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The « hybrid » scenario in JET: towards its validation for ITER

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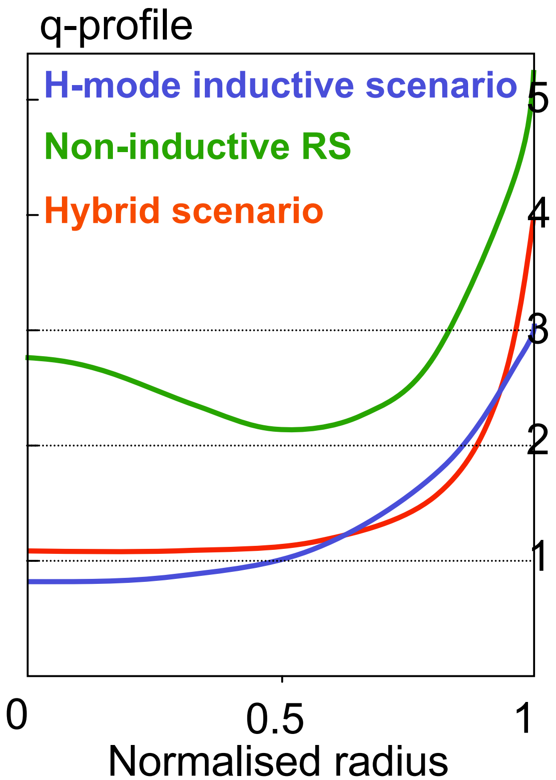
Outline:

- Introduction to the hybrid scenario in JET
- Physics analysis (MHD, current, transport)
- Projections to ITER burning plasma for the hybrid scenario

ITER scenario for steady state burning conditions

Maximise: υ $G = \beta_N \,.\, H / q_{95}^2$ υ $I_{boot} / I_p \sim \beta_N \,.\, q_{95}$ υ $n \sim 0.85\, n_{Greenwald}$



Ip	q_{95}	$\beta_N \,.\, H_{98\,y2}$	Burn time	Q
15MA	3	1.8 x 1.0	400s	10
9MA	5.3	2.95x1.6	>3000s	6
12MA	~4	~3 x 1.0	~2000s	~10

NTM with sawteeth
High Ip disruptions

Current control
High β MHD

AUG: A. Staebler EX/4-4
DIII-D: M. Wade EX/4-1

JET has started the study of the « hybrid » regime in the 2003 campaign

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JET hybrid regime (1.7T, 1.4MA)

Identity experiment with ASDEX Upgrade:

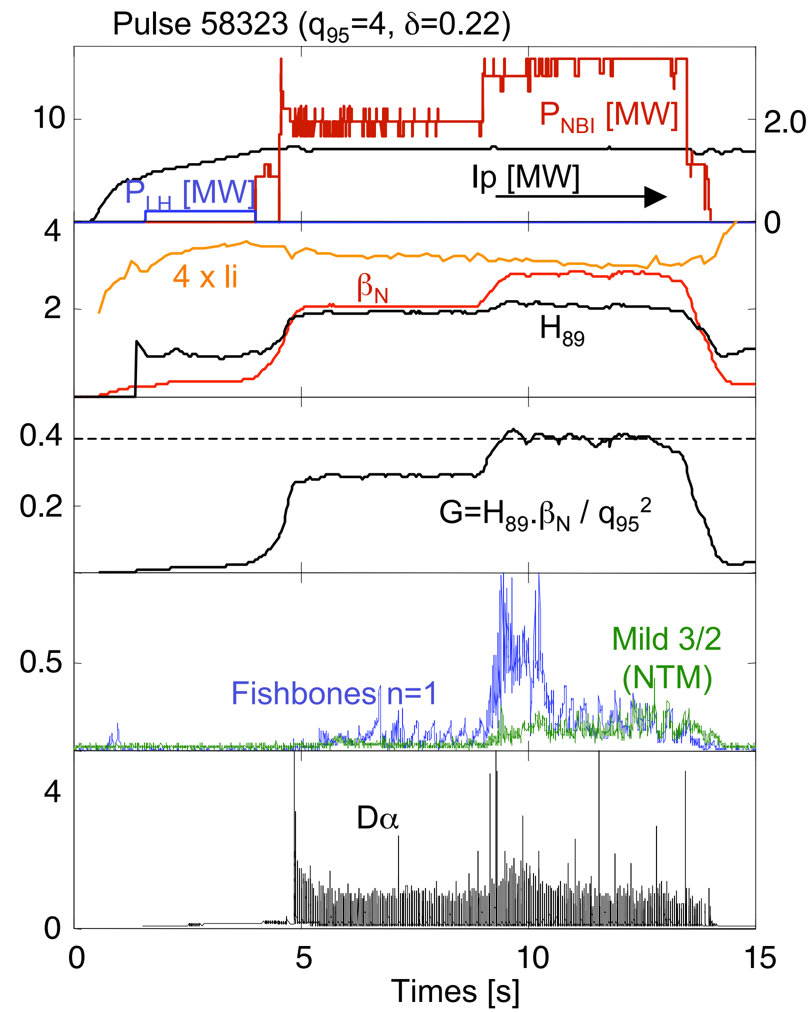
1. Matched magnetic configurations.

