Integrated Modeling of Steady-state Scenarios and Heating and Current Drive Mixes for ITER (ITR/P1-35)

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Outline of the Poster

- **Progress on ITER steady-state scenario modeling by the ITPA-IOS group**
  1) **ITPA-IOS Code-to-code benchmarking** for two ITER SS integrated modelings:
     1) **Weak magnetic shear scenario**
     2) **ITB scenario**
  2) **Recent advances in weak shear scenario development** including limitation/uncertainties in ITER prediction
  3) **Effects of H&CD mixes/upgrades** on SS scenarios

Code BENCHMARK for Weak Shear Steady-State Scenario

- **Target scenario integrates the core and the edge by combining a theory-base (GLF23) transport model with scaled experimental boundary profiles**
- **"Guideline" fixed significant assumptions for the simulations**

I_p = 8 MA
B_T = 5.3 T

R_b,Z_b : given

$n_e(0 \leq \rho \leq 1)$ = given (flat)
N_{GW} = 0.85
$f_D/(f_D+f_T)$ = 0.5
f_{He4} consistent with τ_P^*/τ_E = 5.0
f_{Be} = 2 %
f_{Ar} = 0.12 %

$n_Z(\rho)/n_Z(0)$ same as electrons
$T_Z(\rho)$ same as fuel ions

T_e,T_i $(0.8 \leq \rho \leq 1)$ = given [from exp. $\beta_N(\rho)$]

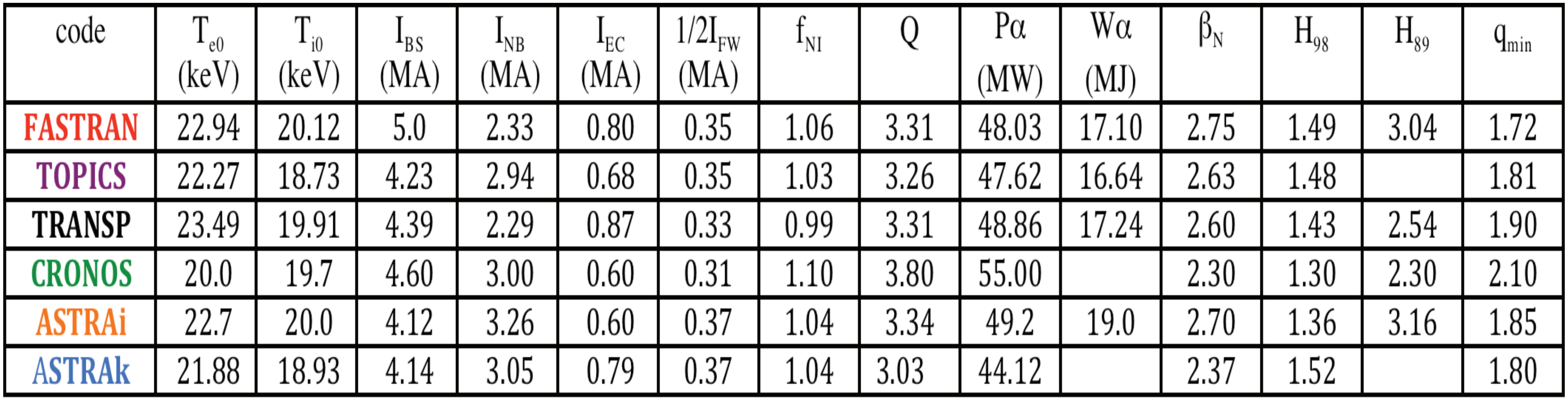
GLF23 settings
Boundary condition at ρ_b = 0.8
α_{ExB} = 1.0
Turn off alpha stabilization
$\chi_\phi(\rho)=\chi_i$(GLF) + 2 χ_i(C-H neo)

Heating and CD sources
P_{NB} = 33 MW (1 MeV, far off-axis, EDA spec.)
P_{IC} = 20 MW (56 MHz,90-deg phasing)
P_{EC} = 20 MW (170 GHz, equatorial upper launcher α=0°, β=40°)

Data
(1) radial profiles – netcdf self-descriptive
(2) equilibrium – geqdsk format
Plasma boundary – Text file format R_b,,Z_b

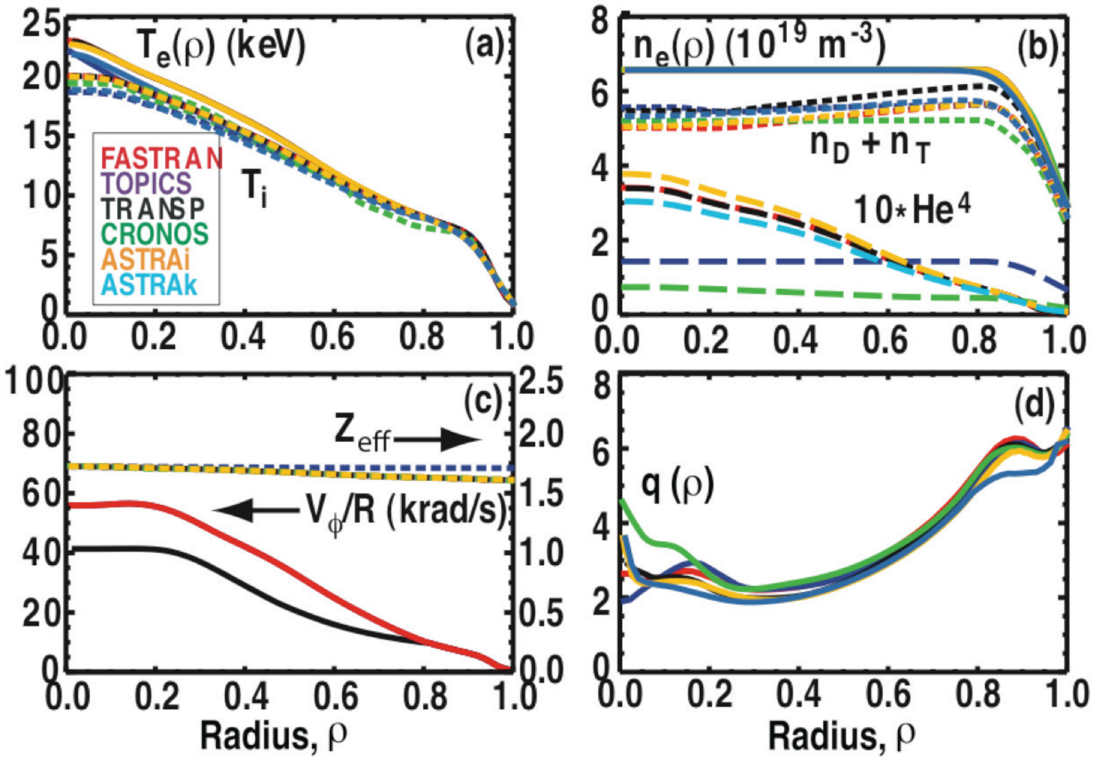
Overall Results From Different Codes Agree Well

