EX/9-1

Progress in Preparing Scenarios for ITER Operation

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For the IOS-TG of the ITPA

FEC 2014, St Petersburg, Russia

17 October 2014

Outline

The **Integrated Operation Scenarios** Topical Group of the ITPA has coordinated experiments and simulations

1. Joint experiments, demonstrating ITER scenarios

- Plasma formation
- Ramp-up to 15MA and ramp-down
- Scenarios for operation at high Q~10

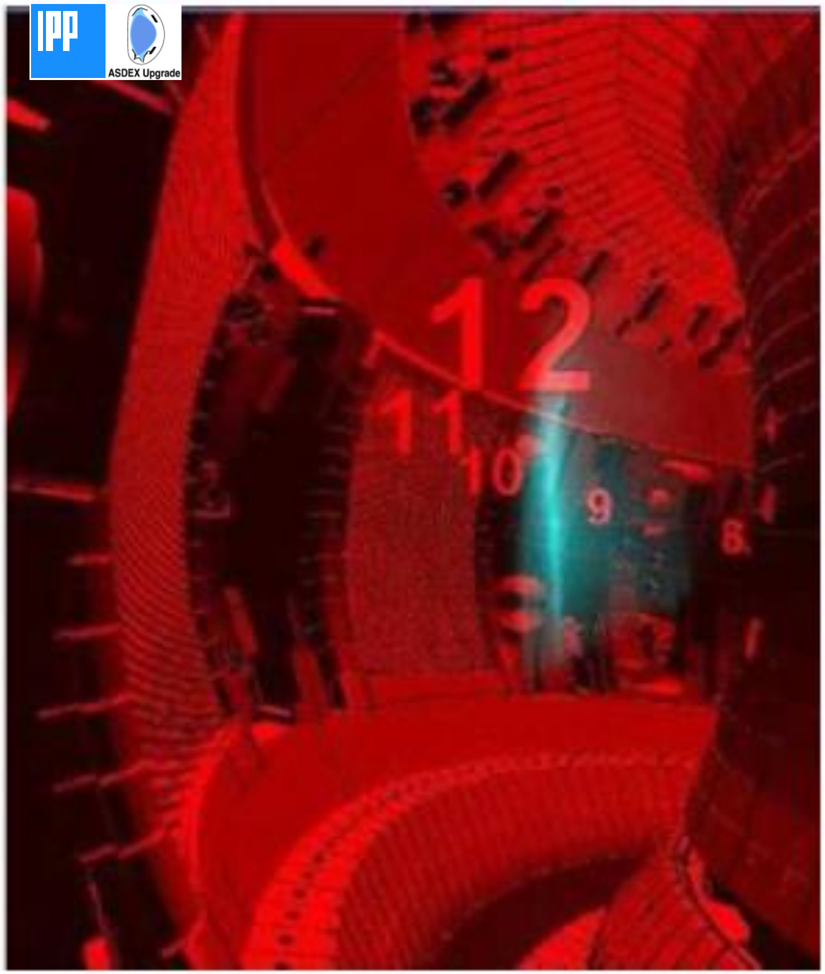
2. ITER scenario modelling using several codes

- Non-active operation in ITER
- Benchmarking scenario codes (using the hybrid scenario)
- Scenario exploration (steady state scenarios)

Conclusions

Joint Experiments: Plasma formation

AUG: ECH, X2



Numbers are segments of AUG

ITER:

