Scientific rationale for the power upgrade on JET: SS operation with high bootstrap current

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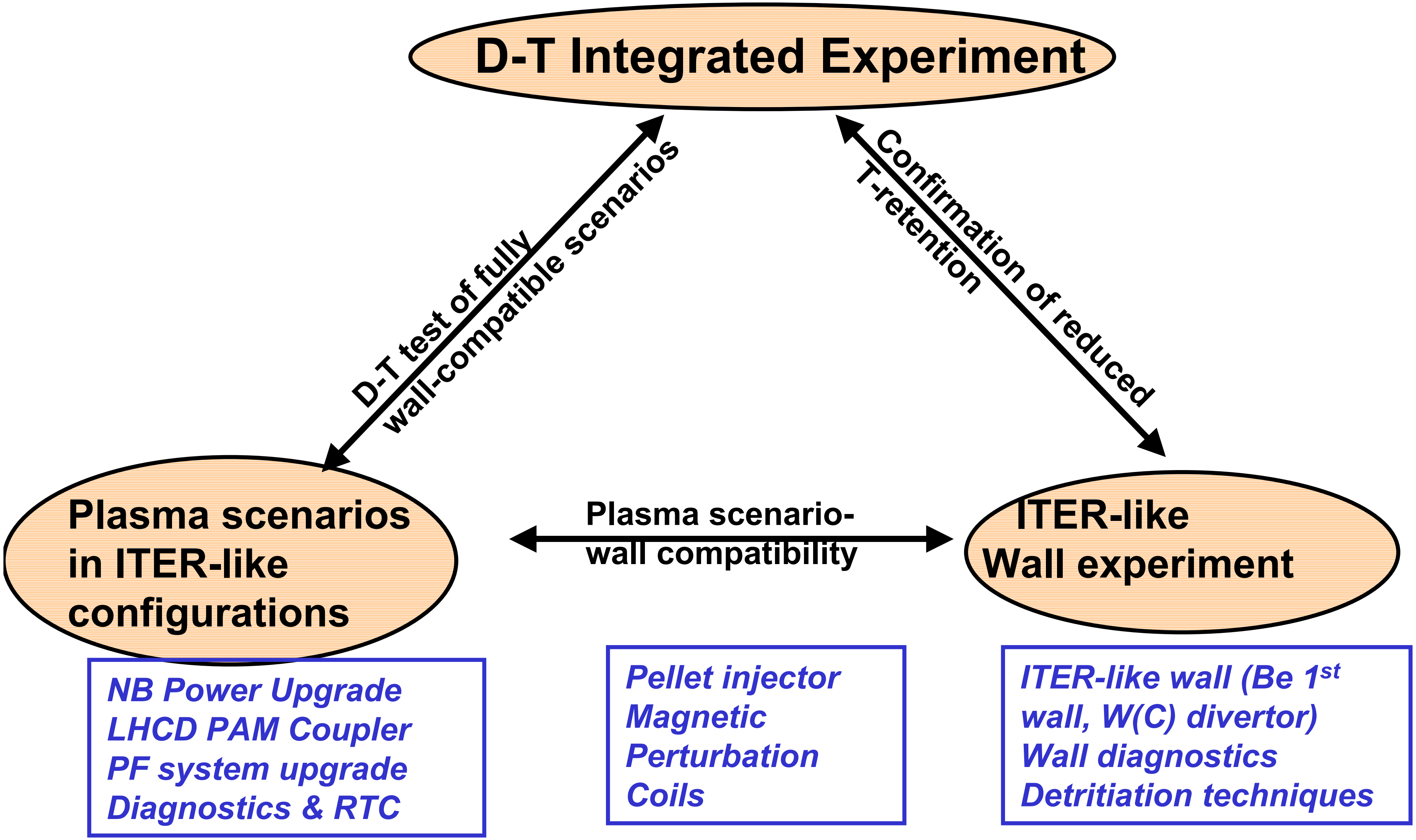
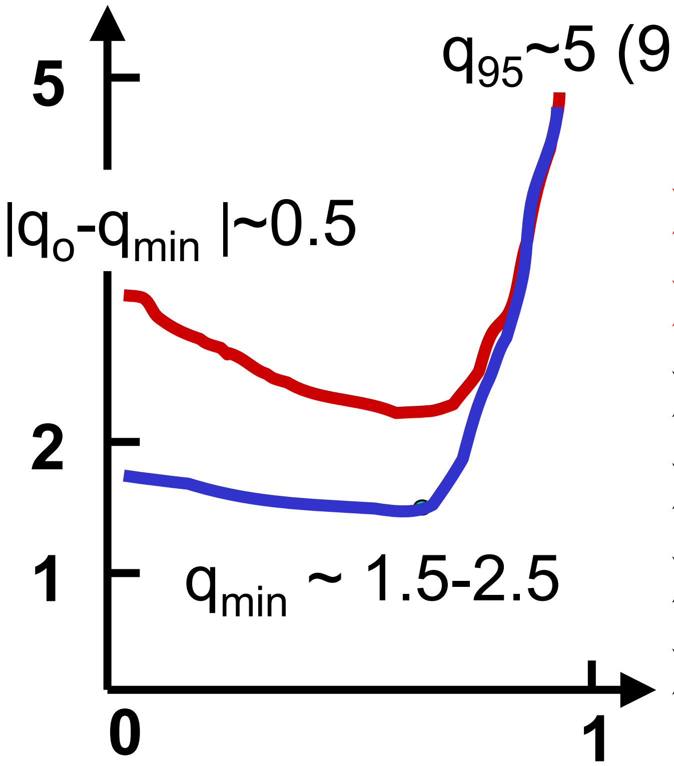
Long term programme at JET (2007-2010) as proposed at STAC AHG (25-26 Nov 2004) by J. Paméla et al



Requirements for ITER advanced operation

- ITER advanced scenario: steady-state operation at Q ~ 5 (P_α~P_{add}) with **full non-inductive current drive**

- Requirements for ITER AT operation (ITPA):



- ➢ $I_{non\text{-}inductive}/I_p$ ~100%, $I_{boot}/I_p \geq 50\%$
- ➢ β_N~3, $H_{98(y,2)}$ ~1.5
- ➢ n_l~$7\times10^{19}m^{-3}$ (n/n_{Gw}~0.7)
- ➢ T_i/T_e ~ 1, at V_ϕ~100-150km/s
- ➢ $M_\phi = V_\phi / c_s$~0.2 , ρ^* ~ 2 $\times10^{-3}$, ν^* ~ 2×10^{-2}
- ➢ τ_D~3000s, τ/τ_E~1000, τ/τ_{res}~4

