Status of and prospects for Advanced Tokamak regimes from multi-machine comparisons

By Xavier LITAUDON

Euratom cea

In collaboration with

E. Barbato, A. Bécoulet, E.J. Doyle, T. Fujita, P. Gohil, F. Imbeaux, G. Sips

for the ITPA Group on Transport and ITB Physics

and for the

International ITB Database Working Group

Acknowledgement : many fruitful discussions with Drs F. Crisanti, A. Tuccillo and among the members of the ITPA Group on Steady-state Operation and Energetic Particles, in particular with Drs C. Gormezano, T. Luce and S. Ide.

Author list

X. Litaudon[1], E. Barbato[2], A. Bécoulet[1], E.J. Doyle[3], T. Fujita[4], P. Gohil[5], F. Imbeaux[1], G. Sips[6],

for the ITPA Group on Transport and ITB Physics: J.W. Connor[7], E.J. Doyle[3], Yu. Esipchuk[8], T. Fujita[4], T. Fukuda[4], P. Gohil[5], J. Kinsey[9], N. Kirneva[8], S. Lebedev[10], X. Litaudon[1], V. Mukhovatov[11], J. Rice[12], E. Synakowski[13], K. Toi[14], B. Unterberg[15], V. Vershkov[8], M. Wakatani[16*] and the International ITB Database Working Group: T. Aniel[1], Yu.F. Baranov[7], E. Barbato[2], A. Bécoulet[1], C. Bourdelle[1], G. Bracco[2], R.V. Budny[13], P. Buratti[2], E.J. Doyle[3], Yu. Esipchuk[8], B. Esposito[2], T. Fujita[4], T. Fukuda[4], P. Gohil[5], C. Greenfield[5], M. Greenwald[12], T. Hahm[13], T. Hoang[1], D. Hogeweij[17], S. Ide[4], F. Imbeaux[1], E. Joffrin[1], Y. Kamada[4], J. Kinsey[9], N. Kirneva[8], X. Litaudon[1], V. Parail[7], K. Razumova[8], F. Ryter[6], Y. Sakamoto[4], H. Shirai[4], G. Sips[6], T. Suzuki[4], E. Synakowski[13], T. Takizuka[4] , T. Tala[18] and J. Weiland[19]

[1] Association EURATOM-CEA, 13108 St Paul lez Durance, France
[2] Associazione EURATOM-ENEA sulla Fusione, C.R. Frascati, Frascati, Italy
[3] University of California, Los Angeles, CA 90095, USA
[4] JAERI, Naka Fusion Research Establishment, Naka, Japan
[5] General Atomics, P.O. Box 85608, San Diego, California, 92186-5608 USA
[6] Max-Planck-Institut für Plasmaphysik, EURATOM Association, Garching, Germany
[7] UKAEA-EURATOM Association, Culham Science Centre, Abingdon, OX14 3DB, UK
[8] Kurchatov Institute of Atomic Energy, Moscow, Russia
[9] Lehigh University, Bethlehem, PA 18015, USA
[10] Ioffe Institute, St Petersburg, Russia
[11] ITER JWS, Naka, Japan
[12] Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[13] Plasma Physics Laboratory, Princeton University, Princeton, NJ 08543, USA
[14] National Institute of Fusion Science, Toki City, Japan
[15] Institut für Plasmaphysik, Association EURATOM-FZJ, Jülich, Germany.
[16] Kyoto University, Kyoto, Japan
[17] FOM Insituut voor Plasmafisica, 'Rijnhuizen', Nieuwegein, The Netherlands
[18] VTT Processes, Association Euratom-Tekes, P.O. Box 1608, FIN-02044 Finland
[19] Chalmers University and EURATOM-VR association, Gothenburg, Sweden
***deceased**

International Tokamak Physics Activity (ITPA)

- The ITPA is a collaboration involving the European Union, Japan, Russia, United States and China
  - Activity formally commenced in September 2001
  - Replaced the ITER Expert Group Activity

- The primary role of the ITPA is the coordination of Voluntary Physics R&D within the the Participant's Fusion Programs

- ITPA structures essentially continue the ITER Physics EG activities, but with broader scope relating to Burning Plasma Physics
  - Organized into seven Topical Groups, including Transport and ITB Physics TG (Chairmain E.J. Doyle)

Research priorities for the Transport and ITB Physics group

- **Develop worldwide multi-machine international database of advanced tokamak regimes : global and profile data**
- **Test of physics of ITB formation & sustainement**
- **Test of transport simulations (empirical and theory based models)**
- **Pursue understanding of critical issues for reactor relevant advanced tokamak regimes**
- **Provide predictive capability of AT regimes for burning plasmas**
- **Demonstrate burning plasma compatible operating regimes based on improved core transport properties**
- **Propose international collaborative experiments**

Recent publications

Fukuda T. et al 2001 in proc. 28th Eur. EPS Conf. (Funchal, 2001)

Sips A C C et al 2002a Plasma Phys. Control. Fusion **44** A391

Hoang G T et al 2002 Proc. 29th EPS Conf. (Montreux, 2002) Vol. 26B P-4.068

Gohil P et al 2003 Nucl. Fusion **43** 708

Fujita T et al 2003 in proc. 30th EPS, 7-11 July 2003, St Petersburg (EPS)

Connor et al 2003 to be published in Nuc. Fusion

Motivation for this paper

- **To date, the international ITB database has been mainly used to study the ITB formation conditions (prelude phase)**
- **In this paper, assessment of the present fusion performance of the advanced tokamak regimes for non-inductive operation (high performance phase of the scenario)**
- **Map the operational domain of AT regimes in terms of performance but also in term of dimensionless plasma physics quantities such as normalised Larmor radius, collisionality, Mach Number and ratio of ion to electron temperature**
- **Quantify the gap between present day and future advanced tokamak experiments**
- **Identify the required experimental effort to reduce the uncertainties when extrapolating non-inductive regimes to next step experiments**

ITER non-inductive scenarios

- **ITER scenarios :**
  - **inductive (high current ELMy H-mode)**
  - **'hybrid' scenario**
  - **Fully non-inductive current drive operation**

