# Role of ripple and ergodic magnetic field in ELM mitigation

V. Parail, T. Johnson, T. Kiviniemi, J. Lönnroth, A. Salmi, P. de Vries, M. Becoulet, C. Gimblett, J. Hastie, T. Hatae, V. Hynönen, D. Howell, Y. Kamada, S. Konovalov, T. Kurki-Suonio, N. Oyama, G. Saibene, R. Sartori, K. Shinohara and EFDA JET contributors

# Outlook

- Transport due to ergodic magnetic field- first principles;
- "Unusual" experimental results;
- Ergodic transport and ELM modelling in JETTO;
- What we can and what we can not explain in the modelling;
- Similarity between Resonance Magnetic Perturbation (RMP) and ripple.

# Transport due to ergodic magnetic field- first principles 1/2

- In case of static magnetic perturbation stochastic diffusion results from the overlap of magnetic islands (Rechester, Rosenbluth etc):

$$W_{m,n} = \sqrt{\frac{16qr}{mq'} \frac{\tilde{B}_r}{B_\theta}(r_{m,n})}$$ - Island width;

- Onset of stochastisity corresponds to island overlap criterion:

$W_{m,n} \geq \Delta_{m,\ m+1} \approx 1/k_\theta s$;

- In this case one can introduce diffusion of magnetic field line, $D_M$:

$D_M = \pi q R (B_r/B_0)^2$, which can be related to stochastic diffusion of electrons and ions:

# Transport due to ergodic magnetic field- first principles 2/2

$$\chi_e^{RMP} \approx D_M V_{Te} \frac{1}{1+\dfrac{\pi q R \cdot \nu_e}{V_{Te}}} \propto D_M \sqrt{\frac{T_e}{m_e}} \cdot \frac{1}{1+\alpha \cdot \dfrac{n_e}{T_e^2}}$$

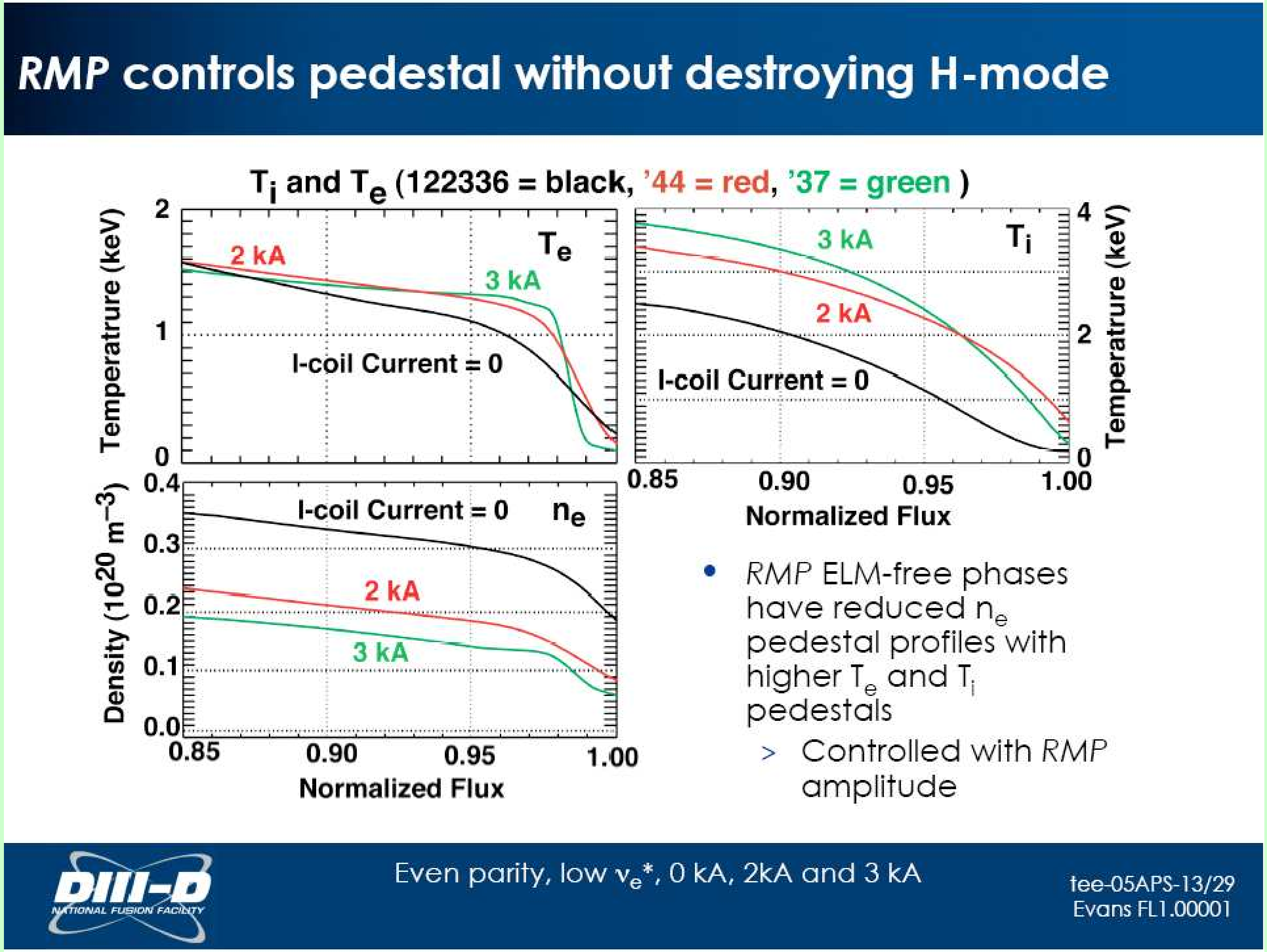
$$\chi_i^{RMP} \approx D_{particle}^{RMP} \approx \chi_e \cdot \sqrt{\frac{m_e}{M_i}}$$

$$\chi_\Sigma \approx \chi_\perp + \chi_{II}^{RMP}$$

- Therefore it is expected that stochastic magnetic field increases electron transport in first place;
- It is also expected that stochastic transport strongly decreases with collisionality (density);

# "Unusual" experimental results 1/4

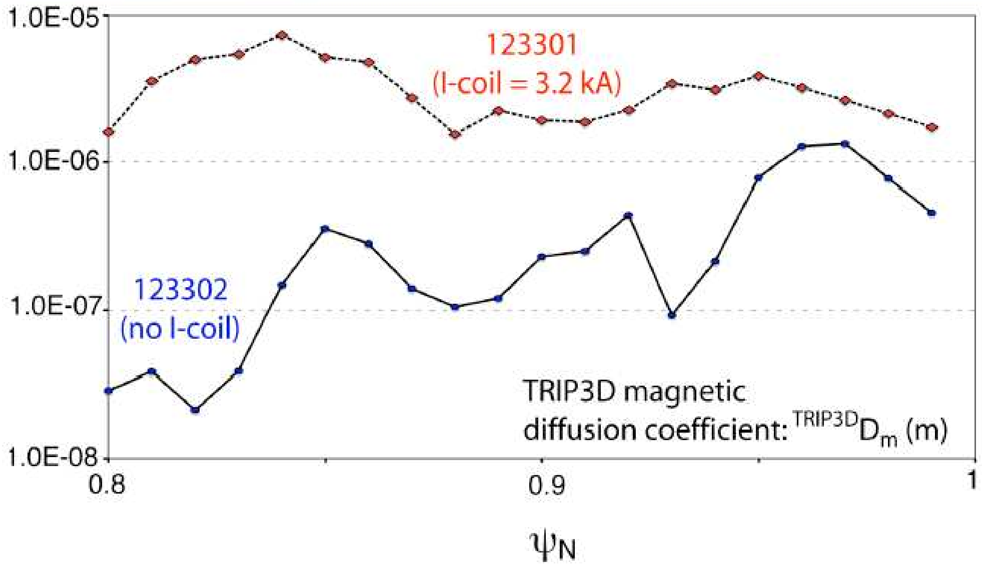
- Application of RMP results in density drop rather than in Te drop!
- Note that Ti increases with RMP so we can't say that electron thermal conductivity is not increased!



# "Unusual" experimental results 2/4

- The level of calculated stochastic electron transport, induced by RMP, exceeds experimentally observed transport by 2 order of magnitude.

## Calculated field line diffusion implies thermal diffusivity that is two orders of magnitude too large




C-coil and field-errors included in each case: I-coil = 3.2 kA (upper) and no I-coil (lower).

- At $\psi_N = 0.95$, ${}^{TRIP3D}D_m = 3.9E\text{-}6$ m and ${}^{quasi\text{-}linear}D_m = 3.5E\text{-}6$ m:
  - > ${}^{quasi\text{-}linear}\chi_e = v_{Te} D_m \sim 49\ m^2/s$ but to match experimental $T_{e,ped}$ ${}^{simulation}\chi_e \sim 0.2\ m^2/s$
- Need more comprehensive edge *RMP* transport theory
  - > Is *RMP* screening due to plasma rotation or pressure a significant factor?