2. Similar ρ^* & q (q_o ~1 and q_{95}=4).
   $B_o\, \tau_{IPB98(y,2)} \,\alpha\, \rho^{*-2.70}\, \beta^{-0.90}\, \upsilon^{*-0.01}\, q^{-3.0}\, \varepsilon^{0.73}\, \kappa^{3.3}$

3. β_N controlled in real time with P_{IN}

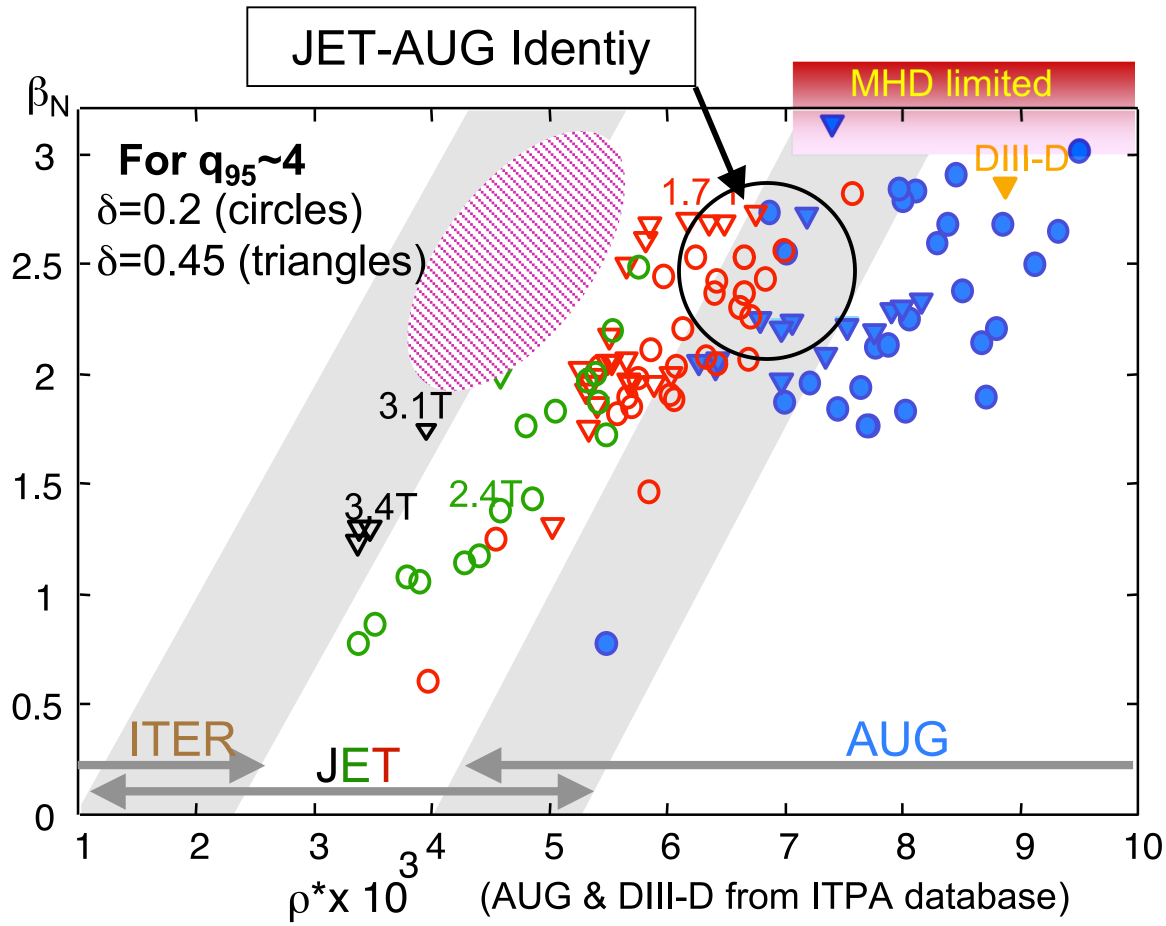
4. ν^*(JET)=0.08 $\neq$ ν^*(AUG) = 0.15

Hybrid scenario reproduced in JET with similar phenomenology than in AUG.



Hybrid regimes in JET

Development of the hybrid regime towards the ITER domain



The hybrid regime has been achieved in JET:

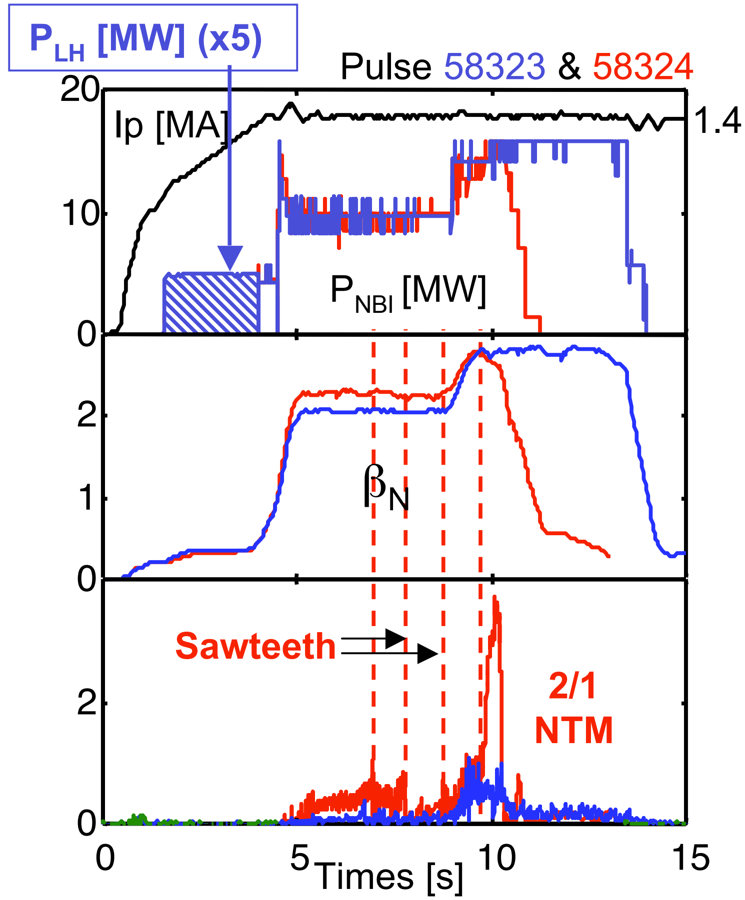
- with AUG configuration δ=0.45
- with ITER configuration δ=0.45
- at 2.4T (lower ρ*) and δ=0.22
- at 2.4T (lower ρ*) and δ=0.45

