DE LA RECHERCHE À L'INDUSTRIE

ROLE OF FAST IONS IN HYBRID SCENARIOS

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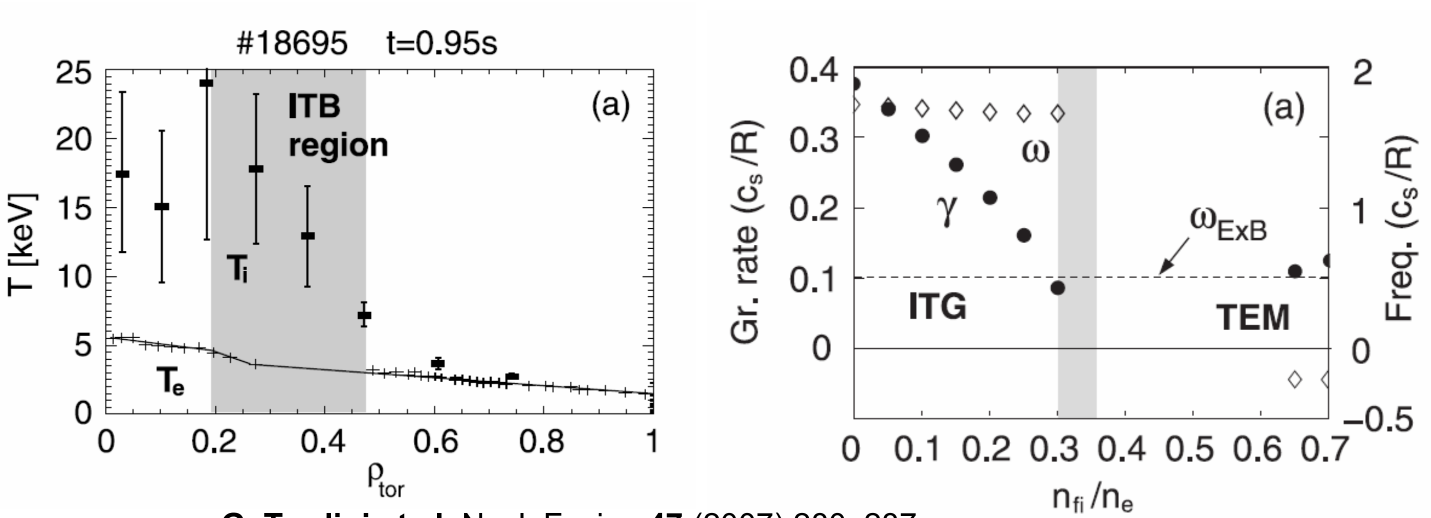
OUTLINE

- Motivation: why analyzing fast ions in Hybrid Scenarios (HS)
- Two hybrid discharges selected from JET (75225) and JT-60U (48158) with high fast ions population
- Impact of fast ions in the core (Turbulence) and at the edge (linear MHD analysis) for both discharges
- Importance for ITER
- Conclusions

Fast ion analysis in hybrids: Motivation

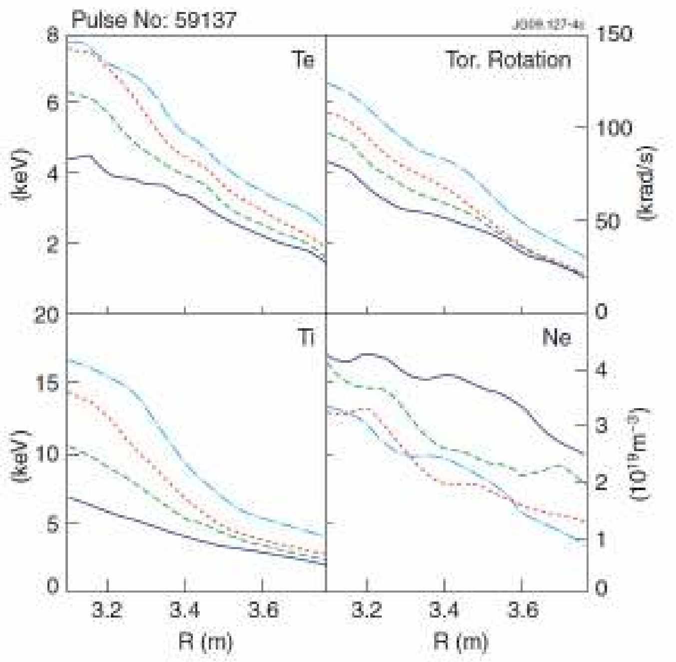
ASDEX FAST IONS DILUTION

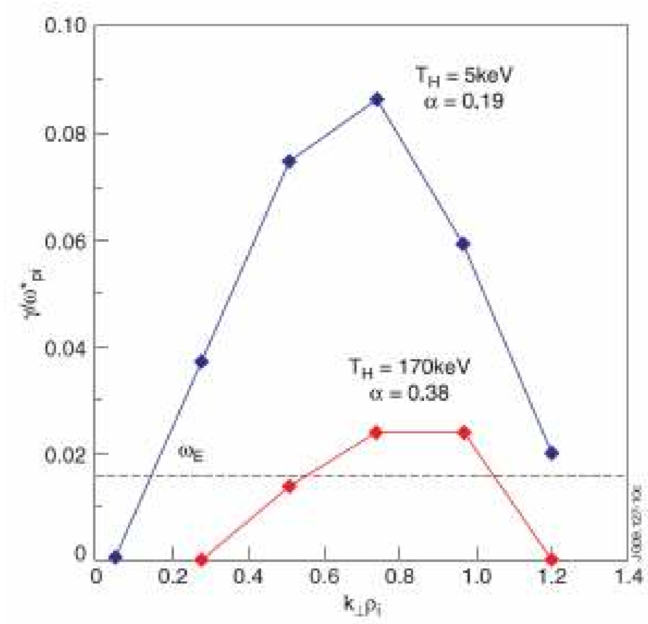


G. Tardini et al. Nucl. Fusion **47** (2007) 280–287

- Low density and high NBI power experiments performed in ASDEX
- ITB developes in the region with high fast ion density concentration
- Gyrokinetic analysis with GS2 show ITG growth rate decays with fast ion concentration
- At n_{fast}/n_e~0.3 ITG modes are completely stabilized

JET FAST IONS MODIFY ALPHA

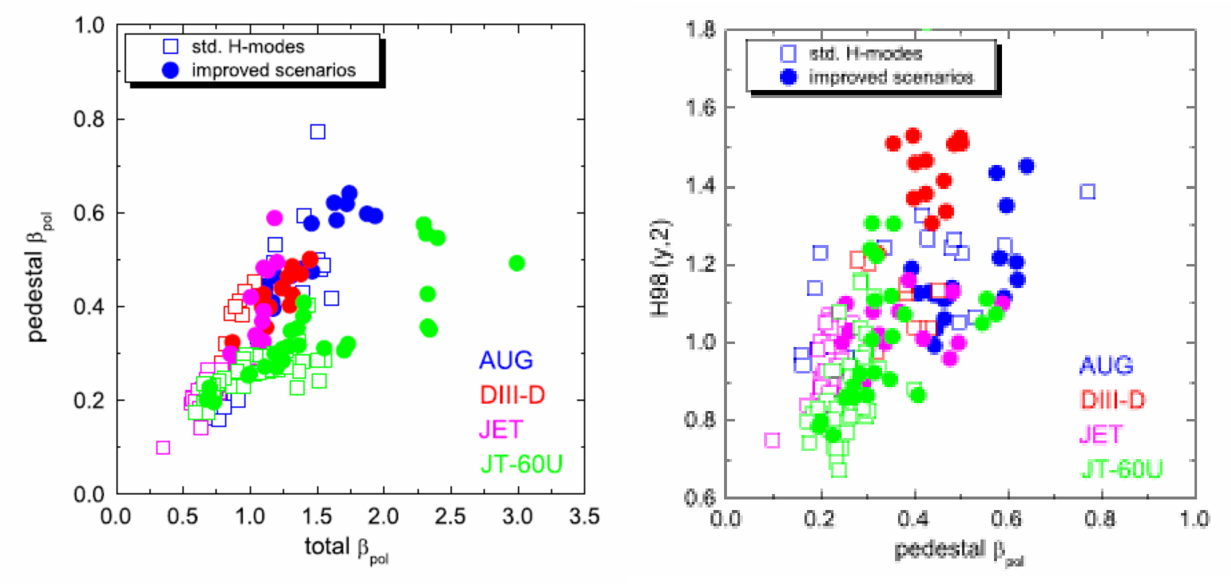




M. Romanelli et al., Plasma Phys. Control. Fusion **52** (2010) 045007

- Hybrid scenario with high ICRH power in JET
- An ITB develops in the ion channel
- n_{fast}/n_e is low but very high fast ion energy changes local alpha
- Gyrokinetic analysis with GS2 show ITG growth rate decays because very high local alpha
- No clear ITB obtained in many HS, is this mechanism still valid for them?

