Internal Transport Barriers at JET

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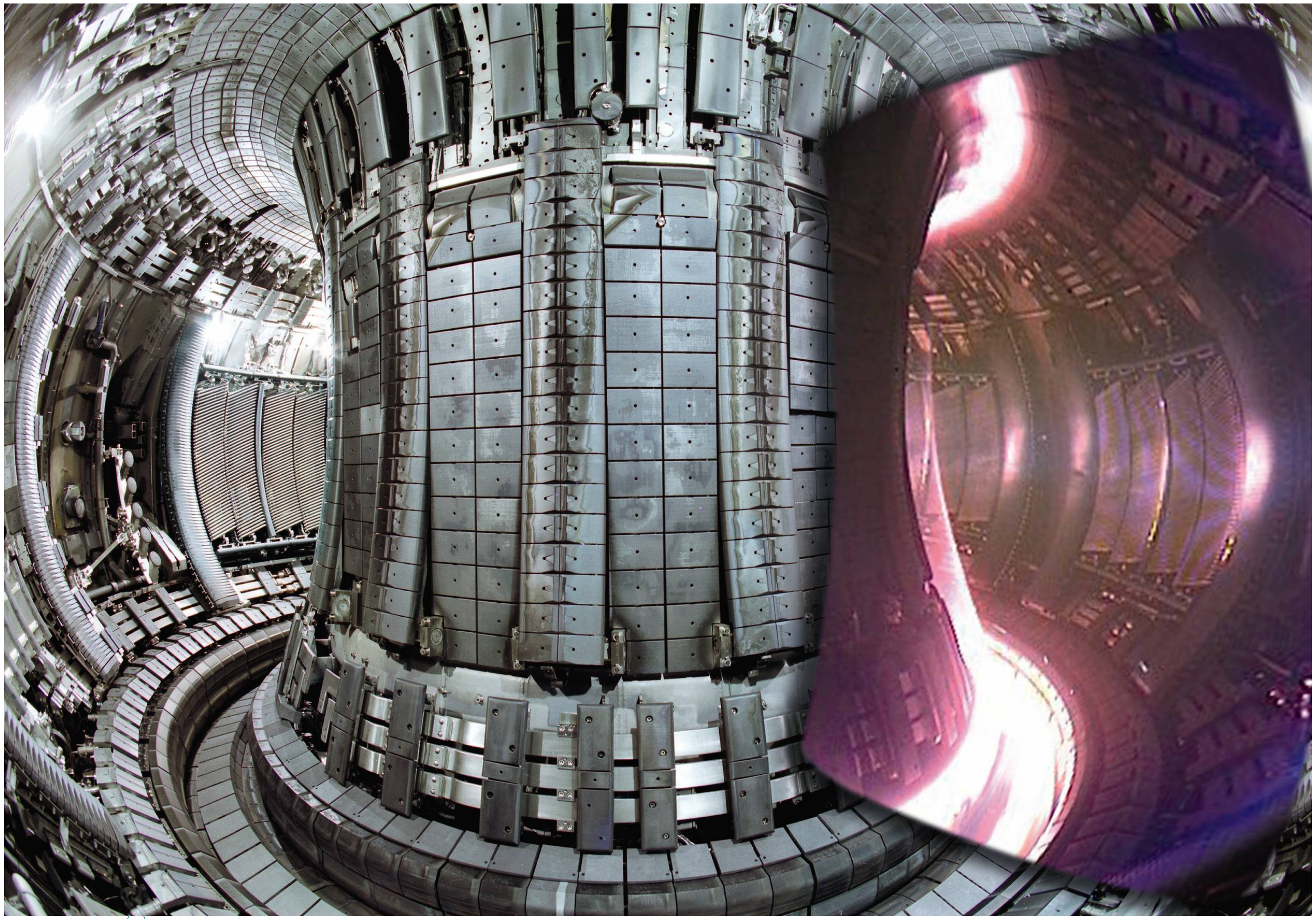
Joint European Torus: JET

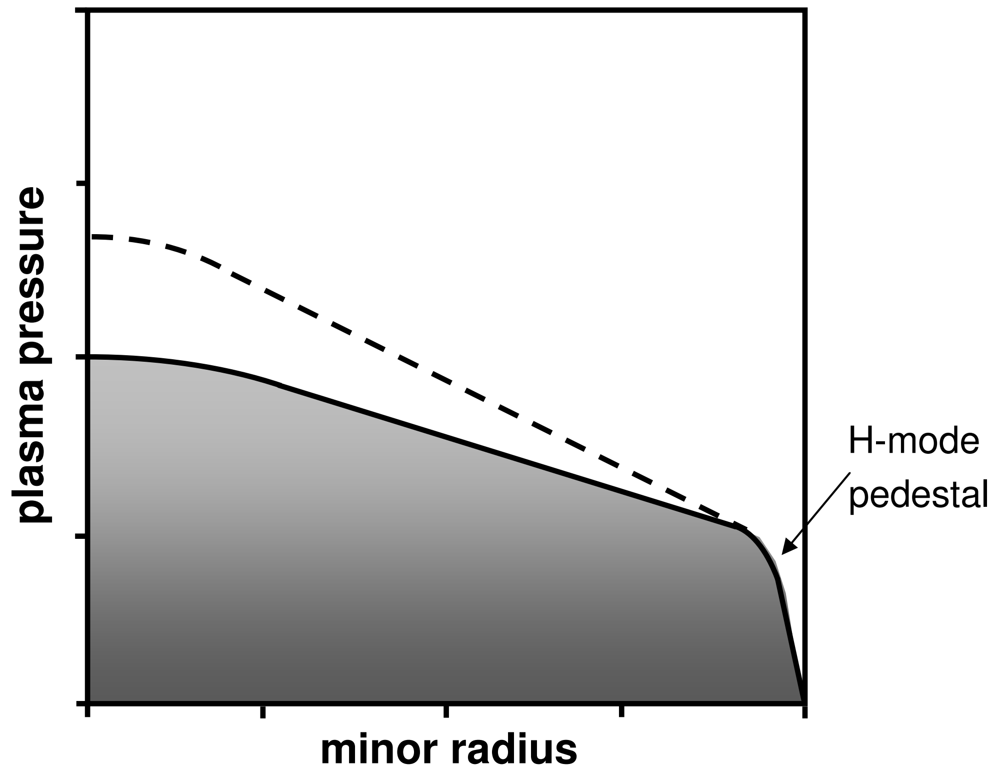
- JET is the largest fusion device in the world capable of operating with mixture of Deuterium/Tritium.
  - Tokamak: plasma confinement in a torus by means of magnetic field



Plasma volume: 80m^2
Magnetic field: 2.0-3.4T (4T)
Current: 1.0-3.5 (4.5MA)

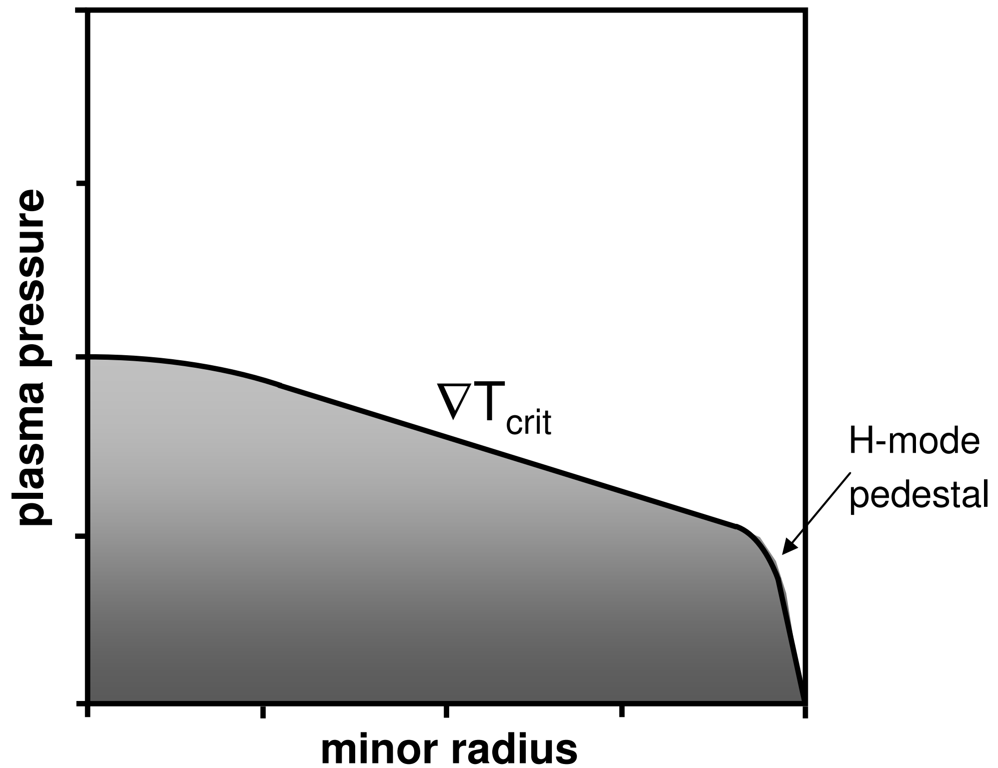
Tokamak confinement

- In order to achieve fusion conditions one aims to obtain the best possible (energy) confinement with high temperatures and pressures in the core.
- This requires large gradients in the pressure (temperature)



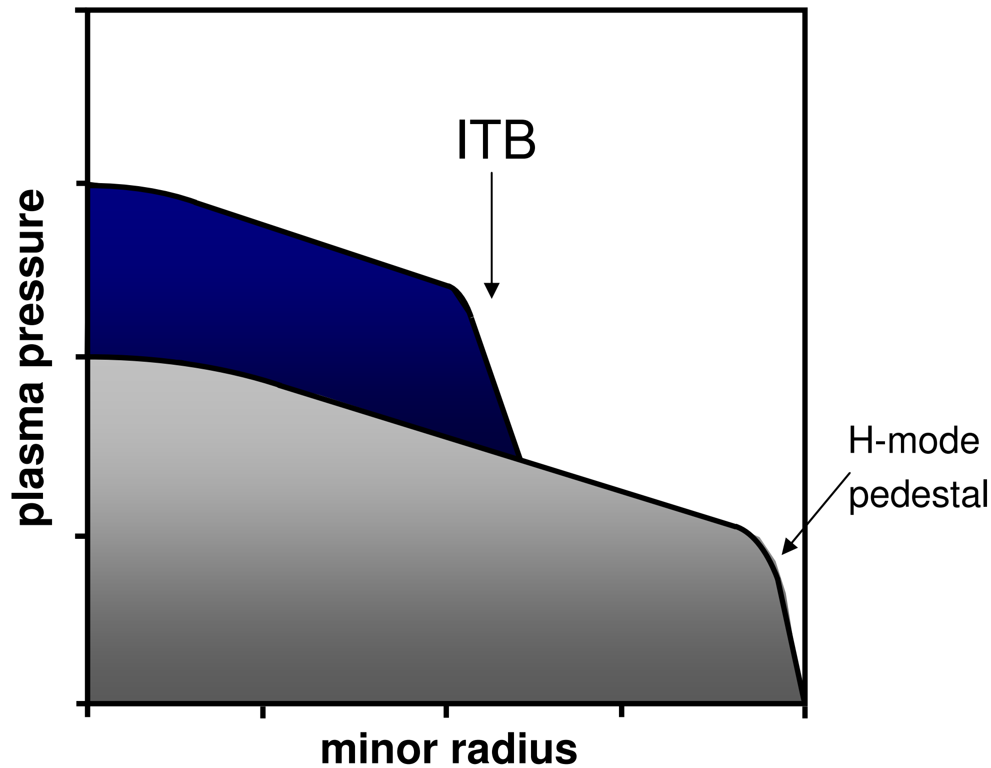
Transport in Tokamak plasmas

- At high gradients, turbulent modes may grow in Tokamak plasmas that dominate the transport processes.
  - Thus transport is not diffusive and these turbulent modes will set a critical gradient yielding so-called stiff (ion) temperature profiles.



