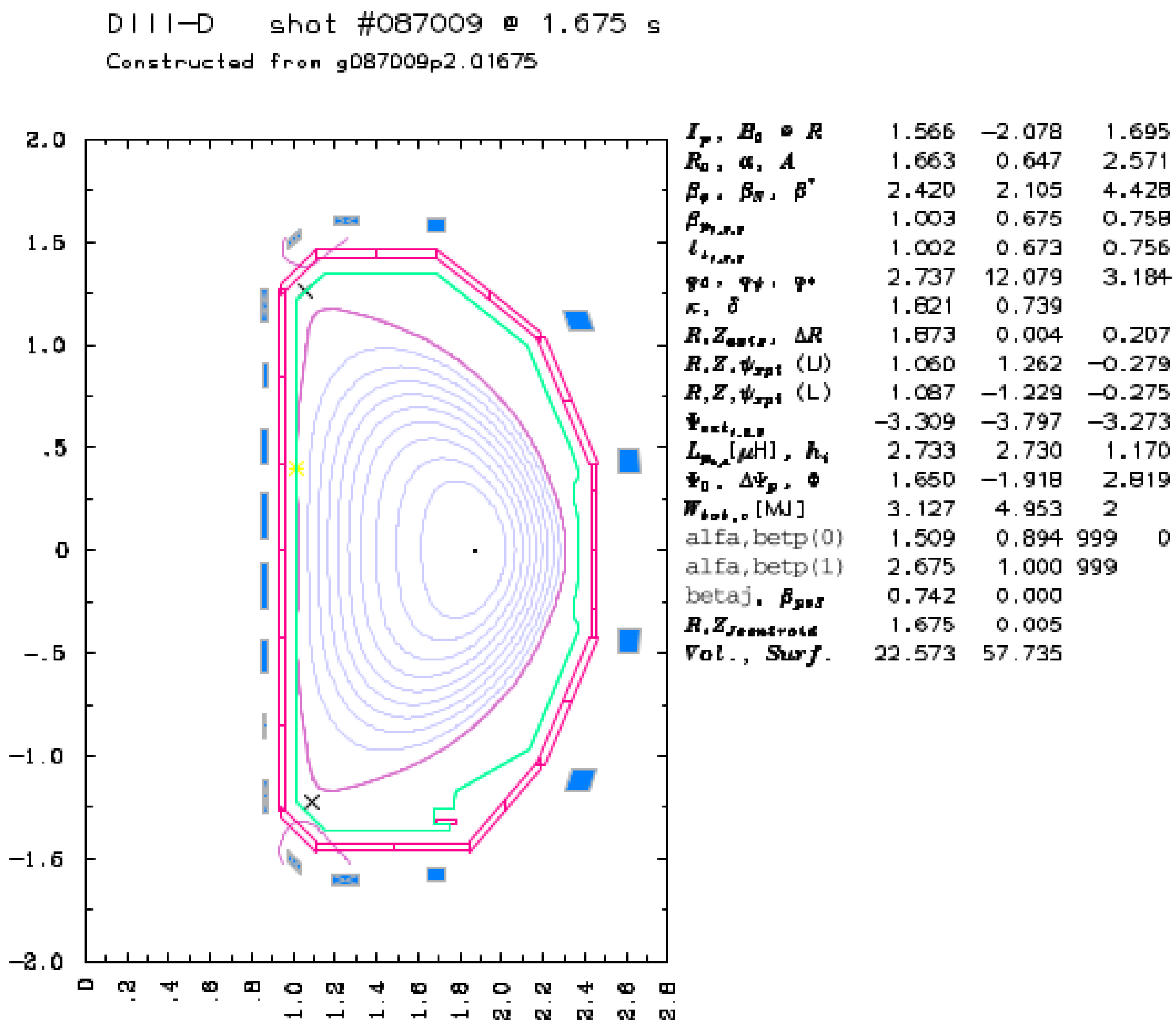
DIII-D Shot #087009: initial condition

Kinetic EFIT at t=1.675ms.

Pressure increased to marginal stability with CORSICA/DCON.

Fixed-boundary:
S~1e5 - 1e6
n=0,1

Free-boundary:
S~1e5
n=0,1

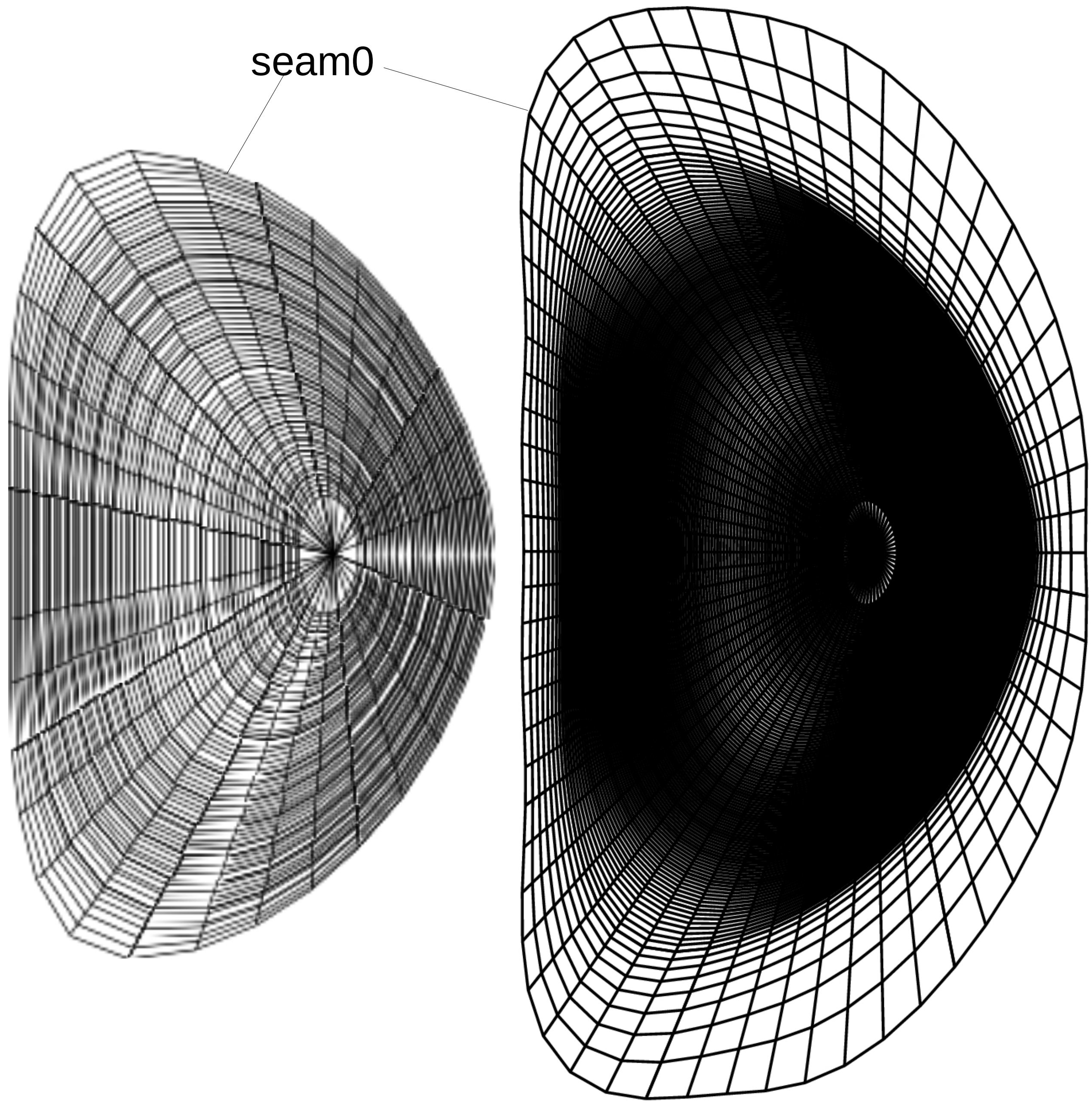


DIII-D Shot #087009: meshes

Fixed and free boundary simulations run with different meshes.

Conducting boundary conditions applied to seam0.

