Fusion Reactor Technology I
(459.760, 3 Credits)

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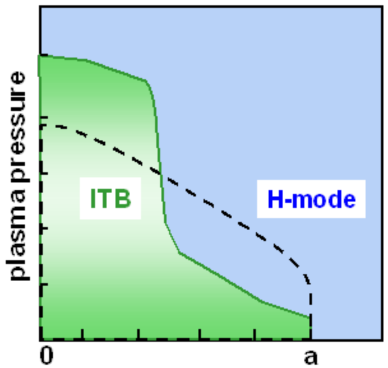
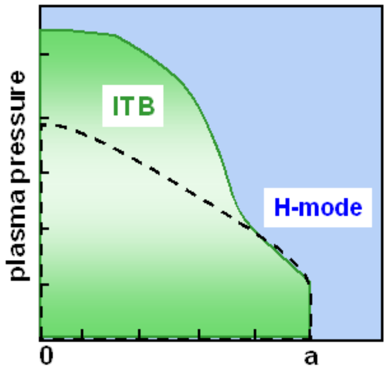
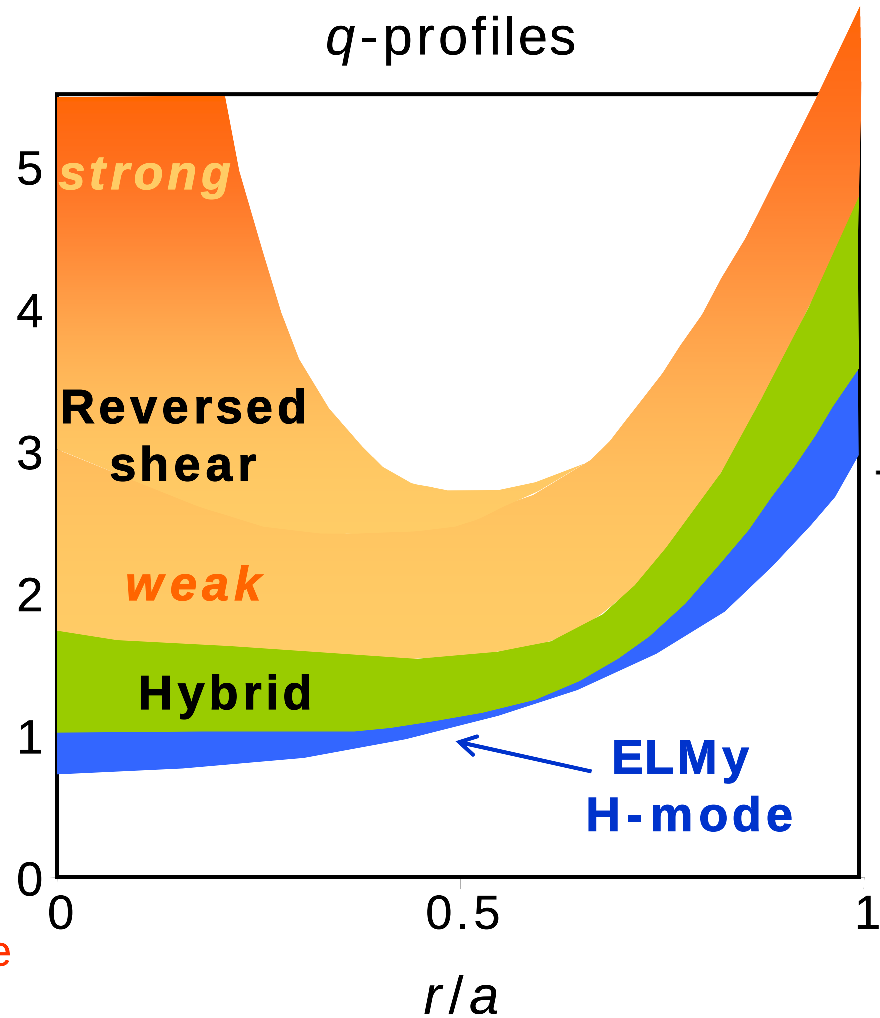
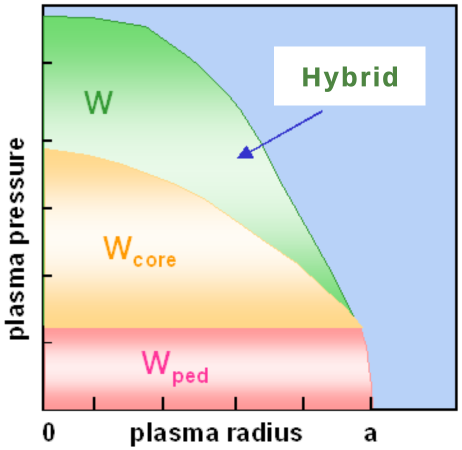


- Good confinement
- Poor stability



- Only "weak" RS plasmas are stable but they require a delicate active control





- Good confinement together with high stability w/o active control

Introduction – What is hybrids scenario?

for *ITER*	Reference H-mode with ELMs	Hybrid	Steady-state with fully non-inductive currents
Q value	10	10	5
Operating time	400s	3000s	5000s
Plasma current	15MA	12MA	9MA
q_{95}	3.0	~4	~5
B_T	5.3T		

✓ Producing a high fusion yield at a significantly lower current than the reference H-mode scenario with a small fraction of inductively driven current

✓ Operating with a high fusion gain for a very long pulse duration by the combination of a lower current and a lower loop voltage for engineering tests of reactor-relevant components, such as breeding blankets.

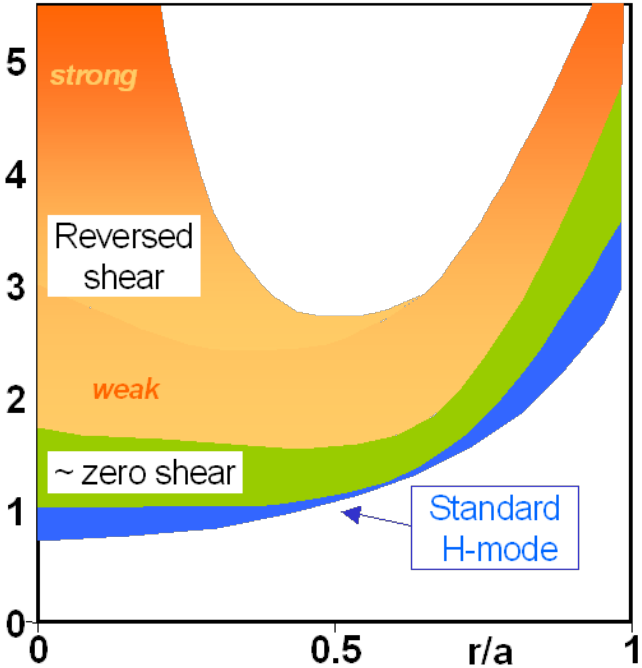
Introduction – Features of hybrids scenario

Key feature

- A higher beta limit than for the reference ELMy H-mode.

✓ *q-profile seems to be the dominant parameter*

→ Scenarios are classified by the plasma current profiles

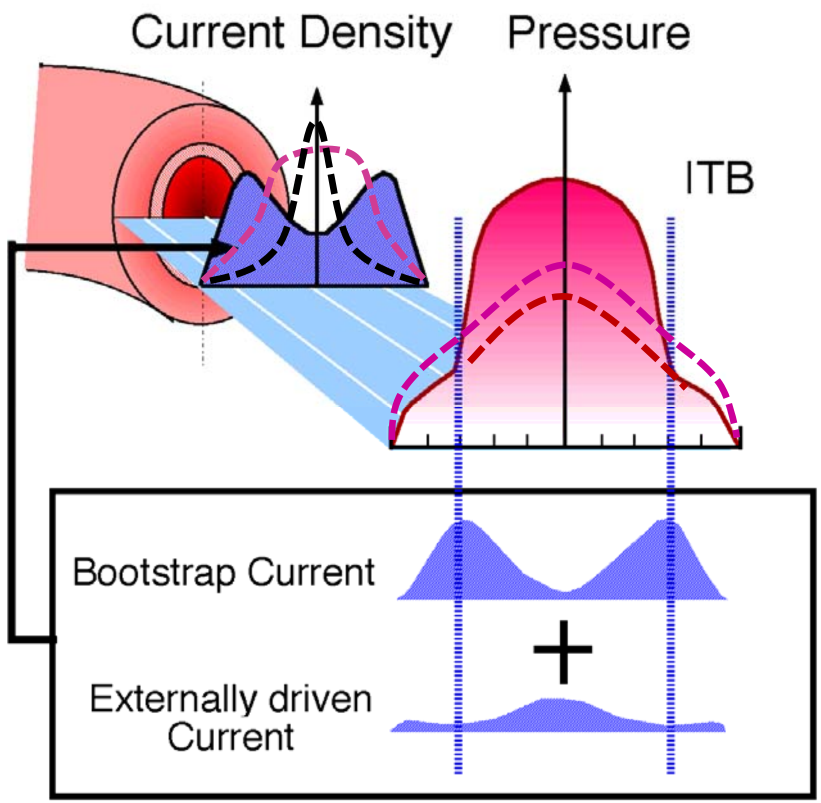


RS+ITB mode (Challenging demands in terms of control):
Very strong reversed shear lead to the development of 'current hole' configurations where the plasma current does not penetrate to the plasma centre.

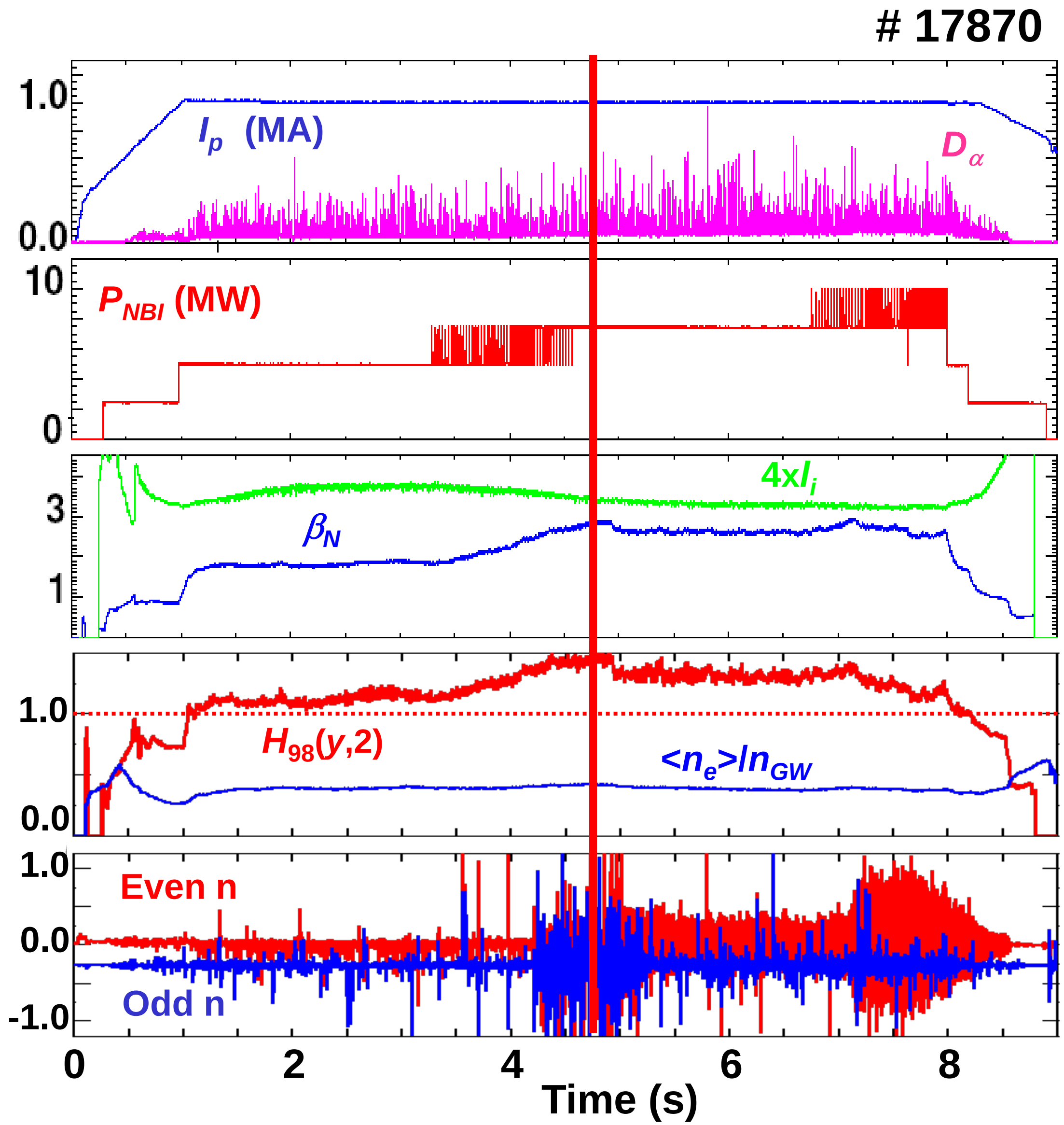
Conventional Hybrid mode :
A large volume of low magnetic shear and a central value of q close to one have resulted in stationary discharges with improved confinement and high values of normalized beta.

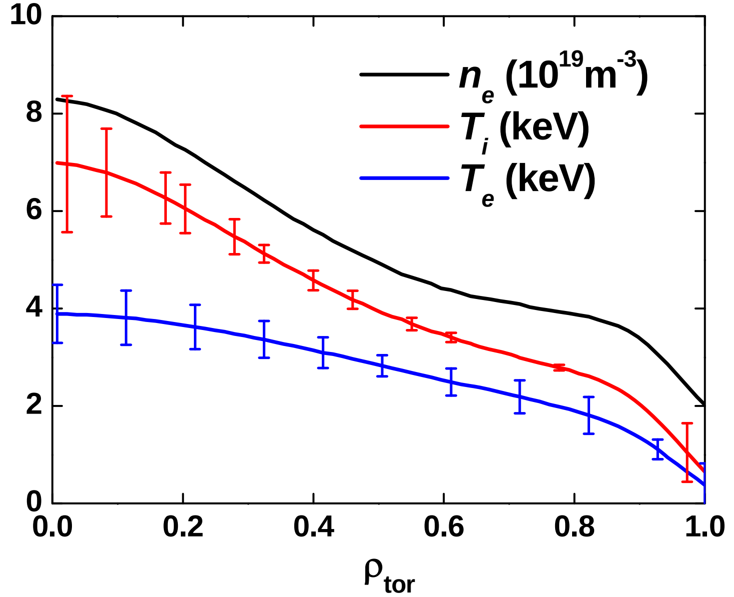
Reference H-mode (with assumption of NTM suppression): Plasma current is fully diffused and q-profile has monotonic form with a large positive magnetic shear