- **'Hybrid' scenario**
  - Long pulse operation
  - Q ~ 5
  - q_{95} ~3-4
  - monotonic q-profile

  q_0 ~ 1-1.5
  - H_H ~ 1 β_N ~ 2
  - I_{bs}/I_p ~ 20%

- **'Steady-State' scenario**
  - fully non-inductive operation
  - Q ~ 5
  - q_{95} ~4-5
  - Non-monotonic q-profile

  q_{min} ~ 2 ± 0.5 $q_0 - q_{min}$ <0.5
  - H_H ~ 1.5-2 $\beta_N \sim 3$
  - I_{bs}/I_p > 50%

- Attractive Steady-State reactor operation I_{bs}/I_p > 80% $\beta_N > 4$

References : Green B J et al 2003 Plasma Phys. Control. Fusion **45** 687
ITPA Group on Steady-state Operation and Energetic Particles

Data selected for this paper (1/2)

- **New entries have been added to the international database that consist of data taken during the well developed high performance phase of the discharges**

- **Data from both the 'hybrid' (without necessarily an ITB) or the 'steady-state' scenarios. These scenarios are the two candidates for the ITER non-inductive current drive operation [1-2] .**

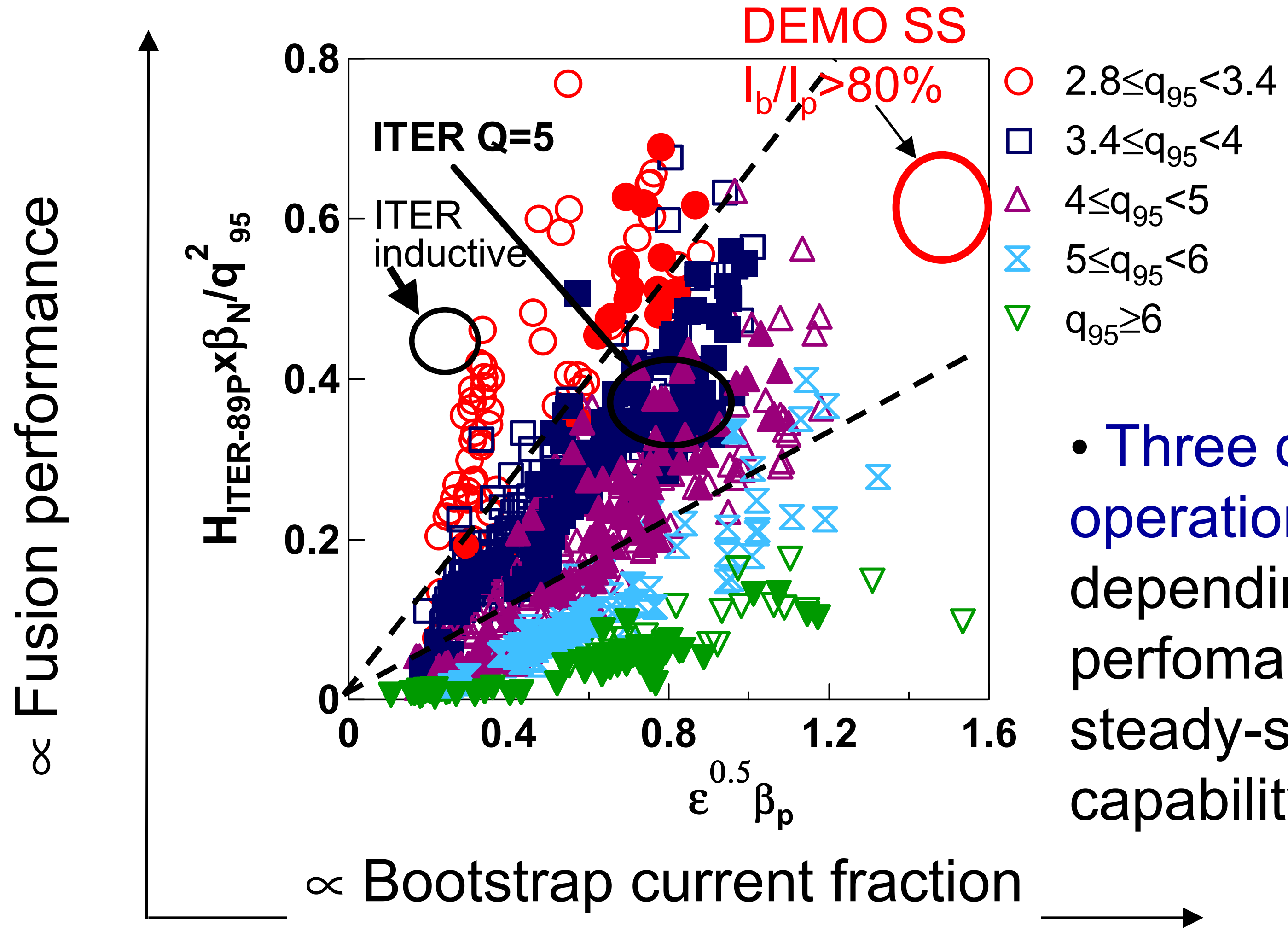
- **Advanced regimes from ASDEX Upgrade, DIII-D, FT-U, JET, JT-60U and TORE SUPRA**

[1] Campbell D.J. et al 2001 Phys. of Plasmas **8** 2041
[2] Green B J et al 2003 Plasma Phys. Control. Fusion **45** 687

Data selected for this paper (2/2)

Tokamak	Entries	Advanced regime	References
ASDEX Upgrade	372	Ion ITB 'Hybrid' scenario	Wolf et al 1999 Sips et al 2002b
FT-U	3	Electron ITB	V. Pericoli et al 2003
DIII-D	9	ITB with weak and reversed magnetic shear 'Quiescent Double Barrier' High bootstrap regime 'Hybrid' scenario	Strait E J et al 1995 Wade et al 2003 Doyle et al 2001 Luce et al 2003
JET Undertaking EFDA-JET	23 275	ITB regime with weak and reversed magnetic shear 'Hybrid' scenario	JET team 1999 Gormezano et al 1999 Challis et al 2001&2002 Litaudon et al 2003 Joffrin et al 2001 Sips et al 2003
JT-60U	18	High β_p regime (weak magnetic shear) Negative magnetic shear	Kamada et al 2001 Ide et al 2002 Fujita et al 2001 Fujita et al 2002
TORE SUPRA	40	Full current drive operation Electron ITB High β_p (Fast Wave electron heating) Pellet Enhanced mode	Jacquinot et al 2002 Litaudon et al 2001 Equipe TS 1996 Saoutic et al 1994 Géraud et al 1994

