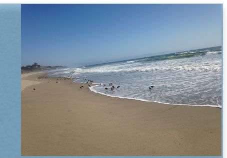
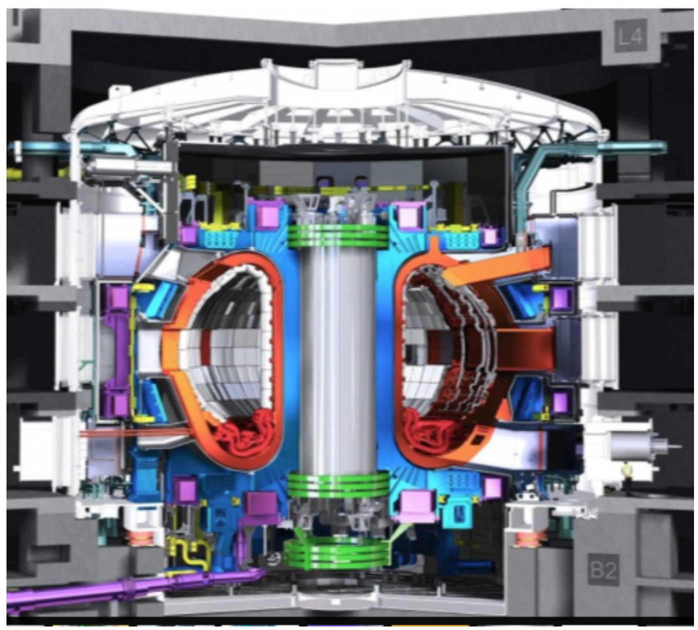


CORSICA Modeling at ITER

Motivation

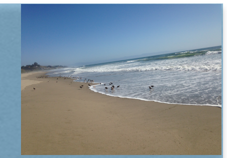
Demonstrate how CORSICA has been applied for the ITER Organization

Tom Casper
Woodruff Scientific, Inc. (consulting)
ITER (retired)
Lawrence Livermore National Laboratory (retired)



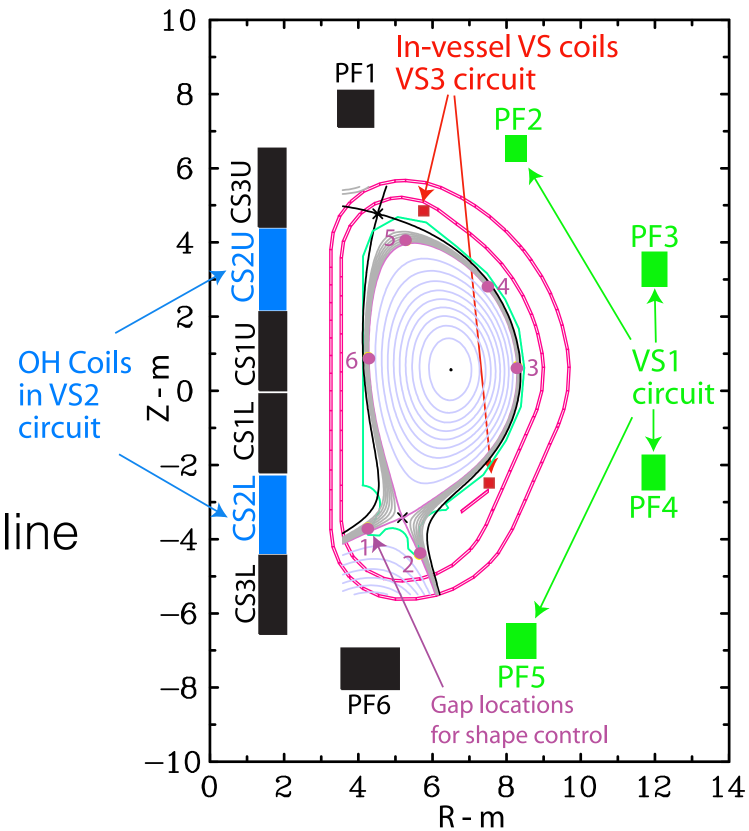
January 2016

Modeling for scenario development, shape evolution, system constraints, and control



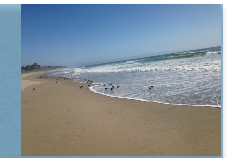
Tom Casper

- Scenario development: determination of plasma characteristics to achieve experimental goals of ITER
  - ★ $Q = P_{fusion}/P_{total} \sim 10$
  - ★ Burn time > 400s
  - ★ Alternatives: inductive, advanced inductive (e.g. hybrid) and pre-DT operation
  - ★ Heating and current drive effects
  - ★ HL transitions
- Shape evolution
  - ★ Performance for differing shapes
  - ★ First wall design
- System constraints
  - ★ Superconducting coil limits: UFC = B_C vs I_C coil load line
  - ★ Plasma mapping to divertor
  - ★ Interaction with walls
  - ★ Heating and current drive



- Control - feedback for shape, vertical stability and heating and current drive

CORSICA modes of operation

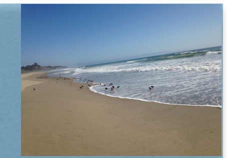


Tom Casper

- Equilibrium design: user variations or constrained equilibria
- Fixed boundary (seldom used now)
  - ★ no changes in boundary - good for equilibrium studies
  - ★ fastest running
- Prescribed boundary evolution (most often used)
  - ★ 2D-interpolation between fiducial shape boundaries read in at startup
  - ★ nearly as fast as fixed boundary but requires shape evolution file
- Backing out mode
  - ★ Prescribed boundary evolution with free-boundary solution each time step
  - ★ Factor of 2 or 3 slower due to free-boundary convergence time
  - ★ Gives “feed-forward” currents for controlled evolution
- Forward, free-boundary
  - ★ Uses controller for shape and vertical instability control
  - ★ Feed-forward currents from “backing out” to define shape evolution
  - ★ Time-consuming and more difficult to run, e.g. ~ 20,000 free-boundary solves.

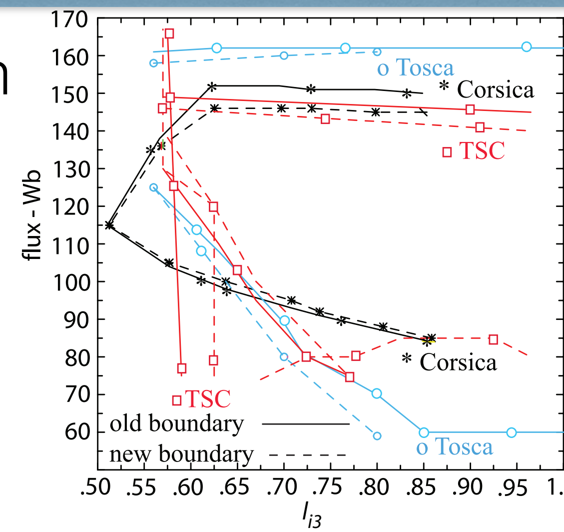
15MA Inductive scenario, ITER baseline

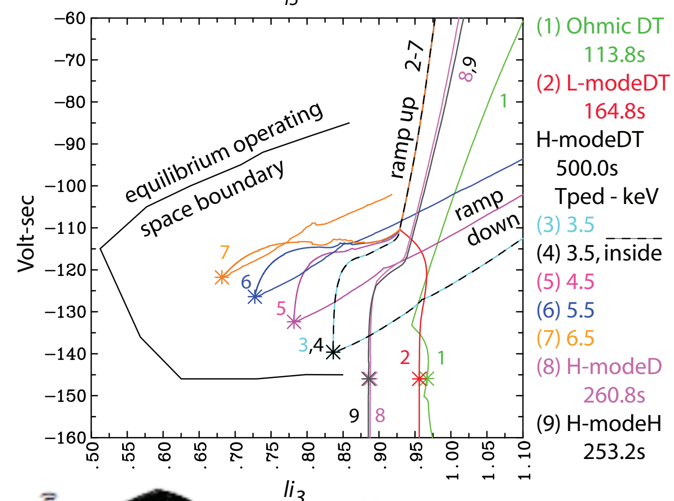
T. Casper *et al*, Nucl. Fusion 54 (2014) 013005

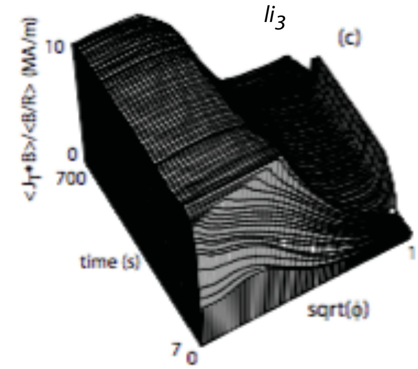


Tom Casper

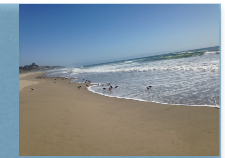
- Revised scenario to update current ITER design
  - ★ Modification of coil geometry
  - ★ Change in first wall geometry
  - ★ New limits on coil currents
  - ★ Change in startup using breakdown simulations
- Updated operating space, equilibrium study
- Confirm consistency of time-dependent scenarios with operating space
  - ★ Mapping of scenarios onto operating space
  - ★ multiple scenarios run: DT, DD, H, Ohmic
- Current density profile consistent with transport
  - ★ Neoclassical conductivity and bootstrap current
  - ★ Time-average saw tooth model







Free-boundary forward controlled scenario for baseline 15MA inductive case



Tom Casper

- JCT2001 controller with VS1 circuit
  - ★ Feed-forward currents from backing out
  - ★ Controlled shape and vertical position
- Vertical stability assessed

