Time-Dependent Integrated Modeling of Burning Plasmas

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- Need better understanding of burning plasmas to increase the chances of practical fusion power
- Time-dependent integrated modeling will help meet this goal

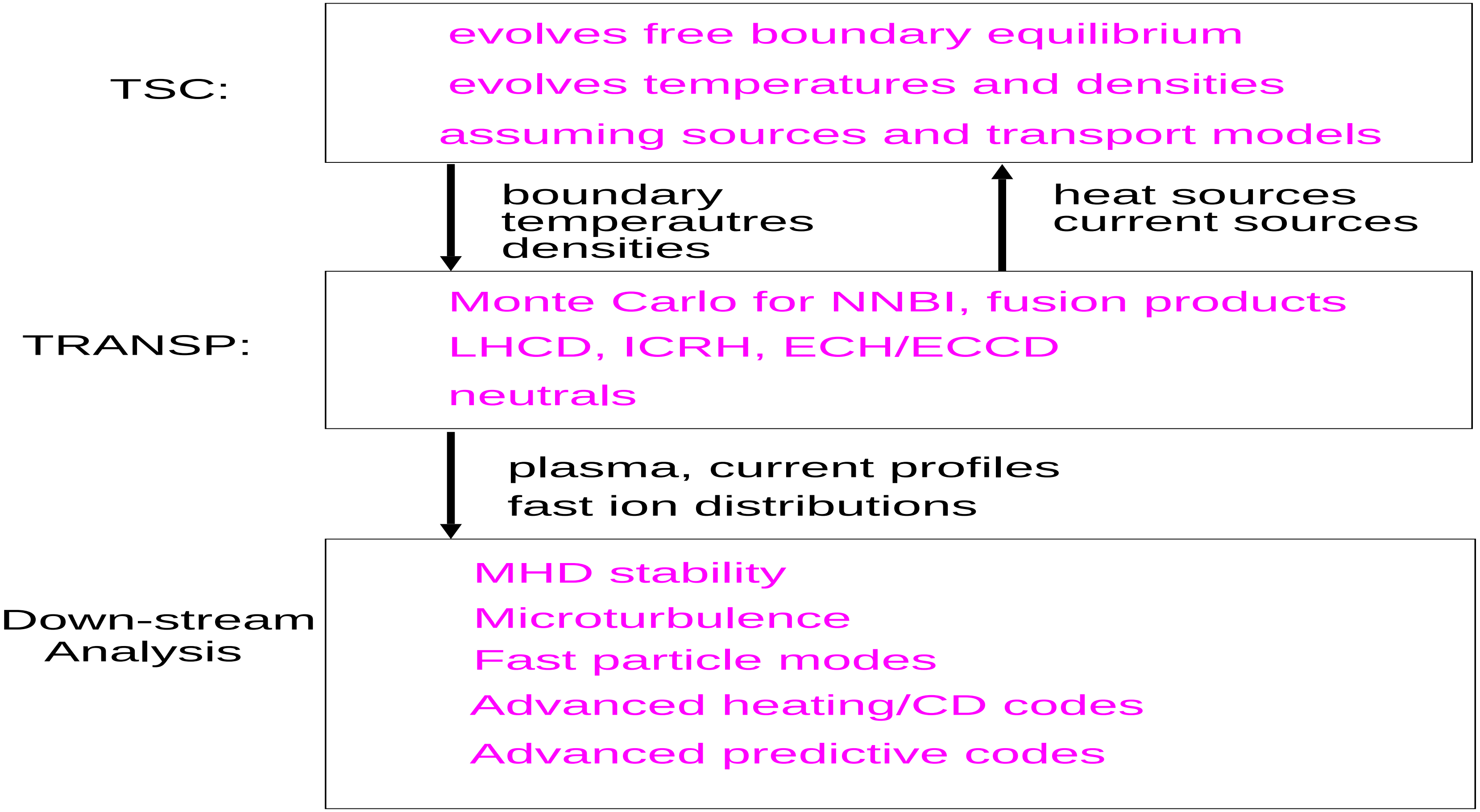
1. Check the ITER design (ex, P$_{aux}$ sufficient? rotation sufficient? ash removal sufficient? will the diagnostics work?)
2. Provide quality data for theoretical studies (ex, TAE)
3. Will need to certify each plasma before it is tried

Overview of this Talk

- We used a prototype of PTRANSP to generate ITER shots
- Examples of uses of the modeling

1. distributions of the fast alpha and NNBI ions
2. estimates of toroidal rotation and E_r profiles
3. gyrokinetic simulations of energy, momentum, and particle flows
4. estimates of alpha ash profile

Prototype Integrated Modeling using the TSC and TRANSP codes



TSC:

evolves free boundary equilibrium

evolves temperatures and densities

assuming sources and transport models

boundary
temperautres
densities

heat sources
current sources

TRANSP:

Monte Carlo for NNBI, fusion products

LHCD, ICRH, ECH/ECCD

neutrals

plasma, current profiles

fast ion distributions

Down-stream
Analysis

MHD stability

Microturbulence

Fast particle modes

Advanced heating/CD codes

Advanced predictive codes

ITER Plasmas studied

- Steady-State plasma: low current, fully non-inductive
- Day-one hybrid plasma: q(0) $\simeq$1.0-2.0, low β_n (2.1)
- Sawtoothing ELMy H-mode

units	I_p MA	I_{boot} MA	I_{nnbi} MA	I_{Oh}/I_p	$n_e(0)$ $10^{20}/m^3$	f_{GW}	$T_e(0)$ keV	P_{DT} MW	$\beta_\alpha(0)$ per cent
Steady-State	9	4.3	4.3	0.0	0.6	0.63	33	305	1.3
Hybrid	12	2.8	2.4	0.50	0.8	0.64	24	333	1.0
ELMy	15	2.7	1.1	0.70	1.1	0.80	22	403	0.6

