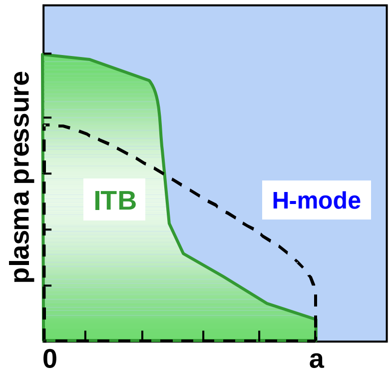
Fusion Reactor Technology 2
(459.761, 3 Credits)

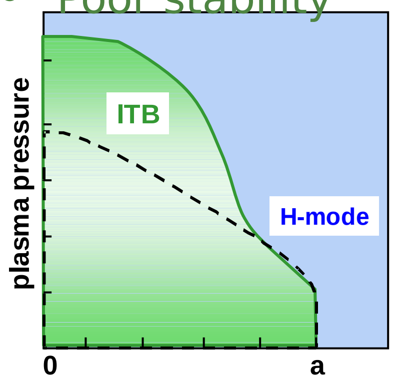
Prof. Dr. Yong-Su Na

(32-206, Tel. 880-7204)

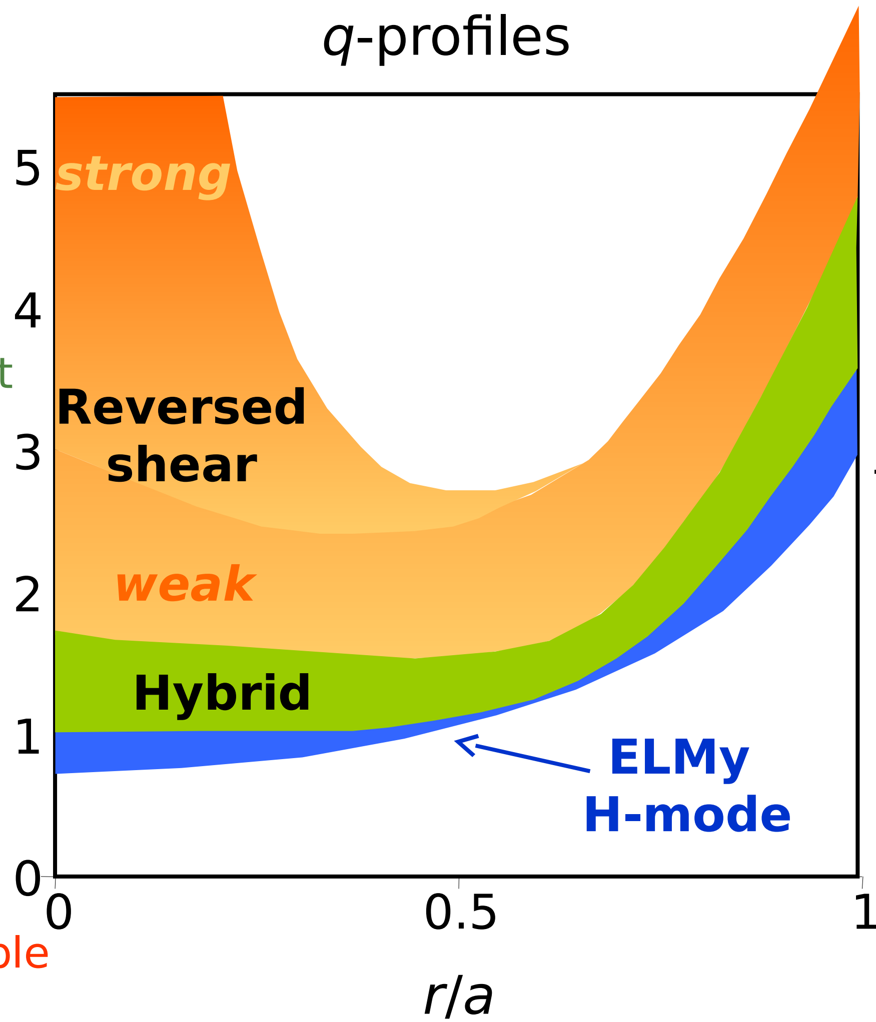
Tokamak Operation Scenario

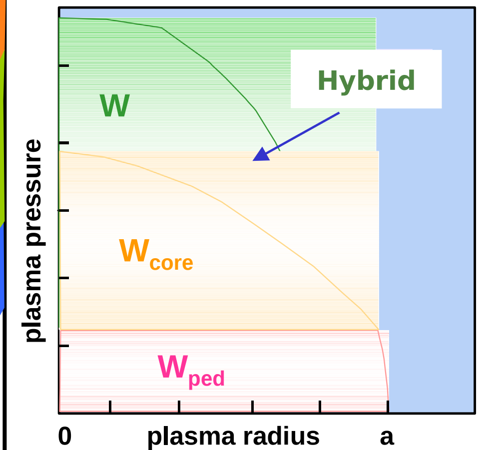


- Good confinement
- Poor stability



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

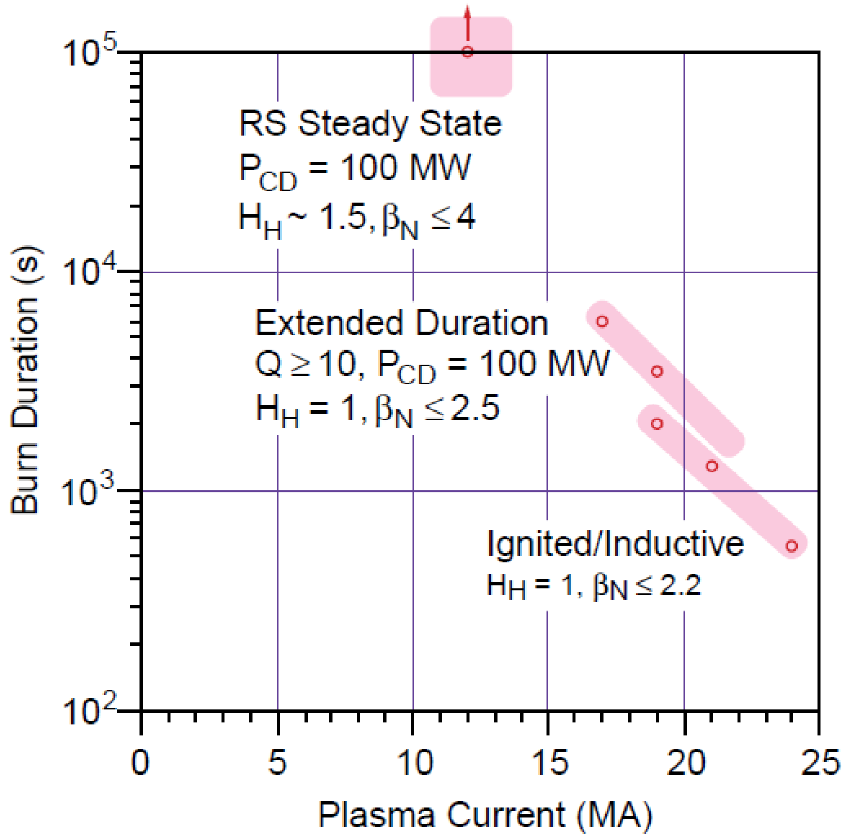




- Good confinement

together with high stability w/o active control

1999



Chapter 8: Plasma operation and control, ITER Physics Basis
Nucl. Fusion 39 2577 (1999)

5. Hybrid operation

Very long pulse operation, i.e. more than 1000 s, can be achieved even with $H_H = 1$ by increasing the non-inductively driven current (I_{CD}), decreasing the plasma current I_P and consequently decreasing the Q value. The safety factor can be increased to 3.5 which could provide a mode with very small or no ELMs with high triangularity [13] and could give a sufficiently long lifetime of the divertor target. A pulse length of more than 1000 s is also suitable for the blanket test because a thermal quasi-steady-state of the front part of the breeding blankets is achieved within this pulse length. Accumulation of 14 MeV neutron fluence of 0.3 MW m^{-2} on the first wall of a test blanket will be achieved with about 14 000 shots of this kind of a conservative hybrid operation at $I_P \sim 13$ MA which will consume about one-third of the machine lifetime. Further improvement of plasma operation will provide a higher fluence. In any case, a large fraction of the lifetime can be used for the study of burning plasmas and development of reactor core plasmas.

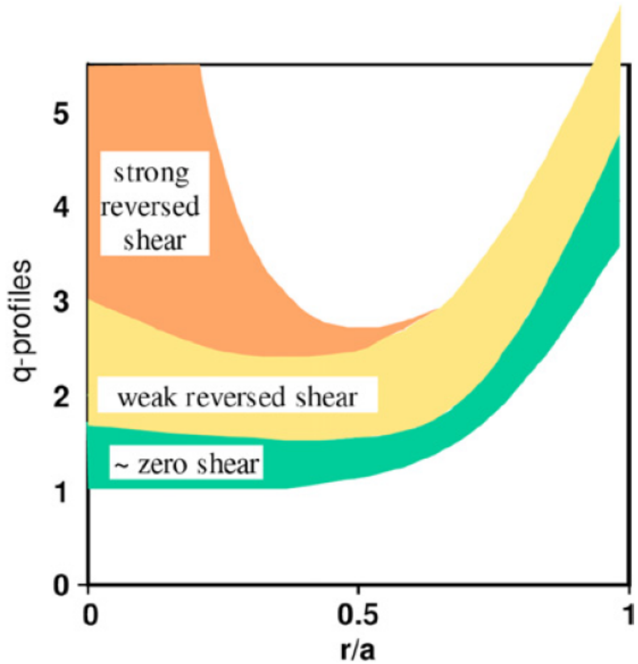
A hybrid operation provides a sawtooth free plasma and also an important step towards the establishment of true steady-state modes of operation.

ITER: opportunity of burning plasma studies

Y. Shimomura et al PPCF 43 A385 (2001)

2007

- **More recently, the development of magnetic configurations with a wide volume of low magnetic shear and a central value of q close to 1 has resulted in quasistationary discharges with improved confinement and high values of normalized beta. They are also characterized by a low level of MHD activity. These discharges extrapolate to the performance needed for the 'hybrid' scenarios foreseen for ITER.**

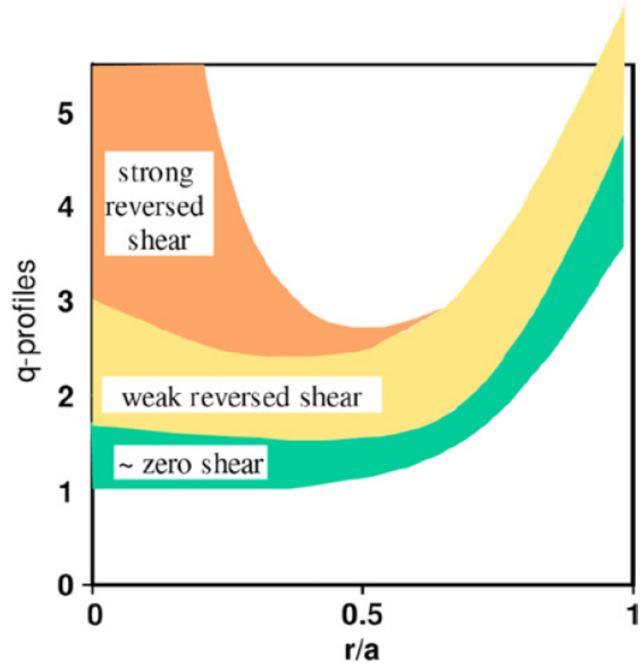


Chapter 1: Overview and summary, Progress in the ITER Physics Basis

Nucl. Fusion 47 S1 (2007)

Scenario	Plasma current (MA)	Non-inductive fraction	H98(y,2)	li	β_N	Burn duration (s)
Inductive (Scenario 2)	15	0.15	1.0	0.8	1.8	~400
Hybrid (Scenario 3)	~12	~0.50	1–1.2	0.9	2–2.5	⩾1000
Steady-state (Scenario 4)	~ 9	1.00	⩾1.3	0.6	⩾2.6	3000[a]

- **Improved confinement and beta have been observed with low shear (= high βp = 'hybrid') operation scenarios in many tokamaks.
If similar normalized parameters were achieved in ITER, it would provide an attractive scenario with
high Q (>10), long pulse (>1000 s)
operation with beta < no-wall limit and
benign ELMs.**



***Chapter 1: Overview and summary,
Progress in the ITER Physics Basis
Nucl. Fusion 47 S1 (2007)***

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2007

- A **hybrid scenario** in which the plasma current is driven by a combina tion of inductive and non-inductive currents is intended to provide op eration with a long burn time (>1000 s), high fluence/shot and Q > 5 w ith a high reliability for engineering tests.
  (Ip = 12-14 MA, *H*98*(y, 2)* = 1 and *β*N ~ 2)
- An **advanced hybrid scenario** is a **hybrid scenario**, aiming at produci ng high fusion yield and features a higher beta limit with an optimize d current profile, a lower current and a lower loop voltage, which wou ld allow operating with a high fusion gain (Q ~ 10) for long pulse dur ation. Examples for this type of operation using zero magnetic shear in the centre achieving βN near 3 were given. The **advanced hybrid sc enarios** are often simply called **hybrid scenarios**.
- the rapid progress made recently, and described below, implies that t he hybrid scenario is now considered as an advanced reactor relevan t scenario. Future developments of such a scenario might even lead t o the concept of '**quasi steady state**' reactor.

Chapter 6: Steady state operation, Progress in the ITER Physics Basis
Nucl. Fusion 47 S285 (2007)

2014

- **Operation at high normalized pressure (β_N) and $q_{95} < 4$ may provide an alternative means to enhance the fusion power while still operating at 15 MA, rather than raising the current to 17 MA, which is the present contingency plan. Operation at high β_N and 15MA would also be a potential route to very high fusion gain ($Q > 20$) in the event the confinement quality is high. To take into account the broader possibilities of these scenarios for ITER, the term 'advanced inductive' scenario, rather than the often-used term 'hybrid' scenario, will be applied here to plasmas meeting the criteria of $\beta_N \geq 2.4$ and $H_{98y2} \geq 1$ in stationary operation ($t_{dur} \geq 5\tau_E$) in present-day experiments.**

Development of advanced inductive scenarios for ITER

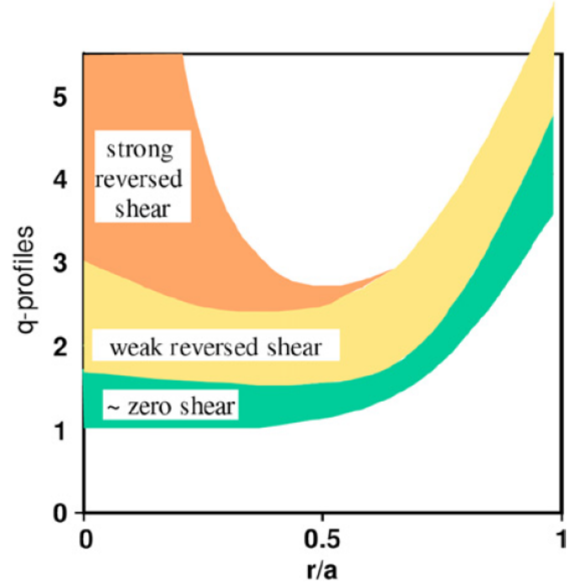
T.C. Luce et al, Nucl. Fusion 54 013015 (2014)

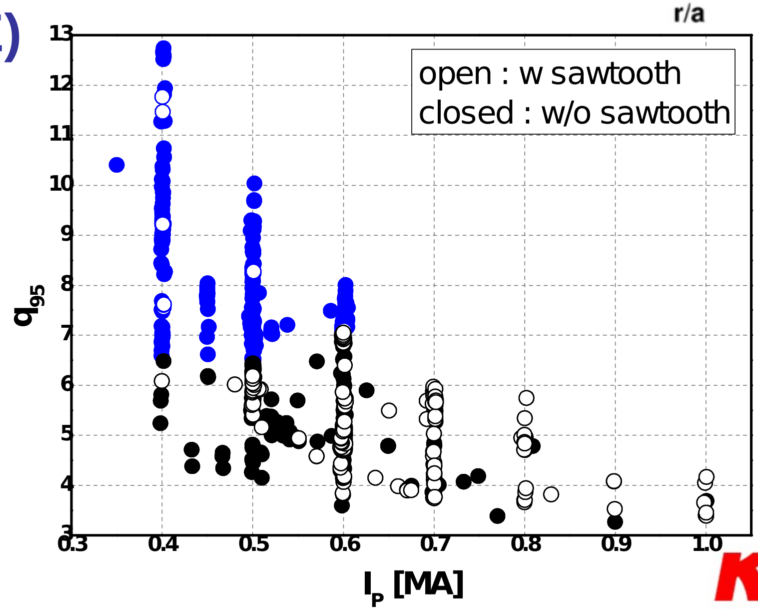
Summary of Definitions

	Ip (MA)	H98	Q
Hybrid	< 15	1	> 5
Advanced hybrid	< 15	$\gtrsim 1$	~ 10
Advanced inductive	15	$\gtrsim 1$	> 20

Definition of Hybrid Scenarios

- q_0 above (around, slightly below,…) 1
- Broad *q*-profile, low magnetic shear
- No (or mild) sawteeth
- With mild (no) NTMs
- Improved confinement (H98y2 ≥ 1, H89 ≥ 2)
- High beta (βN ≥ 2.4, βp ≥ ?)
- Stationary operation (tdur ≥ 5τE)
- Target operation window?
  q95?





roduction – What is hybrids scenari

β_t = 2.547 for all scenarios
(the same stored energy)

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

- ✓ 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.

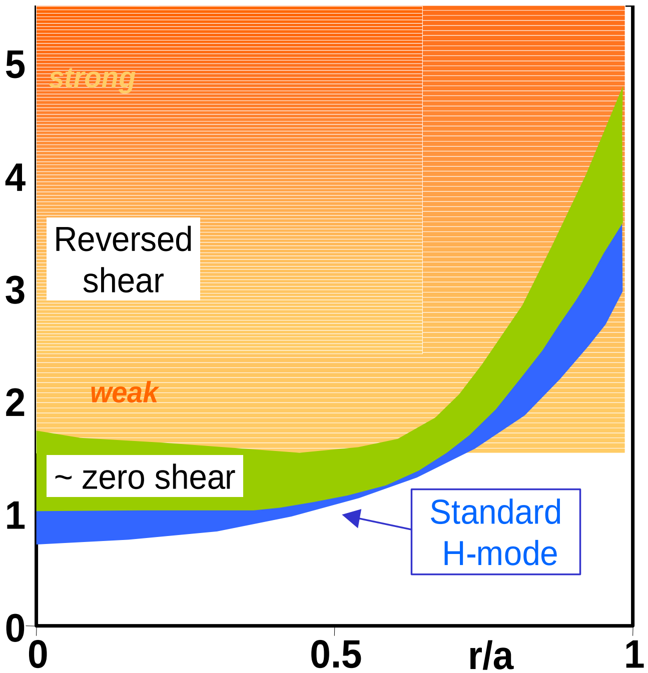
roduction – Features of hybrids scer

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

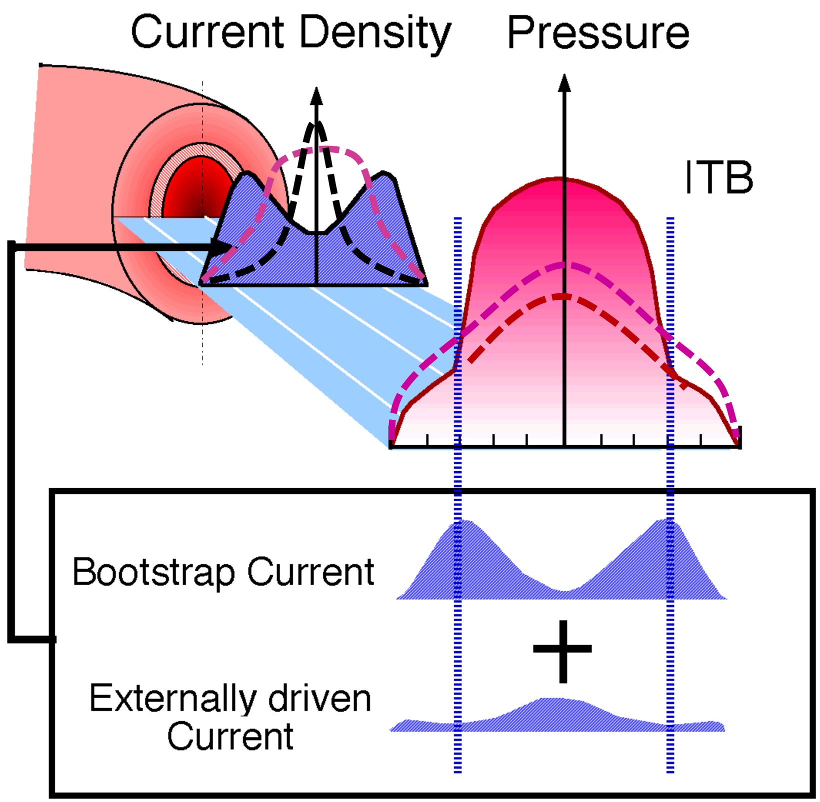


RS+ITB mode (Challenging demands in terms of control):
Very strong reversed shear can lead to the development of 'current hole' configurations where the plasma current does not penetrate to the plasma centre.