Tokamak Operation Scenario



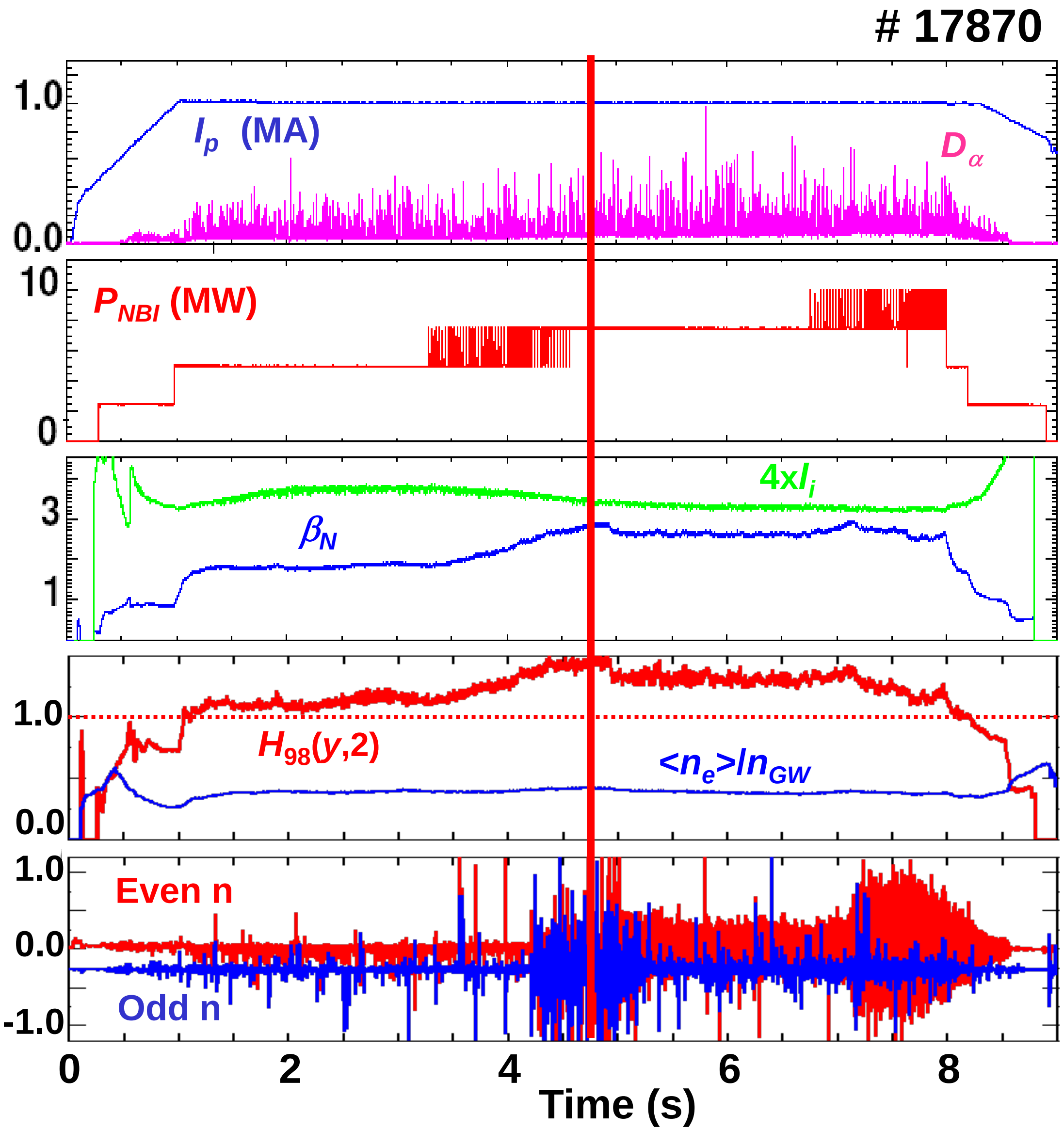
Hybrid Scenario

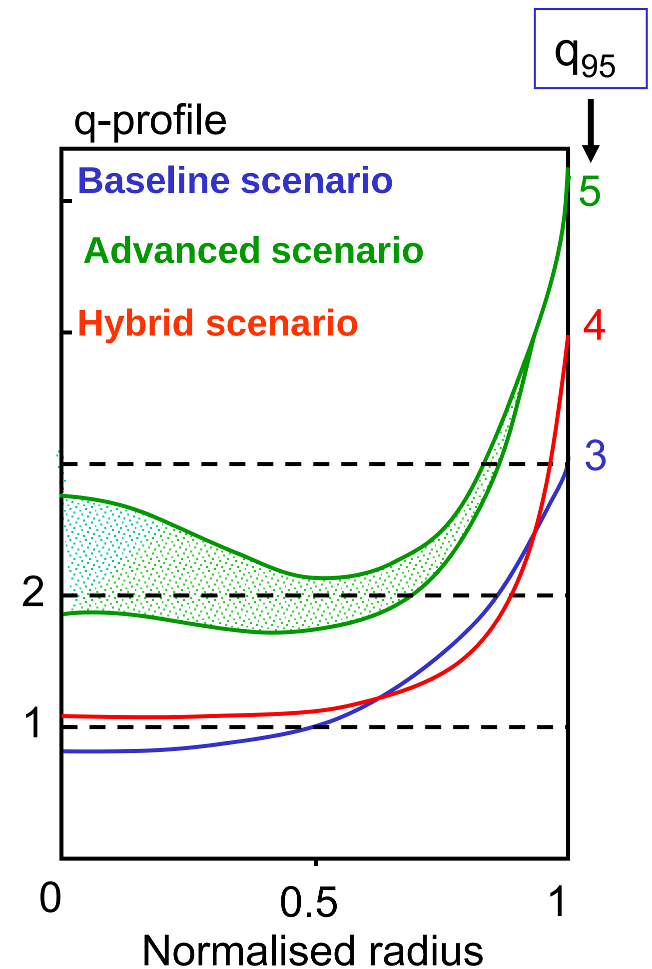




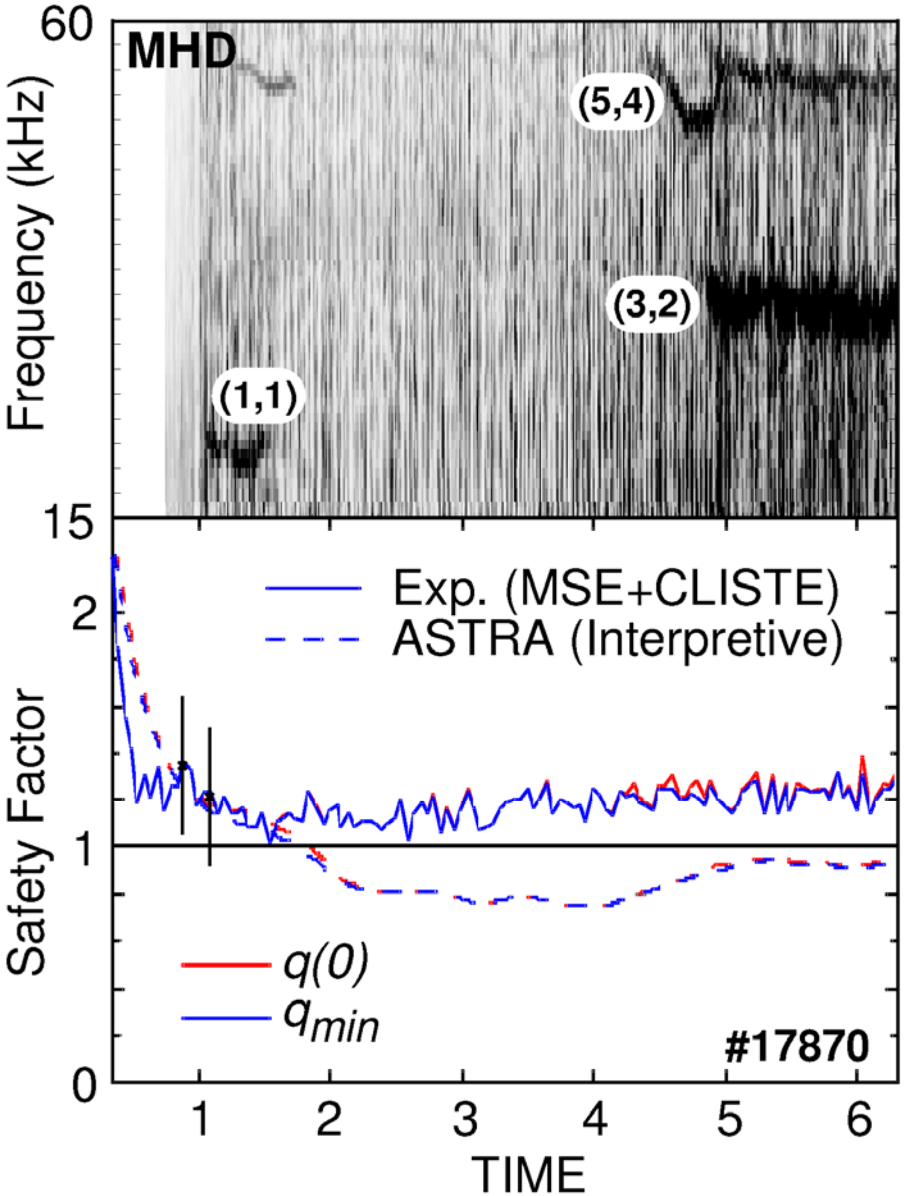
- $H_{98}(y,2) \sim 1.4$
- $\beta_N \sim 2.8$
- $IBS = 34\%$
- $INB = 31\%$

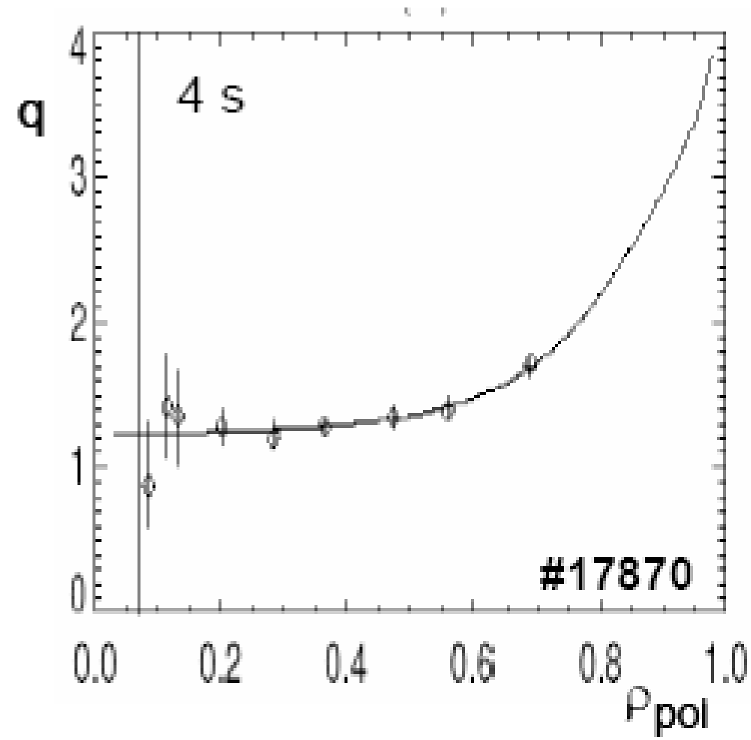
Hybrid Scenario



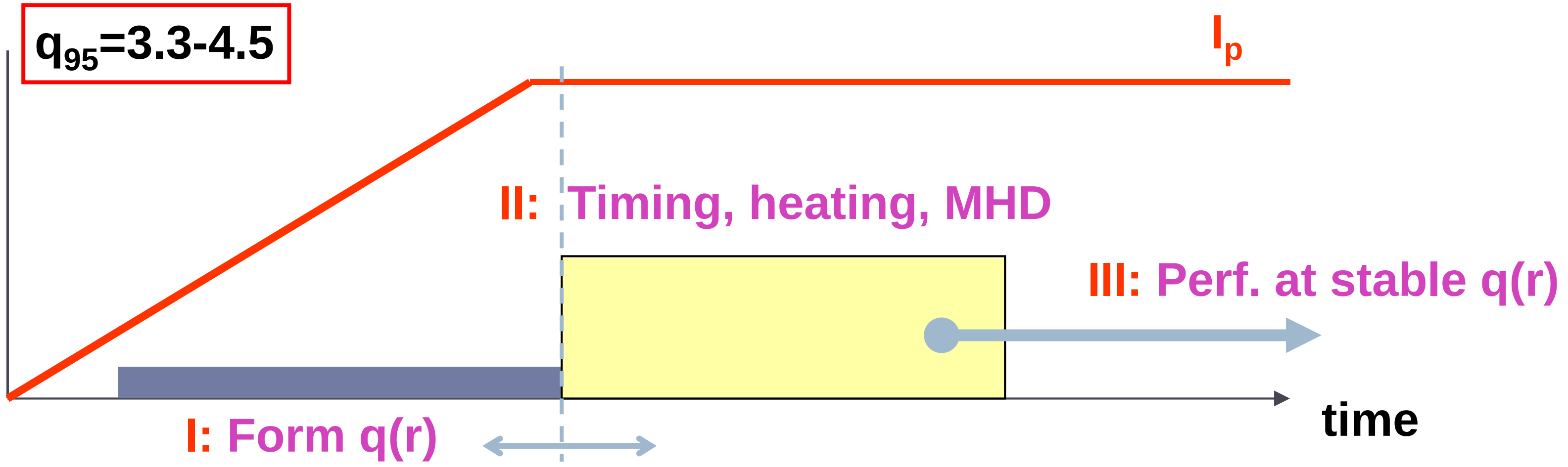


Hybrid Scenario





Hybrid Scenario



I: Obtain low magnetic shear in the centre $q_0 > 1$

II: Timing and amount of the heating are important.

MHD behaviour: (no sawteeth, but fishbones and/or small NTMs).

H-mode, but no confinement transients (ITBs).

III: Mild MHD events to obtain stable q(r).

Ultimate goal: $H_{89}\beta_N > 6$ stationary, ~50% non-inductive drive.

A method to produce Hybrid Scenarios

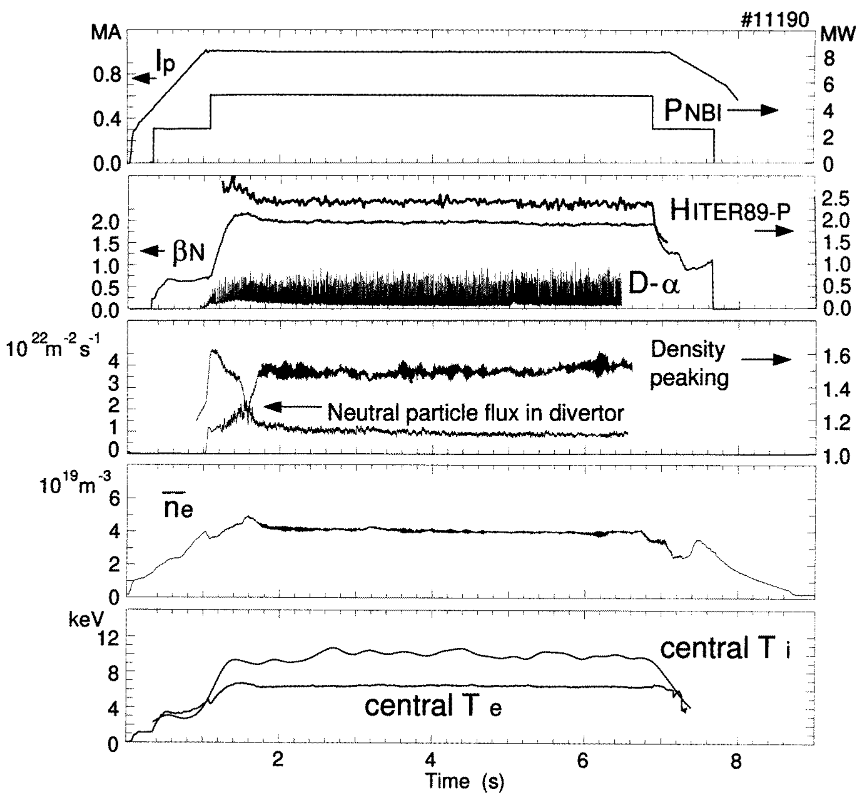
✓<u>Careful timing of the heating in the plasma current ramp-up phase.</u>

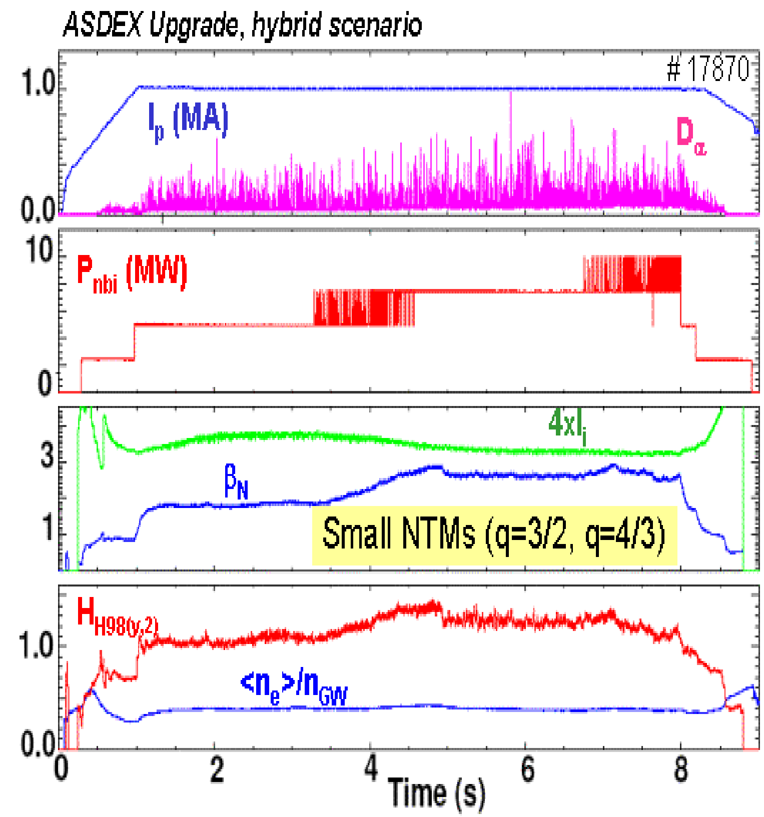
- The current ramp-up rate and the density rise are carefully adjusted in order to form a low magnetic shear configuration with $q_0>1$
- Plasma shape and fuelling levels are set to provide the required flat q profile with $q_0>1$ at the start of the current plateau.
- The level of heating is adjusted to provide an H-mode but to avoid the establishment of an ITB.
- By checking MHD behavior, the feasibility of the hybrid scenario could be confirmed.
- Some modes have to be triggered before sawteeth begin

\- e.g. an n>1 tearing mode in DIII-D and fishbones(or small NTMs) in ASDEX-U

Progress for Hybrid Scenario

A discovery of stationary regime of operation with improved core confinement with an H-mode edge in AUG (1998)





✓ Possible to gain high beta to β_N~3 with improvement in confinement

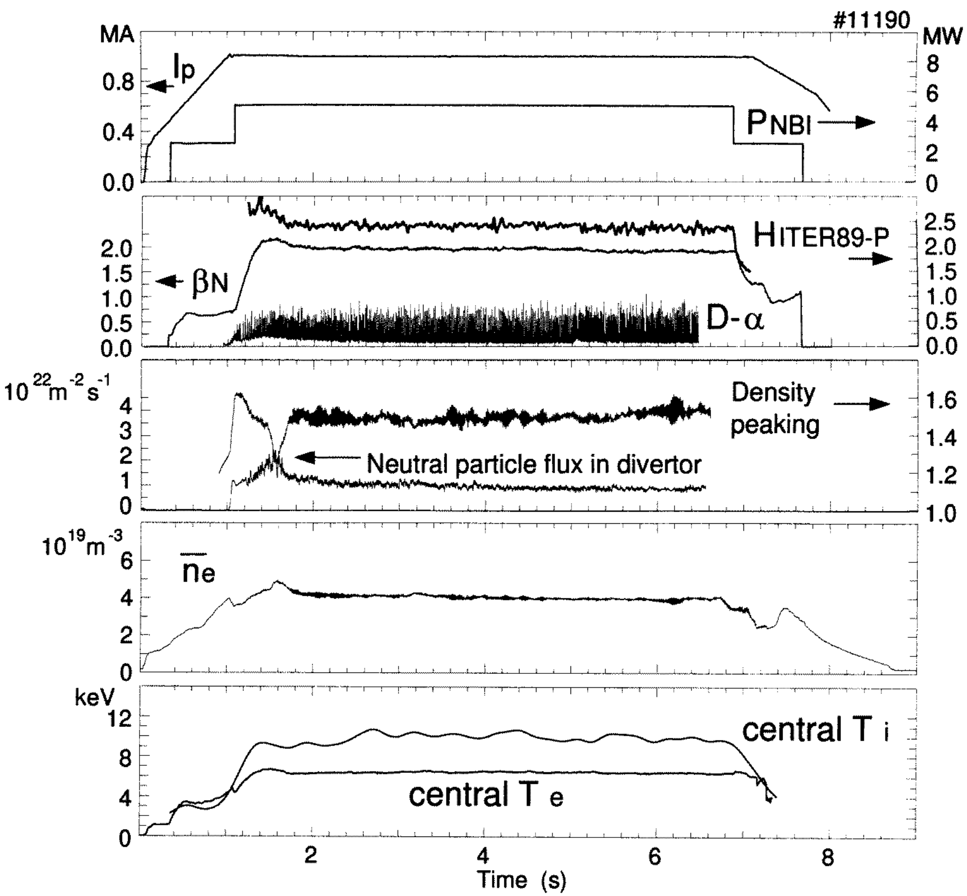
✓ Avoiding of the severe MHD activities lead to disruption – Central q is in the vicinity of one.

✓ Type-I ELMs are observed in the edge region.

Some example of existing experiments

ASDEX-U(1), "Improved H-mode"

A discovery of stationary regime of operation with improved core confinement with an H-mode edge in AUG (1998)



✓The highest fusion production rate was achieved by that time.