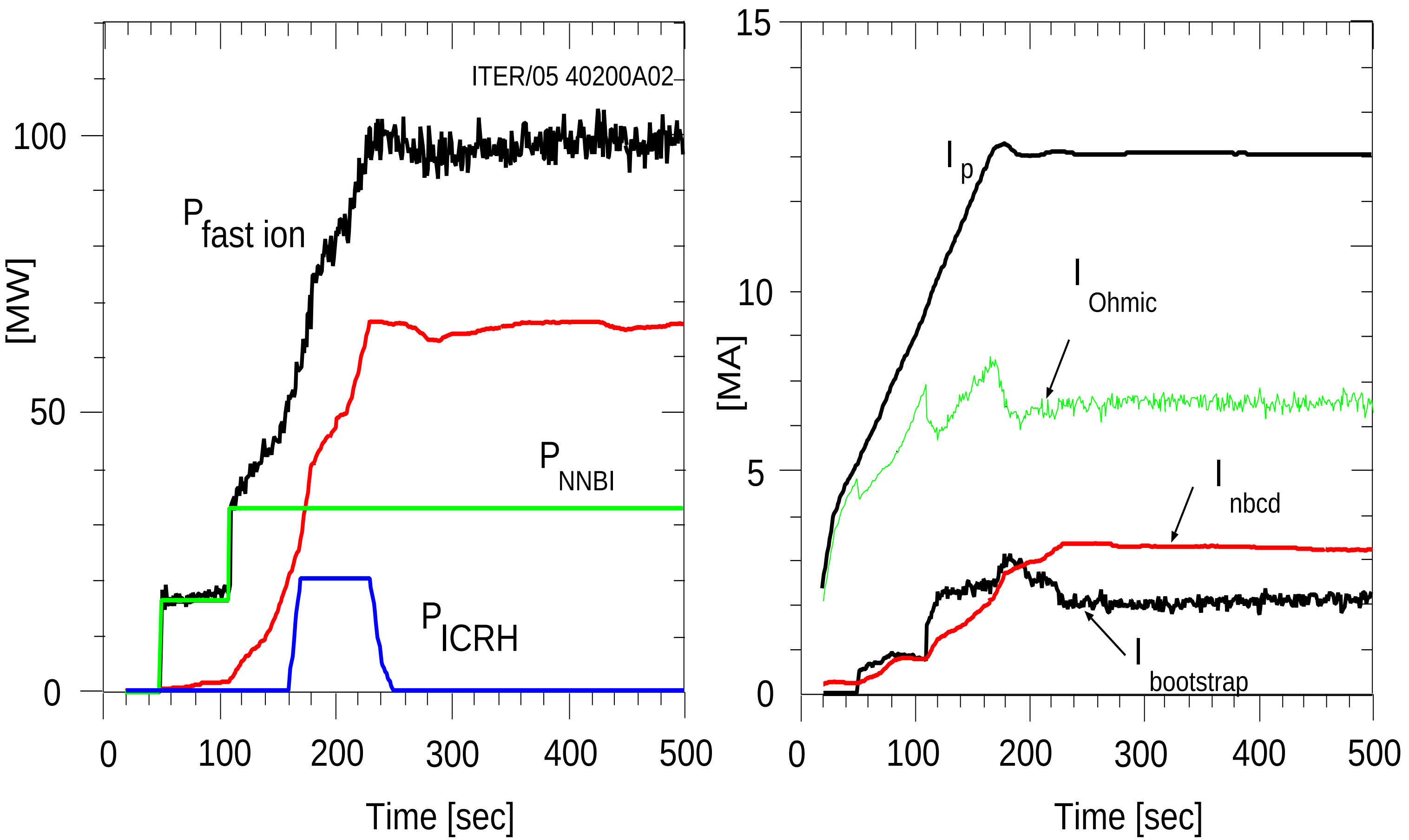
Examples of Findings

- High pedestal temperatures appears required by GLF23 (in TSC) to achieve P$_{DT} \simeq$ 400MW with the planned ITER auxiliary heating
- Good NNBI penetration and current drive
- Modest toroidal rotation from NNBI torques if $\chi_{mom} \approx \chi_i$
- Intense TAE activity predicted

Construction of the Hybrid plasma

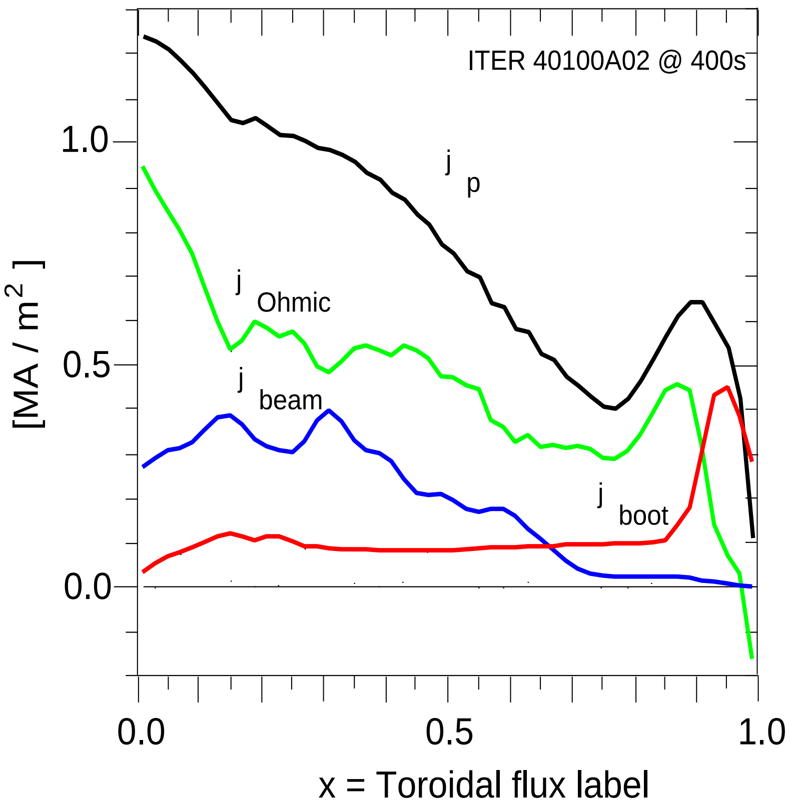
- Use GLF23 model to predict temperatures
- High pedestal temperatures to achieve P$_{DT}$ $\simeq$ 400 MW
- Reduced I$_{p}$ (12 MA) to decrease inductive-current fraction
- Moderate density for good NNBI penetration
- Sufficient current drive to keep q(0) above unity