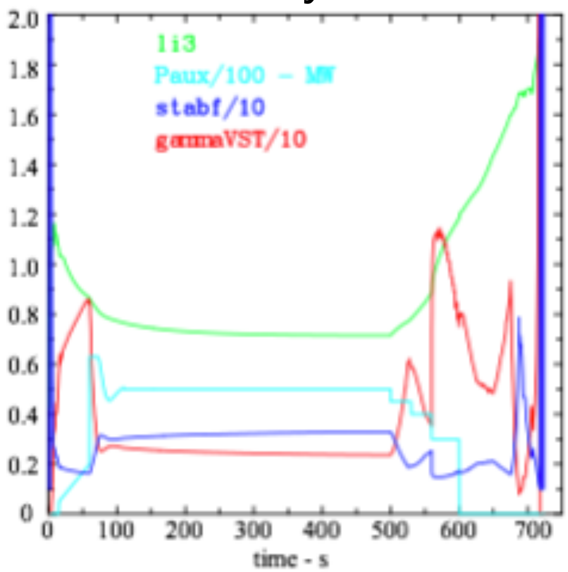
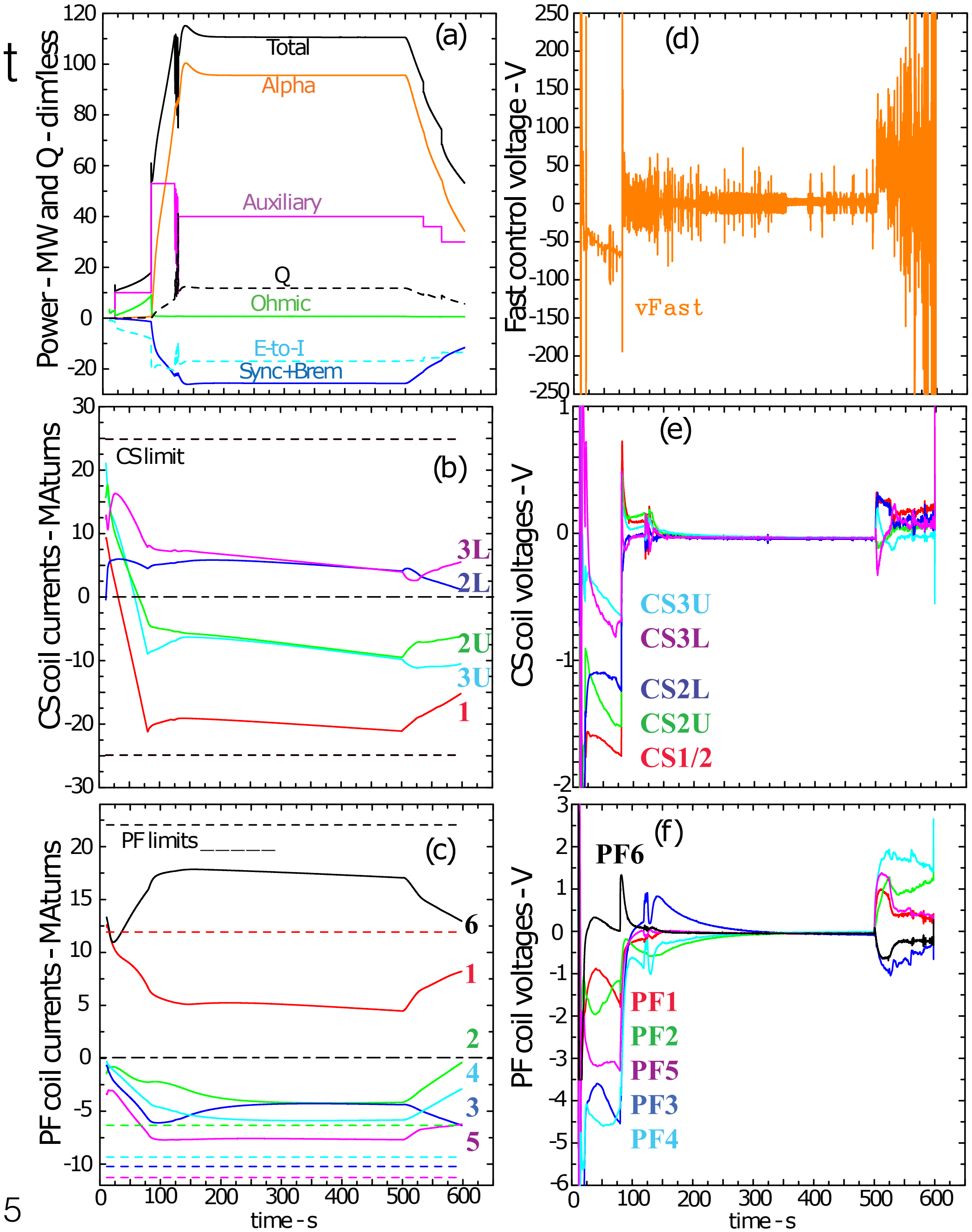
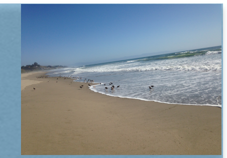


Figure 12 Scenario stability paramters; internal inductance li3, vertical growth rate gammaVST, and stability parameter stabf where stabf=1+1./gammaVST/tauLR and tauLR is the L/R time.



15MA inductive scenario revised 2013 (unpublished)
Optimize Q=10 performance



Tom Casper

- ITER contract results used with permission (T. Casper IDM report_M45W9Z_v1)
- Backing out simulations with coil current limits
- Heating feedback control to reduce T_e-overshoot
- LtoH transition model
  - ★ Martin power threshold: P_{tot}, P_{aux}, $P_{MartinLH}$
    - Y.R. Martin *et al* Journal of Physics 123 (2008) 012033
  - ★ Density profile evolution model: N_{eaxis}, N_{eL}, N_{eH}

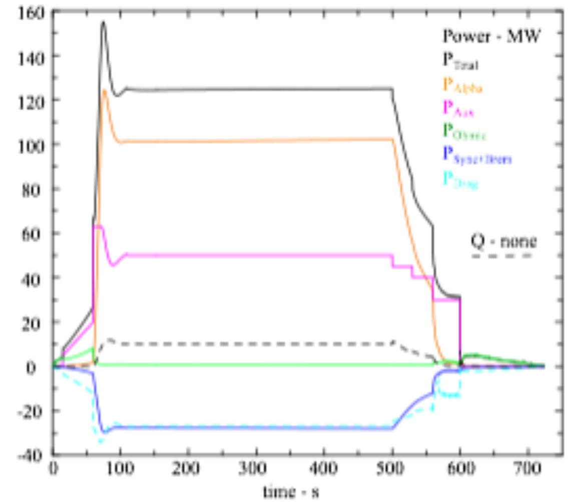


Figure 4. Heating waveforms, radiated power and fusion performance factor Q

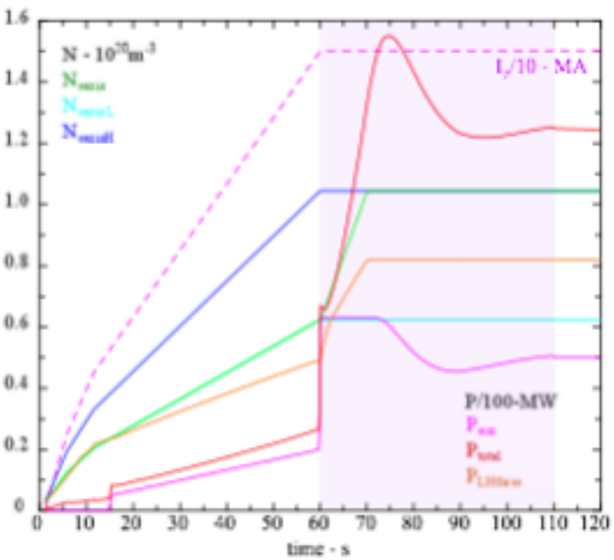


Figure 6 Details of the L-to-H transition during ramp up; feedback P_{aux} in shaded region.

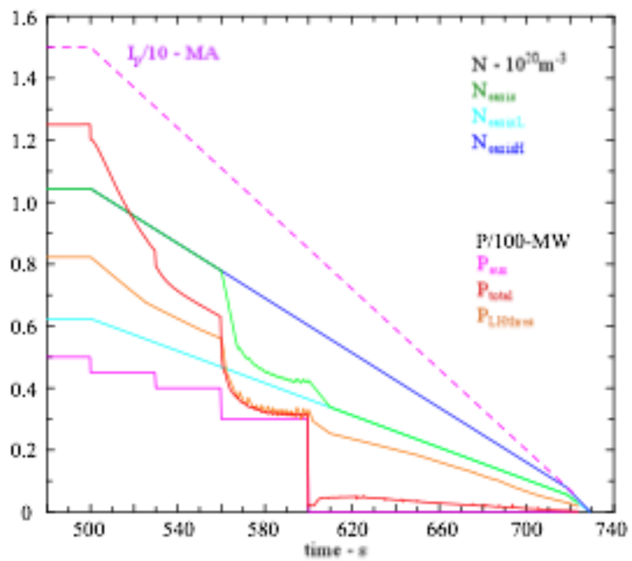


Figure 7 Details of the H-to-L transition during ramp down.

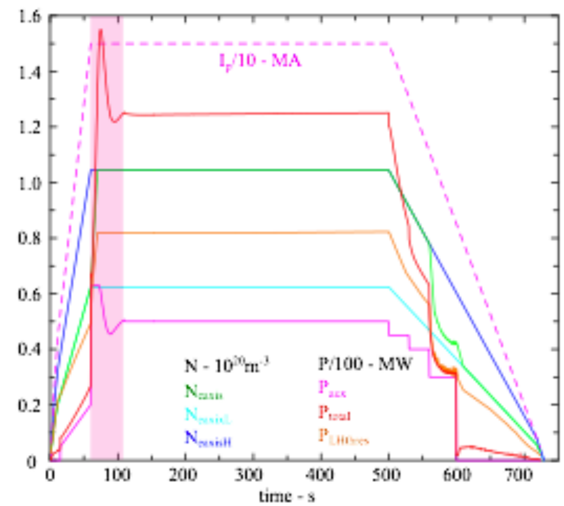
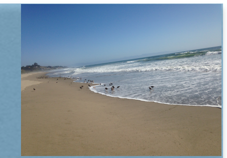


Figure 5. Waveforms of I_p-MA, Power-MA for P_{aux}, P_{Total}, $P_{LHthresh}$, and on-axis electron density evolution N_{eaxis} between assumed density for L- (N_{eaxisL}) and H-mode (N_{eaxisH}) states. Shaded area is under P_{aux} feedback control.