- **Results obtained so far from**
  - FASTRAN/ONETWO
  - CRONOS (CEA)
  - TOPICS-IB (JAEA)
  - ASTRAi (ITER)
  - TRANSP
  - ASTRAk(KSTAR)



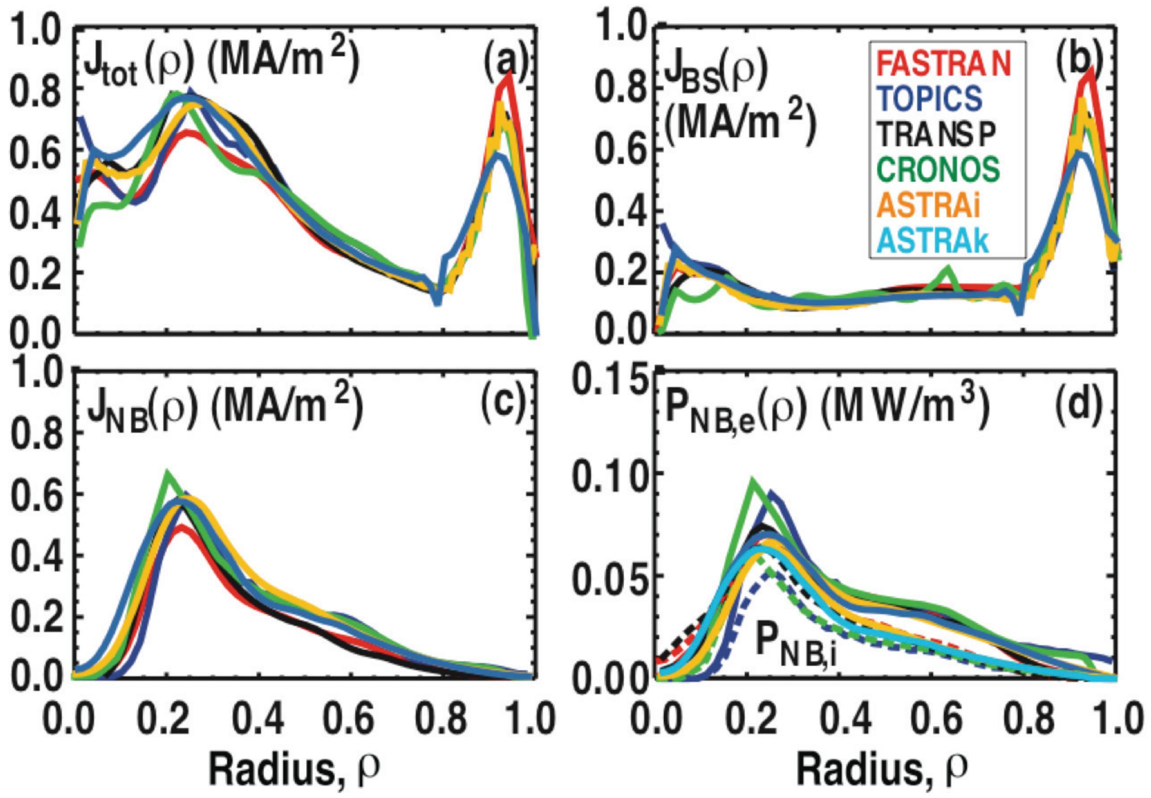
code	T_{e0} (keV)	T_{i0} (keV)	I_{BS} (MA)	I_{NB} (MA)	I_{EC} (MA)	$1/2I_{FW}$ (MA)	f_{NI}	Q	Pα (MW)	Wα (MJ)	β_N	H_{98}	H_{89}	q_{min}
FASTRAN	22.94	20.12	5.0	2.33	0.80	0.35	1.06	3.31	48.03	17.10	2.75	1.49	3.04	1.72
TOPICS	22.27	18.73	4.23	2.94	0.68	0.35	1.03	3.26	47.62	16.64	2.63	1.48		1.81
TRANSP	23.49	19.91	4.39	2.29	0.87	0.33	0.99	3.31	48.86	17.24	2.60	1.43	2.54	1.90
CRONOS	20.0	19.7	4.60	3.00	0.60	0.31	1.10	3.80	55.00		2.30	1.30	2.30	2.10
ASTRAi	22.7	20.0	4.12	3.26	0.60	0.37	1.04	3.34	49.2	19.0	2.70	1.36	3.16	1.85
ASTRAk	21.88	18.93	4.14	3.05	0.79	0.37	1.04	3.03	44.12		2.37	1.52		1.80

Excellent Agreement of the Predicted T_e and T_i Profiles Obtained Using The GLF 23 Model



- **Need to match particle transport model, especially for He ash**
  - $\tau_p^*/\tau_E = 5$ vs D&V model
- **Effects of ExB stabilization are small (with $H_{98} \approx 1.5$)**
  - But even modest rotation could benefit RWM stability…

Global And Local Current Balance (i.e., with Good Alignment) Is Important for Steady State Scenarios