Power increase rationale for advanced scenario development

- With the presently available H & CD powers, **non-inductive CD operation is strongly limited** to a narrow operational domain

- By increasing the H & CD (**P_{tot}~45MW**), the operational space is dramatically extended in terms of **current** and **density**

  - **Access to high bootstrap I_{boot}/I_p>50% at 2.5MA, n_l>3, β_N>2.5**
  - Improving compatibility with a **Be wall** and the **divertor** requirements

- Confinement dependencies not established in ITER relevant AT regimes & **no reliable 0-D scaling** or **multi-machine model**

  - Development, validation of 1-D transport and theory based models to predict the ITB characteristics & SS regimes in ITER conditions

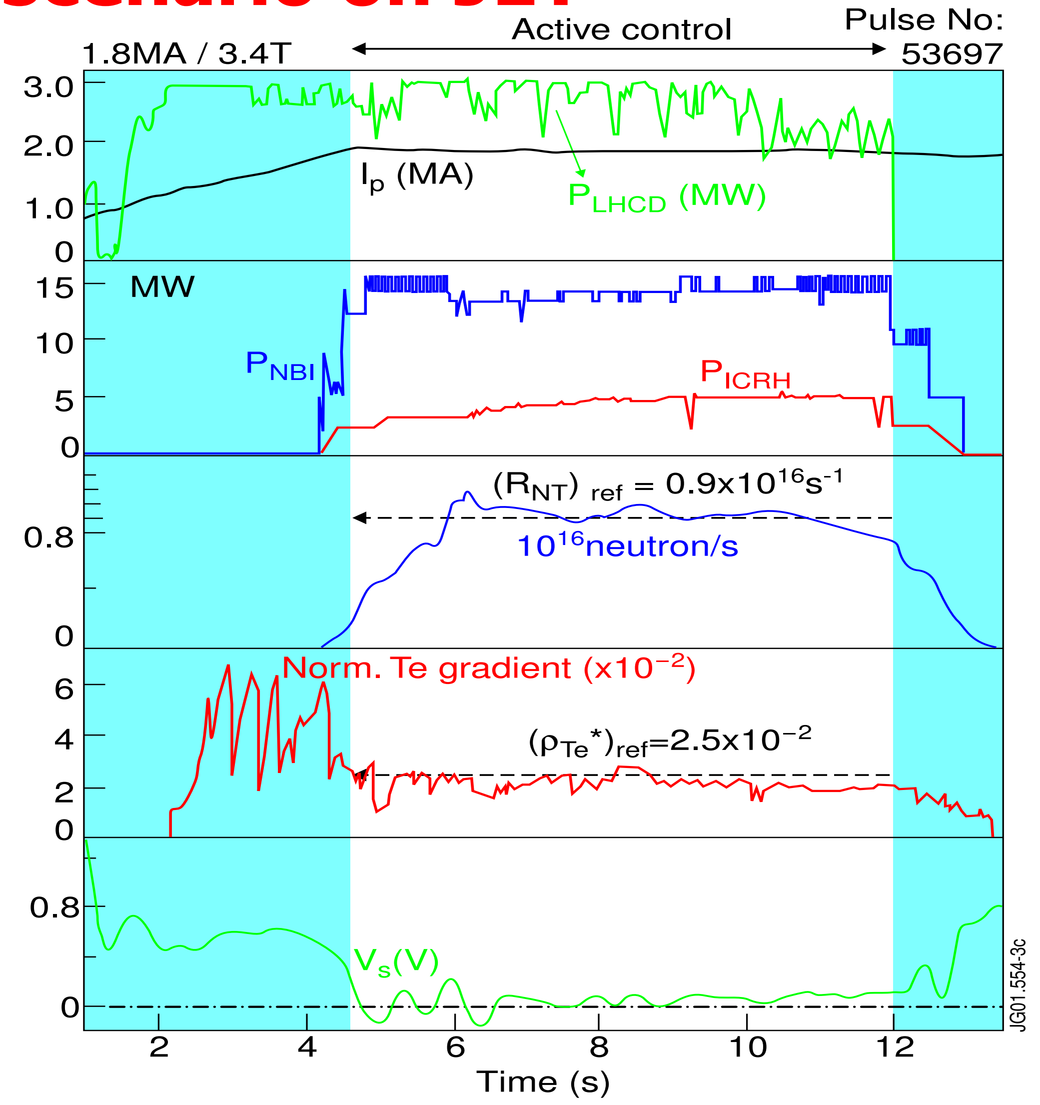
- At **P_{tot}≥35MW** the confinement physics and ITB threshold condition with β could be studied at ITER-relevant

  - **q-profile**, I_{boot}/I_p , ρ* and ν* (and **T_i/T_e~1** at reduced power)
  - V_ϕ with a third NBI box in counter injection