With more available power, future experiments are planning to explore the low ρ* region reachable by ITER

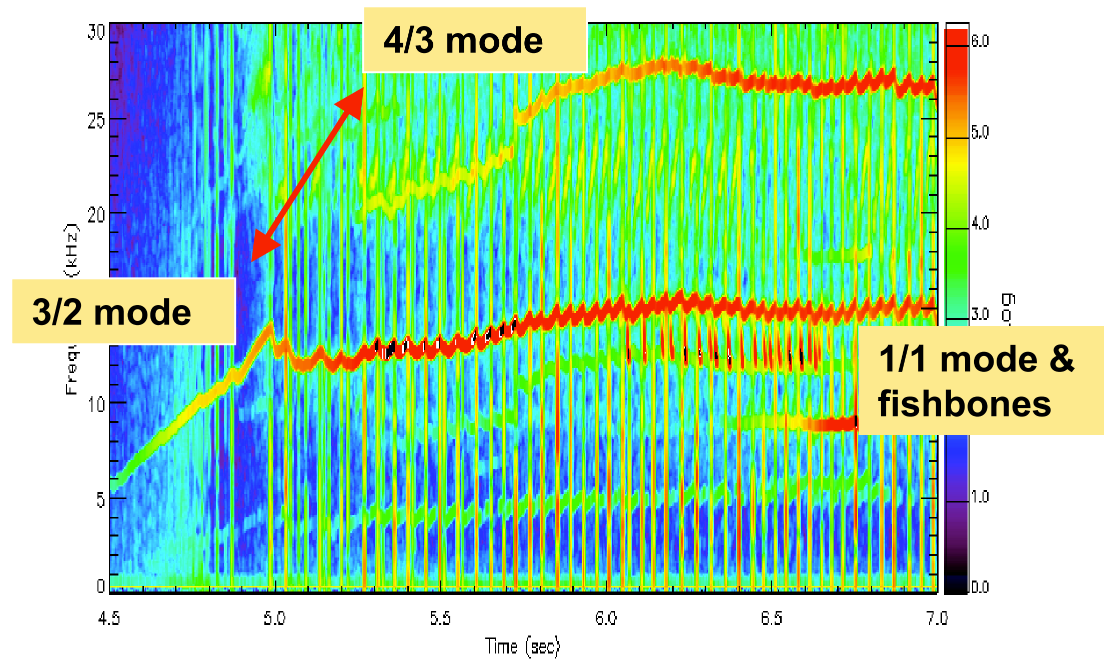
JET can bridge the gap between machines like ASDEX Upgrade and ITER

NTM control in hybrid regime

In JET, NTM are avoided by tuning the target q profile above 1 in the preheat phase



Benign NTMs in main heating phase at high β_N
W_{island}~3-4cm → impact on confinement ~5%

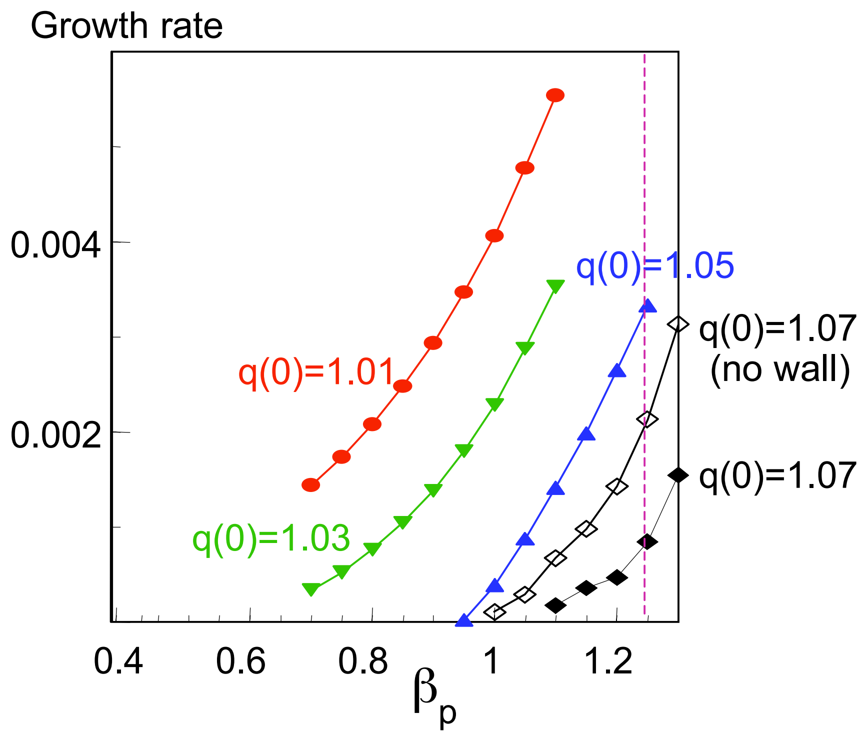


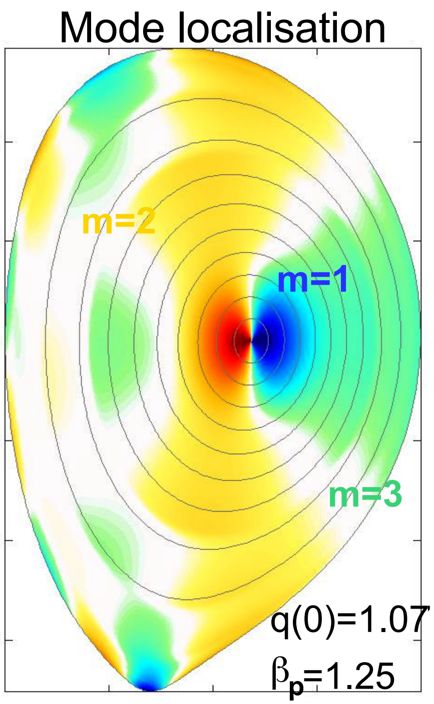
<u>In JET, the hybrid scenario can operate at β_N>2.5 with moderate NTM activity as in other devices (ASDEX Upgrade & DIII-D)</u>

Ideal MHD in hybrid regime

JET has reached ~95% of the ideal kink limit so far.

