Integrated Plasma Simulations

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Workshop Toward an Integrated Plasma Simulation

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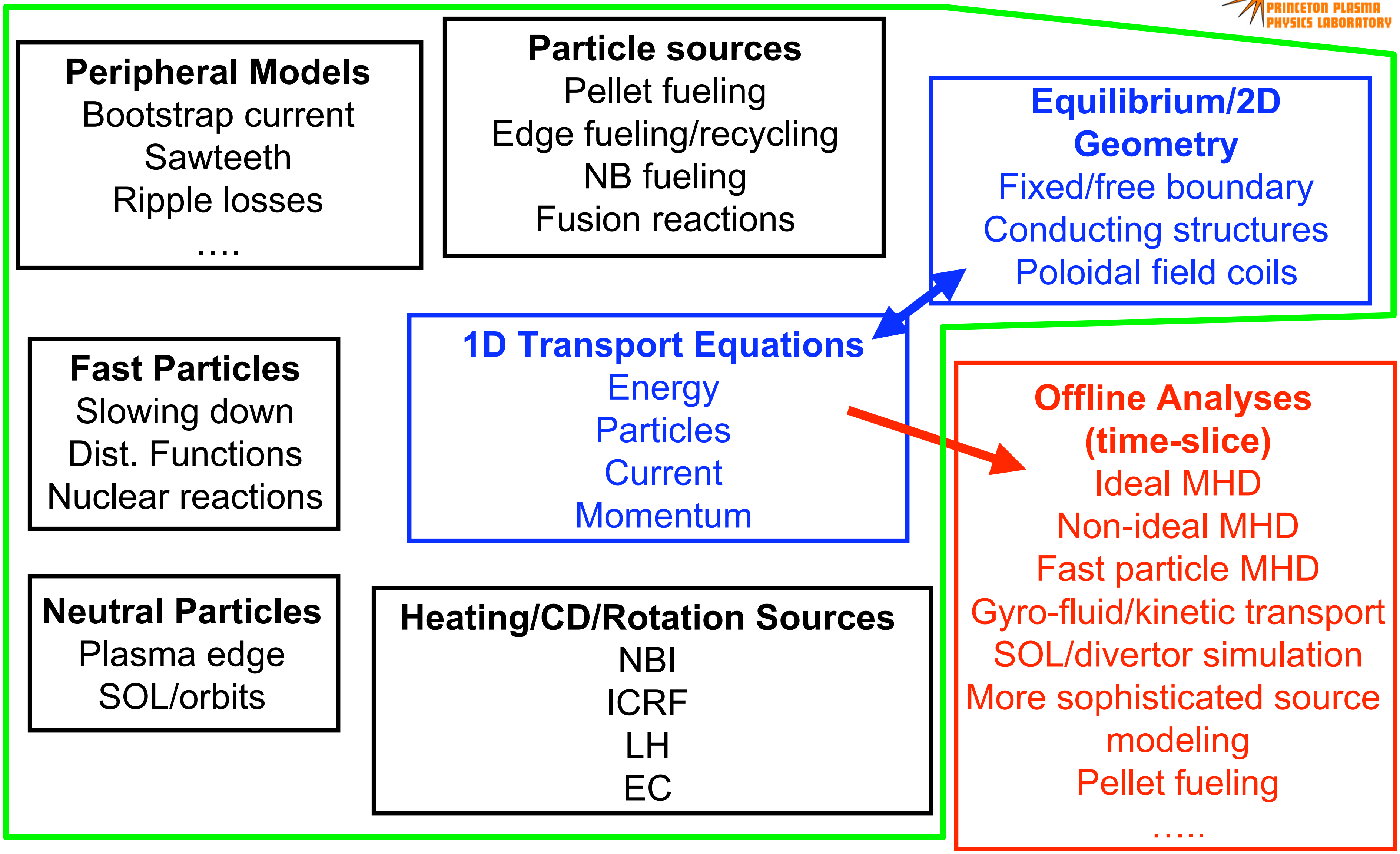
Time-Dependent Transport Simulations of Tokamak Plasmas



Peripheral Models
Bootstrap current
Sawteeth
Ripple losses
….

