Scenario Development Constraints – Operation Limits and Control constraints

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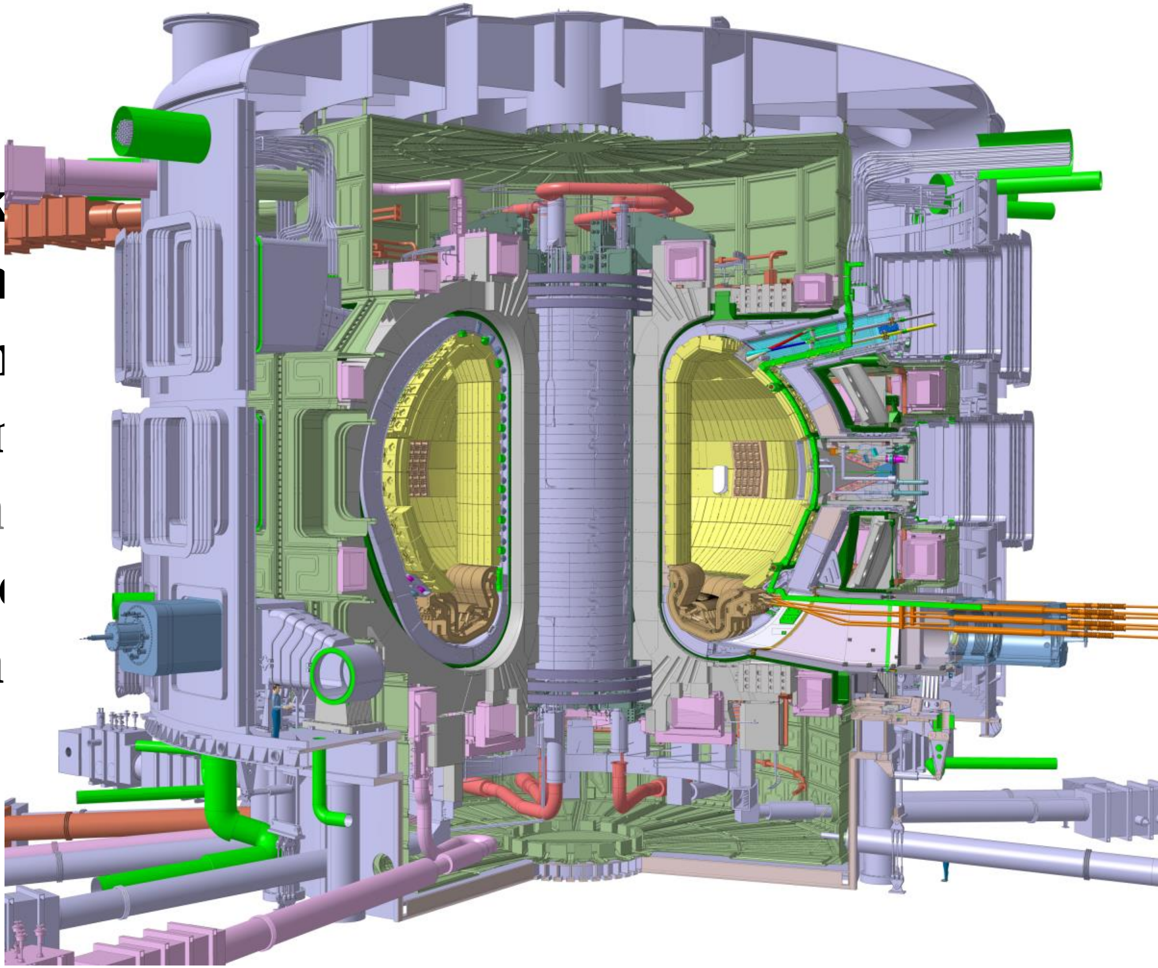
Topics to cover

- Parameters to optimize
- Parameter space for tok
  - Density limits – high
  - Safety factor (q_a) lim
  - Beta limits – ideal ar
  - Vertical stability lim
- Actuators available for
- Parameter optimization
- Summary



What tokamaks try to optimize?

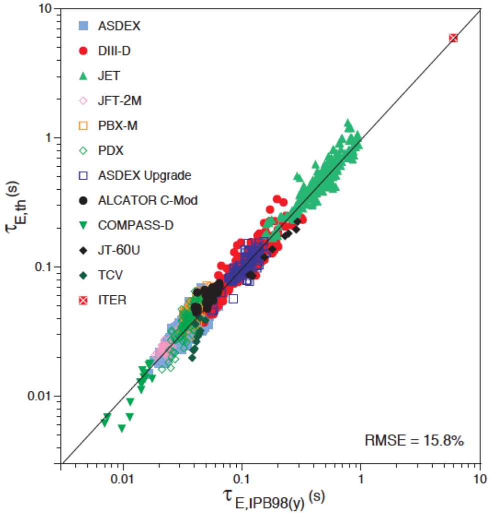
- Goal of a fusion reactor, e.g. ITER is to maximize fusion power output
- Fusion power density in a 50-50 DT plasma :

$$p_{DT} = n_D n_T \langle \sigma v \rangle \varepsilon_{DT} \propto n^2 T^2$$

n_D: D density, n_T: T density
$<\sigma v>$: average D-T fusion reaction cross-section $\propto T^2$ for T~10-20keV
ε_{DT}: 17.6MeV

- Remember plasma beta $\beta = \dfrac{\langle p \rangle}{B^2 / 2\mu_0}$
- Thus total fusion output: $P_{fus} \propto <p^2> V \propto \underline{\beta^2 B^4 V}$
- Global Energy Confinement Time of ELMy H-mode IPB98(y,2)

$$\tau_{E,th}^{ELMy} \propto I_p^{0.93} B^{0.15} P^{-0.69} n^{0.41} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa^{0.78}$$