✓ The only MHD activity observed in the core of the plasma is strong fishbones which start at 1.1s and accompany the whole 5MW heating phase

→ Central q is in the vicinity of one

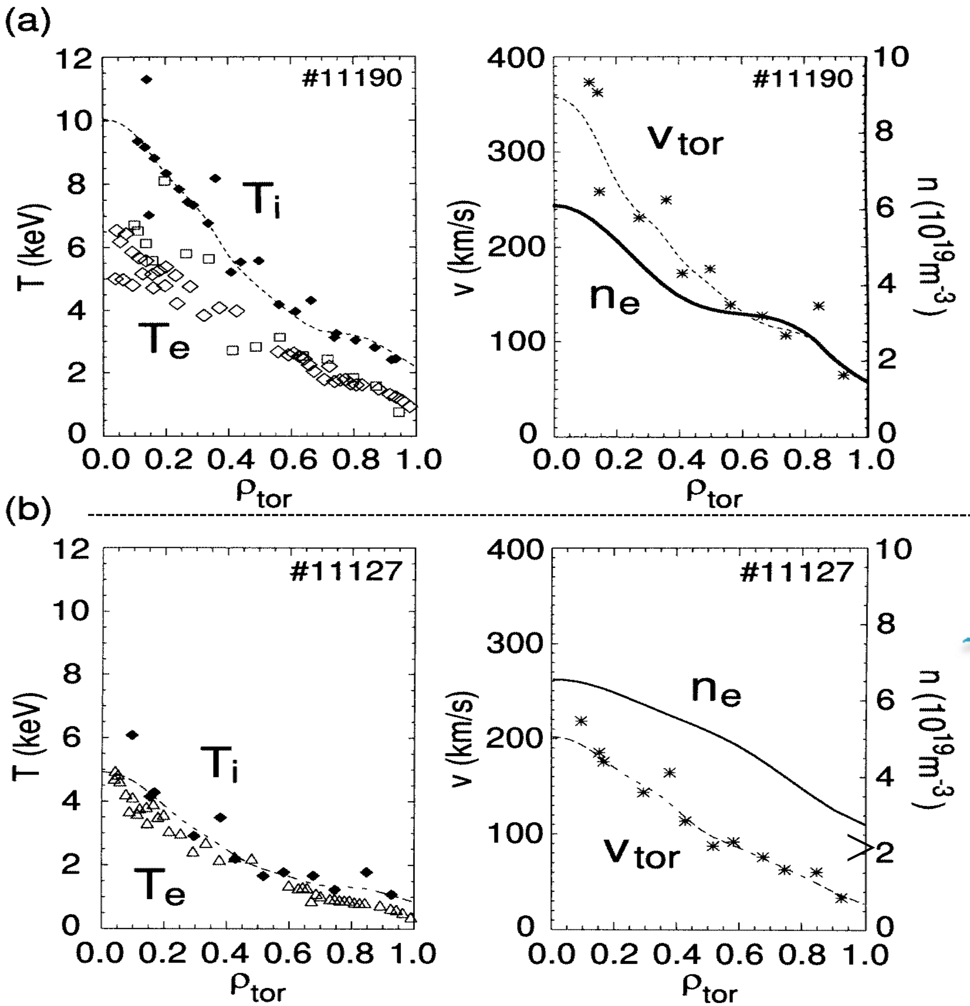
✓A type-I ELMy H-mode phenomena are observed in the edge region

✓ Upper triangularity = 0

Some example of existing experiments

ASDEX-U(2), "Improved H-mode"

Comparison with the profiles of Ti, Te, ne and v_{tor} for a standard ELMy H-mode discharge



Improved H-mode

$\beta_N \sim 2$, $H_{ITER89-P} \sim 2.4$

Except the density, all quantities are lower than the one of the above case.

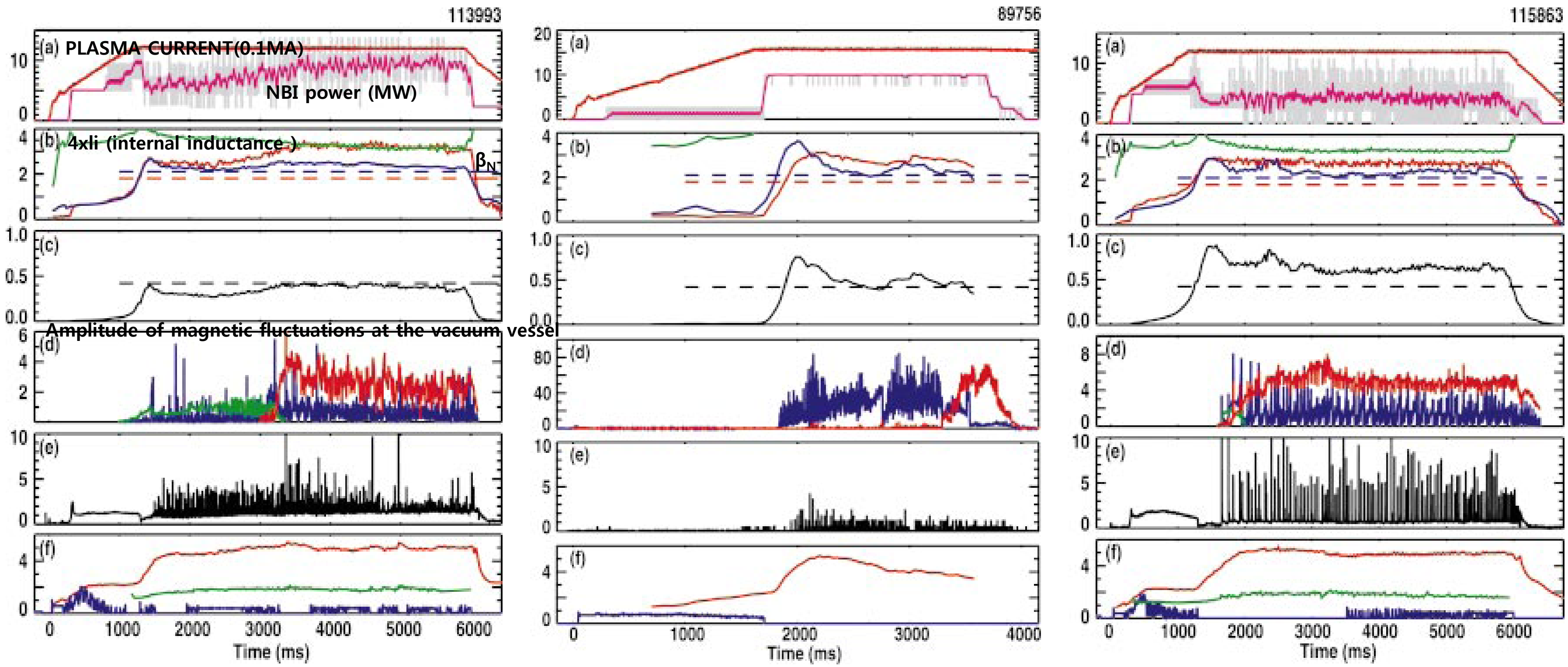
A standard ELMy H-mode

$\beta_N \sim 1.6$, $H_{ITER89-P} \sim 1.8$

Some example of existing experiments

DIII-D

$q_{95}>4$ without sawteeth | $q_{95}=3.6$ without sawteeth | $q_{95}=3.2, \beta_N=2.7, H_{89P}=2.3$



limited by tearing modes | limited by fishbones | limited by sawteeth

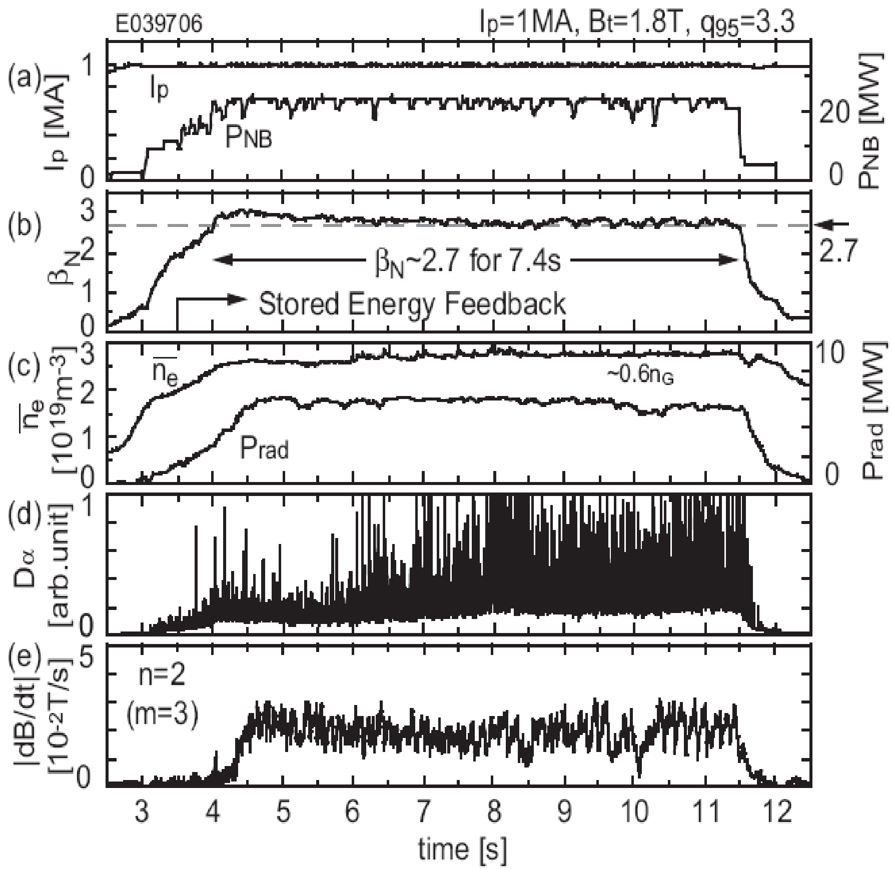
✓ *These discharges are a generic class of operations for tokamak hybrid mode.*

Some example of existing experiments

JT-60U, “High β_p ELMy H-mode discharges”

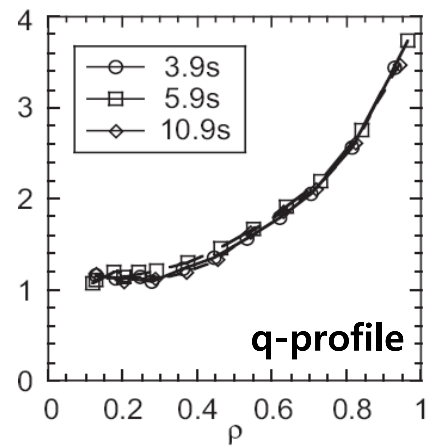
<u>With upgraded systems since 2000 :</u>

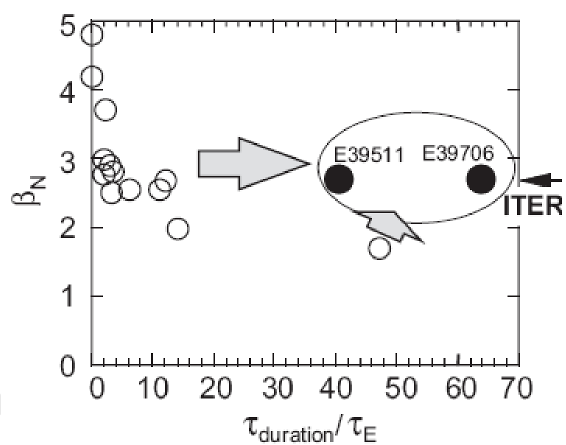
Poloidal field coil, NBI system, EC wave injection system and pellet injection system are upgraded



A high-beta plasma with β_N=2.7, β_p=1.5 has been sustained for 7.4s at q_{95}=3.3.

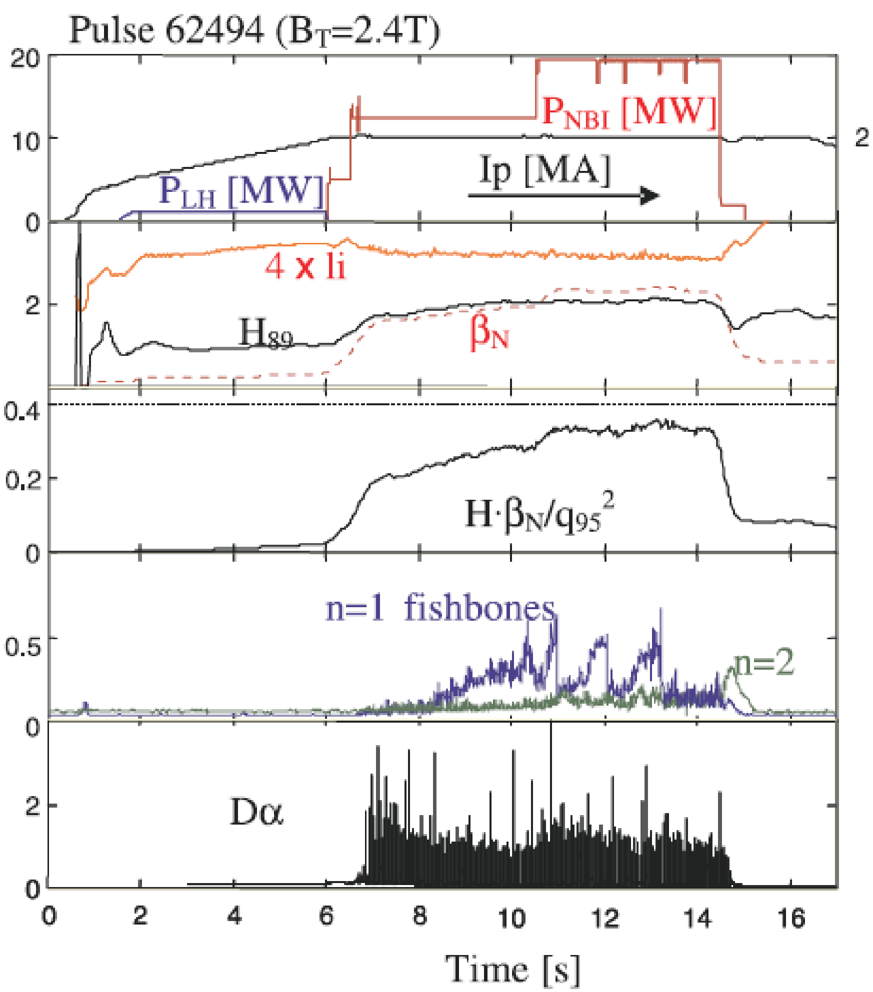
The duration time of high-beta extends to ~60τ_e, which is limited by the facility’s capability





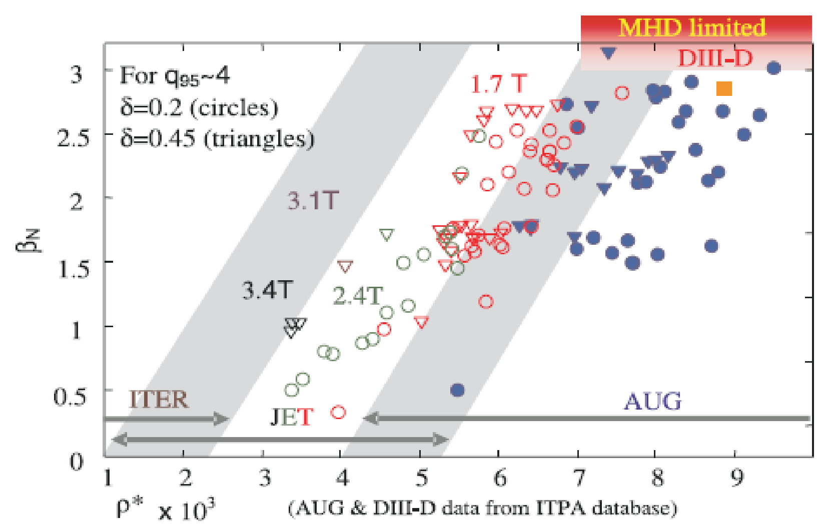
Some example of existing experiments
JET(1)

✓ Reproducing the ASDEX-U hybrid regime has been achieved.



