TOWARDS THERMONUCLEAR (BURNING) PLASMAS
CONFINEMENT AND TRANSPORT

GYROKINETIC - SIMULATIONS

S. M. Mahajan

Based on work done in conjunction with M. Kotschenreuther, D. Hatch, P. valanaju

The University of Texas at Austin, USA

IFS

H-mode –The Basic Savior of Fusion

- The largest ever, scientific experiment and an understudy of an eventual fusion power reactor, the ITER tokamak , plans to demonstrate high energy-gain (Q~10) by operating in the so-called High-energy confinement H-mode

- In an H-mode, the energy (temperature) confinement time is boosted up (to sustain the requisite ``thermonuclear" temperatures) through a spectacular suppression of the turbulent thermal transport resulting in the spontaneous appearance of a sharp "transport barrier" (pedestal) at the plasma edge

- **A high quality barrier (high pedestal top temperature) is crucial to fusion:**
  - **The core temperature profiles are rather "stiff" - Requisite central temperatures of ~20keV for high Q fusion, is possible only if the pedestal temperature is ~ 4-5 keV**
  - **To get to Such high temperatures, the thermal transport in the pedestal cannot be too high**

- For reasons part practical and part mysterious, the plasma community till recently, had not invoked its sharpest tools to ``calculate'' thermal transport in pedestals of future machines like ITER- Simple extrapolations from "smaller" current machines may not be enough-ITER could be in a different transport-regime; it is, for instance, larger and has a larger magnetic field.

★IFS

Attempts to Understand Why- Need for Transport simulations

- MHD stability limits have dominated the theoretic discourse and understanding of pedestal dynamics-its formation and characteristics

- And since the anomalous thermal transport was really suppressed in current machines like the DIIID-AUG etc, it was assumed that only MHD was enough to not only determine the pedestal characteristics of the current machines but also to predict it for the future machines like ITER/Reactor.

- **Let us pose a couple of crucial probing questions:**
- How much power is needed to reach such an MHD limit?
  - Confinement time = ***Stored Energy/ HEATING POWER***
- What determines the pedestal T – not the nT (limited by MHD)?
  - If temperature is too low, fusion cross sections are very low, and fusion power is low even if the nT "figure of merit" indicates "good confinement"

- **Analysis of MHD stability boundaries cannot answer either question**

- **Analysis of pedestal TRANSPORT is what needs to be done**

IFS

Nonlinear simulations of pedestals – First-Principle Gyrokinetics via GENE

- We have used nonlinear electromagnetic gyrokinetic simulations using GENE to compute pedestal transport
- We find pedestal energy transport which agrees, in many respects, to experimental results on JET and other tokamaks
- We've examined:
  - Many simulations for JET parameters
  - Differences between JET-ILW and JET-C (low Z impurities reduce energy transp.)
  - Effects of separatrix density n_{SEP} (gas puffing and divertor pumping)
  - Other major experiments (ASDEX/DIII-D)
  - Projected ITER pedestals, and how they compare to present experiments
- **The instabilities causing transport are not MHD-like modes (Kinetic Ballooning Modes) as posited by the reigning paradigm underlying EPED**
  - Our KBM results similar to the linear analysis of JET pedestals by Saarelma et.al. for JET- KBM is in second stability
- **Our nonlinear results obtain due transport levels through important micro-instabilities**

*Saarelma et. al. "**MHD and Gyro-kinetic Stability of JET Pedestals"** 2013 Nucl. Fusion 53 123012

IFS

Gyrokinetic simulations- close to "first principles"

- These codes solve the fundamental nonlinear equations describing micro-instabilities and turbulence
  - Gyrokinetic ordering applied to the Vlasov equation
  - This ordering captures micro-instability modes: ITG, trapped electron, micro-tearing (MTM), Kinetic MHD ballooning (KBM), ETG, electron drift wave, etc.
  -
- GENE* and other gyrokinetic codes (GS2*, GYRO*) have been used very successfully for many years
  - To explain many features of ``core'' transport
  - To examine *linear* pedestal instabilities

- Here we present results of the first extensive campaign of NONLINEAR gyrokinetic pedestal simulations

***GENE:** F. Jenko, W. Dorland, M. Kotschenreuther, and B. N. Rogers, Phys. Plasmas **7**, 1904 (2000)
GS2: M. Kotschenreuther, G. Rewoldt, and M. W. Tang, Comput. Phys. Commun, **88**, 128 (1995)
GYRO: Candy J. and Waltz R.E. J. Comput. Phys. **186** 545 (2003)

IFS

What is Unique about the pedestal- Then and Now

- Very strong ExB shear to "tear turbulent eddies apart"**-** reducing anom. transport
- The qualitative importance of ExB shear has long been recognized:
- ***Fritz Wagner, "A Quarter Century of H-modes":*** (PPCF **49** (2007) B1-B33)

  Abstract "…There is, however, substantial experimental and theoretical evidence that turbulent flows, which normally limit the confinement, are diminished by sheared poloidal flow residing at the plasma edge…"

- The Texas group, for the first time, goes beyond qualitative descriptions of pedestals with large ExB shear

These simulations quantitatively describe suppression for the actual micro-instabilities in the pedestal,

fully including the unique properties of the instabilities due to pedestal conditions)- which directly affects the degree of effectiveness of suppression

- **Enormous improvement in the completeness of the theoretical description of pedestals and ExB shear suppression**

IFS

Is ExB shear suppression always enough?

- The simulations do, indeed, find that ExB shear is crucial in order to obtain heat fluxes that experiments observe

But ExB shear, under certain important conditions, results in only an incomplete turbulence suppression, giving higher heat transport

- GK simulations, thus, give us a clue why pedestal temperatures can, sometimes, be relatively low; GK calculations also suggest pathways to higher tempeartures
- In the largest current machine- the JET-ILW – we are beginning to see manifestations of in complete shear suppression - especially at high B and I_p
- For ITER, this could turn out to be a serious problem
- **Hence, we think that understanding and remedying this situation in JET-ILW is a crucial prerequisite for ITER operation**
- Furthermore, JET-ILW is the only experiment, that can examine this regime of incomplete shear suppression, highly relevant to ITER and all burning plasmas

IFS

Qualitative aspects of the pedestal transport- Testing the model

- Before applying to ITER, we tested our methods/ results by applying them to
  - Current experiments
  - To throw some light on the big puzzle that JET-ILW pedestals cannot attain the projected temperatures
  - The JET_ILW operation is nearest to what ITER would be-Understanding its poor(er) performance is a question of utmost importance to nuclear fusion through tokamaks.

- Simulations compel a very revealing transport scenario:
  - Significantly enhanced heat transport is found under certain conditions; but it is accompanied by little particle transport
  - For a fixed heating power, then, the pedestal temperature will be lower
  - Because of low transport, the density in the pedestal can still rise (due to neutral fueling) until an MHD pressure limit (instability limit) is reached

- **At whatever pressure such an instability occurs, <u>the temperature will be lower when heat transport is higher</u>**

- This is likely the JET-ILW scenario conditions: Thermal transport is larger (we will soon see why) –The MHD pressure limit , therefore, is reached through an increase in density with a corresponding lower pedestal temperatures.

IFS

Shear Suppression and Turbulent Transport

Turbulent transport is caused by instability driven electromagnetic fields. A very complex phenomenon-but essential elements are qualitatively obvious:

- The level of turbulence- some kind of an average magnitude of, say, the electric field)
- The more detailed nature of turbulence- the correlation lengths, correlation times etc.
- The virulence of the instability could be approximately guessed by the linear growth rate(γ)
- In a confined tokamak plasma, the primary source of the instability are the plasma inhomogeneities
- It turns out the temperature gradient driven instabilities (both at the electron and ion scales) are likely the most potent and controlling- We will in fact find that it is , in fact, η, the ratio of the temperature gradient/density gradient that often determines the threshold of the instabilities of interest.

- What is interesting is that even though the threshold of instability is crossed and electric fields grow as to work towards creating anomalous transport (think of the e.m fields as scattering centers increasing the effective momentum changing collision frequencies), there may exist mechanisms that tend to fight against this tendency and limit the total damage (turbulent transport) the instabilities can inflict on the plasma energy confinement

- One such mechanism that may play a decisive role in the pedestal confinement is the turbulence suppression through differential plasma rotation- also called the velocity shear. Particularly effective on ion scale electrostatic modes, its effectiveness must be clearly understood as we move from current (future) machines that have large (much smaller) velocity shear.

Estimating Efficacy of Velocity Shear (Suppression) –the ρ^* Scaling

- The typical growth rates for drift-type modes (via gyrokinetic ordering) scales as

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

  $C_\gamma \sim 1$: a complicated function of dimensionless parameters γ ~the turbulent energy production rate

- The strength of the velocity shear is measured by the shear rate (γ_{ExB}) of what is essentially the equilibrium ExB velocity. the eq. electric field may be estimated by

  $en E_r \sim C_E \, dp_i/dr$ $C_E \sim 1$ verified on ASDEX, DIIID,C-mod etc.,

  - the suppression factor (for a pedestal of width w), then,

    $\gamma_{ExB}/\gamma \sim (C_E/C_\gamma)(\rho/a)(a/w)^2 \sim (C_E/C_\gamma)\rho*$

    scales linearly with $\rho*$= gyroradius, normalized to plasma size, and (C_E/C_γ).