→ Ideal m=1 kink mode behaviour predicted in JET using MISHKA code.



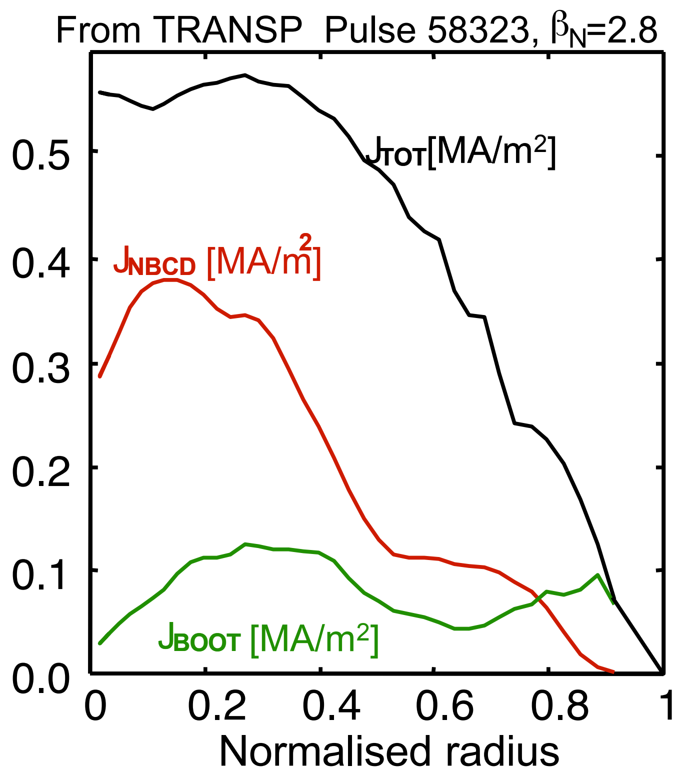


Strong increase of the ideal kink growth rate as plasma pressure increases.

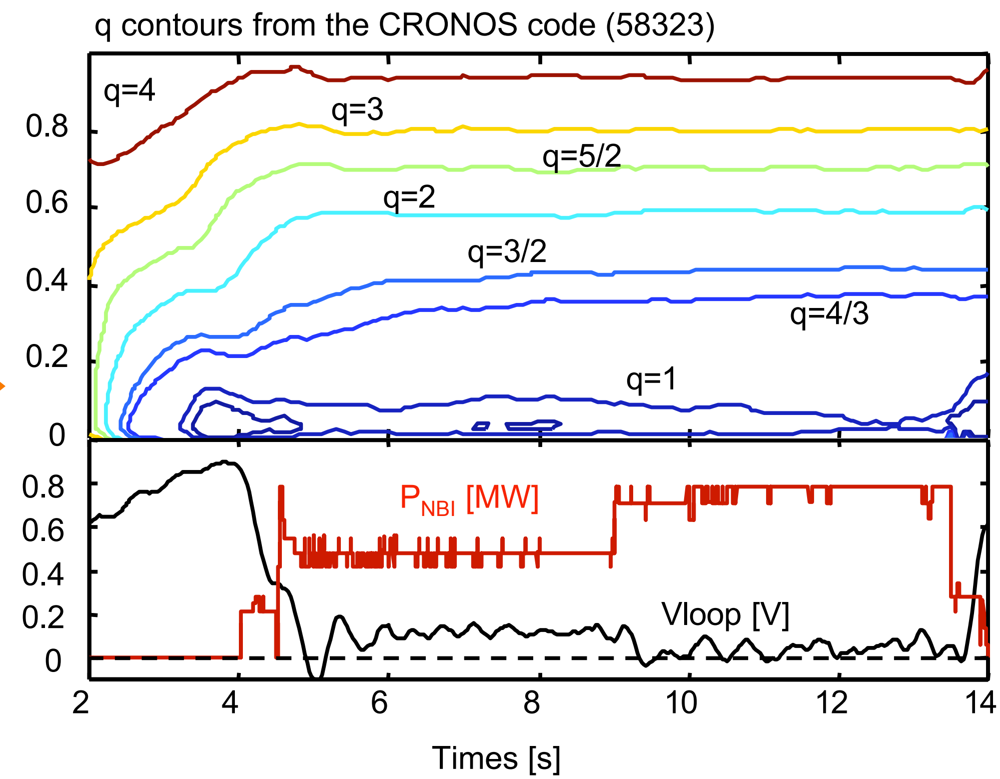
Also suggests that control of the q profile is necessary to keep q away from unity

