ITPA

Study of Advanced Tokamak Performance using the International Tokamak Physics Database

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[13] For full list: X. Litaudon et al *2004*, Plasma Physics and Controlled Fusion 46 (2004), A19

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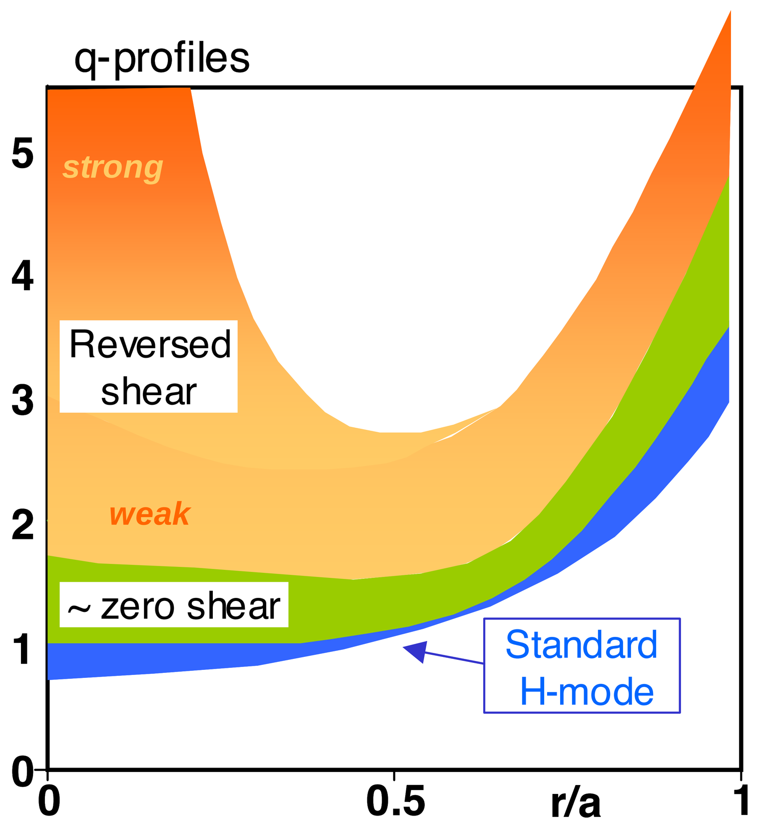
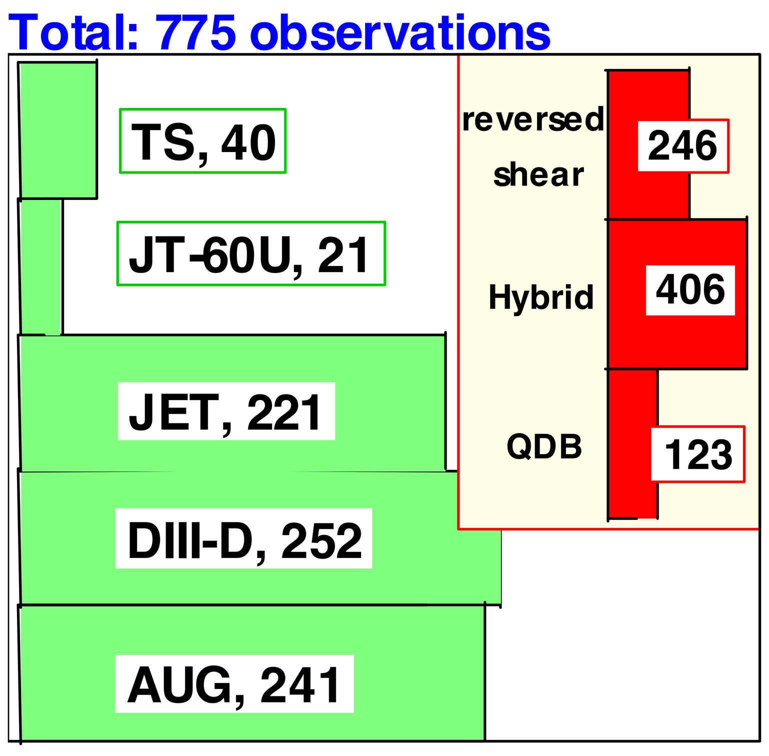
Introduction

Advanced scenarios in tokamaks:
Improve confinement and stability over standard ELMy H-modes.