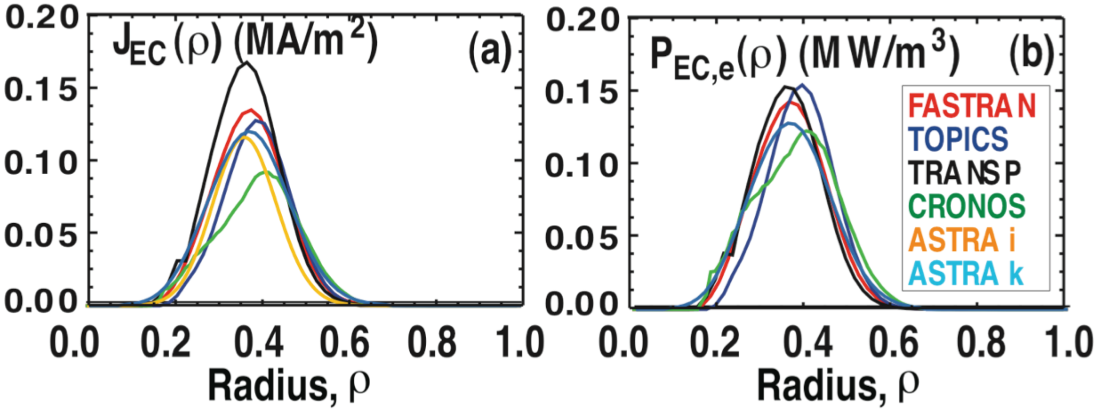


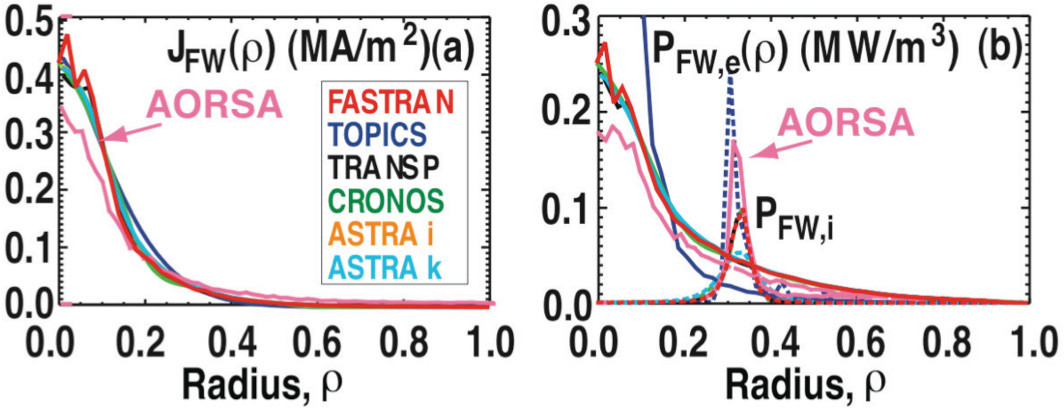
- **Difference of edge bootstrap from $n_e(\rho)$**

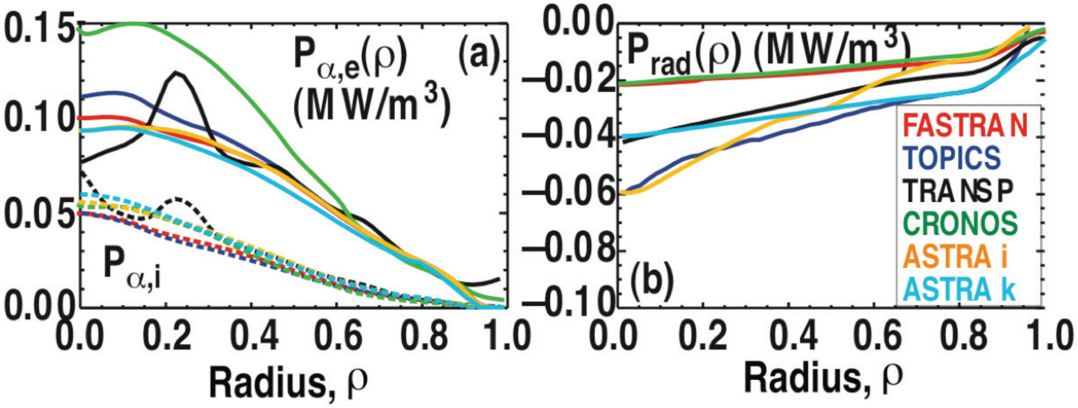
- **Differences in integrated NBCD are large (up to 30%)**
  - ≈10% due to the NB magnetic alignment effect but still others unresolved

- **Good agreement between M-C and F-P codes in heating (but not CD)**

ECCD and FWCD are Important for Fine-tuning the Current Alignment While DT Fusion Power Starts Dominant







- **ECCD differences in the momentum conservation effects**
  - CQL3D/TORAY≈1.3 not included in other codes

- **FW results mostly imported from the guideline profile (CURRAY)**
  - Only ½ full FWCD capability needed to avoid overdrive near the axis

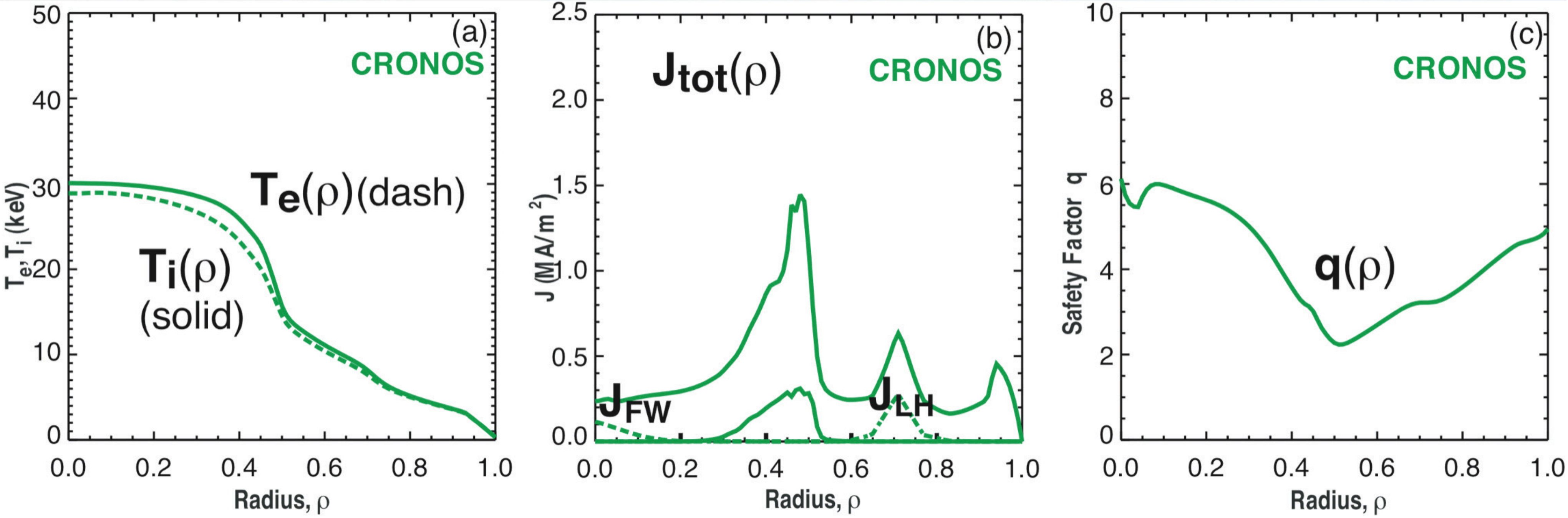
- **CURRAY benchmarked well with AORSA3D**