Operational diagram for AT operation : Fusion Performances versus bootstrap fraction



- Three domains of operation depending on perfomance & steady-state capability

- **The filled symbols $\tau_D/\tau_E > 10$, where τ_D/τ_E the duration of the high performance phase, t_D , normalised to the energy confinement time, τ_E**
- **τ_D is defined as the duration where $W_{dia} \geq 85\% max(W_{dia})$**

Relevance of this new operational diagram

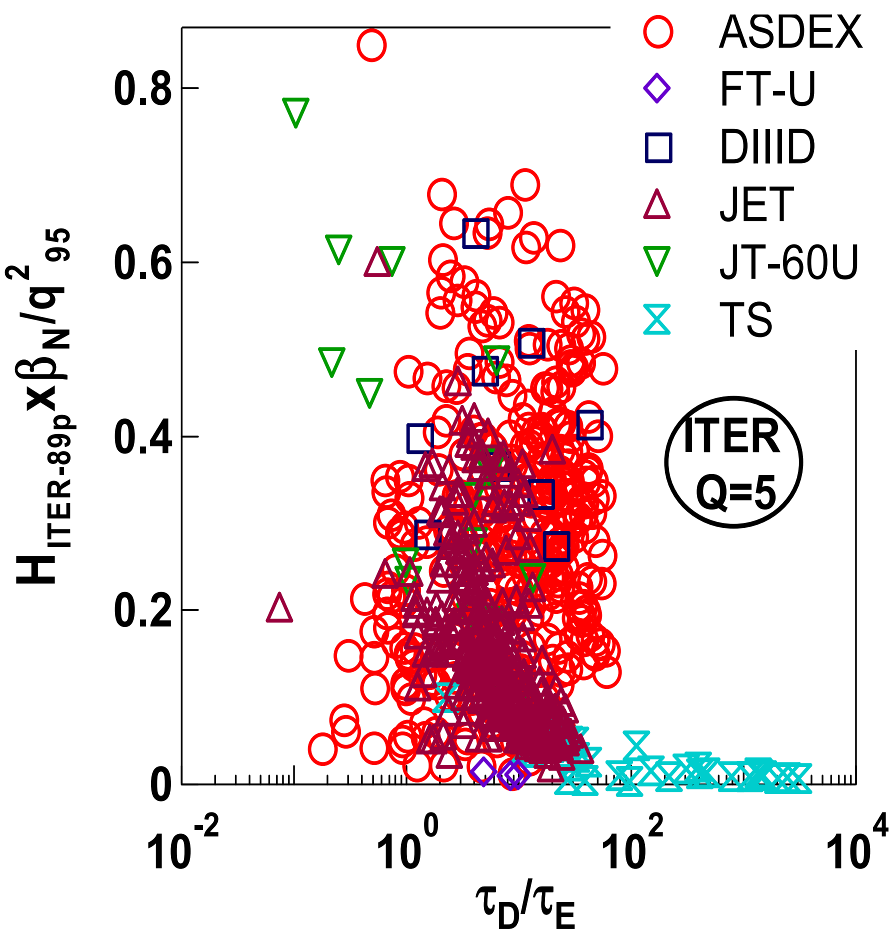
- **Assess the progress both in terms of Fusion Performances and prospect for steady-state through the optimisation of the bootstrap current fraction**
- **Machine size independent that allows a multi-machine and multi-regime comparison:**

➢ $H\beta_N/q^2_{95}$ is machine size independent parameter that quantifies both the fusion power density $\propto \beta^2_N/q^2_{95}$ and triple fusion product $\propto H^2/q^2_{95}$

➢ Bootstrap current fraction $\propto \varepsilon^{0.5}\,\beta_p$: The machine dependence is included within ε

- **In this diagram, there is a continuous progression from the 'inductive' to the 'hybrid' and 'steady-state' tokamak operating mode**