Key is the current density profile:
For the inductive operation mode of ITER, q(r) is monotonically decreasing with $q_0 < 1$ and $q_{95} \sim 3$. Advanced scenarios (see Figure): **Reversed shear scenarios and Hybrid scenarios (~ zero shear).**

„A continuum of regimes between the reference non-inductive and inductive scenarios in which the current profile is modified externally but not completely driven non-inductively".





The ITPA database (a scalar database [1])

Document the operational domain of the advanced scenarios → ITER.
Previous analyses on ITB formation [2] and performance [3]. **Following improvements:**

1. The data are averaged over the duration of the high performance phase. The duration: W > 85% of the maximum stored energy during the pulse.

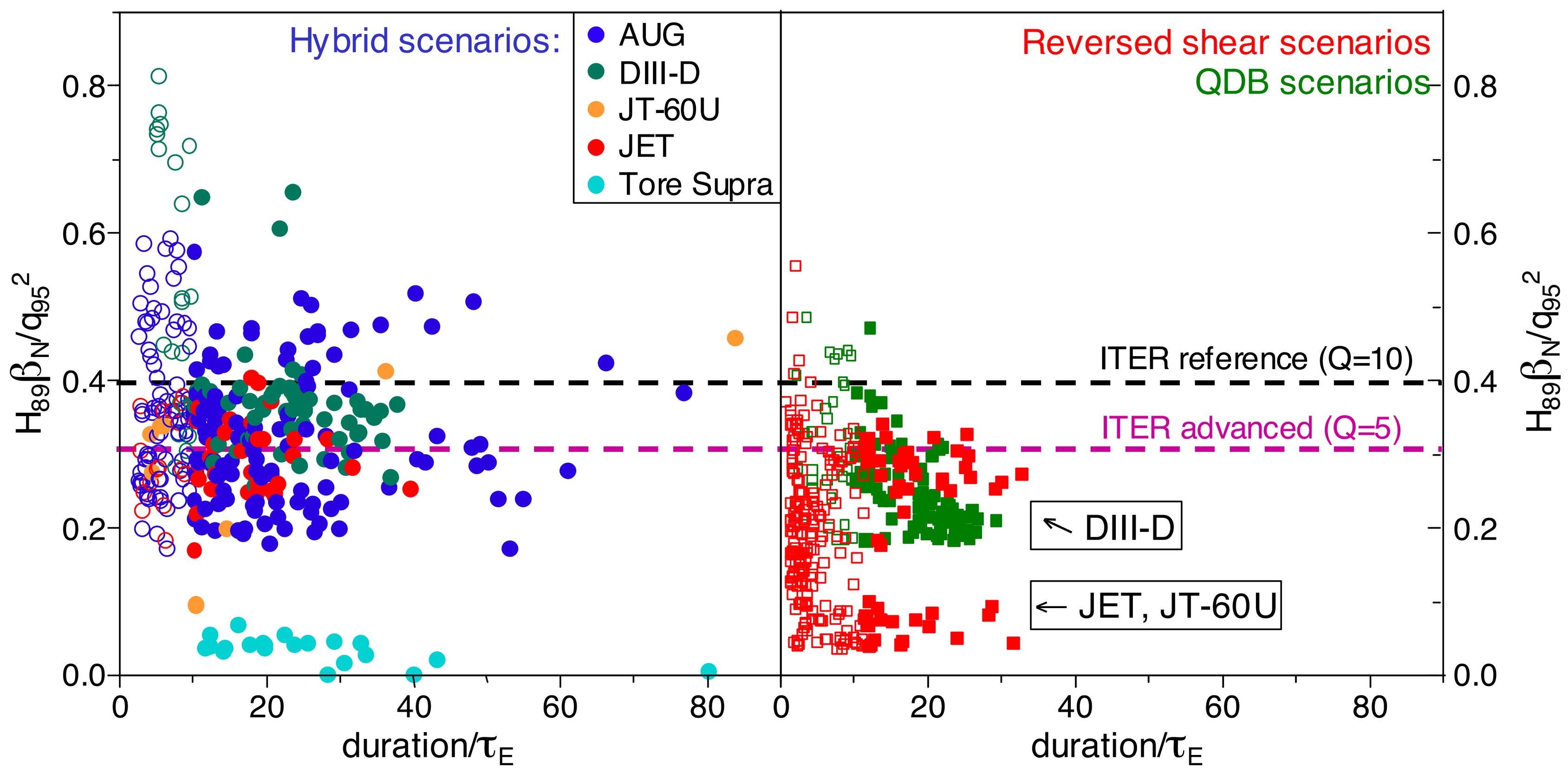
2. Better conditioned dataset, removing shots from ASDEX Upgrade and JET that were not advanced. More data from DIII-D are now available, including data from Quiescent Double Barrier (QDB) discharges (for this regime, the values used for τ_E and H_{89} in the dataset are not corrected for prompt losses).

