EUROfusion

IAEA Fusion Energy Conference 2025, Chengdu, China

Core and edge transport of scenario with internal transport barrier in tritium and deuterium-tritium plasmas in JET with Be/W wall

EX/11-1

Costanza Maggi

UKAEA, Culham Campus

UK Atomic Energy Authority

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

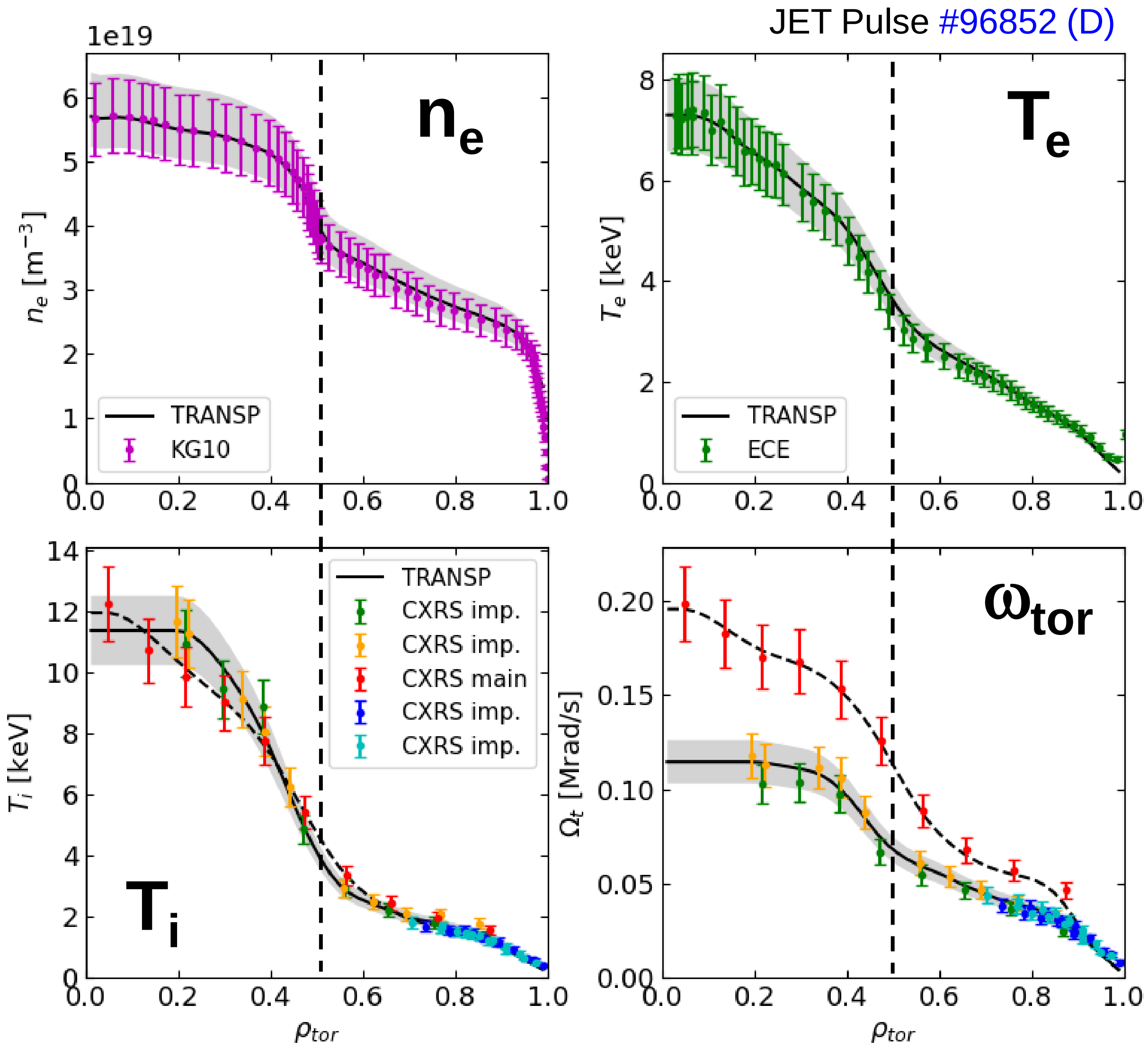
Co-authors

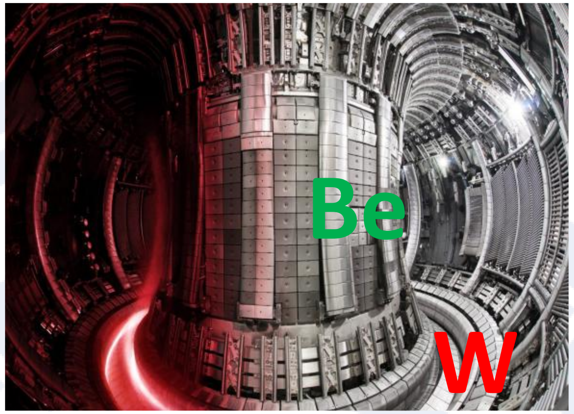
M Fitzgerald[1], H Dudding[1], J Eriksson[2], S Menmuir[1], M Nocente[3], C Olde[1], M Poradzinski[4], I Predebon[5], D Rigamonti[3], I Balboa[1], C Challis[1], E Delabie[6], FA Devasagayam[7], A Field[1], E Joffrin[8], D King[1], E Lerche[1], X Litaudon[8], E Litherland-Smith[1], S Saarelma[1], Ž Stancar[1], T Tala[7], I Voitsekhovitch[1], JET Contributors* and EUROfusion Tokamak Exploitation Team[$]

[1]United Kingdom Atomic Energy Authority, Culham Campus, Abingdon, Oxfordshire OX14 3DB, United Kingdom of Great Britain and Northern Ireland
[2]Department of Physics and Astronomy, Uppsala Universitet, Uppsala, Sweden
[3]Dipartimento di Fisica, Universita' degli Studi Milano-Bicocca, Milan, Italy
[4]Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland
[5]Istituto per la Scienza e Tecnologia dei Plasmi, CNR, Padova, I-35127, Italy
[6]Oak Ridge National Laboratory, Oak Ridge, TN 37831-6169, USA
[7]VTT, PO Box 1000, FI-02044 VTT Espoo, Finland
[8]CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France

See the author list of CF Maggi et al. 2024 Nucl. Fusion **64 112012*
*[$]See the author list of E Joffrin et al 2024 Nucl. Fusion **64** 112019*

Internal Transport Barrier in JET-ILW





Strong ITB at mid-radius in both i- and e- channel

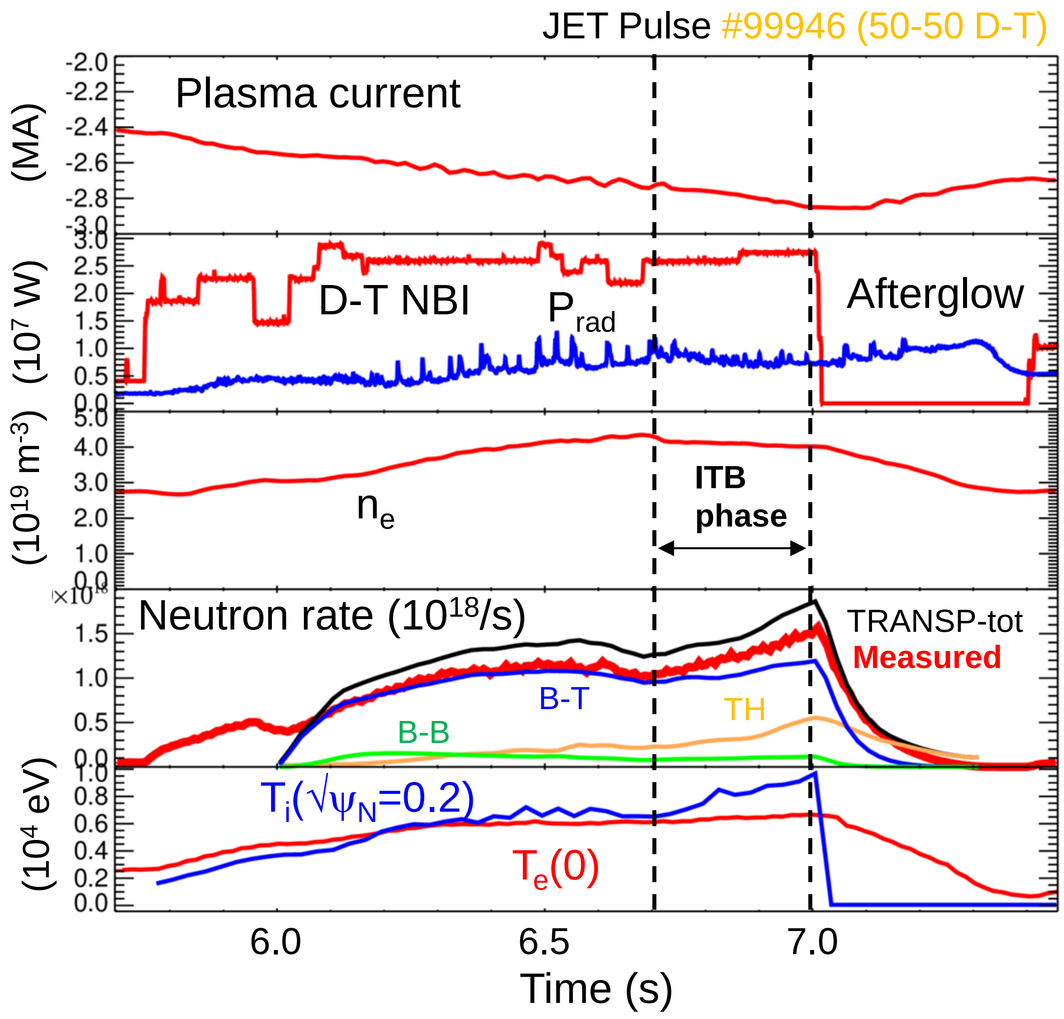
Kinetic profiles:

- n_e: HRTS, profile reflectometer
- T_e: ECE, HRTS
- T_i, v_{tor}: CXRS (Ne X and main ion)

[Tresset, NF 2002], [Challis, PPCF 2004]

(*) In JET-C, 'strong ITB' was defined as ITB with $\rho^*_{Ti} > 1.5 \times \rho^*_{ITB}$ ($\rho^*_{Ti} = \rho_s/L_{Ti}$)

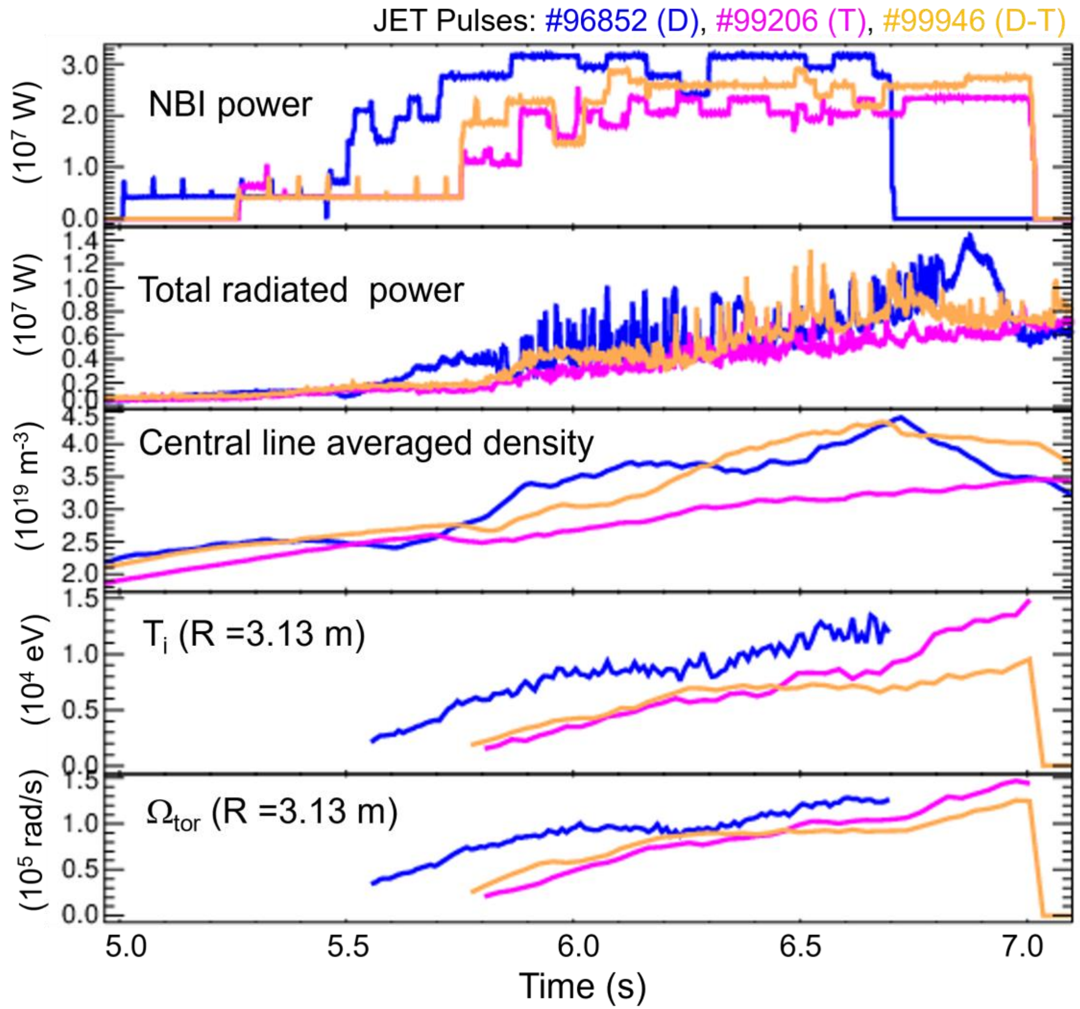
Scenario with ITB in JET-ILW



Target plasma for observation of TAEs destabilized by α's [Fitzgerald, NF 2023]

- B_T / $I_{P,max}$ = 3.43T / 2.8MA (q_{95} ~ 3.8)
- **NBI heating only**
- NBI during I_P ramp-up to slow down current profile diffusion and achieve low, positive magnetic shear
  [Gormezano, PRL 1998], [Challis PPCF 2001], [Joffrin NF 2002]
- Low plasma density (low recycling)
- Transient plasma

Motivation: easier ITB onset and stronger ITB in T



- Best performance ITB pulses are at different NBI powers in D, T, D-T:

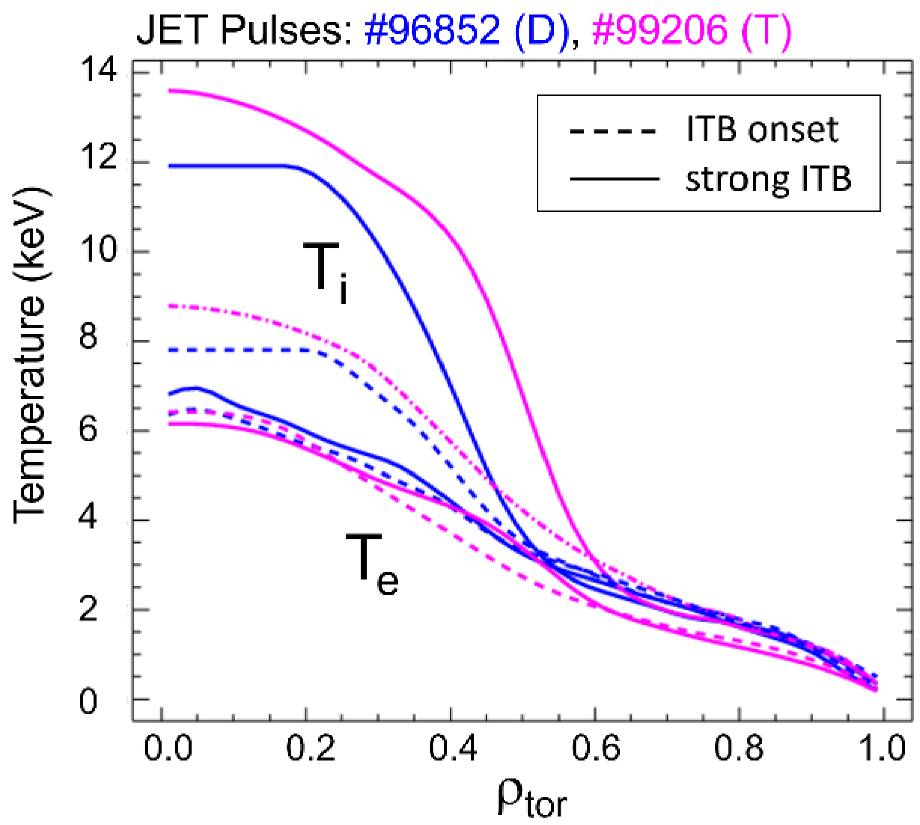
  31 MW (D) > 26 MW (D-T) > 23 MW (T)

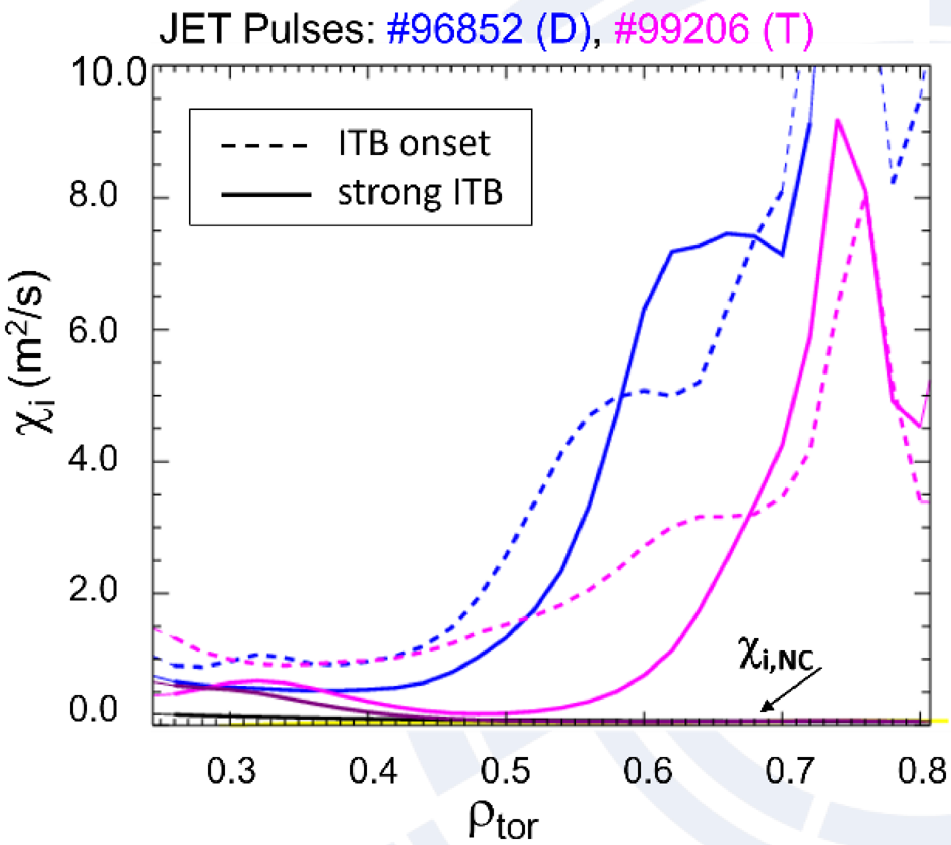
- Easier ITB access & higher T_i & Ω_{tor} in T
  - at lowest NBI power
  - at lowest plasma density

