Heating and current drive requirements towards Steady State operation in ITER

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One of ITER's goals is demonstration of operation with 100% non-inductive current and fusion gain Q (P_{fus}/P_{input})~5

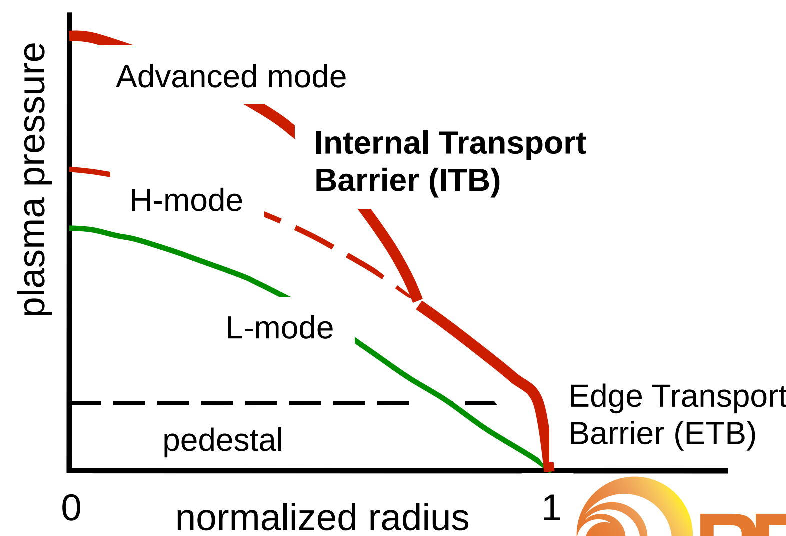
Steady state scenarios target plasmas with current reduced from 15MA to 9MA to minimize external current drive needs

=> will need over 50% of bootstrap current, β_N>2.5 and $H_{98(y,2)}$>1.5

With constraints on pedestal height set by peeling-ballooning instabilities,

these goals may be obtainable only with improved core confinement with internal transport barriers (ITBs)

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

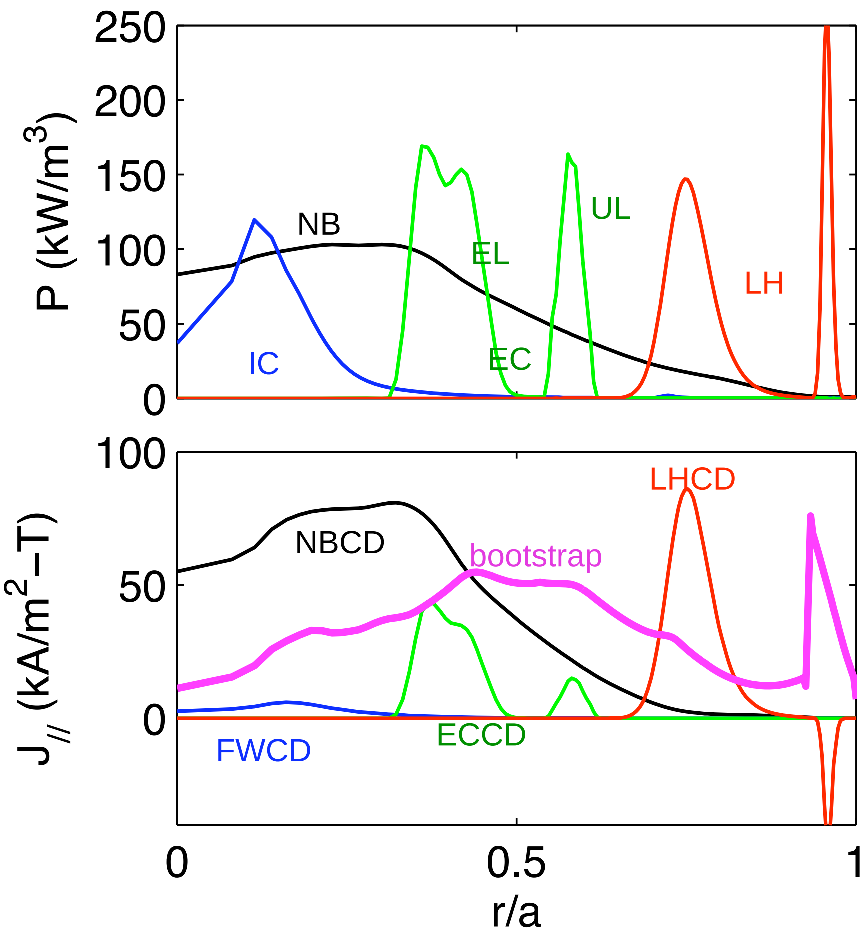


H/CD sources must fulfill requirements for heating to H-mode/ burn, efficient CD, profile control, MHD stability

1. Define a target operational space that is ideal MHD stable
2. Look for fully non-inductive solutions with <u>baseline heating mix</u>
3. Look for <u>optimal upgrade H/CD combination</u> that is compatible with ITER goals