3. Now the advanced scenarios are divided into two groups to allow comparison between (i) reversed shear scenarios and (ii) hybrid scenarios.

Progress towards long pulse or non-inductive operation

$H_{89}\beta_N/q_{95}^2$ is used as a "figure of merit" for performance:
$H_{89}\beta_N/q_{95}^2 \sim 0.4$ for the ITER reference scenario, at 15 MA.
$H_{89}\beta_N/q_{95}^2 \sim 0.3$ for the ITER non-inductive scenario at 9 MA.

The results are plotted separating hybrid and reversed shear scenarios.



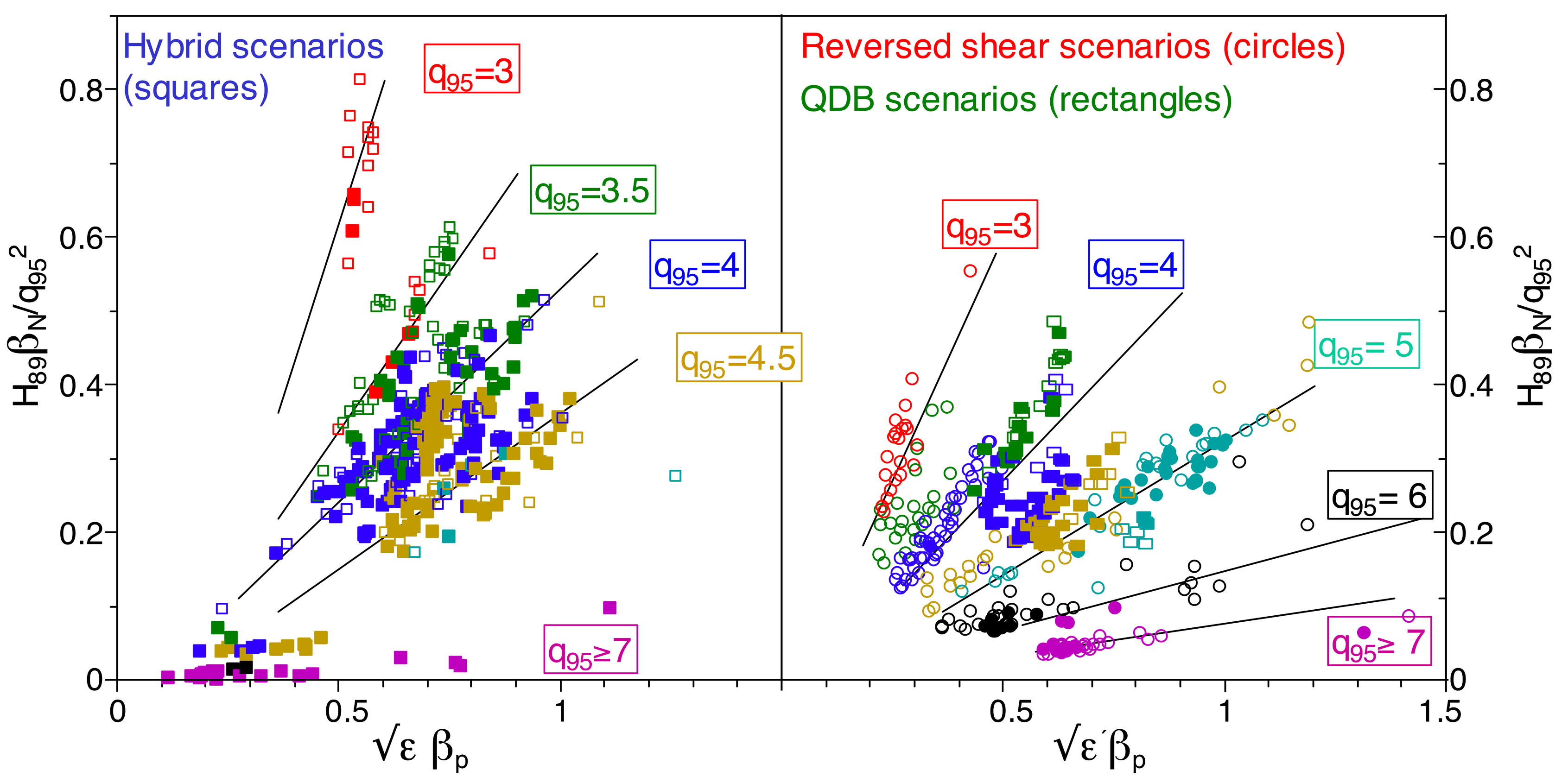
1. Transient discharges (*duration* $< 10\tau_E$, open symbols) can obtain high performance, but this cannot be maintained at these levels in more stationary conditions (*duration* $\geq 10\tau_E$, closed symbols).