Current balance in the hybrid regime

I_{NBCD} / I_p=35%; I_{boot} / I_p=25%



Current diffusion analysis with the CRONOS code



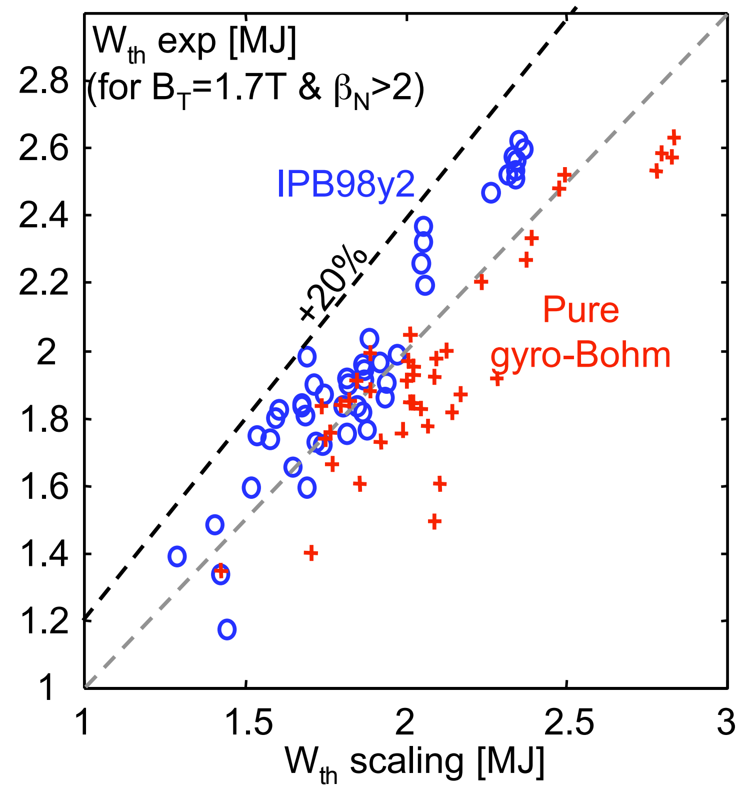
At β_N=2.8, non-inductive current sources are sufficient to maintain a steady state q profile

Confinement in the hybrid regime

- In JET at high β_N hybrid regime have an improved confinement of up to 20 % with respect to IPB98y2.
- IPB98(y,2): $\rho^{*-2.70}$ $\beta^{-0.90}$ $\nu^{*-0.01}$ $q^{-3.0}$

- Recent dedicated studies have shown that confinement has a weaker negative dependence on β:
- Pure gyro-Bohm scaling: ρ^{*-3} β^{0} $\nu^{*-0.1}$ $q^{-1.7}$

Gives a reasonable fit to the data.



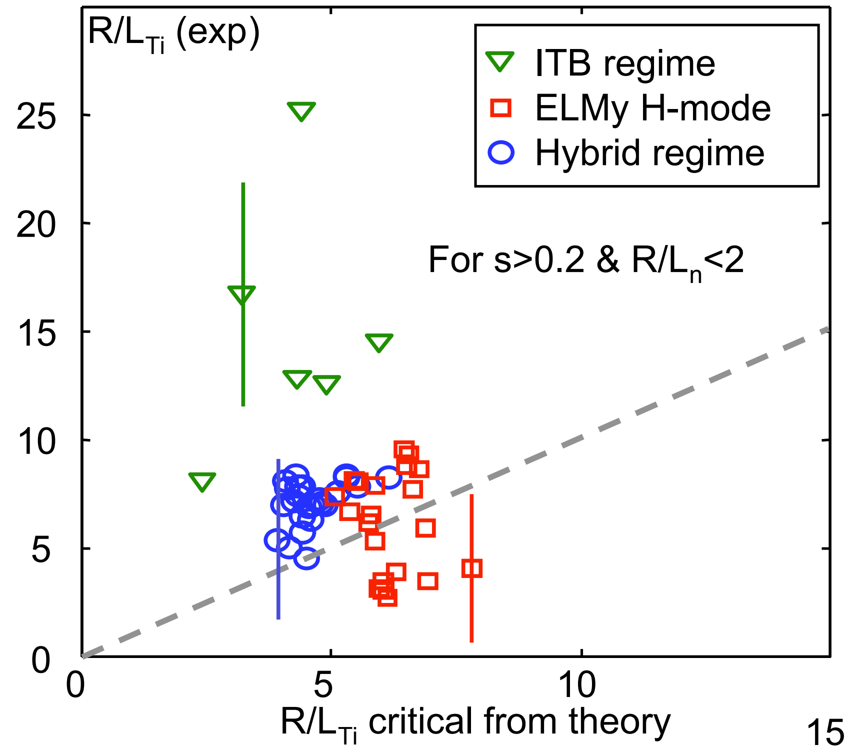
At high β_N, he higher confinement observed in hybrid regime could be related to the $\beta^{-0.90}$ dependence of the IPB98(y,2) scaling

(Cordey et al., IT/P3-32 & McDonald, EX/6-6)

Comparative transport property of the hybrid regime

1. As expected, ITB discharges are showing ion temperature gradients well above the predicted critical gradients for ITGs
2. Hybrid scenario are behaving in the same way as the standard ELMy H-mode.

Supported by turbulence measurements with reflectometry.



(Jenko et al., PoP, 2002)

In JET, it appears that the confinement in hybrid regimes is not significantly different than in the standard ELMy H-mode scenario.

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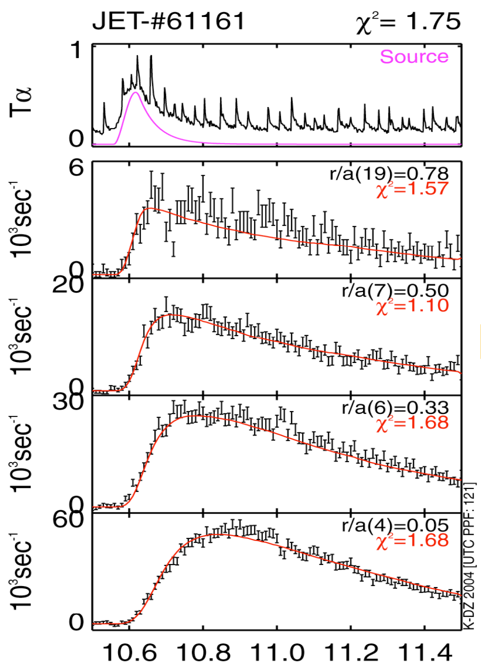
Tritium and impurity transport

