ASDEX Upgrade

Max-Planck-Institut für Plasmaphysik

IPP

EX/4-5

The Improved H-Mode at ASDEX Upgrade: A Candidate for an ITER Hybrid Scenario

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- > Characterisation of Improved H-mode
- > Stability - Role of MHD
- > Existence Domain
- > Improved Confinement
- > Dominant ICRH in Plasma Core

Introduction

ITER baseline scenario

ELMy H-mode, I_p = 15 MA, B_t = 5.7 T, $q_{95} \sim 3$
with: $H_{98(y,2)} = 1$, $\beta_N = 1.8$, $\Rightarrow$ Q = 10

"Advanced scenarios" (by control of current density profile) aim at
Improved confinement and/or stability
$\Rightarrow$ lower current / longer pulses at similar performance
or higher performance

Performance measured by figure of merit for fusion gain Q
$\beta_N \cdot H_{98(y,2)} / q_{95}^2$ (= 0.20 for baseline scenario)

"Improved H-mode" on ASDEX Upgrade (since 1998)
$H_{98(y,2)}$ up to 1.4 / $\beta_N \geq 2.5$ simultaneously, $q_{95} \sim 4$
with stationary q-profile: $q_0 \geq 1$, low central magnetic shear

$\Rightarrow$ Lower current / long pulse ITER operation
"Hybrid" of: steady-state, non-inductive, reversed shear (ITB)
and baseline scenario, monotonic shear ($q_0 < 1$)

Improved H-Mode – Example

Early moderate heating: low magnetic shear in the centre; $q_0 \geq 1$; no ITB

Increase heating at start of I_p flat top: type-I ELMy H-mode, no sawteeth, often MHD (fishbones, small amplitude NTMs) but good confinement

Strong heating: (after ~ τ_R)

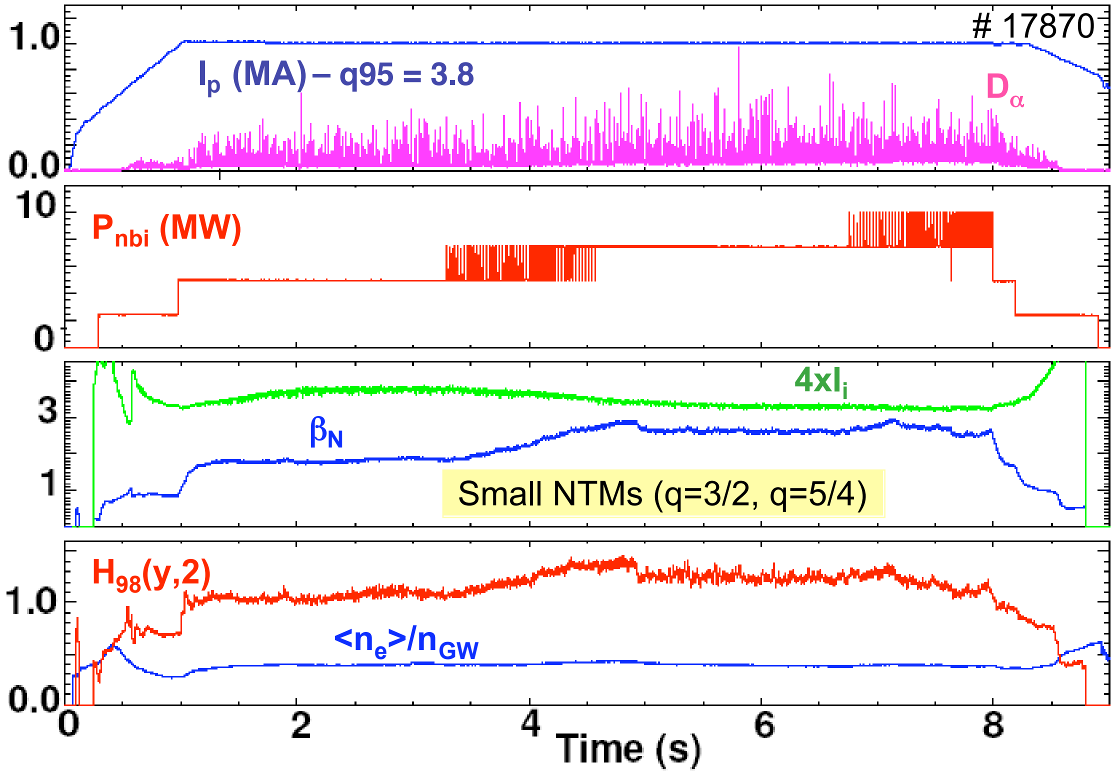
- β_N rises to 2.9 (close to $4 \cdot l_i$)
- H-factor increases
- small drop in β_N and $H_{98(y,2)}$ (NTMs)