Electric field: ≤ 0.35V/m

ECH assist: O1 at 5.3T,
(Up to 8MW) X2 at 2.65T
toroidal launch

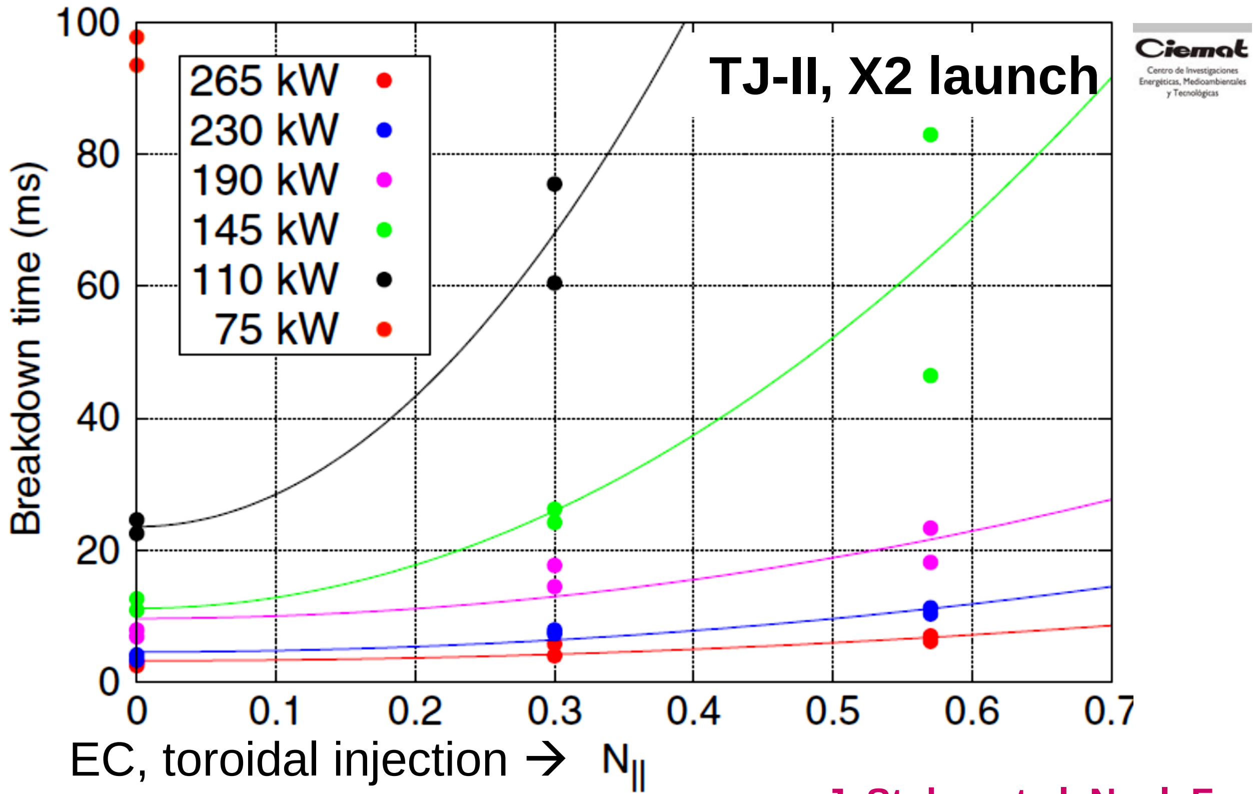
Experiments:

- Low E_{loop} tested (~0.2V/m)
- Robust plasma breakdown in devices with metal walls.
- ECH for pre-ionisation and burn-through assist.

J. Stober et al, Nucl. Fusion 51 (2011) 083031

Experiments: Plasma formation

Experiments using an inclined EC launch angle at plasma formation to mimic the conditions in ITER.