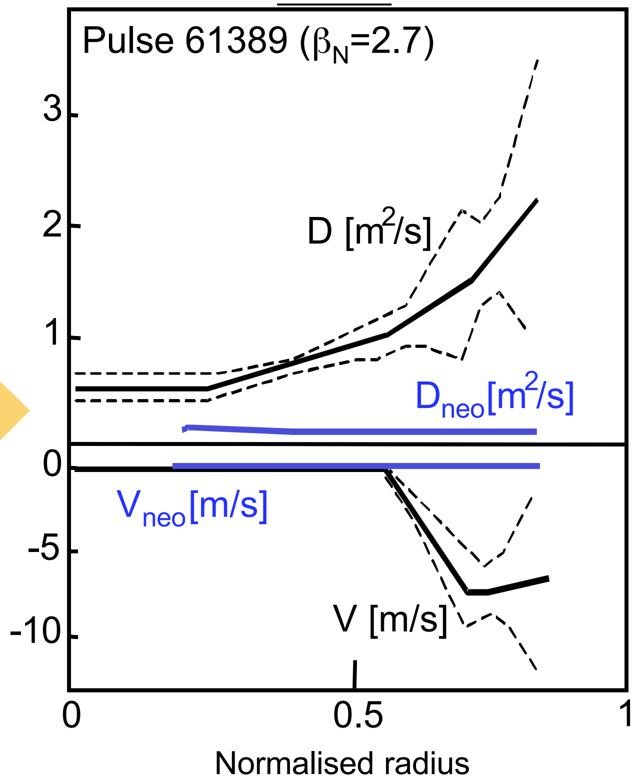
Particle and impurity diffusion and convection inferred from the SANCO + UTC codes constrained by experimental data

Trace tritium injection

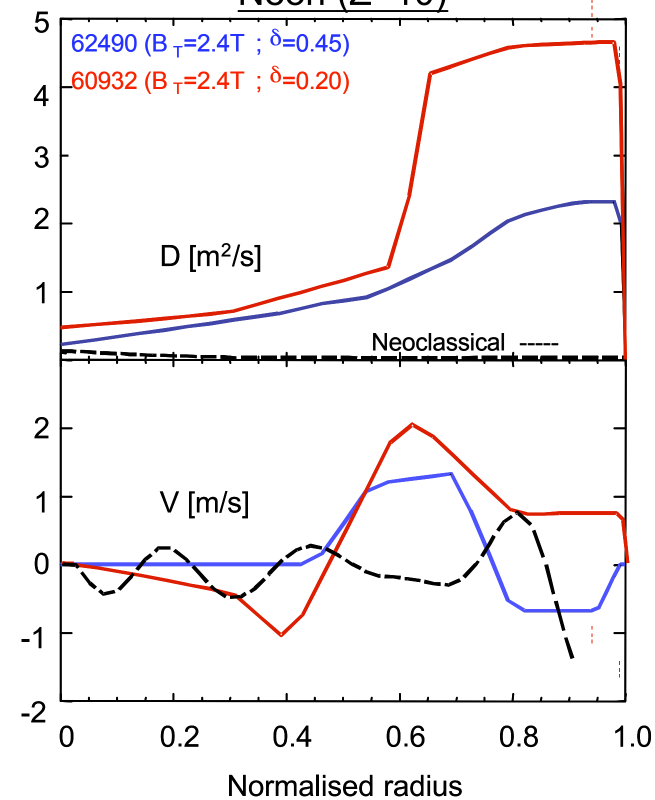
(Neutron monitor + fit)



Tritium



Neon (Z=10)



(D. Stork, OV/4-1 & McDonald, EX/6-6)

Tritium and impurity diffusion and convection in hybrid regime are dominated by turbulent transport.

ITER projections with the hybrid scenario

Projections for burning hybrid regime in ITER with the integrated 1D code CRONOS

Hypothesis:

- HH=1
- Gyro-Bohm transport normalised to scaling laws.
- Pedestal height from pedestal database scaling law.
- Zeff=1.8, He concentration 3%

	Scaling used	P_{fus} [MW]	P_{aux} [MW]	β_N	Density peaking	Q_{fus}	q_{95}	Ip [MA]
Comparison with PPA	IPB98y2 (PPA)	400	73	1.9	0	5.4	3.3	13.8
	IPB98y2	570	73	2.1	0	7.8	3.3	13.8
Scaling comparison	IPB98y2	160	73	1.6	0	2.2	4	11.3
	Pure Gyro-Bohm	285	73	2.25	0	3.9	4	11.3
With ne peaking	Pure Gyro-Bohm	337	73	2.4	ne_o=1.5 x ne_{ped}	4.6	4	11.3
Lower q_{95}	Pure Gyro-Bohm	600	50	2.85	ne_o=1.5 x ne_{ped}	12	3.5	13

Reaching high β_N requires the fine tuning of plasma current

Conclusions

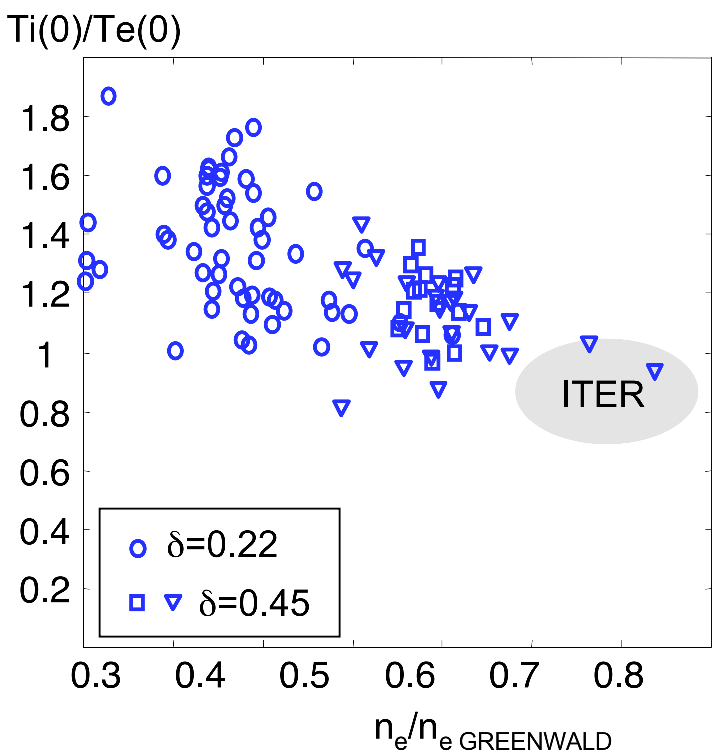
1. The steady state "hybrid" scenario has been successfully reproduced in JET by the mean of an identity experiment approach with ASDEX-Upgrade.