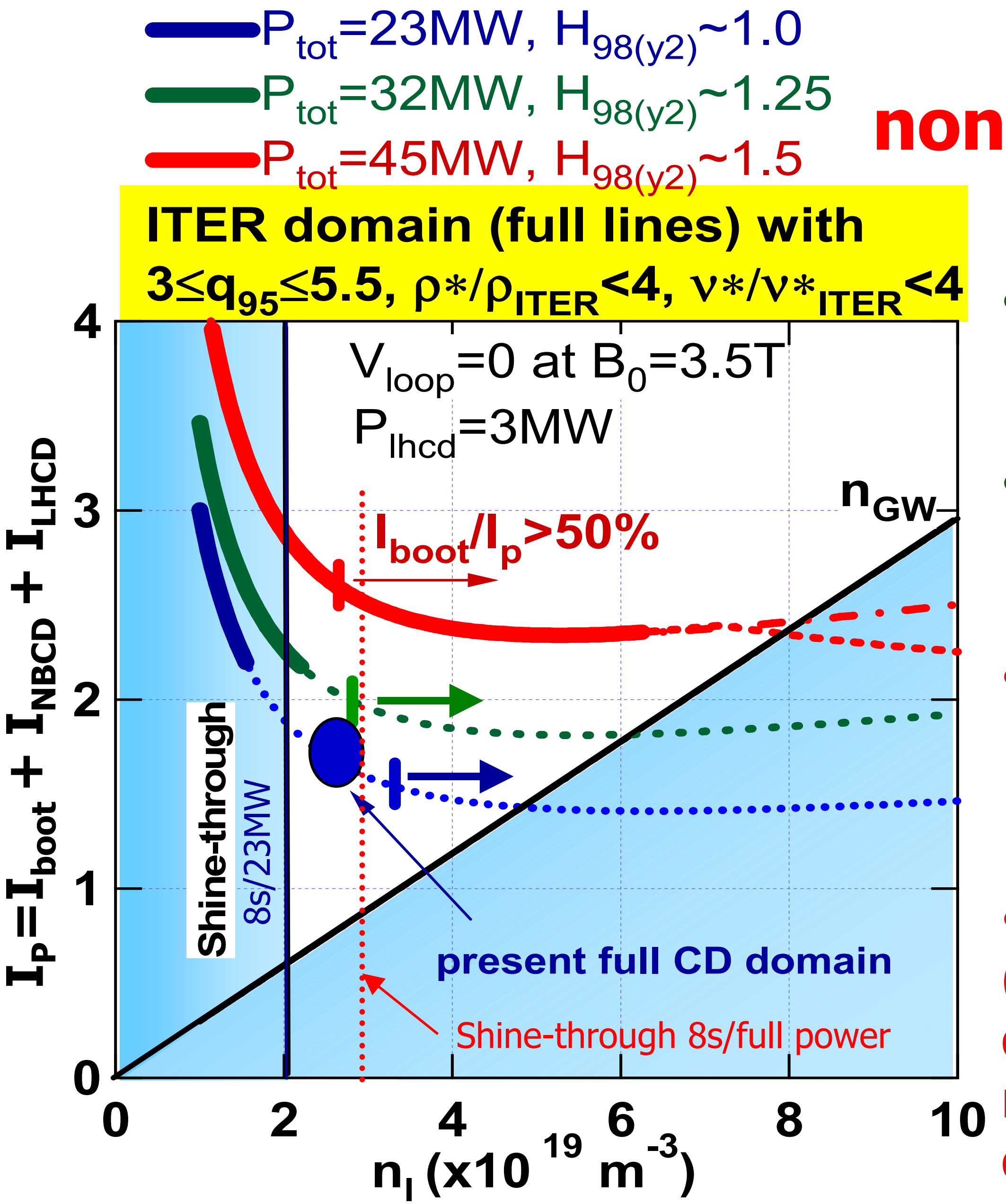
Strategy for developing ITER relevant advanced scenario on JET

- Begin with existing non-inductive regime:
  - 1.8MA/3.4T; q_{95}~6.2
  - $H_{98(y,2)}$~1
  - β_N~1.6; n_l~2.6x10^{19}m^{-3}
  - I_{boot}/I_p~30-40%
  - Q_{DT-EQ}~0.1-0.15

- **Increase performance with higher LHCD, ICRH & NBI powers** allowing increase of :
  - current and bootstrap
  - density
  - confinement & β_N (wider ITB)
  - duration (long pulse heating)



ITER relevant non-inductive CD regimes



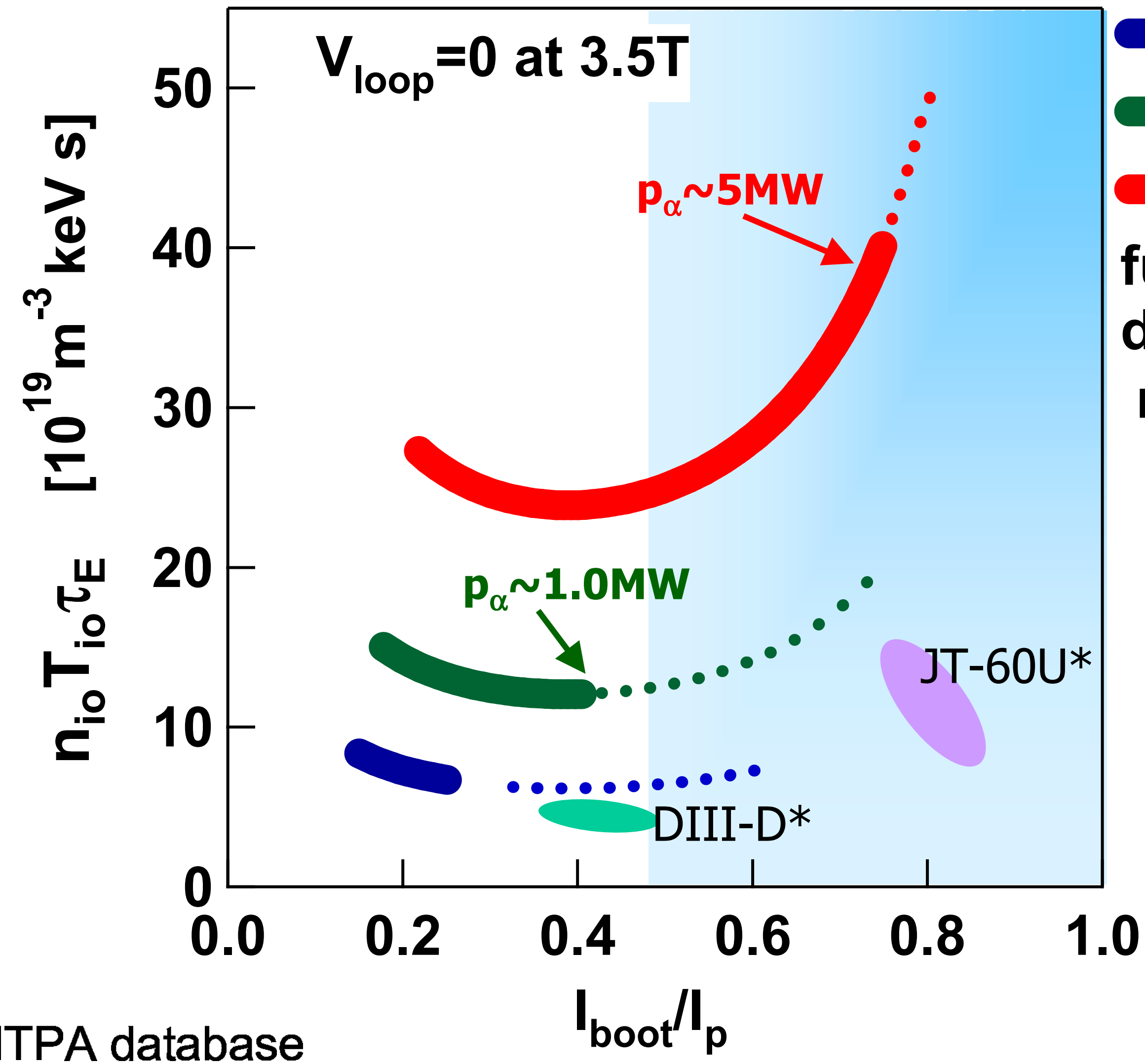
32 MW

- ITER relevant AT regimes:
  - low densities & $I_{boot}/I_p<40\%$
- High density regimes :
  - low I_p <2MA & β_N <2.5

45MW

- Operational space is extended
  - I_p ~2.5MA (q_{95}~5), density
  - I_{boot}/I_p ~50-75% , β_N ~2.5-3.5
- **Exploration of β_N limits (~3.5) at $I_{boot}/I_p>50\%$ & densities above shine-through more compatible with divertor/Be**

Scientific feasibility of a bootstrap-dominated regime at high fusion performance ?