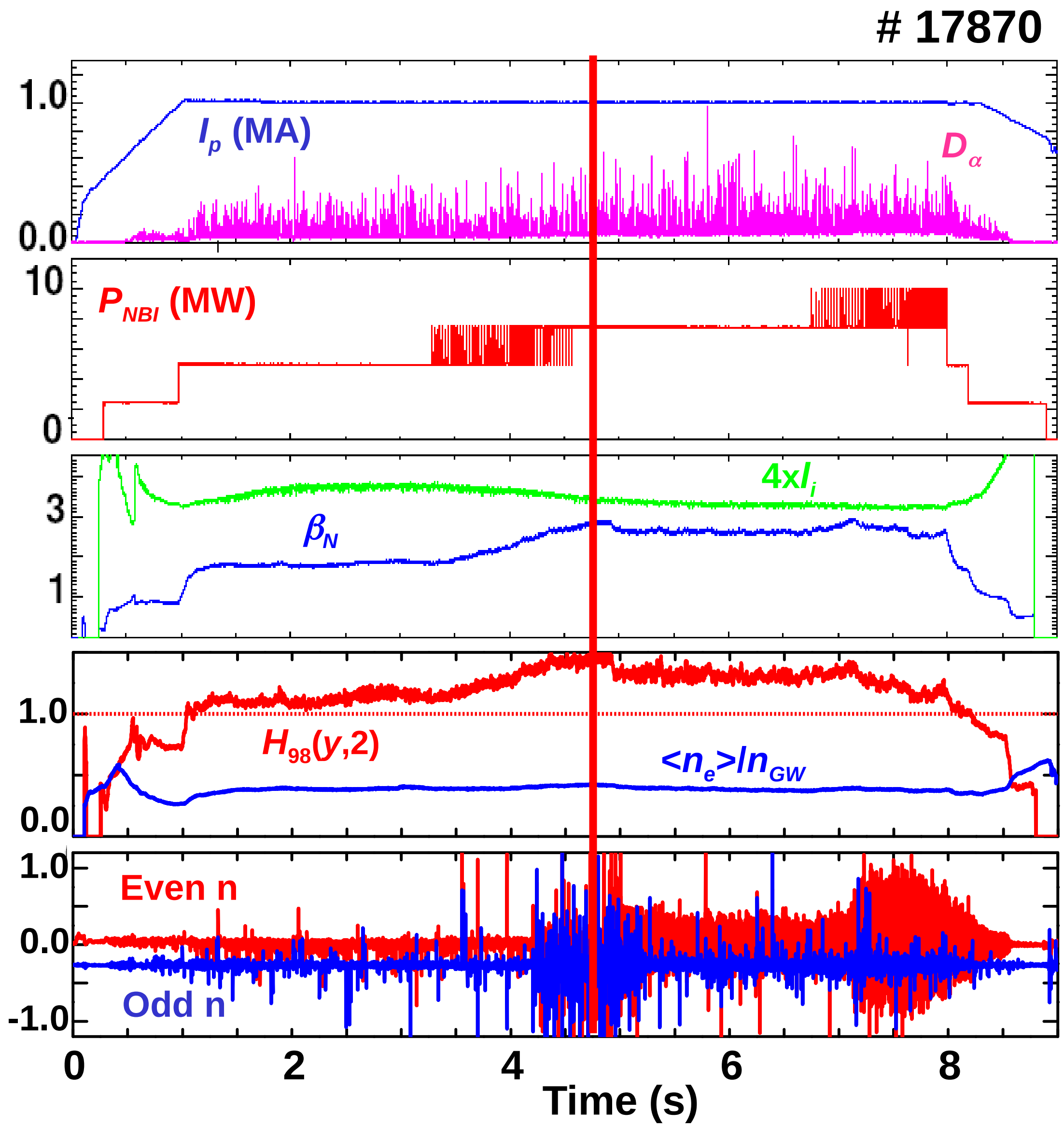
Conventional Hybrid mode :
A large volume of low magnetic shear and a central value of q close to one have resulted in stationary discharges with improved confinement and high values of normalized beta.

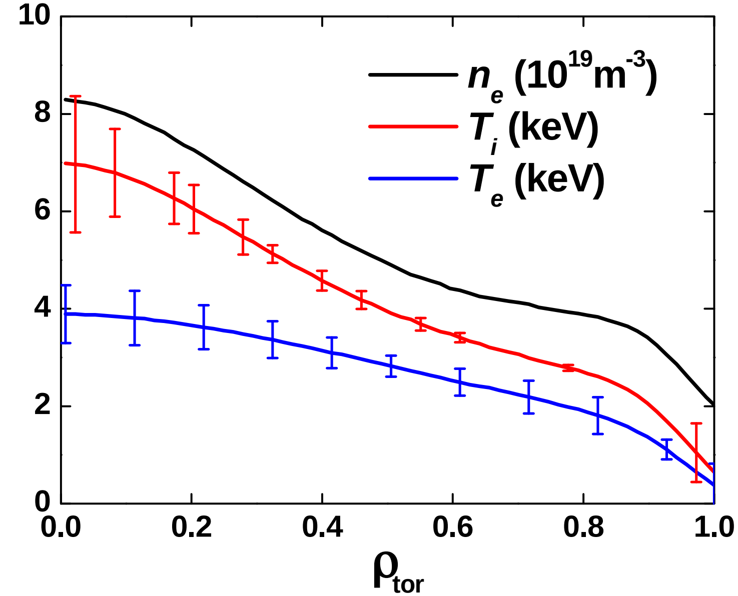
Reference H-mode (with assumption of NTM suppression): Plasma current is fully diffused and q-profile has monotonic form with a large positive magnetic shear

Tokamak Operation Scenario



Hybrid Scenario

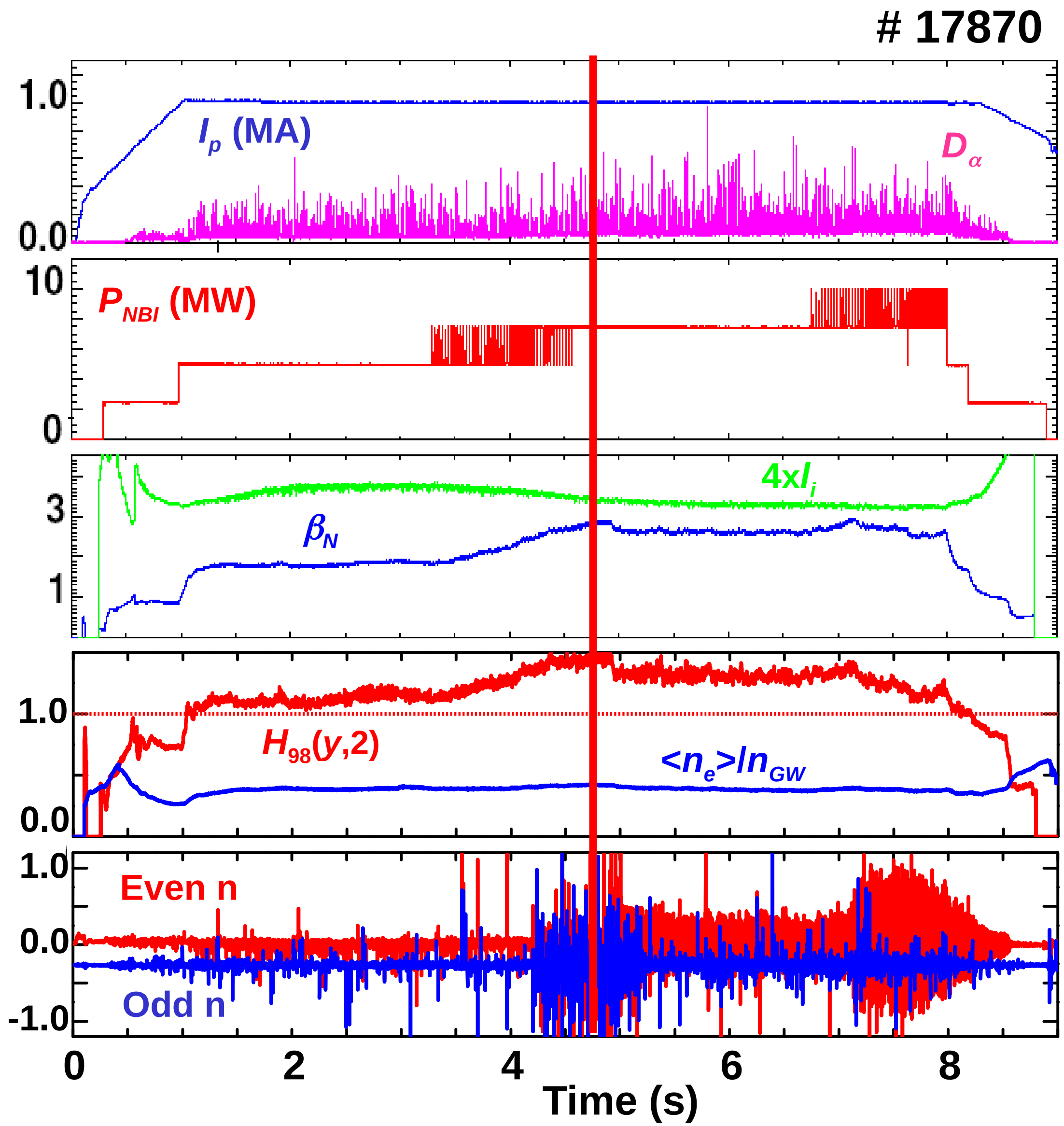


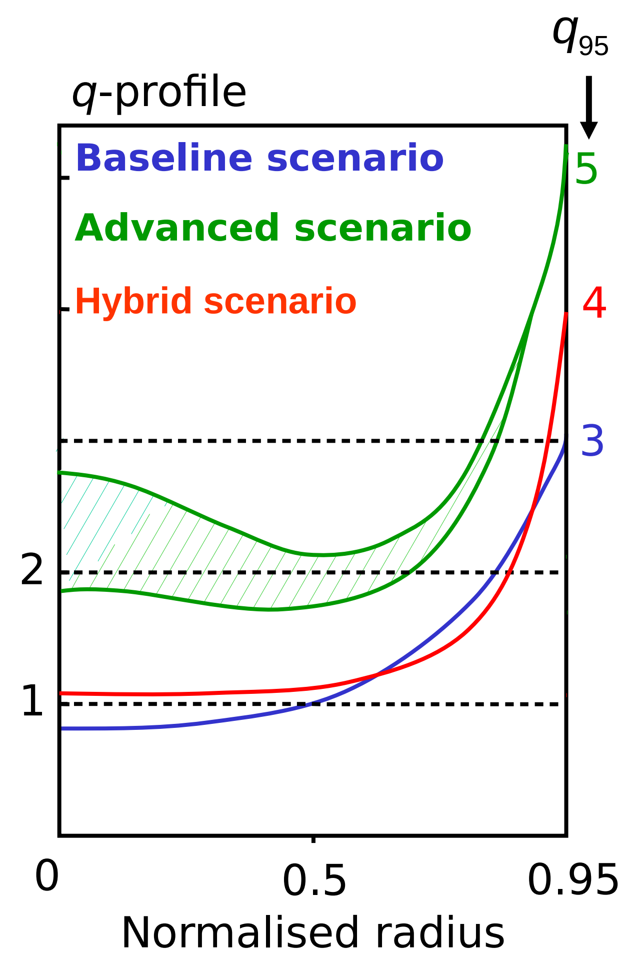


- $H_{98}(y,2) \sim 1.4$
- $\beta_N \sim 2.8$
- $IBS = 34\%$
- $INB = 31\%$

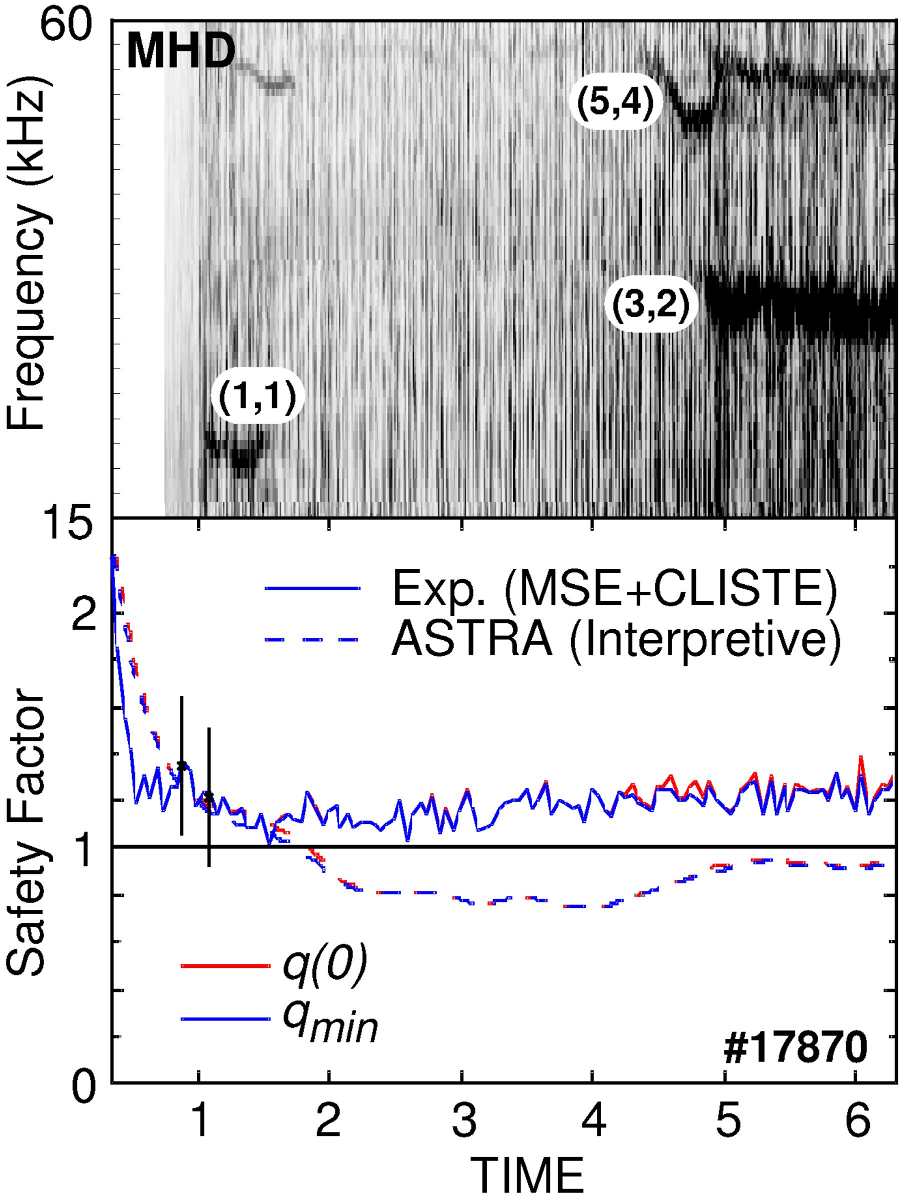
Hybrid Scenario

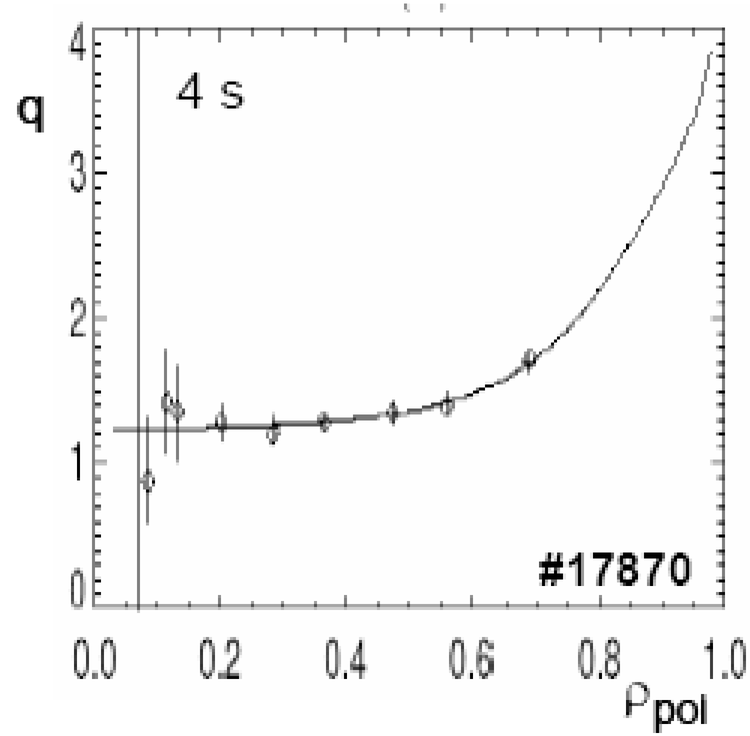
ASDEX Upgrade



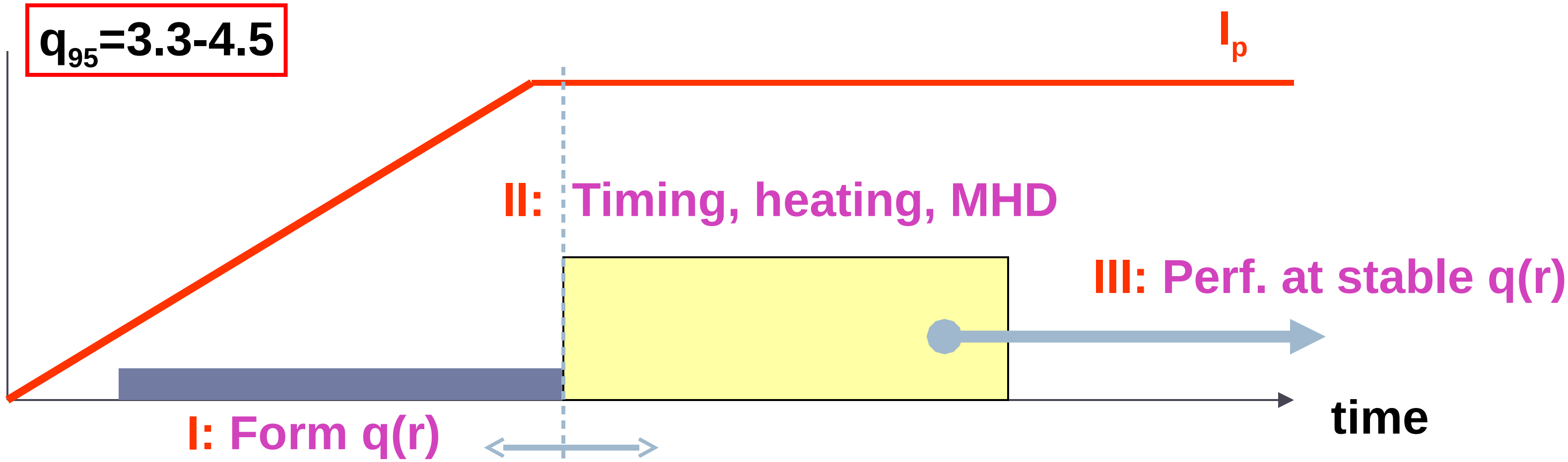


Hybrid Scenario





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.

