Time-Dependent Integrated Modeling of Burning Plasmas

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- Need better understanding of burning plasmas to increase the probability of practical fusion power
- Time-dependent integrated modeling will help meet this goal
  1. Time-dependence for startup, steady state, termination
  2. Physics integration for nonlinearities of self-organizing plasmas
- Applications
  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. Evaluate benefit / cost of each plasma before the experiment

- ITER plasmas generated using a prototype of PTRANSP
- Examples of applications
  1. estimates of alpha ash profile
  2. distributions of the fast alpha and NNBI ions
  3. estimates of toroidal rotation and E_r profiles
  4. gyrokinetic simulations of energy, momentum, and particle flows
- Introduction to PTRANSP

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

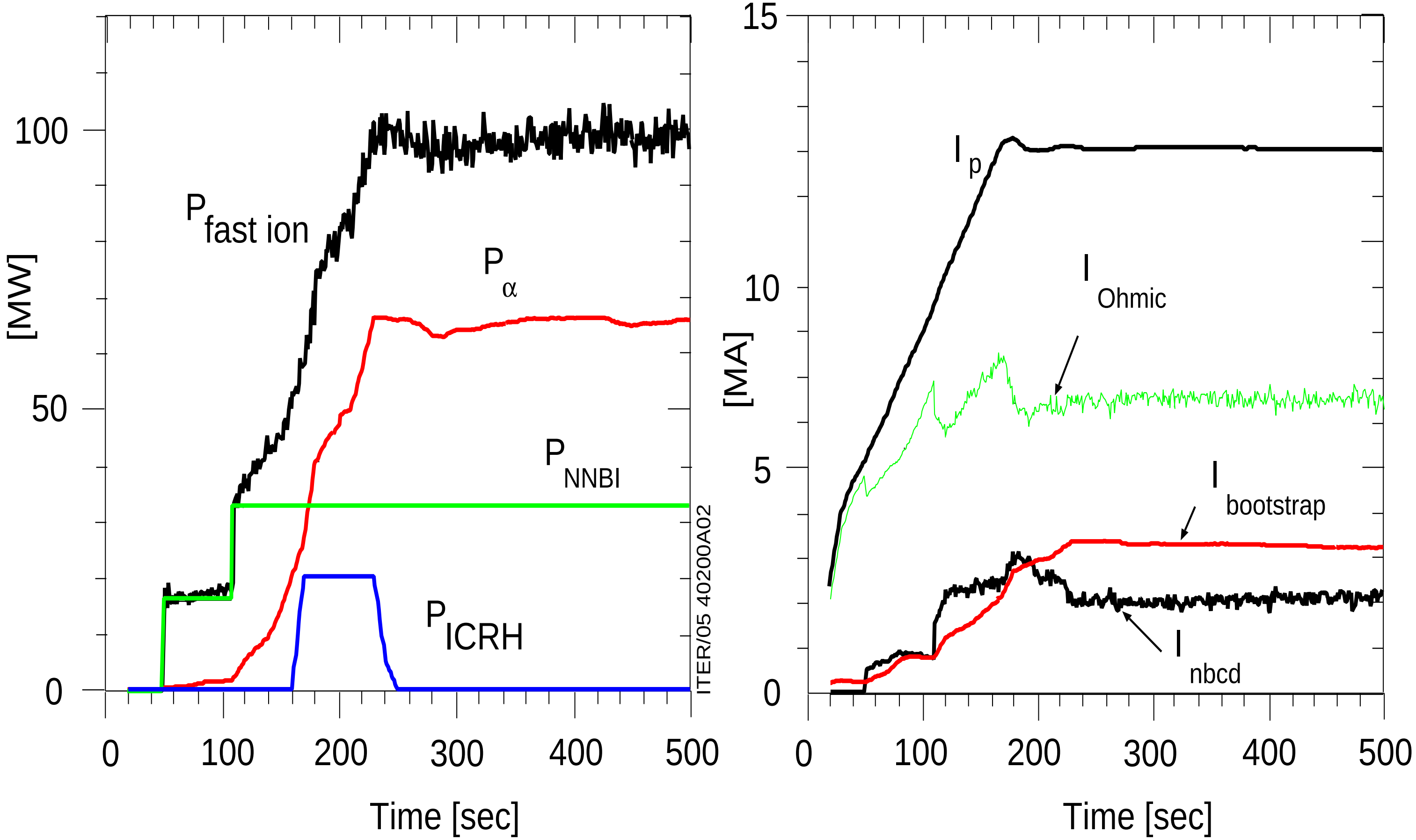
Examples of Findings

- High pedestal temperatures appears required by GLF23 (in TSC) to achieve P$_{DT}$ $\simeq$ 400MW with high β_n and 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 is some cases

