Heating and current drive requirements towards Steady State operation in ITER

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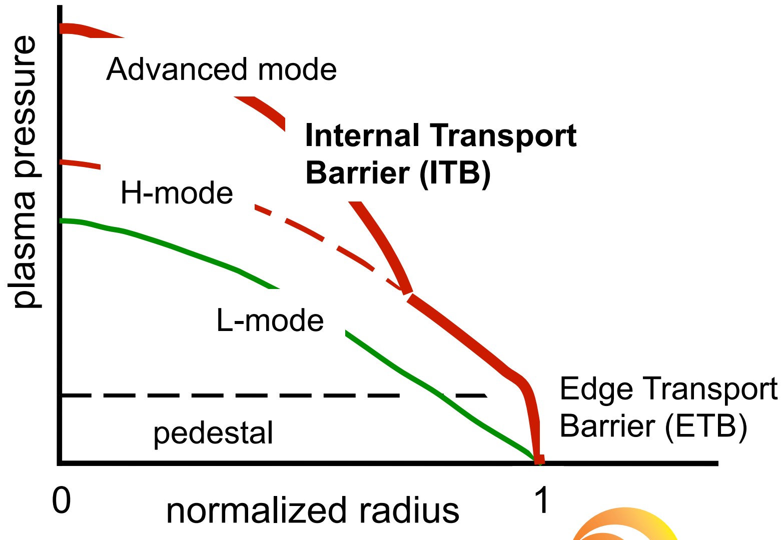
ITER will need to demonstrate continuous operation with 100% non-inductive current and fusion gain Q (P_{fus}/P_{input})~5

- Steady state scenarios target plasmas with current reduced from 15MA to 9MA to minimize external current drive needs
  - More than 50% of the current has to be driven by the bootstrap mechanism
- to get Q~5 at I_P~9 MA => will need $H_{98(y,2)}$~1.6 ➔

improved core confinement with internal transport barriers (ITBs)

large pressure gradients at ITBs are conducive to MHD instabilities that reduce the beta limits



What are the H&CD requirements towards ITER goal?

H&CD sources must fulfill requirements for

- Heating to H-mode/burn
- CD efficiency
- profile control
- MHD stability

Will show that

⇒ a current distribution over ρ~0.3-0.8 better at sustaining ITBs

⇒ SS operation at low current can be demonstrated with the day-one heating mix

⇒ Case for LH upgrade

more expanded ITBs, higher current and Q, MHD stability at larger β_N

Scenario simulation results depend on models and assumptions:

particle transport (density profiles), energy transport, actuators, pedestal height

⇒ Will look for TRENDS within the same transport model

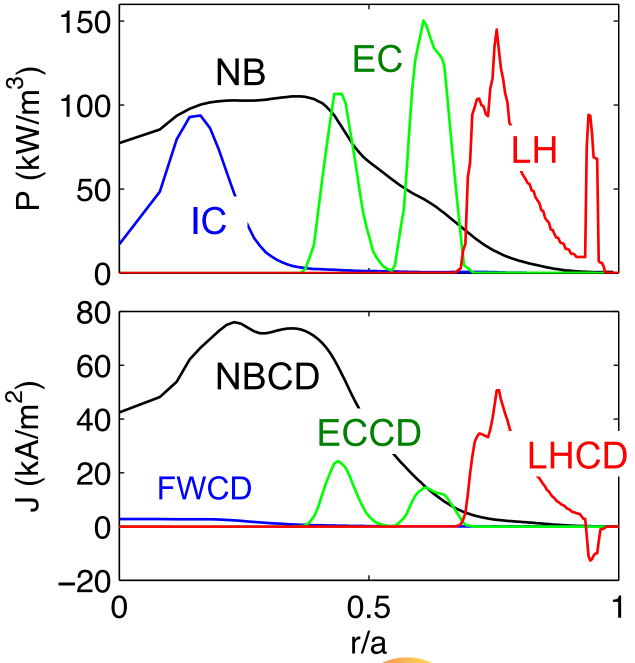
Combining H&CD sources to control the q-profile

NB: 1MeV negative ions	on/off-axis	ρ~0.1-0.35	**current drive**
IC: 48MHz	on-axis	ρ<0.2	**core heating**
EC: 170GHz	off-axis	ρ~0.2-0.8	**flexible deposition**
LH: 5GHz $n_{\|\|}=2.15$, $P_+=67\%$, $P_-=23\%$	off-axis	ρ~0.65-0.8	**current drive**

Power Levels, MW

	TOTAL	NB	IC	EC	LH
baseline	**73**	**33**	**20**	**20**	**/**
upgrades	**73**	33	/	20	20
	93	33	20	/	40
	93	33	20	20+20	/

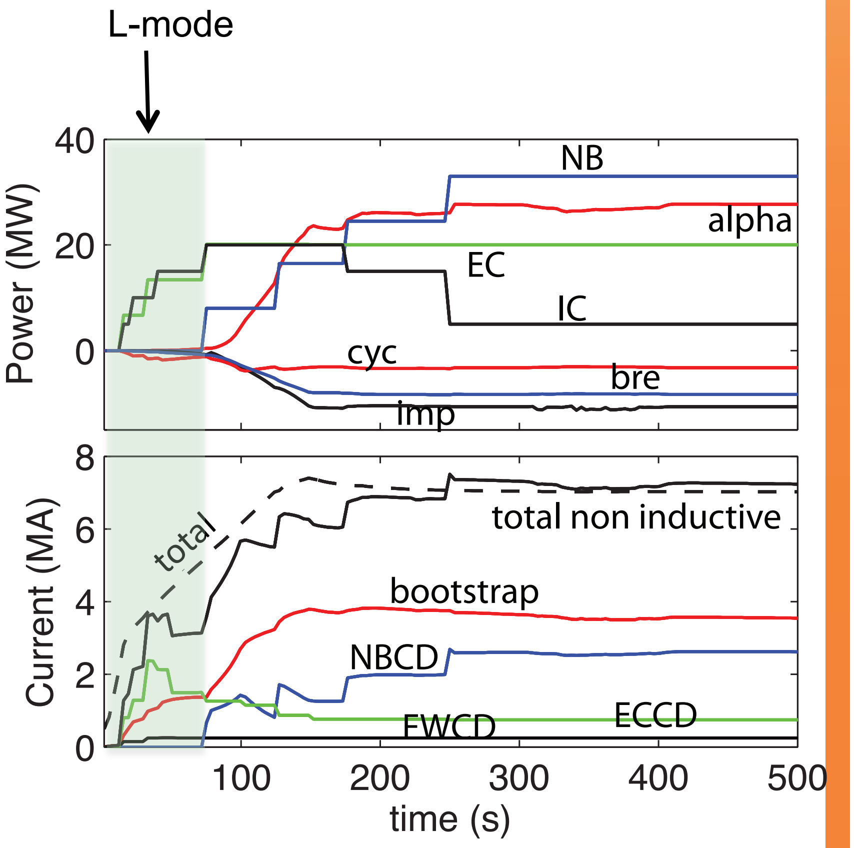
Kessel et al, IAEA 2010



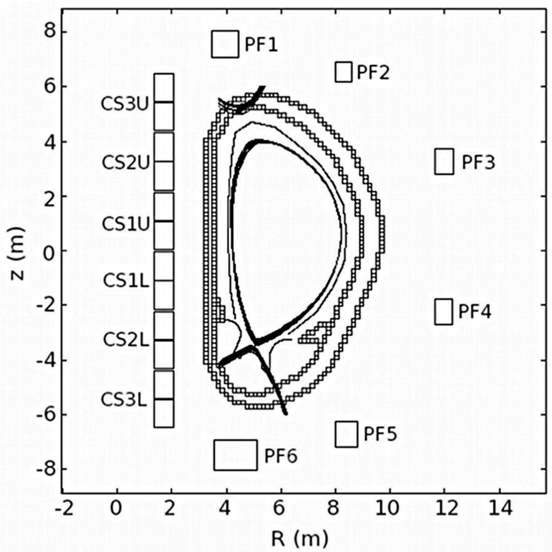
Simulate the rampup and relaxation in flattop to self-consistently study the current drive and the MHD stability evolution

