GYROKINETIC SIMULATIONS OF THE PEDESTAL- PRESENT EXPERIMENTS AND EXTRAPOLATION TO BURNING PLASMAS

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Extrapolation of H-MODE Pedestals to burning plasmas

- ***Burning plasmas based on H-mode require a pedestal temperature T ~ 4-5 keV***
  - → ~4 keV: from most recent gyrokinetic core transport models

- ***With the heating power supplied mainly by α particles, the pedestal top will get to this temperature, only if the energy transport in the pedestal is low enough***

- ***Present experiments find roughly gyroBohm scaling for H-mode confinement***

  GyroBohm: heat flux ~ ρ^{*2} (ρ^* = gyroradius/plasma minor radius)

  Similar scaling (ITER98H(y,2)) was the basis for designing ITER

- ***But: H-mode burning plasma pedestals, several times more gyroradii wide than present experiments, may be in a different physics regime –Such an extrapolation in ρ^*, must be examined. This is what we describe here.***

- ***For the first time, gyrokinetic simulations have been conducted to examine the scaling of pedestal transport in the ρ^* range of present experiments through to ITER***
  - → Note that gyrokinetics becomes more strongly valid as one goes to burning plasma with pedestals that are more much wider in gyroradii.

Nonlinear simulations of pedestals via GENE-Recent Successes

- *Recent nonlinear simulations presented by Hatch et. at. using GENE for a JET ITER-like wall (ILW) experiment successfully matched the experimental heat flux (submitted to Phys. Rev Letter)*

- *The inclusion of velocity shear was crucial to matching simulations with experiments- otherwise electrostatic ion scale transport would have been far, far too large*

- *One expects the velocity shear to decrease as ρ^* is decreased*

- *Here, we performing gyrokinetic simulations of pedestal transport, for a sequence of dimensionlessly similar pedestals based on ITER H-modes, where only ρ^* is varied - to examine the ρ^* scaling of pedestal transport, going from DIIID/ASDEX through JET to ITER*

- *We were surprised to find a good correlation between our results and JET behavior with an ITER-Like Wall (ILW), which we explore by changing other dimensionless parameters other than ρ^*, one at a time, to see if their effect correlates with JET experience*

THE CRUCIAL ISSUE FOR ρ^*

- ***From basic scaling of the gyrokinetic equation, growth rates scale as***

$$\gamma \sim C_\gamma v_{th}/a \qquad \text{(a = minor radius)}$$

- ***C_γ ~1: a complicated function of many dimensionless parameters***
- ***In a pedestal: turbulence is suppressed by velocity shear arising from E_r***
- ***Shearing rate γ_{ExB} can be estimated using***

$$en\, E_r \sim dp_i/dr \qquad \text{: verified on DIIID, C-mod, ASDEX, etc.}$$

- ***Trivial algebra from these: for a pedestal of width w***

$$\gamma_{ExB}/\gamma \sim C_\gamma^{-1} (\rho/a)(a/w)^2 \sim \rho^* \text{ ; becomes weaker with lower } \rho^*$$

- ***Crucial Questions: As we march towards lower ρ^*, say from ASDEX / DIIID to ITER,***

Will an "insufficiency of velocity shear" eventually arise?

Will this result in transport trends less favorable than gyroBohm?

Investigation: *dimensionless scaling paradigm* plus GENE *simulations*

- ***We construct MHD equilbria that keep constant all dimensionless parameters at the value expected for ITER, but vary only ρ****

1) E.g. β, ν*, q, w / a_{minor} , shape, etc.

2) Use values consistent with published pedestal predictions for ITER from EPED

3) We use published ITER-like wall profile shapes* of density and temperature in the pedestal from JET, and scale in magnitude and pedestal width to conform to ITER pedestal projections (T = 4 keV, n = 0.8 Greenwald limit, etc. for ITER)

4) Use numerical equilibria (from VMEC) including the bootstrap current

5) Include the Er from neoclassical theory -neglecting contribution from toroidal rotation

→Toroidal velocity contribution expected to be small in the pedestal of ITER

- ***Starting from ITER, we scale these back to equilibria on present devices with the same dimensionless parameters, varying only ρ*:***

A ρ* SCAN

*Leyland et. al. Nucl. Fusion 2015 013019

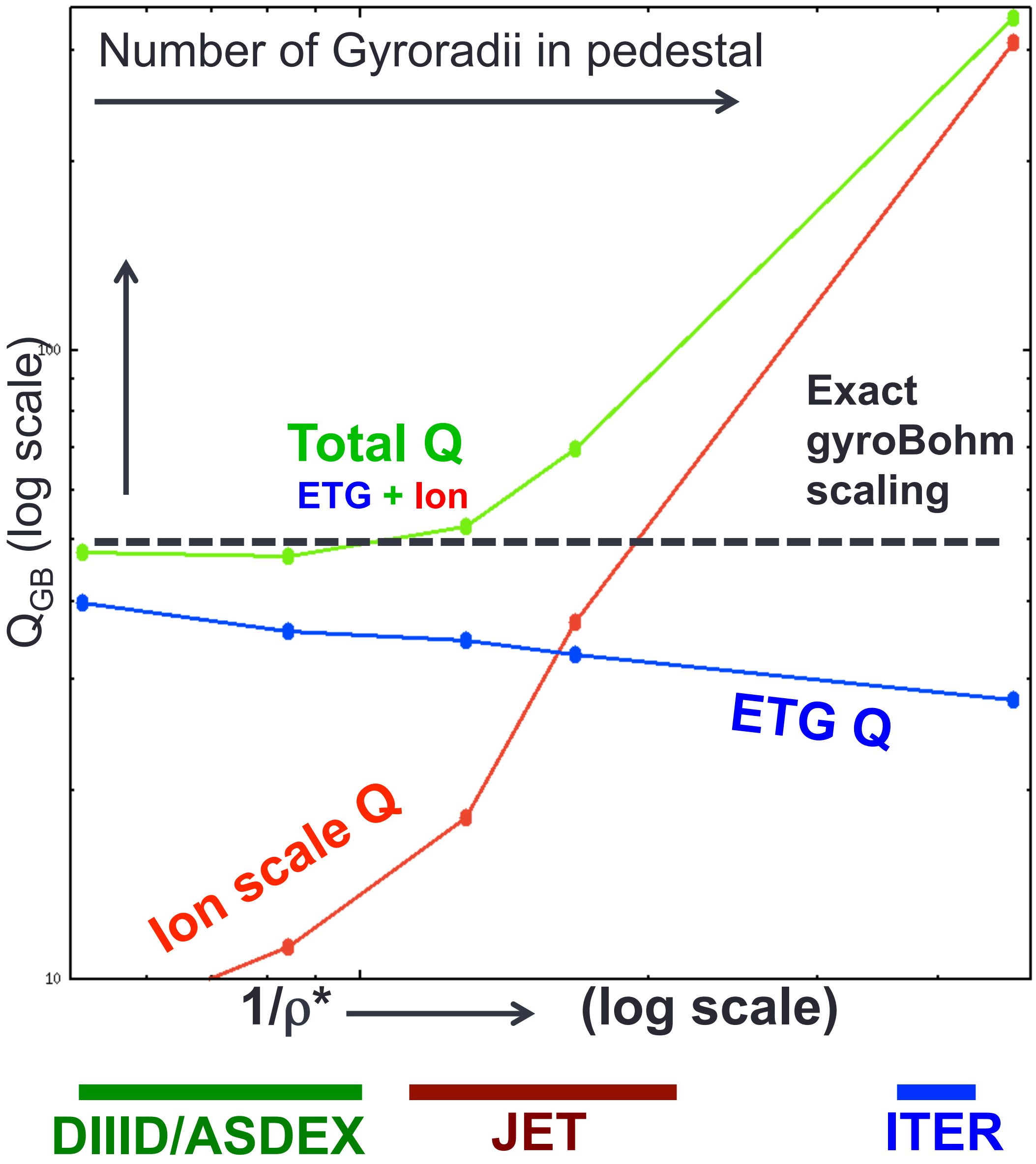
We simulate five cases with decreasing ρ^* (increasing I_p, R and B)