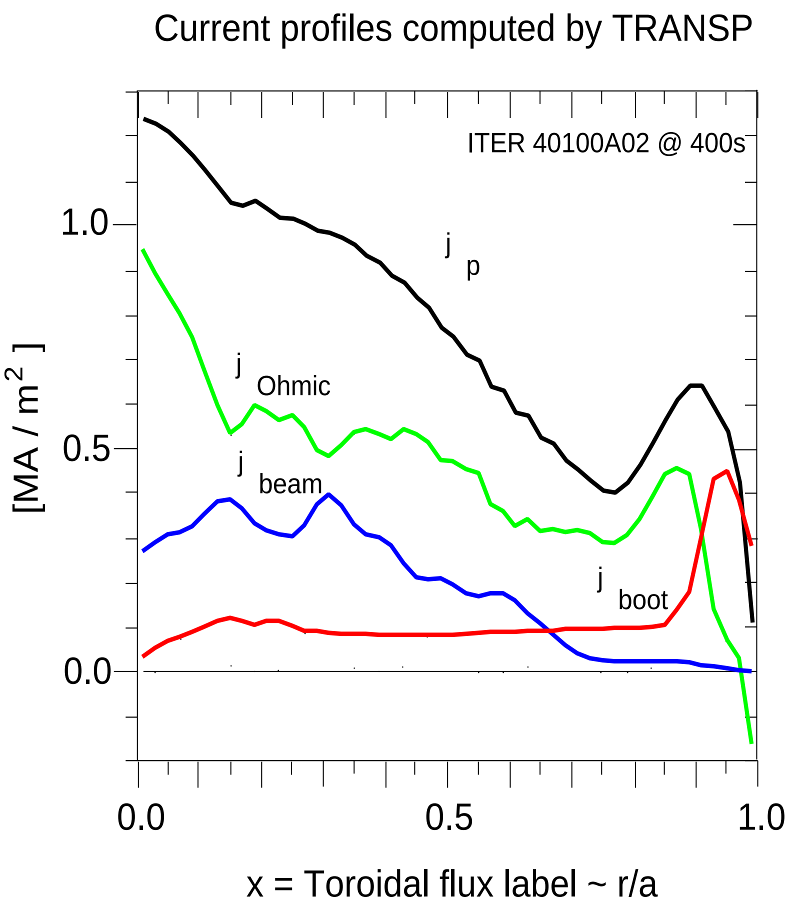
Construction of the Hybrid plasma

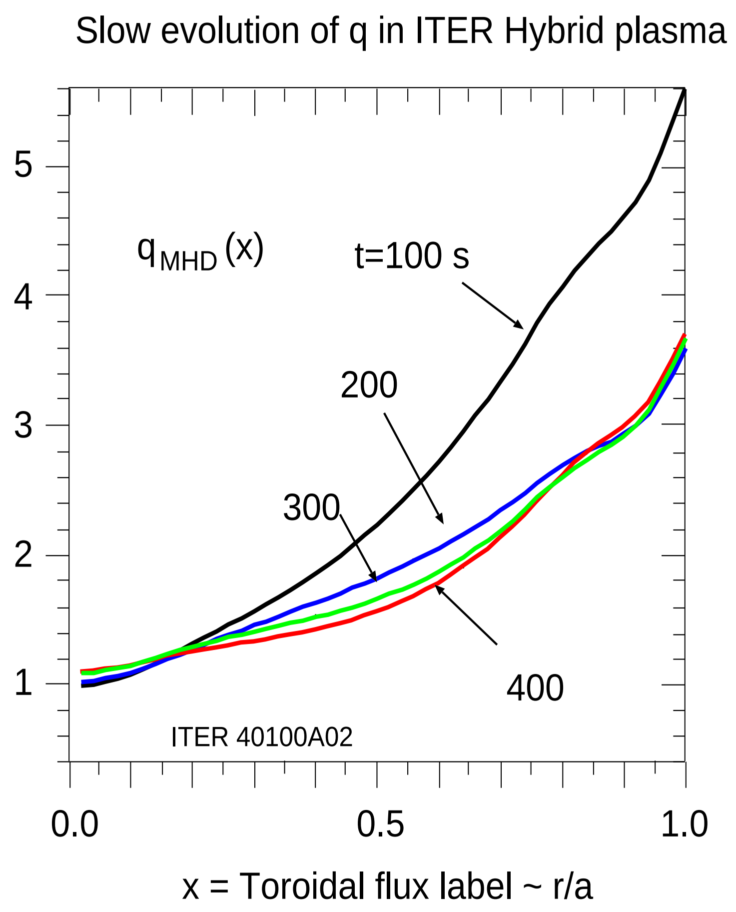
- Use GLF23 model to predict temperatures
- Very high pedestal temperatures to achieve $P_{DT} \simeq$ 400 MW and high β_n
- Reduced I_p (12 MA) to decrease inductive-current fraction
- Moderate density for good NNBI penetration
- Suffi cient current drive to keep q(0) above unity