→ need to decouple isotope mass and density effects on ITB trigger and strength

Data mining (experiments not run to address isotope dependence of ITB)

Core ion heat transport more strongly reduced in T



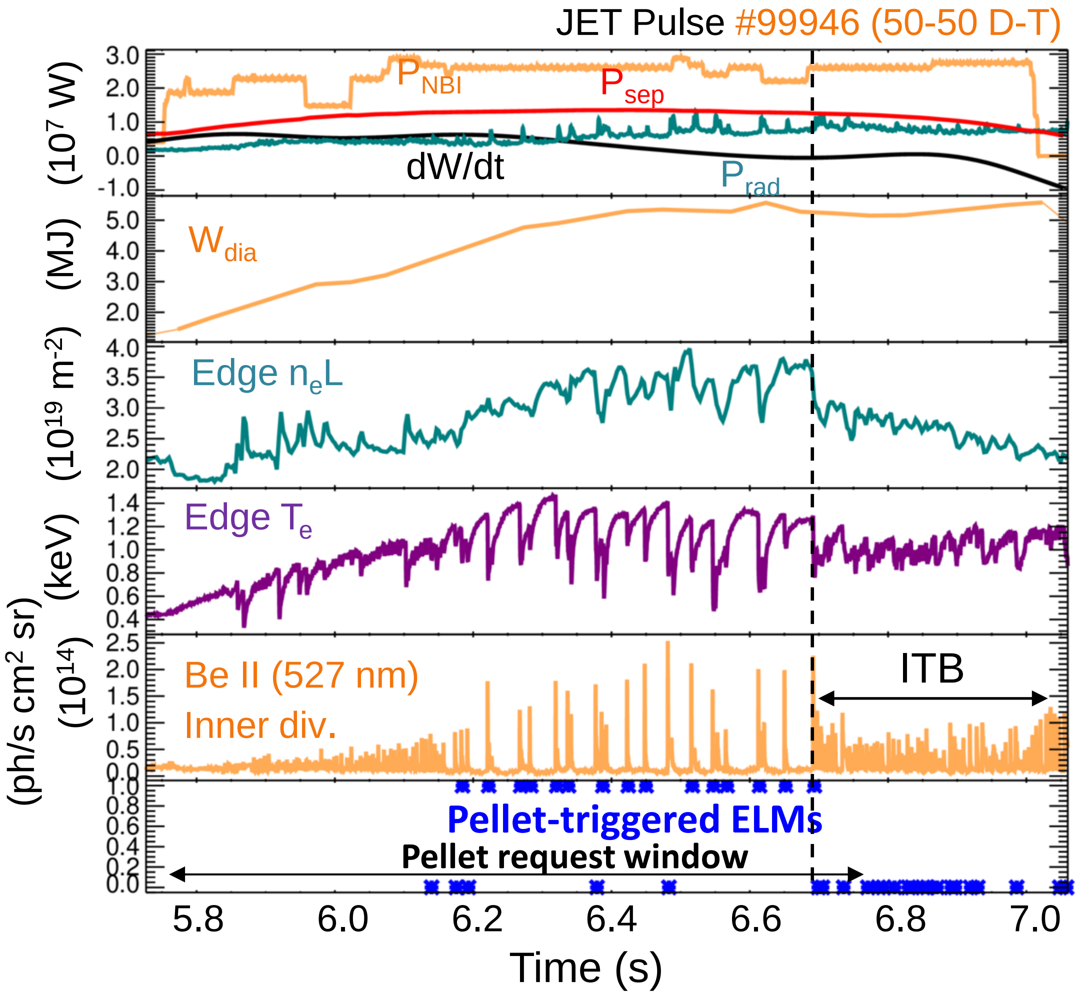


Ion ITB foot at larger radius in T than in D at fully developed ITB

(Time of 'strong ITB' = 50 ms before NBI switch-off)

- χ_i(T) drops to NC level (TRANSP+NCLASS) for $0.3 < \rho_{tor} < 0.6$ in fully developed ITB
- Larger χ_i drop for T shot, and over broader plasma volume, than in D

Scenario with ITB in JET-ILW – with pacing pellets



- HFS pellet pacing to mitigate type I ELMs for W control (2mm, 45 Hz, D pellets)

→ Transition to phase with small / high frequency ELMs

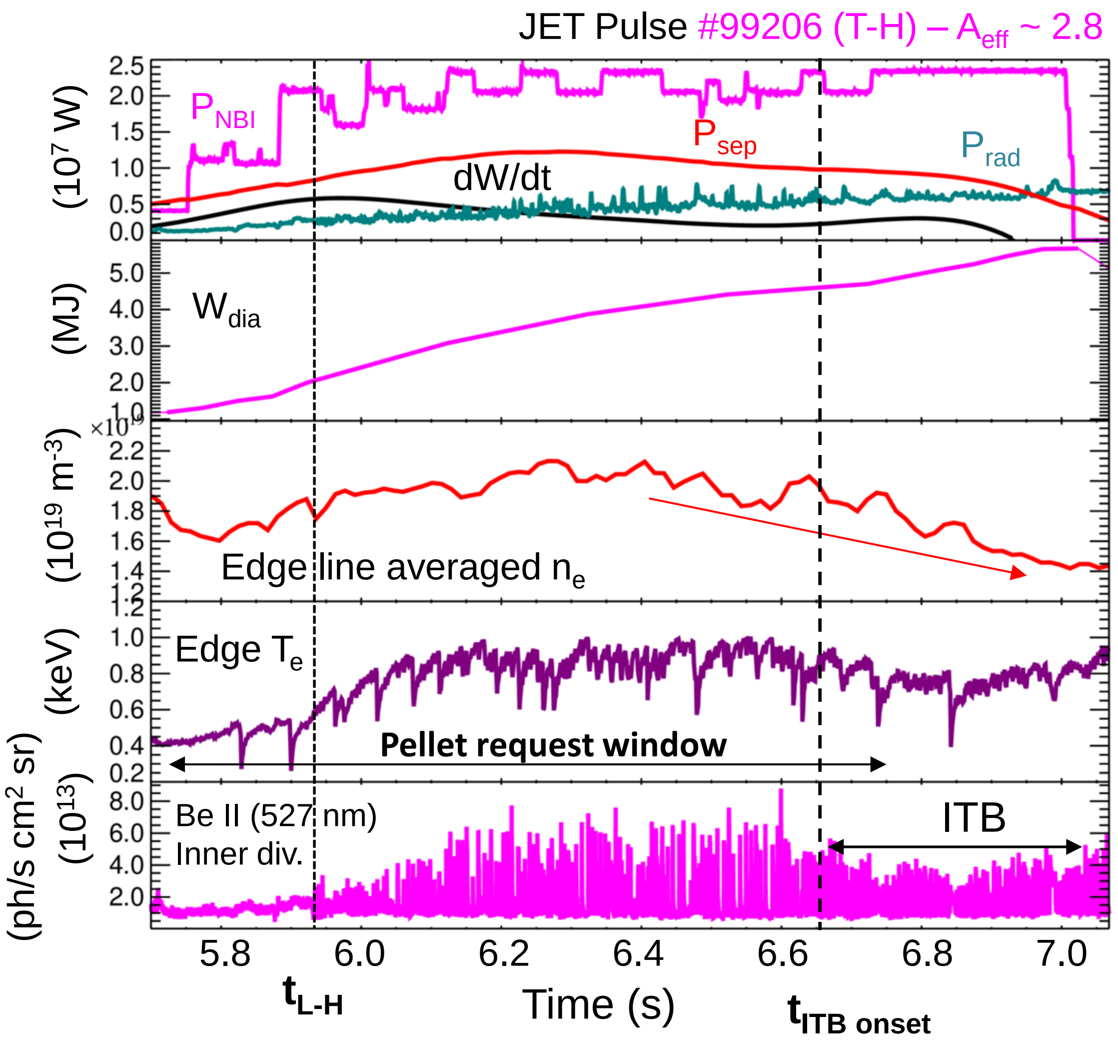
- Decrease in edge n_e and T_e
- type I ELMs → (likely) type III ELMs (*)
- Pellets no longer trigger ELMs

[Chapman, PPCF 2015]

- ITB forms and grows in this phase (cause - effect still unclear)
- Similar picture in D and D-T

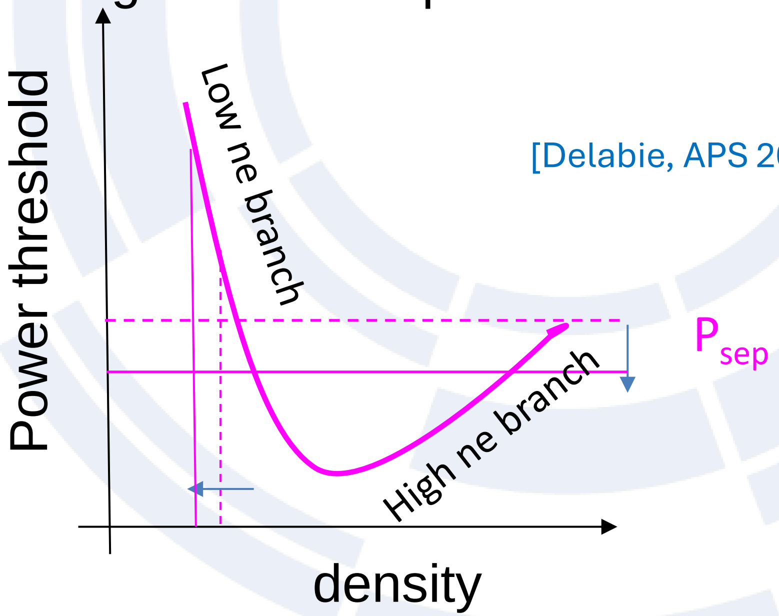
(*) ITB not compatible with type I ELMy pedestal – reported in many tokamaks