Particle sources
Pellet fueling
Edge fueling/recycling
NB fueling
Fusion reactions

Equilibrium/2D Geometry
Fixed/free boundary
Conducting structures
Poloidal field coils

Fast Particles
Slowing down
Dist. Functions
Nuclear reactions

1D Transport Equations
Energy
Particles
Current
Momentum

Offline Analyses (time-slice)
Ideal MHD
Non-ideal MHD
Fast particle MHD
Gyro-fluid/kinetic transport
SOL/divertor simulation
More sophisticated source modeling
Pellet fueling
…..

Neutral Particles
Plasma edge
SOL/orbits

Heating/CD/Rotation Sources
NBI
ICRF
LH
EC

Offline Analyses (time-slice) Ultimately End Up in Integrated Time-Dependent Simulations

More sophisticated models than those inside the transport simulation

Ray tracing versus full wave treatment
Single ion bootstrap current versus multi-species velocity space bootstrap current
Prescribe impurity profiles in plasma versus solving particle transport for their profiles

Sophisticated analyses that probably will not appear inside transport simulations for some time

Ideal, non-ideal and fast particle MHD stability (linear and nonlinear)
SOL/divertor calculations
Gyro-fluid/kinetic calculations of drift wave turbulence

Varying levels of sophistication in physics modeling is a desirable attribute of simulation tools ---> computational time versus physics fidelity is a balance determined by the application

Applications of Time-dependent Transport Modeling

Experimental tokamak modeling
- Reproduction of experimental discharges (interpretive--TRANSP, predictive)
- Project to new discharges based on existing discharges (predictive)
- Simulation of discharges never produced on the device (predictive)

Projections to future tokamak devices
- Near-term (KSTAR) similar to present devices
- Long-term (ITER) significantly different plasma regime

Examples from Tokamak Simulation Code (TSC) and TSC/TRANSP
- ONETWO (GA)
- Corsica (LLNL)
- Baldur (Lehigh)
- TRANSP (PPPL) -- long history and lots of experience

Long Term Projections to ITER

Using Tokamak Simulation Code (TSC) for free-boundary equilibrium and predictive transport

- GLF23 model for energy transport in core of plasma
- Assuming electron and impurity density profiles

Using TRANSP (interpretive) for NBI and ICRF source models

- Monte Carlo orbit following method for NBI (NUBEAM)
- SPRUCE/FPPRF full wave method for ICRF He3 minority heating (switch to TORIC soon)
- Fusion alpha particles and NBI fast deuterons are treated as equivalent Maxwellians for damping of ICRF power

Using Sauter single ion bootstrap current model, Porcelli sawtooth model, artificial pedestal model amended to GLF23

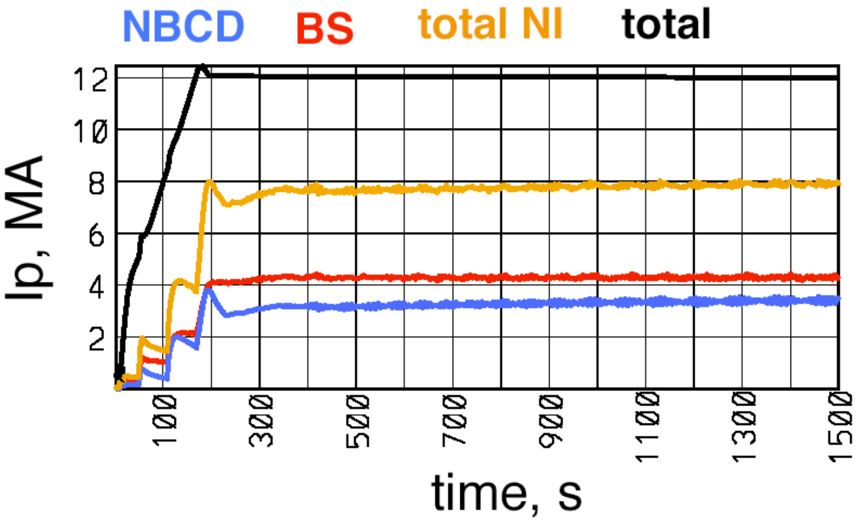
Soon will implement SOL/divertor response from B2/EIRENE database, provided by fit to those results