Heating powers and plasma currents in the Hybrid plasma



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





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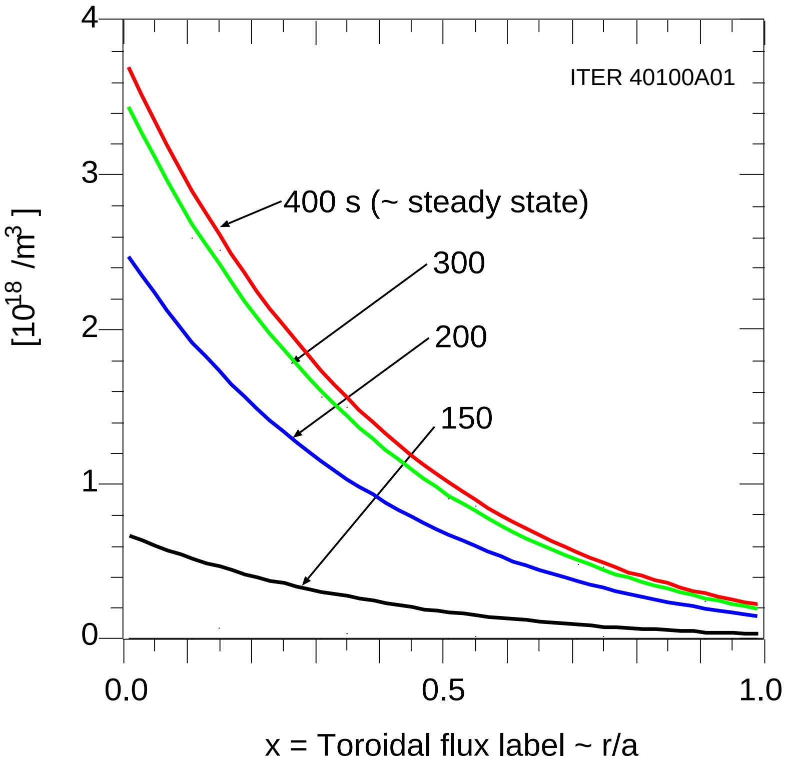
Integrated modeling needed for ash accumulation

He ash accumulation in ITER Hybrid plasma



Sources:

Core - Compute He^4 thermalization

Edge - Assume ash recycl coeff R = 0.7

Transport assumptions

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

$D = 1.0\ m^2/s$

V = - 1.0 m /s

Calculate confinement

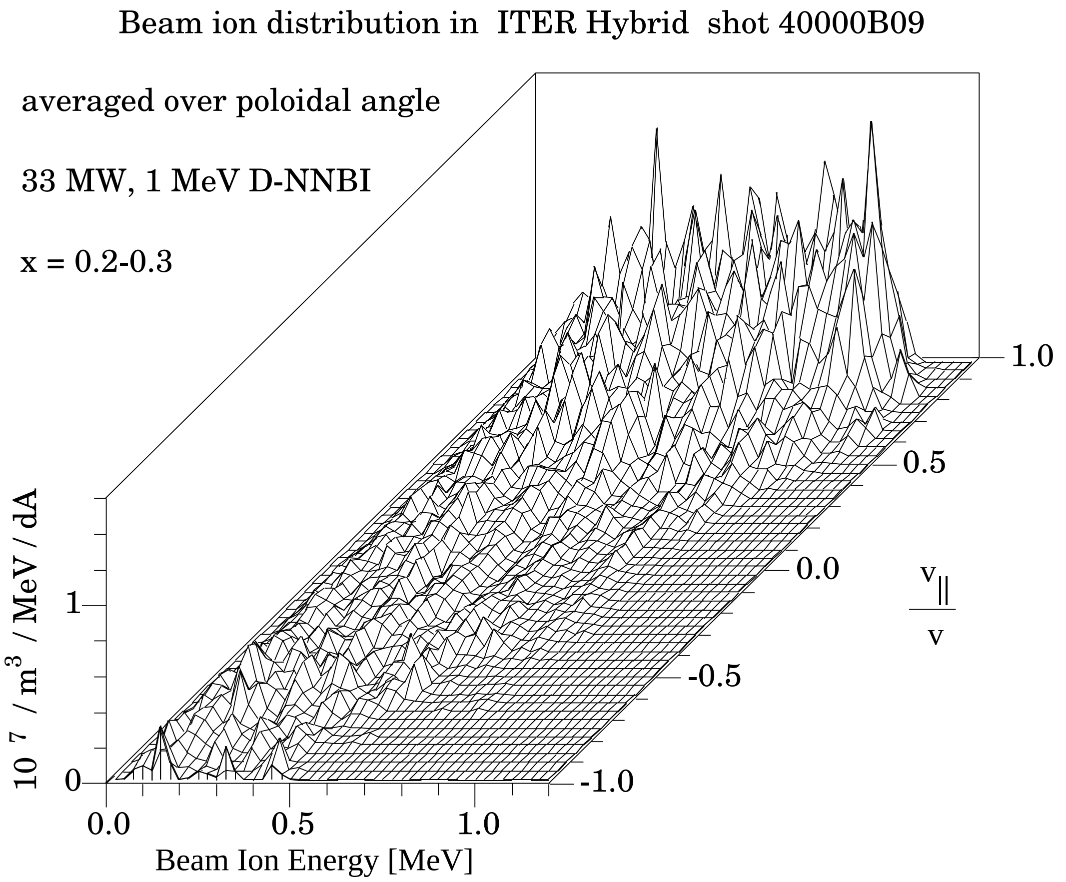
$\tau_{He^4} = N_{He^4} / \Gamma_{He^4} = 5$ s

$\tau^*_{He^4} = \tau_{He^4} / (1-R) = 17$ s

- Need to get Γ_{He^4} from nonlinear gyrokinetic simulations

TRANSP computes distributions of fast ions

- NNBI distribution important for accurate calculations of TAE



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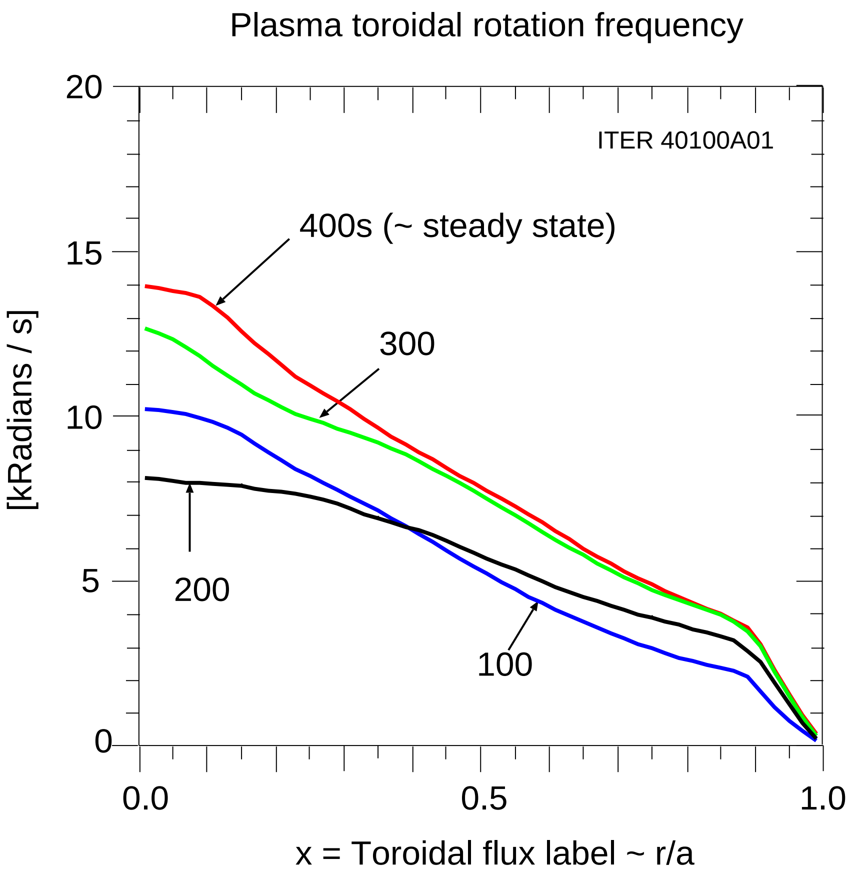
Estimate modest toroidal rotation from NNBI torque