T plasmas in type III ELMy regime, low n_e branch



- H pellets (no T pellets in JET)
- No pellet triggered ELMs
- After L-H transition, plasma always in type III ELMy regime (weak density increase)

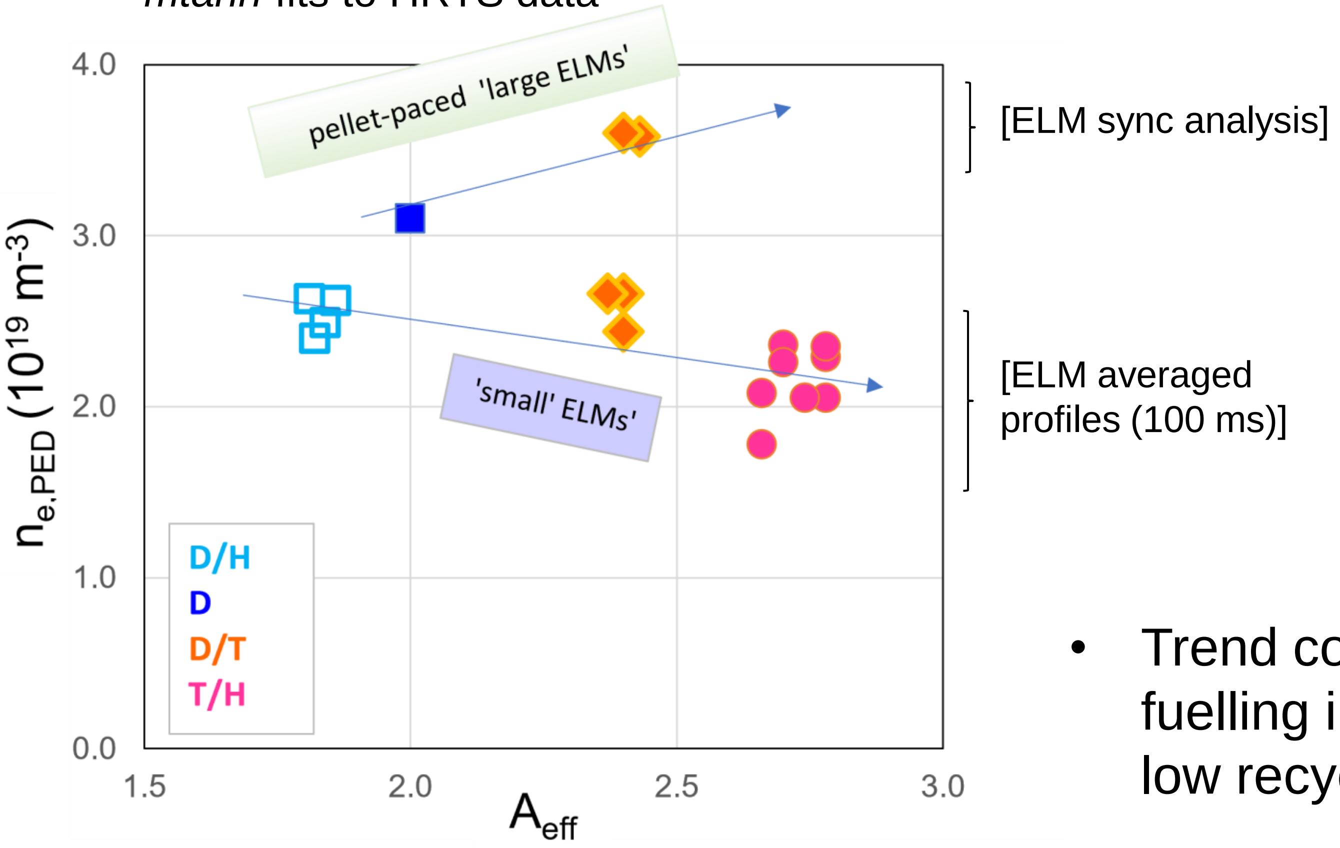
- After max value, P_{sep} decreases in time
- → plasma 'deeper' in type III ELMy regime
- Edge n_e strongly decreases
- ITB forms and grows in this phase



[Delabie, APS 2016]

In phases with type III ELMs, $n_{e,PED}$ *decreases* from D to T

2.8MA/3.43T – **P_{NBI}: 23.5 – 26.5 MW**
mtanh fits to HRTS data



- Low recycling conditions: pedestal density ***decreases*** from D to T (decrease in Δ_{ne})
- Unlike pedestals with type I ELMy H-modes: $n_{e,PED}$ *increases* from D to T

[Frassinetti, NF 2023]
[Schneider, NF 2023]

- Trend consistent with strong contribution of neutral fuelling in setting the pedestal density structure in low recycling conditions: $\lambda_{n0} \sim 1/\sqrt{A}$

In low-n_e plasmas with ITB, T plasmas evolve to lower pedestal density

Known physics affecting ITB onset and strength

Stabilization of dominant core turbulence (ITG) by

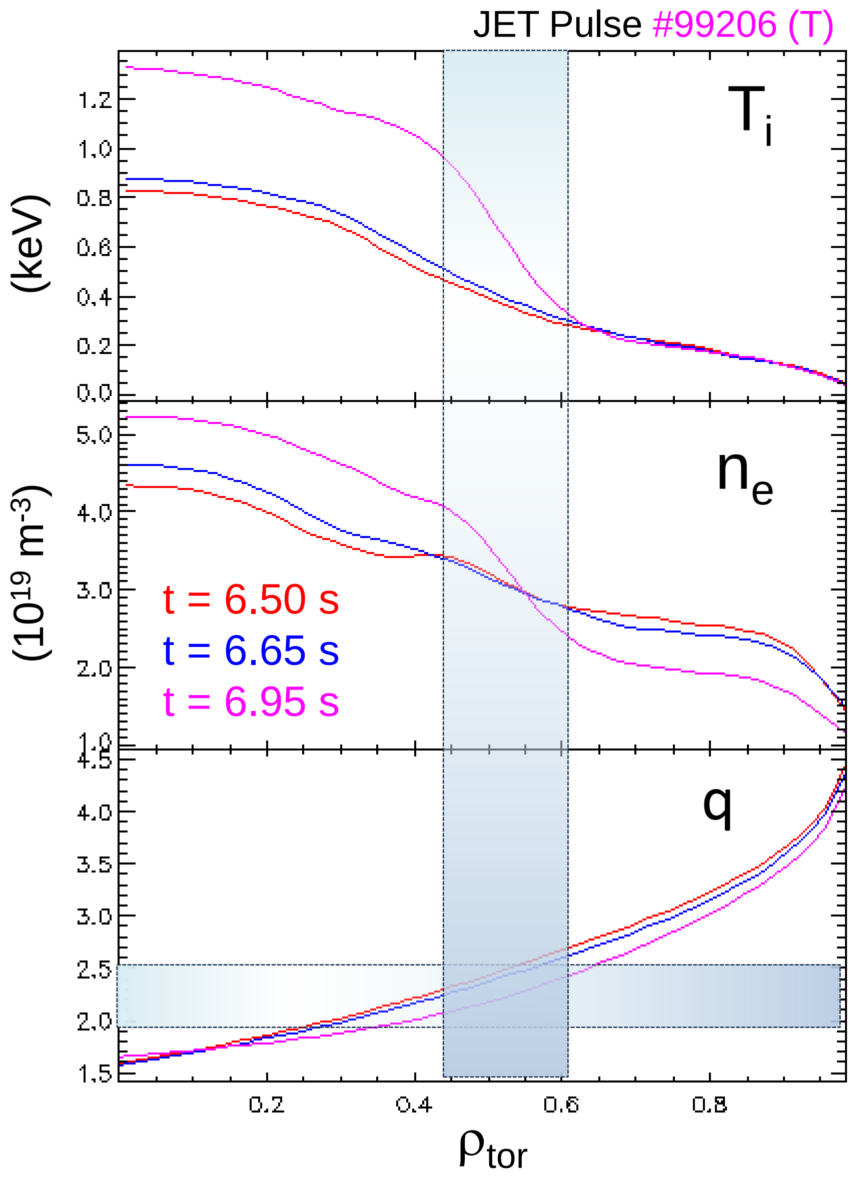
- Magnetic shear $\hat{s} = r/q \, dq/dr$ [Gormezano, PRL 1998], [Challis PPCF 2001], [Joffrin NF 2002] [Volčokas, NF 2023]
- ExB shear $\omega_{ExB} = | RB_\theta/B_\phi \, \partial/\partial r \, (E_r/RB_\theta) |$ (*) [Hahm and Burrell, PoP 1995], [Ernst, PRL 1998] [Tala, PPCF 2001]
- T_i / T_e $P_{e\text{-}i} \sim Z^2/m_i \, (n_e n_i/T_e^{1.5}) \, (T_e - T_i)$

- Fast ions (dilution and pressure) [Tardini, NF 2007] - moderate effect
- Thermal EM effects [Brioschi, NF 2025] - negligible impact of isotope mass

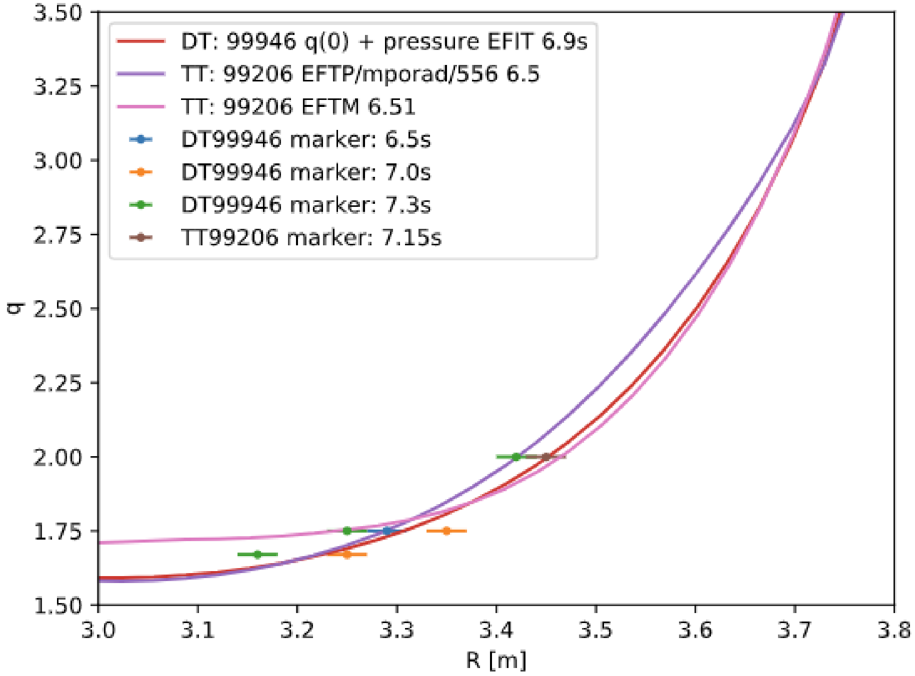
How are they influenced by changes in density and in isotope mass ?

