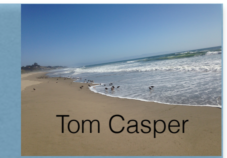
CORSICA Modeling for DIII-D Applications



Motivation

Demonstrate many CORSICA capabilities used in simulation and analysis for the DIII-D experiment

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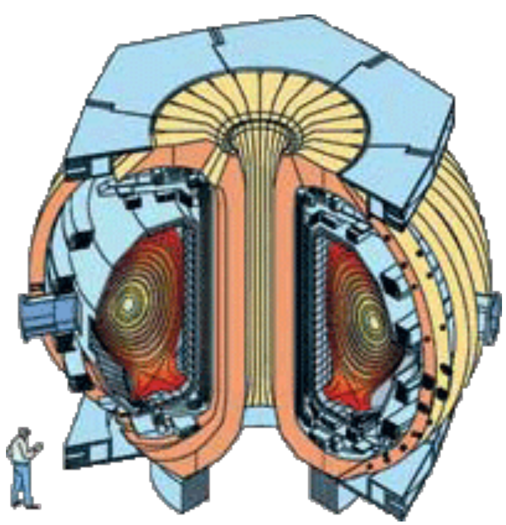


January 2016

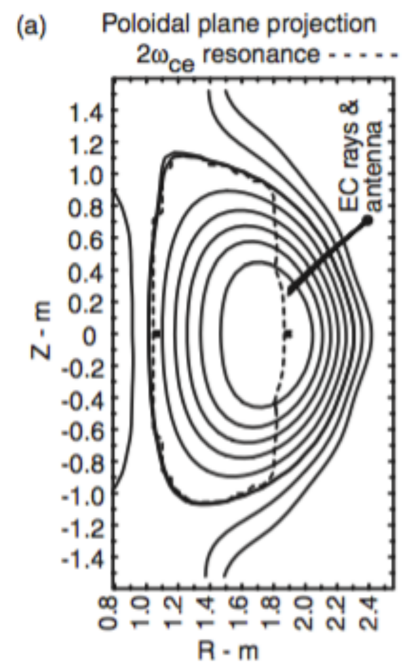
Modeling experimental operation on DIII-D
Examples from published results

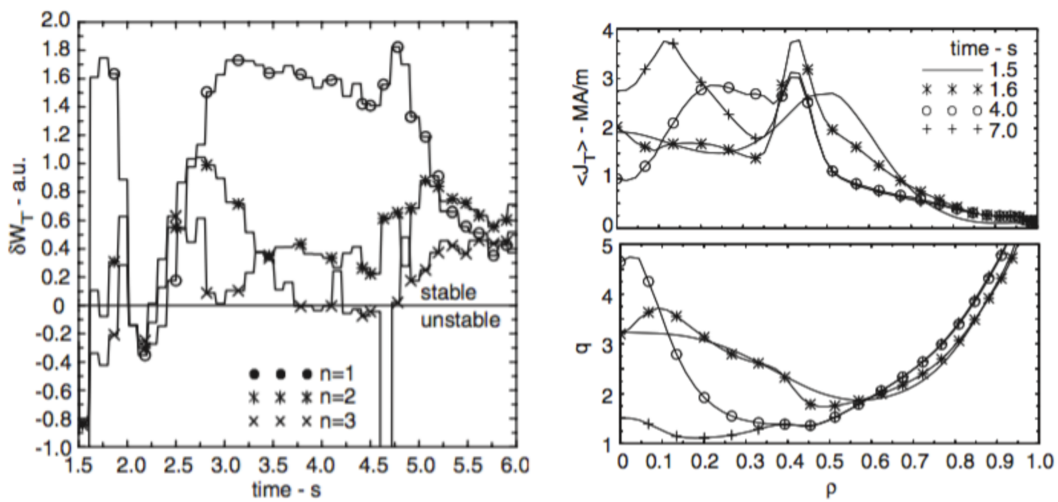
- Predictive time-dependent simulations for experimental design and evaluation of performance
- Data analysis: post-shot and inter-shot with messaging alerts (MDSplus)
  - ★ Equilibrium studies
  - ★ Transport analysis
  - ★ Combined models and experimental data to explore physics issues
    - ✳ Connected to MDSplus for direct access to DIII-D data: measurements and equilibria from EFIT
    - ✳ Mix measured data (I_p, NBI & ECH power, T_e, T_i, N_e, Z_{eff} profiles, etc.) with predictions
  - ★ Optimizations: heating and current drive, shape, scenarios
- Explore upgrades to tokamak, heating/current drive, and diagnostics
- Comparisons with ITER objectives

Time-dependent DCON stability in ECCD sustained NCS simulation T.A. Casper *et al* Plasma Phys. Control. Fusion 45 (2003) 1193-1208

- Predictive simulation to demonstrate ECCD sustaining ITB in negative shear
  - ★ $\chi_e = C_e(T_e^{3/2}/B^2)(T_e/Ti)f(s)q^2 + \chi_e^{neo} + \chi_{edge}$; $f(s)=1/[1+(9/4)(s-2/3)^2]$
  - ★ $\chi_i = C_i \chi_e H(\nabla q) Z_{eff}(T_e/T_i)^{1/2} + \chi_i^{neo}$; $H(\nabla q)$=Heaviside function at q_{min}
  - ★ from R.E. Waltz *et al* 1997 Phys. Plasmas **4** 2482; prior to GLF23
- Starting point for simulation is DIII-D discharge #92668
  - ★ Toray-GA used for ECH/ECCD and CORSICA NBI package
  - ★ Time-dependent DCON to evaluate stability during evolution