2. For **hybrid discharges** there is no clear difference between the various experiments in the dataset (Tore Supra data, have lower performance). Performance in line with $Q \geq 10$ for ITER (long pulse).

3. The **reversed shear** results show two distinct groups:
   (a) Data from DIII-D (weak reversed shear, with $1.5 < q_{min} < 2$), close to the $Q \sim 5$ for ITER non-inductive scenario.
   (b) Data from JET and JT-60U at lower performance (typically at $q_{95} = 6\text{-}9$).

4. **Sufficient bootstrap current ?:**

Figure plotting $H_{89}\beta_N/q_{95}^2$ versus $\varepsilon^{0.5}\beta_p$ (~ bootstrap current for similar q-profiles).



- **Hybrid scenarios:**
  High performance at low q_{95}=3-3.5 (> ITER reference values), or at q_{95}=4-4.5 with $\varepsilon^{0.5}\beta_p = 1$. For this type of q-profile → 40% bootstrap fraction, suitable for long pulse operation.

- **Reversed shear discharges:**
  No stationary conditions for $q_{95} < 5$ (except QDB discharges). At $q_{95} \geq 5$, $\varepsilon^{0.5}\beta_p = 1$ is obtained → ~65% bootstrap current fraction (high q_0). Discharges at $q_{95} \sim 5$ (DIII-D) fulfil ITER requirements. However, at $q_{95} \geq 6$ performance is too low.

SUMMARY

An international scalar database (ITPA): Two advanced scenarios for ITER have been studied.

1. **Hybrid scenarios** with weak magnetic shear and q_0=1-1.5, β_N ~3 operating at ~50% non-inductive current fraction at q_{95} ~ 4, T_{i0} ~ C $T_{i,ped}$. At q_{95} ~ 3, exceeds ITER performance targets for *Q~10.*