(*) $$E_r = \frac{1}{Zen_i}\frac{\partial p_i}{\partial r} - v_\theta B_\phi + v_\phi B_\theta$$

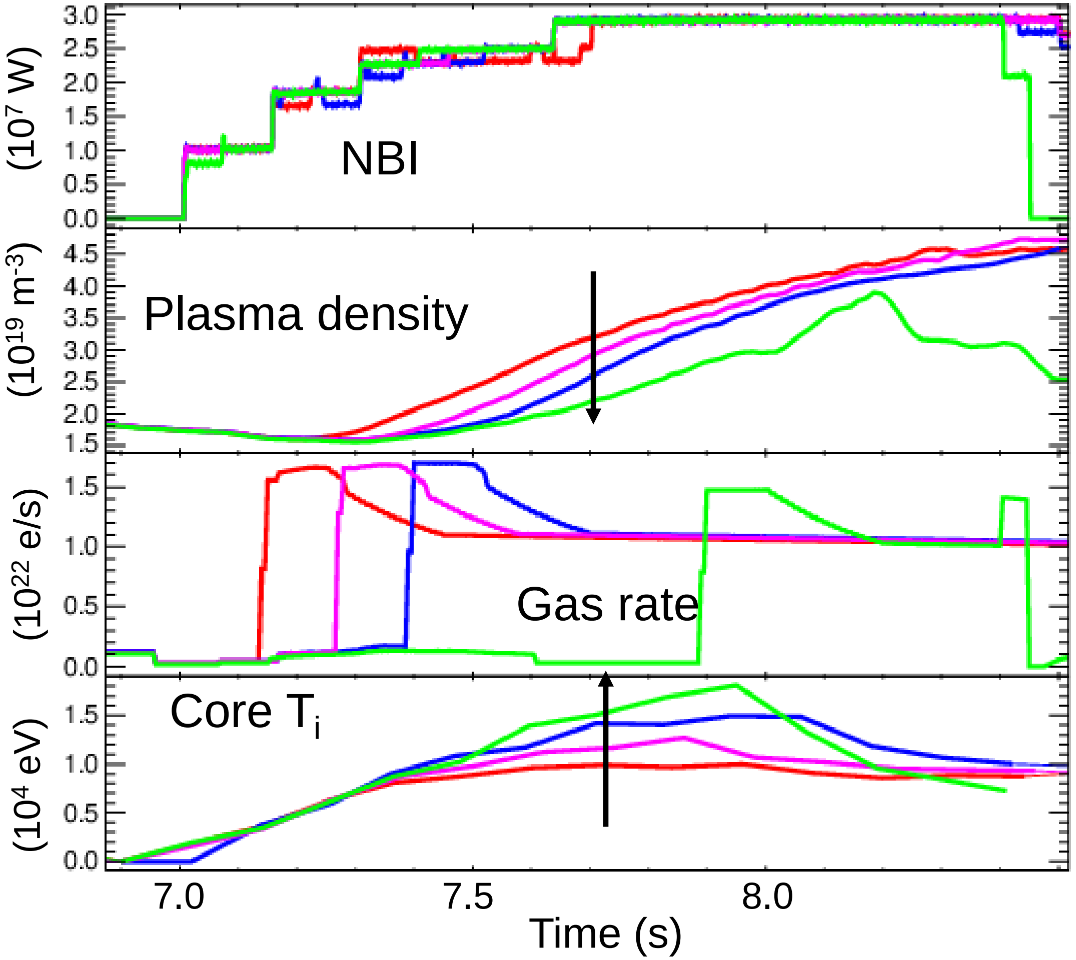
ITB near location of plasma q = 2 surface



- Bespoke EFIT equilibrium with TRANSP pressure constraints, consistent with MHD markers and polarimetry
- ITB foot located near q = 2 surface
- **For D, T and D-T**
- Elevated q_0 >1 (exact value unknown)



Density scan strongly affects T_i and ITB strength

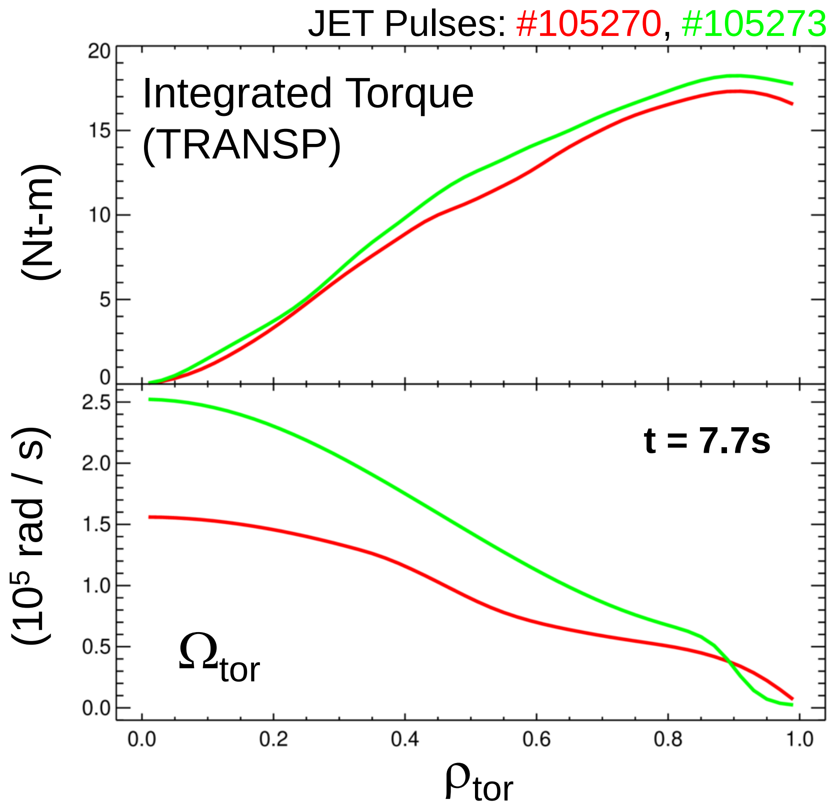


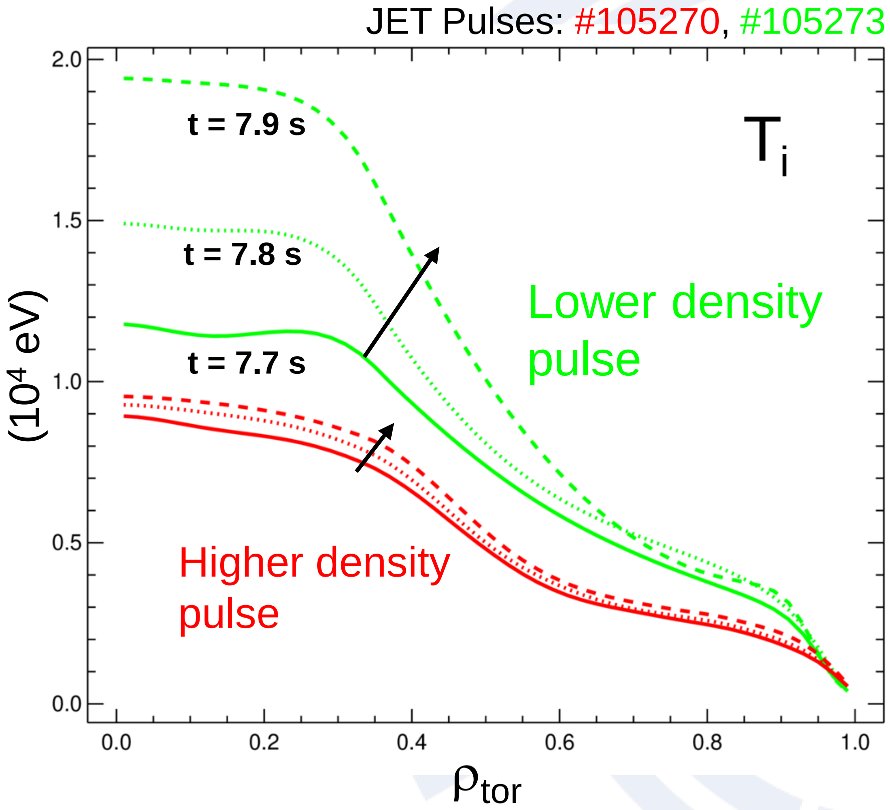
2.1 MA/3.45 T (D plasmas, max P_{NBI} = 29 MW)

n_e scan at constant A_{eff}

- Density scan in early phase of hybrid scenario, with performance overshoot generating high T_i and ITB [King, subm PPCF]
- Density varied at H-mode entry
  - variation of gas level/timing
  - 8 pulses (4 shown here)
- Strongly affects core and edge T_i