Figure of merit versus duration of the high performance phase

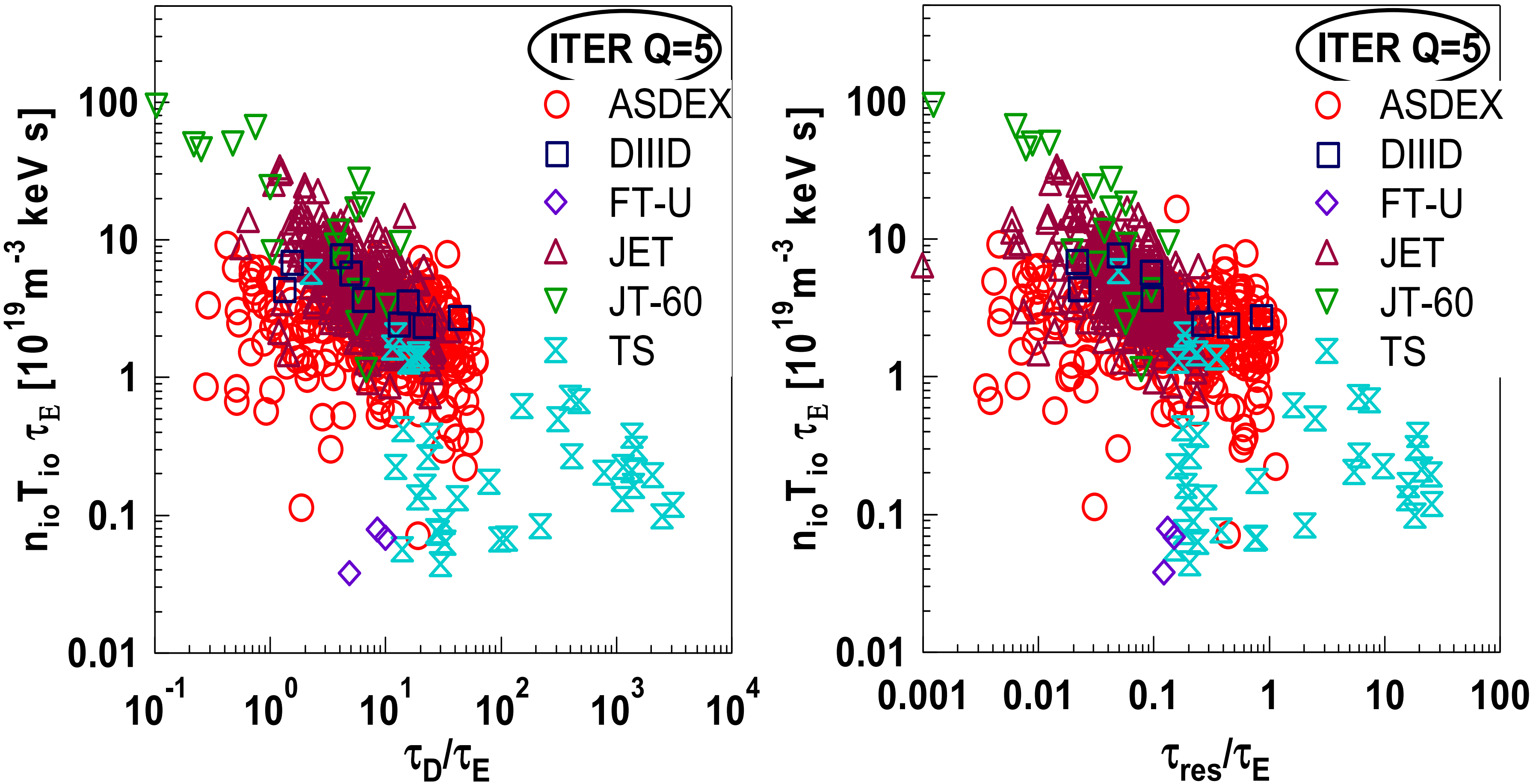


- The challenge is to extend the duration of the fusion performance:
  - ➢ technical and scientific issues

- **τ_D/τ_E the duration of the high performance phase, τ_D , normalised to the energy confinement time, τ_E**

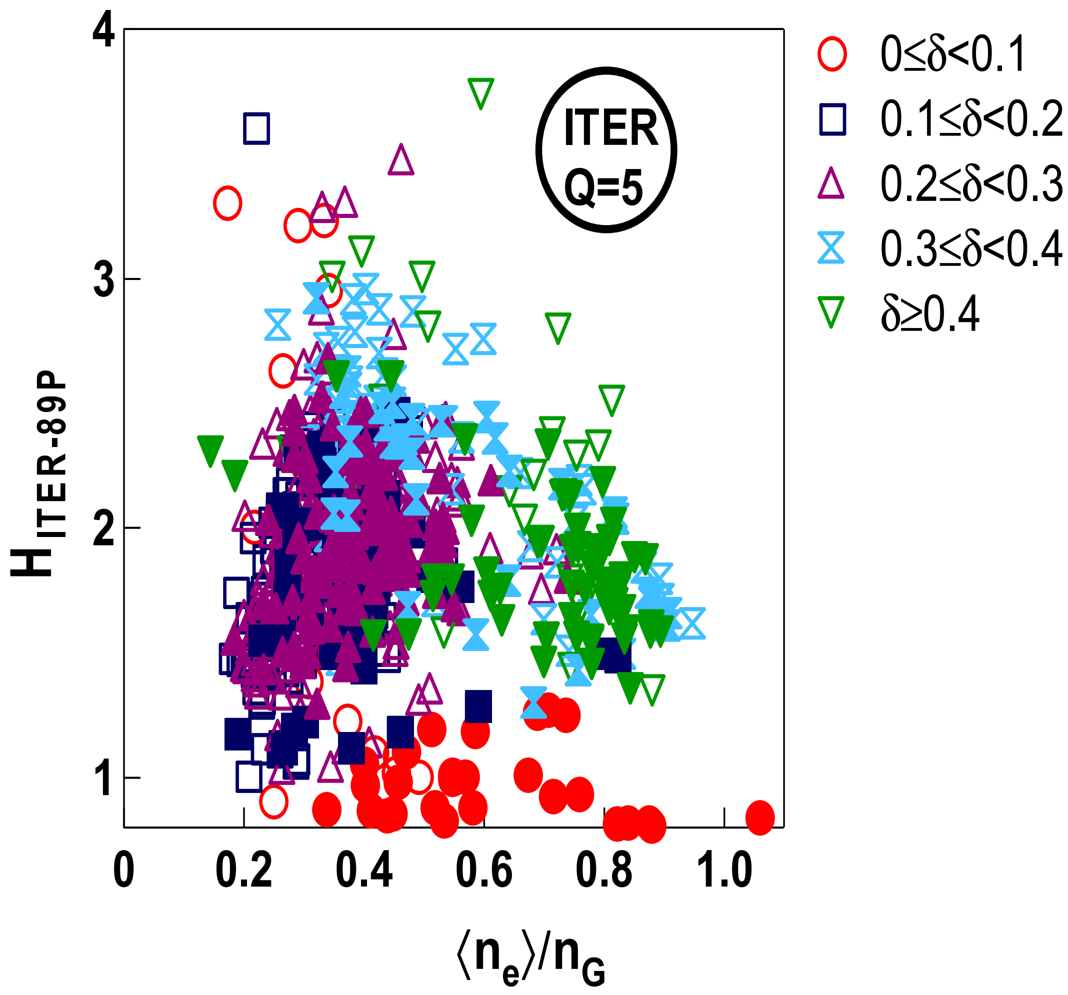
Triple fusion performance versus duration

Maintaining performances for a long duration requires operating relatively far from the maximum operational limit



- τ_{res}/τ_E the duration of the high performance phase, τ_D , normalised to neo-classical resistive time, $\tau_{res} = \mu_o \sigma a^2$