Offline analysis includes ideal MHD stability, fast particle effects, gyro-kinetic transport simulations

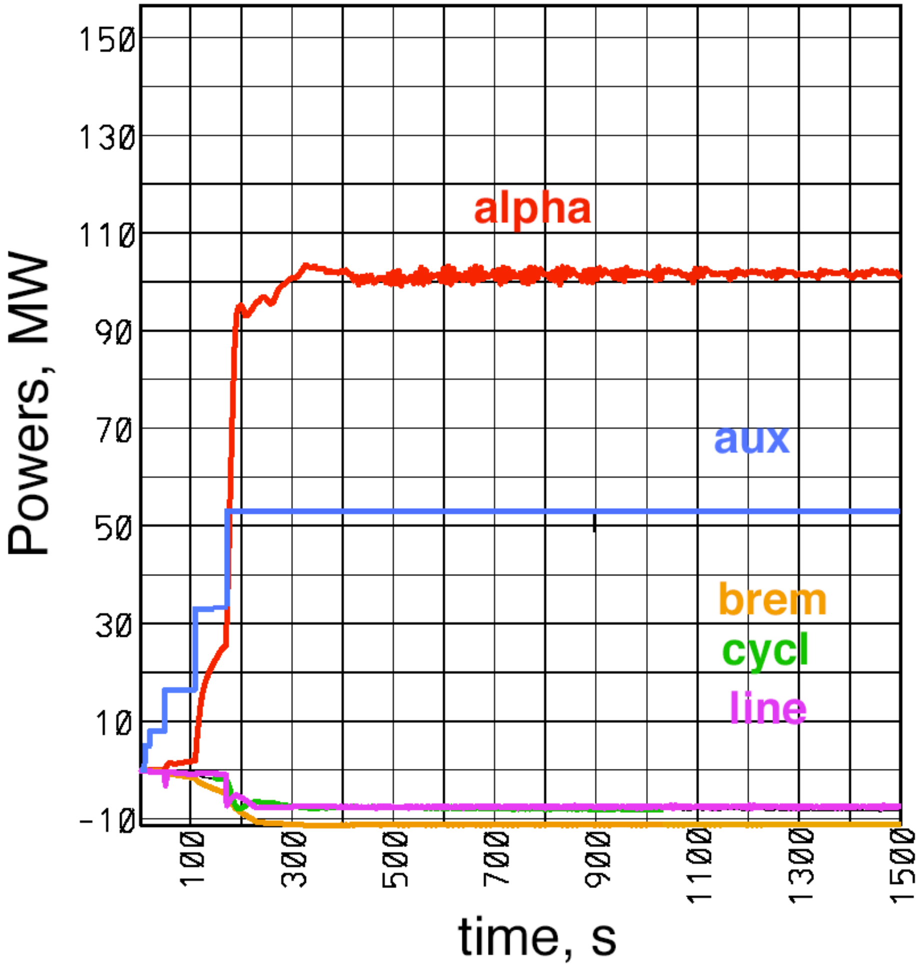
ITER Hybrid at $\beta_N \approx 3$ Produces 500 MW of Fusion Power

I_P = 12 MA
B_T = 5.3 T
I_{NI} = 7.8 MA
β_N = 2.96
n/n_{Gr} = 0.93
$n_{20}(0)$ = 0.93
W_{th} = 450 MJ
H_{98} = 1.6
T_{ped} = 9.5 keV
$\Delta\psi_{rampup}$ = 150 V-s