Time-dependent evolution from limited startup plasma to fully relaxed steady state (3000s), including plasma current/power/density rise phase

- Ramp-up phase
  - RF heating to form reverse shear profiles
  - Inductive rampup still important
- Flat-top phase
  - 100% non-inductive current
- Radiated power keeps divertor loads within acceptable levels



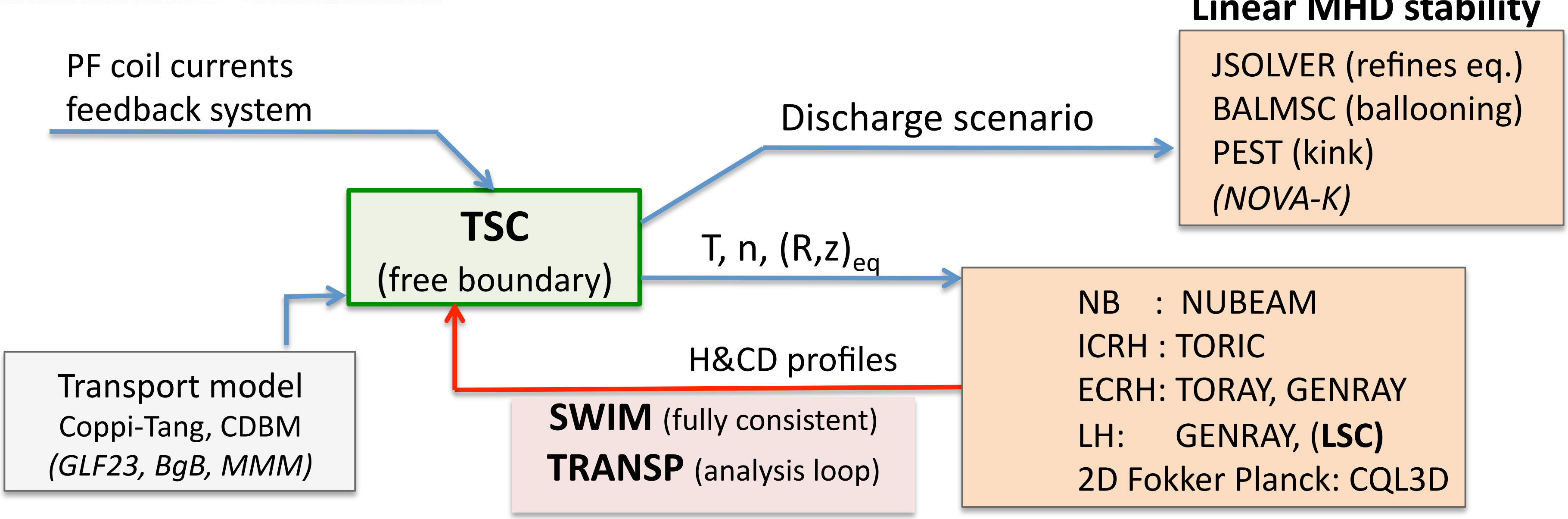
Time-dependent simulations evolve plasma equilibrium and H&CD source profiles consistently



Target plasma

R=6.2, a=2.0, κ=1.8, δ~0.45

n/n_G>0.75



Linear MHD stability

JSOLVER (refines eq.)
BALMSC (ballooning)
PEST (kink)
(NOVA-K)

PF coil currents
feedback system

Discharge scenario

TSC
(free boundary)

T, n, $(R,z)_{eq}$

H&CD profiles

NB : NUBEAM
ICRH : TORIC
ECRH: TORAY, GENRAY
LH: GENRAY, (**LSC)**
2D Fokker Planck: CQL3D

Transport model
Coppi-Tang, CDBM
(GLF23, BgB, MMM)

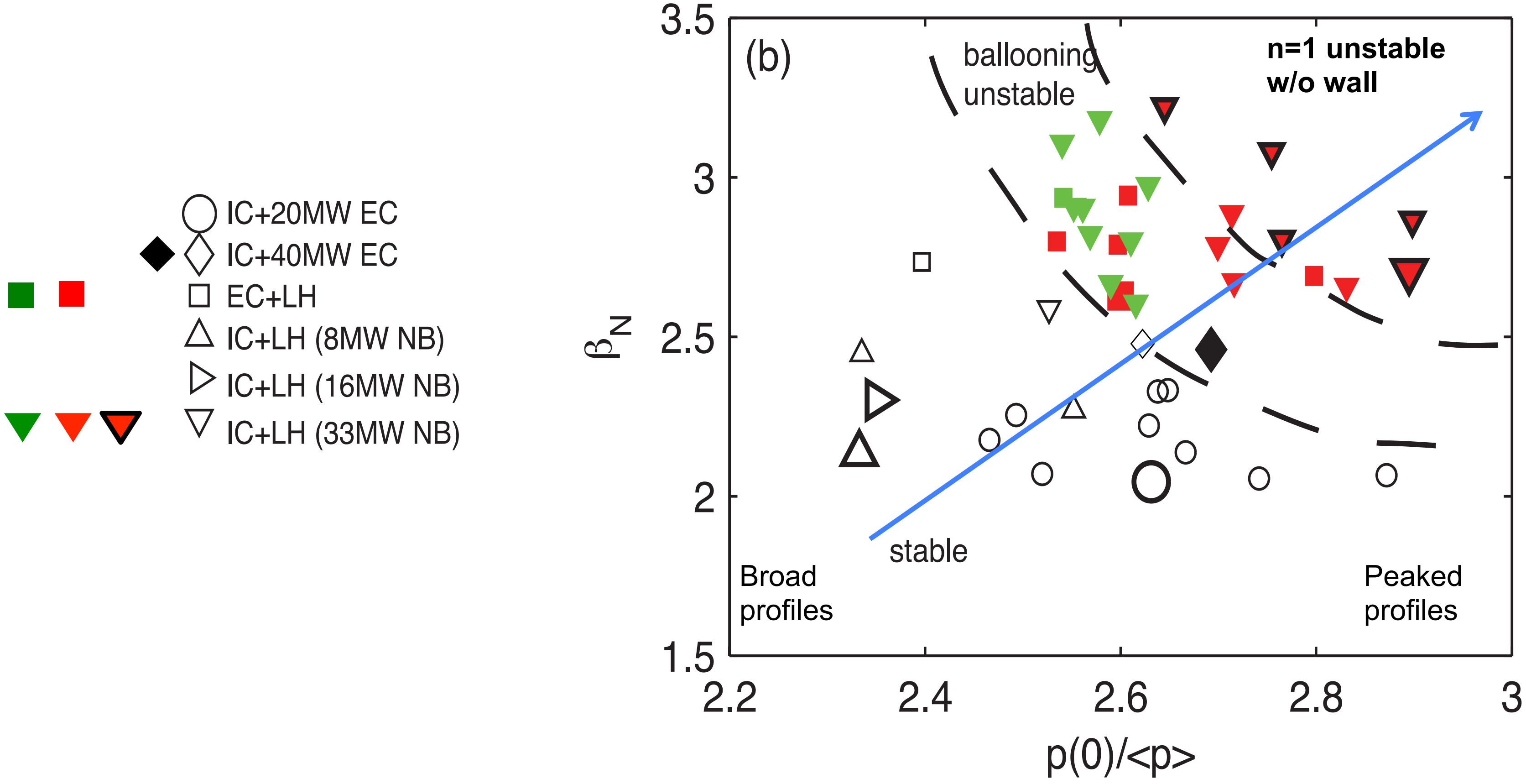
SWIM (fully consistent)
TRANSP (analysis loop)

