MHD stability of ITER SS scenarios with ITBs

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- Studied 5 SS scenarios with ITBs and various mixes of NB, IC, EC, LH
- Analyzed the ideal MHD stability for variations of
  - Greenwald fraction (within 1.2 of n_G)
  - Pressure peaking factor
- Defined an operational space: β_N,q,l_i,p(0)/<p> that is stable to ideal MHD

=> Stable operations have $q_{min}>2$ and ITBs at 2/3 of minor radius

=> Scenarios with LH heating achieve $\beta_N \geq 4 l_i$ with ideal wall stabilization

Time dependent simulations run with TSC/TRANSP

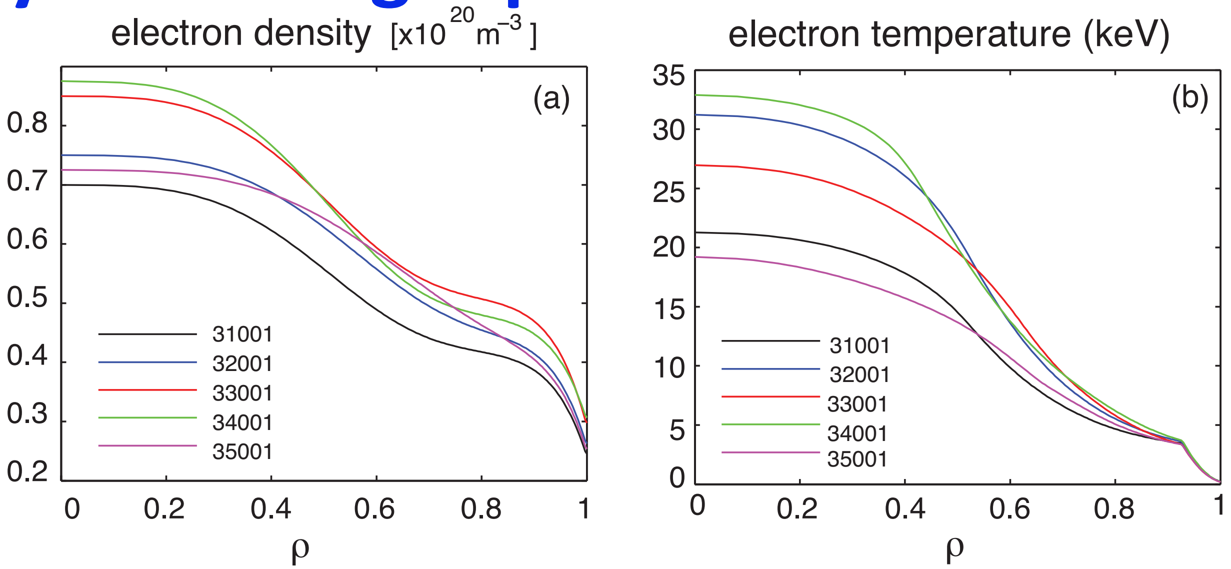
73 MW | 20 MW EC + 20 MW IC
73 MW | 20 MW EC + 20 MW LH
93 MW | 40 MW EC + 20 MW IC
93 MW | 40 MW LH + 20 MW IC
+33 MW NB

68 MW = 40 MW LH + 20 MW IC + 8 MW NB

- **Use H/CD settings for optimized performance** *[Lehigh univ.]*

- NB: off-axis steering, peaked at $\rho=0.35$ => ~3 MA of CD
- IC : 48 MHz, on-axis deposition => 200-400 kA FWCD
  8 MW on thermal ions, 12 MW on thermal electrons
- EC : midplane launchers, $\rho=0.35$ => I_{ECCD}~0.7 MA (1.4 MA)
- LH : $n_{||} = 2.15$, $\Delta n_{||} = 0.2$, (ρ_{LH}~0.65) $P_{+} = 85\%$, $P_{-} = 15\%$ => I_{LH}~0.8 MA

Steady State target plasmas



R=6.2, a=2.0. κ=1.8, δ~0.45

I_P = 7-10 MA

n/n_{Gr} ~ 0.75-1.0

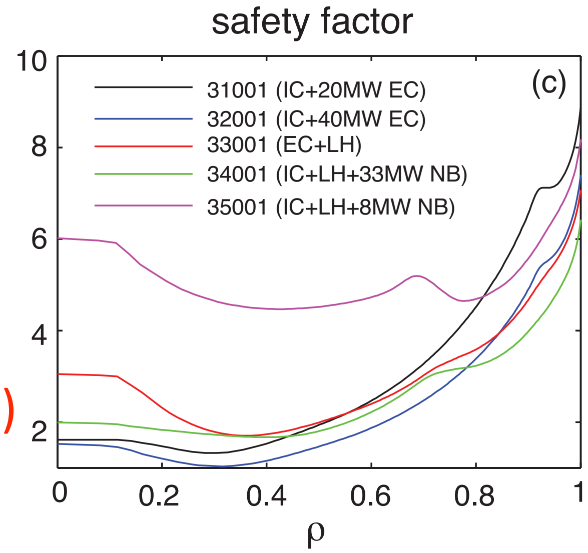
100% non-inductive current

n(0)/<n> = 1.3-1.5

EPED1 estimate: (P. Snyder)