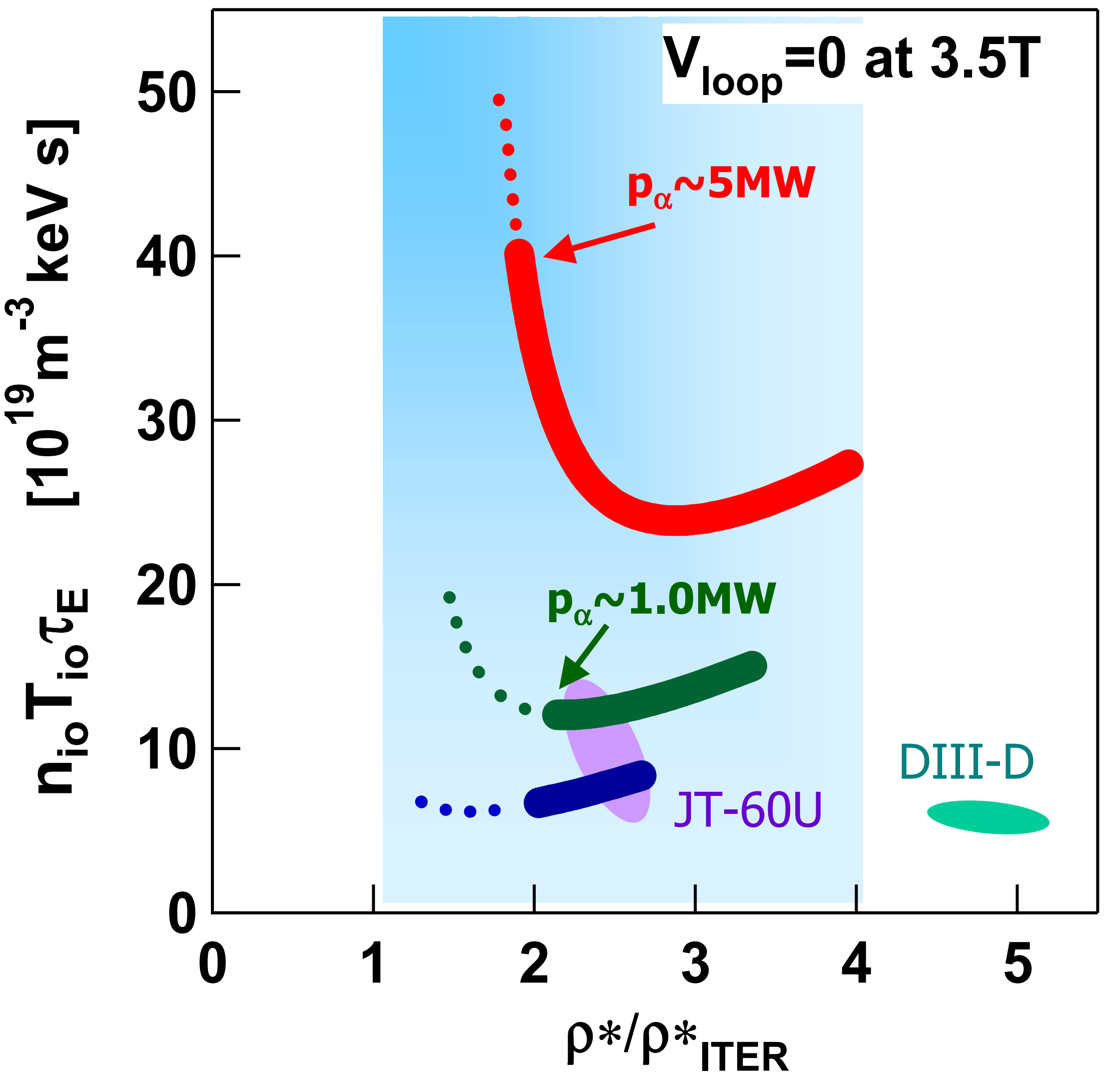


*ITPA database

P_{tot}=23MW
P_{tot}=32MW
P_{tot}=45MW
full lines: ITER domain
dotted lines:
$n_{Shine\text{-}through} \leq n_l \leq n_{Gw}$

- ITER relevance: simultaneous increase of **I_{boot}/I_P and** $nT\tau$
- **I_{boot}/I_P~60-70% ?**
  $I_{boot}/I_P \propto q_{95} x \beta_N$
  at q_{95} ~5 → β_N ~3 and P_{tot} ~ 45MW

Scientific feasibility of a bootstrap-dominated regime at high fusion performance ?



