Coupled TSC & PTRANSP Calculations Using Prototype SWIM Framework

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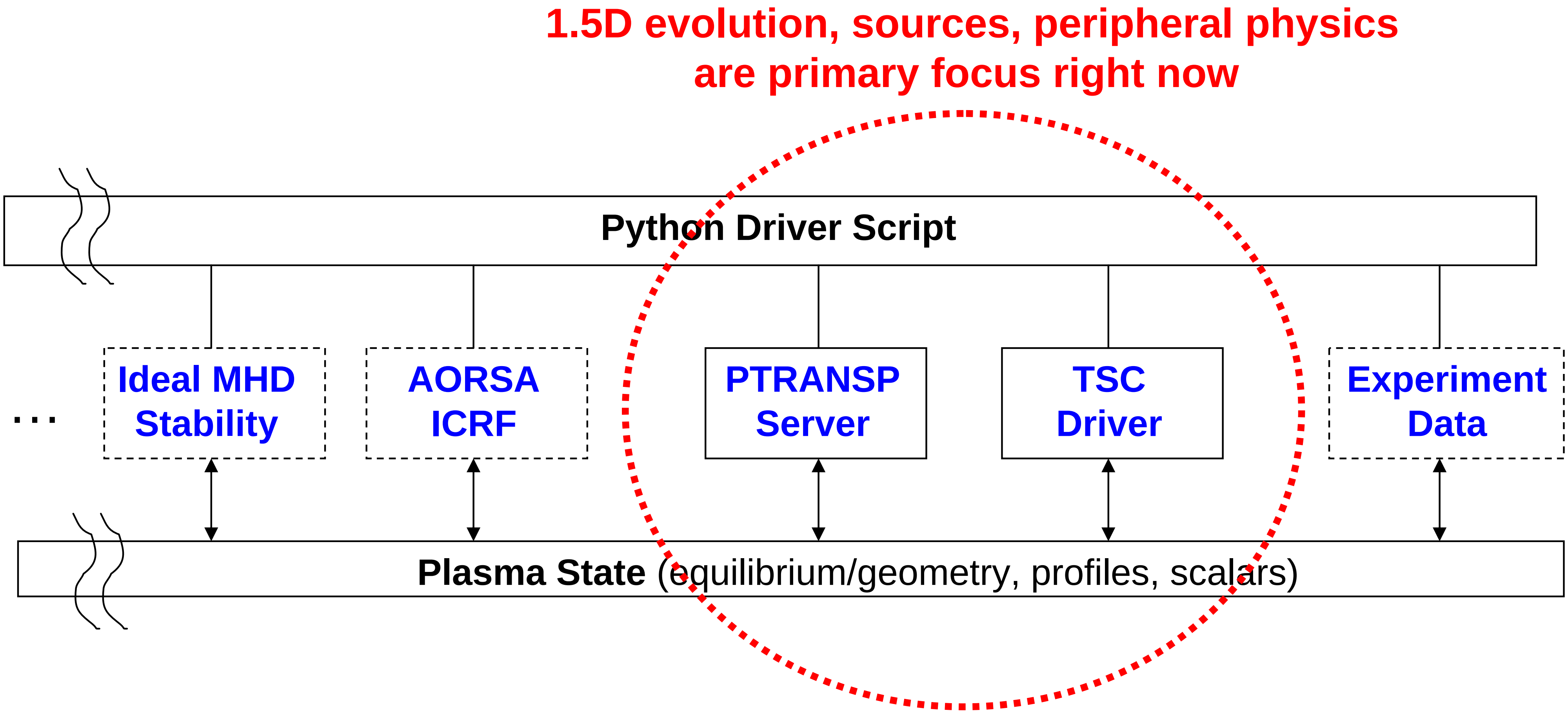
Outline

- SWIM Framework (brief)
- TSC and (P)TRANSP simulation description
- TSC/(P)TRANSP Recent Applications
  - ITER Hybrid simulations thru ITPA SSO
  - ITER Startup Flexibility studies
  - Experimental simulations
    - DIII-D High Beta simulations
    - C-Mod LH and ITB simulations

Applications of TSC and (P)TRANSP are a Continuum Between Interpretive and Predictive

- (P)TRANSP interpretive analysis of experimental discharge
- …..
- Utilize (P)TRANSP experimental discharge data and source calculations ***combine with*** predictive transport GLF23 and a new source superimposed in TSC discharge simulation
- …..
- Fully predictive TSC/(P)TRANSP simulation of ITER (or other future devices like KSTAR)

SWIM Framework for Integrated Fusion Plasma Modeling



TSC and (P)TRANSP Are Used Together

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- **TSC**
- **Predictive**
- **Free-boundary**
- **Structures/PF coils/feedback control systems**
- T, n, j transport with model or data coefficients (η, χ, D, v)
- **LSC** for LH
- Assumed source deposition for NB, EC, and ICRF: typically use off-line analysis

Plasma geometry, T & n profiles, q profile →

Originally done with NETCDF data file over entire discharge

Performed thru XPLASMA every 25 ms

Developing new Plasma State with much larger data set

← **Accurate source profiles fed back to TSC**

- **TRANSP**
- **Interpretive**
- Fixed boundary Eq. Solvers
- Monte Carlo NB and α heating (**NUBEAM**)
- SPRUCE/**TORIC**/CURRAY for ICRF & **FPPRF**
- **TORAY** for EC
- **LSC** for LH
- Fluxes and transport from local conservation; particles, energy, momentum
- **Fast ions**
- Neutrals

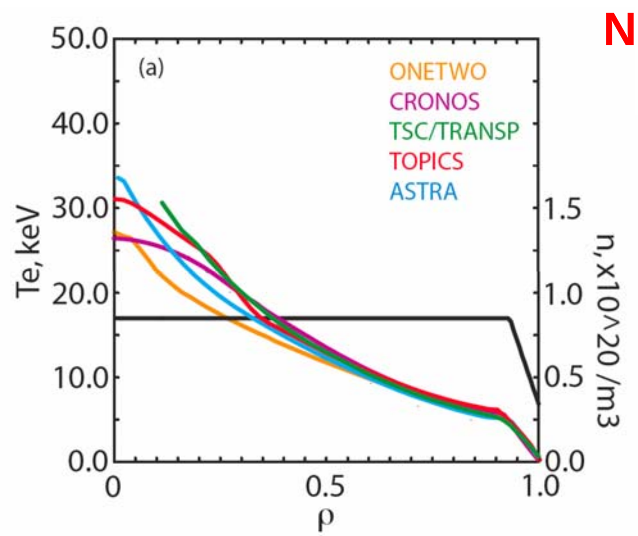
both codes have models for bootstrap current, radiation, sawteeth, ripple loss, pellet fueling, impurities, etc.

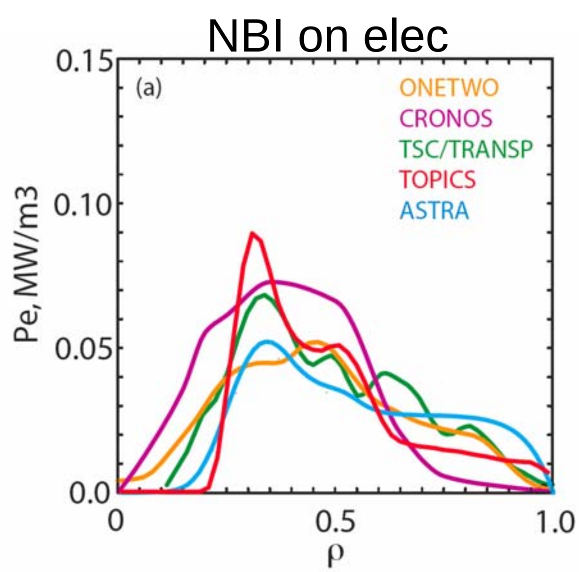
ITPA Steady State Operation Group is Examining Hybrid and SS Scenarios for ITER

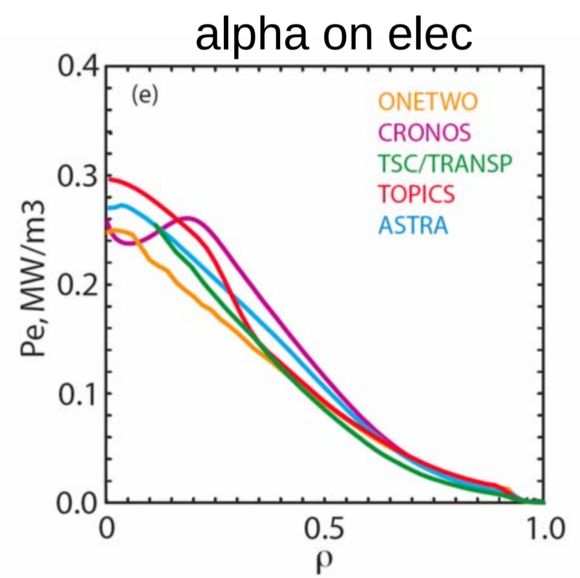
- Establishing a benchmark Hybrid scenario for comparison/benchmarking of modeling tools (**ASTRA, TOPICS, ONETWO, CRONOS, TSC/TRANSP**)
  - Fixed and free-boundary 1.5D evolution
  - GLF23 core transport model, prescribed pedestal features and density
  - NB+IC and NB+IC+EC cases
  - Varying peripheral physics models in codes
- Examining source details and pushing for progressively more sophisticated source modeling on hybrid and SS scenario (NBI, ICRF, EC, LH)
  - This includes off-line analysis with time-consuming analyses
- Exploring steady state configurations with various combinations of the sources (NBI, ICRF, EC, LH)
  - Source modeling has been primary focused to better establish safety factor and current profile modifications from each source to provide f_{NI} = 100%
  - Beginning to establish a benchmark(s) for code comparison
- Pursuing more inclusive simulations
  - Use B2/Eirene simulation database for ITER to provide divertor/core consistency
  - Pedestal parameterization for modeling based on database observations
  - Incorporate nonlinear fast particle MHD effects into high q SS simulations