- Simulate current rampup and relaxation in flattop (3000s) to self-consistently study evolution of kinetic profiles and MHD stability
- Use a transport model that responds to magnetic shear profiles (CDBM)
  - RS necessary for ITB triggering in dominant e-heating
  - Rotation will be non important in ITER compared to present experiments

Combining H/CD sources to control the current profile and optimize the scenario



Maximum power Levels, MW

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

Kessel et al, IAEA 2010

Ideal MHD stability sets limits to available operational space

Fix target H_{98}=1.6 and change H/CD mix

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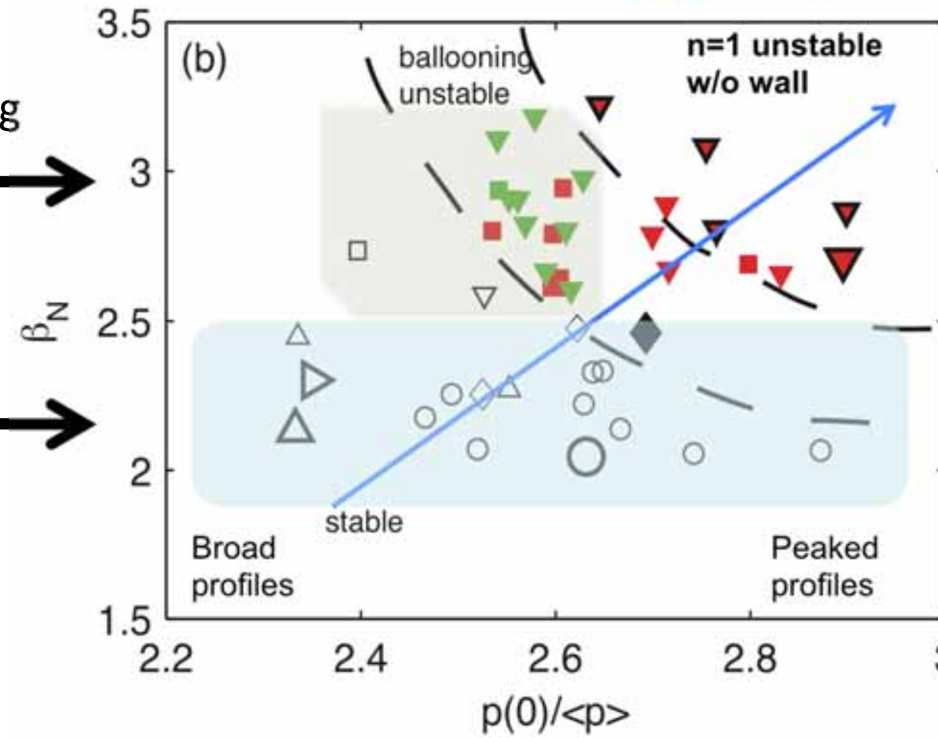
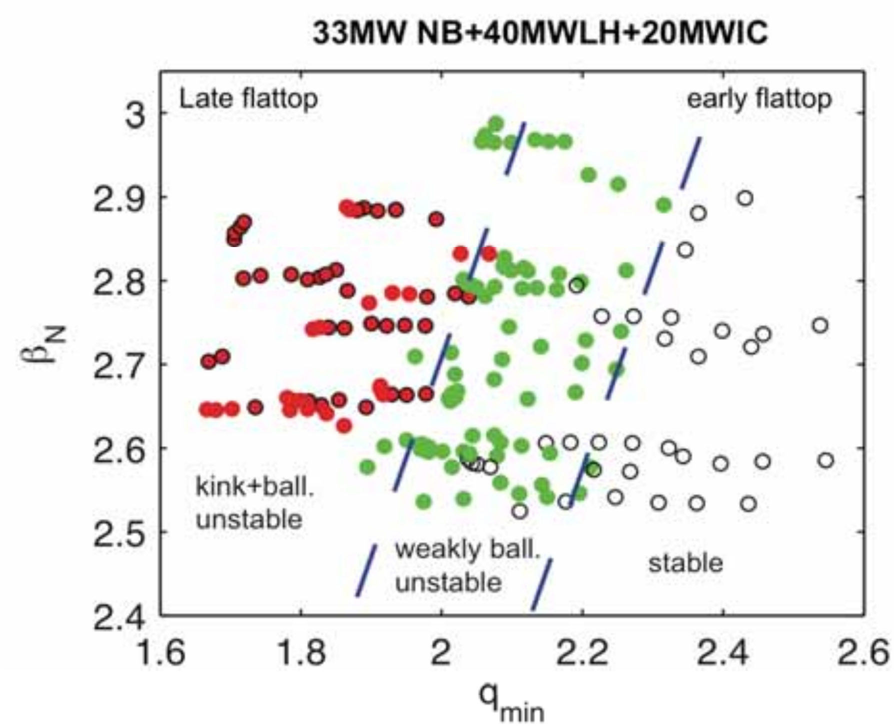
large β_N : stability depends on pressure peaking