Increase in T_i, Ω_{tor} correlated with decrease in density

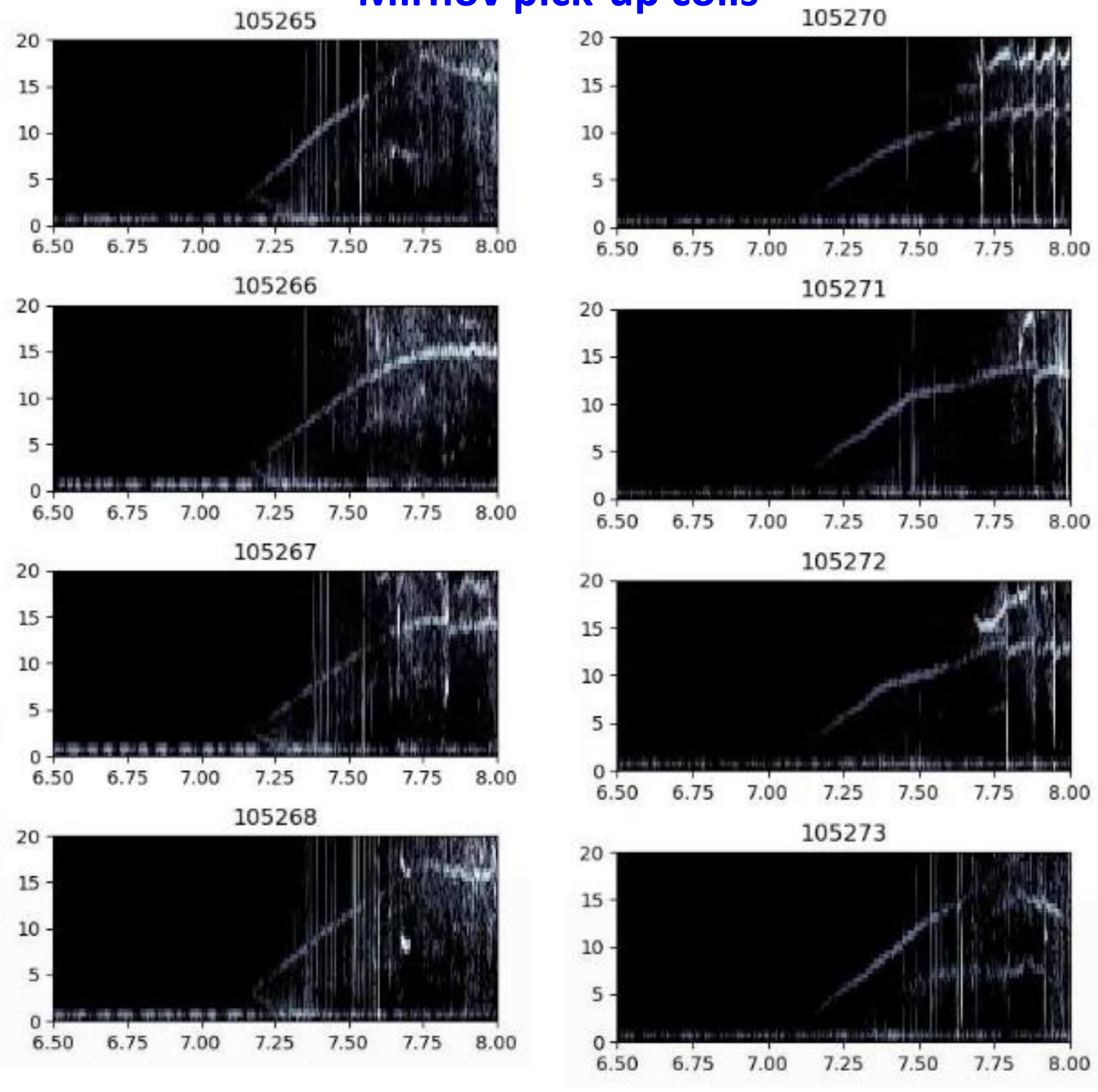




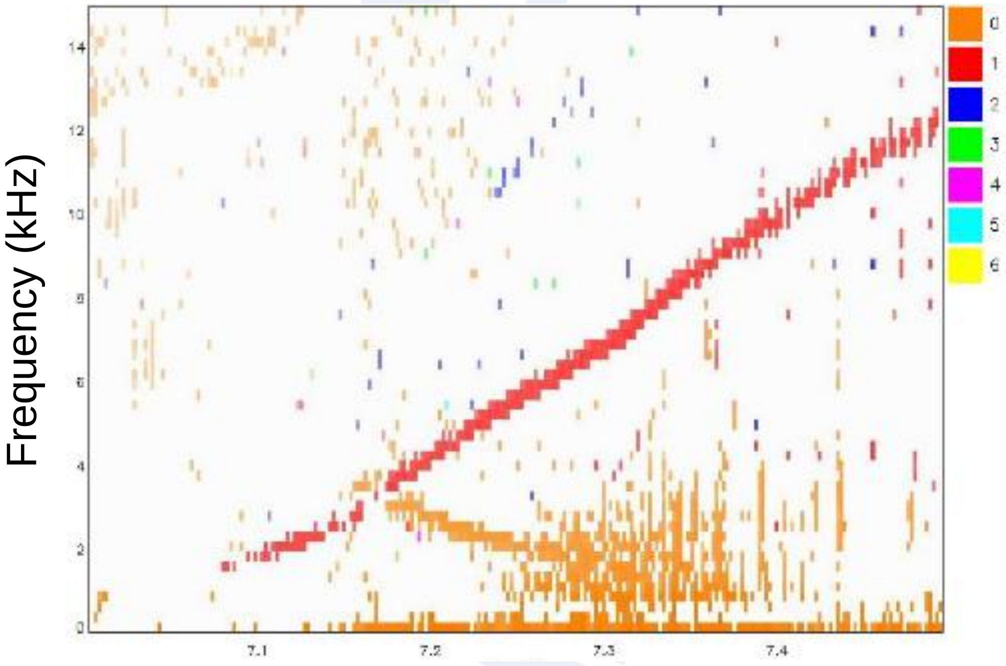
- Increase in T_i , Ω_{tor} and ITB strength correlated with decrease in plasma density
- Higher Ω_{tor} at lower density → expect stronger ExB shear stabilization of core turbulence

n=1 mode appears at same time regardless of density

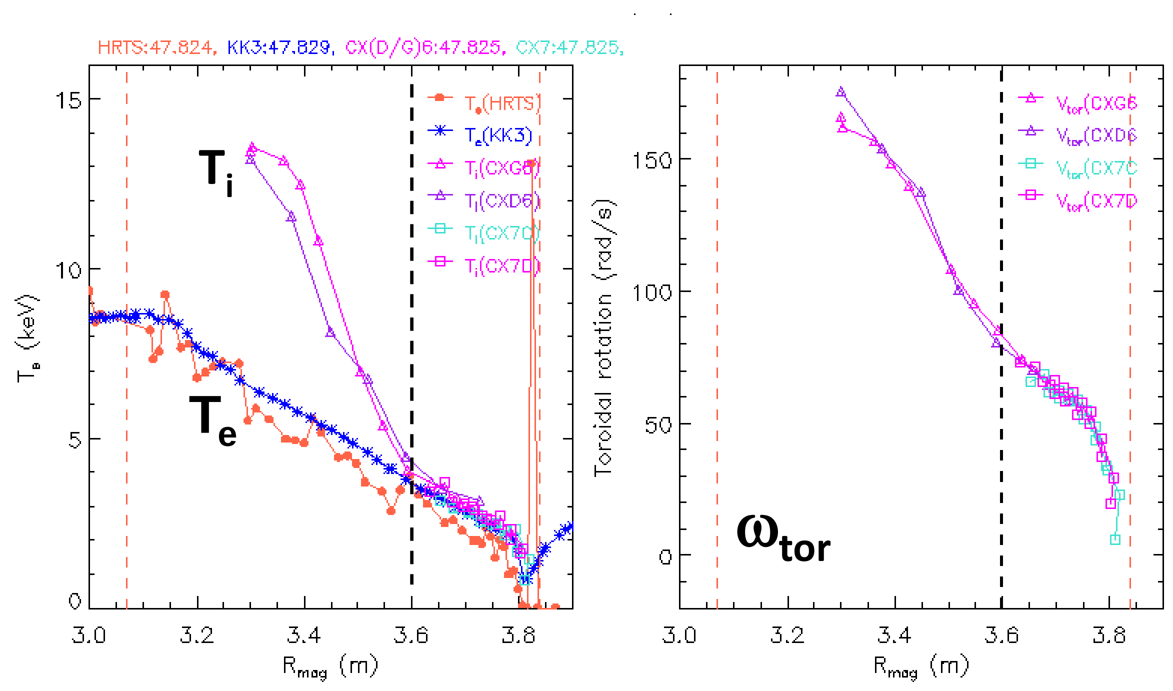
Mirnov pick-up coils



- **n = 1 MHD mode appears at same time in all 8 pulses, regardless of density**
- Magnetic island, rotating with similar frequency f_{MHD} ~ 10-15 kHz in all 8 pulses



Density scan doesn't affect q-profile in early phase of hybrid scenario with performance overshoot