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Even parity, 3.2 kA I-coil current, C-coil and field-error

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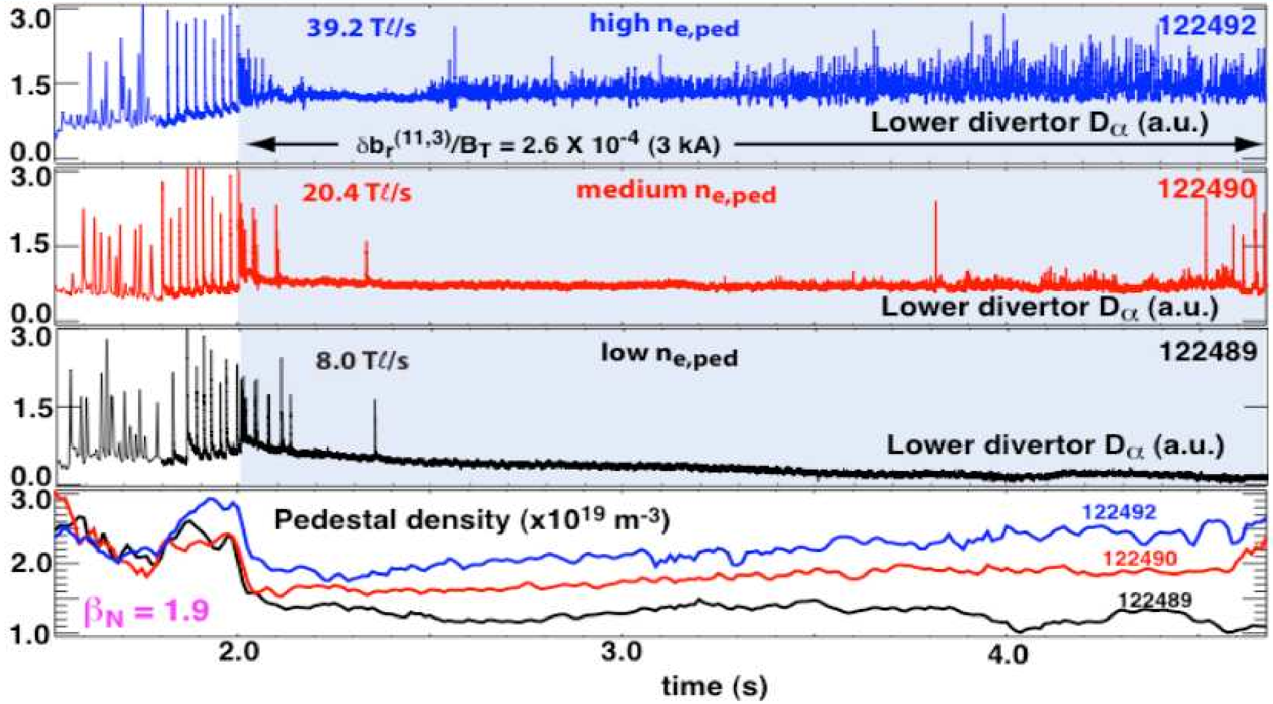
# "Unusual" experimental results 3/4

- Transition from ELMy to ELM-free H-mode goes through the stage with significantly increased ELM frequency, which is not expected from transport modelling.

## ELMs eliminated below a critical pedestal density




- Small, high frequency ELMs return as pedestal $n_e$ increases
  - Similar to previous weak *RMP* (odd parity) with high $n_e$ and $\nu_e^*$

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Even parity, low $\nu_e^*$, high, medium and low $n_{e,ped}$
See: CP1.00008 - J. Watkins, et al.

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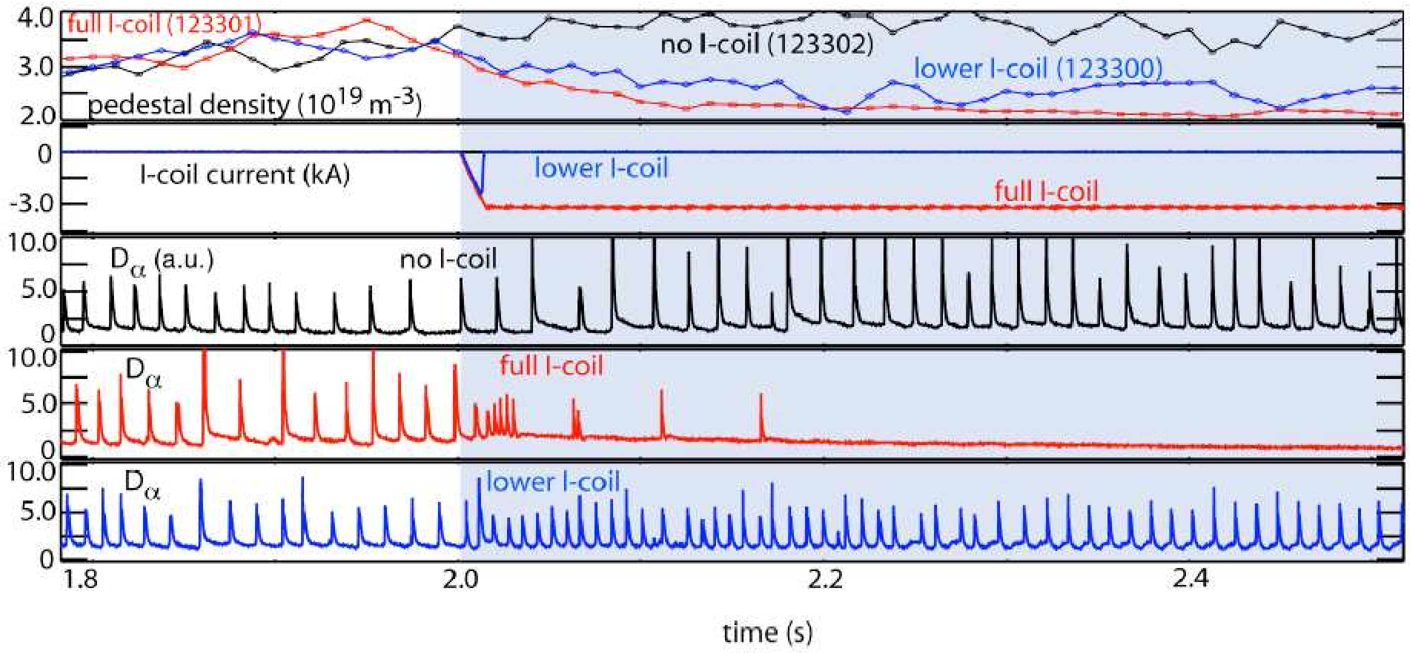
# "Unusual" experimental results 4/4

- Transition from ELMy to ELM-free H-mode goes through the stage with significantly increased ELM frequency, which is not expected from transport modelling;
- There is plenty of other examples, which show the same trend (gas puff scan, ripple losses,...)

**Both the upper and lower I-coil segments are needed to eliminate ELMs**




- Pedestal density evolution is similar with lower half and full I-coil but ELMs are only eliminated when the full I-coil is used

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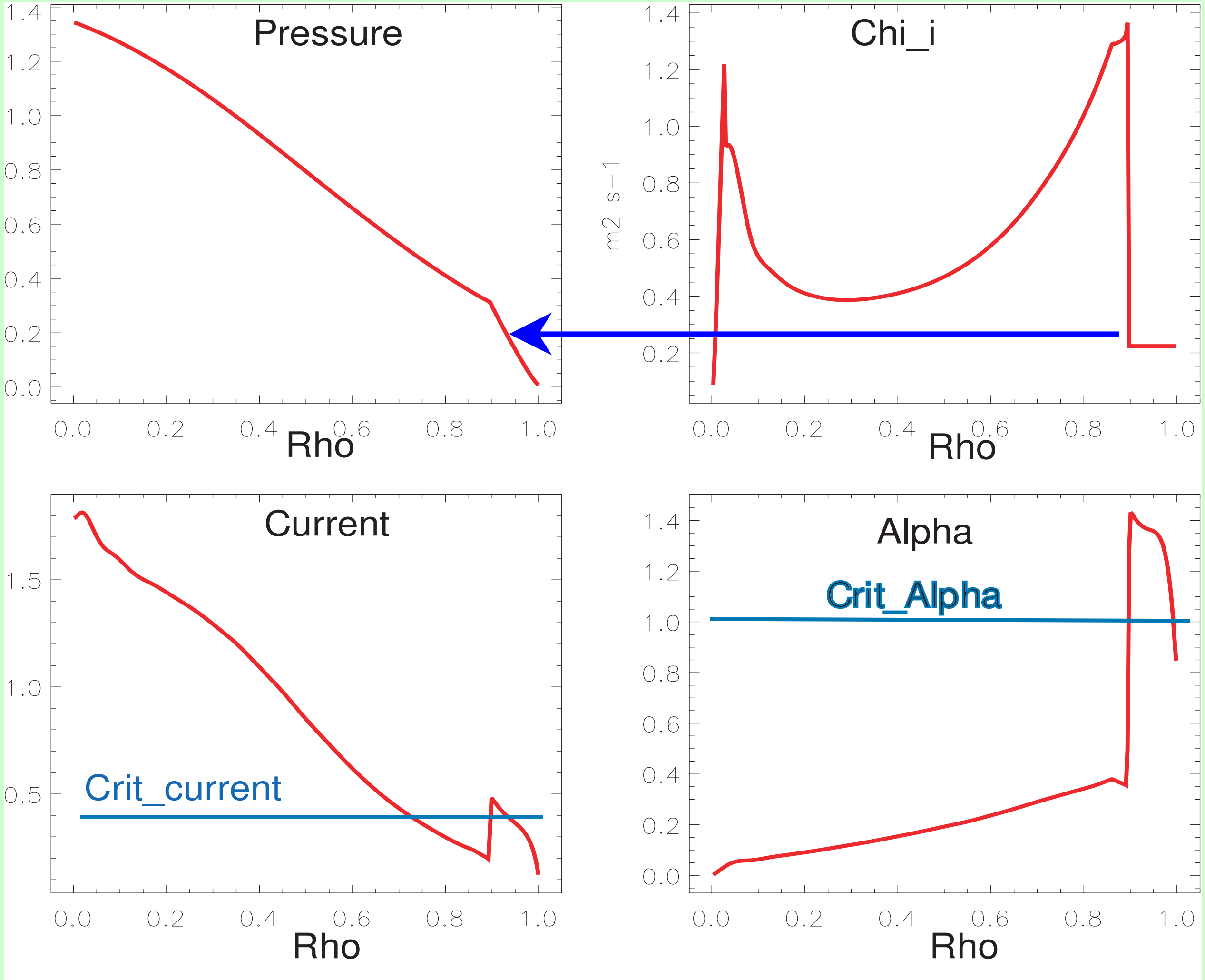
# ELM mitigation: prospective methods 1/2

- Since transport within the ETB is quite small, plasma develops strong pressure gradient to transmit heat flux through the ETB:

$$q \propto \chi \times \nabla nT$$



# ELM mitigation: prospective methods 2/2

- How can we mitigate ELMs or remove them entirely (without sacrificing performance, which means keeping $\left|\nabla nT\right| \le \left|\nabla nT\right|_{CRIT}$ )?

$$q \propto \chi \times \nabla nT$$

① Reduce the heat flux, **which enters ETB** (up to but not beyond the limit, which triggers transition to type-III ELMs):

❶ Increase radiated power (extra impurities at the edge);

❷ Increase CX losses (gas puffing?);

② Increase the heat flux through the ETB **between** ELMs by increasing thermal conductivity:

❶ Increase ion density ( $\chi_i^{neo-cl} \propto n_i \cdot Z_{eff} / \sqrt{T_i} \cdot B_{pol}^2$ );

❷ Increase transport by **magnetic ripples or ergodic magnetic limiter**;

❸ Induce quasi-continuous benign MHD (EDA, type-II ELMs, washboard modes, pellets ???)