Heating powers and plasma currents in the Hybrid plasma

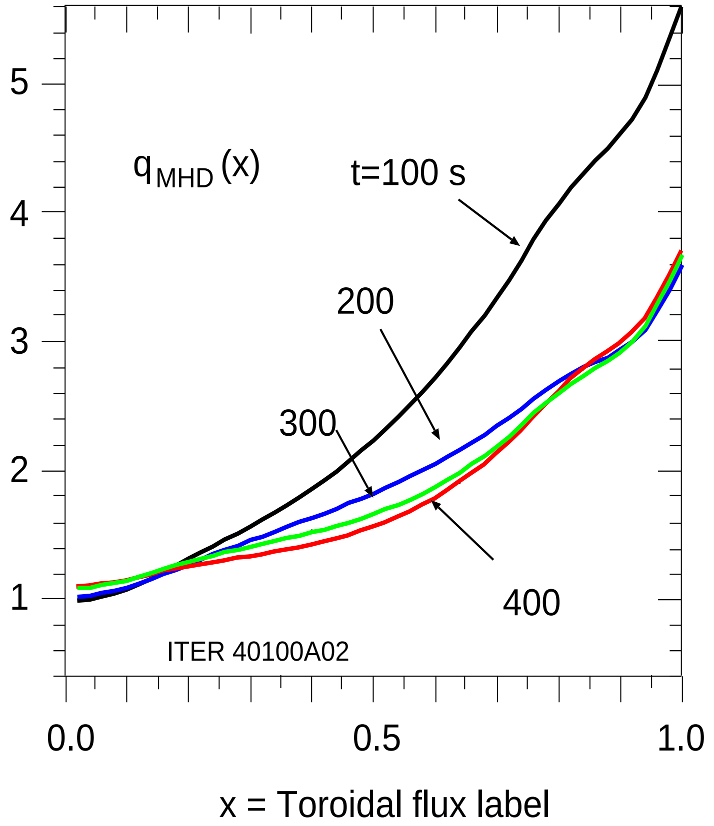


Sustained $q_{MHD} > 1$ with evolving reversal in Hybrid plasma

Current profiles computed by TRANSP

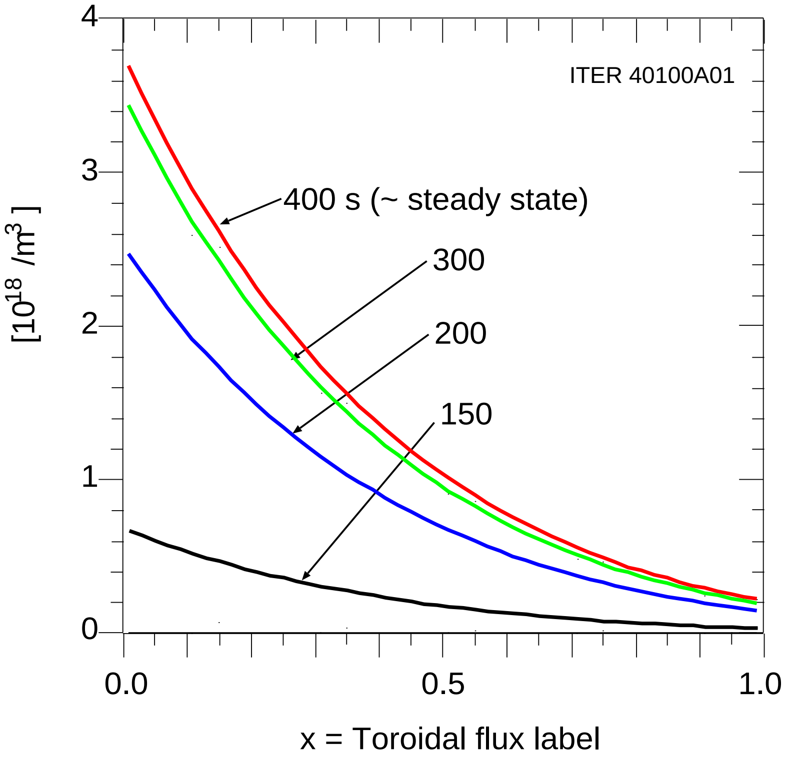


Slow evolution of q in ITER Hybrid plasma



Example of benign ash accumulation in the Hybrid plasma

He ash accumulation in ITER Hybrid plasma



Sources:

Core - Compute He^4 thermalization

Edge - Assume ash recycl coeff R = 0.7

Transport assumptions

$\Gamma = -D \nabla n_{He^4} + V n_{He^4}$

$D = 1.0\ m^2 /s$

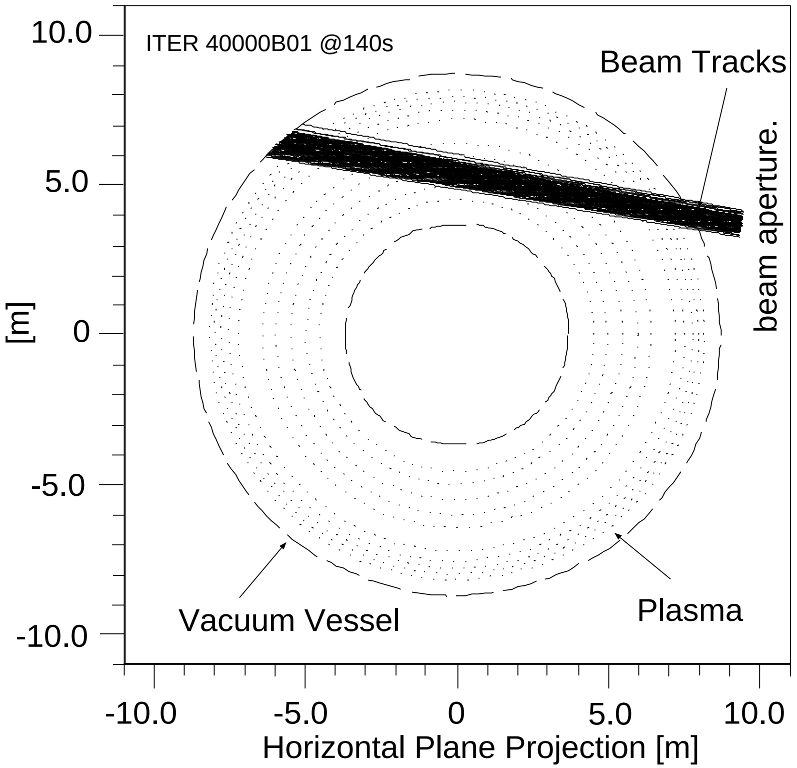
$V = -1.0$ m /s

Calculate confinement

$\tau_{He^4} = N_{He^4} / \Gamma_{He^4} = 5.3$ s

$\tau^*_{He^4} = \tau_{He^4} / (1-R) = 16.0$ s

TRANSP Diagnostics verify NNBI aiming



Inputs

3D geometry of sources

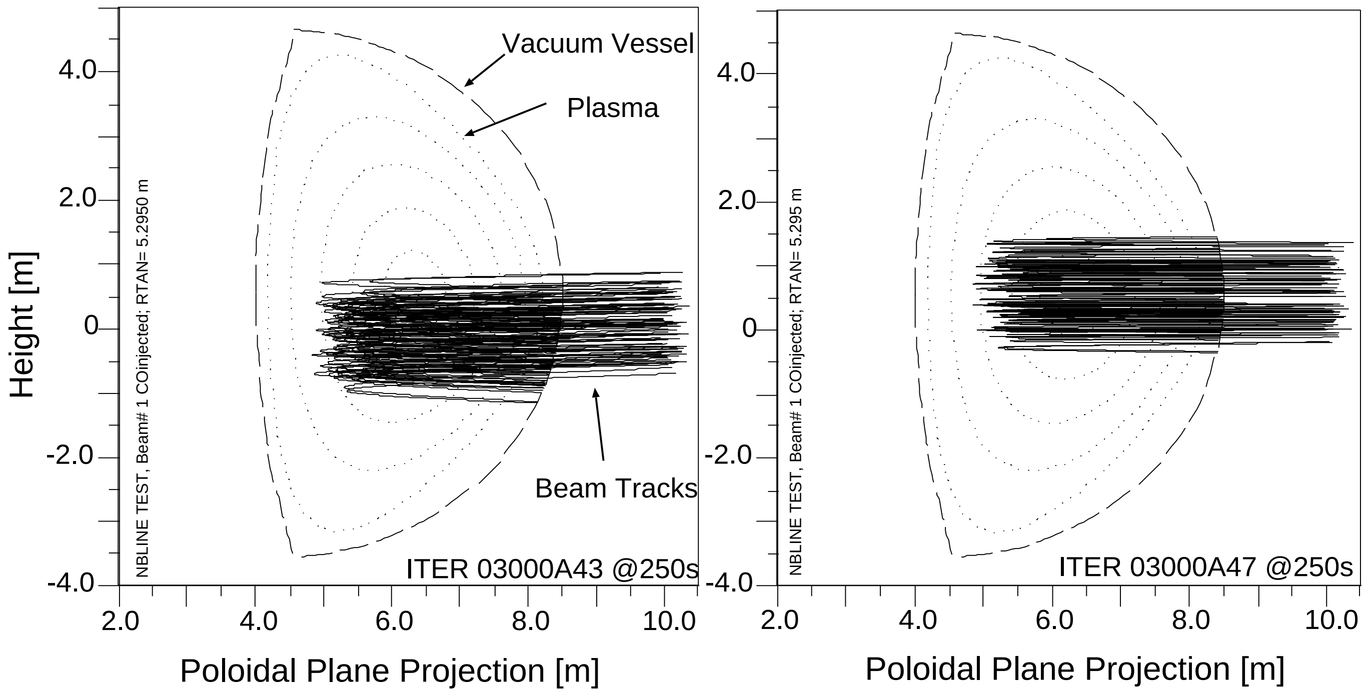