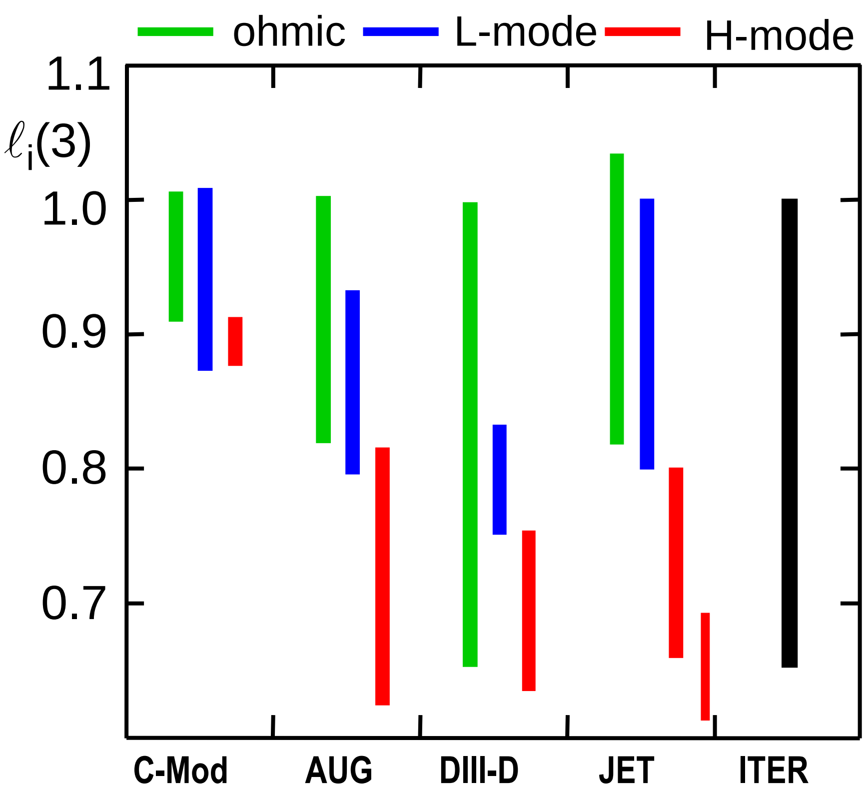


~ 2x more power required compared to radial launch

J. Stober et al, Nucl. Fusion 51 (2011) 083031

To do: Assess EC stray radiation in an “empty torus” in ITER

Experiments: Ramp-up phase



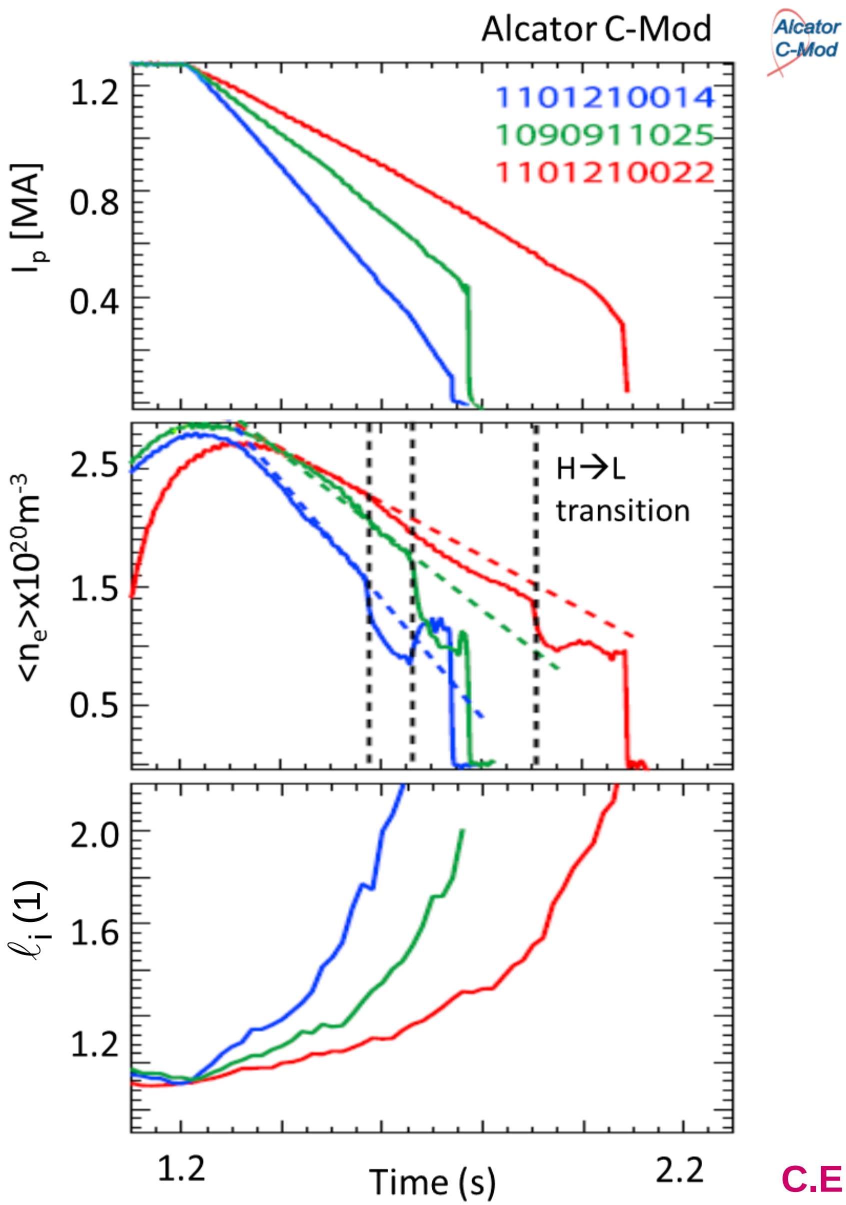
A.C.C. Sips et al, Nucl. Fusion 49 (2009) 085015

For the ramp-up

- ITER ramp up to 15MA:
  - $\ell_i < 1$: Vertical position control
  - $\ell_i > 0.65$: PF force limits
- Early X-point formation
- Heating to control ℓ_i and reduce the flux consumption.
- A range of plasma inductance ($\ell_i(3)$) can be obtained from 1.0 to 0.65 (H-mode).

To do: What is the fastest stable ramp-up ? (reserving maximum flux for flat top burn)

Experiments: Ramp-down phase



For the ramp-down

- For the rampdown, the plasma should stay diverted and maintain H-mode to maintain vertical stability.
- Density decay ~ I_p
- For (ohmic) rampdown a reduction of the elongation from 1.85 to 1.4 would minimise the increase in plasma inductance to 1.3-1.4.