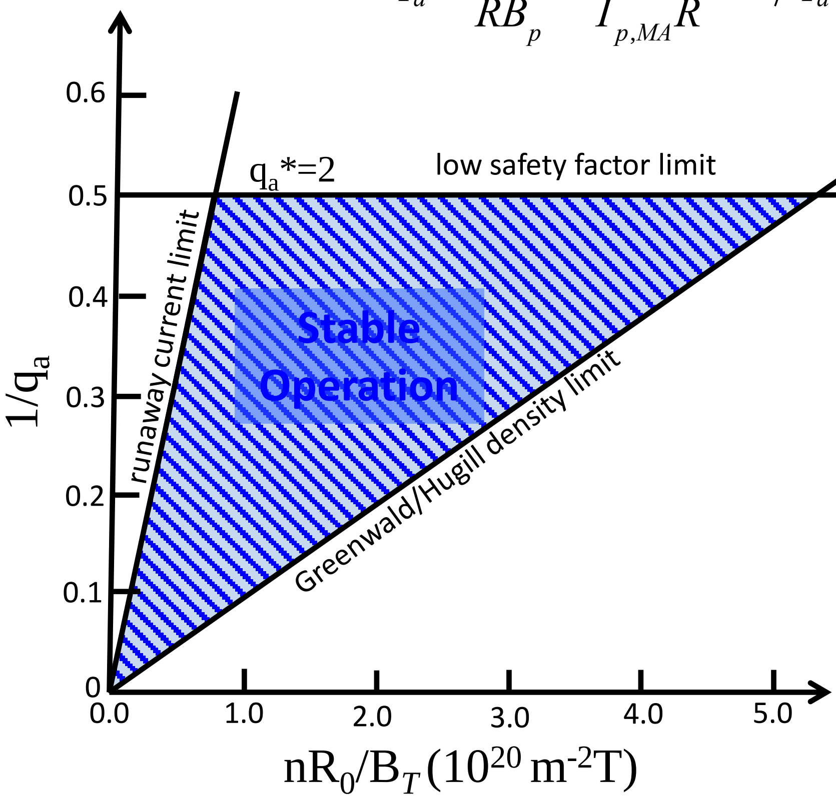
Both fusion power output and confinement time has **strong dependence on *B, R, p,* and I_p**

Ultimately it aims at optimizing the Lawson Parameter: $nT_e\tau_E$

Operational Limits on Plasma Density

Hugill diagram: $1/q_a$ vs. Murakami parameter (nR_0/B_T)

$$q_a = \frac{aB_T}{RB_p} \sim \frac{5a^2 B_T}{I_{p,MA} R} \Rightarrow 1/q_a \propto I_p$$



- Low q_a limit is a limit on the plasma current. Higher current destabilizes external kink modes – **results in plasma disruptions**
- low density limit is due to generation of runaway currents: too low densities → less collisions → electron get accelerated to very high (relativistic) energies
- High density limit: Greenwald/Hugill density limit is a radiation limit. Too high densities→ less edge Te → high impurity radiation from plasma edge, formation of MARFEs - **results in plasma disruptions.**

Operational Limits on Plasma Density

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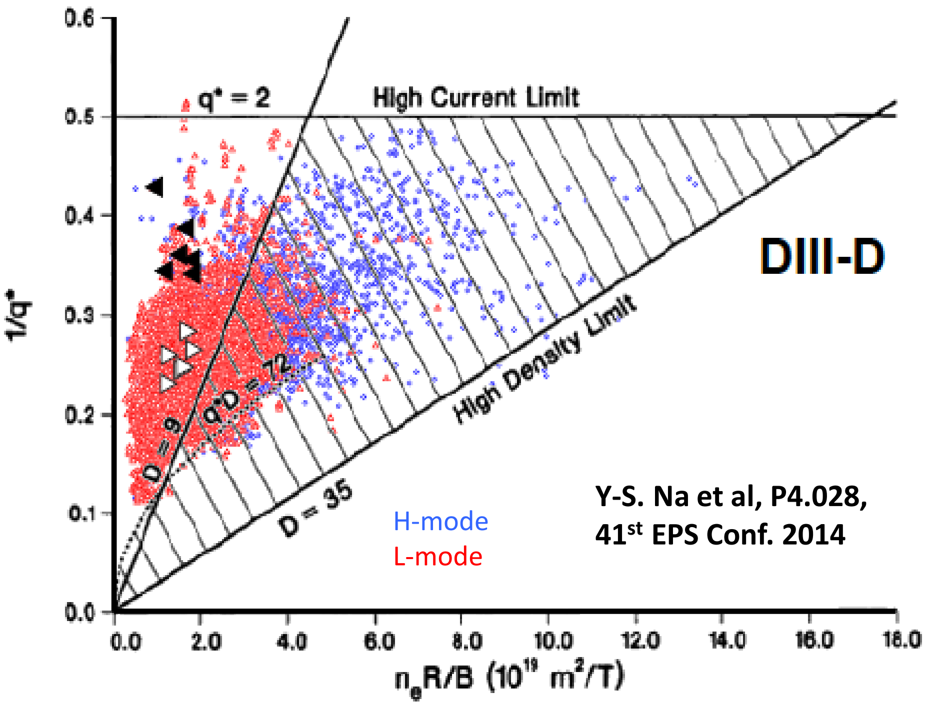

- Greenwald limiting density has a simple expression:

$$n_{GW}(10^{20} m^{-3}) = \frac{I_p(MA)}{\pi a^2(m)}$$

M. Greenwald et al, NF 28 (1988) 2199
M. Greenwald PPCF 44 (2002) R27–R80

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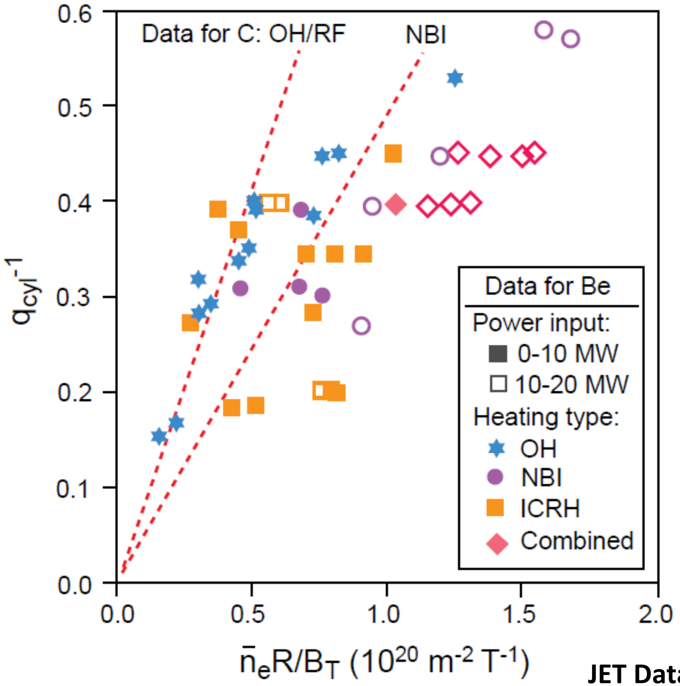