Operational limit: towards high density



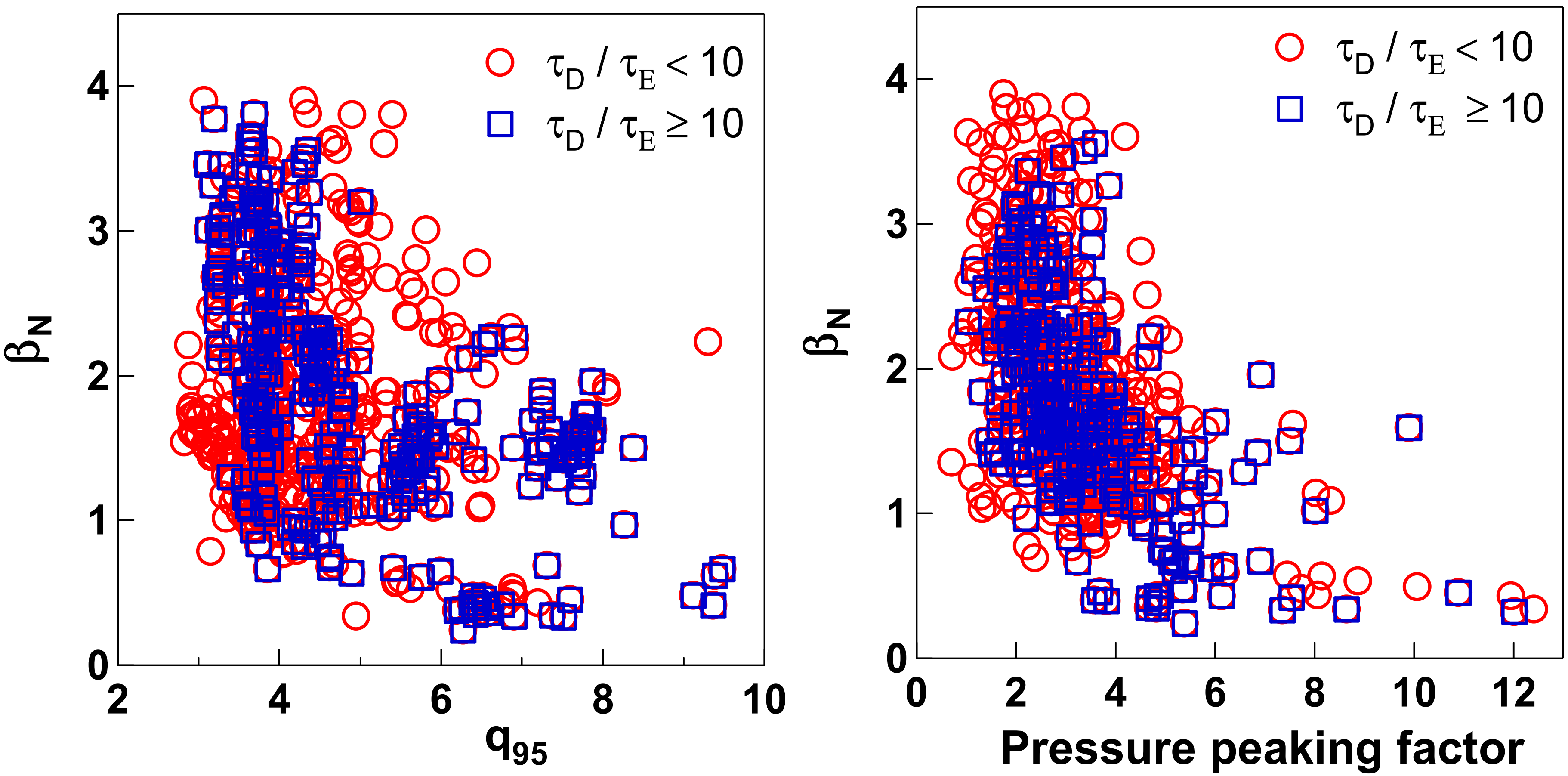
- difficulties to reach high density + confinement : is it an edge or core limit ?

- high δ is favourable

- at $\langle n_e \rangle / n_G \sim 0.8-1$ increasing H > 2 might require a wide ITB ?

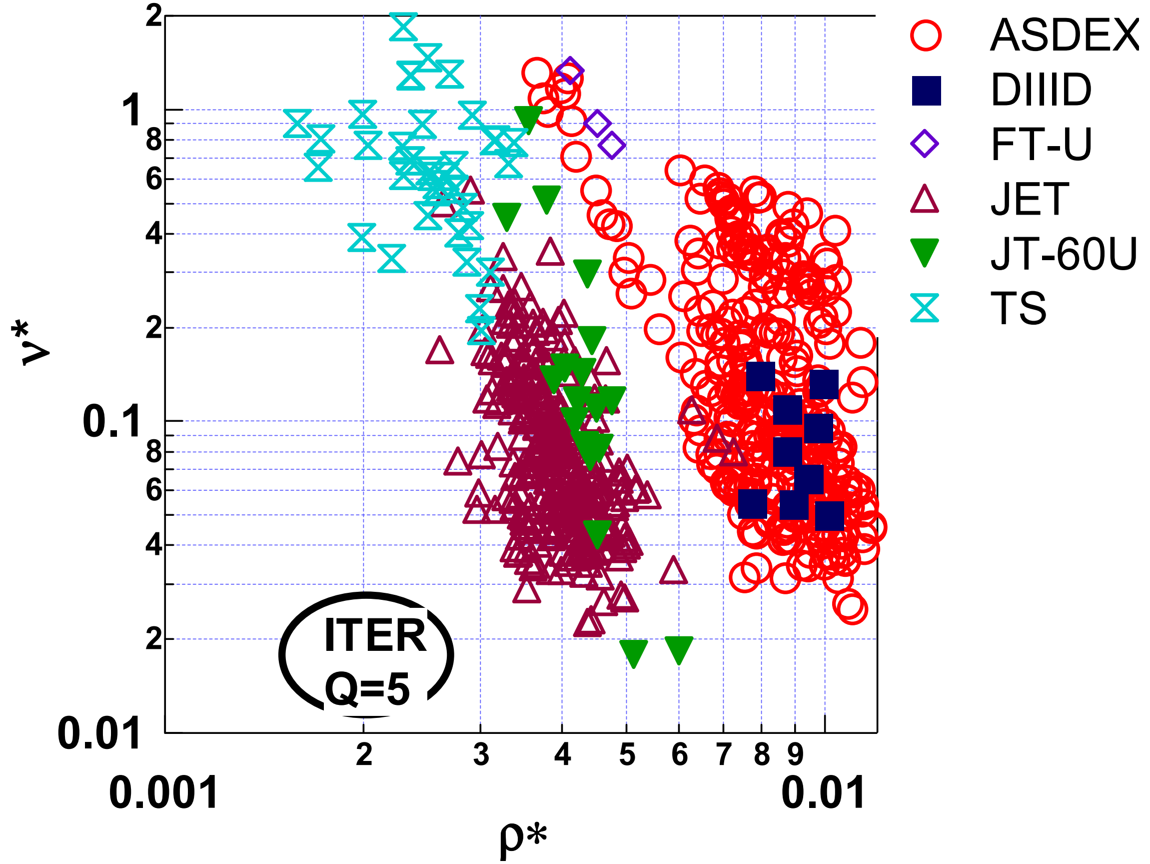
- raising density in AT :
  - Lower non-inductive CD
  - Lower temperature & faster resistive time
  - Lower plasma rotation
  - Higher bootstrap