Define an operational space where ITER steady state scenarios are ideal MHD stable

- Fix the transport model: H_{98}=1.6
- Assume sustained ITBs in H-mode
- Analyze ideal MHD stability of various heating mixes

  for up to 15% of pressure peaking factor and $n<1.1n_G$

ITER steady state should operate with broad pressure profiles



*NF **52** (2012) 063027*

at low β_N : ideal MHD stable for a wide range of pressure peaking factors
at large β_N : stability depends on pressure peaking factor

High performance plasmas can be achieved only with baseline LHCD

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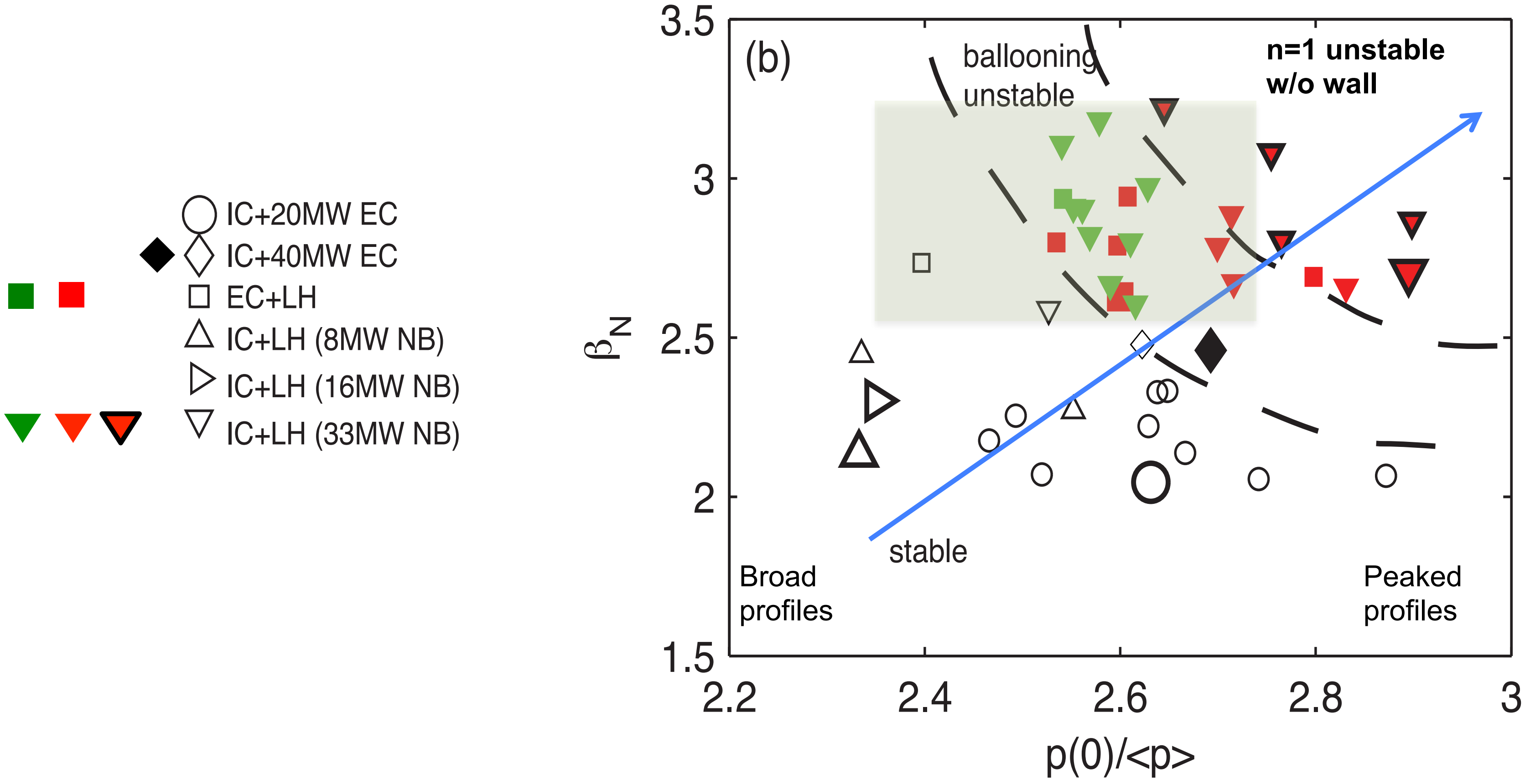
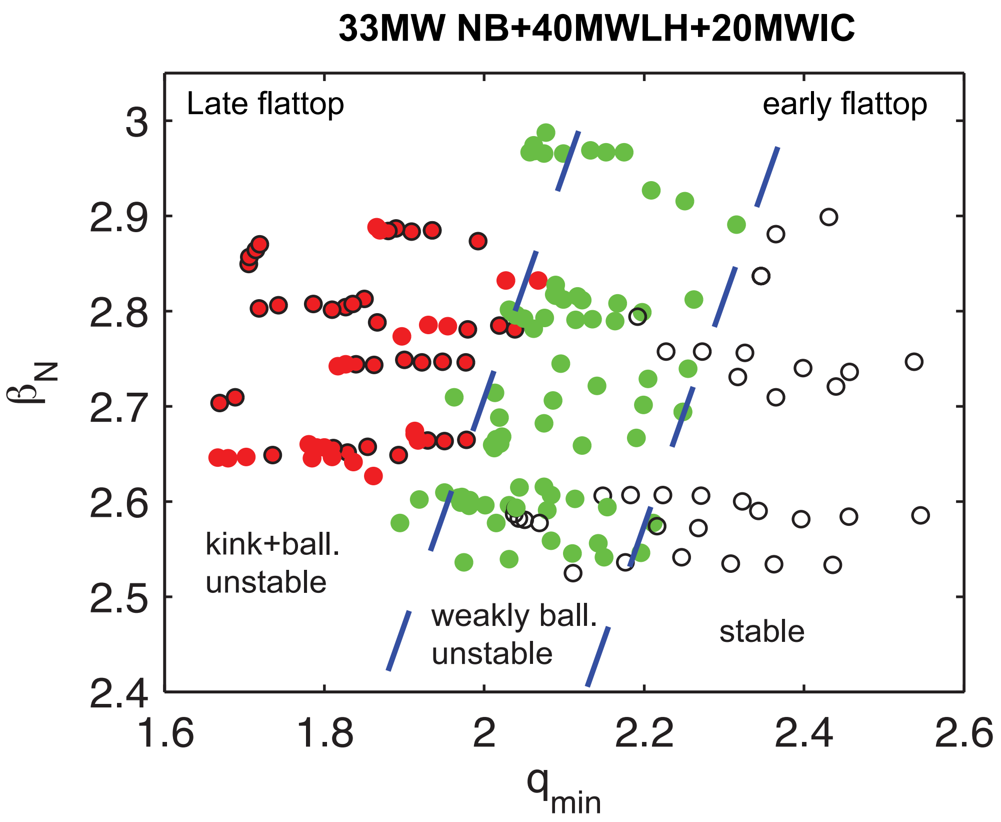


at low β_N : ideal MHD stable for a wide range of pressure peaking factors
at large β_N : stability depends on pressure peaking factor

The H&CD sources should sustain plasmas with q_{min}>2



Transition from MHD stable to unstable observed as q_{min} decreases below 2 during current profile relaxation

How do we get there ?