Device	Major Radius	Toroidal B (T)	I_p (MA)	Pedestal width: ion gyroradii
DIIID/ASDEX	1.6 m	1	0.7	7
DIIID/ASDEX	1.6 m	2.1	1.5	12
JET	3. m	1.8	2.5	18
JET	3. m	2.7	3.7	23
ITER	6.2 m	5.3	15	67

- ***Ion gyroradius scale gyrokinetics might be marginal for the pedestal on smaller devices, however, one expects it to be valid for the larger devices***
- ***Electron gyroradus scale gyrokinetics should always be valid***

Results: Turbulent Heat Q flux normalized to gyroBohm units (Q_{GB})

- ***Exact gyroBohm scaling => Q_{GB} is constant vs. ρ****
- ***Ion scale transport is always increasing rapidly with 1/ρ*- but it starts from a very low value***
- ***At large ρ* (high velocity shear) the ETG dominates***
- ***The total transport scaling (ETG + ion scale) in this range is nearly gyroBohm, in large part because ETG is nearly gyroBohm***
- ***But in the range between low field JET and high field JET, the ion scale transport becomes dominant***
- ***An insufficiency of velocity shear becomes apparent as a strong departure from gyroBohm scaling when ion Q dominates and continues to rapidly increase***



Important Qualitative Conclusions from simulations

- ***The extraordinary nature of this result invites careful scrutiny; caveats:***
  1) Simulation did not attempt to enforce self-consistency of the transport and profiles
  2) Geometrical coefficients and gradients are set to values in the middle of the pedestal
  3) Not “multi-scale” with ion scales and electron scales in the same simulation
  4) Toroidal velocity effects neglected in the pedestal

- ***Nonetheless, even qualitative conclusions are significant:***

  1) **The most robust feature of the simulations: ion scale transport grows as ρ^* is decreased**
     → Quite expected for predominantly electrostatic modes with shrinking velocity shear
  2) GyroBohm processes dominate the transport for these parameters **at large ρ^*- most of the currently accessible regimes**
     → It’s reasonable to expect that gyroBohm scaling would result from self-consistent profiles when this type of transport dominates
  3) **So when ρ^* is small enough, ion scale transport becomes dominant**
  4) **In this range, one expects a breakdown of gyroBohm-like scaling to something less favorable**

Since our simulations show a degradation of ρ^* scaling in JET- does experiment show anything similar?

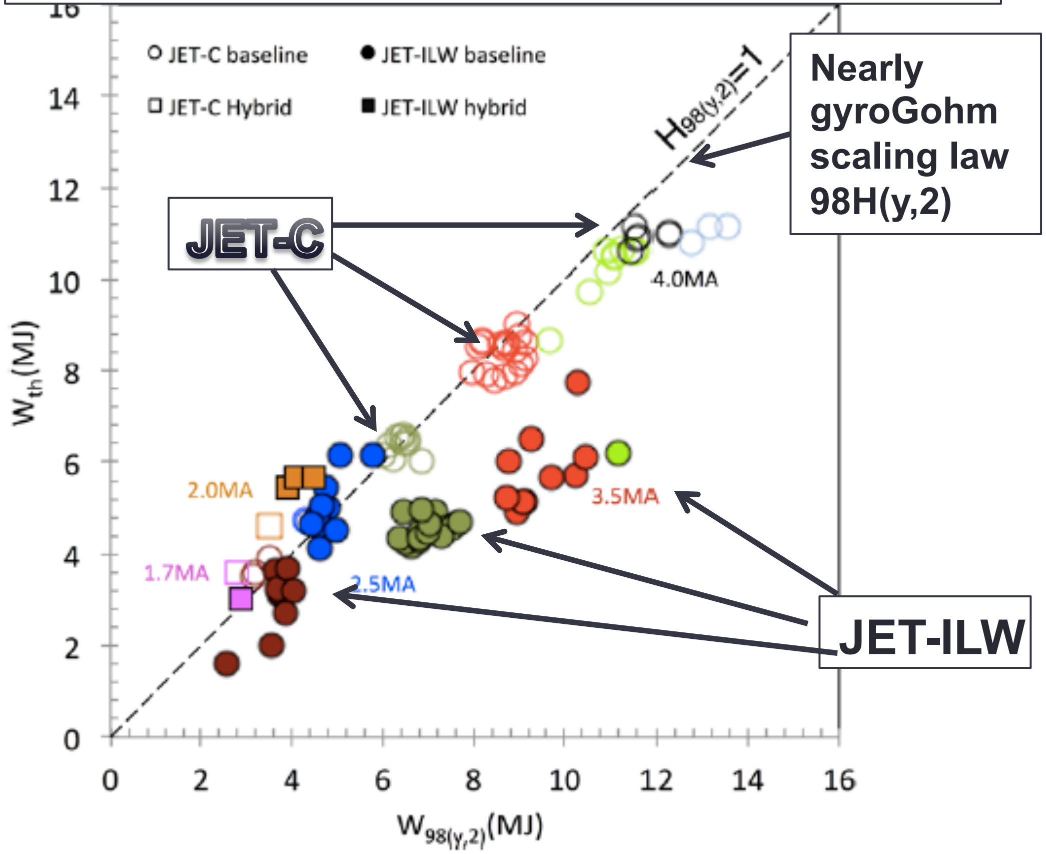
- ***Recall that we used profiles from JET shots with an ITER-Like Wall (ILW) and Z_{eff} =1***
- ***JET with an ILW finds a progressive deviation below the nearly gyroBohm H-mode scaling law at I_p (and B)***
- ***Undoubtedly, some deterioration is due to increased gas puffing***
- ***But some deterioration is hard to attributed to gas puffing***
  - → Even at the SAME puff level, JET-ILW has lower pedestal T than JET-C*

→ ***Hence, we examine if deterioration from the gyroBohm scaling law is partly an insufficiency of veloc. shear***

  - → Higher pedestal energy transport should mean lower T_{PED}

- ***We change one parameter at a time, for JET I_p and B cases, to see if the trend agrees with JET-ILW trends***

RESULTS FROM JET WITH ILW AND CARBON WALL (JET_C)



Nearly gyroGohm scaling law 98H(y,2)