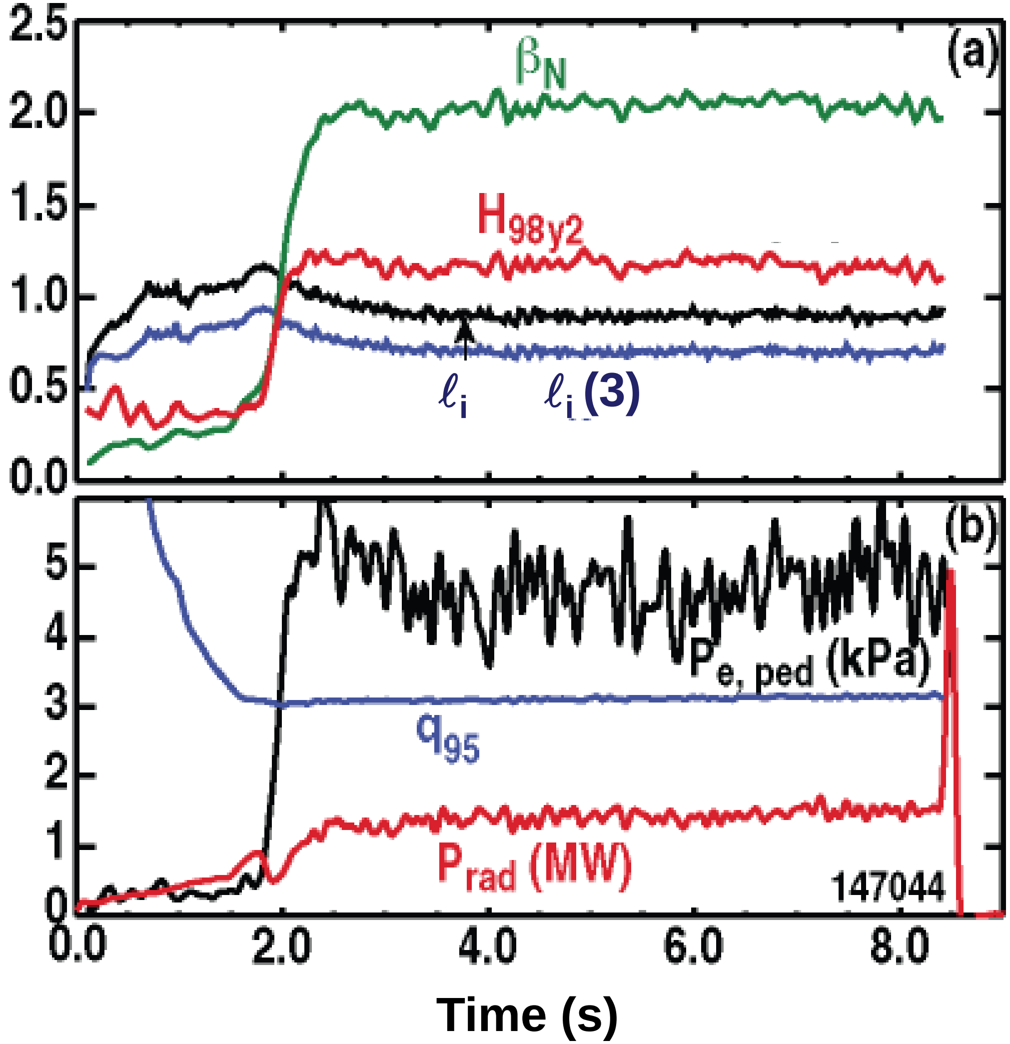
To do:

Plasma termination scenarios following off-normal events

C.E. Kessel et al, Nucl Fusion 53 (2013) 093021

Experiments: Scenarios for Q~10

DIII-D: ITER baseline

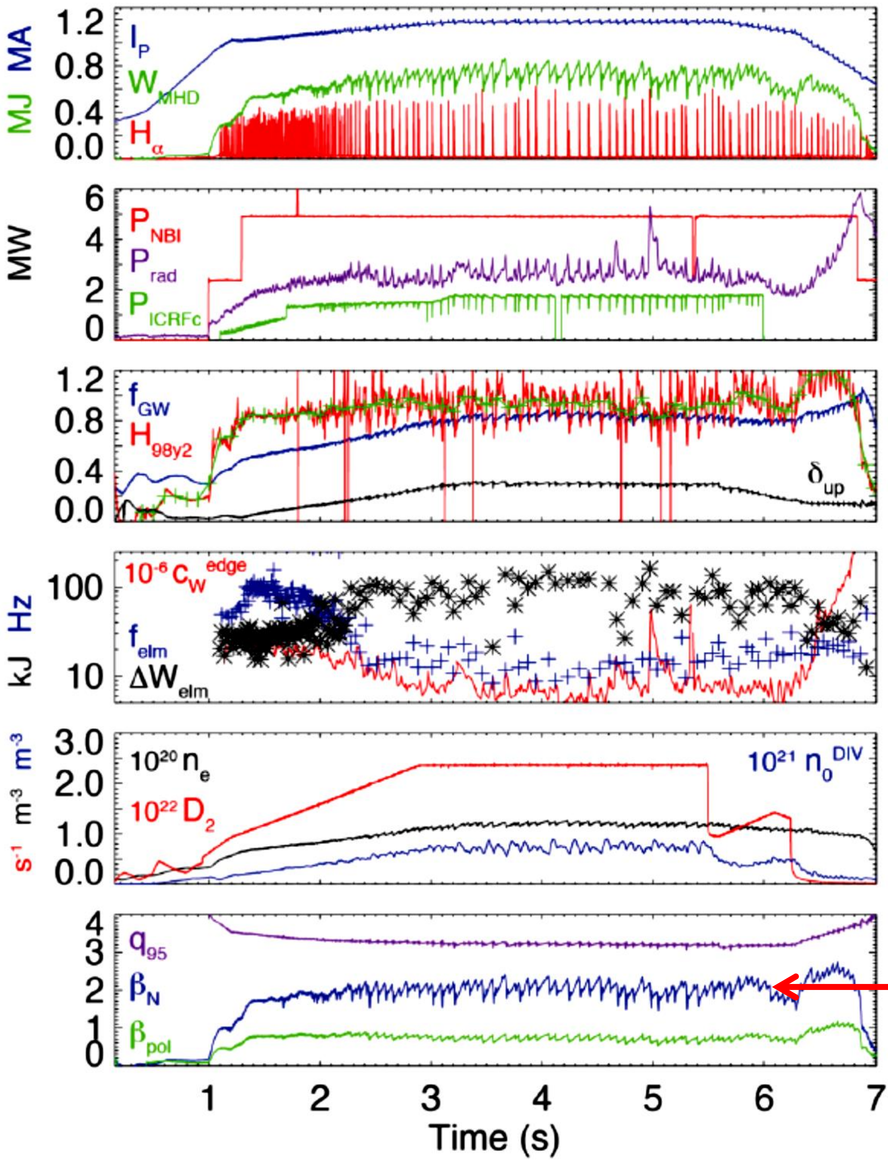


Joint experiments on demonstrating operation with scaled parameters for the ITER baseline scenario at q_{95}~3

- AUG
- C-Mod
- DIII-D
- JET

G.L. Jackson et al, Proc. 24th FEC, San Diego, USA (2012) EX/P2-08

Experiments: Scenarios for Q~10



AUG: ITER baseline

Joint experiments on demonstrating operation with scaled parameters for the ITER baseline scenario at q_{95}~3

- AUG (W wall)
- C-Mod
- DIII-D
- JET

β_N ~ 2 to maintain high enough f_{ELM}

J. Schweinzer, this conference, EX/9-4

Experiments: Scenarios for Q~10

H-modes at q_{95}~3:

- Most experiments obtain $H_{98}(y,2)$~1.0 only for β_N=2.0-2.2. Also, at β_N~2, more stable ELMy discharges
  - ✓ ELM mitigation in ITER baseline discharges is difficult.