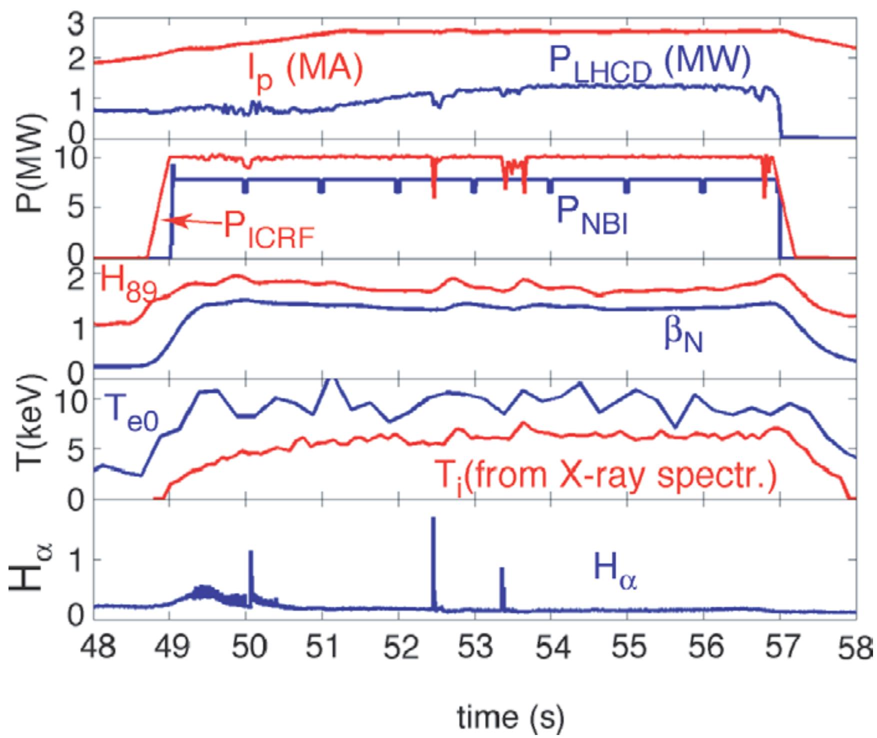
- ITER like magnetic configuration with B_T=2.4T has been adopted (decreasing the normalized Larmor radius, ρ*)

- Electron density and temperature profiles are similar in shape to those observed in hybrid ASDEX-U discharges



Some example of existing experiments JET(2)

✓RF-dominated hybrid scenarios has been examined in JET



- Soft MHD events typical of a hybrid discharge have been observed

- Several RF-only scenarios from various machines (TS, FTU, TCV) with low magnetic shear belong to the same 'family' with improved confinement and 'soft' MHD, although the current profiles would need to be adjusted to have a better match with the hybrid scenarios

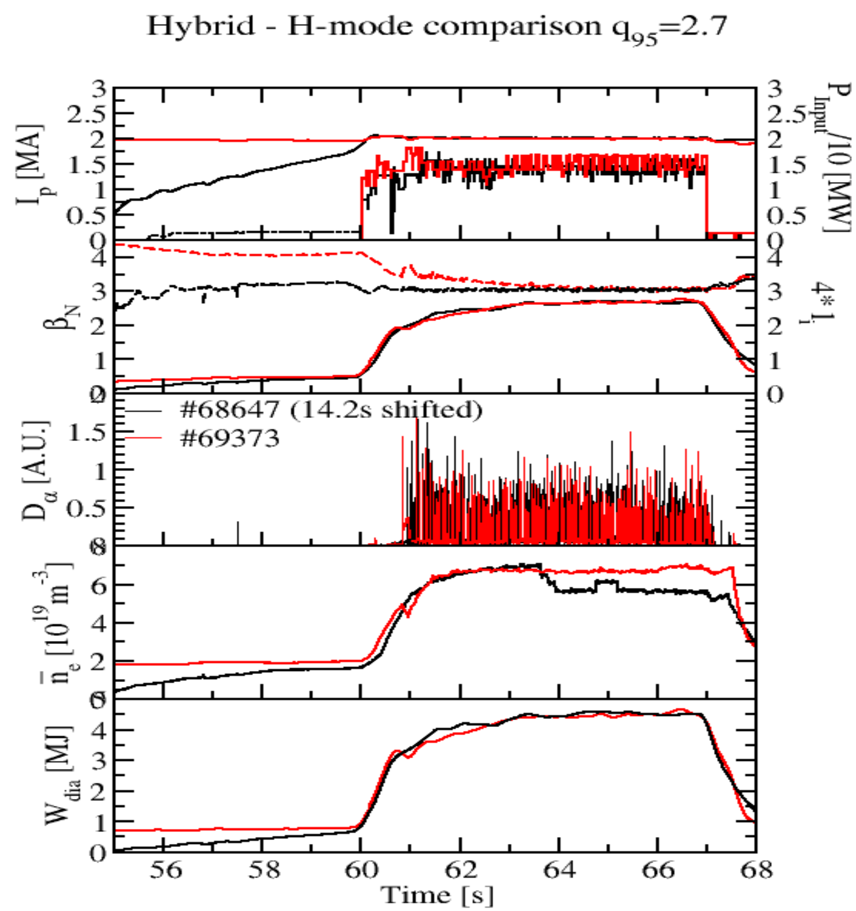
Some example of existing experiments
JET(3)

✓ Comparison between baseline and hybrid operation in JET

- Hybrid (LH preheat) β_N=2.7 I_p=2.0MA B_T=1.7T
- Baseline β_N=2.7 I_p=2.0MA B_T=1.7T

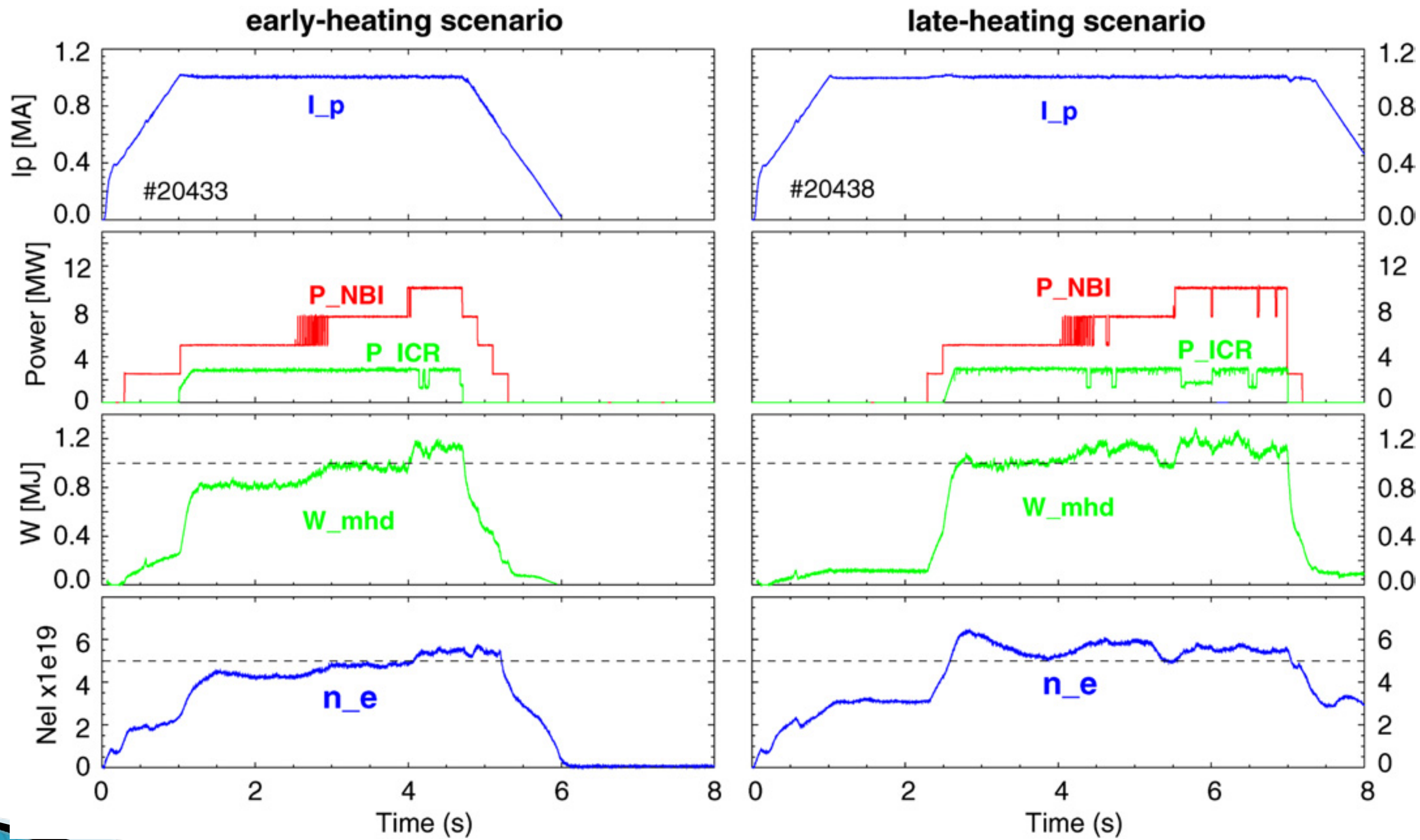
- Good MHD stability at q_{95}=2.7
- Standard type I ELMs
- H_{98} ~1
- n/n_G ~0.85
- $H_{89} x \beta_N / q_{95}^2$ =0.72
- Sawtoothing discharge

The baseline and hybrid scenario are not showing any difference !! →



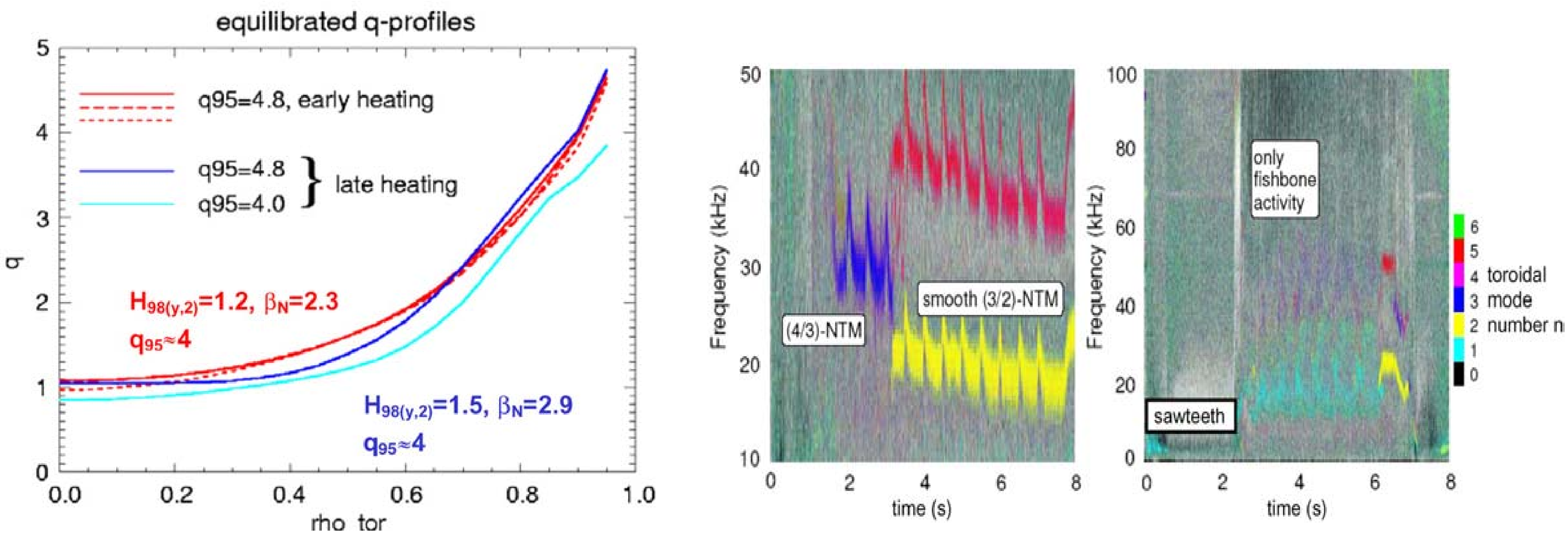
Some example with improved operating scheme
ASDEX-U(1)

✓Improved H-modes have also been obtained with 'late' additional heating well in the current flattop which partly show even better performance



Some example with improved operating scheme ASDEX-U(2)

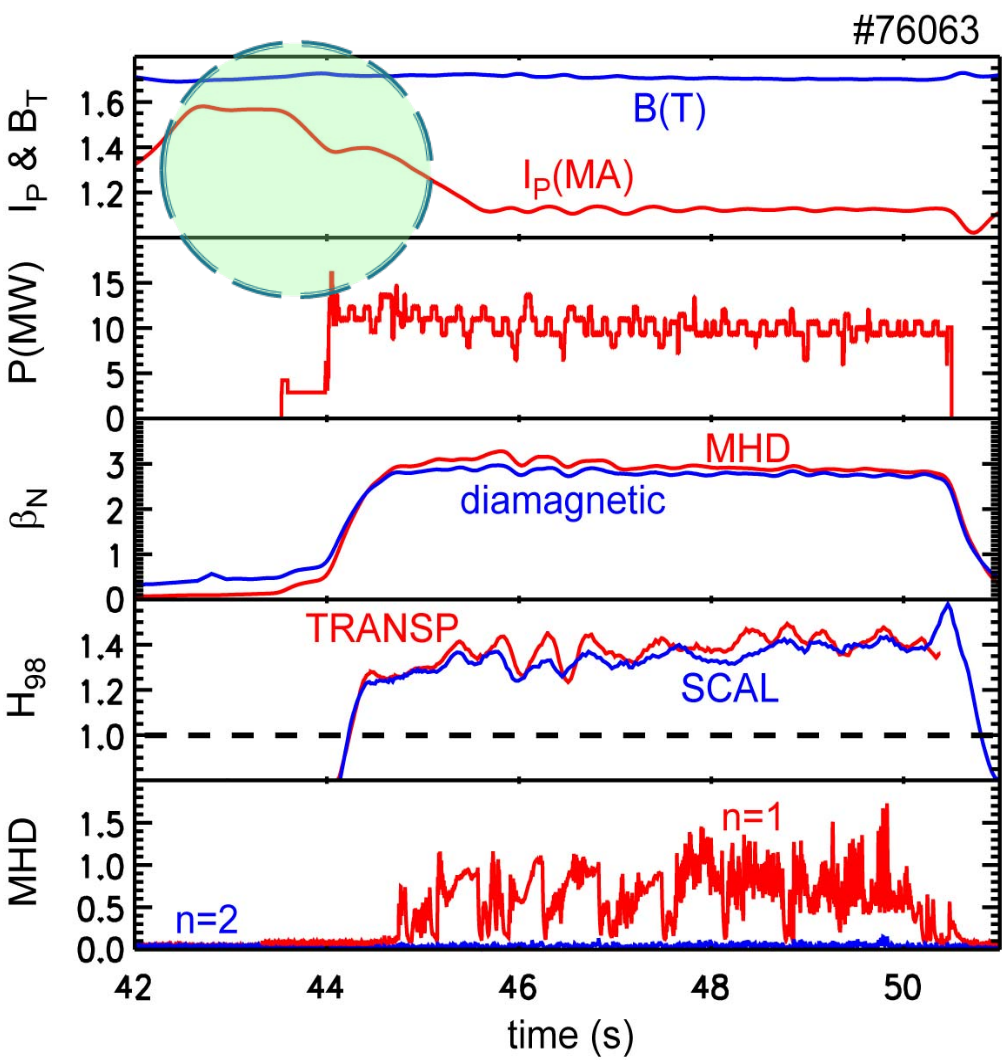
✓The difference of the equilibrated profiles in the flat-top phase seems to be due to different MHD-modes.



early heating late heating

Some example with improved operating scheme JET(1)

✓ Reference pulse of current overshoot scenario obtained at q_{95}≈5 (1.13MA/1.7T)

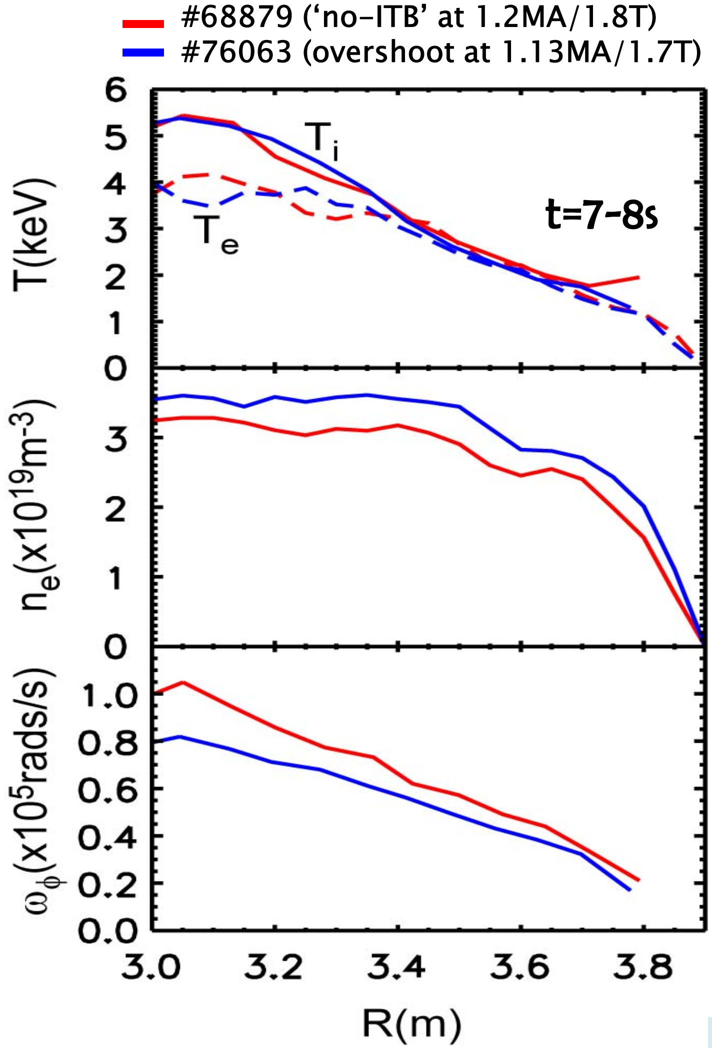


◆ Parameters achieved:

- H_{98}≈1.4
- β_N≈2.8
- l_i≈0.75
- δ≈0.39
- n/n_G≈65%
- W_{th}/W_{dia}≈75%
- τ_R≈5s
- q_{min}≈1 (fishbones & sawteeth)
- No significant 3/2 or 2/1 activity

Some example with improved operating scheme JET(2)

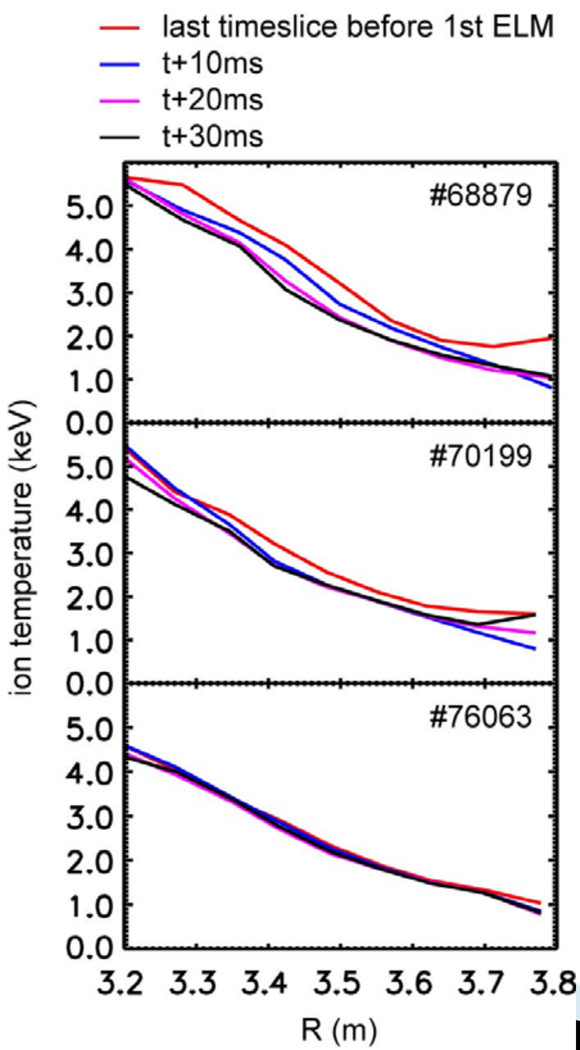
✓Comparison with 1.8T 'no-ITBs' on temperature and density profiles



- Comparison with 'no-ITB' regime at similar power (lower β_N) suggests confinement improvement in #76063 comes from increased density, despite lower rotation.
- Confinement improvement appears to be mainly from edge.