JET-C

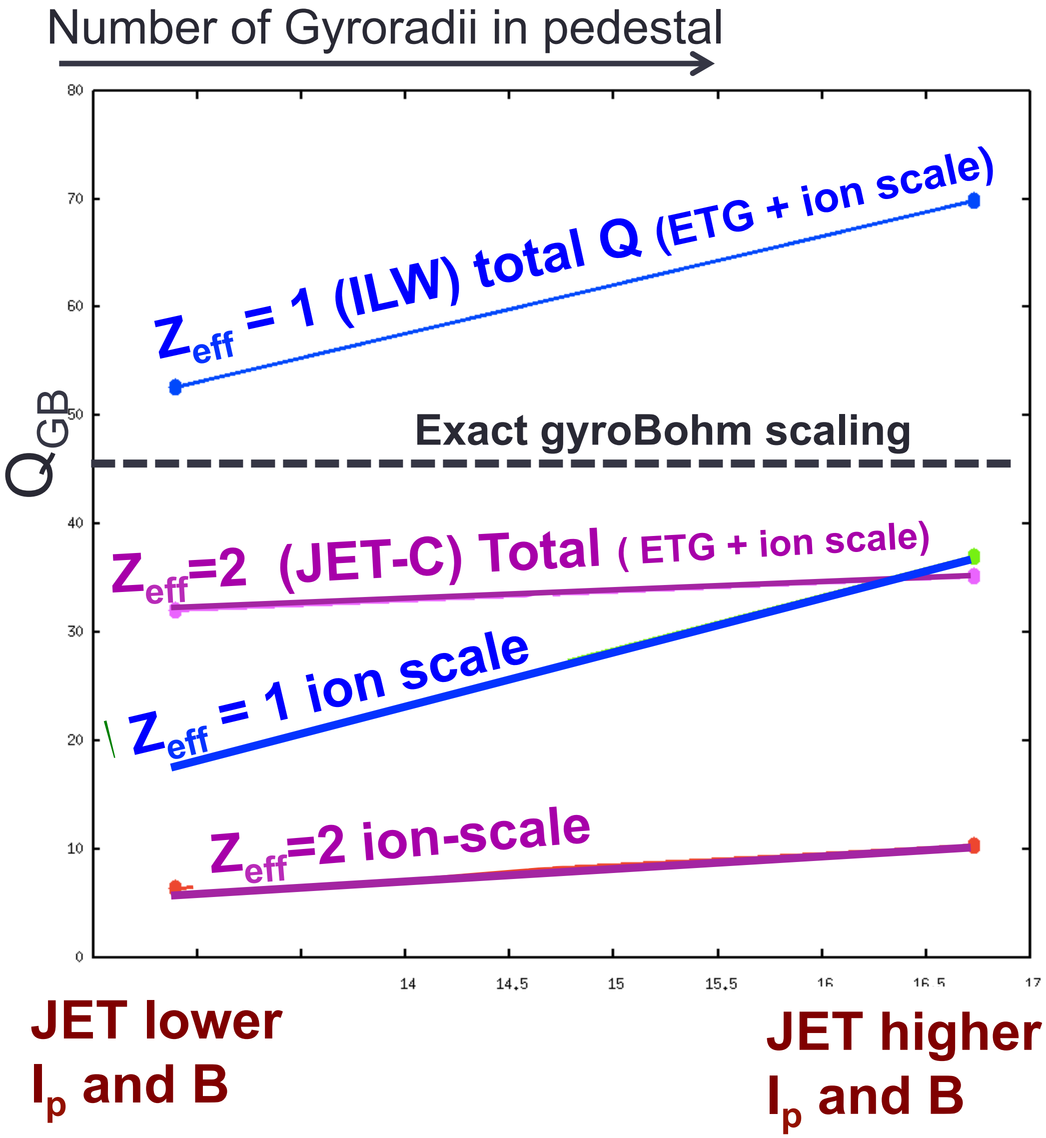
JET-ILW

Graph taken from: Nunes et. al. PPCF 58 (2016) 014034

* Maggi et. al. Nucl. Fus. 2015 113031; Leyland et. al. Nucl. Fus. 2015 013019; Giroud et. al. PPCF 2015 035004

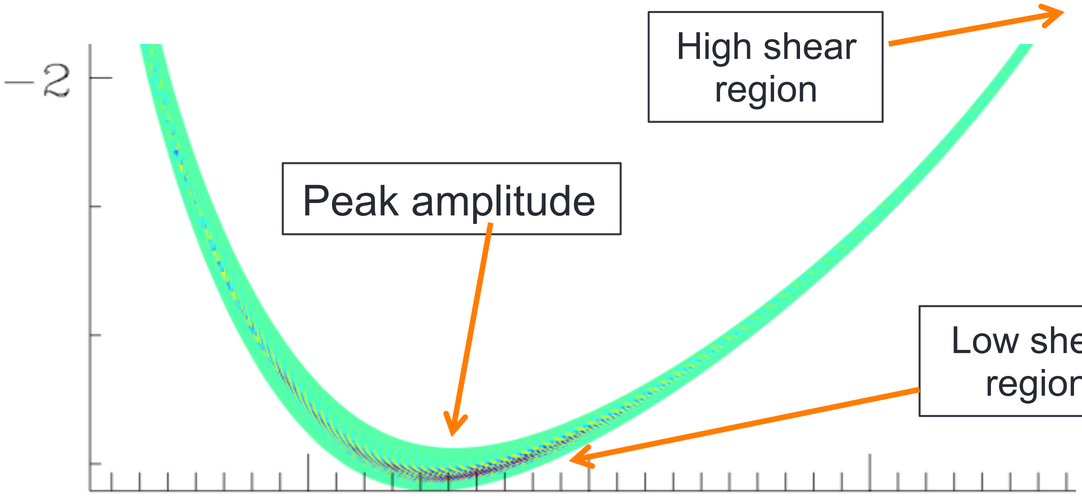
Inclusion of C in nonlinear GENE re-establishes gyroBohm scaling and substantially lowers energy transport- qualitatively like JET experience

- ***Keep all other parameters constant, but include C (at a C density so that Z_{eff} = 2)***
- **GyroBohm scaling is re-established for JET values of ρ^***
- ***C reduces the ion scale transport to a level significantly lower than the ETG***
- ***HENCE, THE GYROBOHM ETG DOMINATES TRANSPORT***
- **C also significantly reduces ETG**
- ***So with C: total* pedestal energy transport is reduced, and gyroBohm transport channels dominate- similar to JET**



What modes are responsible for the pedestal transport when velocity shear becomes insufficient?

- ***The most unstable modes are primarily electrostatic for low ν^* cases (ITER)***
  - →The electrostatic component of $E_{||}$ is considerably larger than the inductive component
  - → **Characteristic of electrostatic drift class modes-** ITG, trapped elect. modes, etc.
  - →**Totally different from MHD-like modes**, where ($E_{||} \sim 0$)
- ***2D eigenfunctions in the simulation region: the modes are strongest where the flux surfaces are much further apart- at the top/bottom***

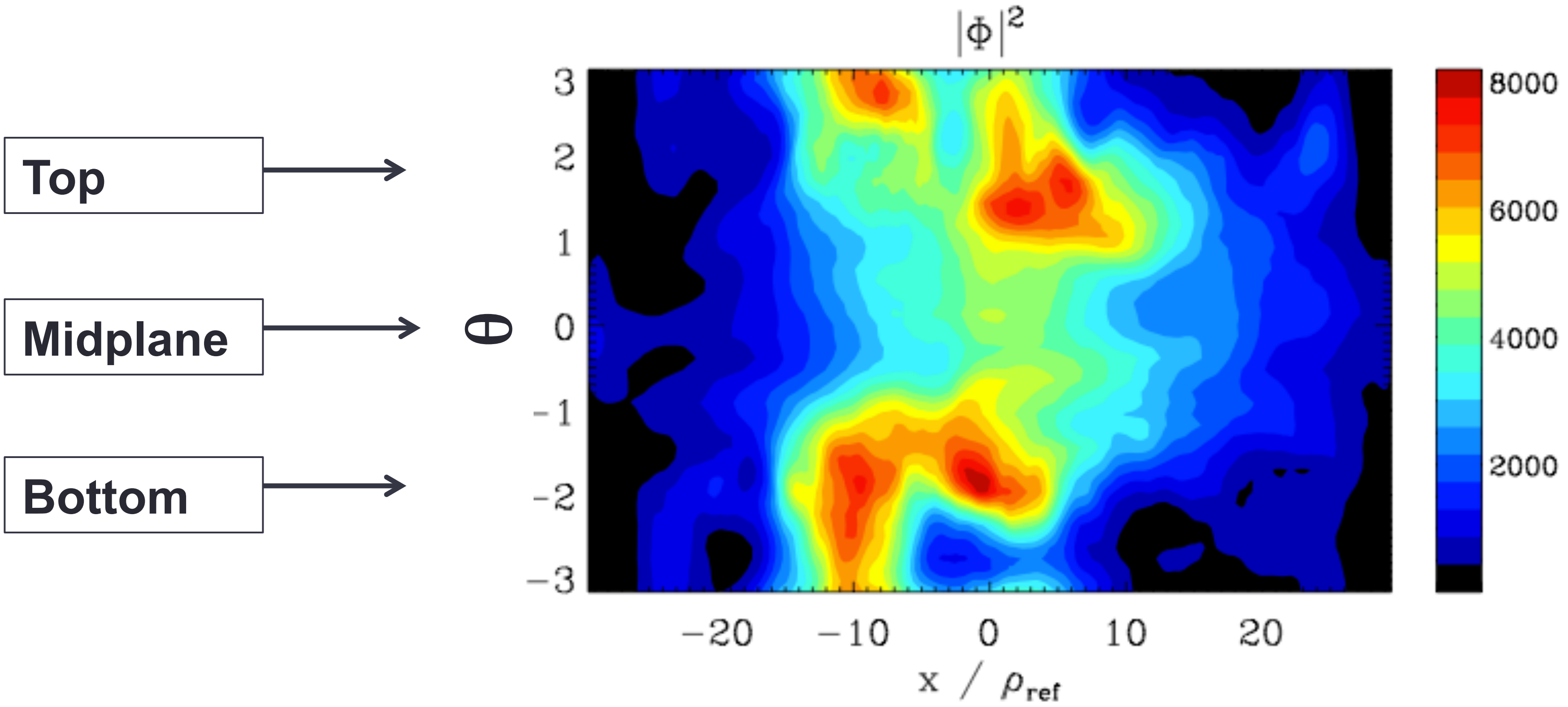


The velocity shear is much weaker in regions where the flux surfaces are further apart:

→As in, for example, the Hahm-Burrell definition of γ_E

- ***Even without shear, the modes "want" to peak where velocity shear is small***
- ***Such pedestal modes are harder to suppress with velocity shear than modes that peak on the outer midplane- where velocity shear is strong***

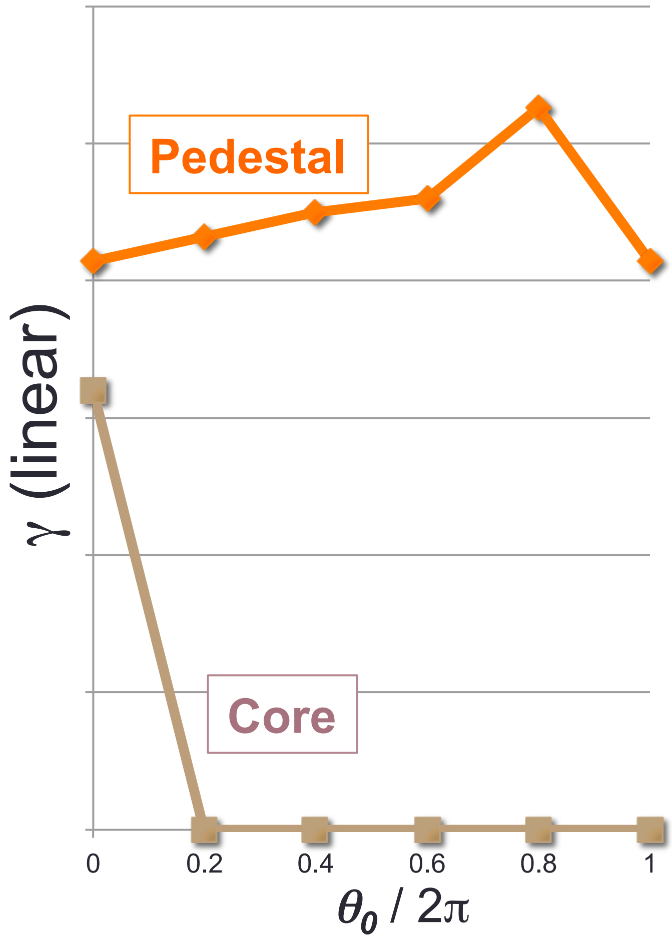
The same spatial distribution holds in the nonlinear simulations: the eddies are strongest where the flux surfaces are further apart



- ***The turbulence is considerably stronger near the top and bottom, compared to outboard midplane – the former are the regions of weakest velocity shear***

1D local linear ballooning calculations with GENE- also indicative of such a poloidal structure

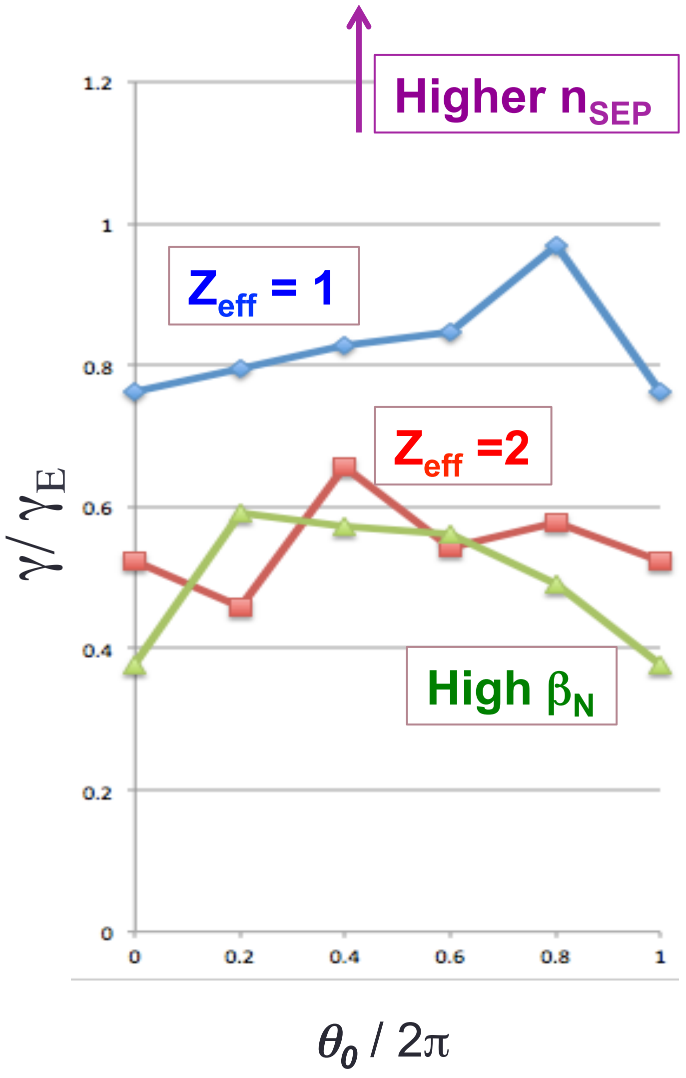
- ***In ballooning coordinates, θ_0 (termed k_{radial} in GENE) is a parameter that is indicative of where the mode peaks in real space***
  - →Usual concept of a mode peaked on the outboard midplane => highest γ at $\theta_0=0$
- **For pedestal parameters, the growth is large for all θ_0**
  - →Modes DO NOT tend to peak at the outboard midplane
  - →A higher velocity shear will be needed for suppression



- ***There is a good qualitative correlation between trends in the ratio γ / γ_E and the nonlinear behavior of GENE, and the behavior of JET***

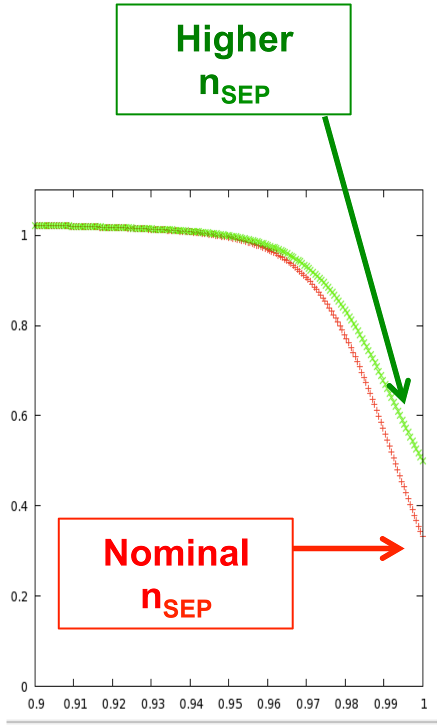
Correlation between the ratio γ/γ_E and the the behavior of JET –ILW and GENE

- ***The ion scale transport is low (minimal pedestal degradation) when this ratio ~ 0.5 for the modes***
  1) *Z_{eff} =2 from low Z (N or C)*
  2) *High β_N (hybrid mode)*
- **Moderate degradation when this ratio ~ 0.8**
  - →*ITER – ILW Z_{eff} ~ 1 (high field)*
- **Stronger degradation when it is larger**
  - →*Higher separatrix density n_{SEP}*
- **Nonlinear GENE simulations find the same trends**



We attempt to investigate gas puffing for JET- ILW and JET-C cases in nonlinear GENE simulations

- JET-ILW (and some JET-C) both find that gas puffing reduces T_{PED}, even though it changes n_{PED} rather little*
  - → *T behavior cannot be trivially explained by saying that T_{PED} drops because pressure is a constant and n_{PED} rises*
  - → *The pedestal broadens, violating $w \sim \beta_p^{1/2}$, indicating that a new pedestal transport mechanism is operative*
- We believe that puffing should increase n_{SEP} even if it does not raise n_{PED}
- Hence we examine profiles where n_{SEP}/n_{PED} is increased, but all other parameters are kept fixed



- **Q_{GB} increases with higher n_{SEP}; this is consistent with T_{PED} dropping with gas puffing, as in JET**

	JET-ILW Energy flux	**JET-C Energy Flux**
Nominal n_{SEP}	70	37
Higher n_{SEP}	150	94