focal lengths

apartures

E = 1 MeV

TRANSP calculates consequences of vertical swing of NNBI

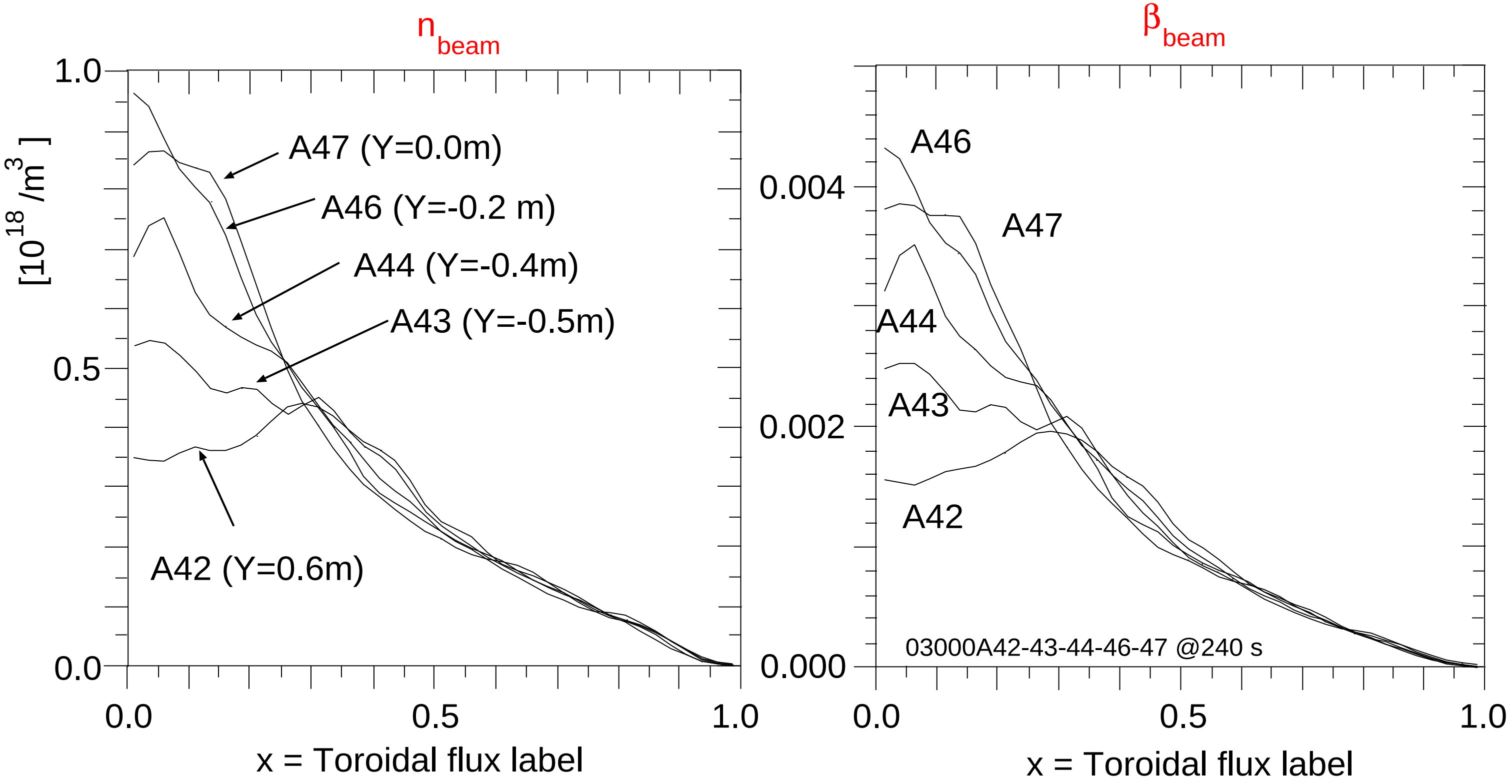
Effects of changing NNBI aiming



0.5 m below magnetic axis midplane

along magnetic axis midpland

Core beam parameters affected by NNBI aiming



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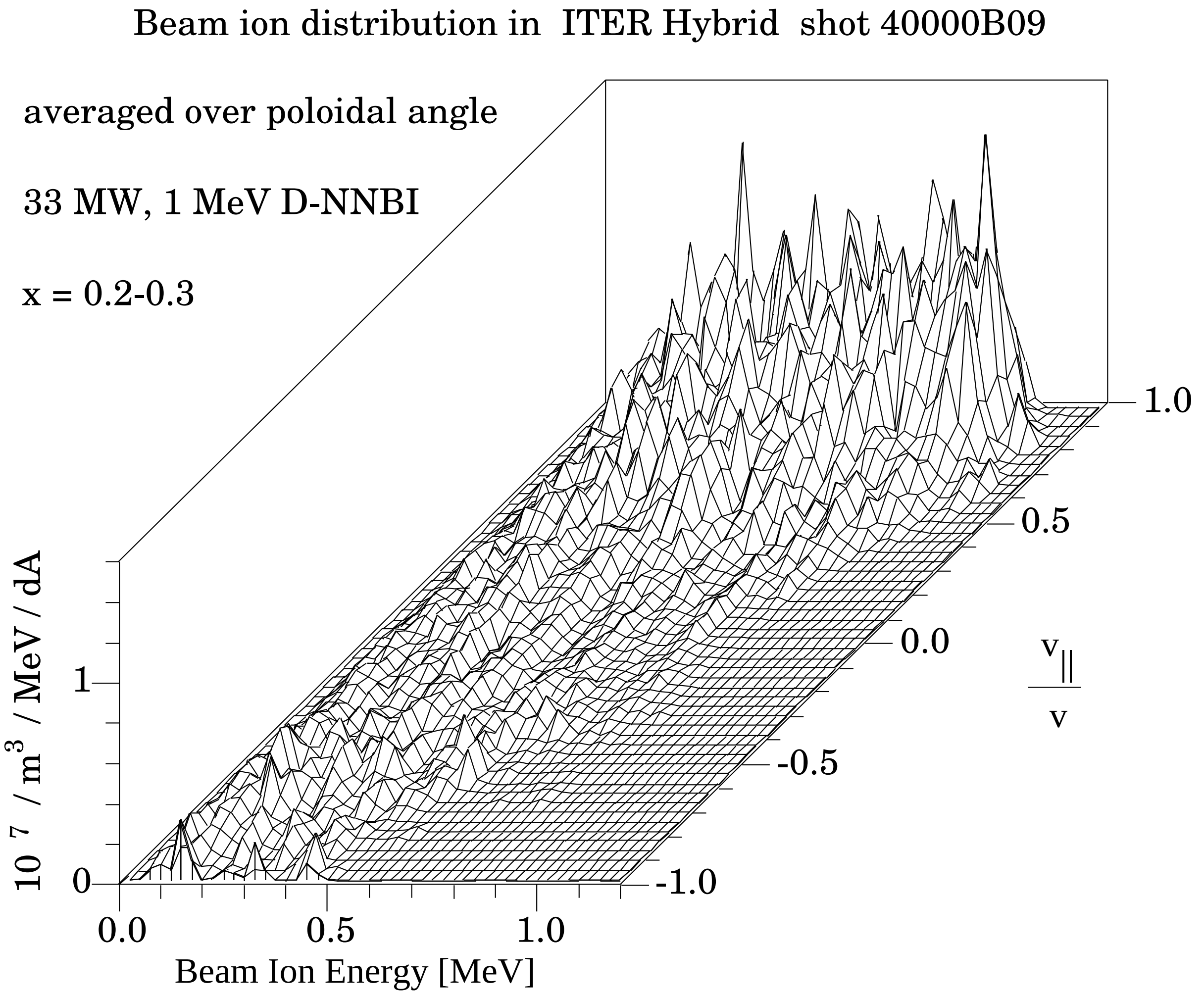
TRANSP computes distributions of fast ions