Some example with improved operating scheme JET(3)

✓Comparison with 1.8T 'no-ITBs' on ion temperature evolutions to ELM



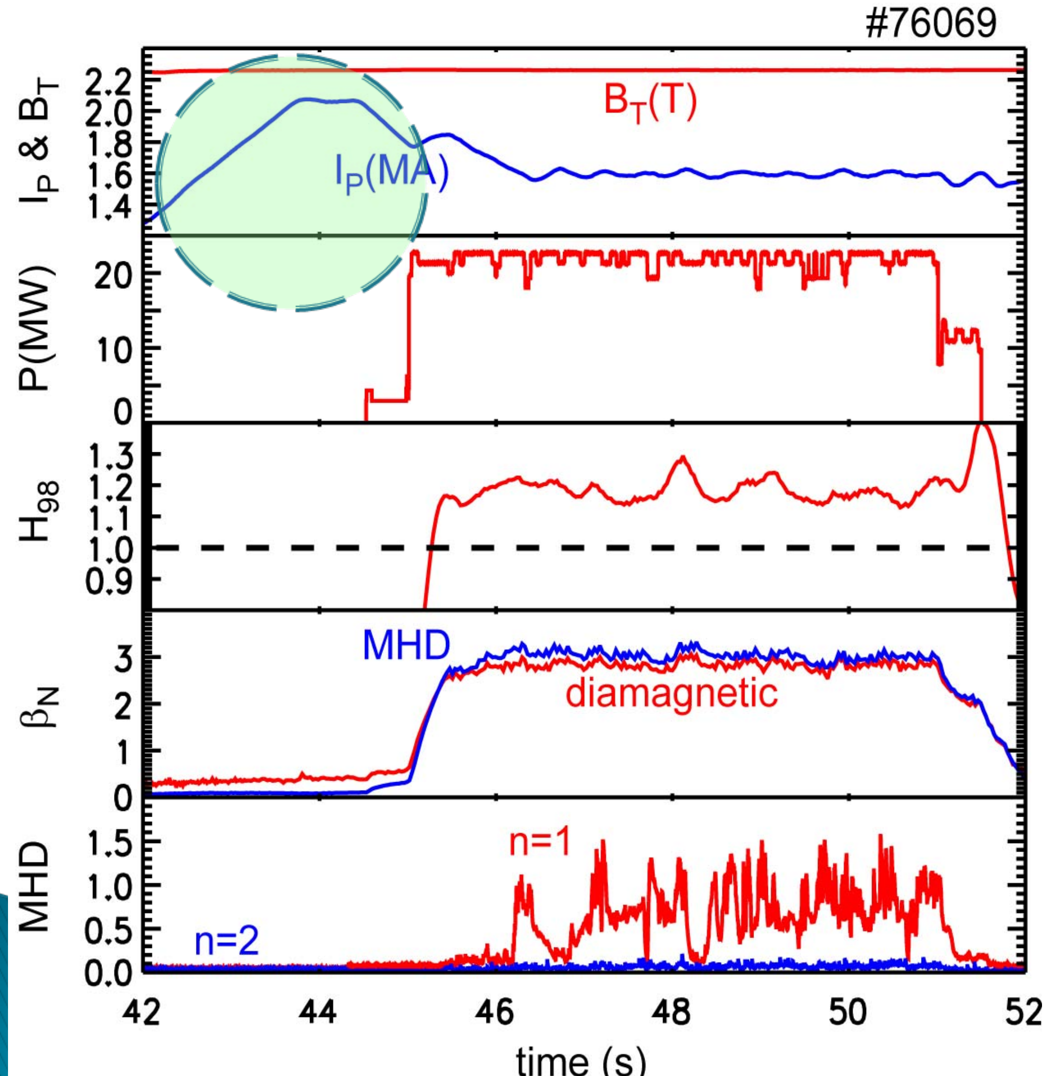
'no-ITB' scenario at 1.8T

current overshoot scenario at 1.7T

- First ELM seems much less destructive on T_i in current overshoot case compared with 1.8T 'no-ITB' scenario

Some example with improved operating scheme JET(4)

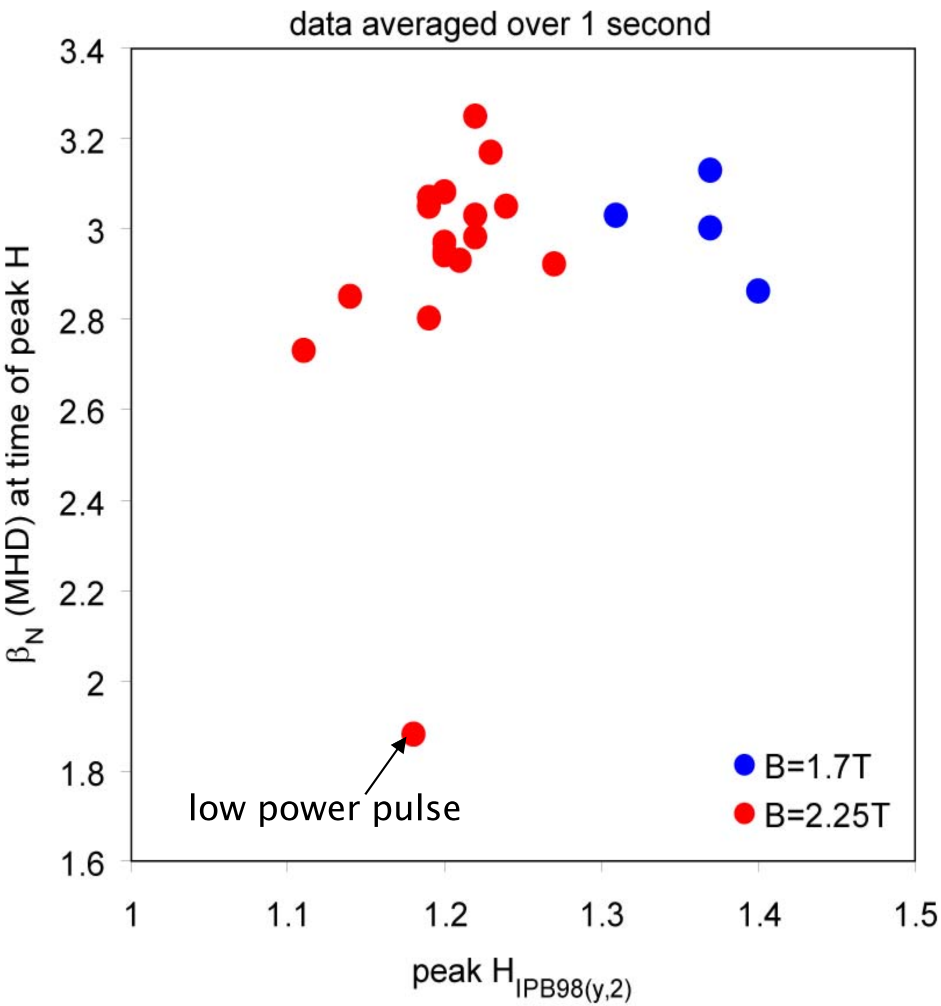
✓Overshoot technique at 2.25T



- Good sustained performance achieved:
  - H_{98}≈1.2
  - β_N≈3
  - n/n_G≈75%
  - W_{th}/W_{dia}≈75%
  - q_{min}≈1 (fishbones & maybe sawteeth)
  - No significant 3/2 or 2/1 activity

✓Higher performance at 1.7T with current overshoot has not been reproduced at 2.3T

Some example with improved operating scheme JET(5)



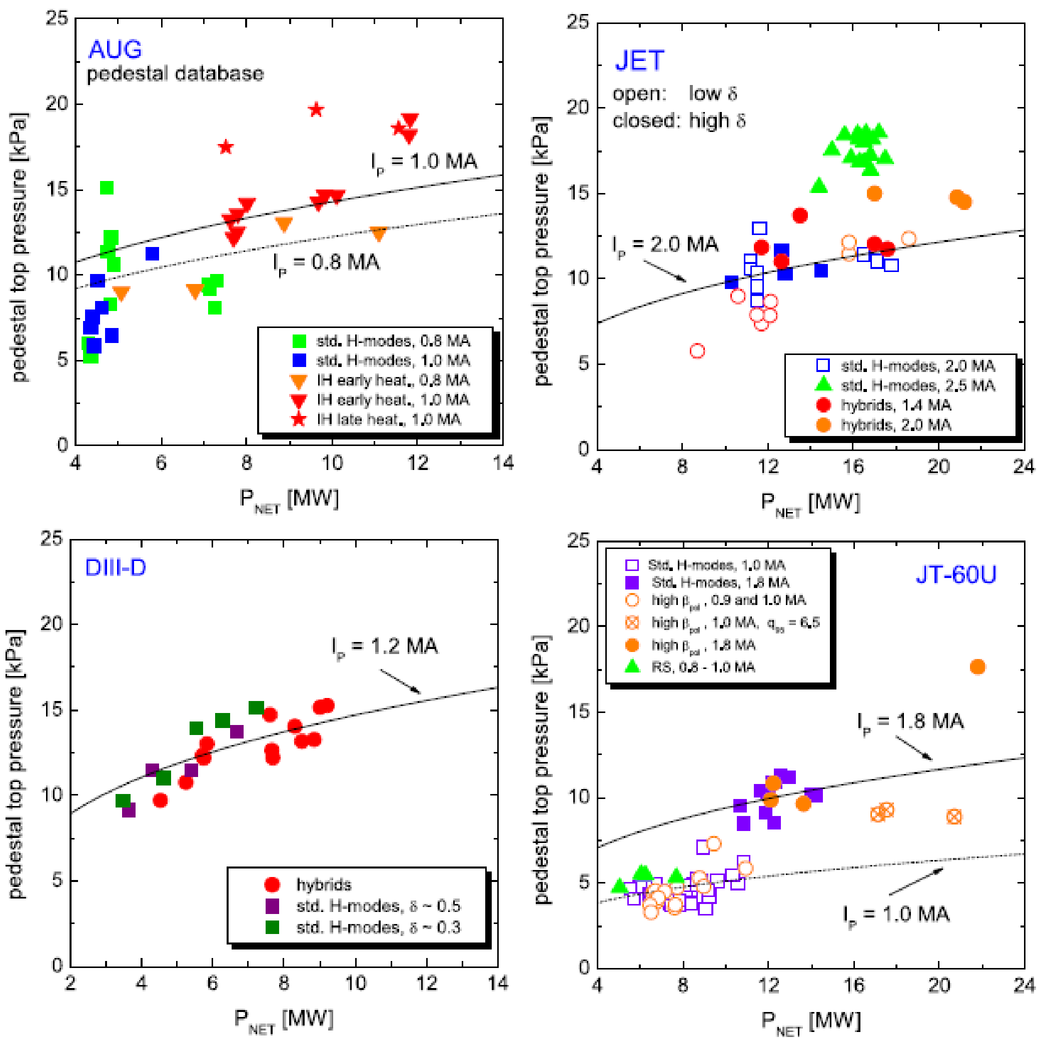
- At 1.7T: H_{98}=1.3-1.4 achieved at q_{95}≈4.3-5.0 with β_N≈3 using hybrid current overshoot technique

- At 2.25T: H_{98}=1.2 achieved at q_{95}=4.7-5.0 with β_N≈3 with and without overshoot

Main plasma parameters of representative discharges for major devices

Tokamak	Scenario	Ip(MA)	ne($10^{19}m^{3}$)	q95	δ	P_{NET}(MW)
AUG	Standard H-modes	0.8 1	5.0–6.7 4.7–6.7	3.7–5.1 3.2–4.4	1.14–0.44 0.13–0.34	4.0–8.0 4.4–5.8
	Improved H-modes	0.8 1	5.3–5.9 4.9–6.0	4.8 4.6	0.22–0.26 7.5–11.8	5.0–11.1
DIII-D	Standard H-modes	1.2	6.4–10.0 ~6.0	4.3 4.2	0.3 0.5	3.5–7.2 3.6–6.7
	Hybrid discharges	1.2	~5.0	4.2–4.5	0.5	4.5–9.2
JET	Standard H-modes	2 2.5	4.8–5.6 6.3–8.0	3.6–3.8 3.0–4.6	0.25–0.43 0.43	10.3–17.8 14.4–17.5
	Hybrid discharges	1.4 2	2.1–3.8 3.1–5.6	3.5–4.1 3.8–4.0	0.22,0.45 0.21,0.42	8.7–17.6 15.8–21.2
JT-60U	Standard H-modes	1 1.8	1.5–3.8 3.3–4.0	3.0–5.3 3.1	0.13–0.49 0.26	5.1–10.9 10.7–14.2
	High β_{pol} H-modes	0.9,1.0 1.8	2.0–3.5 3.3–4.0	3.3–5.2;6.5 3.1;4	0.27;0.47 0.27;0.34	6.6–20.7 13.0;22.0
	RS H-modes	0.8–1.0	1.8–2.8	6.5–9.0	0.38–0.47	5.0–7.7

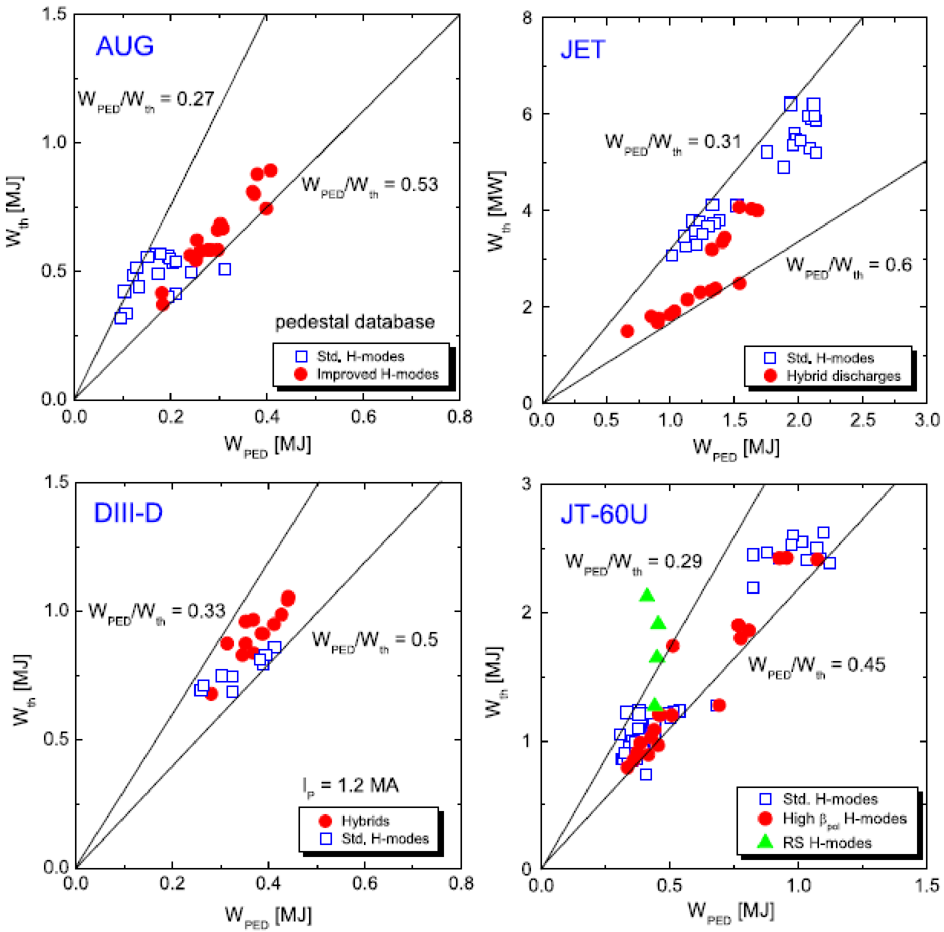
Characteristics of the H-mode pedestal in improved confinement scenarios (1)



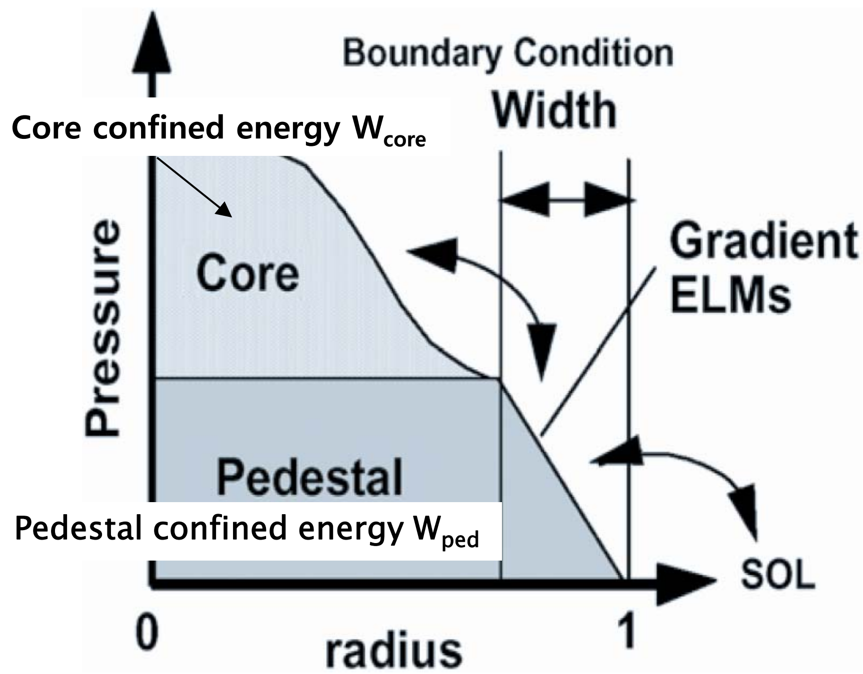
- ✓Pedestal top pressure increases moderately with power in all tokamaks
- ✓Higher pedestal pressures are observed in improved confinement scenarios

Characteristics of the H-mode pedestal in improved confinement scenarios (2)

✓All scenarios has a robust correlation between the total & the pedestal stored energy