Typically:
mx=128
my=64
nxbl=8, nybl=4
poly_degree=3
# procs = 64 to 192



DIII-D Shot #087009 with fixed boundary

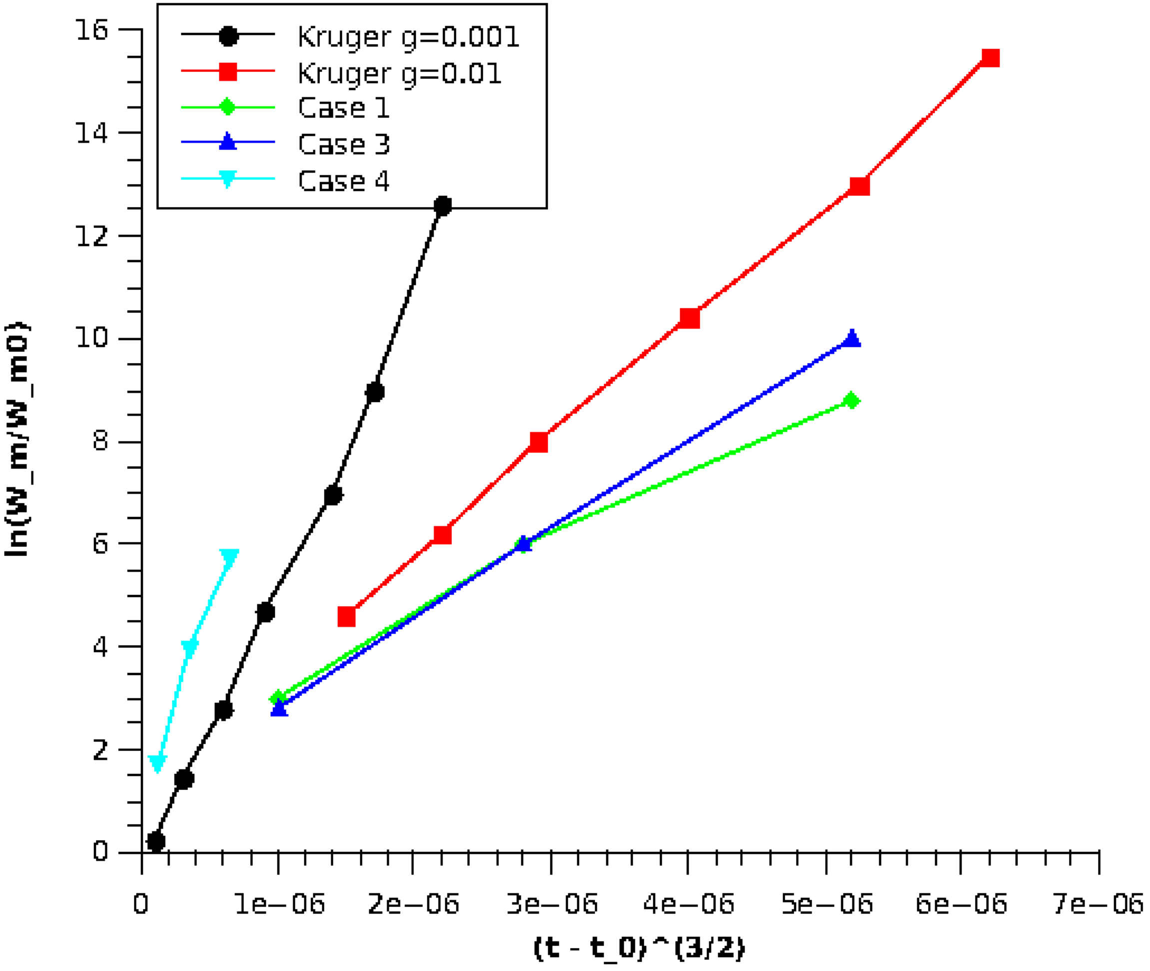
$$\frac{\partial P}{\partial t} = ... + \gamma_H P_{eq}$$

$$\beta_N = \beta_N C(1 + \gamma_H t)$$

Campaign:

- S=1e5, 1e6;
- gamma_heat= 0.1, 0.01, 0.001;
- bamp=1e-1, 1e-5, 1e-20
- l_phi=2 (n=0, 1 modes)
- Continuity and eta n=0
- Anisotropic thermal

Growth rate of n=1 mode measured and compared with scaling of (t-t0)^(3/2).

