Time-dependent Integrated Modeling of Burning Plasmas

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- We need to understand burning plasmas better to improve the chances of achieving practical Tokamak fusion power
  1. Check the ITER design (ex, is P$_{NNBI}$ suff? is ash removal suff?)
  2. Certify plasmas before they are tried
- Strategy to achieve the needed capability:
  1. Create database of self-consistent, time-dependent plasmas
  2. Use Microturbulence, MHD, TAE, .. codes to select plasmas that are stable or marginally stable

Why traditional predictions of burning plasmas are inadequate

- 0D efforts study scaling of confinement with dimensionless quantities
  1. Use globally-averaged values of parameters such as ρ_*, ν_*, β
  2. Insensitive to profile effects (ex, density peaking)
  3. Generally exclude many other candidate dimensionless quantities
  4. Large extrapolations necessary
- 1D efforts to predict temperature profiles, etc
  1. Semi-empirical
  2. Insufficient data on DT plasmas to validate models

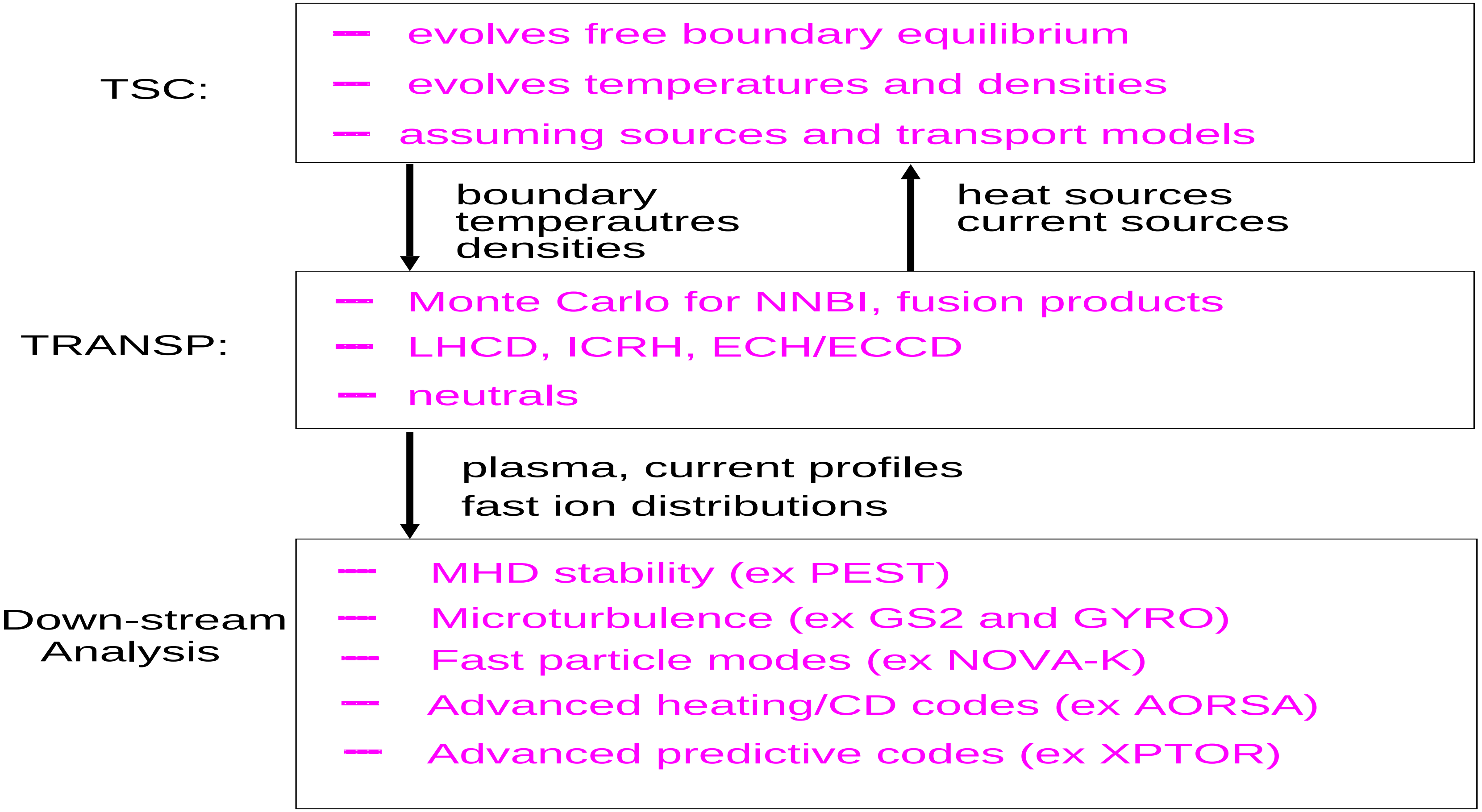
Why Time-Dependent Self-Consistent Integrated Modeling?

- Time-Dependent modeling is needed to address the challenges of creating and maintaining steady state plasmas
- Self-Consistent Integrated modeling is needed for the non-linearities and strong coupling of plasma conditions and current drive

Goals of this Talk

- Describe prototype Time-Dependent Integrated Modeling
- Application to ITER plasmas
- Plans for improved Time-dependent Integrated Modeling

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 (ex PEST)
- Microturbulence (ex GS2 and GYRO)
- Fast particle modes (ex NOVA-K)
- Advanced heating/CD codes (ex AORSA)
- Advanced predictive codes (ex XPTOR)

ITER Plasmas studied

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

	I_p	I_{boot}	I_{nnbi}	$\boldsymbol{I_{Oh} / I_p}$	$n_e(0)$	$\boldsymbol{f_{GW}}$	T_e	P_{dt}	$\boldsymbol{\beta_\alpha}(0)$
units	MA	MA	MA		$\boldsymbol{10^{20}/m^3}$		keV	MW	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