JET Data, IPB, NF 1999

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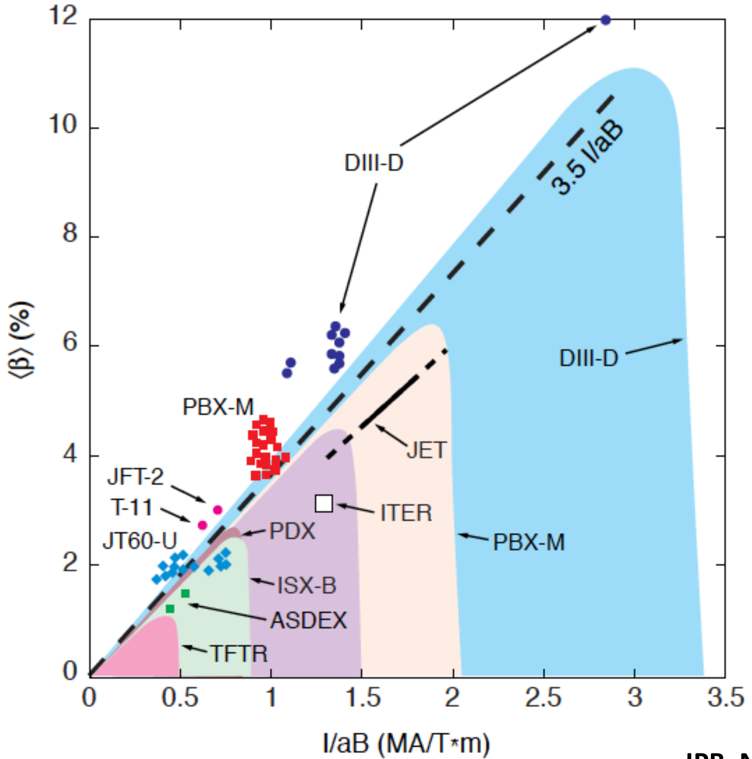
$$n_{GW}(10^{20} m^{-3}) = \frac{I_p(MA)}{\pi a^2 (m)}$$

- High density limit can be enhanced with improved wall conditioning and plasma heating

Operational Limit on Plasma Beta

- The limit on the maximum achievable plasma β comes from the stability of the ballooning modes in a tokamak
- For circular plasmas, β_{max} is given by the Troyon Limit*: $\beta_{\max} = 2.8 \frac{I_p}{aB_t}$



IPB, NF 1999

β is in %, I_p is in (MA), a in (m) and B_t in (T)

For comparison between different machines, normalized β is defined as

$$\beta_N = \frac{\beta}{I_p/(aB_t)}$$

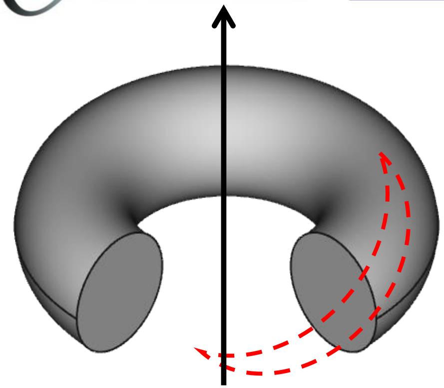
β_N much higher than 2.8 has been achieved in experiments with plasma shaping – elongation helps improve β_N

***F Troyon et al 1988 PPCF30 1597**

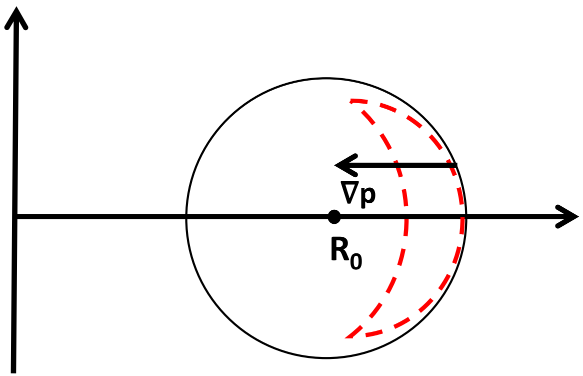
Parameters to Optimize in a Burning Plasma

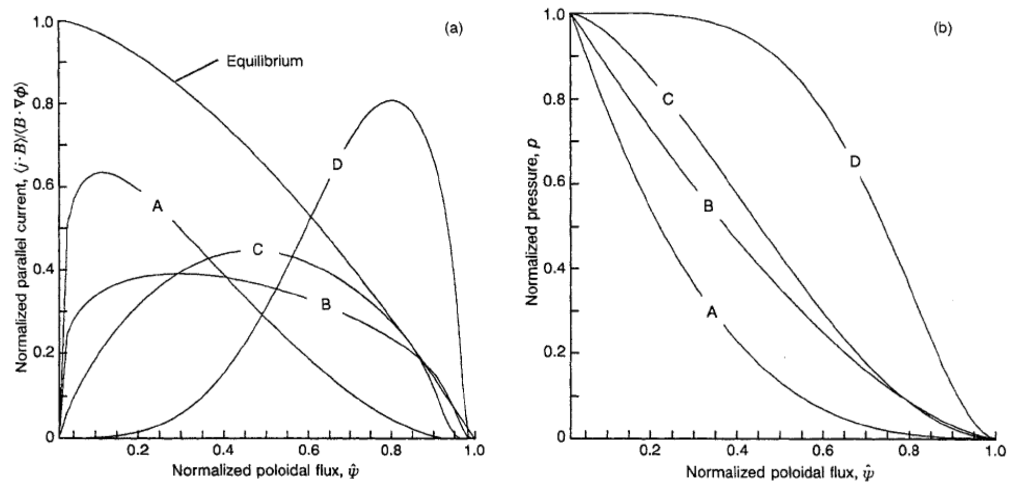
- **Confinement improvement by improved $H_{98y2} = \tau_E/\tau_E^{ELMy}$**
- **Improved fusion performance by as high β_N as permitted by MHD stability**
- **Improved normalized density : n_e/n_{GW}**
- **Improved radiation fraction : $f_{rad}=P_{rad}/P_{loss,tot}$ for less thermal power load to divertors**
- **Fuel dilution control through control of He ash and maintaining $f_{DT} = n_{DT}/n_{i,tot}$**
- **High non-inductive current drive fraction f_{NI} essential for steady-state operations**