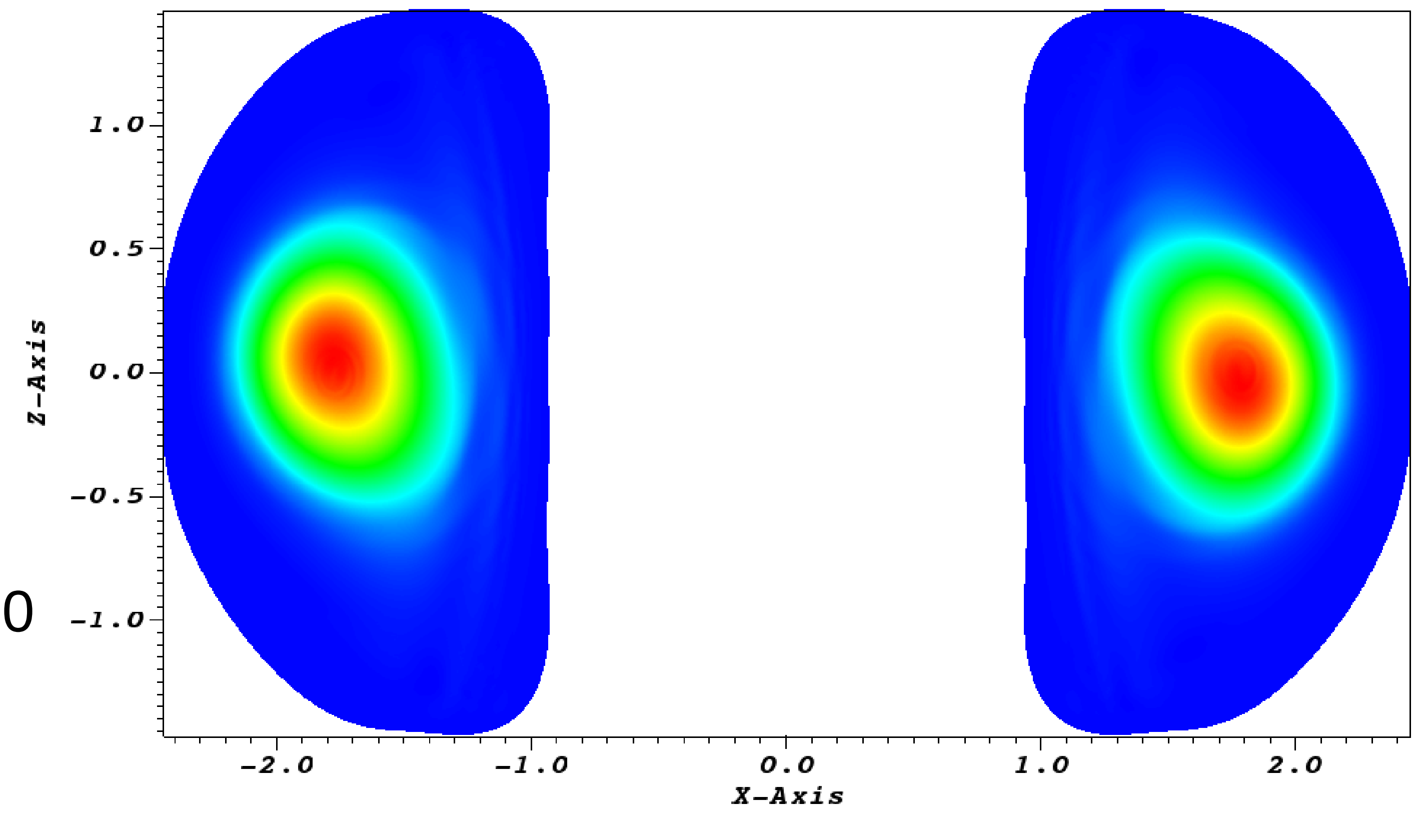


DIII-D results: Shot #087009 with free boundary

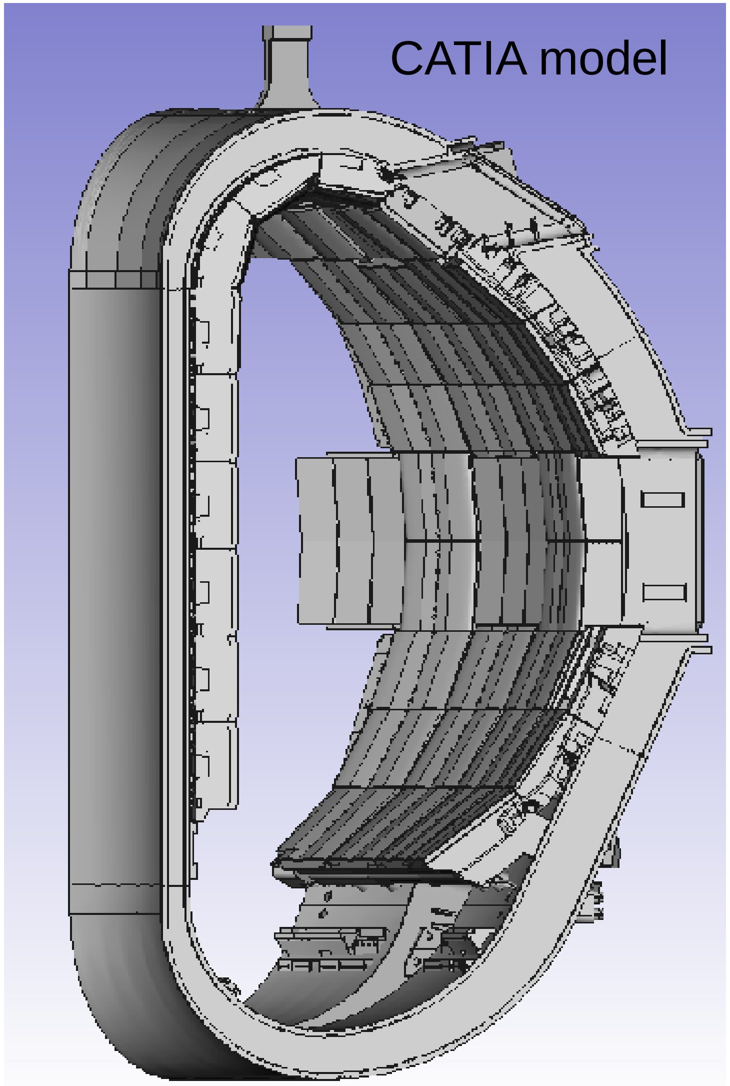
Campaign:

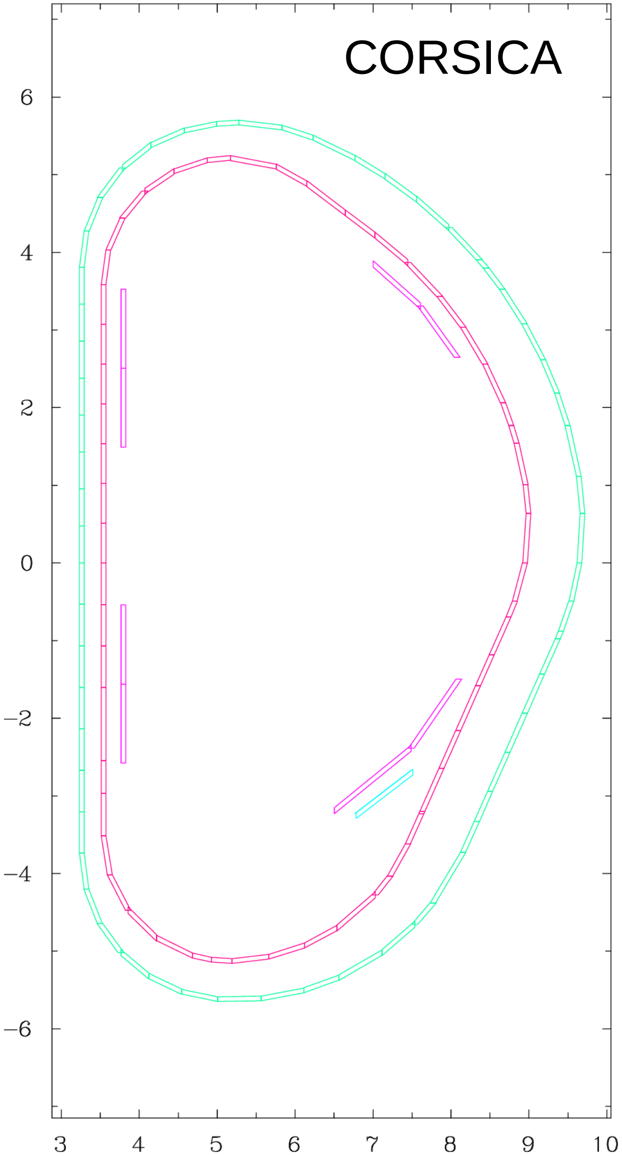
S=1e5;
gamma_heat= 0.1, 0.01, 0.001;
bamp=1e-1, 1e-5
l_phi=2 (n=0, 1 modes)
Continuity and eta n=0
Anisotropic thermal

Mode grows: n=1 distortion in all fields.