T_{ped} ~ 3.3-3.7 keV @ n_{ped} = 5-6.7x10^{19} /m^3

ρ_{ped} ~0.94



Impurities and radiated power

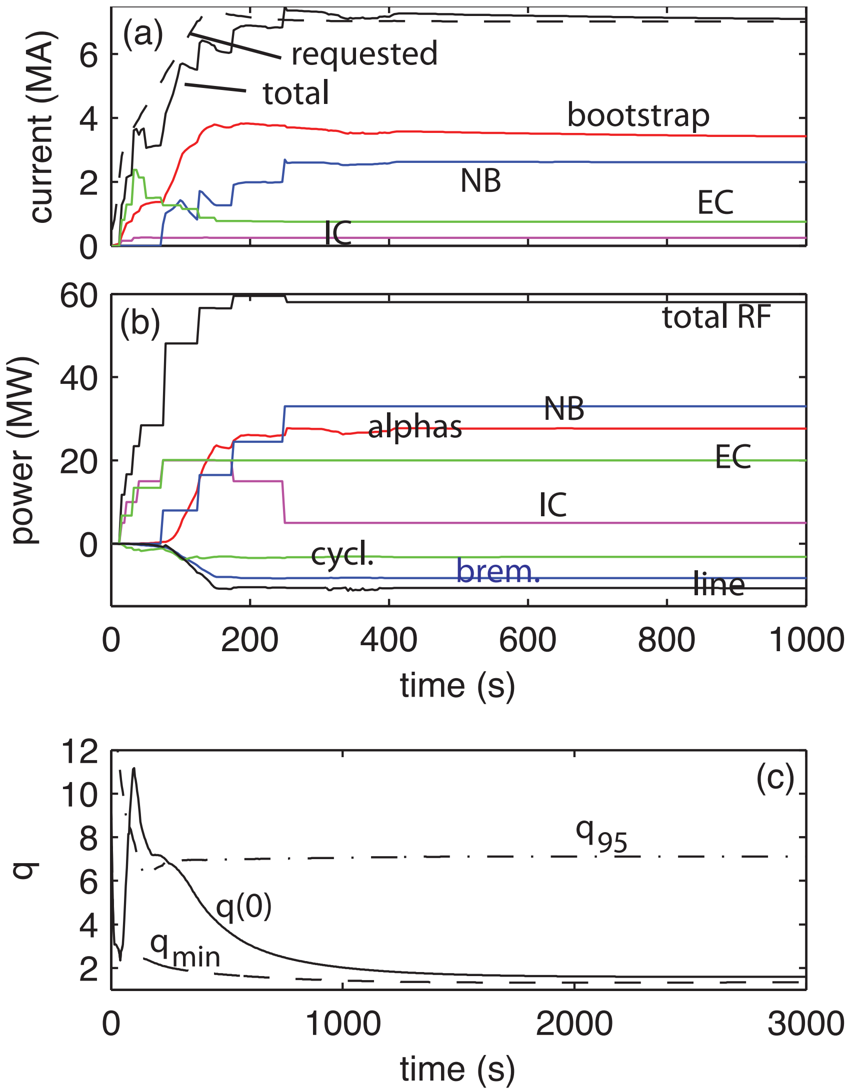
2% Be   0.4% Ar

$P_{core, rad}$ = 25-35 MW (brem+cyc+line)

Core confinement must be enhanced over H-mode IPB98(y,2) to get Q ~ 5 and 100% non-inductive I_p

- Use H_{98} ~ 1.6 as target
- Prescribe the χ profile to produce an ITB and scale to provide H_{98}