Revised 15MA scenario continued … typical profiles in burn



Tom Casper

- Analytic density profiles
- Temperature profiles from Coppi-Tang transport model
- Current from neoclassical conductivity and bootstrap

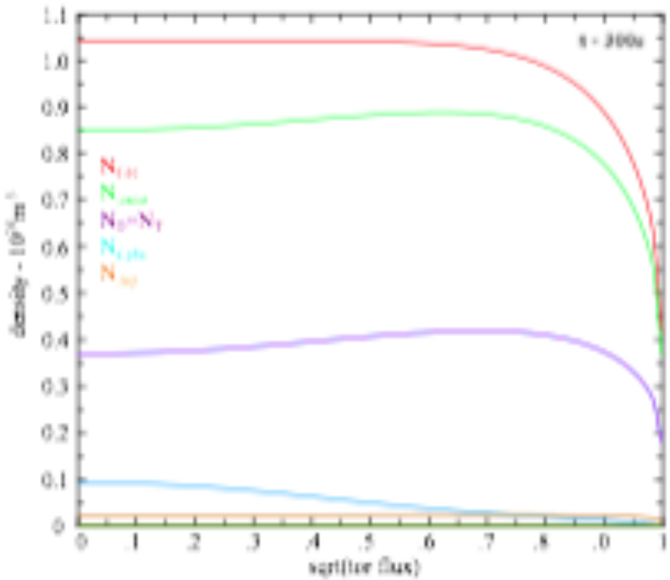


Figure 1 Assumed analytic density profiles for H-mode at 300s in Ip flattop burn; alpha particle density is calculated and reduces the density of D and T in the core and changes Z_{eff}

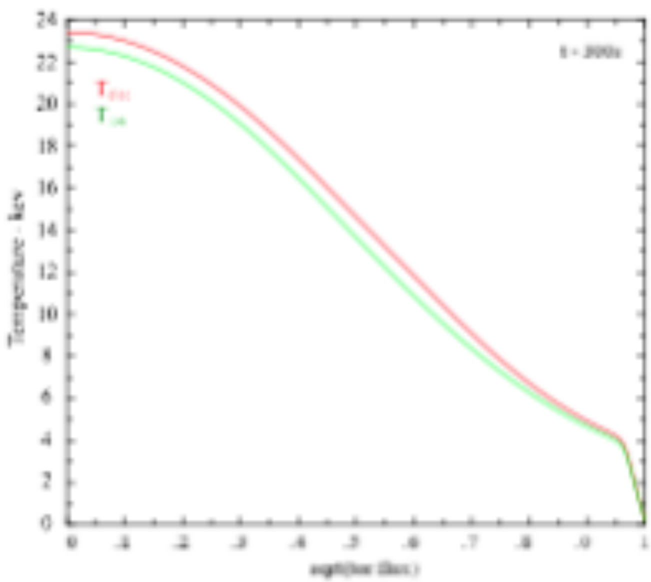


Figure 2 Electron and Ion temperature profiles at 300s from the re-normalized CT transport model. P_{aux} heating to electrons is coupled to the ions by drag.

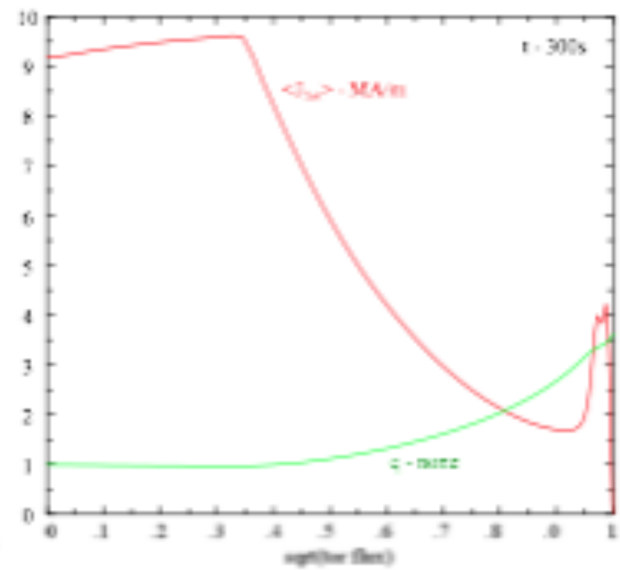
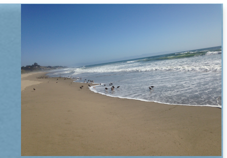


Figure 3 <J_{Total}> - MA/m total flux-surface-averaged current and the q profile at 300s. Note the sawtooth radius to 40% of the minor radius as is usual for the baseline scenario.

Revised 15MA scenario continued … shapes and limits



Tom Casper

- Re-design ramp down shapes to maintain contact with diverter
- Heating control in ramp down
  - ★ Avoid coil current and magnetic field limits
  - ★ Maintain coil forces under maximum values allowed

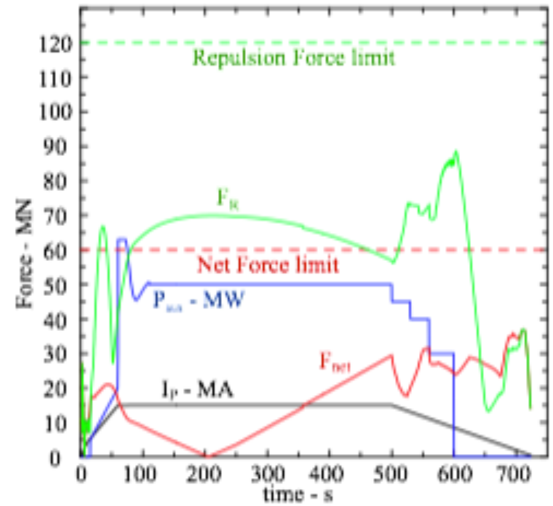


Figure 10. Net and Repulsive forces on the CS coils. The coils are far from force limits during the entire scenario.

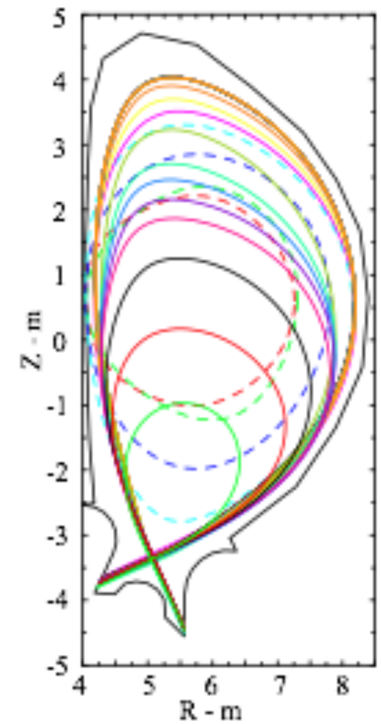


Figure 11 Plasma boundary evolution from limited on inside wall (dashed lines) to diverted in ramp up, flattop, and ramp down. The diverted shape is maintained during the full ramp down.

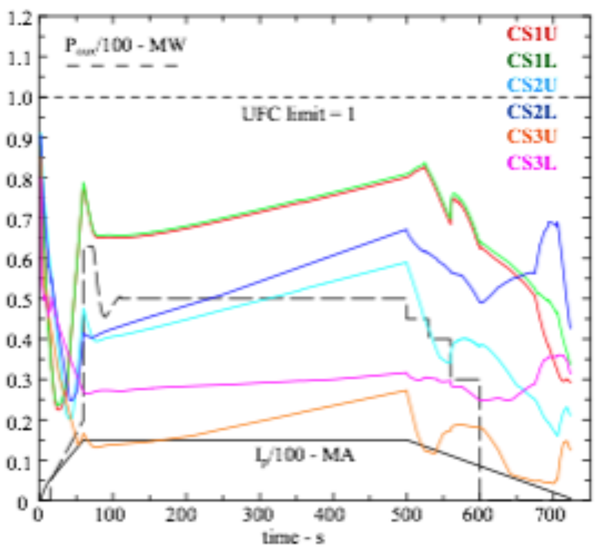


Figure 8 Waveforms for CS coil utilization factors (UFC) where values of UFC > 1 violate the coil current and/or magnetic field limits. All coils are within limits of safe operation.