Internal Transport Barriers

- But the profile stiffness can be broken (locally) yielding so-called internal transport barriers (ITBs)
  - ITBs provide an opportunity to improve the Tokamak confinement
  - Studying ITBs may improve our understanding of turbulence

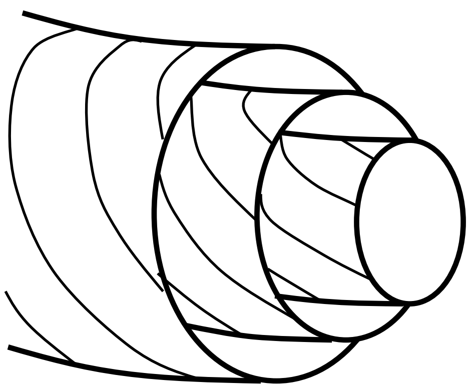


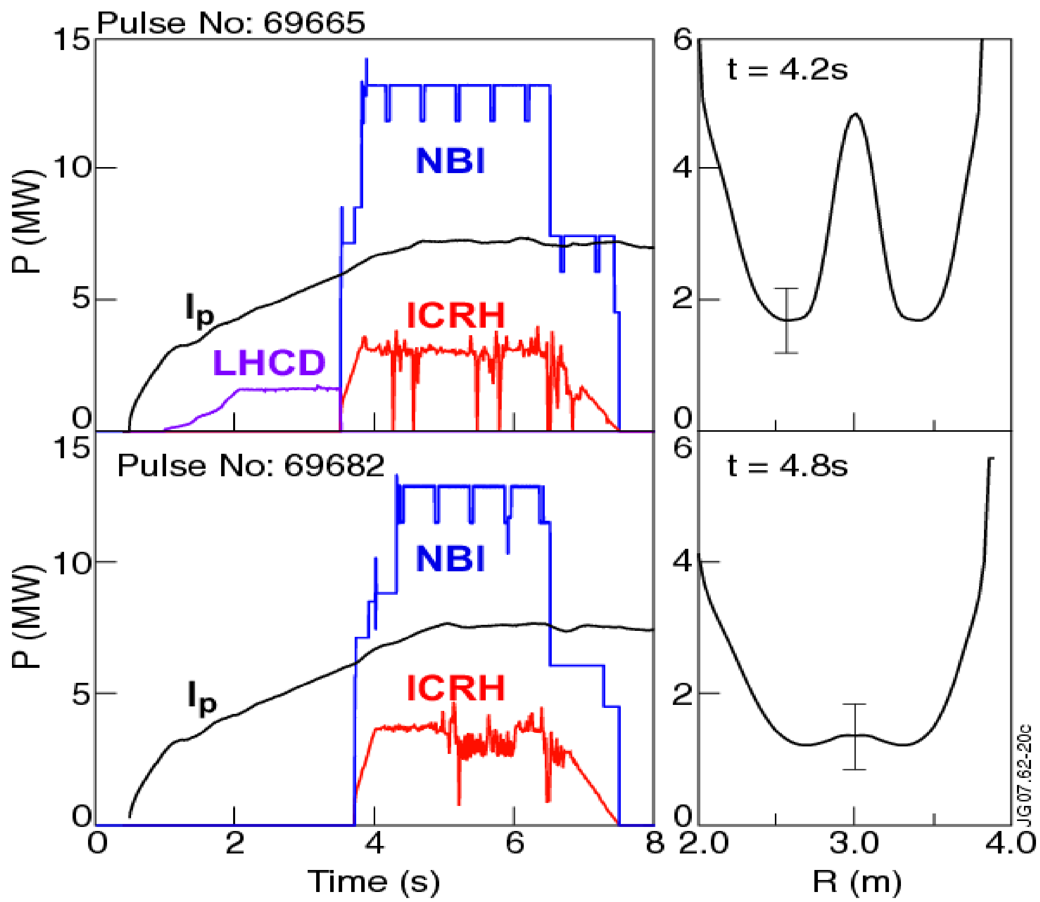
Outline

- How do we make internal transport barriers at JET?
  - What triggers the growth of strong ion ITBs?
  - How important is rotational shear?
- Compare JET ITBs with those in JT-60U
  - What about electron and particle transport?
- Some general remarks about ITB and their use in Tokamaks
- Give references to more detailed descriptions

How to make an ITB at JET

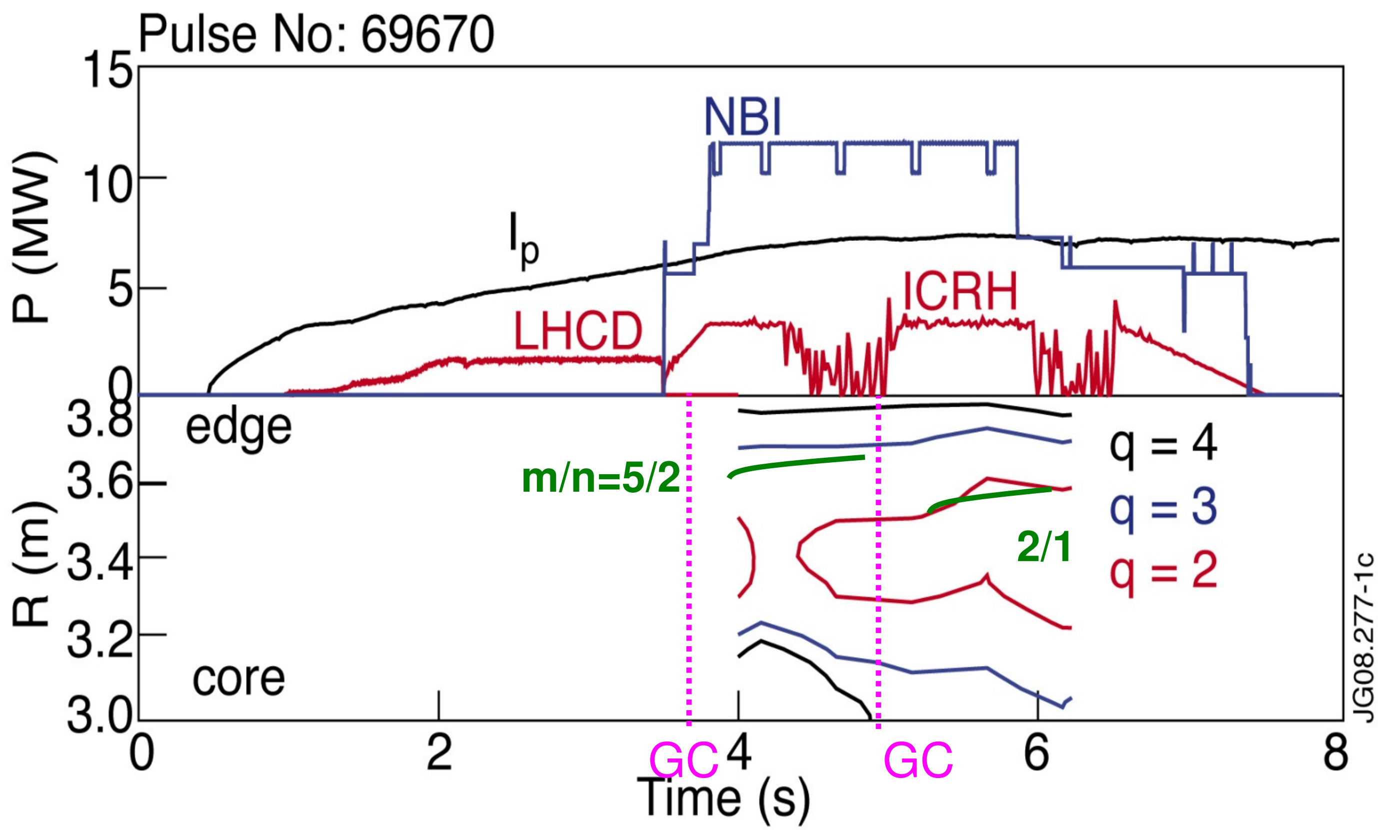
- Empirical recipe to form strong internal ion transport barriers
  - Optimised q-profiles with low or negative magnetic shear (q'/q)
  - Similar recipe used in various Tokamaks (JT-60U, DIII-D, …)