Operational limit : towards high β_N



- β_N ~ 3.9-3.8 DIII-D with ITB & ASDEX 'hybrid regime'
- High β_N requires broad pressure peaking: ➢ in ITB plasmas, a wide ITBs should be formed and sustained.

Operational domain in term of normalised quantities



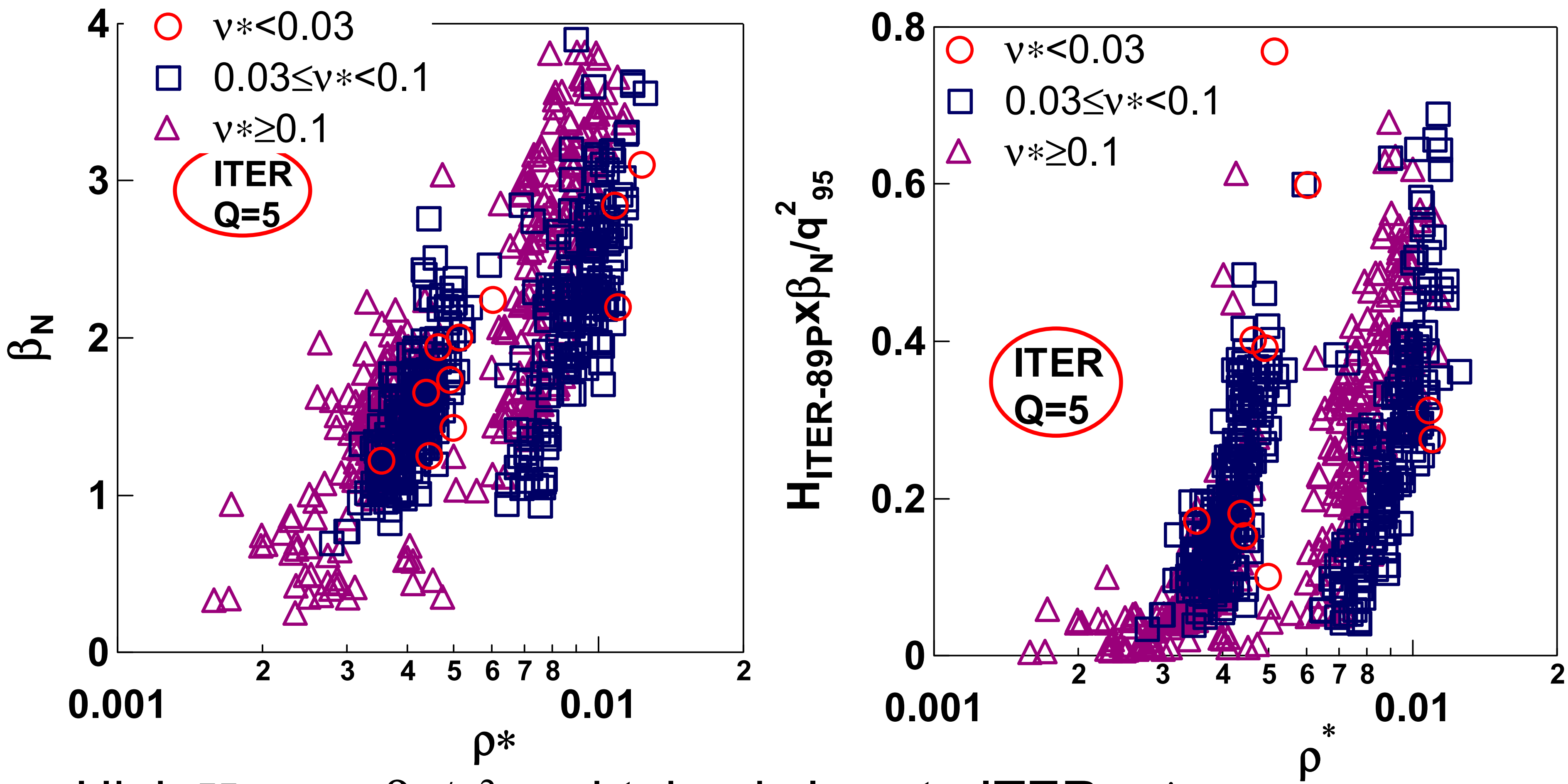
- ν_e* the effective collision frequency for the trapped particles normalised to their bounce frequency, $\nu_e^* \propto n_e q R / (\varepsilon^{3/2} T_e^2)$

- $\rho^* = \rho_s / a$ the normalised ion Larmor radius at the sound speed where $\rho_s = c_s / \omega_{ci} \propto T_e^{1/2} m_i^{1/2} / (ZaB_o)$

JET : domain of reduced ν_e* and ρ* ($\nu_e^* < 0.05$ and $\rho^* < 3\text{x}10^{-3}$)