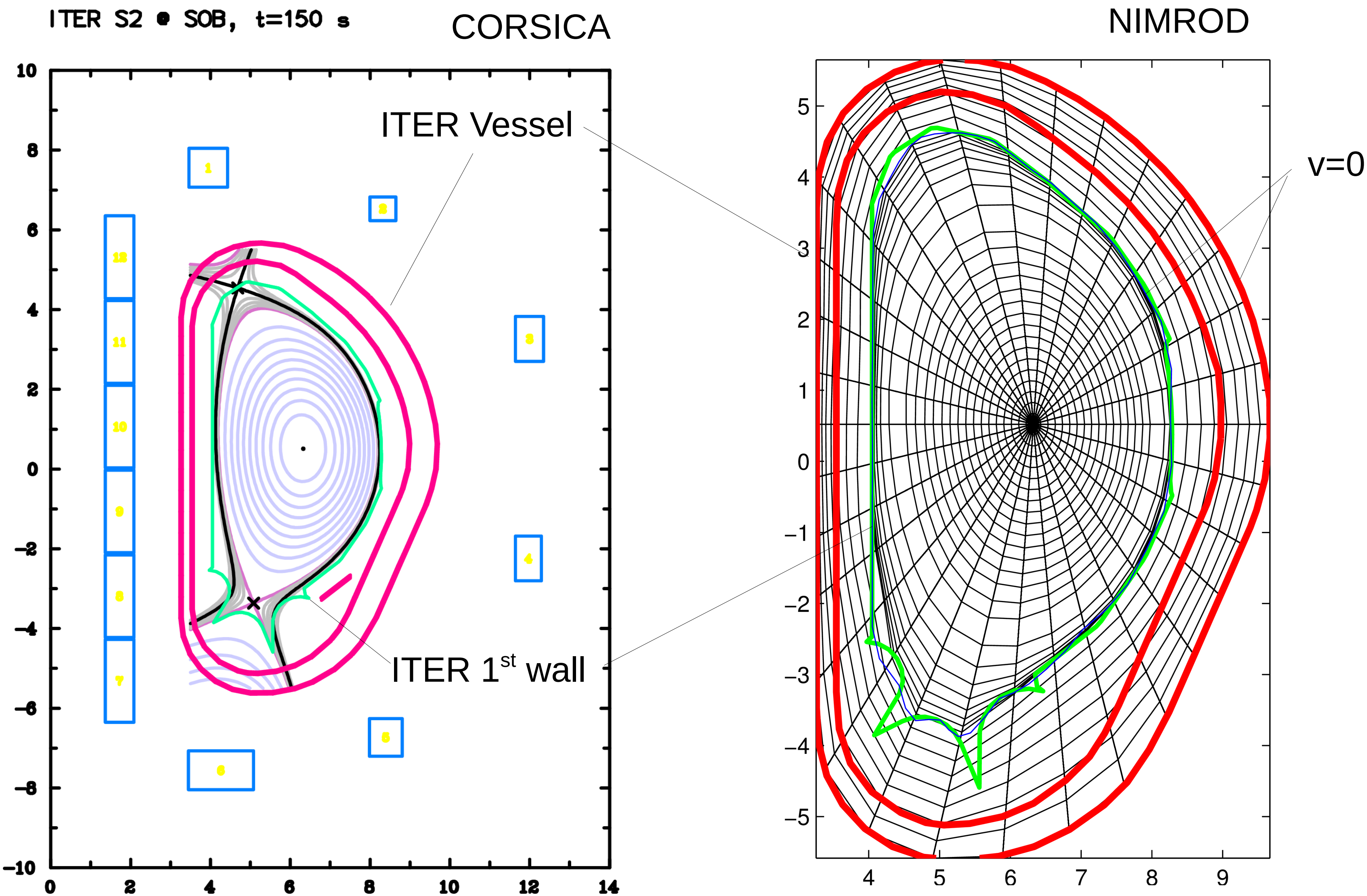


ITER Passive Structure





ITER wall meshed



WOODRUFF • SCIENTIFIC

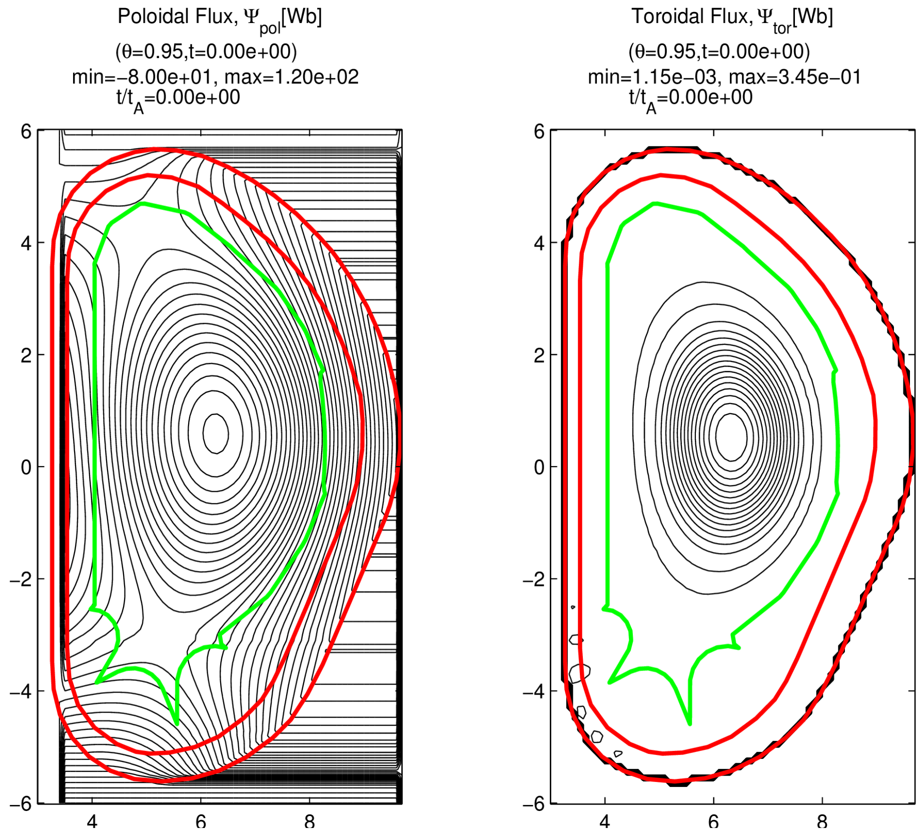
ITER initial condition for VDE

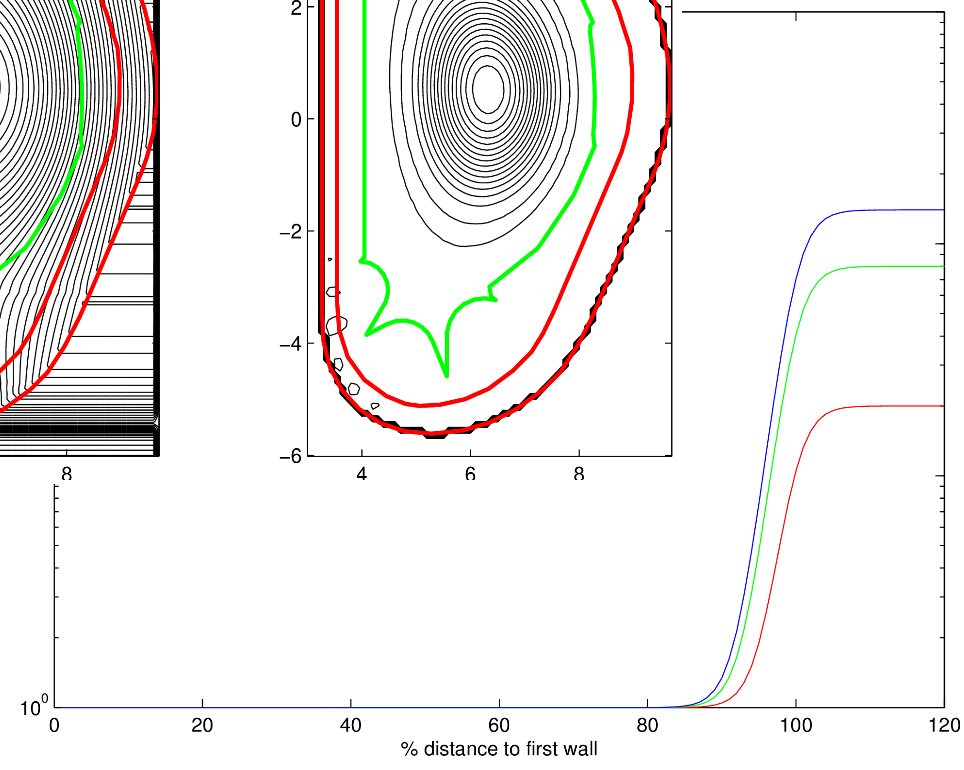
ITER Start of Burn reference case (15MA) (CORSICA: iter_sob.sav)

Campaign 1:
Wall with z_off.

Campaign 2:
CORSICA VST marginally stable IC -> NIMROD heating.

Campaign 3:
dvac= 20, 80, 140;
·bamp=1, 0.2, 0.1;
·S~1e4;
T=5keV;
t/tau_A ~ 1e2
l_phi=2 (n=0, 1 modes)
Continuity n=0 and eta fixed
Anisotropic thermal