Bootstrap Currents in High Beta Plasmas



- **Bootstrap currents are self driven currents due to interplay of 'banana' trapped particles and untrapped particles**
- **High *bootstrap* current fraction f_{BS} essential for steady-state operations.**
- **Remember** $j_{BS} \sim \sqrt{\epsilon}\frac{1}{B_q}\frac{dp}{dr}$ **, thus depends on pressure profile**



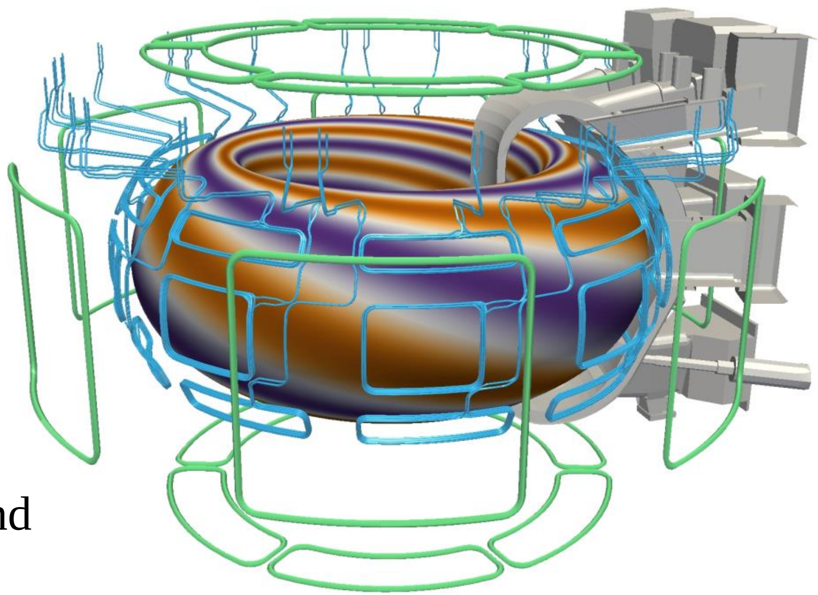


Particles execute *banana* orbits in tokamaks in collisionless plasmas

C. Kessel, NF, 1994 (34) 1221

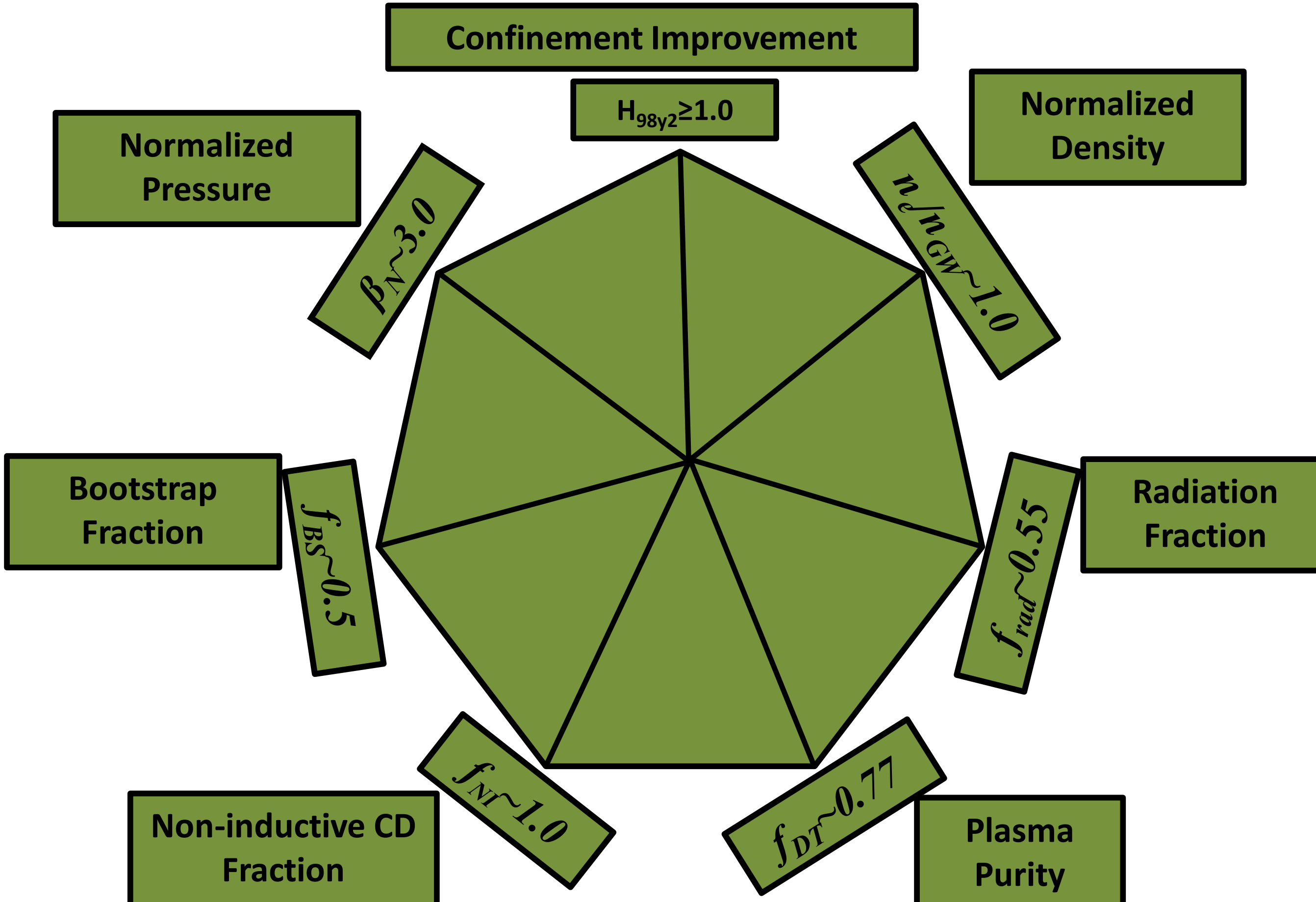
Control of RWMs and ELMs

- **Resistive Wall Modes (RWMs)** : Plasmas with high β, high bootstrap fraction f_{BS} and low internal inductance l_i are prone to be unstable to external kink modes, which grow with the characteristic wall time, τ_w~L/R time of the first wall. Plasma rotation and error field compensation – both static and and active feedback needed to stabilize RWMs.
- **Edge Localized Modes (ELMs)** : Driven by steep pedestal pressure in the H-mode plasmas due to peeling/ballooning modes. Active feedback with resonant magnetic perturbations needed to control ELMs.
- **RWM and ELM stabilization has been extensively studied in the DIII-D tokamak**
