Development on JET of Advanced Tokamak Operations for ITER

presented by

Angelo A. Tuccillo

Associazione EURATOM ENEA sulla Fusione

on behalf of

EFDA-JET Task Force S2 and Contributors to EFDA-JET Work-Programme

With special thanks to X. Litaudon (CEA), F. Crisanti (ENEA) for coordinating the S2 Task Force and UKAEA for JET Operations

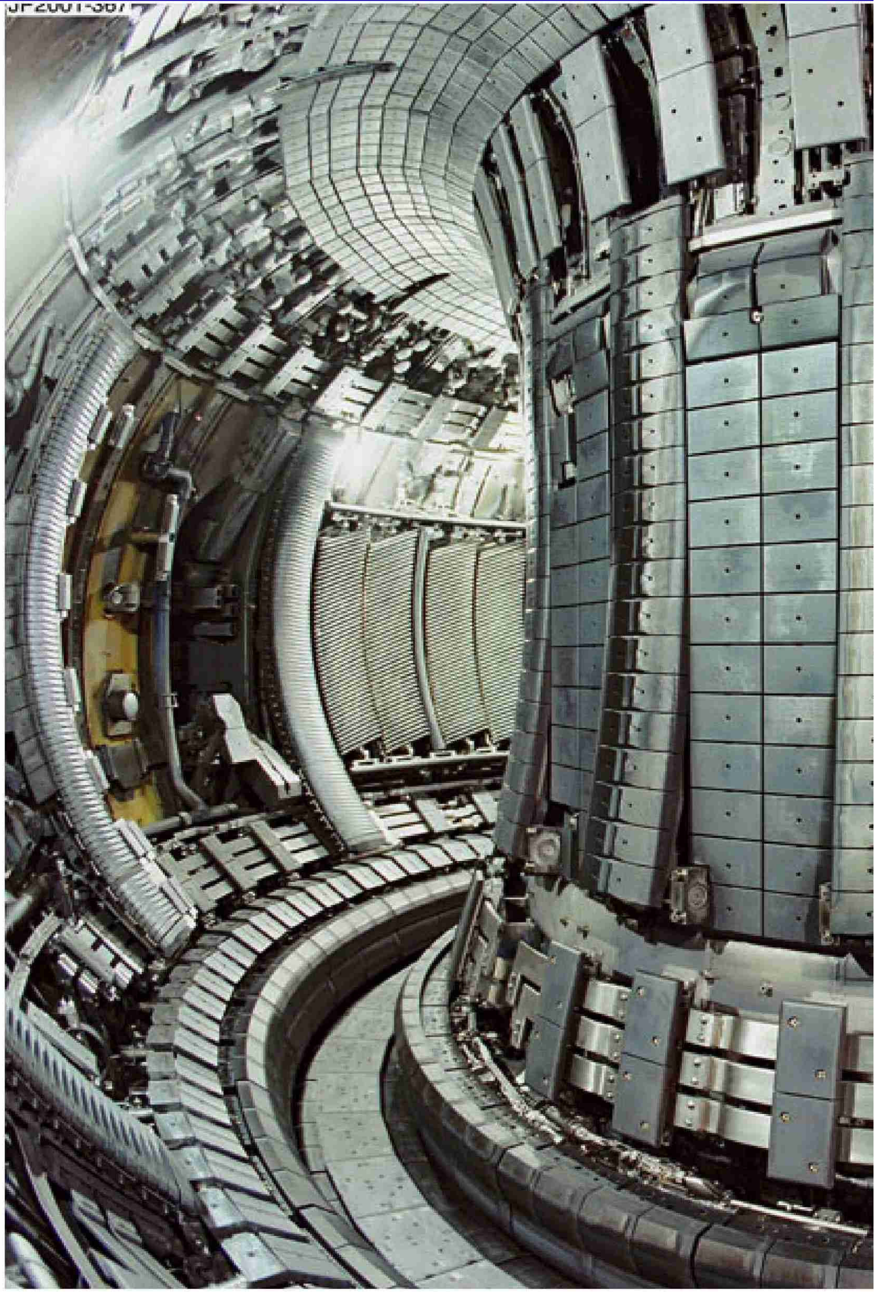
OUTLINE

-Summary of achieved performances
Hybrid Regime (EX/4-2, EX/P2-1)
High Triangularity (EX/P3-11)
RTC (EX/P2-5)

-Highlight of explored scenarios
Similarity experiments
Pellet fuelled ITBs
Mode Conversion ITBs (EX/P6-18)
Long Operation ITBs