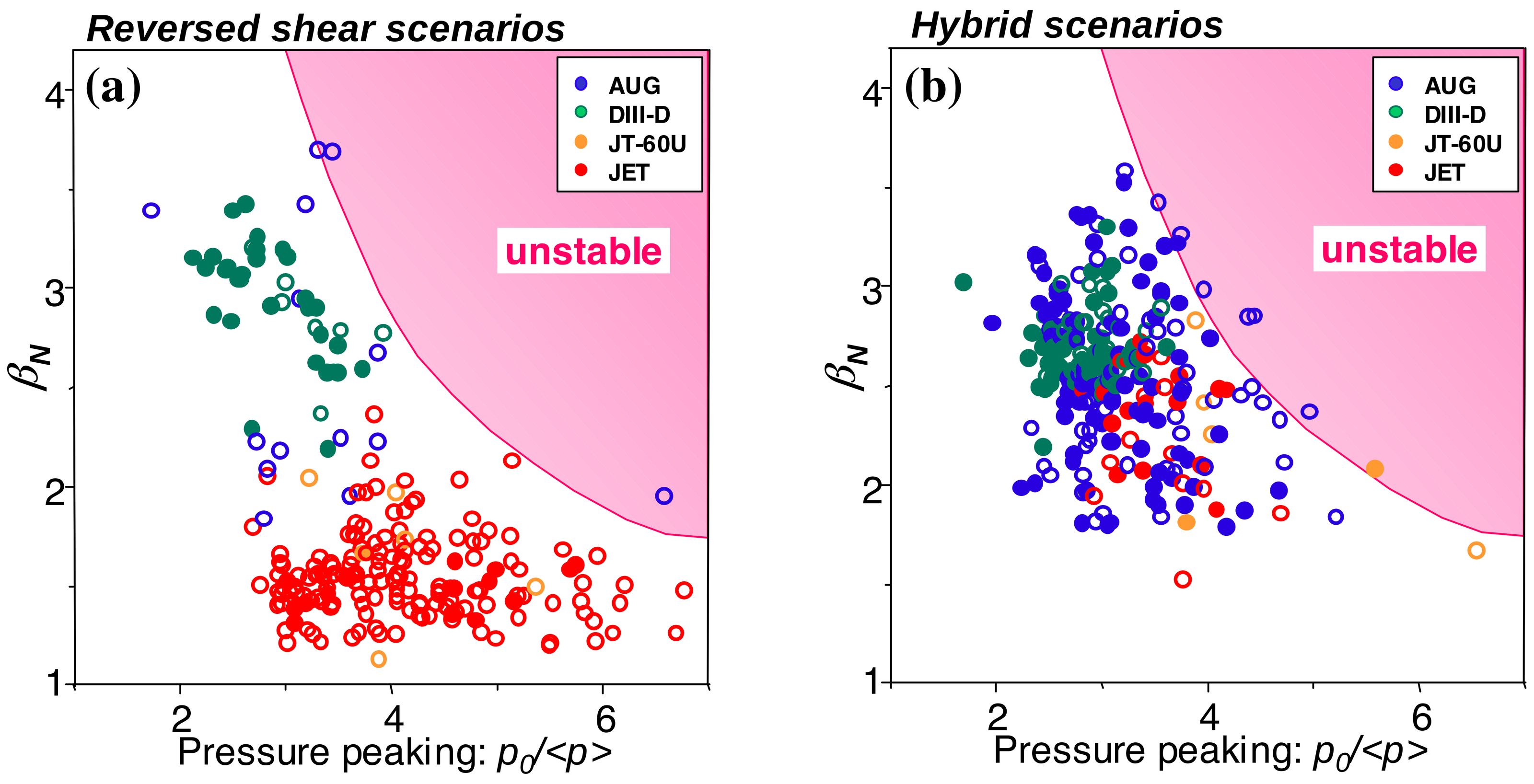
2. **Scenarios with reversed magnetic shear** and $q_0 > q_{min}$. Two groups of stationary discharges: q_{95} ~ 5 with β_N ~3 (DIII-D), q_{95} = 6-9 with β_N < 2 (JET and JT-60U). Includes comparison with QDB discharges.

Common to both regimes: Stationary only when T_{i0} ~ C $T_{i,ped}$.
The normalised confinement (H_{89}) increases with T_{i0}/T_{e0}, or with $(<n_e>/n_{GW})^{-1}$.
At ITER relevant ν^*, high confinement and peaked density profiles.

Scope for further study and collaboration between experiments worldwide (ITPA).

Key: Plasma stability (performance limits)

Advanced scenarios: Maximise beta → near one or more stability limits (see figure).
The maximum β_N drops sharply for high pressure peaking (p_0/<p>).



Reversed magnetic shear:

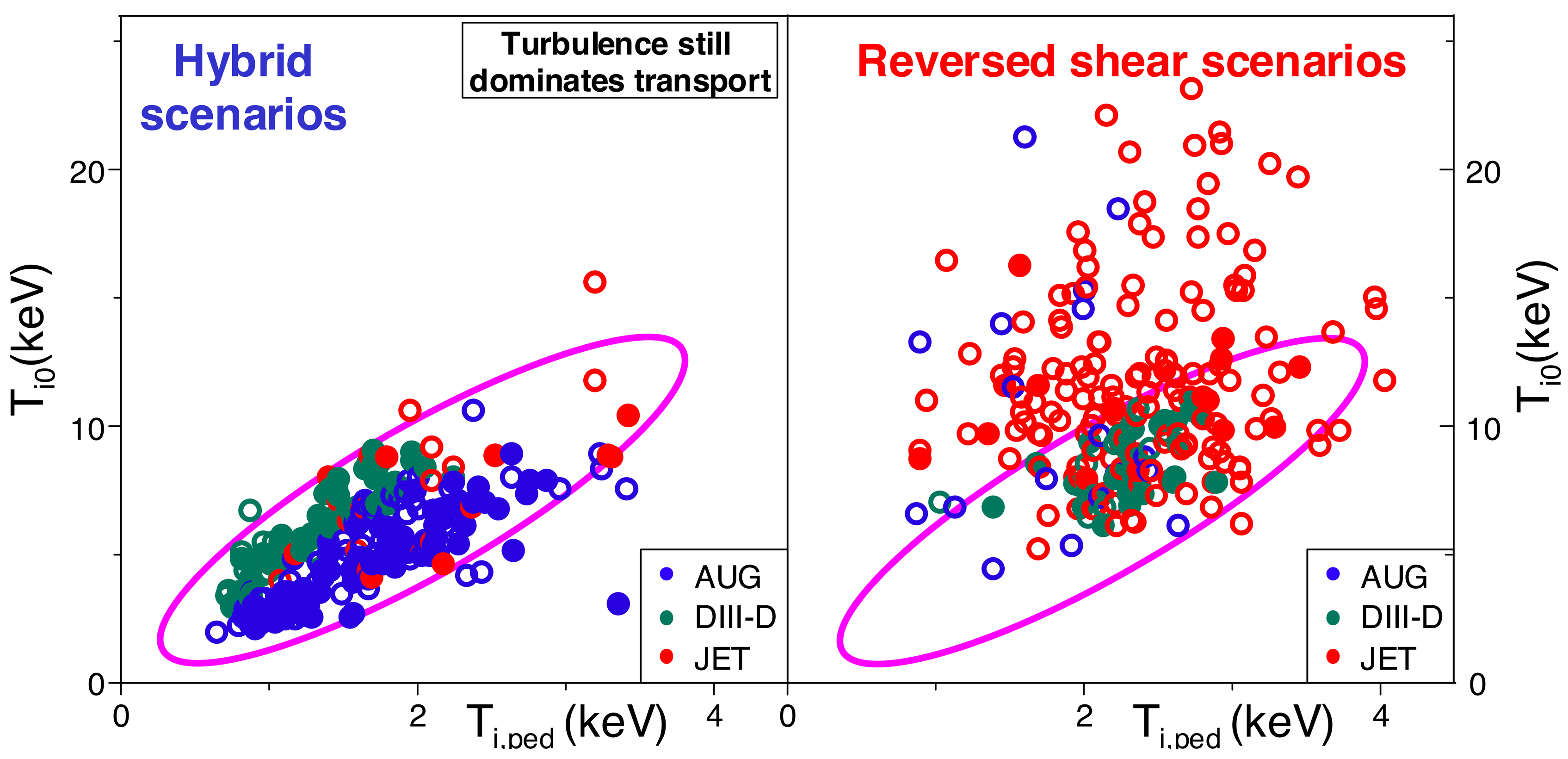
Internal transport barriers (ITBs) have inherently a lower beta limit. Broad pressure profiles are favourable for obtaining high beta (weaker ITBs). Only reversed shear discharges with weak transport barriers (DIII-D at q_{95}~5) just exceed $\beta_N / 4l_i = 1$.

Hybrid scenarios:

Operate with q_{95} = *3 to 4.5.* With pressure peaking p_0/<p> between 2 and 4. Obtain beta values (β_N ~ 3) close to the no wall limit ($\beta_N / 4l_i$ ~ 1).

Implications (see figure below):

Operating at high beta: Without, or with weak, internal transport barriers.
So: Central ion temperature is related to the edge ion temperature (T_{i0} ~ C $T_{i,ped}$).



Confinement of advanced scenarios

Standard H-modes, typically have stiff temperature profiles, advanced scenarios ?
→ Plot ion temperature in the core (T_{i0}) versus the ion temperature at 90% of the minor radius ($T_{i,ped}$) for hybrid discharges, and reversed shear discharges (figure above).

Hybrid scenarios:

Show a strong correlation between the core and edge ion temperatures, for data from several experiments.