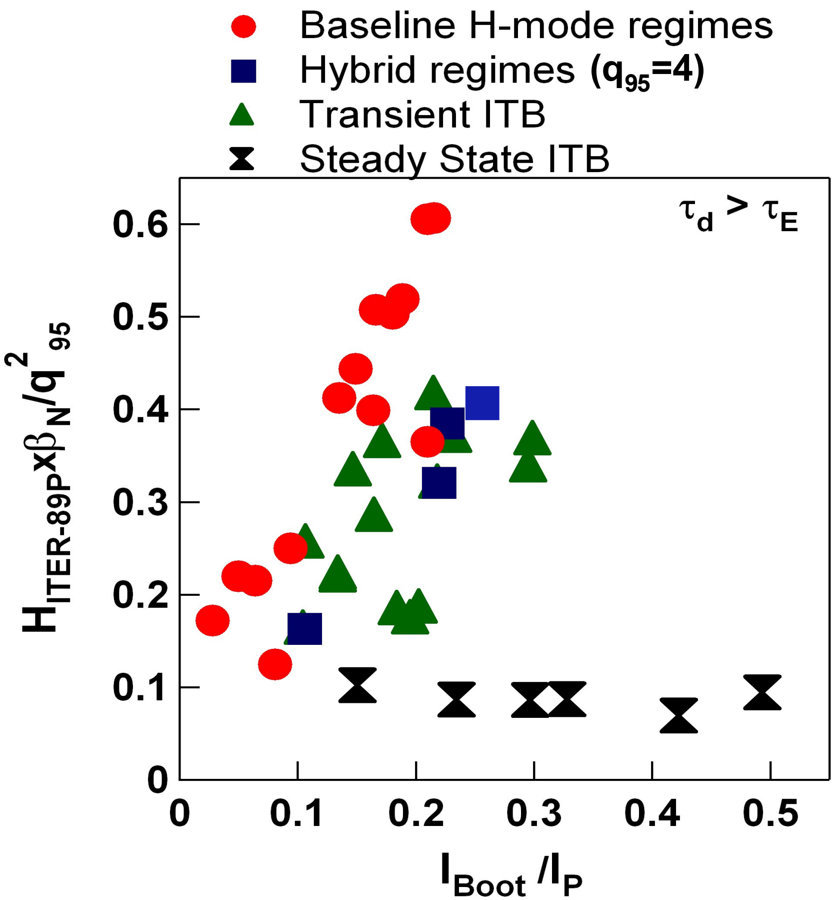
2. In JET, current control is a key factor in avoiding NTM activity during the main heating phase of the scenario.

3. The JET hybrid scenario does not show any obvious sign of improved heat and particle confinement with respect to standard ELMy H-modes. On the other hand, its improved stability allows operation at higher β_N close to the ideal limit.

4. The maximisation of confinement and stability properties provides to the hybrid regime a good probability for achieving high fusion gain at reduced current (~13MA) for more than 2000s.

Performance overview towards ITER





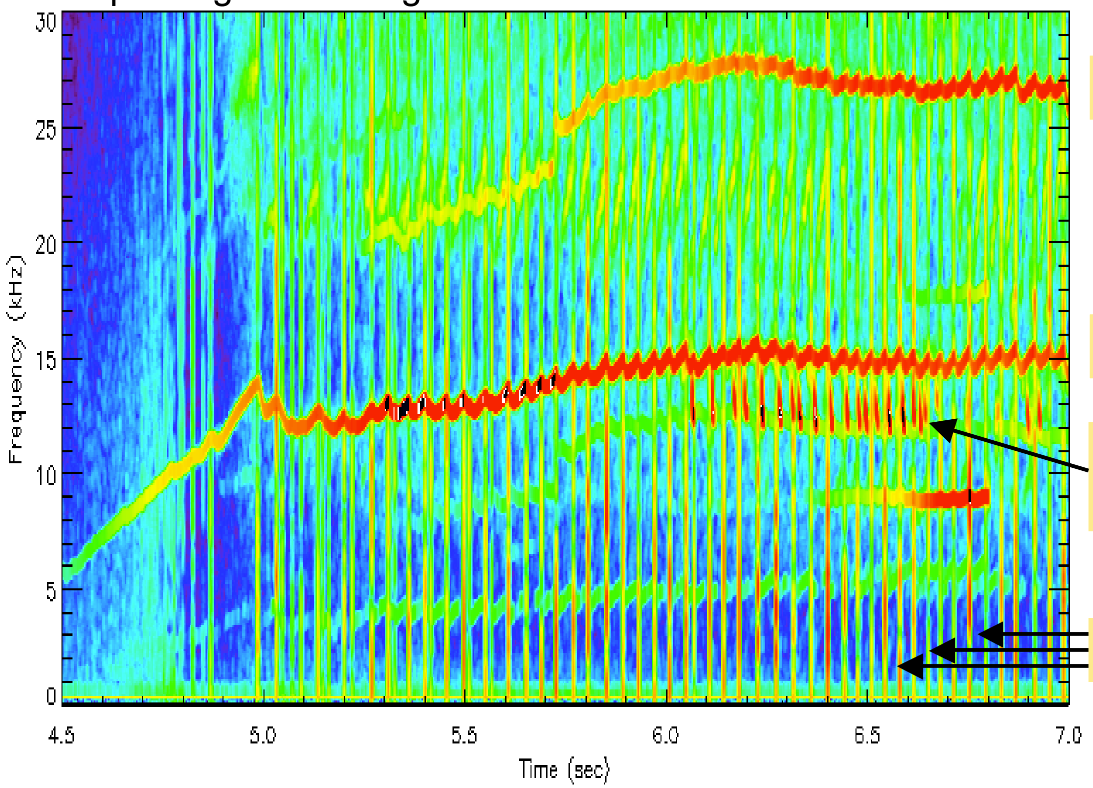
Bootstrap fraction from TRANSP data

JET Hybrid regime are situated in the right ball park in terms of Ti/Te, density and plasma performance