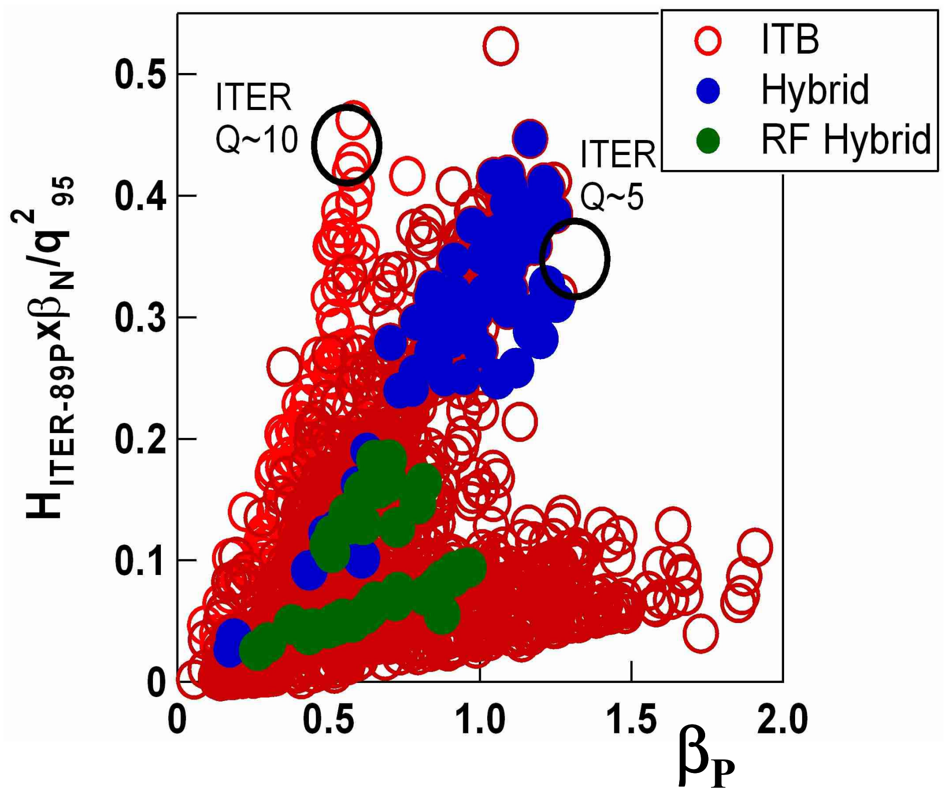
-Fuel-Impurity transport

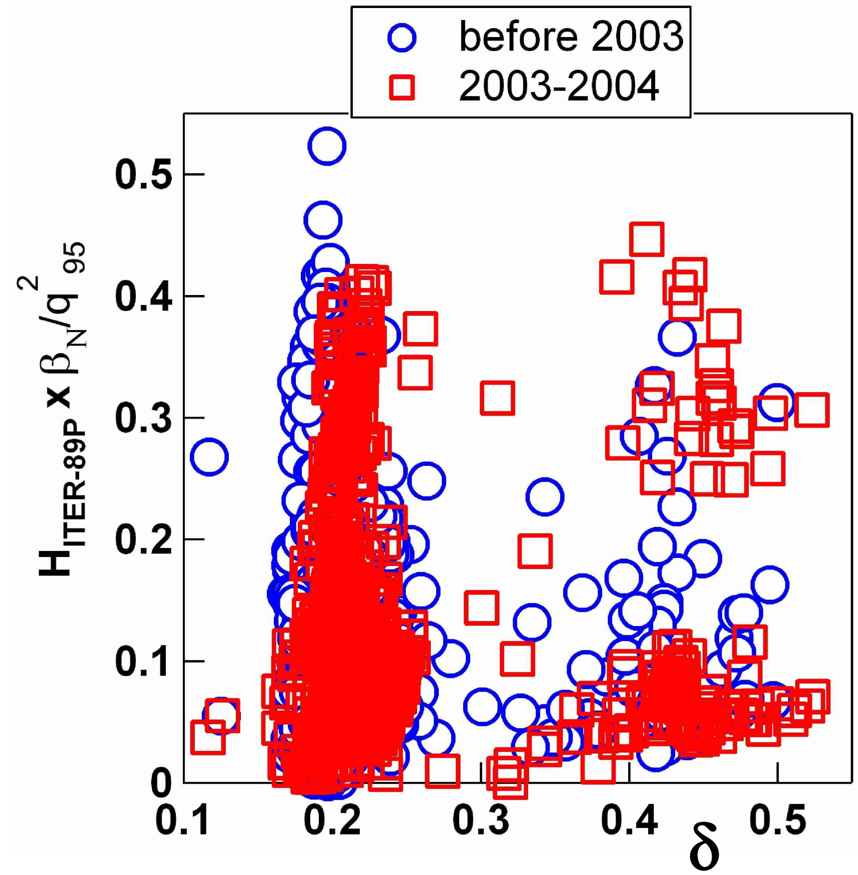
-Conclusions



Recent Progress in AT Research at JET

Focus of campaigns was on scenarios optimisation: increase ITB volume to allow rising H

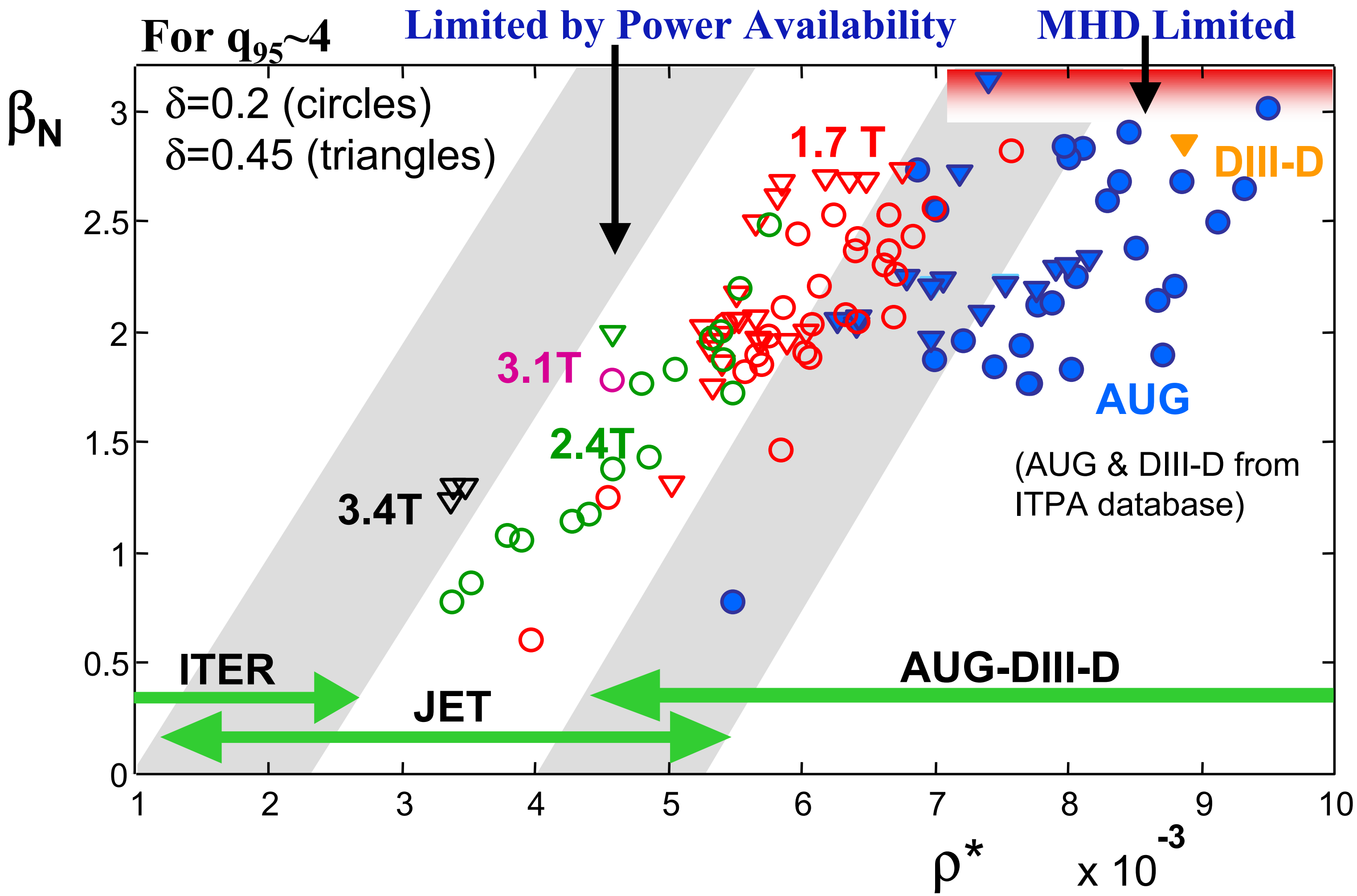




Newly developed Hybrid Regime could represent a path to achieve High Performance and Long Operations

High δ scenarios (Hybrid - ITB) progressed with new divertor configuration

Hybrid Regime: from AUG similarity to ITER like ρ*



EX/4-2 E. Joffrin(CEA, France), A.C.C. Sips(IPP, Germany)