low β_N : ideal MHD stable for a wide range of pressure peaking





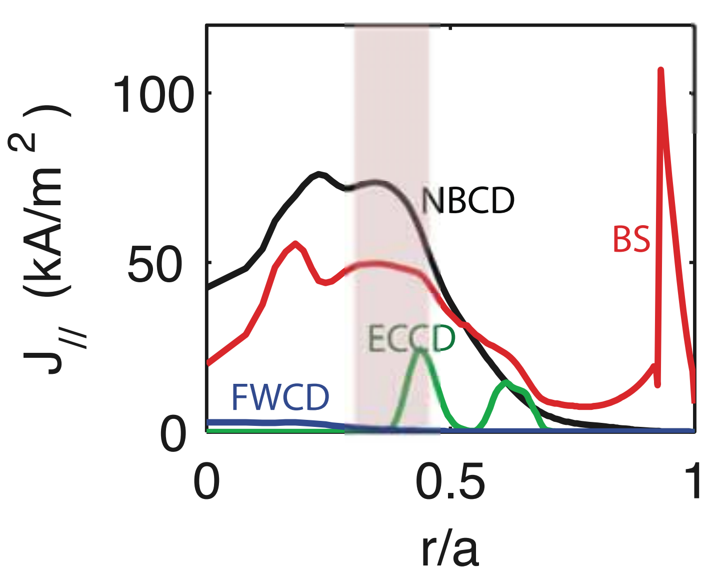
Plasmas should sustain q_{min}>2 during the burning phase

Baseline heating mix results in fully non-inductive discharges at low current and hence low Q

*PoP **20** 0561059 (2013)*

- Distribution of EC power affects ITB formation and sustainment
  - ⇒ EL needed in ramp-up to form e-ITBs
  - ⇒ UL needed in flattop to stabilize ITB foot
- with EL deposition at mid-radius **I_{NI}~6.4 MA**