Total stored energy, $W_{th} = W_{ped} + W_{core}$



Physics issues for hybrid scenarios

Steadiness of the Current Profile

Confinement Enhancement

Physics Effects Limiting β_N

Impurity transport

Role of ρ^*

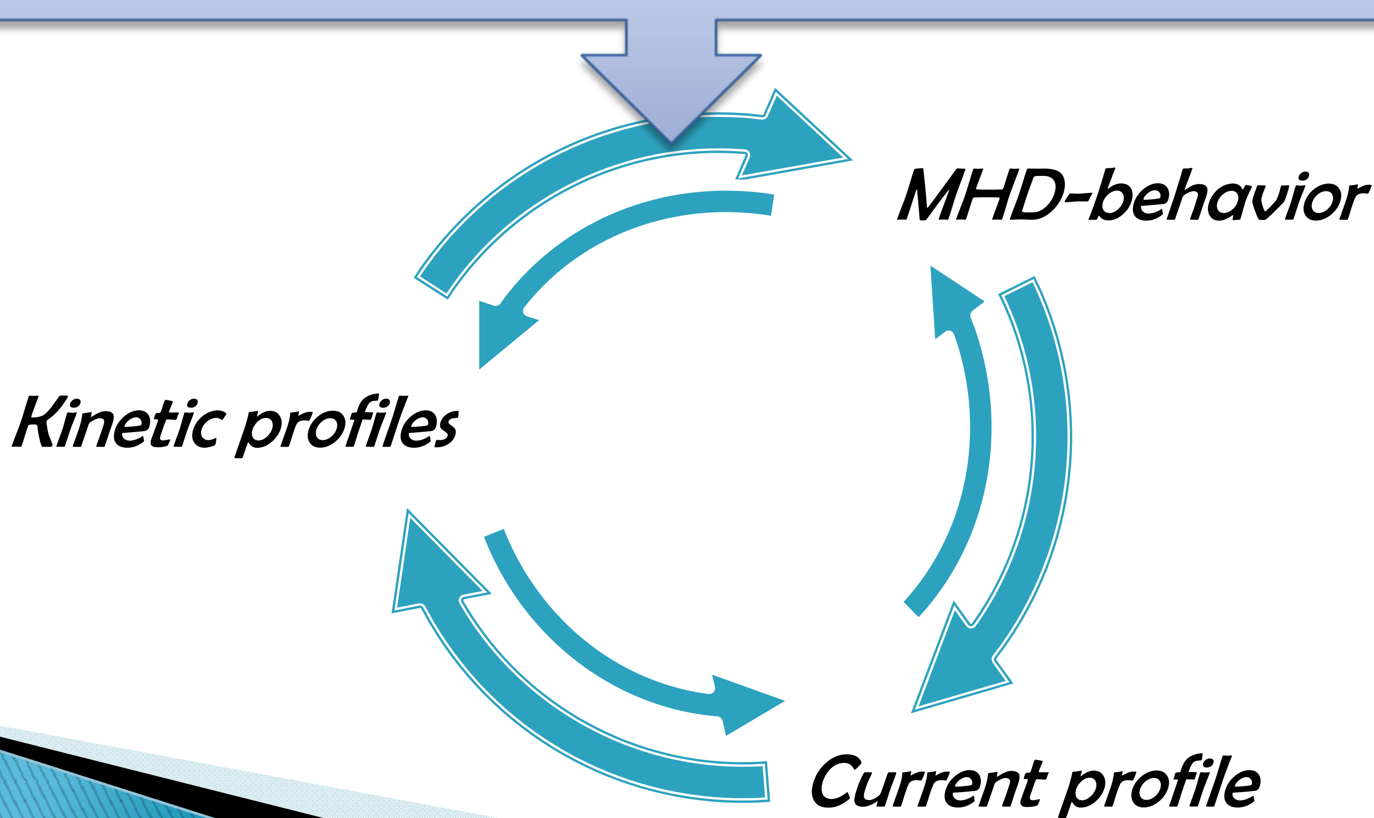
. . .

Normalized Larmor radius which is a significant impact on drift turbulence, on the transport.

Factors to affect tokamak plasma

Three mechanisms seem to play a role :

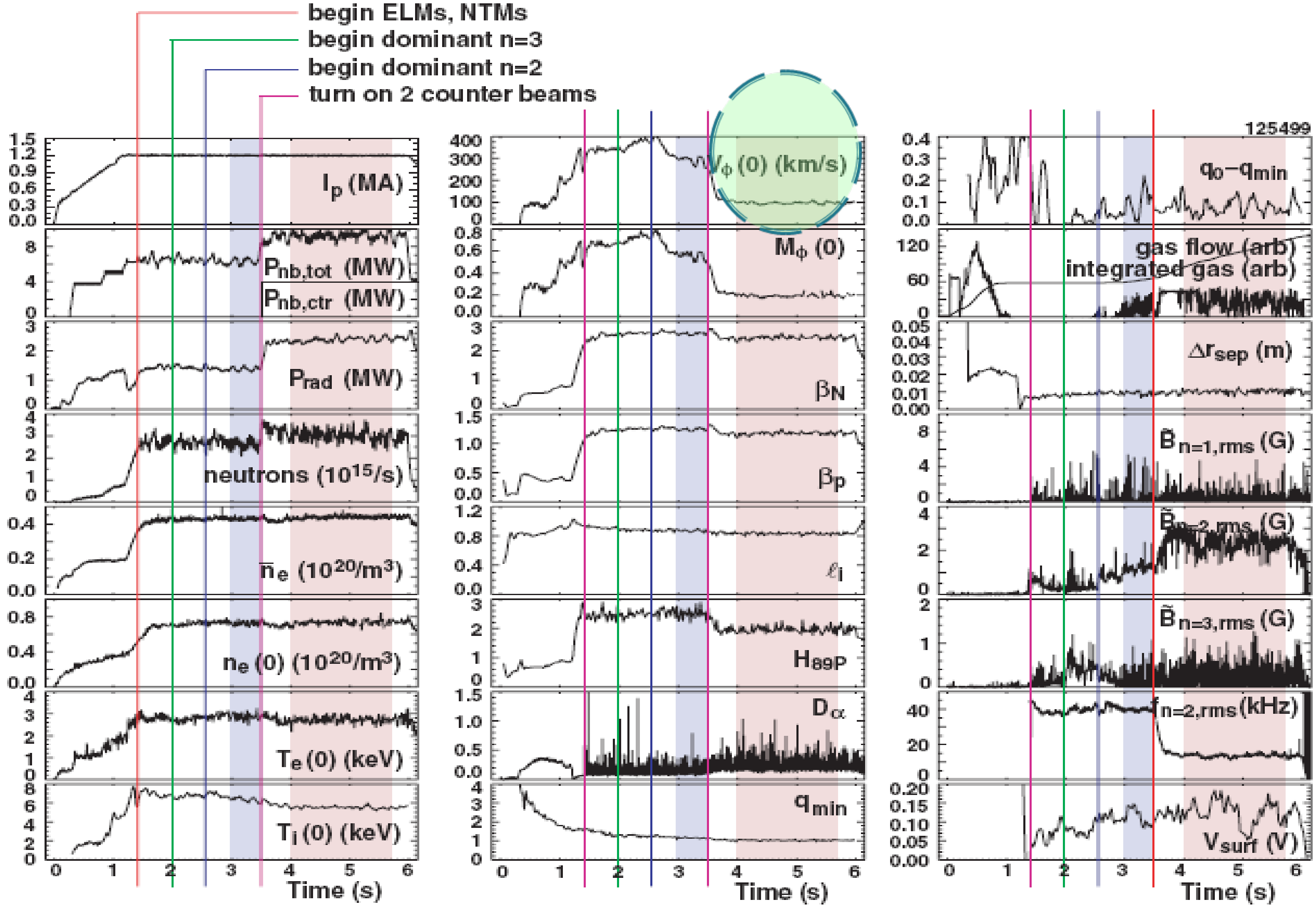
1) The increased transport due to the MHD-modes
2) The variation of the ratio magnetic shear(s) to safety factor(q)
3) Effects on the H-mode pedestal pressure



Attempts to solve physics issues related to confinement

Influence of toroidal rotation(1)

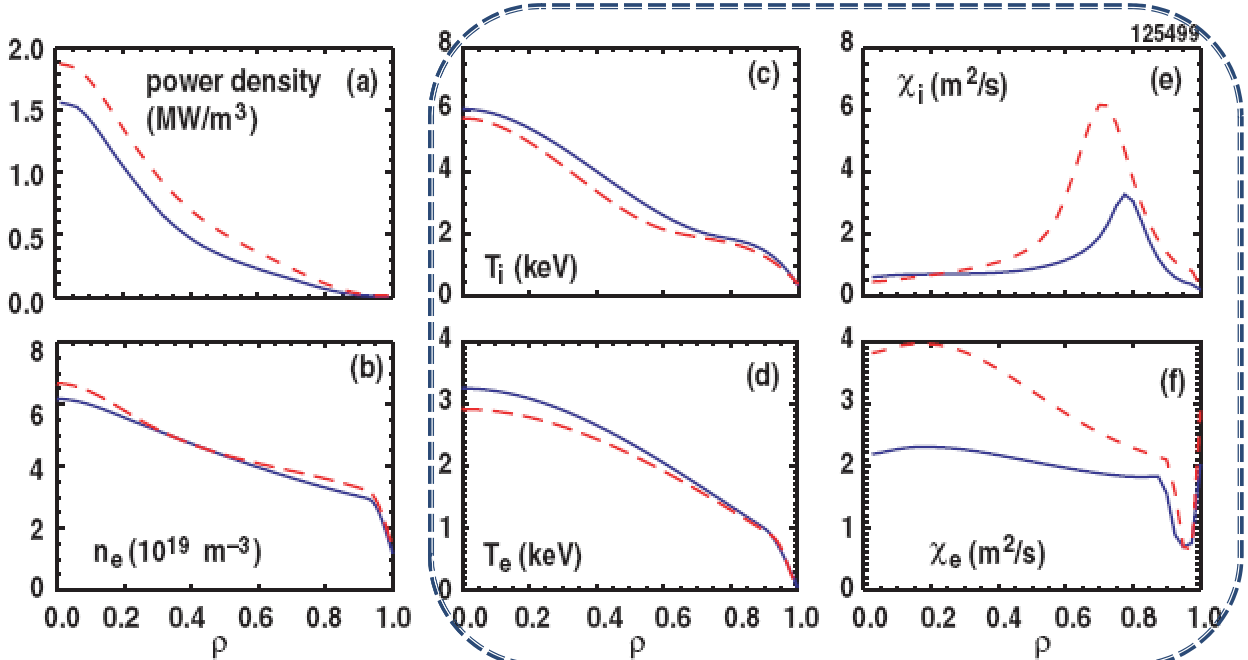
✓Experiment in DIII-D with co- & counter NBI system

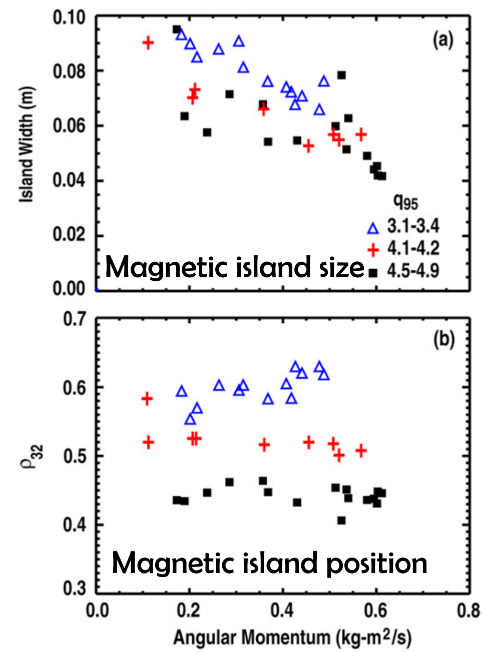


Attempts to solve physics issues related to confinement

Influence of toroidal rotation(2)

✓Comparison between strong (blue) and low (red) toroidal rotation intervals.

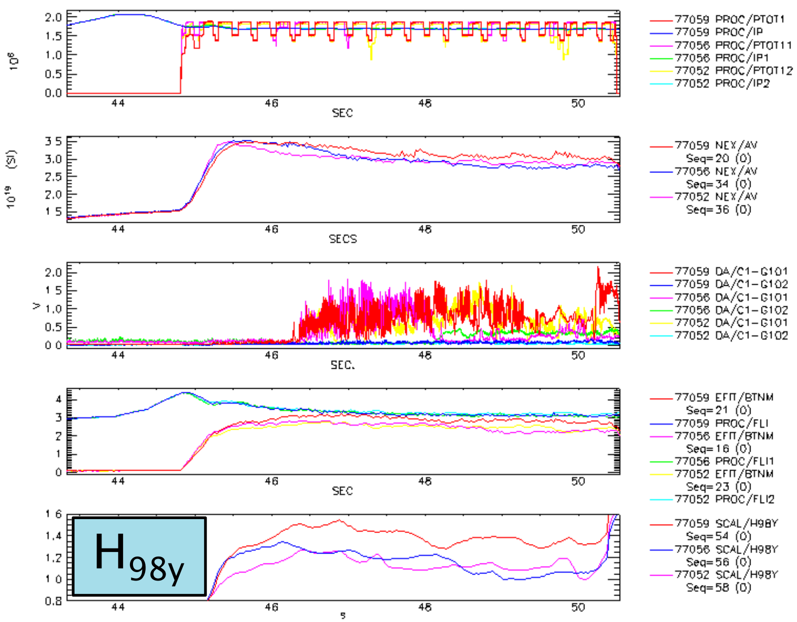


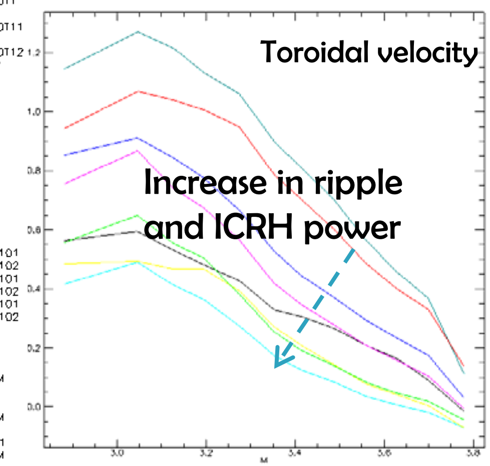


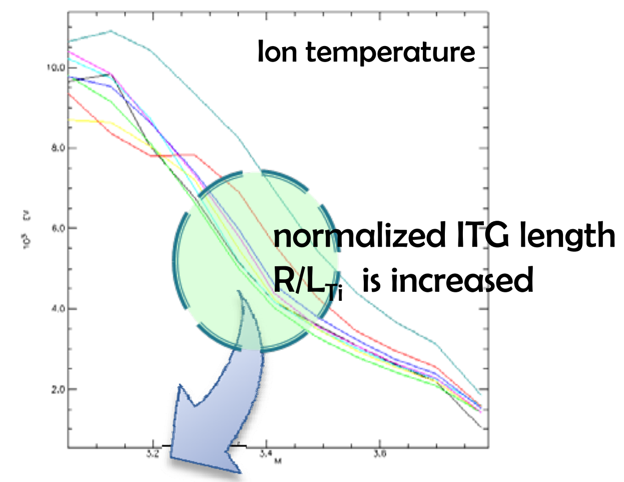
• Although energy confinement decreases and the m/n=3/2 NTM amplitude increases for low rotation speed, the fusion performance figure of merit still exceeds the value required on ITER for Q=10.

Attempts to solve physics issues related to confinement
Influence of toroidal rotation(3)

✓ Strong change in rotation achieved, by ripple and EFCCs in JET







"Ion temperature gradient increases at 3.4m, partially compensating for loss at the edge"

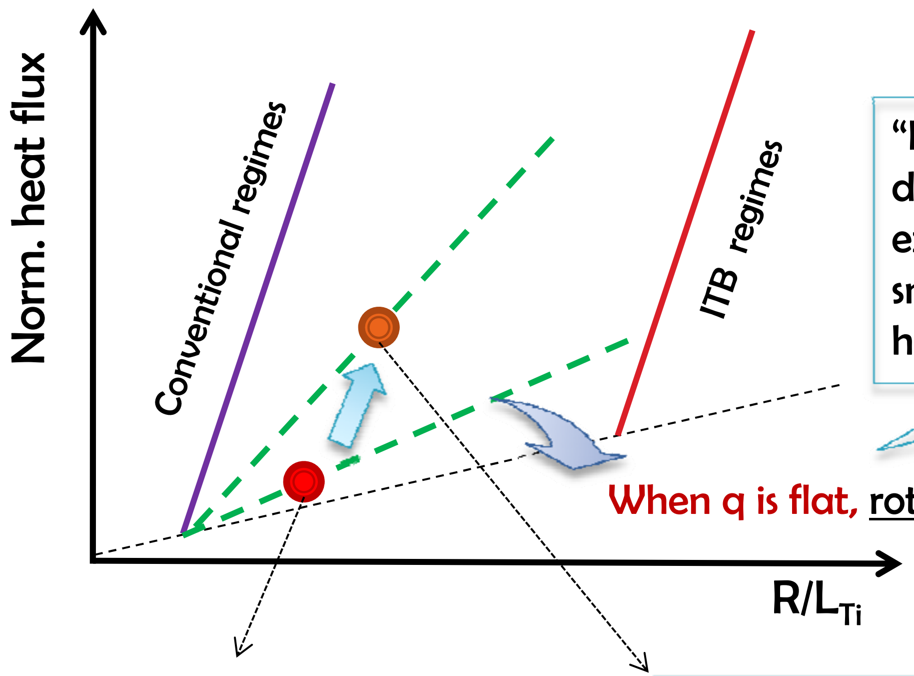
- Clear confinement reduction with ripple and EFCCs
- Density reduced as well, ELMs are different
- q-profile seems to be similar

Attempts to solve physics issues related to confinement

Influence of toroidal rotation(4)

- ✓ the effect of rotation on ion transport

by P. Mantica



"It does not exclude a shift in threshold due to other parameters. It does not exclude Waltz rule but it is a much smaller effect. In fact not enough as we have seen many times."

No ripple, higher rotation, low stiffness, higher pedestal(lower heat flux)

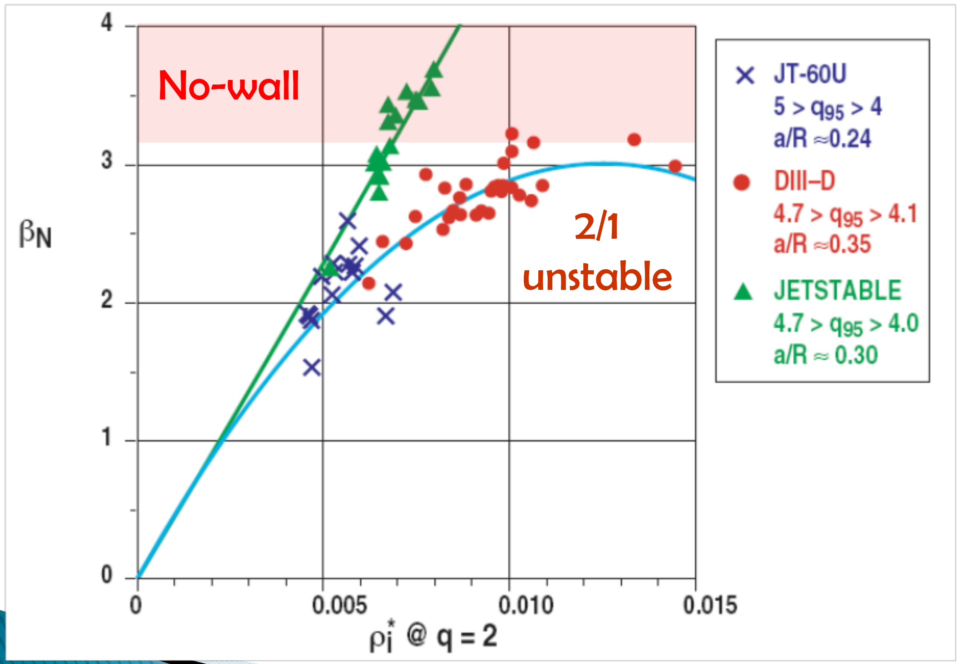
Ripple, bit lower rotation, bit higher stiffness, lower pedestal(higher heat flux)

Attempts to solve physics issues related to confinement
Fast particle effects on the stability limits

JET stable to 2/1 not DIII-D

- **Different fast particle content?**
- **Different q profile?**

2/1 stable



cf.1. Preliminary computation on JET pulses with the HAGIS code indicate that the internal kink mode limit shows a different instability limit when a fraction of fast ion pressure is included in the total pressure.