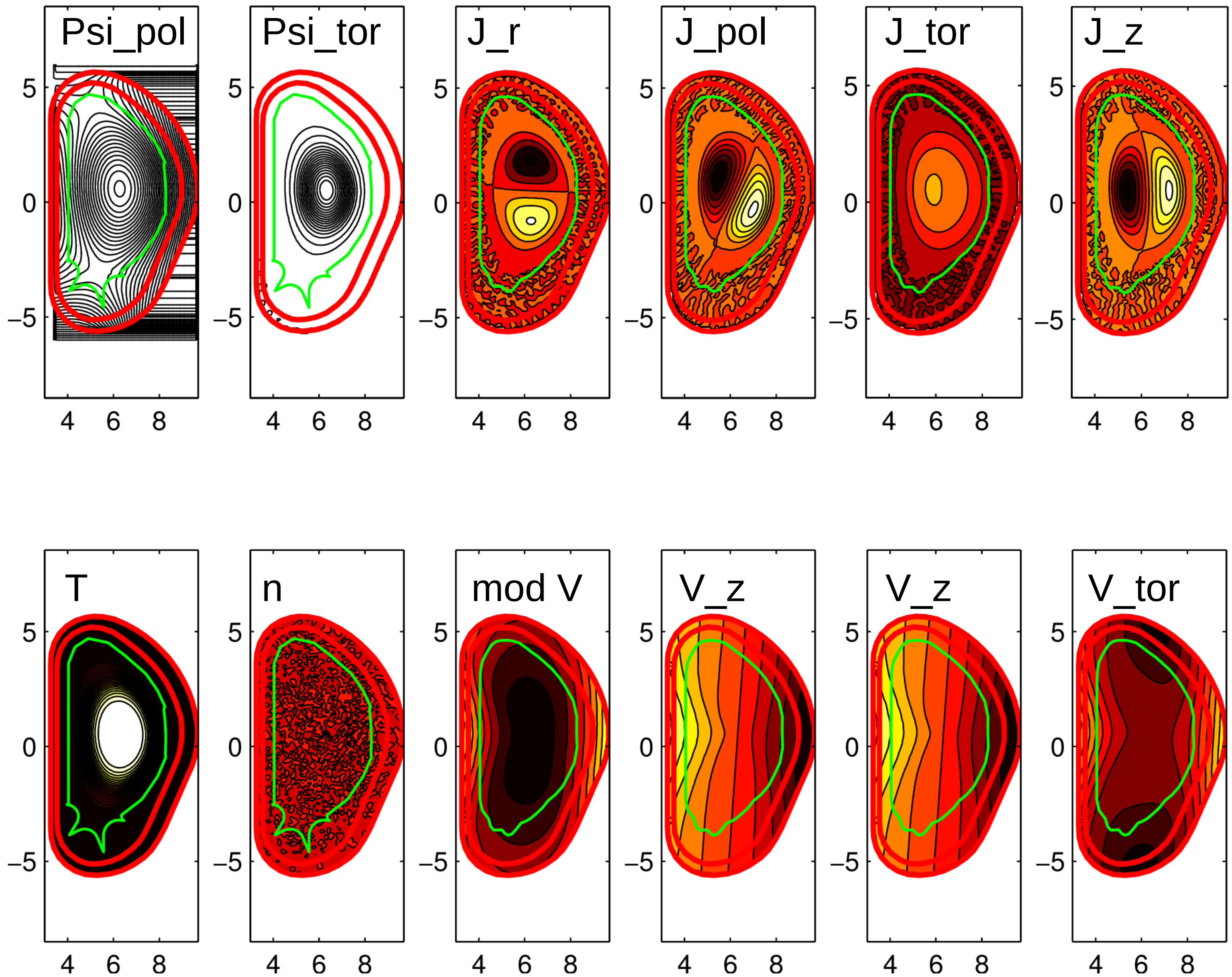




ITER CQ following VDE

$t/t_A=0$

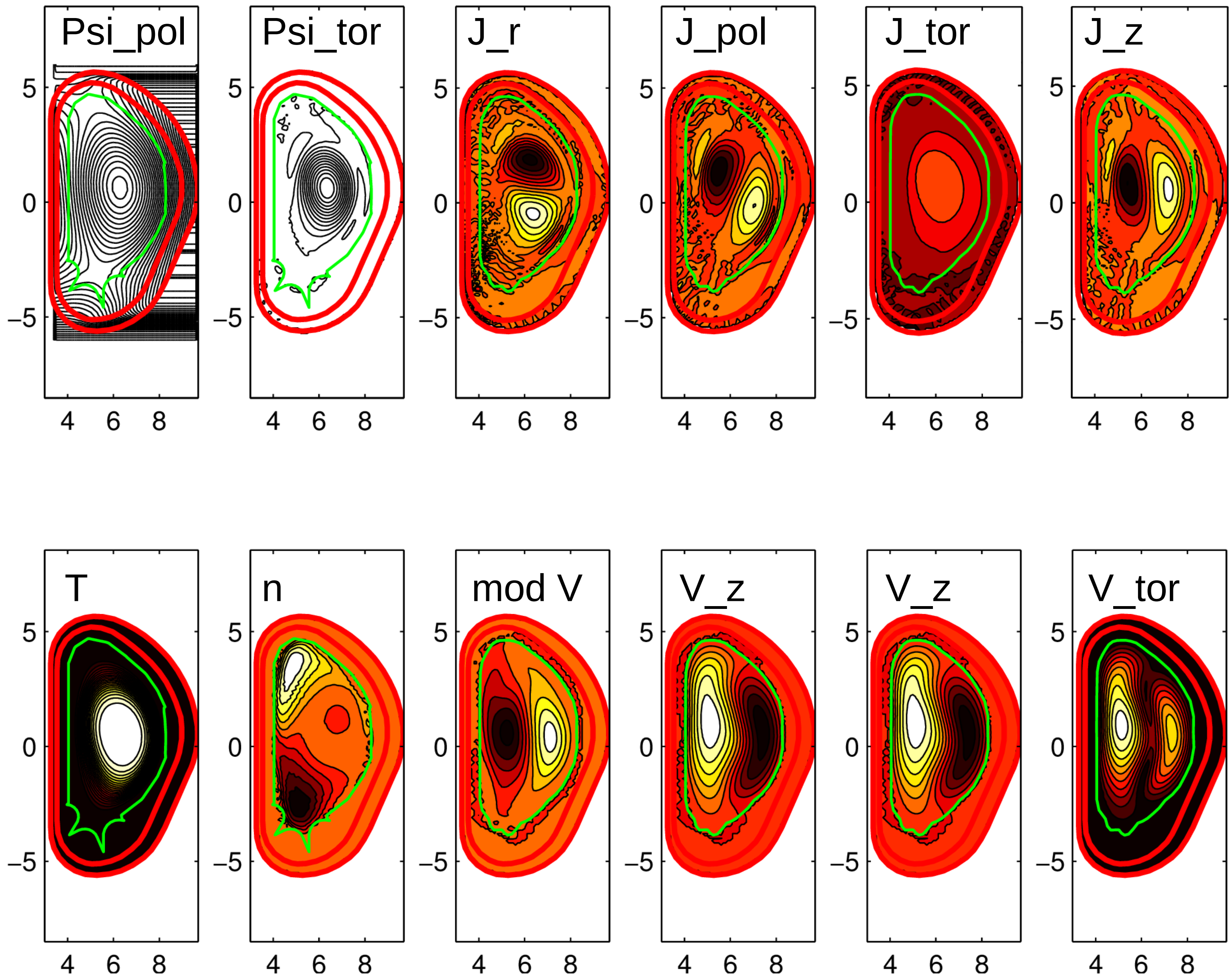
dvac=20
bamp=1



ITER CQ following VDE

t/t_A=26

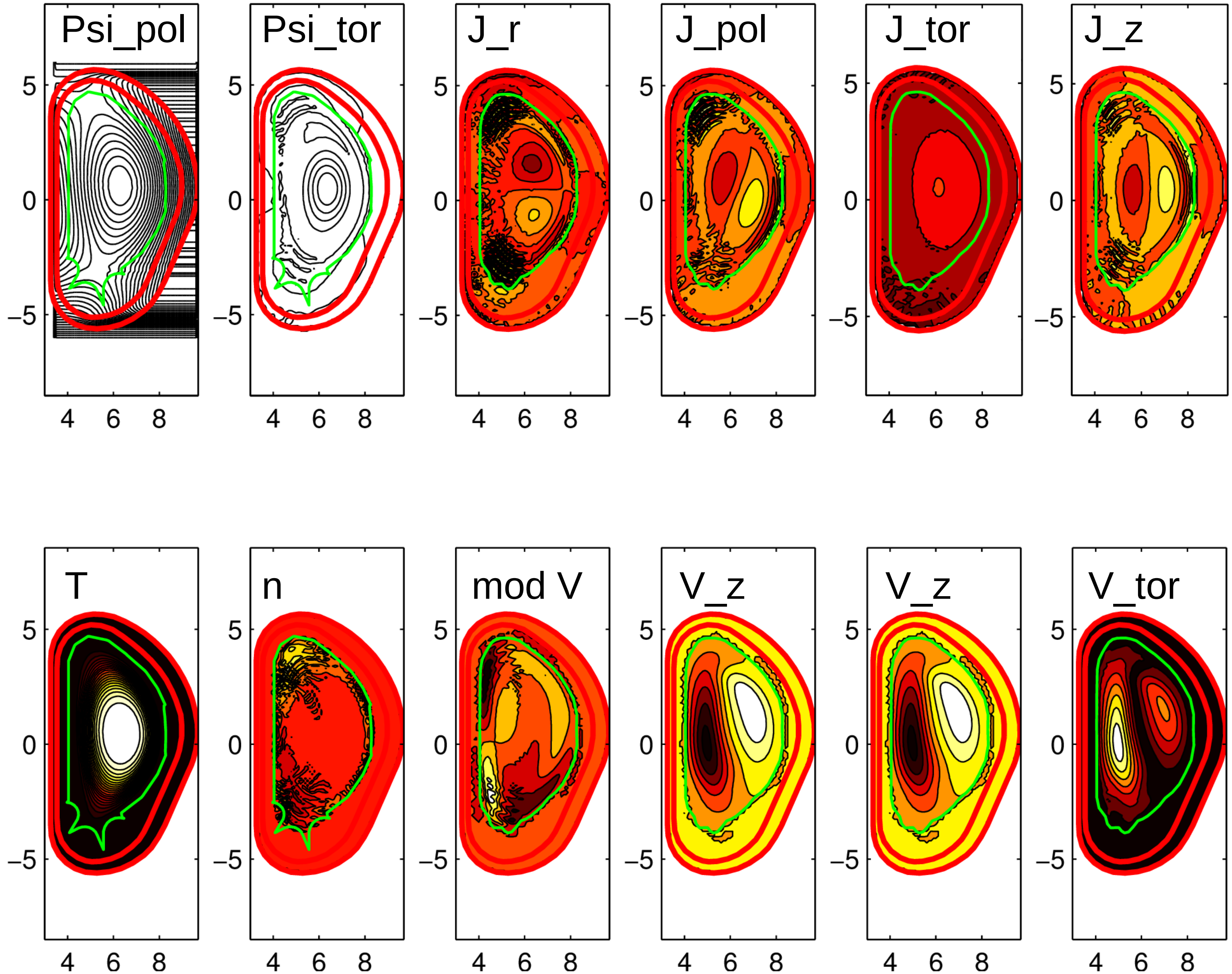
dvac=20
bamp=1



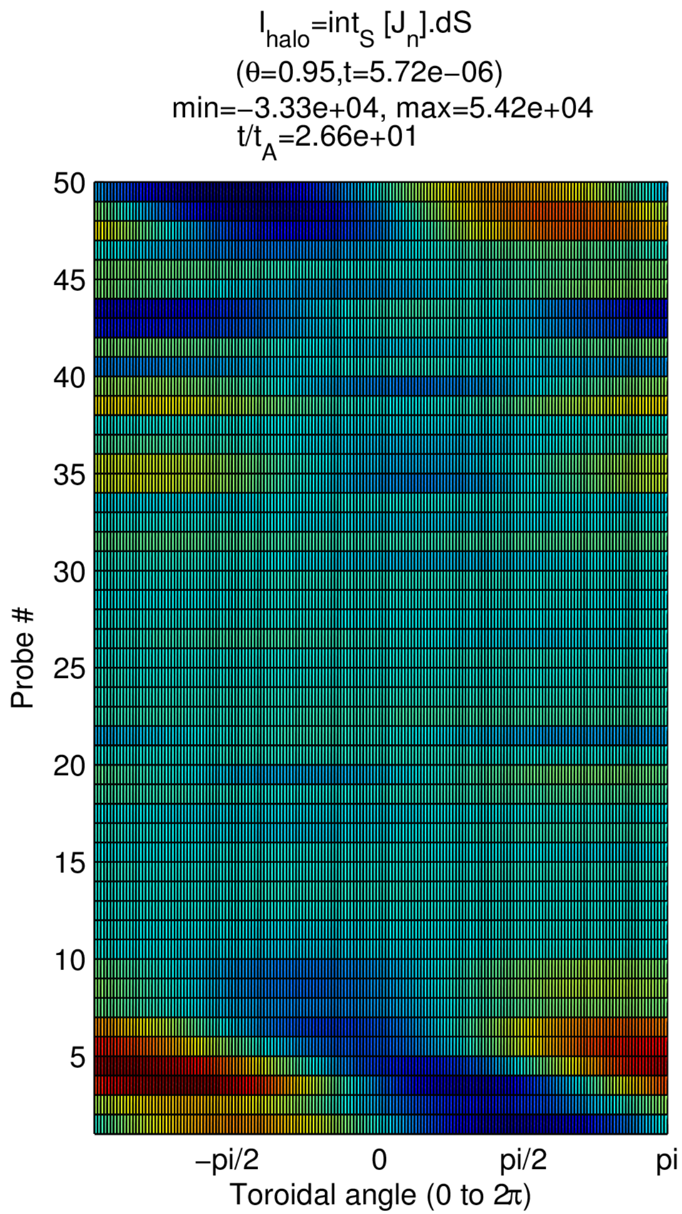
ITER CQ following VDE

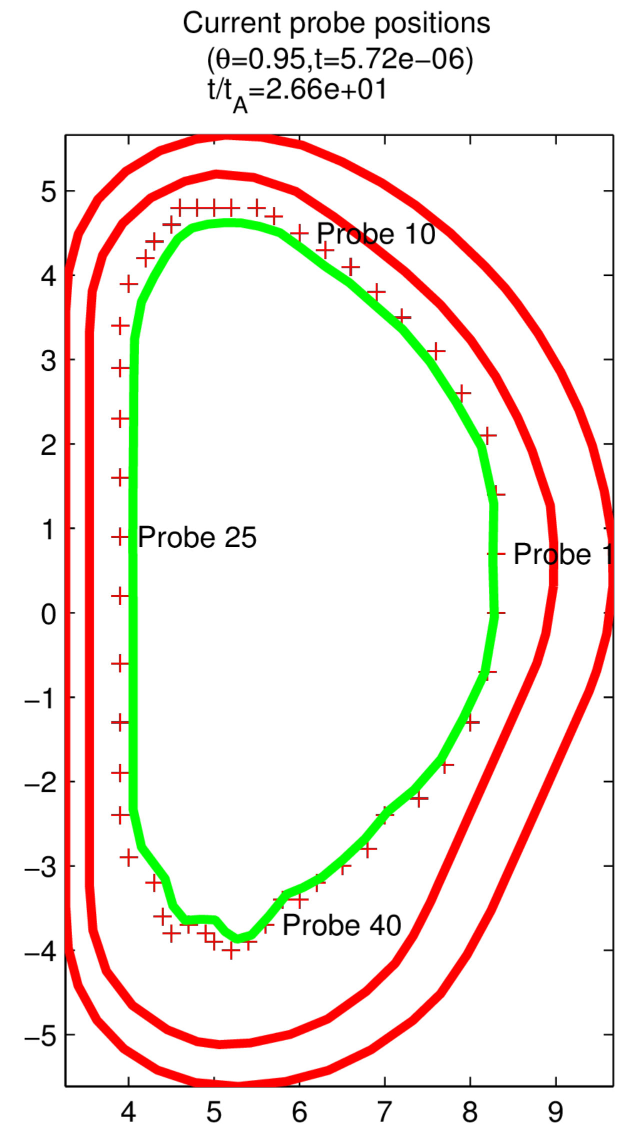
