# Fusion Reactor Technology I
## (459.760, 3 Credits)

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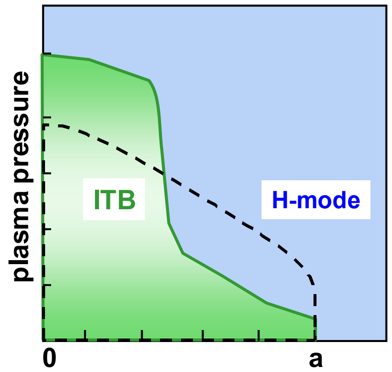
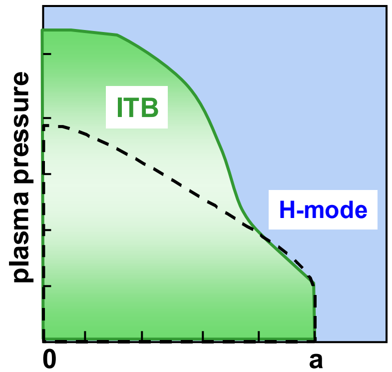
# Contents

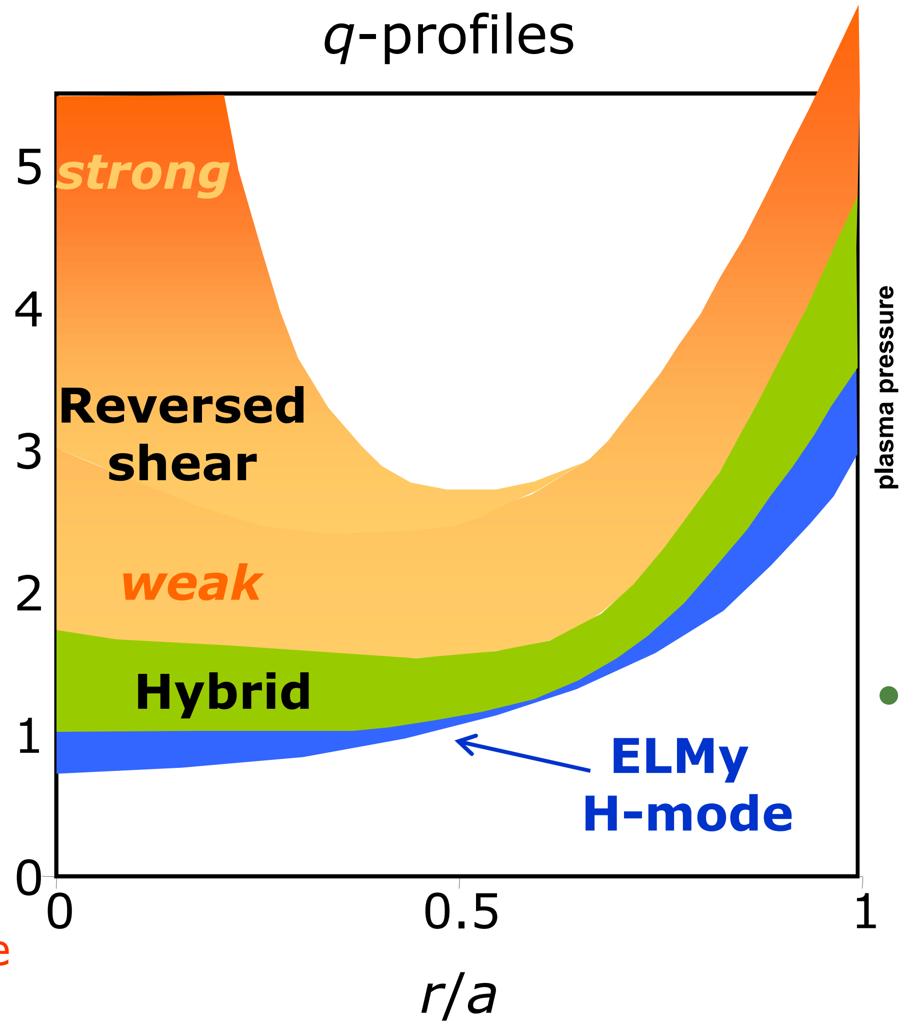
# Tokamak Operation Scenario

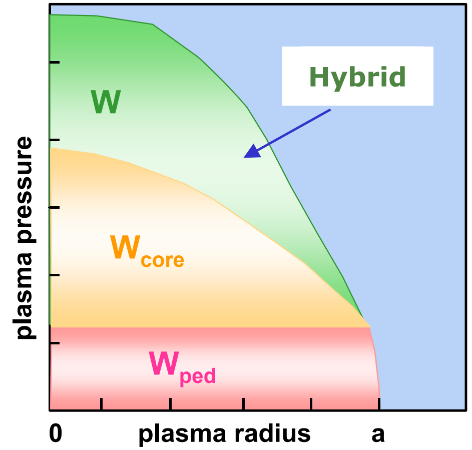



- Good confinement
- Poor stability




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




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

# 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.**

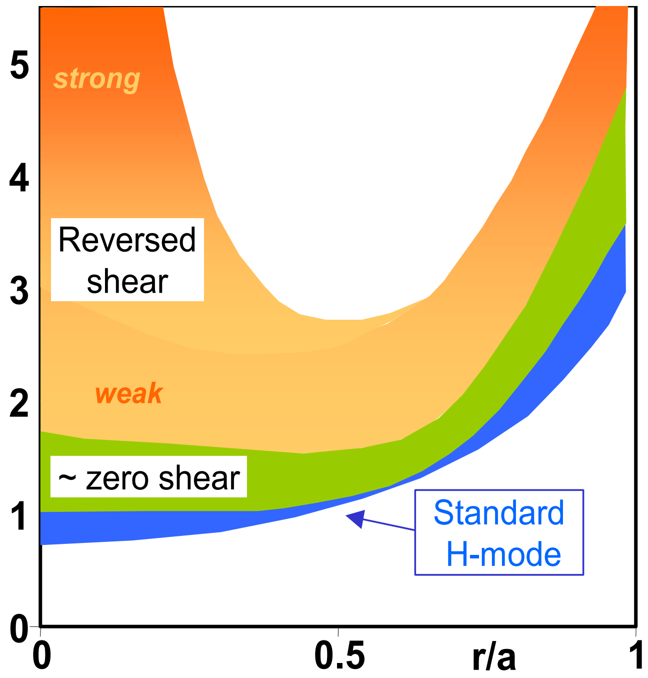
# Introduction – Features of hybrids scenario

## 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

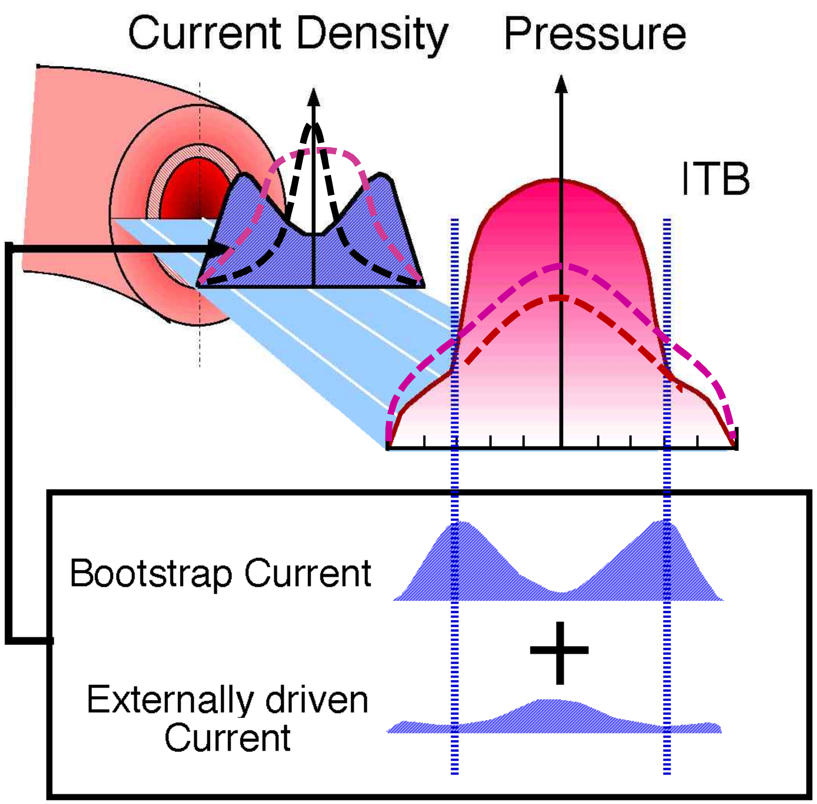



**<u>RS+ITB mode (Challenging demands in terms of control):</u>** Very strong reversed shear lead to the development of 'current hole' configurations where the plasma current does not penetrate to the plasma centre.