- As we march from ASDEX / DIIID to JET to ITER, $\rho*$, gets lower and lower, Efficacy of shear suppression, consequently, becomes smaller and smaller

- A serious implication is that if the H-mode transport barrier arose because of the suppression of turbulence (turbulent transport) caused by shear (it is known that current tokamaks are in a regime of large velocity shear), then will such a state of felicity exist say, for instance, in ITER

- Will ITER shear, through comparatively smaller, be adequate to suppress turbulent transport? Naturally, in addition to studying ρ^* effects, we must also delve into the determinants of C_E/C_γ

★IFS

Examining ρ^* dependence only- *dimensionless scaling paradigm* + *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_{95}, 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 baseline projections (T_{PED} = 4 keV, n = 0.85 Greenwald limit, w_ψ = 0.04, etc.)
  4) Density pedestal is somewhat offset from temperature
  5) Use numerical equilibria (from VMEC) including the bootstrap current
  6) Include the E_r 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

IFS

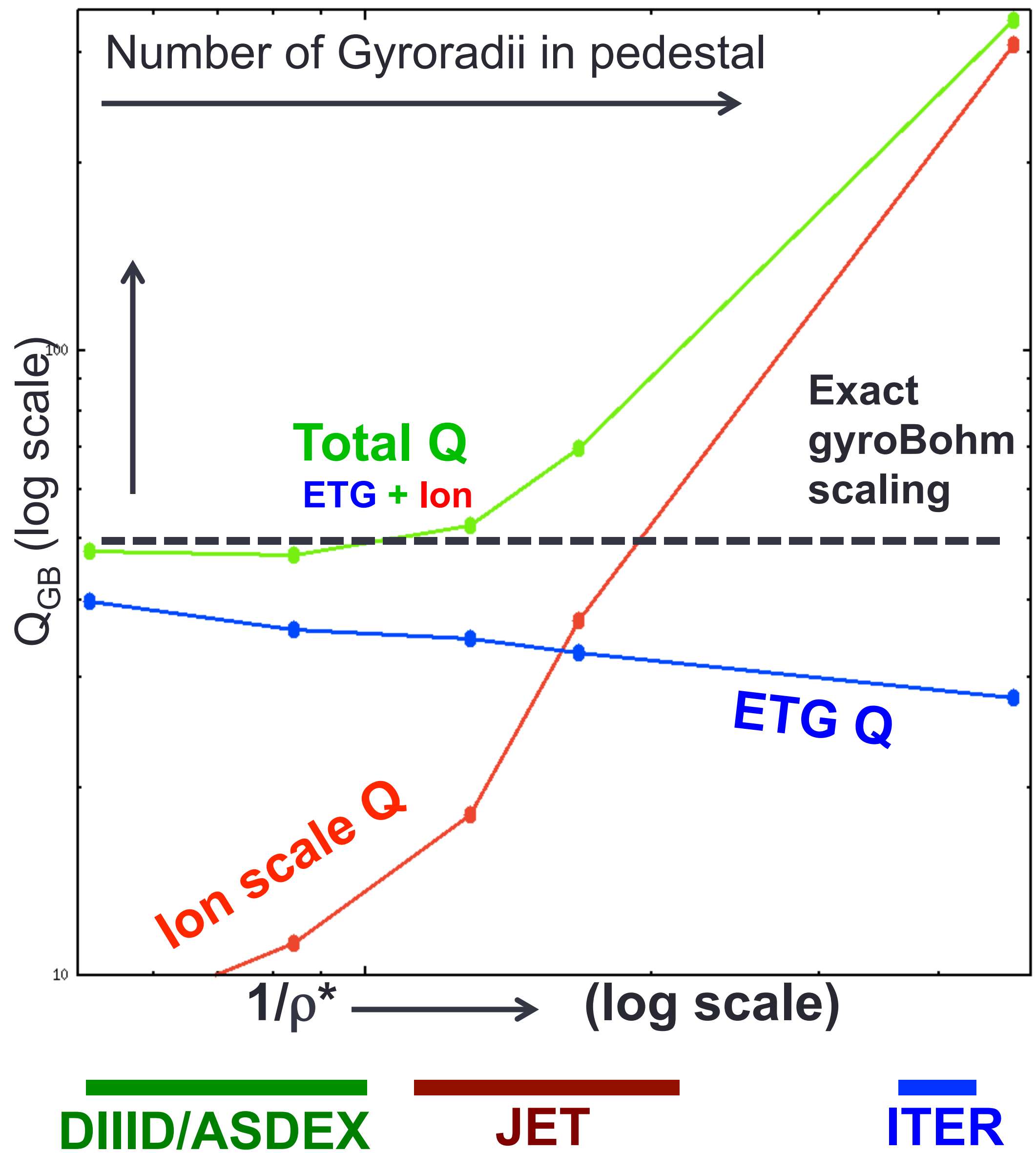
We simulate five cases with decreasing ρ^* (increasing I_p, R and B)

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})

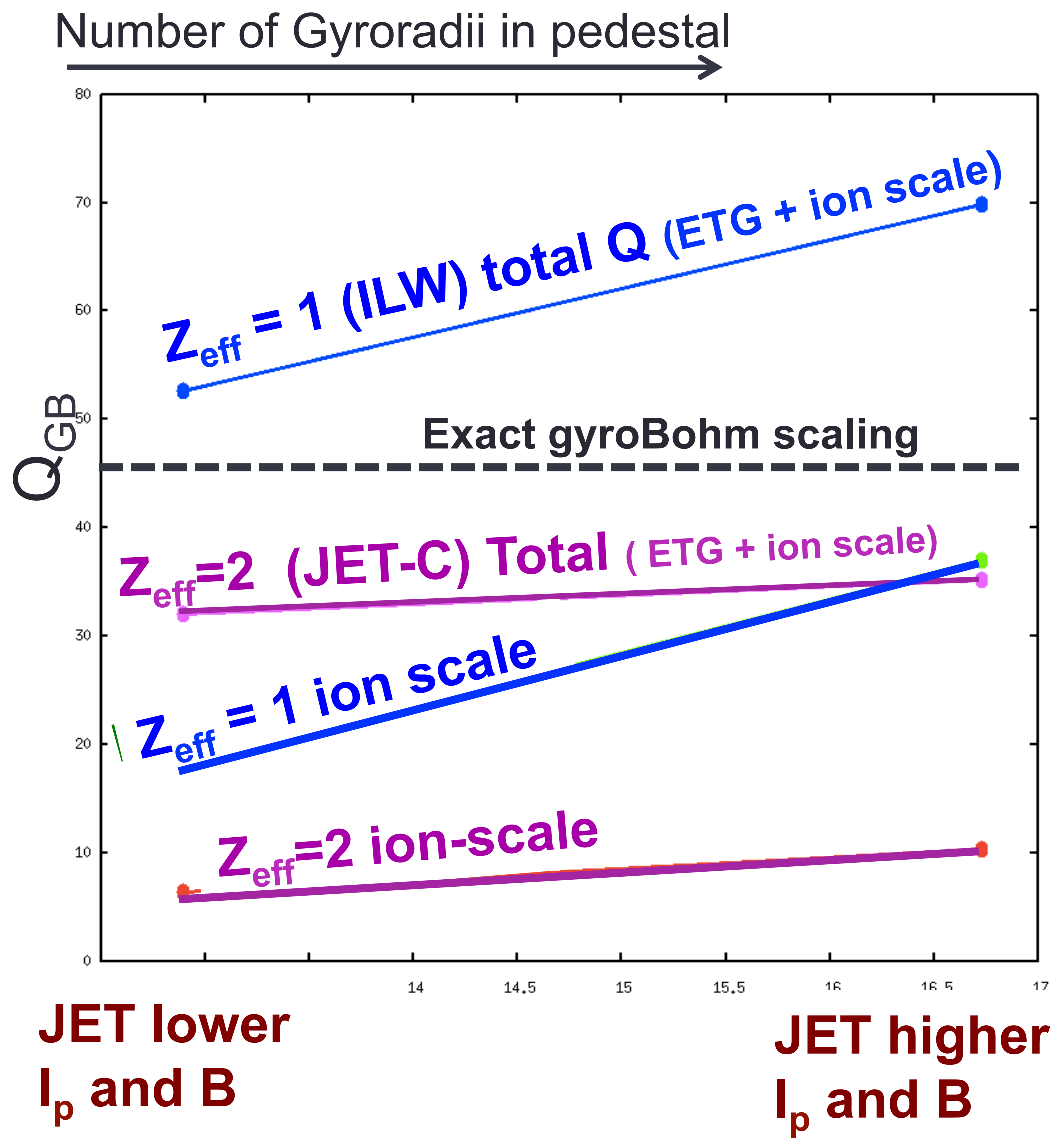
- Exact gyroBohm scaling => Q_{GB} is constant vs. ρ^*
- Ion scale transport is always increasing rapidly with $1/\rho^*$- but it starts from a very low value
- At large ρ^* (high velocity shear) the ETG dominates
- The total transport scaling (ETG + ion scale) in this range is nearly gyroBohm, in large 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



IFS

Nonlinear GENE simulations for JET-Carbon -- gyroBohm scaling - 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*
- Carbon significantly reduces ETG
- with C: *total* pedestal energy transport is reduced, and gyroBohm transport channels dominate- similar to JET



IFS

Extraordinary Results Invite Careful Scrutiny- Shortcomings

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

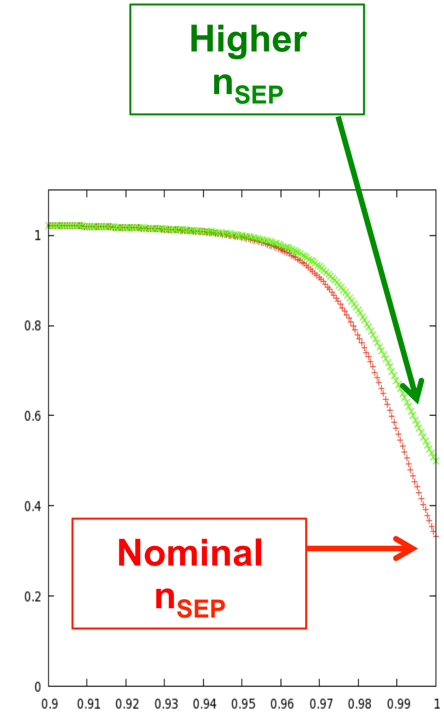
★IFS

Qualitative Conclusions are highly Significant

- The most robust feature of the simulations: ion scale transport grows as ρ^* is decreased
  - →Quite expected for the transport from the predominantly electrostatic modes with shrinking velocity shear
- GyroBohm processes dominate the transport at large ρ^*- the currently accessible regimes till JET-ILW at high I_p & B
  - →It is reasonable to expect that gyroBohm scaling would result from self-consistent profiles when this type of transport dominates
- JET-ILW: The first experiment exposing insufficiency of velocity shear: it is not enough to, adequately, bring down the overall thermal transport
- Lowering of ρ^* or lowering of (C_E / C_γ) can both lead to enhanced transport relative to the conventional expectations (gyroBohm)
- ITER is susceptible to low ExB shear even more strongly