To be checked at ITPA meeting @ Seoul

- **Alpha power difference**

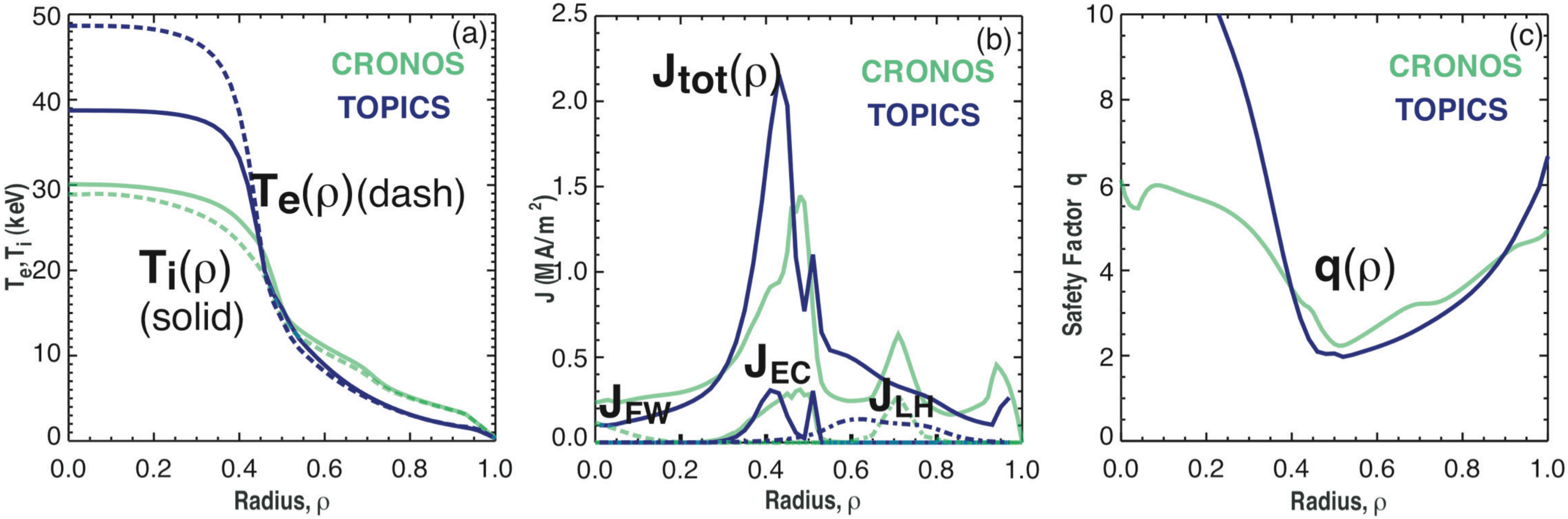
- **Large variation of radiation profiles**

Code BENCHMARK: ITB Steady-State Scenario (1 of 3)
CRONOS



- **Developed by a prescribed transport model similar to that used in developing the official SS scenario (Scenario-4)**
  - $\chi_i = \chi_e = \chi_{i,neo} + 0.4(1 + 3\rho^2) \bullet F(s)$
    where F(s) is a shear function [F(s) → 0 for s<0]
- **ECCD at mid-radius: key role in triggering and keeping the ITB (via j_{BS})**
- **In order to keep the ITB, no high amount of CD inside ITB ⇒ no NBI**
- **CD needed for $V_{loop} = 0$; outside ITB ⇒ LHCD**
- **$I_p = 8$ MA, $f_{NI} = 100$ %, $f_{BS} = 70$ %, $Q = 6.5$**

Code BENCHMARK: ITB Steady-State Scenario (2 of 3)
TOPICS-1B Simulation



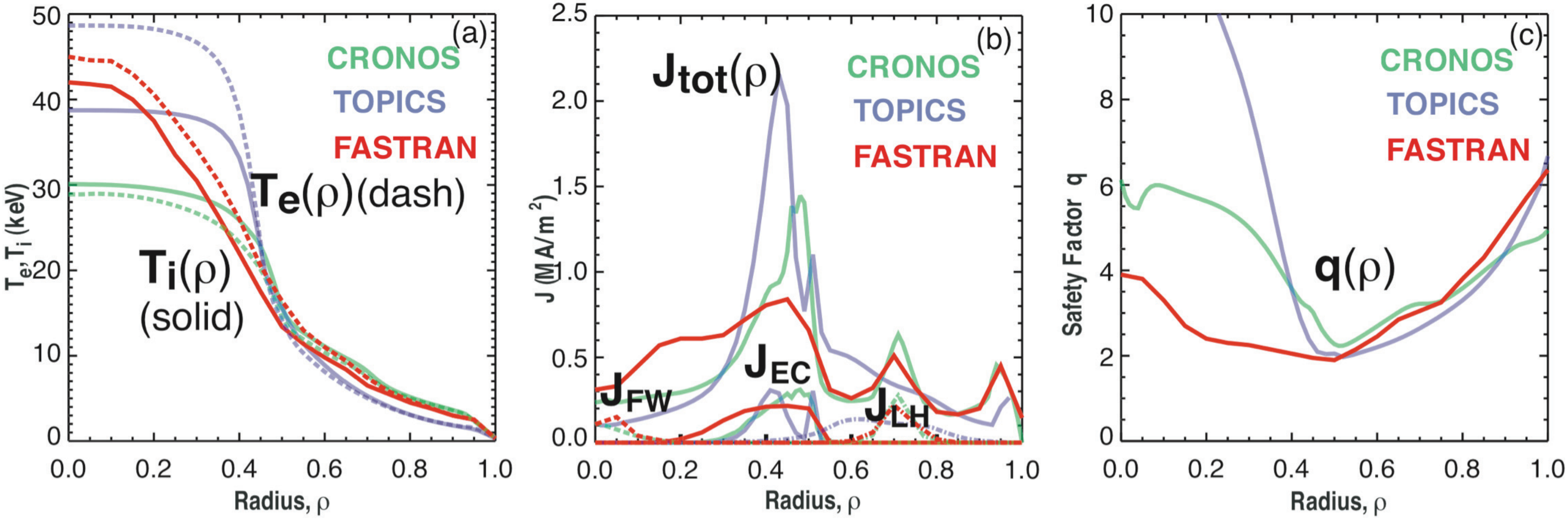
<u>**Same ECCD launcher to that used in CRONOS shows**</u>