Presentation Material
By Hyun-Sun Han (SNU/NFRI)

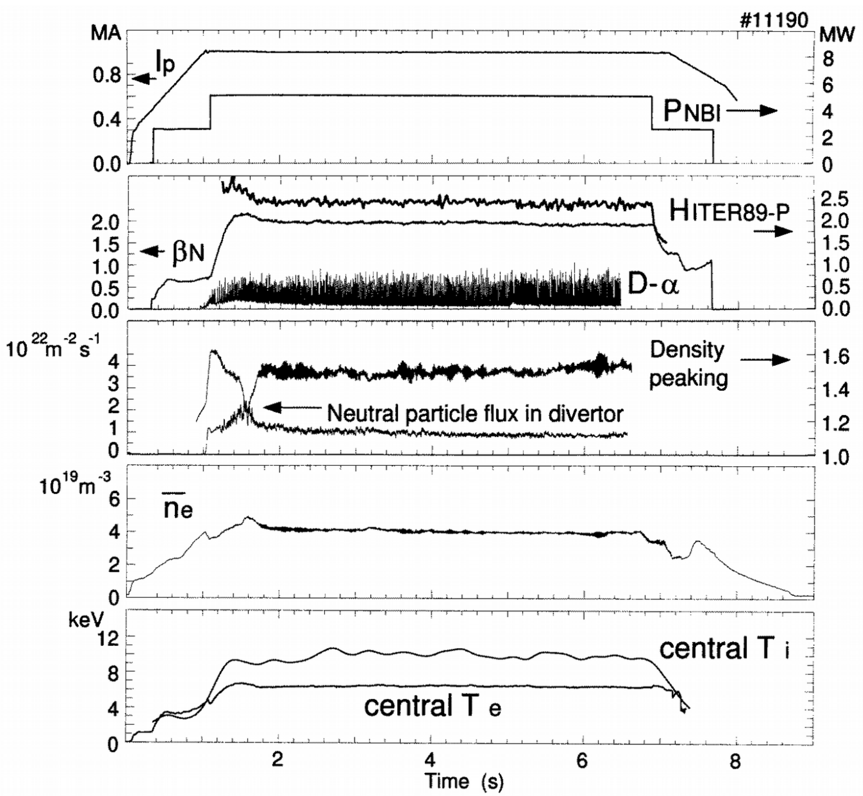
A method to produce Hybrid Scenarios

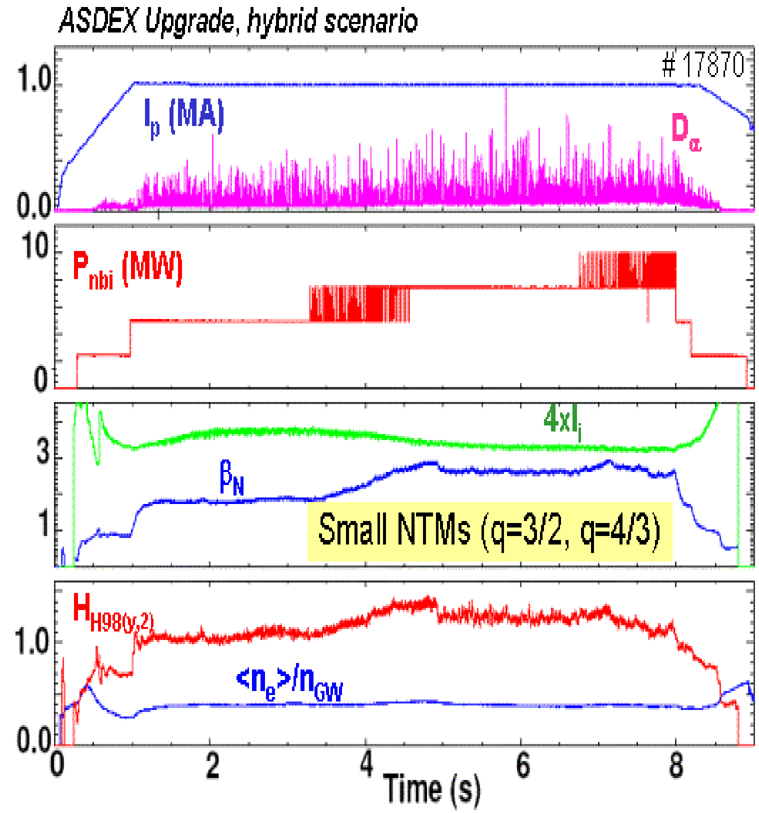
✓ Careful timing of the heating in the plasma current ramp-up phase.

- 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 Upg

ogress for Hybrid Scenario

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



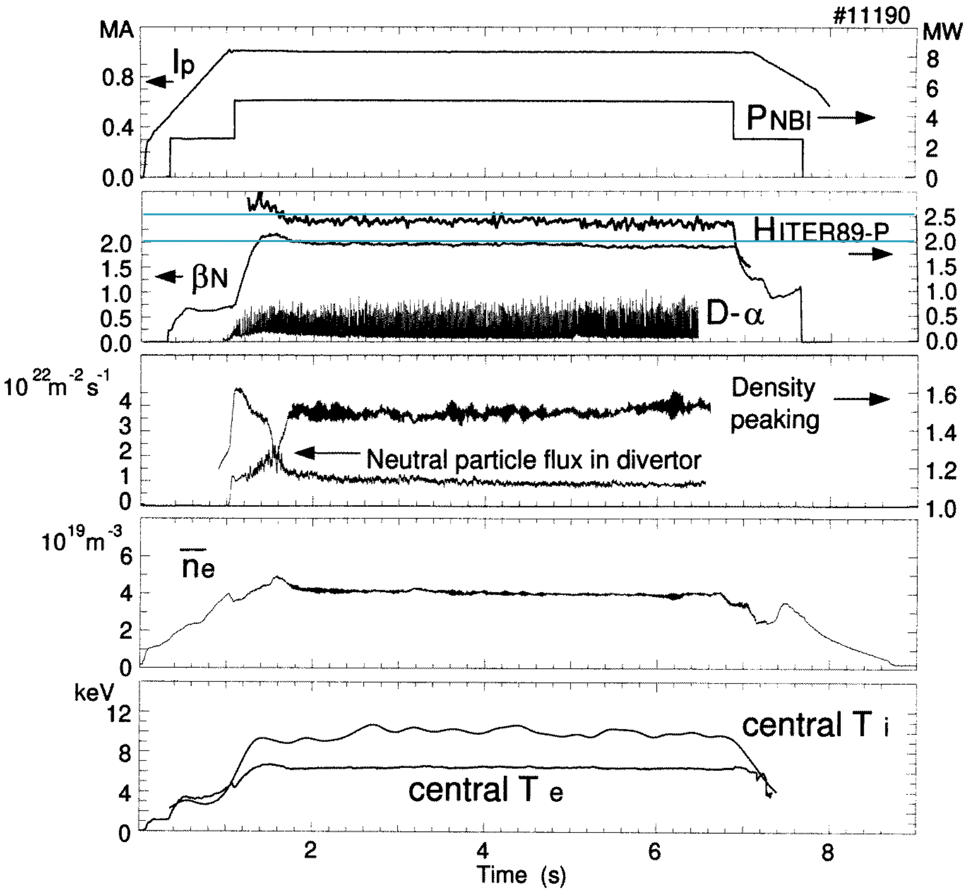


- ✓ Possible to gain high beta to β_N ~ 3 with improvement in confinement
- ✓ Avoiding of the severe MHD activities lead to disruption – Central q is in the vicinity of one.
- ✓ Type-I ELMs are observed in the edge region.

Some example of existing experiments

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

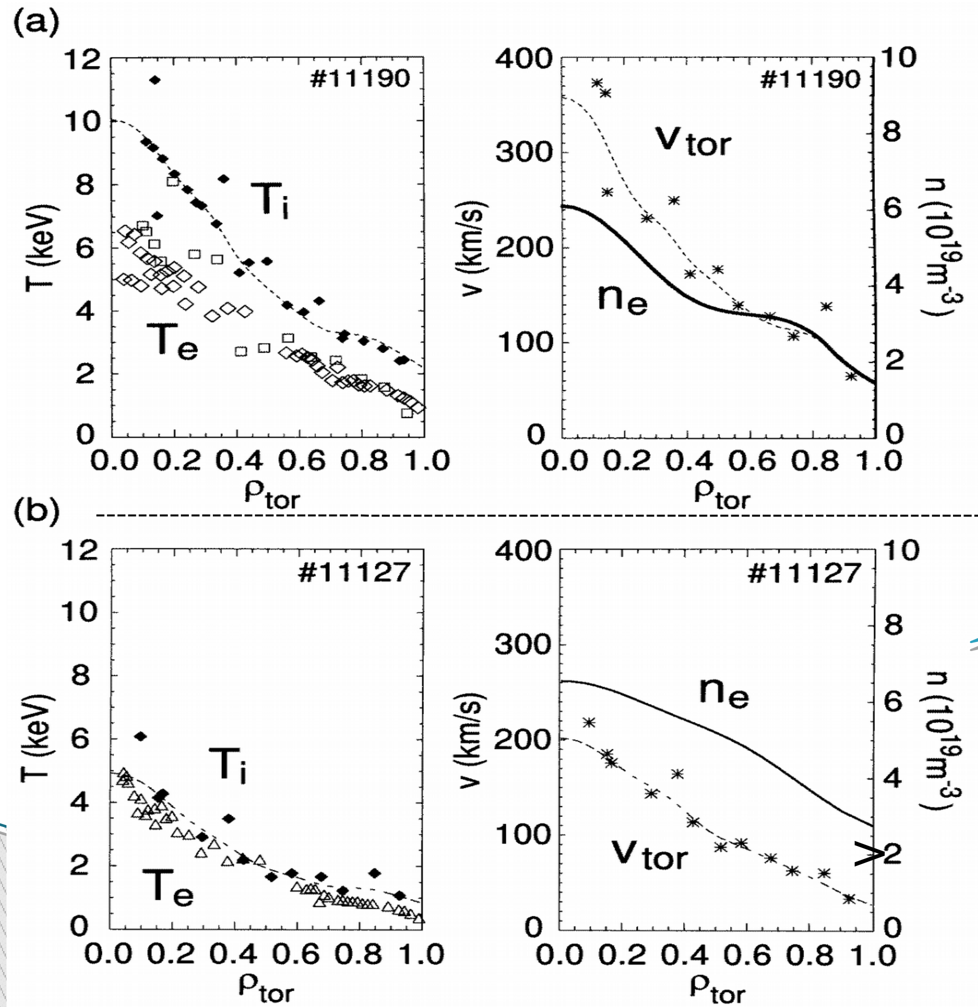
A discovery of stationary regime of operation with improved core confinement with an H-mode edge in AUG (1998)



- ✓ 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 1.1 s and accompany the whole 5 MW heating phase.
- ✓ A typical 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

β_N ~ 2 , $H_{ITER89-P}$ ~ 2.4

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

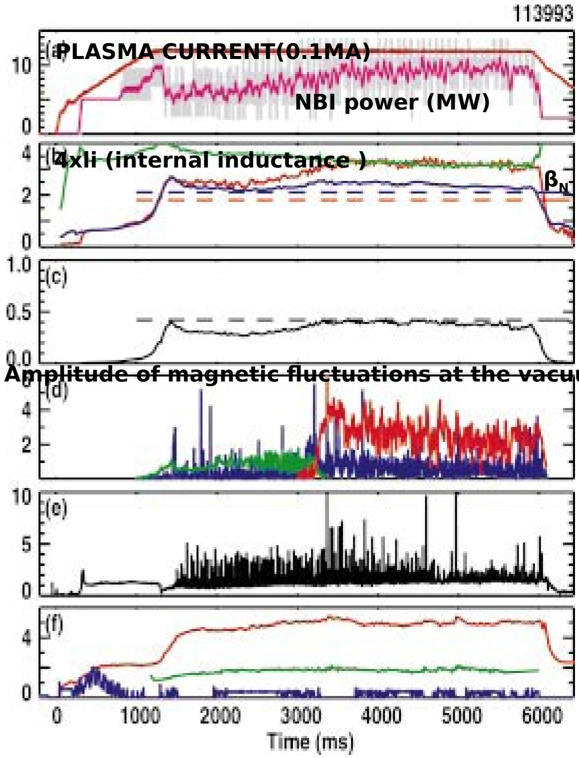
A standard ELMy H-mode

β_N ~ 1.6 , $H_{ITER89-P}$ ~ 1.8

Some example of existing experiments

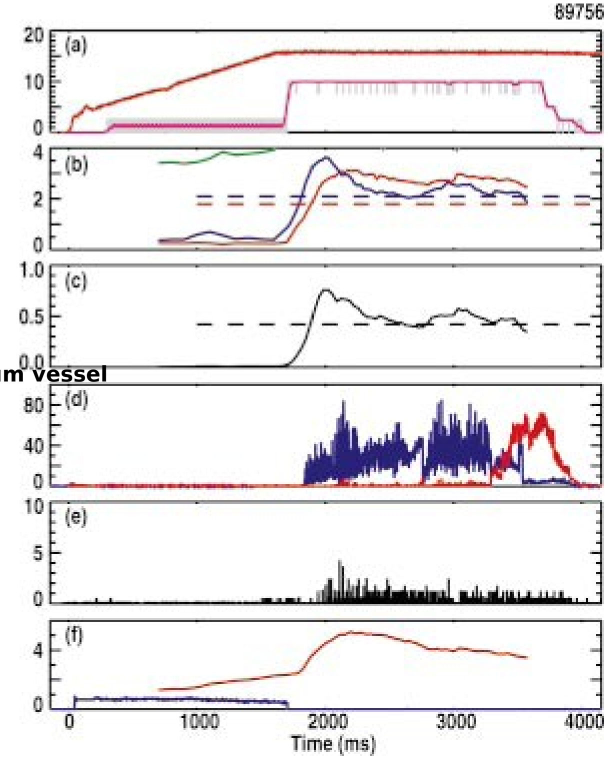
DIII-D

$q_{95} > 4$ without sawteeth



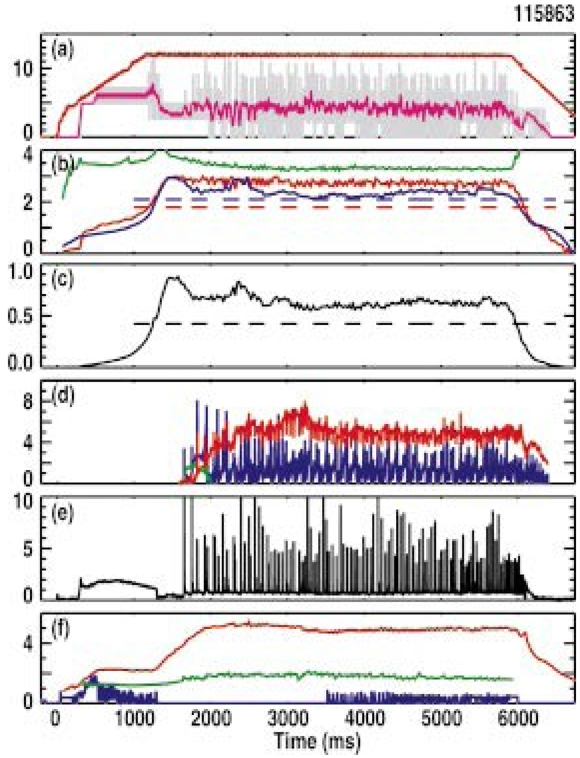
limited by tearing modes

$q_{95} = 3.6$ without sawteeth



limited by fishbones

$q_{95} = 3.2, \beta_N = 2.7, H_{89P} = 2.3$



limited by sawteeth

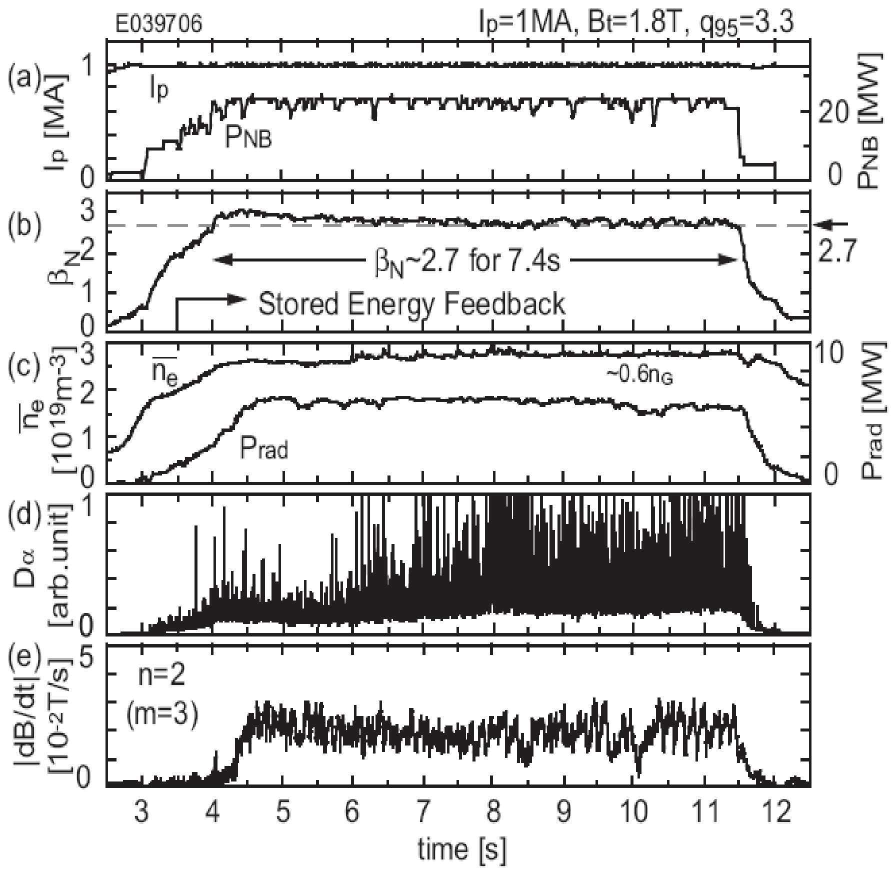
- ✓ *These discharges are a generic class of operations for tokamak hybrid mode.*

Some example of existing experiments

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

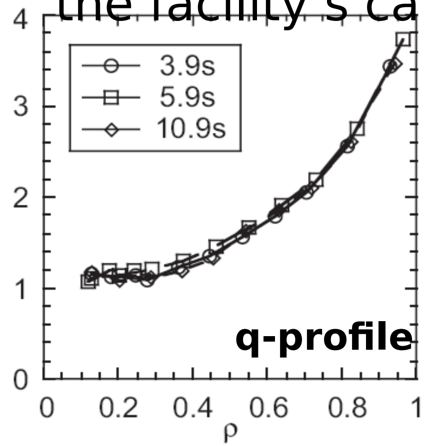
With upgraded systems since 2000 :

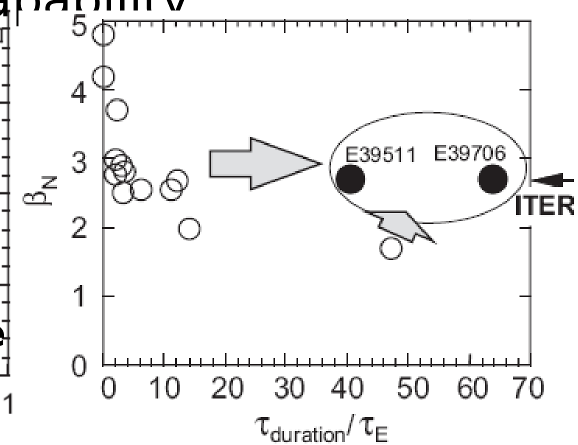
Poloidal field coil, NBI system, EC wave injection system and pellet injection system are upgraded