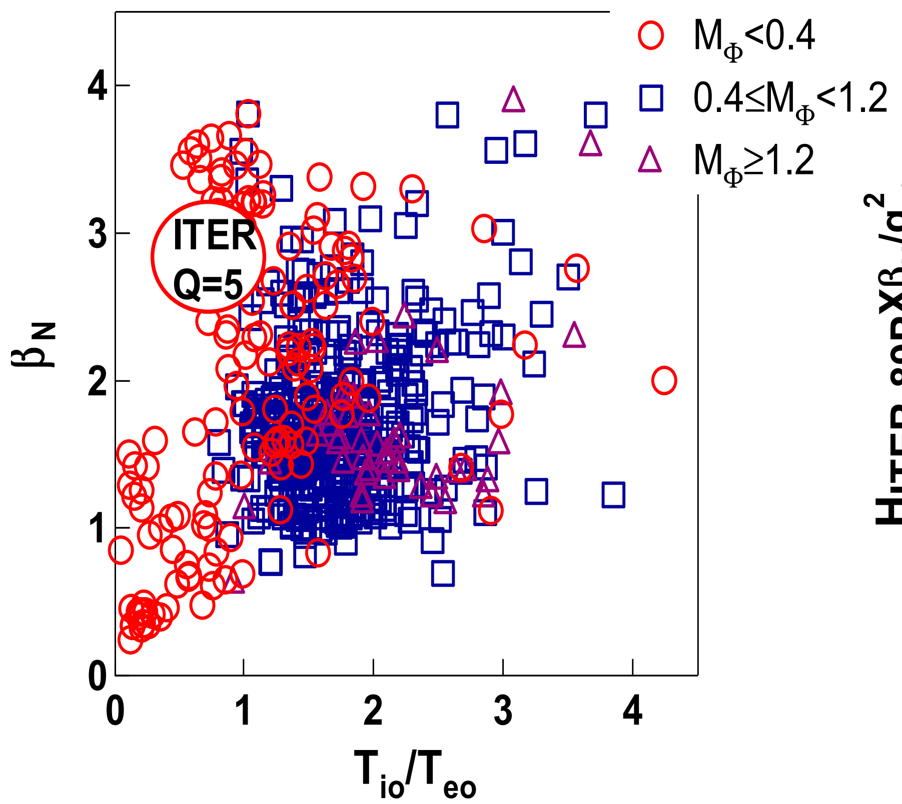
➢ high field, $B_o \geq 3.5$T, high $\langle t_e \rangle \sim 3$keV, moderate density, $\langle n_e \rangle \sim 2\text{x}10^{19}\text{m}^{-3}$ at $q_{95} \sim 4\text{-}5$ ($I_p \sim 3$MA)

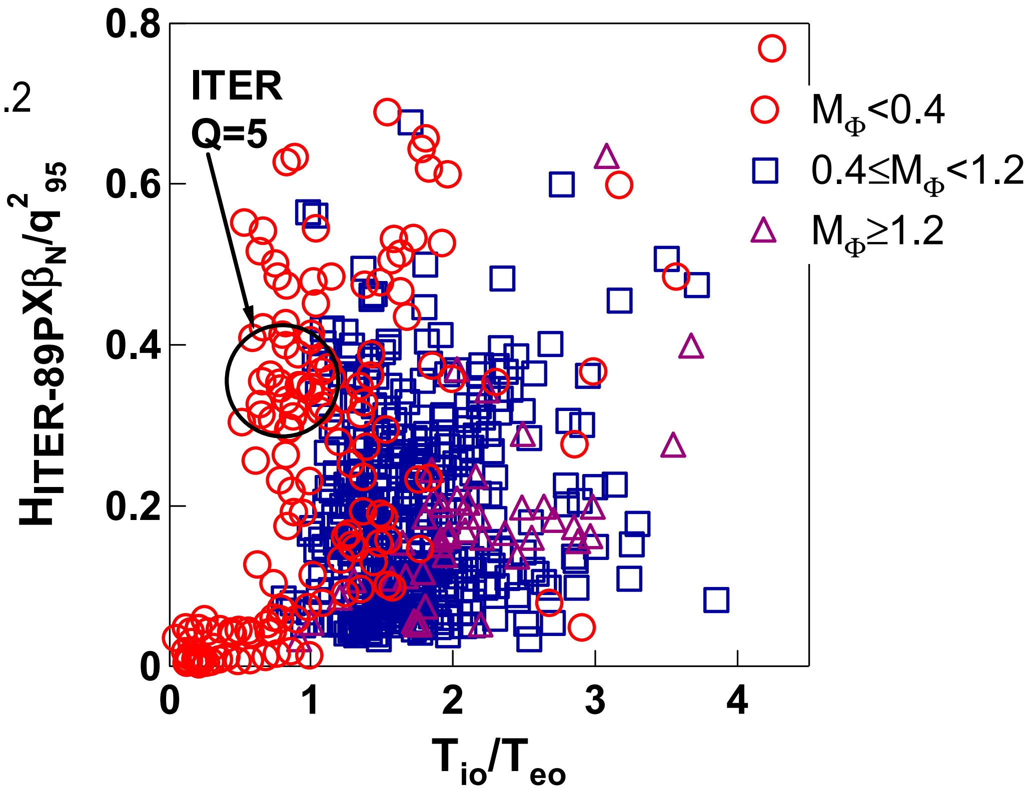
β_N and fusion figure of merit versus ρ^* for various ν^*



- High $H_{ITER-89P}\beta_N/q^2_{95}$ obtained close to ITER ν_e^*
- Low values of ρ^* expected in ITER have been obtained but at low performances ($\beta_N < 1.5$ and $H_{ITER-89P}\beta_N/q^2_{95} < 0.2$) and high collisionality ($\nu_e^* \sim 0.1$)