- ITER will have an elaborate set of 9x3=27 ELM control coils with independent power supplies and 6x3=18 error field correction coils with 9 independent power supplies (DC). Radial ELM control coils also double up for RWM control



ITER Correction Coils (out-vessel) and ELM control coils (in-vessel

Multi Parameter Spider Plot for Scenario Control



Actuators for Scenario Control & Constraints

	Actuators	Constraints
Magnetic Control	Central Solenoid	Voltage and current saturation limits, total flux storage (especially for CS), slew rate limits, **J** x **B** forces on coils etc.
	PF coils	
	Error Field correction coils for control of RWMs	
	ELM control coils	
Kinetic Control	Fueling – gas puff, pellet fueling, NBI	Fueling, heating and CD efficiencies, power and current deposition profiles, resonance layer or RF waves, NB shine-through, various technical limits with injectors
	Heating and Current Drive using NB, ECRF, ICRF, LH	

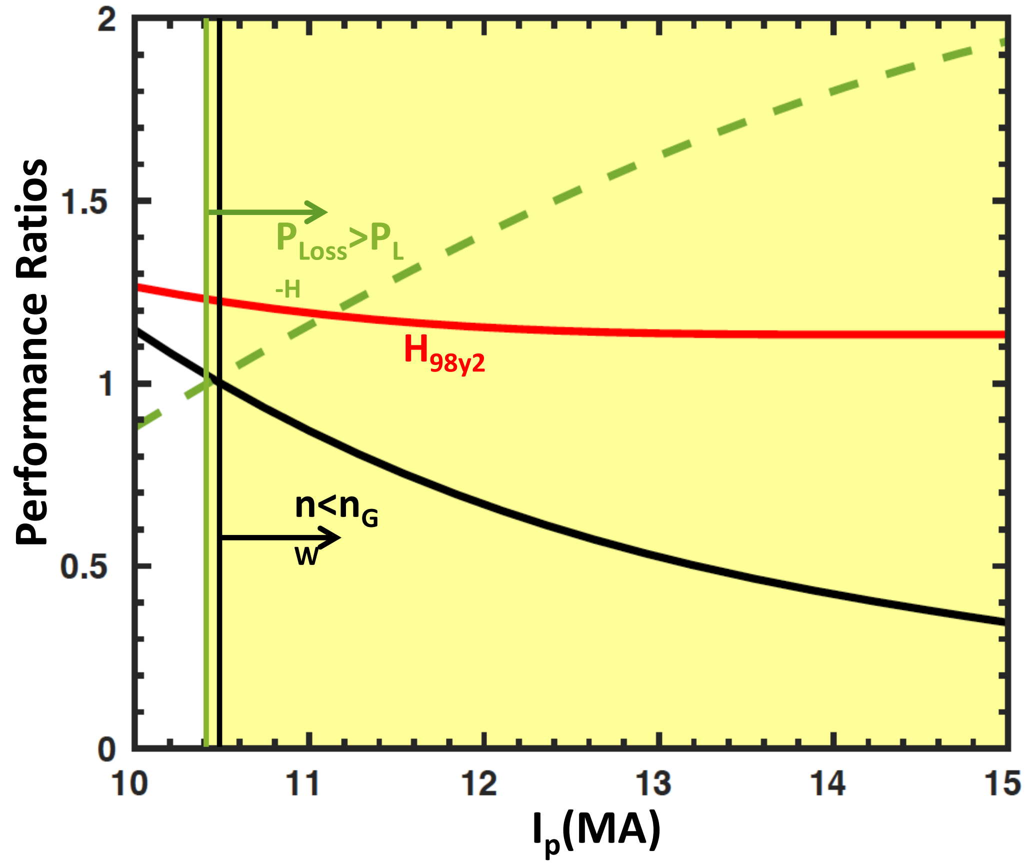
Operation Space of ITER Inductive Scenario

ITER operational space diagram for advanced inductive operation at the nominal ITER toroidal field of B = 5.3 T with P_{aux} = 50 MW

Ratio of the power loss across the separatrix to the predicted L–H threshold power

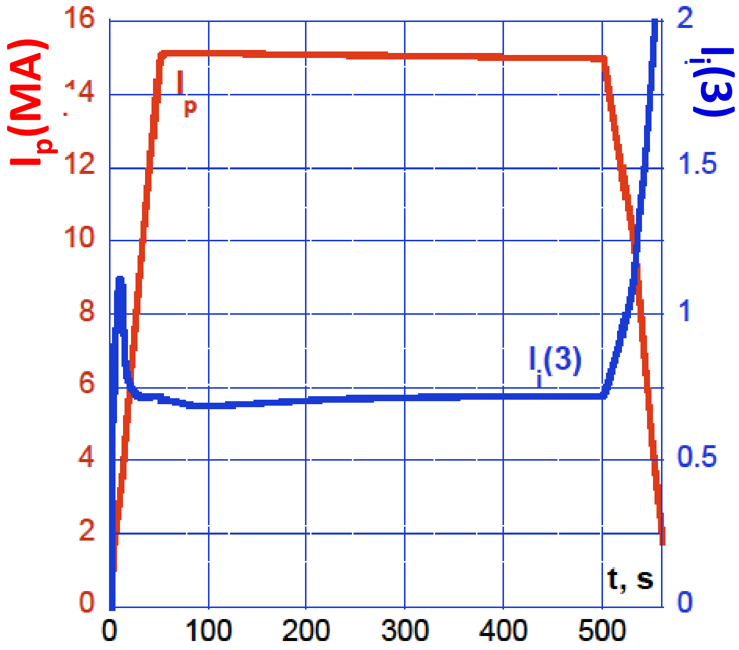
Ratio of calculated confinement time to the H-mode scaling