For 3.7 s (= $25 \cdot \tau_E$)

$\beta_N \cdot H_{98(y,2)} / q_{95}^2 = 0.25$

$n_e/n_{GW} \sim 0.4$

$\nu^*/\nu^*_{ITER} \sim 1.5$



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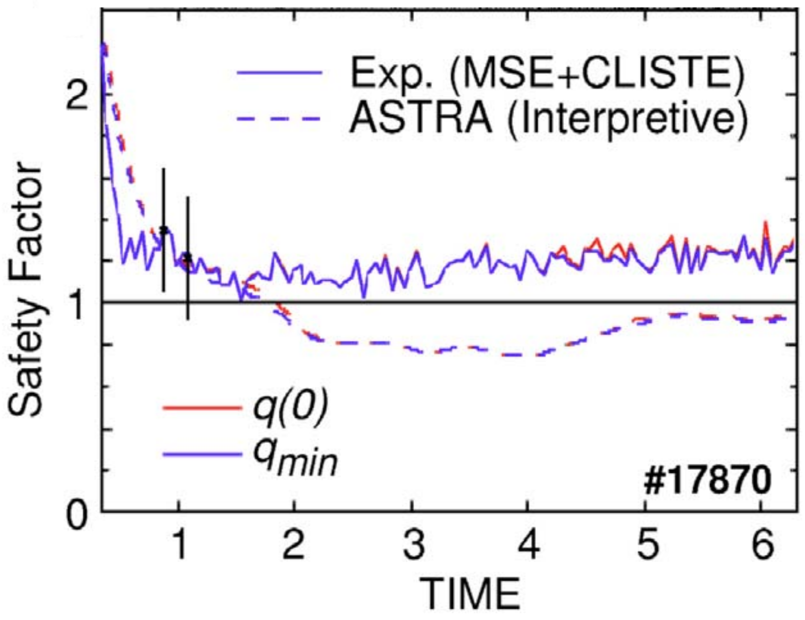
Strong heating
(after $\sim \tau_R$)

Central / minimum q value
(MSE & ASTRA simulations)

- $q_0 = q_{min}$, i.e. no reversed shear
- Simulation, including NBCD from off-axis, tangential beams and bootstrap current, fails to reproduce measured $q_0 > 1$



Role of MHD in Improved H-Modes

Stationary q-profile (q_0 ~ 1, low central shear)

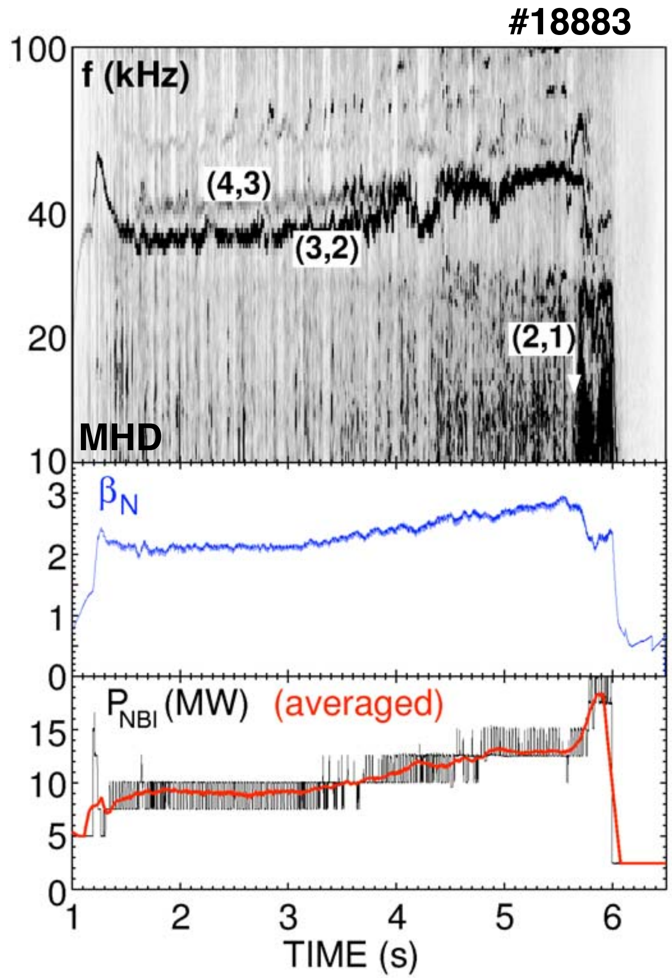
fishbones (not always present)
small amplitude NTMs ?
bootstrap current, NBCD ?