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

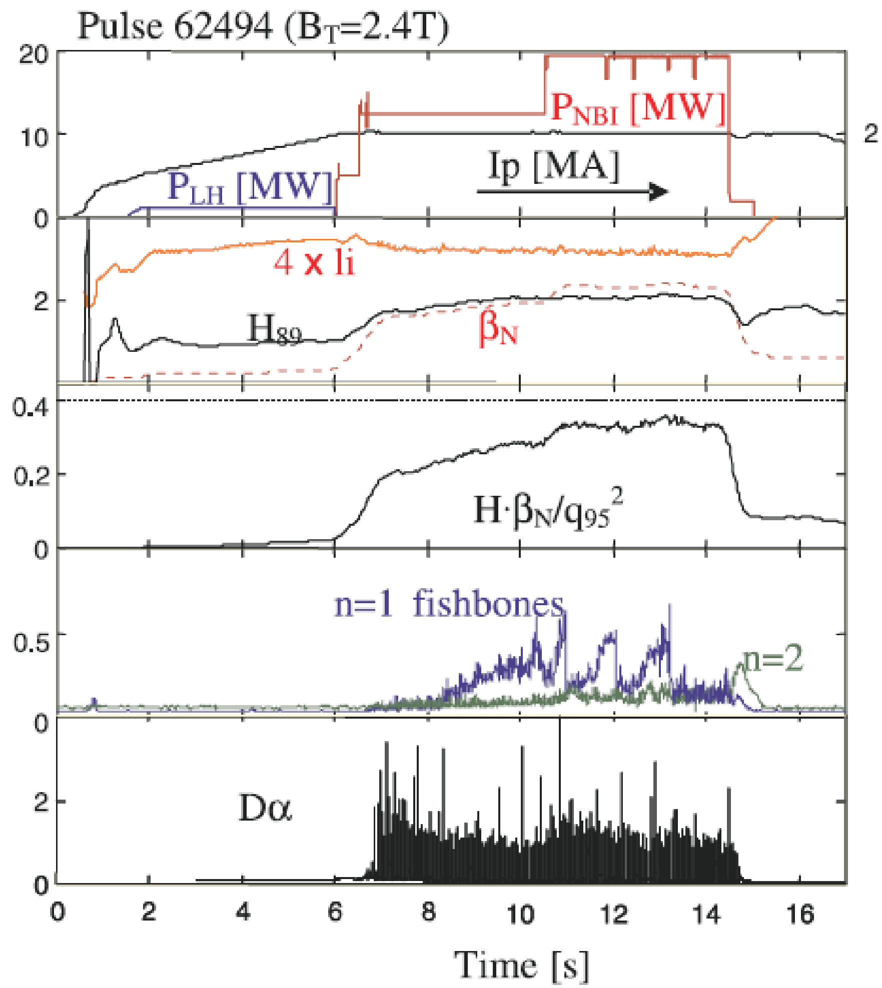
The duration time of high-beta extends to ~60τ_e, which is limited by the facility’s capability



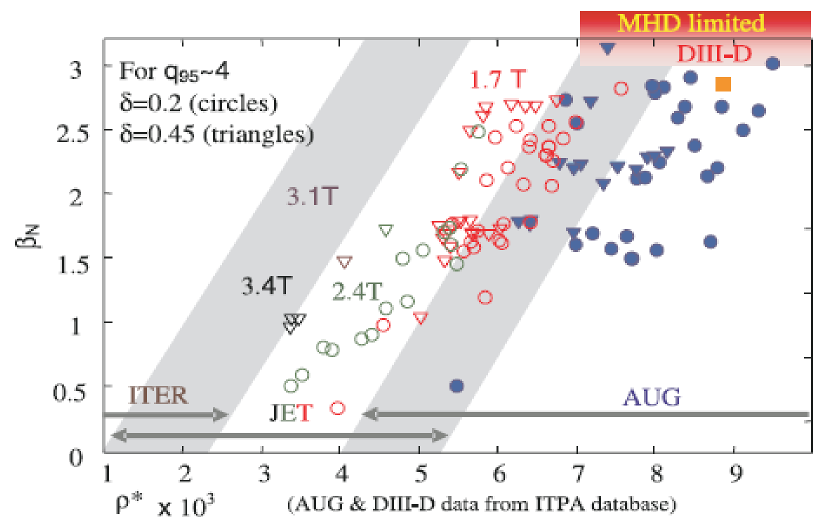


Some example of existing experiments JET(1)

<u>Reproducing the ASDEX-U hybrid regime has been achieved.</u>

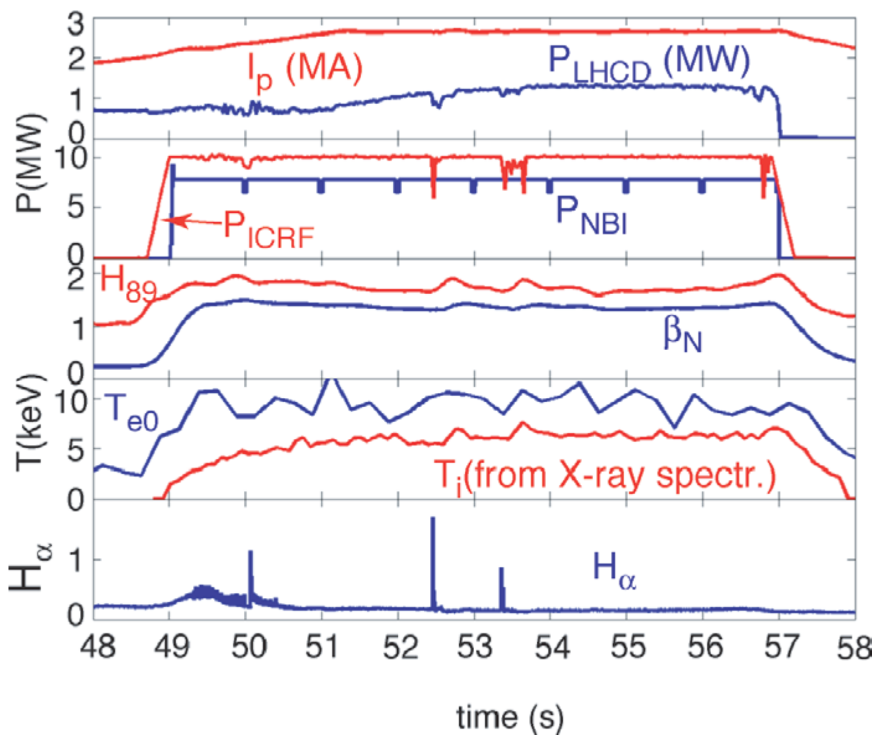


- ITER like magnetic configuration with B_T = 2.4T has been adopted (decreasing the normalized Larmor radius, ρ*)
- Electron density and temperature profiles are similar in shape to those observed in hybrid ASDEX-U discharges



Some example of existing experiments
JET(2)

RF-dominated hybrid scenarios has been examined in JET



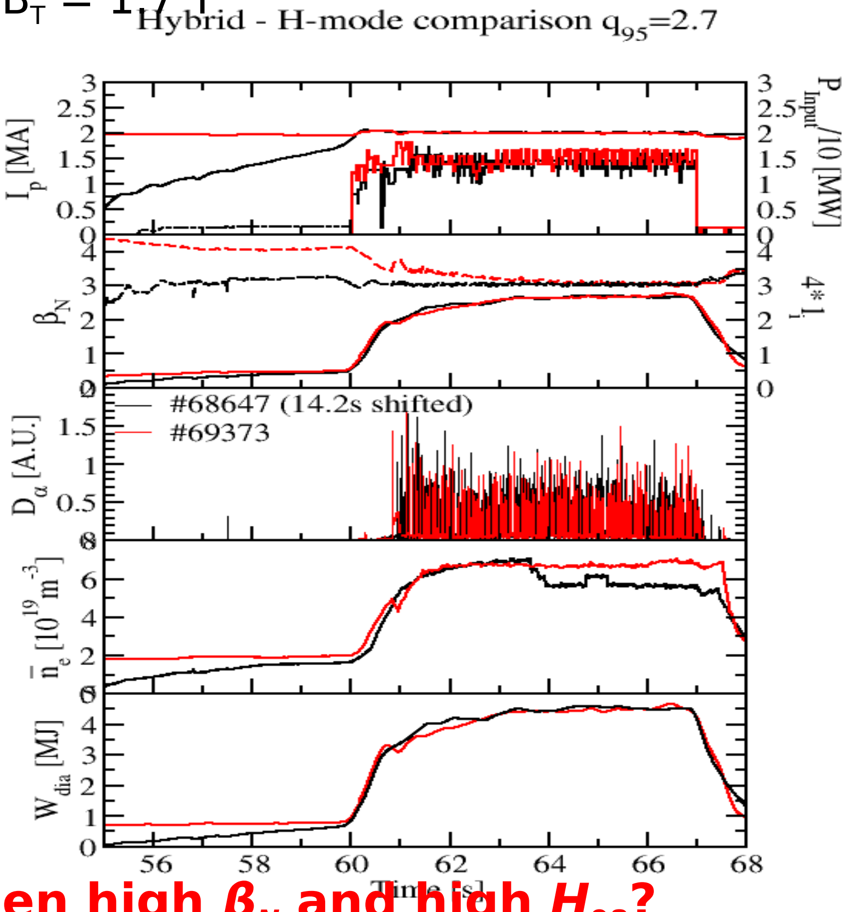
- Soft MHD events typical of a hybrid discharge have been observed
- Several RF-only scenarios from various machines (TS, FTU, TCV) with low magnetic shear belong to the same 'family' with improved confinement and 'soft' MHD, although the current profiles would need to be adjusted to have a better match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

Some example of existing experiments JET(3)

Comparison between baseline and hybrid operation in JET

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

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

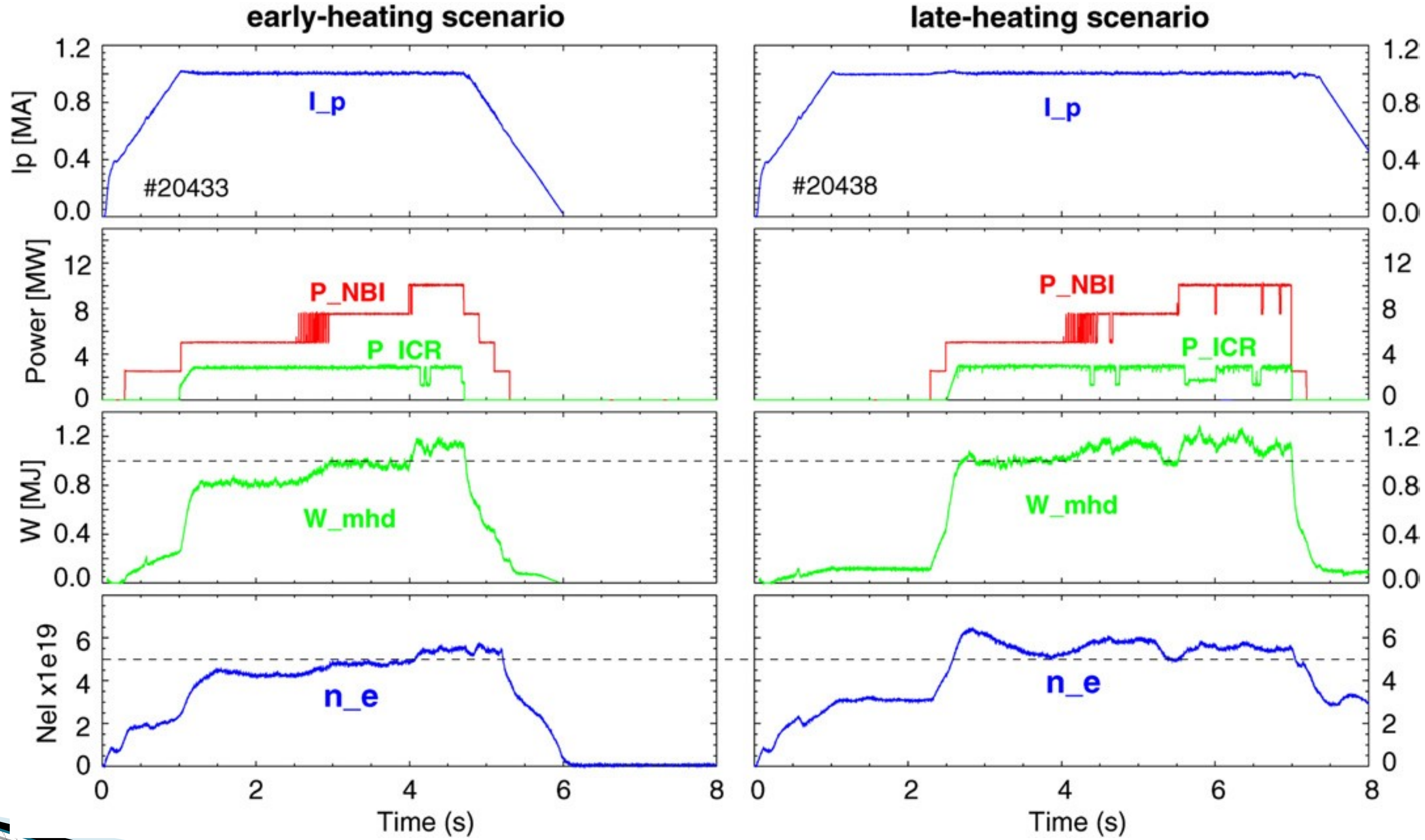


The baseline and hybrid sce-nario are not showing any dif -ference !!

HW. What is the difference between high β_N and high H_{98}?

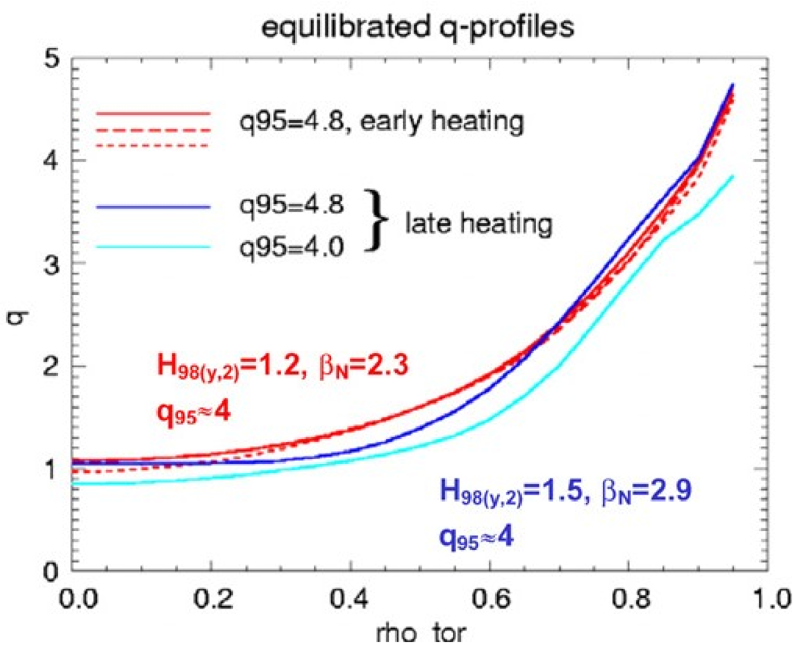
Some example with improved operating scheme ASDEX-U(1)

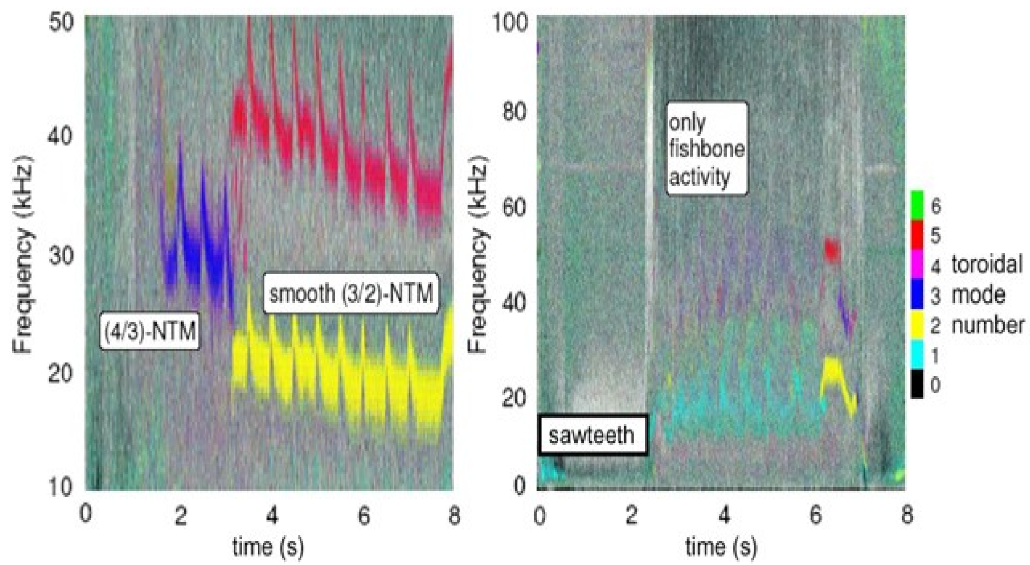
✓ Improved H-modes have also been obtained with 'late' additional heating well in the current flattop which partly show even better performance



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.

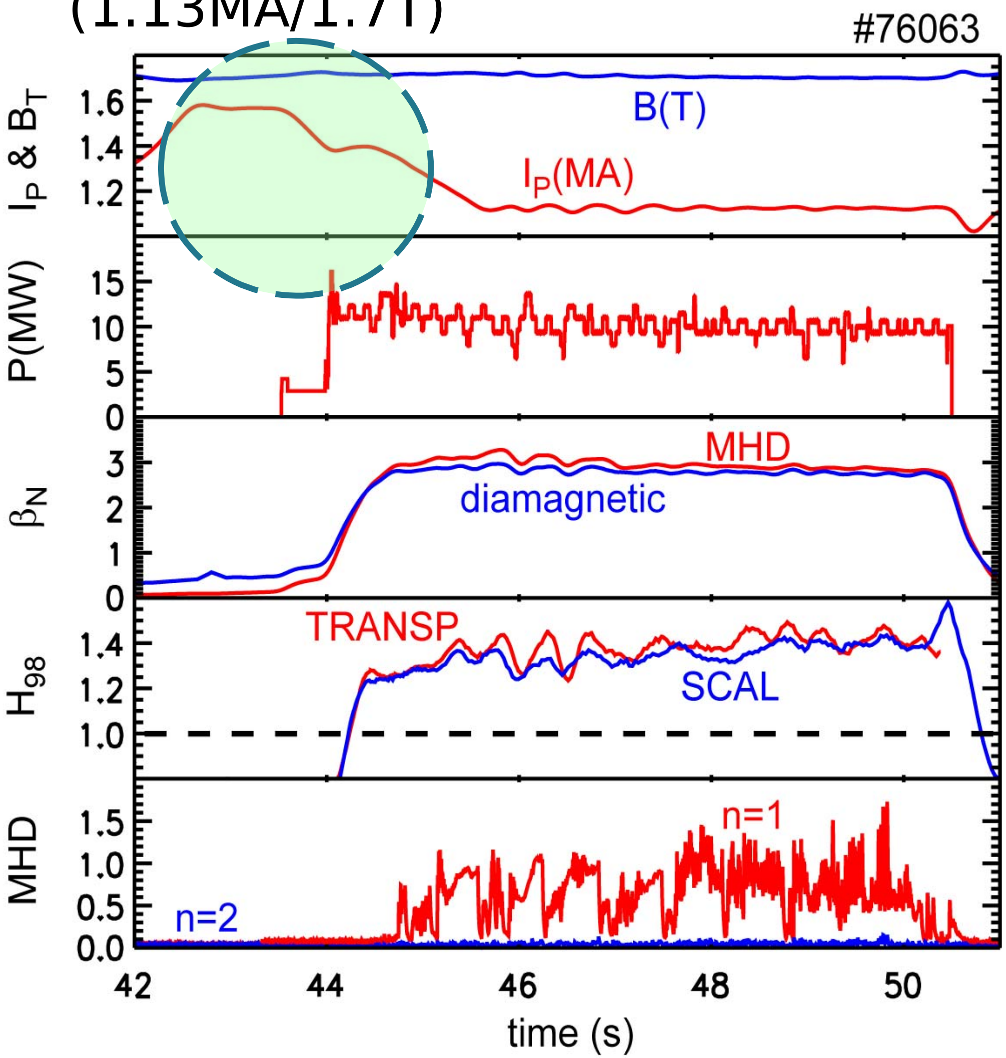




early heating late heating

Some example with improved operating scheme JET(1)