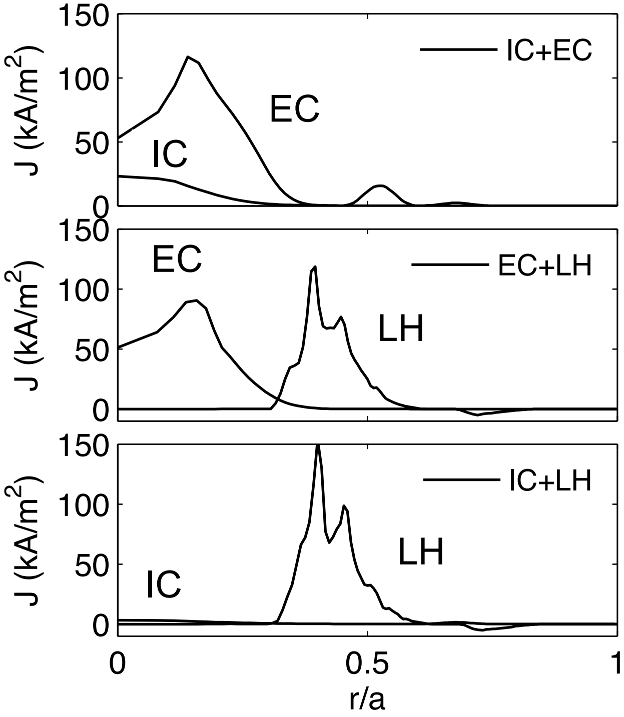
1) Need a combination of H&CD sources that favors ITB formation
2) H&CD sources must sustain ITBs in the flattop phase **in the MHD stable region**

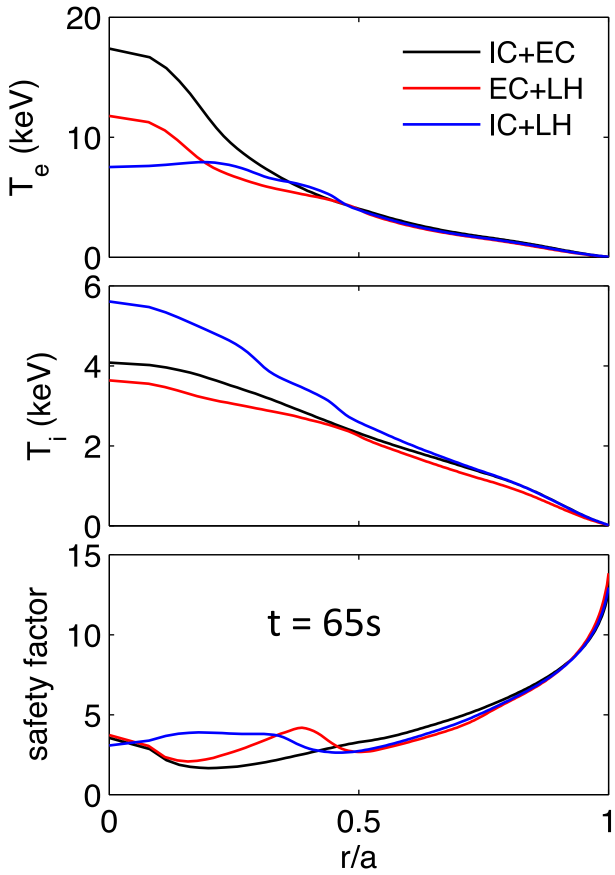
- Use experimental evidence that, in electron heating dominated plasmas
  - ITBs form in core-reversed shear plasmas
  - ITB foot set by $\rho(q_{min})$
- Use transport model that responds to reverse shear
  - CDBM (Current Diffusive Ballooning mode) [*Itoh et al, PPCF **35** 543*]

[*Fukuyama et al, PPCF **37** 611, PPCF **40** 653*]

[*Hayashi, ITPA-IOS, April 2012*]

Using RF heating in L-mode delays current penetration and favors formation of reverse shear profiles and ITB triggering