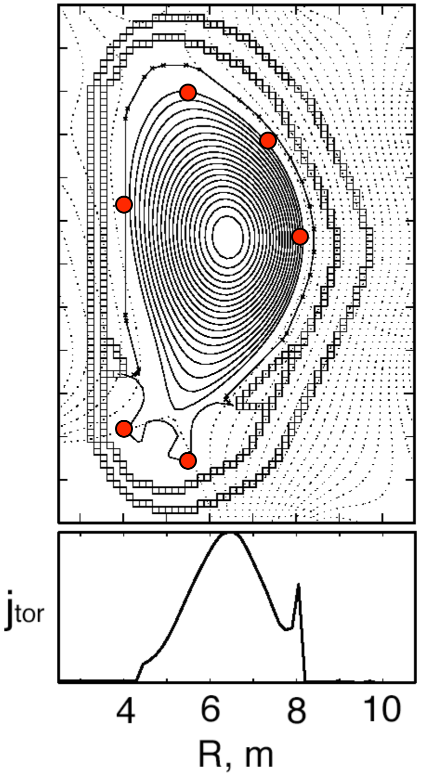
V_{loop} = 0.025 V
Q = 9.43
P_α = 100 MW
P_{aux} = 53 MW
P_{rad} = 28 MW
Z_{eff} = 2.25
q(0) < 1, ≈ 0.93
r(q=1) = 0.45 m
li(1) = 0.78