BETA DEPENDENCE ON PEDESTAL

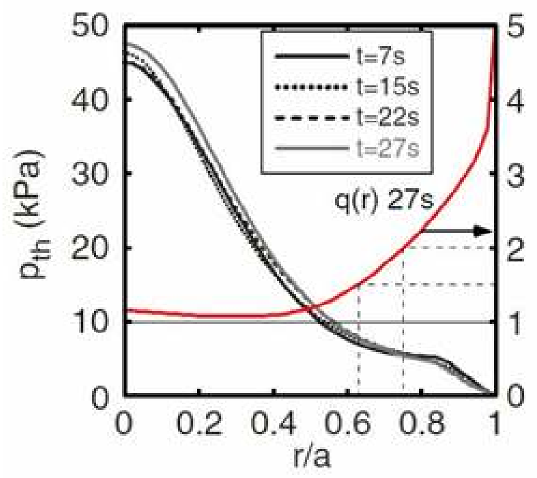


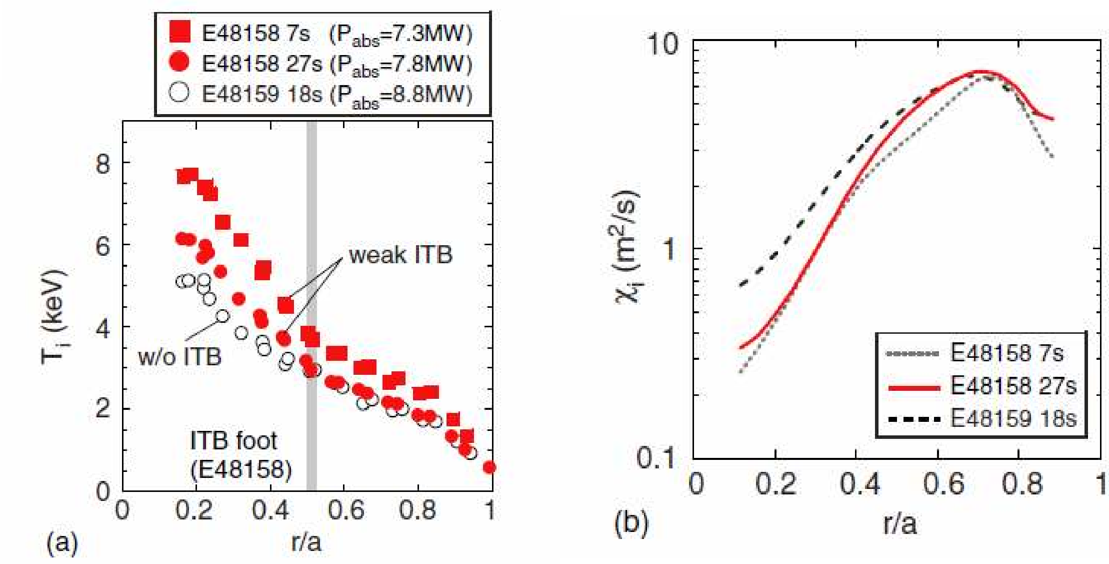
C.F. Maggi et al., 2007 *Nucl. Fusion* **47** 535

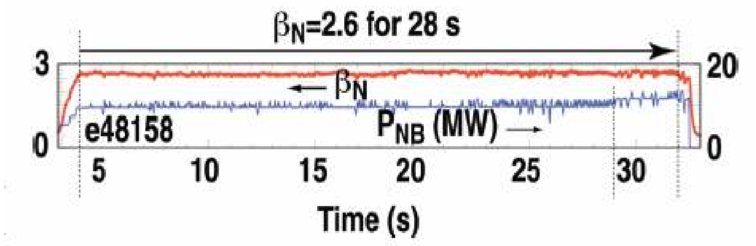
- A roughly linear correlation between pedestal β_{pol} and total β_{pol} is found for the four devices
- It is not possible to distinguish if an improvement in the edge stability leads to a higher total beta or if an increase in the Shafranov shift is a cause for improved edge stability.
- It is also possible that both mechanisms are at play simultaneously, reacting with each other in a continuous loop.
- A big concentration of fast ions in HS can play a role here?