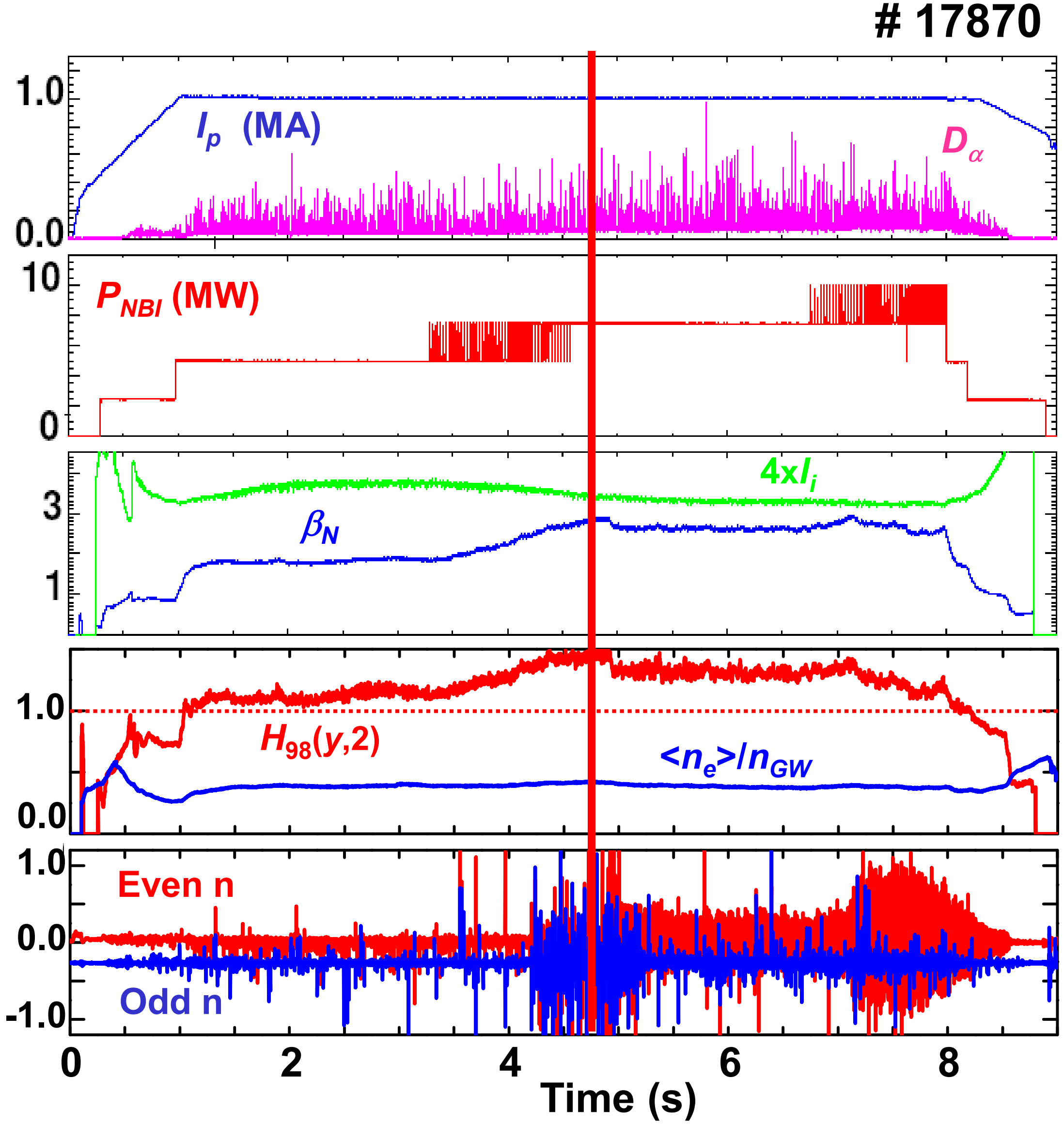
**<u>Conventional Hybrid mode :</u>** A large volume of low magnetic shear and a central value of q close to one have resulted in stationary discharges with improved confinement and high values of normalized beta.

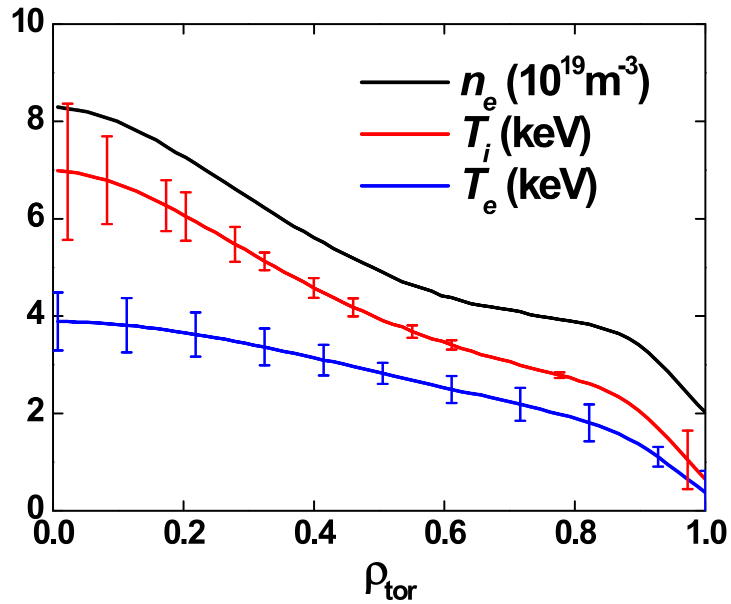
**<u>Reference H-mode (with assumption of NTM suppression):</u>** Plasma current is fully diffused and q-profile has monotonic form with a large positive magnetic shear