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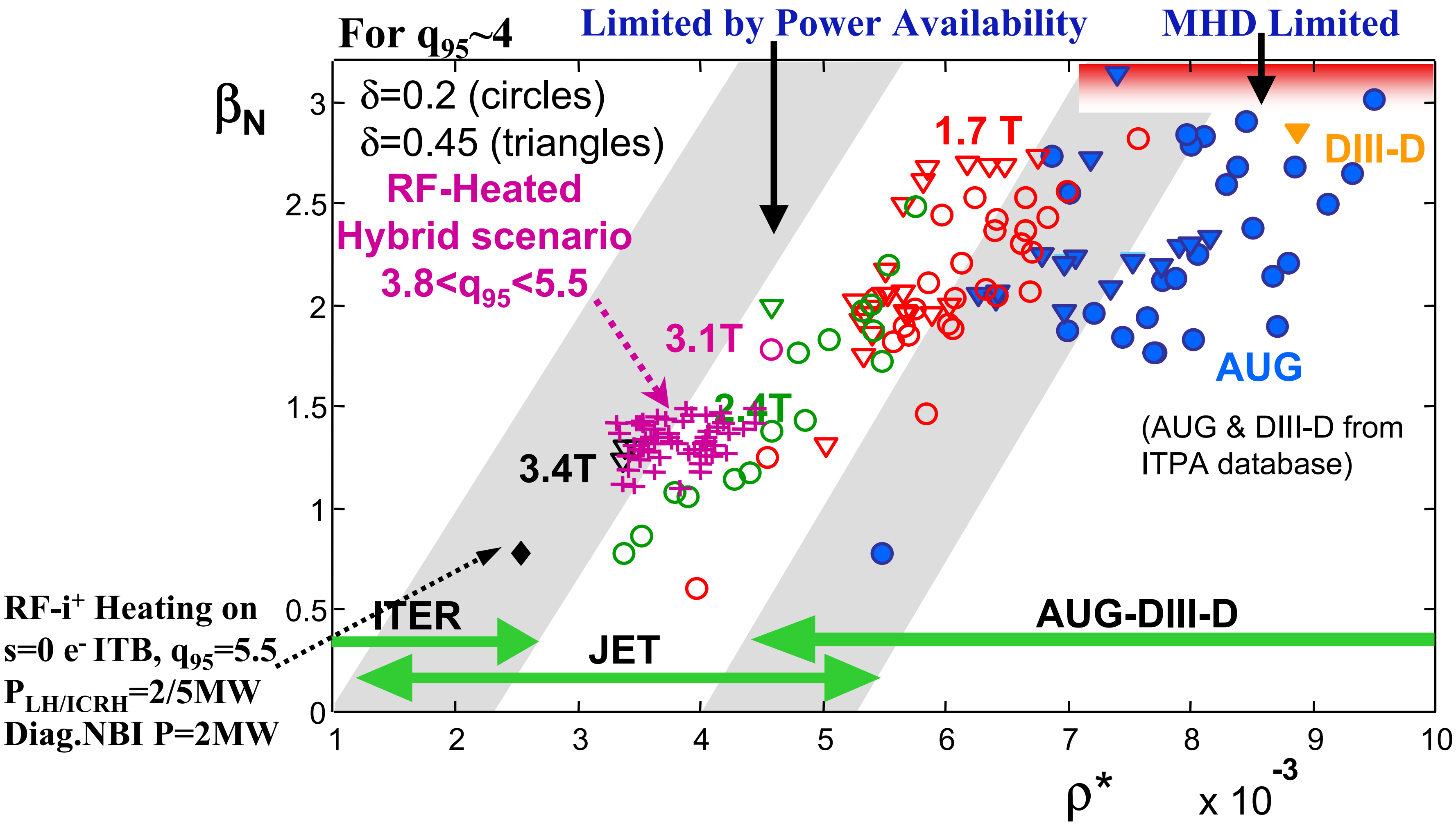

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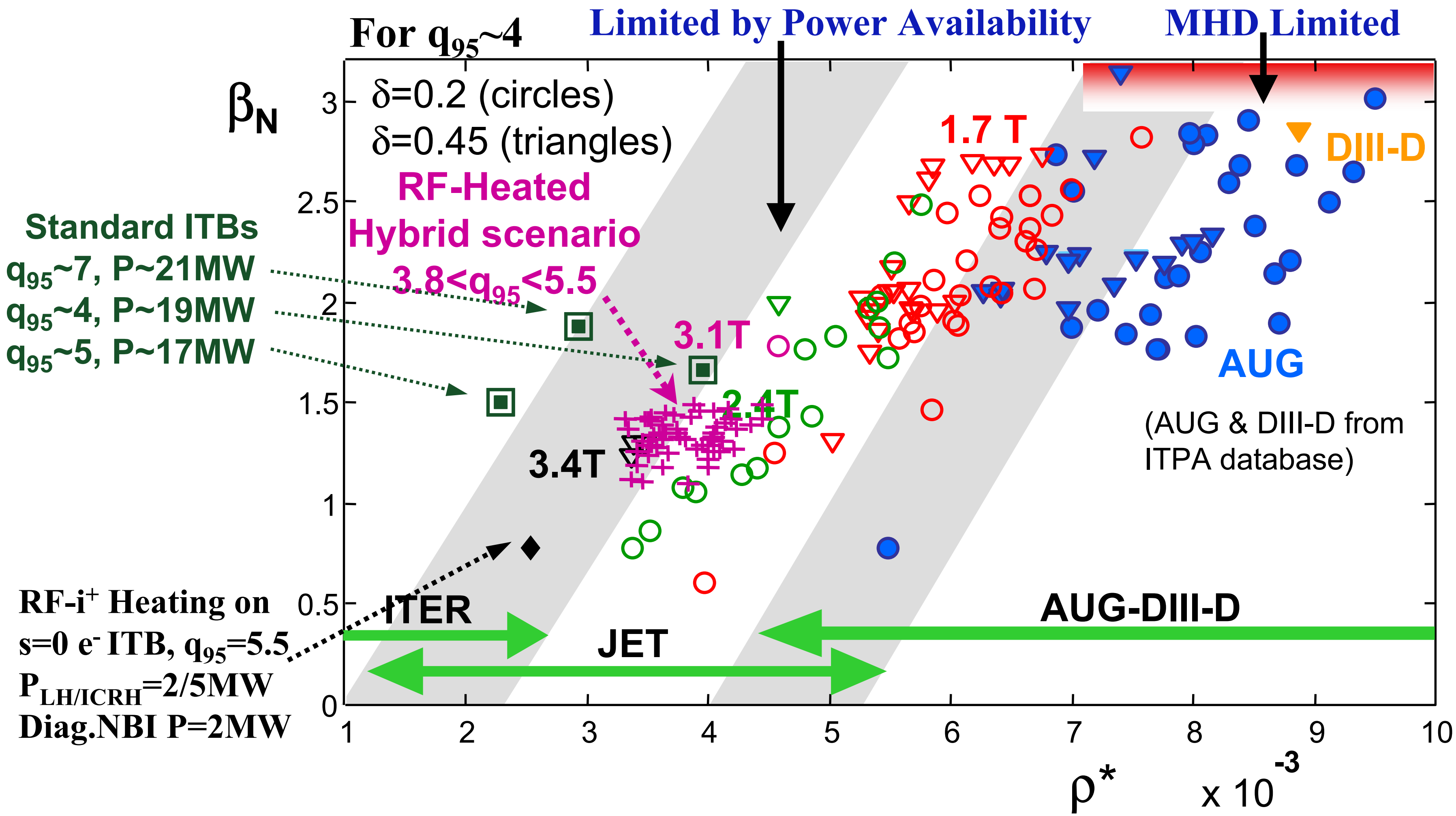