Fast ions on HS in JT-60U and JET

JT-60U DISCHARGE 48158



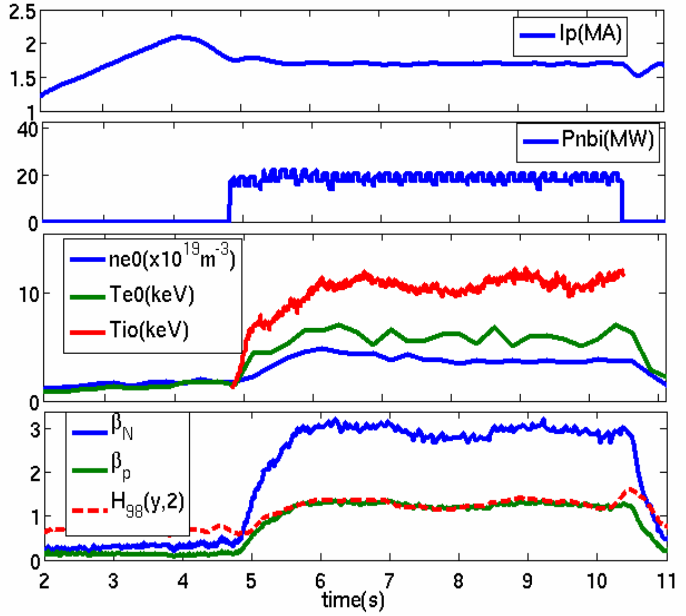


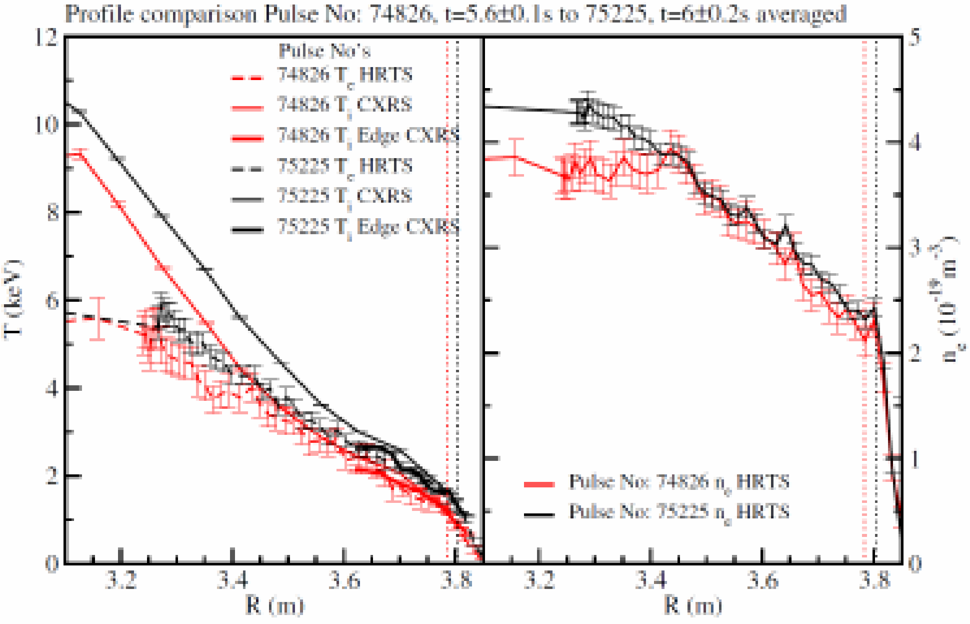


N. Oyama et al., Nucl. Fusion **49** (2009) 065026

- JT60U Hybrid discharge 48158 has very peaked core pressure profile (both thermal and total) and very low rotation and rotation shear
- Flat q profile in the core and high β_N=2.6 with H_{98}(y,2)=1.1 sustained for several current diffusion times
- A weak ITB develops in the ion channel in the region 0 ≤ρ≤0.4
- Discharge representative of the High-β_P discharges in JT-60U

JET DISCHARGE 75225





J. Horbik et al, Plasma Phys. Control. Fusion **54** (2012) 095001

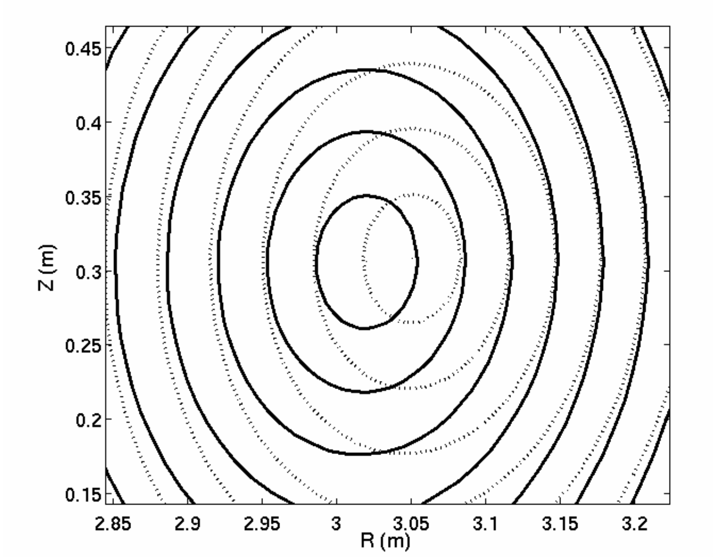
- JET Hybrid discharge 75225 (at low triangularity) has very peaked ion temperature profile in the core obtained with current overshoot
- Flat q profile in the core and high β_N=3.0 with H98(y,2)=1.3 sustained for one current diffusion time
- Unlike JT-60U shot 48158, it has high level of rotation
- Improved confinement obtained both from the core and the edge

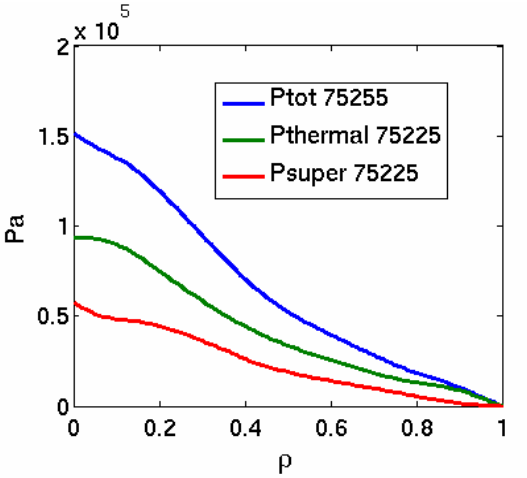
JT-60U and JET: Fast ions

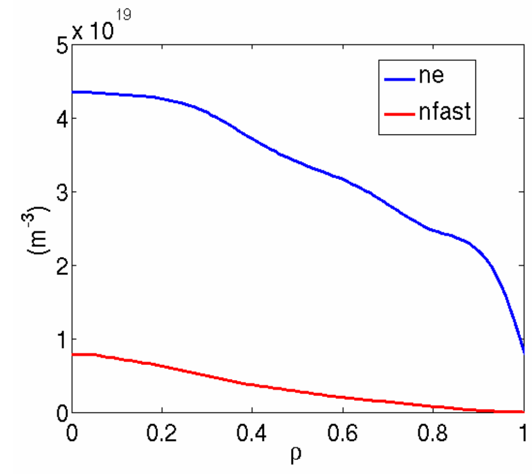
Discharge	JT-60U #48158	JET #75225
Ip (MA)	0.9	1.7
Bt (T)	1.5	2.0
q_{95}	3.2	4.15
κ/δ	1.40/0.33	1.64/0.23
β_N/β_p	2.6/1.50	3.0/1.30
f_{Gw}	0.5	0.45
$H_{98}(y,2)$	1.1	1.30
P_{nbi}(MW)	7.5	17
Wfast/Wdia	45%	35%

- Both discharges have low Greenwald density, high β_N/β_p and high NBI power
- Fast ions contribution to the total energy is very important for hybrid discharge 48158 in JT-60U (45%) and in JET 75225 (35%).
- This high contribution of fast ions can have an impact through the mechanism previously shown