# Tokamak Operation Scenario



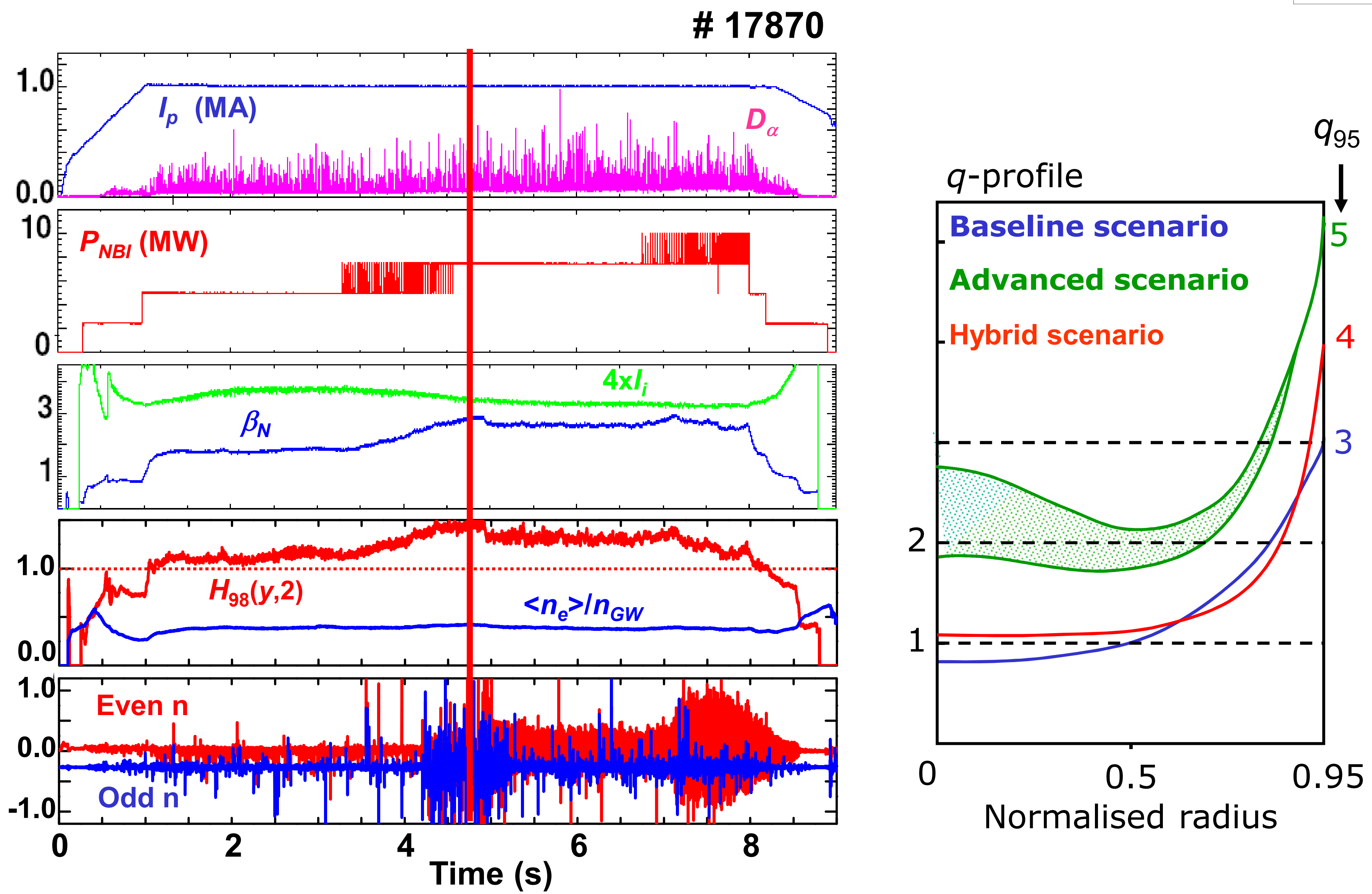
# Hybrid Scenario



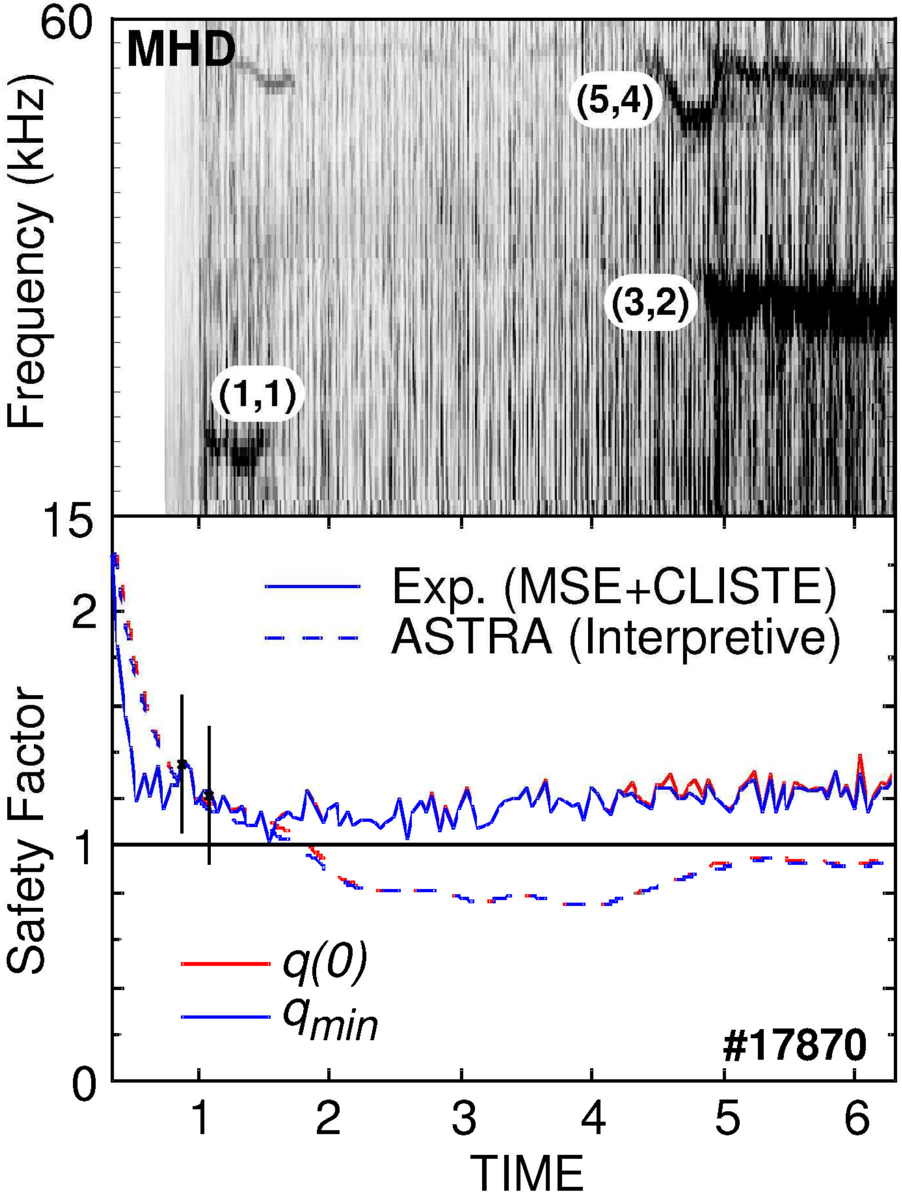



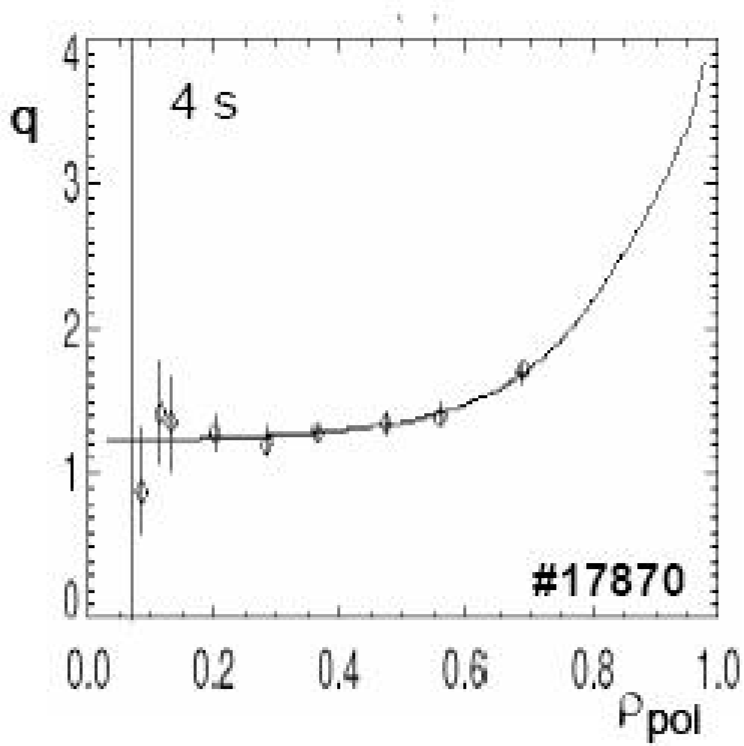

- $H_{98}(y,2)$ ~ 1.4
- $\beta_N$ ~ 2.8
- $IBS$ = 34%
- $INB$ = 31%

# Hybrid Scenario

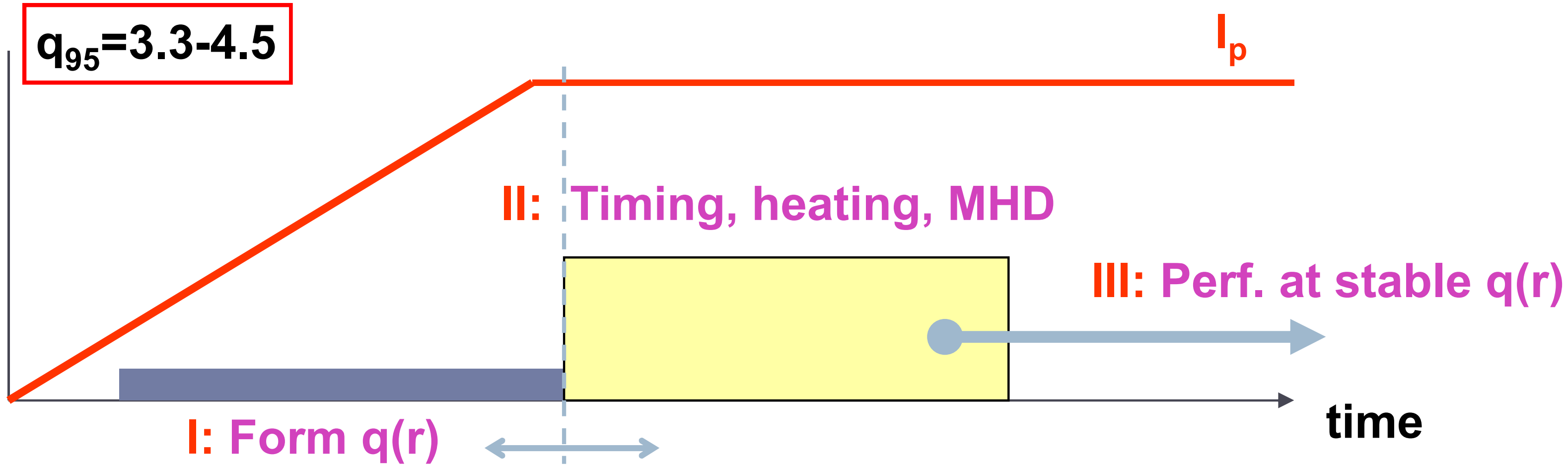


# Hybrid Scenario



# 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

✓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.

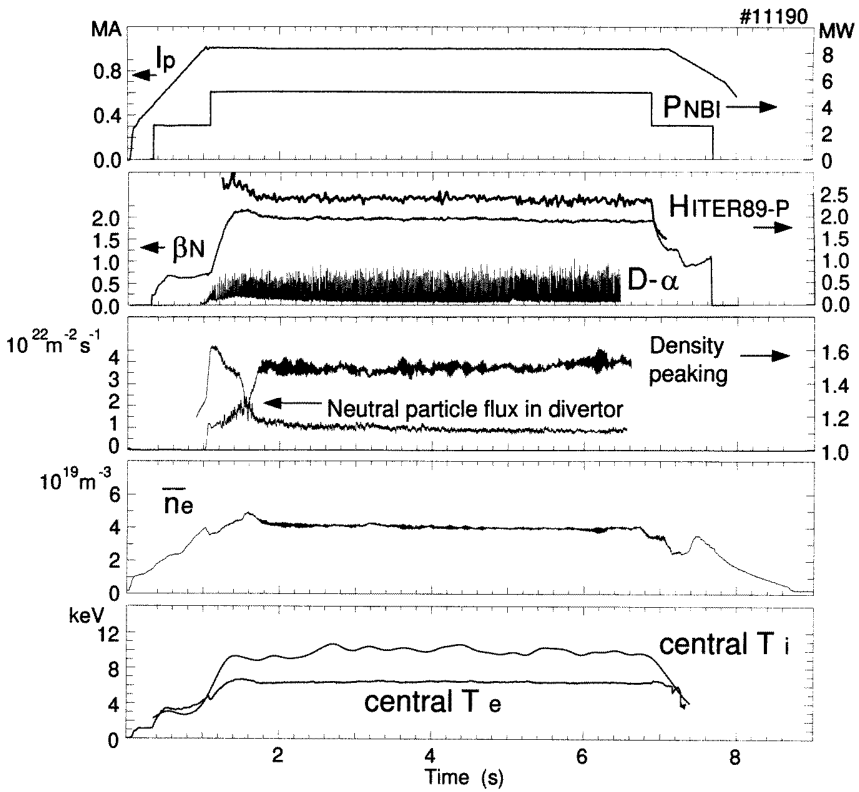
- By checking MHD behavior, the feasibility of the hybrid scenario could be confirmed.