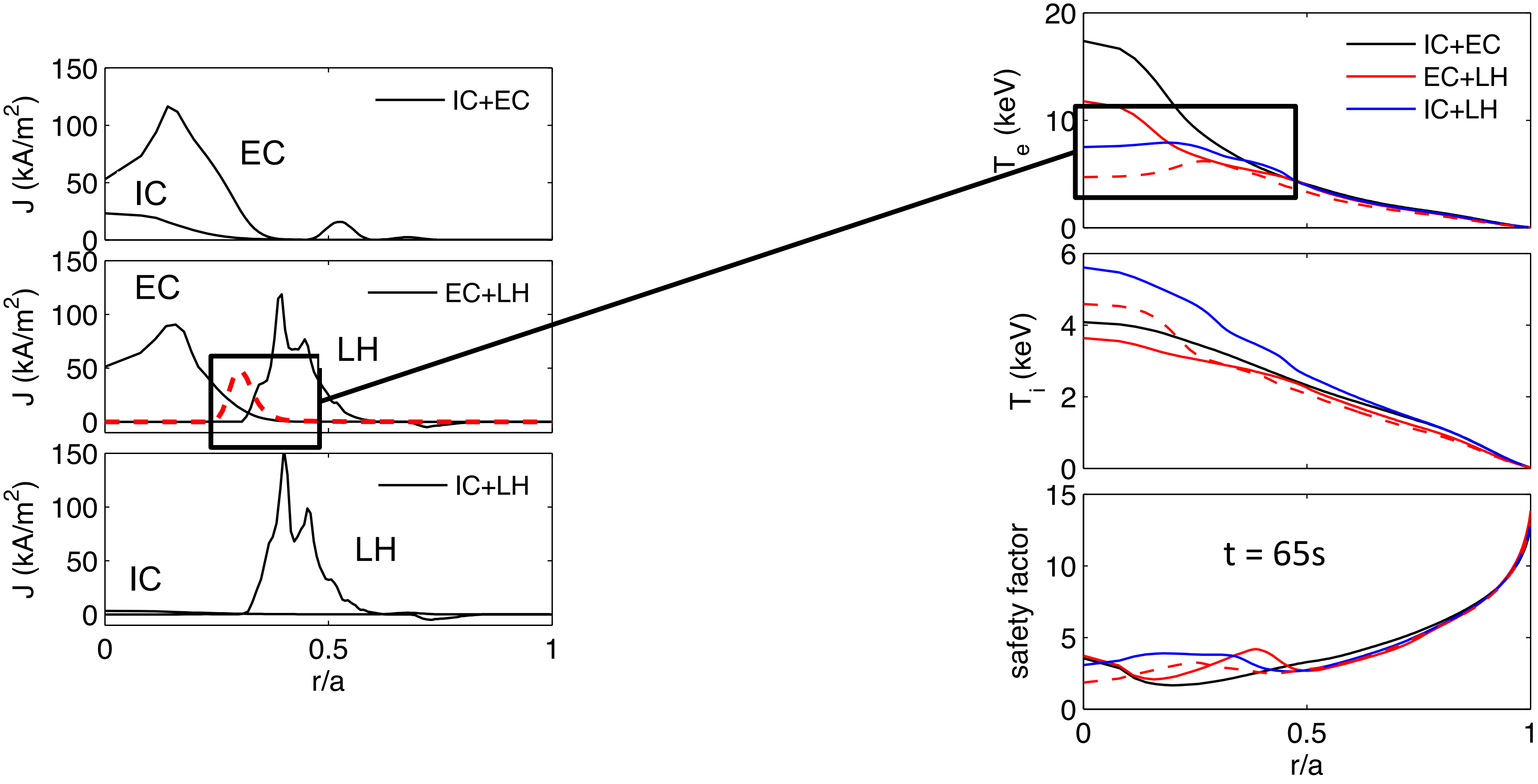


Baseline heating mix forms stronger ITBs in the electron channel

EC deposition in the core => magnetic shear reversed in the core

higher central electron temperature

Core electron heating in the ramp-up phase for reverse shear formation and triggering of stronger ITBs



Hollow temperature profiles form if EC deposition is moved outward

The ITER baseline H&CD sources are adequate to trigger ITBs in L-mode and to sustain them in the ramp-up phase (… according to the CDBM model …)

Using RF core heating early in the ramp-up phase favors triggering of stronger ITBs

Are the baseline H&CD sources adequate towards the steady state target?

1) Are the H&CD sources planned for ITER adequate
   - To sustain reverse shear, ITBs and stationary current in the flattop?
   - To maintain the plasma in the ideal MHD stable operational space?

   Yes => steady state operation at low current could be demonstrated with the baseline heating mix

2) Are the planned H&CD sources adequate to sustain 9MA and achieve Q~5?

   No => low current and low confinement

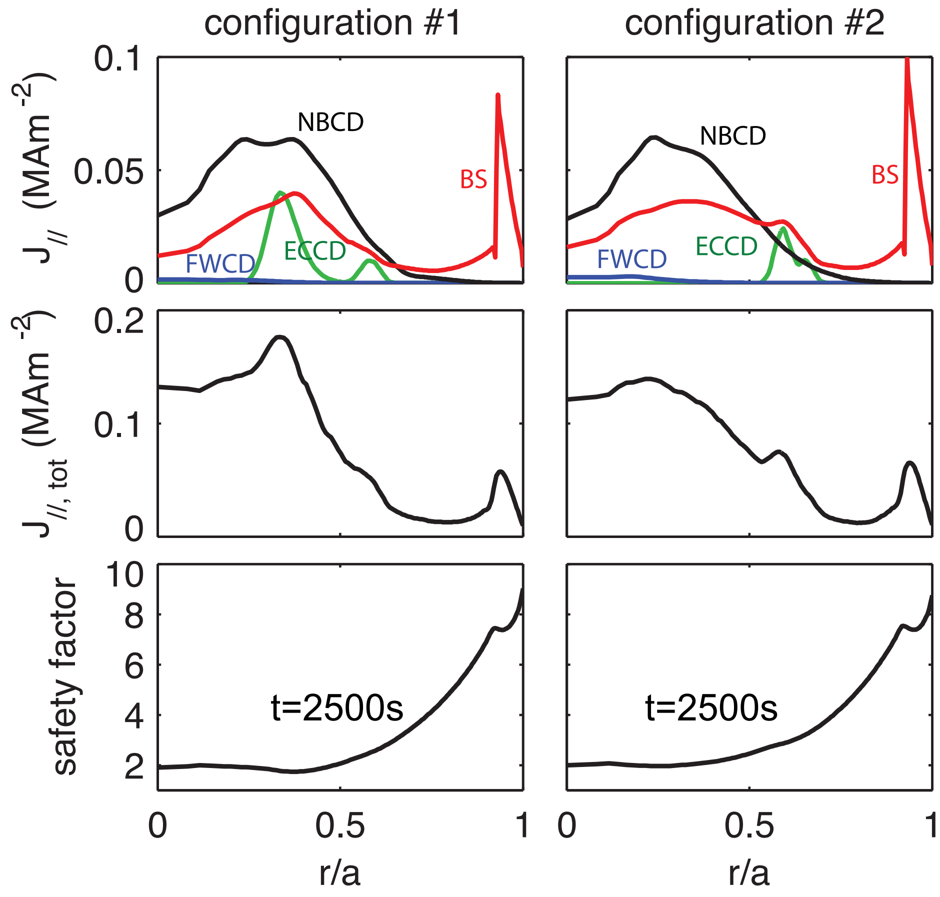
3) Would an upgrade improve plasma performance towards the ITER goals?

   Yes => simulations performed here indicate with baseline LHCD

EL/UL trade-off sustains RS and stationary ITBs for 3000s

- two configurations with 20MW of EC power:
    - 2/3 of EC power to the EL, 1/3 to the UL
    - all power to the UL
- more power to the EL => better in ramp-up
- more power to the UL => better in flattop
    - larger bootstrap current, broader profiles
- not steady-state, OH power needed

	conf. #1		conf. #2
• n/n_G	1.0		1.0
• I_{NI}	4.9 MA	➔	5.1 MA
• I_{EC}	0.43 MA	➔	0.25 MA
• I_{BS}	2.3 MA	➔	2.8 MA
• q_{min}	1.74	➔	1.97
• H_{98}	1.06	➔	1.2
• β_N	1.25	➔	1.49



*PoP **20** (2013) 056105*

Temperature and safety factor profiles stiff to EC steering

Keep 1/3 of power to the EC and 2/3 to the UL in the flattop and scan the EC steering angle