JT-60U and JET: Fast ions

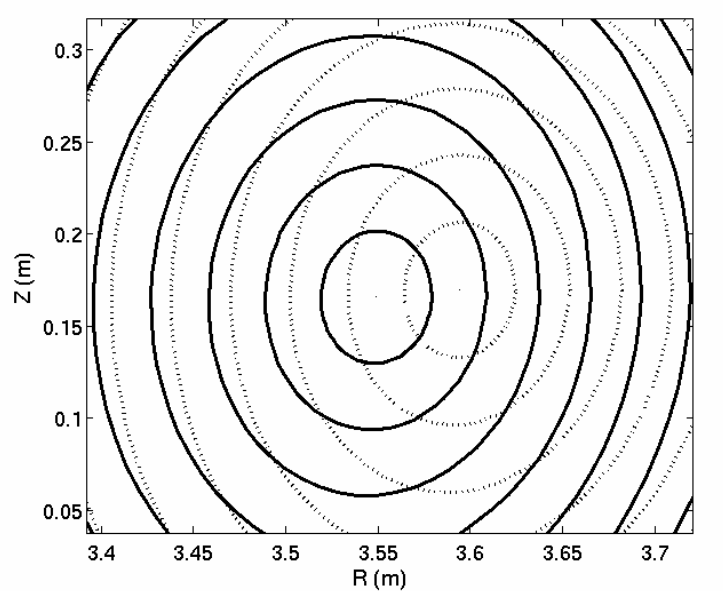


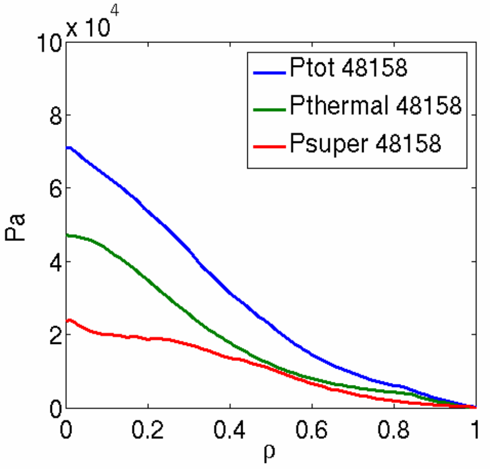


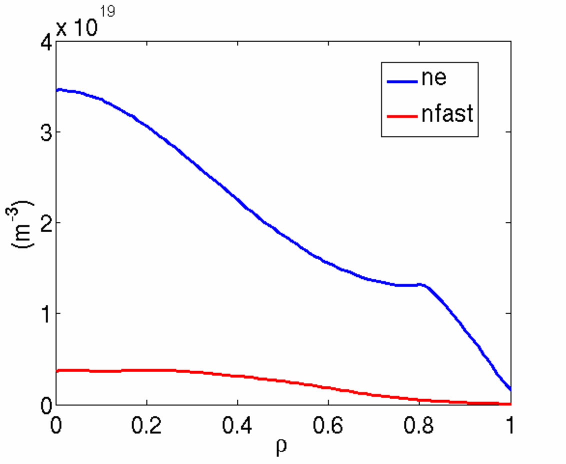


- Fast ion pressure and density calculated with interpretative analysis done with code SPOT
- Equilibrium with and without fast ions is also calculated with HELENA
- Fast ions highly change plasma properties:
  - $\beta_{N,total}$=2.9, $\beta_{N,thermal}$=2.15. Thermal beta is close to typical H-mode values
  - n_{fast}/n_e~0.13 at ρ=0.33
  - q95(fast ions)=4.15, q95(no fast ions)=4.05
  - Local pressure highly changed
  - Equilibrium is highly modified by fast ions with a high impact on Shafranov-shift

JT-60U and JET: Fast ions







- Fast ion pressure and density calculated with interpretative analysis done with CRONOS
- Equilibrium with and without fast ions is also calculated with HELENA
- Fast ions highly change plasma properties:
  - $\beta_{N,total}$=2.6, $\beta_{N,thermal}$=1.8. Thermal beta is similar to typical H-mode values
  - n_{fast}/n_e~0.10 at ρ=0.4
  - q95(fast ions)=3.2, q95(no fast ions)=3.05
  - Local pressure highly changed
  - Equilibrium is highly modified by fast ions with a high impact on Shafranov-shift

Analysis of core turbulence and edge linear MHD analysis

Codes used

- GENE (**Gyrokinetic Electromagnetic Numerical Experiment**) code used for analyzing electromagnetic turbulence (necessary because of high beta)
- Linear stability analysis performed for JET 75225 and JT-60U 48158 discharges
- Plasma geometry and thermal values obtained from interpretative analysis performed with CRONOS
- The fast ions are introduced by adding a new specie with the density and energy obtained in the interpretative analysis
- Equilibrium is recalculated when removing fast ions
- Edge peeling ballooning MHD ideal analysis performed with MISHKA code.
- EQDSK files obtained from CRONOS and used by the MISHKA code.

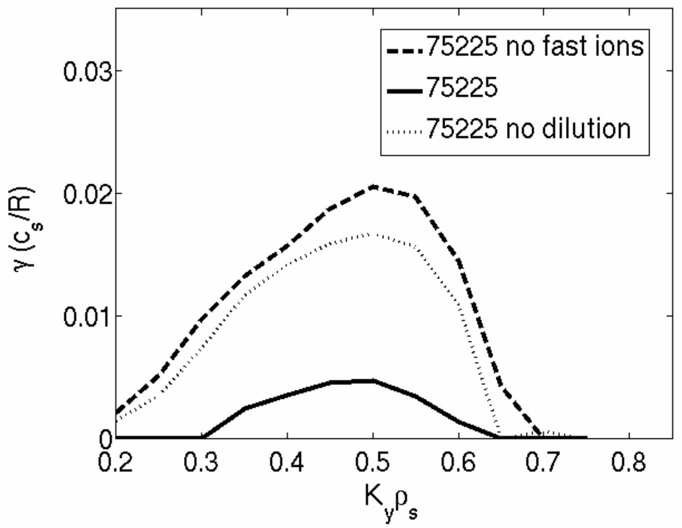
Analysis of JET shot 75225

Ti=5.5keV, Te=4.7keV, ne=3.9x10^{19} m^{-3}

RTe'/Te=3.51, RTi'/Ti=4.49, RNe'/Ne=2.34

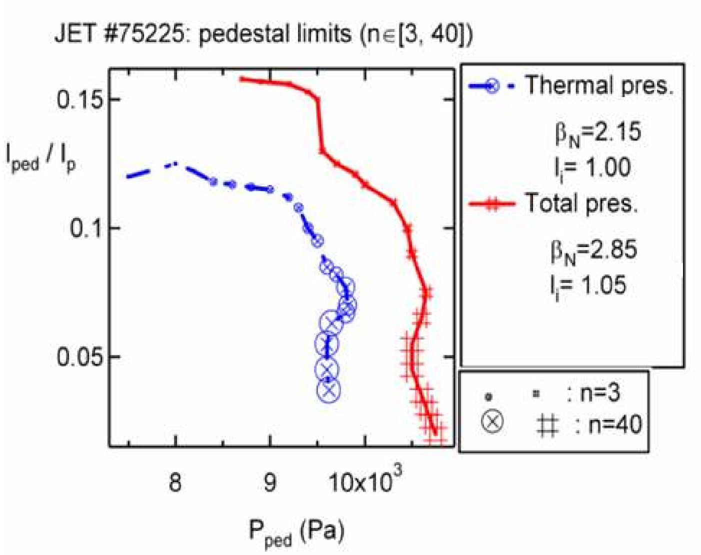
q=1.14, s=0.16, α=0.5

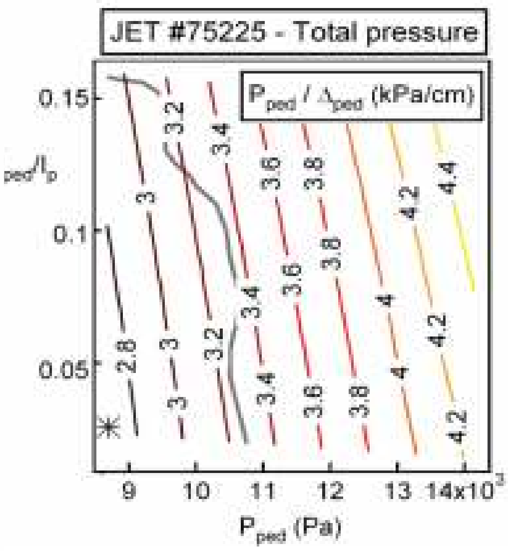
Zeff=1.63

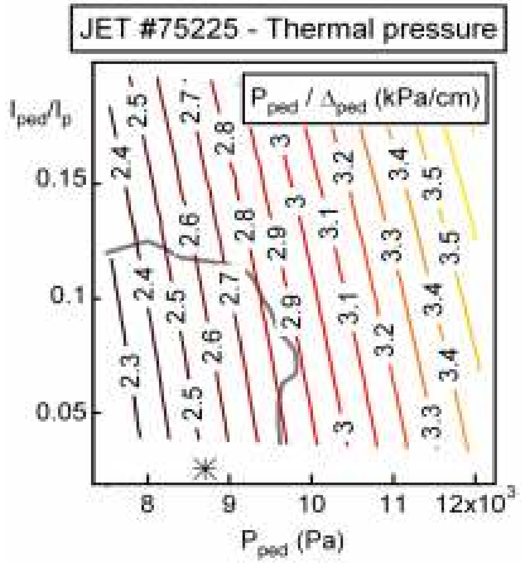


- Linear growth rate analysis for shot 75225 at t=6.0s performed at ρ=0.33 with GENE.
- Geometry and fast ion density previously calculated with CRONOS
- Growth rate of the shot 75225 is very low and turbulence type is ITG. The plasma is close to stability
- When removing fast ions, growth rates highly increase. Maximal growth rate is reduced by 65% including fast ions.
- Same analysis done removing fast ion density and just taking into account Shafranov shift
- Fast ion dilution is the main mechanism for the reduction of turbulence in this discharge