- Islands form where magnetic tension vanishes

$$B \cdot \nabla \ldots = k_{\parallel} \ldots = 0$$

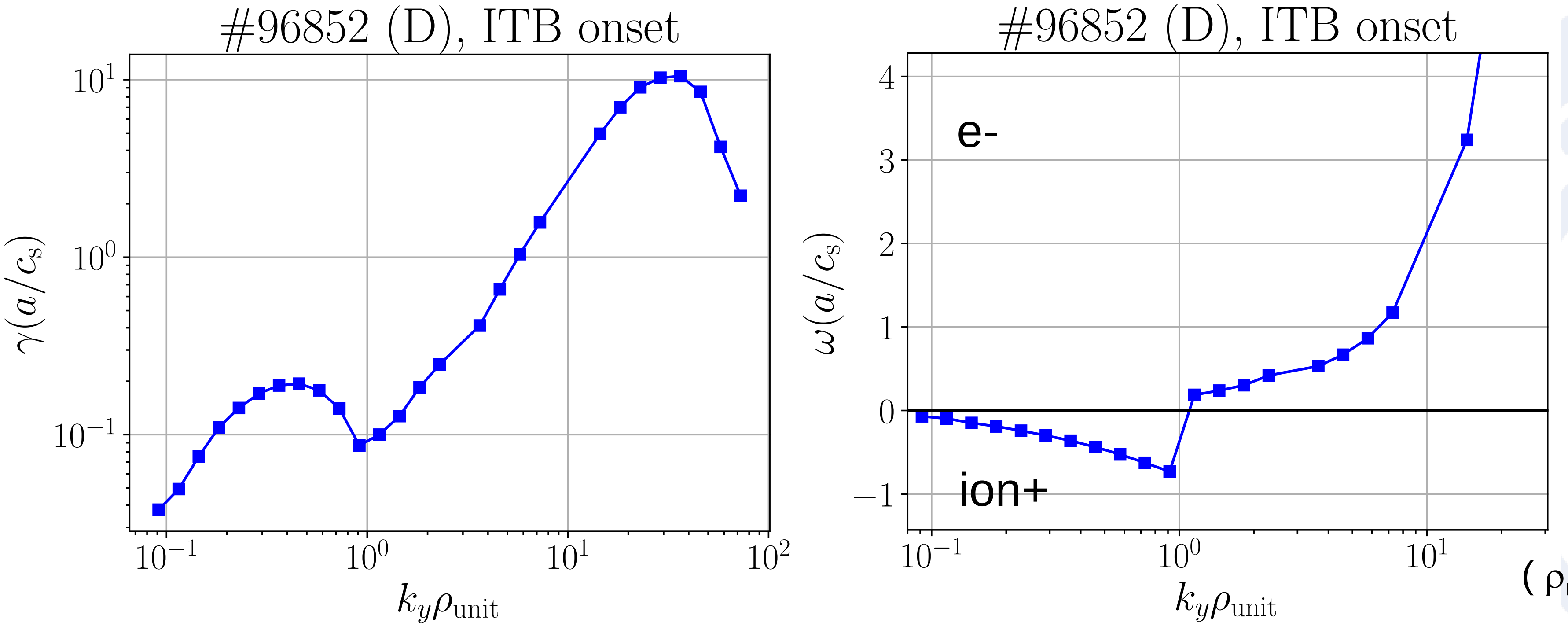
- $k_{\parallel} \propto (m - nq)$, with m, n integers
- When n = 1, q must also be integer for $k_{\parallel}$ to vanish
- $f_{MHD} \sim n\, f_{tor} \longleftrightarrow$ at $R_{mag} \sim 3.6$m
- Coincides with location of q = 2 surface and ITB foot
- → q-profile very similar in all 8 pulses in early phase of discharge

ŝ largely independent of plasma density variations in phase leading to ITB

→ Favourable q-profile with low, ŝ > 0 and q = 2 surface necessary for ITB onset, but not sufficient condition for strong ITB

ITG is dominant micro-instability in core plasma

CGYRO linear simulations (ρ_{tor} = 0.43)



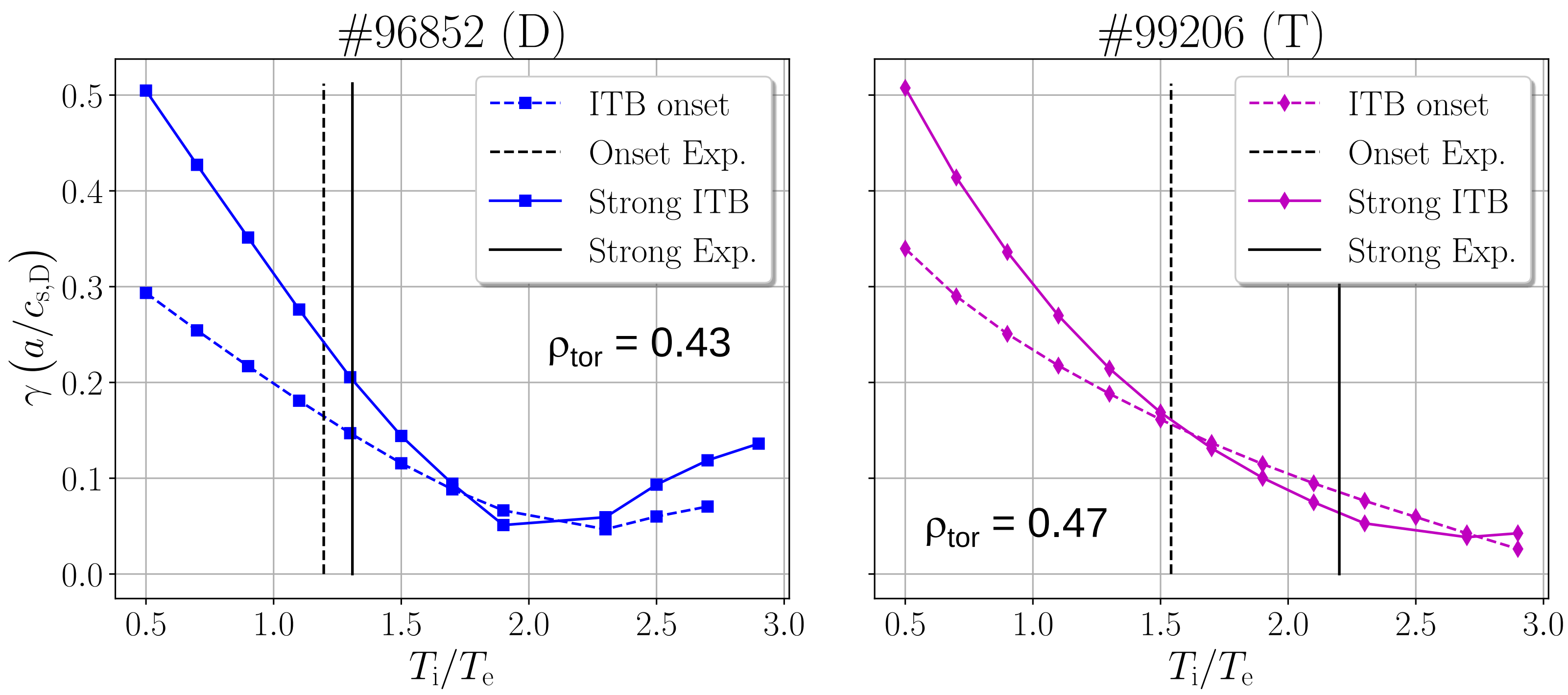
- ITG dominant modes at ion scale
- electrostatic ETG mode at e- scale

(ρ_{unit} = sqrt(m_D*T_e)/(e*B))

- Before and during ITB; at ρ_{tor} = 0.4, 0.55 and 0.7; both for D and T
- Confirmed by scans in a/L_{Te}, a/L_{Ti} and a/L_{ne}
- Isotope mass dependence in line with g-B dependence of ITG turbulence ~ 1/√A
- Confirmed stabilization of core ITG modes with decreasing ŝ

Stronger T_i/T_e stabilization of ITG modes in tritium

CGYRO linear simulations (T_i/T_e scans at $k_y\rho_i$ = 0.3)



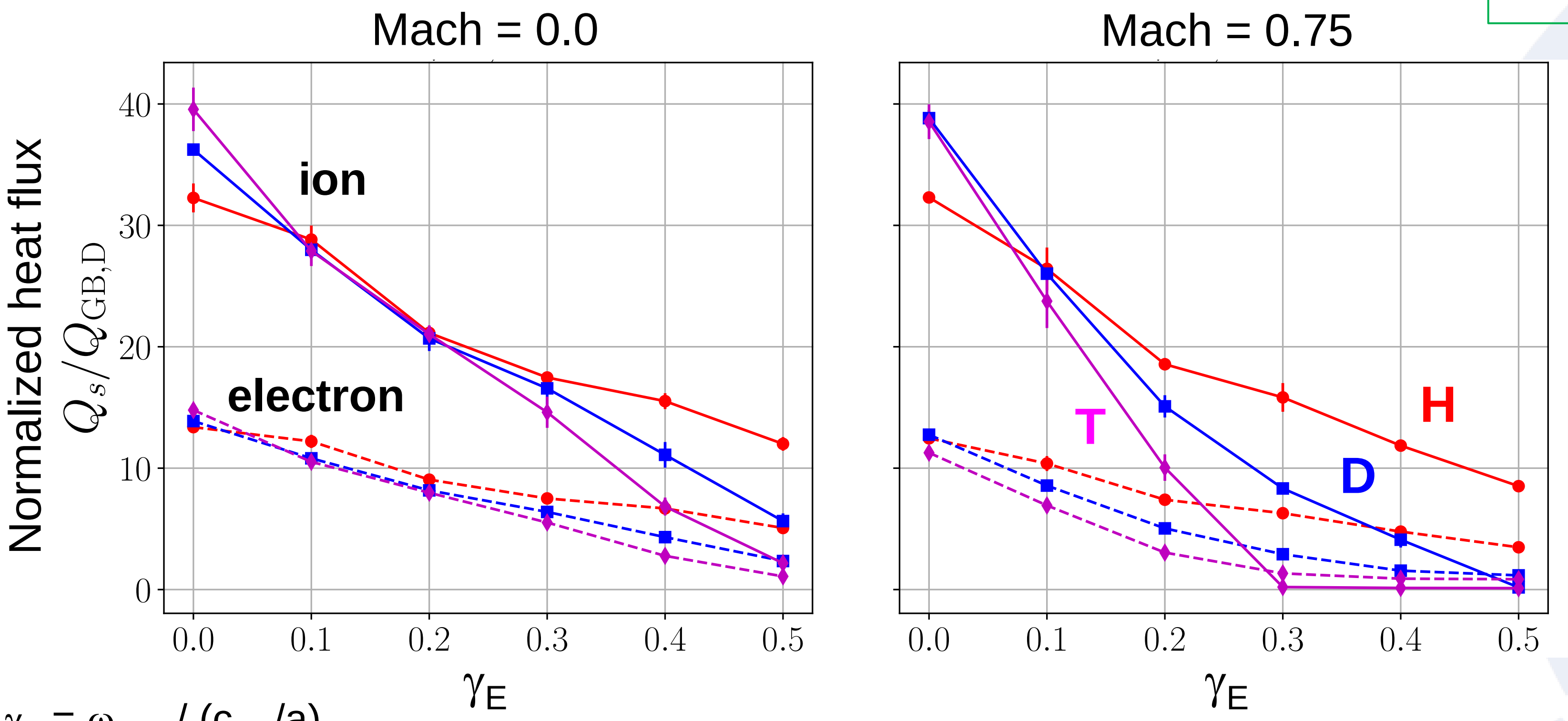
$P_{e\text{-}i} \sim Z^2/m_i\,(n_e n_i/T_e^{1.5})\,(T_e - T_i)$