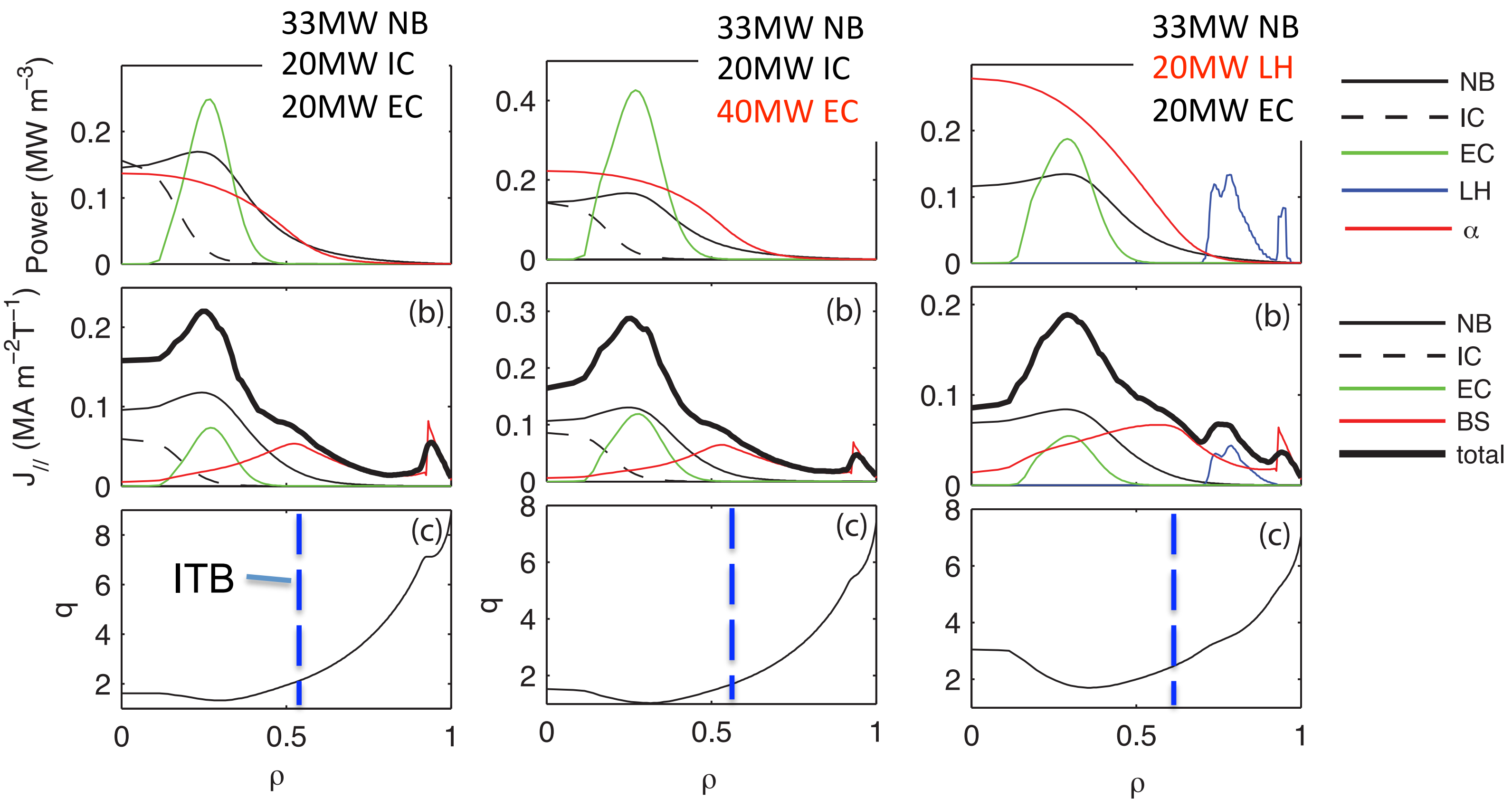
Current profiles relax over ~2000s


33MW NB + 20MW IC +20MW EC

- Simulate the whole 3000s burning phase
- Plasma diverted at 14s, I_P=3 MA
- RF heating starts at 15s
- NB heating at 75s
- L-H transition at 75s
- IC stepped down in flat-top: 20->5 MW
- OH heating assists during the rampup
- 100% non-inductive current in the flattop
- Rampup phase fixed at 150s
  - To avoid too much inductive current
- Keep driven current below I_P during rampup to avoid overdrive

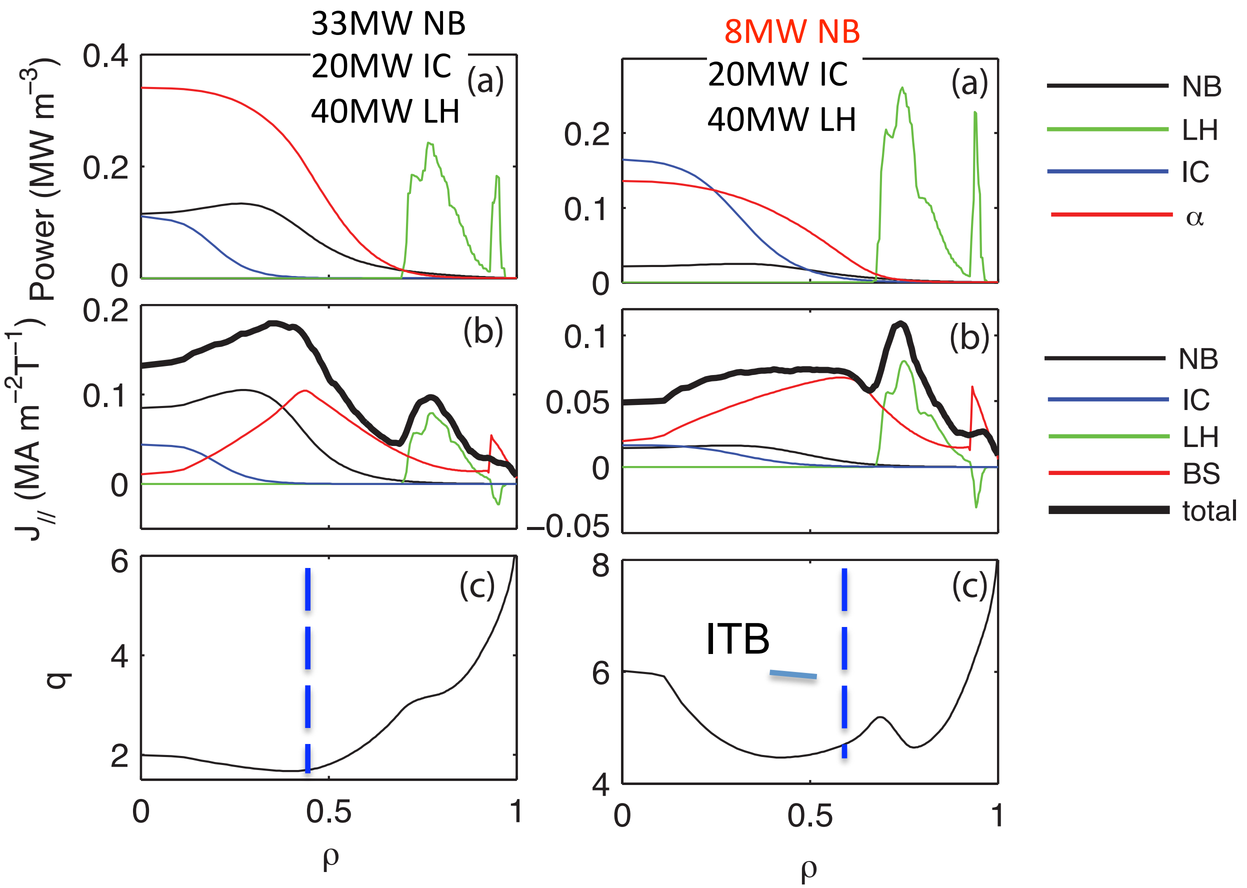
P_{NB} (MW) P_{IC} (MW) P_{EC} (MW) P_{LH} (MW)	33 20 20 /	33 20 40 /	33 / 20 20	33 20 / 40	8 20 / 40
I_P (MA)	7.0	9.0	8.85	10.0	7.25
I_{NB} (MA)	2.6	3.1	2.4	2.8	0.56
I_{BS} (MA)	3.4 (49%)	3.8 (42%)	4.8 (54%)	5.2 (52%)	**4.9 (65%)**
I_{EC} (MA)	0.74	1.66	0.73	/	/
I_{LH} (MA)	/	/	0.83	1.8	1.75
β_N	2.04	2.4	**2.6**	**2.7**	2.13
H_{98}	1.55	1.58	1.63	1.63	1.55
q_{min}	1.35	0.96	1.71	1.67	4.5
$l_i(1)$, $l_i(3)$	1.1 , 0.9	1.2 , 1.0	0.85 , 0.69	0.80 , 0.66	0.58 , 0.48
$p(0)/\langle p \rangle$	2.63	2.56	2.6	2.90	2.33
n/n_G	1.0	0.87	0.95	0.85	1.0
P_α (MW)	28	52	64	76	33
Q	2.4	3.3	**4.3**	**4.9**	2.4