Analysis of JET shot 75225

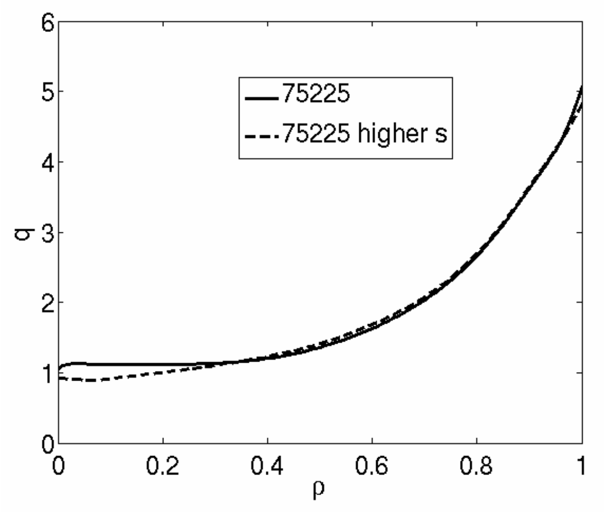


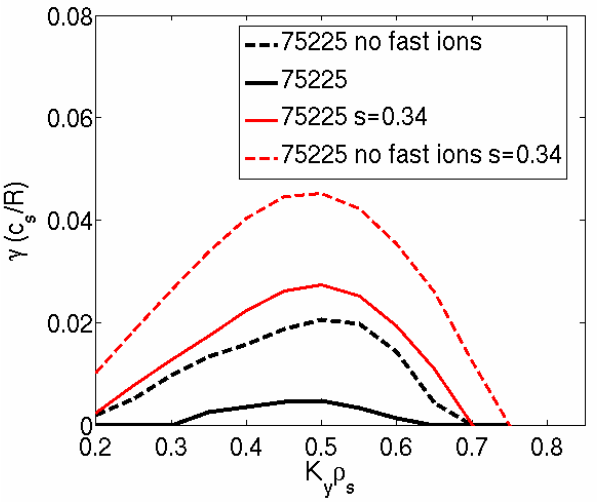




- The peeling ballooning diagram is modified by the fast ions. This allows for higher pedestal pressure due to the higher Shafranov shift obtained at very high total beta.
- The contours of constant pressure gradient calculated in the peeling ballooning diagram
- The pedestal pressure gradient is also modified by the Shafranov shift: Maximum 3.4kPa/cm with fast ions and 2.9kPa/cm for thermal pressure
- For a pedestal width of 3.4cm the pedestal pressure increases from 9.57 kPa to 11.56 kPa (17%)
- The higher pedestal can lead to higher core temperatures through stiffness
- Fast ions and thermal channel interact through the pedestal
- Improvement confinement obtained from the edge and the core due to the strong modification of plasma geometry

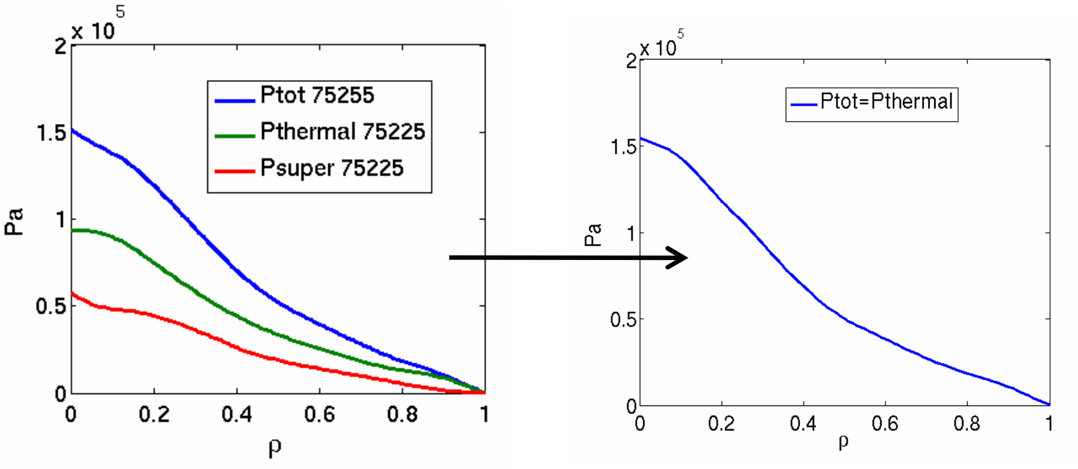
Analysis of JET shot 75225

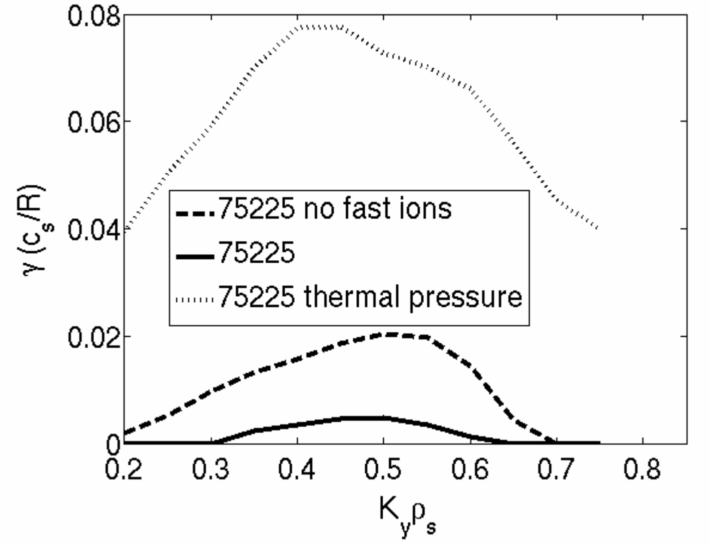




- Sensitivity analysis performed with alternative q profile with higher magnetic shear at ρ=0.33
- The relatively effect of magnetic shear and fast ions is similar with respect the original calculation
- When both effect are combined, growth rates highly increase
- The impact of fast ions is different at different magnetic shear:
  - (γ_{max}(no fast, s=0.34)-γ_{max}(fast, s=0.34))/ γ_{max}(no fast, s=0.34)=0.37
  - (γ_{max}(no fast)-γ_{max}(fast))/ γ_{max}(no fast)=0.67

Analysis of JET shot 75225





- Sensitivity analysis performed to the thermal pressure
- Fast ions pressure is removed and temperature gradients increased to match Pthermal=Ptot
- Shafranov-shift is the same than the original case but now $\beta_{N,total}=\beta_{N,thermal}=2.9$
- Growth rates highly increased reaching $\gamma_{max}=0.08$ (four times higher than the original case with no fast ions and with $\beta_{N,total}=2.13$)
- The possible improved transport from the edge and core obtained by Shafranov-shift compensated by higher core turbulence
- No peaked ion temperature expected in HS mainly driven by thermal processes