CORSICA graphics





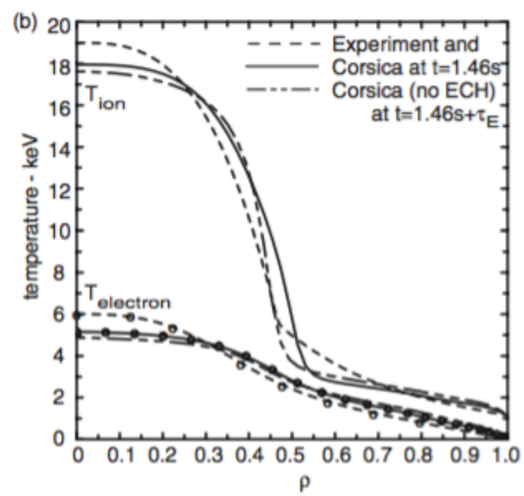
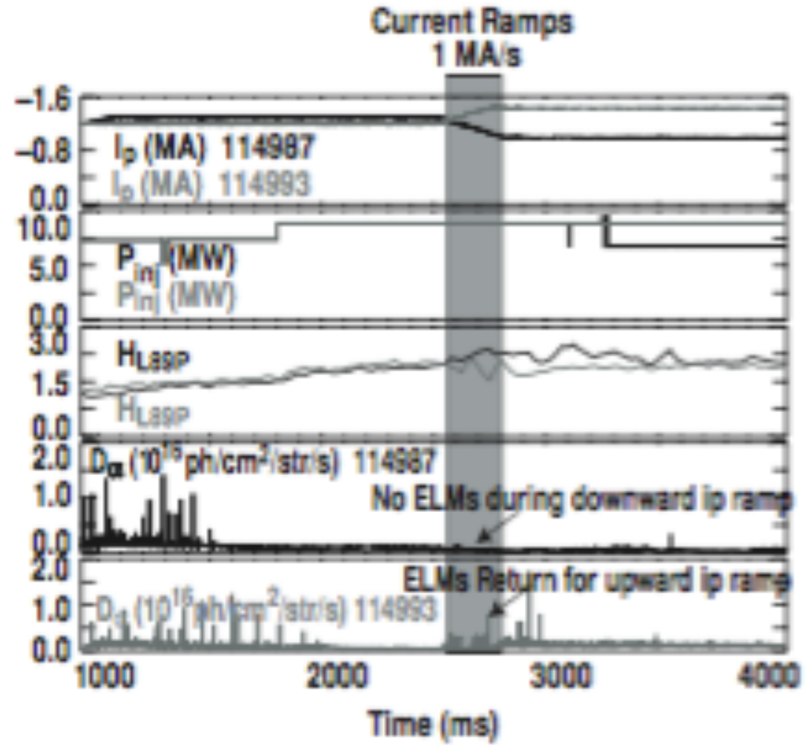
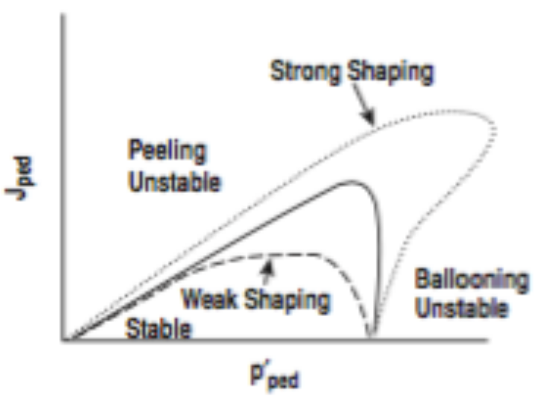


Figure 7. Evolution of δW_T (total energy = plasma + vacuum) for 4.5 MW heating case using DCON for ideal stability analysis for toroidal mode numbers $n = 1, 2$ and 3. $\delta W_T < 0$ for instability.

CORSICA equilibria used to validate peeling-ballooning model W.P. West *et al* Plasma Phys. Control. Fusion **46** (2004) A179-A186

- Current ramp QH-mode experiment to modify edge current density
- Equilibrium solutions for QH-mode plasmas with peaked edge current
  - ★ Use T_e, N_e measured profiles
  - ★ Calculate bootstrap current (NCLASS) that dominates edge
- Evolution of J_{edge} consistent with crossing peeling-ballooning mode boundary





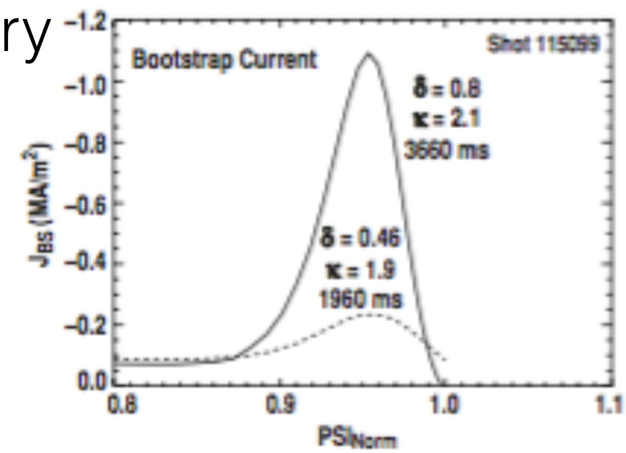
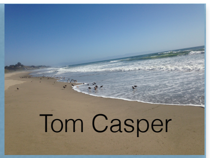


Figure 7. The calculated edge bootstrap current profiles are shown for shot 115099 during QH phases before (- - - -) and after (——) a sweep to strong shaping similar to shot 115062 in figure 6.