LH heating favorable to raise q_{min} above 1.5



I_P = 7.0 MA	I_P = 9 MA	I_P = 8.85 MA
I_{BS}= 3.4 MA	I_{BS}= 3.8 MA	I_{BS}= 4.8 MA
P_α = 28 MW	P_α = 52 MW	P_α = 64 MW
Q = 2.4	Q = 3.3	Q = 4.3
n/n_G= 1.0	n/n_G= 0.87	n/n_G= 0.95
β_N = 2.04	β_N = 2.42	β_N = 2.6
q_{min}=1.4	q_{min}=0.96	q_{min}=1.7

40MW LH – control q_{min} position only with low NB



I_P = 10.0 MA	I_P = 7.25 MA
I_{BS}= 5.2 MA	I_{BS}= 4.9 MA
P_α = 76 MW	P_α = 33 MW
Q = 4.9	Q = 2.4
n/n_G= 0.85	n/n_G= 1.0
β_N = 2.7	β_N = 2.13
n(0)/<n>= 1.5	n(0)/<n>= 1.3
ρ_{ITB} = 0.45	ρ_{ITB}= 0.65
q_{min}=1.67	q_{min} = 4.5

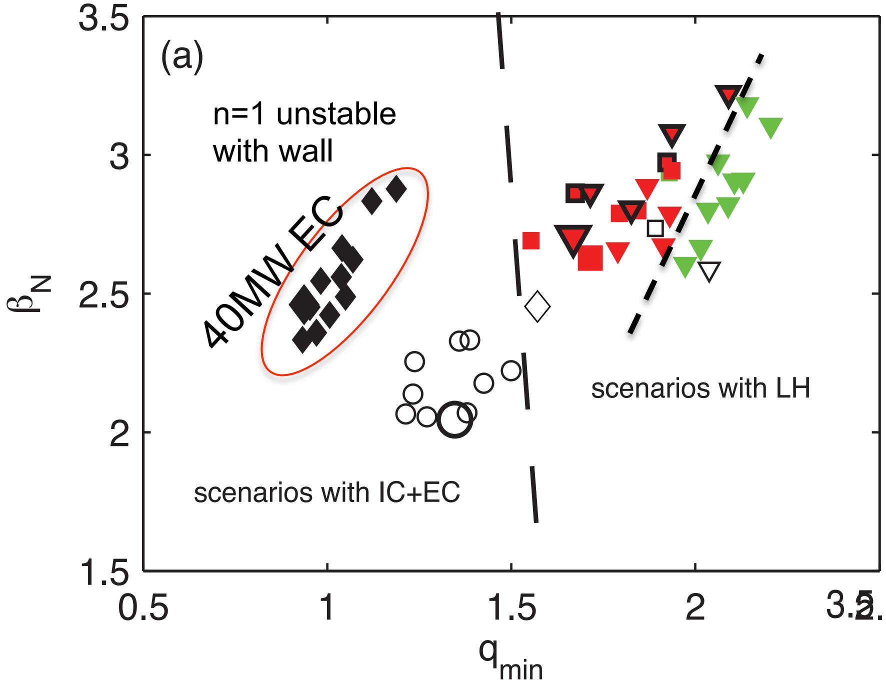
- The current profile is dominated by the NB, EC adds up
- In IC+EC scenarios large, localized current density causes q_{min} <1.5
- LH can effectively control the q_{min} position when coupled to low NB power
- All configurations have $\rho_{ITB} > \rho(q_{min})$ and RS in the core after profile relaxation

40MW LH plasma is operating above no-wall limit

P_{NB} (MW)	**33**	**33**	**33**	**33**	**8**
P_{IC} (MW)	**20**	**20**	**/**	**20**	**20**
P_{EC} (MW)	**20**	**40**	**20**	**/**	**/**
P_{LH} (MW)	**/**	**/**	**20**	**40**	**40**
I_P (MA)	7.0	9.0	8.85	10.0	7.25
β_N	2.04	2.4	2.6	2.7	2.13
q_{min}	1.35	0.96	1.71	1.67	4.5
p(0)/<p>	2.63	2.56	2.6	2.90	2.33
n/n_G	1.0	0.87	0.95	0.85	1.0
Ballooning			unstable	unstable	
n=1		Unstable with wall		Unstable w/o wall	
n=2		unstable			