# Ergodic transport and ELM modelling in JETTO 1/7

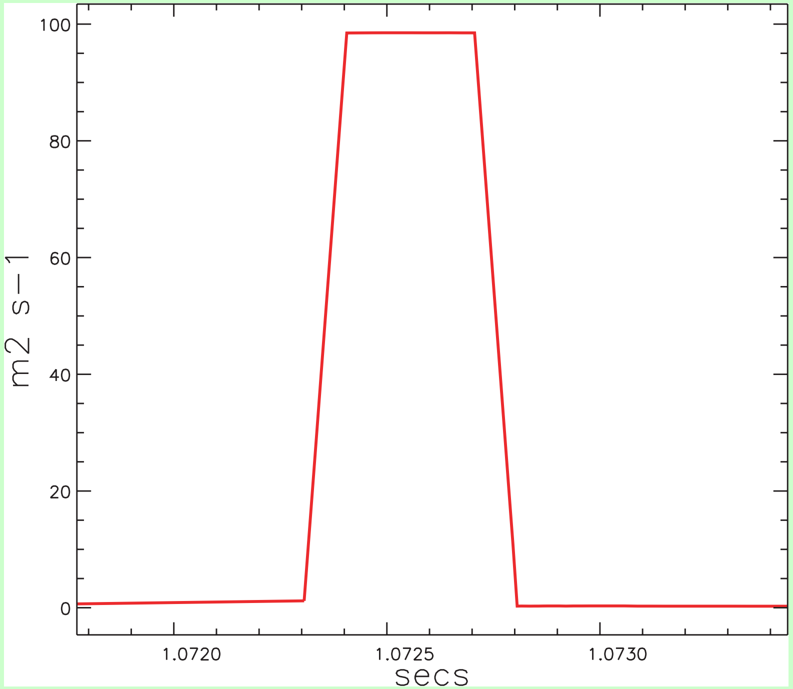
- To simulate ETB JETTO assumes that all kind of anomalous transport is eliminated within the specified region near the separatrix;
- The only remaining transport within the ETB is neo-classical plus additional transport due to either stochastic magnetic field or ripple;

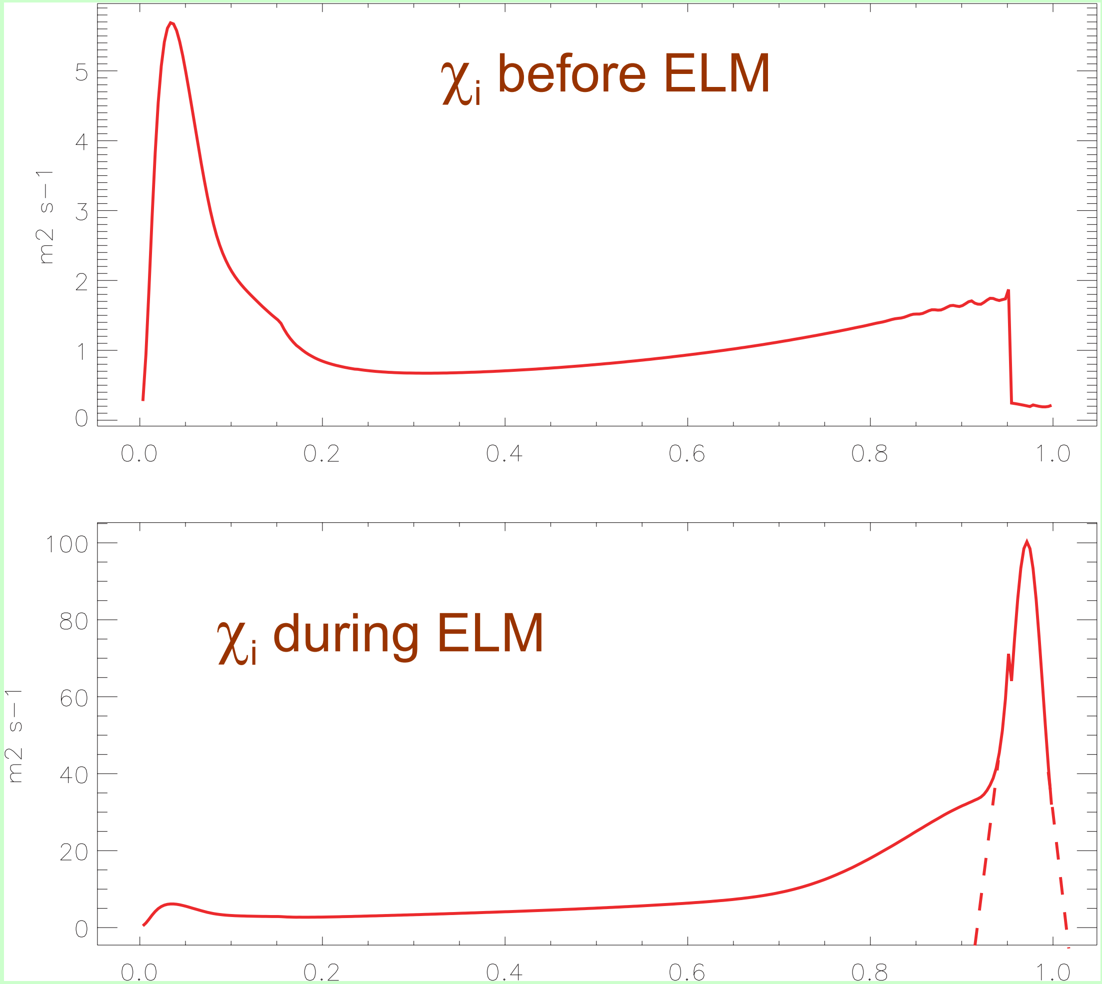
$$\frac{\chi_{i,e}}{D} \approx \left(\frac{\chi_{i,e}}{D}\right)_{neo-cl} + \left(\frac{\chi_{i,e}}{D}\right)_{RMP} \left(\frac{\chi_{i,e}}{D}\right)_{Ripple}$$

- Sometimes we assume that anomalous transport is not fully suppressed within the ETB, we will indicate if this is the case;

# Ergodic transport and ELM modelling in JETTO 2/7

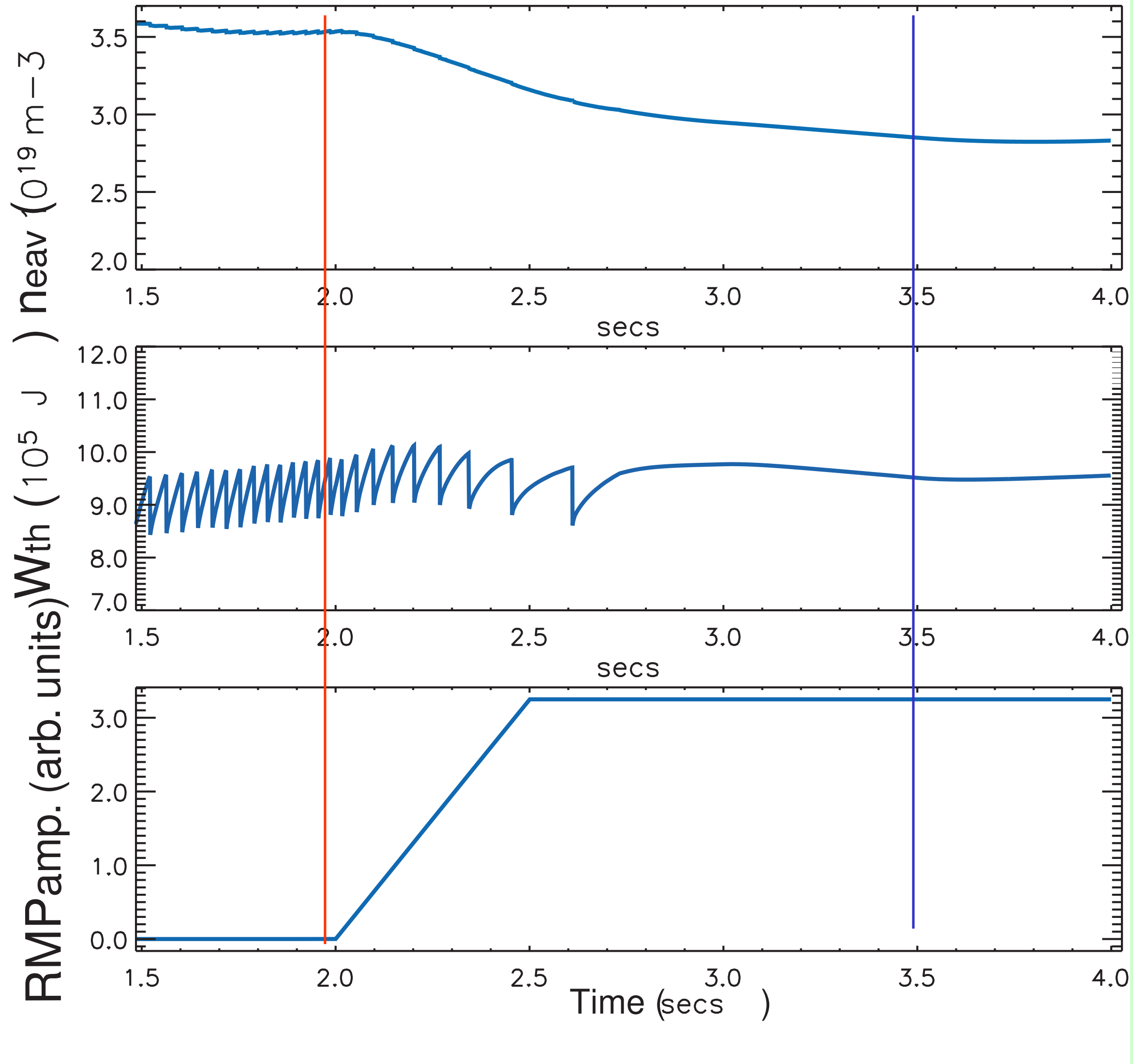
- Simple *ad hoc* model for ELM-induced transport is usually used in JETTO:
  - ELM is triggered if ballooning or peeling mode stability criterion is violated;
  - ELM amplitude, duration and localisation are prescribed by user:



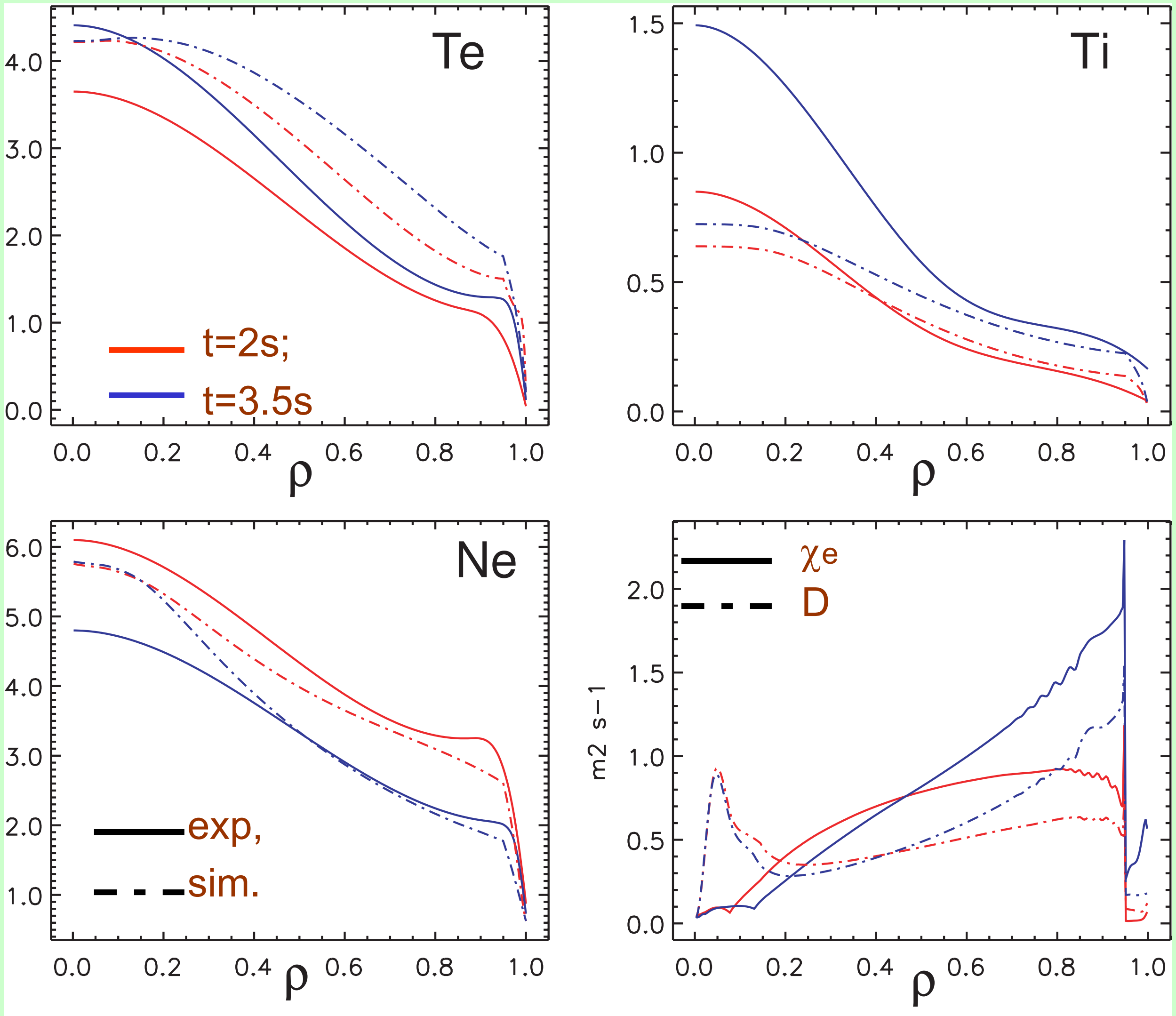
# Ergodic transport and ELM modelling in JETTO 3/7

- Using abovementioned transport model, we manage to reproduce experimentally observed temporal evolution of DIII-D plasma with RMP;
- To reproduce density drop we should assume wall recycling R=0.95;
- BUT, we should assume that R=1 DURING ELMS!:



# Ergodic transport and ELM modelling in JETTO 4/7

- Generally, we also reproduce profiles (apart from ITB);
- To reproduce correctly density and temperature profiles in RMP plasma we should scale stochastic transport down to $\chi_e^{stoch} \leq 0.4 \, m^2/s$ within the ETB;
- We can ***not*** reproduce an increase in ELM frequency before transition to ELM-free H-mode;



# Ergodic transport and ELM modelling in JETTO 5/7

- Two questions remain unanswered:
  - Why stochastic transport is much less than predicted by theory?
  - How we can reproduce a non-monotonous behaviour of ELM frequency with RMP amplitude?
- The answer on first question most probably lies in plasma rotation, which can partially screen radial magnetic field;
- This might lead to less overlapping islands (particularly inside ETB), which should reduce the level of stochastic transport.
- To find if screening is important, we have done the following estimate (C. Gimblett and J. Hastie):

# Ergodic transport and ELM modelling in JETTO 6/7

- Radial magnetic field screening by rotating plasma was considered in a simple Visco-Resistive approximation in a cylindrical plasma (R. Fitzpatrick, PoP 1998, 2006):

$$B_r = \frac{\tilde{B}_{r,vac}}{\sqrt{1+\left(\frac{\Omega\tau_L}{2m}\right)^2}}$$

Where $\Omega$ is local toroidal rotation frequency,

$\tau_L$ - visco-resistive layer time: $\tau_L=2(6\,\tau_A)^{2/3}\,\tau_\eta^{2/3}\,\tau_V^{-1/3}$;

$\tau_L=R/V_a ns$ - Alfven time; $\tau_\eta=\mu_0 r_s^2/\eta$ - resistive time;

$\tau_V=\rho r_s^2/\mu$ - viscous time;

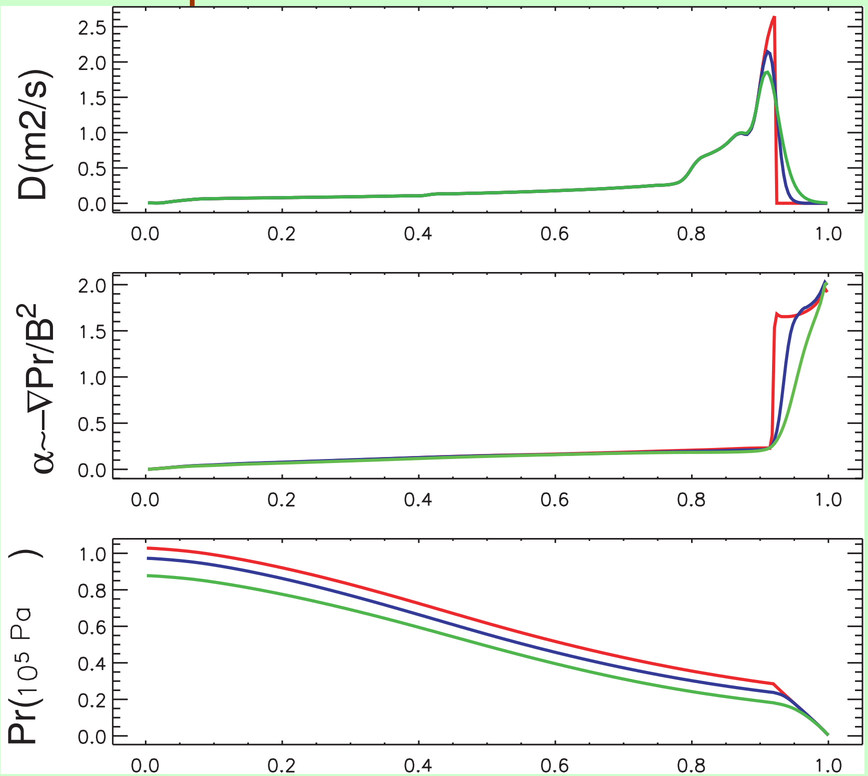
Please note that $\Omega\tau_L/2m \approx 0.15$ at $\rho=0.97$ but it scales as:

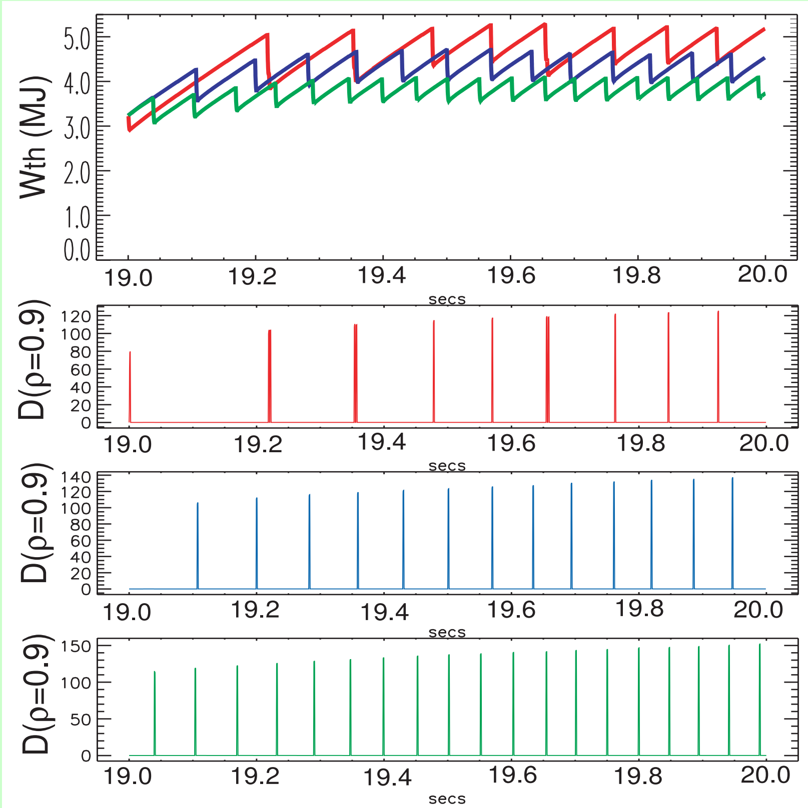
$\Omega\tau_L/2m \sim \Omega/m \times (n_e/s^2)^{1/3} \times T\mu^{1/3}$ and it increases 20 times when $\rho$ decreases from $\rho=0.97$ to $\rho=0.9$.