Q~1.6

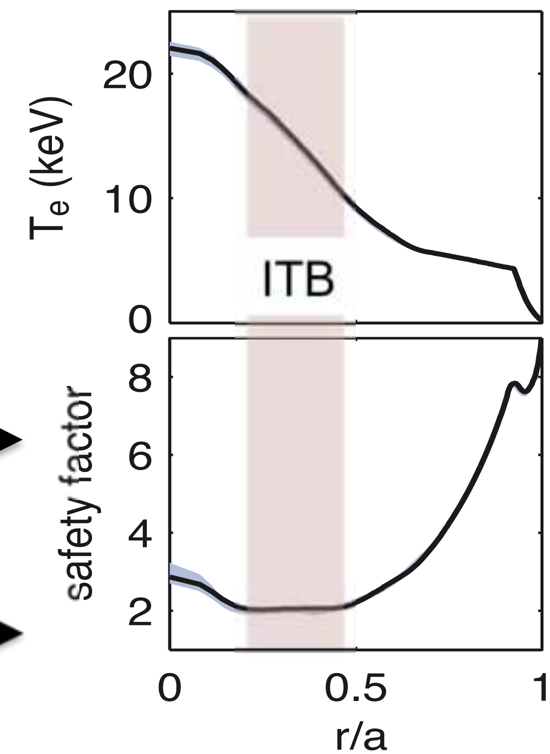


Bootstrap current peak and ρ_{ITB} inside mid-radius

H_{98} ~ 1.3
β_N ~ 1.77

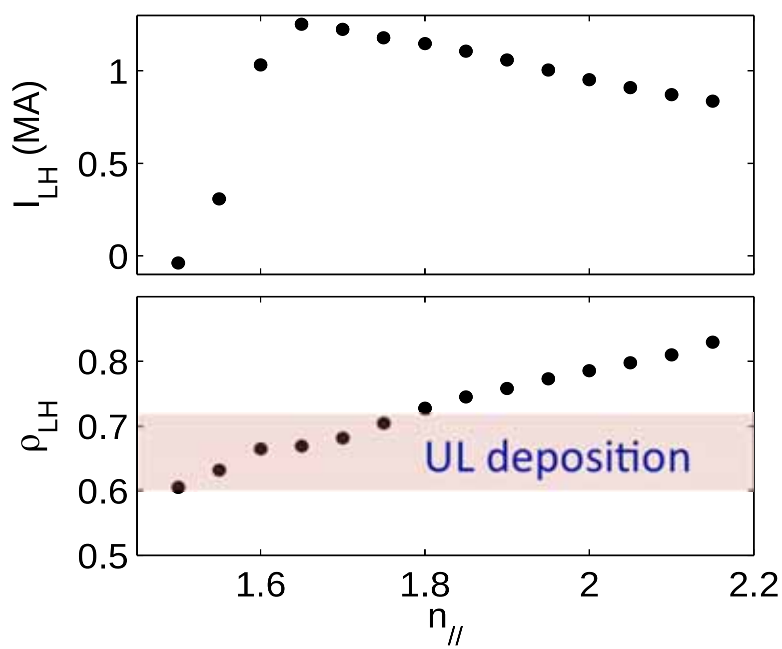
q_{min}~2

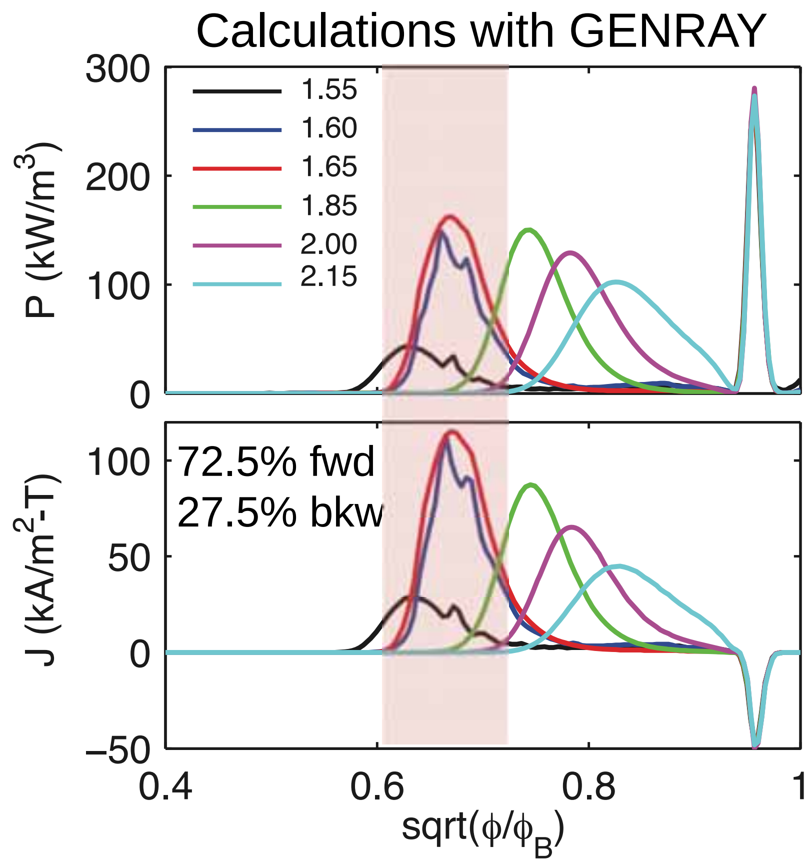
Ideal MHD stable



Baseline heating mix good candidate for demonstration of fully non-inductive operation with ITBs at low current

LHCD has high CD efficiency and its off-axis deposition sustains more expanded ITBs