Ratio of the plasma electron density to the Greenwald density

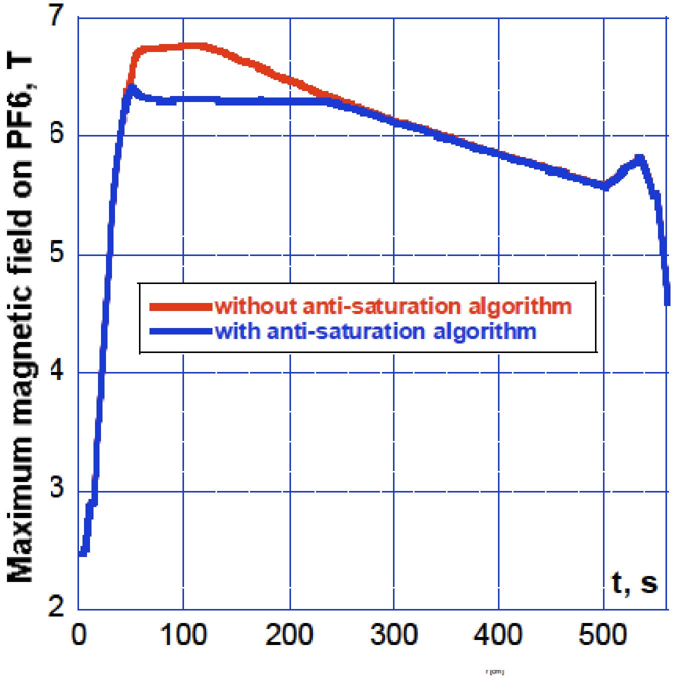


T. Luce et al, NF, 54 (2014) 013015.
Also in ITER Research Plan.

ITER 15MA Q=10 Inductive Scenario



ITER_D_4CL4MP,
STAC-10, May 2011



- DINA simulation of 15 MA inductive scenario with low-l_i and anti-saturation controller:
  - Without anti-saturation, field on PF6 rises to 6.8 T (needs Pf6 subcooling by 0.4K)
  - With anti-saturation, field on PF6 remains < 6.4 T (no Pf6 subcooling needed)
  - Acceptable error on position of outer divertor leg (gap-2 - inset)

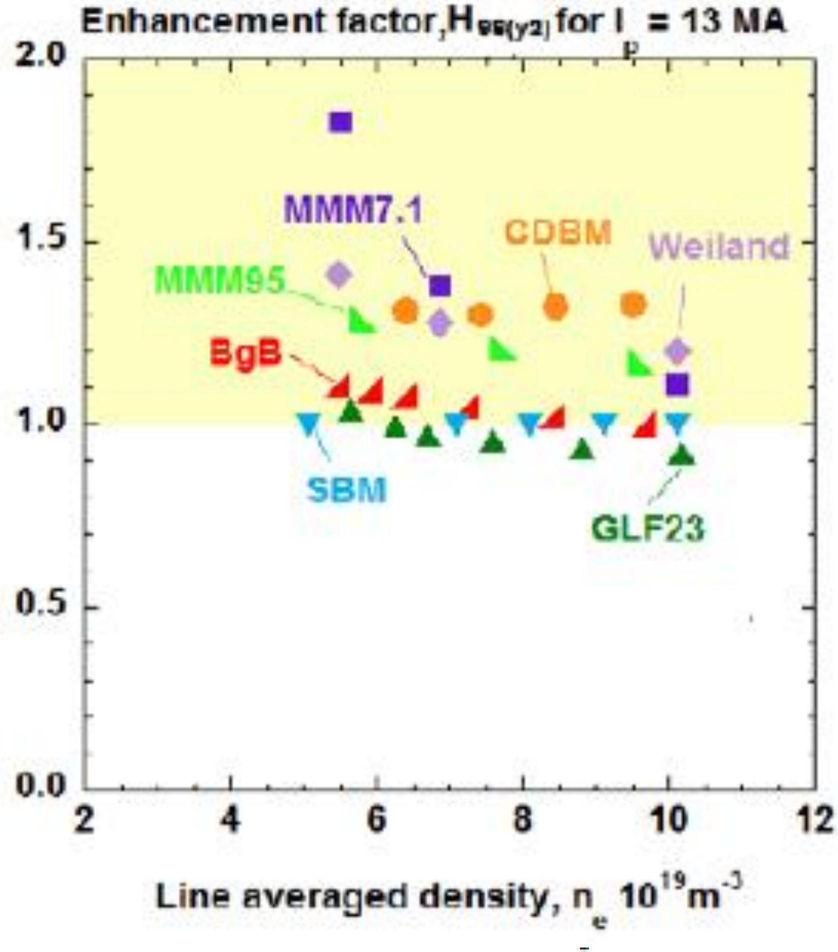
ITER Steady-state Scenario

- Long-pulse operation (Q > 5, Δt > 1000 s) in ITER at high currents (I_p >13MA) does not require too high confinement ($H_{98,y2}$ ~1)

- Increase of the pulse length, Δt > 1000 s, is possible due to reduction of plasma density

- Following increase of electron temperature T_e, CD efficiency also improves

- No significant change in transport properties



A.R. Polevoi, NF, 55 (2015) 063019]