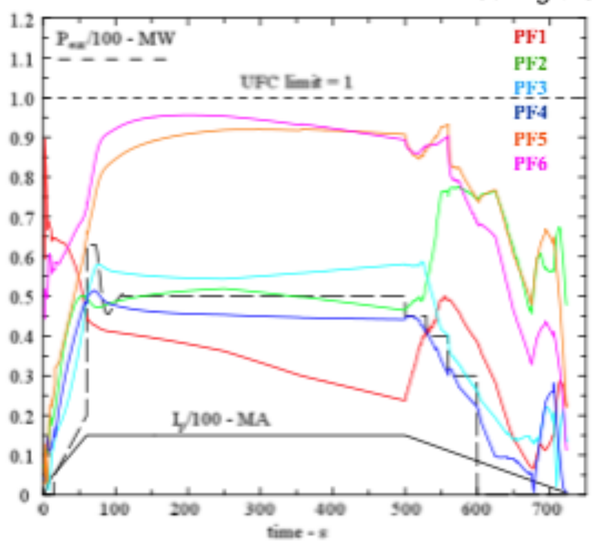
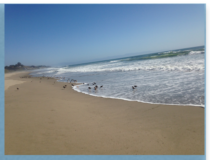


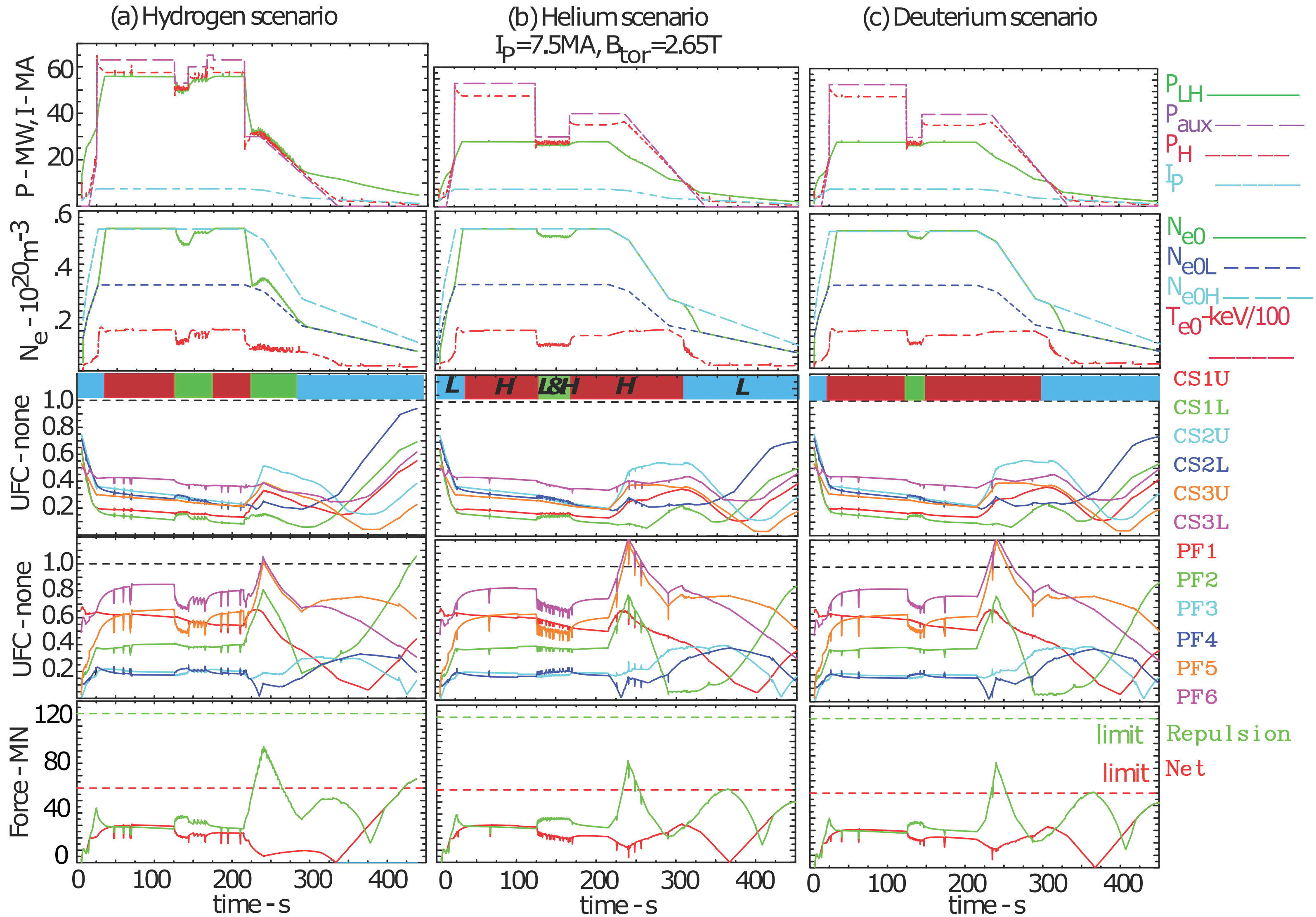
Figure 9 Waveforms for PF coil utilization factors (UFC) where values of UFC > 1 violate the coil current and/or magnetic field limits. All coils are within limits of safe operation.

Pre-DT, low activation scenarios developed with CORSICA for startup T.A. Casper *et al* IAEA 2012 paper ITER/P1-15


Tom Casper

- H, He, and D scenarios
  - ★ $I_p/2$=7.5MA
  - ★ $B_T/2$=2.65T
- Latest models from 15MA development applied
- On-going development ITER/ITPA by Sun Hee Kim, please collaborate

Mass scaling: H-plasma has too high H-mode threshold (Martin)



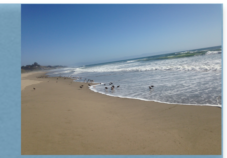
Advanced-inductive (hybrid) scenario (Sun Hee Kim)

S.H. Kim *et al.*, 24^{th} IAEA Fusion Energy Conference, San Diego, USA, 2012, ITR/P1-13

Tom Casper

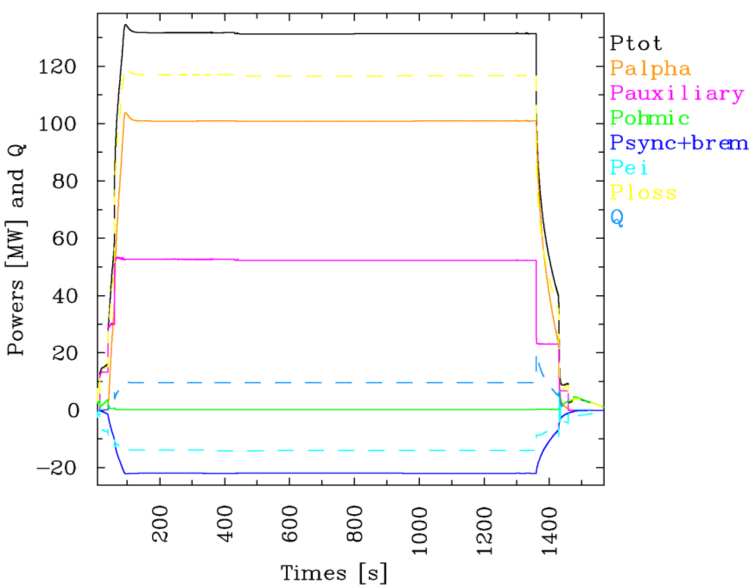
- Modeling by Sun Hee Kim
  - ★ Originally completed as Monaco post doc at ITER
  - ★ Now at ITER - scenario updated and being submitted to Nucl. Fusion
- Backing out and forward controlled scenario simulations with additions
- Full source modeling: NBI, ECH/ECCD, LH and ICH
  - ★ NBI (NFREYA+orbit model) internal to CORSICA
  - ★ EC from TORAY-GA with permission from General Atomics
  - ★ LH from LSC (code modules library)
  - ★ ICH from TORIC with permission from IPP-Garching
- Pedestal model based on EPED1 (PPCF **46**, P. Snyder *et al*, GA)
  - ★ 9-parameter fit
  - ★ Uses hyperbolic-tangent edge density model

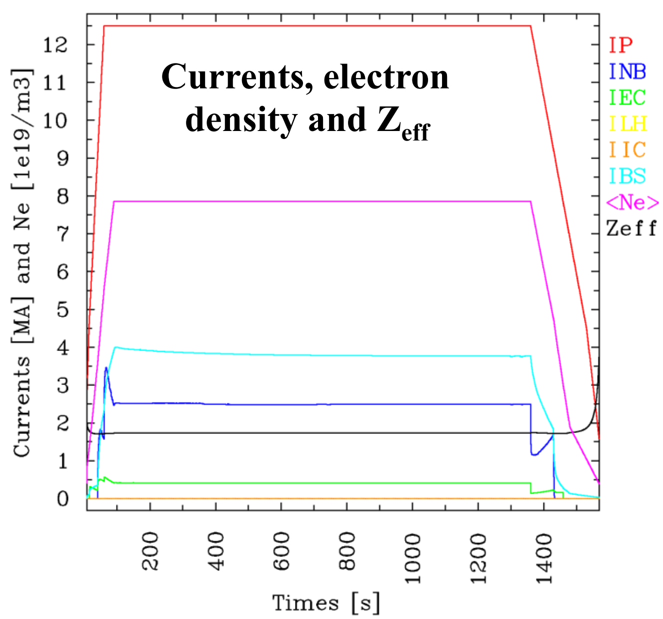
Advanced-inductive scenario time evolution
(S.H. Kim)

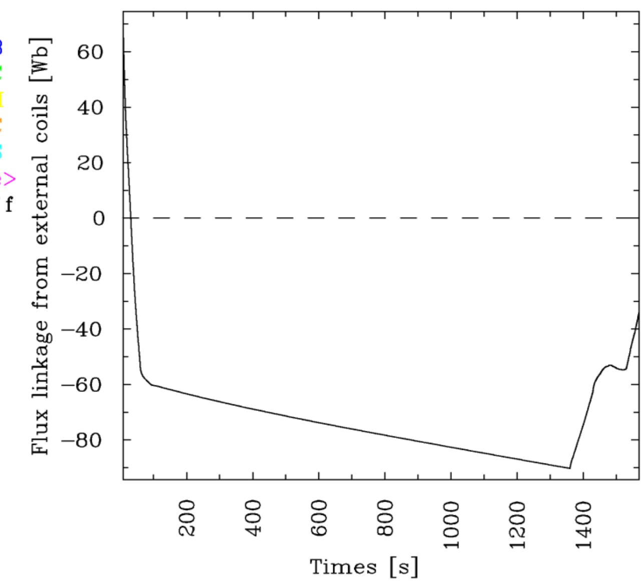


Tom Casper

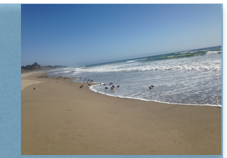
- Tailored 15MA scenario for advanced-inductive: I_p=12.5MA, B_T=5T with heating and current drive to control q-profile
- Heating, current, density and Z_{eff} evolution for burn time of ~1000s
- Flux consumption: optimization to avoid current limits uses pre-magnetization advance (initial breakdown flux)
- Shape evolution from 15MA inductive scenario; not optimized