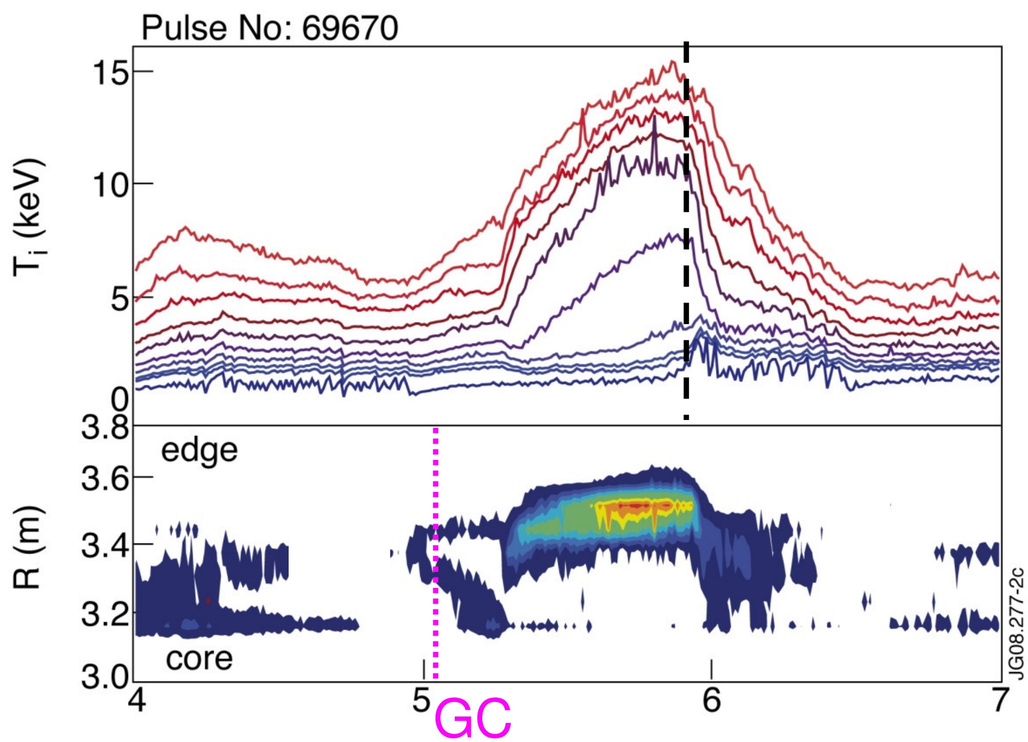
How to make an ITB at JET

- Empirical recipe to form strong ion internal transport barriers
  - Focus here on q-profiles with central negative magnetic shear (q'/q)
    - The q profile develops in time (current diffusion, impact of bootstrap current)
  - Use significant Neutral Beam Injection (NBI) heating (rotation?)



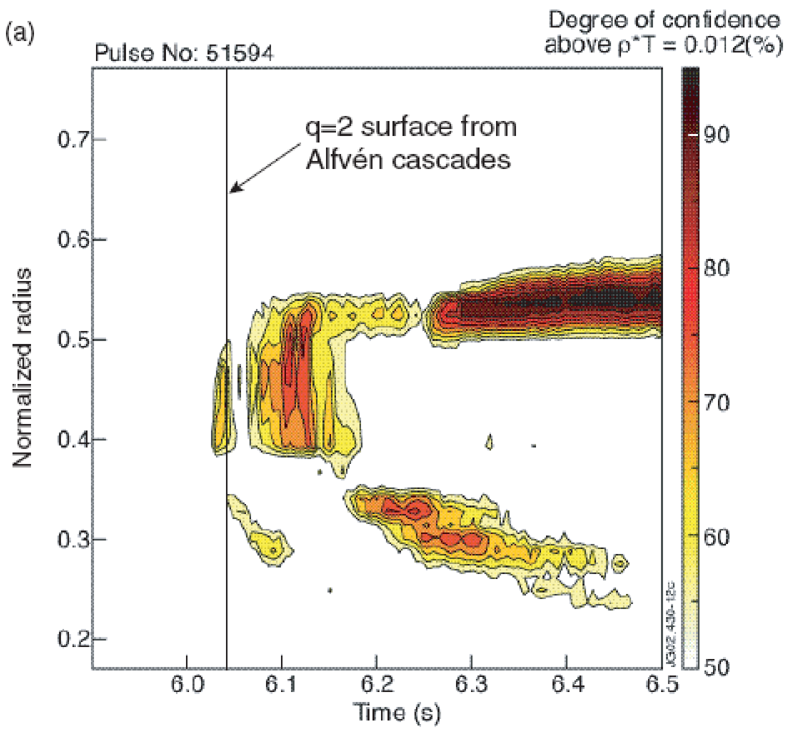
- A sudden appearance/growth of a strong ITB can be seen
- The growth of the ITB could eventually be limited by the onset of disruptive kink modes (infernal modes)

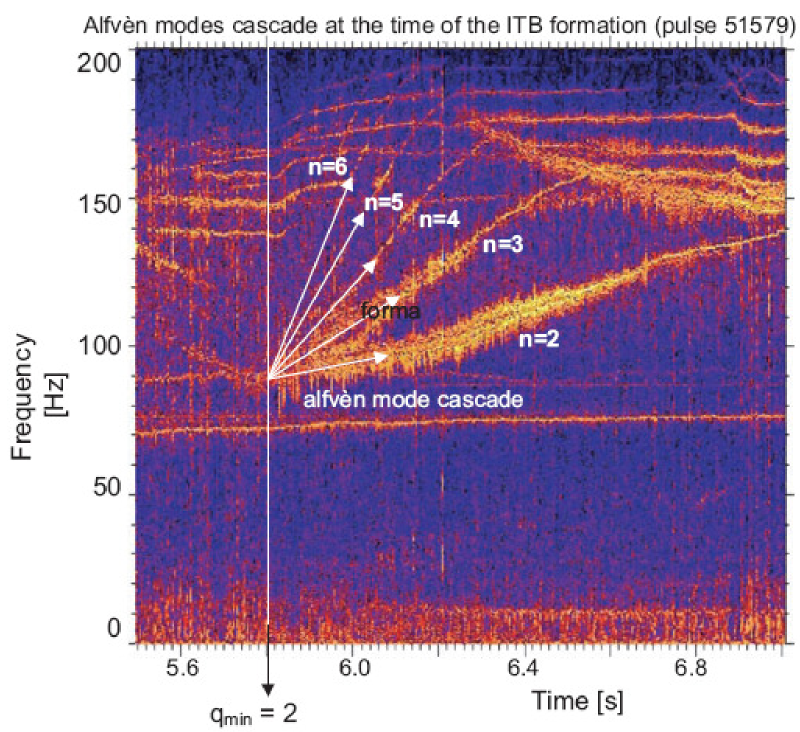
$$\rho_T^* \equiv \frac{\rho_L}{L_T} \propto \nabla T$$



Triggering ITBs in JET plasmas

- A trigger mechanism starts the ITBs growth
  - The physics mechanism is however not well understood
  - Different for plasmas negative[1] or low[2] central magnetic shear
  - For the latter it is related to the appearance of a rational q_{min}





[1] E. JOFFRIN, Nucl. Fusion **43** (2003) 1167

[2] E. JOFFRIN, et al., Nucl. Fusion **42** (2002) 235

Triggering ITBs in JET plasmas

- A trigger mechanism starts the ITBs growth
  - The physics mechanism is however not always understood
  - The formation of ion ITBs in JET are usually not predicted from theory based transport/turbulence models[1,2]
  - Such triggers are also found to act in JT-60U, DIIID, ...

[1] Y.F. BARANOV, et al., Plasma Phys. Control. Fusion 46 (2004) 1181.
[2] T. TALA, T, et al., Nucl. Fusion 46 (2006) 548.

ITBs and plasma rotation at JET

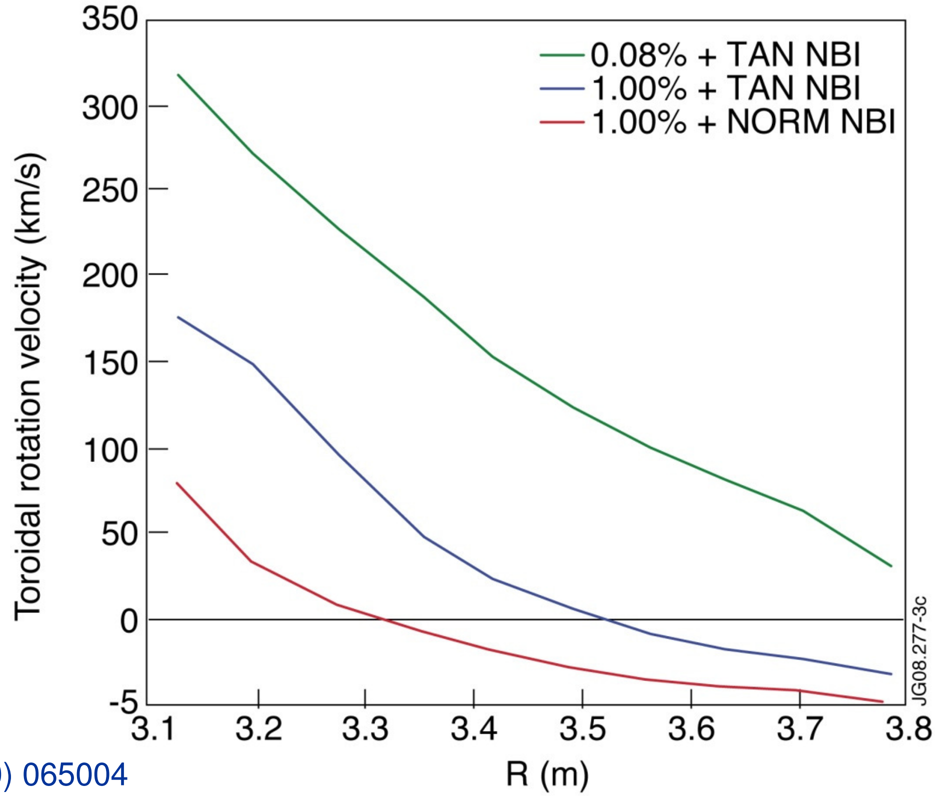
- How important is the NBI ingredient? $\rightarrow$ rotation?
  - Can we make strong ITBs without fast plasma rotation?

- Experiments on ITBs at JET were carried out, where the plasma rotation was changed by:
  - Replacing the NBI by ICRH ion heating[1,2]
    - Not easy to keep the heat flux unchanged
  - Applying larger toroidal field ripples[2,3]
    - Change rotation independent from heat flux

[1] N.C. HAWKES, et al., Contribution to the 32nd EPS Conference (Warsaw) 2008.
[2] P.C. DE VRIES,, et al., Nucl. Fusion **49** (2009) 075007.
[3] P.C. DE VRIES, et al., Plasma Phys. Control. Fusion **50** (2008) 065008.