Simulations of ITER non-Inductive Scenarios

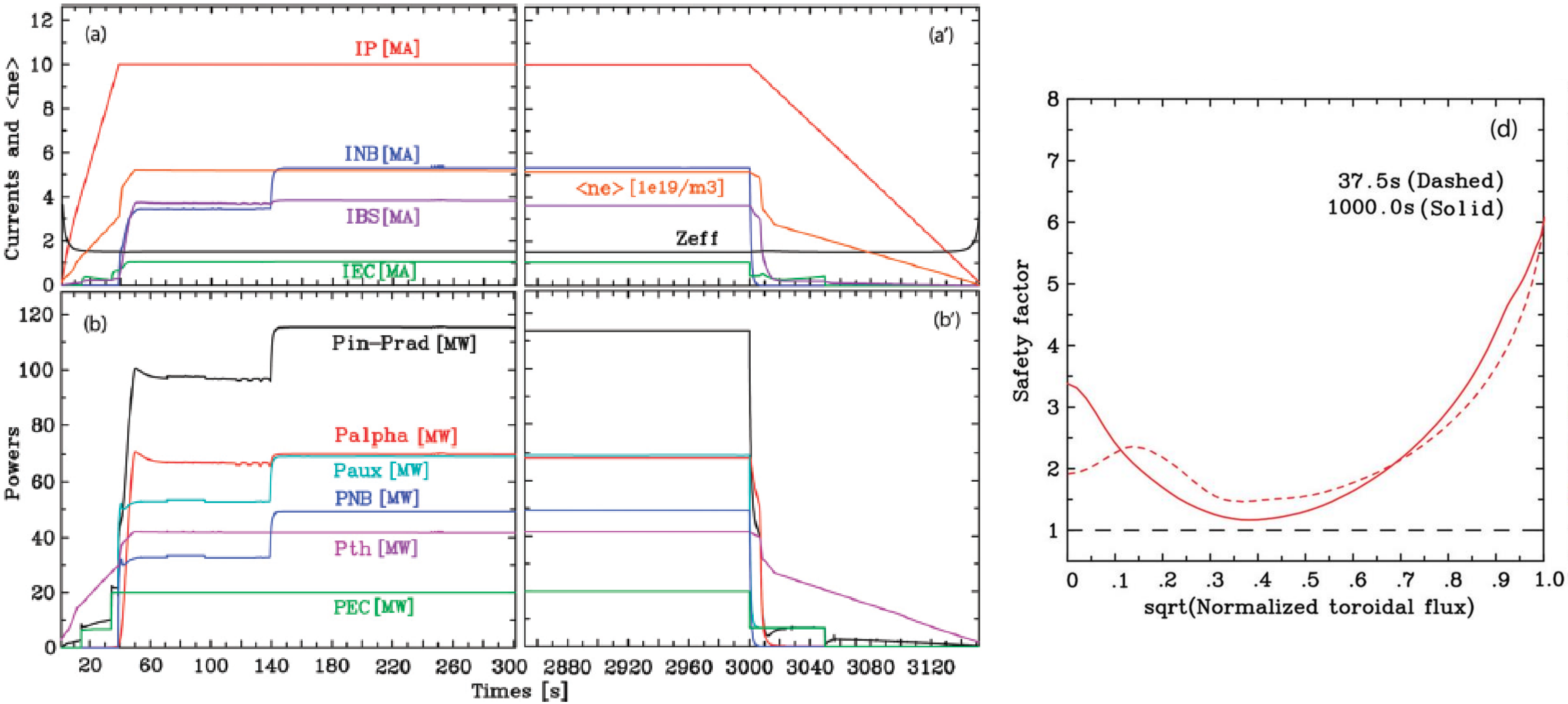
ITER-India

Table 3. Fully non-inductive ITER operation scenarios developed using METIS. The plasma current was allowed to vary to find a fully non-inductive plasma state at an assumed H_{98} value in the range of 1.2–1.6. The plasma density was assumed to be below the Greenwald density limit and a density profile peaking factor of 1.3 was used in all cases.

Case	P_{NB} [MW]	P_{EC} [MW]	P_{IC} [MW]	P_{LH} [MW]	P_{Aux} [MW]	H_{98}	I_p [MA]	Q	f_{GW}	f_{NI}	β_N
1	33	20	20	0	73	1.6	7.5	3.7	0.90	1	2.8
2	33	20	20	0	73	1.2	5.9	1.3	0.85	1	1.9
3	33	20	0	20	73	1.6	9.1	4.9	0.93	1	2.8
4	33	20	0	20	73	1.2	7.4	1.7	0.91	1	1.8
5	33	40	0	0	73	1.6	8.2	4.1	0.95	1	2.8
6	33	40	0	0	73	1.2	6.6	1.2	0.89	1	1.8
7	49.5	20	0	0	69.5	1.6	8.5	4.7	0.91	1	2.9
8	49.5	20	0	0	69.5	1.2	7.0	1.6	0.84	1	1.9
9	49.5	40	0	0	89.5	1.6	10.1	5.3	0.84	1	3.4
10	49.5	40	0	0	89.5	1.5	9.2	4.3	0.92	1	3.0
11	49.5	40	0	0	89.5	1.4	8.6	3.0	0.90	1	2.6
12	49.5	40	0	0	89.5	1.2	7.9	1.8	0.85	1	2.0