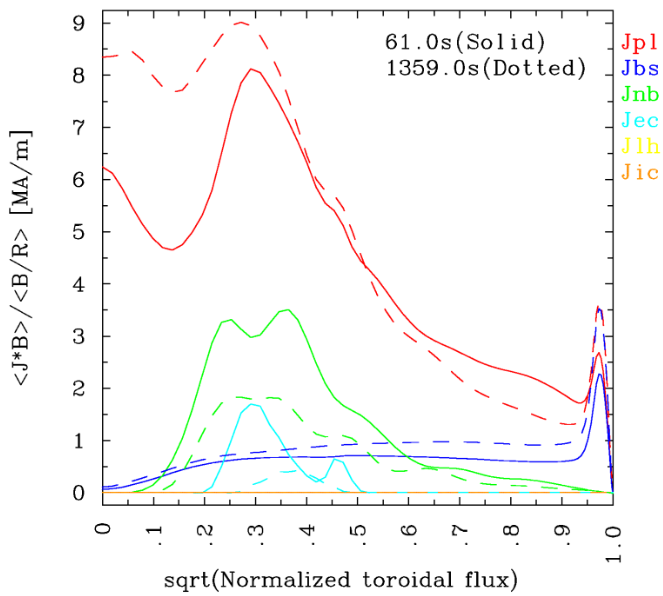


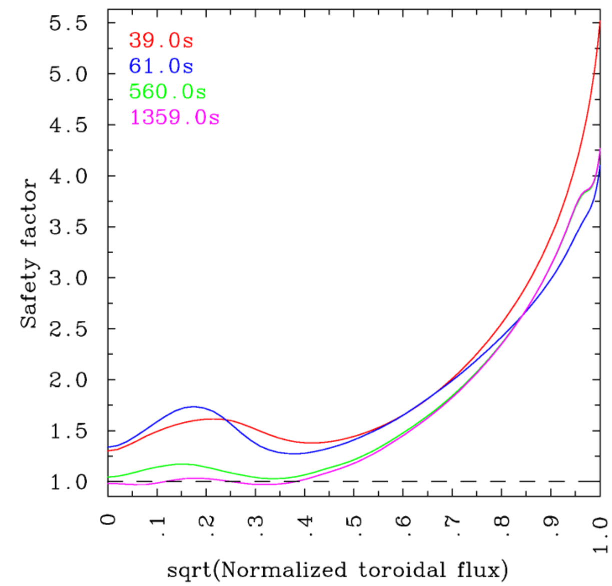
Profiles achieved with heating and current drive source modeling (S.H. Kim)



Tom Casper

- Current density profiles at end of ramp up and end of burn
- Evolution of q-profile. Optimization of sources to maintain q>1 in progress





- Pedestal model evolution

❑ A hyperbolic tangent shape pedestal density profile applied [PPCF**46**, P. Snyder].

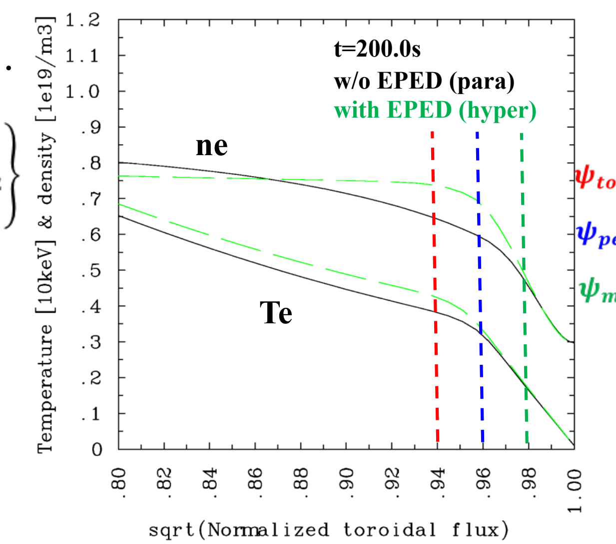
$$n_e(\psi) = n_{e0}\left\{(1-r_2)\left(c_1\left[H\left(1-\frac{\psi}{\psi_{ped}}\right)\left(1-\left(\frac{\psi}{\psi_{ped}}\right)^{\alpha}\right)^{\beta}\right] + c_2\left[tanh\left(2\frac{1-\psi_{mid}}{1-\psi_{ped}}\right) - tanh\left(2\frac{\psi-\psi_{mid}}{1-\psi_{ped}}\right)\right]\right) + r_2\right\}$$

❑ 9 inputs : (I_p, $n_{e,ped}$, Z_{eff}, β_N, R, a, κ, δ, B_t)

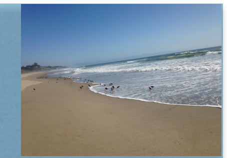
❑ 4 outputs : (Δ_{ped}, P_{ped}, Δ_{top}, P_{top})

❑ Multi-dimensional interpolation/extrapolation (up to 9 input dimensions)

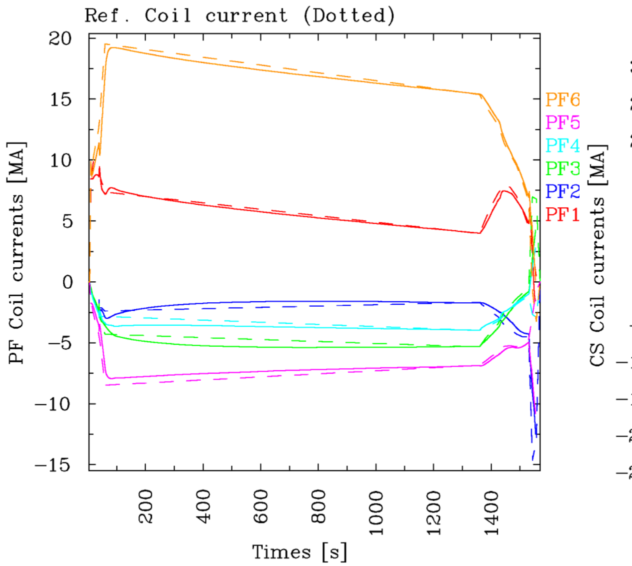
❑ Feedback control on the pedestal width and height

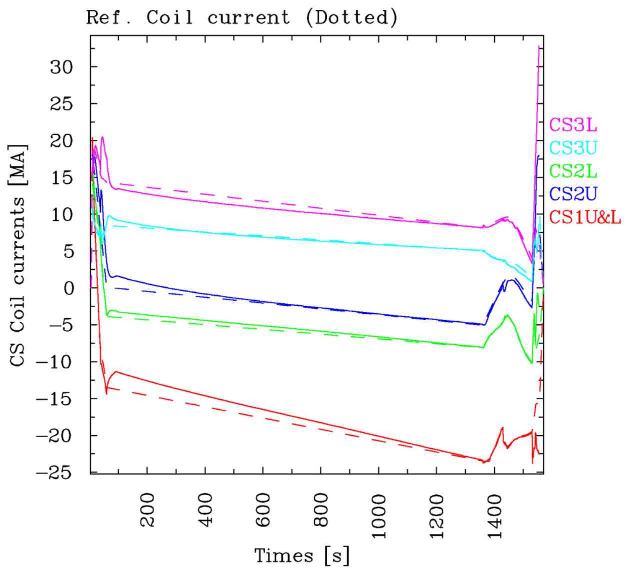


Free-boundary controlled advanced-inductive scenario simulation (S.H. Kim)

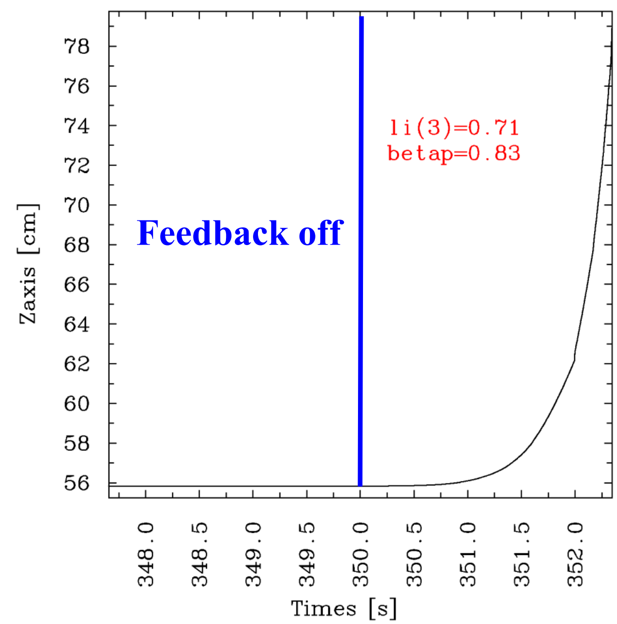

Tom Casper

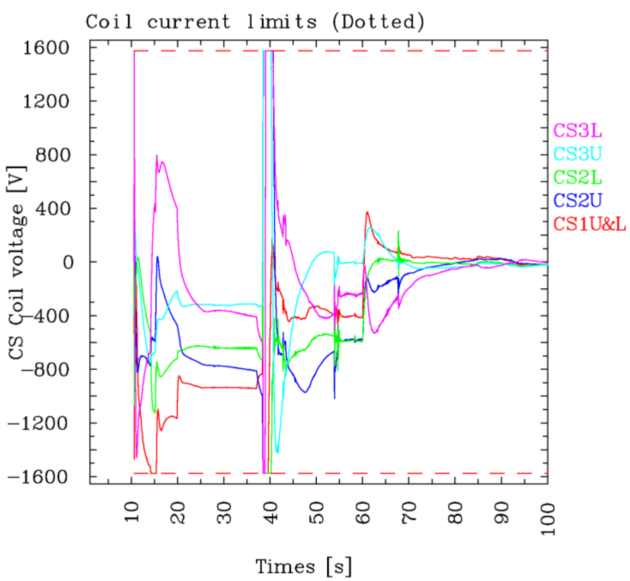
- Evolution similar to backing out case
- Coil currents: Top full duration both cases and bottom is ramp up