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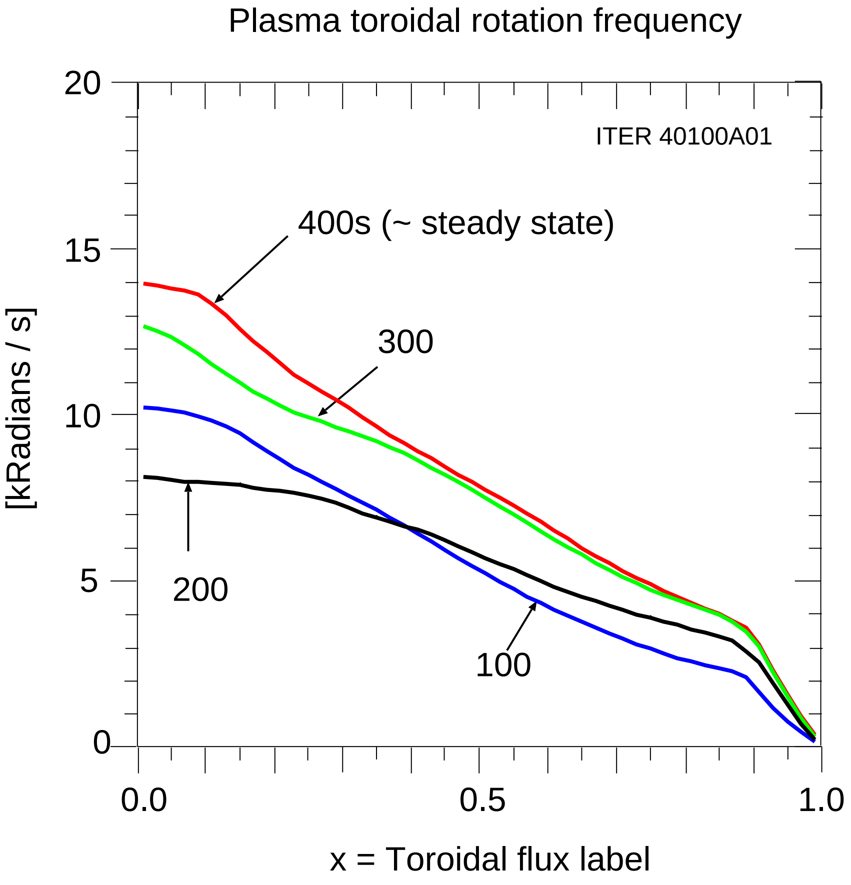
Estimate modest toroidal rotation in the Hybrid plasma



Assume:

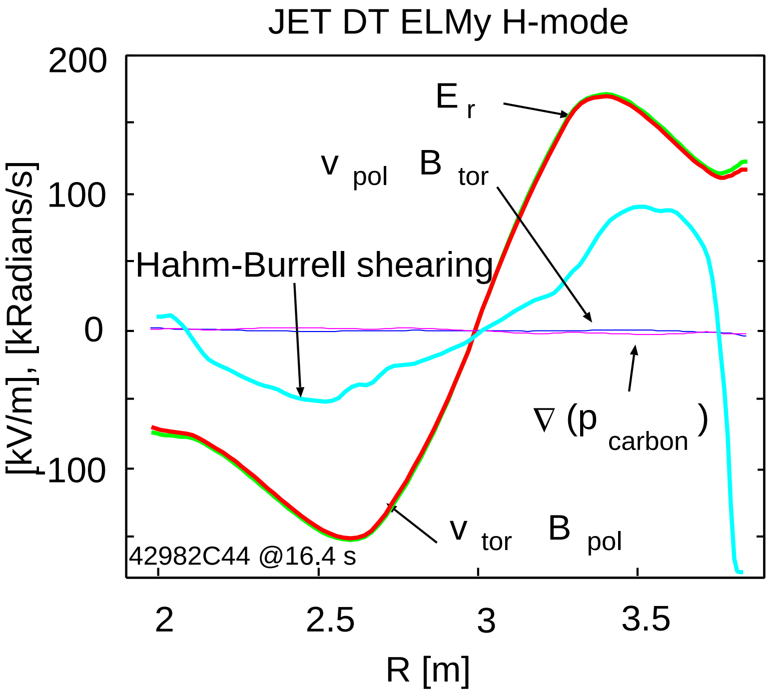
$\chi_{mom} = \chi_i$

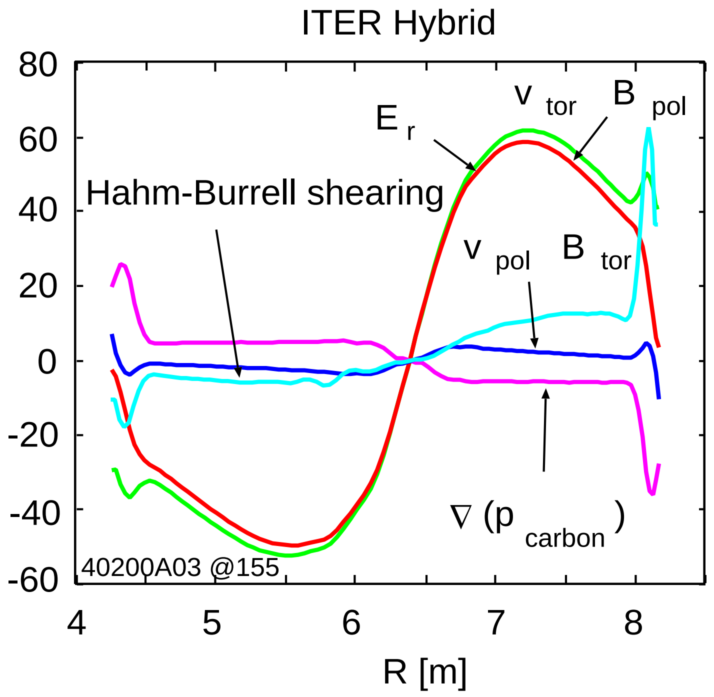
$P_{NNBI} = 33$ MW

Torques from NNBI

Compare E_r in JET DT ELMy and ITER Hybrid plasma

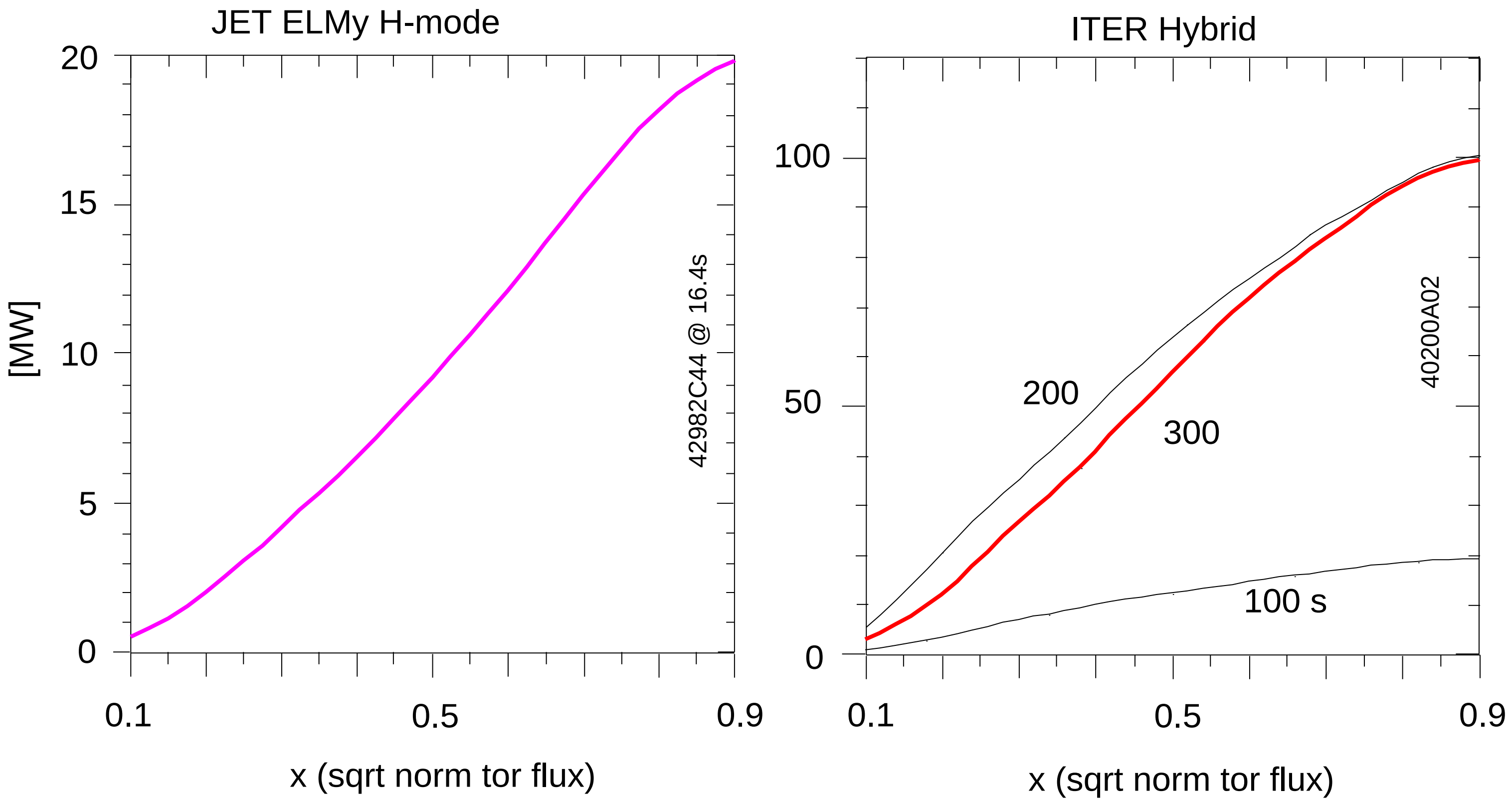
- E_r predicted for ITER Hybrid less than JET ELMy by factor of 3
- E_r dominated by v_{tor} term


JET DT ELMy H-mode


ITER Hybrid

Is ITER heating sufficient to maintain turbulent flows?