t/t_A=247

dvac=20
bamp=1

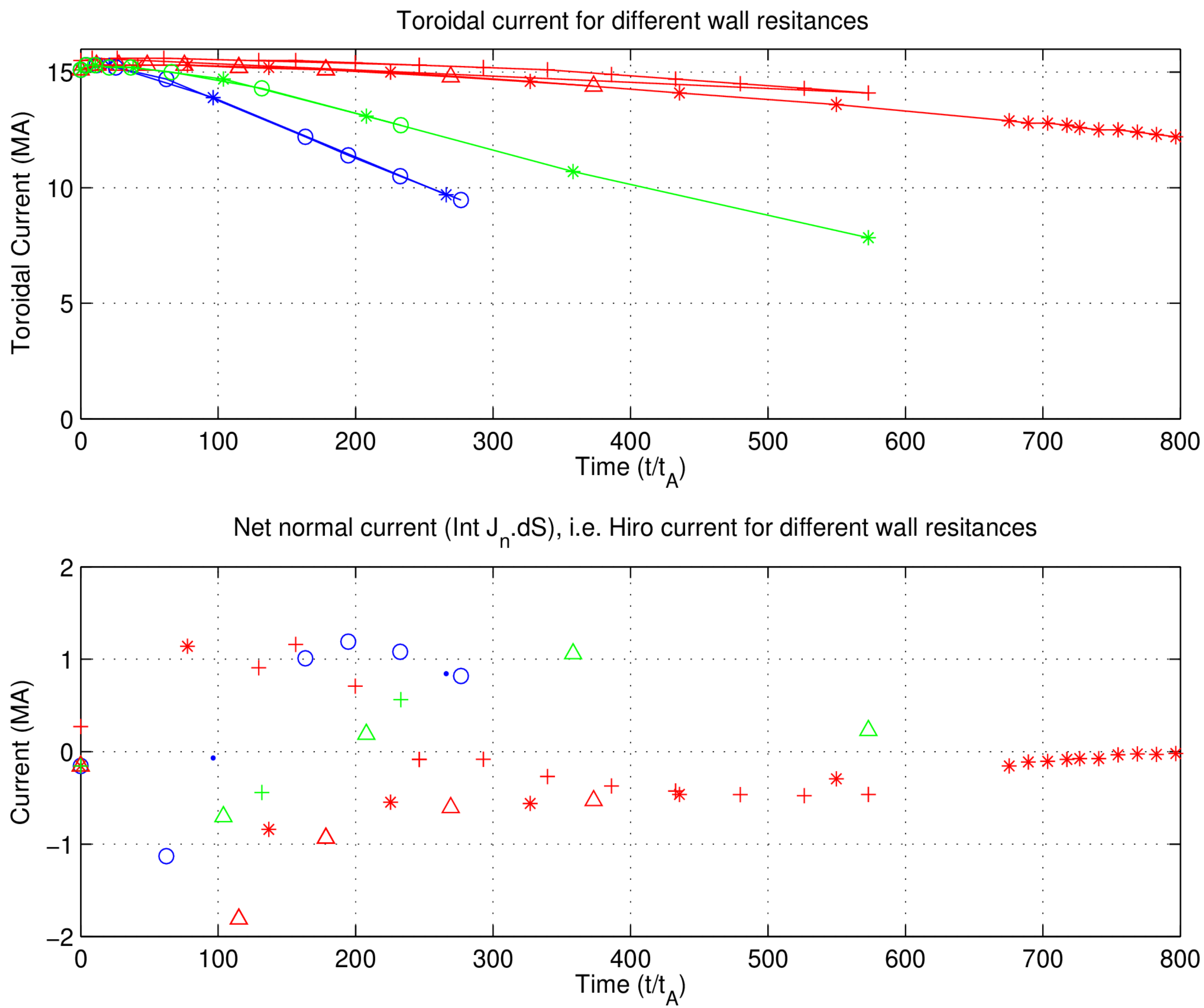


ITER halo current during CQ





ITER: Hiro current during CQ



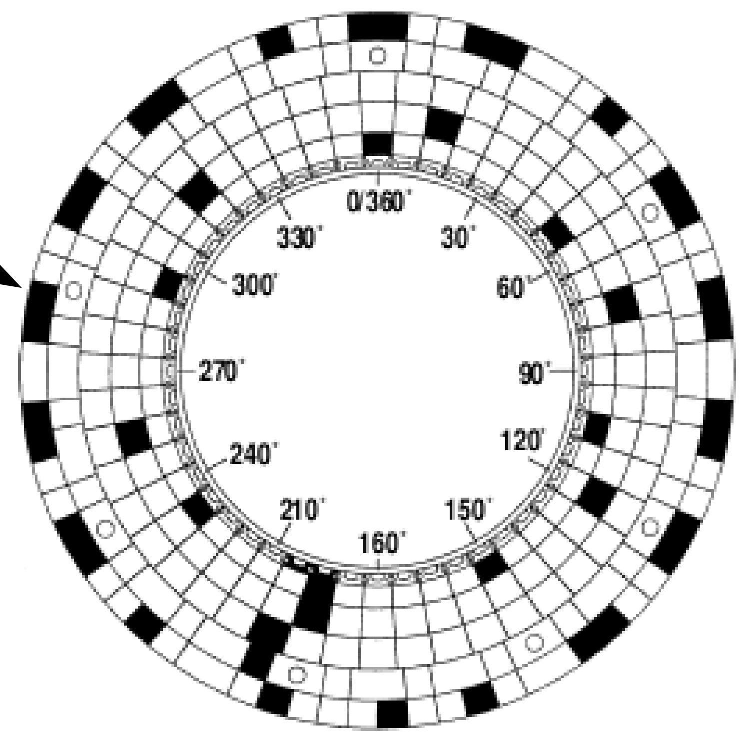
Further work: Validation

Halo current measurement has also been performed (and is ongoing) in many existing tokamak experiments.