* Maggi et. al. Nucl. Fus. 2015 113031; Leyland et. al. Nucl. Fus. 2015 013019

Hence, using simulations where only one parameter is varied at a time, results are ***consistent with several experimental trends on JET:***

1) Low Z impurities reduce pedestal energy transport- thus raising T_{PED}
2) C impurities give gyroBohm scaling
3) Temperature degrades with gas puffing at constant n_{PED} (presuming n_{SEP} increases) - similar to JET-ILW and JET-C
4) Linear indications that higher β_N should also reduce transport for JET-ILW- qualitatively consistent with JET-ILW hybrid operation
5) Other behavior in JET is qualitatively consistent with the hypothesis of enhanced transport in the pedestal with ILW or density puffing
   a) The usual empirical correlation $w \sim \beta_p^{1/2}$ is violated, especially with gas puffing, indicating that a new pedestal transport mechanism is operative
   b) Pedestal pressure increases much faster with heating power in JET ILW– indicative that transport limits are playing a role, rather than only "hard" MHD limits

* Maggi et. al. Nucl. Fus. 2015 113031; Leyland et. al. Nucl. Fus. 2015 013019; Giroud et. al. PPCF 2015 035004

Because of low ρ^*, the ratio γ/γ_E is much higher for ITER than for JET, if all other dimensionless parameters are the same- so transport is much higher than a gyroBohm scaling from JET to ITER

- ***We have found this to be the case in many nonlinear simulations of ITER***
- ***To obtain acceptable heat fluxes for ITER, we believe it will be necessary to have multiple advantageous parameters at once, e.g.:***
  1) Z_{eff} = 2 (N) **AND** low n_{SEP}
  2) Z_{eff}=2 (N) **AND** high β_N
- ***Roughly speaking, JET with Z_{eff} ~ 1 is a good experimental model for ITER, with Z_{eff} =2 and lower ρ****
- ***The cases where we have nonlinear GENE simulations bear this out***

IFS

Nonlinear GENE simulations for ITER

- ***Heating power through the pedestal is only ~ 80-100 MW***
- ***Simulations find transport power often considerably exceed this***

Condition	**Zeff =1**	**Zeff=2 (N)**	**Higher n_{SEP}** Zeff = 2	**Lower n_{SEP}** Zeff = 2	**$\beta_N = 2.5$** Zeff = 2
Transp. Power	500 MW	190 MW	500 MW	60 MW	In prog.

- ***For ITER, JET, and burning plasmas in general, the separatrix density must also be compatible with divertor conditions***
  - →Recently projected small SOL widths (~ 1mm) require higher n_{SEP} (used here)*
  - →The only case above with acceptable transport power has an n_{SEP} which is low (0.2×10^{20}) -likely extremely challenging for divertors (even if SOL width ~5 mm)
- ***Hence, advanced divertors may be needed for burning H-modes***
  - ***Super-X divertor, X-divertor, snowflake, double-decker, etc***
  - ***Low recycling lithium based divertors***
- ***At least for the super-X, we believe that acceptable divertor operation is possible with such low densities***

*Kukushkin et. al. Journal of Nuclear Materials 438 (2013) S203–S207

With limited heating power, HOW does a pedestal readjust to a condition of insufficient velocity shear?

- ***We have varied the pedestal width of ITER by a factor 1.5 up and down***
- ***Surprisingly, there is very little change in the transport power***
  - →While a wider pedestal may improve the MHD limit, it does not relieve transport limitations from insufficient velocity shear for electrostatic drift modes
  - →Previous predictions that pedestal width would adjust to lower ρ* by becoming narrower are not indicated to be the case

- ***We reduce pedestal temperature by 30%, ITER transport power drops from 180MW to ~ 70 MW***
- ***This indicates that a pedestal, with moderate heating power, adjusts to insufficient velocity shear by decreasing T_{PED}***
  - →This is the behavior observed with JET–ILW operation and Z_{eff} ~ 1

- ***These results indicate that a good experimental model for ITER at Z_{eff}~2 is high field JET-ILW at Z_{eff} ~1***
  - → Comparing ITER to JET-ILW, the improvement in ITER due to N is compensated by the degradation on ITER due to lower ρ*
  - → This is consistent with nonlinear GENE results and linear estimates

*Kotschenreuther, Dorland, et. al, IAEA 1996

We have strong indications that an insufficiency of velocity shear in the pedestal is also mitigated by lower Aspect ratio A

- *Linearly, there are indications that lower A has advantages*
- *We have found nonlinear simulations at low A (A=1.7) to be much more challenging and expensive than at normal A*
- *The single nonlinear simulation that we have succeeded in performing shows turbulence that is also dominated near the top and bottom, qualitatively like our experience at A =3*
- *The heat flux is significant, but not as serious as A=3*
- *We are continuing to to examine this, but we are not yet ready to present quantitative results*

SUMMARY/CONCLUSIONS

- ***Nonlinear electromagnetic pedestal simulations with GENE find that an insufficiency of velocity shear can lead to large pedestal transport***
- ***This arises at sufficiently small ρ*- it begins in JET at Zeff ~ 1***
- ***In addition to the ρ* trend, other parametric dependencies are found***
    - Low Z impurities (C, N) mitigate the transport
    - High (low) n_{SEP}/n_{PED} makes the transport worse (better)
    - High β_N mitigates the transport
- ***These generally correlate with JET experience with an ILW***
- ***A good experimental model for ITER, according to these simulations, appears to be that with Z_{eff}=2 (Nitrogen), ITER is qualitiatively like high field JET at Z_{eff} ~ 1***
- ***For adequate pedestal transport, burning plasmas may need low n_{SEP} values that require advanced divertor concepts***
- ***Velocity shear insufficiency also depends on aspect ratio, and lower A may also be advantageous (but simulation is much more challenging)***

Linear calculations of γ / γ_E show that hybrid operation (increased β_N) enhances shear suppression

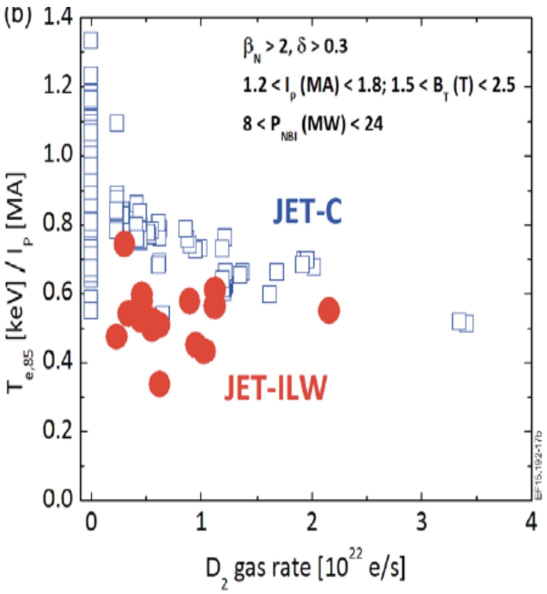
- ***JET finds that operation at higher β_N – so called "hybrid" modes- greatly reduces the confinement deterioration of ILW cases***
  - → The pedestal confinement is degraded less at $\beta_N > 2$
- ***Linear runs at $\beta_N = 2.5$ show that the ratio γ / γ_E is decreased by about a factor of 0.6***
  - → Based on experience, we expect this magnitude of increase should quite substantially reduce nonlinear transport from ion-scale modes
- ***With both Nitrogen and $\beta_N = 2.5$, γ / γ_E is decreased by about a factor of about 0.3***
- ***Nonlinear runs for hybrid modes are in progress***
- ***However, on the basis of these linear comparisons, it seems likely that the best way to ameliorate/eliminate the effects of an insufficiency of velocity is in hybrid operation with low Z impurities at Z_{eff}~2***
- ***Pending nonlinear verification, simulations indicate this may be the best mode of operation for ITER or JET for DT***

IFS

The hypothesis of an insufficiency of velocity shear correlates with *several* features of JET ILW behavior

- ***JET finds significantly lower pedestal temperature with an ILW vs a Carbon wall (JET-C)***
  - → Lower pedestal temperature T_{PED} would be a corollary of higher pedestal energy transport, **as found here**
- ***This problem was initially attributed to high gas puffing for ILW cases, but recent JET publications*:***
  1) State that for the **SAME** puff rate, the ILW has lower pedestal temperature than JET-C
  2) Conjecture that reduced T_{PED} in ILW could be caused somehow by lack of low Z impurities
  3) **The simulations show the latter to be the case**

From Maggi et. al.