Assume:

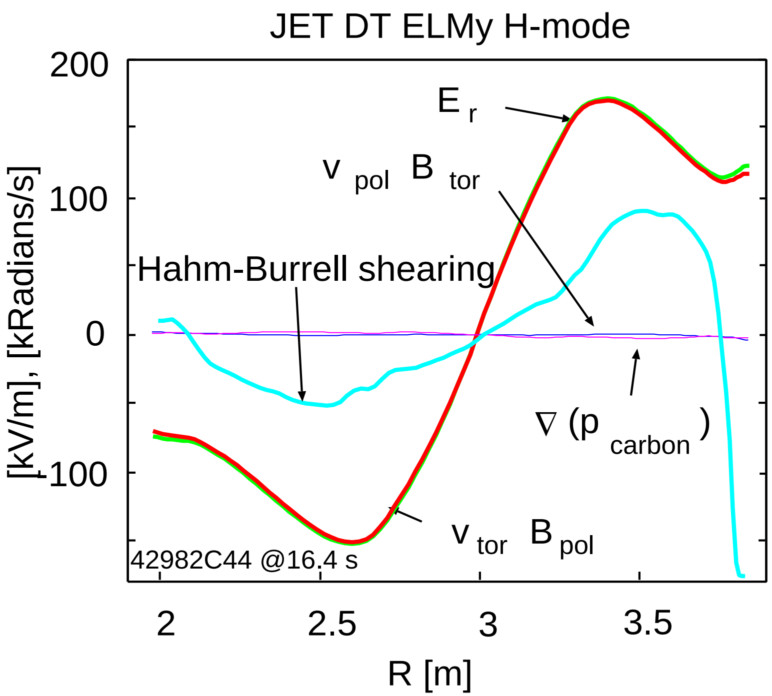
$\chi_{mom} = \chi_i$

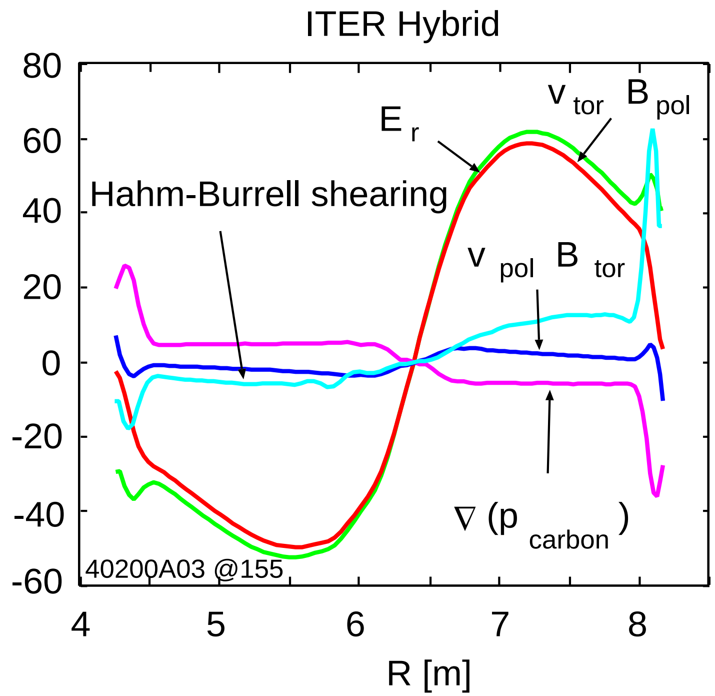
$P_{NNBI} = 33$ MW

Torques from NNBI

Compare E_r in JET DT ELMy and ITER Hybrid

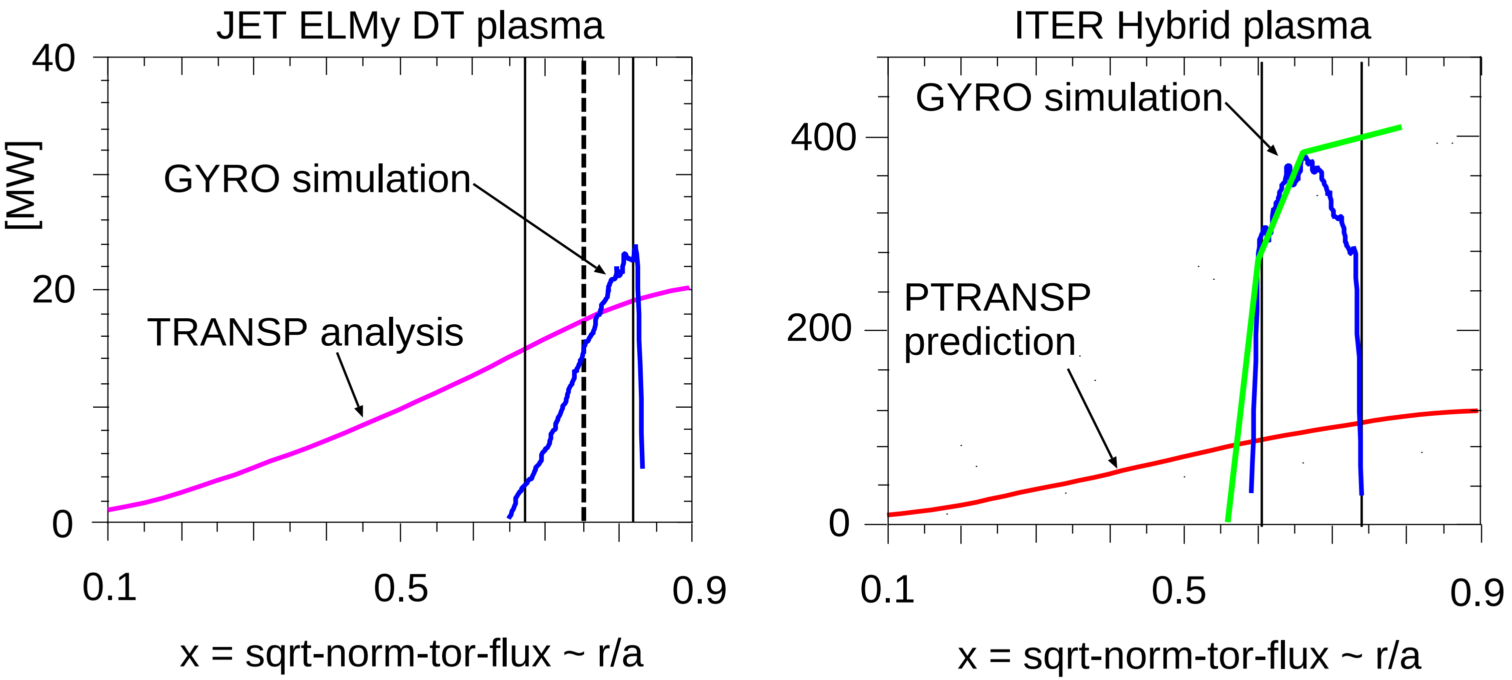