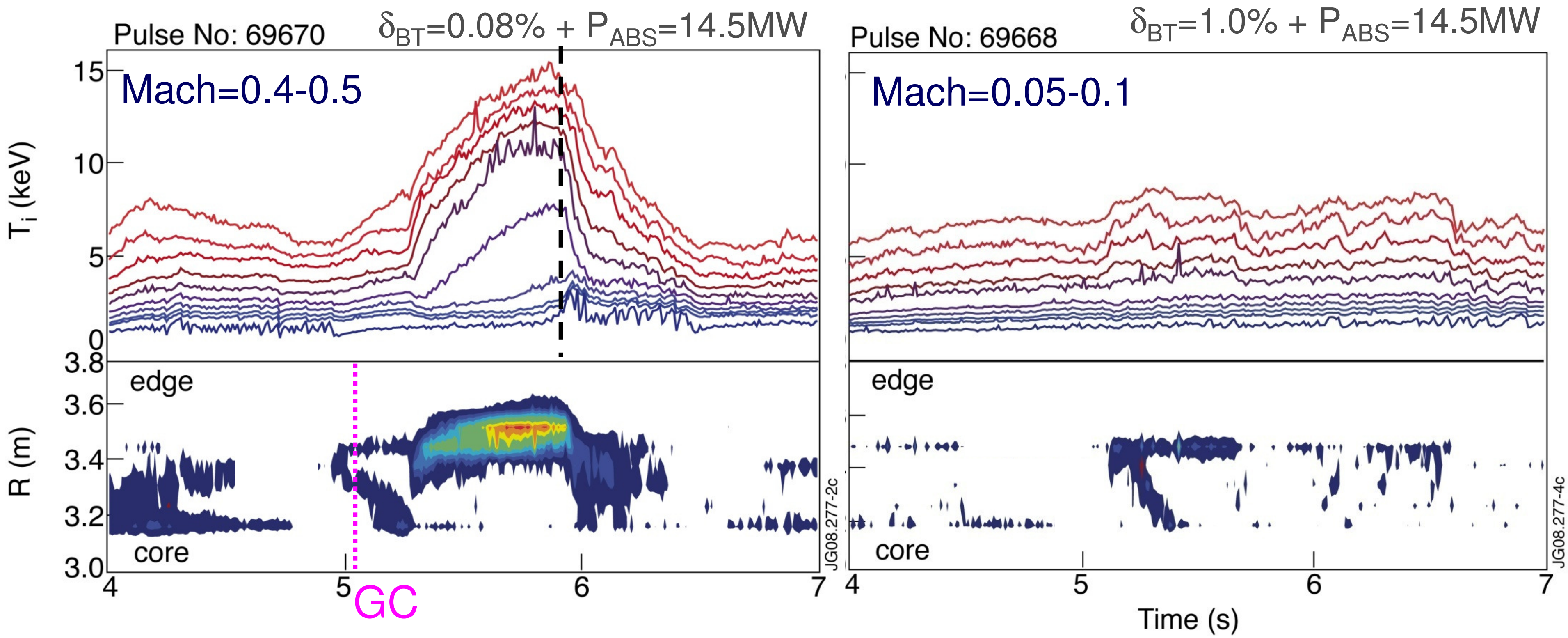
TF ripple and plasma rotation

- JET has the unique capability to alter its toroidal field ripple.
  - This has a significant effect on the torque on the plasma[1] but less on the heat deposition by NBI and ICRH
  - In combination with momentum transport effects (pinch) a higher TF ripple yields a lower rotation and smaller rotation gradients[2].



[1] P.C. DE VRIES, et al., Nucl. Fusion **48** (2008) 035007.
[2] P.C. DE VRIES, et al., Plasma Phys. Control. Fusion **50** (2010) 065004

- Increasing the TF ripple amplitude results in a reduction of the rotational shear:
  - has a detrimental effect on the growth of the ITB[1].
  - But an ITB triggering event is still visible![2]



[1] P.C. DE VRIES, et al., Plasma Phys. Control. Fusion **50** (2008) 065008.
[2] P.C. DE VRIES, et al., Nucl. Fusion **49** (2009) 075007.

ITBs and plasma rotation

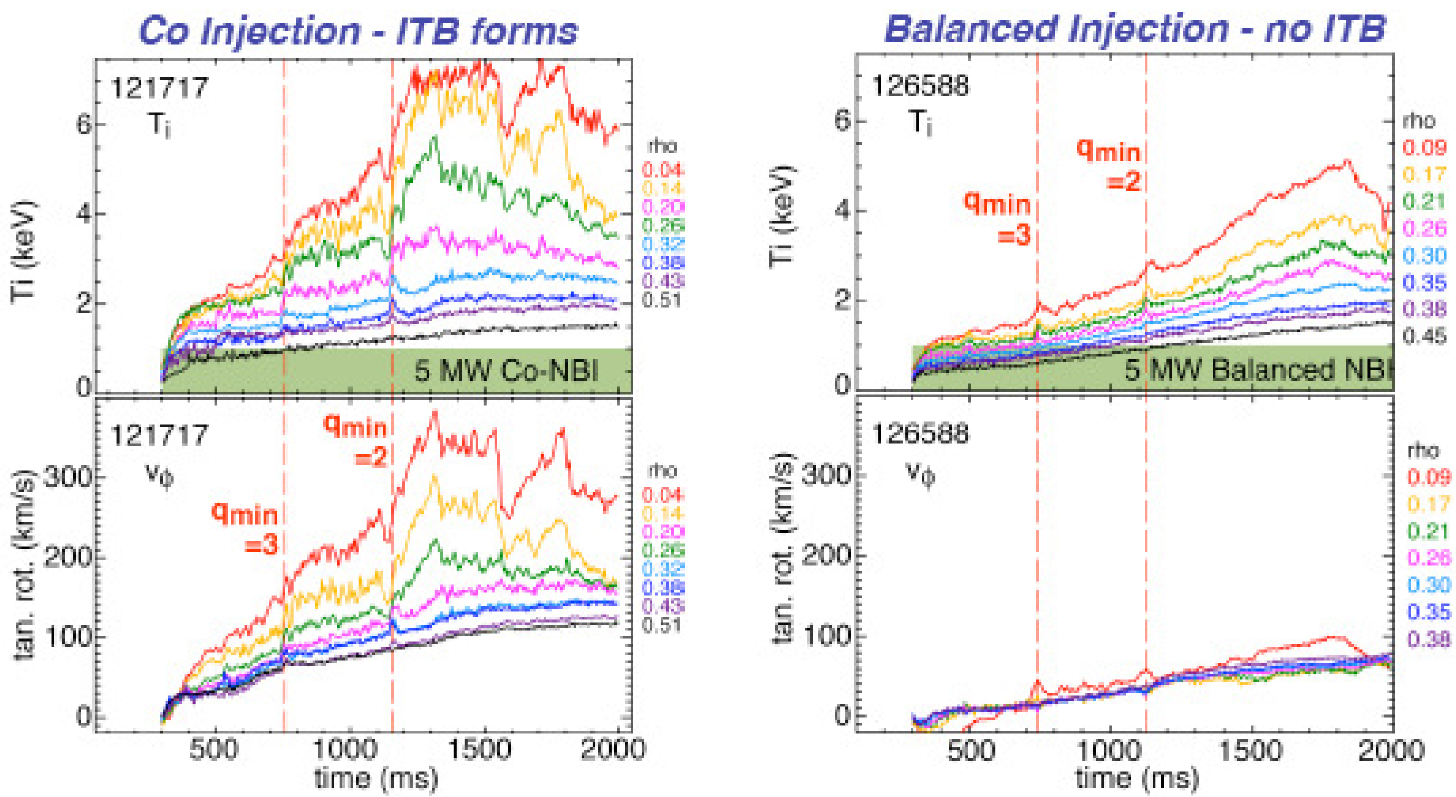
- At JET, replacing NBI by more ICRH and hence reducing the rotation, had similar effects[1,2]
  - Detrimental effect on the growth of the ITB.
  - But an ITB triggering event is still visible!

- JT-60U and DIII-D were able to do such experiments using balanced NBI[4,5]

[1] N.C. HAWKES, et al., Contribution to the 32nd EPS Conference (Warsaw) 2008.
[2] P.C. DE VRIES,, et al., Nucl. Fusion **49** (2009) 075007.
[3] P.C. DE VRIES, et al., Plasma Phys. Control. Fusion **50** (2008) 065008.
[4] Y. SAKAMOTO, et al., Nucl. Fusion **41** (2001) 865
[5] M.W. SHAFER, M.W, et al., Phys. Rev. Lett. **103** (2009) 075004.

Example from DIII-D

- Similar observations have also been made at DIII-D[1].



[1] M.W. SHAFER, M.W, et al., Phys. Rev. Lett. **103** (2009) 075004.

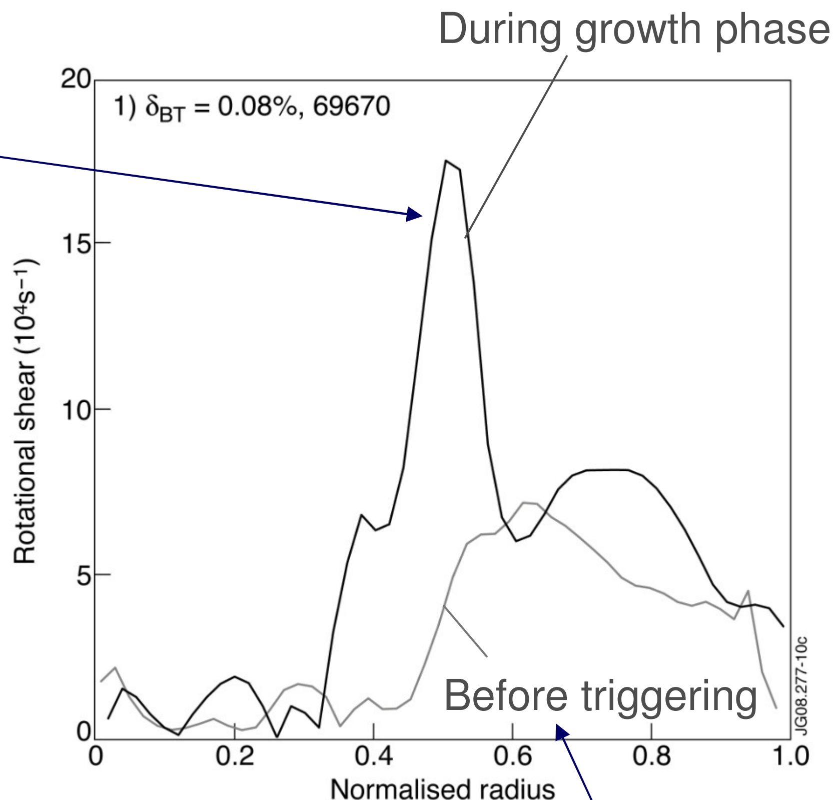
Interpretation

- At the time the transport barrier forms/triggers:
  - for high TF ripple or a larger ICRH fractions: ω_{ExB}~1-2·10^4 [s^{-1}] almost one order of magnitude below the ITG growth rate γ_{ITG}
  - for low TF ripple and high NBI fractions: ω_{ExB}~6·10^4 [s^{-1}] of the order of ITG growth rate γ_{ITG}
- Detailed modelling with the GYRO[1] code showed
  - That γ_{ITG}=6-7 10^4 s^{-1} without rotational shear (high TF ripple)
  - For low TF ripple and rotational shear:
    - At time of triggering: γ_{ITG}=1.5 10^4 s^{-1}
    - During the growth phase ITG modes are fully stabilized.
- The JET plasmas are sub-critical to suppress the turbulence, but the trigger of a seed barrier pushes it over the threshold
  - Reversed shear/minimum q not needed for ITG stabilization

[1] J. CANDY, and R.E. WALTZ, Phys. Rev. Lett. (2003) 045001

- The ITB will enhance the gradient in toroidal rotation
  - Thus the ITB itself may be able further increase $\omega_{ExB}/\gamma_{ITG}$.
  - That γ_{ITG}=6-7 10^4 s^{-1} without rotational shear (high TF ripple)

ITG fully stabilised
neo-classical transport



ITG growth rate reduced to γ_{ITG}=1.5 10^4 s^{-1}

[1] P.C. DE VRIES, et al., Nucl. Fusion **49** (2009) 075007.