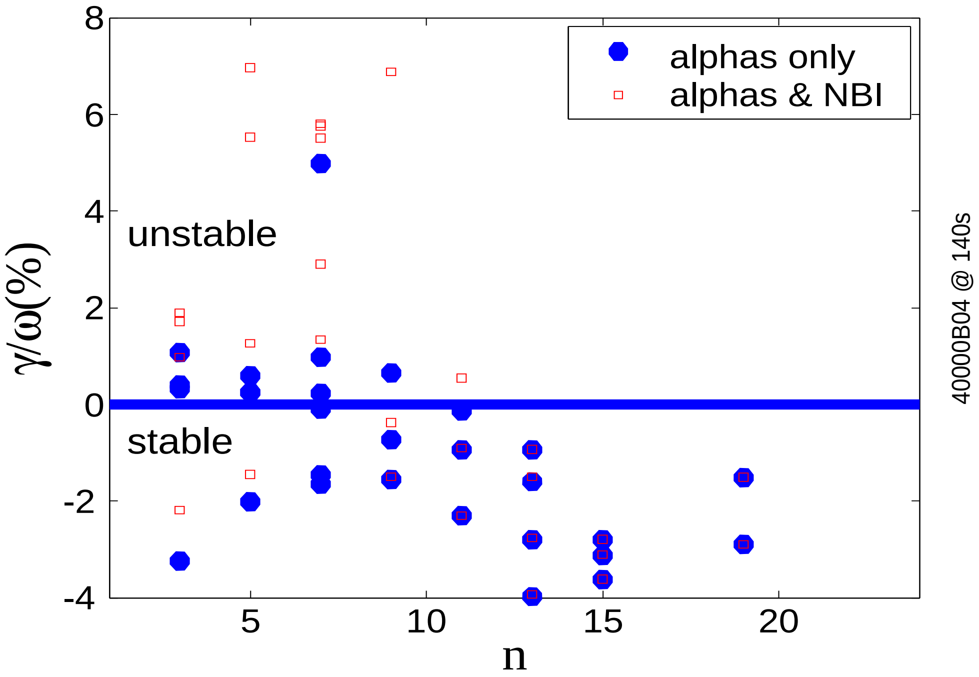
Examples of Findings

- High pedestal temperatures 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