**Therefore there is a room for magnetic field screening in real experiment!**

# Ergodic transport and ELM modelling in JETTO 7/7

- Non-monotonic evolution of ELM frequency with RMP amplitude might be explained by the non-uniformity of plasma parameters within the ETB;
- In first place this non-uniformity relates to a non-uniformity of residual transport within the barrier:



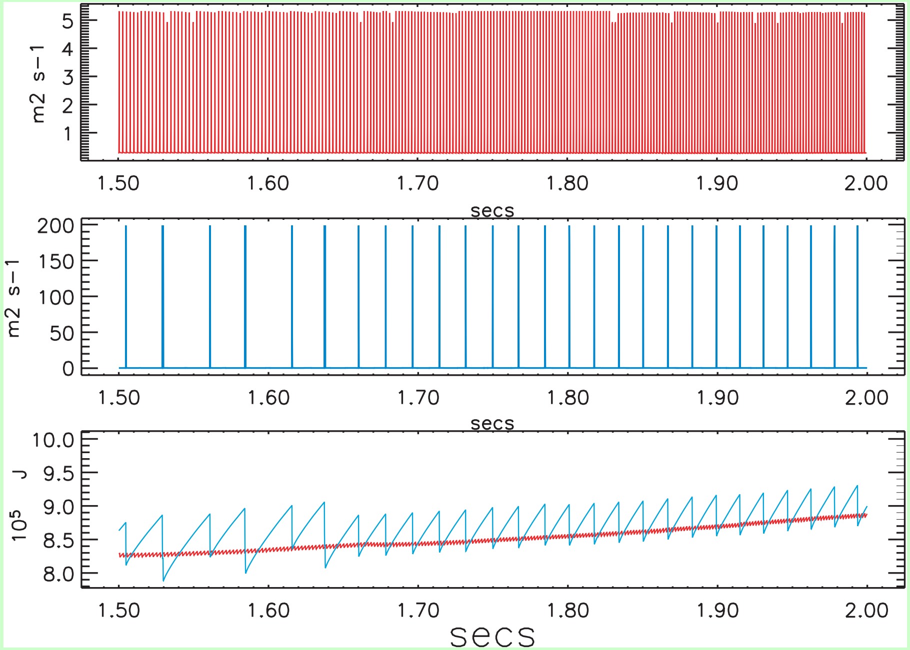
# Summary

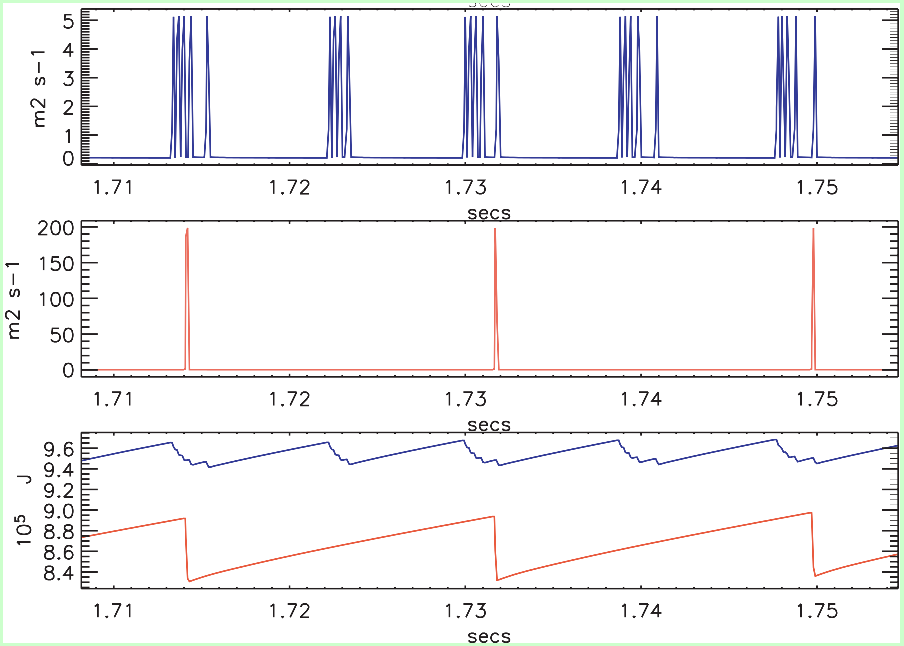
- Qualitatively developed model of stochastic transport reproduce the main experimentally observed trends;
- More theoretical analysis should be done in order to clarify ergodic magnetic field screening by plasma rotation;
- Transport properties within ETB can dramatically influence ELM behaviour;
- Non-linear ELM model is needed to validate the simplified *ad hoc* assumptions, made in predictive modelling;

# SPARE

# Predictive Transport Modelling 1/3

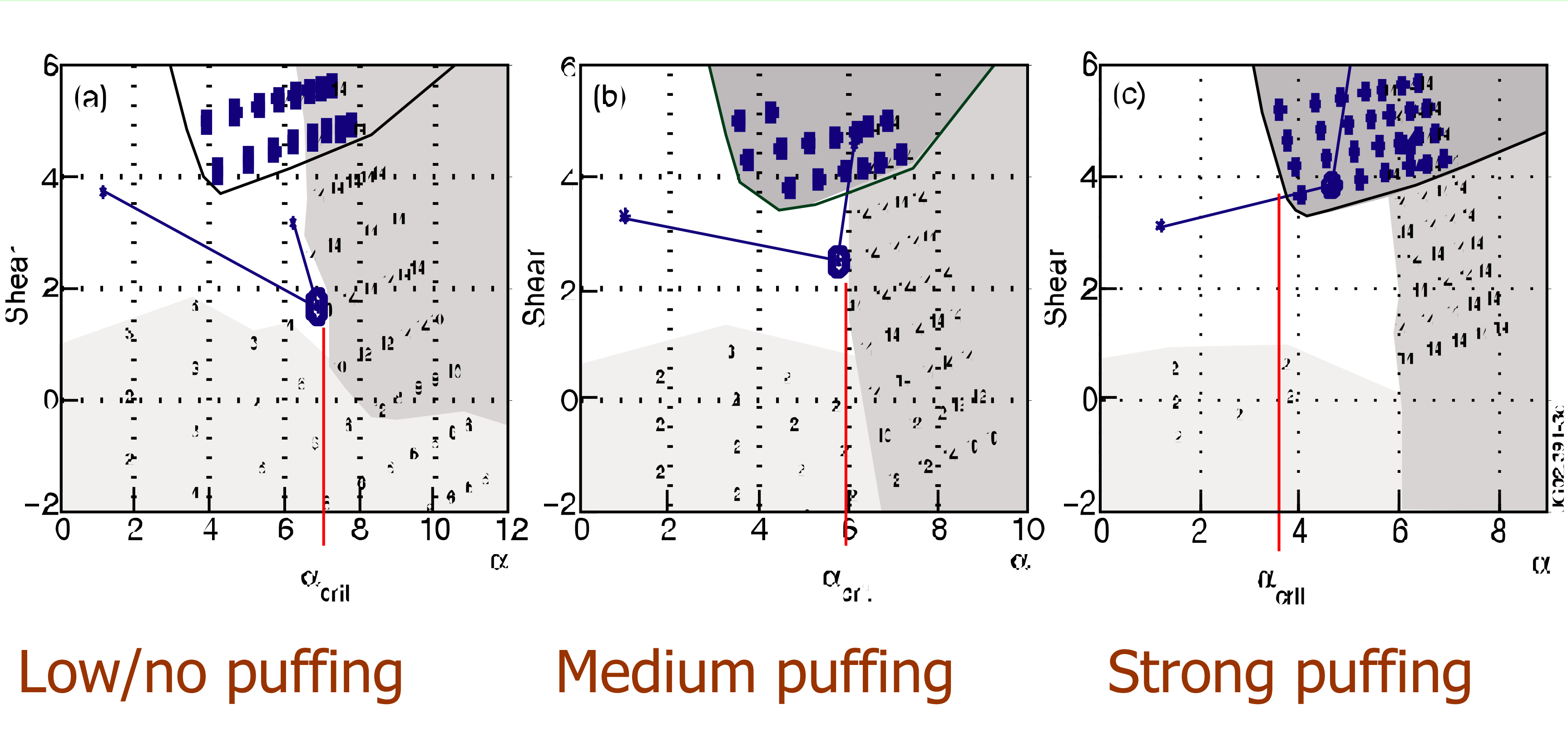
- If we would like to study how ELM frequency depends on plasma parameters, we shorten the duration of ELM and/or reduce its amplitude;
- Two distinctly different situations have been identified depending on heat and particle transport distribution within the ETB:
  - ① ELM frequency remain relatively unchanged when ELM amplitude is reduced but each ELM is getting composed of several short events;
  - ② ELM frequency increases inversely proportional to ELM amplitude/duration;