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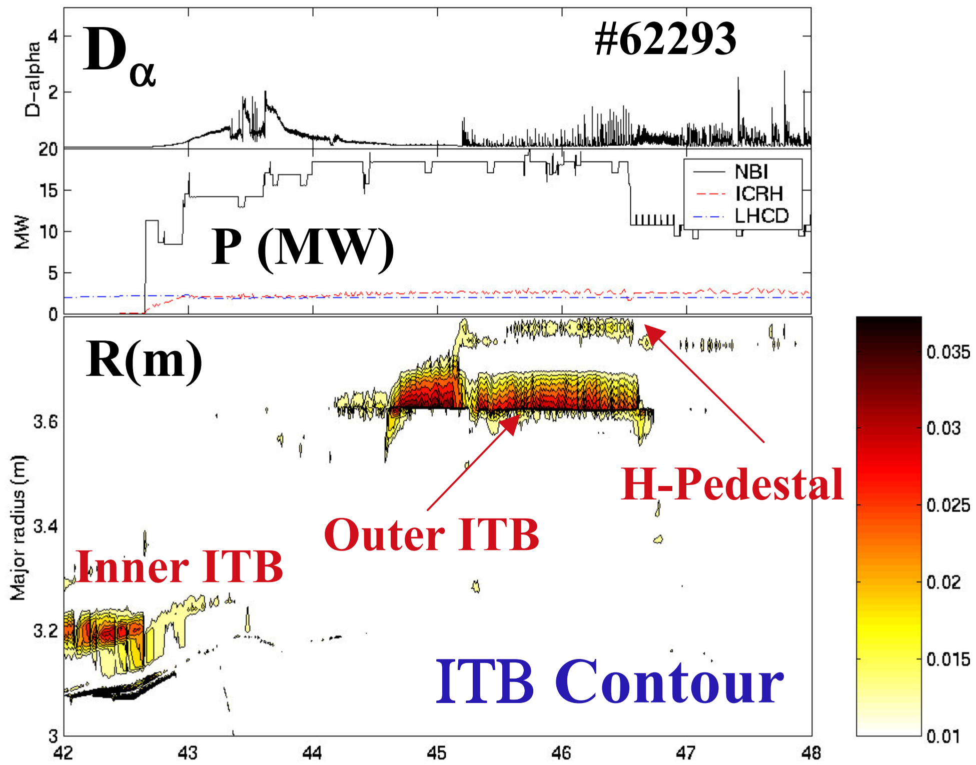
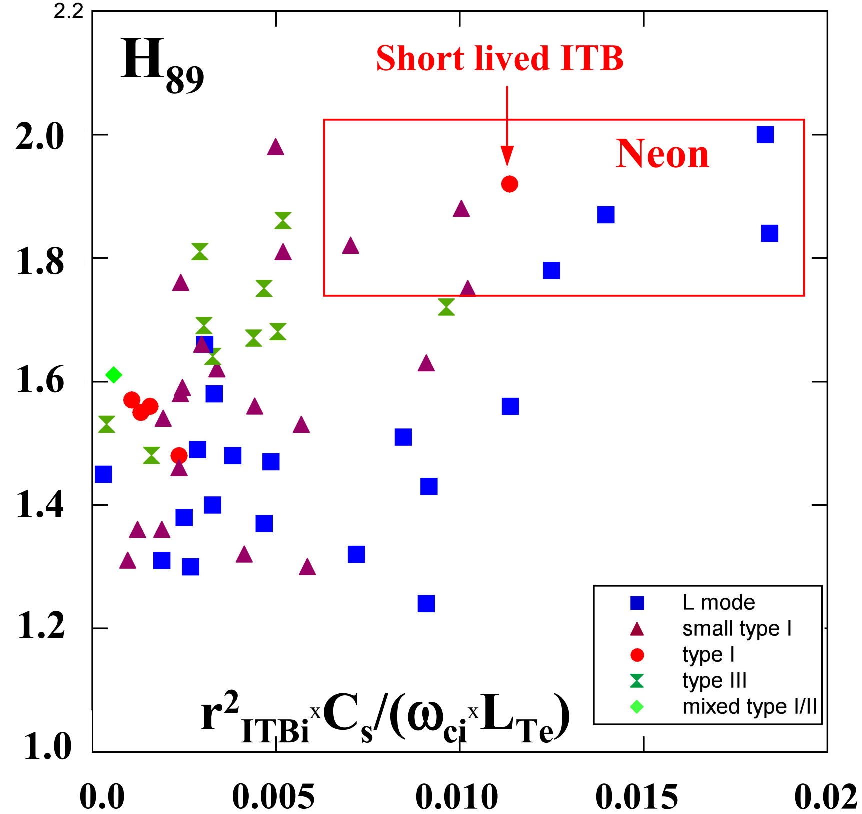
Development of ITB at ITER-Relevant Triangularity

Integrated optimisation of core (double barrier) and edge (ELM mitigation by Ne injection) produces long lasting ($t \sim 10\tau_E$):

Wide barrier (R=3.7m) at $\delta \sim 0.45$



$H_{89}\beta_N/q^2_{95} \sim 0.1$; $n/n_{GW} \sim 60\%$

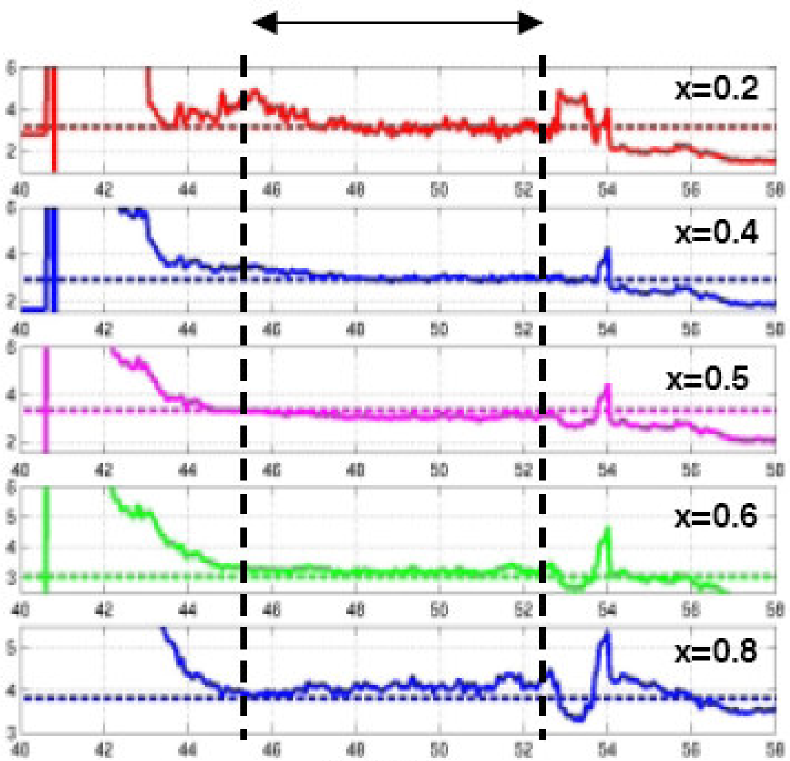


EX/P3-11 F. G. Rimini, M. Becoulet (CEA, Fr), P.J. Lomas (UKAEA, UK), E. Givannozzi, O. Tudisco (ENEA, It)