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*
  - → *The pedestal broadens, violating $w \sim \beta_p^{1/2}$, indicating that a new pedestal transport mechanism is operative*
- We assume puffing increases n_{SEP} but not 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**
- **Lack of low Z impurities makes transport worse with or without puffing**

	JET-ILW	JET-C
Nominal n_{SEP}	28 MW	15 MW
Higher n_{SEP}	61 MW	38 MW

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

IFS

Degradation with ρ^* in JET- Comparing Simulations and experiments

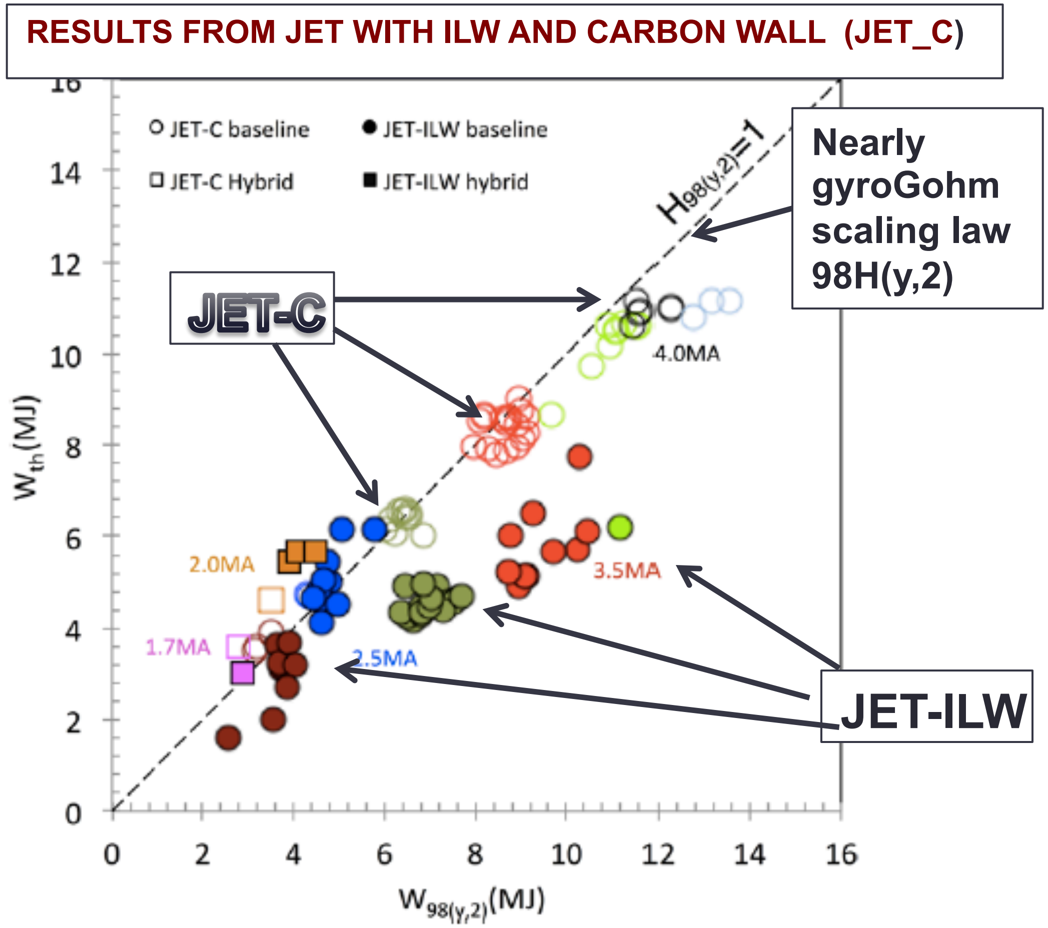
- We used profiles from JET shots with an ITER-Like Wall (ILW) and Z_{eff} =1

- JET with an ILW finds a progressive deviation below the nearly gyroBohm H-mode scaling law at high I_p & 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}

- First, let us consider the relavant physics involved



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

★IFS

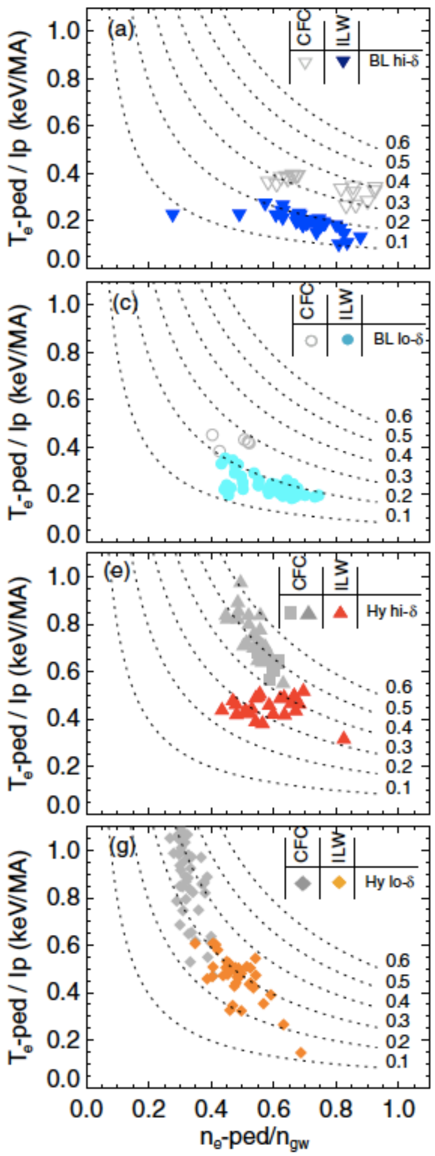
At constant heating power, higher pedestal heat transport implies lower T_{PED}

- The simulations show very little density transport; hence, in principle, n_{PED} can increase to reach an MHD limit (ELM)

- According to our simulations, T_{PED} in JET-ILW should be lower than in JET-C (at the same heating power)- because heat transport in higher in JET-ILW

- **In JET-ILW, T_{PED} is, in fact, lower than in JET-C over a wide range of conditions**

- Sometimes the Pedestal pressure is lower, sometimes not, but temperature is consistently lower on JET-ILW compared to JET-C



Beurskens et. al. NF 2014

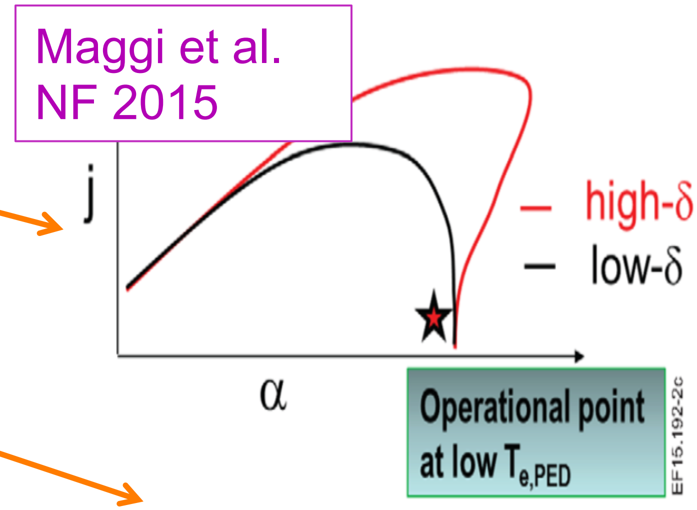
IFS

Consequences of lower T_{PED} to confinement and fusion

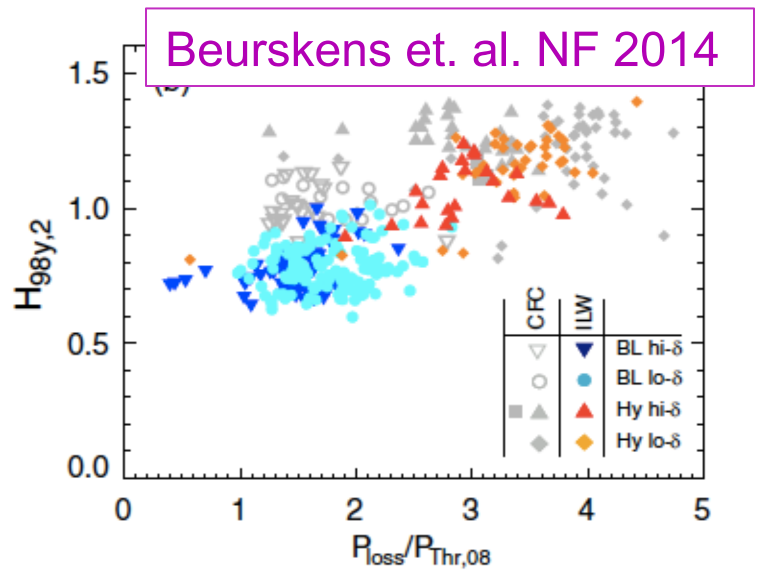
- Though, n_{PED} might increase to give the same pressure n_{PED} T_{PED}, under some conditions, this will not be possible

1) Lower T_{PED} can lead to lower MHD pressure limit

2) If density is constrained from increasing because of operation near the density limit and threshold power $P_{L->H}$, confinement will decrease
   → This is seen on JET-ILW; near density limit and H ->L power threshold, confinement is decreased