Resistive shunts under tiles in **DIII-D** and ASDEX Upgrade, Rogowski coils in **JET,** and a combination of Rogowski and tile measurements in **NSTX**.

Whole problem validation (calibration or validation) would be a logical next step for DIII-D, NSTX or JET.

Unit problem validation also of interest (perhaps for an EPR expt.)

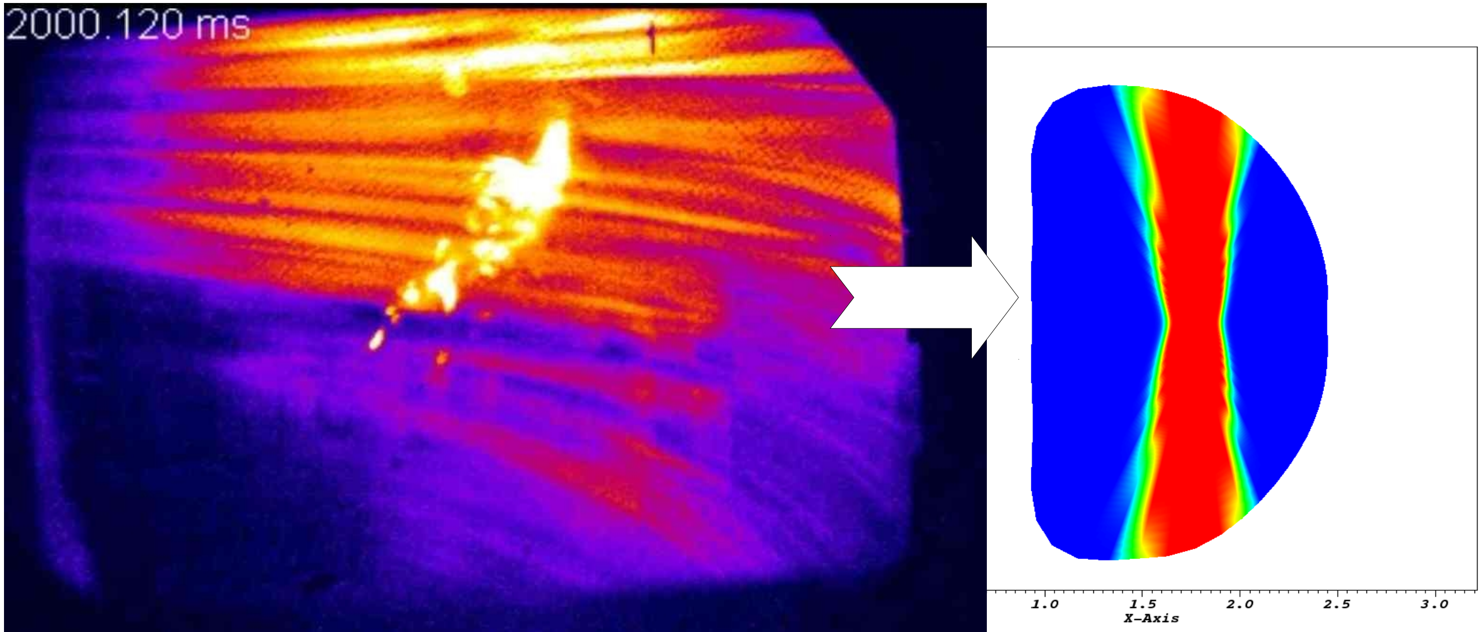


DIIID shunt locations, permission Hollmann

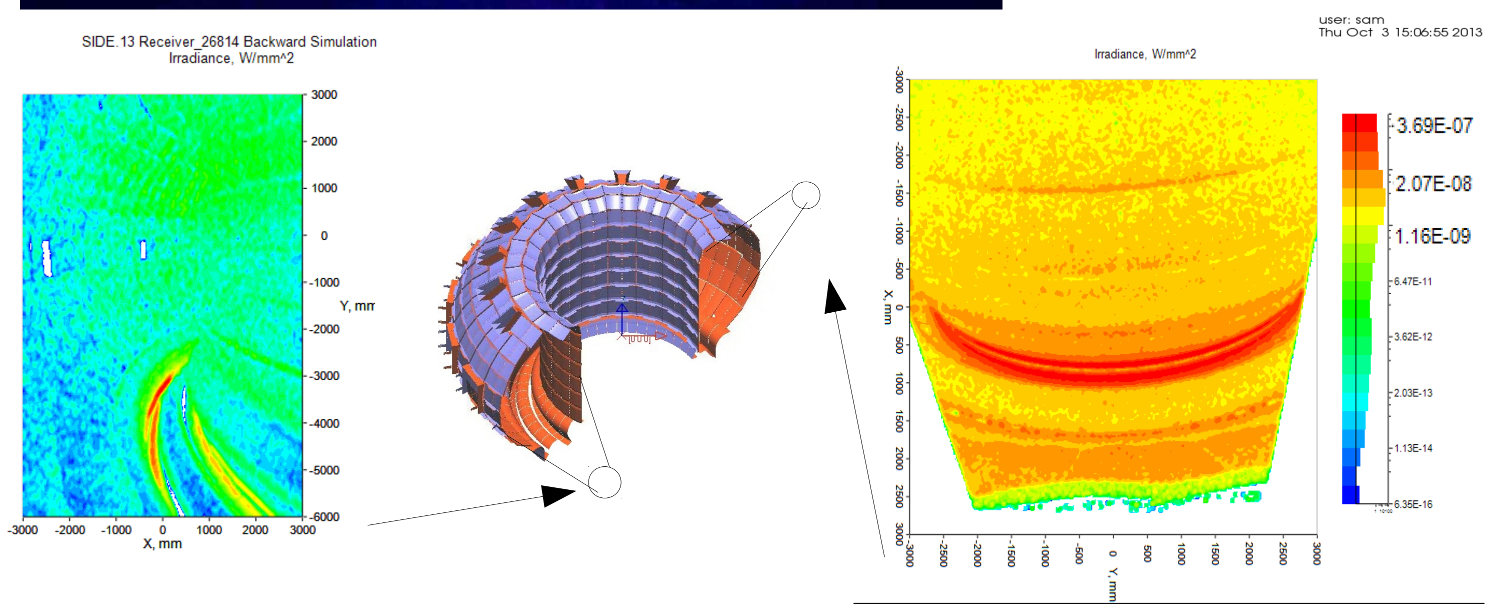
Further work: Shattered pellet simulations

1. *plasma* density azimuthally localized (per Strauss);

2. consider neutral / radiation model (per Izzo / Shumlak)