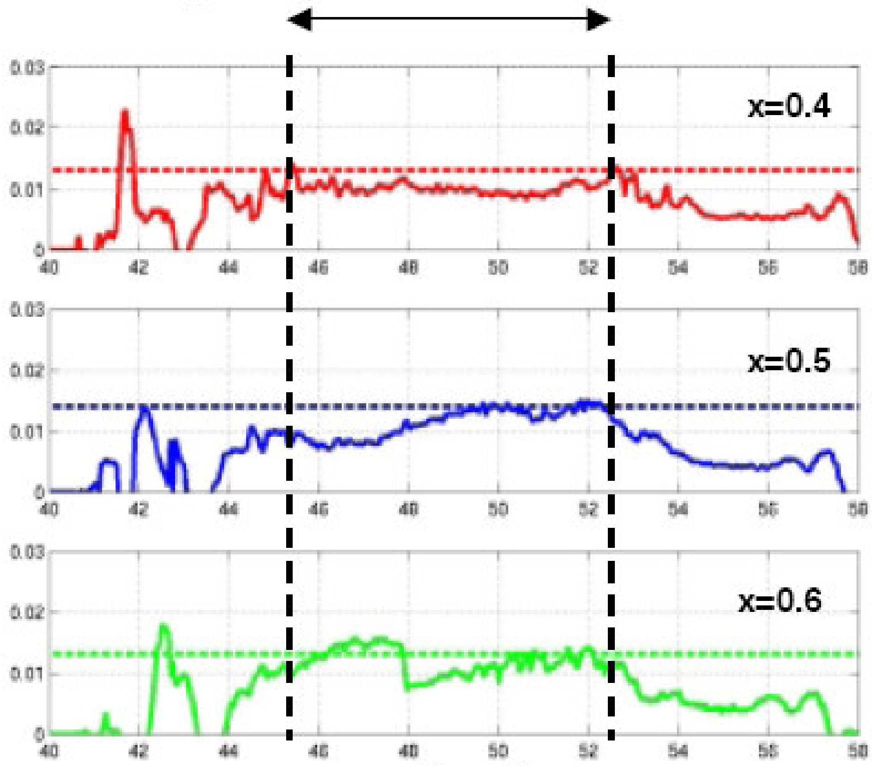
Integrated Real-Time Control of Advanced Scenarios

Simultaneous Control of Current and Electron Temperature profiles with LHCD-ICRF-NBI as actuators

q-profile control



Te-gradient control in e-ITB



 # 62160 $V_{Loop} = 0.05$

EX/P2-5 D. Moreau, D. Mazon (CEA, France), A. Murari (RFX, Italy) et al

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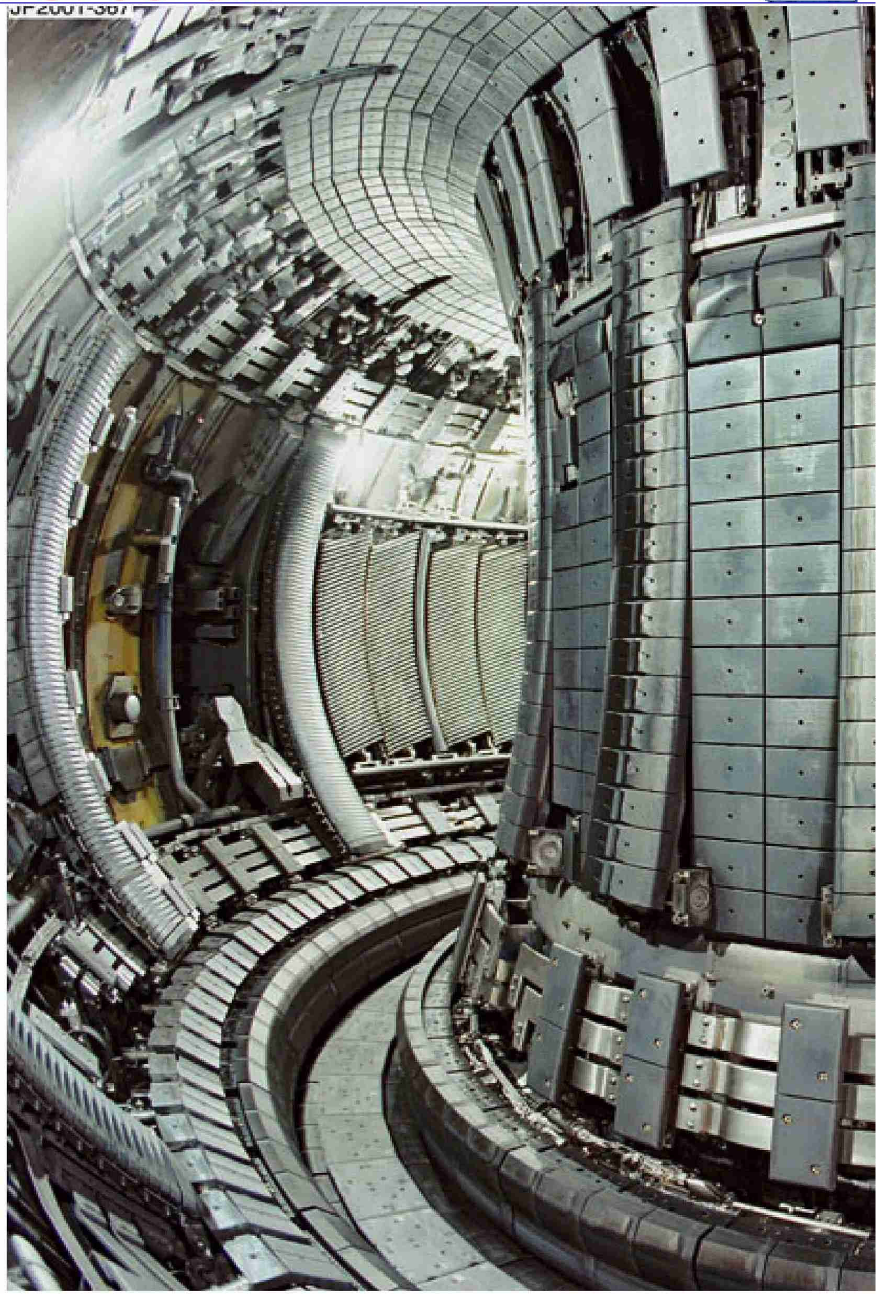
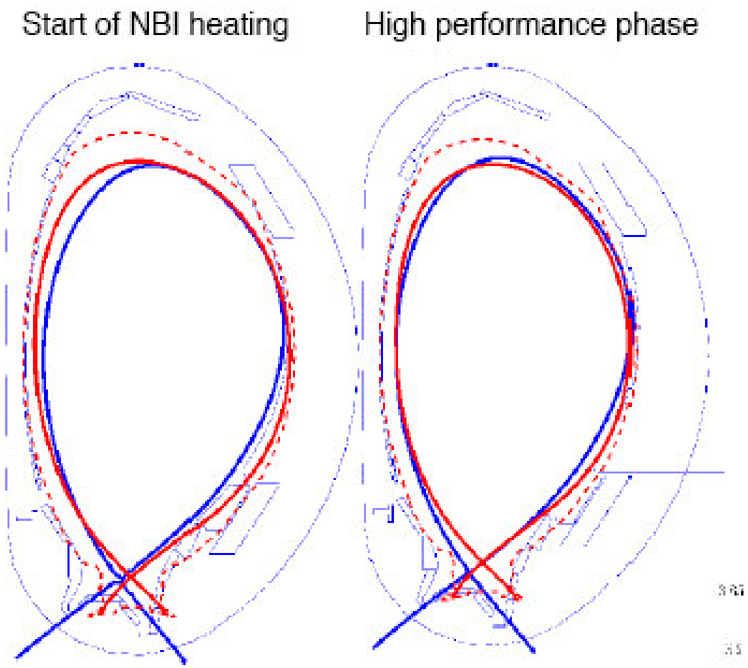
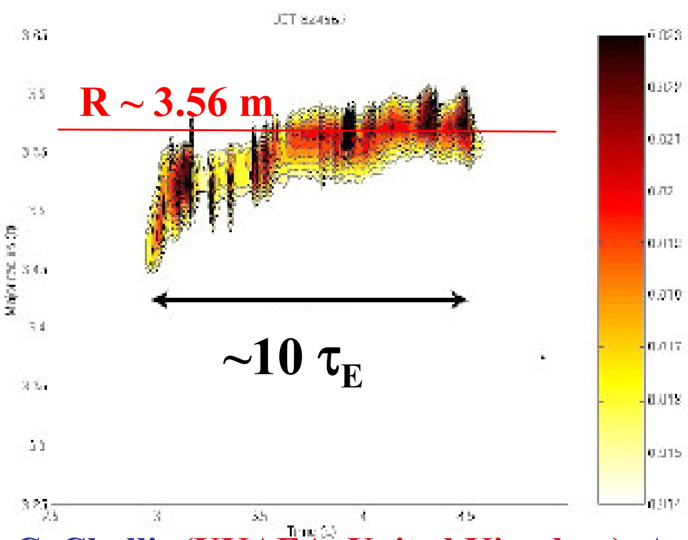