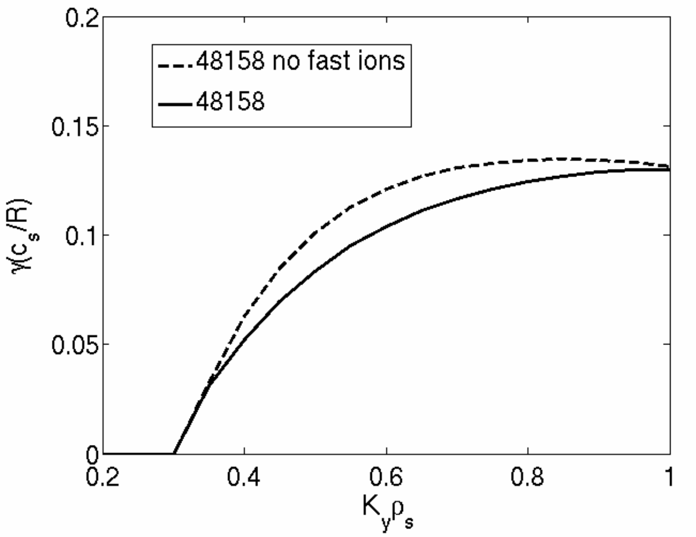
Analysis of JT-60U shot 48158

T_i=3.6keV, T_e=3.2keV, n_e=2.25x10^{19} m^{-3}

RT_e'/T_e=6.93, RT_i'/T_i=7.82, RN_e'/N_e=5.46

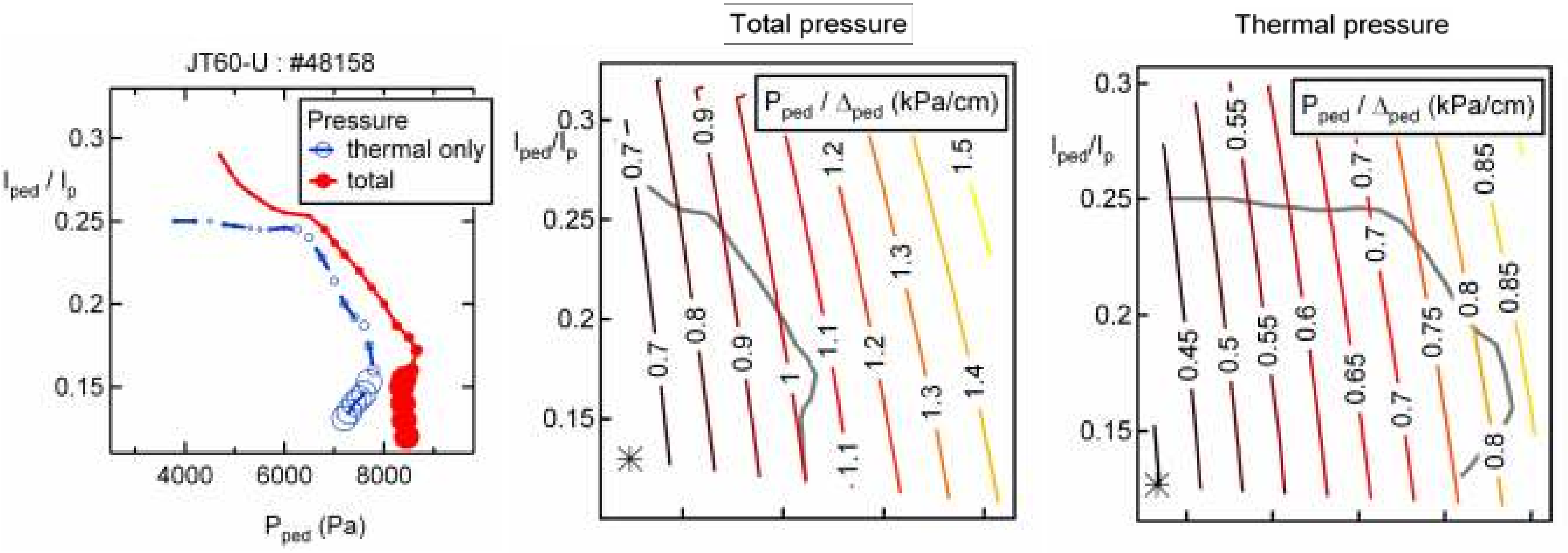
q=1.05, s=0.24, α=0.45

Zeff=3.0



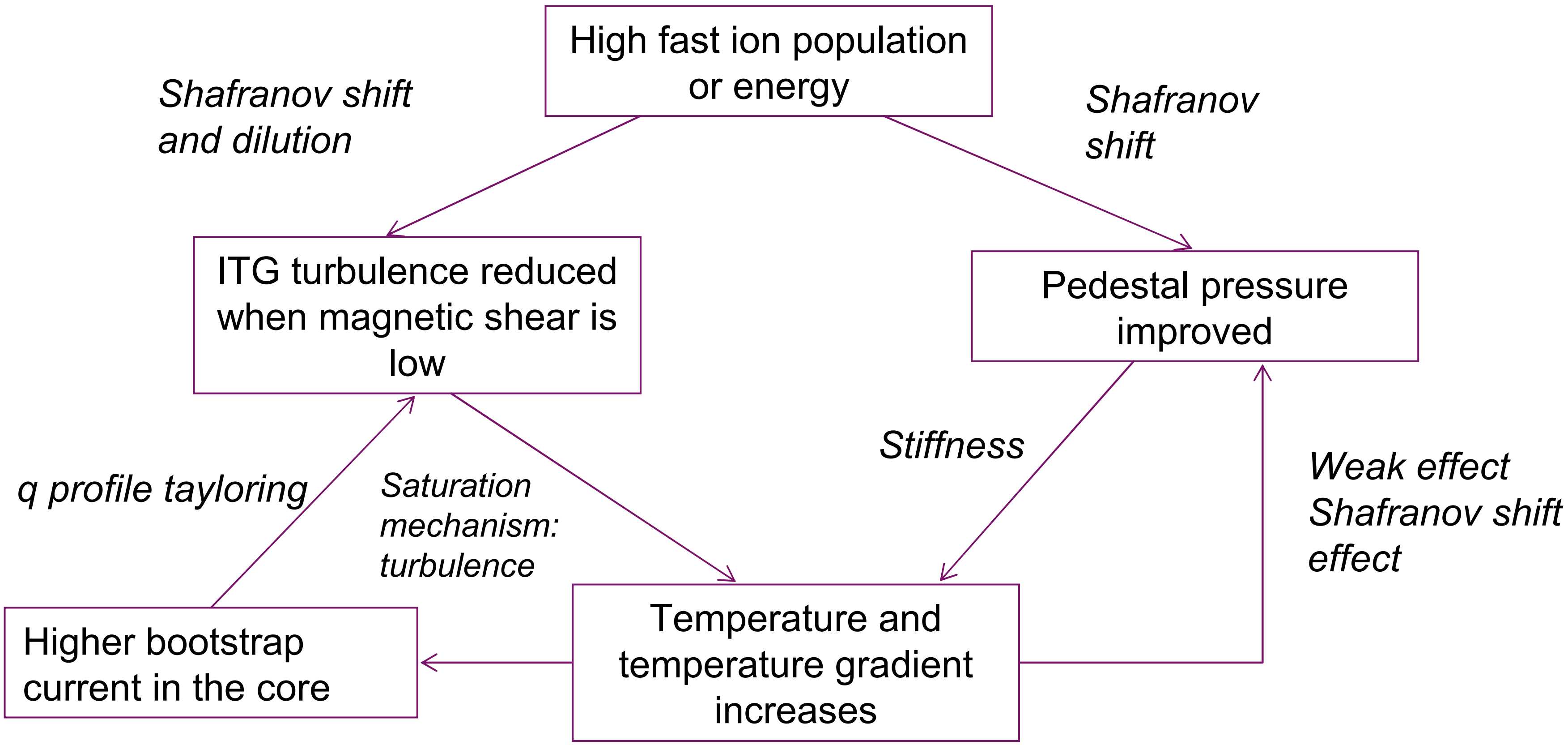
- Linear growth rate analysis for the JT-60U discharge 48158 at t=27s performed at ρ=0.4 with GENE.
- Geometry and fast ion density previously calculated with CRONOS
- Turbulence type very different to the JET case due to the higher density peaking: ITG and TEM modes coexist
- Growth rates decrease by including the fast ions
- The improved transport obtained for this discharge at ρ=0.4 can be explained by the fast ions in absence of external torque and low rotation
- Similar conditions than in ITER?