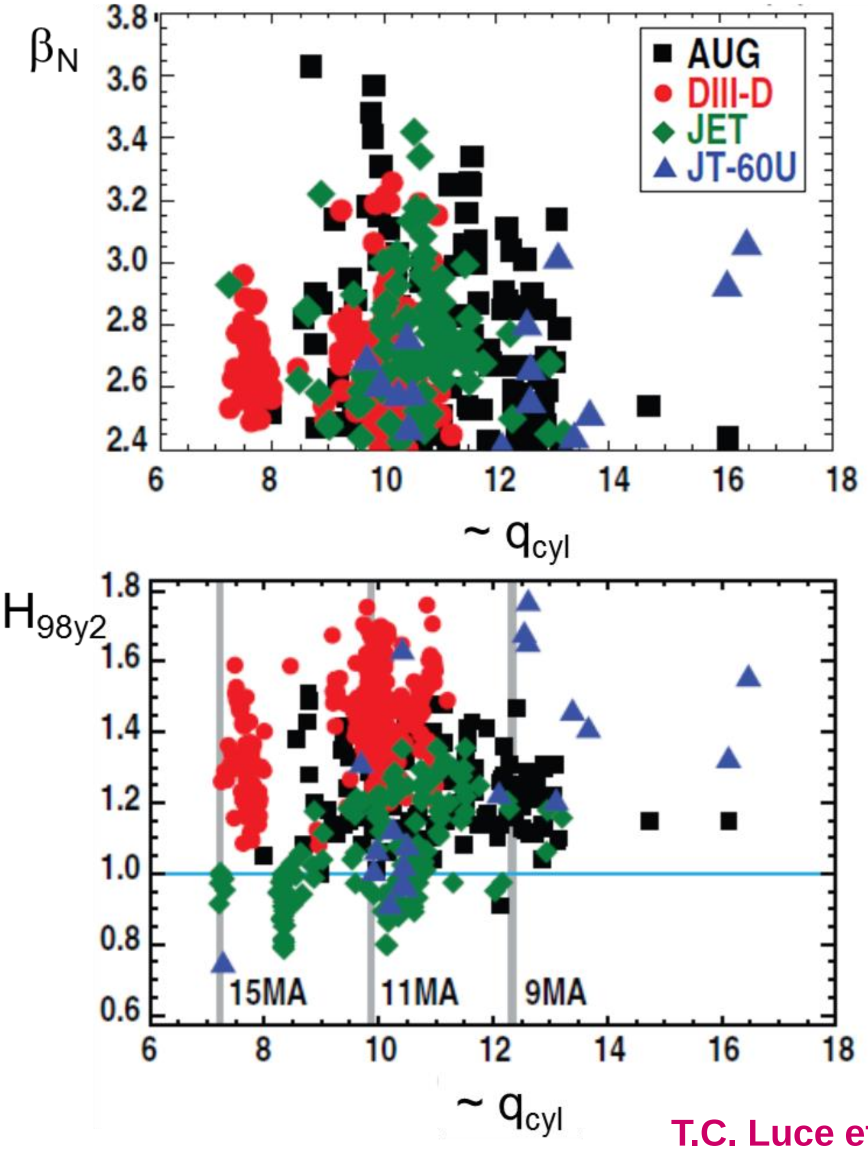
- However, with a metal wall in AUG and JET (and C-Mod) the confinement in baseline scenarios is lower: $H_{98}(y,2)$~0.85-0.9.
  - ✓ JET has made progress in demonstrating $H_{98}(y,2)$~1

I. Nunes, this conference, EX/9-2

To do:

- Experiments with dominant electron heating (in progress)
- Transient and stationary heat flux handling (ELMs & seeding)
- Simulate entry to burn and burn control

Experiments: Scenarios for Q~10



Operation at higher beta,
$\beta_N>2.4$, with $H_{98}(y,2)$ significantly above 1

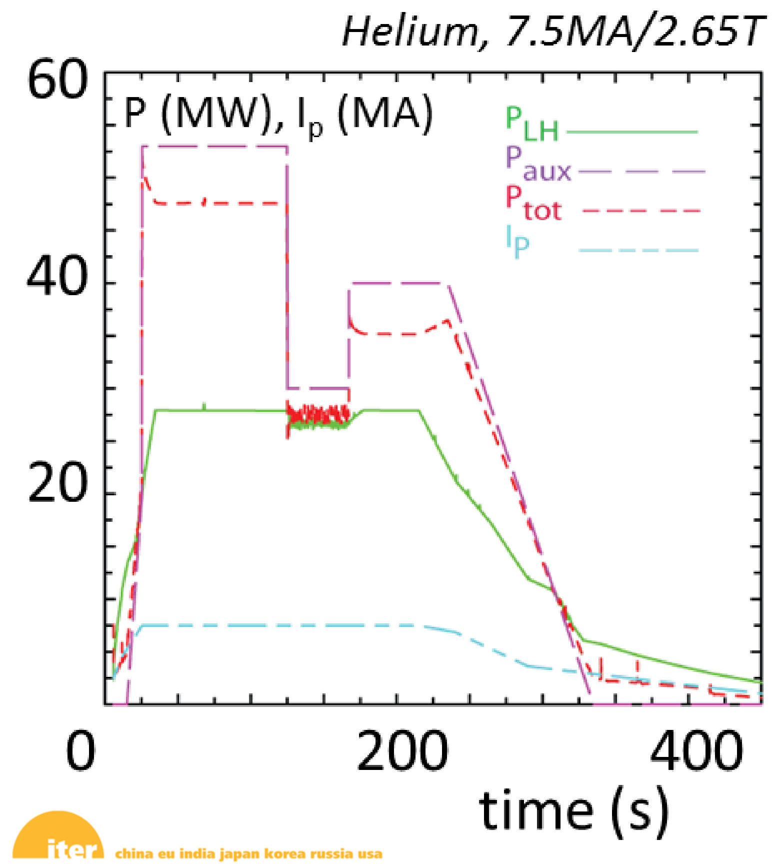
→ Q>10 at 15 MA or Q~10 at reduced plasma current of 11MA.