⇒ temperature profiles are peaked

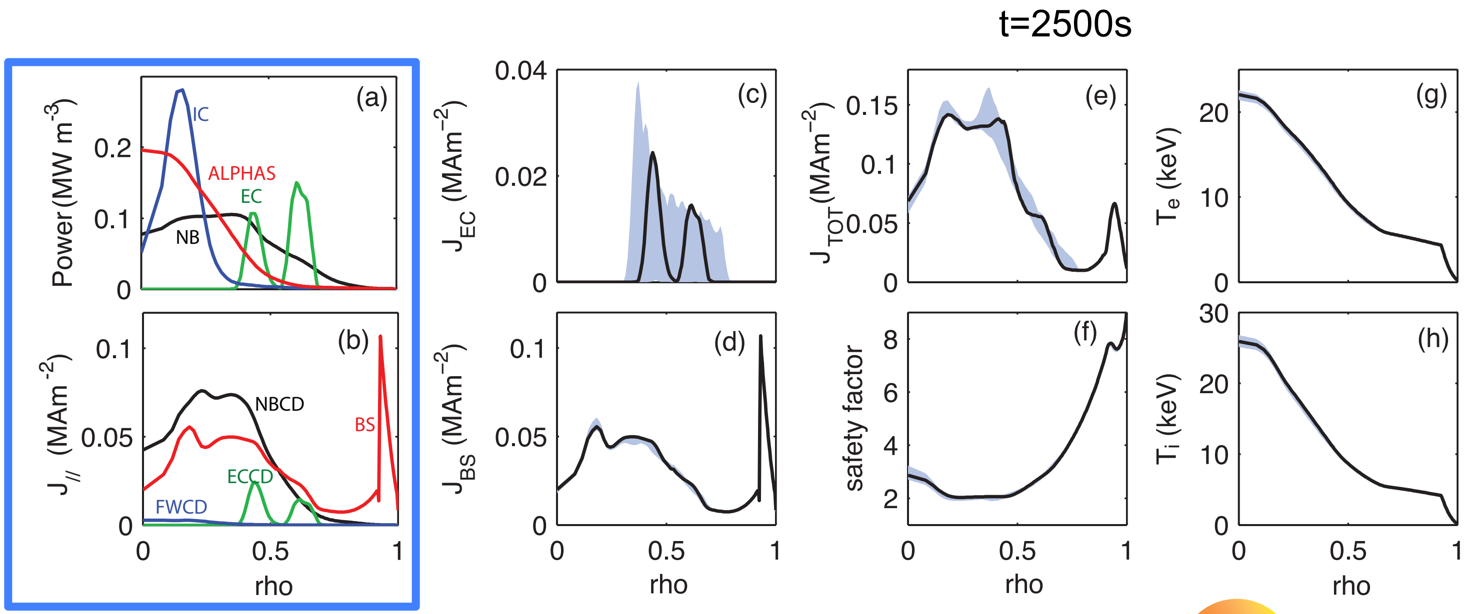
⇒ ECCD efficiency rapidly decreases when deposition moves outward

⇒ profiles are weakly affected by EC steering

⇒ real-time control needed to deposit EC inside ITB and progressively expand

Day-one heating mix sustains ~6.4 MA non-inductively with EC deposition at mid-radius

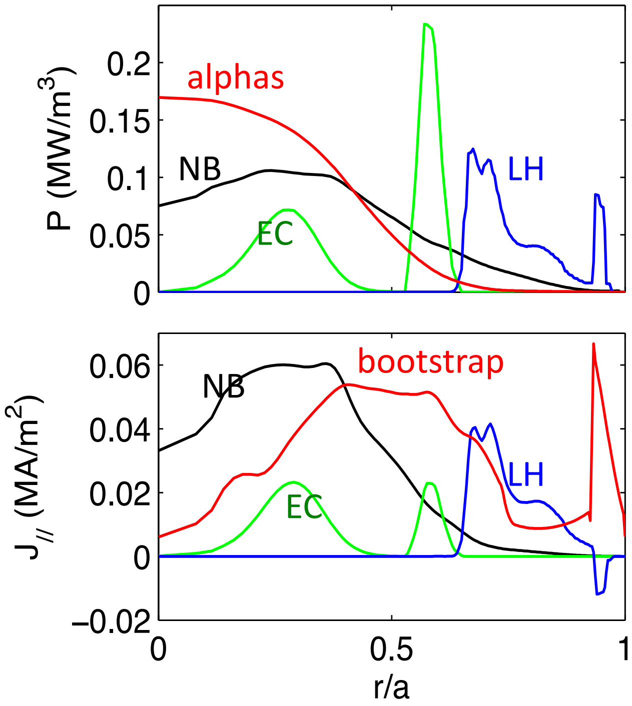
- q_{min}~2 => stable (low β_N)
- H_{98} ~ 1.3
- β_N ~ 1.77
- Q~1.6



Combine EC and LH for broad pressure and bootstrap profiles

33MW NB + 20MW EC + 20MW LH

- replace IC with LH in the day-one heating mix configuration
    - sustains 8MA, with 50% bootstrap
    - $q_{min}>2$ => MHD stable
    - H_{98} ~ 1.4-1.45
    - β_N ~ 2.0
    - Q~2.2-2.7



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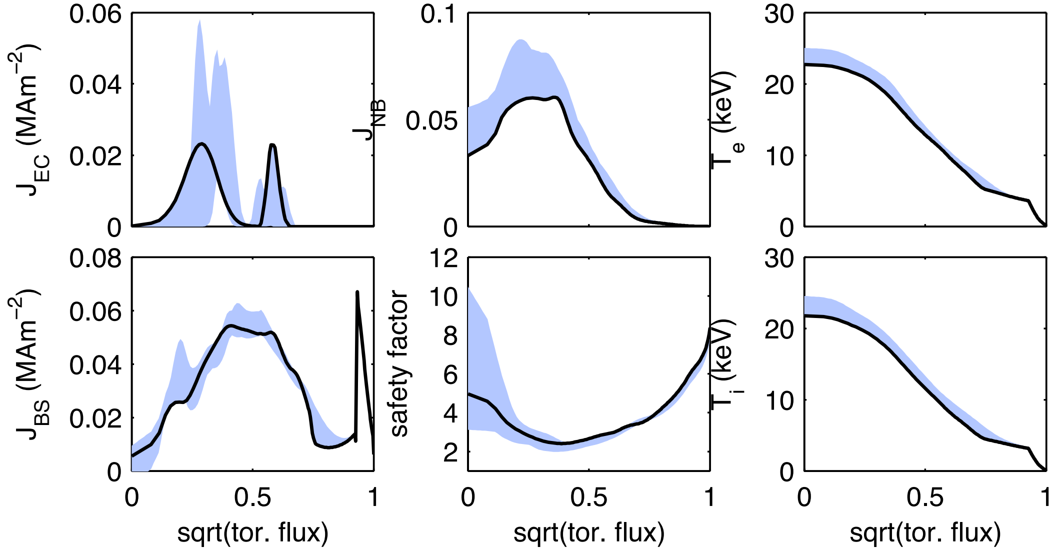

EC deposits inside ITB =>

steering more effective in modifying profiles.