- ***The insufficiency hypothesis ALSO agrees with other trends observed on JET***
  1) The effect of edge density sources
  2) The effect of higher β_N

* Maggi et. al. Nucl. Fusion 2015 113031; Leyland et. al. Nucl. Fusion 2015 013019; Giroud et. al. Plasma Phys. Control. Fus. 2015 035004

Experimenting with increasing the pedestal width
From DIIID (strongly suppressed) to ITER (weakly suppressed)

- ***We run GENE for the original cases, but increase the pedestal width by a factor of 1.5 (for ITER and DIIID): decreasing the velocity shear by~2***
- ***Strikingly different responses:***
  - ***For the over sheared DIIID, increasing the pedestal width is "good"***
  - The is so much velocity shear to start off with, that even if it is reduced by x 2, ion scale transport still remains negligible
  - ETG transport is low enough that the pedestal height can increase with an appropriate heating power
  - When an MHD stability boundary is reached, it will be at a higher pedestal height (larger width allows higher MHD stable pedestal height)
  - So wider pedestal => higher pedestal => more stored energy

- ***For the weakly sheared ITER, however, the situation is quite different- increasing the pedestal width further increases the transport power***
  - Recall $\gamma_E \sim 1/w^{2}$; increasing the pedestal width makes low velocity shear even lower
  - Transport, which was already far too high for the available heating power, gets **even worse**

Exploring Spherical Tokamaks

- ***STs have higher velocity shear relative to growth rates, compared to A ~ 3 (at least for investigations of core parameters)[1]***
- ***But like standard A, burning STs have smaller ρ* than today's ST experiments- will an insufficiency of velocity shear arise for fusion STs?***
- ***To consider whether velocity shear is sufficient for a burning ST, we consider parameters used in the Princeton Pilot plant study for a small ST with major radius 1.4m (~150 MW fusion)***
- ***We estimate the pedestal width from published analysis of NSTX data[2]***
  - →These pedestal widths are a larger fraction of the minor radius than for normal aspect ratio
- ***We develop numerical ST equilibria from VMEC (similar to those previously discussed)***

[1] Kotschenreuther et. al. Nucl. Fusion 2000 677

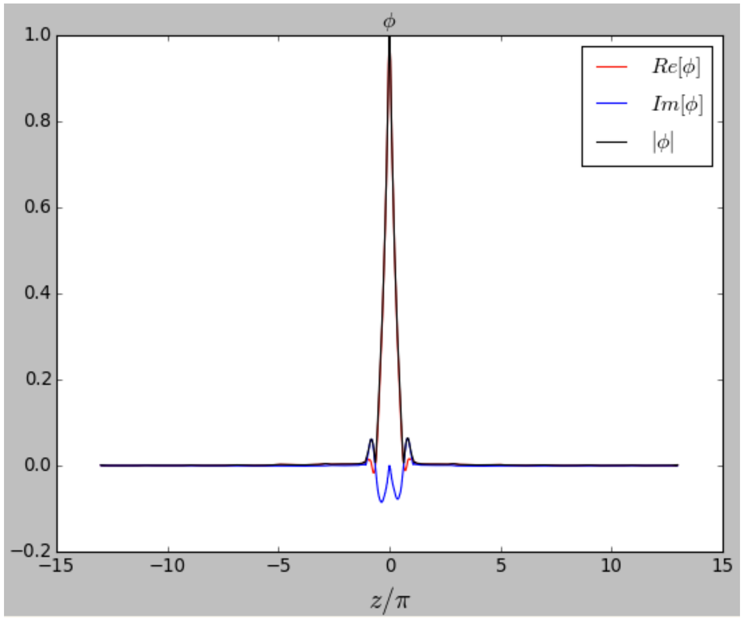
[2] *Diallo et. al. Nucl. Fusion 2013* 093026

A welcome surprise:

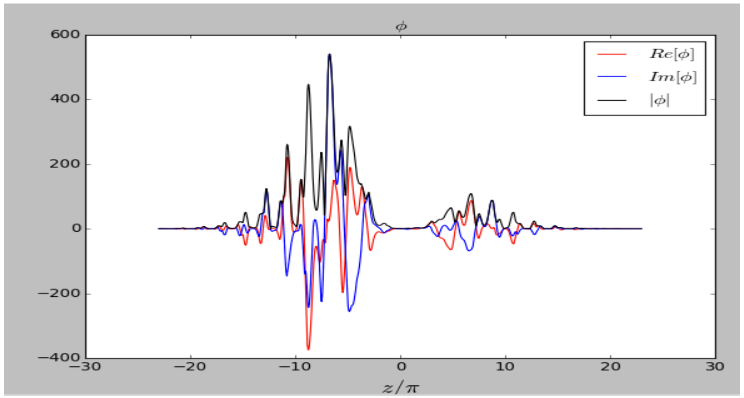
- ***For all cases considered so far (with significant variations in parameters), ST eigenfunctions have a structure much like the core:***

The modes are localized on the outboard midplane - where velocity shear is <u>strongest</u>

Typical ST pedestal eigenfunction



Recall: typical A ~ 3 pedestal eigenfunction



Summary

- ***The first nonlinear electromagnetic simulations of a ρ* scan of tokamak pedestals has been performed***
- ***Rough consistency with gyroBohm scaling is found on existing devices (with C)***
- ***A breakdown of gyroBohm scaling was found at a small enough ρ*, due to an insufficiency of velocity shear to quench the ion scale turbulent transport***
- ***There are significant commonalities between the observed degradation of confinement with the JET ILW and simulation trends***
  - Carbon reduces pedestal transport, and the problem is worse at JET ρ* than at ASDEX ρ*
- ***The eignfunctions of pedestal instabilities can be more resistant to velocity shear than for core paramters; even without shear, they tend to peak in regions where velocity shear is weak***
  - Existing rough criteria for when velocity shear quenches turbulence need to be reformulated to account for this
- ***There are unexpected, potentially crucial differences in the pedestals of normal aspect ratio tokamaks and spherical tokamaks***
- STs may be less prone to an insufficiency of velocity shear at burning plasma parameters, but nonlinear runs must be done to verify this

Summary

- ***Under burning plasma conditions, velocity shear suppression of an H-mode pedestal appears considerably more propitious for an ST than for A ~ 3***

- ***We are hopeful that a small high Q burning ST will be possible, and intend to work toward this***

ADDITIONAL SLIDES:

Further aspects of the ρ^* scan

- ***Perform electromagnetic simulations of both:***
  1) Ion gyroradius scale turbulence
     → All the "usual" modes are present in the simulations: ITG, microtearing, Kinetic Ballooning Mode (KBM), Trapped electron mode, etc., etc.

  2) And *separately*, electron scale turbulence (ETG) (multi-scale left for future work)

- ***We do not attempt to make the pedestal profiles self-consistent with the transport (left for future work)***
  → We examine the ρ^* scaling and magnitudes of the transport channels

- ***Nonlinear electromagnetic global simulations of the pedestal with the full profile variation too numerically challenging. We made reasonable simplifications:***
  1) Set the geometrical coefficients and gradients to constant values, chosen in the steep gradient region of the pedestal
  2) Perform nonlinear electromagnetic simulations with that gradient
  3) Simulate over a domain size of the pedestal steep gradient region
  4) As is conventional, buffer zones are added just outside the boundary of the simulation region to damp fluctuations there

QOUTES- Nunnes et. al. Plasma Phys. Control. Fusion 58 (2016) 014034

- Plasma performance is recovered for conditions of optimum pumping where the neutral pressure at the divertor is reduced and at high normalised plasma pressure(βN) [8–10].
- Increasing the additional input power and reducing the gas puffing rate gives access to high βN (> 2.5) plasmas with high pedestal temperature as shown in figure 7.
- Recent studies show that JET-ILW low collisionality plasmas can reach confinement values comparable to those of JET-C [30] and that at similar collisionality the pedestal temperature and stored energy are similar
- With increasing pumping efficiency, an improvement of the pedestal confinement is observed as shown in figure 8 . It is not clear if this effect is related to the change of neutrals and recycling in the main chamber or changes in the pedestal stability. However, the impact of particle source on plasma confinement is confirmed by its degradation as gas puffing is increased.
- Simulations using SOLEDGE2D confirm that the total power losses inside the separatrix exhibit a minimum for the configuration with higher pumping. However, these results are not conclusive as the amplitude of the power losses are too small relative to the total heating power, making it unlikely to be responsible for such large variations in confinement [32 , 33].
- The injection of nitrogen has an opposite effect on plasma confinement for the JET-C and JET-ILW discharges. In JET-C the injection of nitrogen reduced the plasma global confinement whereas in the JET-ILW discharges an increase in the pedestal temperature led to an increase of the global confinement as shown in figure 10 (b)
- These results show that the core transport for the electrons is similar for both the JET-C and JET-ILW plasmas indicating that the core plasma behaves in a similar way to that with the carbon wall [43]. The increase of core pressure is due to the increase of density peaking and the increase of the ion temperature profile gradient as already observed in JET-C [44].