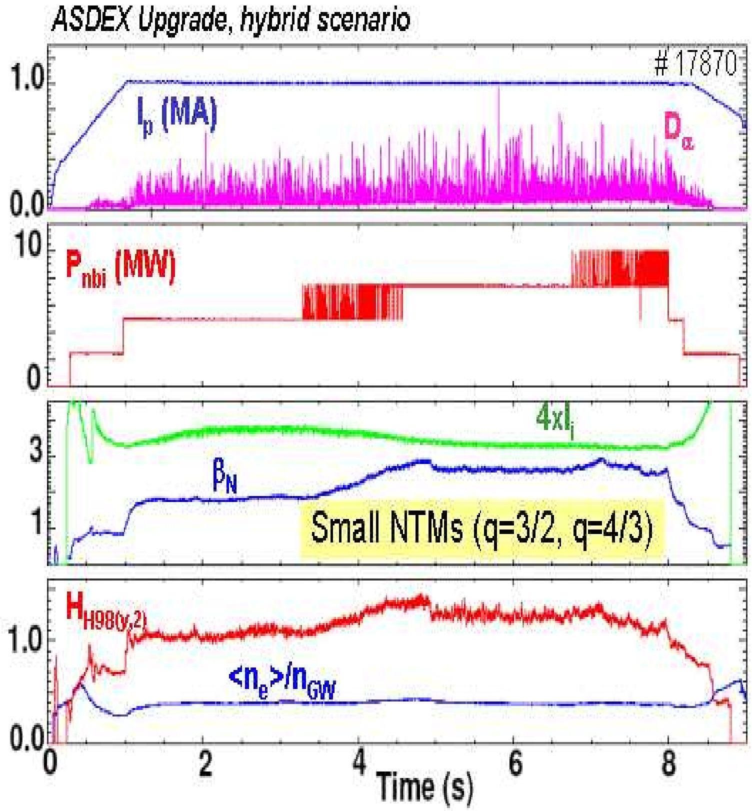
- Some modes have to be triggered before sawteeth begin

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

# Progress for Hybrid Scenario

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

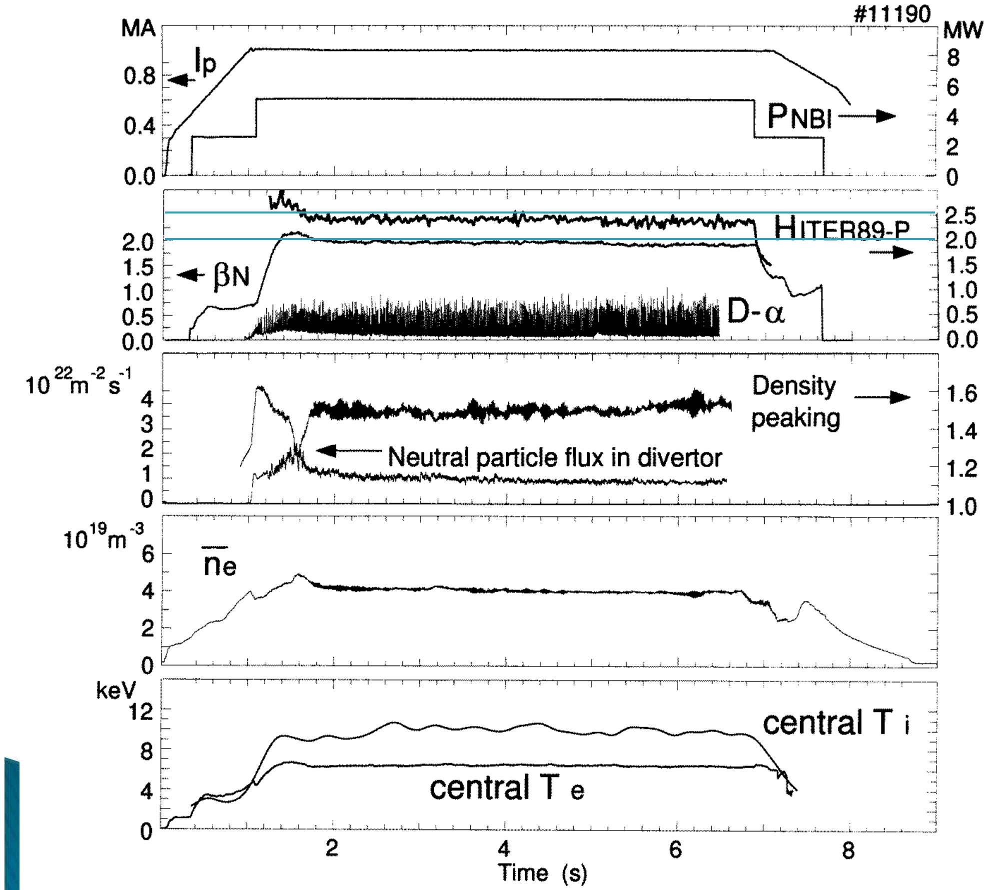



- ✓ Possible to gain high beta to $\beta_N$~3 with improvement in confinement
- ✓ Avoiding of the severe MHD activities lead to disruption – Central q is in the vicinity of one.
- ✓ Type-I ELMs are observed in the edge region.

# 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

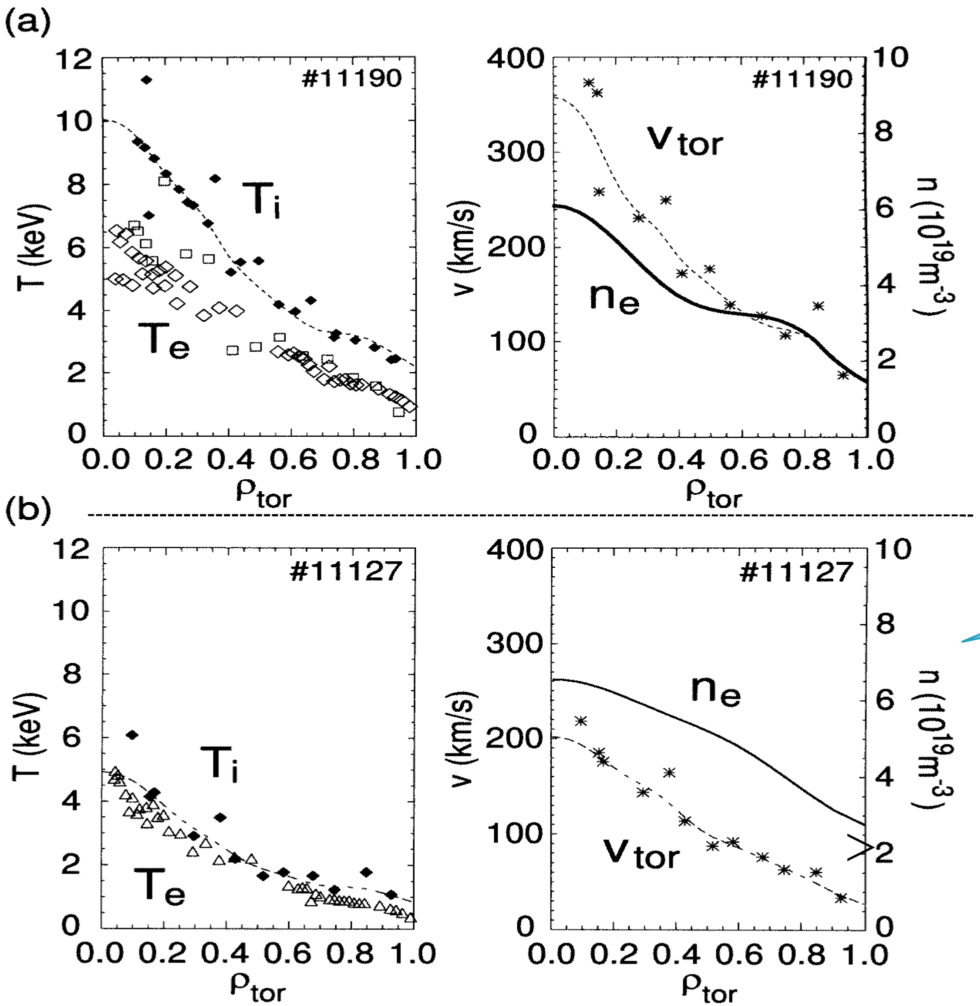
→ Central q is in the vicinity of one

✓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.