- **ITB shrinkage without achieving stationary state due to split** (double-humped) **ECCD** (owing to Shafranov shift caused by large α-heating)

<u>**Additional outward aiming of EC deposition**</u> (from a top launcher) **together with LH was used to lock the outer ITB location**

- **Although this made it steady state, the temperature ITB profiles are different from that obtained by CRONOS**

Code BENCHMARK: ITB Steady-State Scenario (3 of 3)
FASTRAN/ONETWO



- **With a narrower ECCD as the guideline**
  - ITB was generated using same ECCD as the guideline, but different ITB
  - Strength of ITB depends on width and height of ECCD
- **With a broader ECCD deposition,**
  - <u>Weak</u> ITB generated in steady state
  - ECCD broadness provides better control over stability and confinement
- **Similarity to the DIII-D experience**
  - Broad ECCD depositions leads to more stability at higher β

Integrated Modeling of Weak Shear Steady State Scenarios for ITER

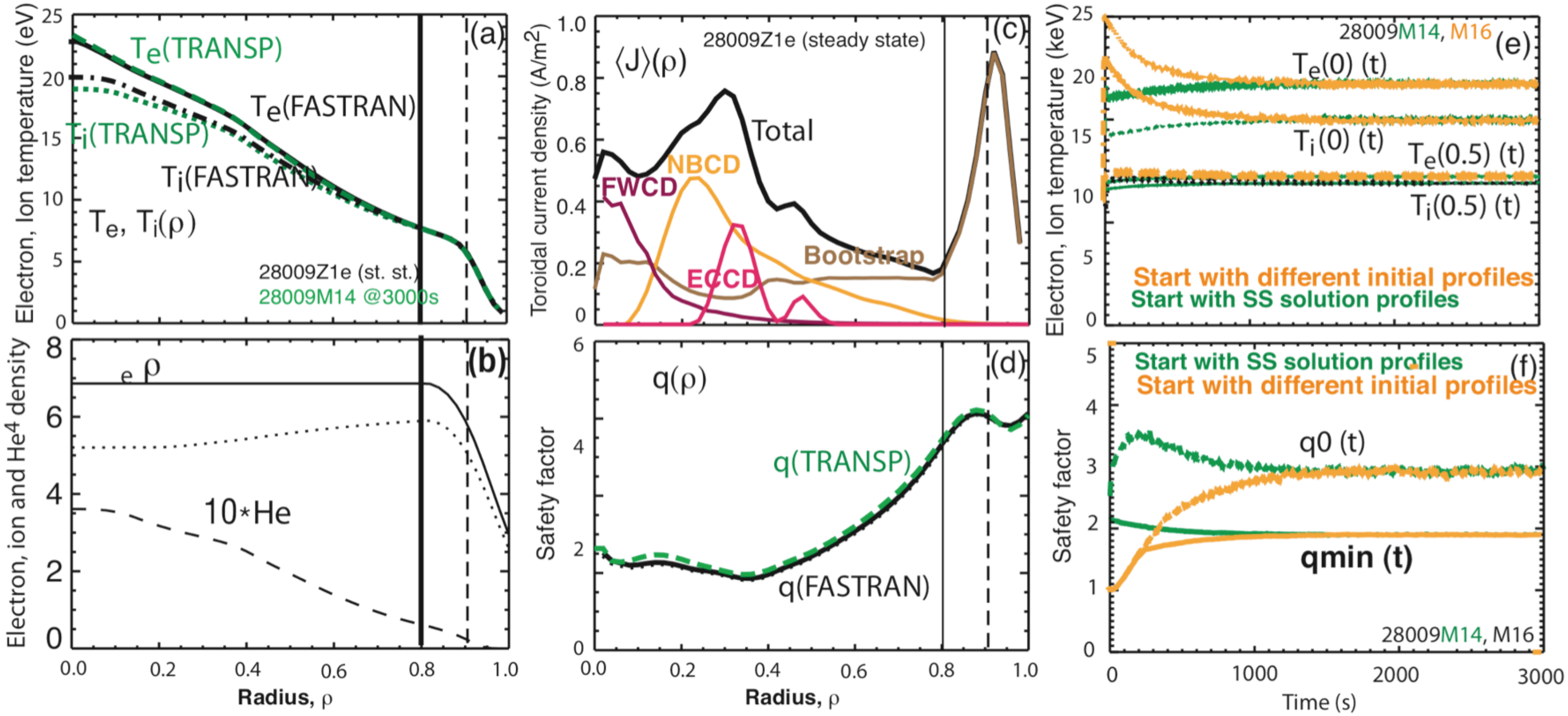
RECENT ADVANCES

- **Treatments of the boundary conditions**
  - Use scaled experimental edge profiles rather than required for achieving the goal
  - Affected some conclusions
- **New efficient, iterative steady state (*d*/*dt*=0) solution procedure using FASTRAN/ONETWO/EFIT [JM Park:EXC/ P2-05]**
  - Benchmarked well with a number of time-dependent simulations
  - Application to H&CD studies
- **Updates of CD modules**
  - ECCD with parallel momentum conservation (x1.1 – 1.3)
  - NBCD