QOUTES- Nunnes et. al. Plasma Phys. Control. Fusion 58 (2016) 014034

- A set of power scans were performed at constant plasma parameters where it was found that the power dependence of the energy confinement. The improvement of the thermal stored energy with the heating power is due to a rise in both pedestal pressure, consistent with the P– B boundary, and core pressure peaking linked with the reduction of collisionality.
- Summary:
- The most striking effects on plasma behaviour resulting from the change of the plasma wall facing components were the reduction of pedestal temperature leading to the loss of plasma confinement and the change of edge stability.
- In terms of the core confinement, it has been shown that both electron and ion stiffness are similar for both the carbon and Be/W wall.
- Nitrogen seeding was shown to be beneficial not only for reducing the power load but an increase of the pedestal temperature was also observed and its effect is dependent on plasma triangularity. The mechanism that leads to the increase of pedestal temperature has not yet been identified (regarding nitrogen puffing).

QOUTES- Maggi et. al. Nucl. Fusion 55 (2015) 113031

- Typically, increasing gas injection leads to a degradation of the pedestal energy confinement, while ne, PED remains largely unvaried, and overall to a reduction in normalized global confinement
- The high beta JET-ILW ELMy H-modes, typically achieved with low gas injection and low main chamber neutral pressure, exhibit instead good normalized global confinement, comparable to JET-C, although they are not long term stable with respect to core W accumulation.
- Extension of the JET H-mode database with the addition of the 2013/14 experiments allows us to confirm that in JET-ILW not only the H-modes at high gas injection but also those at lower gas rate and lower main chamber neutral pressure have reduced $T_{e,PED}$, and thus reduced pedestal performance, compared to JET-C.
- It can be seen that the pedestal temperature is lower with ILW at all values of pedestal densities…$T_{e,PED}$ is lower in JET-ILW at all values of D2 gas puffing rate.
- Changes in wall recycling associated with the changes in wall composition from C to Be/W, in particular the dynamic phase associated with ELM crash and recovery (as discussed in section 4.3), may be responsible.
- ..it could be that the strong reduction in C impurity concentration with the ILW is connected, in some way not yet understood, to the observed reduction in pedestal temperature
- …low D2 gas injection rates or by divertor configurations with optimum pumping, and high beta are necessary conditions for good pedestal (and core) performance.
- In particular, N2 seeding was found to increase Te,PED in JET-ILW to values approaching those of JET-C at similar ne, PED /nGW , while core confinement was not improved, as pressure peaking remained unaffected by N2 seeding.
- Also in the case of high beta H-modes the pedestal pressure appeared to be lower in JET-ILW, but the global normalized energy confinement remained comparable to that in JET-C as the reduction in pedestal confinement was compensated by increased core profile peaking

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- In general, the experiments indicate that while the pedestal energy confinement has been affected by the changes in wall material from JET-C to JET-ILW, the pedestal density has remained largely unaffected.
- Typically, Te,PED is lower than in JET-C at similar values of $n_{e,PED}/n_{GW}$
- On the other hand, H-mode operation at high N and low D2 gas injection rates has not led to energy confinement degradation after the JET wall changeover from CFC to Be/W plasma facing components, both at low and high triangularity, as reported in [15].
- On average $n_{e,PED}$ is largely insensitive to the increase in D2 gas rate and also decreases weakly with increasing input power. On the other hand, Te,PED is mostly affected by the increase in gas injection, on average decreasing by a factor of two as the D2 gas rate increases from lowest to highest and it increases with power for a given D2 gas rate.

Aren’t calculations of pedestal MHD limits sufficient?

- ***ITER is based on an ELMing H-mode: the pedestal operates at an MHD stability limit***
- ***We must note that calculations based purely on MHD (MHD pressure limits, for instance) are only part of the story: they cannot address the crucial question:***

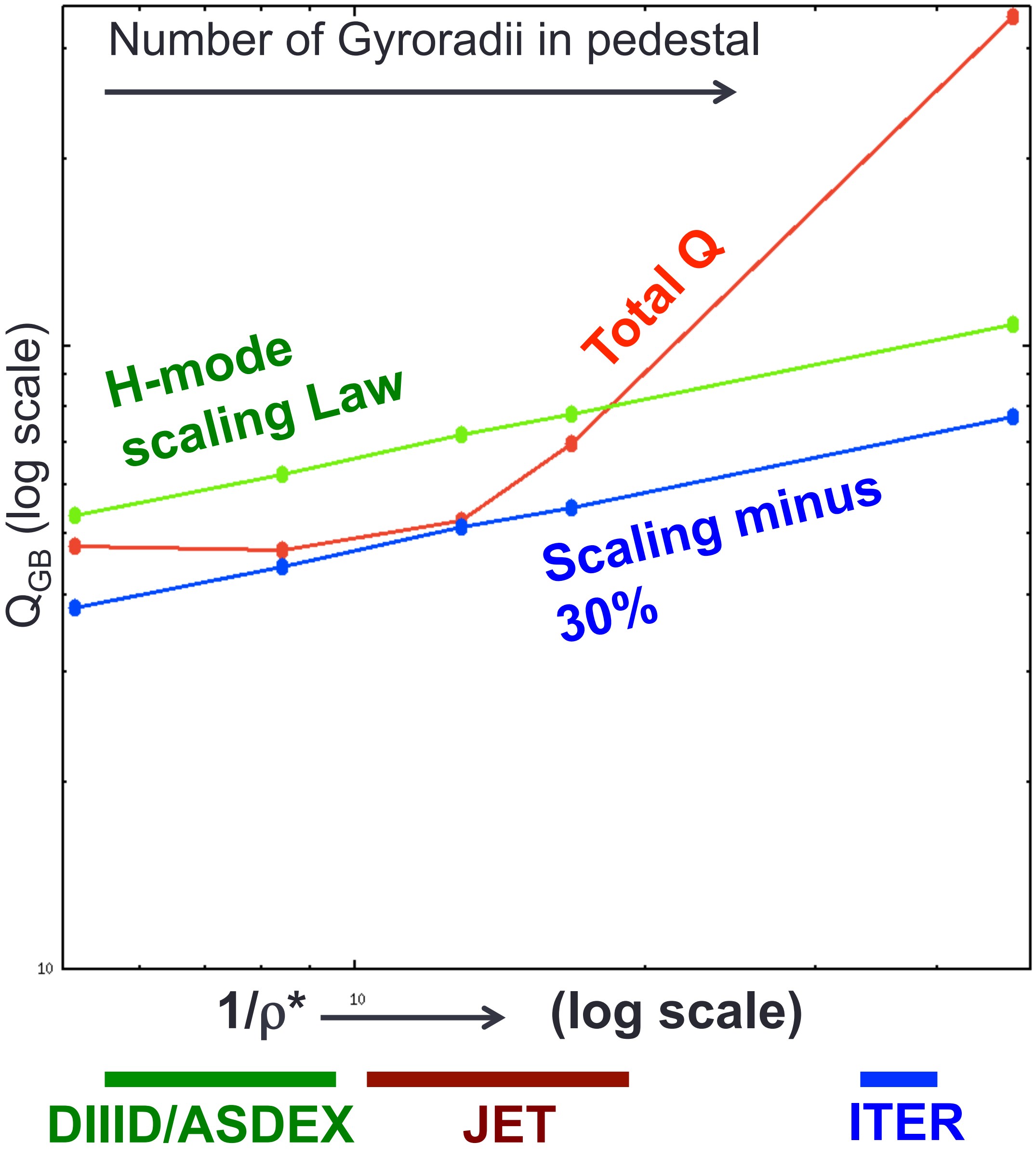
What is the scaling of the heating power needed to reach these limits for a given pedestal temperature?