JET-ASDEX Upgrade ITB Comparison Experiments



- T_i/T_e AUG > JET ==> JET NBI more e^- heater
- Higher T_i in AUG ==> more favourable for ITG
- ρ^*–ν^* not perfectly matched
- Both devices generated an ion ITB at 7-10MW
- Neither machine exhibited an electron ITB
- Both made transient ITBs which collapsed at the onset of large ELMs

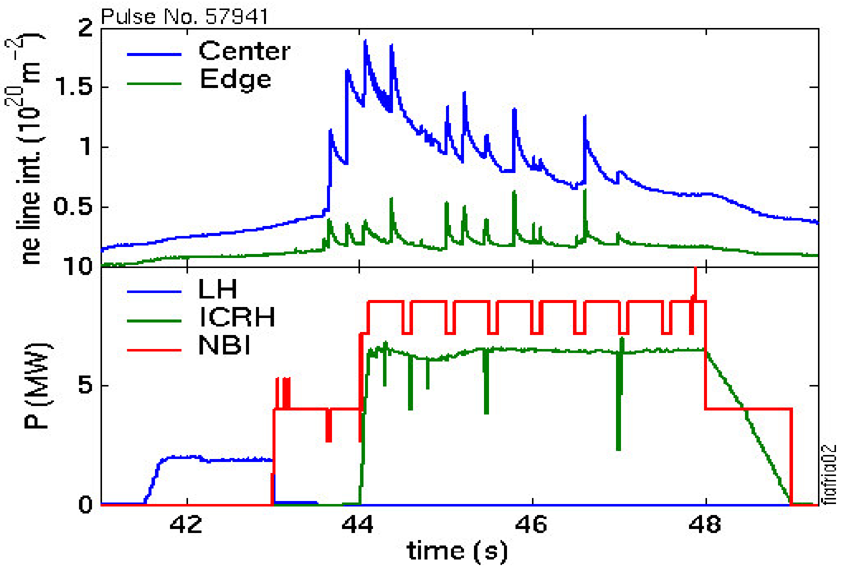
AUG #16147 (0.7s)/JET #62175 (2.5s)
B_T = 3.0 T / 1.8 T
I_P = 0.78 MA / 0.81 MA
q_{95} = 6.8 / 7.6
<ne> = 2.3×10^{19} m^{-3} / 1.1×10^{19} m^{-3}
<Te> = 1.2 keV / 0.6 keV

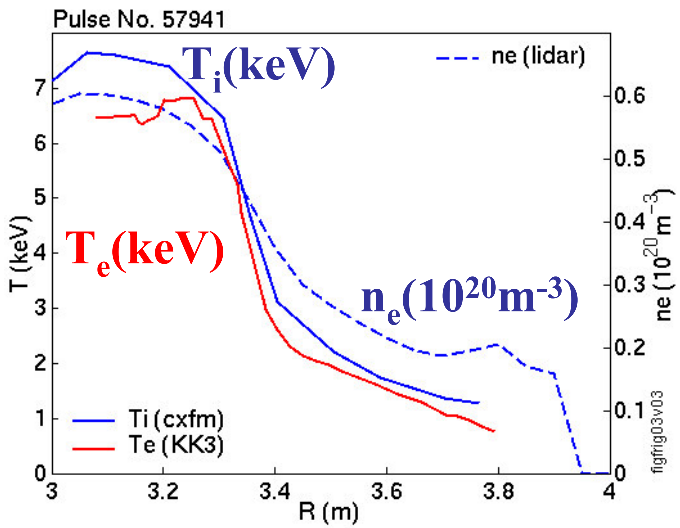


Wide e^-, $-i^+$ ITB @ 60% n_{GW} with Ne moderating the edge but H_{89} ~1.7
- on JET
- not yet on AUG