Example of down-stream analysis

- NOVA-K analysis of TAE modes in ITER Steady-State / Hybrid plasmas

TAE instability in Hybrid and AT plasmas

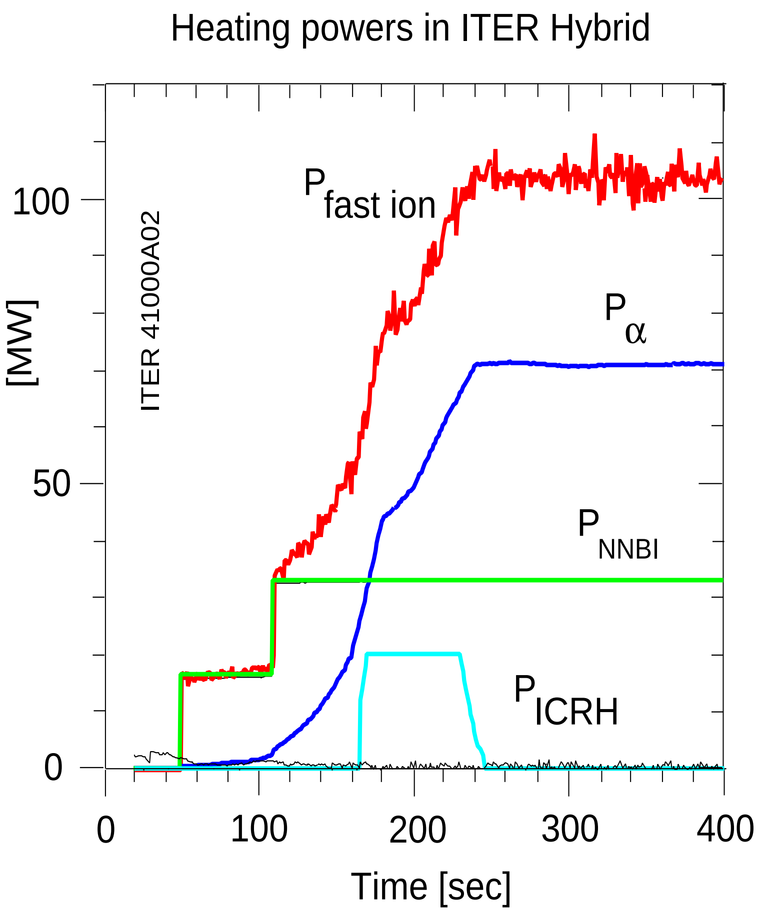


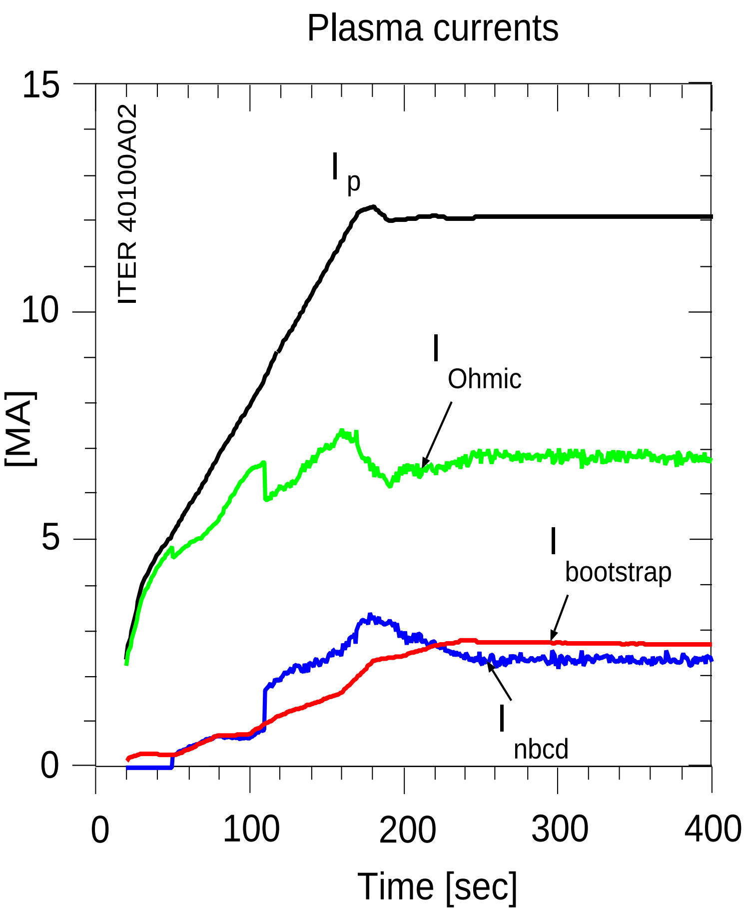
N. Gorelenkov

Construction of the Hybrid plasma

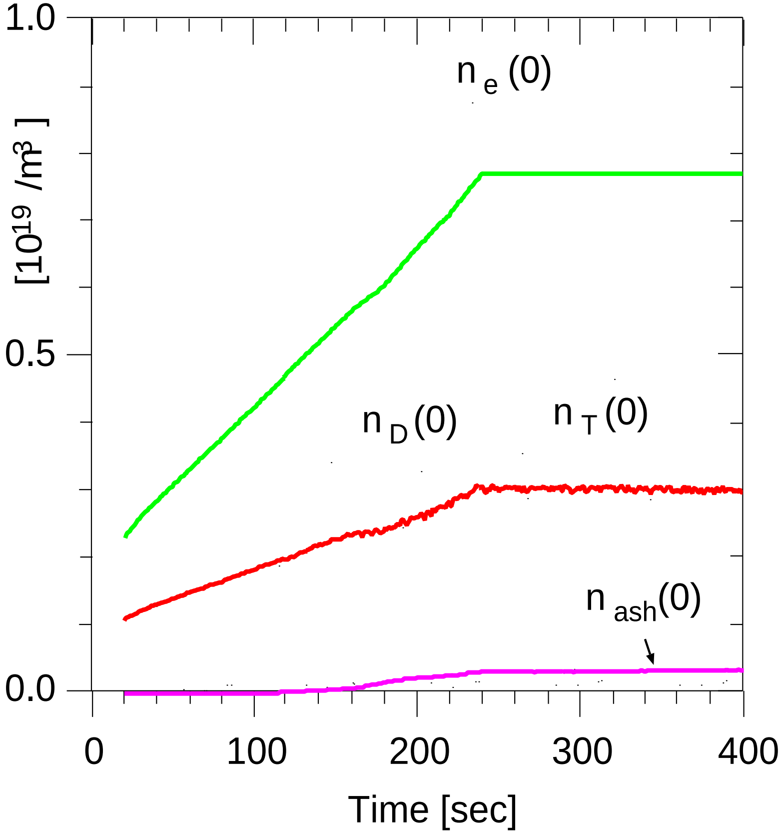
- Use GLF23 model to predict temperatures
- High pedestal temperatures to achieve P$_{DT}$ $\simeq$ 400 MW
- Reduced I$_p$ (12 MA) to decrease inductive-current fraction
- Moderate density for good NNBI penetration
- Sufficient current drive to keep q(0) above unity