- ***MHD stability can only give stability limits as a function of β ,q, ν*, etc.***

But before ITER operates,
only a gyrokinetic transport calculation can determine
how much heating power is needed to reach required pedestal parameters,
and the scaling of that heating power with ρ*

How does the magnitude of the gyrokinetic heat flux compare to typical experimental values ?

- ***Employ a rough estimate: use the H-mode scaling law to estimate the power required to produce these plasmas***
- ***The transport found in GENE for these model profiles is somewhat lower than the scaling law, but within ~ 30%***
- ***But beyond some ρ^* of JET, the transport trend is clearly much worse than the scaling law***



The density can still increase despite the fact the temperature is low

- ***The gyrokinetic simulations predict low density transport***
  - → Hence, pedestal density can still increase -and hence pressure increase- so that a pedestal MHD stability boundary is reached (an ELM)
- ***Nonetheless, in ELMy JET discharges with an ILW, the low temperature can reduce the MHD pressure limit for an ELM***
  - → Through the effect of low temperature on the bootstrap current and hence ped. MHD stability*
- ***Lower pedestal pressure (whose ultimate origin is the low temperature*) leads to low energy confinement on JET***
- ***In a fusion plasma, with a large drop in temperature, fusion power is not effectively recovered by increasing density (pertinent to both JET and ITER)***
  - → The fusion cross section drops very rapidly at low temperature
- ***Furthermore, for ITER, there is very little margin to increase the density to compensate for lower temperature***
  - → Operating density is already ~ 80% of the density limit
  - → Operation is similarly close to the projected H -> L threshold; increasing density would, of itself, cause the discharge to fall out of H-mode

*Giroud et. al and Maggi et. al., previous pages

An approximate criterion that captures this effect is to take the eigenmode average of the Hahm-Burrell ExB shearing rate

- ***For core parameters (where modes peak on the outer midplane), a rough criterion for strong suppression of turbulence* (based on many nonlinear runs) was found:***

$$\gamma / \gamma_{E\ \text{H-B midplane}} \sim 1/2$$

- ***To account for the variation of γ_E and much more general mode structures, it would seem more accurate to define an ``eigenmode weighted average of the Hahm-Burrell ExB shear"***

$$< \gamma_E > = \int |\phi|^2(\theta)\ \gamma_{E\ \text{Hahm-Burrel}}(\theta) \Big/ \int |\phi|^2(\theta)$$

- ***For eigenfuctions with a structure like those in the core- peaked at the outer midplane- this new definition is only modestly different from the midplane value***
- ***But for pedestal-like eigenfunctions the average shear is several times lower !***
- ***This ``integral" criterion explains most of the observations noted above***

*Kinsey et. al. Phys. Plasma 2007 102306

Nonlinear GENE simulations for ITER

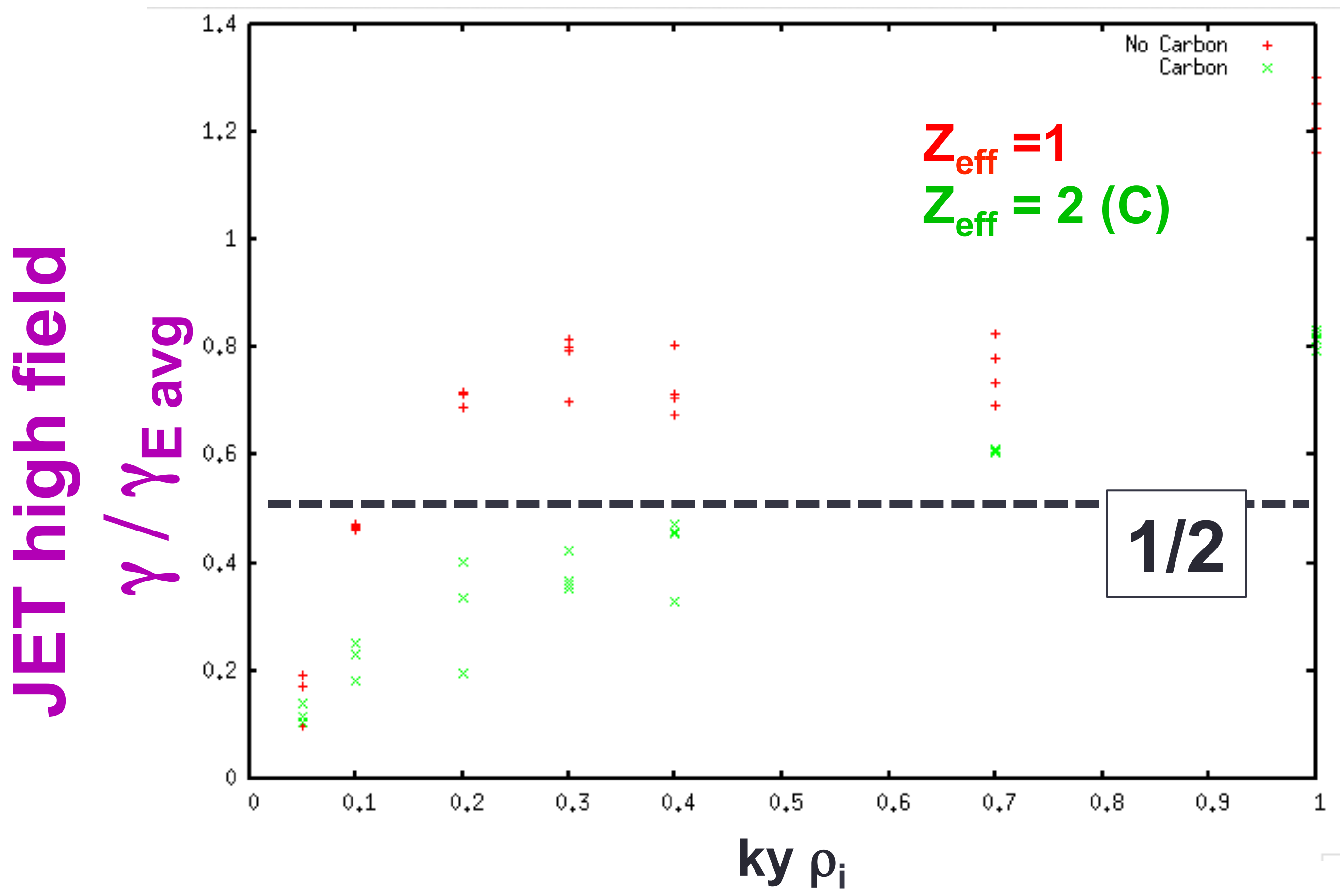
- ***Heating power through the pedestal is only ~ 80-100 MW***
- ***Simulations find transport power often considerably exceed this***
- ***For ITER, JET, and burning plasmas in general, the separatrix density must also be compatible with divertor conditions***
  - Recently projected small SOL widths require the higher n_{SEP}*
- ***The only case with acceptable transport power has an n_{SEP} which is very challenging***
- ***Hence, advanced divertors may be needed for burning H-modes***
  - ***Super-X divertor, X-divertor, snowflake, double-decker, etc***
  - ***Low recycling lithium based divertors***
- ***At least for the super-X, we believe that acceptable divertor operation is possible with such low densities***

Conition	Transport power
Zeff = 1	500 MW
Zeff = 2 (N)	190 MW
Higher n_{SEP} (0.5×10^{20})	500 MW
Lower n_{SEP} (0.2×10^{20})	60 MW
$\beta_N = 2.5$	In progress

*Kukushkin et. al. Journal of Nuclear Materials 438 (2013) S203–S207

The ``Integral” criterion: gives a heuristic explanation of the simulation results

- ***Considering $<\gamma_E>$, it is consistent that JET with $Z_{eff} = 1$ experiences significant turbulence at the value found here***
- ***With the addition of C ($Z_{eff} = 2$): γ is reduced and the eigenmode structure changes to increase $<\gamma_E>$, hence reducing $\gamma / <\gamma_E>$***



- ***For Zeff = 1 suppression criterion fails***
- ***For Zeff = 2, marginally satisfied***