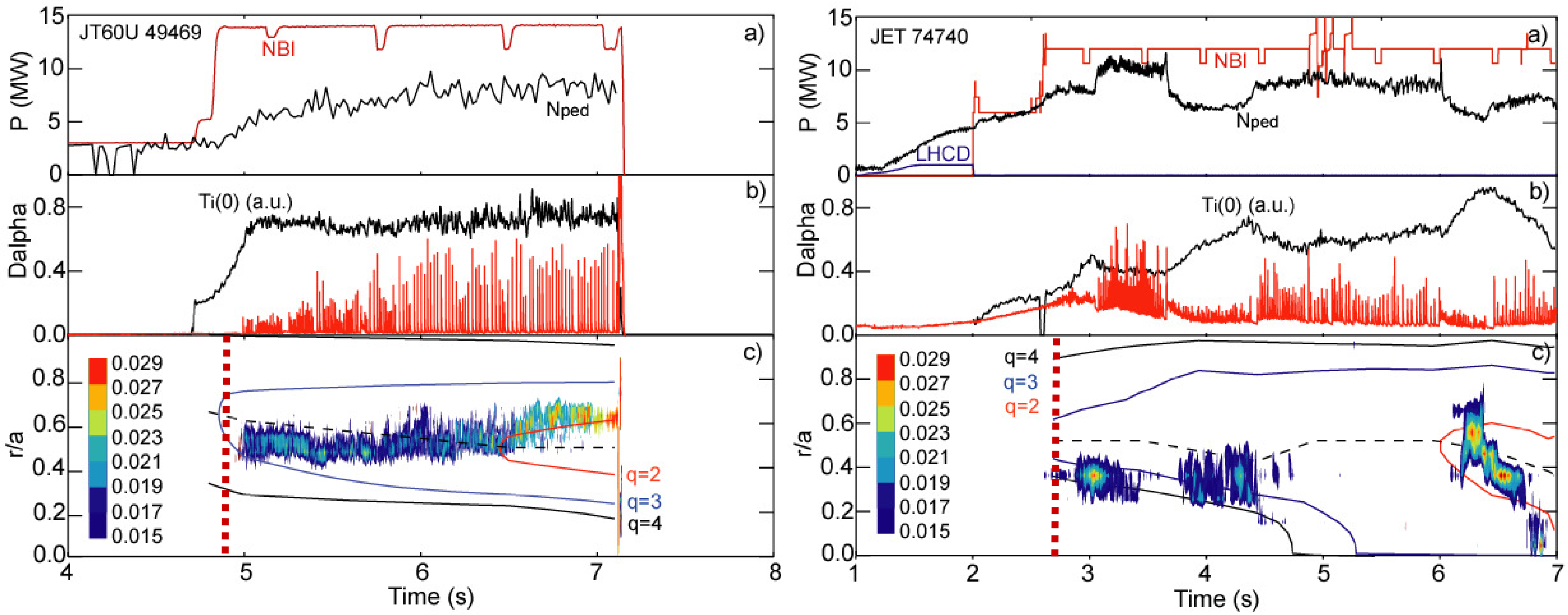
Using ITBs in an AT scenario

- Beside being of interest for the understanding of the underlying transport processes, ITBs could be used in so-called Advance Tokamak (AT) scenarios.
  - AT scenario's aim to have a fully non-inductive current drive

- Requires steady-state, stable and wide ITBs

Comparing JET and JT-60U

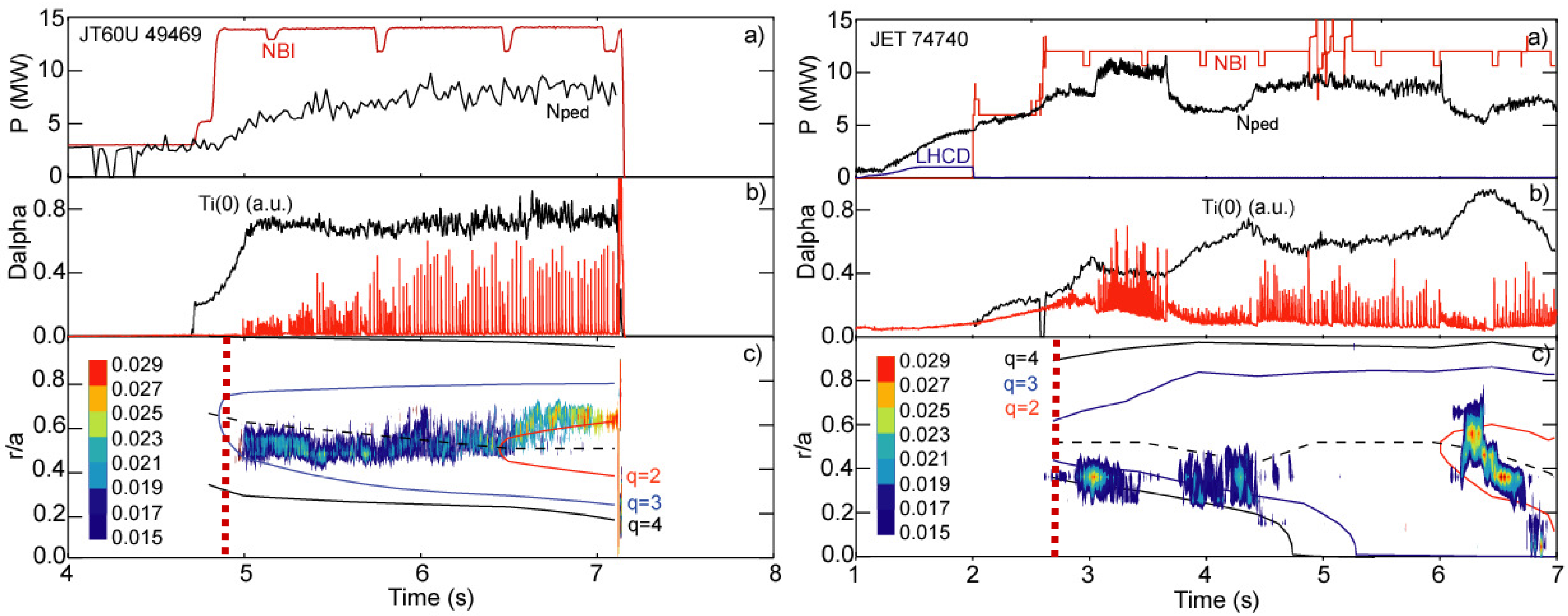
- ITB triggering similar between JET and JT-60U
  - Example: RS q_{min}=3 ITBs for JT-60U and JET (same TF ripple, NBI)
  - Stronger ion ITBs formed in plasmas with more rotational shear at the time they are triggered.



[1] P.C. DE VRIES, et al., Plasma Phys. Control. Fusion **51** (2009) 124050.

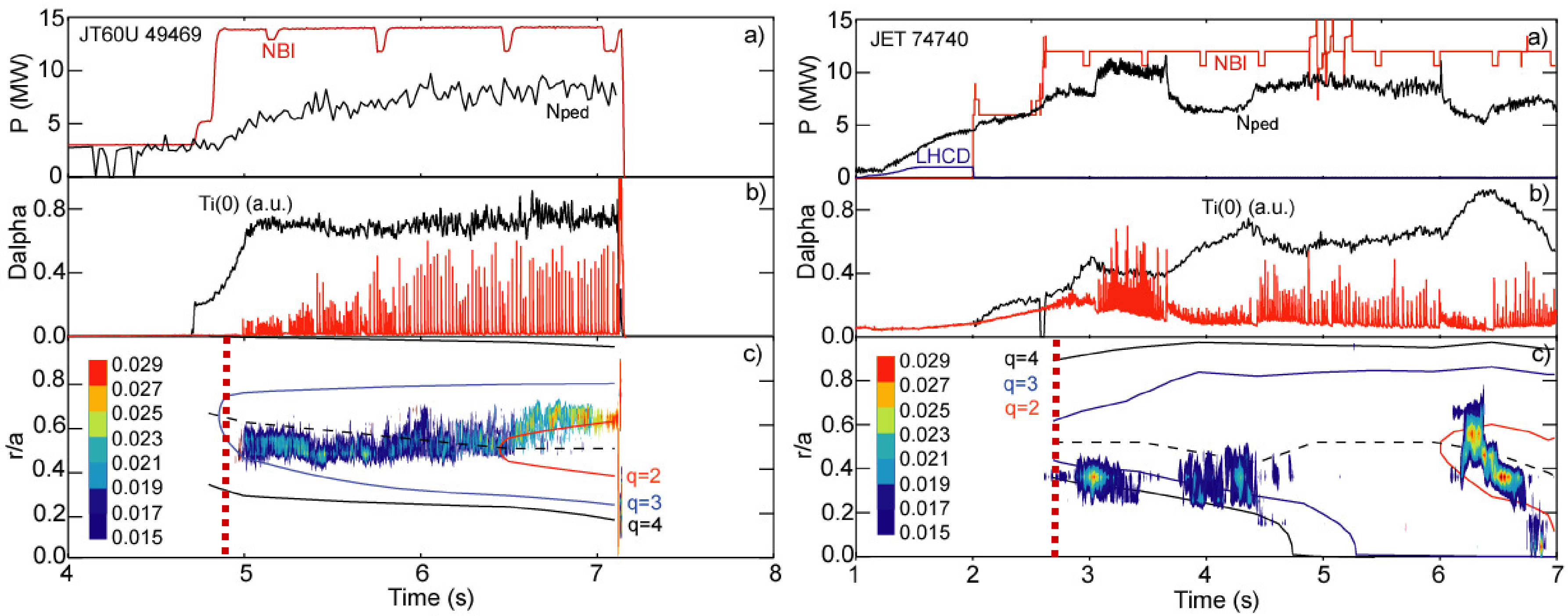
Comparing JET and JT-60U

- The dynamic behaviour is not identical[1]
  - Example: RS q_{min}=3 ITBs for JT-60U and JET (same TF ripple, NBI)
  - It is not always easy to capture the dynamic behaviour of ITBs
    - Difference in density profile → different j_{BS} → different q profile develop
    - Impact of ELMs/pedestal



[1] P.C. DE VRIES, et al., Plasma Phys. Control. Fusion **51** (2009) 124050.