- The low β_N makes the 20MW IC+20MW EC plasma stable even with q_{min} <1.5
- Ballooning => EC+LH and IC+LH+33MW NB [large β_N, large p(0)/<p>]
- n=1 => IC+LH [large β_N, large p(0)/<p>, above no-wall limit]
  => 40 MW IC [q_{min} <1.5 , large edge current]

Stable equilibria have q_{min}>2 and ITBs @r>2/3a

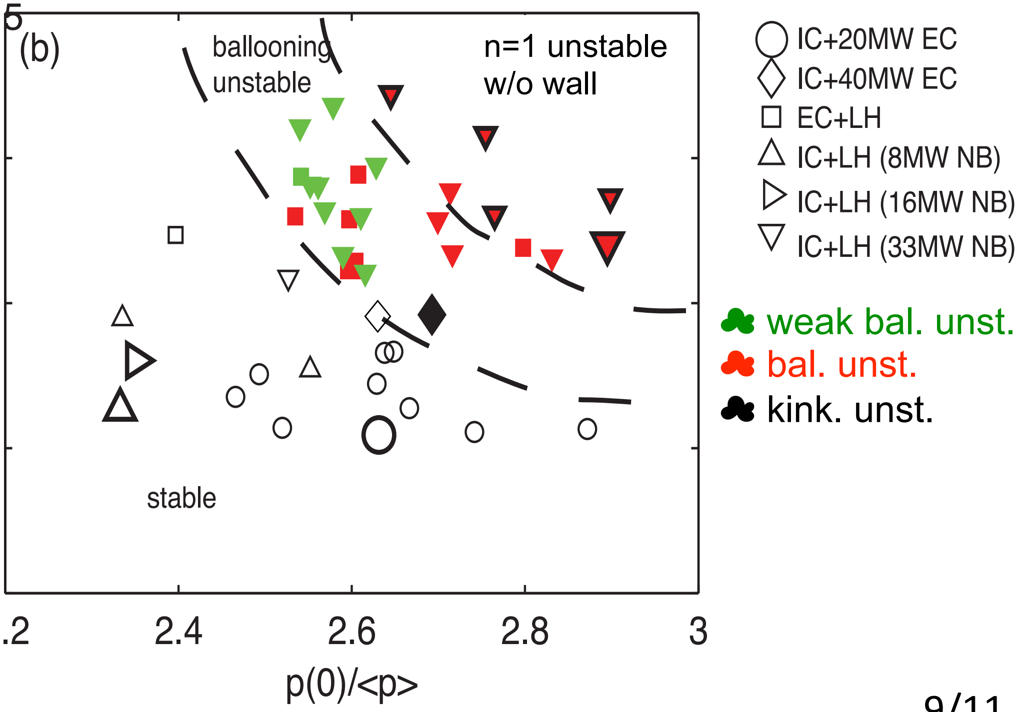


Database $n<1.2\ n_G$
$n(0)/<n>=1.3-1.5$
$\rho_{ITB} = 0.45-0.75$

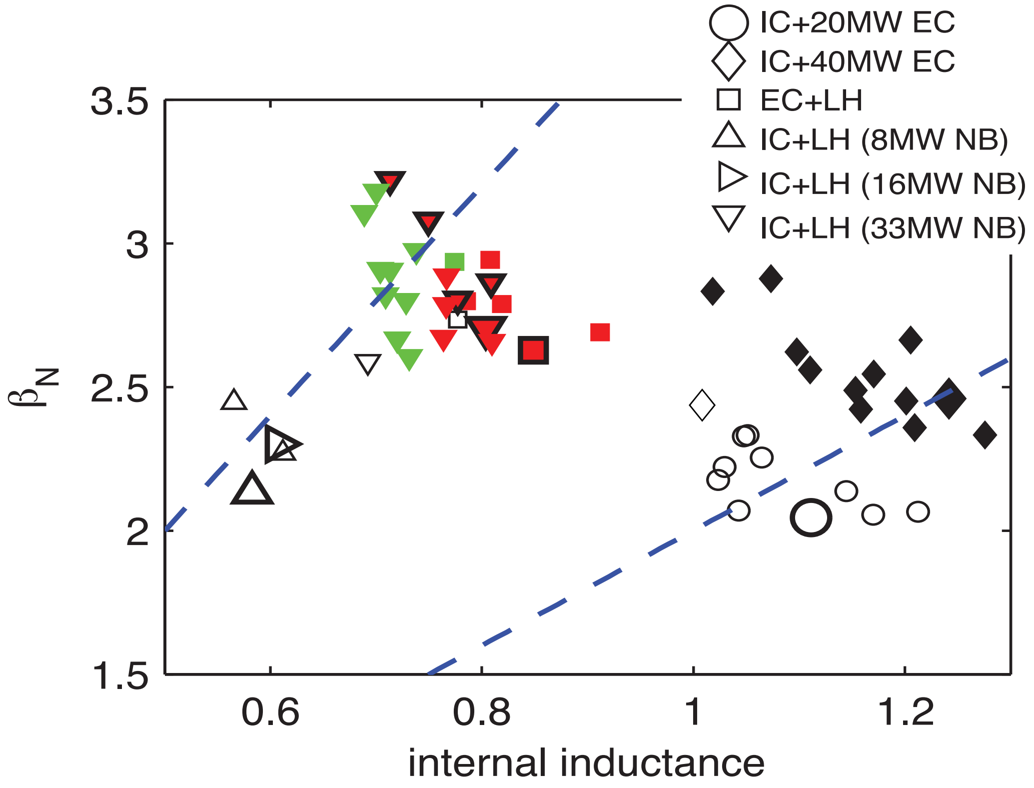
⇒ IC+EC $q_{min}<1.5$
⇒ LH (IC/EC) $q_{min}>1.5$ $\beta_N>2.5$
⇒ EC at $\rho=0.45$ elevates q_{min} and makes
40MW EC stable