Benign MHD in high performance phase

no sawteeth → no seeding of (3,2) NTMs
low shear at (3,2) surface
→ reduced NTM drive
higher m-number NTMs
→ non-linear mode coupling
further reduces (3,2)

Eventual β-limit (strongly degraded
confinement; no disruption)

(2,1) mode, mode locking *(see Fig.)*



Improved H-Mode – Existence Domain

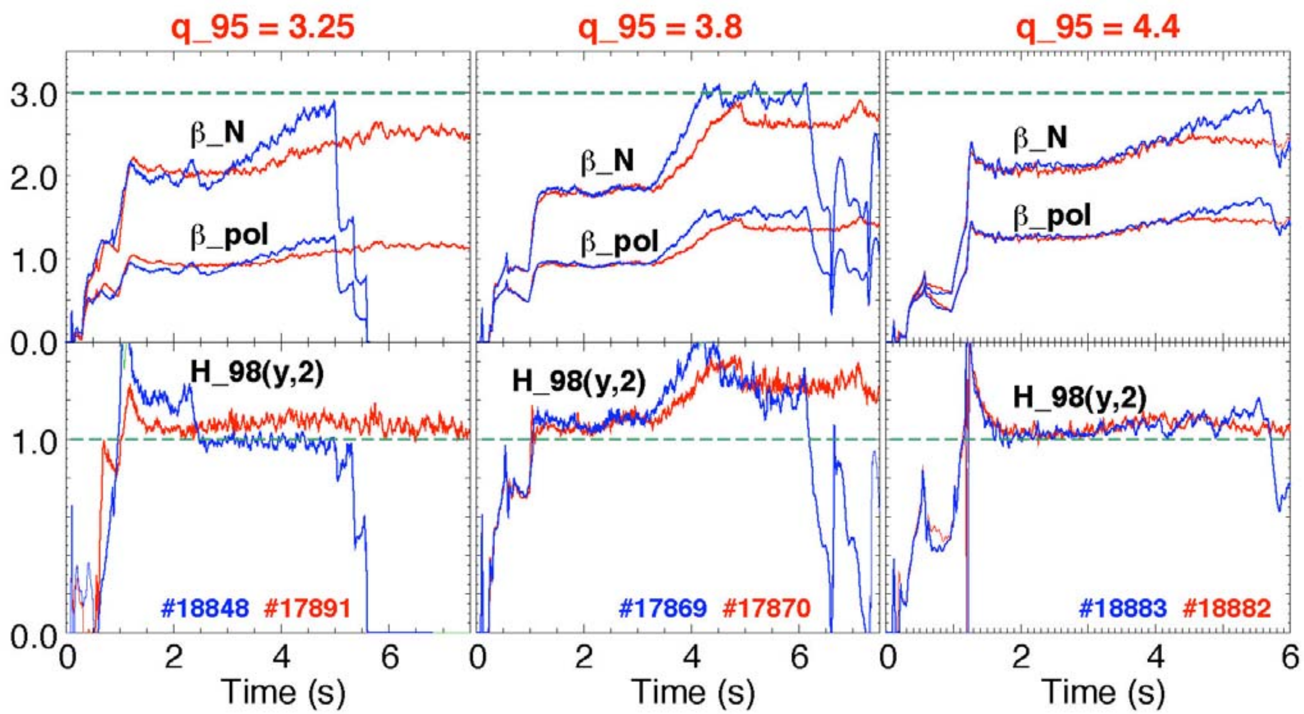
Parameters scans for improved H-modes

q_{95} scan	high-n_e	ρ^* scan
3.25 - 4.4	$0.85 \cdot n_e/n_{GW}$	8 - 13E-03

Improved H-Mode – Existence Domain

q_{95} scan (fixed I_p, $\delta \sim 0.2$, $n_e / n_{GW} \sim 0.4$)

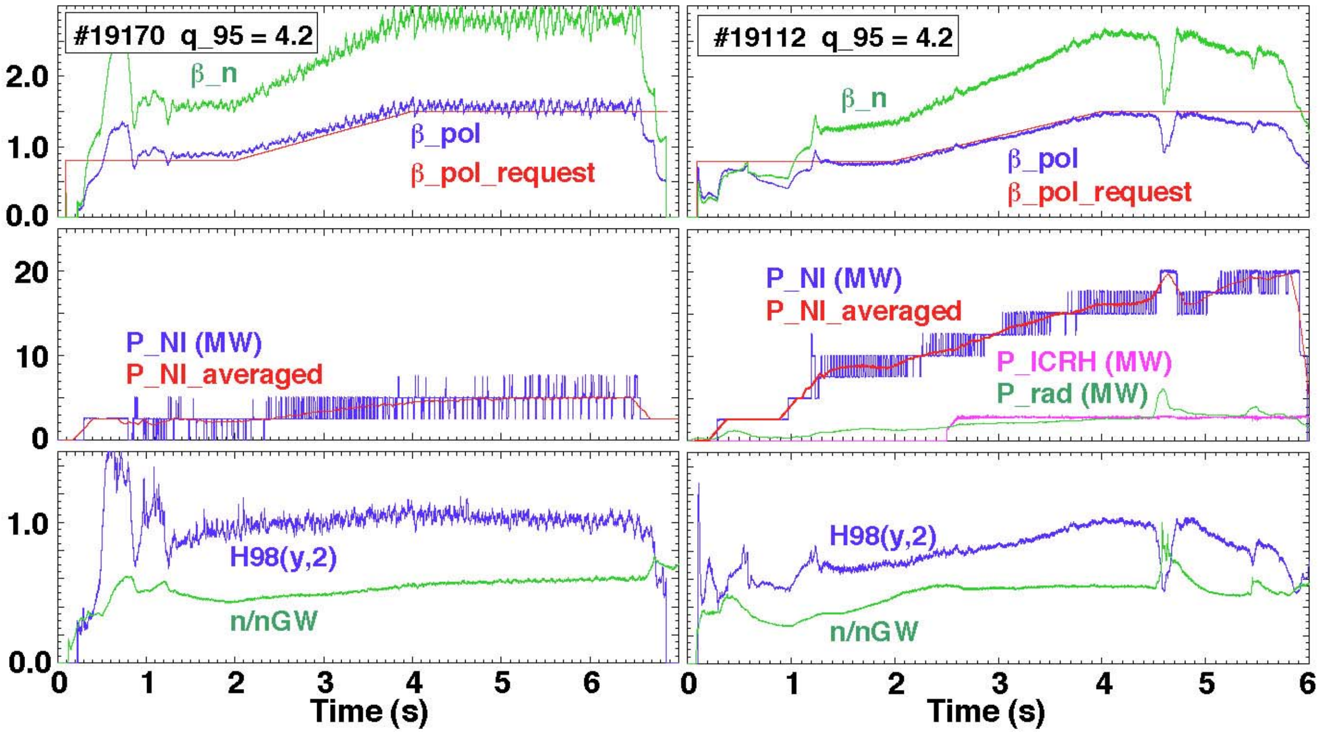
> power ramps
> stationary discharge (techn. limited)