P_{tot}=23MW

P_{tot}=32MW

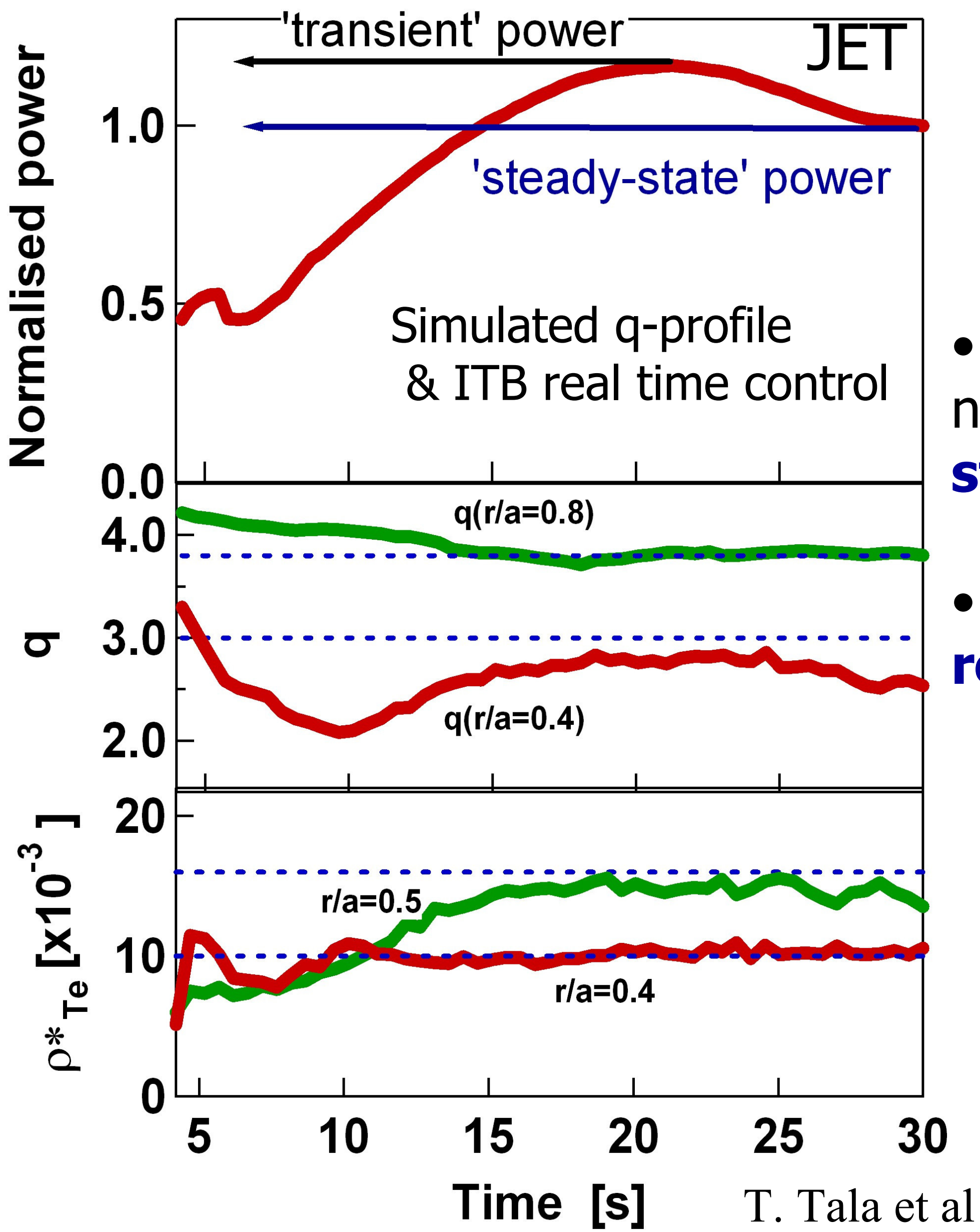
P_{tot}=45MW

full lines: ITER domain

dotted lines:

$n_{Shine\text{-}through} \leq n_I \leq n_{Gw}$

Power margins for Real Time control of high bootstrap regimes ?



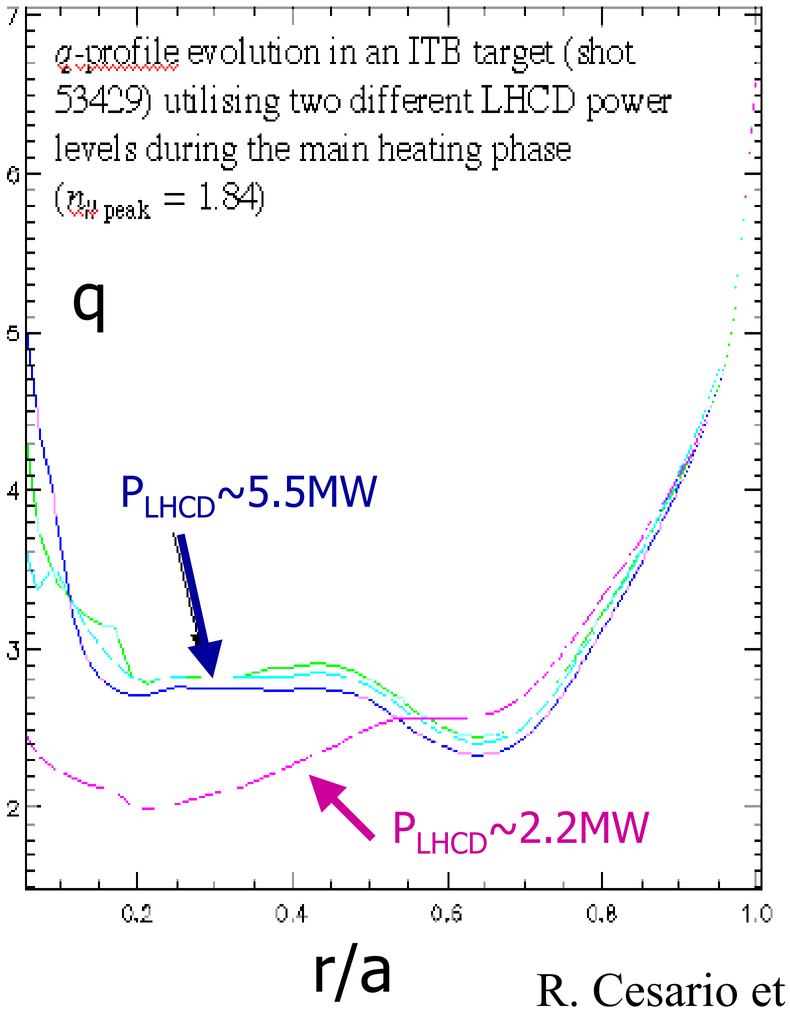
- The powers quoted for the fully non-inductive domain correspond to the **steady-state operating point**

- **Transiently higher power requirements** (±15-20%) required:

  - negotiation of an MHD stable route to steady–state
  - maintaining the optimum plasma profiles
  - avoiding transient MHD collapses or losses of confinement

Current profile control with LHCD

I_p~2.4MA; B_T~3.4T;
q_{95}~4.8, $n_l \sim 2.5 \times 10^{19} m^{-3}$



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- **Increased LHCD to 5MW → a larger range of q-profiles and density**
  - ➢independent variation of s & q to clarify their roles in ITB formation
- Present use of **LHCD preheat** → strong shear reversal and ITB, but in the core (r/a<0.4) due to good accessibility
- **Main heating**
  - ➢LHCD at larger radius & shear could be reduced to zero at r/a~0.6-0.7 (~ITER WNS scenario)
    → facilitate the conditions for triggering a wide ITB ?
  - ➢**but high power is required**

Explore confinement and ITB formation by varying key dimensionless parameters

- **Confinement physics not established in AT regimes**

  - no reliable 0-D scaling and multi-machine transport model
  - development + validation of 1-D transport and theory based models to **predict with confidence ITB characteristics & SS regimes in ITER conditions**
  - **achievement of ITER Q_{DT}~5 ? $\Delta H_H/H_H$ ~ 20% $\rightarrow$ $1 \leq Q_{DT} \leq 9$**