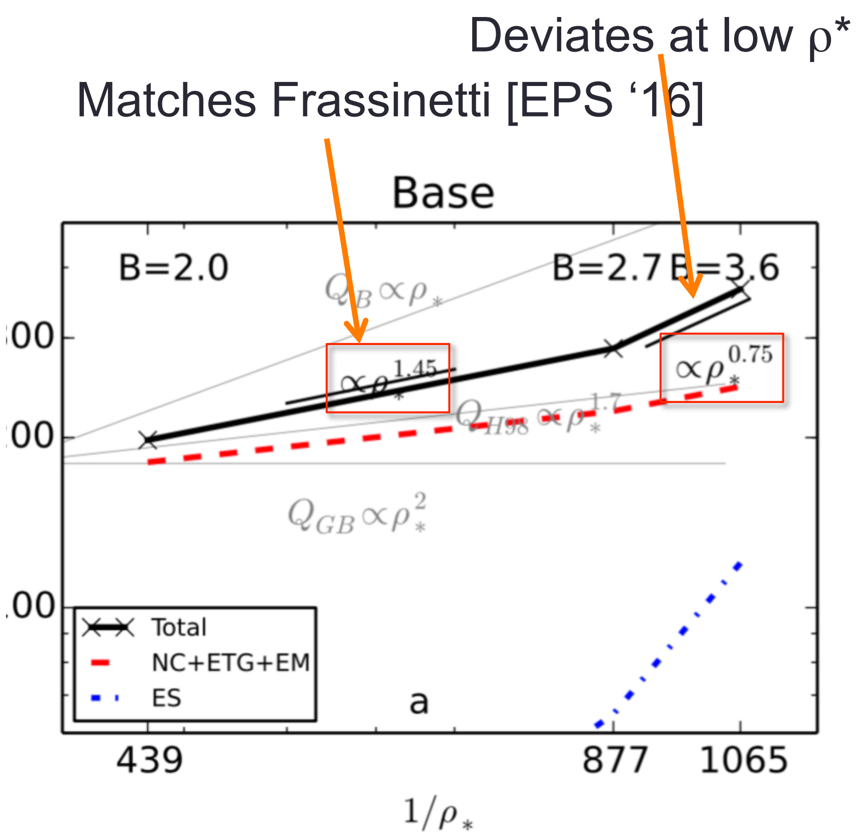
- Also lower T_{PED} can greatly reduce fusion cross sections, leading to low fusion power even if T_{PED} n_{PED} is the same
   → This problem is making it difficult for JET to reproduce previous shots with high fusion power



★IFS

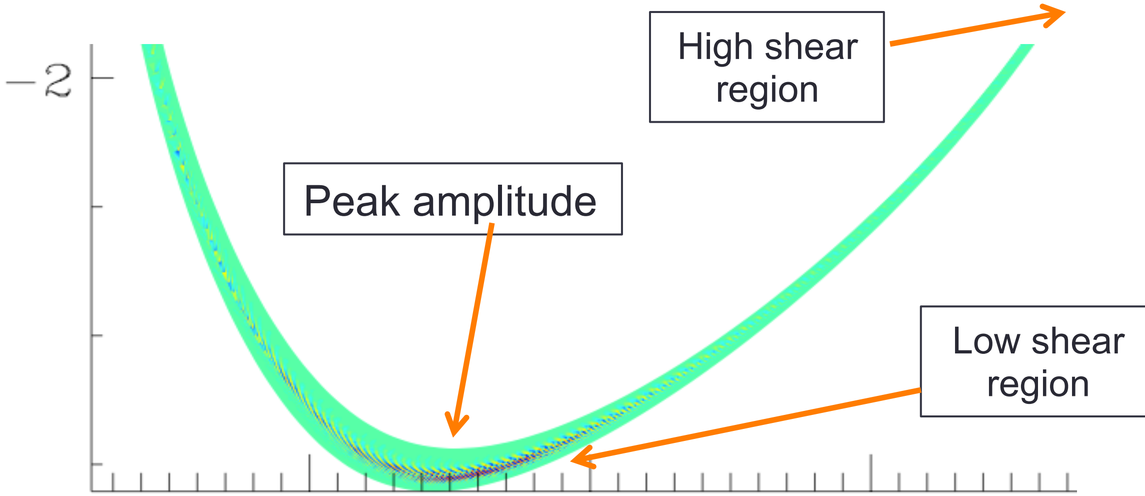
BASE CASE ρ* SCAN

- gyroBohm-ish mechanisms (Neoclassical, ETG, electromagnetic [MTM])
  - ρ* scaling very similar to H98
- ES transport
  - Extremely unfavorable ρ* scaling (due to decrease in ExB shear)
  - Very small at high ρ*
  - Becomes significant only in regime of severe JET-ILW confinement breakdown (B > 2.7 T)



Modes responsible for pedestal transport -Insufficient velocity shear

- 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

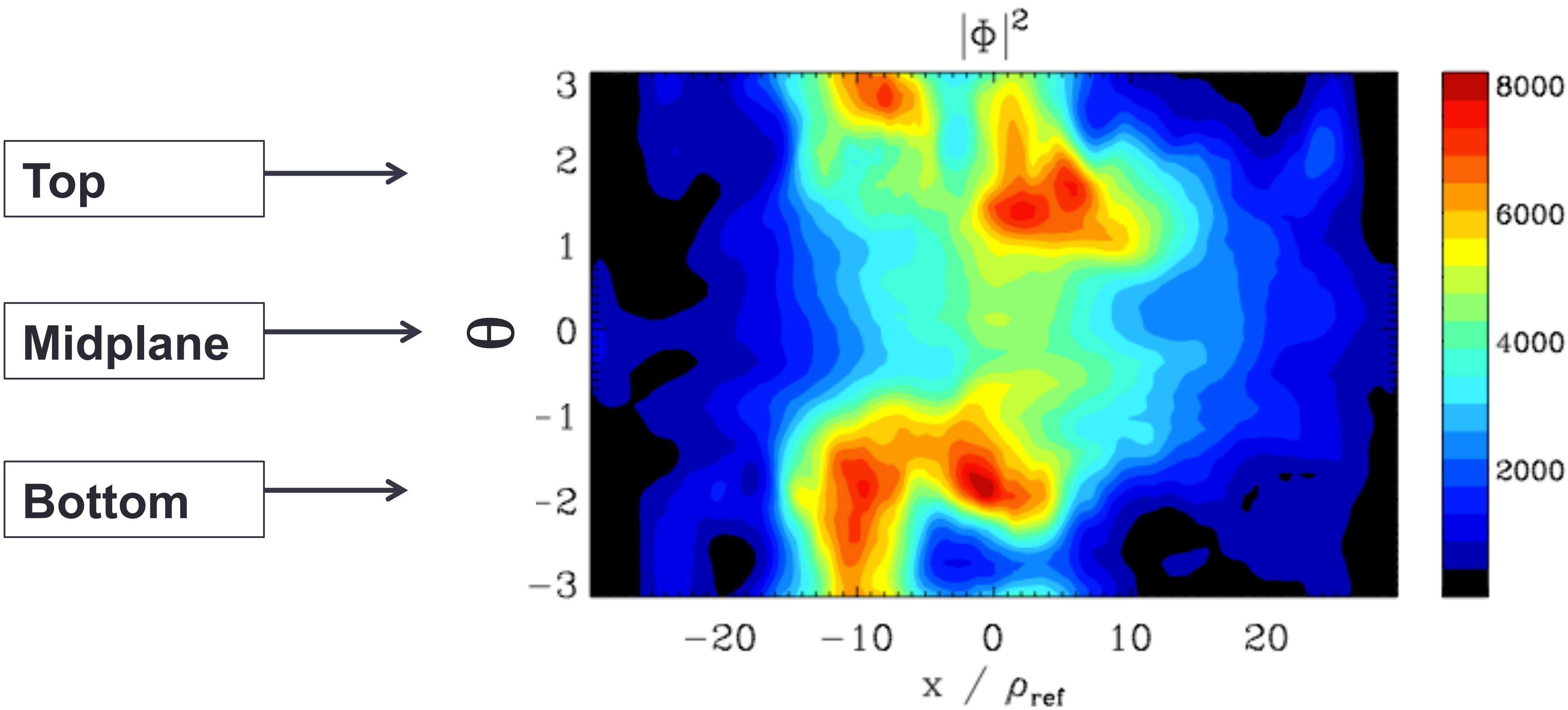


The velocity shear is much weaker in regions where the flux surfaces are further apart:

→ 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

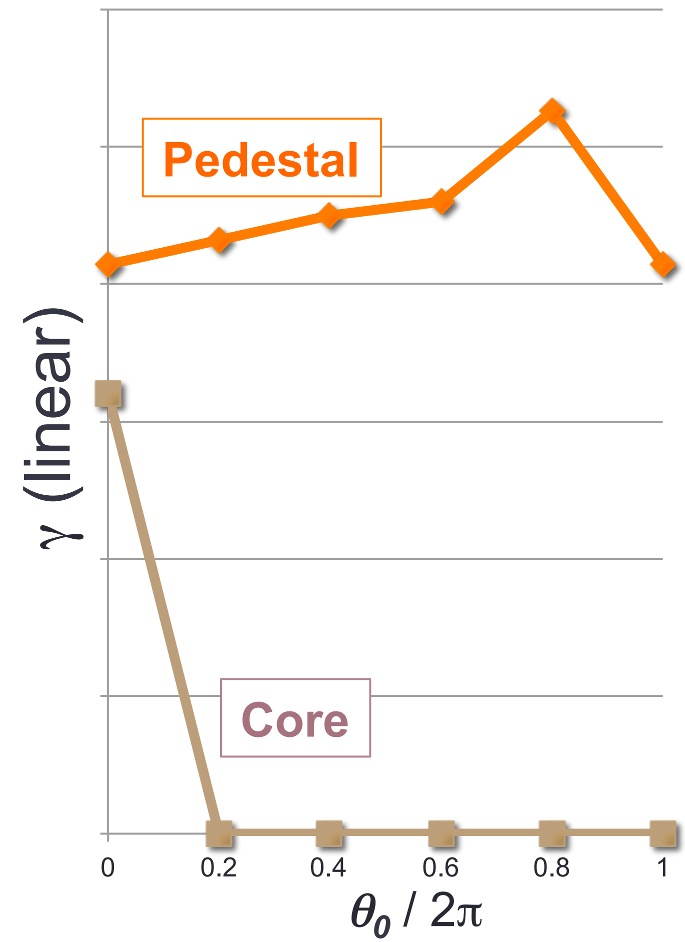


- The turbulence is considerably stronger near the top and bottom, compared to outboard midplane – the former are the regions of weakest velocity shear