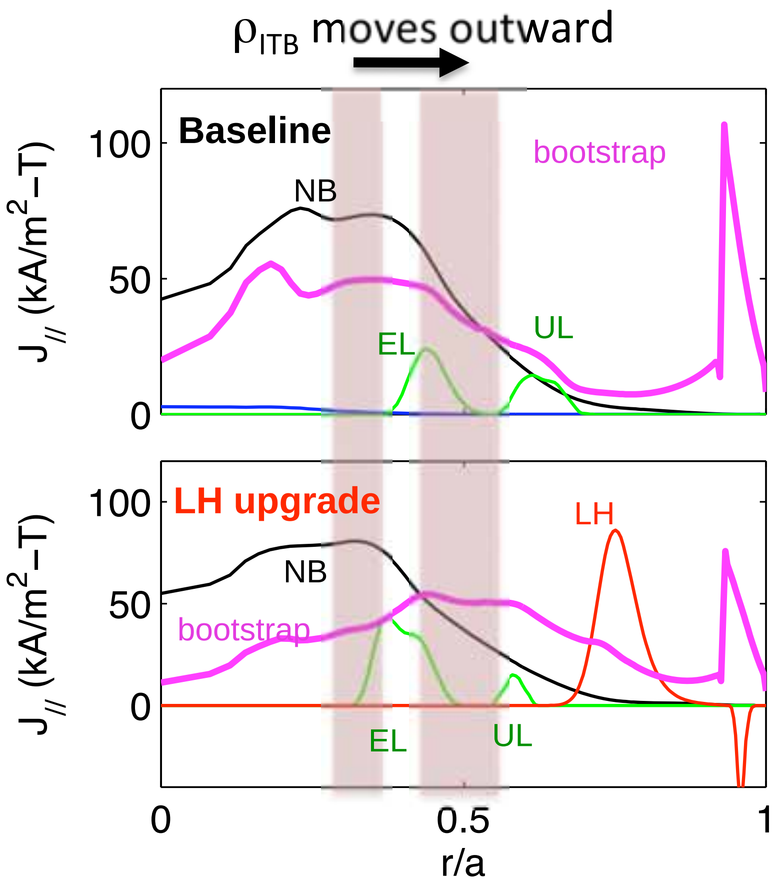


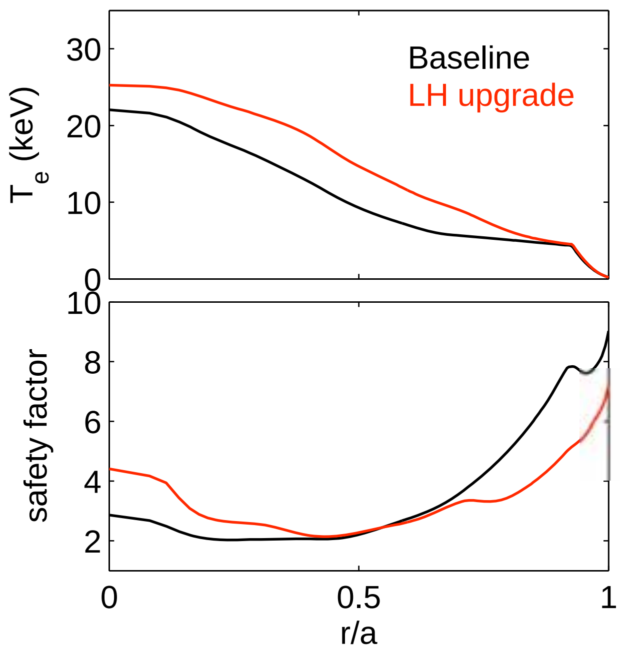
With $n_{//}$=1.75-1.85 LH deposits off-axis outside EC upper launcher deposition

20 MW of LH drive ~ 1MA non-inductive current

20 MW of coupled LH can enhance the plasma performance toward the ITER goals

	Baseline		LH upgrade
n/n_G	1.0	->	0.87
q_{95}	8.1	->	5.6
I_{NI}	6.4	->	8.2 MA
Q	1.7	->	2.9
β_N	1.77	->	1.78
H_{98}	1.38	->	1.42

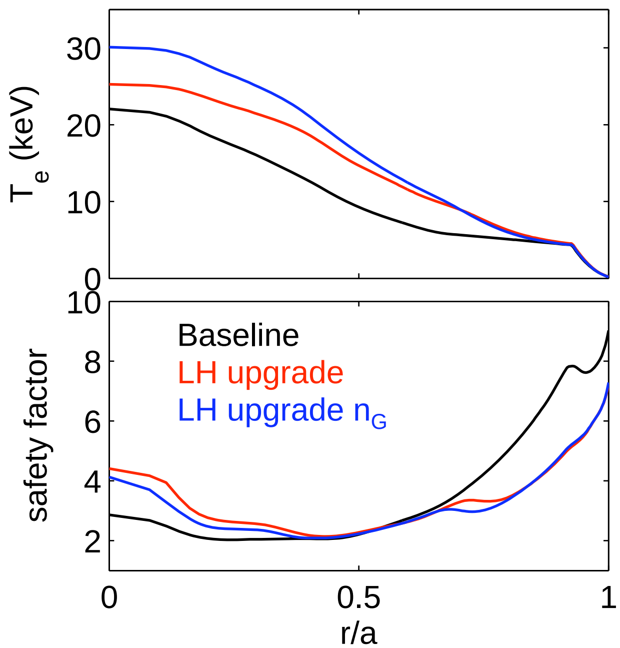


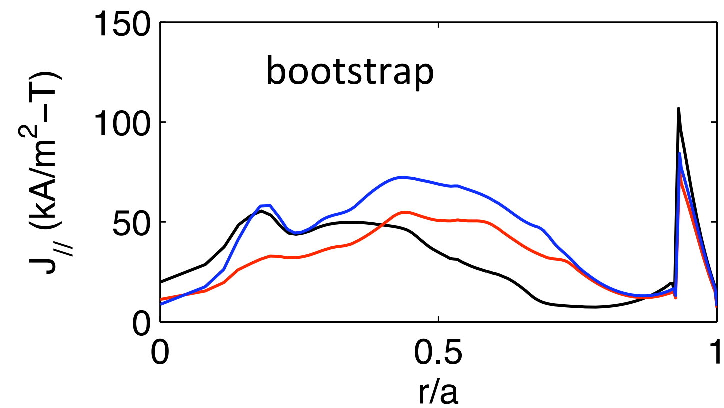


lower q_{95}
Moves $\rho(q_{min})$ outward

20 MW of coupled LH can enhance the plasma performance toward the ITER goals

	Baseline		LH upgrade		LH upgrade and n_G
n/n_G	1.0	->	0.87	->	1.0
q_{95}	8.1	->	5.6	->	5.6
I_{NI}	6.4	->	8.2 MA	->	8.8±0.2 MA
Q	1.7	->	2.9	->	5
β_N	1.77	->	1.78	->	2.3±0.2
H_{98}	1.38	->	1.42	->	1.65±0.03





Combined with LH, EC deposits inside the ITB
=> Effective at modifying the bootstrap current and pressure profiles

The optimal upgrade in support of ITER steady state goals has 20 MW of LH with $n_{//}$~1.75-1.90

LH: current drive efficiency and off-axis deposition => **expanded ITBs**

EC: deposition flexibility => **stabilizes ITB foot by freezing bootstrap profiles**