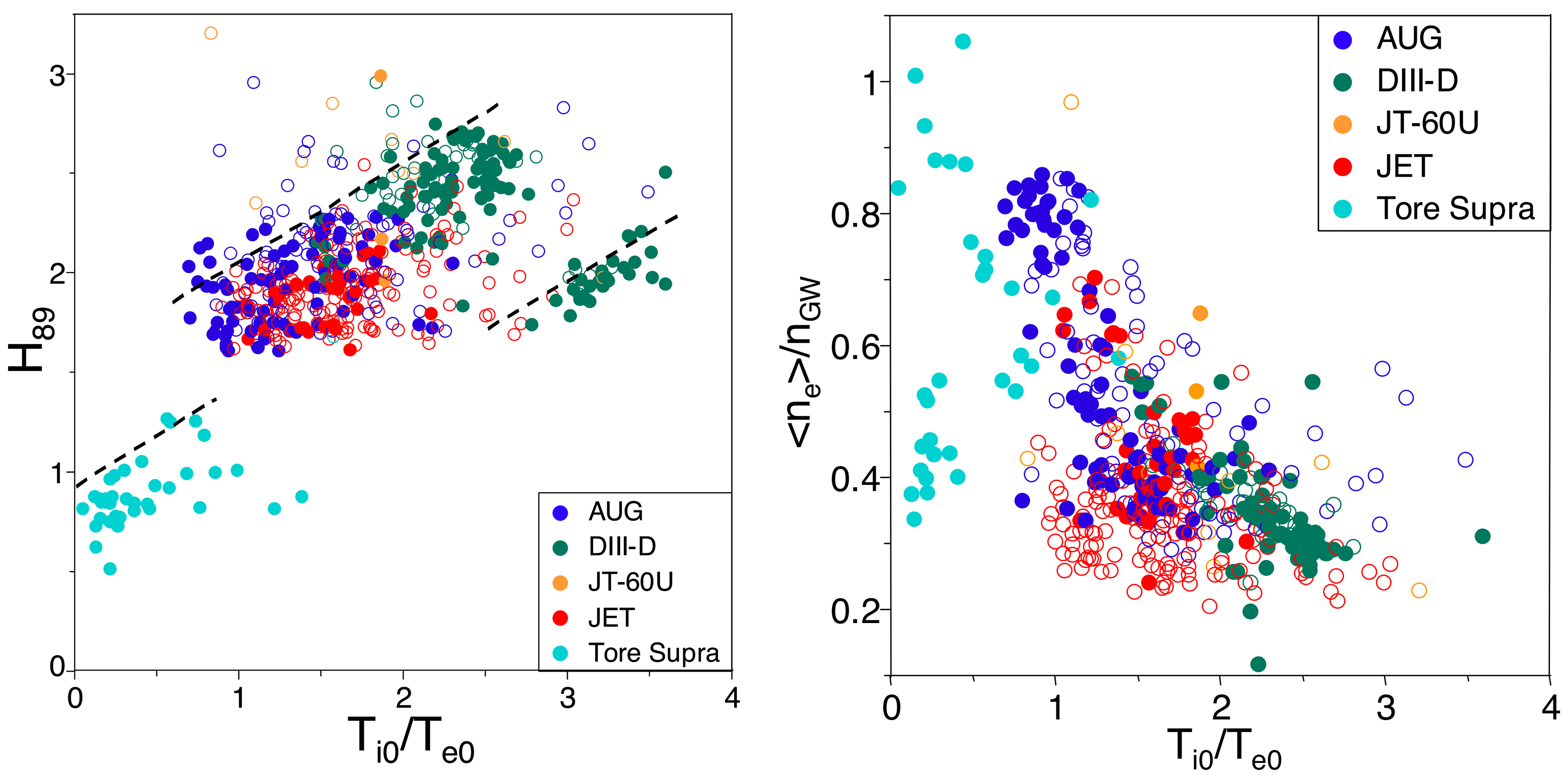
Reversed shear discharges:

Show a scatter plot, specifically for duration < 10τ_E (ITB !).
However, stationary reversed shear discharges cluster around the same ratio of T_{i0} to $T_{i,ped}$ as in hybrid discharges. (Similar behaviour for QDB discharges to some extent, not shown in this figure).

Confinement enhancement ?

Increase of H_{89} with T_{i0}/T_{e0}, for all experiments (same for all advanced scenarios ?).

$T_{i0}/T_{e0} \rightarrow 1$: Neutral beam heating at high density.
So T_{i0}/T_{e0} is strongly correlated with $<n_e>/n_{GW}$.
ASDEX Upgrade [4] uses ICRH at low density, → H_{89} > 2 for $T_{i0} \approx T_{e0}$
(corroborated by recent results from DIII-D [5]).



Extrapolation to ITER

Requirements for advanced operation in ITER can be met.