IFS

1D local linear ballooning calculations with GENE- support 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 θ_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

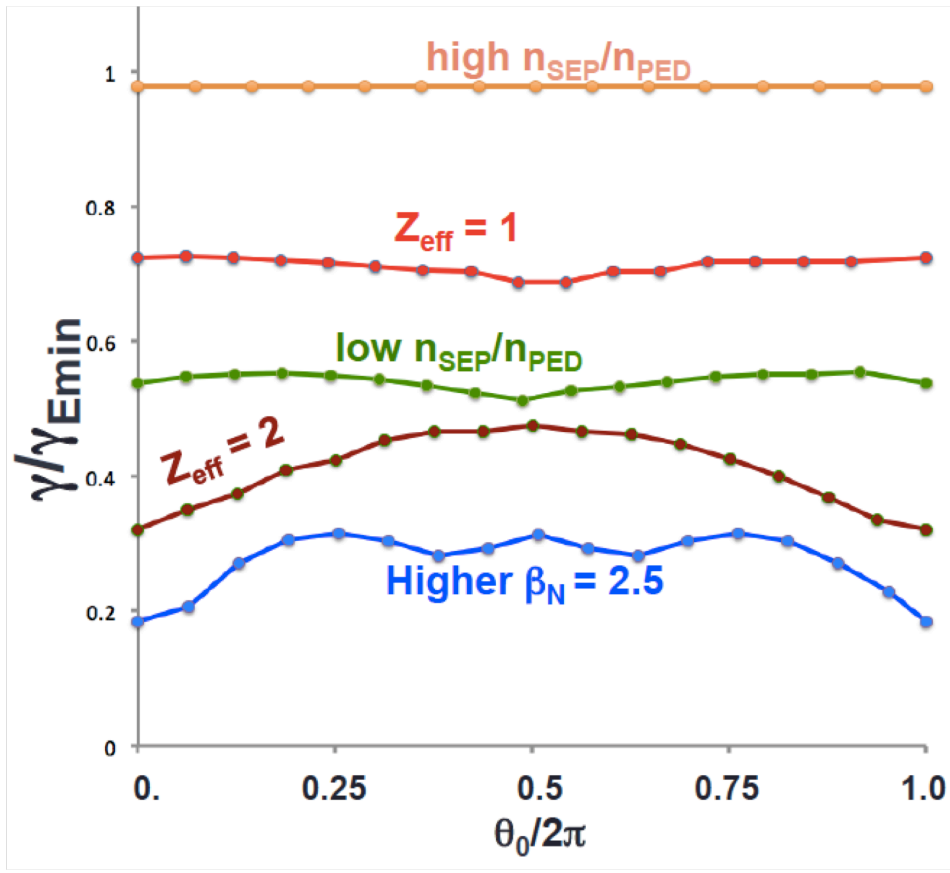


- ***There is good qualitative correlation between trends in the ratio γ / γ_E and the nonlinear behavior of GENE, and the behavior of JET***

IFS

Linear calculations from GENE: good correlation between the ratio $\gamma / \gamma_{E\,min}$ ($\sim C_E / C_\gamma$) and the behavior of JET –ILW

- Compare γ to the velocity shear at the poloidal location where it is weakest $\gamma_{E\,min}$
- Ion scale transport causes significant transport when $\gamma / \gamma_{E\,min}$ exceeds ~ 0.7
  1) Z_{eff} ~ 1 (high field)
  2) high n_{SEP}/n_{PED} (gas puffing)
- Good performance when $\gamma / \gamma_{E\,min}$ ~ 0.5 or less
  1) Z_{eff} =2 from low Z (N or C)
  2) High β_N (hybrid mode)
  3) Low n_{SEP}/n_{PED} (divertor pumping)
- Nonlinear GENE simulations find the same trends



IFS

Controlled Simulation ``Experiments”

- By carefully controlled simulations (varying one parameter at a time) we find results consistent with several experimental trends on JET. We ``observe”:

- Low Z impurities reduce pedestal energy transport- thus raising T_{PED}
- Adding Carbon impurity (JET-C) recovers gyroBohm scaling(similar for N)
- Temperature degrades with gas puffing at constant n_{PED} (presuming n_{SEP} increases) - similar to JET-ILW and JET-C
- Linear indications that higher β_N should also reduce transport for JET-ILW- qualitatively consistent with JET-ILW hybrid operation

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

IFS

Nonlinear GENE simulations for ITER- Principal Results

- **ITER Heating power through the pedestal is only ~ 80-100 MW**
- ***Transport power predicted by Simulations is considerably in excess***

Condition	Zeff =1	Zeff=2 (N) $n_{SEP} = 3x10^{19}$	Zeff=2 $n_{SEP} = 5x10^{19}$	Zeff=2 $n_{SEP} = 2x10^{19}$
Total MW	500	190	500	60
ETG only MW	25	17	34	12

- ***Note that the ETG power, which was dominant for all devices except JET-ILW, is very small on ITER***
- ***ITER transport is in a different regime from current devices-ion scale transport dominates, and it most closely resembles JET-ILW***

* Published SOLPS simulations by Kukushkin

IFS

Compatibility of good confinement with acceptable divertor conditions is even more difficult on ITER than on JET-ILW

- Recall

$$\gamma_{ExB} / \gamma \sim (C_E / C_\gamma)\, \rho^*$$

- Since ITER's ρ^* is lower than JET-ILW, to keep the anomalous transport down, a corresponding boost is required in the value of C_E / C_γ
- Unfortunately, conditions that benefit the divertor (higher n_{SEP}) make C_E / C_γ even smaller and, this, more unfavorable
- The challenge of attaining good confinement together with acceptable divertor conditions will be even harder on ITER than on JET-ILW
- It is crucial that we investigate and understand this problem on JET, and find solutions, before ITER

IFS

Divertor conditions are a strong function of n_{SEP}- a high enough value is a requirement

Condition	Zeff =1	Zeff=2 (N) n_{SEP} = 5 x10^{19}	Zeff=2 n_{SEP} = 3 x10^{19}	Zeff=2 n_{SEP} = 2x10^{19}
Total MW	500	500	190	60
ETG only MW	25	34	17	12

- ***Projected SOL widths (~ 1mm) require: n_{SEP} = 6 x10^{19} ****
- ***Estimated SOL widths (~ 5mm) require: n_{SEP} = 3 x10^{19}***

The only case above with acceptable transport power:

lower n_{SEP} = 0.2 x 10^{20}

This is extraordarily challenging for conventional divertors

- ***Hence, advanced divertors may be needed for burning H-modes***
  - Note that the X-divertor (XD) apparently can be implemented on ITER with the existing coil set
  - Furthermore, recent DIII-D experiments find that the XD gives detachment with much lower gas puffing

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

IFS

With limited heating power, how does a pedestal readjust to a condition of insufficient velocity shear- of boosted thermal transport

- The question is better answered by working out a possible scenario
- Suppose the pedestal temperature is reduced by ~ 30% - the actual range of temperature reduction found in JET-ILW

- ITER's nominal pedestal ~85% of the density limit, no margin for density increase being able to compensate this loss

- This would result in a ~ factor of two reduction in fusion power

- Since most heating power comes from fusion, heating power drops. With core radiation, power through the pedestal could easily drop below the estimated H mode threshold

- Higher external heating required to keep P_{SOL} above the L->H threshold

Q could drop further!

IFS

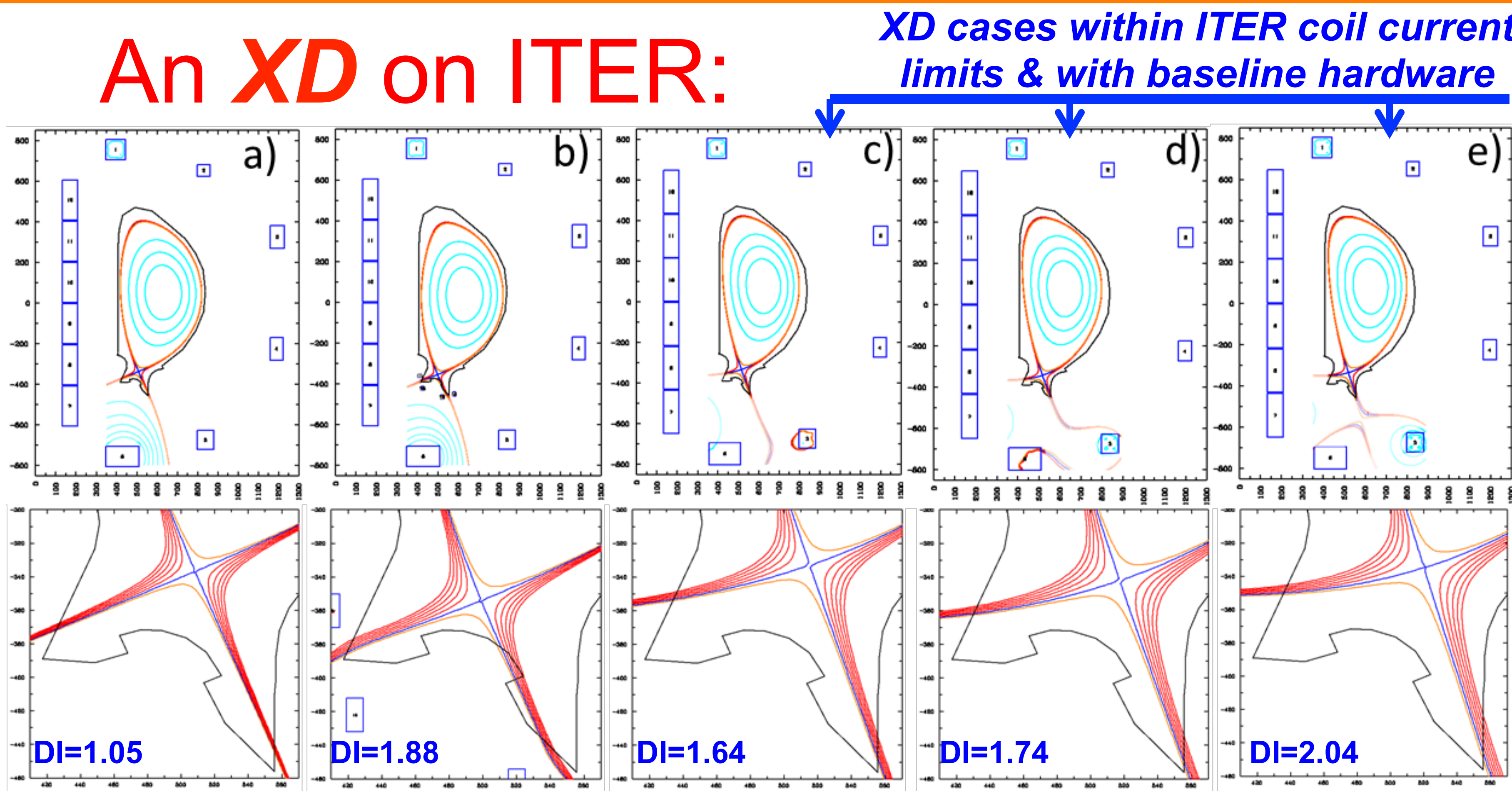
Is there a remedy?