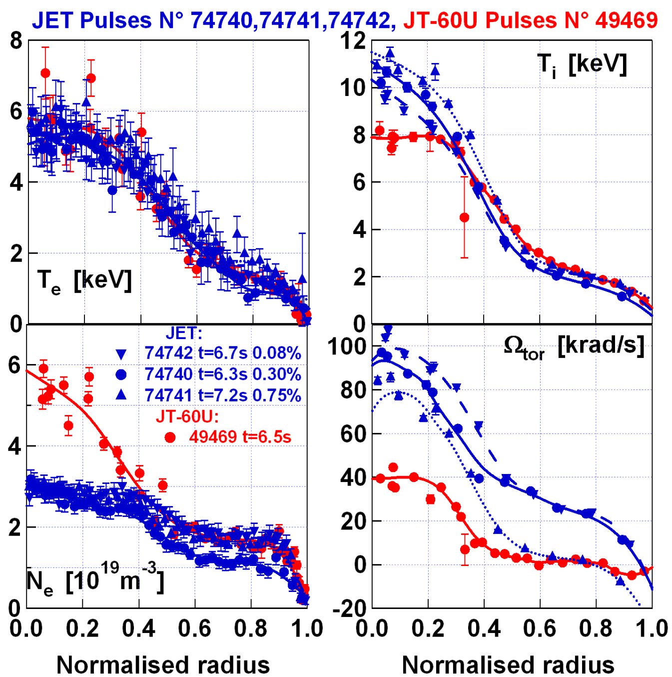
- Beside the ion transport channel also the transport of particles and electron transport channel and that of particles has to be considered.
  - It is known that negative magnetic shear is beneficial for the formation transport barriers in the electron channel[1].

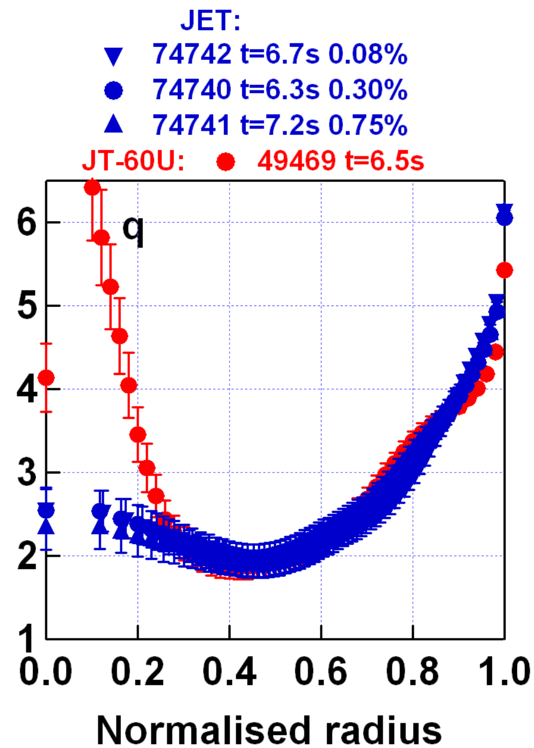


[1] Y.F. BARANOV, et al., Plasma Phys. Control. Fusion 46 (2004) 1181.

Comparing JET and JT-60U

- Beside the ion transport channel also the transport of particles and electron transport channel and that of particles has to be considered[1].
  - The slightly larger negative shear in JT-60U affected the particle transport → more peaked density profiles[1,2]

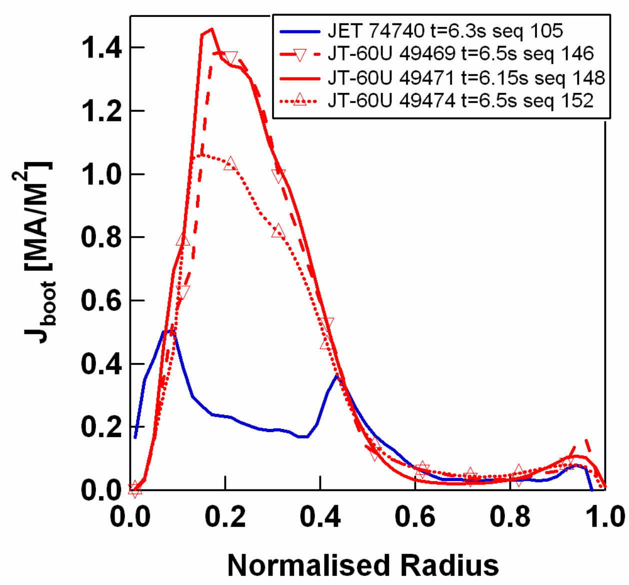


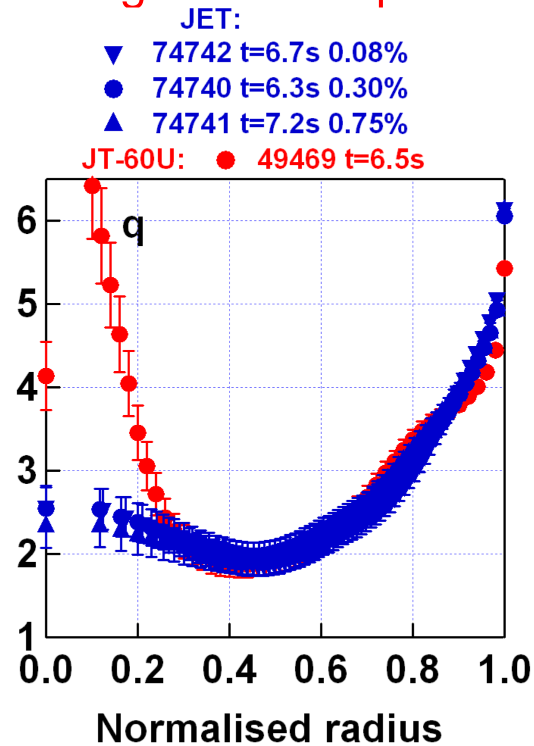


[1] X. LITAUDON, et al., IAEA Fusion Energy Conference (2010) Deajon, Korea
[2] C BOURDELLE, et al., PHYS. PLASMAS **14** (2007) 112501

Comparing JET and JT-60U

- Beside the ion transport channel also the transport of particles and electron transport channel and that of particles has to be considered.
  - The slightly larger negative shear in JT-60U affected the particle transport → more peaked density profiles → larger bootstrap current →





[1] X. LITAUDON, et al., IAEA Fusion Energy Conference (2010) Deajon, Korea

Comparing JET and JT-60U

- Beside the ion transport channel also the transport of particles and electron transport channel and that of particles has to be considered.
  - The slightly larger negative shear in JT-60U affected the particle transport → more peaked density profiles → affects ITG turbulence

[1] X. LITAUDON, et al., IAEA Fusion Energy Conference (2010) Deajon, Korea

Summary & Conclusions (1)

- In JET rotational shear is not sufficient to trigger the growth of ion ITBs and a special trigger mechanism is at play, related to the appearance of a rational q_{min}.

- But the further growth of the ITB is affected by the level of rotational shear at the time of triggering. Larger ion ITBs grow in plasmas with sufficient rotational shear.

- A Very similar picture is found in other devices.
  - Same physics!

- Can ion ITBs form without the need of a trigger mechanism, but just because of sufficient rotational shear?
  - In JET basic rotational shear is usually not enough (need trigger)
  - May well be possible in devices with very large Mach numbers

Summary & Conclusions (2)

- An ITB is a local reduction in transport or turbulence and this can be achieved in many different ways
  - Sharapov shift, strongly peaked density profiles, fast particles,..
  - Transport channels for electrons/particles and ions differ

- Hence these results do not necessarily apply to all ITBs one has to be careful comparing ITBs but basically:
  - Rotational shear seems to be important for the formation of ion ITBs, while magnetic shear affects electron heat and particle transport.

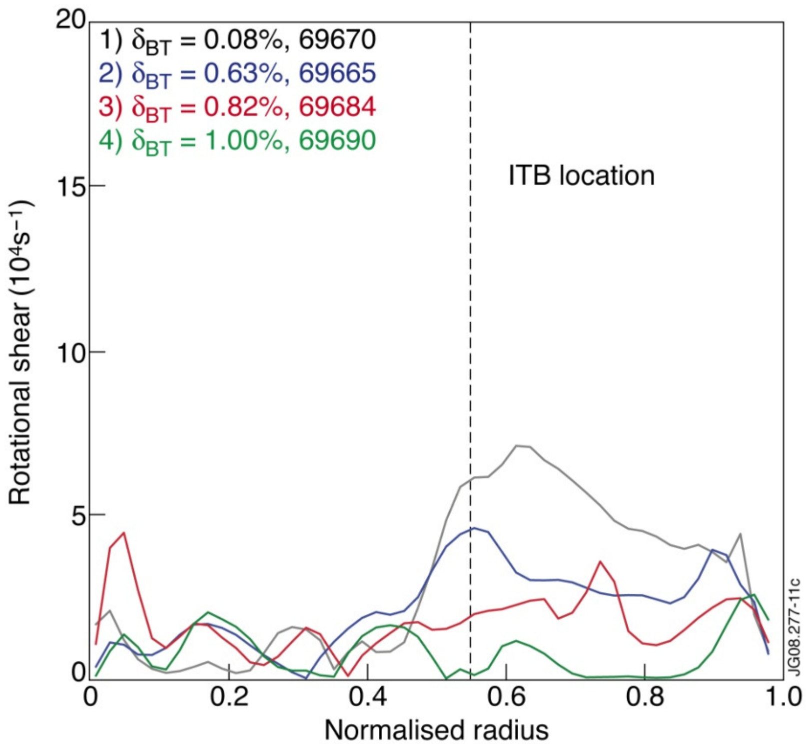
- When developing (or modelling) an ITB Tokamak scenario the complete picture of all transport channels/turbulence and the interplay between them needs to be considered.

Rotational shear and TF ripple

- The rotational shear or shearing rate ω_{ExB} has been calculated under the assumption of neo-classical poloidal rotation.