Analysis of JT-60U shot 48158



- The peeling ballooning diagram is modified by the fast ions in the same way than for the JET shot 75225
- Maximum pressure gradient 1.1kPa/cm with fast ions and 0.85kPa/cm for thermal pressure
- For a pedestal width of 4 cm the pedestal pressure increases from 3.4 kPa to 4.4 kPa
- Again, improvement confinement obtained from the edge and the core due to the strong modification of plasma geometry due to fast ions

INTERACTION BETWEEN FAST AND THERMAL CHANNEL



High fast ion population or energy

Shafranov shift and dilution

Shafranov shift

ITG turbulence reduced when magnetic shear is low

Pedestal pressure improved

q profile tayloring

Saturation mechanism: turbulence

Stiffness

Weak effect Shafranov shift effect

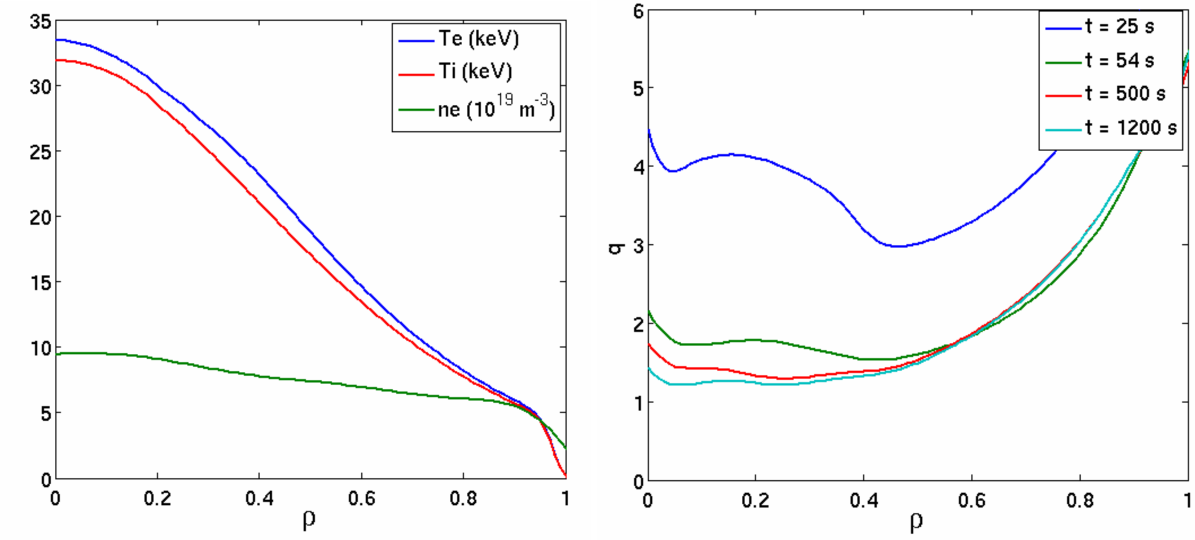
Higher bootstrap current in the core

Temperature and temperature gradient increases

Is this relevant to ITER?

ANALYSIS OF ITER HYBRID SCENARIO

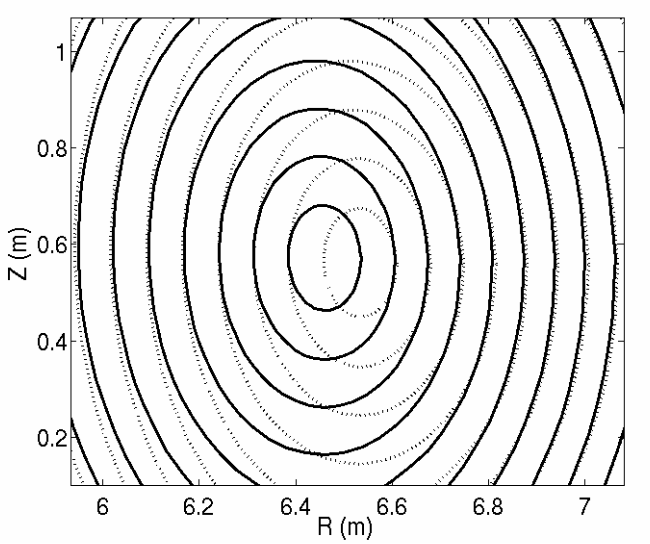
	ITER hybrid
I_p (MA)	12
B_t (T)	5.3
q_{95}	4.3
κ/δ	1.8/0.4
β_N/β_p	2.65/1.15
f_{Gw}	0.8
P_{ped} (kPa)	80
H_{98}(y,2)	1.30
P_{NBIi}(MW)	33
P_{ECRH}(MW)	20
P_{ICRH}(MW)	20
P_{LH}(MW)	0
Wfast/Wdia	25%

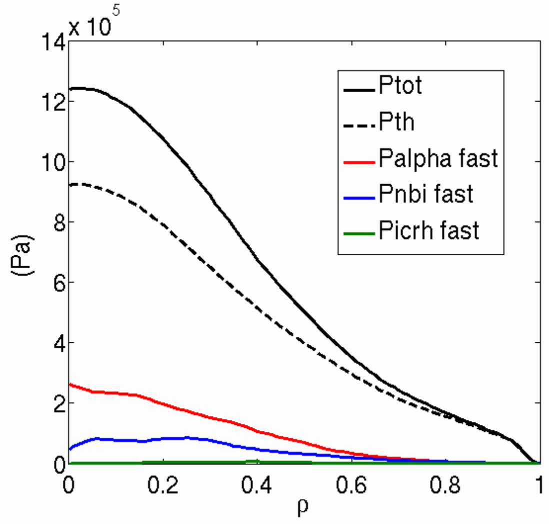


K. Besseghir, J. Garcia et al., « Achieving and sustaining advanced scenarios in ITER modelled by CRONOS and DINA-CH” submitted to Plasma Phys. Control. Fusion

- Hybrid scenario obtained with free boundary simulations performed with DINA-CH and CRONOS
- A fixed H98(y,2)=1.3 factor with Bohm-GyroBohm shape difusivites used
- q profile shaped by means of bootstrap current and ECCD current drive. A broad region of low shear obtained
- $\beta_{N,total}$=2.65 (but not including fast ions generated by alphas), $\beta_{N,th}$=2.5

ANALYSIS OF ITER HYBRID SCENARIO





- Fast ion pressure and density calculated with CRONOS for all the sources of fast ions (alpha, beams and ICRH)
- Fast ion density is low: $n_{fast,\alpha}/n_e \sim 0.009$, $n_{fast,beams}/n_e \sim 0.006$ at $\rho=0.33$
- Fast ions pressure is high due to high fast ion temperature mainly from alphas: $T_{fast,\alpha}=1.1$MeV, and beams $T_{fast,beams}=0.5$ MeV
- Equilibrium with and without fast ions is also calculated with HELENA
- Fast ions change plasma properties:
  - $\beta_{N,total}=3.0$, $\beta_{N,thermal}=2.5$
  - Local pressure highly changed
  - Equilibrium is highly modified by fast ions with a high impact on Shafranov-shift