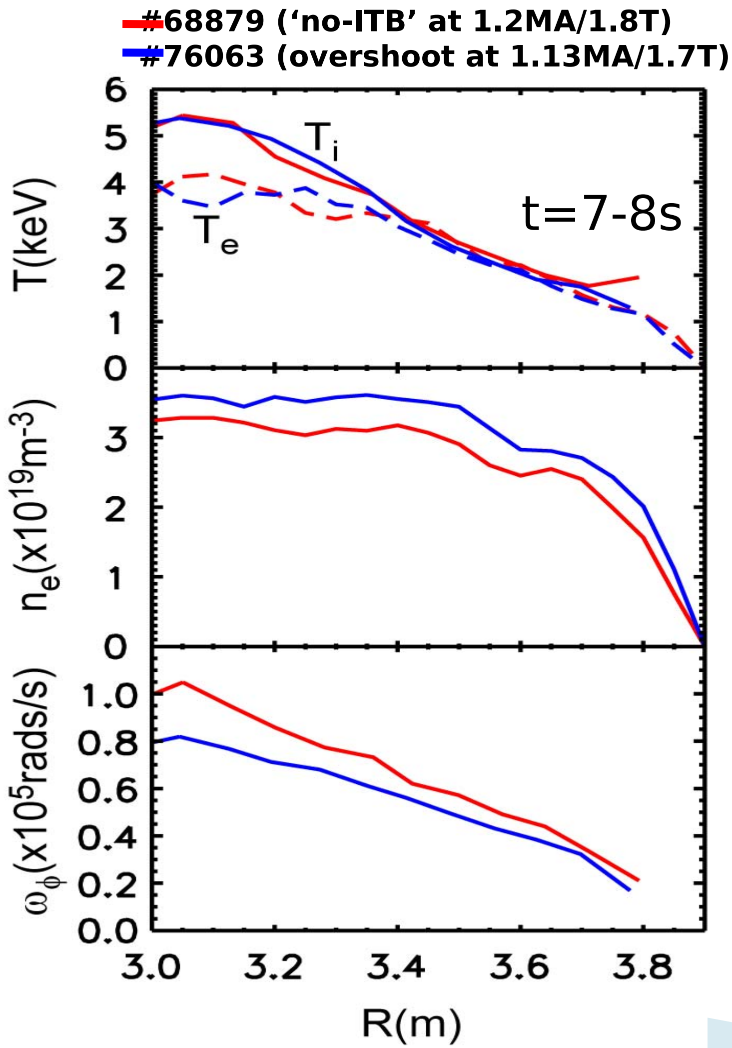
✓ Reference pulse of current overshoot scenario obtained at $q_{95}\approx5$ (1.13MA/1.7T)



- Parameters achieved:
  - $H_{98} \approx 1.4$
  - $\beta_N \approx 2.8$
  - $l_i \approx 0.75$
  - $\delta \approx 0.39$
  - $n/n_G \approx 65\%$
  - $W_{th}/W_{dia} \approx 75\%$
  - $\tau_R \approx 5s$
  - $q_{min} \approx 1$ (fishbones & sawteeth)
  - No significant 3/2 or 2/1 activity

Some example with improved operating scheme JET(2)

omparison with 1.8 T 'no-ITBs' on temperature and density profil

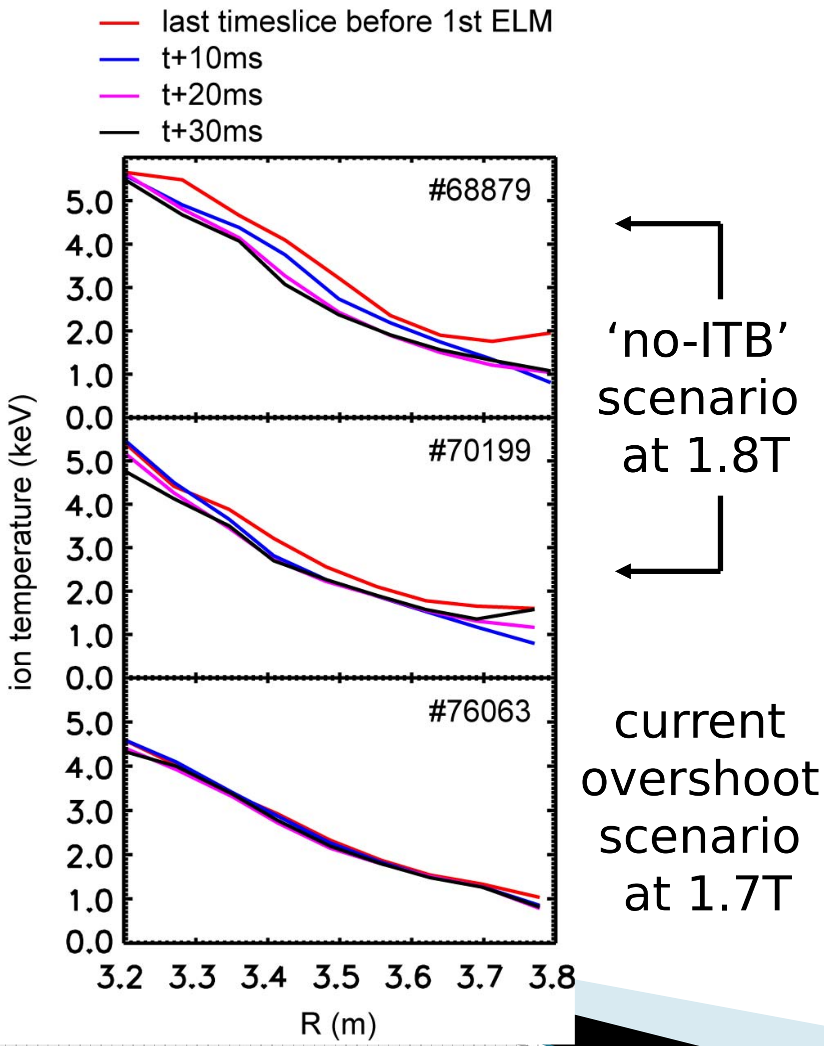


- Comparison with 'no-ITB' regime at similar power (lower β_N) suggests confinement improvement in #76063 comes from increased density, despite lower rotation.

- Confinement improvement appears to be mainly from edge.

Some example with improved operating scheme JET(3)

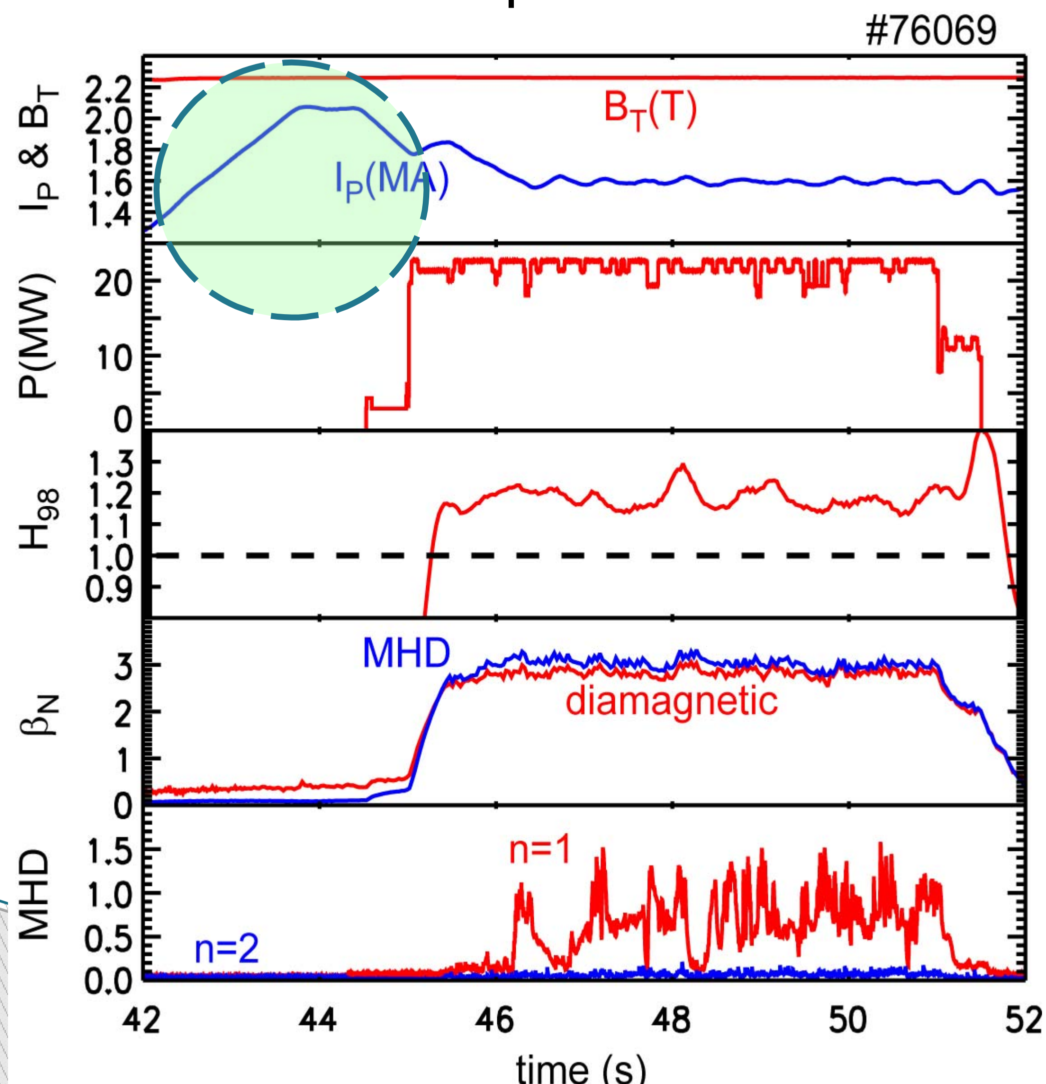
omparison with 1.8 T ‘no-ITBs’ on ion temperature evolutions to I



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

Some example with improved operating scheme JET(4)

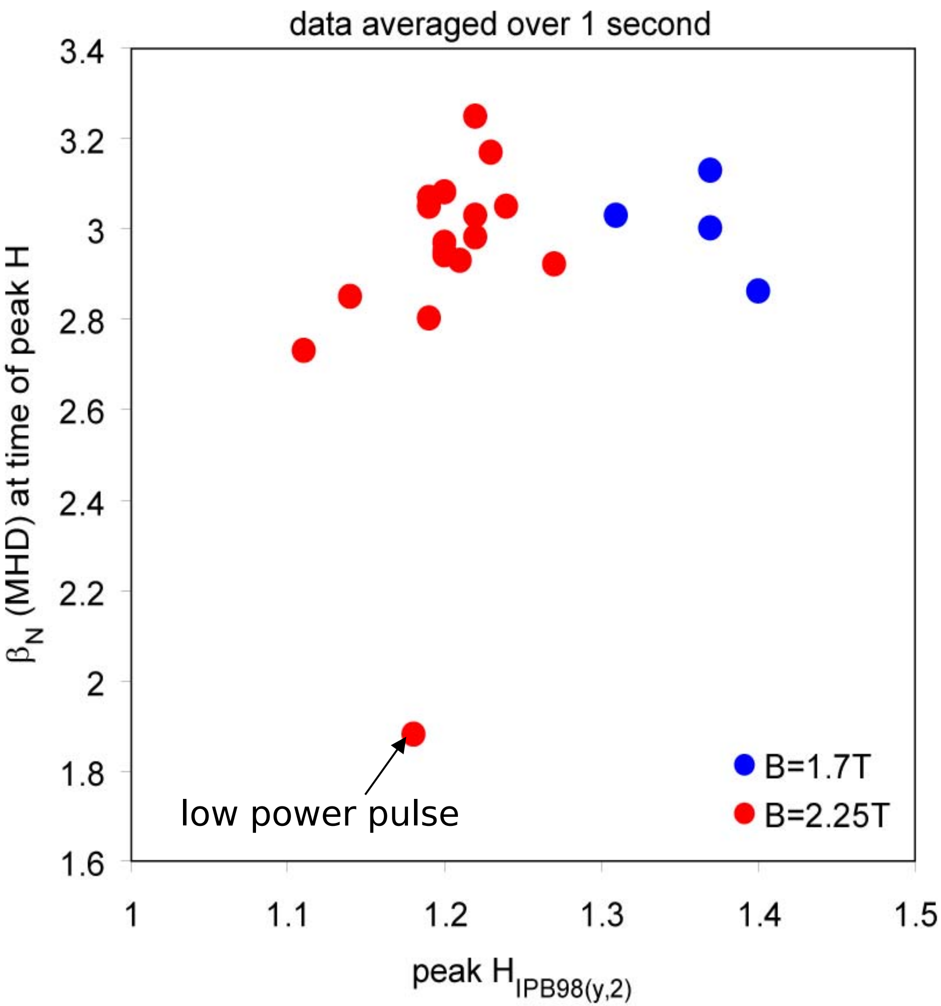
✓ Overshoot technique at 2.25 T



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

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

Some example with improved operating scheme JET(5)



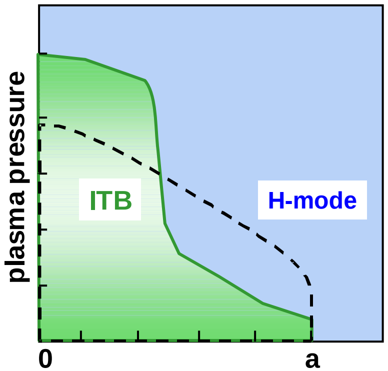
- At 1.7 T: H_{98} = 1.3-1.4 achieved at $q_{95} \approx$ 4.3-5.0 with $\beta_N \approx 3$ using hybrid current over-shoot technique
- At 2.25 T: H_{98} = 1.2 achieved at q_{95} = 4.7-5.0 with $\beta_N \approx 3$ with and without overshoot

Fusion Reactor Technology 2
(459.761, 3 Credits)

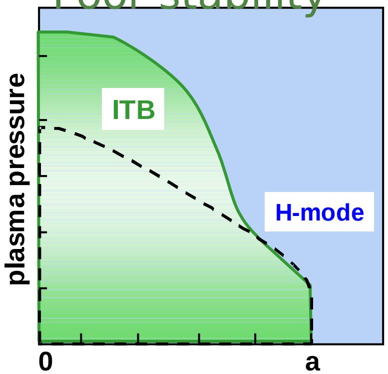
Prof. Dr. Yong-Su Na

(32-206, Tel. 880-7204)

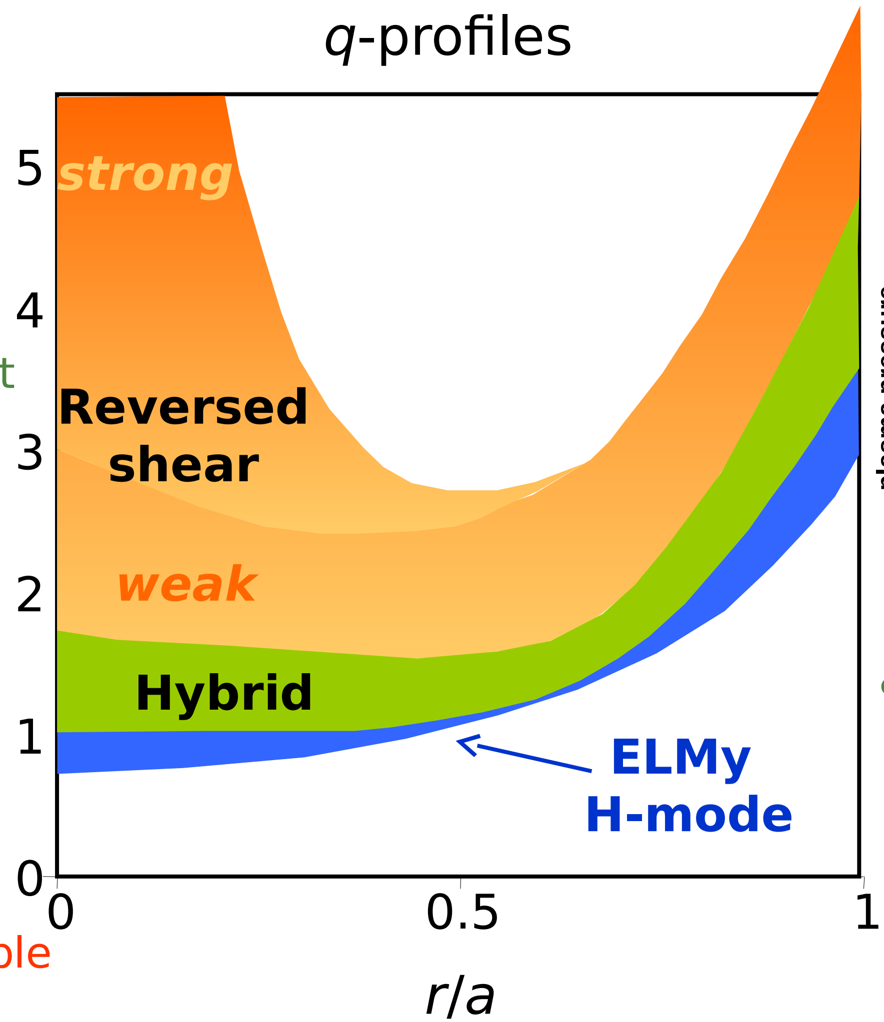
Tokamak Operation Scenario

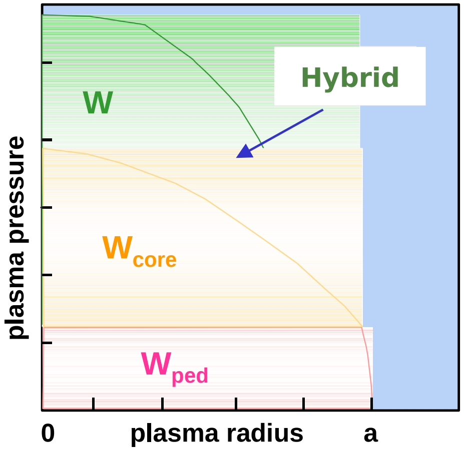


- Good confinement
- Poor stability



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





- Good confinement

together with high stability w/o active control

Physics issues for hybrid scenarios

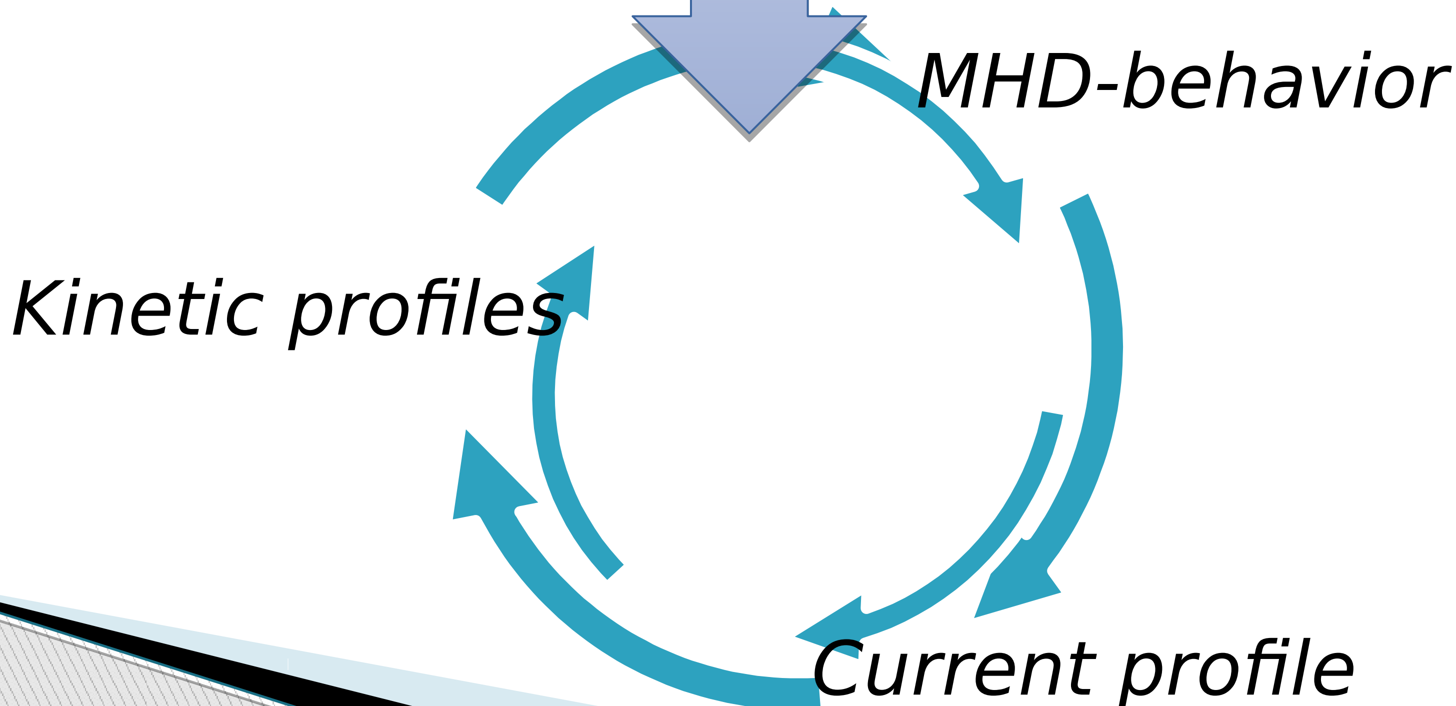
- Steadiness of the current profile
- Confinement enhancement
- Physics effects limiting β_N
- Impurity transport
- Role of ρ^*
- ...