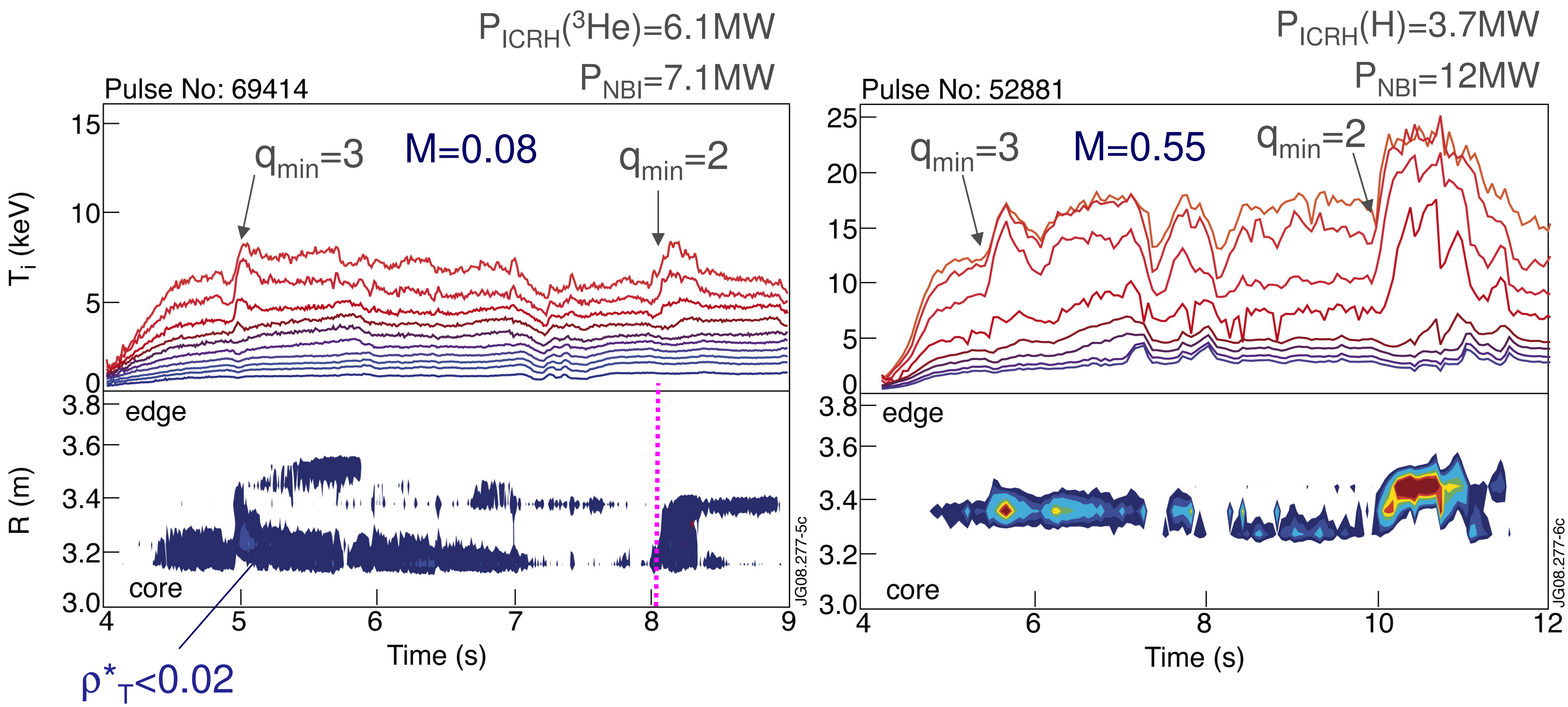
$$\omega_{ExB} = \frac{RB_\theta}{B}\frac{\partial}{\partial r}\left(\frac{E_r}{RB_\theta}\right)$$

$$E_r = v_\phi B_\theta - v_\theta B_\phi + \frac{1}{Zne}\frac{\partial P}{\partial r}$$



[1] P.C. DE VRIES, et al., Nucl. Fusion **49** (2009) 075007.

- Increasing the ICRH fraction and reducing the rotation
  - Even in plasmas with little torque/rotation ITB triggers were found
  - But the growth of ITB was limited in these plasmas

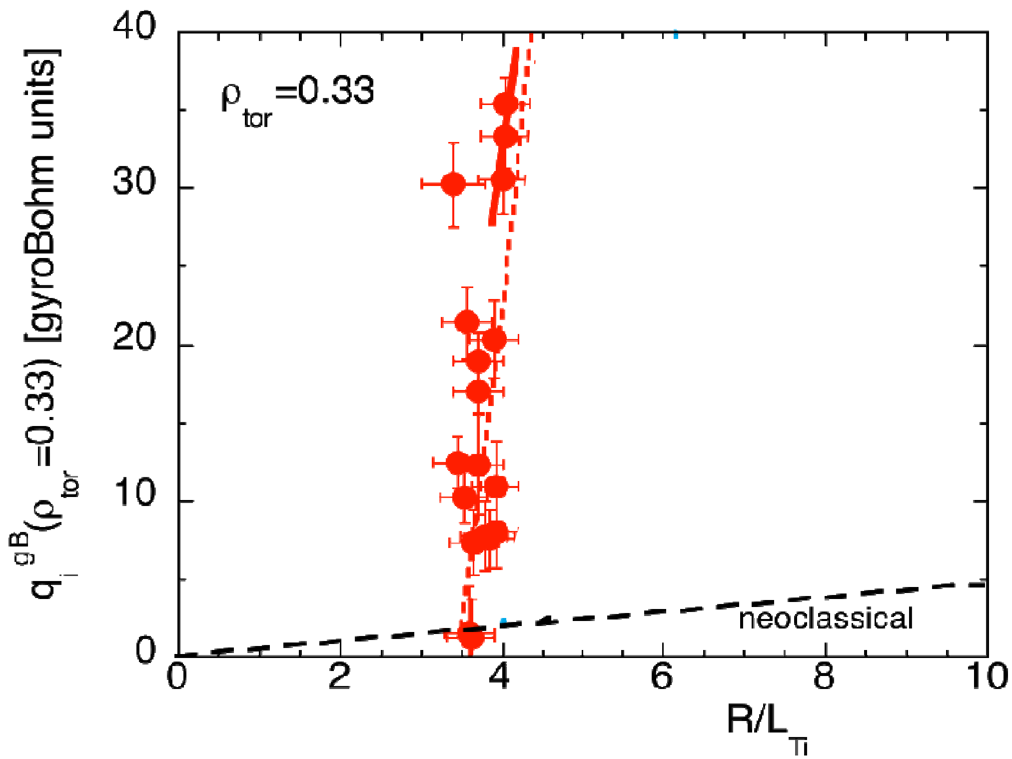


[1] N.C. HAWKES, et al., Contribution to the 32nd EPS Conference (Warsaw) 2008

[2] P.C. DE VRIES, et al., Nucl. Fusion **49** (2009) 075007.

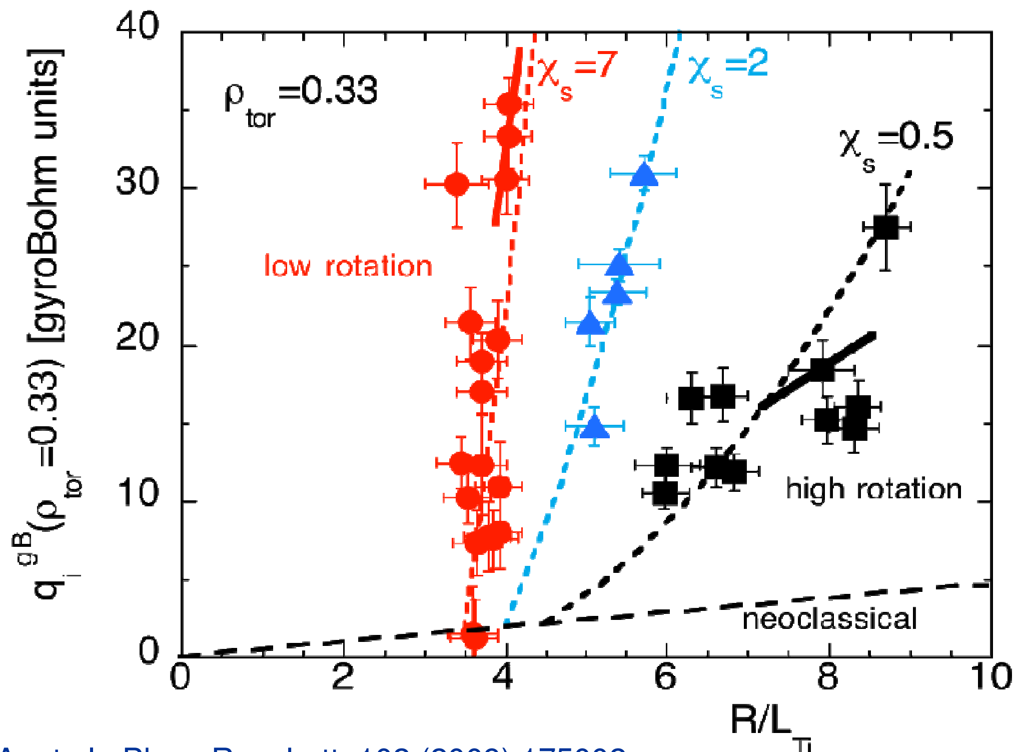
Turbulence and Profile Stiffness

- Turbulence plays a dominant role in Tokamak transport
  - Ion temperature gradient driven modes → 'stiff' temperature profiles
  - Profile gradient is determined by ITG stability, not by the heat flux and neo-classical diffusivity.