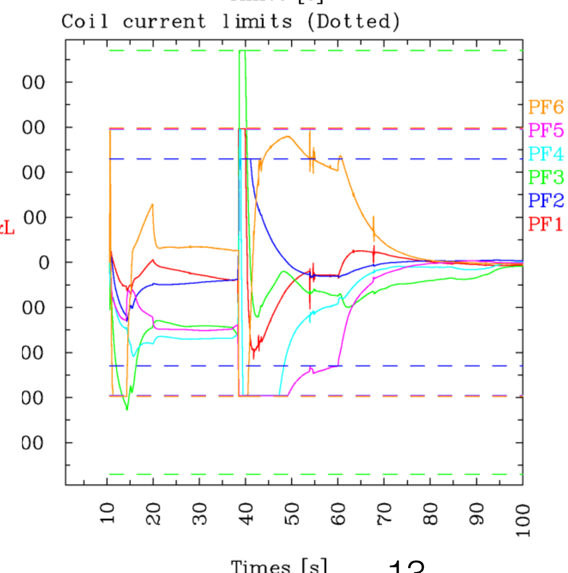




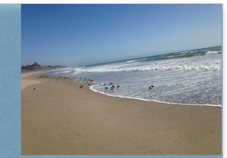
Note: plasma vertically unstable when feedback loop turned off





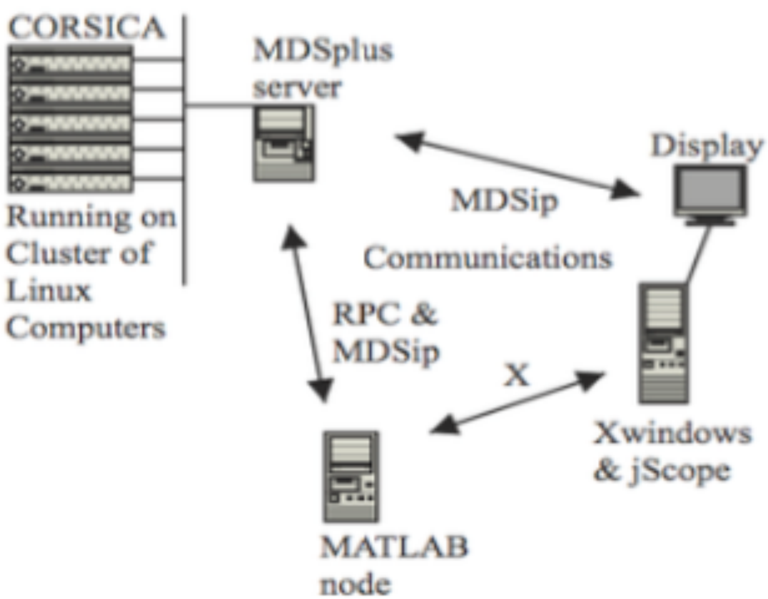


CORSICA forward control connected to MATLAB and MDSplus T.A. Casper *et al* Fus. Eng. Design 83 (2008) 552-556

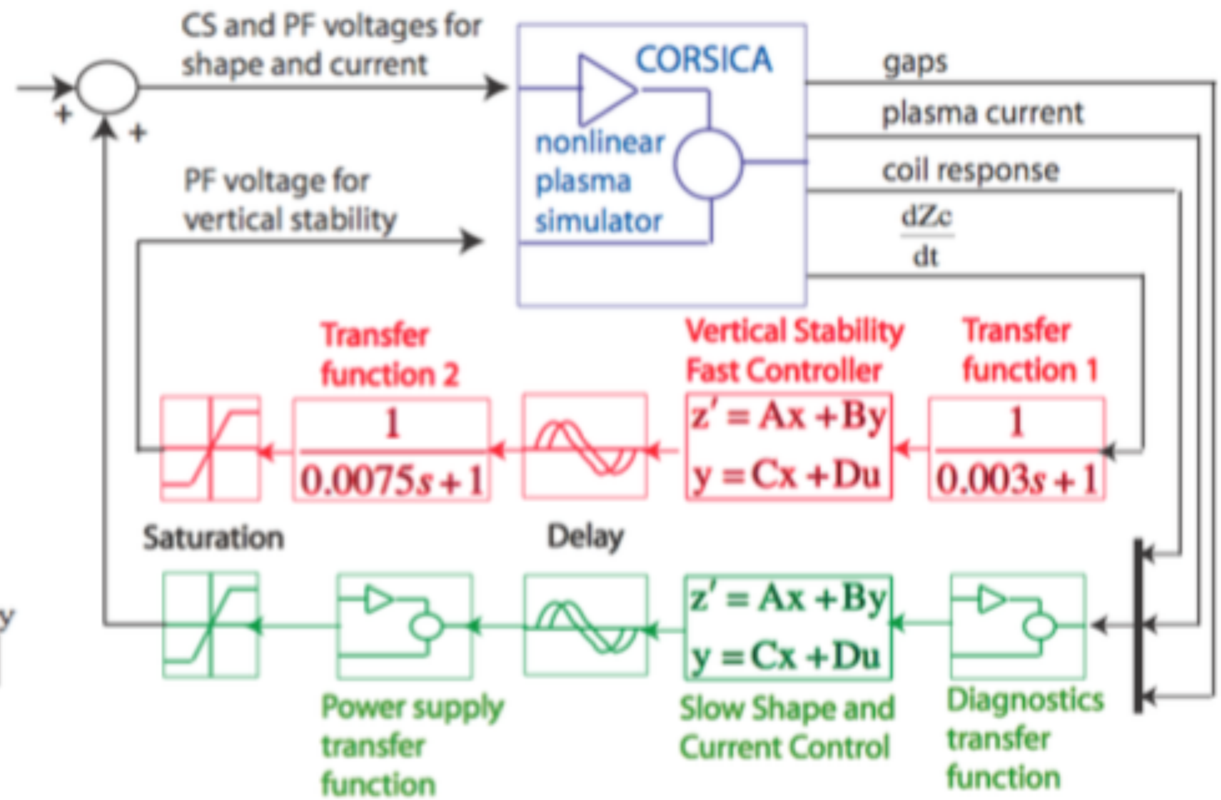


Tom Casper

- **ITER JCT 2001 controller from A. Portone**
- **Two implementations**
  - » Internal to Corsica for speed
  - » Corsica coupled to Matlab/Simulink for design flexibility - Bill Meyer

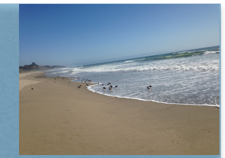


  - » T.A. Casper, et al., Fus. Eng. Design 83 (2008) 552-556.



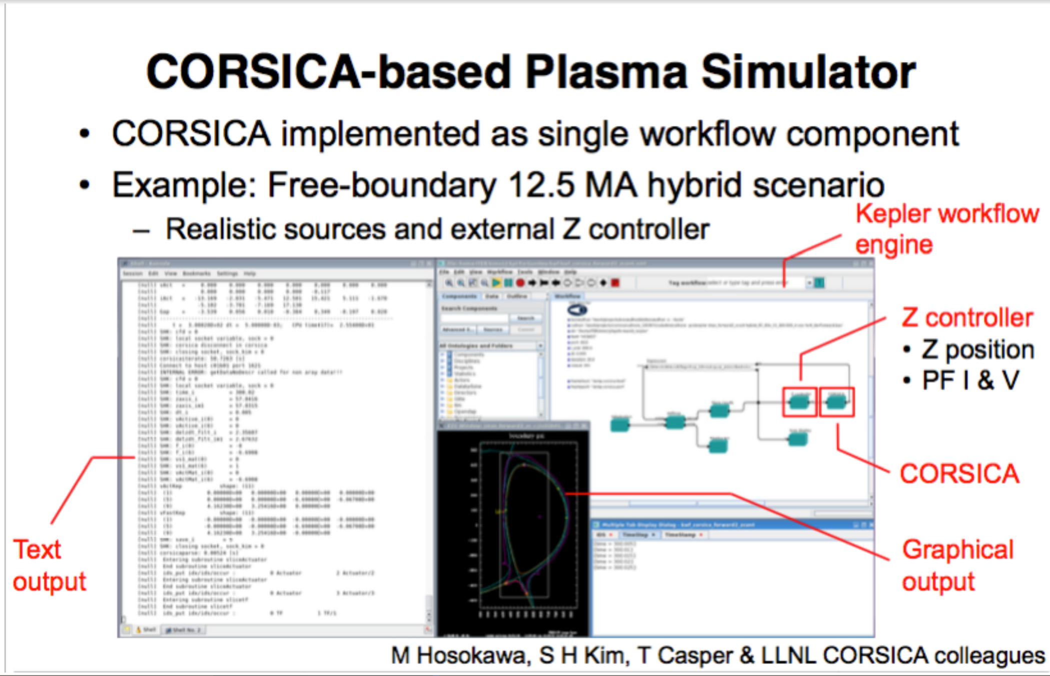
- **Fiducial states for controller references**
  - » Plasma current and gaps
  - » Pf and CS coil currents
- **Reference gap positions "backed out" in scenario control simulation**