CORSICA edge current calculations for Libeam diagnostic D.M. Thomas, *et al* Physics of Plasmas **12**, 056123 (2005)



- DIII-D shot 119089: ELMing H-mode plasma with L to H transition
- Development of lithium-beam diagnostic to measure edge current profile
  - ★ LiBeam measurement green
- CORSICA - analysis blue
  - ★ Experimentally measured T_e,N_e profiles
  - ★ NCLASS bootstrap current
  - ★ Good agreement with evolution of current density
    - ✳ (a) L-mode
    - ✳ (b),(c) H-mode

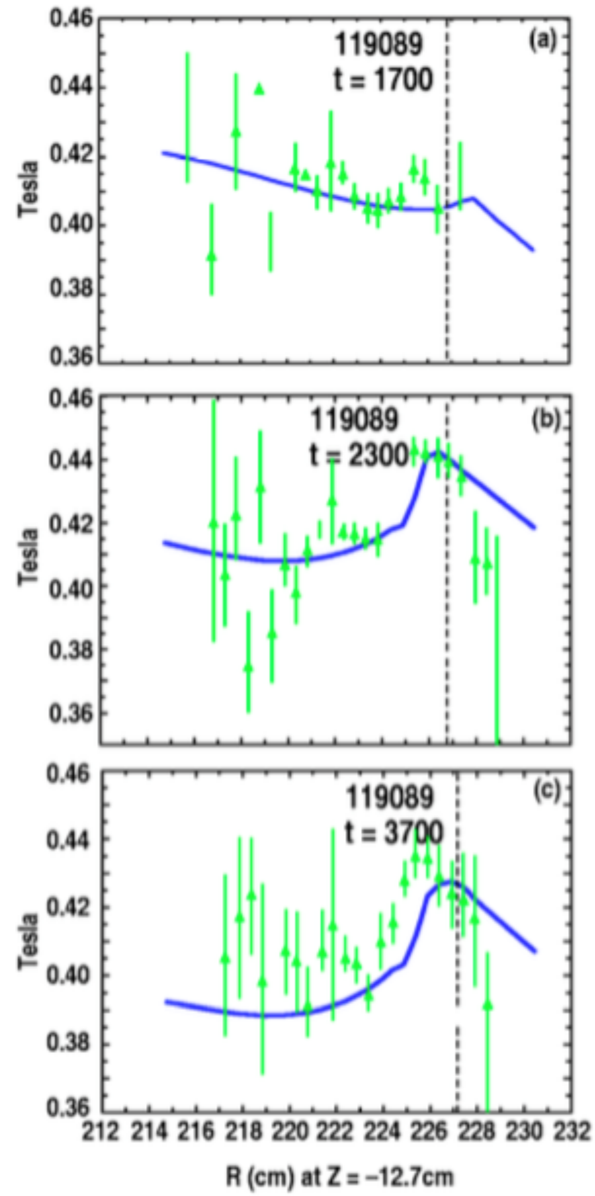
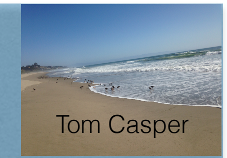


FIG. 10. (Color online). Measured B_{VIEW} profiles in tesla (green data) compared to CORSICA predictions (blue curve) using NCLASS bootstrap current constraint; (a) t=1700 ms, early *H* mode; (b) t=2300 ms, late ELM-free *H* mode, (c) t=3700 ms, ELMing *H* mode.

Design of profile control experiment and transport analysis T.A. Casper *et al* Plasma Phys. Control. Fusion **48** (2006) A35-A43



- Particle transport consistent with ITG destabilization in ITB plasma
- CORSICA designed ECCD experiment on profile control
  - ★ Simulations prior to experiment to predict result
  - ★ Observed electron heating rate and current drive in good agreement with code predictions
  - ★ Density "pumpout" observed (particle transport not modelled)
- Transport analysis: ITG stability effects driven by T_e/T_i ratio in ITB plasma
  - ★ CORSICA run in transport analysis mode to evaluate diffusivities; χ_e, χ_i, and D
  - ★ Stability threshold R/L_{Ti} and R/L_{Te} from Weiland model (Weiland J. *et al* 2006 Plasma Phys. Control. Fusion **47**, 441)