Turbulence and Profile Stiffness

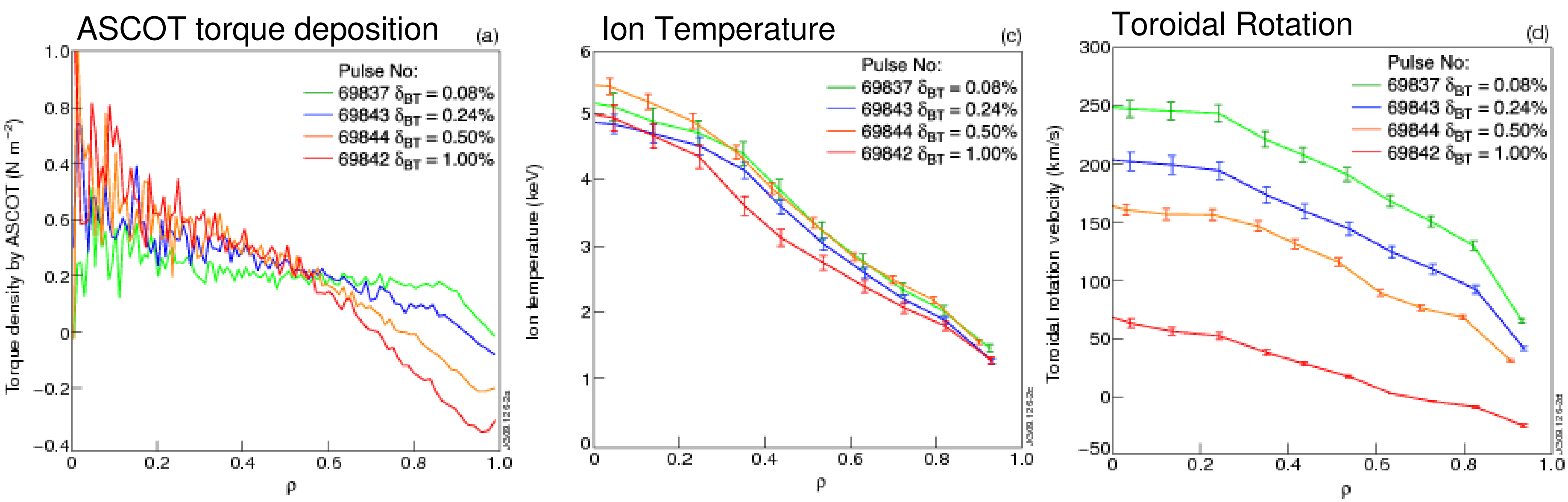
- However, detailed experiments at JET have shown that the stiffness is reduced in plasmas with more rotation[1].
  - Rotation is thought to reduce the (ITG) turbulence growth rate
  - Here the profile stiffness is found to be affected
  - How do ion ITBs fit into this picture?



[1] P. MANTICA, et al., Phys. Rev. Lett. 102 (2009) 175002

TF ripple experiments and Pinch

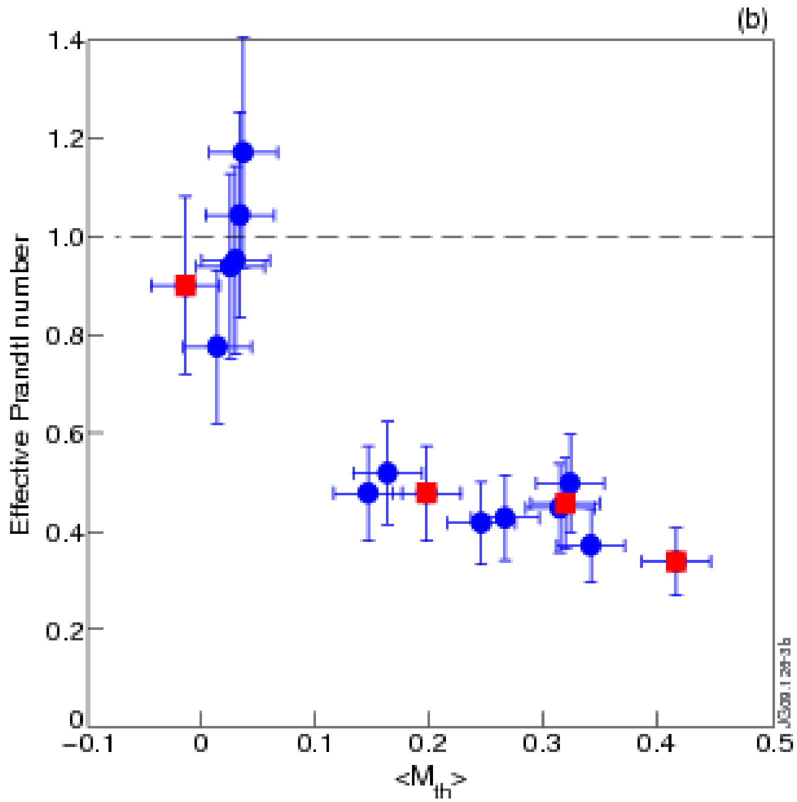
- TF ripple affects the toroidal rotation
  - When the TF ripple is increased, the toroidal rotation profile is affected but torque flux (ρ=0.5) is not
  - This suggests momentum transport is altered.



- Increasing TF ripple reduces the rotation/momentum in the outer part of the plasma, yielding a smaller effect of pinch
  - Hence, less peaked rotation profiles and larger effective Prandtl nr.

$$\Gamma_\phi = -\chi_\phi^{eff}\nabla\Omega \longrightarrow \Gamma_\phi = -\chi_\phi \nabla\Omega - V_p\Omega$$

$$P_r^{eff} = \frac{\chi_\phi^{eff}}{\chi_i}$$



[1] P.C. de Vries, et al. PPCF **52** (2010) 065004.

- What is the magnitude of the momentum pinch to explain these observations?

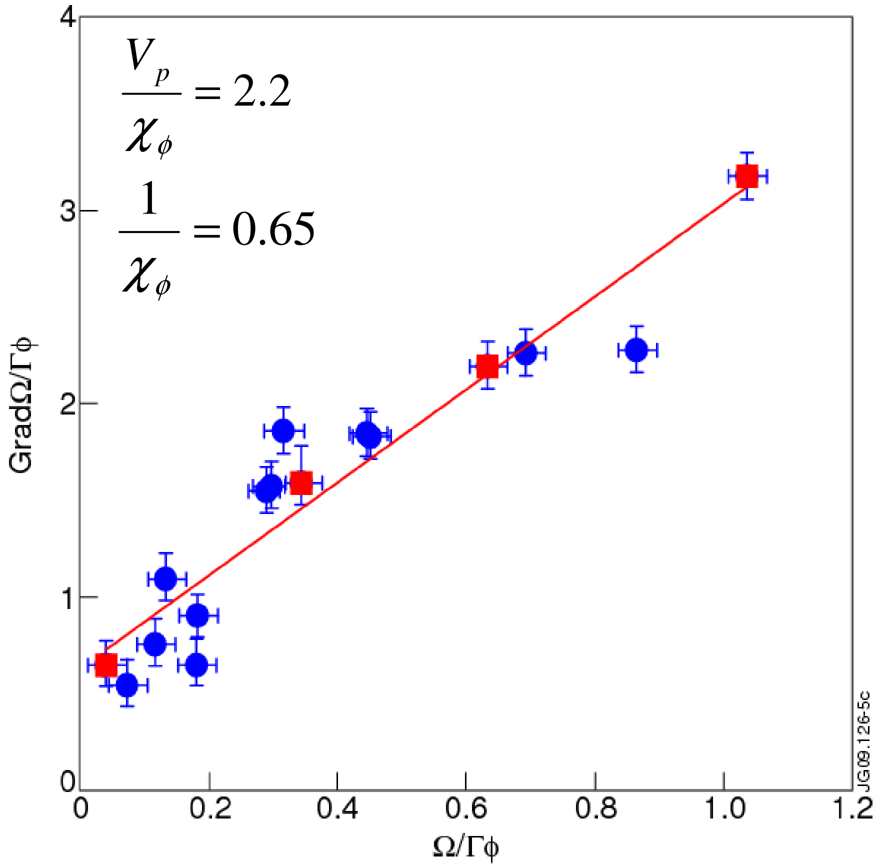
$$\frac{\nabla\Omega}{\Gamma_\phi} = -\frac{V_p}{\chi_\phi}\frac{\Omega}{\Gamma_\phi} - \frac{1}{\chi_\phi}$$

Averaged over discharges

$$\chi_\phi = 1.5(m^2/s)$$

$$\chi_i = 1.2(m^2/s)$$

$$V_p = 1.4(m/s)$$



[1] P.C. de Vries, et al. PPCF **52** (2010) 065004.

Estimated pinch from Database

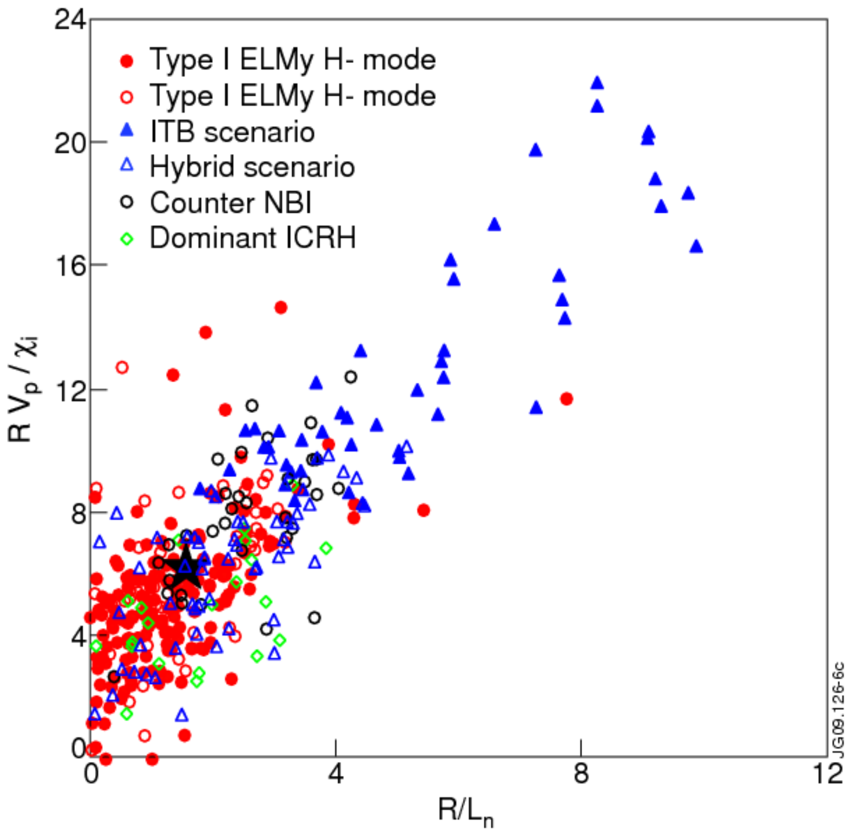
- Assuming that the momentum diffusivity is equal to the ion heat diffusivity one could estimate the magnitude of the pinch for all entries in the database.

$$\Gamma_\phi = -\chi_\phi^{eff} \nabla\Omega$$

$$\Gamma_\phi = -\chi_\phi \nabla\Omega - V_p \Omega$$

$$\downarrow$$

$$\frac{V_p}{\chi_i} \approx (1 - P_r^{eff}) \frac{\nabla\Omega}{\Omega}$$



– Scales with R/L_n [1,2]

– For H-modes: $2 < RV_p/\chi < 10$

[1] P.C. de Vries, et al. PPCF **52** (2010) 065004.

[2] A.G. Peeters, Phys. Rev. Lett. **98** (2007) 265003.