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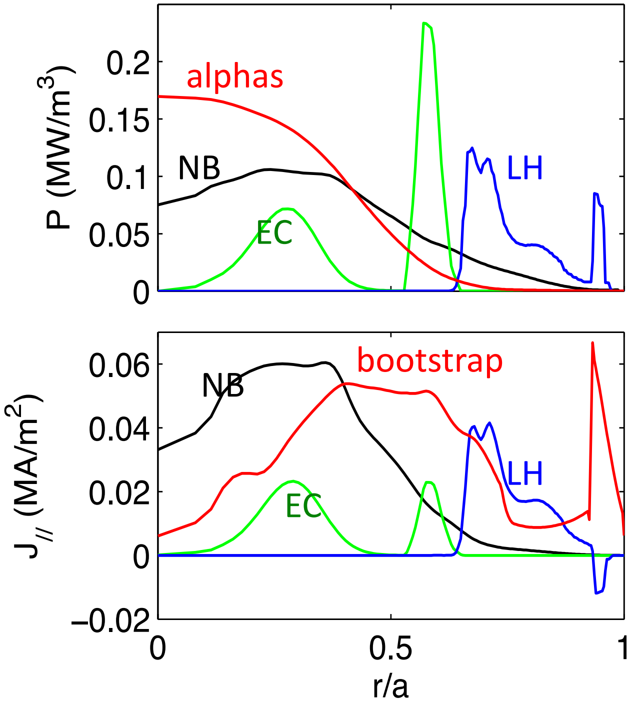
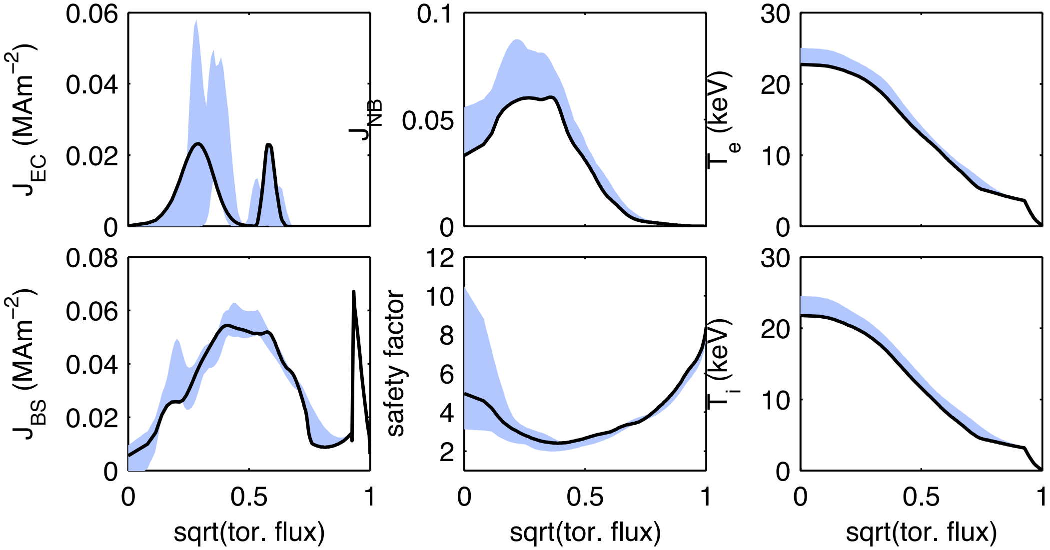


sustains 9MA if H_{98}=1.6



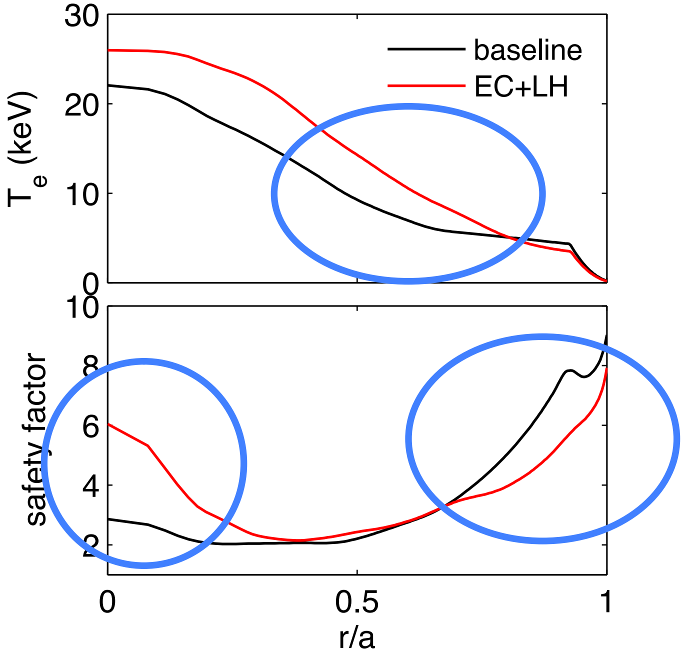
EC deposits inside ITB =>

steering more effective in modifying profiles.

A (scenario simulation) path towards steady state operation

$\mathbf{F} = \beta_N H_{89}/q_{95}^2$

Replaced IC with LH in the baseline mix
q_{95}~7.7 -> 6.0
H_{98}~1.3 -> 1.45 F~0.1 -> 0.14
β_N ~1.77 -> 1.96
I_{NI}~6.5 -> 8.0 MA



Set ITB foot at larger radii

Reduces q_{95}

Stronger RS (this depends on EC steering)

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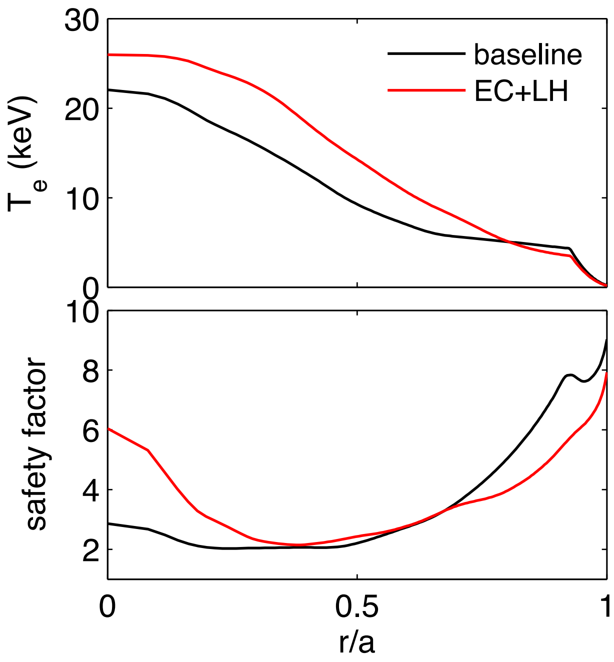
Increase density: 0.85 n_G -> n_G
bootstrap 50% => 55%
H_{98} ~ 1.54
β_N ~ 2.4
Q ~ 3.4
F ~ 0.17
but **still 8MA**



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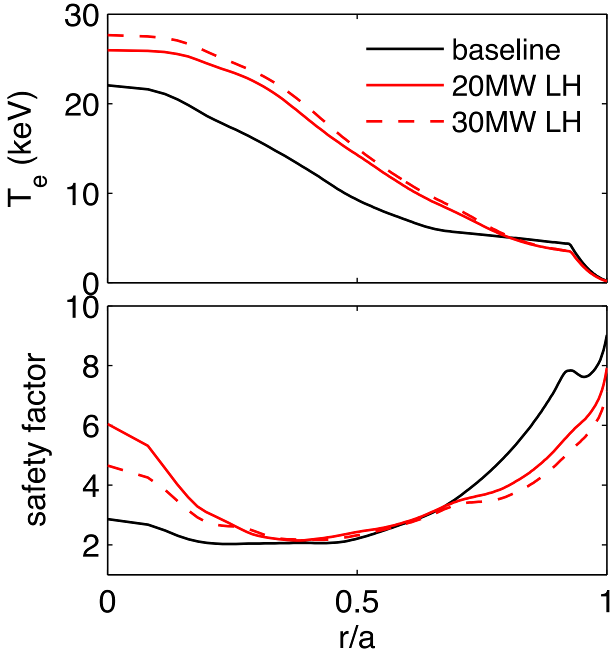
but **still 8MA**

Increase LH power
(and decrease EC power)