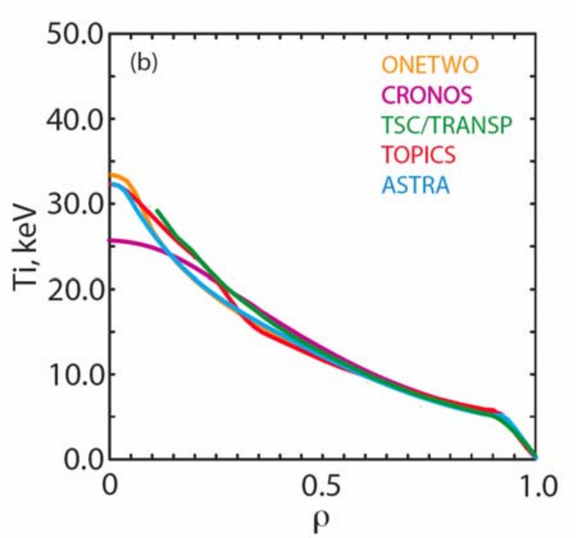
ITER Hybrid Benchmarking Will Compare Several “Integrated” Evolution Codes

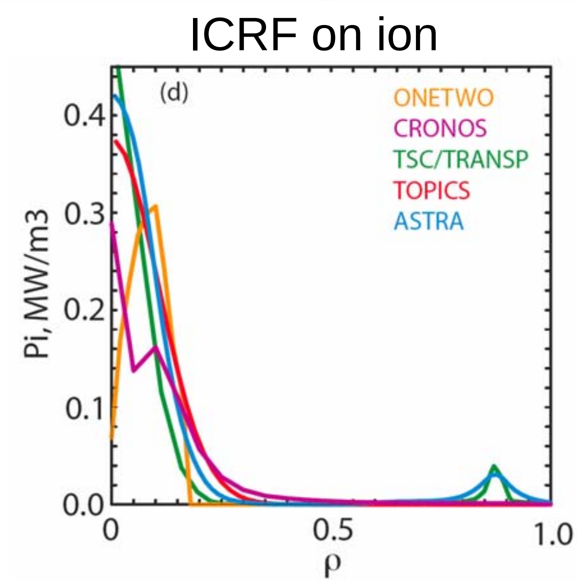
NB + IC Hybrid simulations

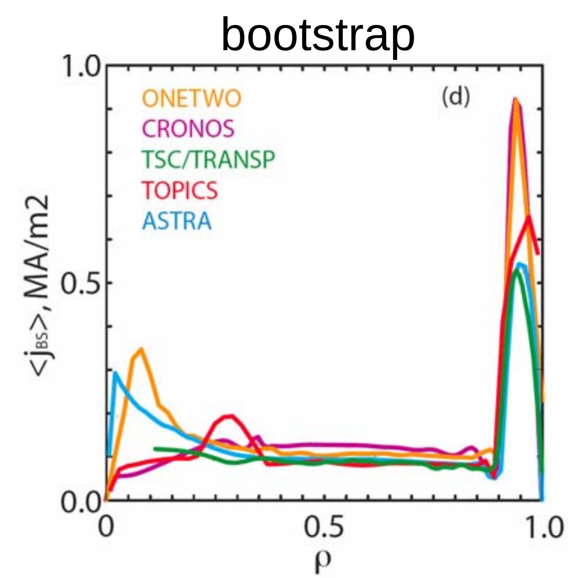












ρ_{ped} = 0.925, T_{ped} set to 5 keV, n profile is prescribed

ITER Hybrid Benchmark Will Continue in Stages to Isolate Code Differences

- GLF23 dedicated comparison
  - Te and Ti channels only
  - V = 0
  - α stabilization off
  - Apply prescribed source heating and CD profiles
  - Then begin adding features back into model

- Prescribed T and n profiles (transport off) configurations to examine source and peripheral physics
  - NB, IC, EC
  - Fusion reactivity
  - Bootstrap current
  - Resistivity
  - Radiation

- Some initial SS benchmark studies will be performed

USBPO & ITPA SSO ITER Issue Card -- ITER Startup Flexibility

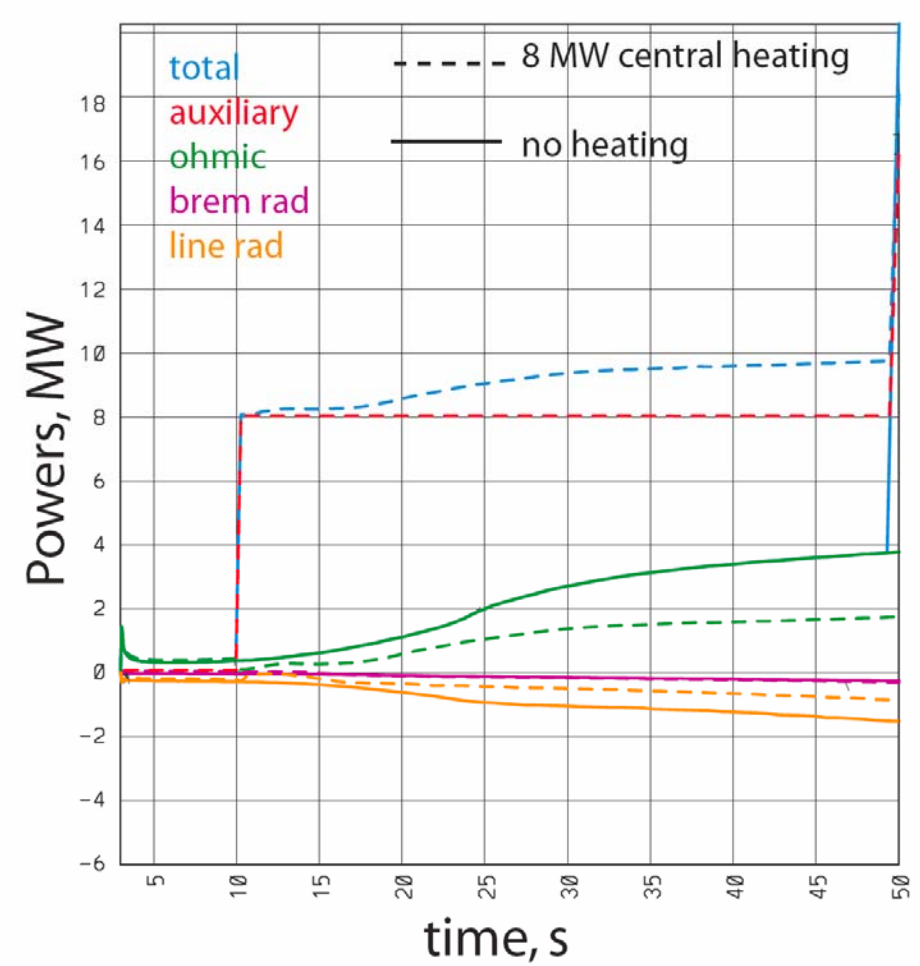
- USBPO Integrated Scenarios group has identified “ITER Startup Flexibility” as its highest priority
  - **Can the j/q profile be modified in the Ip rampup by available ITER hardware and discharge timing**
- ITPA SSO also identified this as one of its high priority issue cards
- USBPO has also identified “Critical Review of Heating/CD/Rotation Sources for ITER” as its next highest priority issue