Normalized Larmor radius which has a significant impact on drift turbulence,

Factors to affect plasma confine-ment

Several mechanisms seem to play a role :

1) Effect of H-mode pedestal pressure
2) Effect of plasma rotation
3) The variation of the ratio magnetic shear(s) to safety factor(q)
4) Effect of fast particle
5) Effect of β_e

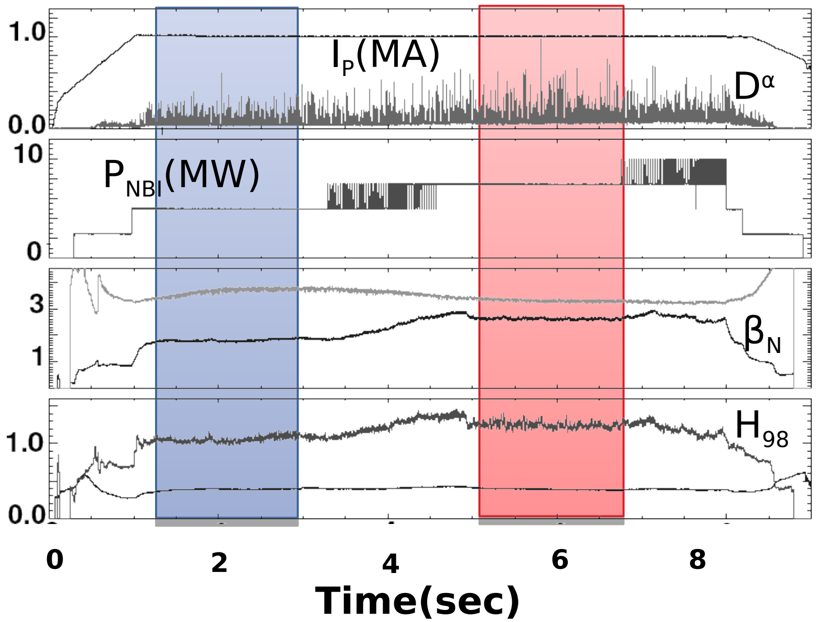


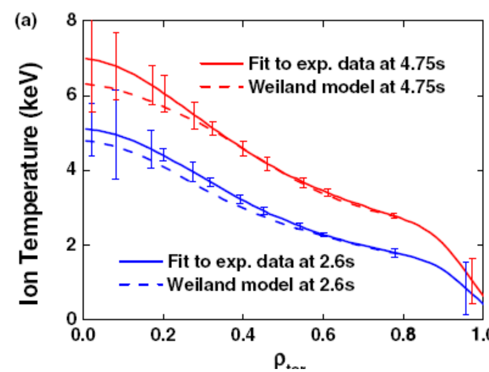
Attempts to solve physics issues related to confinement

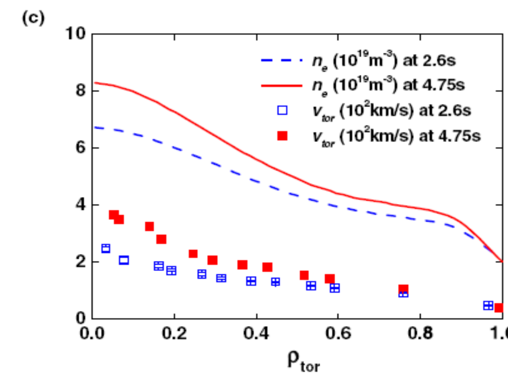
Role of Pedestal in Hybrid Performance(0)

ASDEX-U, #17870

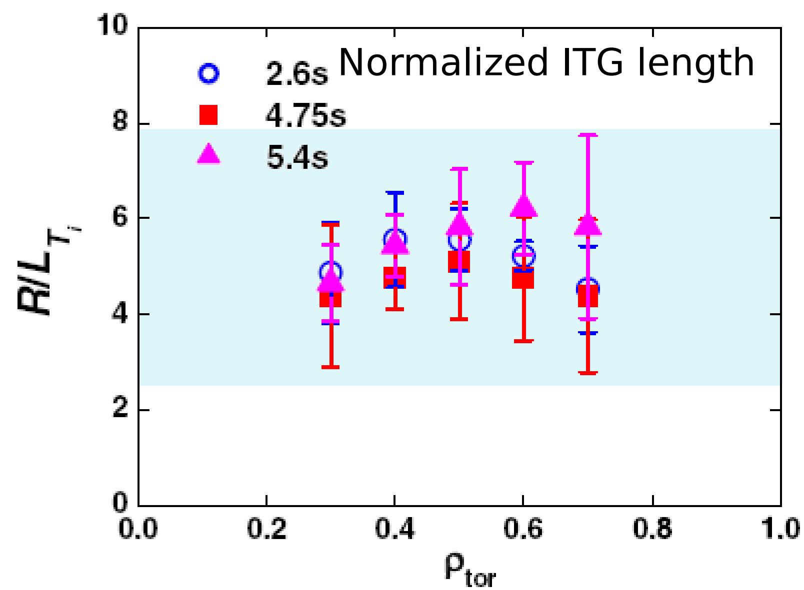
Lower heating phase **Improved H-mode phase**



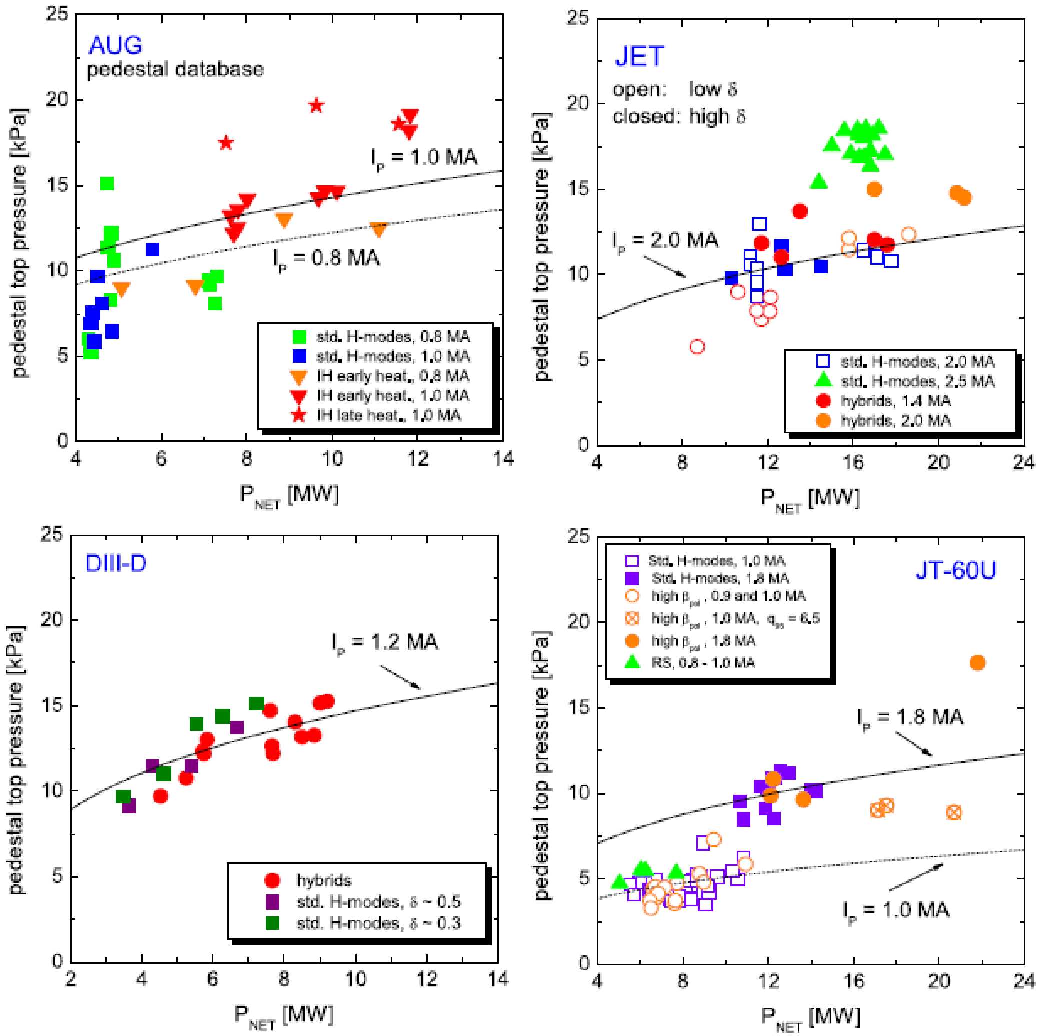




- ✓ Both phase are still governed by drift-wave turbulence as in standard H-modes
- ✓ No difference is found in the behavior of turbulence in the confinement region of the plasma between two phase from the results of the analysis of phase fluctuations.



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

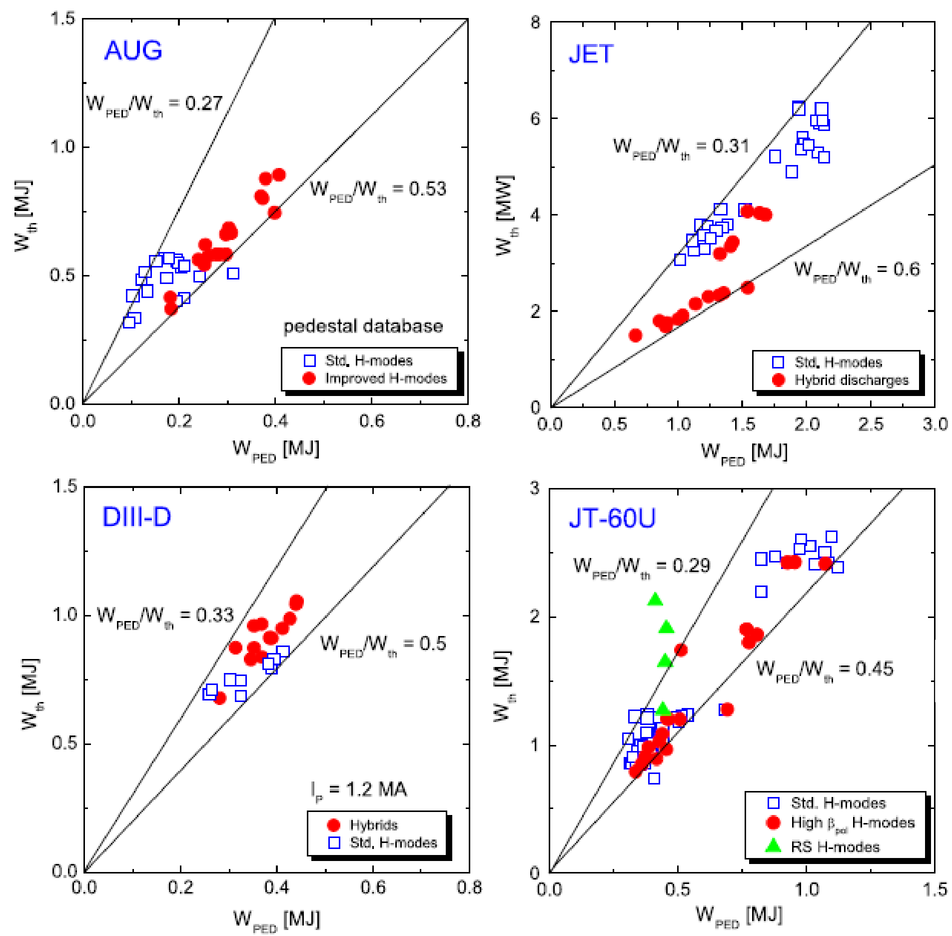


✓Pedestal top pressure seems to increase moderately with power.

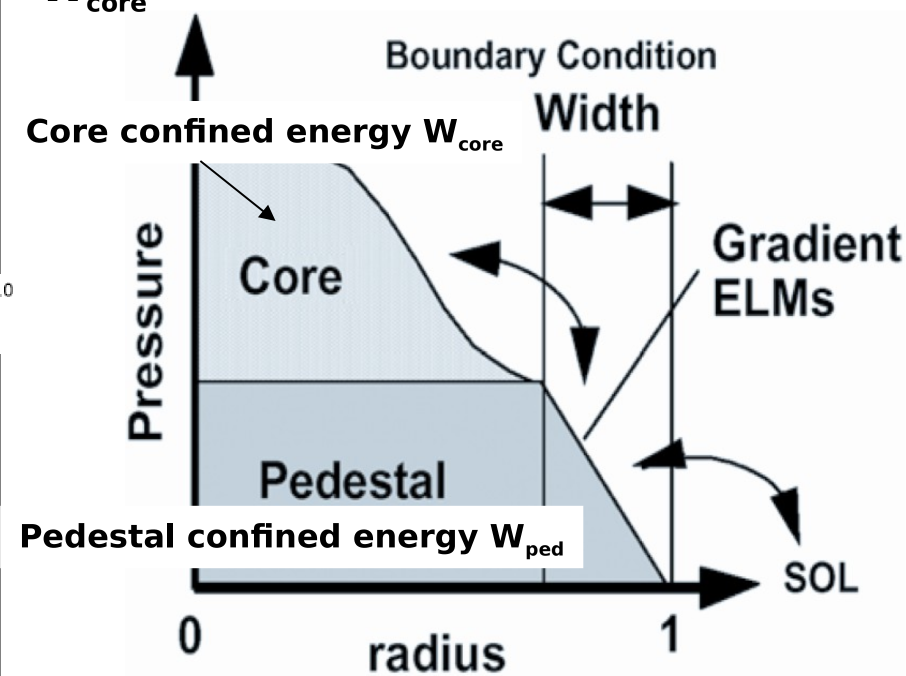
✓Higher pedestal pressures are observed in improved confinement scenarios?

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, $W_{th} = W_{ped} + W_{core}$

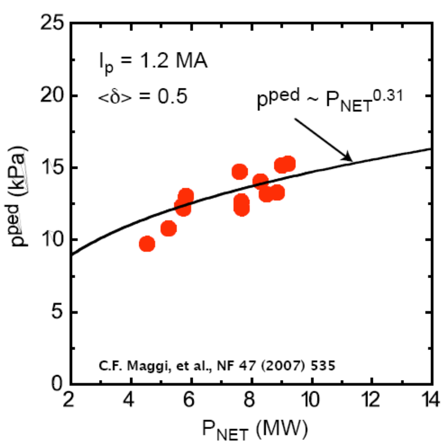


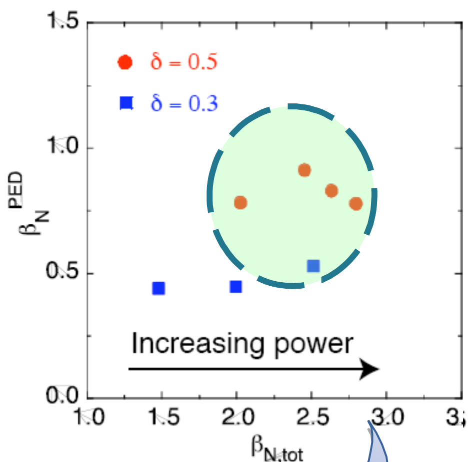
Attempts to solve physics issues related to confinement

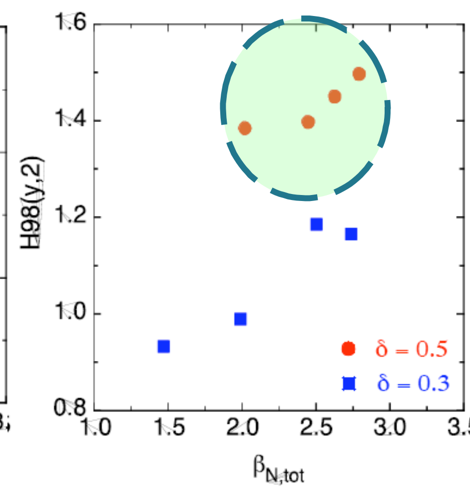
Role of Pedestal in Hybrid Performance(1)

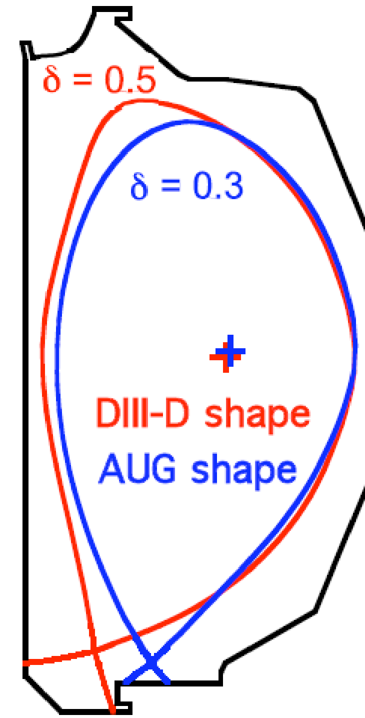
✓ Initial survey showed that
"There is a trend for pedestal pressure to increase with heating power."