Heating powers and plasma currents in the Hybrid plasma

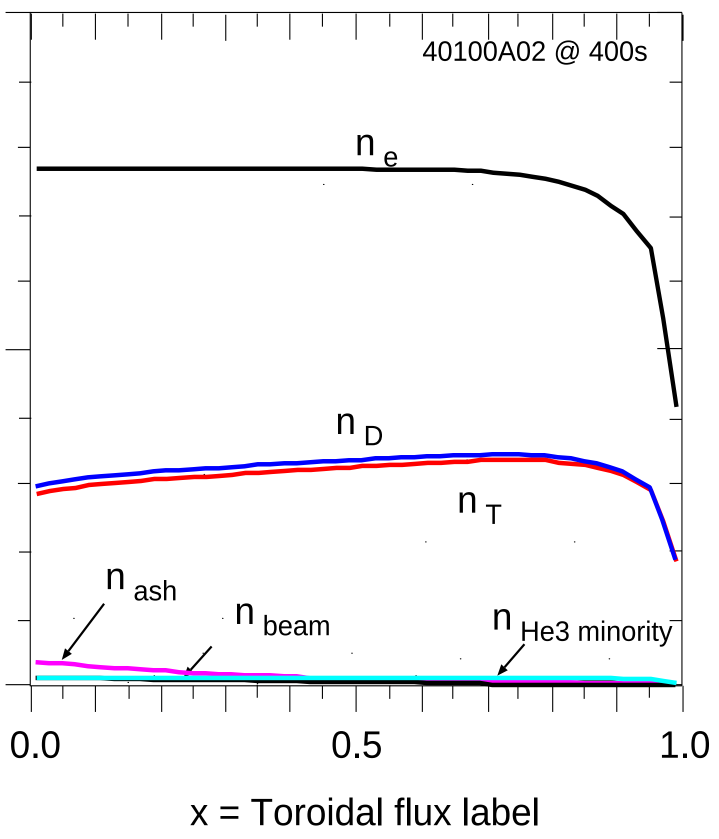

Heating powers in ITER Hybrid


Plasma currents

Densities in the Hybrid plasma

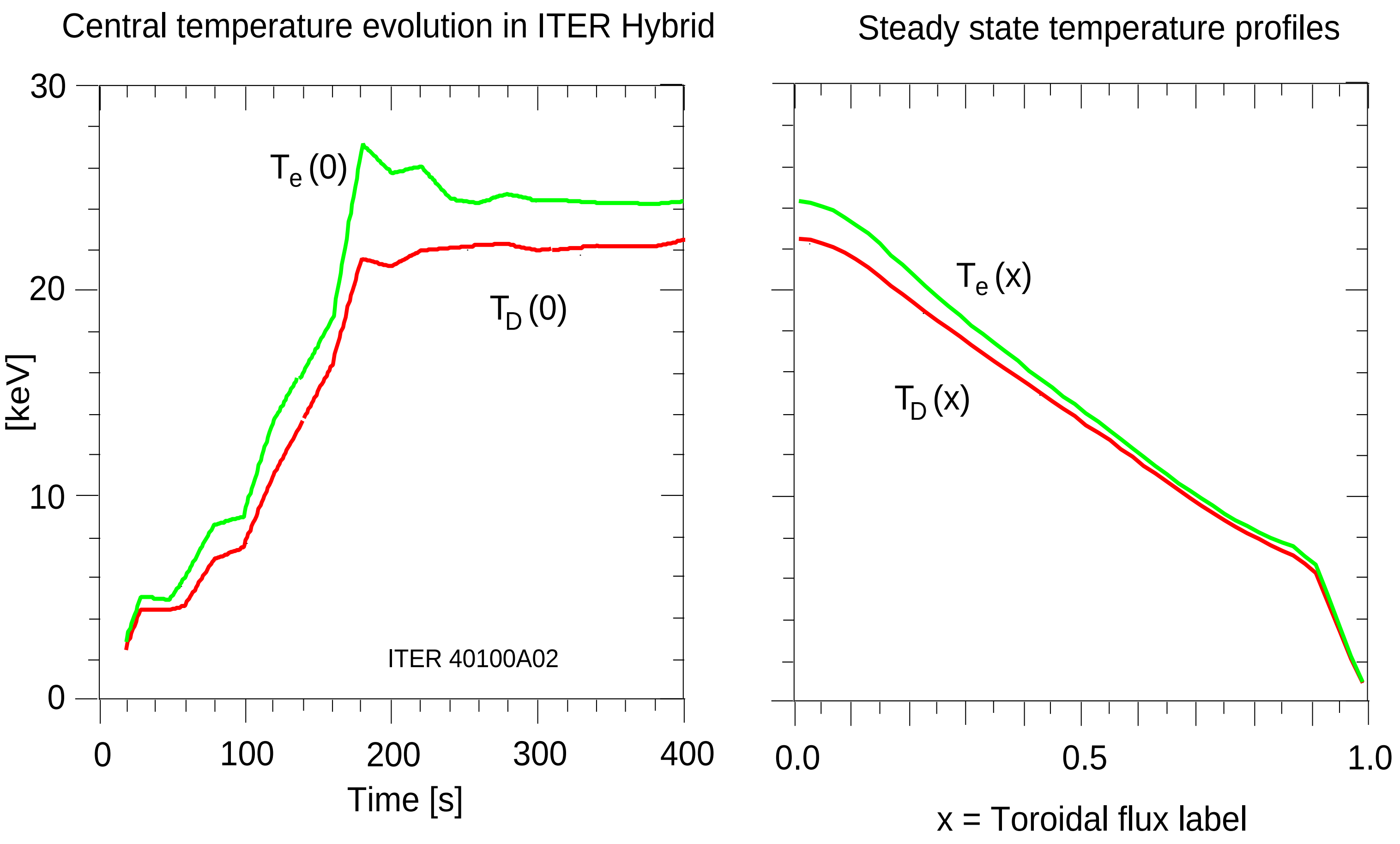


Central density evolution in ITER Hybrid



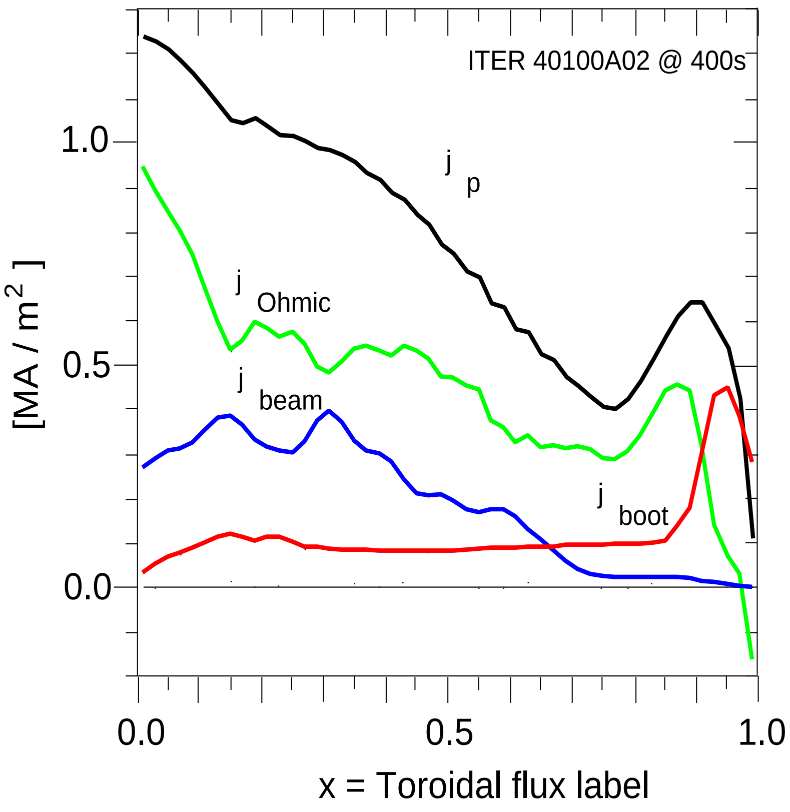
Steady state density profiles

Temperatures in the Hybrid plasma

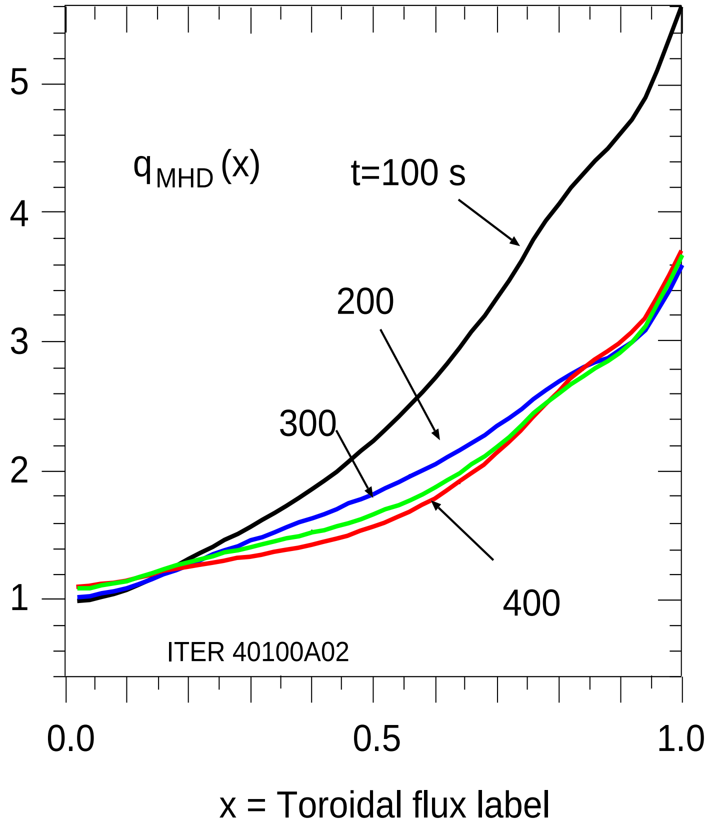


Sustained $q_{MHD} > 1$ with evolving reversal in Hybrid plasma