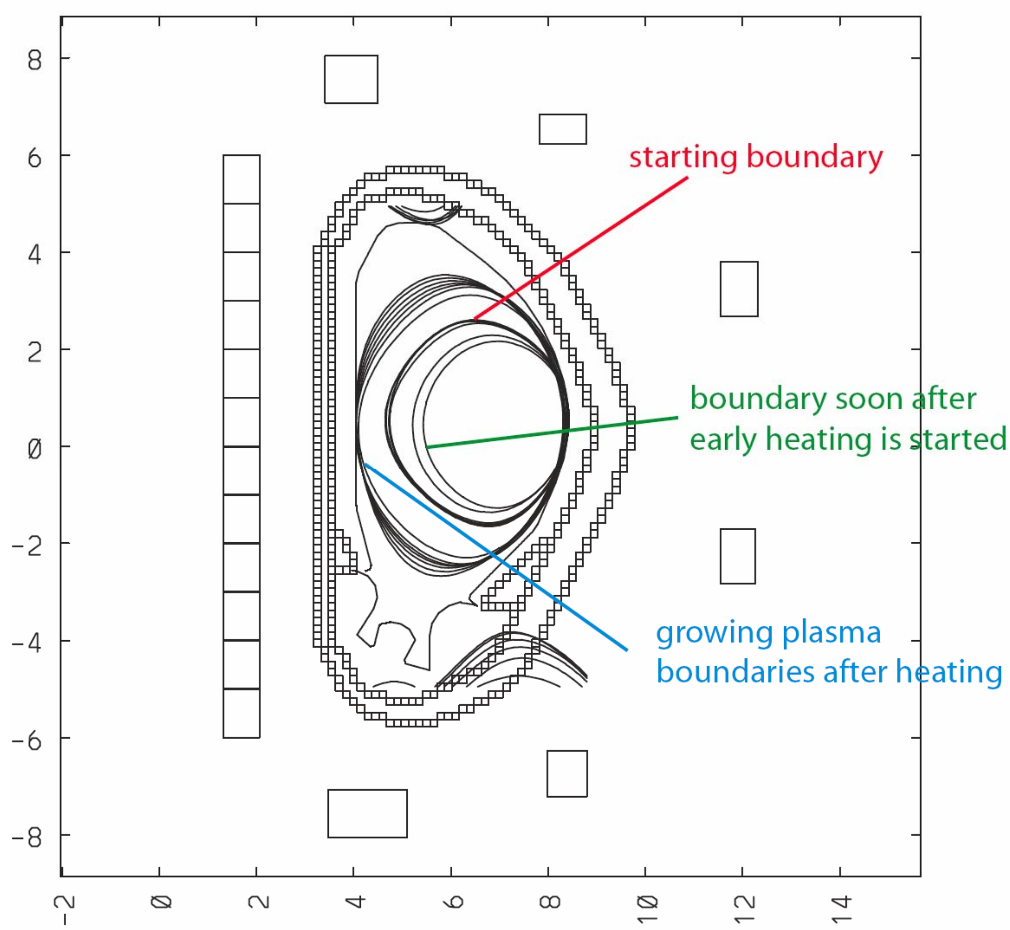
- PPPL evolution codes combination of TSC and PTRANSP is ideally suited to examine both of these issues

- After TSC free-boundary simulations of startup phase are getting established we can begin PTRANSP runs
- Examining different heating sources in early discharge phase with PTRANSP

Flexibility in ITER Startup/Current Rampup To Produce Various q-profiles

How much can ITER utilize early heating, early plasma diverting, L-H mode transition, density control to manipulate the j/q profile in the current rampup -- **within engineering constraints**

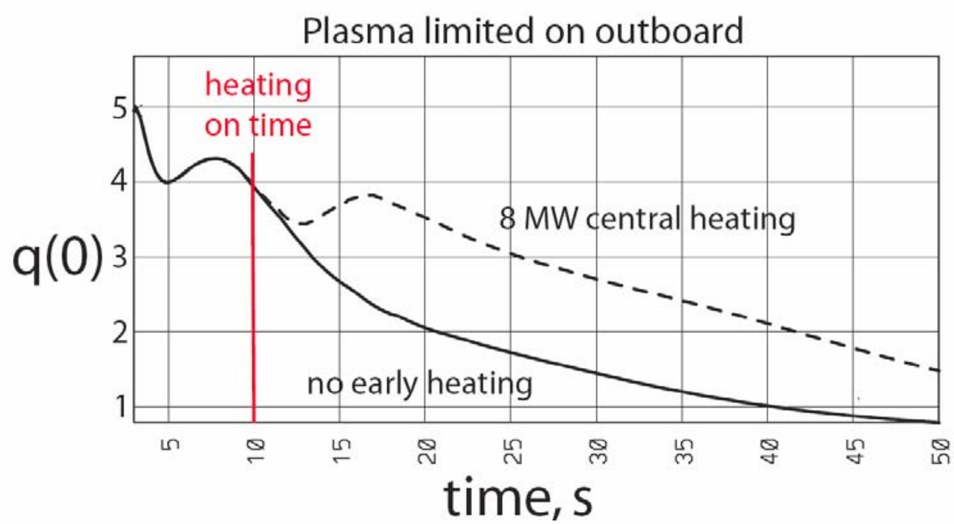


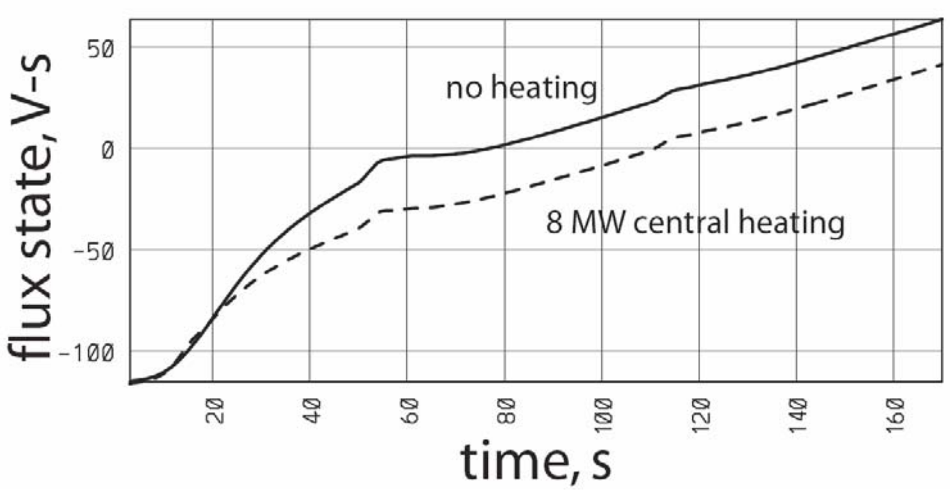


Early Heating Elevates the Safety Factor

Heating reduces V-s consumption which reduces the flux state

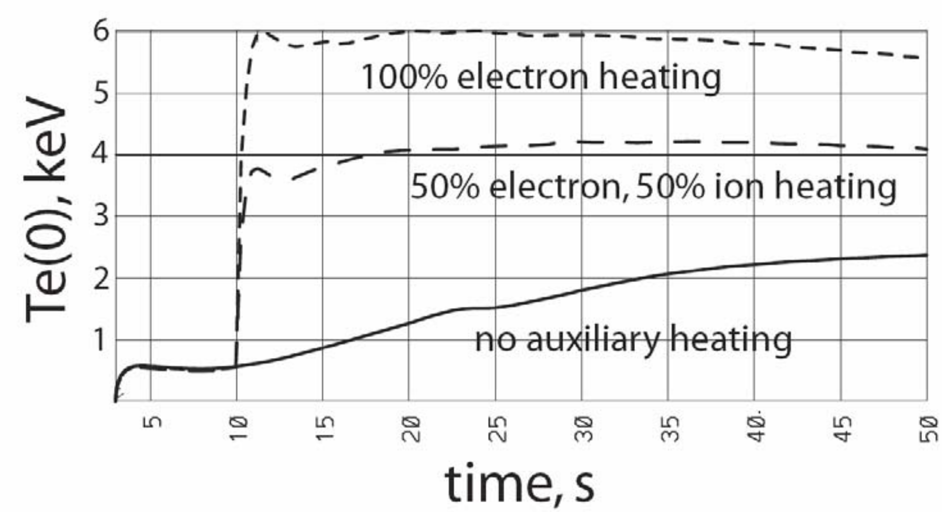
---> this actually increases PF coil currents
---> primary method for relieving PF currents is to advance the flux state





Different heating methods will heat electrons differently, and so have a varying influence on slowing j evolution