CORSICA development for ITER plasma simulator

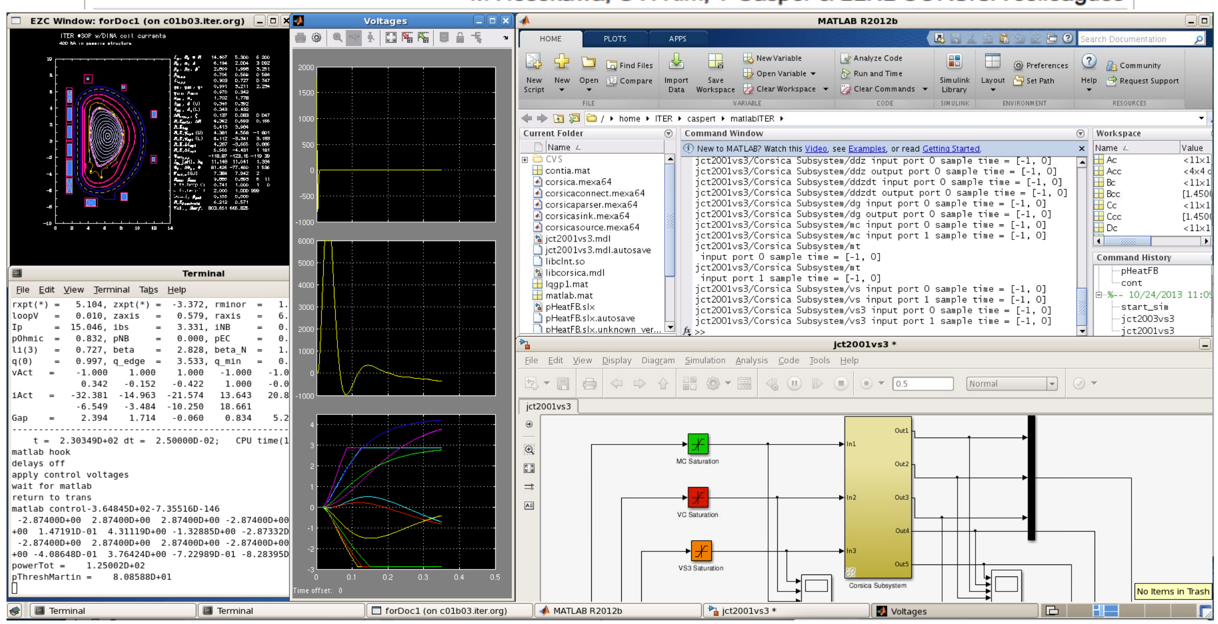


Tom Casper

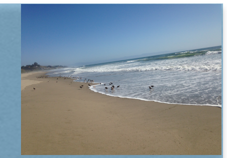
- CORSICA was the first code added to the ITER IMAS (Integrated modeling and analysis suite) … S. Pinches, American Physical Society meeting 2013.



- CORSICA-matlab coupled code used to demonstrate ITER PCSSP operation (Plasma Control System Simulation Platform)

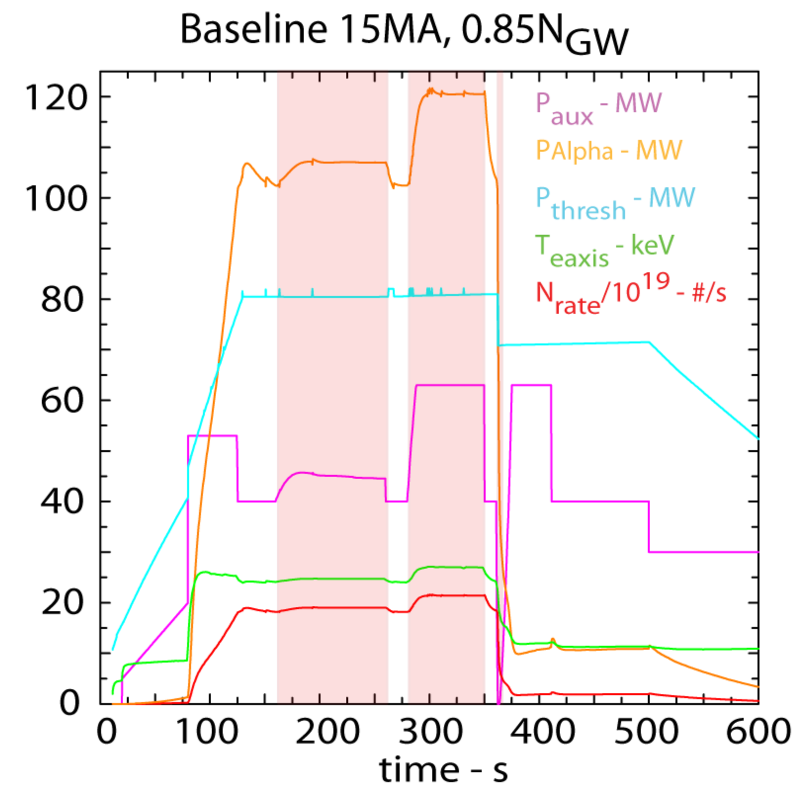


Demonstrate burn control for baseline 15MA inductive scenarios at high density $N_e(0)=0.85N_{GW}$

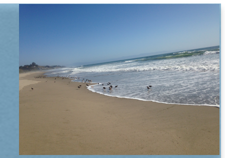


Tom Casper

- Feedback control of DT neutron rate using P_{aux} (analytic shape)
- P_{fus} ~ 500MW, Q~10
- Feedback "on" in shaded regions
  - ★ 1st – 1.9×10^{20}
  - ★ 2nd – 2.5×10^{20}; power limited to ~2.15×10^{20}
  - ★ 3rd - 0.75×10^{20} but error in programming feedback off time
- Early and late use pre-programmed P_{aux}
- T. A. Casper, presented at ITPA meeting San Diego, 2012. Unpublished ITER results used with permission.



Simulations to study fusion power with varying ratio of N_T/N_D



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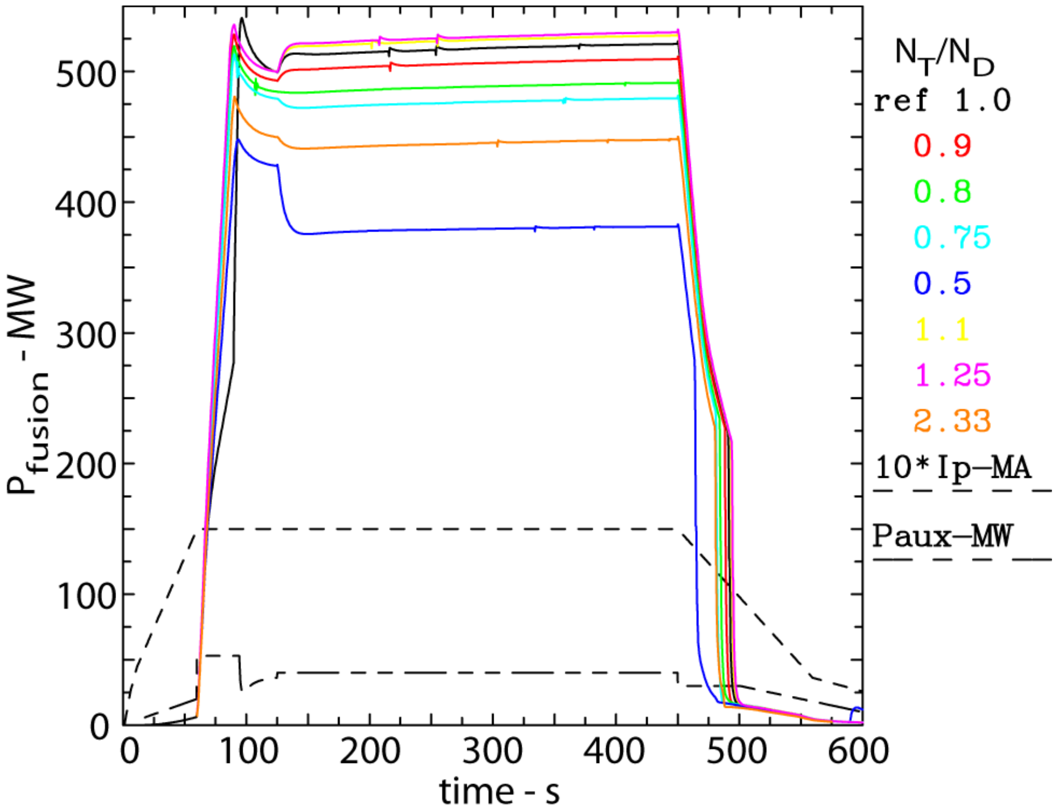
- J.Snipes, et al Controlling ITER Plasma Operation Scenarios, 39th EPS Conference on Plama Physics, Stockholm, Sweden 6 July 2012



CORSICA simulations of the fusion power produced for various values of nT/nD in the core for the 15MA inductive scenario with flat density profiles.

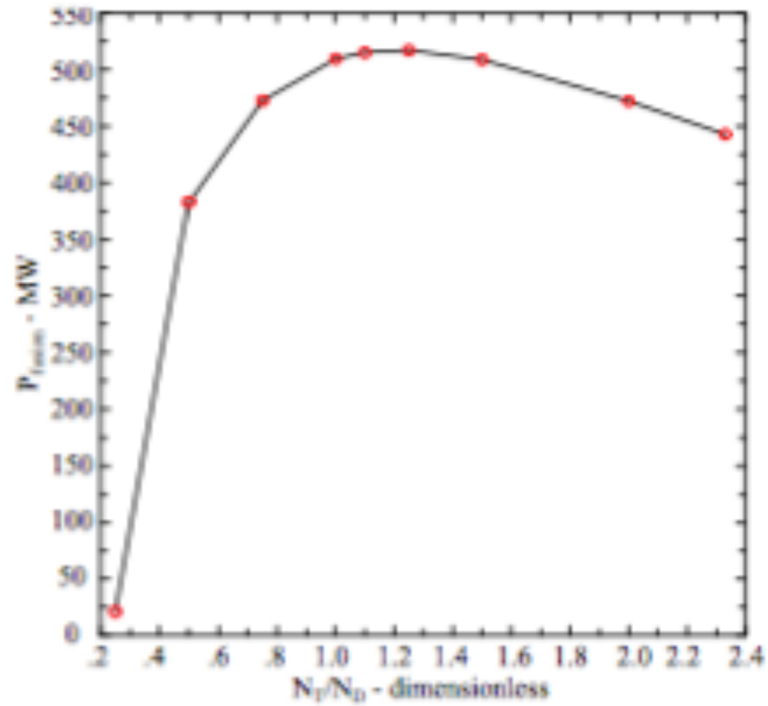
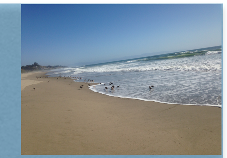


Fig. 3 Fusion power scaling with N_T/N_D at 300s, Ip flattop middle of burn. Note the decrease in P_{fusion} as N_T/N_D is reduced below 1 (50/50 mix).