Te,i(0) = 30 keV

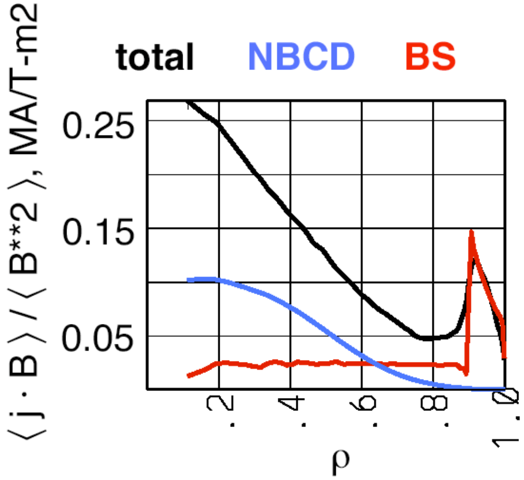


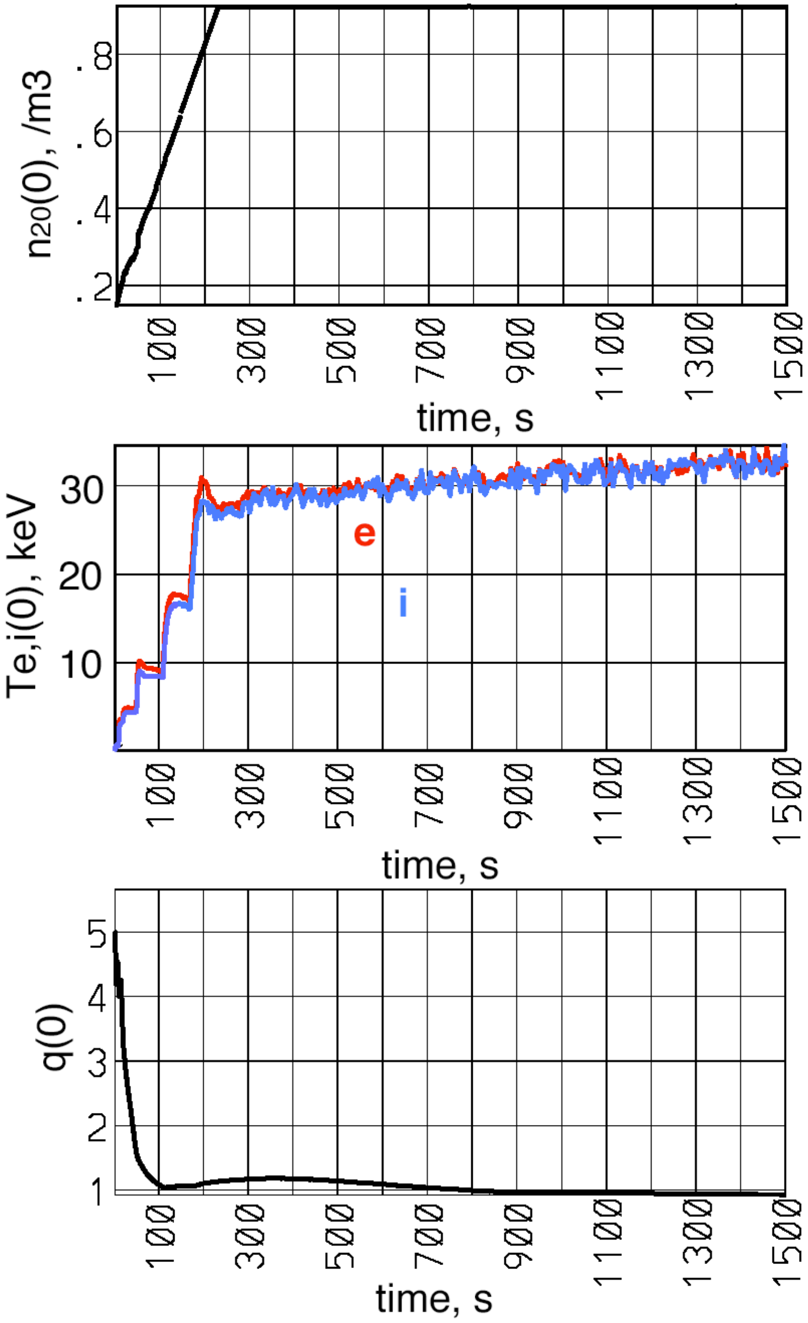
Available $t_{flattop}^{V\text{-}s}$ > 4000 s
$t_{flattop}^{nucheat}$ ≈ 400 s