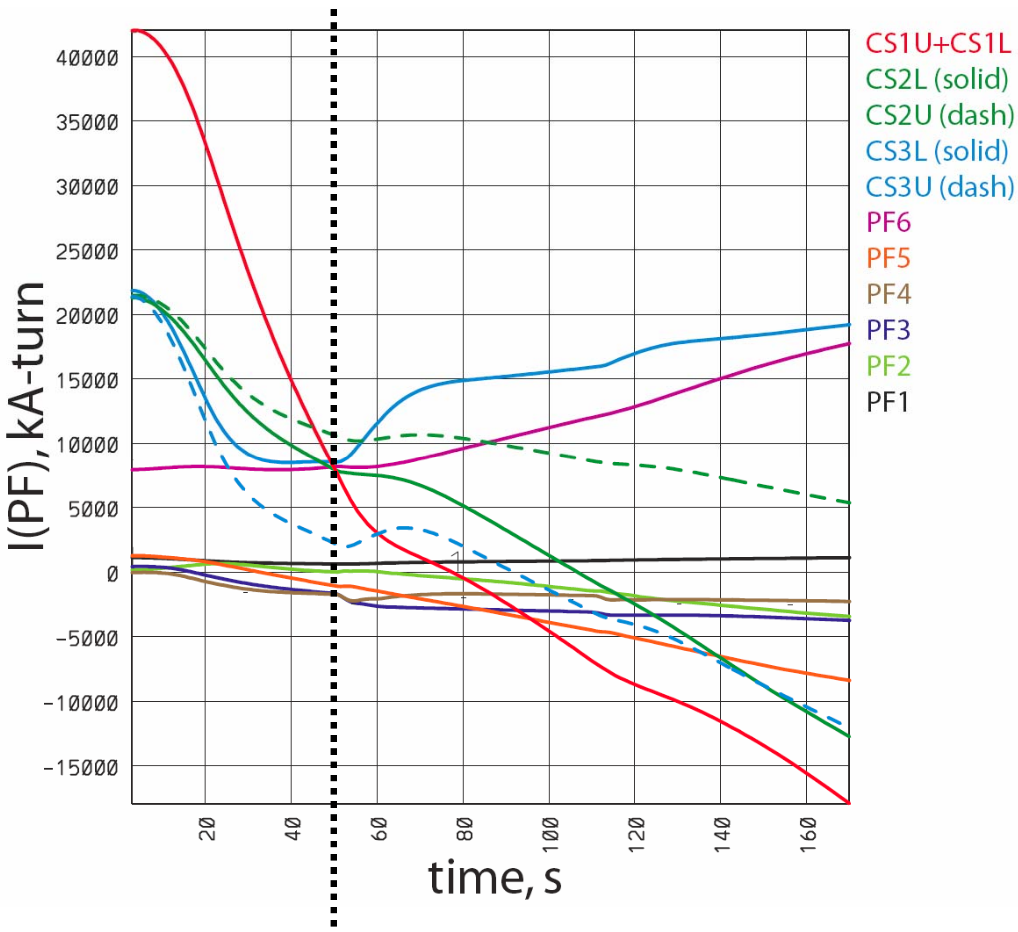
---> 100% electron, typical of ECRH and LH
---> 50% electron, typical of ICRF 2nd harmonic



PF Coil Current Exceed Their Limits With Early Heating -- Must Advance Flux State

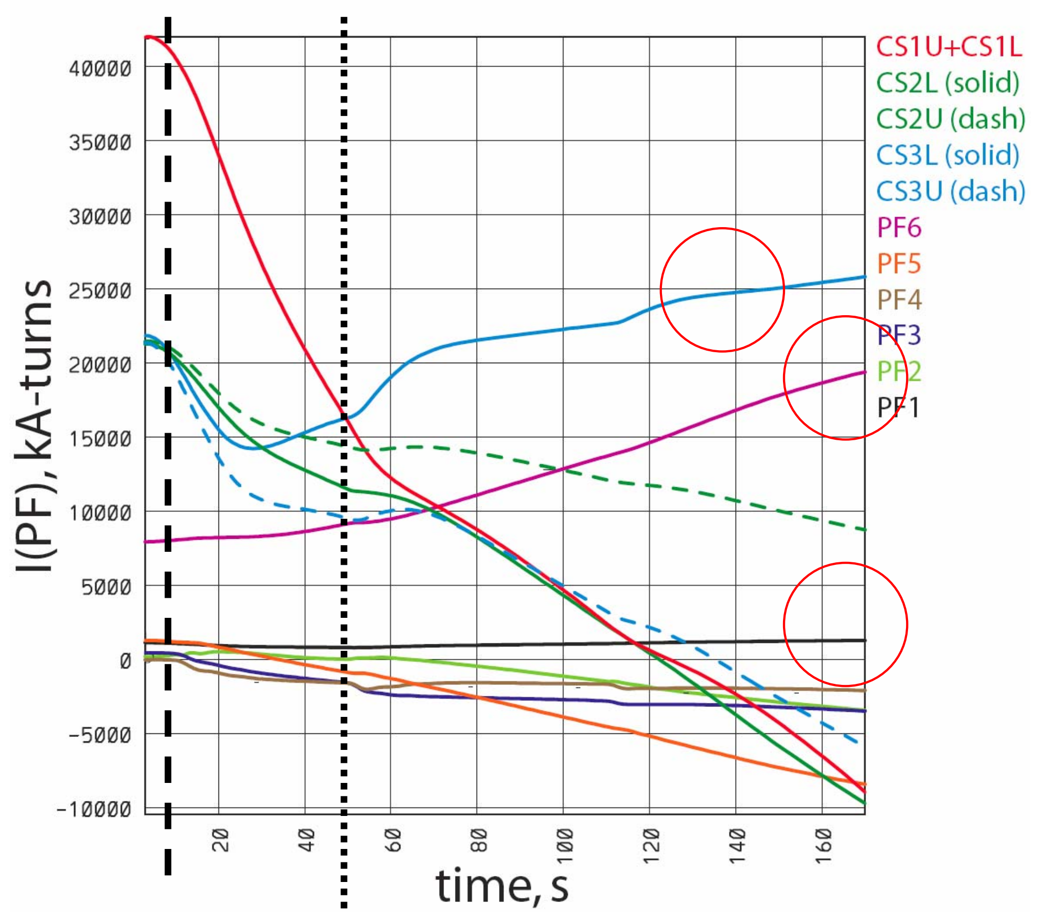
I_{PF} limits, P_{PF} limit, B limits on coils, vertical stability, plasma-wall gaps, dB/dt limits

No early heating



H-mode, high power, divert

Early heating



Early heat on time

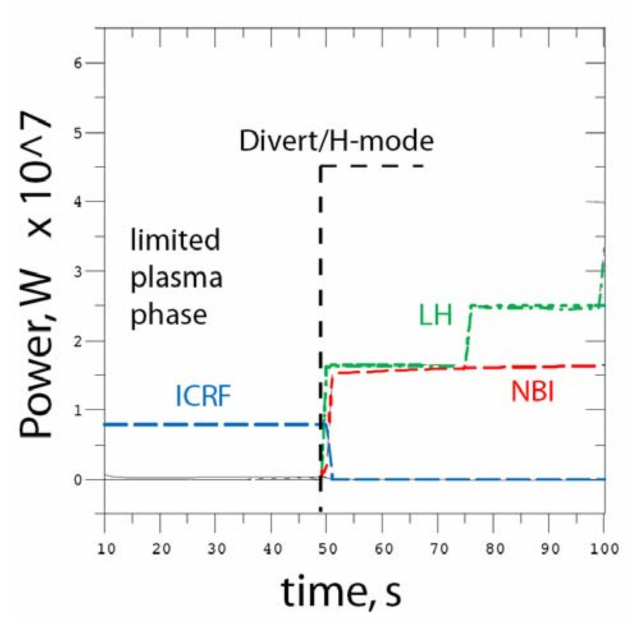
H-mode, high power, divert

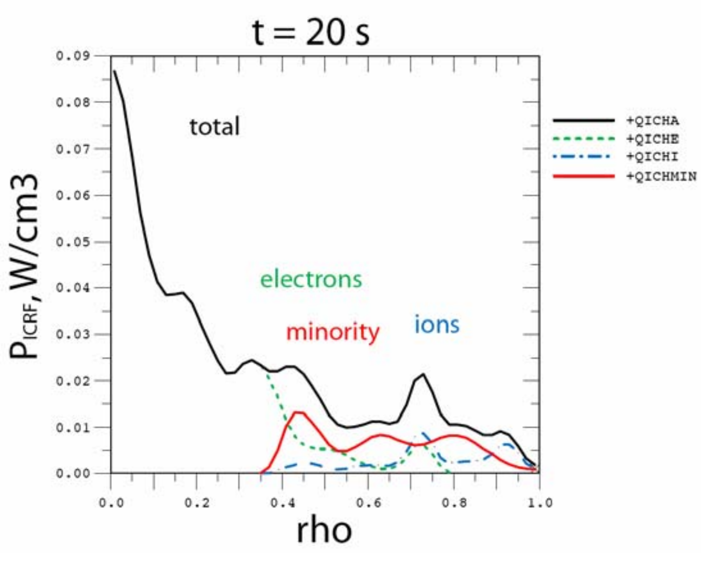
Examining Viable Heating Sources in Early Limiter Phase in ITER Startup

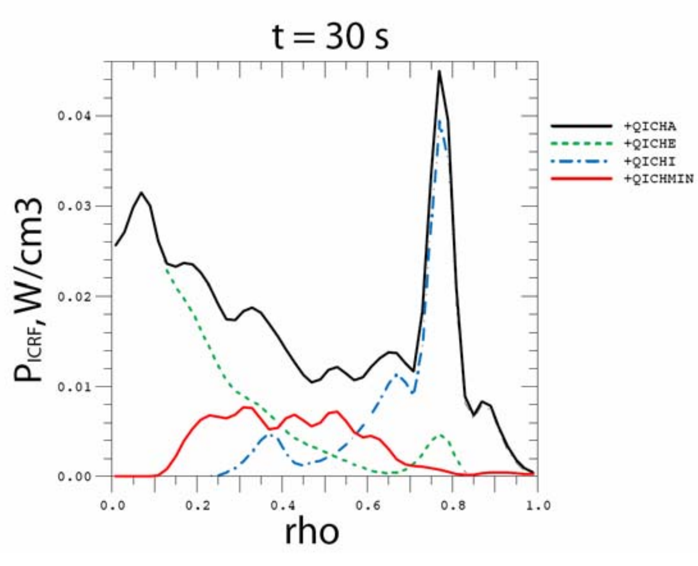
PTRANSP is used with TSC free-boundary plasma description to examine ICRF in the early limited phase