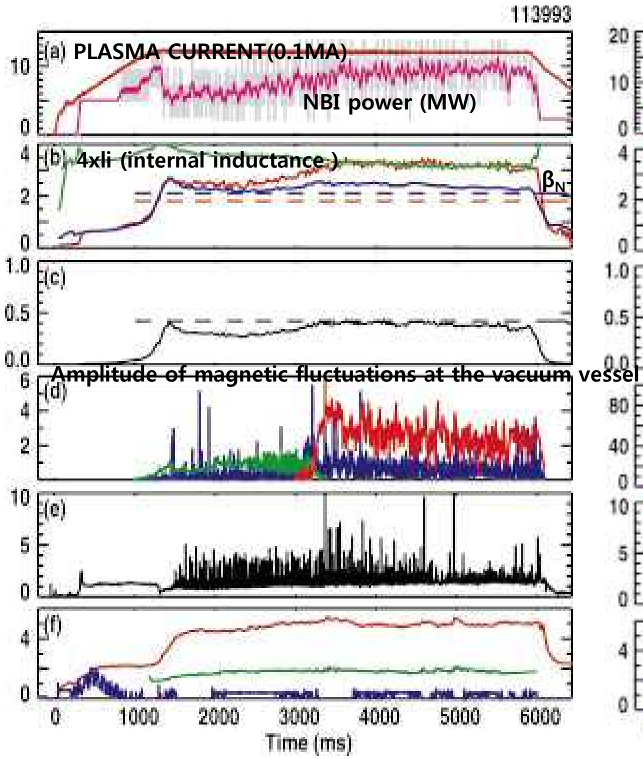
**A standard ELMy H-mode**

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

# Some example of existing experiments

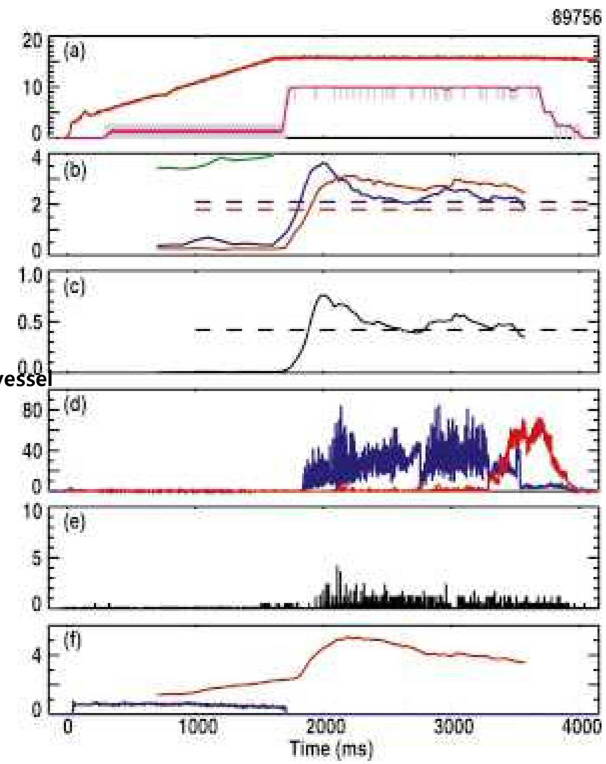
# DIII-D

$q_{95}>4$ without sawteeth



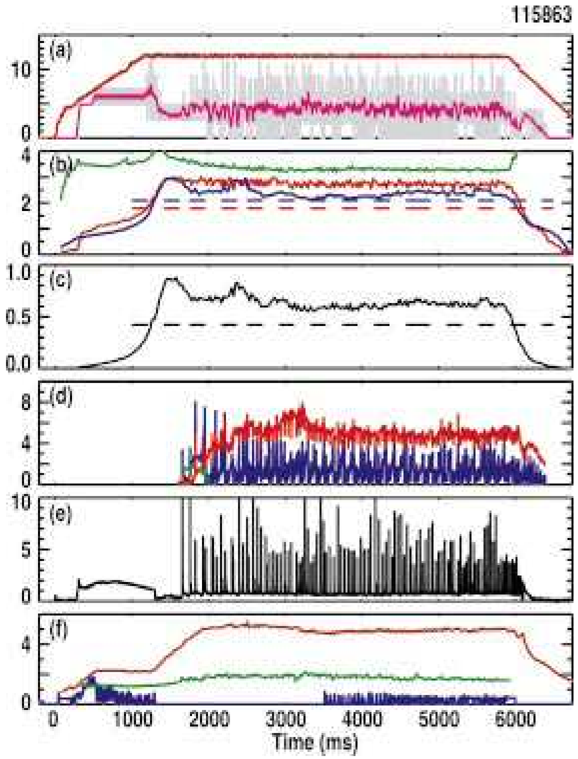

**limited by tearing modes**

$q_{95}=3.6$ without sawteeth




**limited by fishbones**

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




**limited by sawteeth**

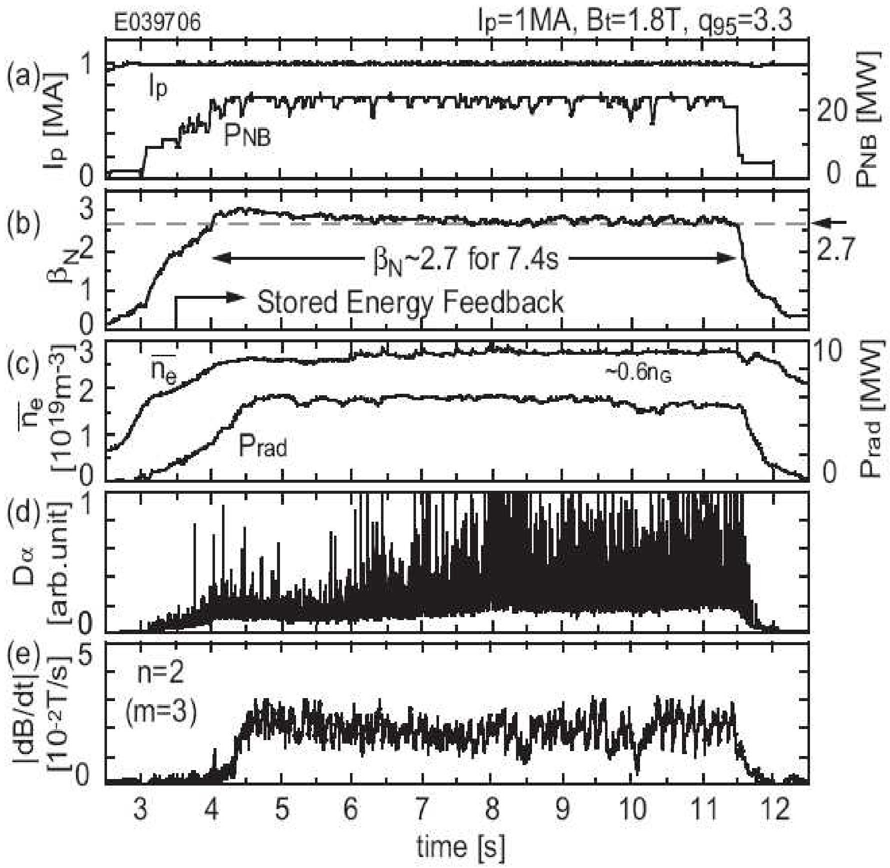
✓ *These discharges are a generic class of operations for tokamak hybrid mode.*

# Some example of existing experiments

# JT-60U, “High $\beta_P$ ELMy H-mode discharges”

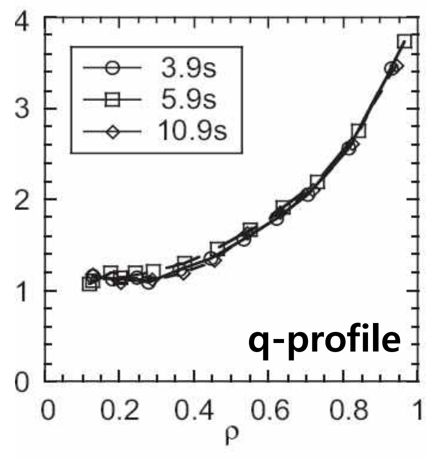
<u>With upgraded systems since 2000 :</u>

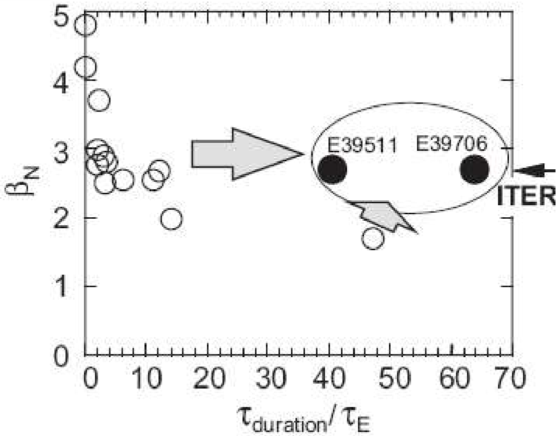
Poloidal field coil, NBI system, EC wave injection system and pellet injection system are upgraded




A high-beta plasma with $\beta_N$=2.7, $\beta_P$=1.5 has been sustained for 7.4s at $q_{95}$=3.3.

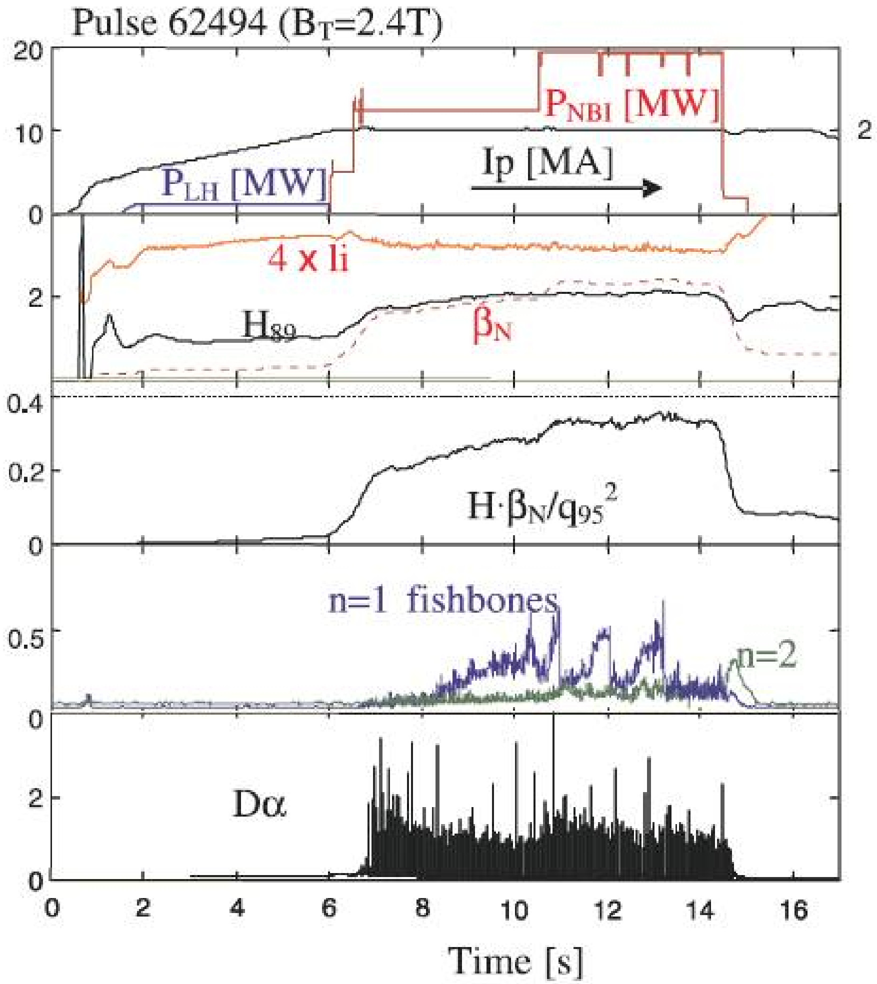
The duration time of high-beta extends to ~60$\tau_e$, which is limited by the facility’s capability



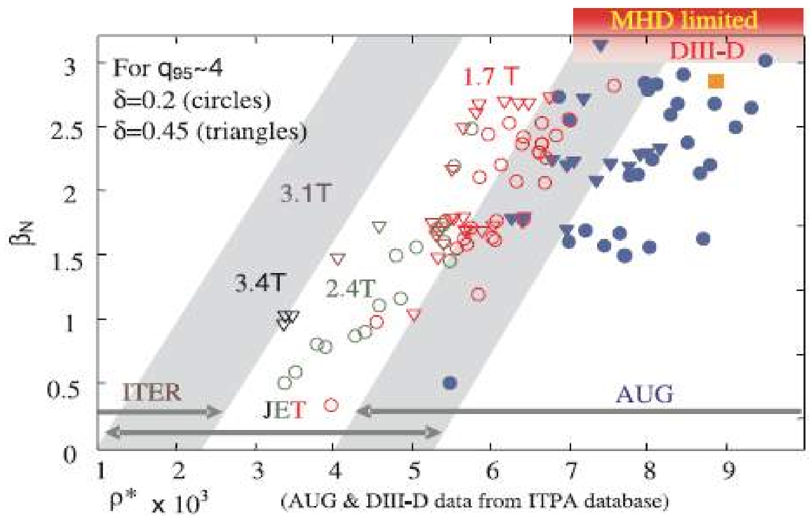
# Some example of existing experiments
# JET(1)