- **Similarity experiments and scans of key dimensionless parameters**

  - q-profile, T_i/T_e, E×B shearing rate and β (α-stabilisation) to investigate physics of core confinement
  - β_N above 2 to investigate the β scaling of the confinement
  - **JET a unique contribution by providing data with the lowest ρ^* , ν^* at high β**

45MW required for β-scaling of highly non-inductive AT regimes

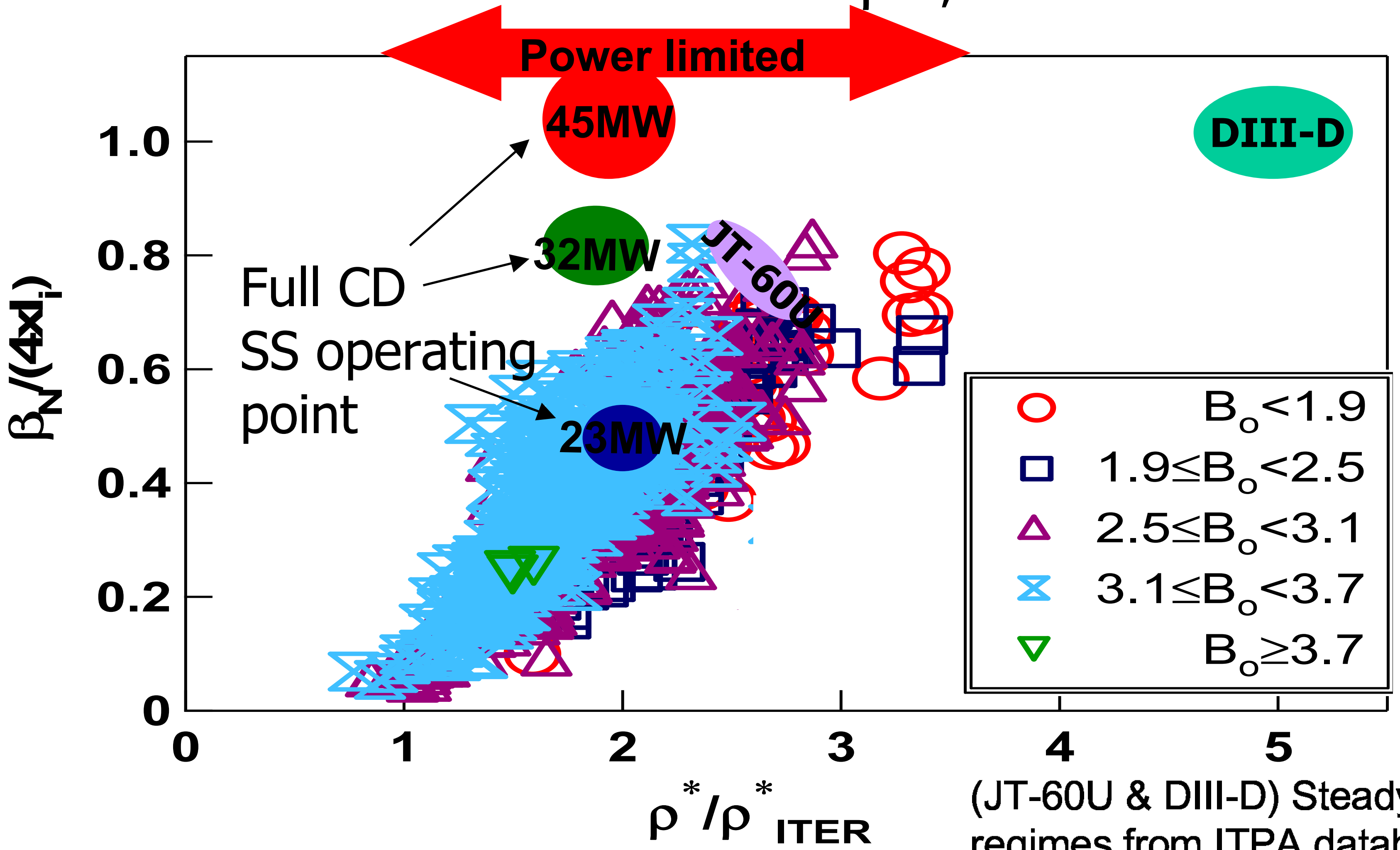
- Explore β-scaling of core confinement while keeping ρ^*, ν^*, q fixed in fully non-inductive CD regimes:
  - $n \propto B^4$ $T \propto B^2$ $I \propto B$
  - $n > n_{shine\text{-}through}$
  - $P_{tot} > 20MW$ for ITB at $V_l \sim 0$
- β-scan at $q_{95} \sim 5$ and $\rho/\rho^*_{ITER} \sim 2$ and $\nu/\nu^*_{ITER} \sim 1.5$

P_{tot}[MW]	45	32	23
B_o [T]	3. 5	3.3	3.1
β_N	2.8	2.3	1.9
n_l	4	3.3	2.7
I_p [MA]	2.4	2.0	1.9

- with 32MW $\Delta\beta/\beta \sim 20\%$ close to error bar whereas at 45MW $\Delta\beta/\beta \sim 50\%$