- To make up for lower ρ^* (and hence lower γ_E), ITER must operate in regimes with lower growth rates γ (γ/γ_E as the figure of merit)
- We have found that each of following effects individually reduce γ.:

  1) $Z_{eff} = 2$ (N)
  2) Low n_{SEP}
  3) High β_N

- Fortunately, we find these favorable effects are multiplicative: hence, ITER will have to operate with two or three of them at once
- But how could we possibly lower n_{SEP} on ITER with acceptable divertor operation?
- Need For Advanced Divertors- The XD or the Super XD

An *XD* on ITER:



ITER X-Divertors: Within coil limits, and with baseline hardware, an XD appears to be possible on ITER

Simulations ith SOLPS and DIII-D experiments find that divertor detachment occurs at lower gas puffing (and presumably upstream SOL density)

The challenge JET Q ~1 for JET , Q=5-10 on ITER

- Factors making pedestal transport high are similar for the two
- Good confinement consistent with divertor operation-very challenging for either
- JET-ILW cases suitable for DT are reasonably representative examples of pedestals needed for successful ITER operation
- Consider the previous 1998 JET-C record fusion shot (Q a bit less than 1): the pedestal is not far from what is needed for ITER !
  1) T_{PED} ~ 5 keV (!)
  2) ν^* <<1 (even lower than ITER)
  3) Pedestal β_N close to ITER
- How might a shot with a pedestal close to 1998 record shot be reproduced on JET-ILW?

Gunning for Q ~ 1 on JET- ILW

- We have carried out GENE simulations to explore and analyze variations in the following parameters :
  a) Higher β_N
  b) Higher Z_{eff}
  c) Lowering SOL density
  d) And some other possibilities suggested by the simulations

- The first two are not new to JET. The 3rd- the SOL density is perhaps the most powerful knob for boosting confinement

- Unlike higher β_N, lower n_{SEP} does not suffer problems from NTMs

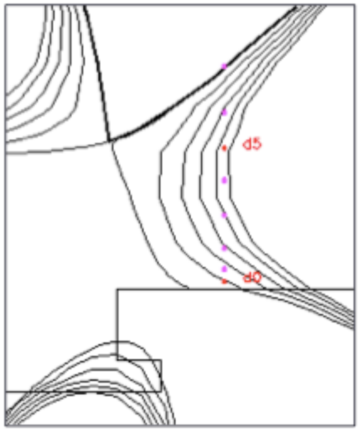
- Achieving lower n_{SEP} with acceptable divertor conditions is what the advanced divertors like XD-SXD do (in addition to managing heat exhaust)

*Paper by Texas and DIII-D team et. al. at 2016 IAEA

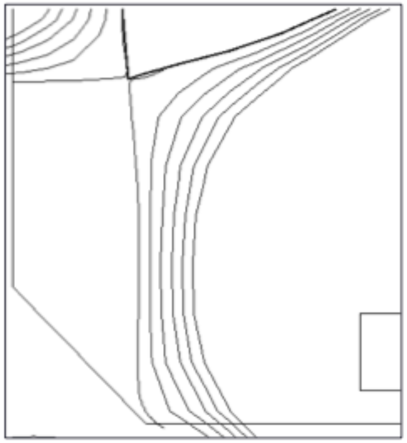
DIII-D has already implemented an X-divertor

1) DIII-D: just reprogrammed existing coils
2) Only a modest number of shots were needed to arrive at much higher flux expansion on the plate
3) Found that detachment could be achieved with considerably less gas puffing
4) We are analyzing how much benefit this might have for JET
5) Is this possible with JET PF coil set?
6) This could be a crucial element in having JET-ILW reproduce JET-C performance- or better it

X-Divertor geometries run on DIII-D
Less gas puffing was needed for a given level of detachment*



EFIT 160448



EFIT 160553

*Paper by Texas- DIII-D team at 2016 IAEA

IFS

SUMMARY/CONCLUSIONS

- Nonlinear EM pedestal simulations with GENE find reveal boosted pedestal transport low ρ^* (weak velocity shear suppression of turbulence)- Experimental manifestation: JET at Zeff ~ 1

- In addition to the ρ^* trend, other parametric dependencies are found
  - Low Z impurities (C, N) mitigate (reduce) the transport problem
  - High (low) n_{SEP}/n_{PED} makes the transport worse (better)
  - High β_N mitigates the transport

- These findings generally correlate with JET experience with an ILW
- For adequate pedestal transport, burning plasmas may need low n_{SEP} values- low n_{SEP} require advanced divertor concepts
- JET-ILW is the only good experimental model for the ITER pedestal parameter regime-It is crucial for JET to ``determine'' options for good ITER performance
- Over time, a better theoretical understanding of the problem should also lead to new options to improve performance

IFS

Simulating 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**

★IFS

Summary

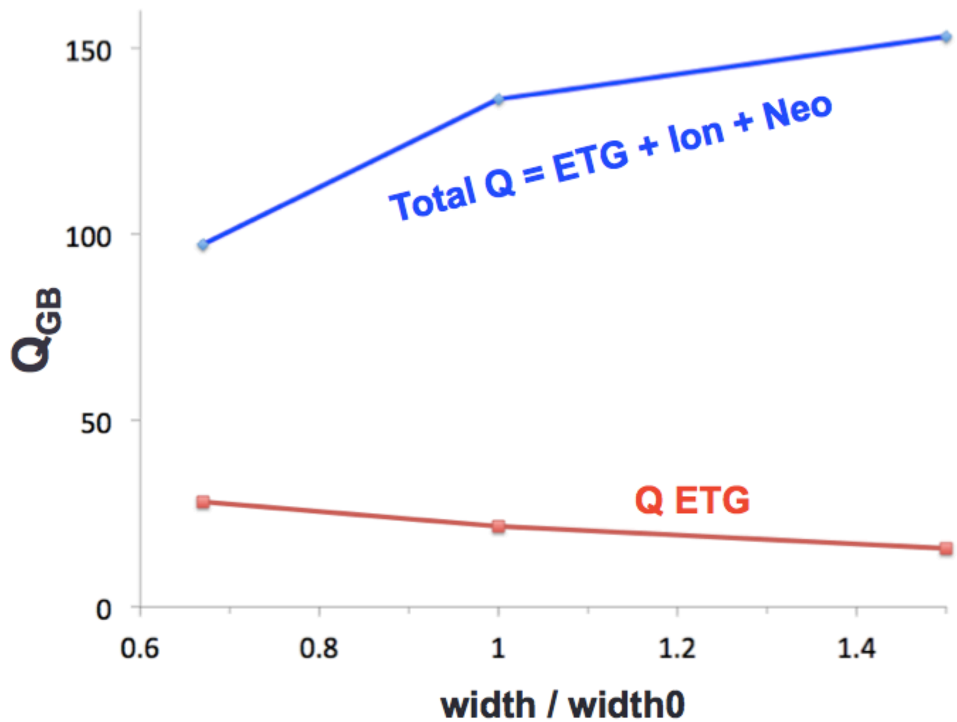
- The first nonlinear electromagnetic simulations of a ρ^* scan of tokamak pedestals has been performed
- Rough consistency with gyroBohm scaling is found on existing devices (with C)
- A breakdown of gyroBohm scaling was found at a small enough ρ^*, due to an insufficiency of velocity shear to quench 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

IFS

If the pedestal width is higher the problem is worse

- ***We have varied the pedestal width of ITER by a factor 1.5 up and down***
- ***Surprisingly, the transport power increased for a wider pedestal-the opposite of naïve expectations; $Q \sim \chi\, ndT/dr \sim \chi\, nT/w$***
- ***But since $\gamma_E \sim 1/w^2$ - larger w reduces γ_E and increases χ***
- ***In a regime of low velocity shear, wider pedestals degrade the pedestal further***

- ***On JET-ILW: gas puffing increased the pedestal width while the pedestal temperature and pressure drop: like a regime of insufficient velocity shear***
- ***Whereas if ETG dominated, wider pedestals would reduce transport- allowing a higher pedestal top.***



IFS

ADDITIONAL SLIDES:

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

IFS

Exploring Spherical Tokamaks

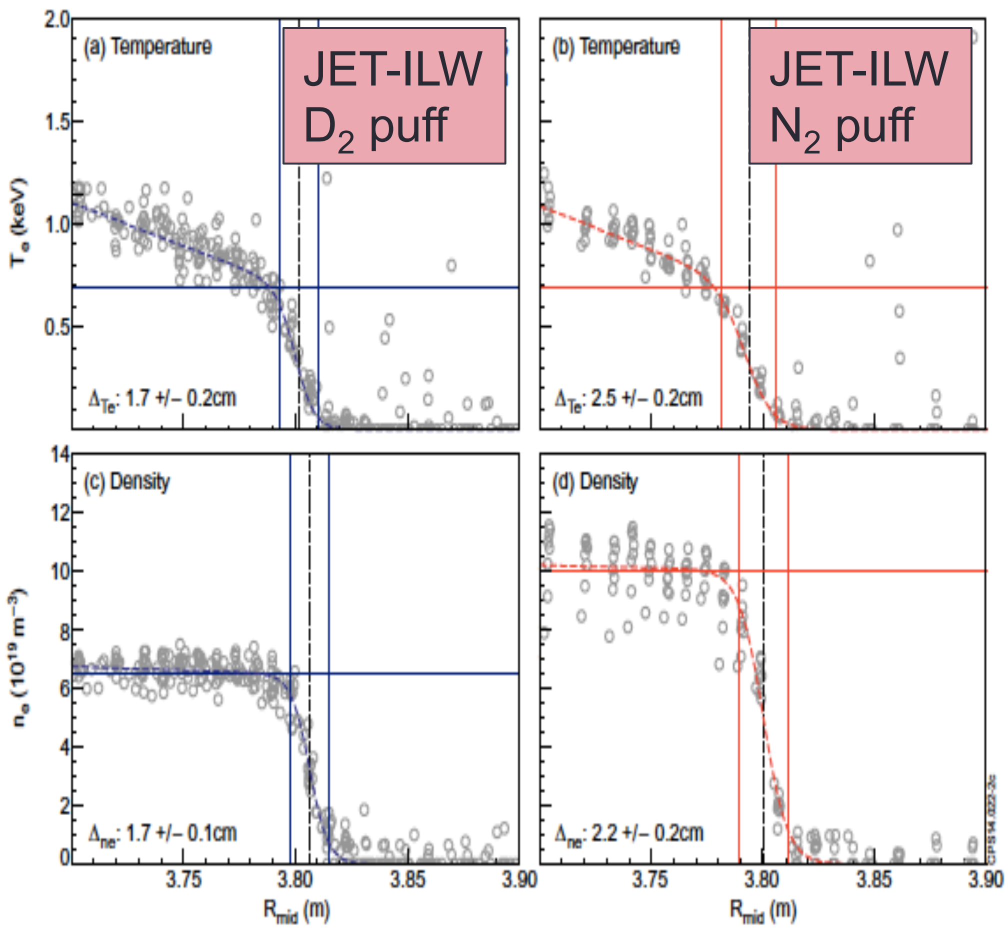
- ***STs have higher velocity shear relative to growth rates, compared to A ~ 3 (at least for investigations of core parameters)[1]***
- ***But like standard A, burning STs have smaller ρ^* than today's ST experiments- will an insufficiency of velocity shear arise for fusion STs?***
- ***To consider 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)***

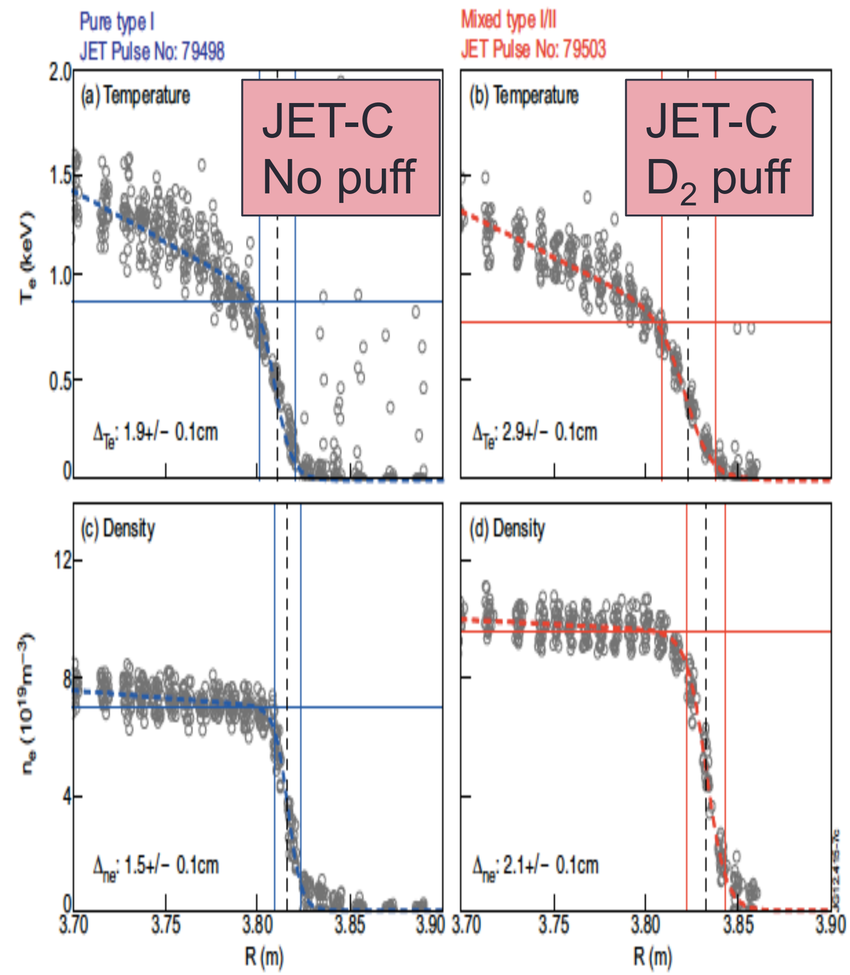
[1]Kotschenreuther et. al. Nucl. Fusion 2000 677
[2]*Diallo et. al. Nucl. Fusion 2013* 093026

IFS

THE PROFILES OF DENSITY AND TEMPERATURE ARE SHIFTED FOR BOTH JET-ILW AND JET-C

- ***This increases the instability drive η at mid-top of pedestal***

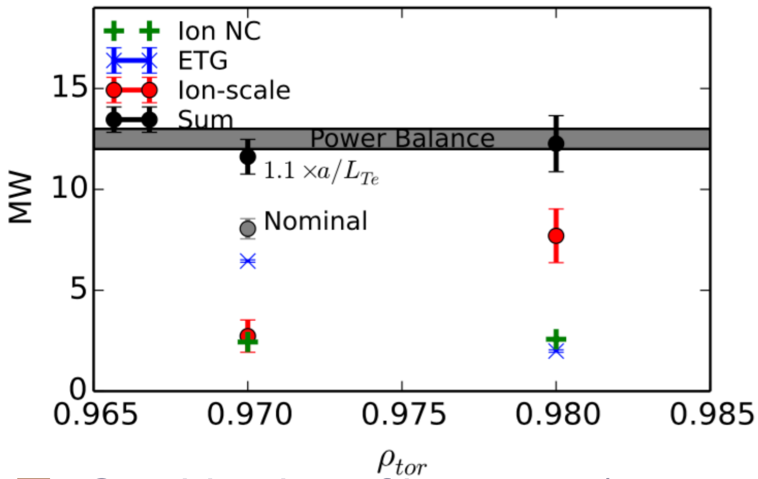




DETAILED MODELING OF REPRESENTATIVE JET-ILW DISCHARGE

D. R. Hatch, M. Kotschenreuther, S. Mahajan, et al., *Nucl. Fusion*, vol. 56, no. 10, p. 104003, 2016.

- JET shot 82585:
  - I=2.5 MA, B = 2.7 T, triangularity δ = 0.38 Zeff ≈ 1.2
  - Shift between temperature and density pedestals, resulting in high eta toward pedestal top
- GENE Simulations
  - Linear analysis (local and global):
    - Self-consistent beta scan identifies KBM to be in second stability regime and MTM as dominant instability

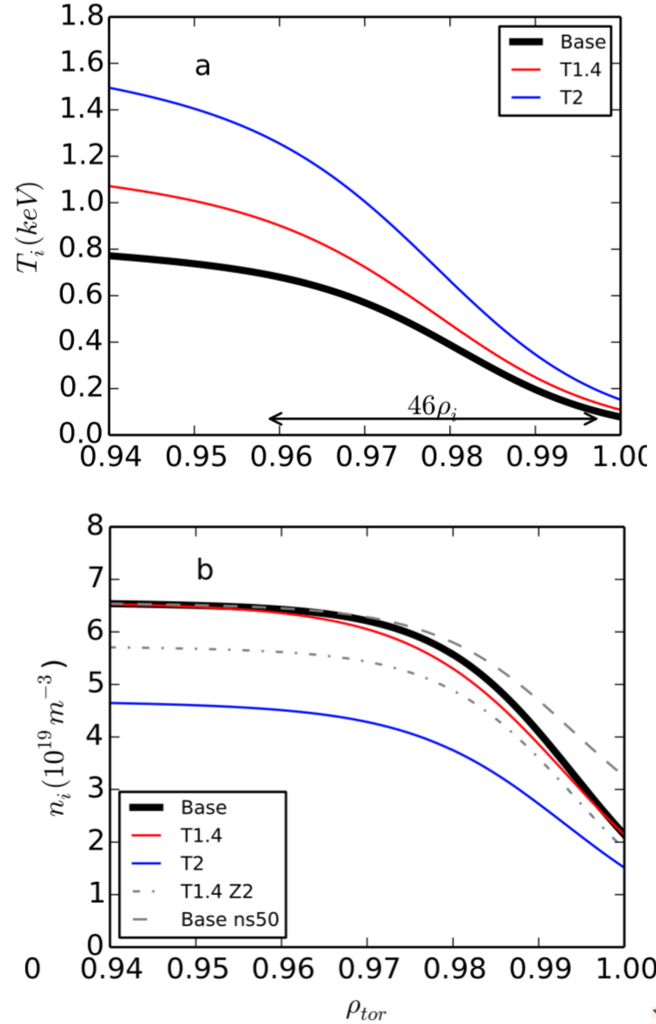


- Combination of ion-scale (mostly MTM), electron scale ETG and neoclassical quantitatively captures experimental power balance over most of the pedestal
- Note: recent AUG observations with similar properties to this MTM (and dissimilar from KBM) [Laggner PPCF '16]