With constraints on the pedestal height from peeling-ballooning instabilities

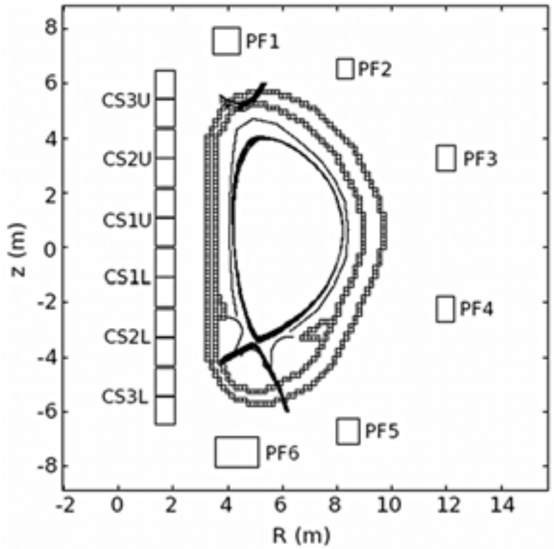
steady state solutions exist with
Q~5
I_{NI}~9 MA
l_i~0.8
β_N~2.5
H_{98}~1.6

Steady state exploration for ITER is an evolving research that NEEDS:

- investigation of steady state access in present day experiments
- Continuous work on improving our predicting modeling capabilities, using these experiments to benchmark our models: actuators, transport, control …

BACKUP SLIDES

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 (time slice - offline)

JSOLVER (refines eq.)
BALMSC (ballooning)
PEST (kink)

PF coil currents feedback system

Discharge scenario

EPED1*

TSC **(Tokamak Simulator Code)** (free boundary)

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

NB : NUBEAM
ICRH : TORIC
ECRH: TORAY, GENRAY
LH: GENRAY, (**LSC**)
3D Fokker Planck CQL3D

H&CD profiles

Transport model
Coppi-Tang, CDBM

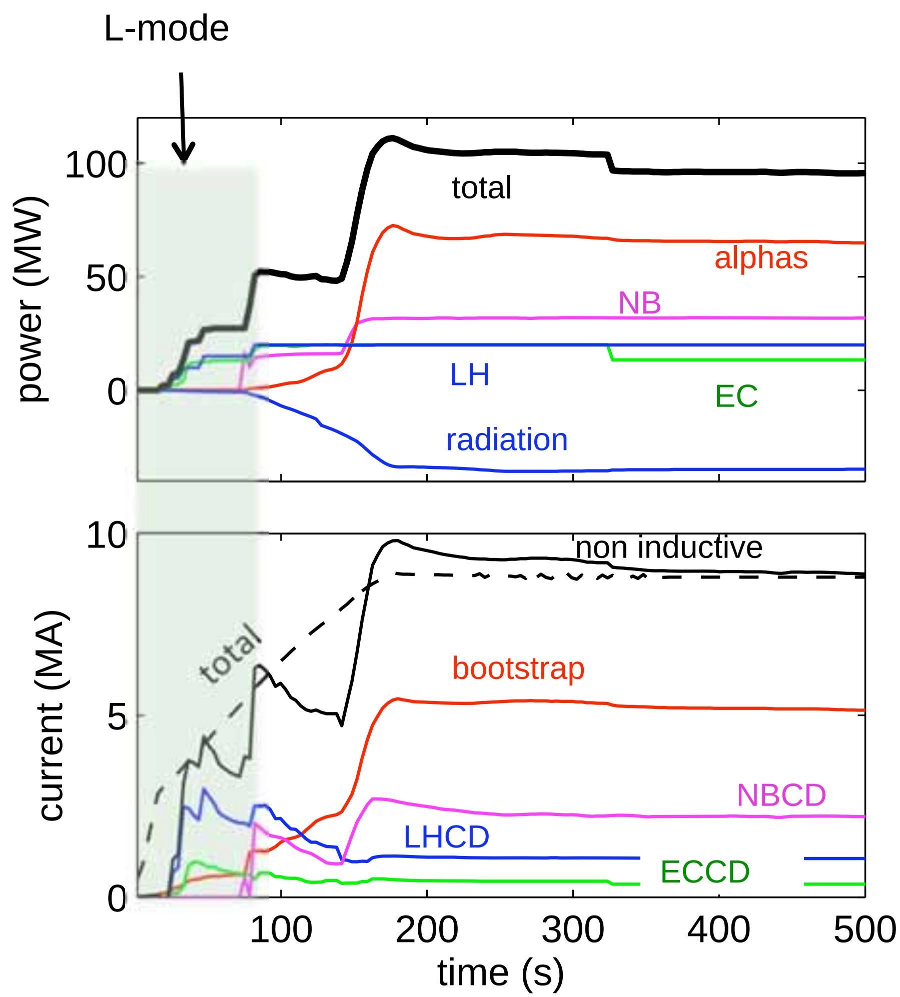
IPS **(Integrated Plasma Simulator)** (fully consistent)

TRANSP (analysis loop)