Current profiles computed by TRANSP

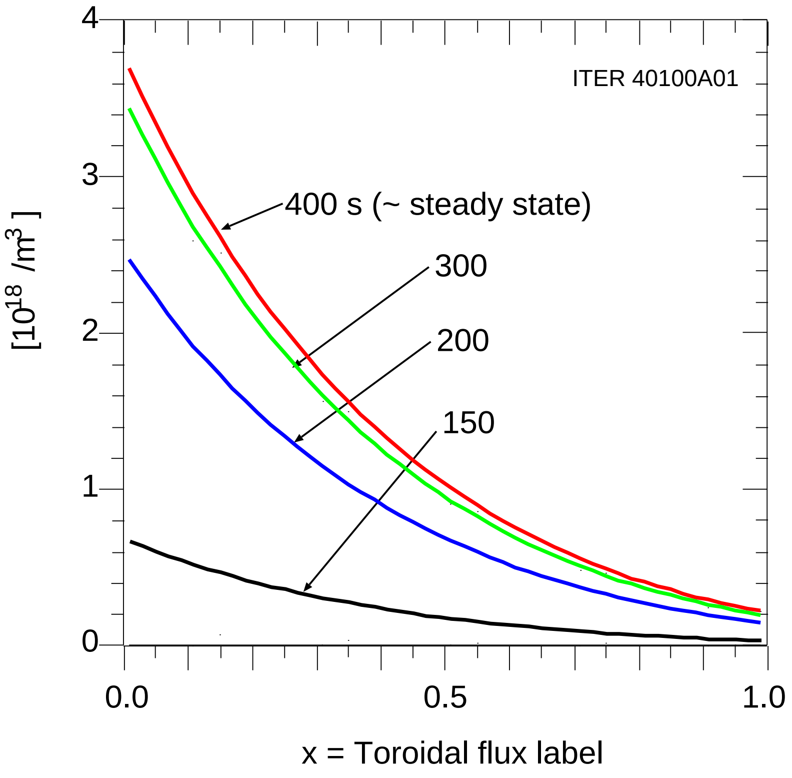


Slow evolution of q in ITER Hybrid plasma



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 = 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

$\tau_{He^4} = 5.3\ s$

$\tau^*_{He^4} = 16.0\ s$

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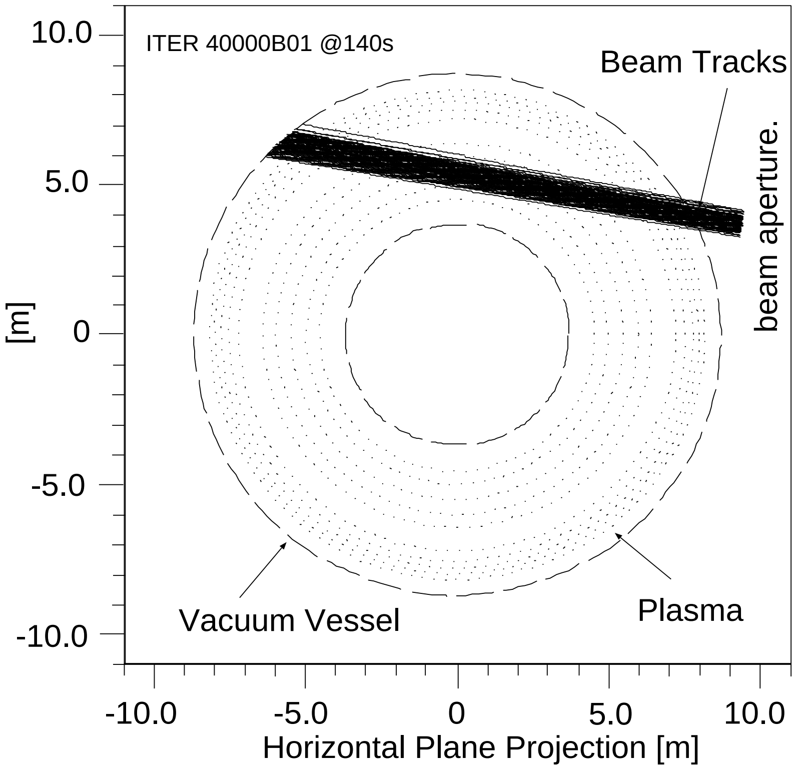
TRANSP Diagnostics verify NNBI aiming