Improved H-Mode – Existence Domain

Max. ρ*-variation at constant q_{95}, β, n_e / n_{GW}

0.6 MA / 1.4 T **1.2 MA / 2.8 T**



Improved H-Mode – Existence Domain

Table: Parameters of selected improved H-modes during various scans

q_{95} scan / high-n_e / ρ^* scan

Values averaged over period with: $0.85 \cdot \beta_{N,max} \le \beta_N \le \beta_{N,max}$

#	I_p (MA)	B_t (T)	q_{95}	dur / τ_E	n_e/n_{GW}	β_N	$H_{98(y,2)}$	ρ_i^*	ν^*/ν^*_{ITER}
1	1.0	1.85	3.31	30	0.38	2.52	1.06	7.8E-03	1.7
2	1.0	2.10	3.82	25	0.41	2.81	1.39	11.4E-03	1.5
3	1.0	2.34	4.26	15	0.41	2.55	1.15	11.3E-03	1.6
4	1.0	2.34	4.25	9	0.45	3.02	1.22	10.7E-03	1.5
5	0.8	1.69	3.61	44	0.85	3.49	1.11	9.3E-03	10.7
6	0.6	1.39	4.19	30	0.56	2.80	1.02	12.8E-03	5.2
7	1.2	2.78	4.19	14	0.52	2.60	1.00	8.2E-03	2.5

Dimensionless parameters

- ν^* close to ITER value at moderate n_e
- ρ_i^* above ρ_i^*-ITER ($\sim 2 \cdot 10^{-3}$) within ASDEX Upgrade:
  no ρ_i^*-dependence of performance
- n_e/n_{GW} high n_e possible $\Rightarrow$ reactor relevant edge conditions

Summary – Improved H-Mode Existence Domain

Data base: All improved H-mode experiments during 2003/04, different time slices, also at low heating power; plus earlier high-n_e plasmas

Performance vs. measure of bootstrap fraction ($\varepsilon^{0.5}\beta_p$)

Achieved

$H_{98} \cdot \beta_N / q_{95}^2 > 0.2$

for $3 < q_{95} < 4$

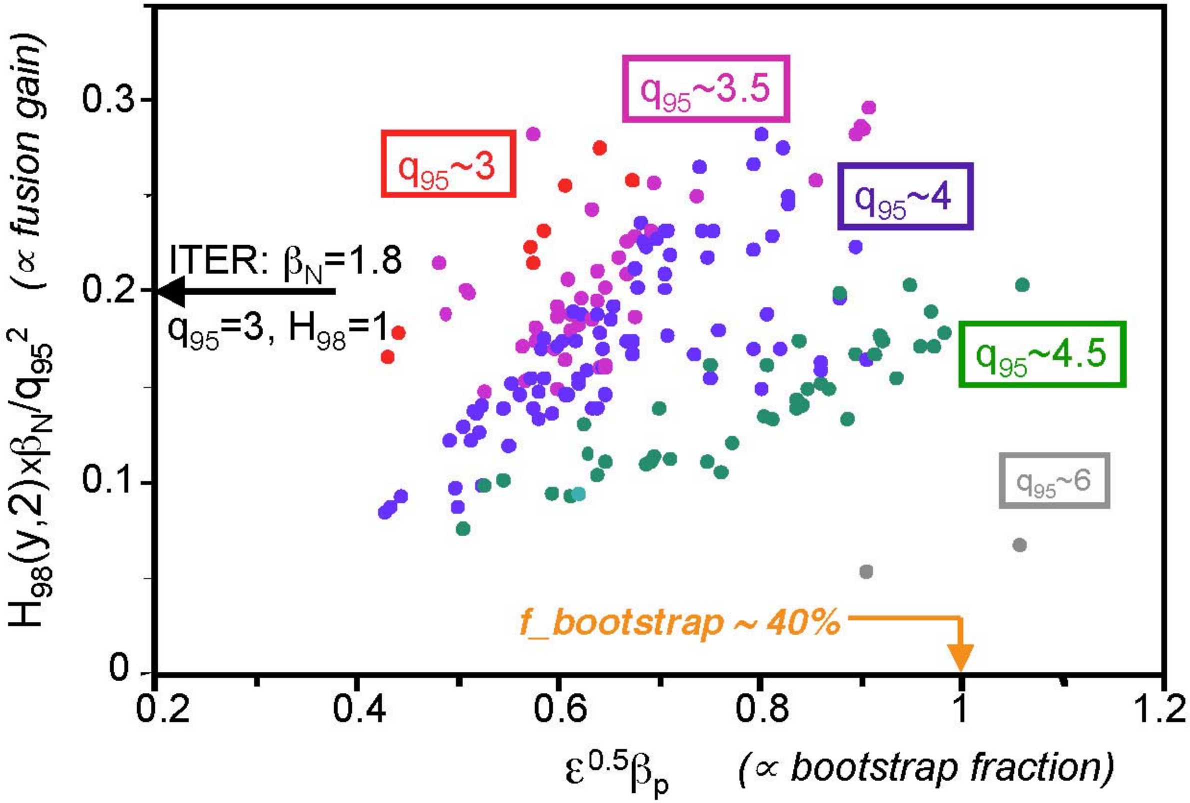
$H_{98} \cdot \beta_N / q_{95}^2 \sim 0.2$