Weak Magnetic Shear Scenario Developed Using Theory-Based GLF23 Model with Scaled Experimental Boundary Condition

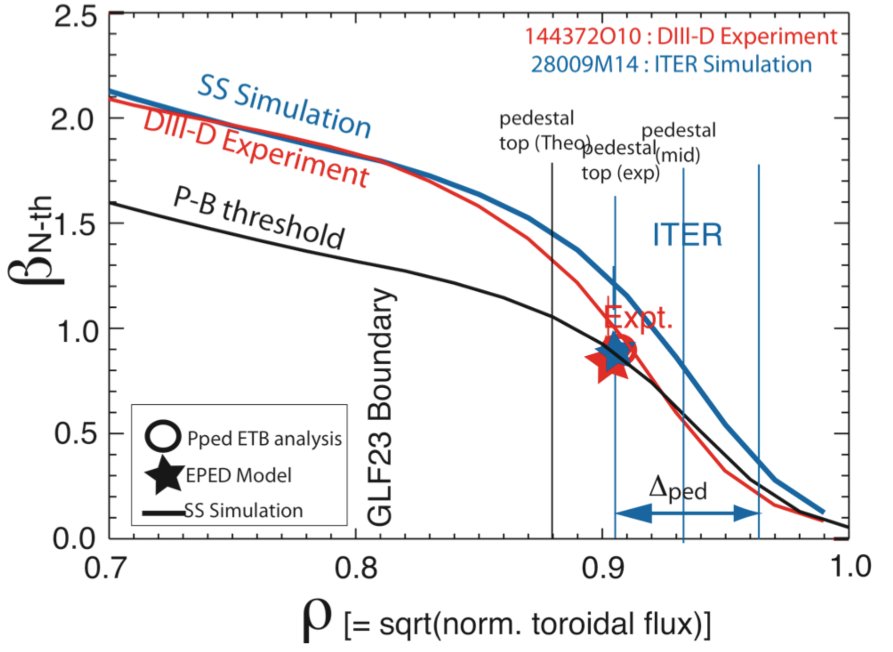
Fully Noninductive Steady-State Scenario at I_p = 8 MA

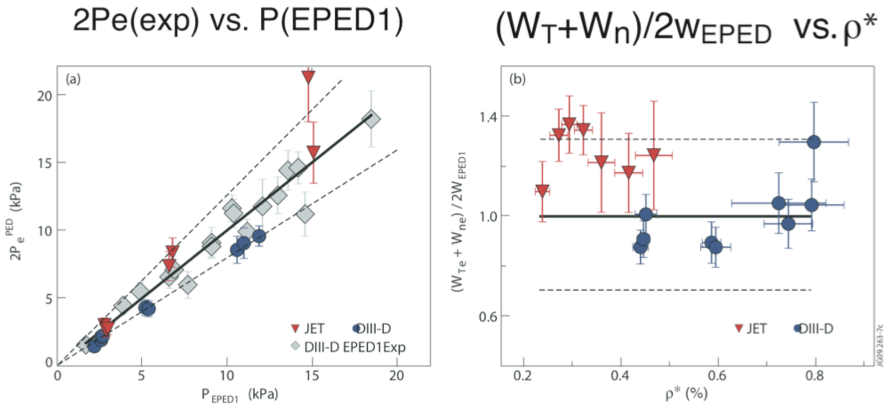
P_{NB}	33 MW
P_{FW}	33 MW
P_{EC}	20 MW
B_T	5.3 T
I_p	8.0 MW
q_{95}	5.73
N_{GW}	0.90
f_{BS}	63.5%
f_{NB}	26.4%
f_{FW}	4.0% (1/2 CD)
f_{EC}	7.5%
f_{NI}	101.3%
Q	3.38
H_{98y}	1.48
H_{89p}	3.01
β_N	2.76
$\beta H/q^2$	0.253



- **Maximize ρ_{qmin} with flat q > 2 by using the ITER day-1 H&CD**
  - NB: providing most of off-axis CD to sustain q > 2 ⇒ farthest off axis steering
  - EC: tailoring j(ρ) ⇒ aiming to maximize ρ_{qmin} combined with off-axis NBCD
  - FW: control of q_0 ⇒ 56 MHz to maximize FWCD efficiency
- **Fully relaxed steady-state**
  - No current evolution with nearly zero V_{loop} (= -0.4 mV)
- **High plasma confinement with H_{98y2} = 1.5**
  - No ExB stabilization in GLF23, Magnetic shear controls confinement
- **Steady state solution obtained independent of initial conditions within τ_R ~ 1000 s**

Uncertainties In Predicting The ITER Boundary Makes The ITER SS Predictions Difficult