NTM in hybrid regime

Neoclassical tearing mode behaviour in the hybrid regime

Spectrogram of magnetic fluctuations



4/3 mode

Coupled

3/2 mode

1/1 mode & fishbones

ELMs ~40Hz

1 < q < 1.3 in plasma core

Islands size is 3 to 4cm located at r/a=0.3-0.4

Limited impact on global confinement few percent

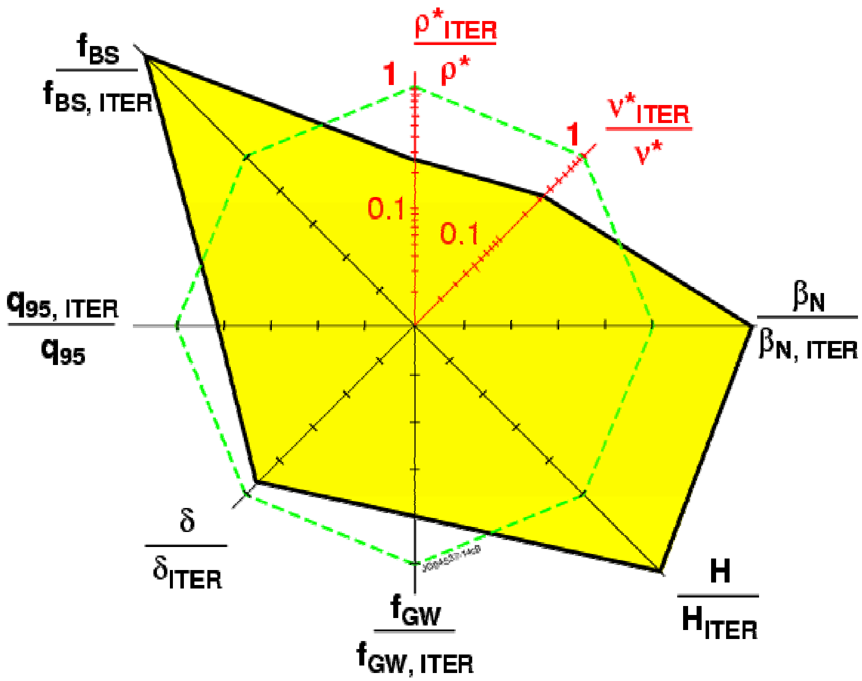
In JET, the hybrid scenario can operate at β_N>2.5 with moderate NTM activity as in other devices (ASDEX Upgrade & DIII-D)

Summary of advanced modes development

Hybrid Mode or improved H-mode

(new on JET)

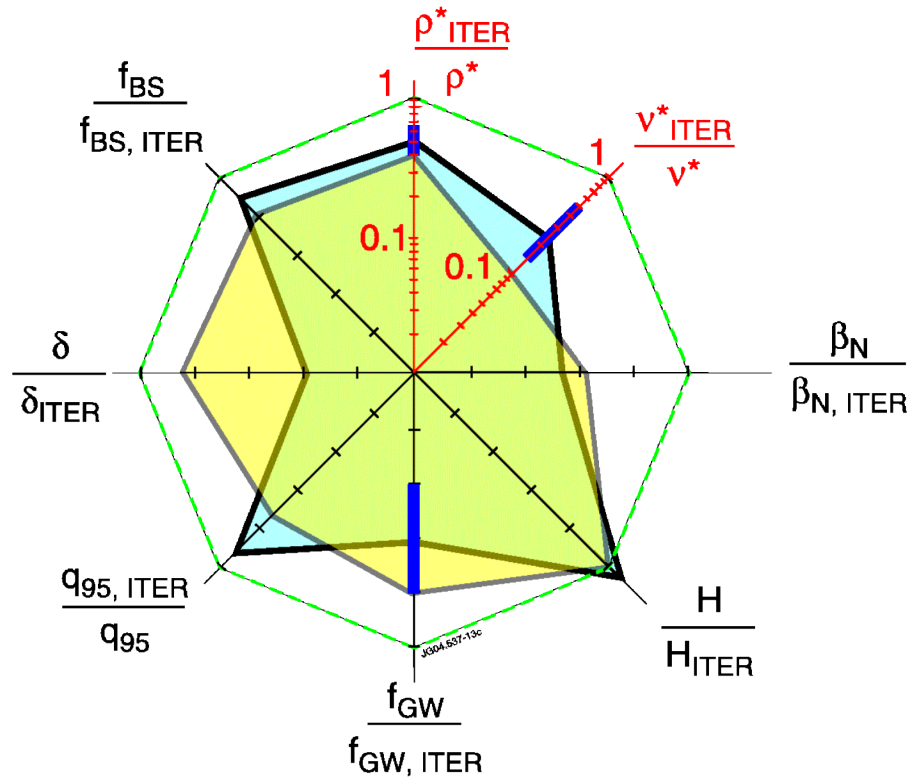
Pulse No: 60927



ITER (PPA Q=5.4, T_{burn}=1000s):
δ= 0.48 q_{95}=3.5 f_{GW}=0.85 H=1
β_N=1.9 f_{BS}=17%

Plasmas with ITBs

Pulse No: 53521 Pulse No: 62293



ITER (Q=5 Steady State):
δ=0.49 q_{95}=5.5 f_{GW}=0.8 H=1.5
β_N=3 f_{BS}=50%