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



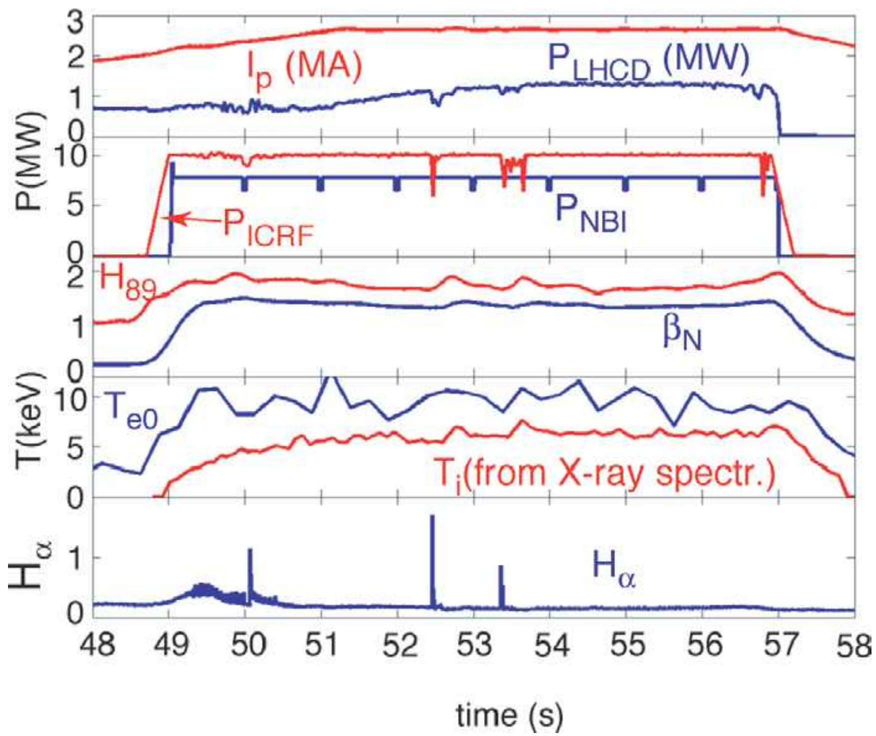

- ITER like magnetic configuration with $B_T$=2.4T has been adopted (decreasing the normalized Larmor radius, ρ*)

- 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

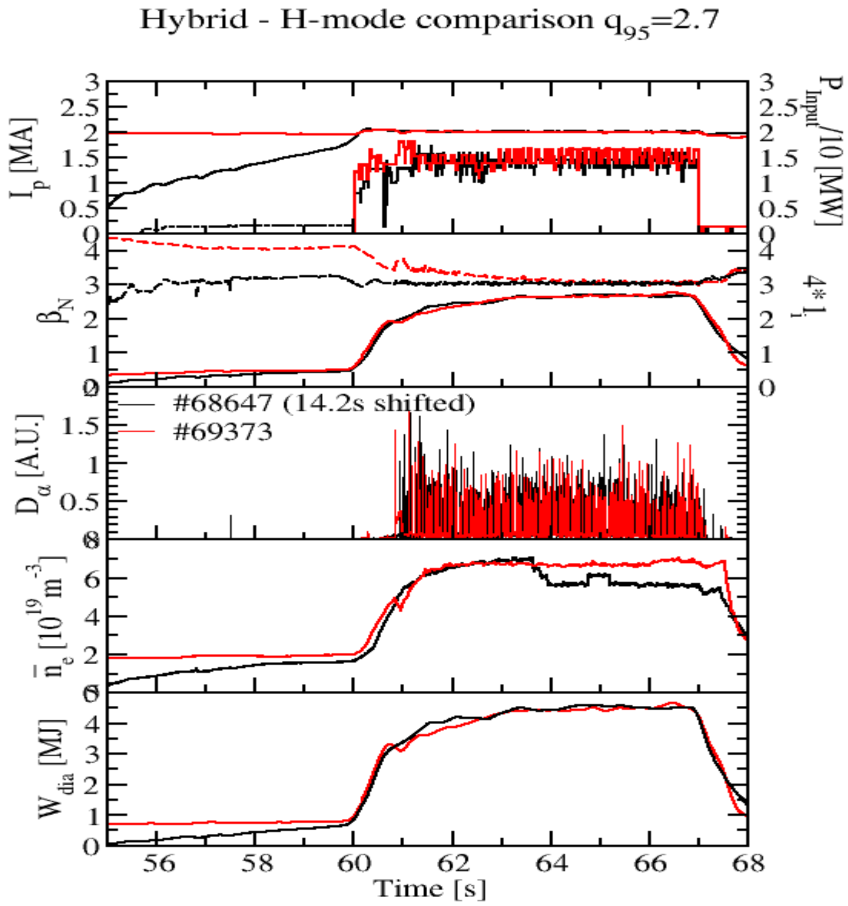
# Some example of existing experiments
# JET(3)

✓ <u>Comparison between baseline and hybrid operation in JET</u>

- Hybrid (LH preheat) $\beta_N$=2.7 $I_p$=2.0MA $B_T$=1.7T
- Baseline $\beta_N$=2.7 $I_p$=2.0MA $B_T$=1.7T

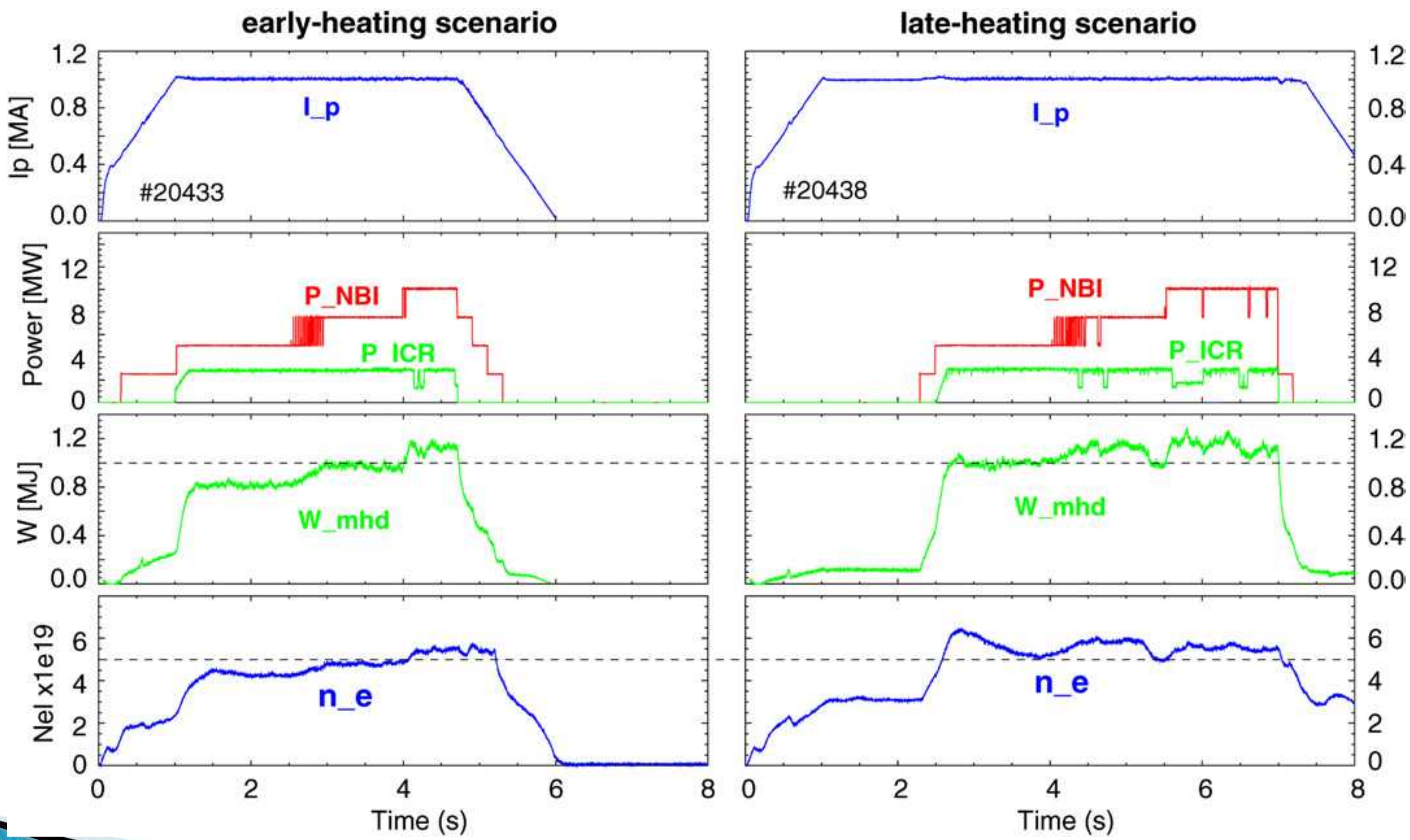
- Good MHD stability at $q_{95}$=2.7
- Standard type I ELMs
- $H_{98}$ ~1
- $n/n_G$ ~0.85
- $H_{89} x \beta_N / q_{95}^2$ =0.72
- Sawtoothing discharge