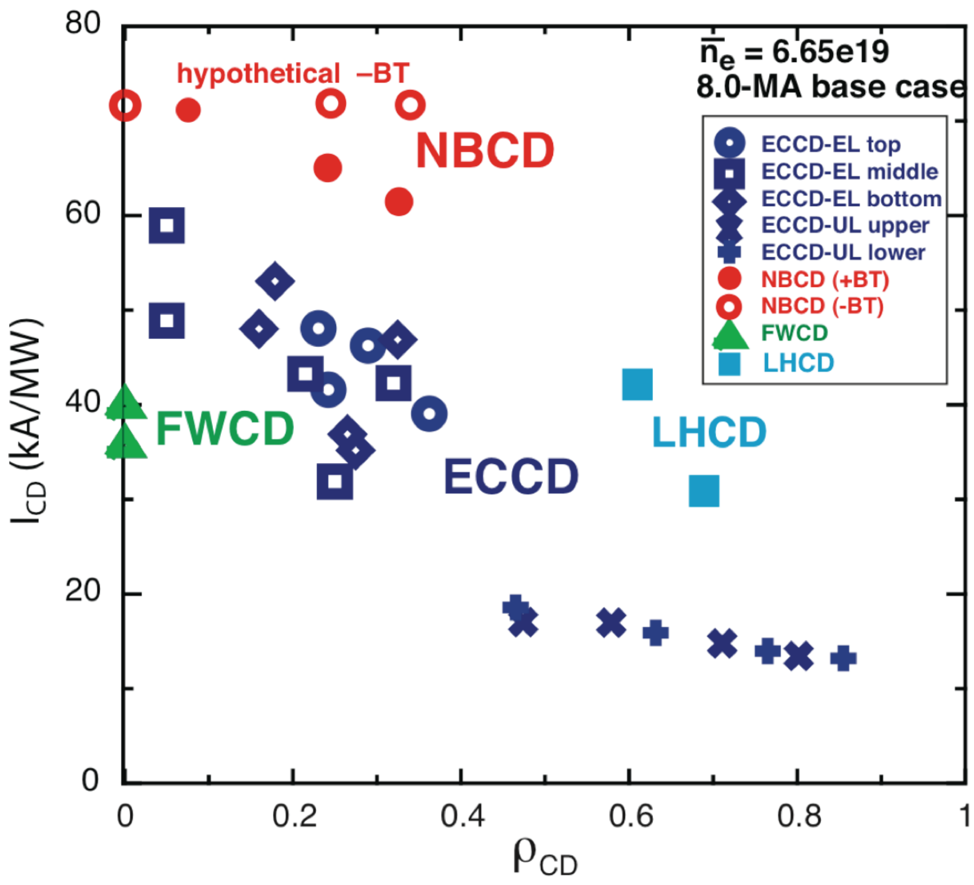

2Pe(exp) vs. P(EPED1)

$(W_T+W_n)/2w_{EPED}$ vs. ρ*

Beurskens et al., PPCF 2009

- **ELITE analysis based on a set of a series of simulations indicates that P-B threshold is ~25% below the simulation edge** **[P. Snyder: THS/1-1]**
- **Recent Experiment on ρ* Scaling of Pedestal in JET/DIII-D**
- **Weak inverse (or zero) ρ* dependence of pedestal width and height**
- **Most of theory-based models predict positive ρ* dependence**
- **Analysis still in progress**
  - Uncertainties in predicting pedestal widths and heights range at ±(25-30)%
  - The simulation $\beta_N(\rho)$ ≈ an upper end of the uncertainties
- **This tends to compensate the GLF23 which is known to be pessimistic among the models**

Heating and Current Drive Mixes for ITER

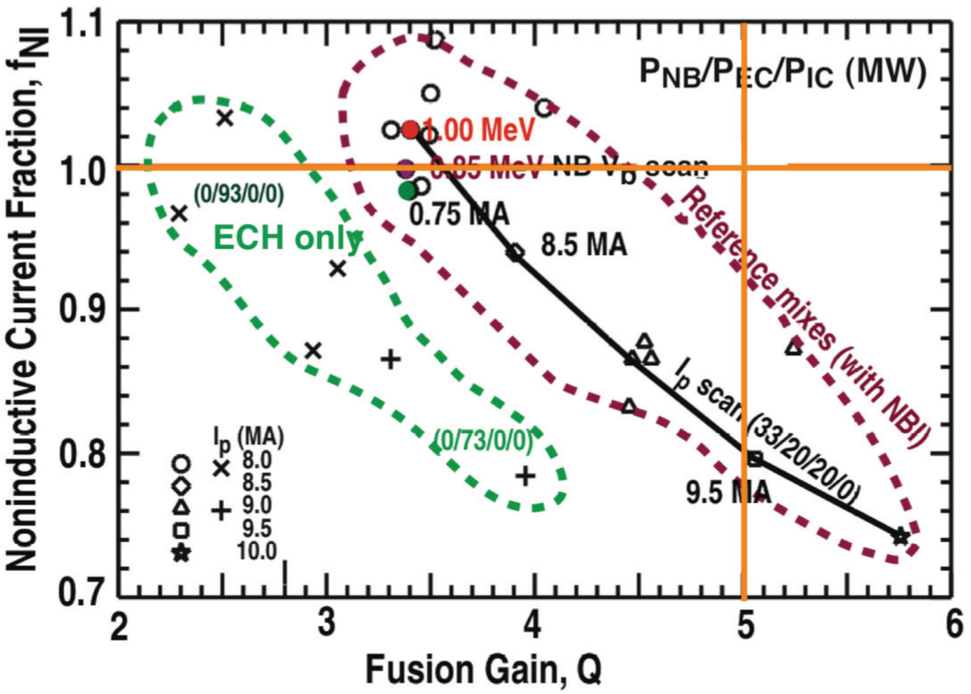


- **Steady state scenarios need well-aligned current drive sources for desired fusion performance**
  - Need for multiple, efficient CD sources at different locations

- **Shown on the right is comparison of CD efficiency (kA/MW) for the ITER main H&CD sources for a fixed profiles (8-MA Baseline)**

- **In scenario simulations, CD calculations need to be self-consistently evolved with transport and equilibrium**

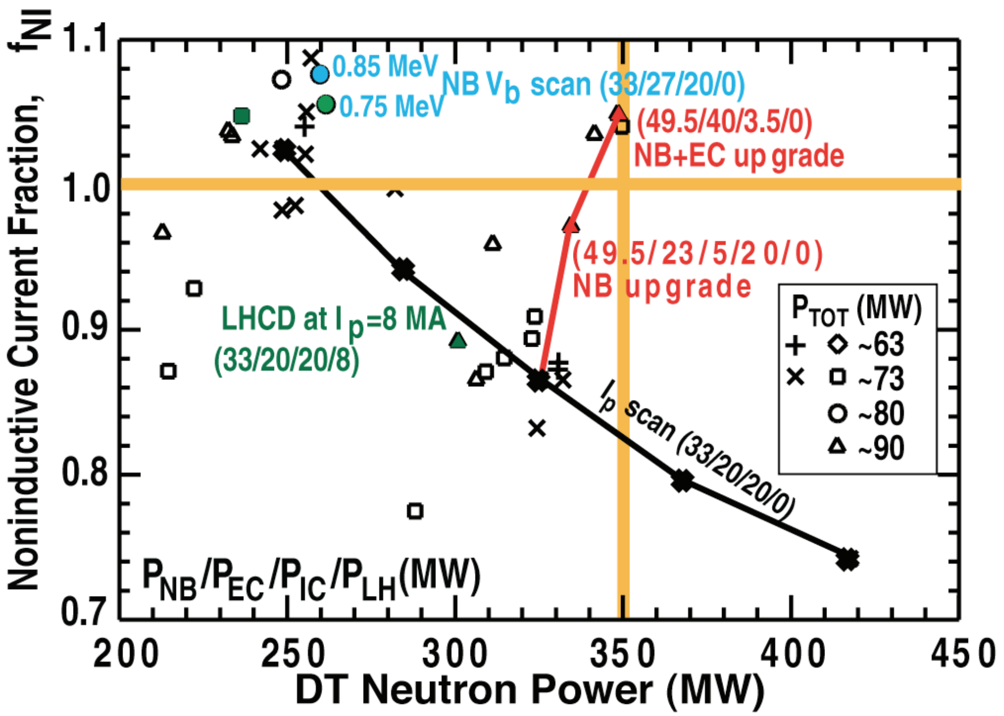
Operation Space for f_{NI} and Q with Different H&CD Mixes Examined in a Wide Range of Stationary State Conditions