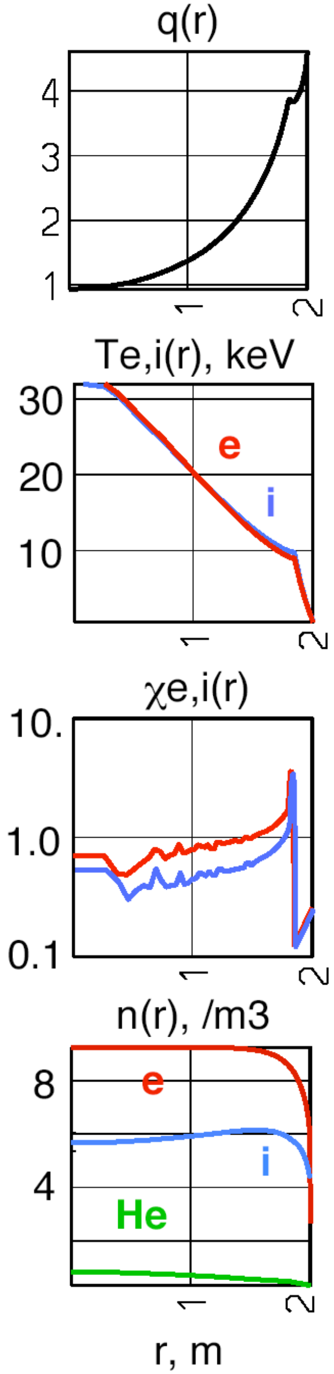


● Shape control points







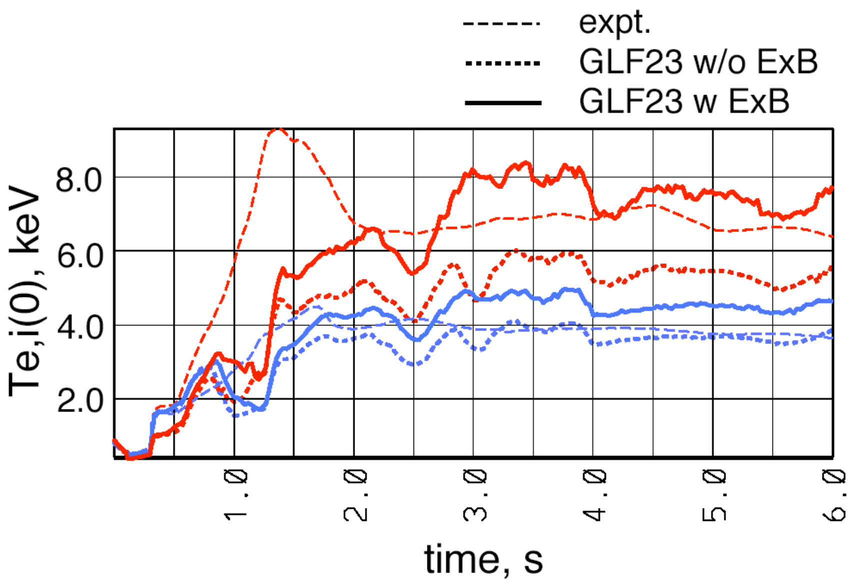


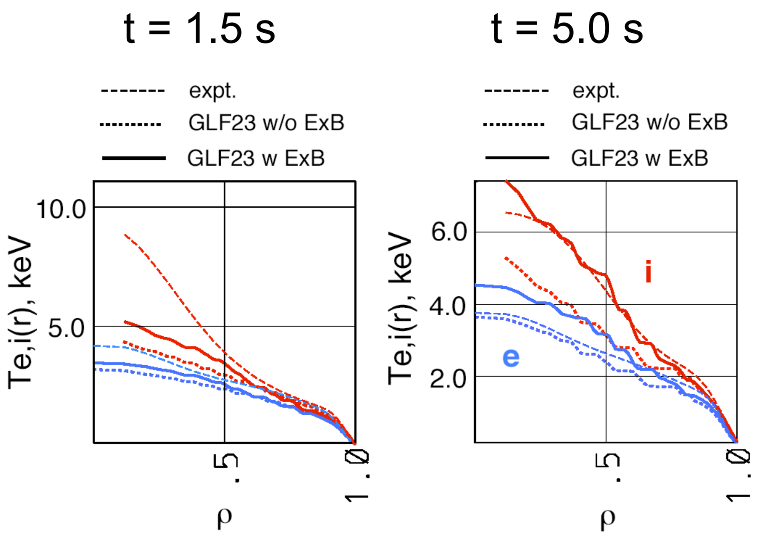
Experimental Application to DIII-D

Using Tokamak Simulation Code (TSC) predictive simulation to reproduce experimental discharge

Input $n(\rho)$, $T_e(\rho)$, $T_i(\rho)$, $Z_{eff}(\rho)$, $I_{PF}(t)$, $v_\phi(\rho)$ from experiment
Use TRANSP run of discharge to obtain NBI data
Derive thermal diffusivities in experiment

Rerun discharge simulation with GLF23 theoretically based thermal diffusivities in place of experimental ones