To do:

Integrate high power scenarios with divertor solution (seeding).

T.C. Luce et al, Nucl. Fusion 54 (2014) 013015

Simulations: Non-active phase



T. Casper et al, Proc. 24th FEC, San Diego, USA (2012) ITR/P1-15

For hydrogen and helium:

Complete scenario simulations with CORSICA and JINTRAC at high input power (>50MW).

At 2.65T:

- In helium, H-mode operation may be possible for ≥ 35MW.
- In hydrogen, H-mode operation is expected to be marginal, even with 60 MW of input power.

At 5.3T:

L-mode for both helium and hydrogen, with flat top duration at 15MA of 20-50s.

Simulations: Non-active phase

ITER scenario simulations at 7.5MA/2.65T

	Hydrogen	Helium
P_{add}	53 – 63MW	63MW
P_{LH} at 0.85% n_{GW}	54MW	27 – 38MW
Min-n_e for H-NBI	4.5×10^{19} m^{-3}	2.5×10^{19} m^{-3}
Fuelling	gas + pellets	gas only
CORSICA & JINTRAC		
Plasma regime	L-mode/type III H-mode	H-mode
Flat top length	200-500s	200-2000s

Key issues:

- L → H mode threshold
- Fuelling of helium plasmas
- High minimum density limit for use of NBI in hydrogen
- The PF coil set in ITER has large margins for operation at 7.5MA

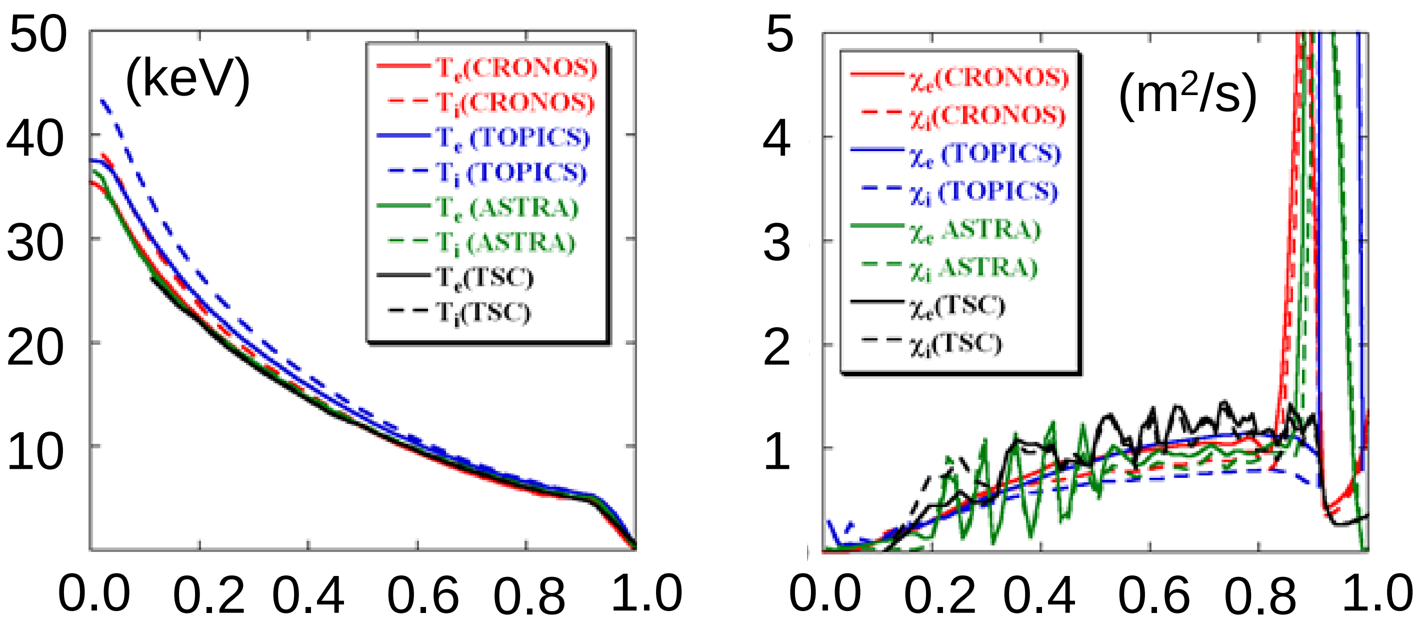
To do: Joint Experiments to provide data to benchmark codes

Simulations: Code benchmarking

Using parameters for the ITER hybrid scenario at 12MA/5.3T:

- Same heating schemes (NBI and ICRH) to test codes
- Assume pedestal (T_e = 5 keV) and fixed density profile
- GLF23 transport model

→ Test scenario codes, developed by different groups.