- E_r predicted for ITER Hybrid less than JET ELMy by factor of 3
- E_r dominated by v_{tor} term





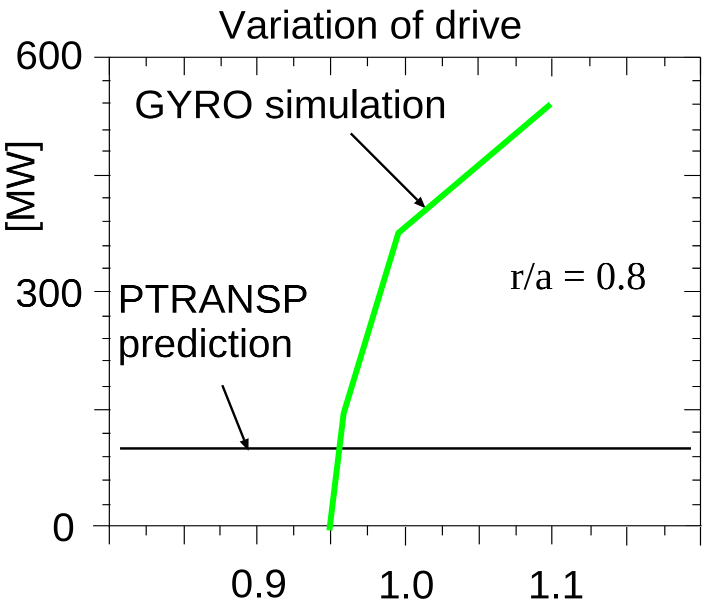
Nonlinear GYRO simulations predict energy flow rates