20MW -> 30MW
-> I_{NI}~8.0 -> 8.6
-> q_{95}~5.6
-> Q~4
No change in H_{98}



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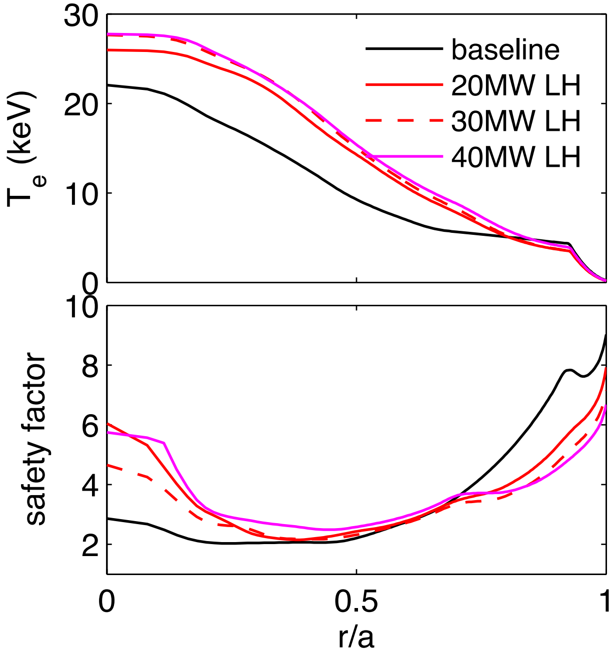
but **still 8MA**

Increase LH power
(and decrease EC power)

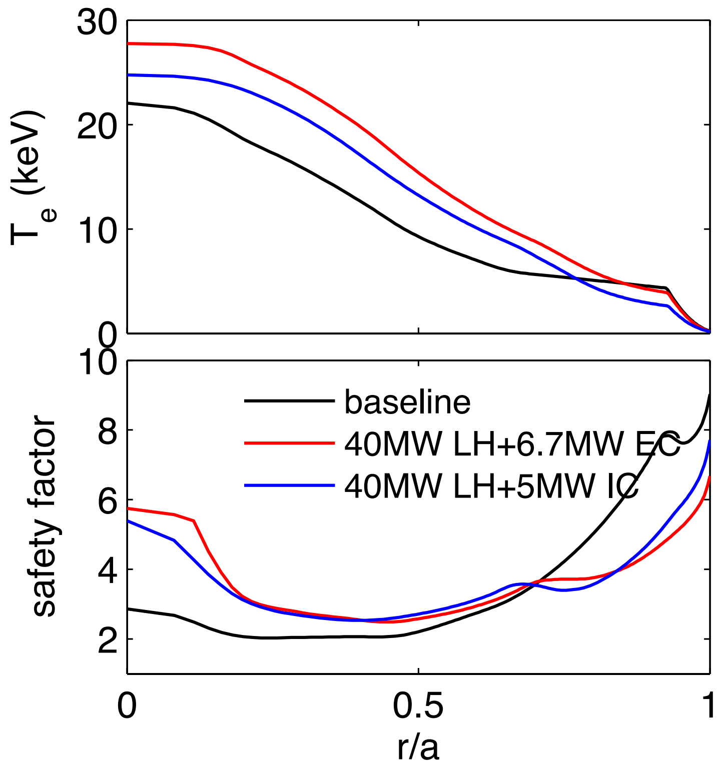
20MW -> 30MW
-> I_{NI}~8.0 -> 8.6
-> q_{95}~5.6
-> Q~4
No change in H_{98}

30MW -> 40MW
-> I_{NI} ~9.1MA
-> q_{95}~5.3
-> Q~4
H_{98} ~ 1.54 -> 1.44



P_{EC}: 6.7 MW ← 13.4 MW

40MW of LH sustain 9MA with 6.7MW of EC, but not with 5MW of IC



with 6.7MW of EC	with 5MW of IC
I_{NI}~9.1 MA	I_{NI}~8.3 MA
I_{EC}~148kA	I_{FW}~43kA
I_{BS}~5.0MA	I_{BS}~4.25MA

LHCD needed to set ITB foot at large radii (high CD efficiency + off-axis deposition)

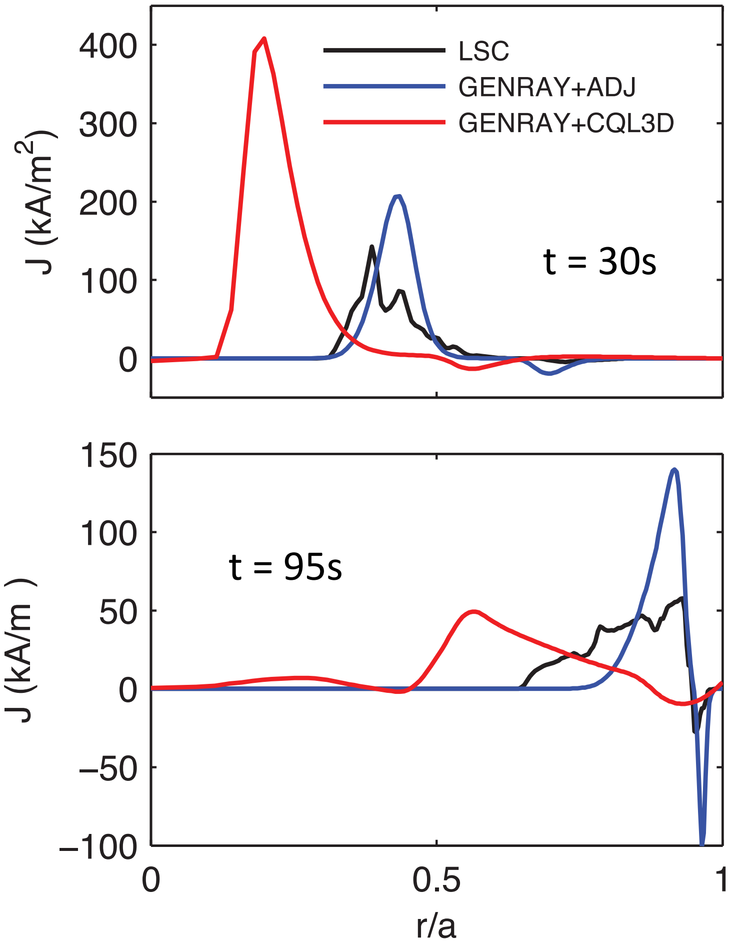
EC needed for current profile control at normalized radii of 0.3-0.7

Conclusions

Within the applicability of our transport model (CDBM)

- The H&CD sources planned for ITER are adequate to trigger and sustain ITBs
  - day-one can sustain ~6.4MA for 3000s with ideal MHD stable ITBs
  - Baseline good candidate to demonstrate continuous operation at low current
- LHCD needed towards ITER goals
  - High CD efficiency sets ITB foot at large radii => higher bootstrap and confinement
  - 30-40MW of LH sustain ~8.6-9.1 MA and Q~4
- EC steering flexibility necessary for current profile control and optimization
  - EC steering more effective when combined with LH
- ITER steady state operation would benefit from a trade-off of all sources
  - 33MW of NB needed for current (2-3MA depending on the scenario)
  - IC + core EC to form strong ITBs in the ramp-up phase
  - Off-axis EC + LH to sustain expanded ITBs and weakly reversed core magnetic shear
- NEED, NEED and still NEED model benchmark and experimental validation to reduce uncertainties on ITER predictions

Flattening of the electron distribution function affects the LH absorption at low density in the ramp-up phase



LSC: 1D, single launching position, modified spectrum

GENRAY: 1D, poloidal distribution of rays

CQL3D: 2D Fokker-Planck

Plateau flattening of the distribution function

affects deposition profiles

at low density in the ramp-up phase

⇒ deeper LH deposition

Correctly accounted for when including

2D Fokker-Planck calculations.