- ~30 ITER SS scenarios evaluated with different H&CD mixes
- Trade off between Q and f_{NI}, as in the I_P scan (8 – 10 MA)
- High Ip operation (I_p = 9 MA) would be important to achieve Q=5, but would lack 1-2 MA of NI current in the Day-1 H&CD
- However, the long-pulse goal (3000 s) with Q=5 at I_p = 9 MA may be possible, if a sufficient (15–30 Weber) remains in the poloidal system for the SS burn phase

- Scenarios with NBI achieve highest f_{NI}
- In the Q=5 steady state objective, NBI provides the main CD with ECH tailoring j(ρ)
- For NBI, CD does not suffer too much even with 850-kV injection
- Direct ion heating with ICRF is beneficial in increasing Q

H&CD Upgrades Need for High Neutron Power and Long Pulse Operation (High f_{NI}) During the ITER Engineering Phase



- Scenarios with NBI achieves highest P_{DT} and f_{NI} (or long pulse operation) with benefit from ion heating
- Better yet is combination of ECCD and NBCD for current profile control
- Preliminary LHCD is included. Although LHCD can increase f_{NI} at radii larger than the present NBCD can reach, its heating is penalized by being far off-axis and no ion heating

Summary (1 of 2)

Recent progress on ITER Steady State scenario modeling by ITPA-IOS group is reviewed

- **Progress in ITPA-IOS code benchmarking for steady state scenarios is made for two types**
  - Weak shear scenario
    - Integrate the plasma core and edge by combining a theory-base (GLF23) transport model with scaled experimental boundary profiles
    - Good agreements in overall kinetics and profiles
  - ITB scenario
    - Concerns: Sensitivities to transport model and hardware
- **Benchmarking ECCD revealed**
  - Shows excellent agreement in the basic part (ray-tracing), but need to include the parallel momentum conserving effects (up to x1.3)
- **Benchmarking NBCD showed**
  - Differences between Monte-Carlo and Fokker-Planck codes coming from a part of NBI-magnetic alignment effects and the other unresolved part

Summary (2 of 2)

- **Weak shear scenarios are exploited by a steady-state solution procedure**
  - Using GLF23 transport model in the core (T_e, T_i and Ω_{rot}) prescribed flat density with scaled experimental boundary profiles
- **Fully noninductive steady state scenario is achieved:**
  - f_{NI} = 101%, Q=3.4, f_{BS} = 64%, β_N = 2.8 at I_p = 8 MA and B_T = 5.3 T using ITER day-1 H&CD system
- **Uncertainties/limitations**
  - Estimated from theoretical instability limits and experimental scaling laws
  - Underscores uncertainties in predicting pedestal and transport for ITER
- **Operation at 9 MA to achieve Q=5 would lack 1–2 MA of noninductive current using the day-1 H&CD system**
  - However, Q=5 can be sustained for >3000 s at I_p = 9 MA if a sufficient flux (15–30 Weber) remains for the SS burn phase
  - Simultaneous achievement of Q = 5 and f_{NI} = 100% requires H_{98y2} = 1.7 – 1.8, as in scenario-4
- **NBI and EC upgrade will achieve P_{DT}=350 MW, steady state (f_{NI}>100%) at I_p = 9 MA**

Code Descriptions (Options Applied to the Benchmark Simulation)

codes / area	**FASTRAN/ ONETWO**	**TOPICS**	**TRANSP**	**CRONOS**	**ASTRAi**	**ASTRAk**
GLF23 solved	Te,Ti,Vt Ste-state-sol	Te,Ti,Vt Time-dep	Te,Ti,Vt; Time-dep	Te,Ti,Vt?; Time-depend	Te,Ti,Vt Time-dep	Te,Ti,Vt Time-dep
Equilibrium	EFIT	MEUDAS	VMEC		SPIDER	ESC
Bootstrap Current	Sauter	matrix Inv. Model	Sauter	NCLASS	NCLASS	Sauter
NBCD	NUBEAM (M-C)	FP 2D/OFMC (F-P)	NUBEAM	SPOT (M-C)	NBI pack. (analytic)	NBI pack (analytic)
ECCD	TORAY/CQL3D (w/ PMC effects)	EC-Hamamatsu (w/ PMC effects)	TORAY-GA (w/ PMC effects)	REMA	GRAY	TORAY-GA
FWCD	CURRAY	TASK/WM no JCD calc.	[CURRAY]/ TORIC	PION		CURRAY in KSTAR
LHCD	GENRAY/CQL3D	ACCOME	LSC	DELPHINE	FRTC	LSC
Fusion	NUBEAM (M-C)	STIX formula	NUBEAM (M-C)	SPOT (M-C)	FP 2D	FP 2D
Fusion Reactivity	Bosche-Hale	Bosche-Hale	Hively	Bosche-Hale	Putvinski	Putvinski
Radiation (Brems;Cyclr; Line)	no Brems; DPost1997	w/ Brems; CYTRON; coronal;	Trubnikov; coronal	EXATEC; coronal	w/ Brems. CYNEQ coronal	Brems. CYNEQ coronal
Comments	PMC=paral. moment conserv				ASTRAi= ASTRA in ITER	ASTRAk= ASTRA in KSTAR