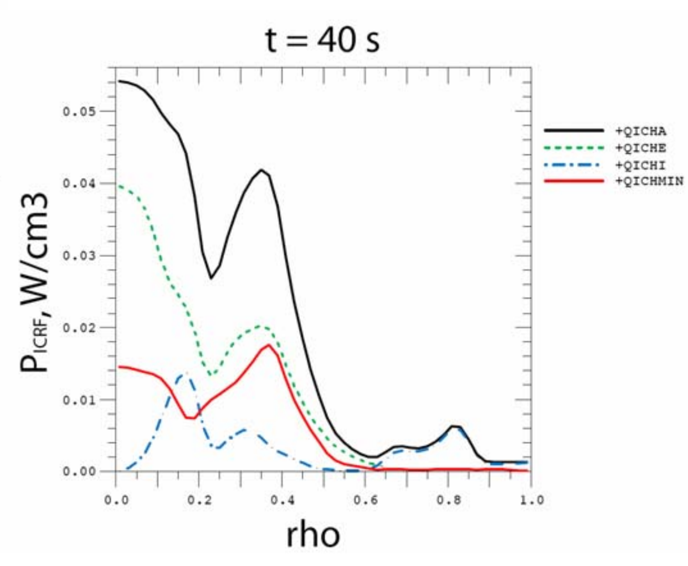
Vary ICRF frequency from 40 MHz @ t=10s to 53 MHz @ t=50s to track plasma size/position using TORIC

Coupling ICRF to plasma is still THE issue ---> will examine EC, LH, and NB









Simulation of an Experiment to Project to Different Operating Conditions

- TRANSP was run on DIII-D discharge 122976, a High Beta plasma

- TRANSP data used in TSC
  - Te, Ti, n passed thru
  - Thermal diffusivities, source heating and current depositions

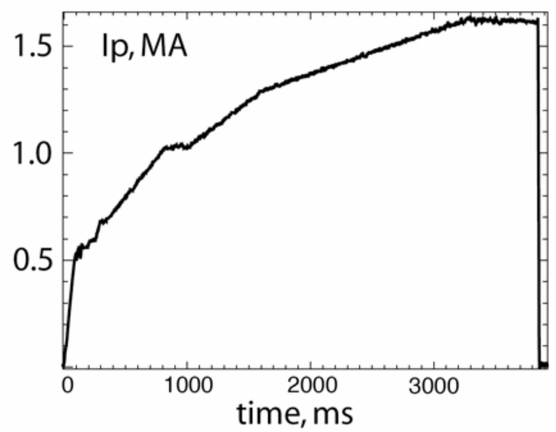
- CURRAY was used offline to calculate the ICRF-FWCD
  - n_{fast} and $<E_{fast}>$ taken from TRANSP to produce effective maxwellian
  - Injected powers based on L-mode and H-mode operating experience
  - Spectra from ORNL
  - Impurities specified as 2% H, 2% C for L-mode, 5% C in H-mode
  - Have 2 frequencies, 60 and 83 MHz launchers on DIII-D

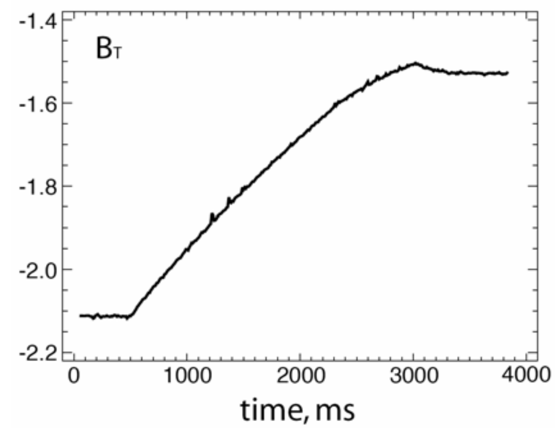
- TSC was run with TRANSP data, time-slicing out to CURRAY every 250 ms
  - Density evolution was modified to reflect new lower divertor

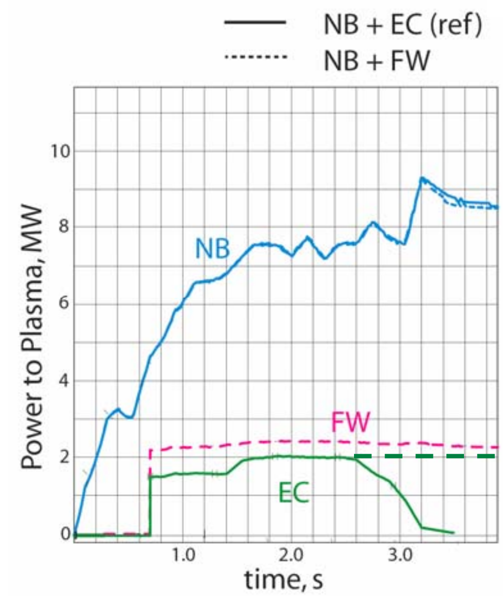
DIII-D High Beta Discharge 122976 Has Obtained $\beta_N \approx 4$ for 2 s

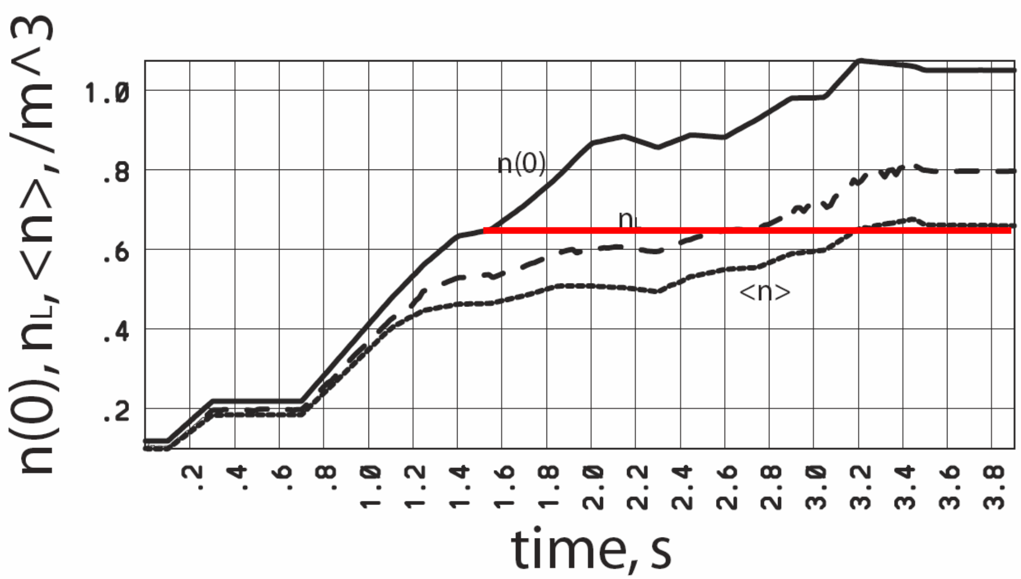
HOWEVER, n is uncontrolled & EC is eventually cutoff

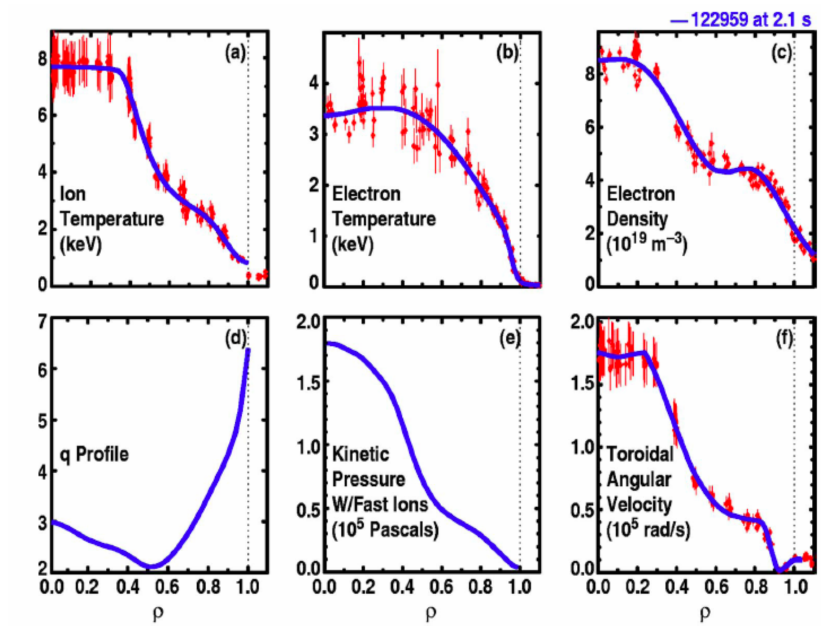
How can FWCD alter the discharge & how can stopping the density rise improve the discharge?