S.H. Kim et al 2021 Nucl. Fusion 61 076004

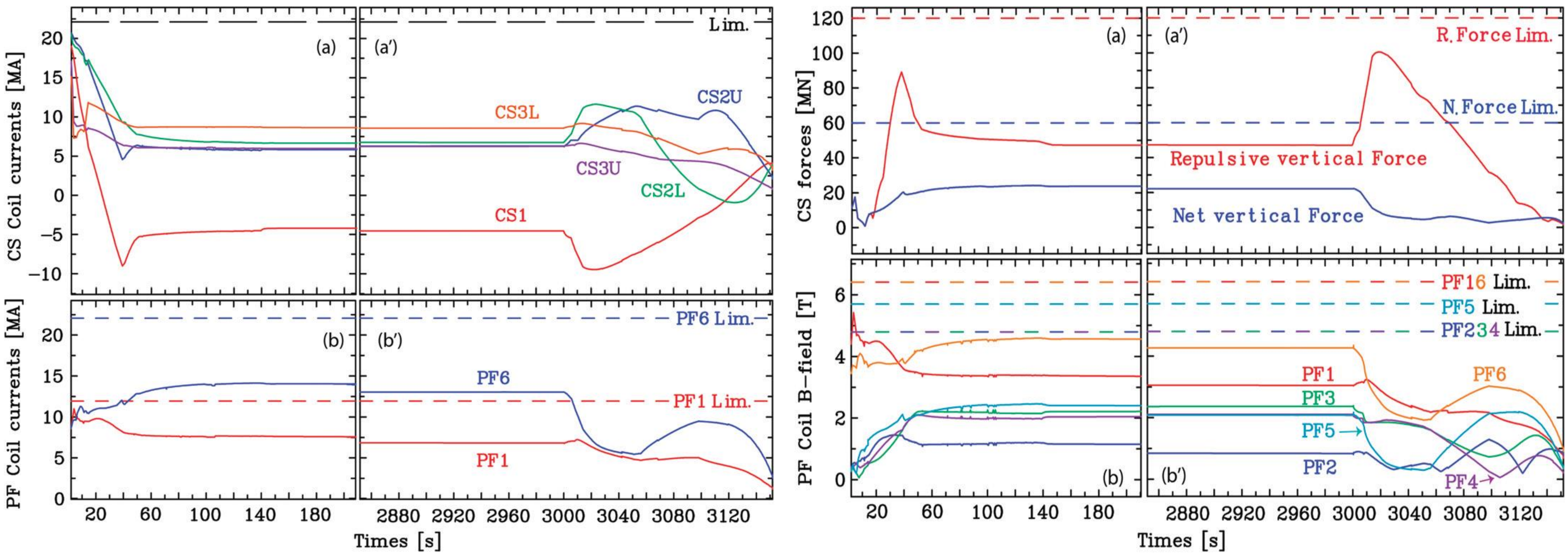
ITER Steady-State Scenarios…(1)



CORSICA Simulations of fully non-inductive operation scenario for Ip=10MA with 49.5MW NB and 20MW EC power

S.H. Kim et al 2021 Nucl. Fusion 61 076004

ITER Steady-State Scenarios…(2)

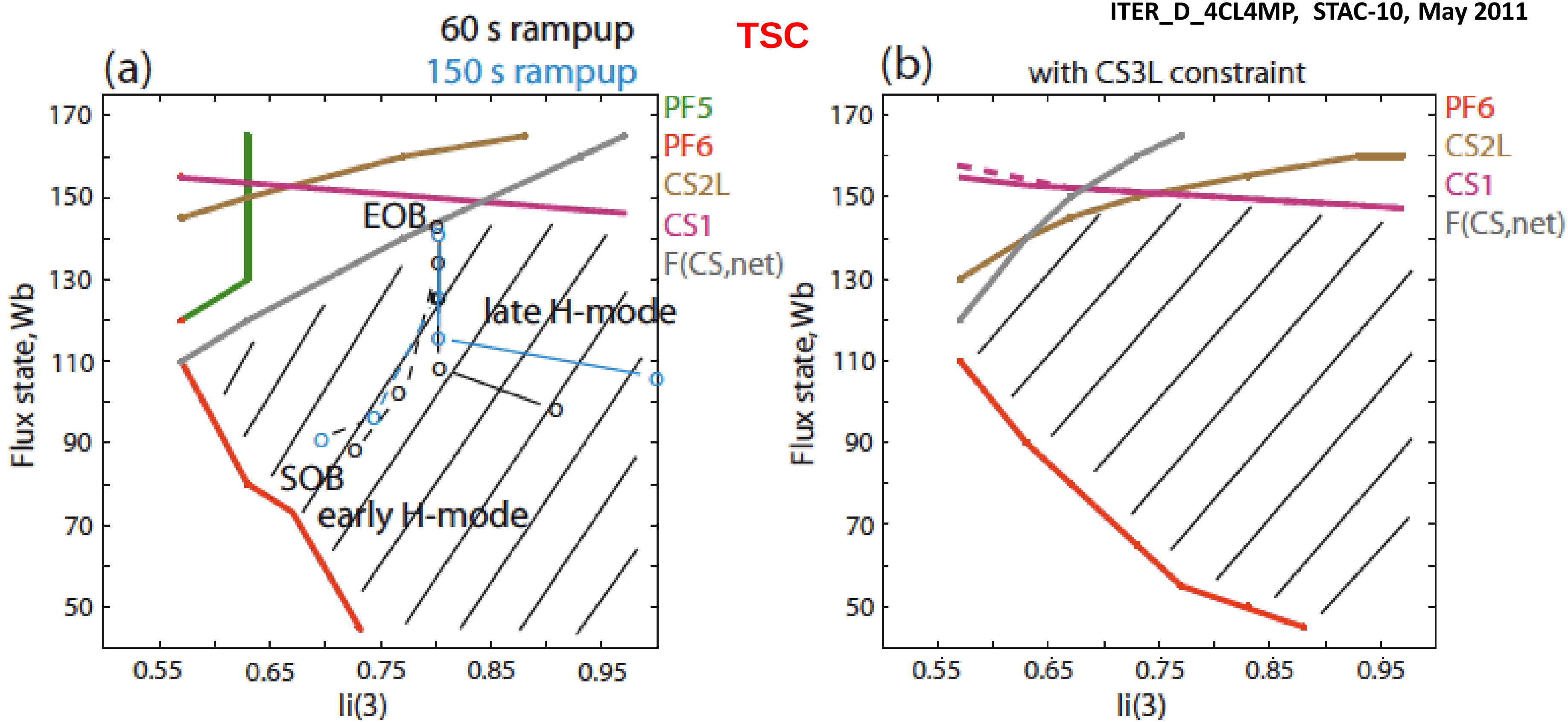


Note that all the CS and PF coil currents, Voltages, Fields and Forces are within the allowable limits

S.H. Kim et al 2021 Nucl. Fusion 61 076004

Operating space in Hybrid Scenario

ITER_D_4CL4MP, STAC-10, May 2011



- **Equilibrium operating space for hybrid scenario at I_p = 12.5 MA shows additional constraint on I_{CS3L} can expand operating space at low-l_i**

Summary

- **Parameter Optimization for various operation scenarios is a complex problem**
- **Often the parameters fight against each other for achieving ultimate goal of fusion performance – detailed analysis of comparative benefits needs to be done using scenario simulations**
- **Open field of research through integrated modeling, experiments and analysis of experimental data**
- **ITER, JT-60SA and existing machines like DIII-D, KSTAR & EAST are great platforms for scenario control, modeling and optimization studies**

Thank You!!