LH with IC or EC
⇒unstable for $\rho_{ITB}=0.5$
⇒stable for $\rho_{ITB}>0.6$

40 MW EC
⇒unstable for $\rho_{ECRH}=0.35$
⇒stable for $\rho_{ECRH}>0.45$



LH scenarios achieve $\beta_N \geq 4l_i$ with ideal wall stabilization



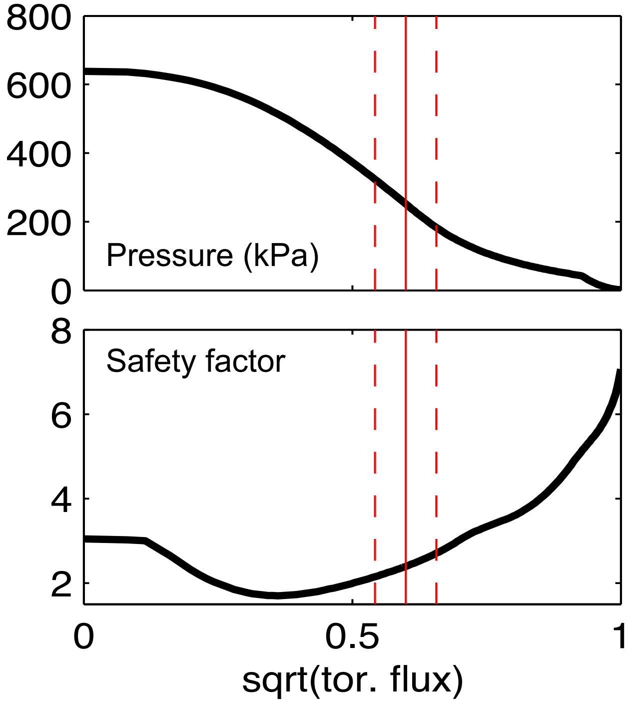
- Higher β_N at intermediate inductance with LH heating
- adding 20 MW LH to 20MW EC+33MW NB provides control of l_i and raises q_{min}
- adding 20 MW EC to 20MW EC+33MW NB makes the plasma unstable
- ECRH off-axis loses 200 kA CD, but improves stability and controls l_i
- 40 MW LH achieve $\beta_N > 4l_i$

Future work on SS scenarios

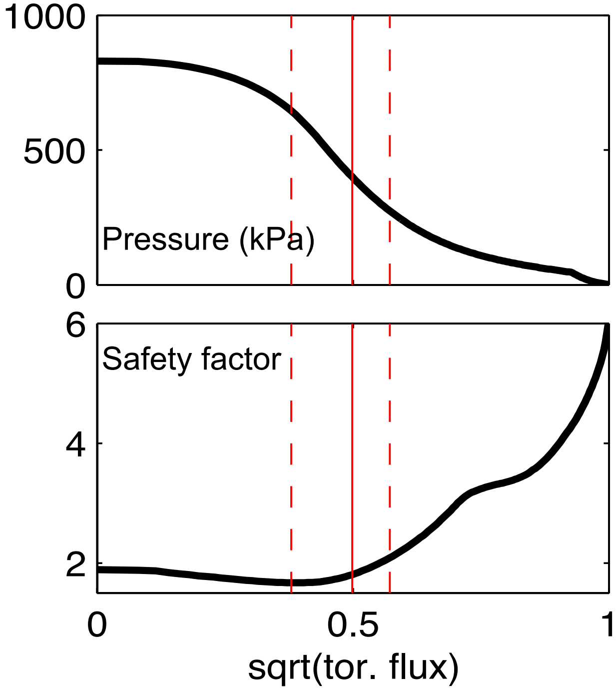
- Will analyze stability in the ramp-up and work on q-profile optimization
  - ECRH steering to broaden current profile and control q_{min}
  - NB steering to control q on axis
- Will study more in detail stability of configurations with lower P_{NB} (8-24 MW) and higher q_{min} (EP vs MHD inst.)

- Will refine the T_{ped} estimates from EPED for cases at high current and higher density
- Will use first principle transport models (e.g. CDBM) to predict formation and sustainment of ITBs
- Benchmark non-inductive scenarios on existing tokamak ITB databases (JT-60U, JET)
- Project results to ITER scenarios