Simulations with TSC and (P)TRANSP Examine Effects of ICRF in D3D High Beta Plasmas

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Take existing discharge and modify it with FWCD and density control

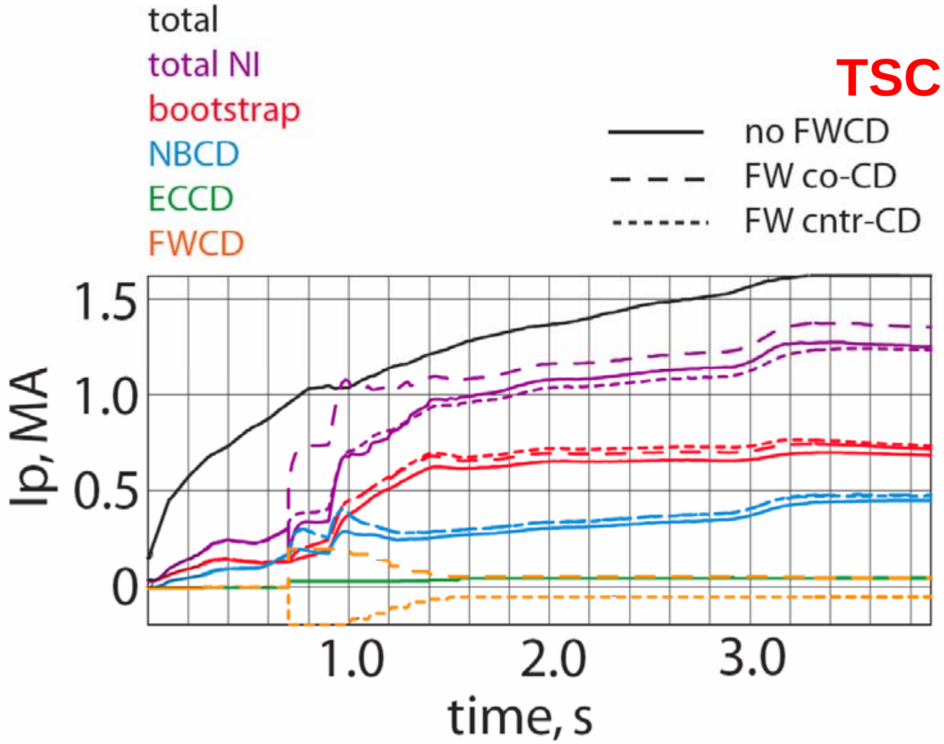
Stop density rise at 6.5×10^{20} /m^3

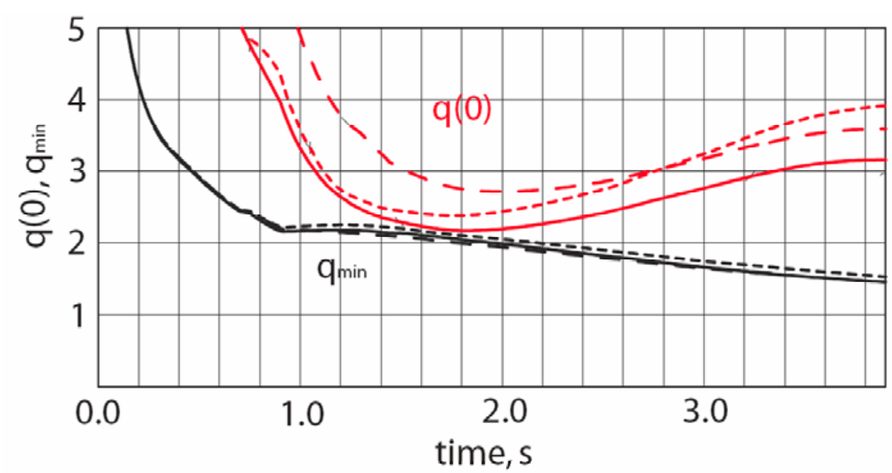
Inject FWCD at same time as EC

Examine co-CD and cntr-CD

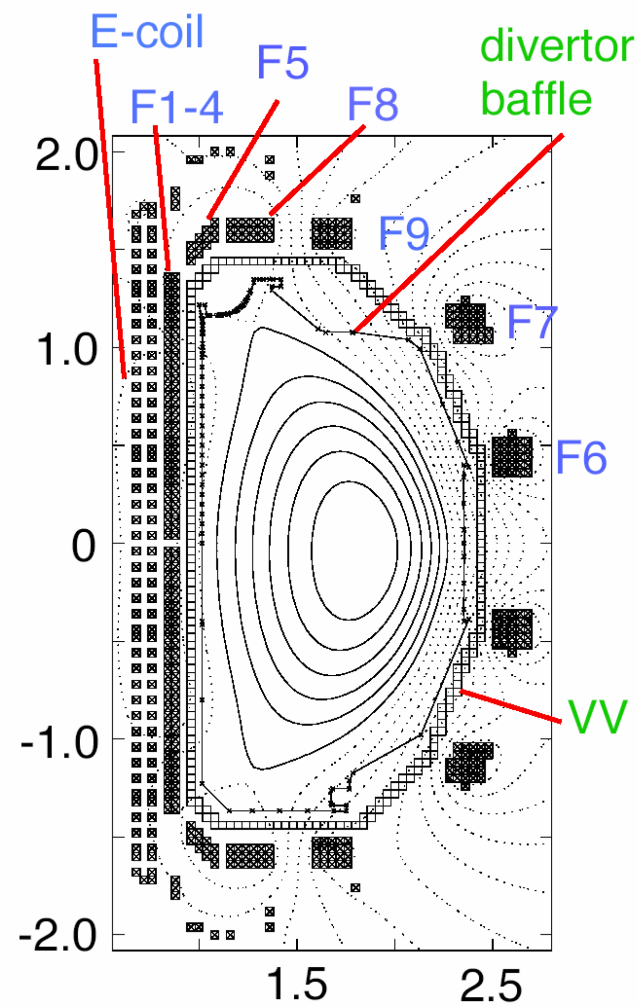
Some improvement in NICD

Changes in q(0) evolution

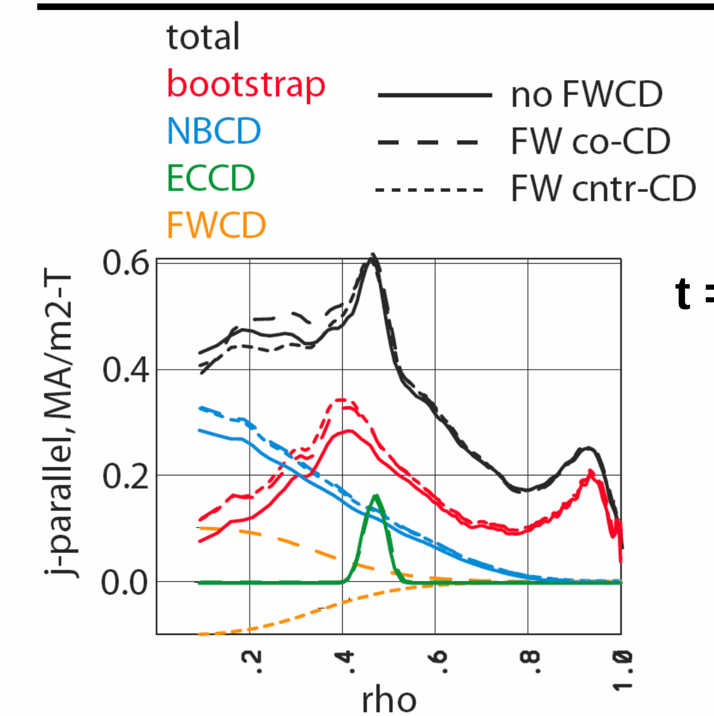




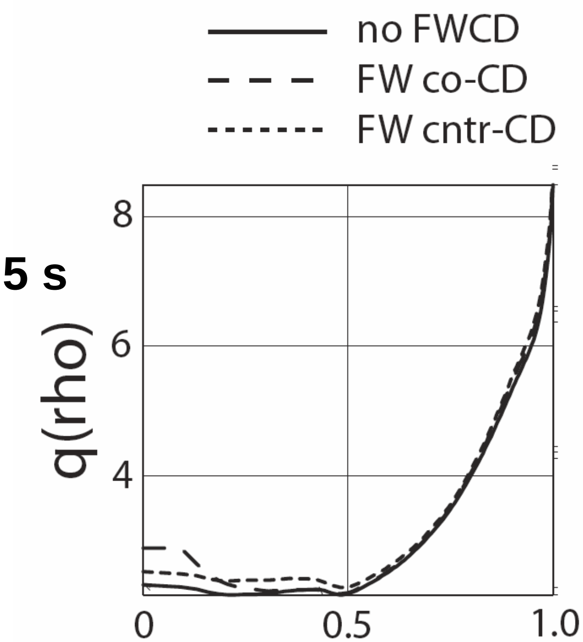
TSC simulation of 122976

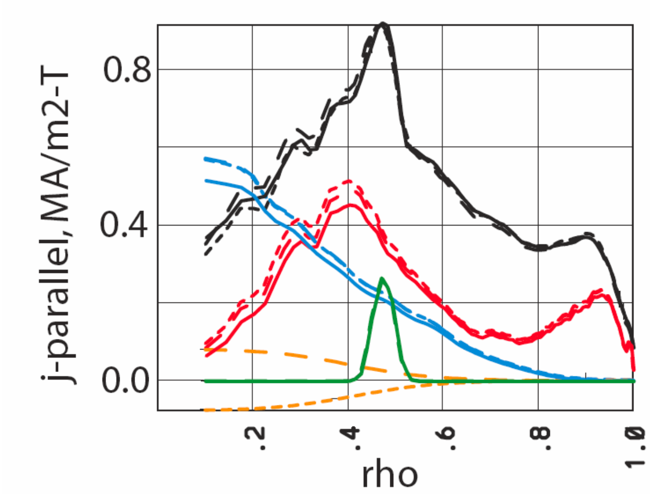


D3D 122976 is a Complex Discharge with Ip & B_T Ramps, But it Can Be Modeled

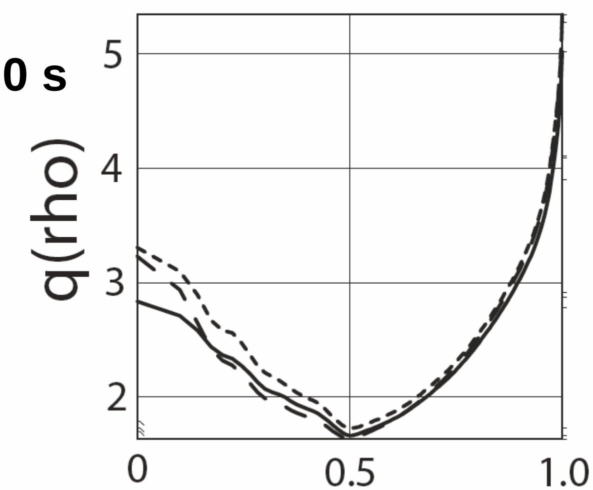


t = 1.5 s





t = 3.0 s



Complex and transient discharges are difficult to understand experimentally

Modeling can provide insights into internal plasma behavior that is difficult to measure