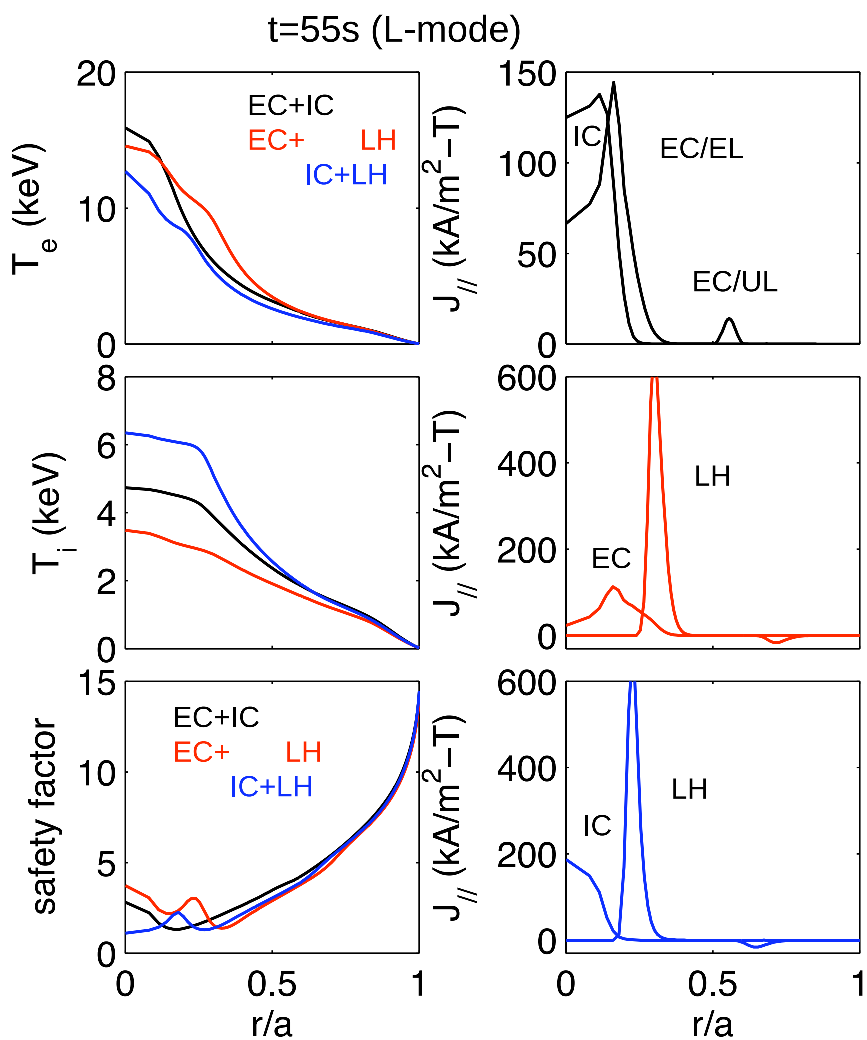
* P. Snyder

Simulate rampup and relaxation in flattop to self-consistently study kinetic profiles and MHD stability evolution

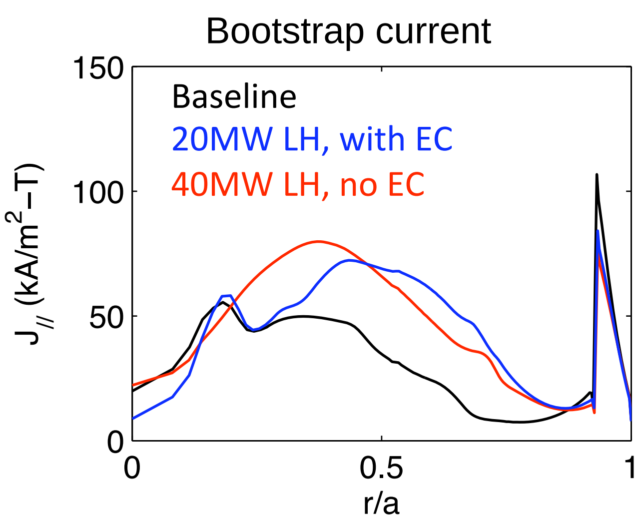
- Ramp-up phase
  - RF to form reverse shear profiles
  - Inductive rampup still important
- Flat-top phase
  - 100% non-inductive current
  - Sustain moderate reverse shear
- Radiated power keeps divertor loads within acceptable levels