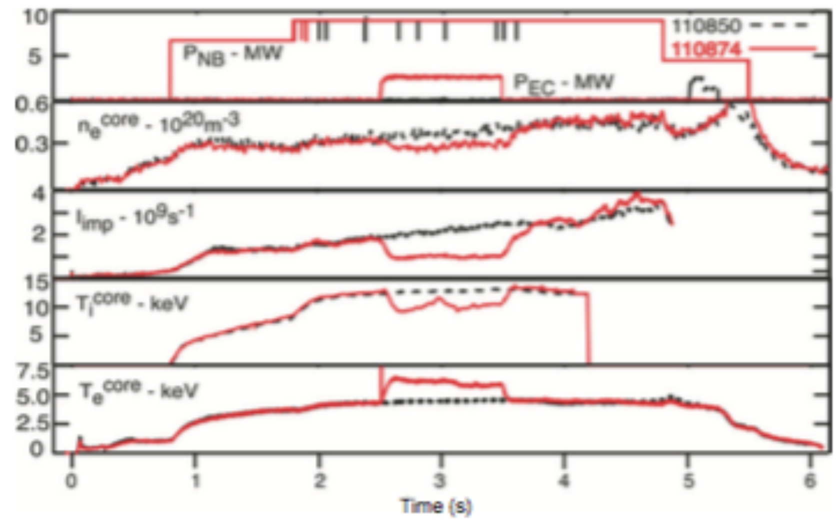
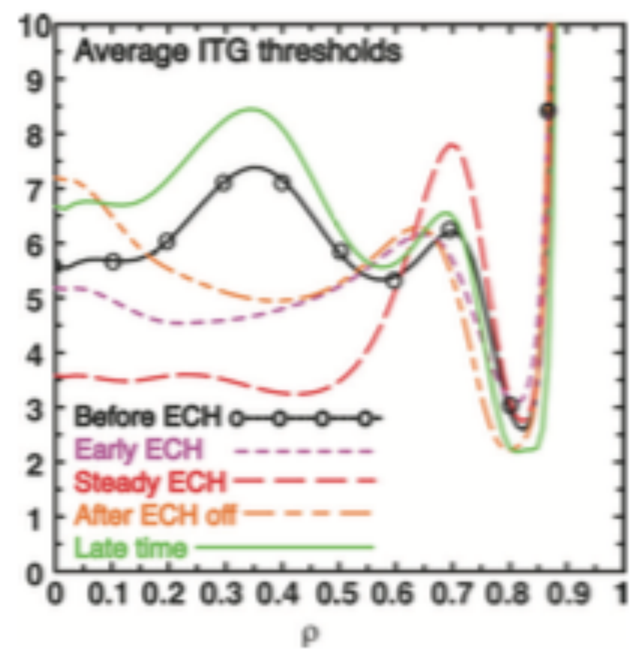
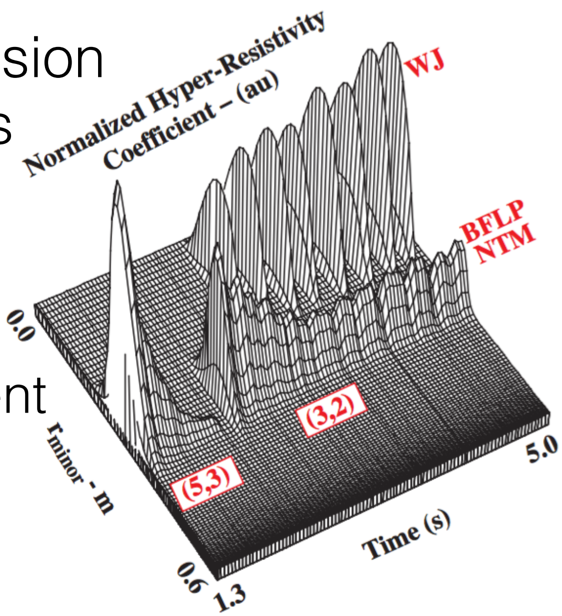


Figure 2. Shot 110874 typical of changes in parameters induced by ECH power injection; 110850 is a no-ECH reference. I_{imp} is the impurity photon emission rate.



CORSICA hyper-resistivity (HR) study of DIII-D Hybrid mode MHD activity T.A. Casper *et al* Nucl. Fusion **47** (2007) 825-832

- DIII-D hybrid mode exhibits MHD activity related to maintaining the q-profile > 1.
  - ★ Typically observed n=2 or 3 neoclassical tearing modes (NTM) outside half-radius
  - ★ Steady parameters without significant degradation in confinement
- CORSICA direct current diffusion from hyper-resistivity[1] models
  - ★ Island evolution ~ modified Rutherford equation
  - ★ Sawtooth HR model[2] ~ current redistribution near the axis
  - ★ BLFP HR model[3] ~ current diffusion in NTM island



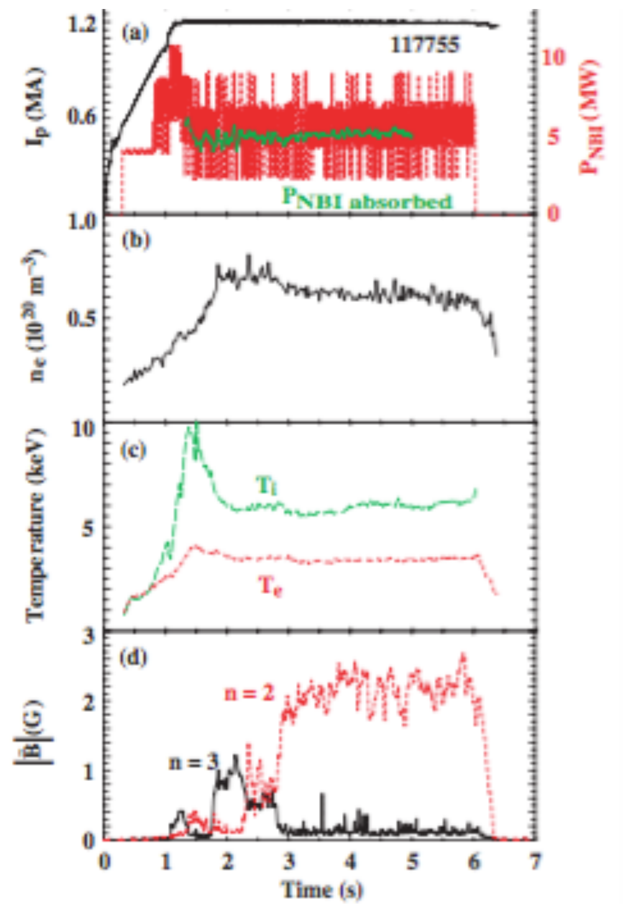
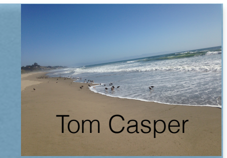


Figure 1. DIII-D hybrid shot 117755 experimental parameters: (*a*) plasma current and injected neutral-beam power under β_N-feedback control, (*b*) electron density, (*c*) electron and ion temperatures and (*d*) edge $n = 2, 3$ fluctuation amplitudes. Also shown in (*a*) is the simulated neutral-beam power computed in the CORSICA simulations.