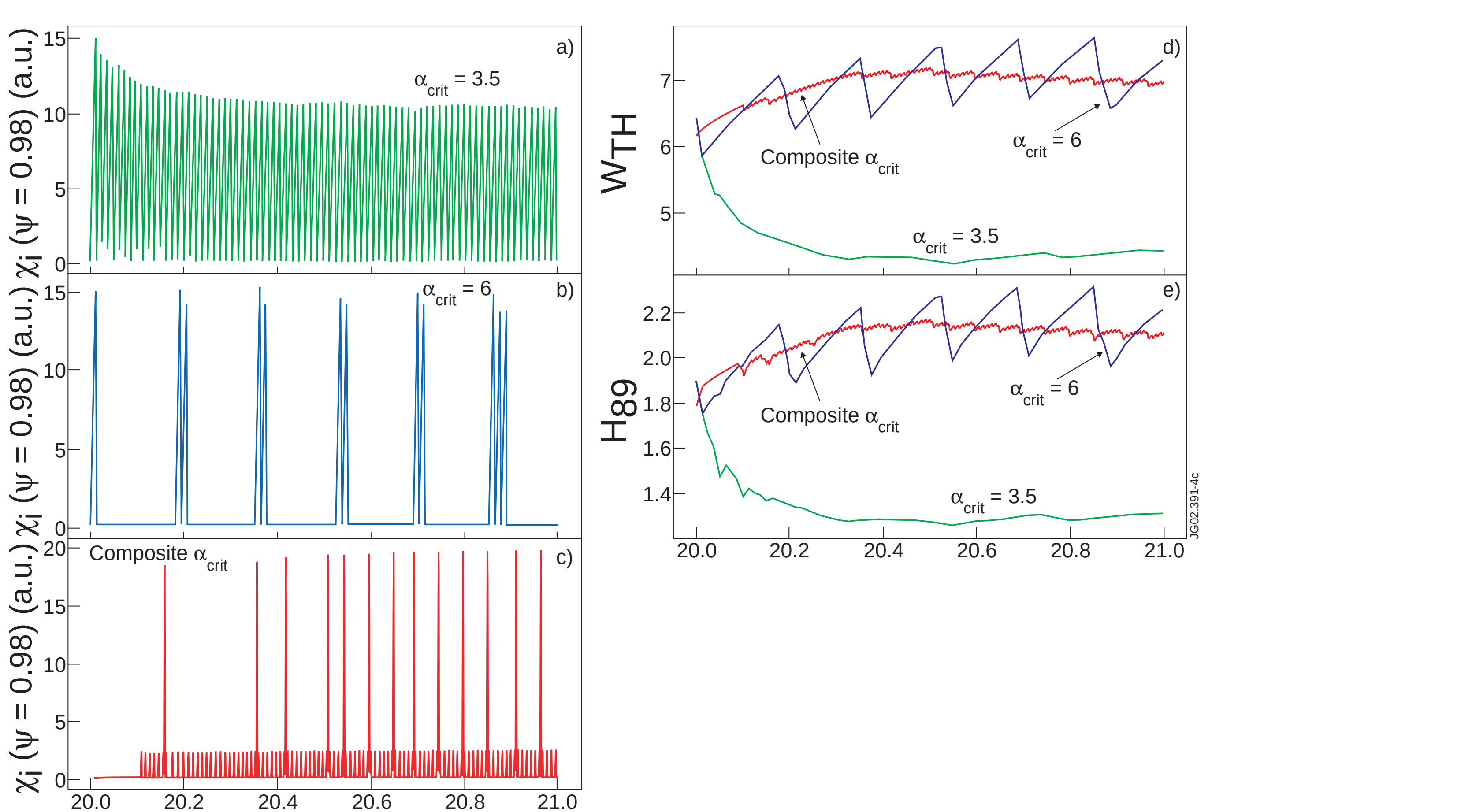
# Possible causes for ELM variability- transport within ETB 1/2

- Predictive transport modelling with JETTO and EDGE2D show that external gas puffing changes collisionality within ETB;
- This changes bootstrap current, which directly influences position of the operational point (J. Lonnroth et al., PPCF, 2004)



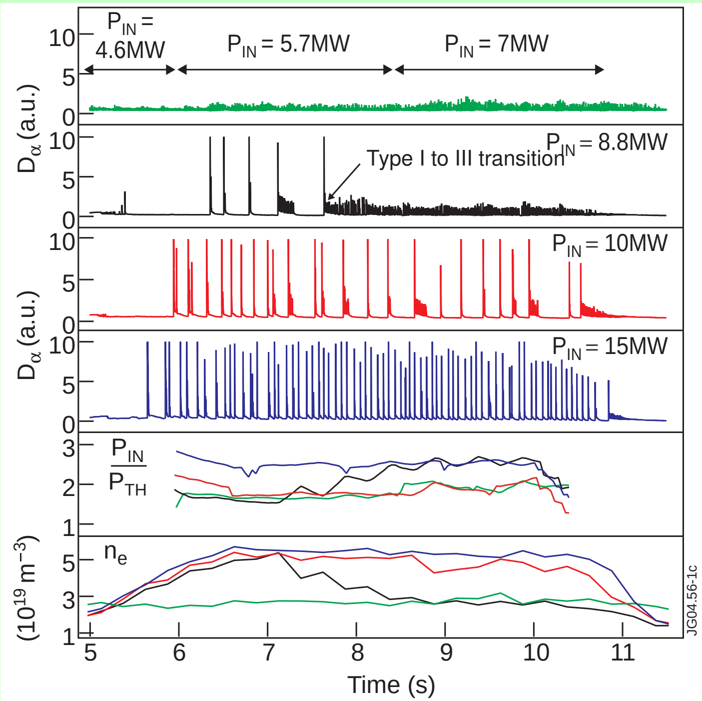
# Possible causes for ELM variability- transport within ETB 2/2

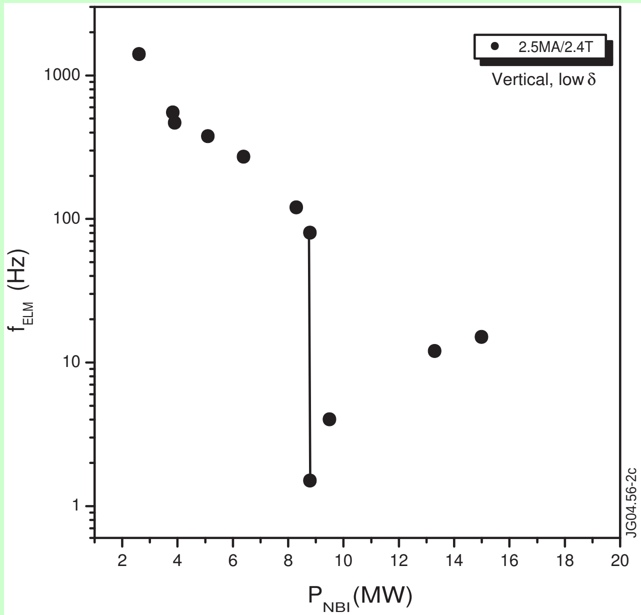
- This allowed us to explain the observed difference between ELMs amplitude and frequency;



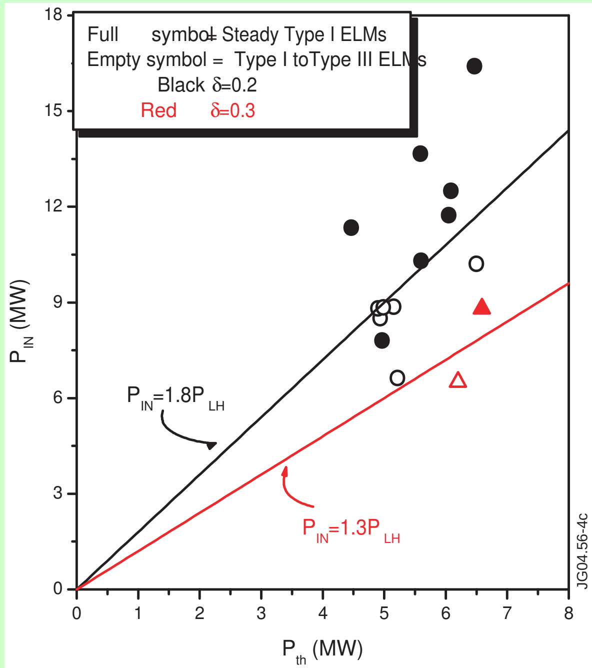
# Non-uniform transport within ETB: can it be part of the explanation of a transition from type-I to type-III ELMs?

- Experiment shows that when heating power exceeds L-H transition threshold, plasma develops small, high frequency type-III ELMs (poor quality ETB?);
- Further increase in the heating power above the level $P_{III\text{-}I} \cong 2P_{L\text{-}H}$ triggers transition to high quality type-I ELMy H-mode (good quality ETB?)




R. Sartori et al., PPCF 2004



# Why ripple transport might be important for H-mode 3/3

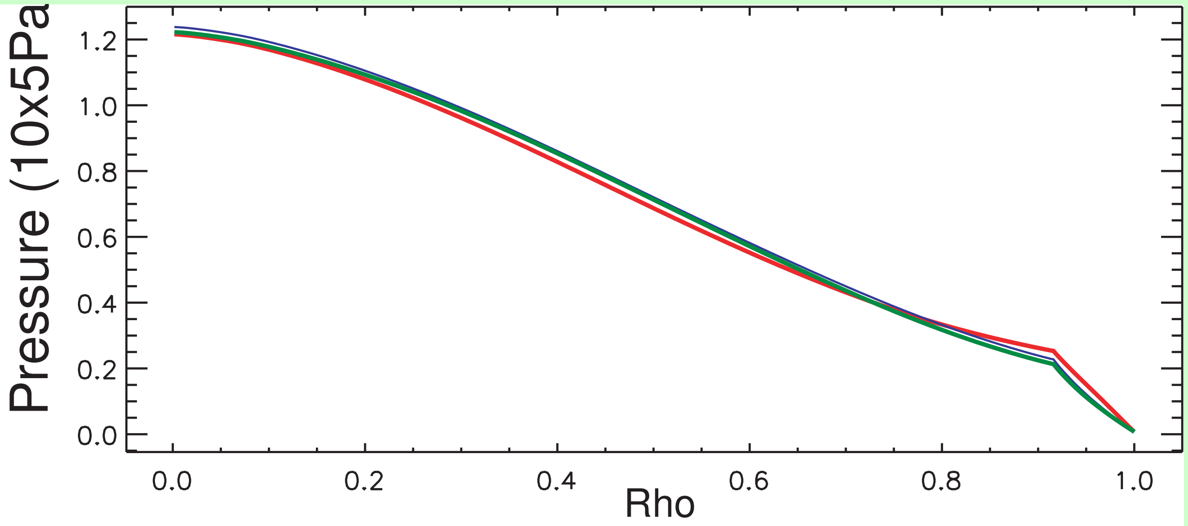
- If transition to type-I ELMs corresponds to a condition that the shearing rate $\omega_{ExB}$, which is generated by the heat flux through the edge barrier $P_{loss}$ exceeds the growth rate of a resistive interchange instability $\gamma_{RIM}$ (O. Pogutse et al, EPS 1999), one can obtain:

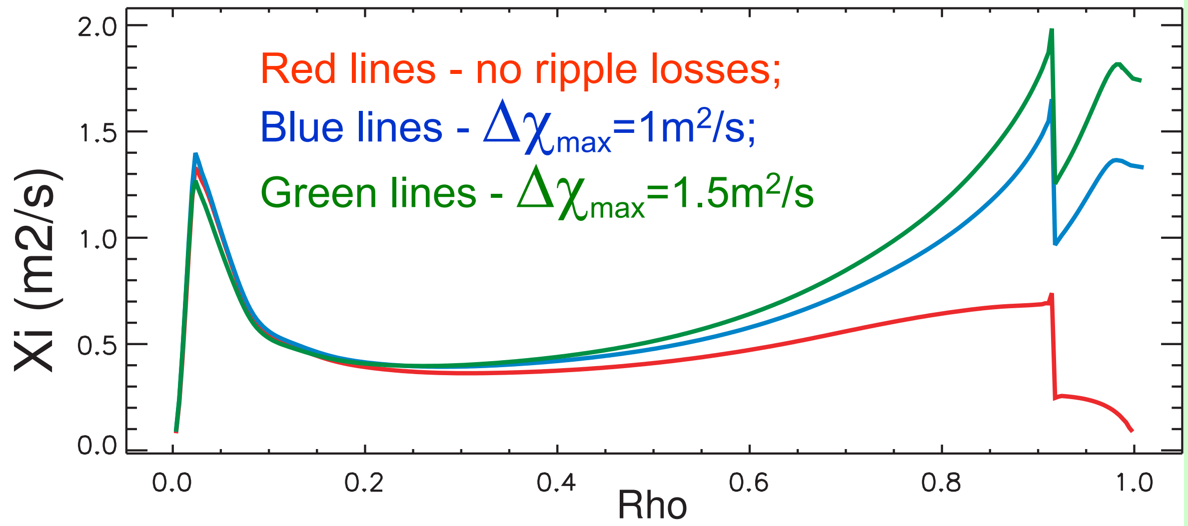
$$\omega_{ExB} \propto \nabla \frac{\nabla nT}{nB} \propto \nabla \frac{P_{Loss}}{\chi_i^{coll} \cdot nB} \geq \gamma_{RIM}$$

- which leads to a dependence of the power threshold on the level of ripple losses since $\chi_{coll} = \chi_{neo} + \chi_{ripple}$;

- Finally ripple losses generate radial current, which should induce counter-B plasma rotation (observed in experiment);

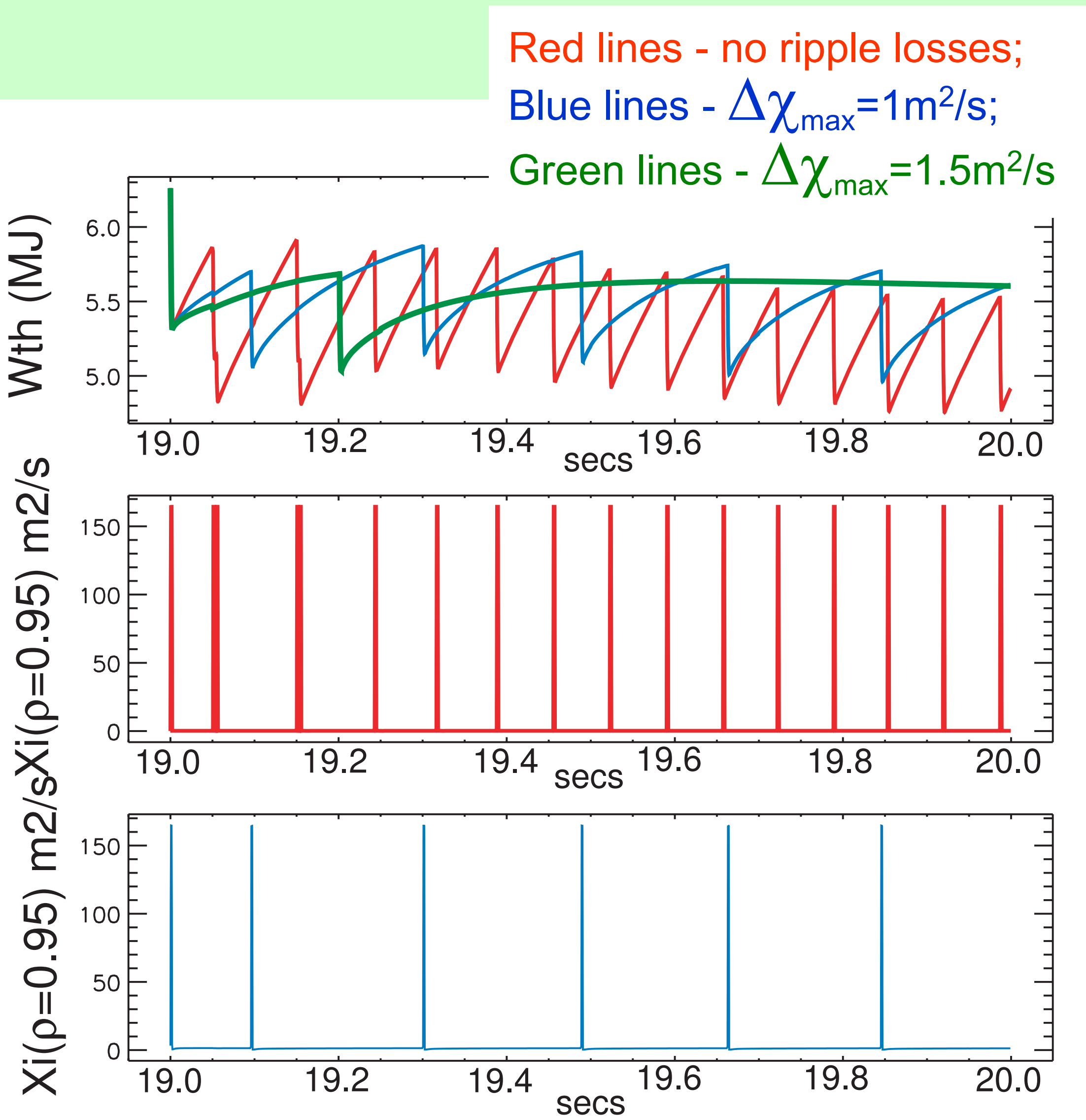
# Predictive modelling of JET plasma with ripple losses




- We assume that ripple losses are diffusive with **wide ripple** localisation;
- since transport is nearly uniform within ETB, pressure profile **just before ELM** is practically the same for all levels of ripple losses;
- What is different however it's the ELM frequency, which goes down when we increase ripple transport;

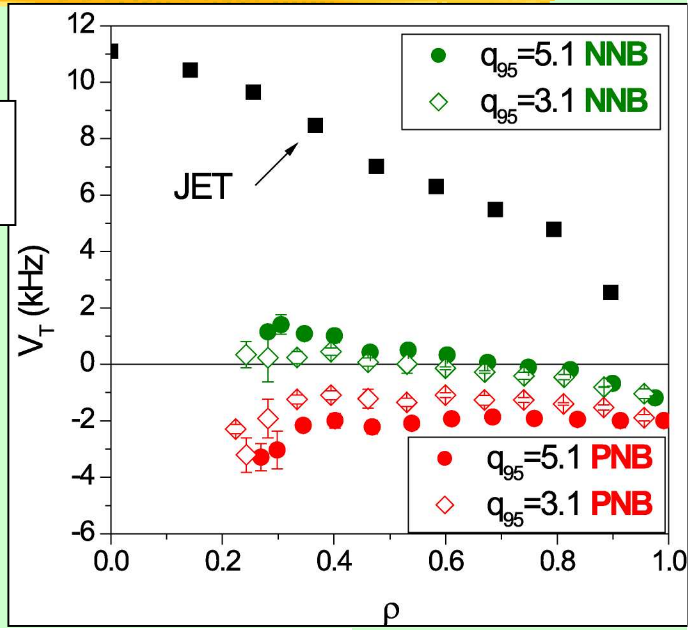
# Predictive modelling of JET plasma with ripple losses



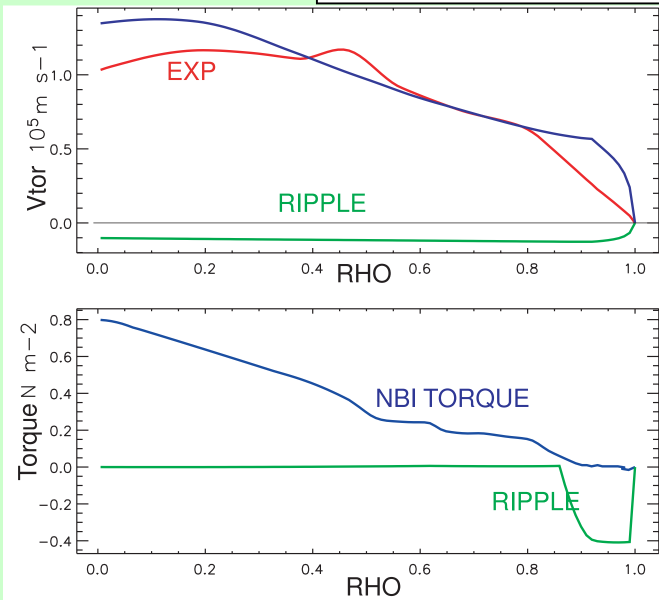

- The ELM frequency decreases due to larger edge losses between ELMs with increased ripple transport;
- The time-average pressure and plasma energy content increase with increased ripple losses (even if max. pressure stays the same);
- *A reduction in the ELM frequency and rise in the energy content were seen in JET ripple experiments in 1995;*
- *This result resembles the improved performance obtained with a stochastic magnetic boundary in DIII-D (T. Evans et al., 2004 IAEA Fusion Energy Conference).*