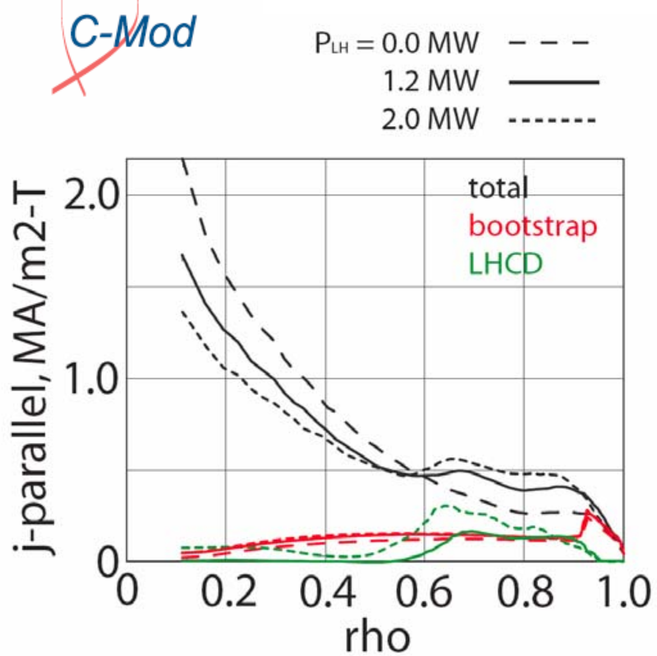
Subtle effects can be important in advanced tokamak scenarios

Learning how to control plasma profiles will require significant time-dependent modeling

C-Mod Has Successfully Commissioned the LH System, and AT Discharges are Targeted

- LHCD will be used in existing H-mode discharges at lower plasma currents to produce large f_{NI}
- Current ramps with LHCD and ICRF heating will be examined for producing reversed shear profiles
- Sustainable reversed shear plasmas will be sought at varying LH power levels
- Internal transport barrier (produced by off-axis ICRF heating) plasmas are being pursued at lower plasma currents to examine transport control
- Scenarios that maximize β_N and are consistent with H/CD sources

Simulations of C-Mod are Being Used to Develop Advanced Tokamak Experiments

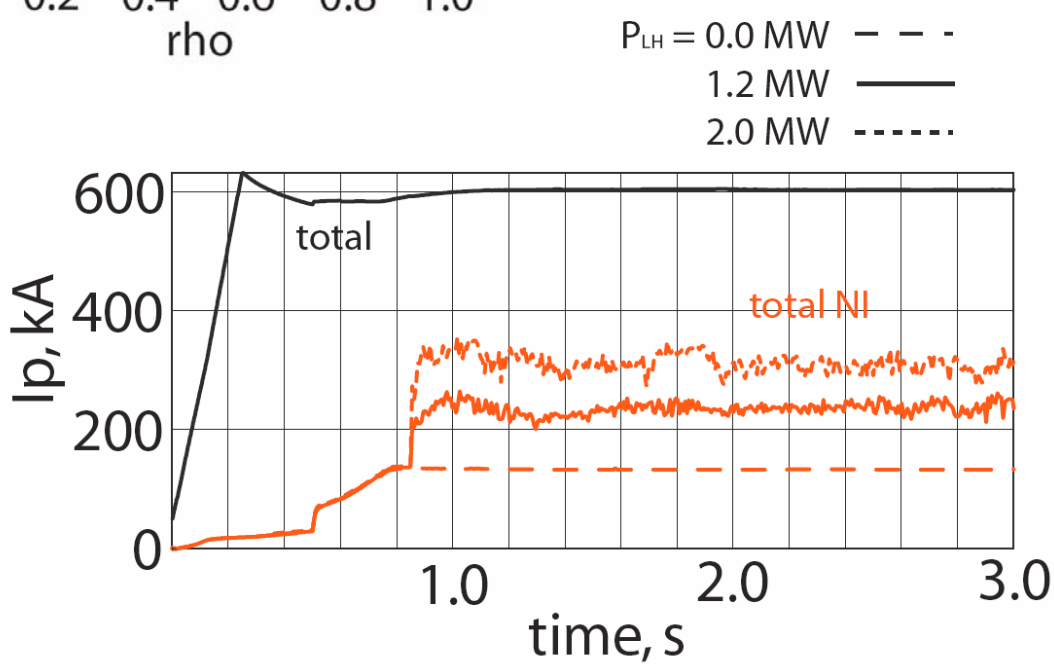


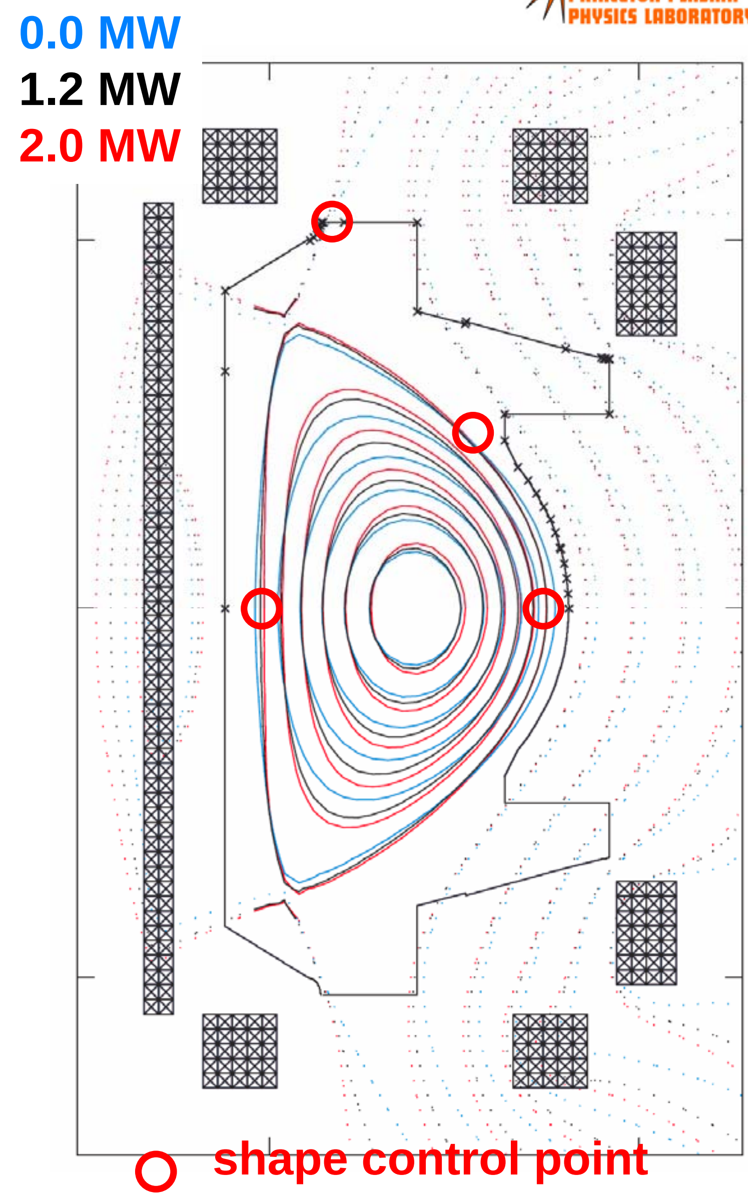
Use existing H-mode plasma from expt.