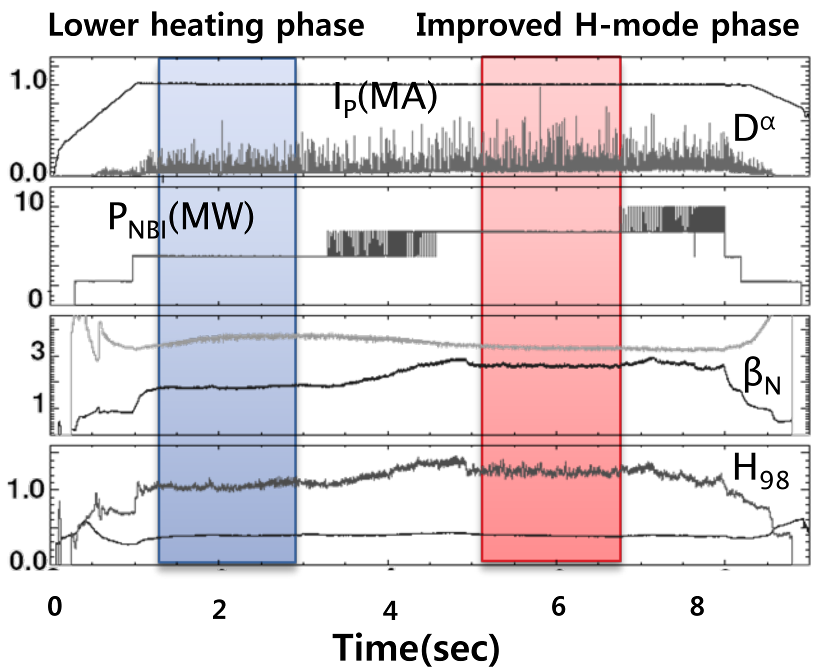
β_N limit can change by ~20%

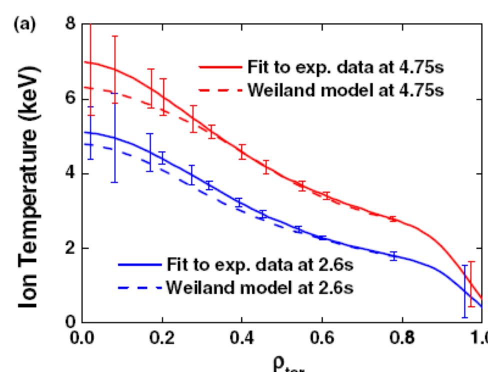
cf.2. Fast particles have a stabilizing effect on ITG driven modes through a modification of the magnetic equilibrium (incidentally improve the gyro-kinetic ordering)

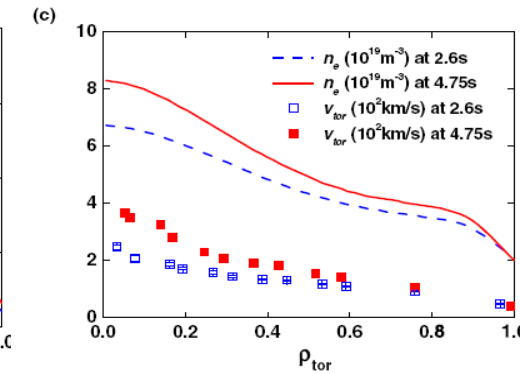
Attempts to solve physics issues related to confinement

Role of Pedestal in Hybrid Performance(0)

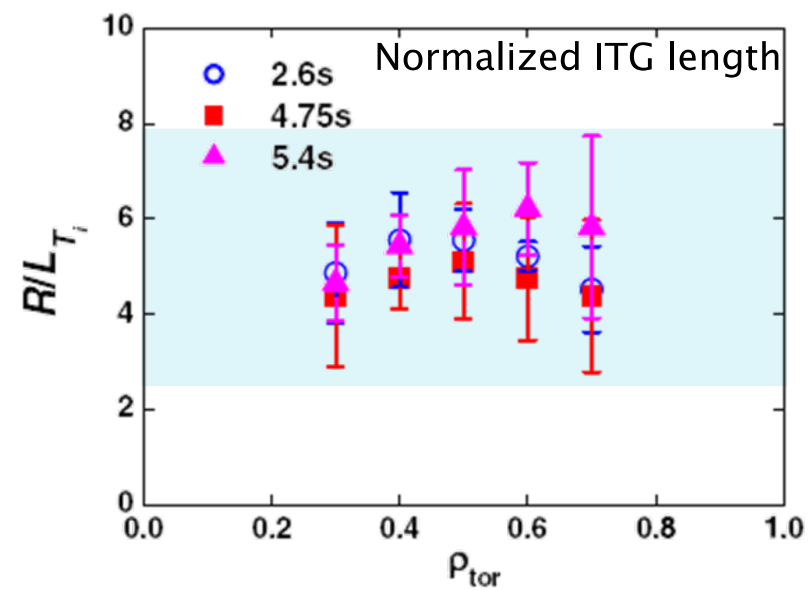
ASDEX-U, #17870







✓ Both phase are still governed by drift-wave turbulence as in standard H-modes.



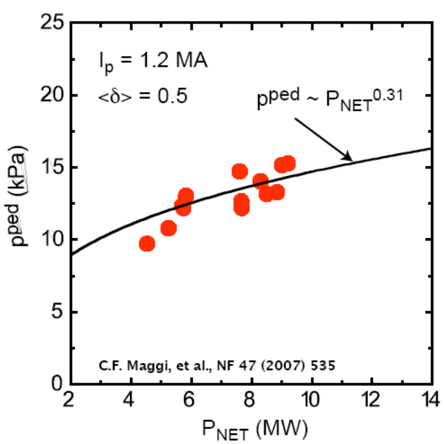
✓ No difference is found in the behavior of turbulence in the confinement region of the plasma between two phase from the results of the analysis of phase fluctuations.

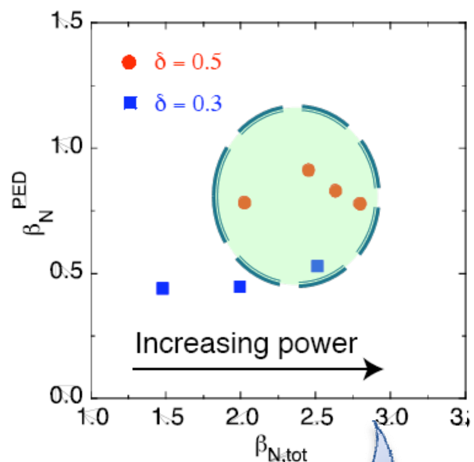
Attempts to solve physics issues related to confinement

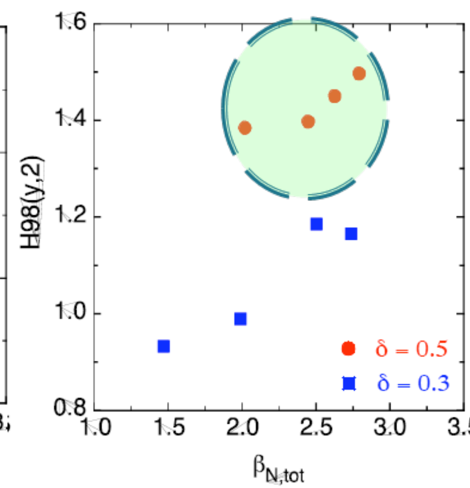
Role of Pedestal in Hybrid Performance(1)

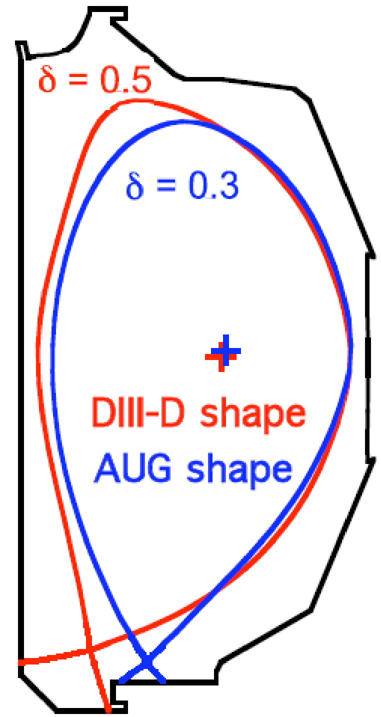
✓ Initial survey showed that
"There is a trend for pedestal pressure to increase with heating power."

✓ Also, plasma shape can be used to improve hybrid performance through pedestal effects.







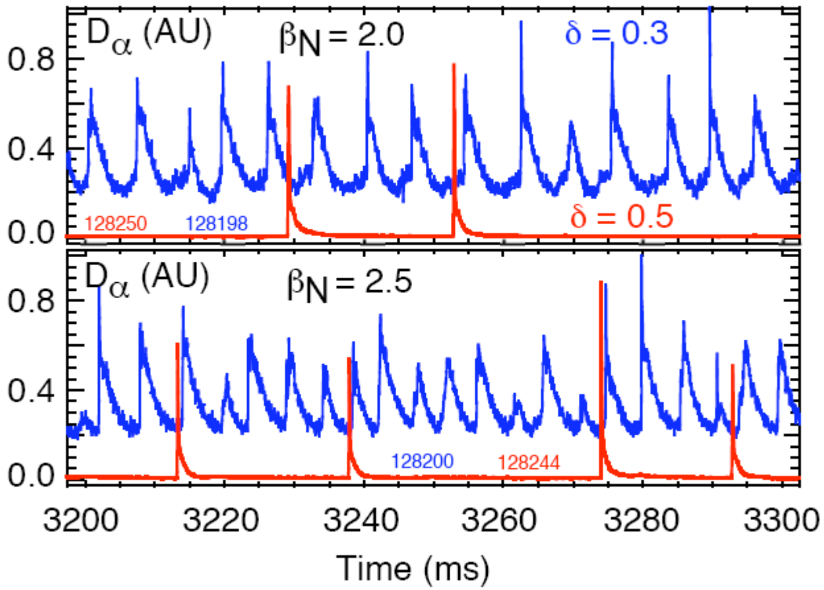


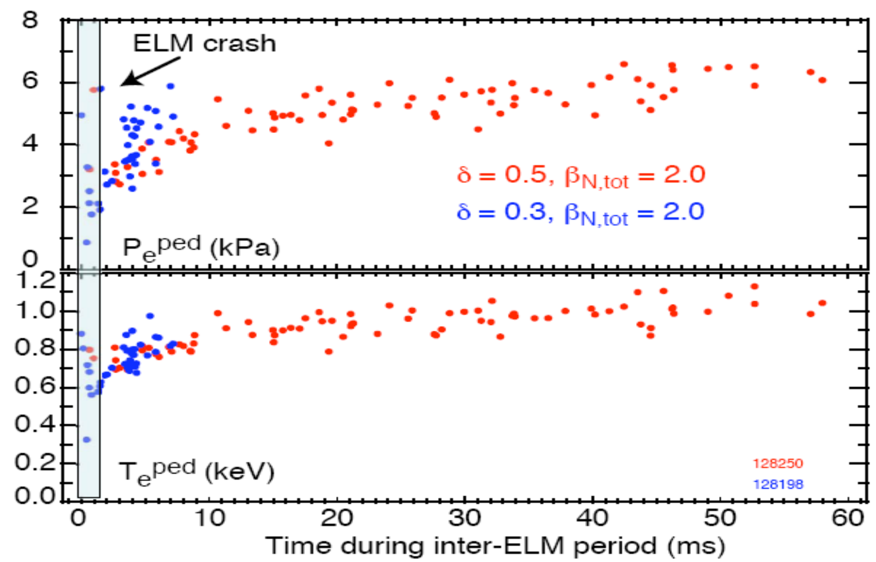
✓ Hybrids exhibit some confinement enhancements which cannot be attributed to pedestal
: Core stored energy can increase even when pedestal pressure does not increase with increased power

Attempts to solve physics issues related to confinement

Role of Pedestal in Hybrid Performance(2)

✓ Higher pedestals are correlated with lower ELM frequencies.
- Lower ELM frequency may allow more complete recovery of pedestal after an ELM and thus higher time-averaged pedestal pressure.
- Physics relation between high and low ELM frequency not clear.

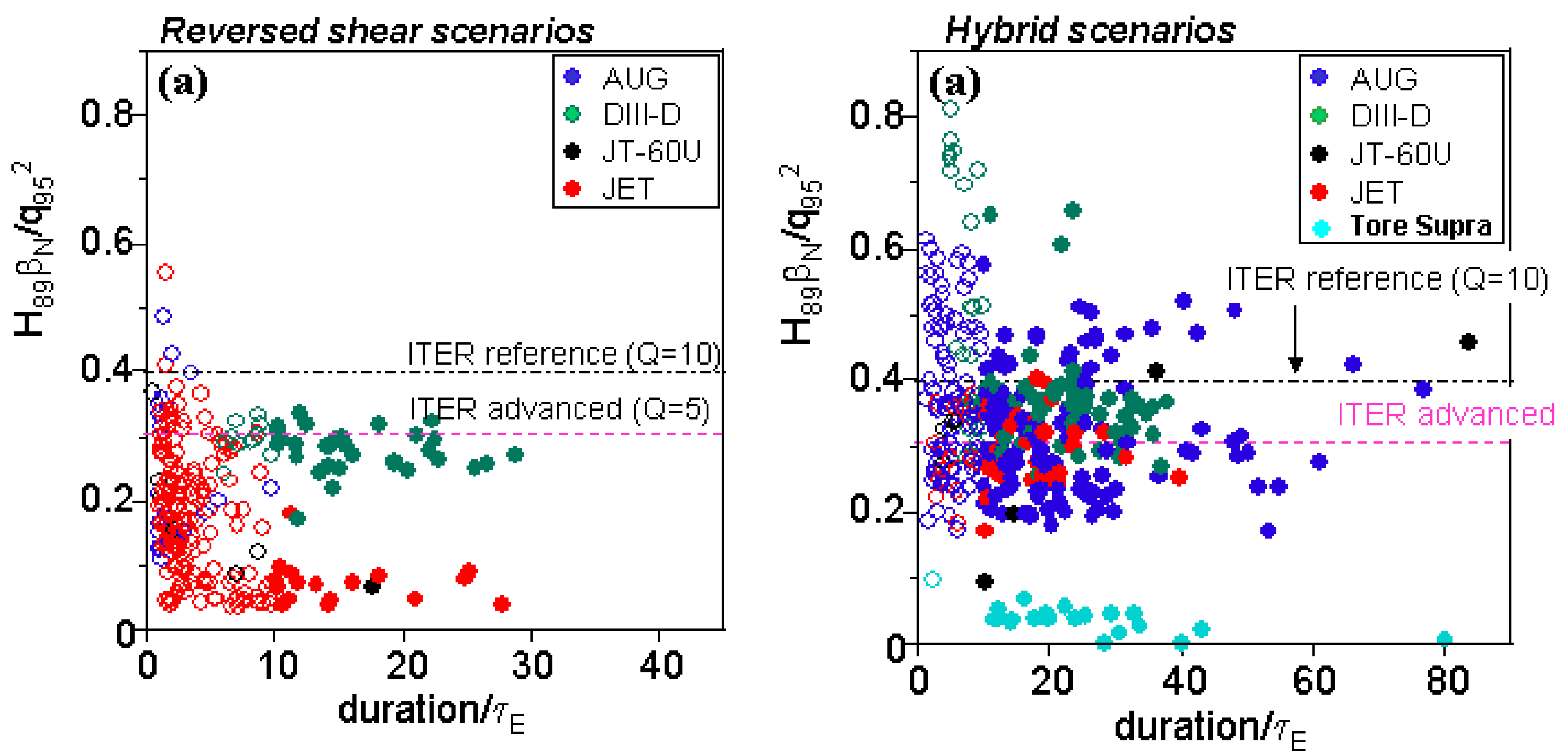




Progress for Hybrid Scenario

ITPA database for plasma performance as duration time

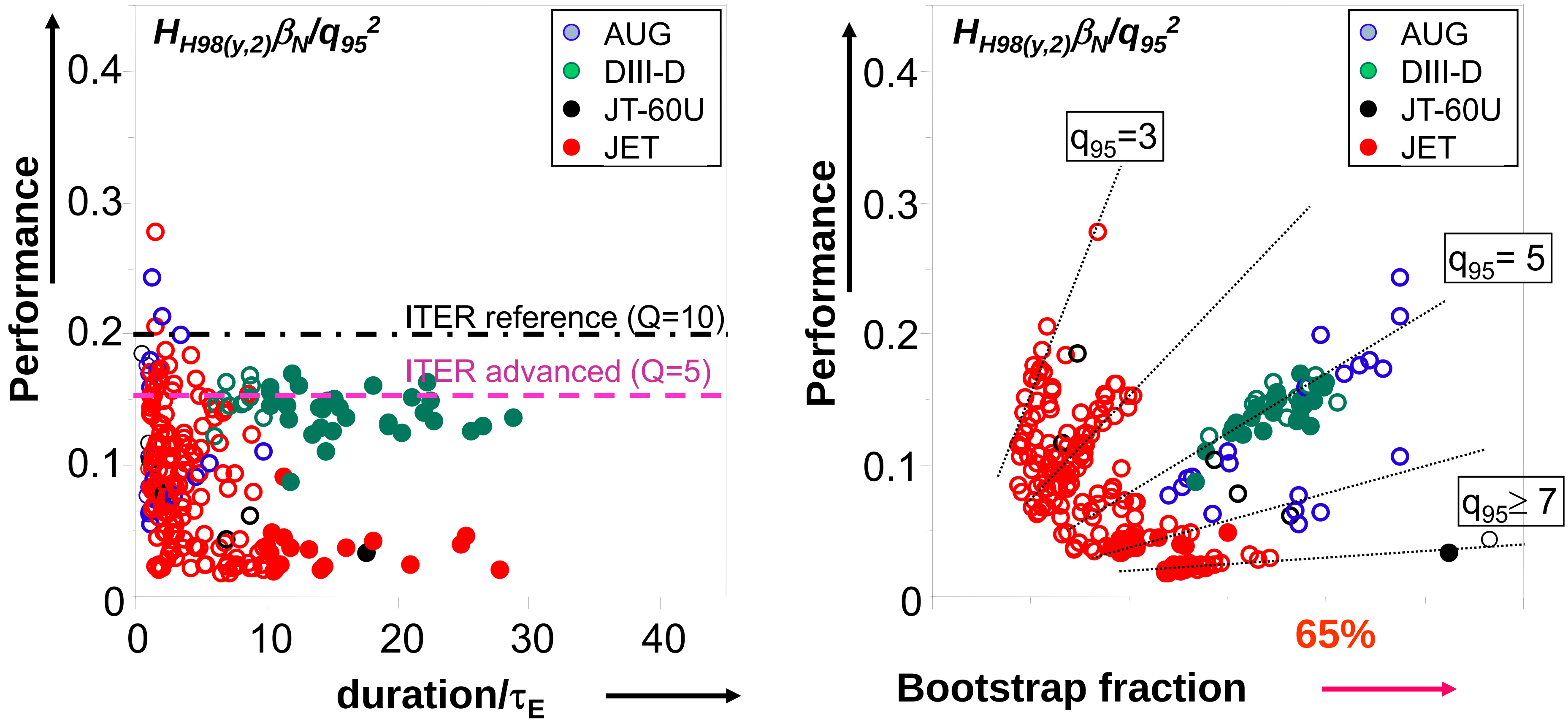
(open symbols are transient discharges, closed symbols are stationary ones)



✓ The duration of hybrid discharges is typically longer compared to reversed shear plasmas.