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



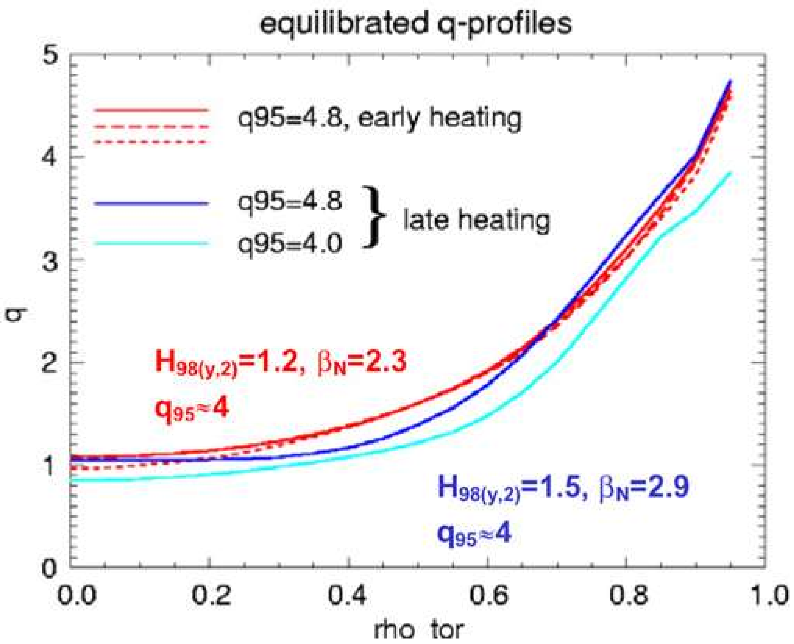
# Some example with improved operating scheme
# ASDEX-U(1)

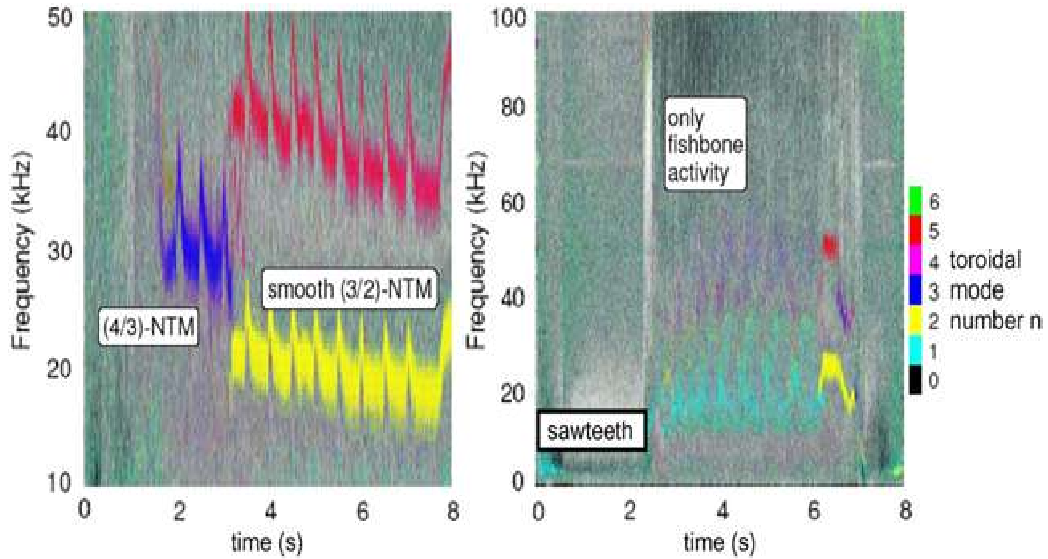
✓Improved H-modes have also been obtained with 'late' additional heating well in the current flattop which partly show even better performance



# 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.

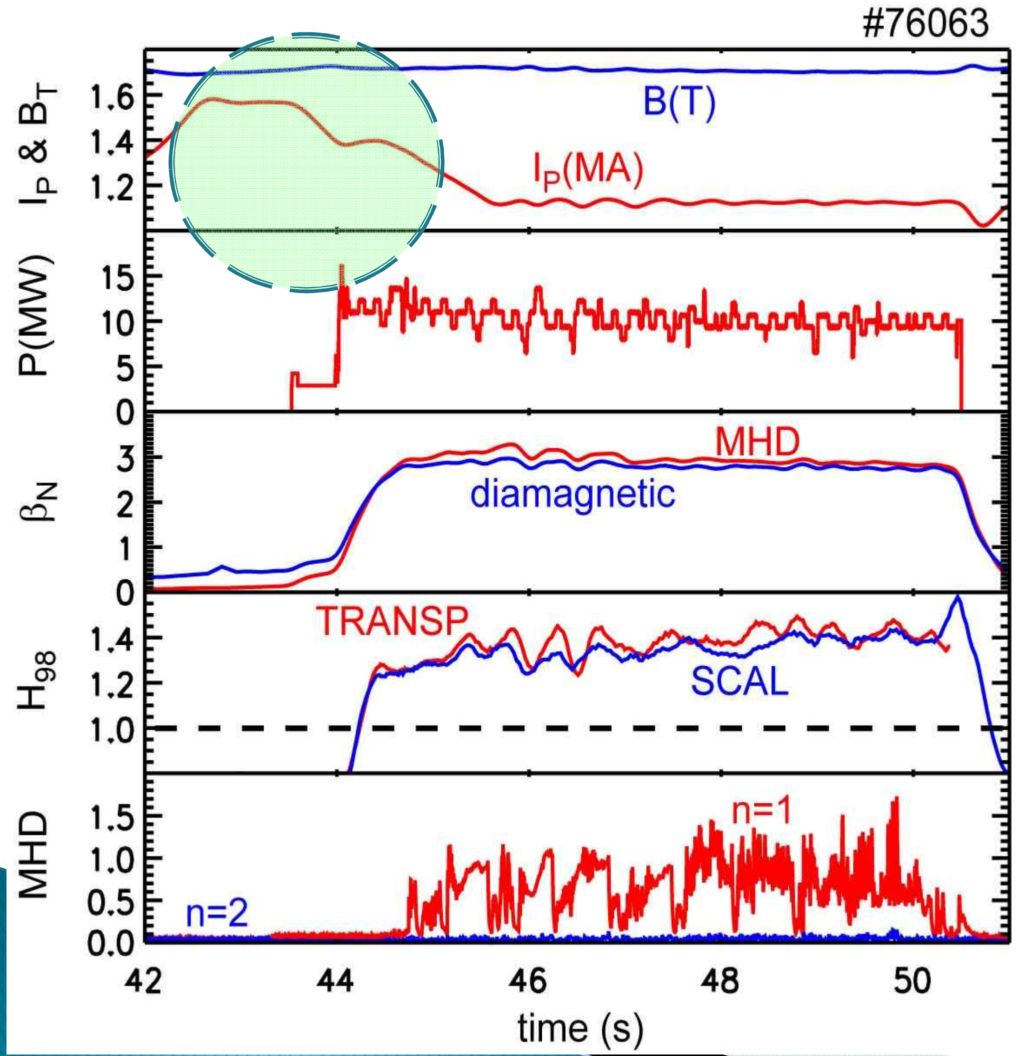



early heating late heating

# Some example with improved operating scheme
# JET(1)

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

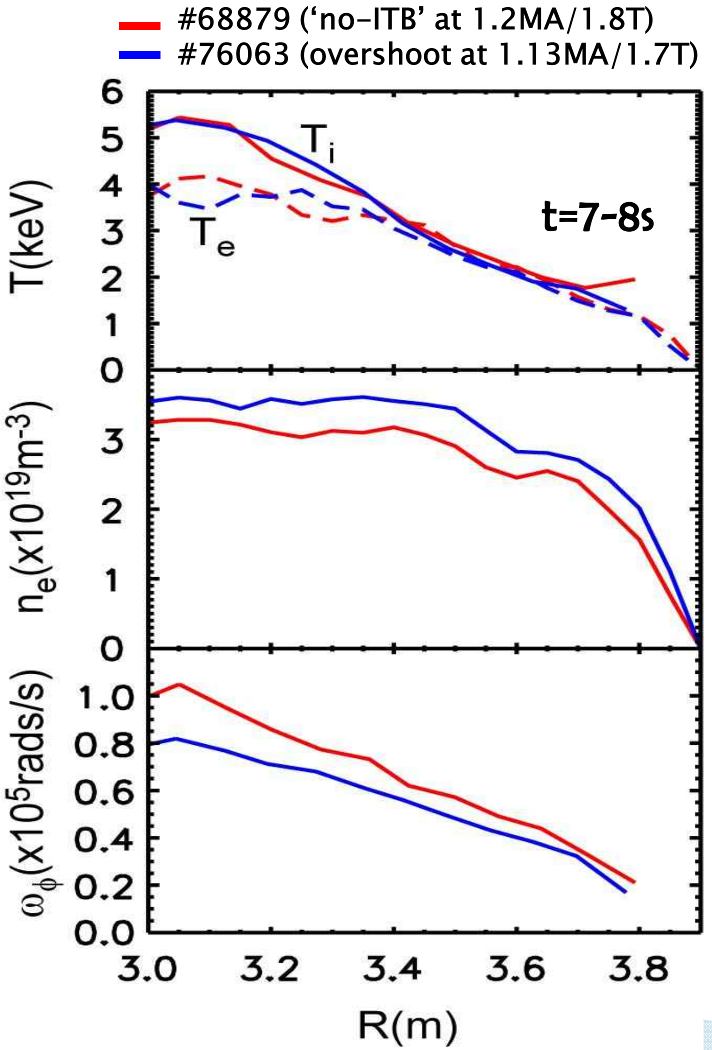



- Parameters achieved:
  - $H_{98}$≈1.4
  - $\beta_N$≈2.8
  - $l_i$≈0.75
  - $\delta \approx$0.39
  - $n/n_G$≈65%
  - $W_{th}/W_{dia}$≈75%
  - $\tau_R$≈5s
  - $q_{min}$≈1 (fishbones & sawteeth)
  - No significant 3/2 or 2/1 activity