[1] Boozer, A.H. 1986 J. Plasma Phys. **35** 133
[2] Ward, D.J. and Jardin, S.C. 1989 Nucl. Fusion **29** 905
[3] Berk, H.L, Fowler, T.K., LoDestro, L.L. and Pearlstein, L.D. LLNL 2001 LLNL report UCID-ID-126284 142741 http://www.osti.gov/bridge

HR models provide redistribution of current density

T.A. Casper *et al* Nucl. Fusion **47** (2007) 825-832



- CORSICA simulation with HR exhibits NTM island formation and redistribution of current profile consistent with EFIT analysis
  - ★ Sawteeth from Ward-Jardin HR “reconnection”
  - ★ NTM current redistribution from BFLP model
- Addition of HR term in Ohm’s law leads to consistency in evolution of q_0, q_{min}, and r_{qmin}
  - ★ Sawteeth HR when triggered maintains higher q_0
  - ★ NTM HR when triggered diffuses current around half-radius
  - ★ Neoclassical evolution leads to q << 1.
- Hybrid evolution, however, requires additional coupling between NTM and on-axis current

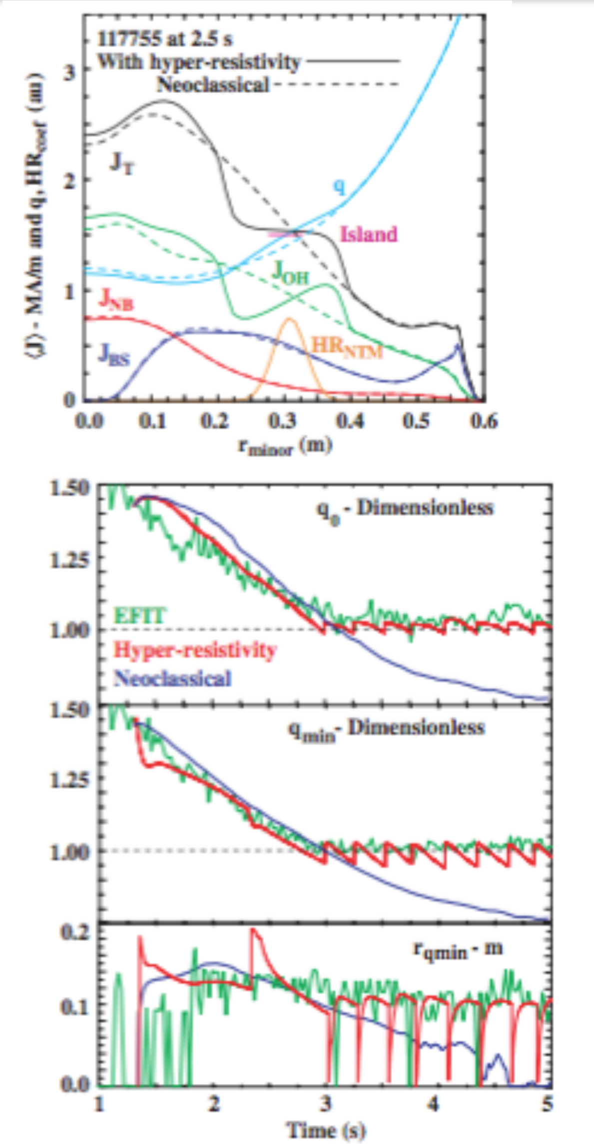


Figure 6. Consistency of q_0, q_{min} and $r_{q\,min}$ evolution among HR-simulations, MSE-constrained EFIT and the comparison with a neoclassical evolution. The q profile responds to the change in mode from (5, 3) to (3, 2) at 2.3 s. The quasi-constant q is due to a combination of WJ limited by BFLP and flux diffusion rebuilding the current at the axis.

Synthetic diagnostic in CORSICA provides direct comparison with MSE measurements in HR study.

- Added a synthetic Motional Stark Effect (MSE) diagnostic to CORSICA for further comparisons of simulation and experimental data for hybrid
  - ★ Implemented detector geometry of DIII-D MSE instrument
    - ✳ 3 detector arrays
    - ✳ Optical viewing locations inside plasma
  - ★ Computed synthetic data for simulated shot
    - ✳ Simulation uses measured T_e, N_e profiles
    - ✳ Evolve the current density with HR effects
- Good agreement between simulated data and measurements indicates simulated current density profile evolution consistent with experiment