Inputs

3D geometry of sources

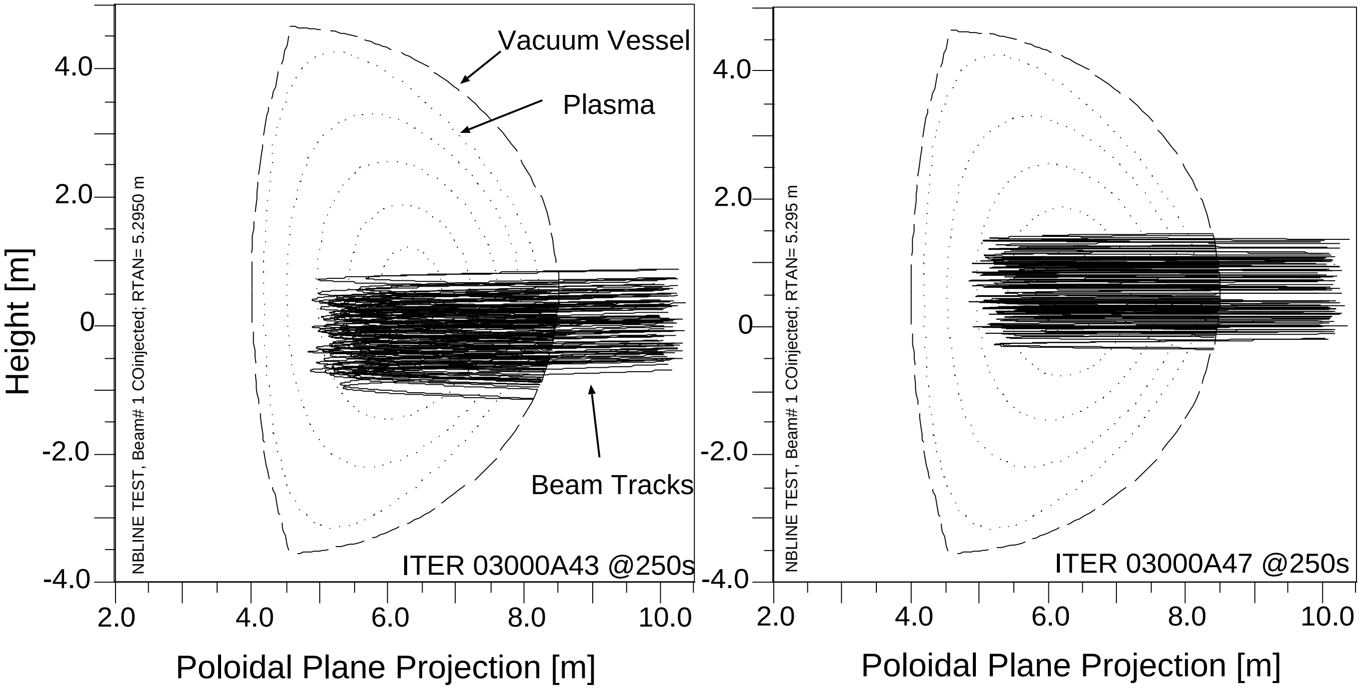
focal lengths

apartures

E = 1 MeV

TRANSP diagnostics check vertical swing of NNBI

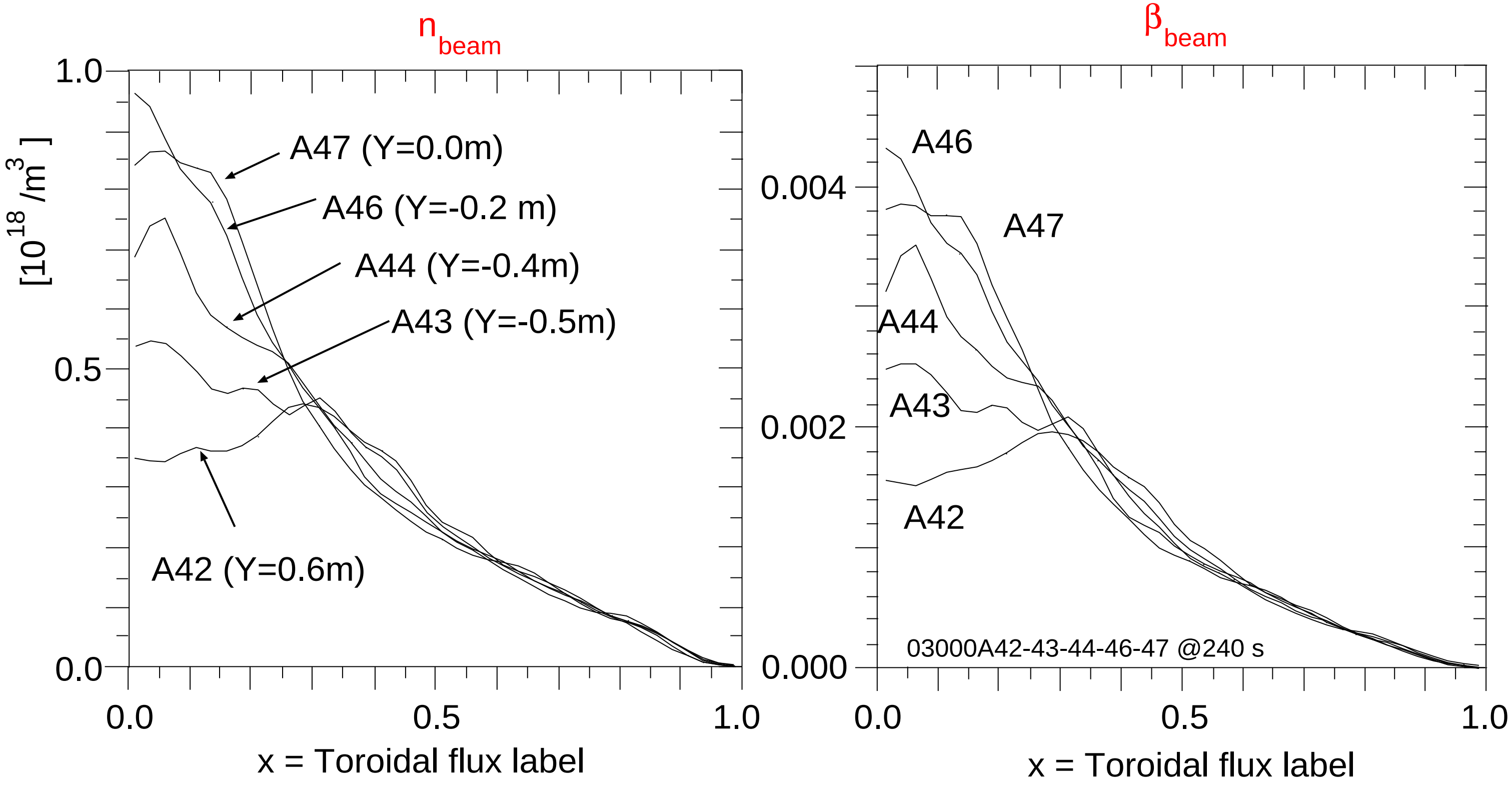
Effects of changing NNBI aiming



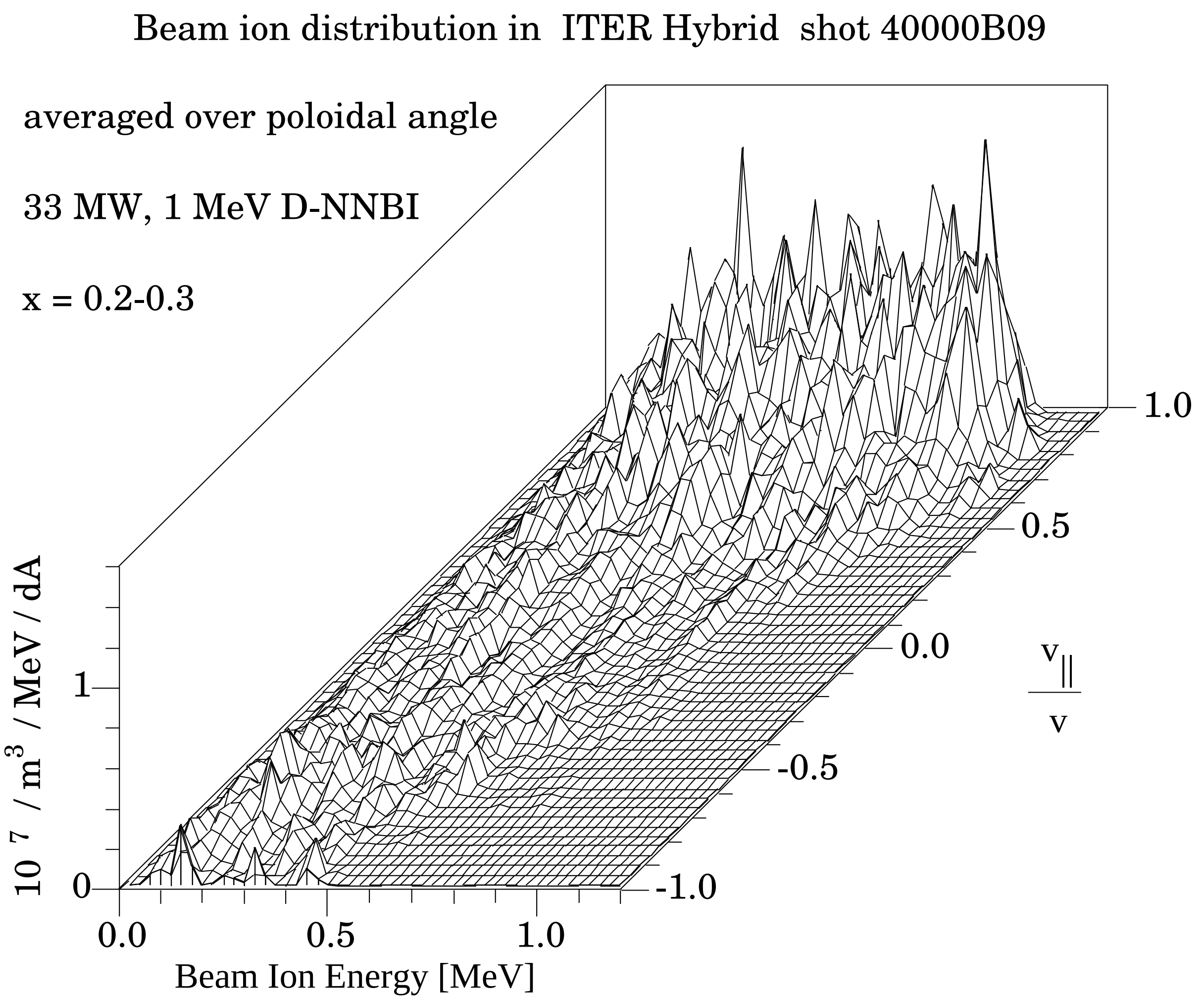
0.5 m below magnetic axis midplane

along magnetic axis midpland

Core beam parameters affected by NNBI aiming



TRANSP computes distributions of fast ions