Most experiments are at low density → close to ITER ν^* values:

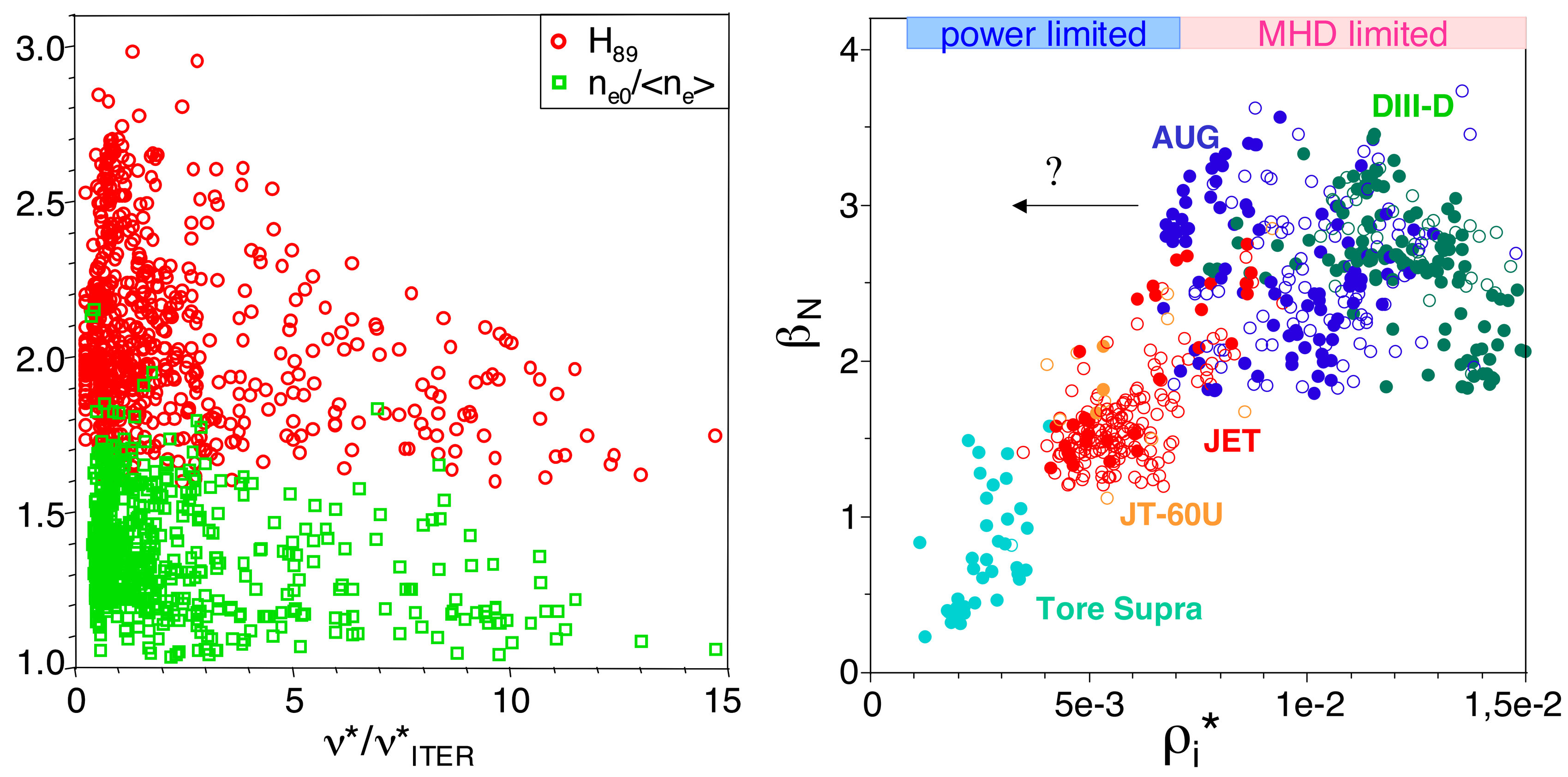
- Highest values for H_{89} at low ν^*.
- Peaked density profiles for ITER ν^* values.

However: Density peaking and H_{89} are not strongly correlated (~ 0.3).

NEED: Comparison with standard H-modes in similar conditions (future work in the ITPA groups).

High beta at low normalised ion larmor radius (ρ_i^*) ? (ITER ρ_i^* =1-2x10^{-3}).

ASDEX Upgrade and DIII-D: β_N ~ *3* (mostly Hybrid scenarios).
Drop in β_N going to low ρ_i^* ?: Some experiments do not have sufficient input power to achieve β_N ~*3* at low ρ_i^* (JT-60U and JET). Tore Supra: $T_{e0} > T_{i0}$ (hence low ρ_i^*)



References

[1] T. Fukuda et al *2001*, Proc. 28th EPS Conference (Funchal).
[2] T. Fujita et al *2003*, 30th EPS Conference (St. Petersburg).
[3] X. Litaudon et al *2004*, Plasma Physics and Controlled Fusion 46 (2004), A19
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