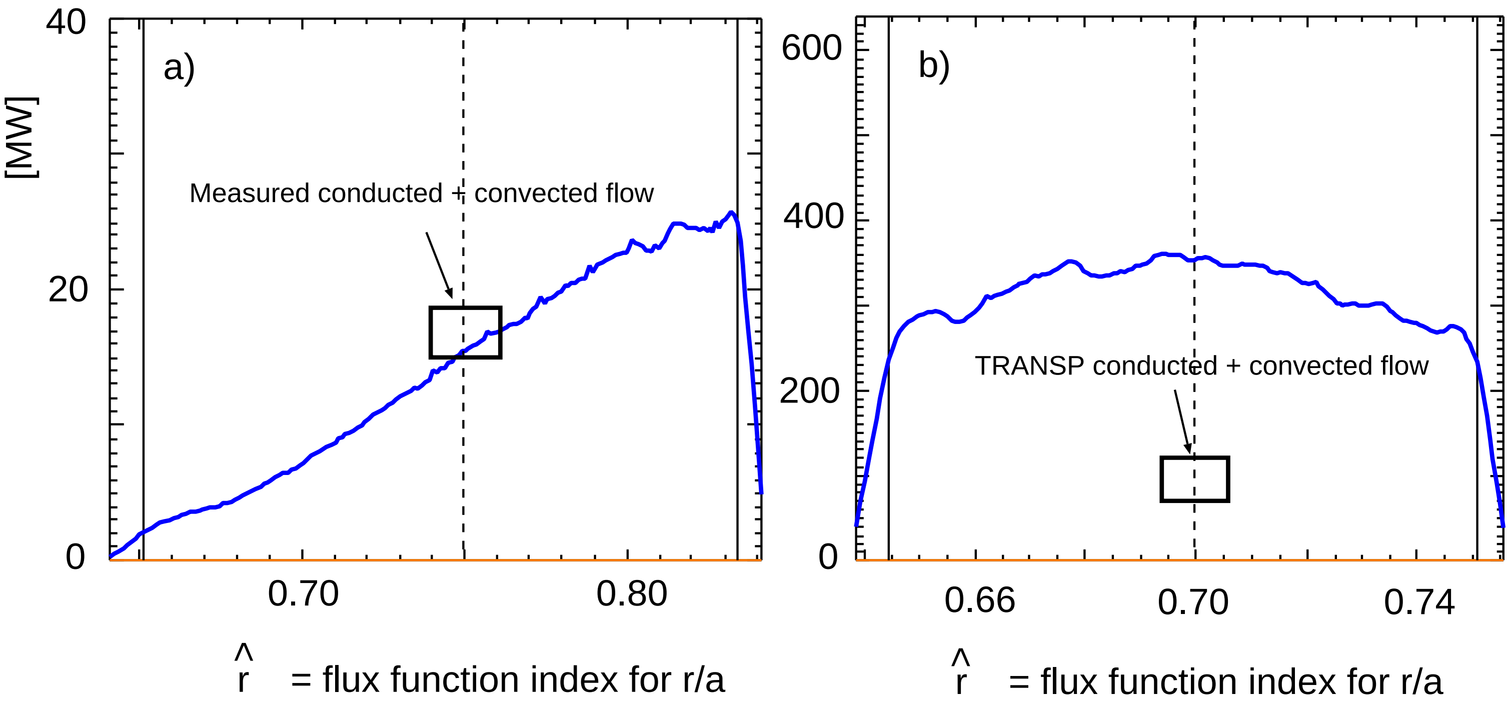
Ion + electron conducted + convected energy flow



Nonlinear GYRO simulations of heat flow in JET and ITER

- Agreement for the JET DT ELMy H-mode
- Factor of 3 too high for ITER Hybrid

GYRO simulation of energy flow in a) JET DT plasma b) ITER Hybrid plasma



Discussion of gyrokinetic simulations

- Want to close the loop: GYRO $\Rightarrow$ GLF23 $\Rightarrow$ TSC $\Rightarrow$ TRANSP $\Rightarrow$ GYRO
- My EPS discussed nonlinear simulations of JET and DIII-D ELMy plasmas
  1. Energy, momentum, and electron species flows depend sensitively on $\nabla(T_i)$ and $\nabla(E_r)$
  2. Slight changes get approximate agreement for energy flow in 3 out of 4 plasmas studied
- Also find strong sensitivity to $\nabla(T_i)$ in ITER
- For ITER Hybrid get Γ_E higher than TRANSP result by $\times 3$ for $r/a \simeq 0.7-0.8$
- Find turbulence suppressed for $r/a \leq 0.6$
- Plan to explore sensitivity to $\gamma_{E\times B}$
- Plan GYRO runs with more than 2 ion species to explore D, T, and impurity transport

Plans for Integrated Modeling using PTRANSP

- New PPPL - Lehigh - GA - LNL Collaboration
- Planned near-term upgrades to PTRANSP
  1. Ability to stop, steer, and restart
  2. Free boundary adjusted by varying coil currents
  3. Improved temperature predictive capabilities
  4. Improved Verification and Validation
- Planned long-term upgrades to PTRANSP
  1. Scrape-off model
  2. density prediction

Summary

- The TSC-TRANSP codes have been used to prototype time-dependent integrated modeling of burning plasmas

  1. Steady-State, Hybrid, and ELMy H-mode ITER plasmas

- moderate toroidal rotation estimated from NNBI if $\chi_\phi \simeq \chi_i$
- LHCD effective at altering q around x=0.8
- TAE activity is predicted for ITER
- High pedestal temperatures required by the GLF model in TSC
- ash accumulation modeled for various transport assumptions
- sawtooth mixing of fast alphas, beam ions, and ash predicted for ELHy H-mode
- Upgrade (PTRANSP) in progress
- Nonlinear GYRO runs simulated energy, momentum, and electron flow in ITER

Work needed

- Continued PTRANSP collaboration important for integration of more physics
- Submit more ITER plasmas to ITPA profile database
- Gyrokinetic studies
- TAE studies
- MHD studies
- Improved RF modeling