Synthetic MSE diagnostic to study ITER design issues

T.A. Casper *et al.*, Review of Scientific Instruments 75 No. 10 (2004)



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- Very early CORSICA ITER scenario studies and MSE design
- 15MA inductive case
- Neutral beam HNB4 in Port #3: ITER technical report GAO FDR 1 02-07-13R1.0
- Design version: P. Lotte, ITPA report, Padua, Italy, 2003

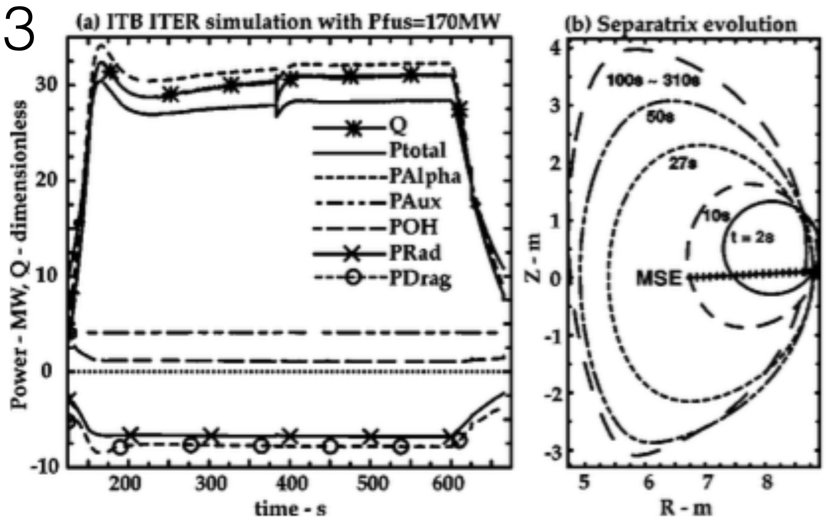


FIG. 1. ITER internal transport barrier (ITB) simulation showing (a) time histories of the heating powers and (b) time variation of the separatrix shapes during discharge evolution with the MSE detector locations indicated (+).

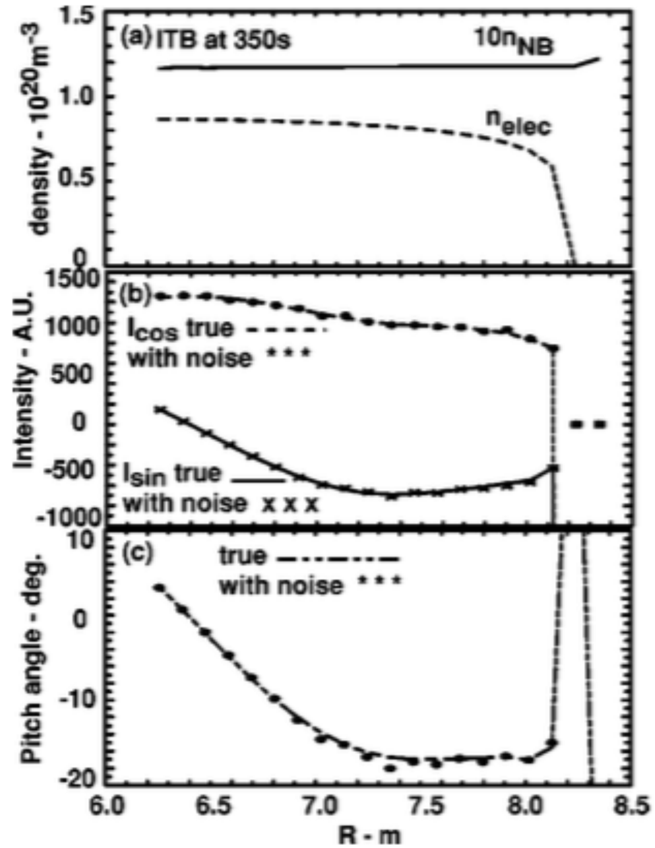
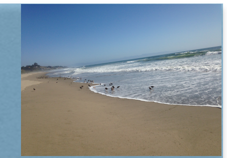


FIG. 2. Simulation results at t=350 s for the ITB discharge simulation: (a) electron and beam densities, (b) simulated intensities detected for both signal and signal plus noise, sin and cosine components and (c) true and measured pitch angles indicating good measurement capabilities in the core with some degradation in measurements at larger radii assuming only photon noise is present.

CORSICA ITER scenarios provide data for many edge physics studies - validates assumptions in scenarios



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- For example, Nonlinear ELM simulations with BOUT++ code

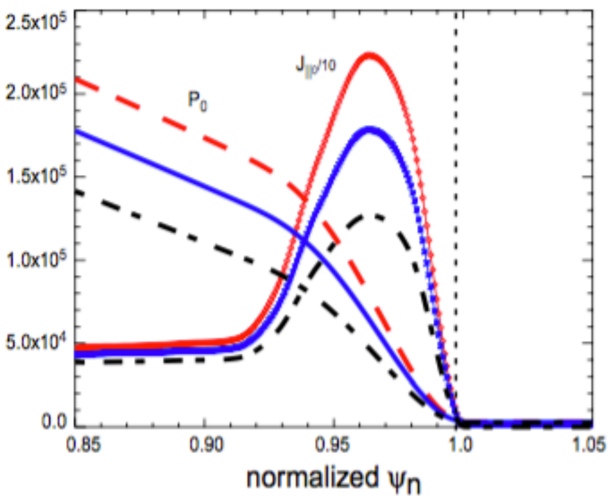


Figure 7. (*a*) The pressure P_0(Pa) and current profiles $J_{\|}$(A m^{-2}) from Corsica transport code: the dotted–dashed line $T_{ped} = 4.5$ keV, the solid line for $T_{ped} = 5.5$ keV and dashed line $T_{ped} = 6.5$ keV. The parallel current is scaled down by a factor of 10 on the plot.

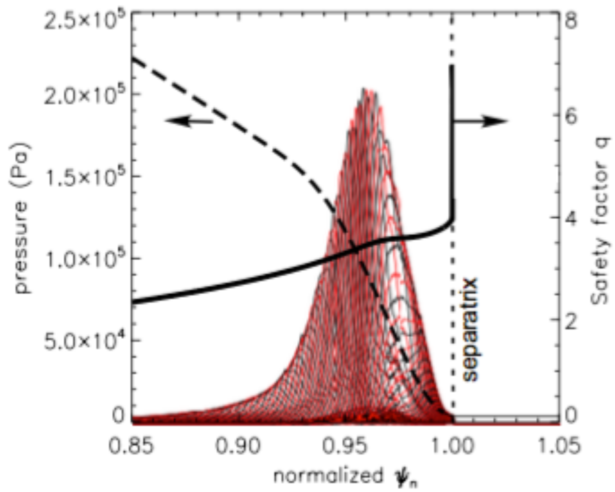
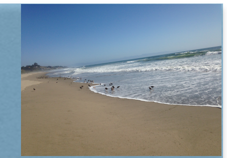


Figure 9. The radial profiles of pressure P_0 (dashed curve) and safety factor q (solid curve). It is over-plotted for the linear radial mode structures of toroidal mode number $n = 35$ with various poloidal Fourier harmonics for ideal MHD model. Here mesh size is $n_x = 1028$ and $n_y = 256$.

- ✦ X.Q. Xu, et al., Nucl. Fusion **51** (2011) 103004

- Several papers use data from CORSICA scenario studies, a few recent are:
    - ✦ A. Loarte, et al. Nucl. Fusion **54** (2014) 033007
    - ✦ Y. Sun, et al. Nucl. Fusion **53** (2013) 093010
    - ✦ P. Maget et al. Nucl. Fusion **53** (2013) 093011
    - ✦ T.E. Evans et al. Nucl. Fusion **53** (2013) 093029
    - ✦ M. Becoulet et al. Nucl. Fusion **52** (2012) 054003
    - ✦ S. Saarelma, et al Nucl. Fusion **52** (2012) 103020

Summary: CORSICA is a very powerful and flexible tool in use for modeling ITER



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- CORSICA has revised many operation scenarios
  - ★ 15MA Inductive baseline and a 5.5MA reduced inductive scenario
  - ★ Advance inductive for long pulse operation
  - ★ pre-DT operations for startup of ITER experiment (low activation)
  - ★ DT fueling performance
- Several ITER internal design studies supported by CORSICA scenarios and equilibrium analysis
- Latest simulation data provided for world fusion community research and participation in research efforts
- Innovative research supported … former Monaco post doc at ITER
  - ★ Application of the parareal algorithm to CORSICA simulations of advance plasma operation scenarios, D. Samaddar, et al 39th EPS Converence on Plasma Physics 2-6 July, 2012, Stockholm, Sweden, paper 2.140
  - ★ Time parallelization of advanced operation scenario simulations of ITER plasma, D. Samaddar, et al, Journal of Physics: Conference Series **410** (2013) 012032