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







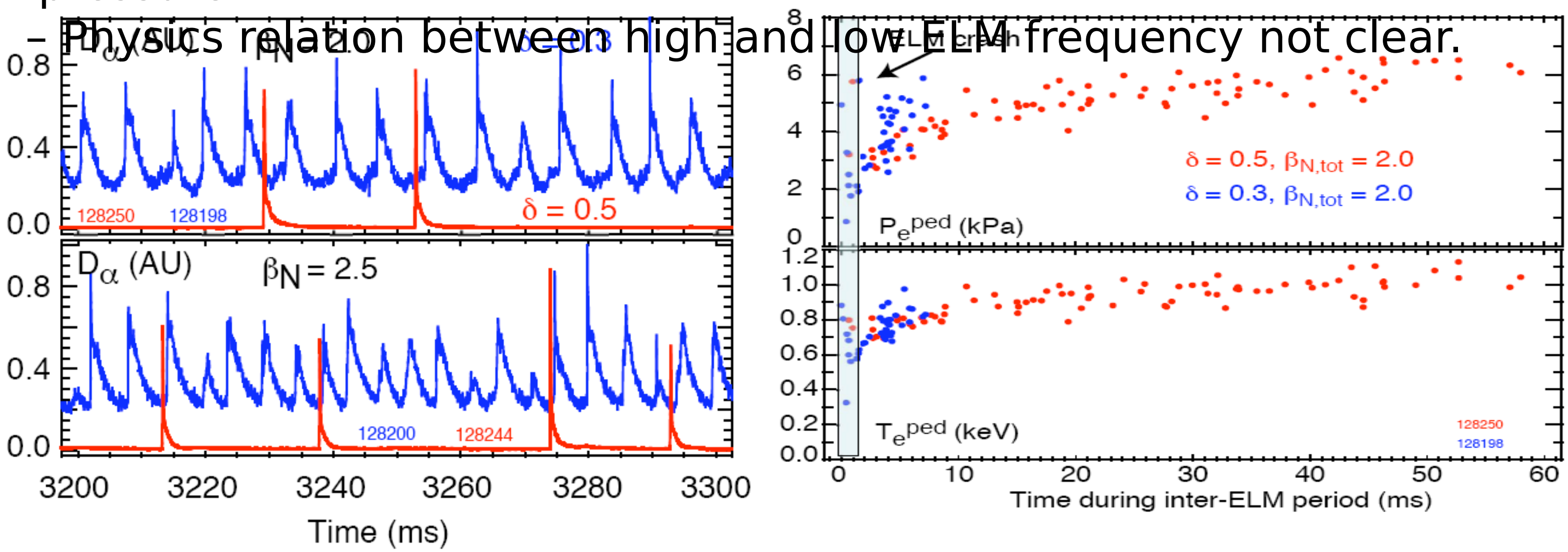


✓ Hybrids exhibit some confinement enhancements which cannot be attributed to pedestal
: Core stored energy can increase even when pedestal pressure does not increase with increased power

Attempts to solve physics issues related to confinement

Role of Pedestal in Hybrid Performance(2)

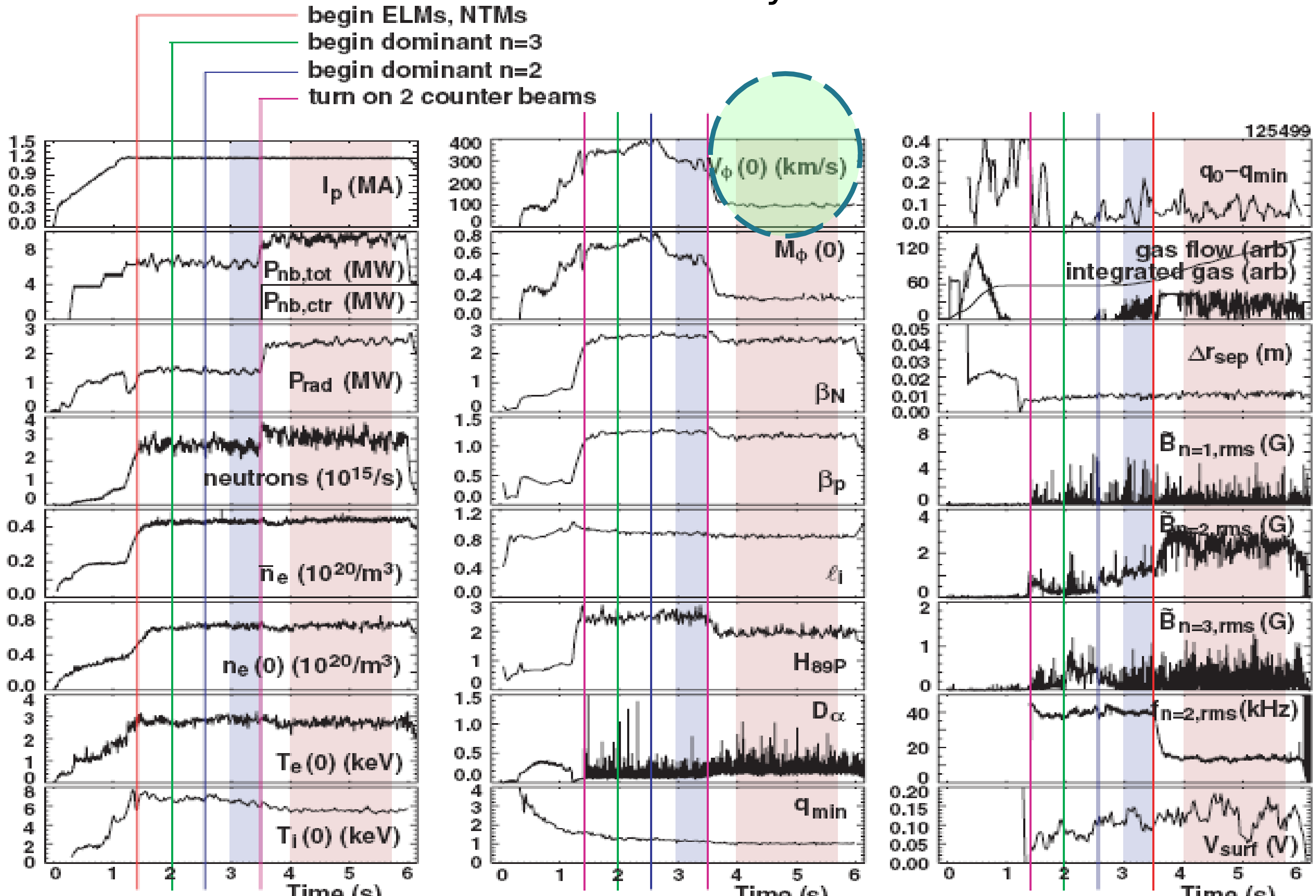
- ✓ Higher pedestals are correlated with lower ELM frequencies.
  - – Lower ELM frequency may allow more complete recovery of pedestal after an ELM and thus higher time-averaged pedestal pressure.
  - – Physics relation between high and low ELM frequency not clear.



Attempts to solve physics issues related to confinement

Influence of toroidal rotation(1)

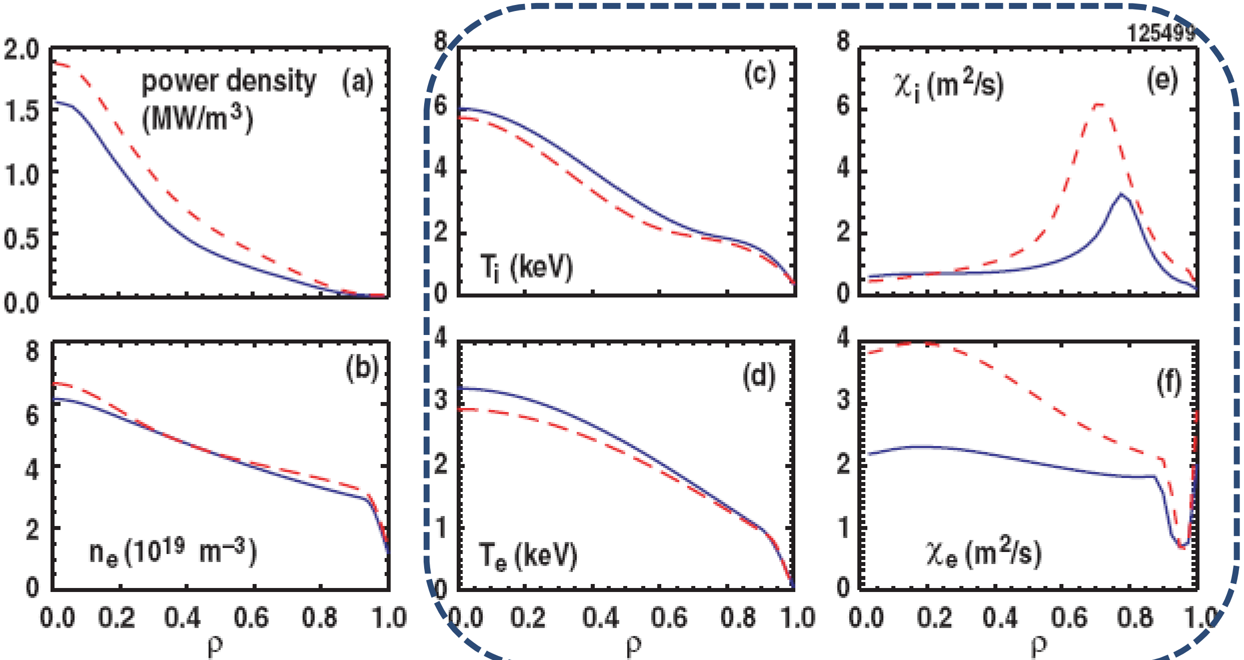
Experiment in DIII-D with co- & counter NBI system

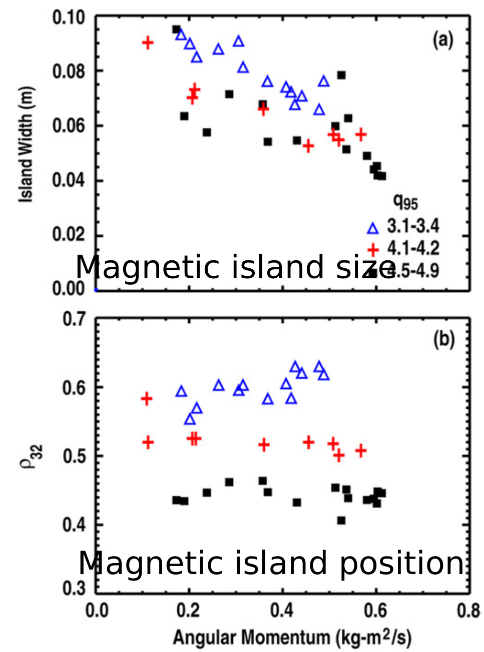


Attempts to solve physics issues related to confinement

Influence of toroidal rotation(2)

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



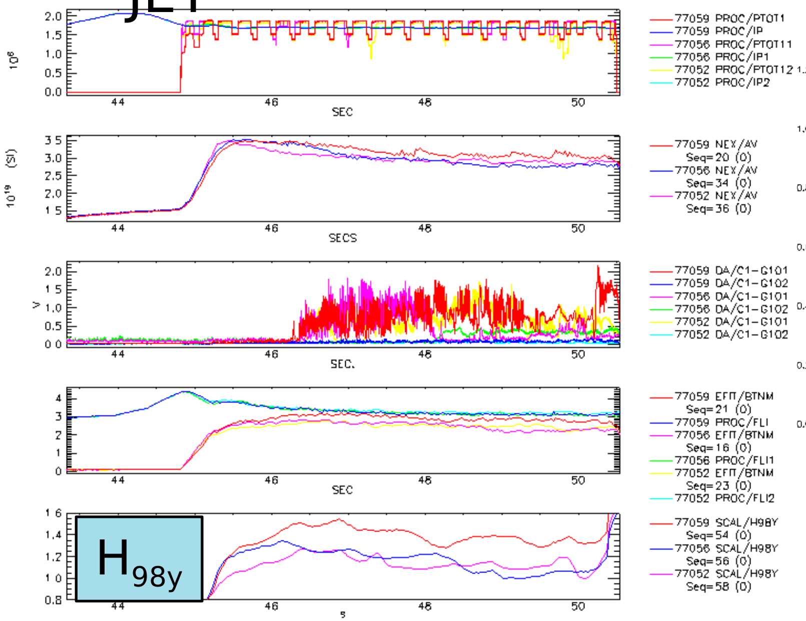


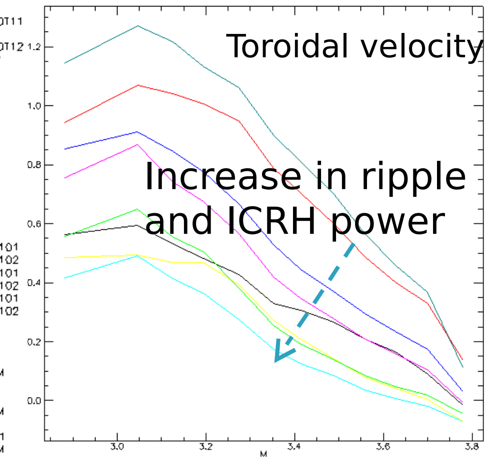
- Although energy confinement decreases and the m/n=3/2 NTM amplitude increases for low rotation speed, the fusion performance figure of merit still exceeds the value required on ITER for Q=10.

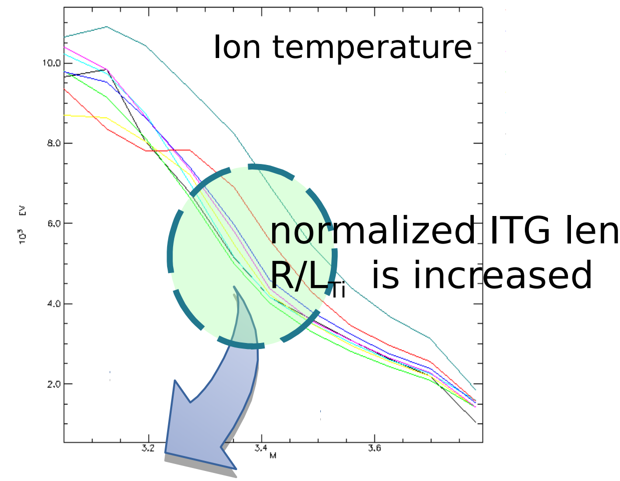
Attempts to solve physics issues related to confinement

Influence of toroidal rotation(3)

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







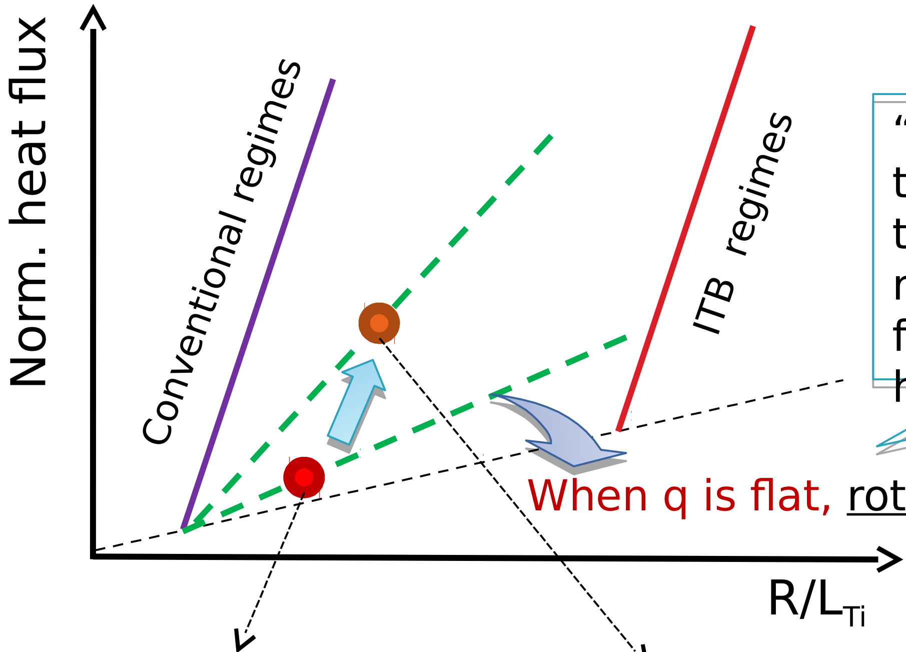
"Ion temperature gradient increases at 3.4m, partially compensating for loss at the edge"

- 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."

When q is flat, rotation reduces stiffness

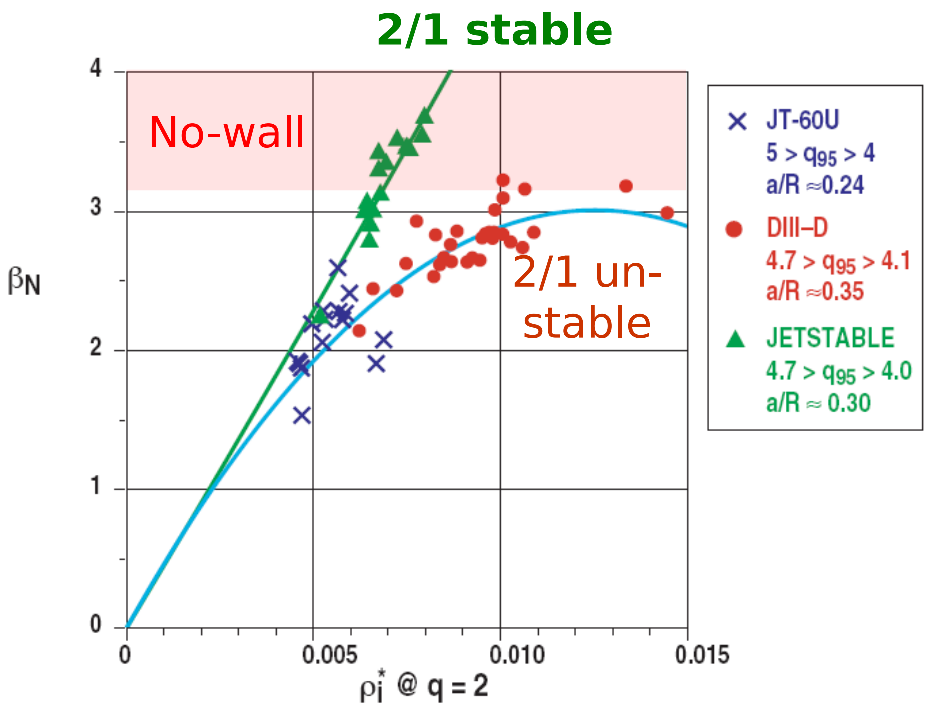
No ripple, higher rotation, low stiffness,
higher pedestal(lower heat flux)

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

Fast particle effects on the stability limits

JET stable to 2/1 not DIII-D

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



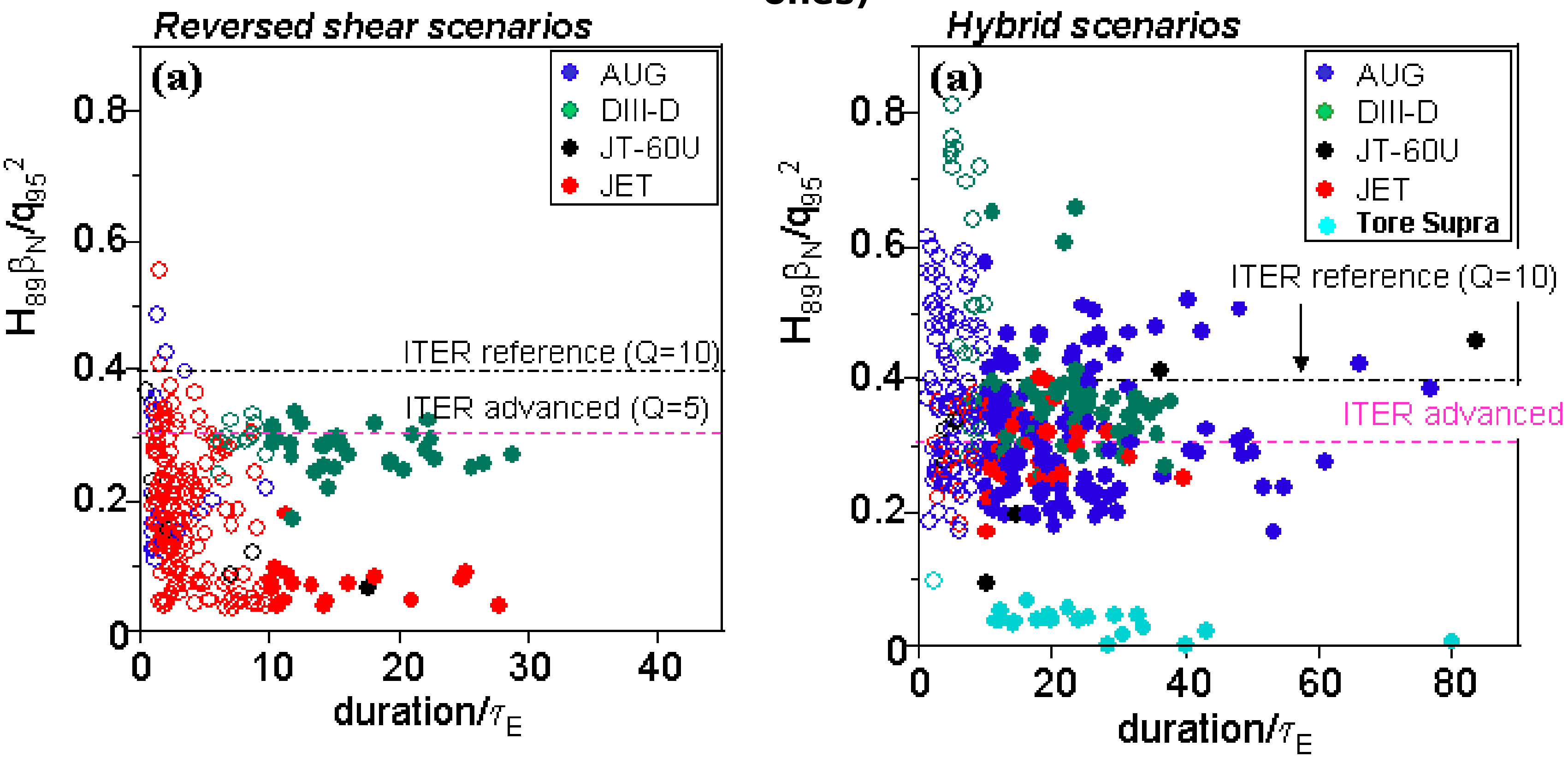
cf.1. Preliminary computation on JET pulses with the HAGIS code indicate that the internal kink mode limit shows a different instability limit when a fraction of fast ion pressure is included in the total pressure.