IFS

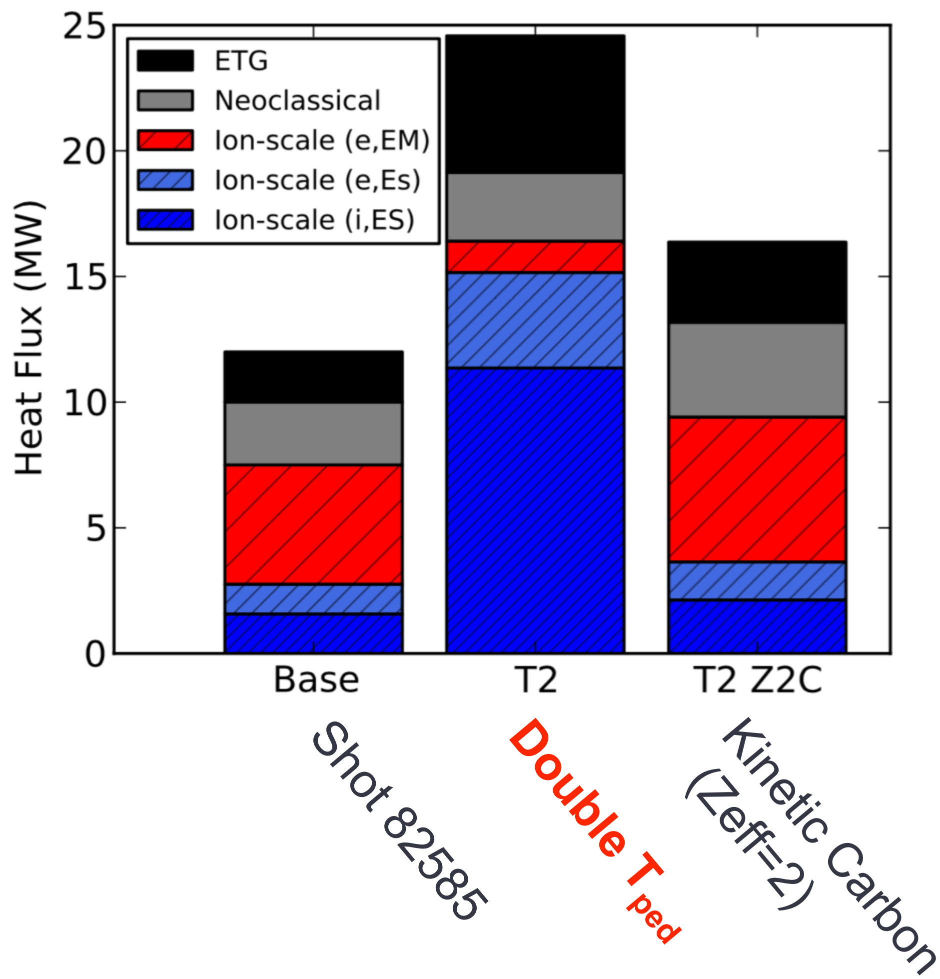
EXAMINE SEVERAL SCENARIOS TARGETING JET TRENDS

- Black: experimental base case (described above)
- Blue: high temperature case (double pedestal temperature)
  - Why is high T inaccessible?
- High temperature case with impurity
  - Why is high T accessible with C or impurity seeding?
- High separatrix density case
  - Gauge effects of gas puffing



INACCESSIBILITY OF HIGH T_{PED} IN JET-ILW: HIGH ν^* CASES

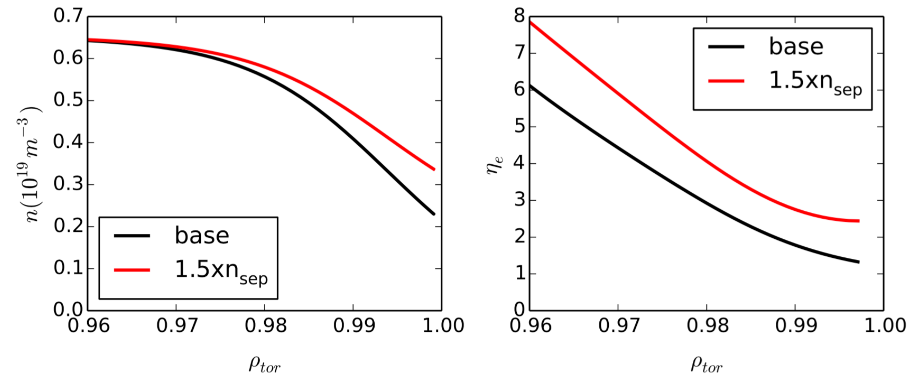
- High Temperature case (Zeff=1):
  - Well above heating power ➔ inaccessible
  - EM component decreased due to decrease in collisionality
  - Most striking change: **large increase in ES (ITG and ETG) transport**
  - Attributable to:
    - For ITG: Higher β ➔ broader pedestal ➔ Lower ExB shear (proportional to w^{-2})
    - For ITG and ETG: Higher temperature ➔ higher gyroBohm heat flux ➔ more MW for given level of turbulence

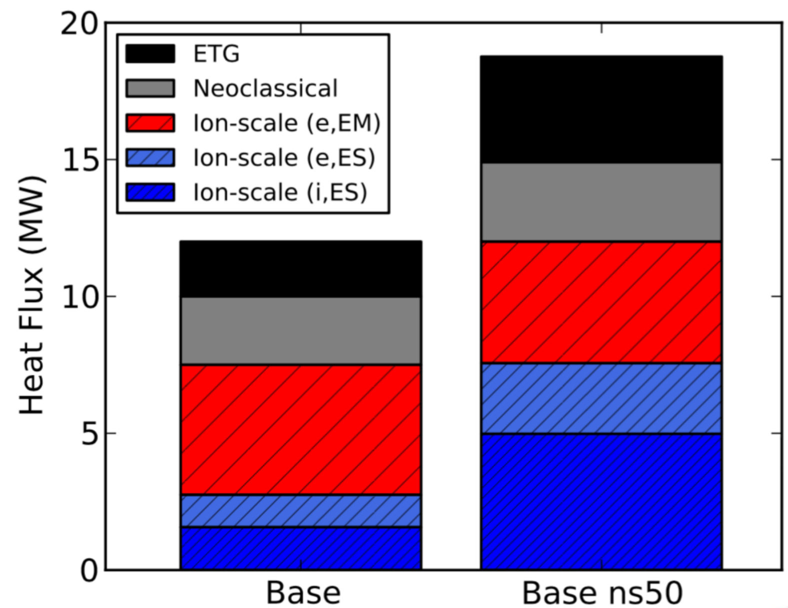


IFS

EFFECTS OF GAS PUFFING

- Sharp increase in electrostatic transport
- Increased eta affects both ITG and ETG
- ITG additionally affected by corresponding decrease in ExB shear
- **Note: decreased separatrix density has opposite effect → striking decrease in transport**
  - **Further emphasizes crucial role of divertor**





IFS

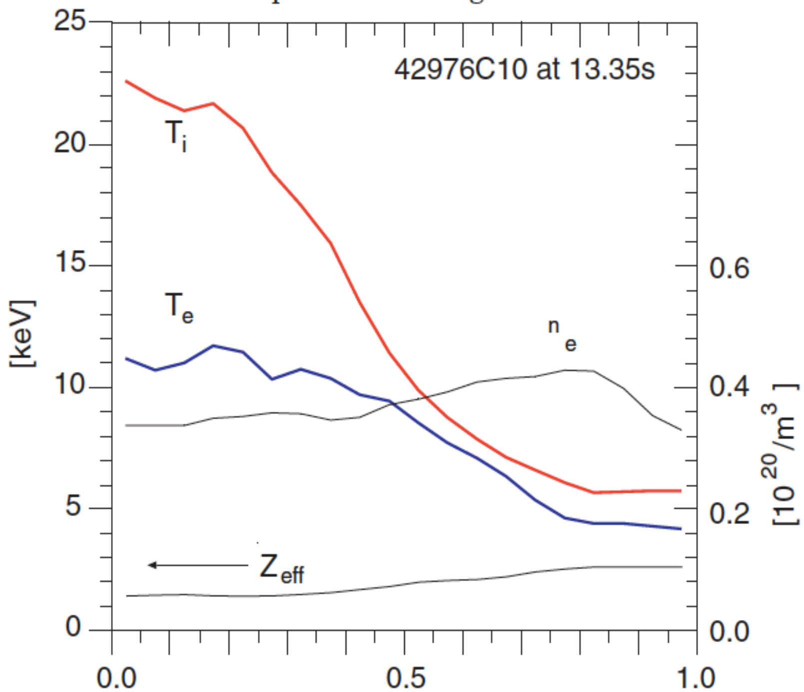
For initial estimates, we started with 1998 JET record fusion shot:

1) ***Estimate the pedestal profiles as well as possible***
   a) *Use empirical width ~ $\beta_p^{1/2}$*
   b) *Use plausible density profiles for those parameters*
   c) *Separatrix density consistent with Kallenbach multi-machine data*
2) ***Can gyrokinetics match power balance for reasonable profiles?***
   a) ***YES!** Reasonable density profiles give heat fluxes ~ 20 MW from ETG*
   β) *γ/γ_E in a range where ion transport expected to be small*

- ***How does ILW operation affect this?***
- ***With higher $n_{SEP,}$ and Ne or Ar impurities, transport power jumps up to unacceptable values!***
- ***We are simulating: WHAT CAN BE CHANGED to make a shot with a similar pedestal accessible ?***
- ***Also: is there a better set of parameters to start from?***

Previous JET-C shot with Q ~ 1:
pedestal not far from ITER !
T ~ 5 keV
ν^* <<1
Pedestal β_N close to ITER

JET profiles before giant ELM



IFS

Other possiblilites for collaboration:

- ***GENE simulations of specific shots***
- ***Comparisons of any measurements of fluctuation spectra vs shear rate***
- ***Results of experiments where E_r is modified (e.g. counter injection or RMP)?***

- ***Examinations of possible way to achieve Q = 1***
- ***Pellet injection of impurities***
- ***Advanced divertor geomery (with existing hardware- reprogram coil currents only)***
- ***Avoid shift of density with respect to temperature***
  - Use specially tailored RMP to resonate only in the outer pedestal, to increase desnity losses near separatrix
  - Combine this with pellet injection to maintain core density
  - If this is possible, we would like to analyze this further

IFS