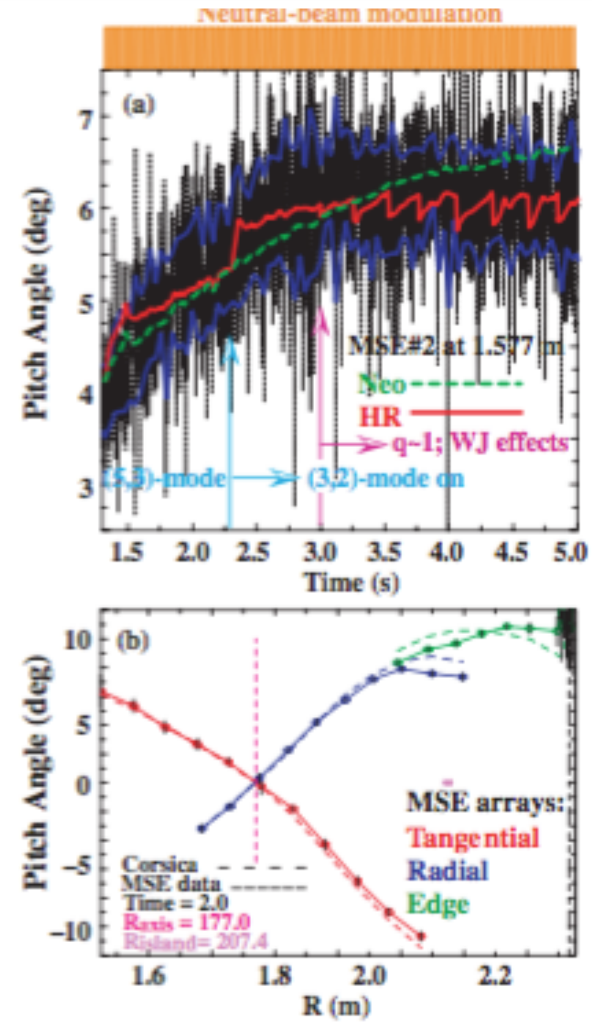
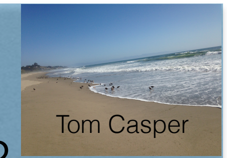


Figure 7. MSE pitch angles (B_P/B_T): (*a*) measured data (dotted), ⟨MSE⟩-averaged over the modulated 20 ms beam-on times (modulated at 50% duty cycle for background noise subtraction of MSE data), ⟨MSE⟩ ± one standard deviation and the simulated MSE data at $R = 1.577$ m for the HR (solid) and for the neoclassical (dashed) simulated evolution and (*b*) comparison of simulated and average measured MSE data over the plasma cross-section at $t = 2$ s.

ITER ramp-up experiments validated conductivity and (core) transport model G.L. Jackson *et al* Nucl. Fusion **48** (2008) 125002

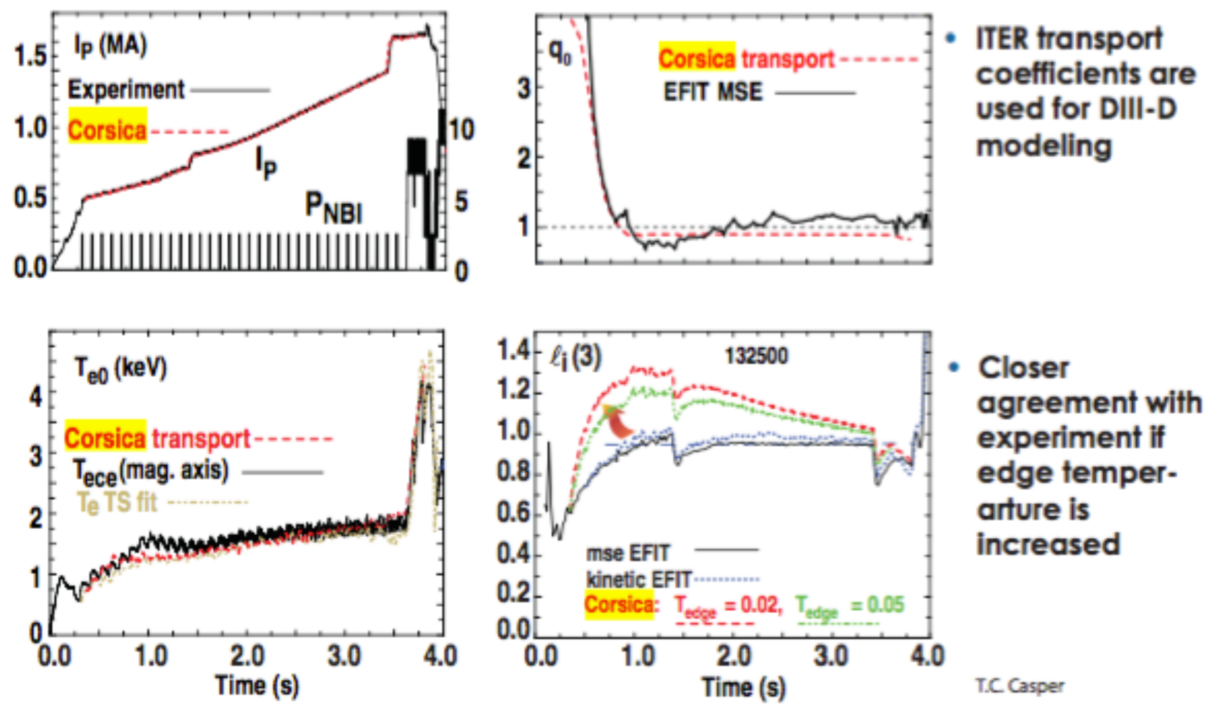


- Results validated CORSICA's neoclassical transport model
  - ★ Simulations using measured kinetic profiles, T_e and N_e
  - ★ Neoclassical conductivity resulted in current density evolution in agreement with EFIT equilibrium analysis
- Simulations using Coppi-Tang thermal transport model with NBI pulsed heating provided good agreement with on-axis evolution, .e.g $T_e(0)$,q_0, r_{qmin}

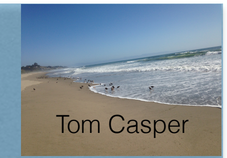
Errors in predicting internal inductance, l_{i3}, resulted form current density profile errors concentrated near the separatrix.