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)

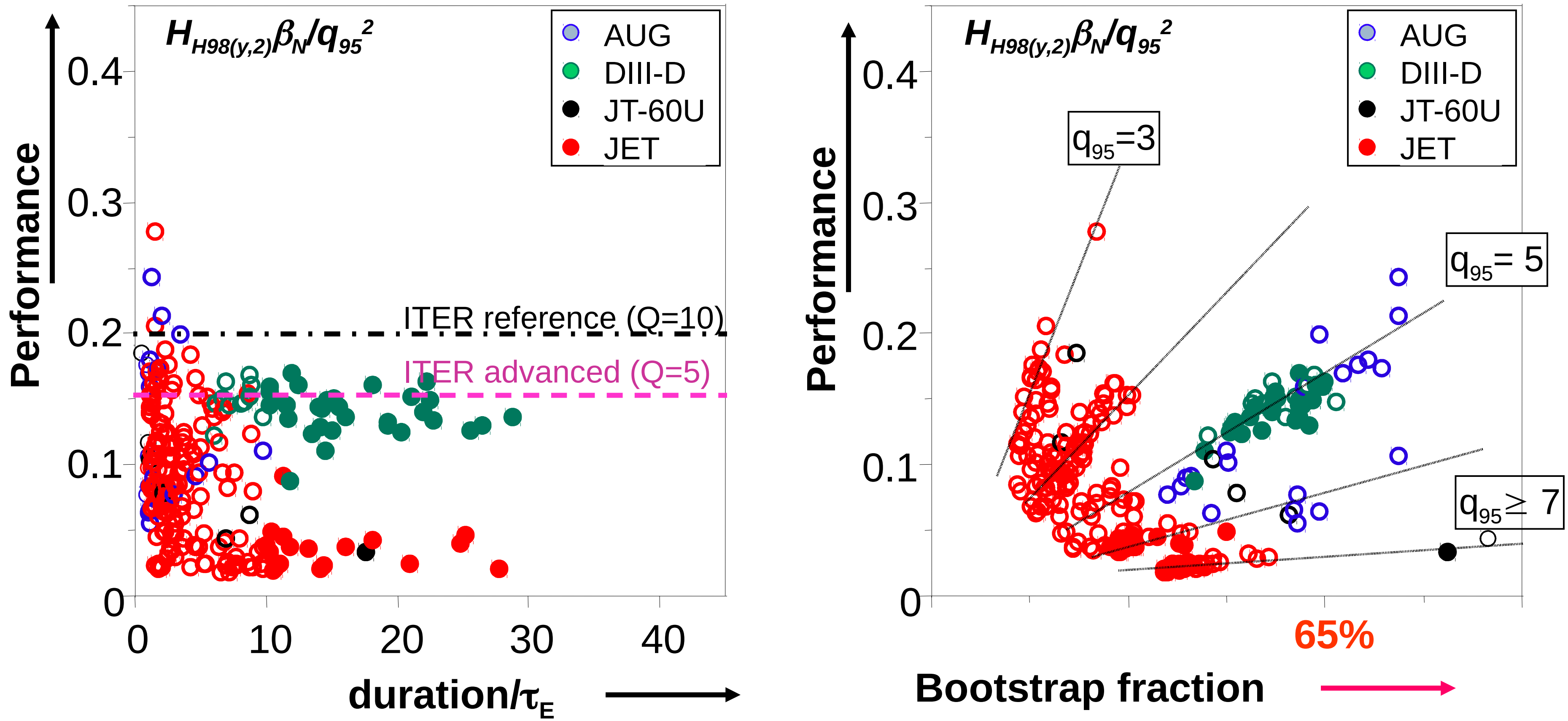
ogress for Hybrid Scenario

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.

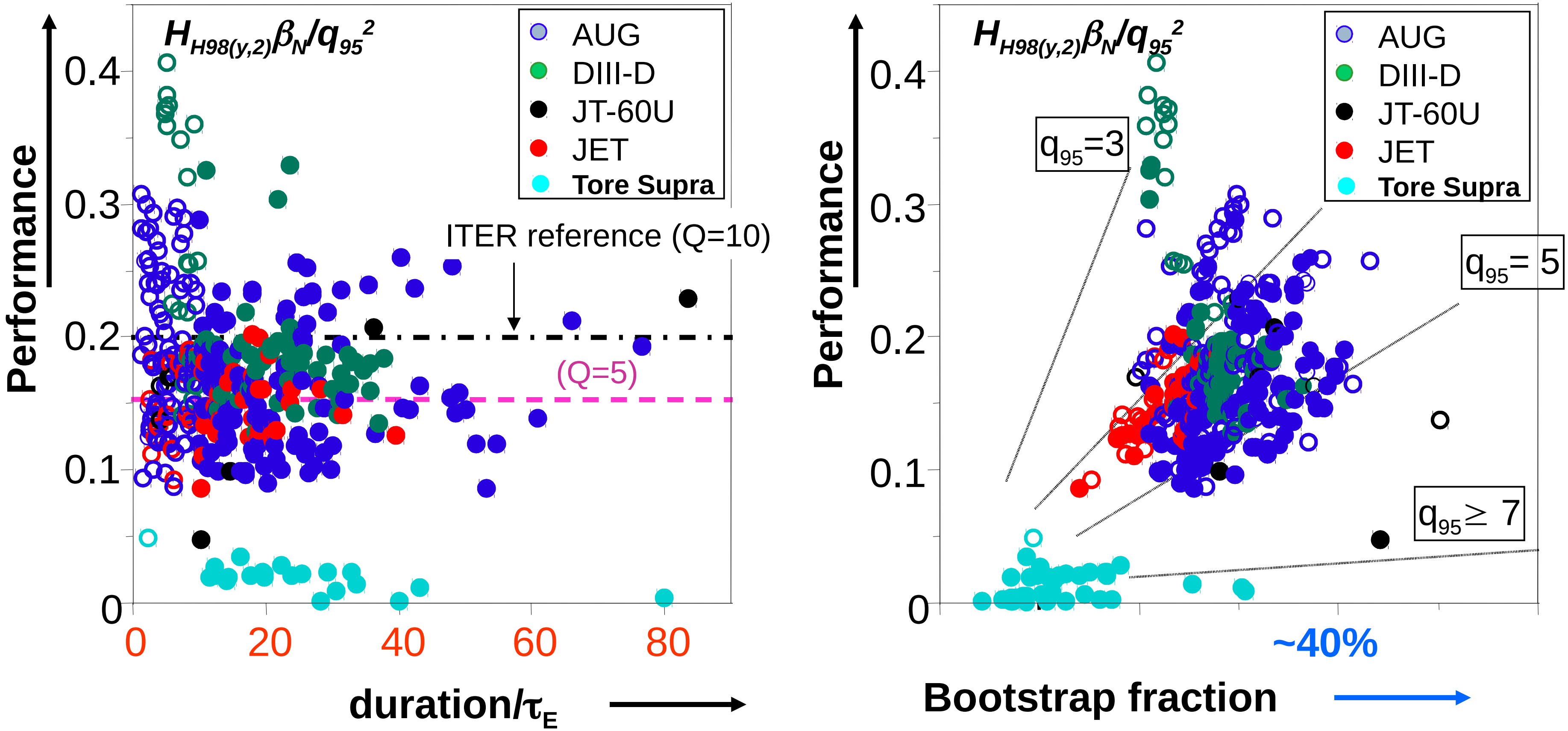
Reversed Shear Scenario



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

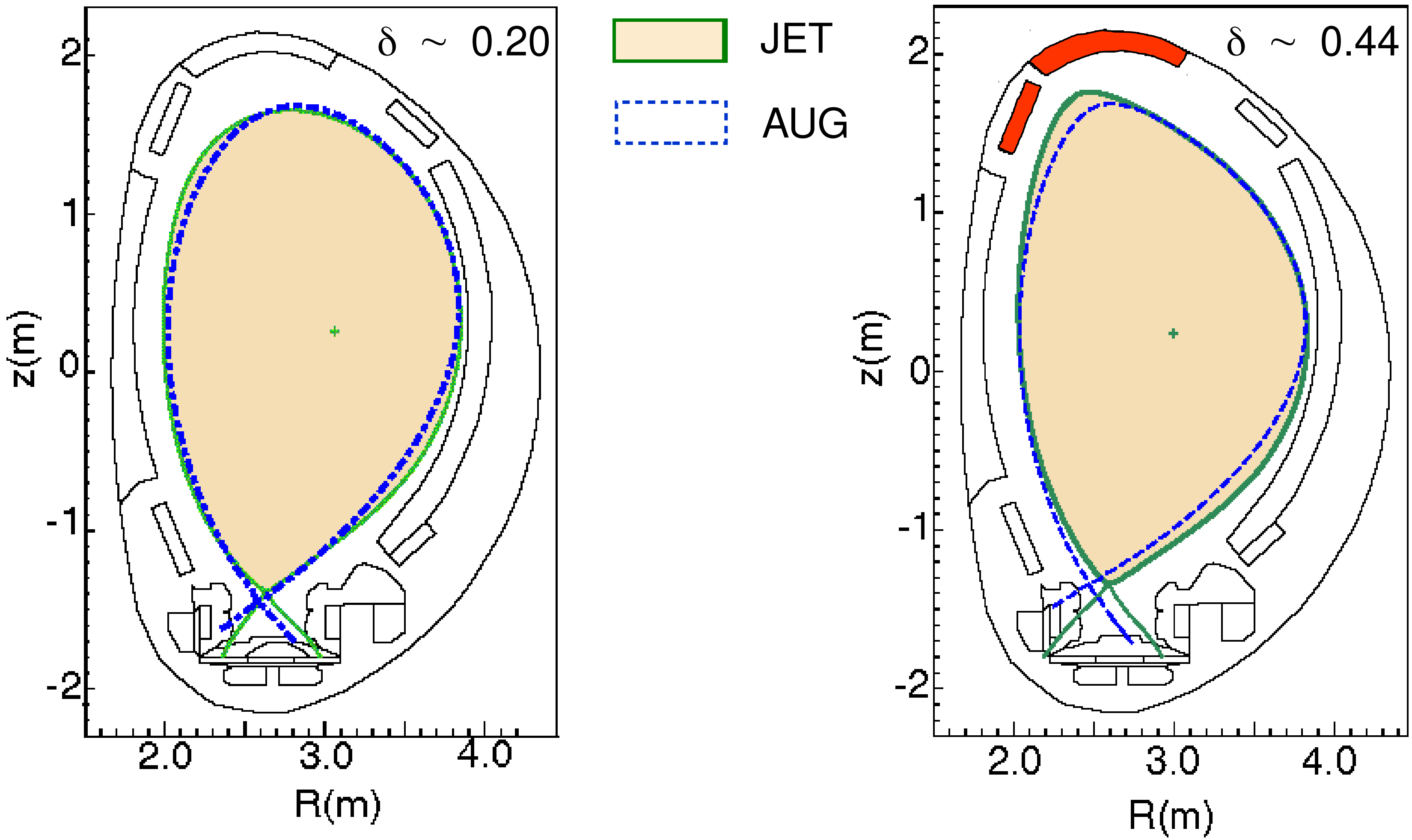


Similar results from all machines, Q>10 possible (ignition?).

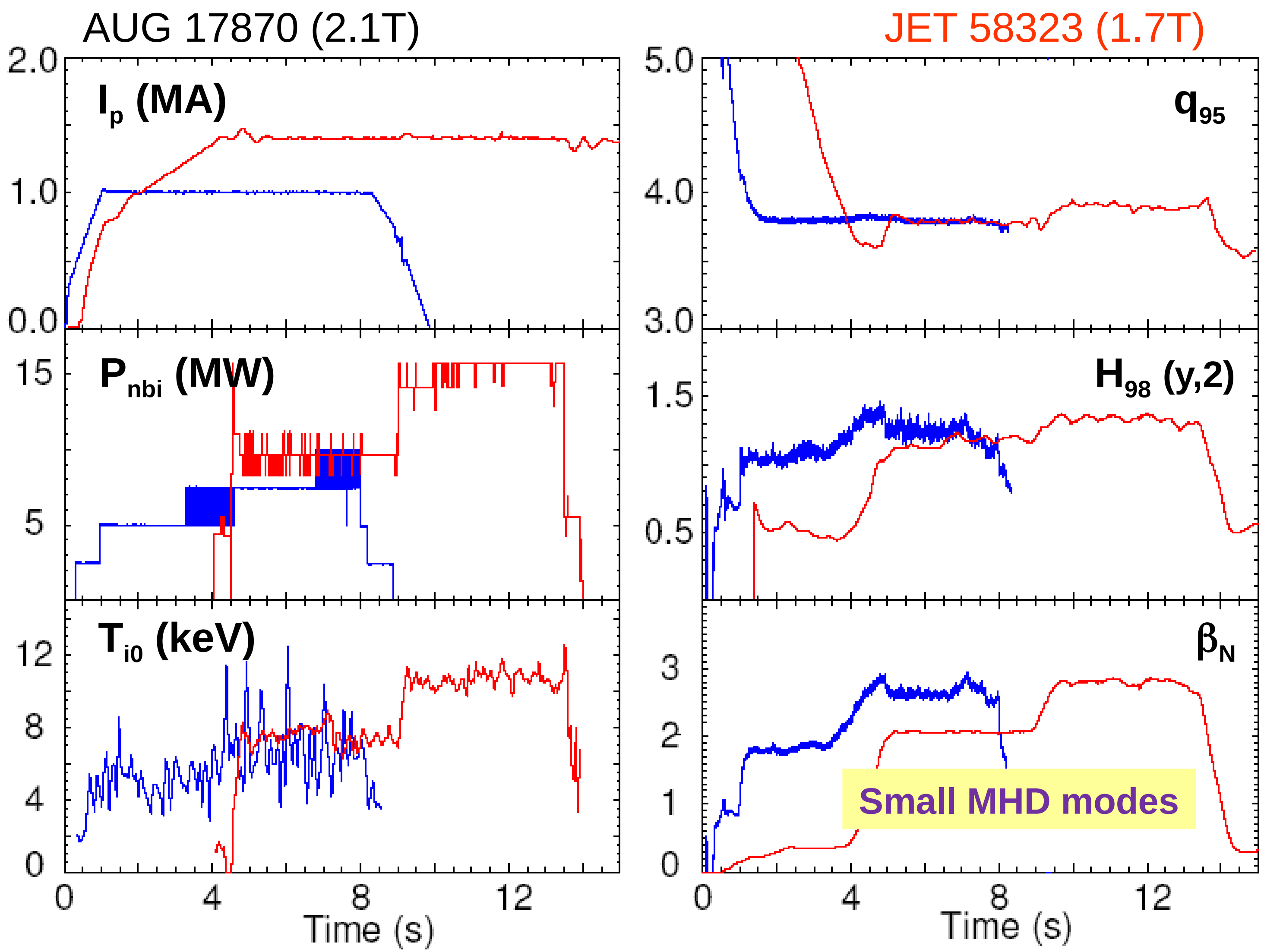
2x ITER target at q_{95}=3, or long pulse (2000s) at q_{95}=4-4.5.

Identity Experiments

Plasma shapes used in JET compared to ASDEX Upgrade

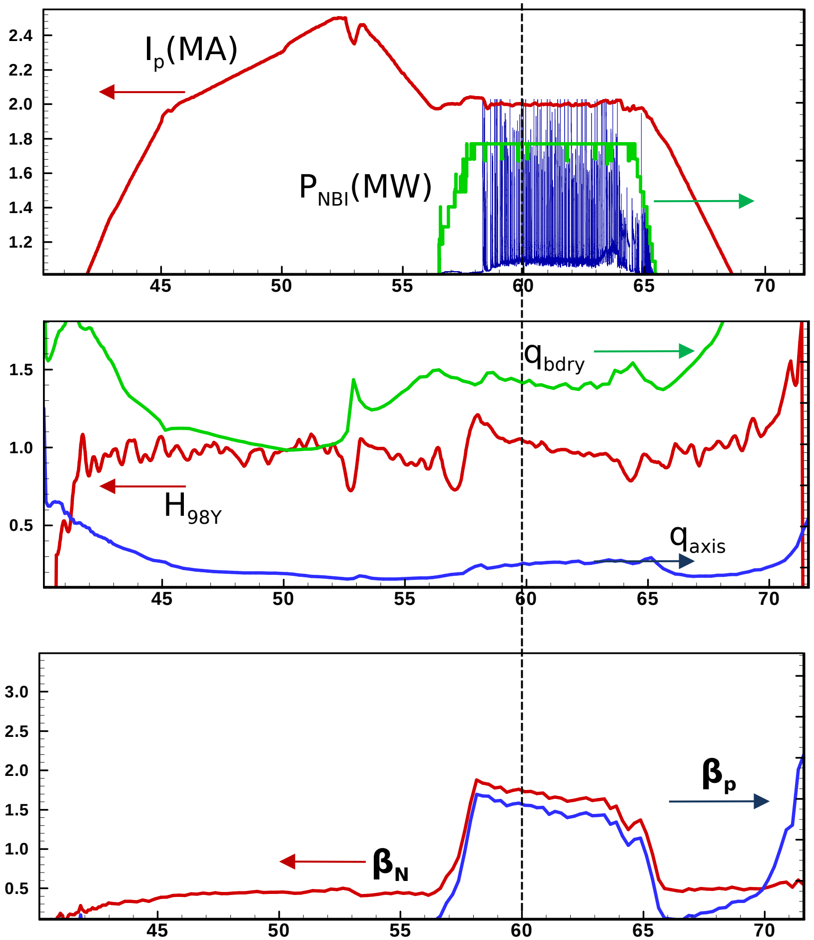


Identity Experiments

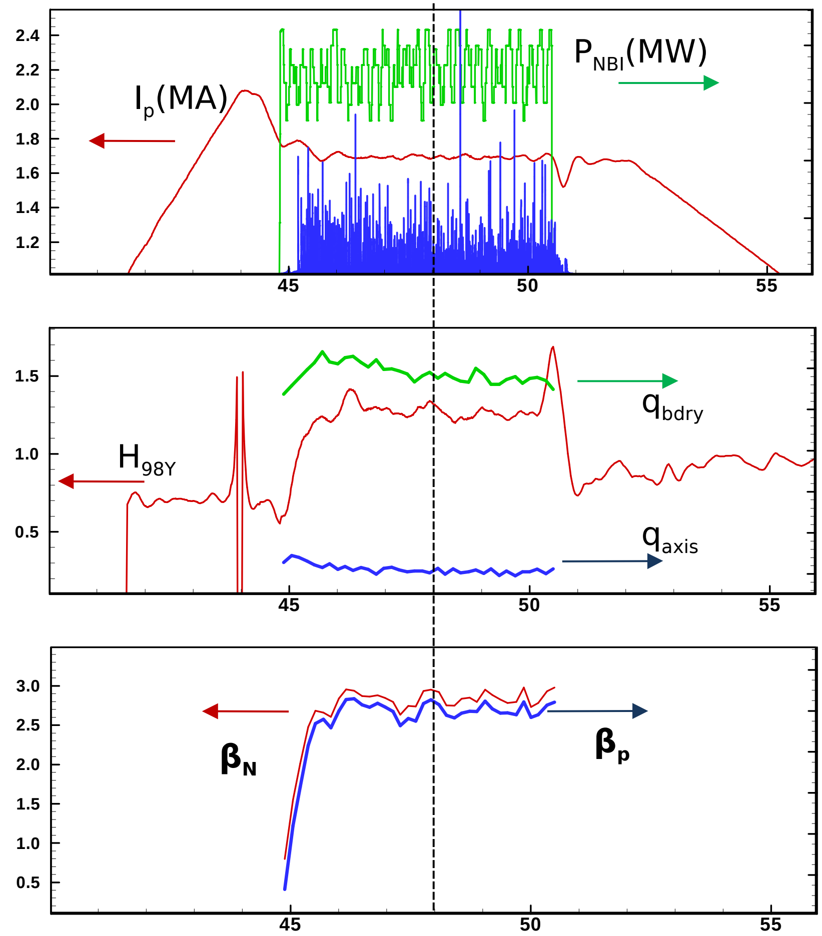


HD Analysis on JET Shots

#55937 (an example of conventional H-mode)



#75738 (an example of Hybrid scenario)



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