for q_{95} up to 4.5

In whole q_{95} range

stationary

(technical limit)



"Improved confinement"

Transport studies

Heat transport in improved H-mode described by ITG / TEM turbulence; threshold in R/L_T
→ "stiff" temperature profiles

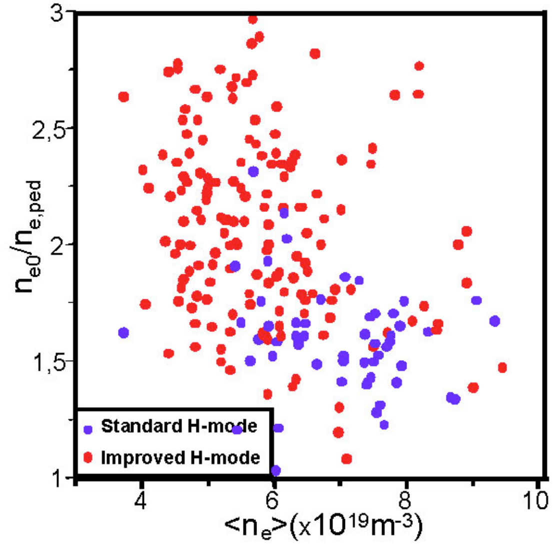
Improved H-mode: Stronger peaked n_e-profiles
Density peaking correlated with lower ν^*

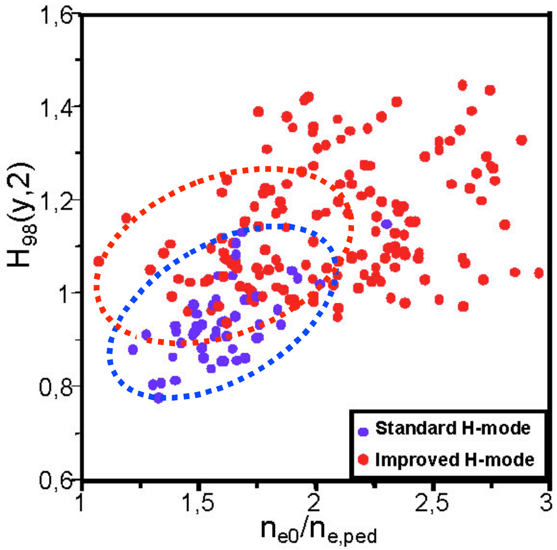
⇒ account to some extend for higher H-factors

However, for $n_{e0}/n_{e,ped} \leq 2$: H-factors of improved H-modes somewhat higher at same peaking

Possible reasons:

- Higher pedestal pressure ?
  (indications, needs detailed experiments)
- ITER-H98(y,2) scaling
  n_e- and β_N-dependence ?