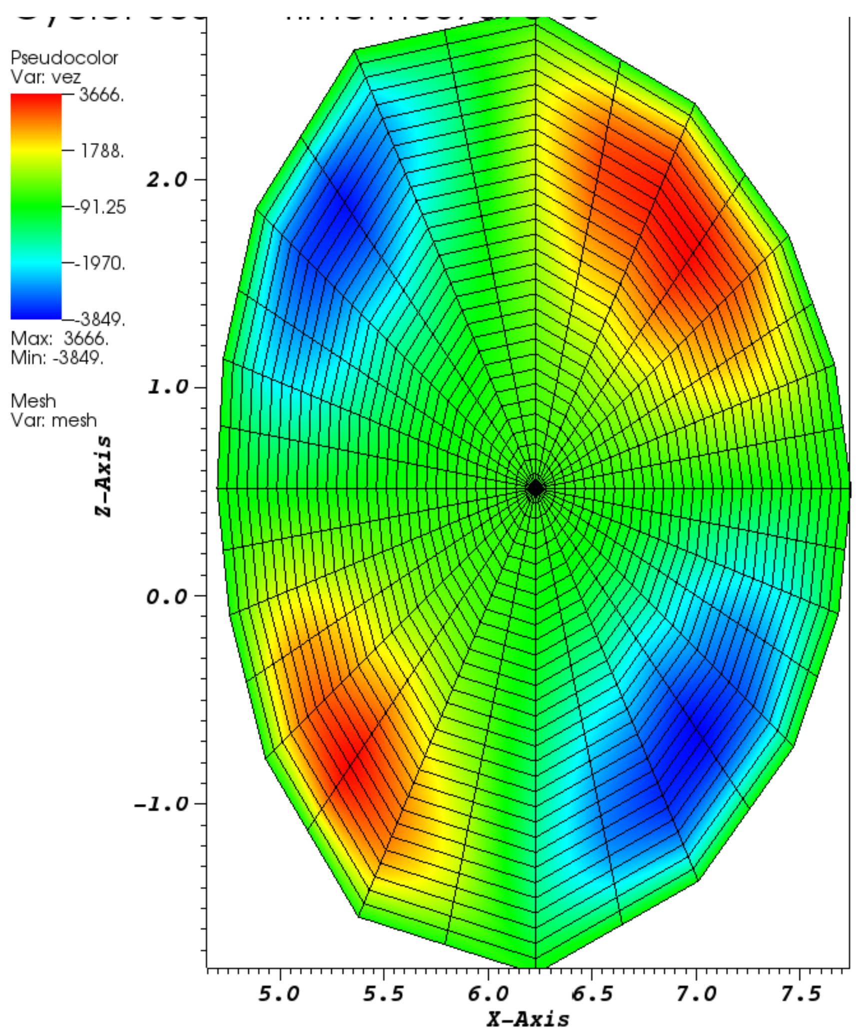
Synthetic diagnostics could include LightTools, IR, vis, h-alpha already modeled for ITER.

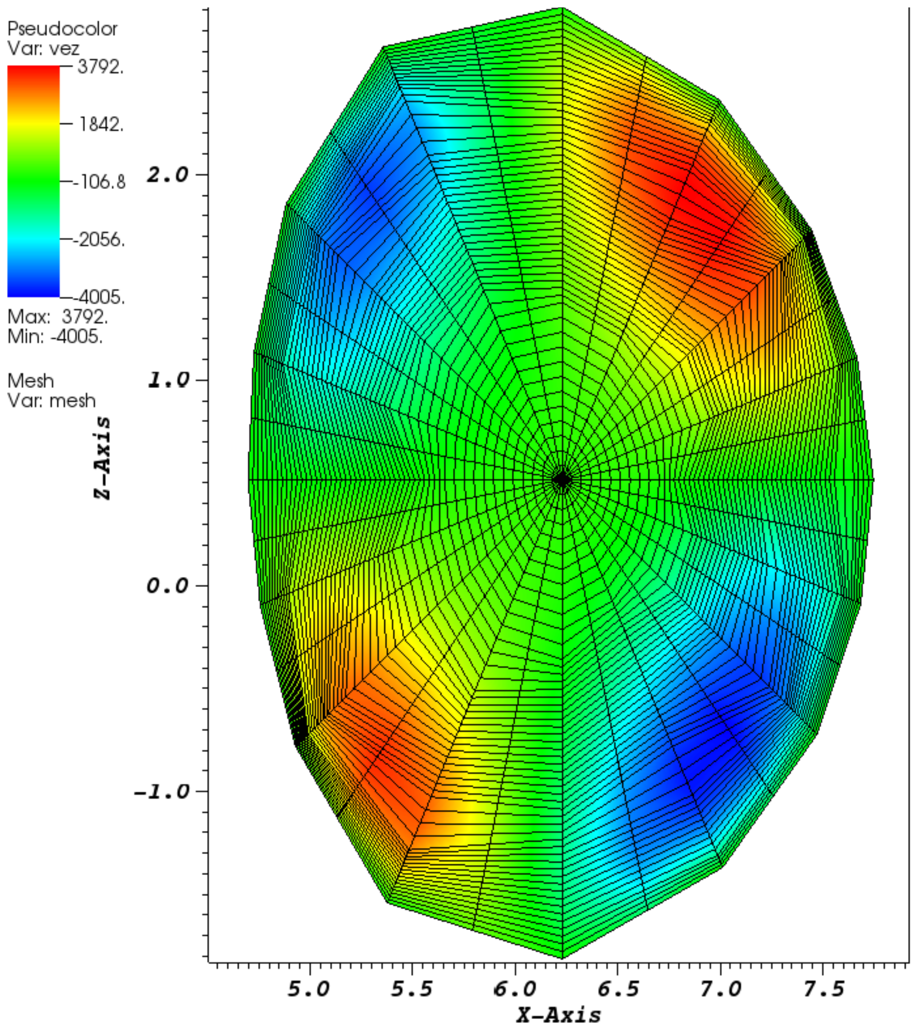


WOODRUFF • SCIENTIFIC

Further work: adaptive mesh

New mesh adaptation for NIMROD: user-defined parameters (here: gradients in the solution) [12] - [16].





Summary

Two prior simulations of disruptions have been investigated with the CORSICA and NIMROD codes.

We find that the primary results of prior studies are verified:

--pressure-driven mode in DIII-D is reproduced with most recent version of NIMROD (nimdevel)
--vertical displacements and subsequent current quench (and disruptions) are reproduced for ITER using NIMROD with a resistive wall.

Next steps are:
--VALIDATE code capabilities with experiment (DIII-D, NSTX, EPRs);
--SIMULATE the effects of shattered pellets on disruptions;
--continue DEVELOPMENT of new code capabilities (inc. adaptation).

WOODRUFF • SCIENTIFIC

References

[1] P.C. de Vries, M.F. Johnson, I. Segui and JET EFDA Contributors Statistical analysis of disruptions in JET *Nucl. Fusion* **49** 055011 (2009)
[2] E. Hollmann – Private Communication October (2012) figure is idealized version of one that he showed in his presentation 'Overview of DIII-D rapid shut-down experiments' presented at the BPO Disruption Mitigation Workshop March 12 2012.
[3] D. Rasmussen – DM topic workshop, Organized by the BPO, San Diego, March (2012)
[4] V A Izzo, EM Hollmann JC Wesley, EJ Strait, GM Olynyk, RS Granetz, DG Whyte Impurity Mixing and Radiation Asymmetry in MGI Simulations of DIII-D 54th Annual APS Meeting Division of Plasma Physics Providence, Rhode Island October 29 — November 2, 2012
[5] S.E. Kruger, D.D. Schnack 2), C.R. Sovinec 3) Dynamics of the Major Disruption of a DIII-D Plasma Physics of Plasmas, Volume 12, Issue 5, pp. 056113-056113-10 (2005)
[6] H.R. Strauss, W.Park, S. Jardin, J. Breslau, A.Pletzer, R. Paccagnella, L. Sugiyama Halo Current and Resistive Wall Simulations of ITER Active Control of MHD Stability: Back to the Basics PPPL, NJ, (2004)
[7] R. Fitzpatrick and A. Aydemir Stabilization of the resistive shell mode in tokamaks IFSR-694
[8] James A. Crotinger, et al., CORSICA: A Comprehensive Simulation of Toroidal Magnetic-Fusion Devices, Report UCRL-ID-126284, Lawrence Livermore National Laboratory, CA, April, (1997)
[9] C.R. Sovinec, A.H. Glasser, D.C. Barnes, T.A. Gianakon, R.A. Nebel, S.E. Kruger, D.D. Schnack, S.J. Plimpton, A. Tarditi, M.S. Chu and the NIMROD Team, "Nonlinear Magnetohydrodynamics with High-order Finite Elements," Journal of Computational Physics, 195, 355 (2004).
[10] Light Tools http://www.opticalres.com/lt/ltprodds_f.html
[11] A. H. Glasser, see e.g. https://fusion.gat.com/THEORY/dcon/
[12] S. Schetterer, S. Woodruff, J. E. Stuber Mesh optimization for 3D resistive MHD simulations Washington NASA Space Grant presentation (2013) available online:
[13] Knupp, P. M. Algebraic mesh quality metrics for unstructured initial meshes-develops a priori error metrics for FEM meshes based on the Jacobian for the element
[14] Oberkampf, W. Verifrication and Validation in Scientific Computing-discusses various methods of mesh improvement including a priori and adaptive meshing, mainly error
[15] Lowrie, W.; Lukin, V. & Shumlak, U. A priori mesh quality metric error analysis applied to a high-order finite element method-shows correlation between a priori error metrics and actual solution error, Knupp metrics are most correlated
[16] Li, P. S.; Martin, D., A Stable, Accurate Methodology for High Mach Number, Strong Magnetic Field MHD Turbulence With Adaptive Mesh Refinement: Resolution and Refinement Studies-Demonstrates that block-refinement AMR methods improve solution accuracy using fewer elements.