# Some example with improved operating scheme

# JET(2)

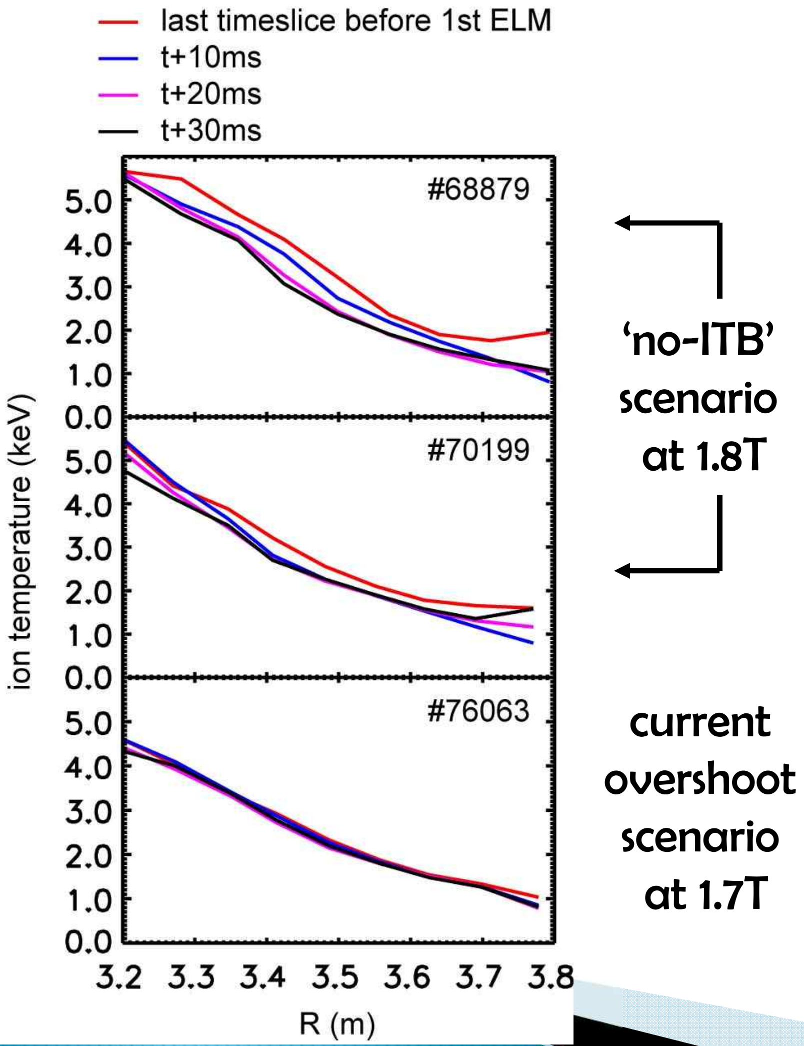
✓Comparison with 1.8T 'no-ITBs' on temperature and density profiles




- Comparison with 'no-ITB' regime at similar power (lower $\beta_N$) 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)

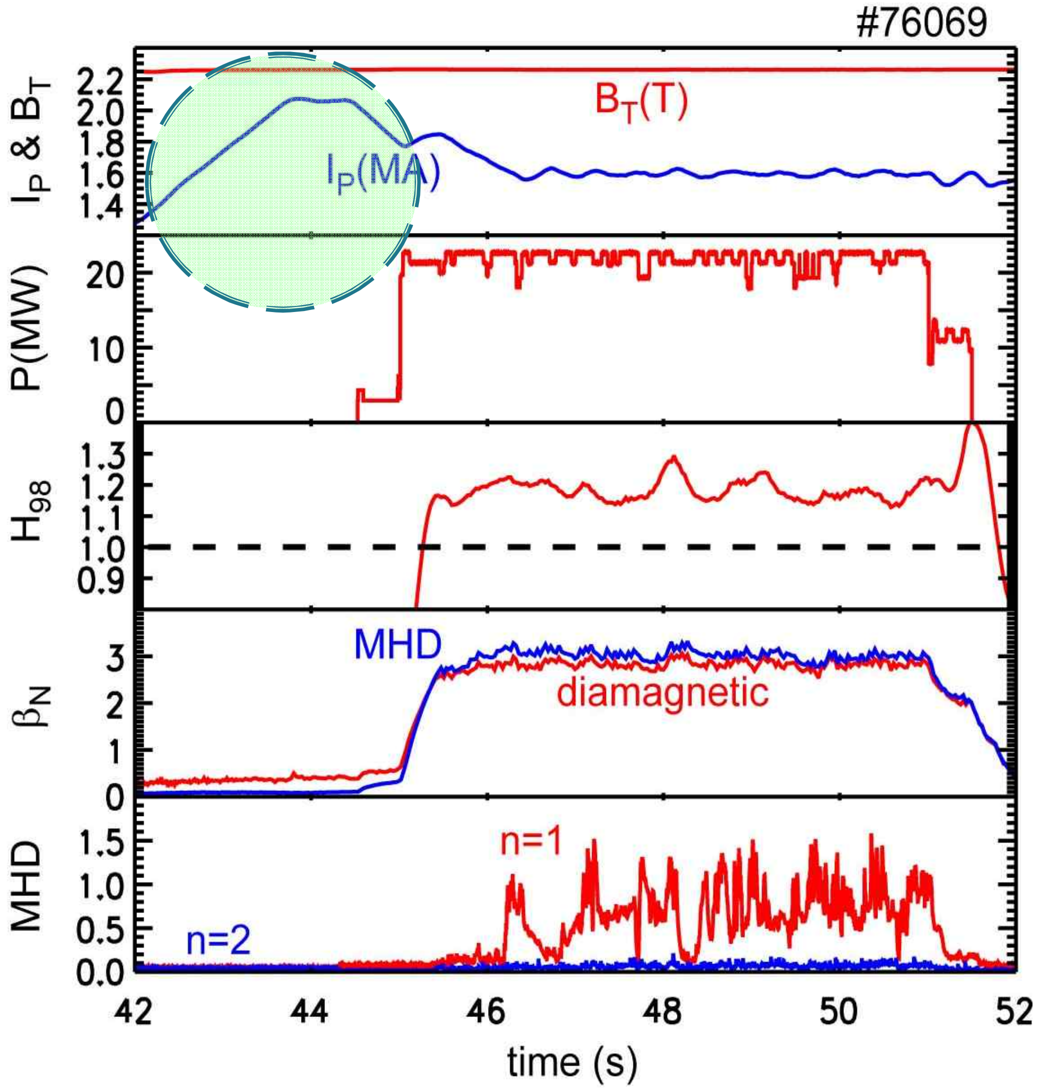
✓Comparison with 1.8T 'no-ITBs' on ion temperature evolutions to ELM




- **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)

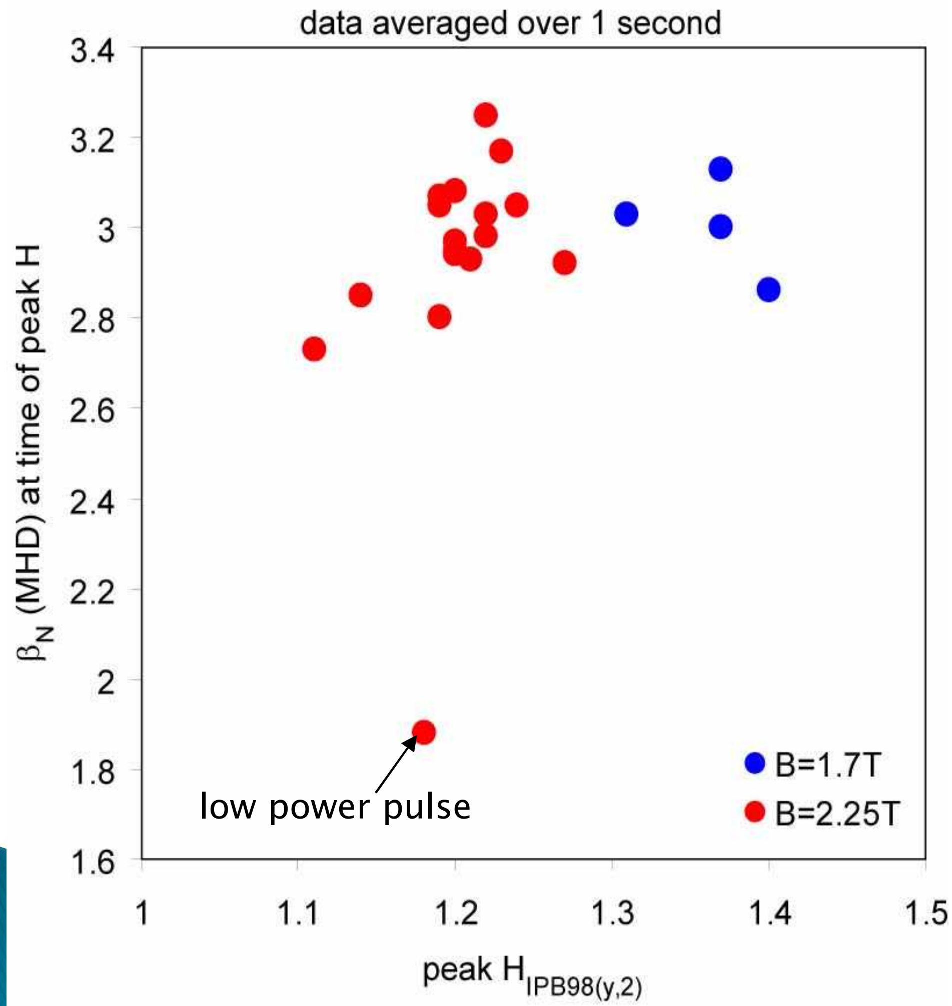
✓Overshoot technique at 2.25T




- Good sustained performance achieved:
  - $H_{98}$≈1.2
  - $\beta_N$≈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 $\beta_N$≈3 using hybrid current overshoot technique
- At 2.25T: $H_{98}$=1.2 achieved at $q_{95}$=4.7-5.0 with $\beta_N$≈3 with and without overshoot