✓ There is no clear difference between the various experiments in hybrid dataset.

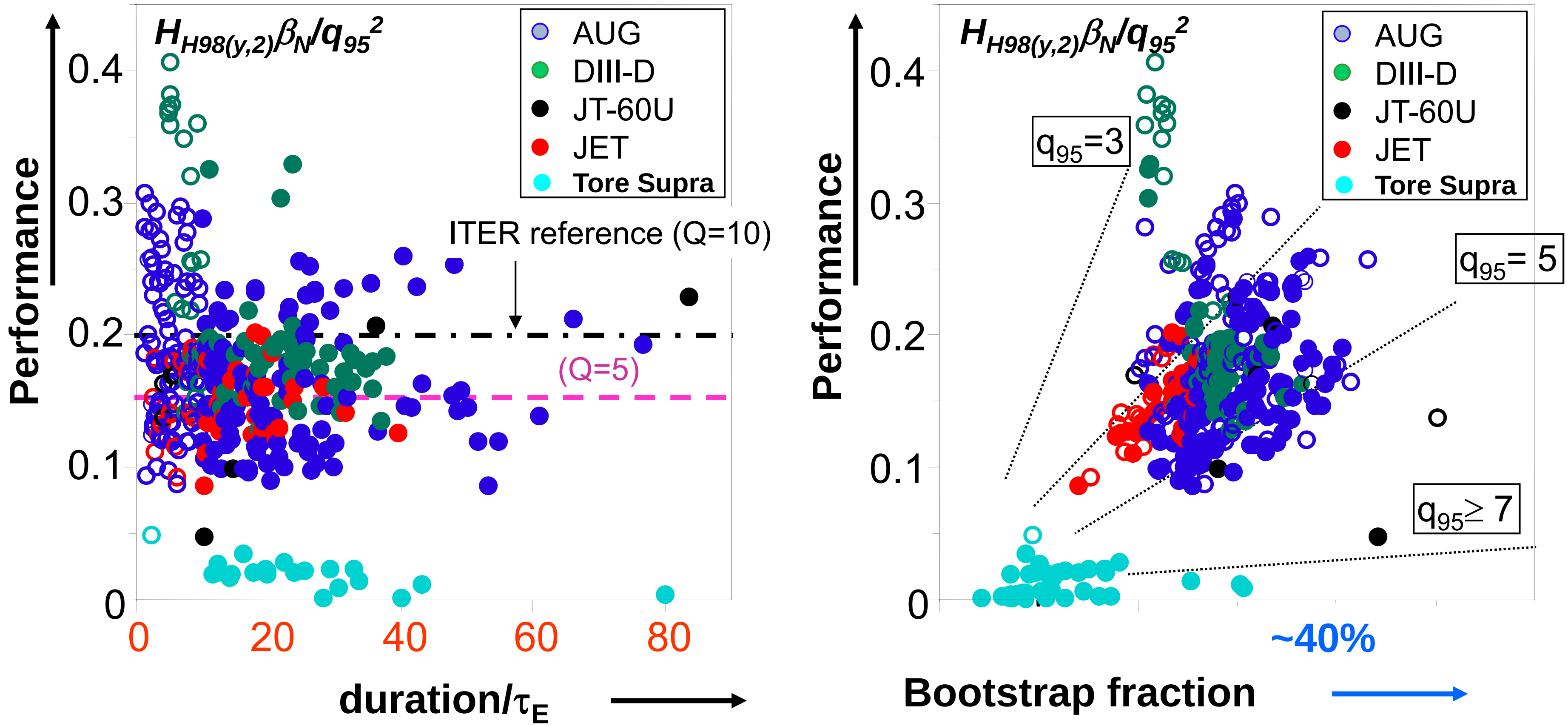
Reversed Shear Scenario



Distinct groups of results, best ones just fine for Q~5.

Transient for $q_{95} \leq 4$, ITER target for q_{95}=5 only.

Hybrid Scenario

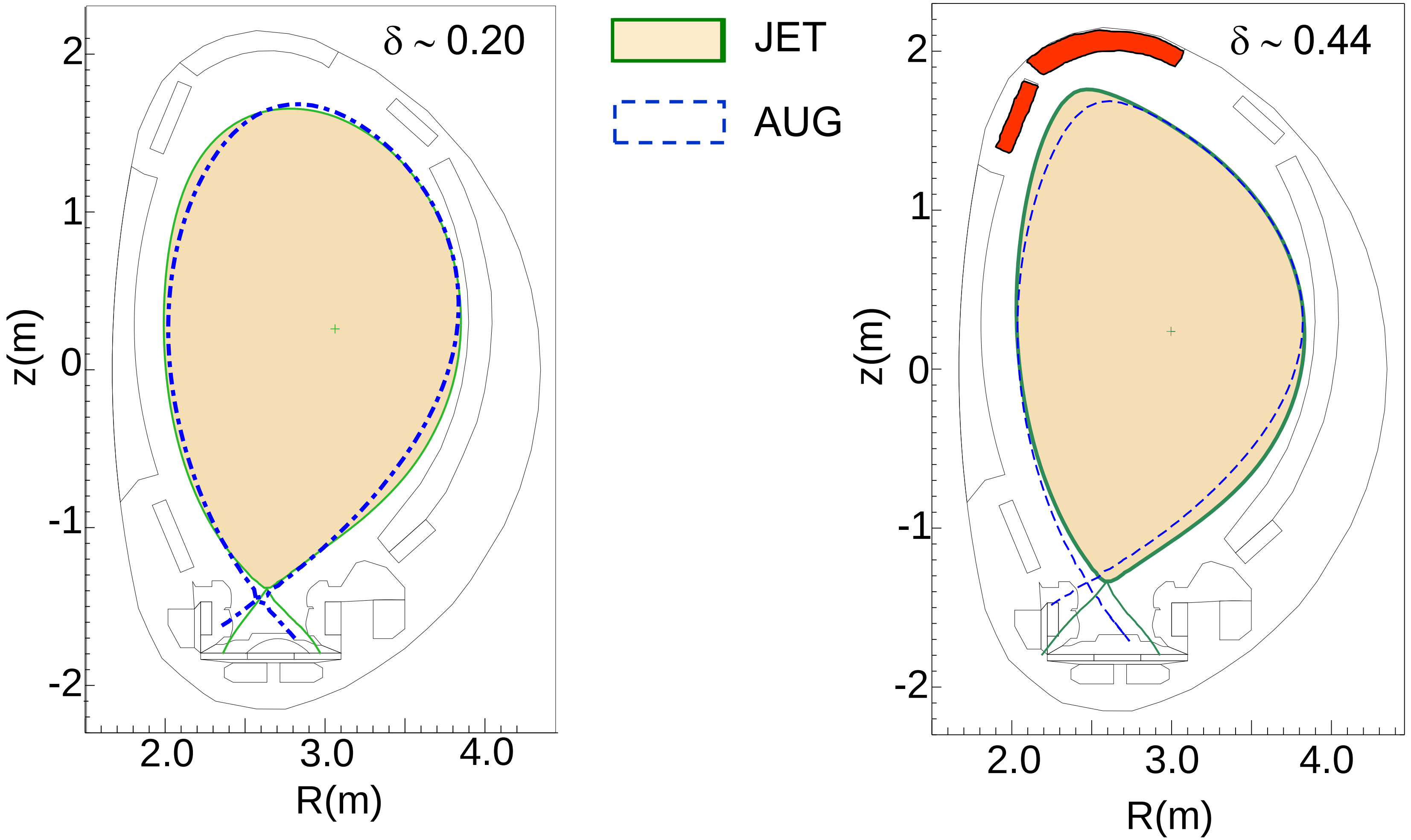


Similar results from all machines, Q>10 possible (ignition?).

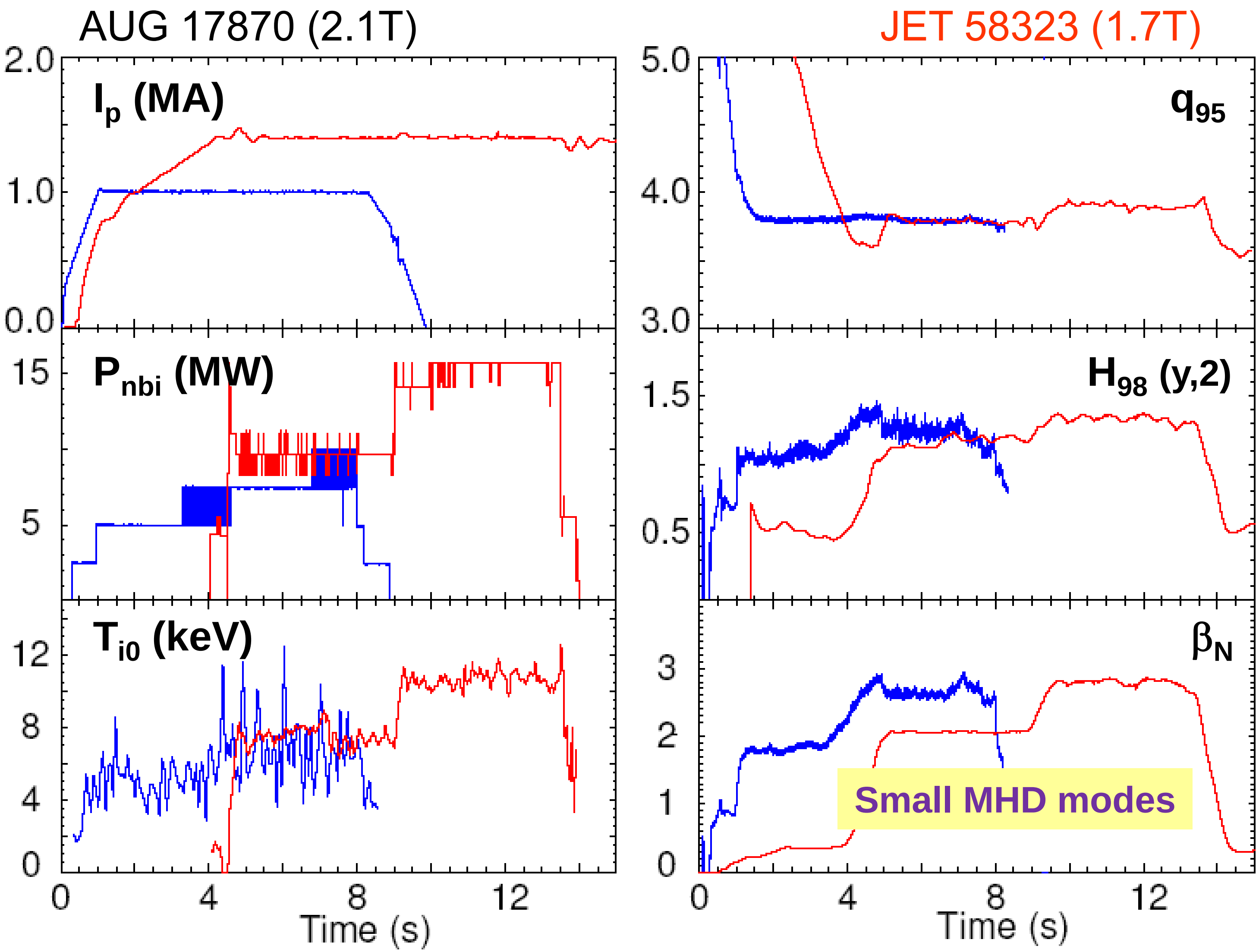
2x ITER target at q_{95}=3, or long pulse (2000s) at q_{95}=4-4.5.

Identity Experiments

Plasma shapes used in JET compared to ASDEX Upgrade

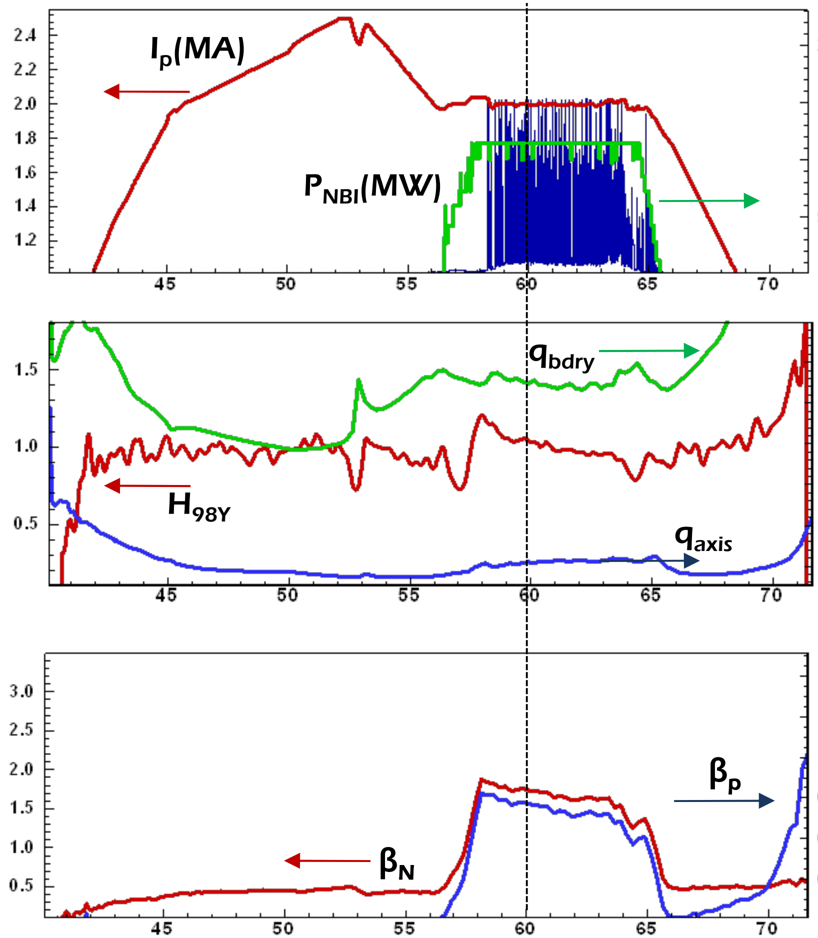


Identity Experiments

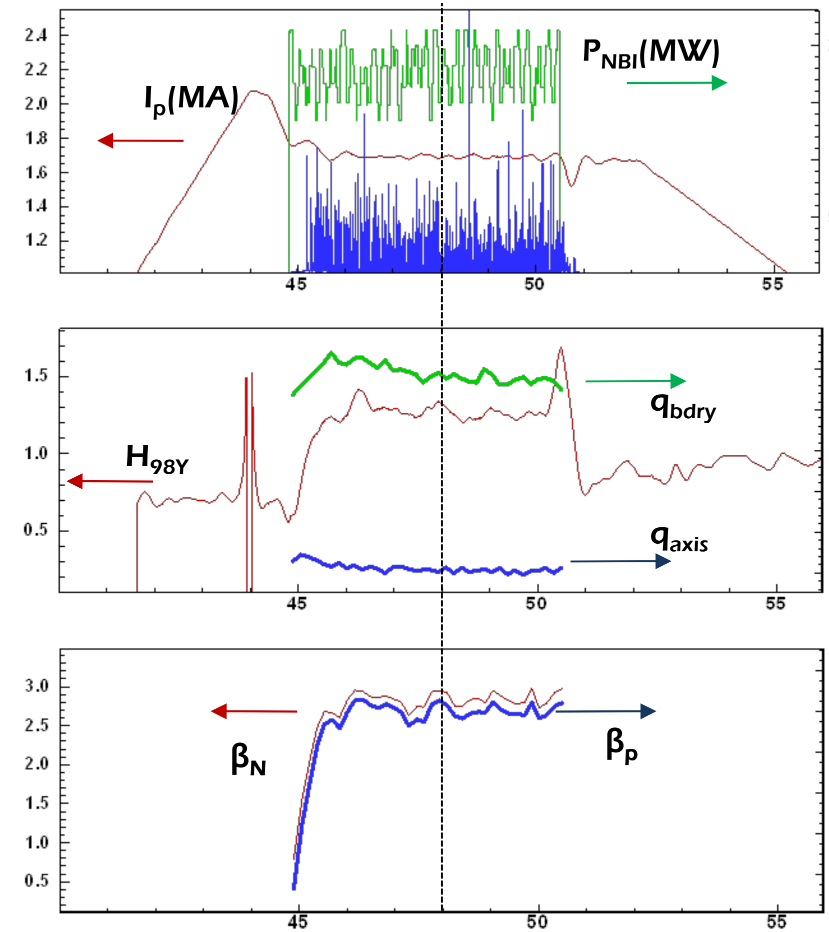


MHD Analysis on JET Shots

#55937 (an example of conventional H-mode)



#75738 (an example of Hybrid scenario)



------------------- analyzed time (before ELM burst)