- Agreement for the JET DT ELMy H-mode with $\nabla(E_r)$ reduced 10%
- Factor of 3 too high for ITER Hybrid at r/s τ 0.7

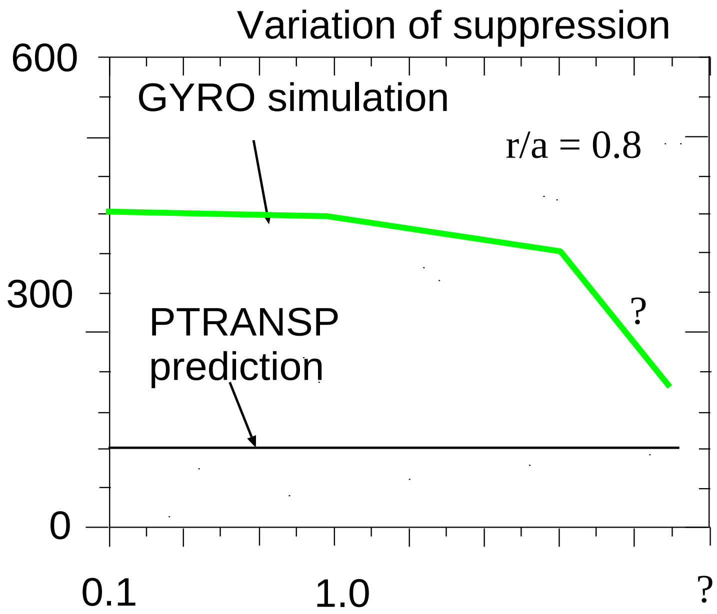


Sensitivity of GYRO simulations for ITER

- Strong sensitivity to $\nabla(T_i)$
- Adjust $\nabla(E_r)$ to look for sweet spot



$$\frac{|\nabla(T_i)|^{gyro}}{|\nabla(T_i)|^{ptransp}}$$



$$\frac{|\nabla(E_r)|^{gyro}}{|\nabla(E_r)|^{ptransp}}$$

- Want to close the loop: GYRO $\Rightarrow$ GLF23 $\Rightarrow$ TSC $\Rightarrow$ TRANSP $\Rightarrow$ GYRO
- EPS 2005 paper on GYRO 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
- Preliminary GYRO results for ITER Hybrid
  1. Also fi nd strong sensitivity to $\nabla(T_i)$
  2. Γ_E higher than TRANSP result by $\times 3$ for $r/a \simeq 0.7 - 0.8$
  3. Find turbulence suppressed for $r/a \leq 0.6$
  4. Plan to explore sensitivity to $\gamma_{E\times B}$
  5. Plan GYRO runs with more than 2 ion species to explore D, T, ash, and impurity transport

Plans for Integrated Modeling using PTRANSP

- New PPPL - Lehigh - GA - LNL Collaboration
- Planned near-term upgrades to TRANSP

  1. Ability to stop, steer, and restart
  2. Free boundary adjusted by varying coil currents
  3. Improved temperature predictive capabilities
  4. Improved Verifi cation and Validation

- Planned long-term upgrades to TRANSP

  1. Scrape-off model
  2. density prediction
  3. Pedestal model

Summary

- The TSC-TRANSP codes have been used to prototype PTRANSP time-dependent integrated modeling of burning plasmas
  1. Steady-State, Hybrid, and ELMy H-mode ITER plasmas
- Moderate toroidal rotation estimated from NNBI if $\chi_\phi \simeq \chi_i$
- TAE activity is predicted for ITER in some cases
- High pedestal temperatures required by the GLF model in TSC
- ash accumulation modeled for various transport assumptions
- Upgrade (PTRANSP) in progress
- Nonlinear GYRO runs simulated energy, momentum, and electron flow in ITER

- Continued PTRANSP collaboration important for integration of more physics
- Submit more ITER plasmas to ITPA profi le database
- Gyrokinetic studies

  1. verifi cation and validation
  2. assess need for rotation
  3. predict D, T, ash transport