No transport models do well at the edge; similar results obtained with other transport models, e.g. Bohm-gyroBohm

Figure from G.L. Jackson DPPS APS meeting 2009



ITER vertical stability motivated by DIII-D stability experiments D.A. Humphreys, *et al* Nucl. Fusion **49** (2009) 115003



- Z-perturbations of $|\Delta Z/a|_{max}$~2% result in VDE for DIII-D experiments and CORSICA ITER free-boundary simulation with controller turned off
- For stability margin, ITER added the internal stabilization coils

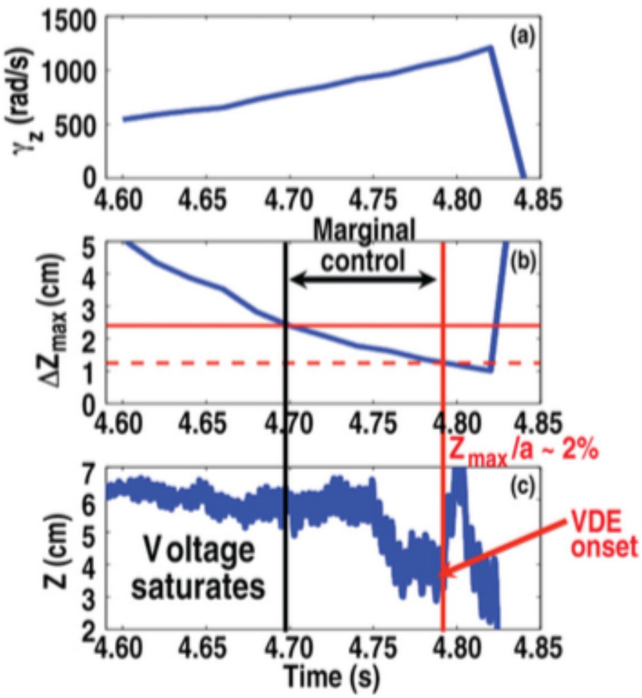


Figure 6. DIII-D controllability threshold experiment. (*a*) shows growth rate increasing as the elongation is increased. (*b*) shows calculated ΔZ_{max} decreasing at the same time. The solid (red) horizontal line (*b*) and solid black vertical line (*b*), (*c*) indicate the point at which the vertical control command is fully saturated for increasingly long periods and control becomes marginal. The dashed (red) horizontal line (*b*) and solid grey (red) vertical line (*b*), (*c*) indicate the point at which vertical control is actually lost and a VDE begins, corresponding to $\Delta Z_{max}/a \sim 2\%$. (Colour online.)

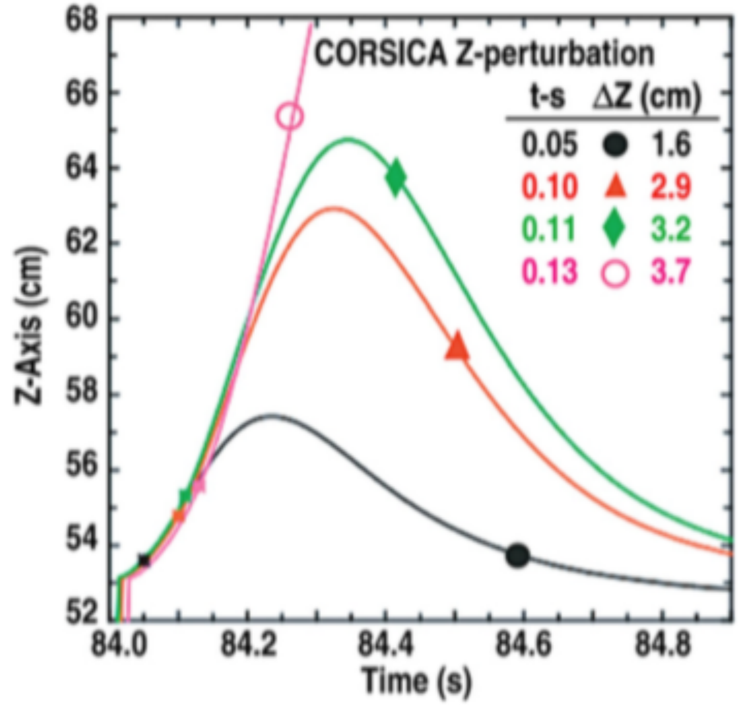
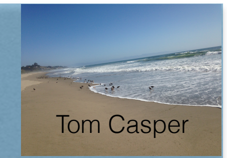


Figure 4. Corsica simulations of ITER ΔZ_{max} scenario for end-of-rampup scenario, $\ell_i(3) = 1.0$, show ITER maximum controllable displacement of 3.5 cm, corresponding to ~2% of the ITER minor radius. (Colour online.)

CORSICA simulation of DIII-D ITER current ramp-up similarity discharges T.A. Casper *et al* Nucl. Fusion 51 (2011) 013001



- Similarity discharges model ITER plasma shape on DIII-D
- Scaled comparison of DIII-D and ITER shape
- CORSICA simulated the current ramp discharge for benchmarking ITER scenario studies