Ballooning instabilities likely not harmful to these plasmas



EC+LH



IC+LH

q_{min}~1.7 ρ_{ITB} =0.55

Max of instability at q=2.4

Radial extent ~12% of minor radius

n_{cr} = 44

q_{min}~1.6 ρ_{ITB} =0.45

Max of instability at q=1.8

Radial extent ~17% of minor radius

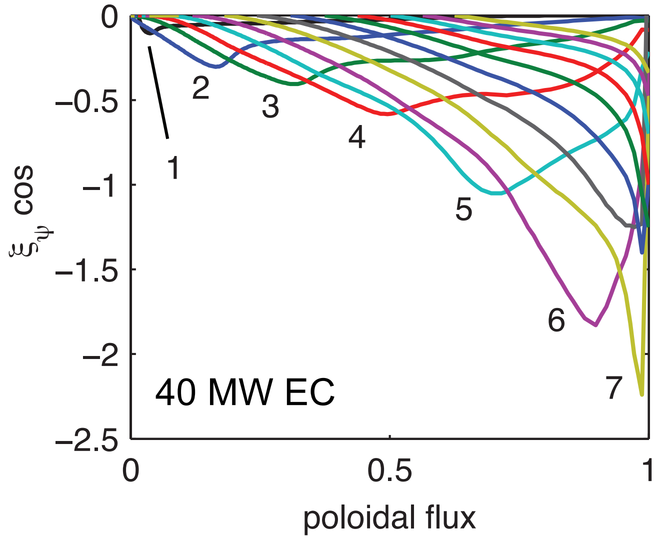
n_{cr} = 17

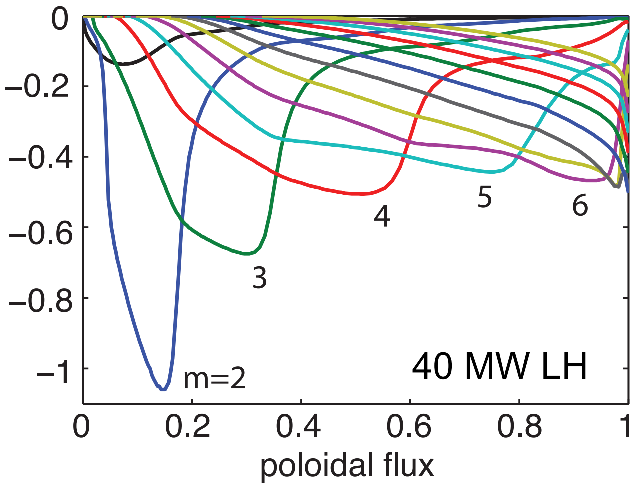
Mercier unstable on axis (q=1.8)

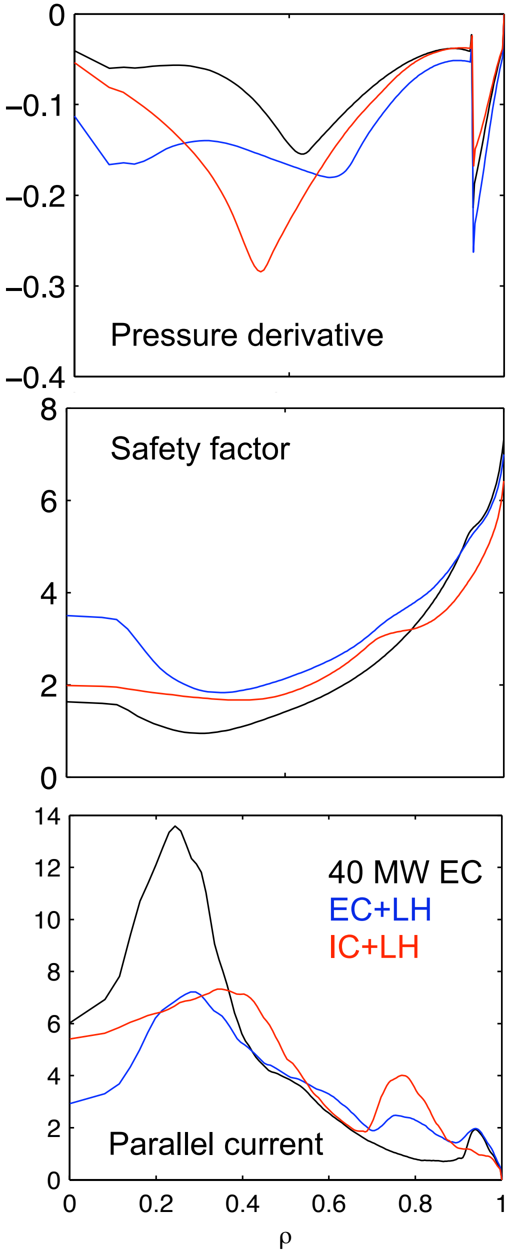
Large critical mode number combined to small radial extent