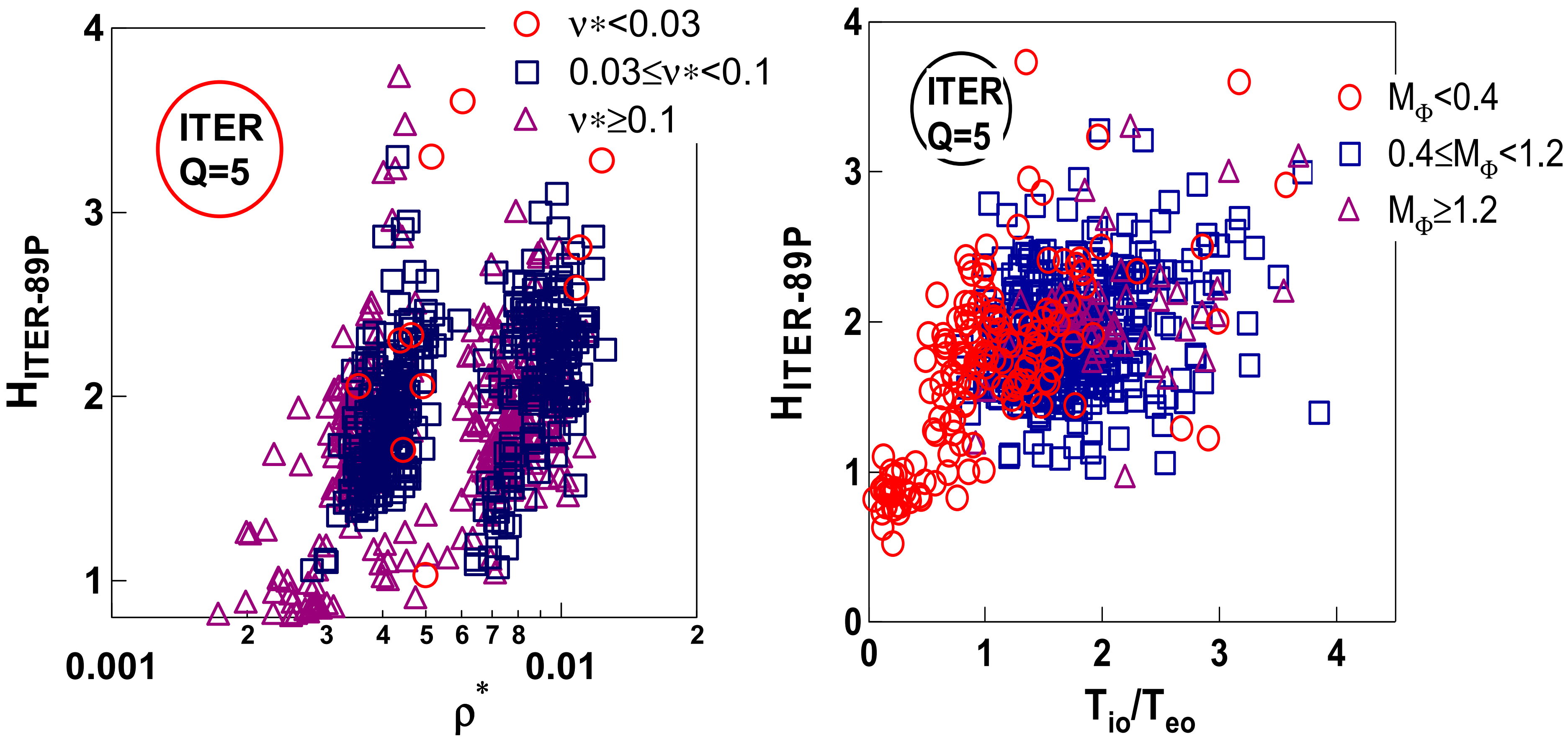
β_N and fusion figure of merit versus T_{io}/T_{eo} for various Mach numbers





- $M_\Phi = V_\Phi / c_s$ where V_Φ is the core toroidal rotation and c_s is the ion sound speed
- Data at T_{io}/T_{eo}~1 and $H_{ITER\text{-}89P}\beta_N/q^2_{95}$~0.3-0.4 have been obtained in the 'hybrid' regime : ASDEX, JET and JT-60U ('high β_p')
- High performances at low M_Φ (β_N >2, $H_{ITER\text{-}89P}\beta_N/q^2_{95}$>0.4 and M_Φ <0.4): ASDEX-U (hybrid regime) and JT-60U with a combination of co and counter current NBI

Confinement enhancement versus ρ* and T_{io}/T_{eo}



- Higher confinement factor should be obtained at $T_i/T_e \sim 1$

Discussion and conclusion (1/3)

- **Extensive database on Advanced Tokamak operation**
- **A new operational diagram characterising advanced tokamak operation using multi-machine database : the figure of merit for fusion performance and confinement $H_{ITER-89P}\beta_N/q^2_{95,}$ versus the bootstrap current fraction $\propto \varepsilon^{1/2}\beta_p$**
- **In this diagram, there is a continuous progression from the 'inductive' to the 'hybrid' and 'steady-state' tokamak operating mode**
- **Significant progress: $H_{ITER-89P}\beta_N/q^2_{95}$~0.3-0.4 at β_p ~ 1 at q_{95} ~ 5. This range of performances is expected for Q=5 non-inductive current drive operation for ITER**

Discussion and conclusion (2/3)

- **fusion performances tend to decrease with the pulse duration : extending the plasma performances achieved on a short time scale requires operating safely far from the operational limits**

- **difficulties to reach high density + confinement : at $\langle n_e \rangle / n_G \sim 0.8\text{-}1$ $H \leq 2$**
  - **is it an edge or core limits ?**
  - at $\langle n_e \rangle / n_G \sim 0.8\text{-}1$ increasing $H > 2$ might require a wide ITB ?

- **High $\beta_N \sim 3$ (at $q_{95} < 5$) requires broad pressure profiles**
  - **wide region with improved core confinement**

Discussion and conclusion (3/3)

- **ITER plasmas : different domain of dimensionless parameters, low values of $\rho*$, ν_e*, M_Φ and with T_i/T_e~1.**
- **These parameters have been widely scanned in present day AT experiments**
- **Advanced regimes allow to operate close to ITER ν_e* . At ITER ν_e* ($\nu_e* < 0.03$) , $H_{ITER-89P}\beta_N/q^2_{95}$ ~0.3-0.4 at $\rho* \sim 5 10^{-3}$, i.e. 2 or 3 times above $\rho*$ for ITER Q=5 non-inductive regime.**

➢ **cross-machine experiments : assess the variation of $\rho*$ & ν_e*** on AT performances ?

- **Data at T_{io}/T_{eo}~1, $M_\Phi < 0.4$ and $H_{ITER-89P}x\beta_N/q^2_{95}$~0.3-0.4 obtained in the 'hybrid' regime : ASDEX, JET and JT-60U**