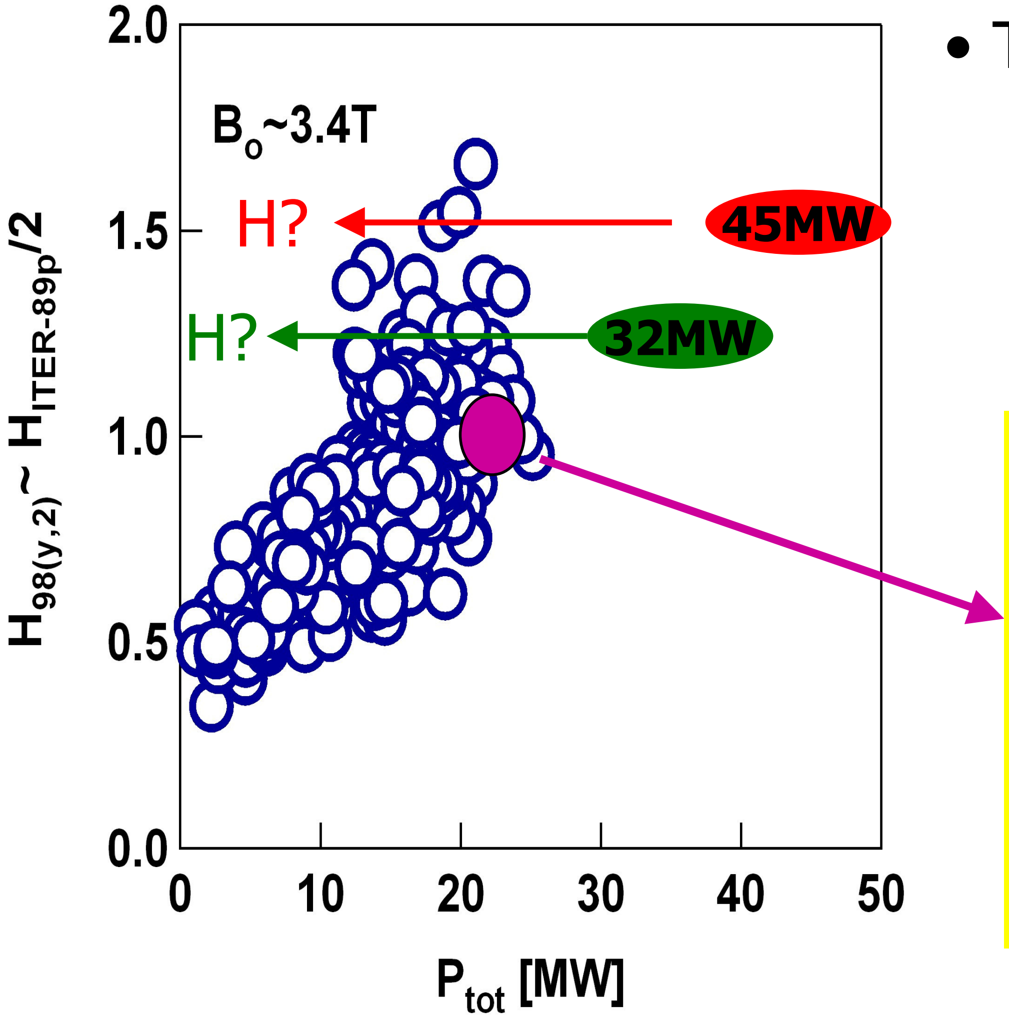
Physics of Confinement/stability at high β_N ?

A critical issue for steady-state regimes is to **operate at β_N~3 but at relevant ρ^* , ν^***



(JT-60U & DIII-D) Steady-state regimes from ITPA database

Physics of core confinement with wide ITB ?

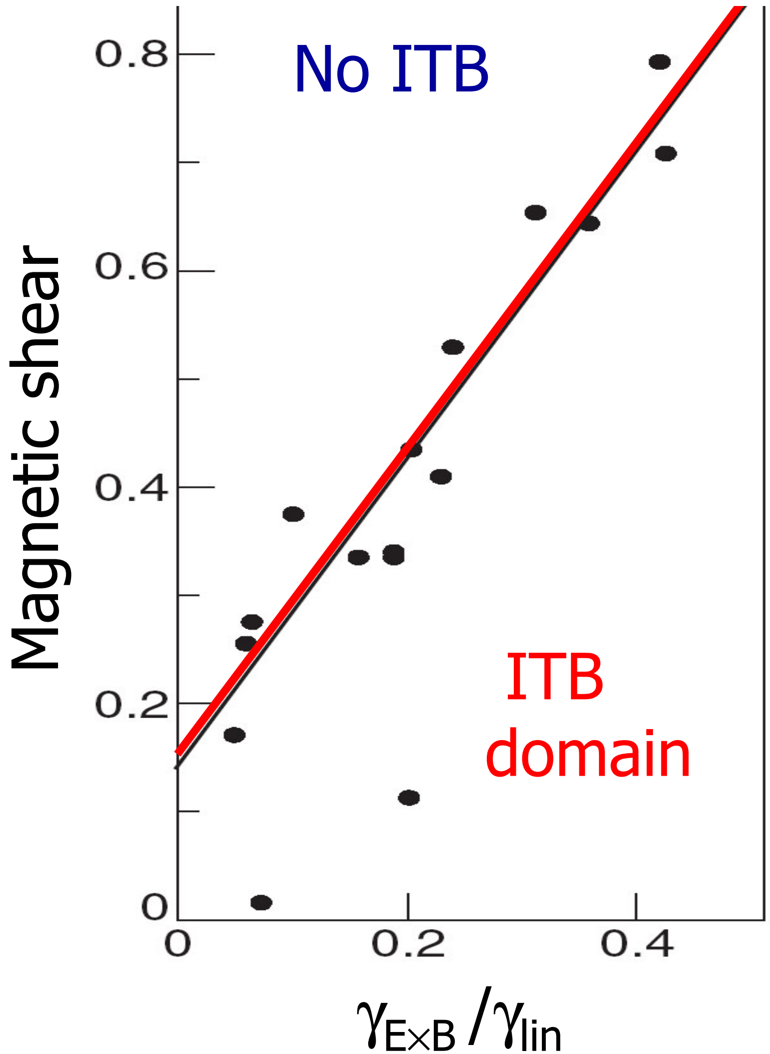


- To form & sustain wide ITBs
  - ➢ **high heating power** (off-axis J_{boot}) **+ off-axis non-inductive current is mandatory**

- Steady-state full CD ITB regimes $H_{98(y,2)}$ ~1 $H_{ITER-89p}$~2 at n_I~2.6
- H ? Factor n_I ~ 4 - 6

Formation of ITB at large radius ?

magnetic shear vs $\gamma_{E\times B}/\gamma_{lin}$ at the ITB onset



- ITB formation condition: a linear threshold condition at the ITB onset
  - ➢ $\gamma_{E\times B}/\gamma_{lin} > 0.7s - 0.1$
- ITBs sustained at r_{ITB}~0.5 (s<0.5) with 22MW
- Power to form, sustain & control an ITB at r/a~0.7 ?
  - ➢ if the magnetic shear is doubled, the $\gamma_{E\times B}/\gamma_{lin}$ and **the power should be doubled?**