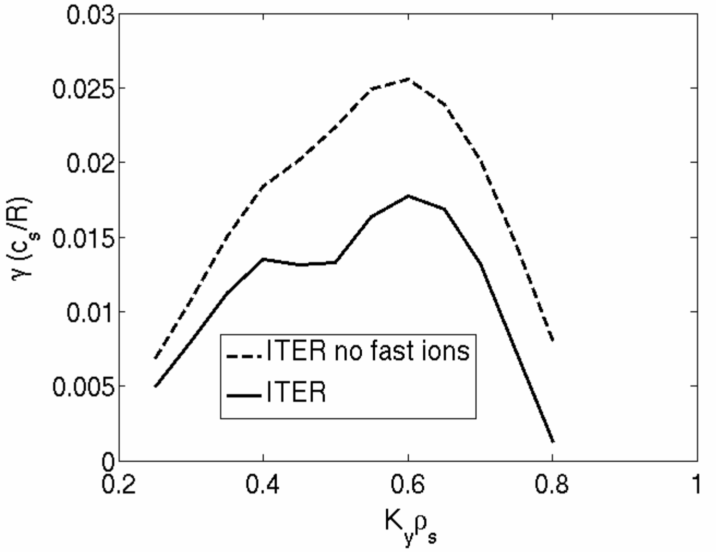
ANALYSIS OF ITER HYBRID SCENARIO

Ti=23.30keV, Te=25.43keV, ne=8.2x10^{19} *m*$^{-3}$

RTe'/Te=2.94, RTi'/Ti=3.45, RNe'/Ne=1.88

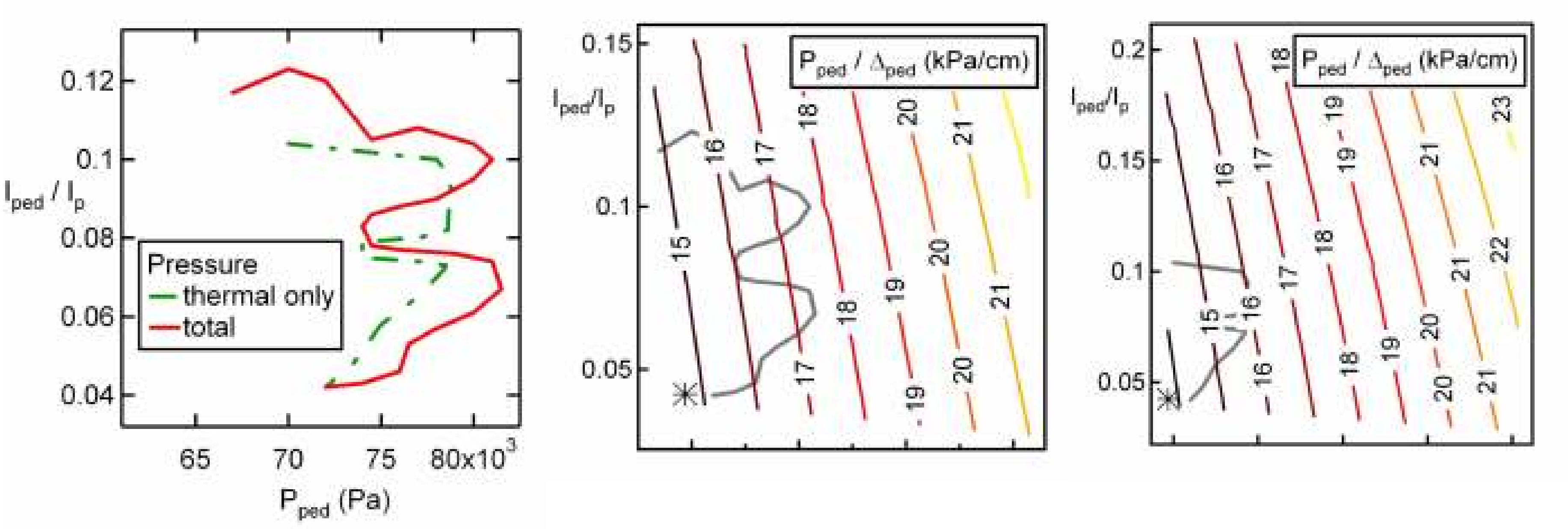
q=1.17, s=0.24, α=0.72

Zeff=1.7



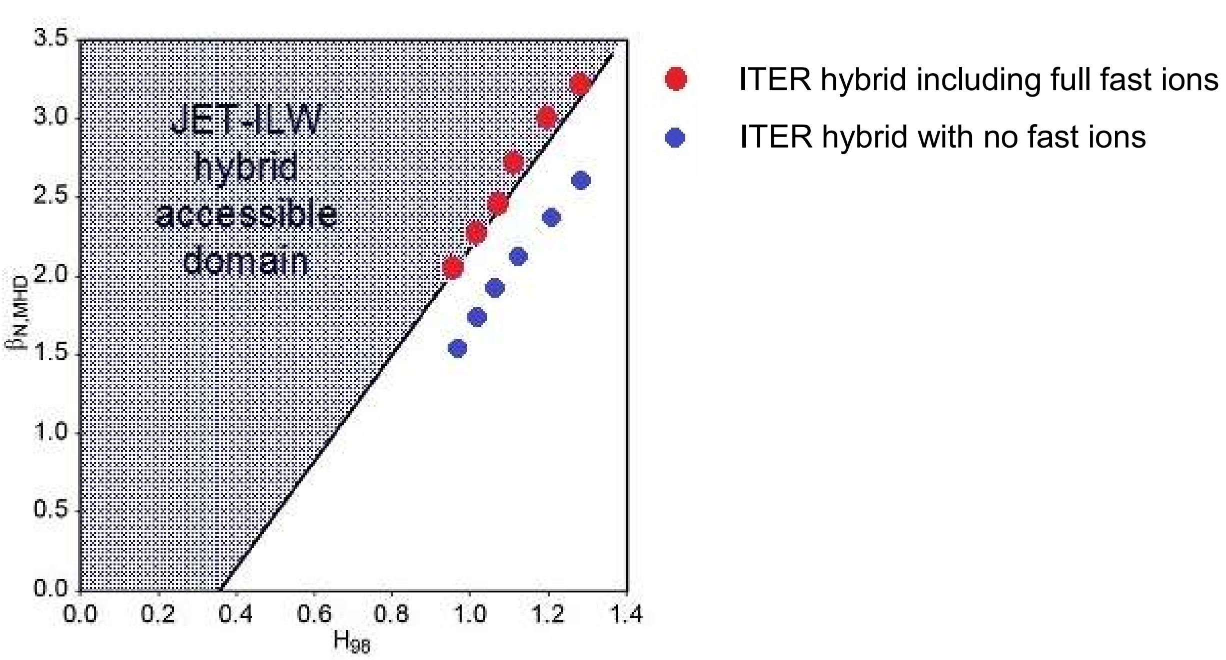
- Linear growth rate analysis for ITER hybrid performed at t=1000s and ρ=0.33 with GENE.
- Geometry and fast ion density previously calculated with CRONOS
- Growth rate is very low and turbulence type is ITG. Growth rates similar to the ones obtained for JET
- When removing fast ions, growth rates increase. Maximal growth rate is reduced by 30% including fast ions.
- Low shear region obtained with ECCD is a key ingredient
- Main reason for this reduction is the alpha fast ions energy and high pressure

ANALYSIS OF ITER HYBRID SCENARIO



- The peeling ballooning diagram is modified by the fast ions. The stable region is extended as happens for JET and JT-60U
- The pedestal pressure gradient is also modified by the Shafranov shift: Maximum 17.5kPa/cm with fast ions and 16kPa/cm for thermal pressure
- For a typical pedestal width of 5cm the maximum pedestal pressure increases from 80 kPa (originally considered in the simulation) to 87.5 kPa (~10%)
- The effect obtained are similar to the ones obtained in JET
- Unlike toroidal rotation, with limited effects on ITER, fast ion contribution to stability can be important for ITER

ANALYSIS OF ITER HYBRID SCENARIO



- High β_N hybrids in JET-ILW obtained at high $H_{98}(y,2)$
- A scan of $\beta_{N,total}$ on $H_{98}(y,2)$ has been performed with the ITER hybrid scenario at fixed pedestal pressure
- When considering all the sources of fast ions, ITER hybrid just relies on the JET-ILW domain
- This shows how important is the proper determination of fast ions in ITER hybrid scenarios

CONCLUSIONS

CONCLUSIONS

- The impact of the fast ions on confinement has been analyzed in HS
- Turbulence linear growth rates and linear MHD analysis performed in the core and the edge
- The high fast ion population in some HS is able to highly reduce ITG modes in the core…
- … and allows higher pedestal pressure and higher pedestal gradient at the edge through Shafranov shift
- Thermal beta is improved through β_{fast} probably allowing higher thermal energy confinement
- Improved transport through thermal beta is less efficient due to stiffness (when turbulence is not fully suppressed as in HS) when the same input power is applied
- Fast ion pressure is high for ITER HS mainly due to alpha particles
- Significant reduction of turbulence, ITG, in the core and improvement pressure at the edge expected
- This mechanism allows for transport thermal improvement in ITER in the absence of significant external torque