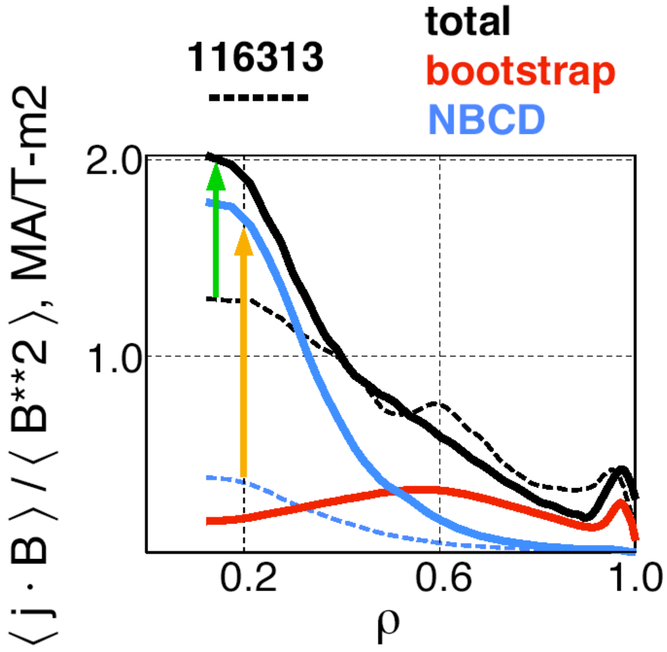


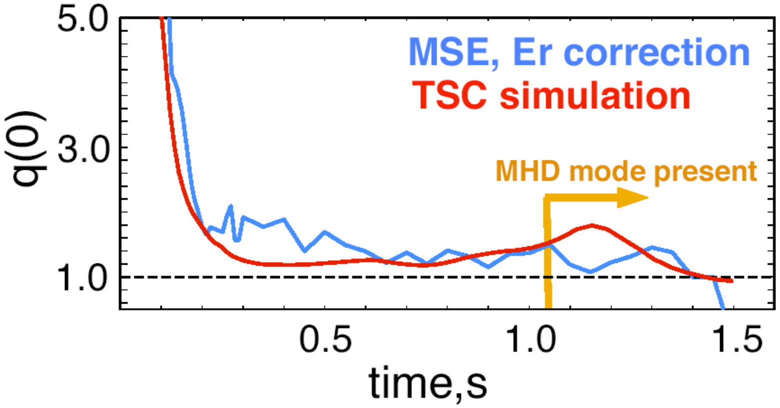
Experimental Application to NSTX

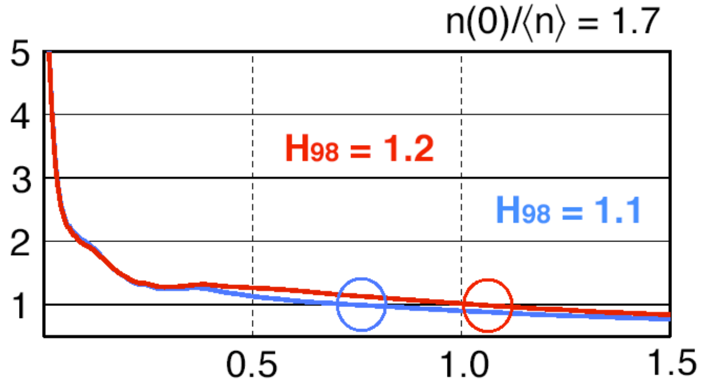
Using TSC predictive simulation to reproduce experimental discharge

- Input $n(\rho)$, $T_e(\rho)$, $T_i(\rho)$, $Z_{eff}(\rho)$, $I_{PF}(t)$ from expt
- Use TRANSP run of discharge to obtain NBI data
- Derive thermal diffusivities in experiment

Using thermal diffusivities from experiment, determine how lowering the plasma density affects the current in the plasma







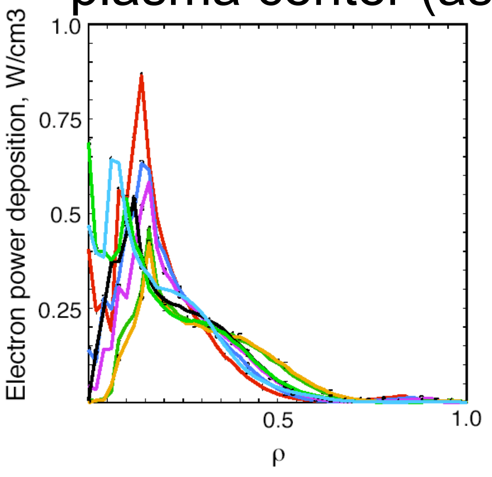
Application to NSTX

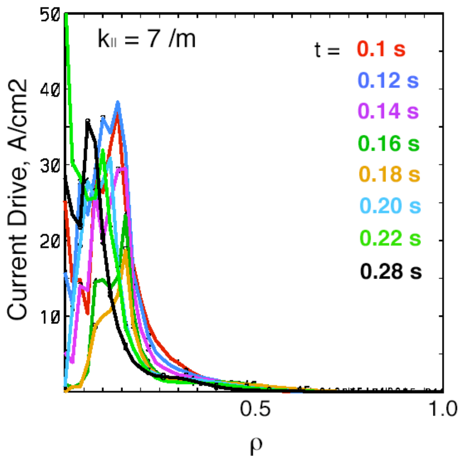
Using TSC predictive simulation of a High Harmonic Fast Wave (HHFW) heated discharge never produced on NSTX