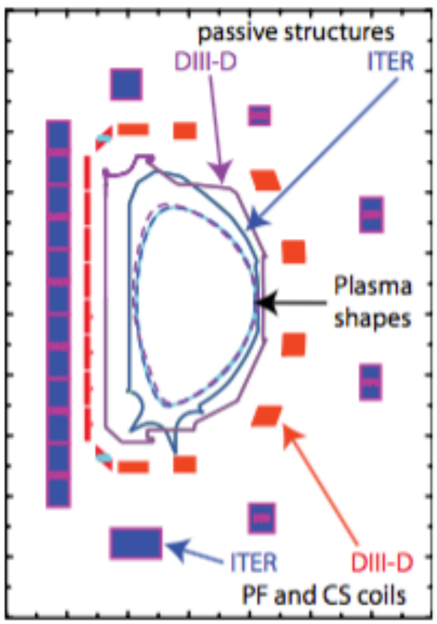
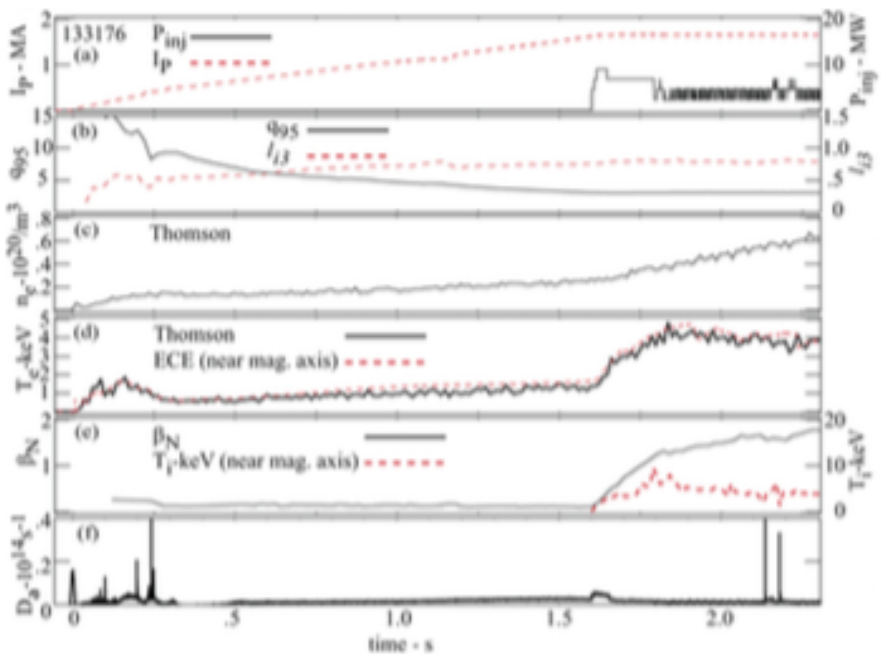


Figure 1. Comparison of a fully diverted ITER shape with that achieved using the DIII-D poloidal-field coil system. The ITER shape, coils and passive structure have been scaled approximately by the ratio of major radii. The scaled coils show the difference in the geometry and flexibility between the ITER and DIII-D coil systems.



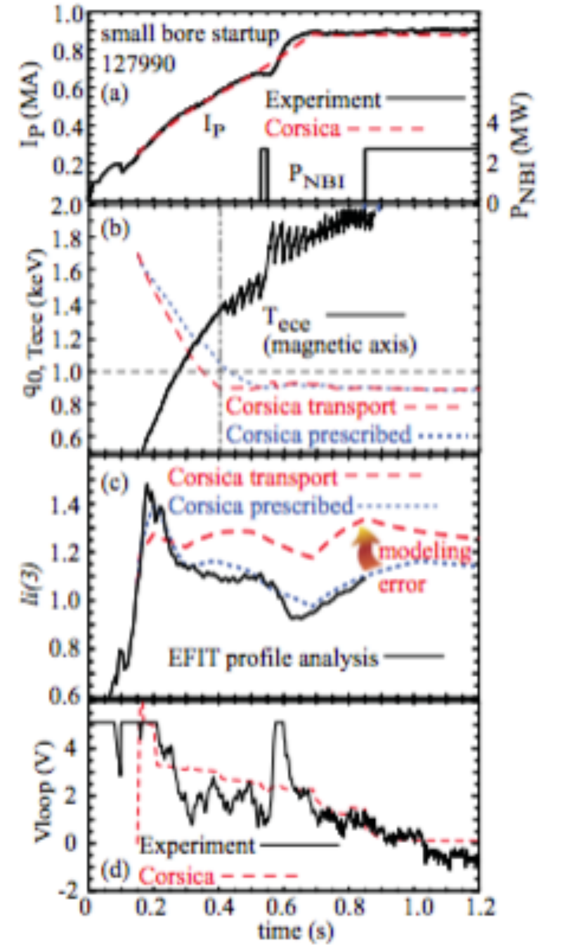
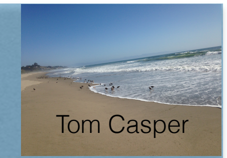


Figure 3. Shot 127990, small-bore startup discharge: (*a*) plasma current from experimental measurements and CORSICA simulation and neutral-beam injection power, (*b*) ECE T_e measurement channel near the magnetic axis and q_0 evolution from CORSICA simulations with prescribed and C–T transport T_e profiles, (*c*) $\ell_i(3)$ evolution for EFIT profile analysis and CORSICA with T_e profiles from the measurements and the C–T transport model. The arrow indicates the error in the magnetic stored energy introduced by modelling the electron temperature evolution. (*d*) Comparison of measured loop voltage with that required to sustain Ohmic current in CORSICA where the difference is due to edge plasma resistivity.

Summary: History of CORSICA applications in the DIII-D experimental program



- Scenarios
  - ★ Sustaining NCS with ECCD - 2003, VG#3
  - ★ Profile control predictions and analysis - 2006, VG#6
  - ★ ITER current ramp up model validation - 2011, VG#12
- Diagnostics
  - ★ LiBeam probe - 2005, VG#5
  - ★ Synthetic MSE diagnostic - 2007, VG#9
- Physics understanding
  - ★ QH-mode stability boundaries - 2004, VG#4
  - ★ MHD in hybrid mode - 2007, VG#7 and VG#8
  - ★ Validation of neoclassical conductivity and transport model - 2008, VG#10
  - ★ ITER vertical stability - 2009, VG#11