Stability improves operating with broader ITBs

ITB gradient close to q_{min} makes 40MW LH kink unstable

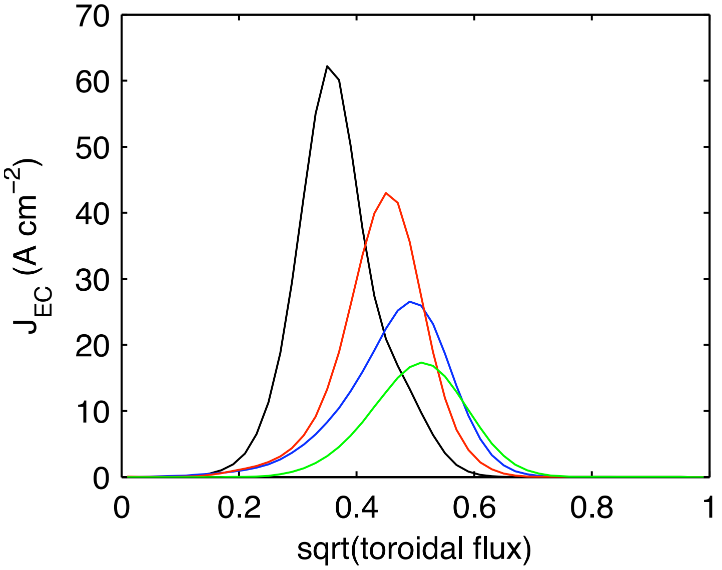


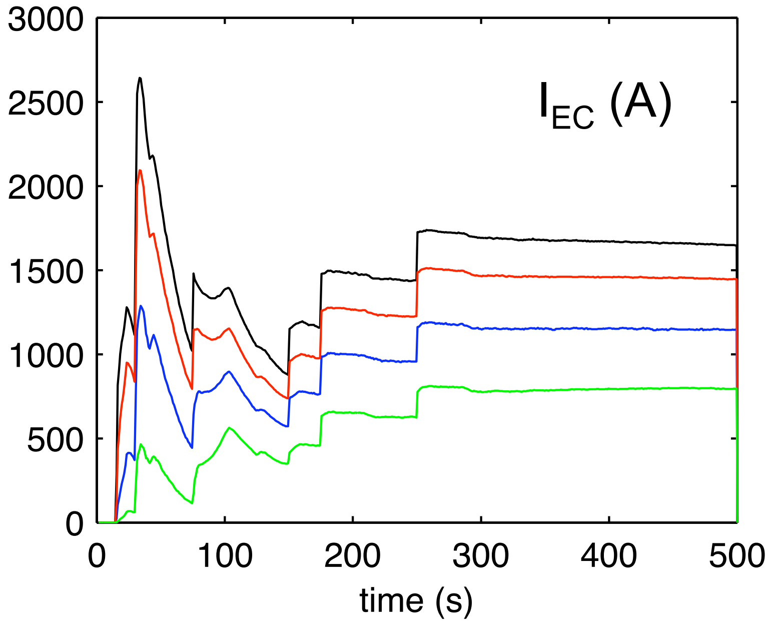


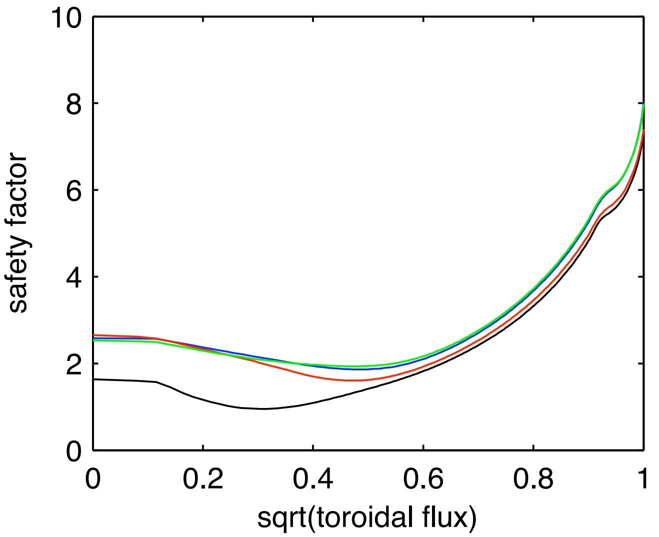


40 MW EC : mode structure at the edge
drive: large edge current
not stabilized by ideal wall

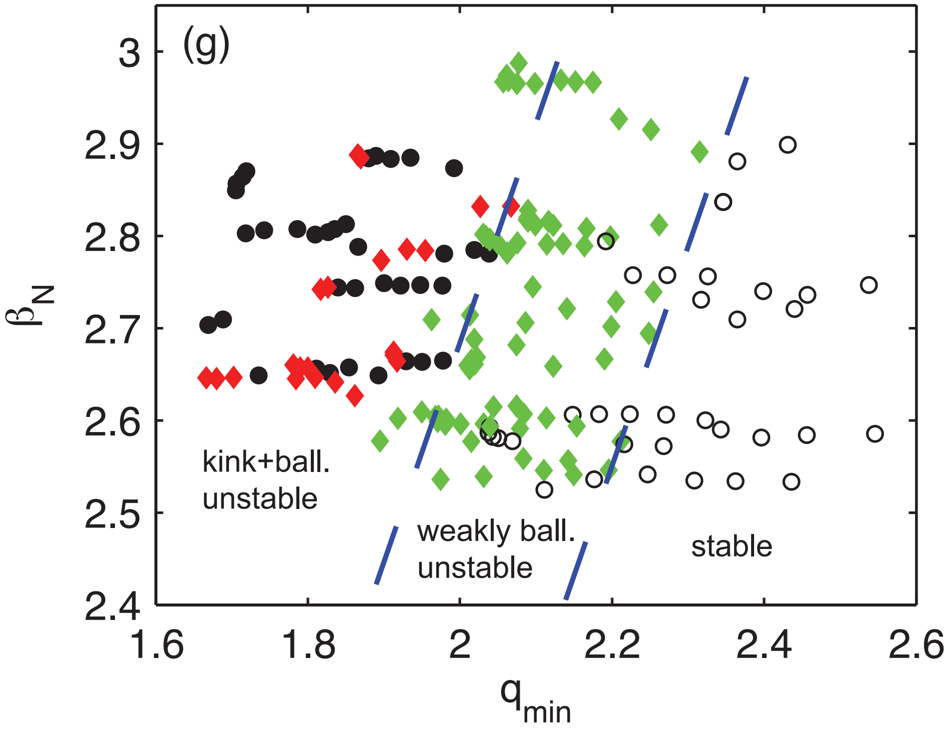
40 MW LH : mode structure in the core
dominant m=2 (structure close to infernal mode)
drive: large pressure gradient at ITB location
$q=2$ close to q_{min}
stabilized by ideal wall


70
60
50
40
30
20
10
0
J_{EC} (A cm^{-2})
0
0.2
0.4
0.6
0.8
1
sqrt(toroidal flux)


I_{EC} (A)
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
time (s)


10
8
6
4
2
0
safety factor
0
0.2
0.4
0.6
0.8
1
sqrt(toroidal flux)

Raising q_{min}>2 significantly improves stability



- Gradual transition from unstable to stable equilibria when q_{min} is raised above 2
- No-wall limit at β_N~2.6
- Above the no-wall limit kink modes are stabilized by the ideal wall
- RWM stabilization needed