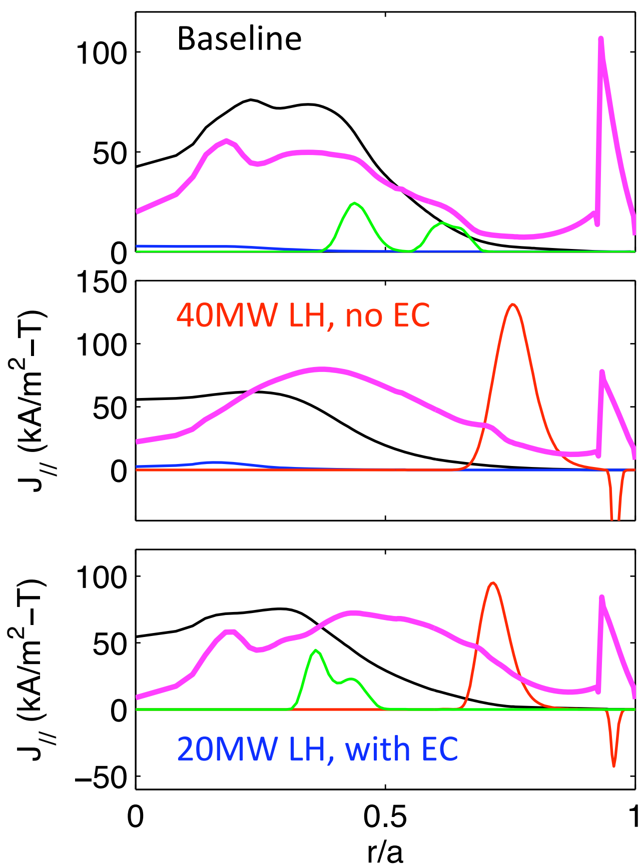


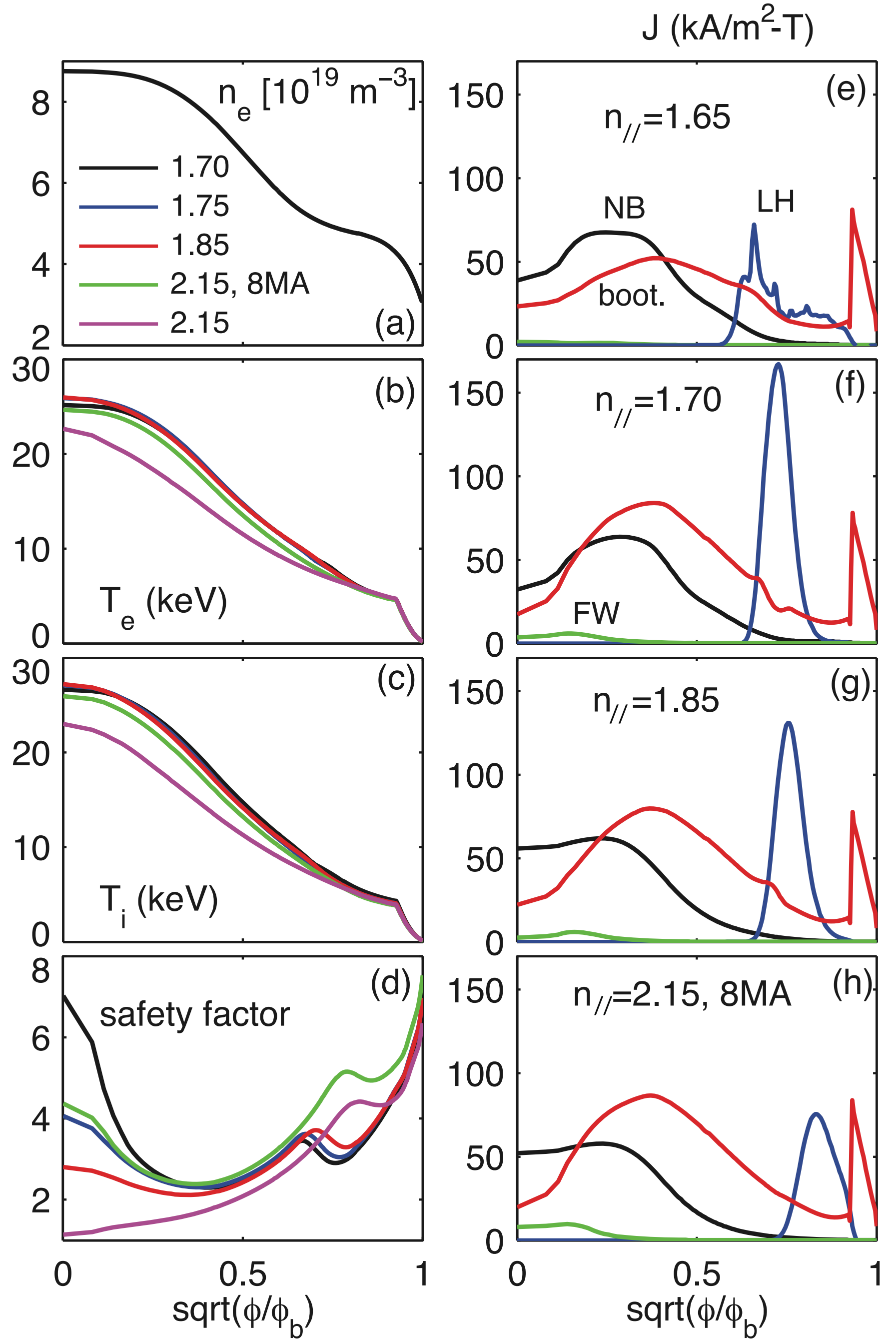
All H/CD mixes form RS in the core and trigger ITBs in the electron channel in L-mode



40MW of LH do not achieve the same performance as 20 MW each of EC and LH






J (kA/m2-T)
n_e [10^19 m^-3]
1.70
1.75
1.85
2.15, 8MA
2.15
(a)
(b)
T_e (keV)
(c)
T_i (keV)
(d)
safety factor
sqrt(ϕ/ϕ_b)
n_//=1.65
(e)
NB
LH
boot.
n_//=1.70
(f)
FW
n_//=1.85
(g)
n_//=2.15, 8MA
(h)
sqrt(ϕ/ϕ_b)