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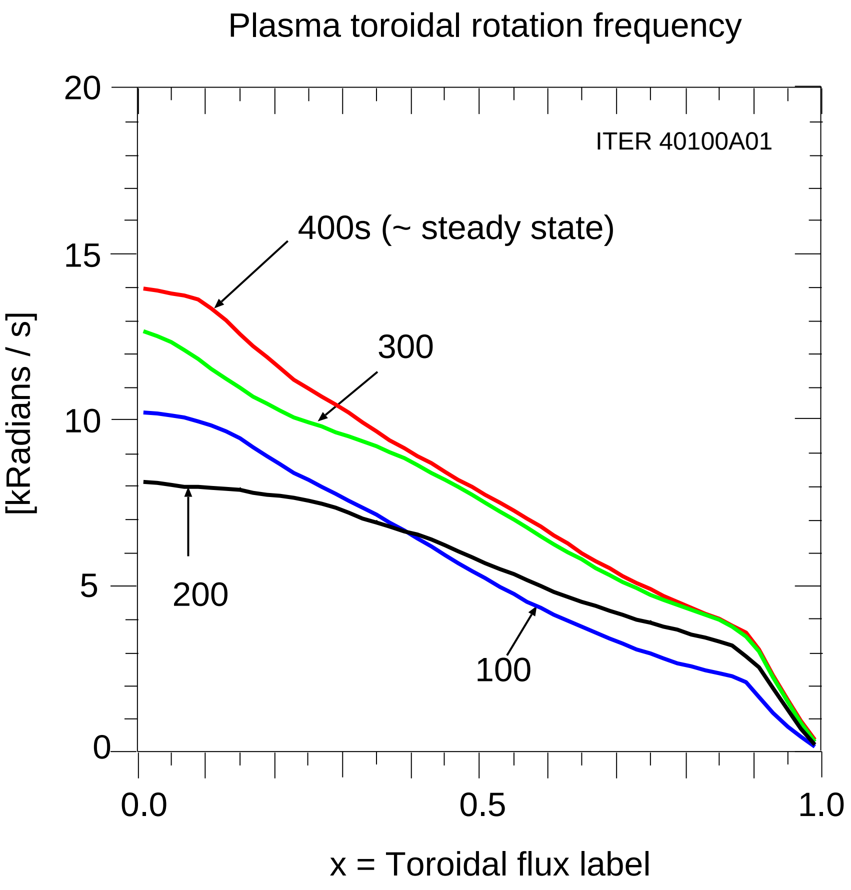
Estimate modest toroidal rotation in the Hybrid plasma



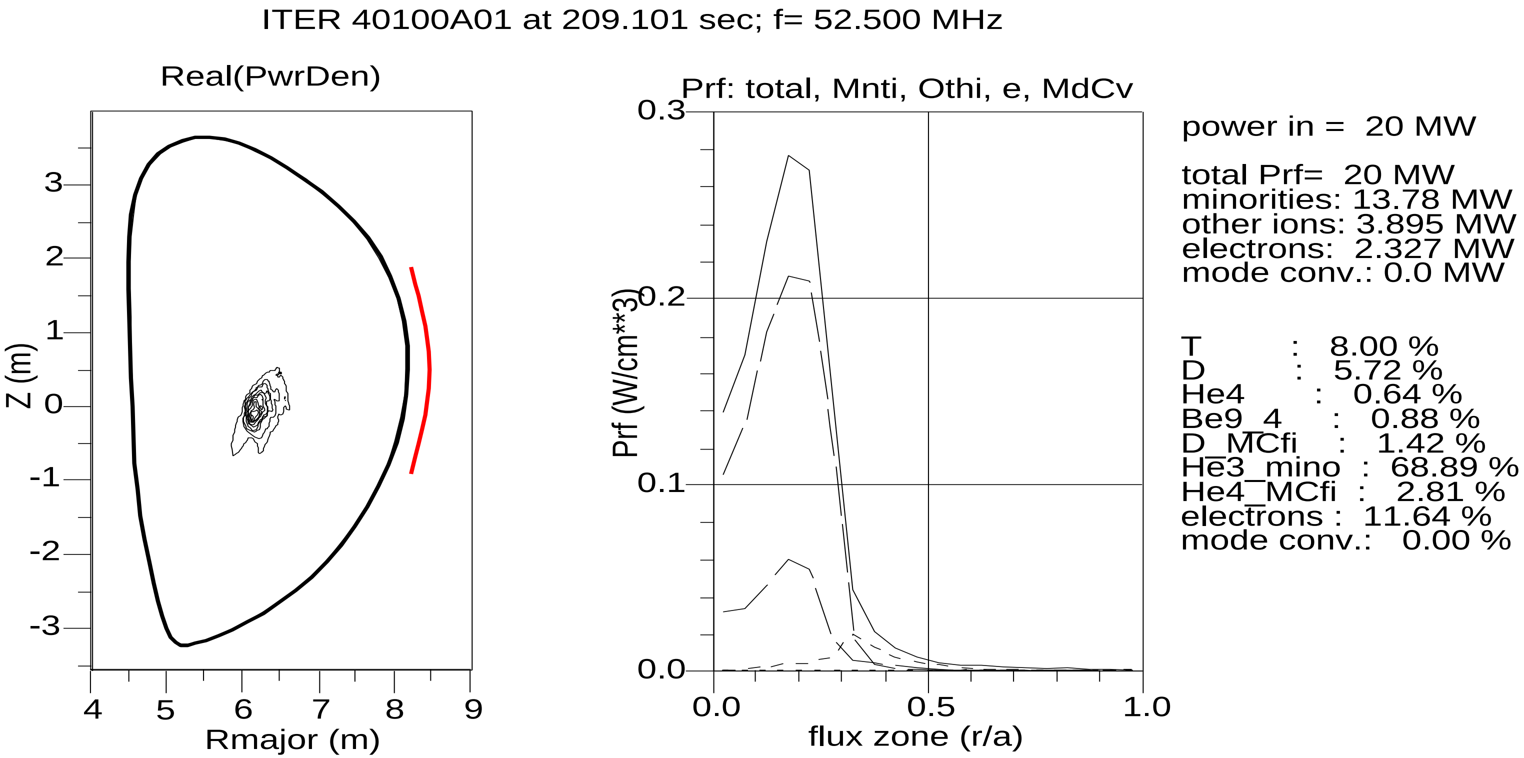
Assume:

$\chi_{mom} = \chi_i$

$P_{NNBI} = 33$ MW

Torques from NNBI

He^3 minority ICRH in the Hybrid plasma



power in = 20 MW

total Prf= 20 MW
minorities: 13.78 MW
other ions: 3.895 MW
electrons: 2.327 MW
mode conv.: 0.0 MW

T : 8.00 %
D : 5.72 %
He4 : 0.64 %
Be9_4 : 0.88 %
D_MCfi : 1.42 %
He3_mino : 68.89 %
He4_MCfi : 2.81 %
electrons : 11.64 %
mode conv.: 0.00 %

Plans for Integrated Modeling using P-TRANSP

- New PPPL - LeHigh - GA - LNL Collaboration
- Near-term upgrades to P-TRANSP
  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
- Long-term upgrades to P-TRANSP
  1. Scrape-off model
  2. density prediction

Conclusions

- 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
- 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