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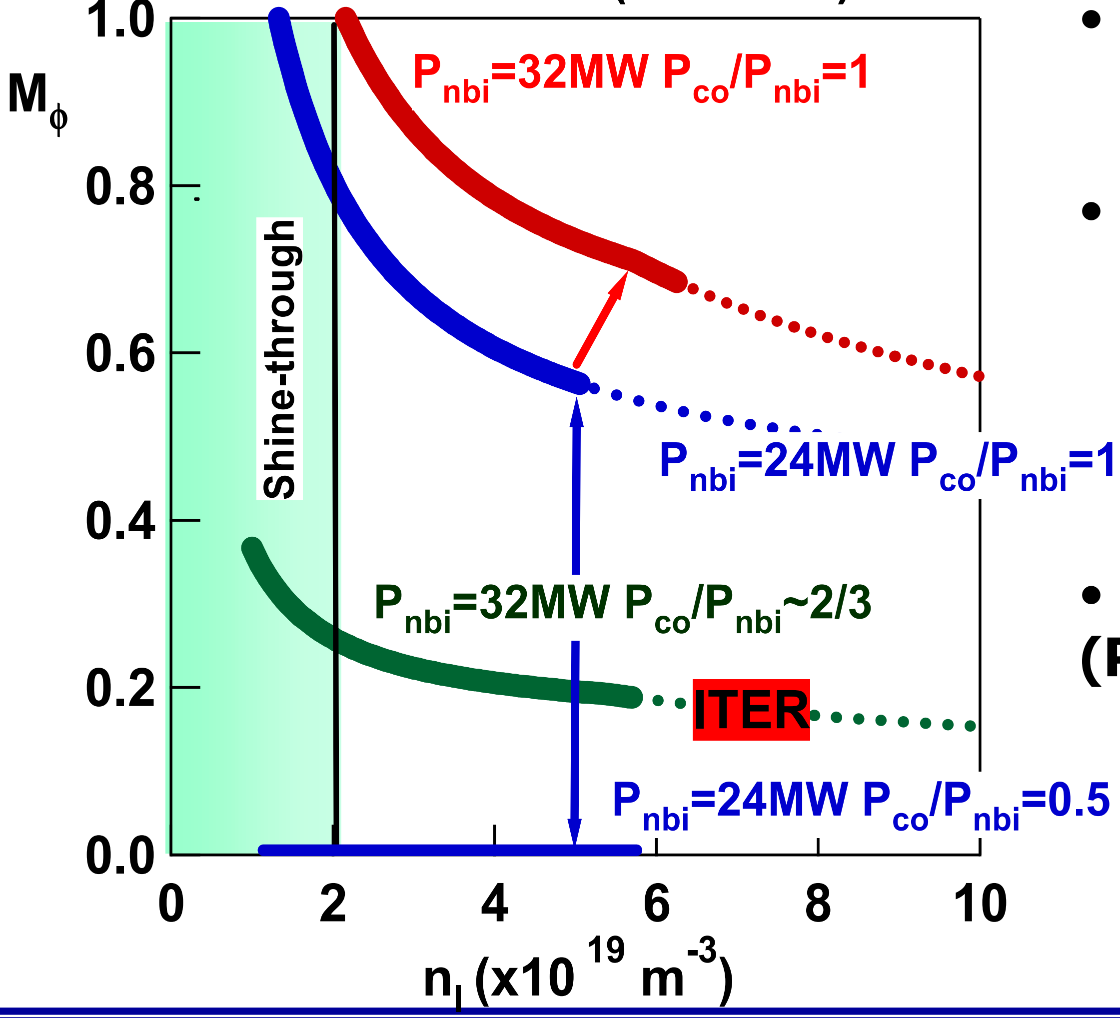
V_{loop}=0 at 3.5T $H_{98(y2)}$=1.5
P_{ICRH}=10MW+P_{LHCD}=3MW
ITER domain (full lines)



Core confinement physics at ITER M_ϕ ?

- $P_{NBI-counter}$=0
  - too high M_ϕ & V_ϕ
- **a 3rd counter NBI box**
  - study confinement, ITB physics at ITER M_ϕ & V_ϕ
  - scan in V_ϕ
- **Balanced NBI injection ($P_{counter}$=P_{co})**
  - **V_ϕ ~0 in the core**
  - **Reduced core heating & V_ϕ<0 at the edge due** to fast ion losses (1D Monte Carlo)

Conclusion on power requirements

- **increasing the H & CD at P_{tot}~45MW (NBI & ICRH upgrade)**
  - **Access to bootstrap-dominated regimes at 2.5MA, n_l>3, β_N>2.5**
  - This opens a **new domain of physics that has to be addressed for the preparation of ITER scenarios**
  - Explore β**-scaling** of confinement by increasing Δβ/β **by 2.5**
  - **~1/3 of P_{NBI} in counter injection could provide the opportunity to vary and actively control V_ϕ**

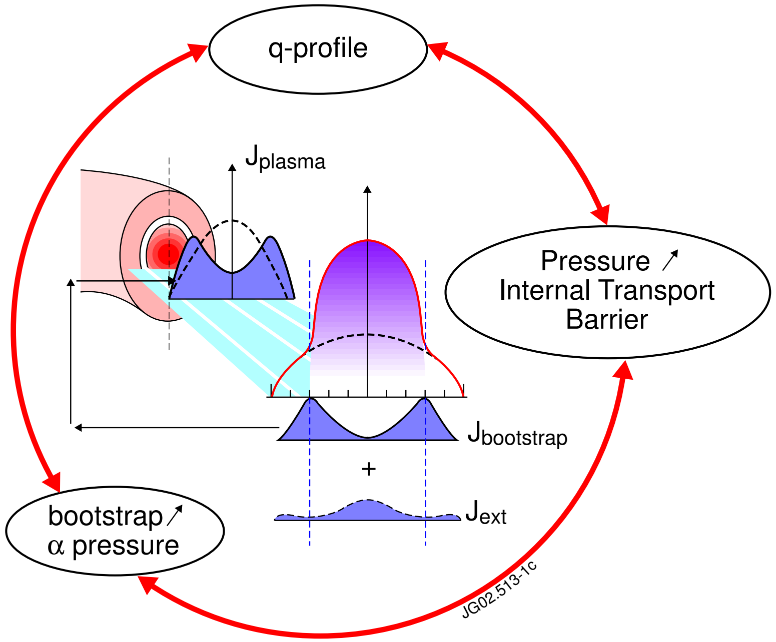
- **An upgrade of the LHCD launcher (PAM system)**
  - **Reliable P_{LHCD}~3MW in H-mode edge**
  - P_{LHCD}~5MW provides margins in particular if we could not reach H_H~1.5 at high density (confinement scaling is an open issue ?)

- **Both upgrades are essential** for full CD operation at high density
  - **LHCD increases the external CD; NBI increases β_N and I_{boot}**

Scientific merits & implication for ITER & DEMO

- **Scientific feasibility of a dominated bootstrap regime at high performance where q-profile, H and bootstrap are strongly coupled**

- **Explore core confinement and ITB physics by varying key dimensionless parameters ➔ Establish a multi-machine transport models** to predict with confidence the SS regimes in ITER conditions



- **Optimisation of ITER-relevant scenarios on JET ➔ save significant time and resources during the first years of ITER operation**

- **Determination of optimum q-profile ➔ reduce experimental development on ITER, assess heating/CD systems for SS operation, assess Real Time Control systems**