Simulations: Code benchmarking

For a hybrid scenario at 12 MA, using 30MW NBI and 20MW ICRH.

	ONETWO	TOPICS	TSC/TRANSP	CRONOS	ASTRA
I_{BS} (MA)	3.87	3.83	3.39	4.26	2.89
I_{NB} (MA)	2.07	2.26	1.42	0.92	1.91
f_{NI}	0.50	0.51	0.40	0.43	0.40
Q	6.5	7.7	7.5	8.3	7.9
β_N	2.1	2.38	2.18	2.3	2.07
$H_{98(y,2)}$	1.1	1.07	1.18	1.23	1.2

C.E. Kessel et al, Nucl. Fusion 47 (2007) 1274

→ **Extensive benchmark studies for heating and current drive codes have been performed: EC, NBI, ICRH and LHCD**

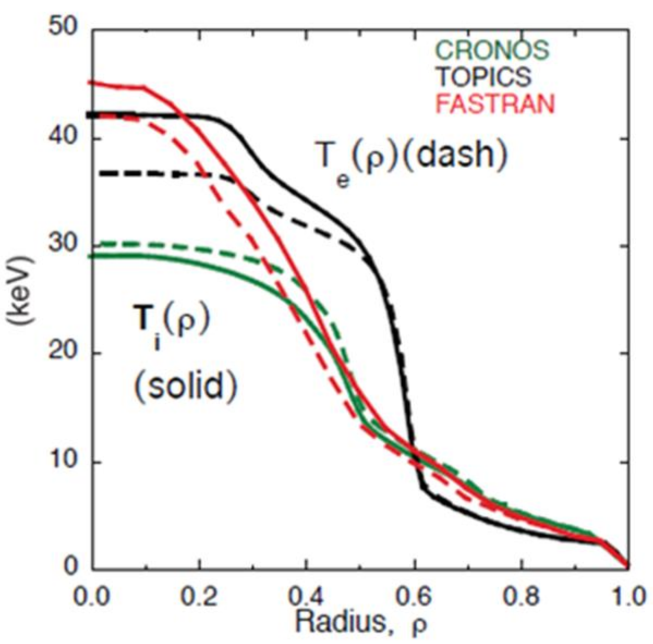
To do: Include particle transport, tungsten (W) for ITER baseline

Simulations: Steady state scenario exploration at 7-9 MA in ITER

Steady state scenarios require high bootstrap current fraction (50-65% at β_N~ 2.6-2.8) and high confinement ($H_{98}(y,2)$=1.5-1.7)

1. High T_{ped}, no Internal Transport Barrier (ITB)

- At T_{ped} ~ 7 keV, several codes predict Q = 3.3 – 3.8 using day-1 heating systems in ITER.



2. Low T_{ped}, with ITB

- Simulations using T_{ped} ~ 3 keV with ECCD at mid-radius
- But require additional 20 MW off-axis current drive (ECCD or LHCD)
- Q = 5 – 6.5, although ITB depends on fine details within the code.

To do: Obtain consistent simulations.

Conclusions

Over the past few years, the IOS-TG of the ITPA has:

- Validated the breakdown scenario for ITER, using inclined ECH
- Tested solutions for the current ramp-up and ramp-down phase
- Demonstrated ITER baseline experiments at $H_{98}(y,2)=1$ at $\beta_N \sim 2$, or higher confinement at $\beta_N > 2$
- Benchmarked sophisticated scenario codes, giving comparable results for the ITER hybrid scenario at 12MA. In addition, benchmarked heating and current drive code modules
- Continued to explore steady state scenarios. However, obtaining both consistent simulations and Q~5 in ITER is challenging

Future work of the IOS-TG

Several issues remain → future "joint" work:

- ✓ Assess EC stray radiation in an "empty torus" in ITER
- ✓ Plasma ramp-down following off-normal events (Joint experiments)
- ✓ **Baseline scenario** (Joint experiments and modelling):
  - Experiments with dominant electron heating
  - Transient and stationary heat flux handling
  - Simulate entry to burn and burn control
  - Include particle transport, & tungsten (W) in simulations
- ✓ Joint Experiments to provide data to benchmark codes for helium and hydrogen scenario simulations (→ next ITPA meetings)
- ✓ Obtain consistent simulations for steady state scenario simulations