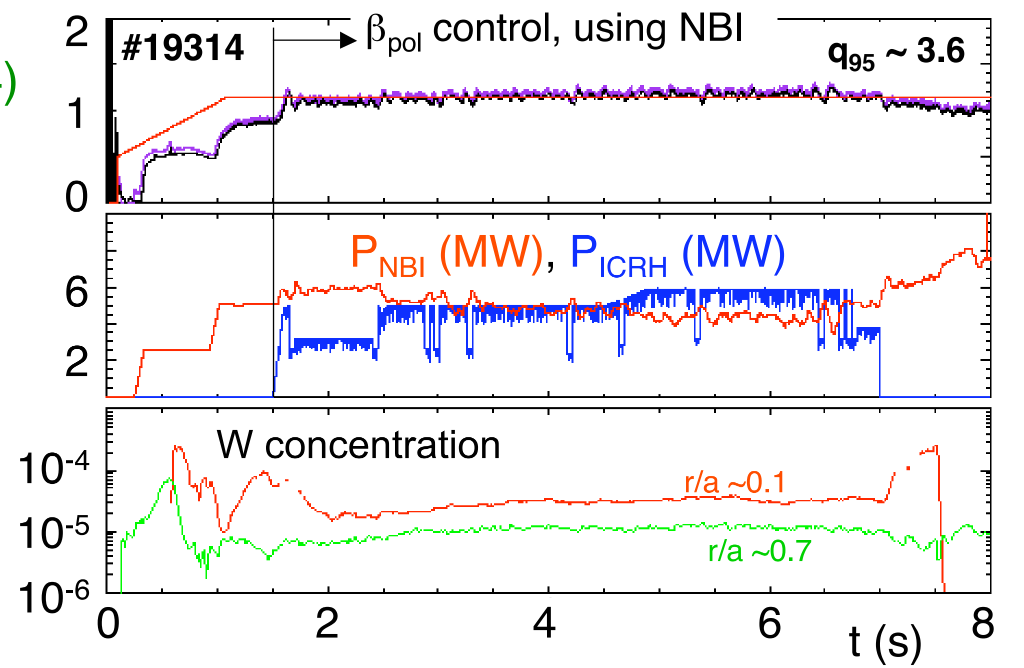


Improved H-Modes with dominant core ICRH

So far: Improved H-mode results obtained with dominant NBI heating
$\Rightarrow$ $T_i > T_e$, input of particles and momentum,
in contrast to α-heating in reactor-type plasma

Demonstration of improved H-mode with $P_{ICRH} \gtrsim P_{NBI}$ (ICRH dominates core)

- $\beta_N \sim 2.6$ / $H_{98(y,2)} \sim 1.2$
  ($\rightarrow \beta_N \cdot H_{98(y,2)} / q_{95}^2 = 0.24$)
- $T_i \sim T_e$



ICRH (6-10% H minority):
$P \rightarrow ion / P \rightarrow ele \sim 2:1$

ICRH + NBI
$P_{ele}(\rho \leq 0.3)$ higher by ~2.5
compared to NBI only

During ICRH
Central W concentration
strongly depressed; *for details on impurities: see R. Dux et al., EX / P6-14*

Summary

Improved H-mode at ASDEX Upgrade

- Stationary, low central shear, q_0 close to 1, with $\beta_N > 2.5$ & $H_{98(y,2)} > 1$
  over wide range in q_{95} and n_e / n_{GW}
- Specific q-profile: avoids sawteeth, benign MHD during high performance
- Reasons for increase in H-factor still under investigation
- Performance: $q_{95} < 4$: $\beta_N \cdot H_{98(y,2)} / q_{95}^2 > 0.2$ (≡ ITER baseline scen.)
  $q_{95} \sim 4\text{-}4.5$: $\beta_N \cdot H_{98(y,2)} / q_{95}^2 \sim 0.2$
- Dimensionless parameters
  ν^* / ν^*_{ITER} close to 1 at low densities
  ρ_i^*: no performance dependence on ρ_i^*
- Obtained also with dominant core RF heating

For ITER: Candidate for lower current, long pulse "hybrid" scenario

Impurity Control

Peaked density profiles, no sawteeth → high central impurity concentration, severe for NBI only heating

Need for impurity control tool

Low level central ECRH (1-1.5 MW) or central ICRH ($P_{ICRH} \geq 0.5 \cdot P_{NBI}$)

see: R. Dux et al., EX / P6-14

- Central W concentration correlated with peaking

Central wave heating:

- Core W concentration strongly reduced
- Reduced peaking
- Minor effect on $H_{98} \cdot \beta_N$

Central C concentration reduced as well