# Predictive modelling of plasma rotation

G. Saibene et al.
IAEA, 2004




- Ripple losses of fast and thermal ions generate toroidal torque, which spins the plasma up in counter-B direction;
- Anomalous viscosity (of the order of ion thermal conductivity) has been used in these simulations to propagate negative plasma rotation to the core;
- Toroidal velocity, calculated with the maximum ripple and without NBI torque reproduces qualitatively velocity profile, observed in JT-60U plasmas with PNB;

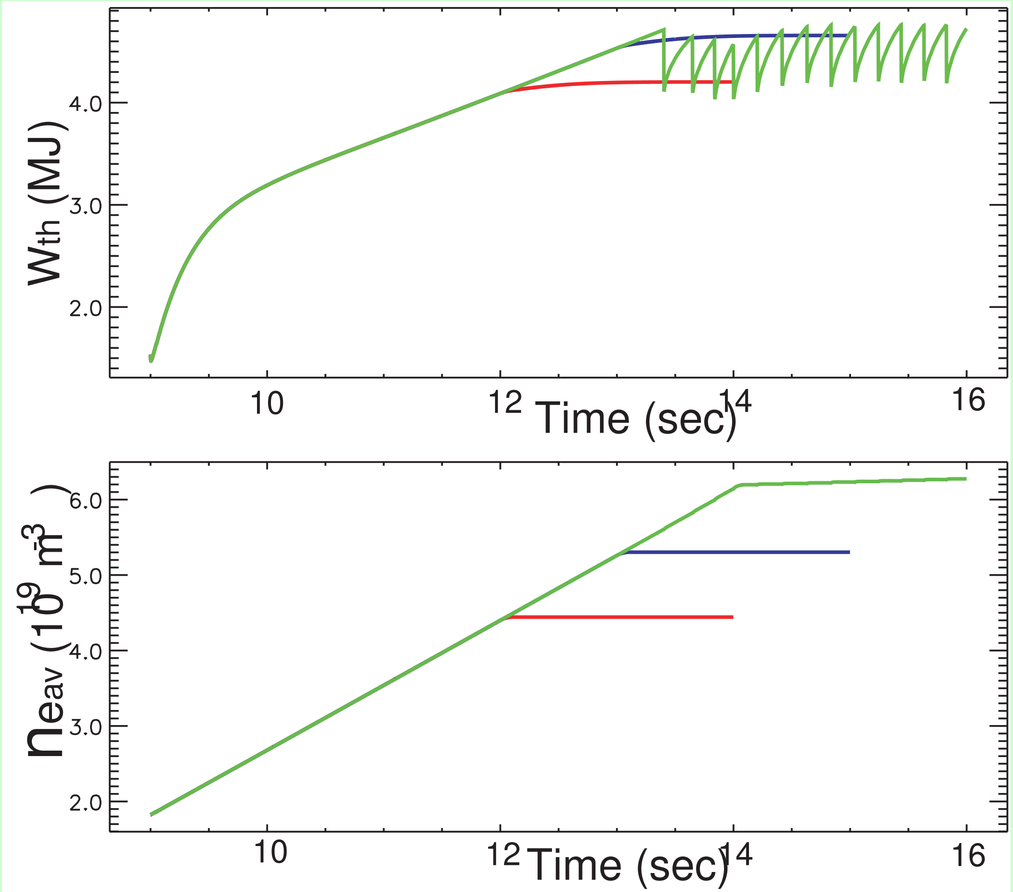


# Ripple transport versus stochastic magnetic field 2/3

- It is worth noting that the dependence of stochastic transport on plasma density and temperature is exactly opposite to that of the neo-classical transport:

$$\chi_e^{stoch} \propto \left|\frac{B_r}{B_0}\right|^2 \cdot \frac{T_e^{5/2}}{n_e};$$

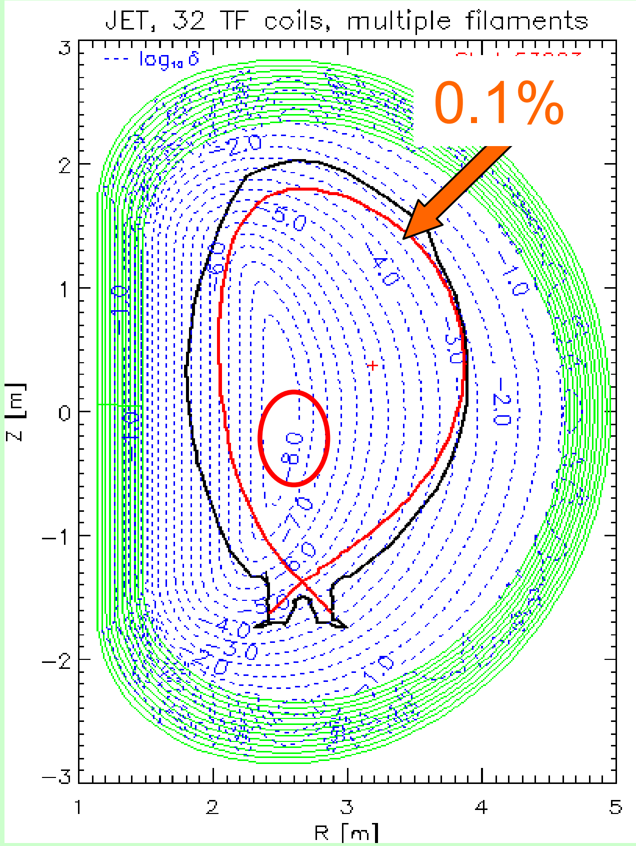
$$\chi_i^{neo} \propto \frac{n_i}{\sqrt{T_i}}$$

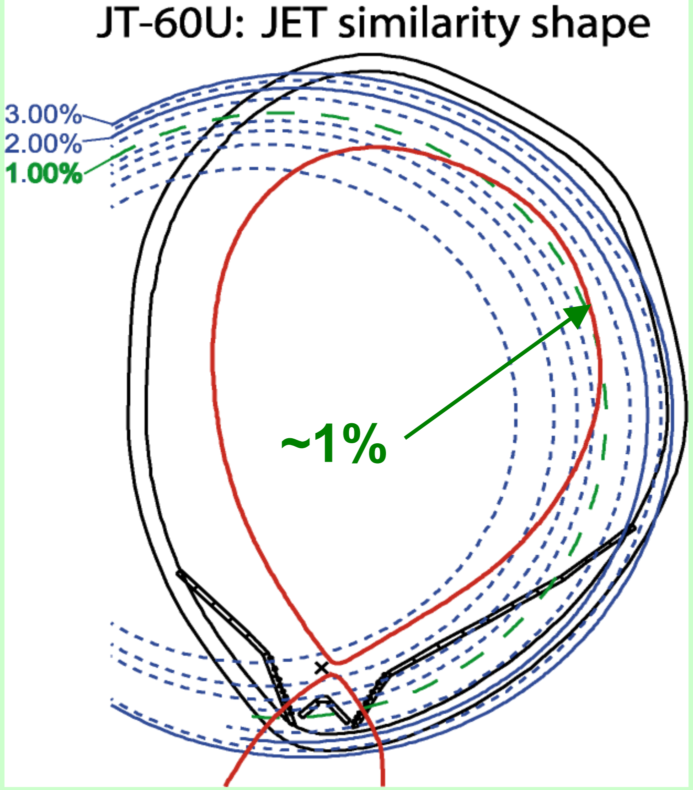


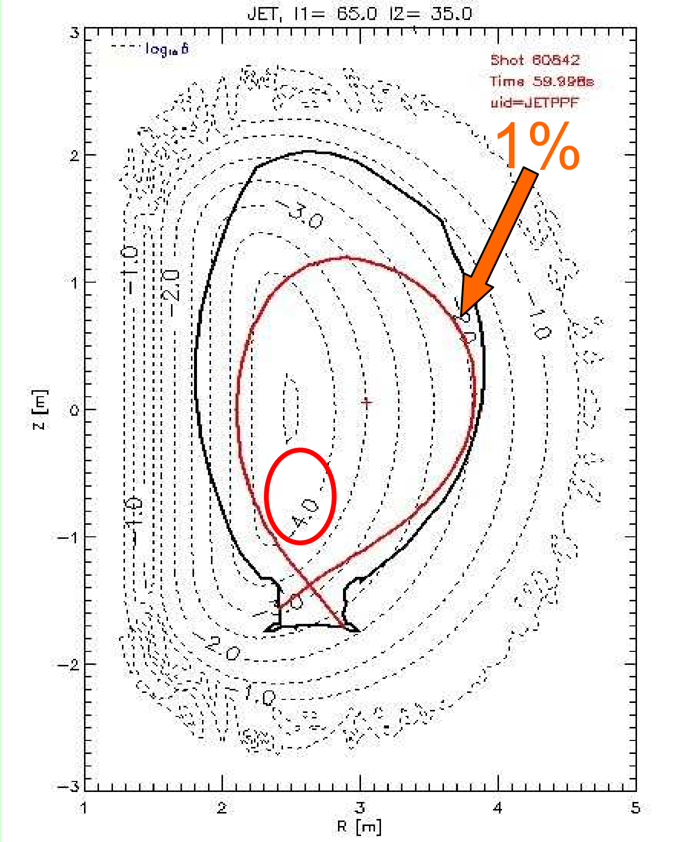

- This means, for example, that stochastic limiter can provide a steady state ELM-free H-mode at low density (which is not possible with the neo-classical transport);

JET 32 coils: ripple is ~0.1%

**JET: JT60-U shape and 0.3 $\delta/\delta_{16}$**




Note: for the same ripple, fast ion losses may be different (NB - ICRF). In JT-60U losses are high also because NB are ⊥