Inject LHCD

NICD is increased and q elevated

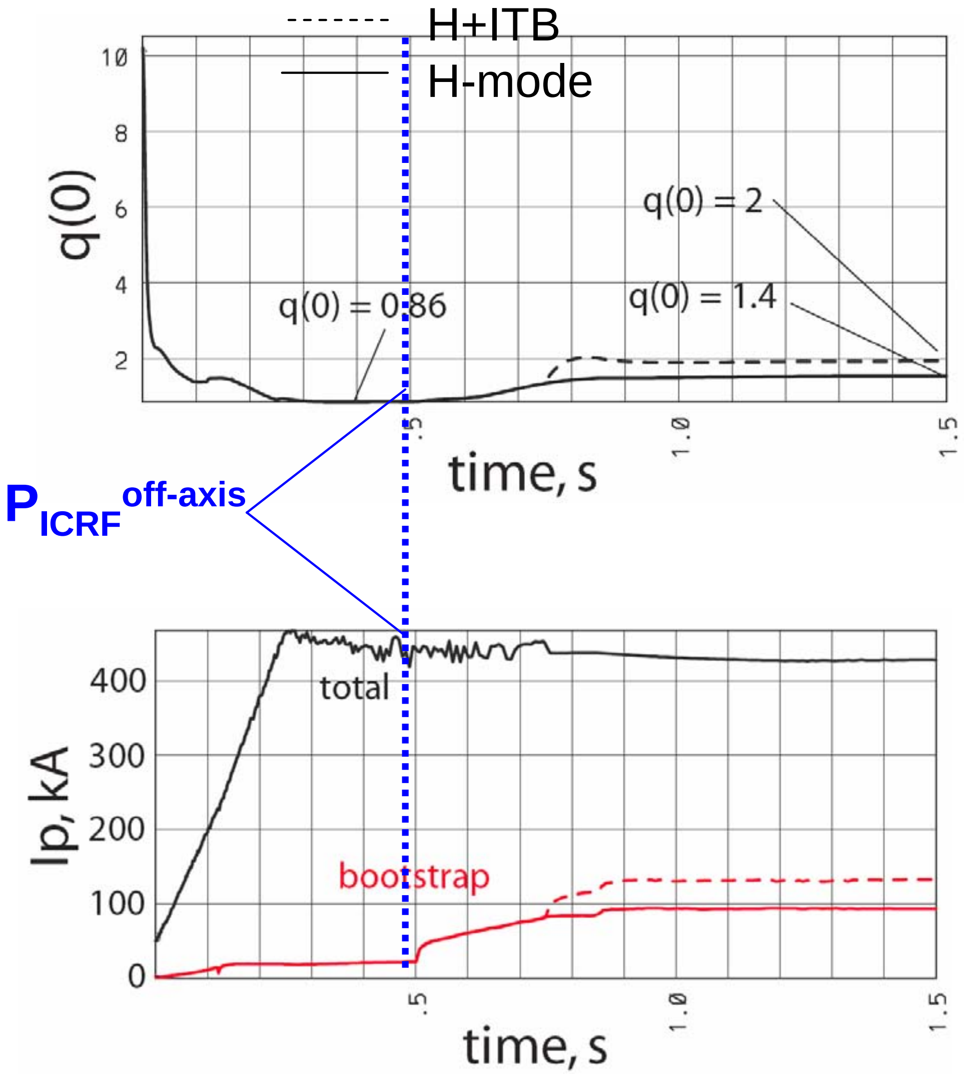
j_{LH} distorts equilibrium surfaces and changes LHCD efficiency

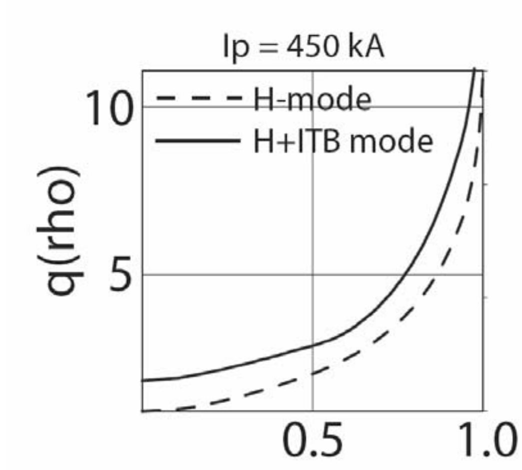


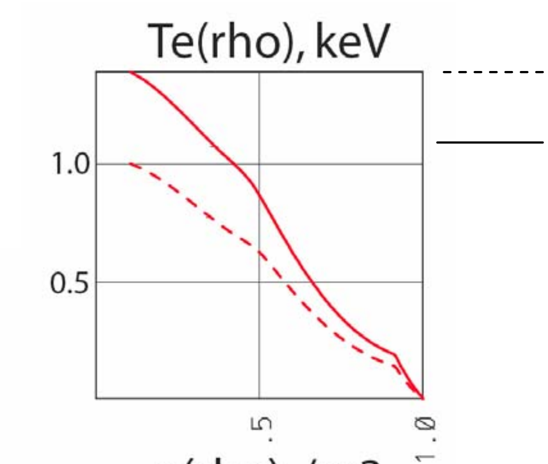


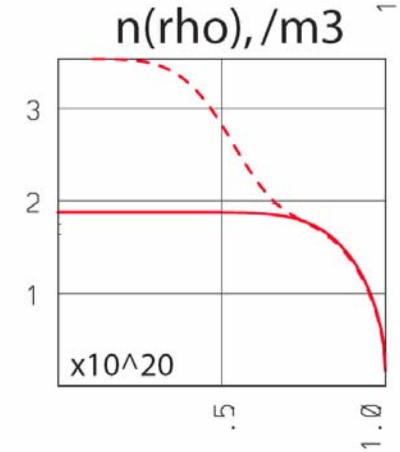
Simulations Show That ITB in C-Mod Can Strongly Affect j/q

TSC simulation of **Ip =450 kA** H and H+ITB mode based on 1060721023









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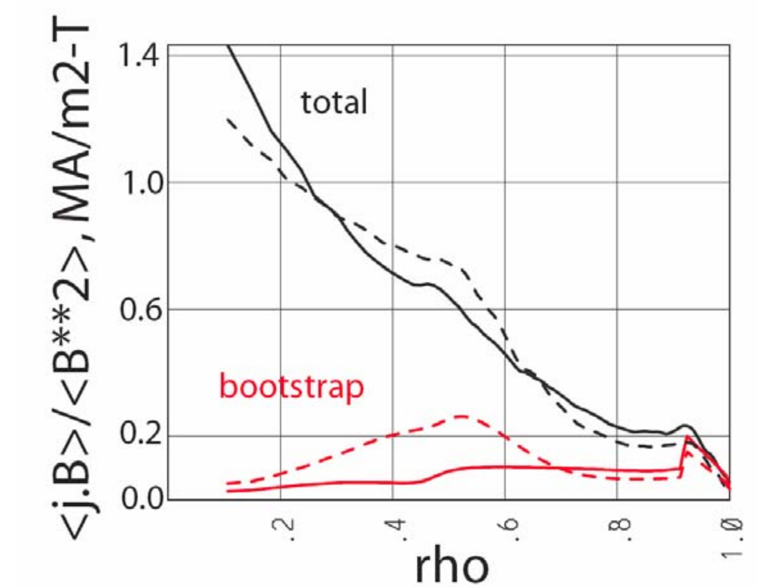

Conclusions

- There are a broad range of applications for integrated modeling that should determine how it is structured
  - Experimental interpretive --- lots of combinations in between ---fully predictive
- TSC/PTRANSP is the basis for the time-dependent integrated simulations for ITER at PPPL
- The connection of TSC and PTRANSP has evolved to include more information and allow a shorter time coupling
- The SWIM framework is a powerful mechanism to couple and drive plasma physics codes
  - Plasma State is critical bridge/interlink for all physics calculations requiring standardized communications
  - Allows use of sophisticated offline analysis or experimental data as part of 1.5D integrated evolution