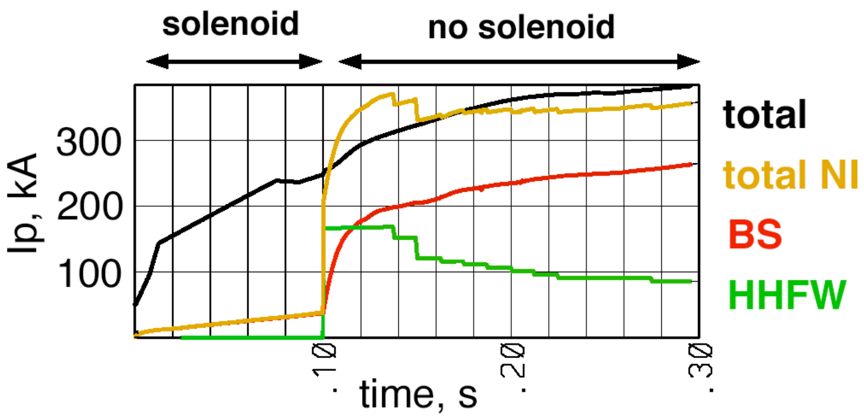
Use assumed thermal diffusivities, density and impurity profiles

Used off-line CURRAY calculations at several time-slices from TSC to determine heating and current drive (CD) profiles, and fed them back into TSC simulation (heating/CD & heating only were indistinguishable)

Subsequent experiments similar to this simulation showed that the plasma current could only be sustained at about 250 kA, not increased, indicating that the total HHFW power is probably not reaching the plasma center (as was assumed in the simulation)







Integrated Plasma Simulation Tool

Experimental discharge simulation capability
- Interface to expt. databases (MDSplus)
- Interpretive and predictive, ability to constrain or not to various data

Stop and restart capability, discharge segment analysis

Free or fixed boundary equilibrium capability
- Rotation in equilibrium
- Free-boundary requires knowledge of $I_{PF}(t)$, need ability to get these

Heating/CD/momentum/particle source modeling with varying levels of sophistication and speed (including prescribed profiles and magnitudes)
- All 4 H/CD sources; ICRF, LH, EC, NB (e.g. CURRAY and TORIC for ICRF, TORAY and GENRAY/CQL3D for EC, CURRAY and LSC/ACCOME for LH, NFREYA and NUBEAM for NBI)
- Varying levels of distribution function treatment
- Varying levels of fast particle treatment
- Synergy effects among sources, and with bootstrap current
- Pellet fueling models

Integrated Plasma Simulation Tool, cont'd

Modular peripheral physics models with varying levels of sophistication and speed

Multiple transport coefficient models available for predictive simulations (as well as non-diagonal and convective terms), including prescribed profile capability

- Theoretically based transport models for energy, particle and momentum
- Pedestal models

SOL/divertor models of varying sophistication and speed

- 2 point models to databases to actual integration into time-dependent simulations

Documented standard data interfaces allowing offline analyses (to MHD, gyro-fluid/kinetic codes, RF, etc.)

Integrated Plasma Simulation Tool, cont’d

Models available in time-dependent modeling should also be available for off-line time slice analysis

Physics models will require testing against experiments, keep this in mind to allow easy comparison and synthetic diagnostics (theoretical calculation of what a diagnostic should measure)

Integrated time-dependent plasma simulations are useful if they are fast enough to make lots of variations allowing us to learn from them

Balance of computation time and physics sophistication

Offline analysis will remain a critical component to integrated simulations