- T case: less e-i coupling with higher m_i and with lower n_e (TRANSP)
- Higher T_i / T_e at ITB onset and at fully developed ITB in T than in D pulse

- Stronger T_i/T_e stabilization of core ITG turbulence in T during ITB phase

ITG heat transport decreases with isotope mass

CGYRO – NL simulations



$\gamma_E = \omega_{ExB} / (c_{s,D}/a)$

Major role played by *ExB* shearing in regulating ITG turbulence

- Scan in ExB shear and Mach-number **for GA-standard case**
- Similar gradients to JET-ILW shots at ITB onset:
  - $a/L_n \sim 1$, $a/L_T \sim 3$
- Variations in γ_E and M encompass experimental ranges:
  - Mach ~ 0.5 - 0.8
  - $\gamma_E \sim 0.1 - 0.2$

- Stronger decrease in core heat transport for T
- Sizeable Mach-numbers in experiment exacerbate isotope dependence of ITB onset and strength [Camenen, PoP 2016]

Core W transport in JET-ILW scenario with ITB

- Core impurity accumulation in plasmas with ITB in JET-C [Chen, NF 2001], [Dux, NF 2004]
  - Dominant NC impurity transport inside ITB (where turbulent transport is stabilized)
  - Impurity peaking increasing with impurity charge (C, Ne, Ni)
  - Core impurity accumulation due to inward particle pinch inside ITB

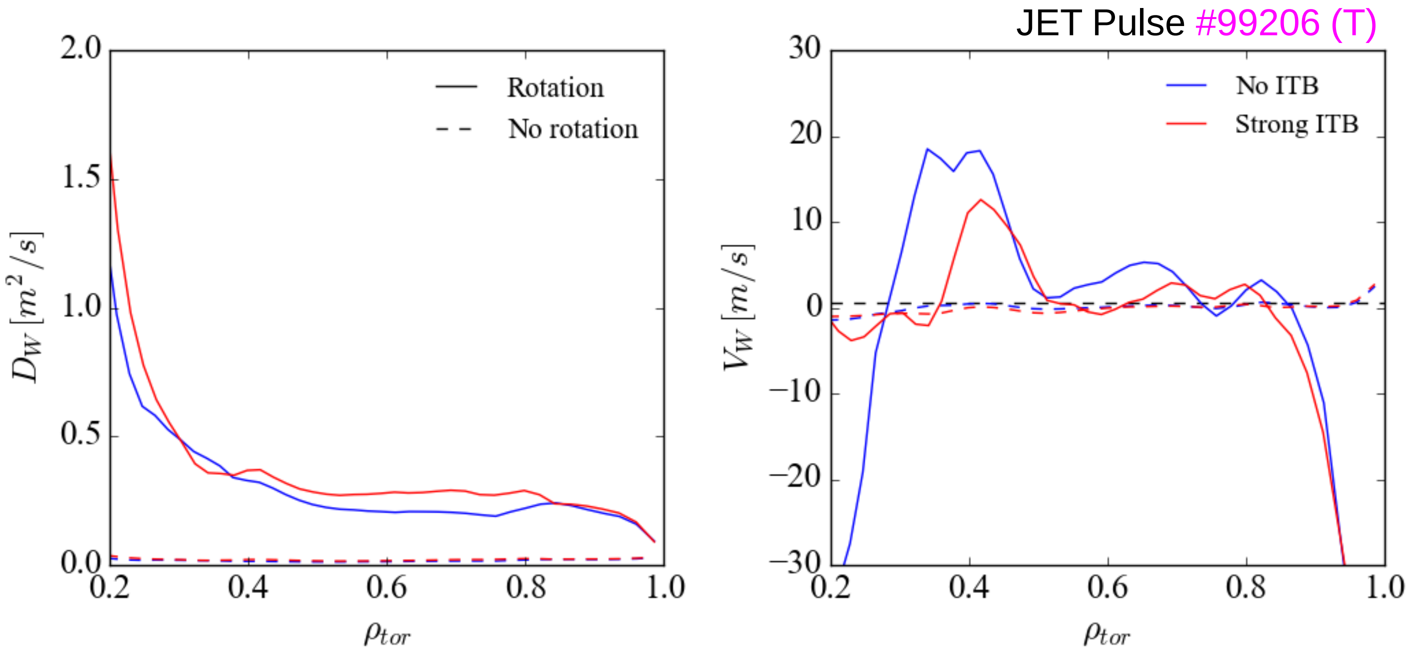
$$\frac{R\Gamma_Z}{n_Z} = \underbrace{-D_Z \frac{R}{L_{n_Z}}}_{\text{NC diffusion}} + \underbrace{H_Z \frac{R}{L_{T_i}} + K_Z \frac{R}{L_{n_i}}}_{\text{NC convection}}$$

screening parameter $C_{TS} = -\frac{H_Z}{K_Z}$

- JET-ILW ITB scenario:
  - Predictive NC transport modelling (NEO)
    - with 2 non trace impurities (Be and Ni) + W as trace impurity
    - impurity-impurity collisions important in these conditions
  - Strong n_i peaking (low collisionality, NBI), strong v_{tor}

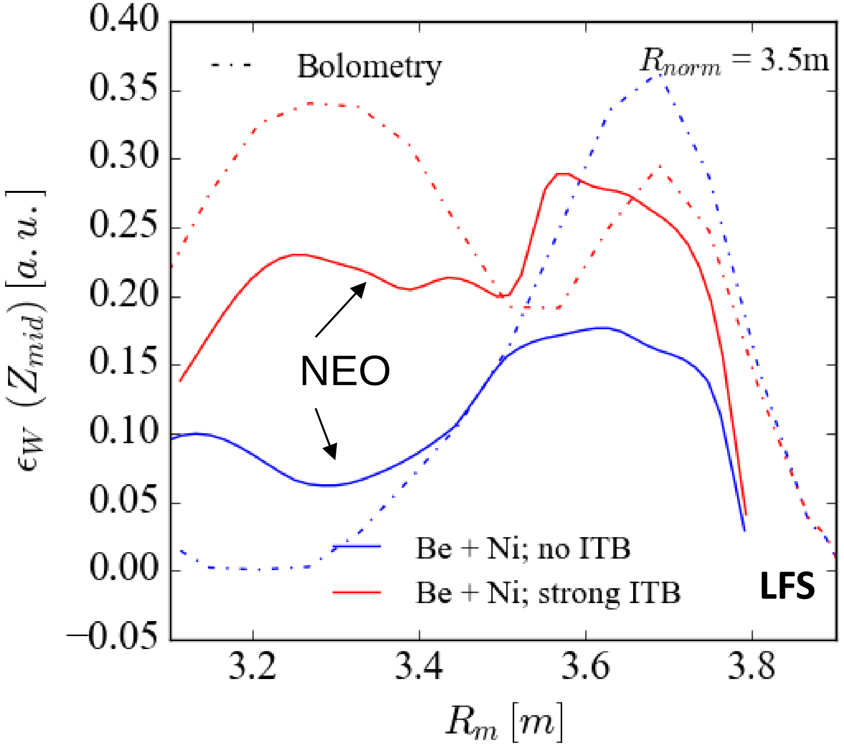
For impact of W transport on H-mode plasmas, see recent review: [Angioni, NF 2025]

Progressive core W accumulation in phase with ITB



$$V_{NC} \propto C_{TS}\left(\frac{R}{L_{T_i}}\right) - \frac{R}{L_{n_i}}$$

Predicted W emissivity (NEO) vs Bolometry tomography (total radiation)



- Outward convection V_W weakens after ITB is formed – $n_i{}'$ effects on NC transport are stronger than $T_i{}'$
- Core W accumulation expected in fully developed ITB phase (but note low P_{rad}, high f_{ELM} of T pulses)
- On-going: sensitivity of NEO predictions to L_{ni} and L_{Ti}

Conclusions

- Strong ITBs achieved in JET-ILW in scenario with NBI only in D, T and D-T, with positive, low magnetic shear and type III ELMy edge
- Scenario designed and executed for physics studies (transient, low density)
- Easier ITB onset and stronger ITB in T (at lower P_{NBI}), favoured by multiple effects:
  - optimal entry to H-mode with type III ELMs (plasma at low density from the start)
  - $n_{e,PED}$ decreasing with A_{eff} in low recycling conditions → higher core toroidal rotation
  - stabilization of core ITGs by T_i/T_e increasing with A_{eff} and with decreasing n_e
  - larger decrease in core heat transport due to ExB shear stabilization of core ITGs for higher A_{eff} and Mach (lower n_e)
- Core W impurity accumulation predicted (NEO) in fully developed ITB, due to NC inward convection inside ITB
  - sizeable Be and Ni concentrations → impurity – impurity collisions important (NEO)