C. Challis (UKAEA, United Kingdom), A. C. C. Sips (IPP, Germany)

Pellet Fuelled ITBs





LHCD

Pellet

+

Low NBI Pw

ITB

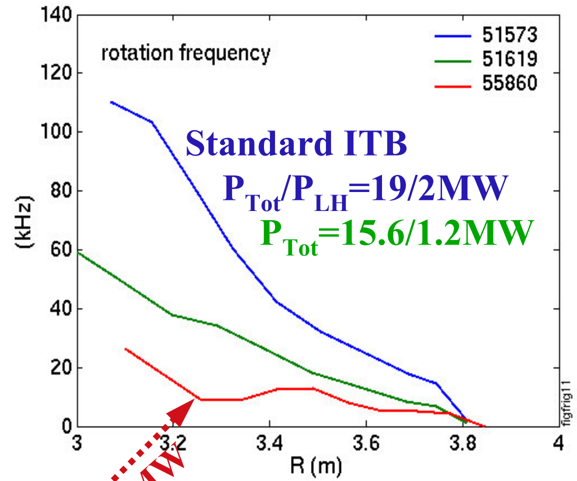
$T_i \sim T_e$

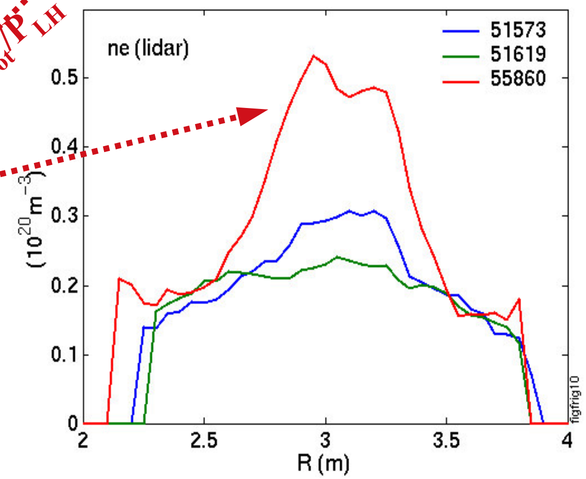
$n_{e0} > n_{GW}$

Pellet ITB P_{Tot}/P_{LH}=16.4/2MW

@

Low Rotation

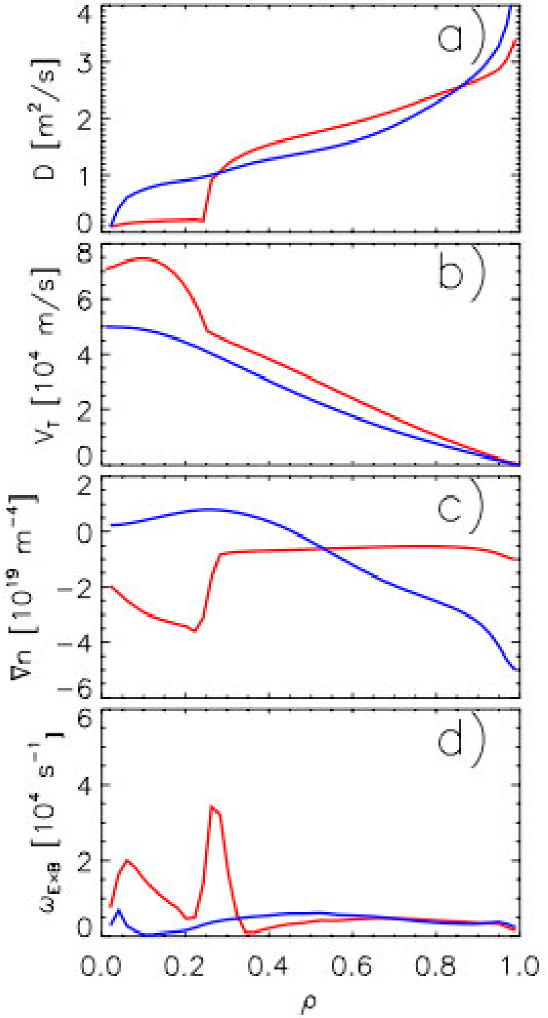




D. Frigione(ENEA, It), C. Challis,, M. De Baar(FOM, Nl), P. De Vries(UKAEA, UK), L. Garzotti(RFX, It)

Pellet Fuelled ITBs

Deep Pellet kills ITB



JETTO Simulation:

Particles diffusion increase

Not much affected

Toroidal velocity shear decreases

Not much affected

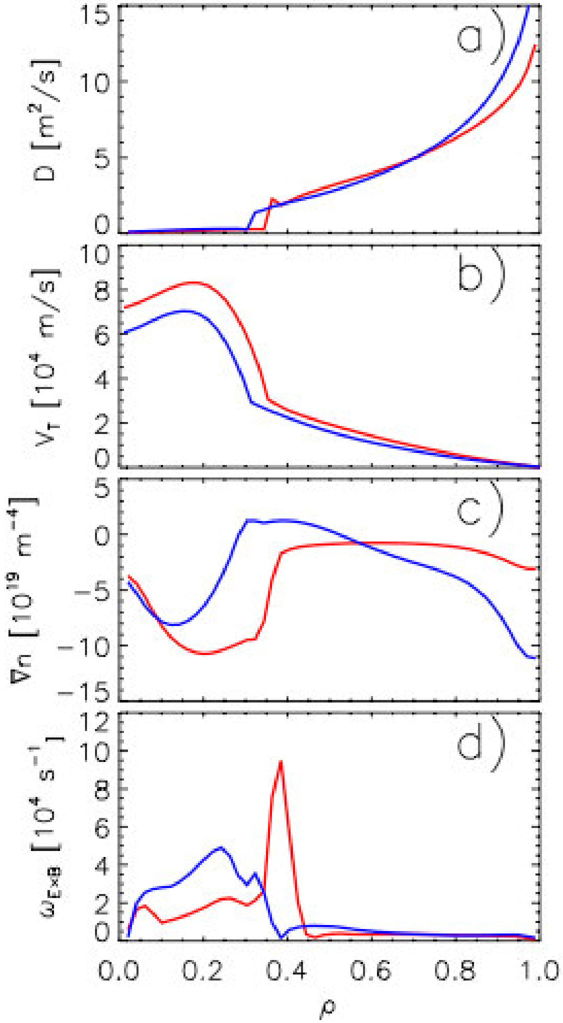
Density flattens at ITB location

Small reduction of gradient and ITB radius

Turbulence stabilisation strongly affected

Less affected

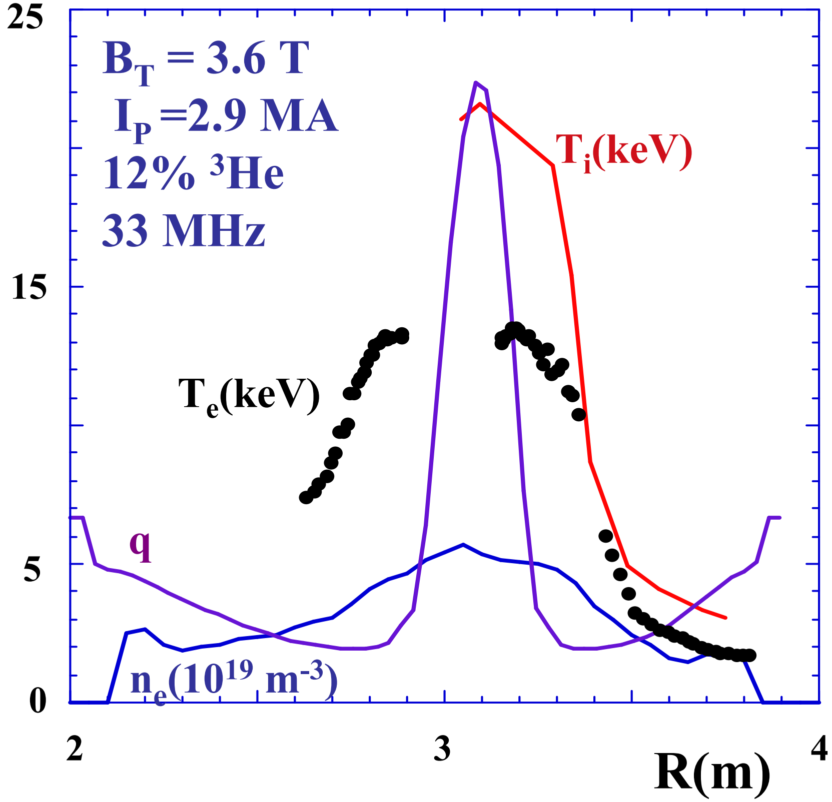
Shallow Pellet does NOT

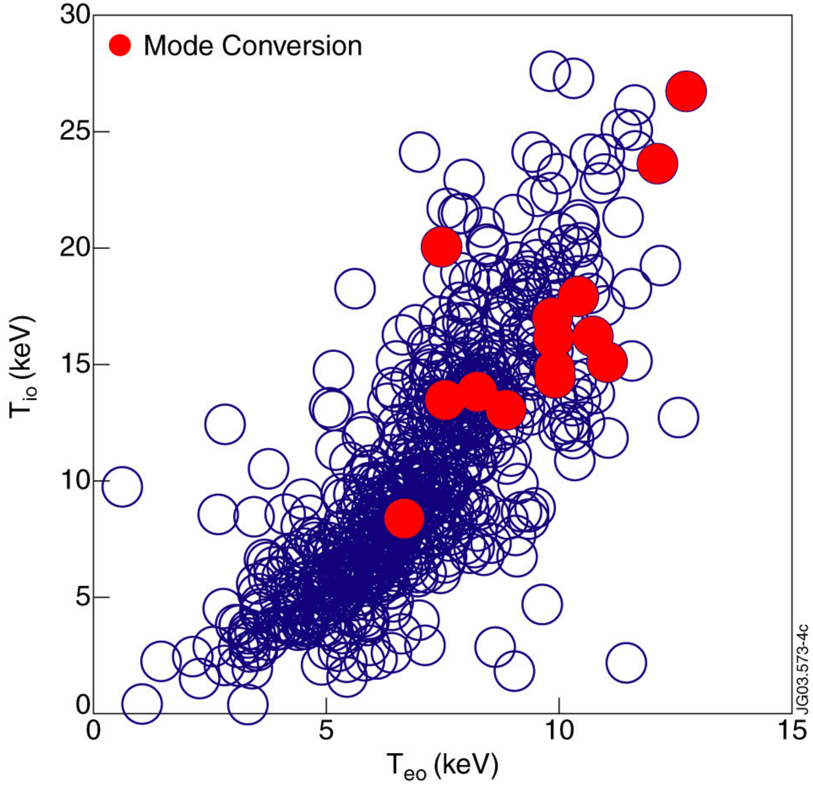


L. Garzotti (RFX, It) et al, EPS London 2004, Vol. 28b p-1.147

Mode Conversion ITBs

#59411 Central MC



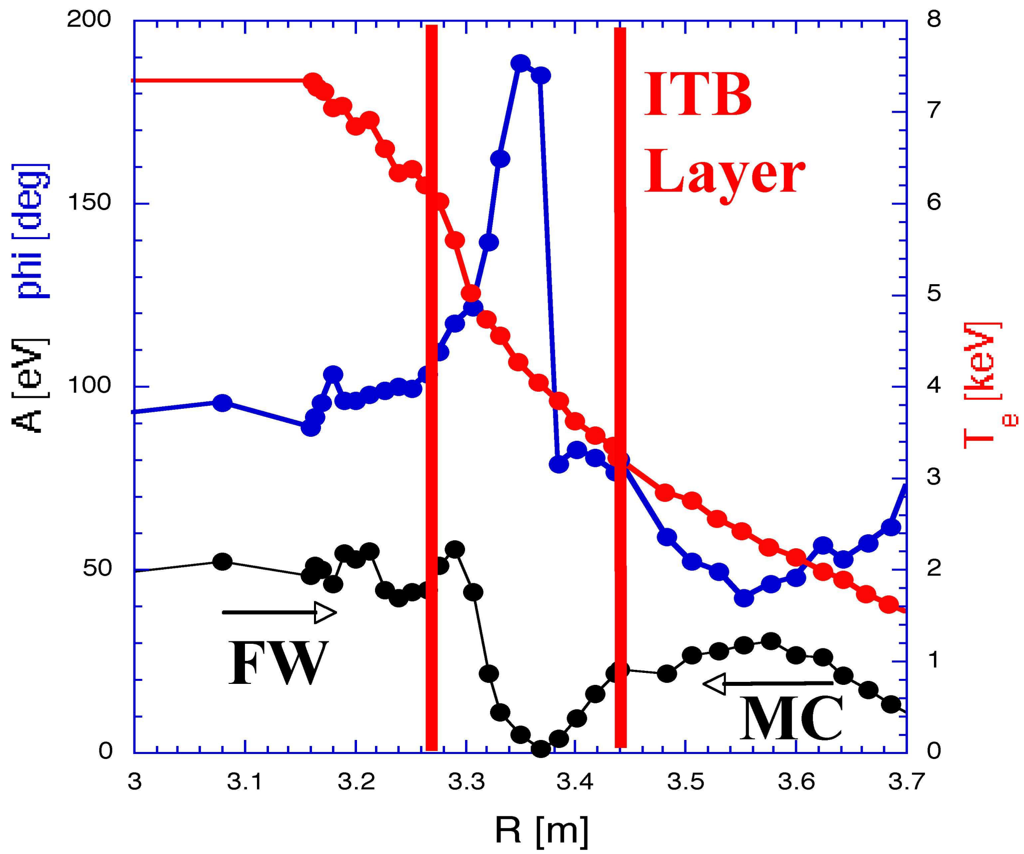


Q_{DT}~0.25 best TRANSP estimate including +FW-MC impurities

Zeff~4-5 off-axis Ni profile

P. Mantica (IFP-CNR, It), F. Imbeaux (CEA, Fr), M. Mantsinen (TEKES, Finland), D. Van Eester (ERM, Belgium)

Mode Conversion ITBs



From ICRH modulation analysis: Two heat waves traveling towards ITB:

MC from outside

FW from centre

Both waves strongly damped at ITB: ITB appears to be a narrow layer with low heat diffusivity, characterized by sub-critical transport and loss of stiffness

EX/P6-18 P. Mantica (IFP-CNR, Italy) et al.

Long pulse operation under development

Long lasting ITBs ($\geq 40\ \tau_E$):

#58179, δ=0.2, n/n_{GW}=0.4

B_T=3T, I_P=1.8MA

~40% I_{Boot}, ~40% I_{LHCD}

$\beta_N \times H_{89}$ = 1.6 x 1.9

q_{95}= 6, R_{ITB}~3.6m (+3.3m)

P_{NBI} = 12MW

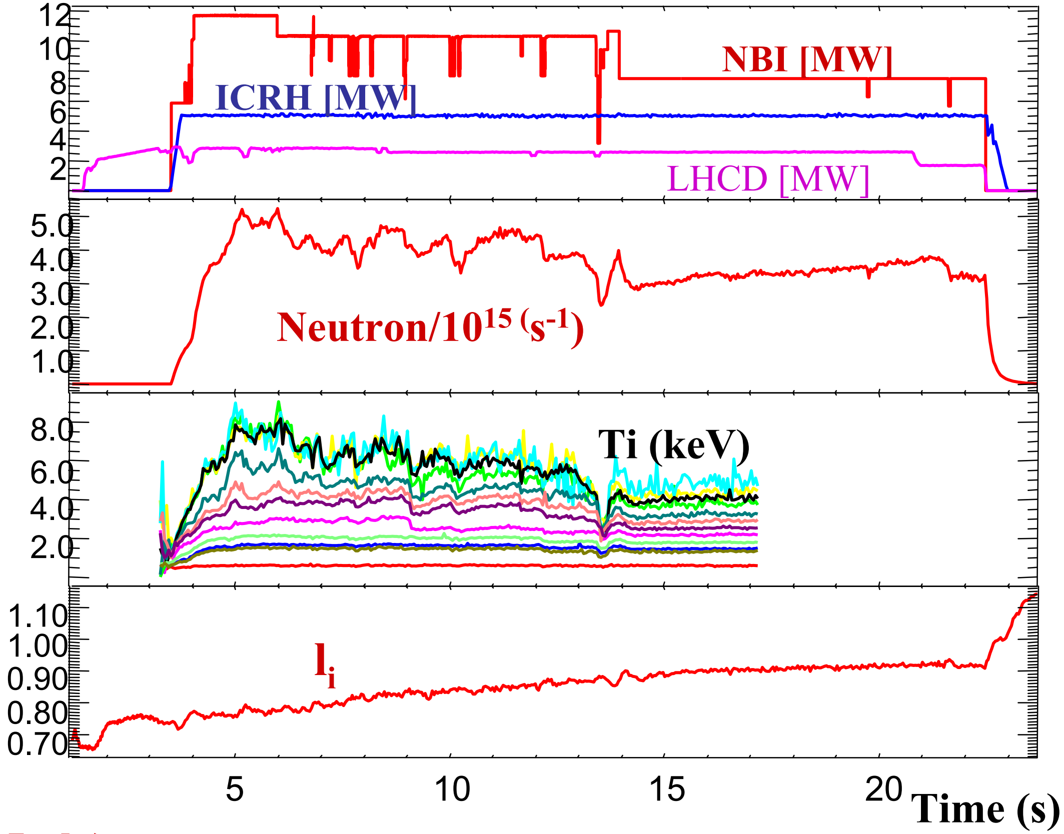
P_{ICRH} = 3MW

P_{LH} = 2.5 MW

First attempts to 20 s pulse:

#62065-1.6MA ==> short ITB (~20 τ_E)

but JET record of ~330 MJ injected



E. Joffrin (CEA, france), V.Pericoli (ENEA, Italy)

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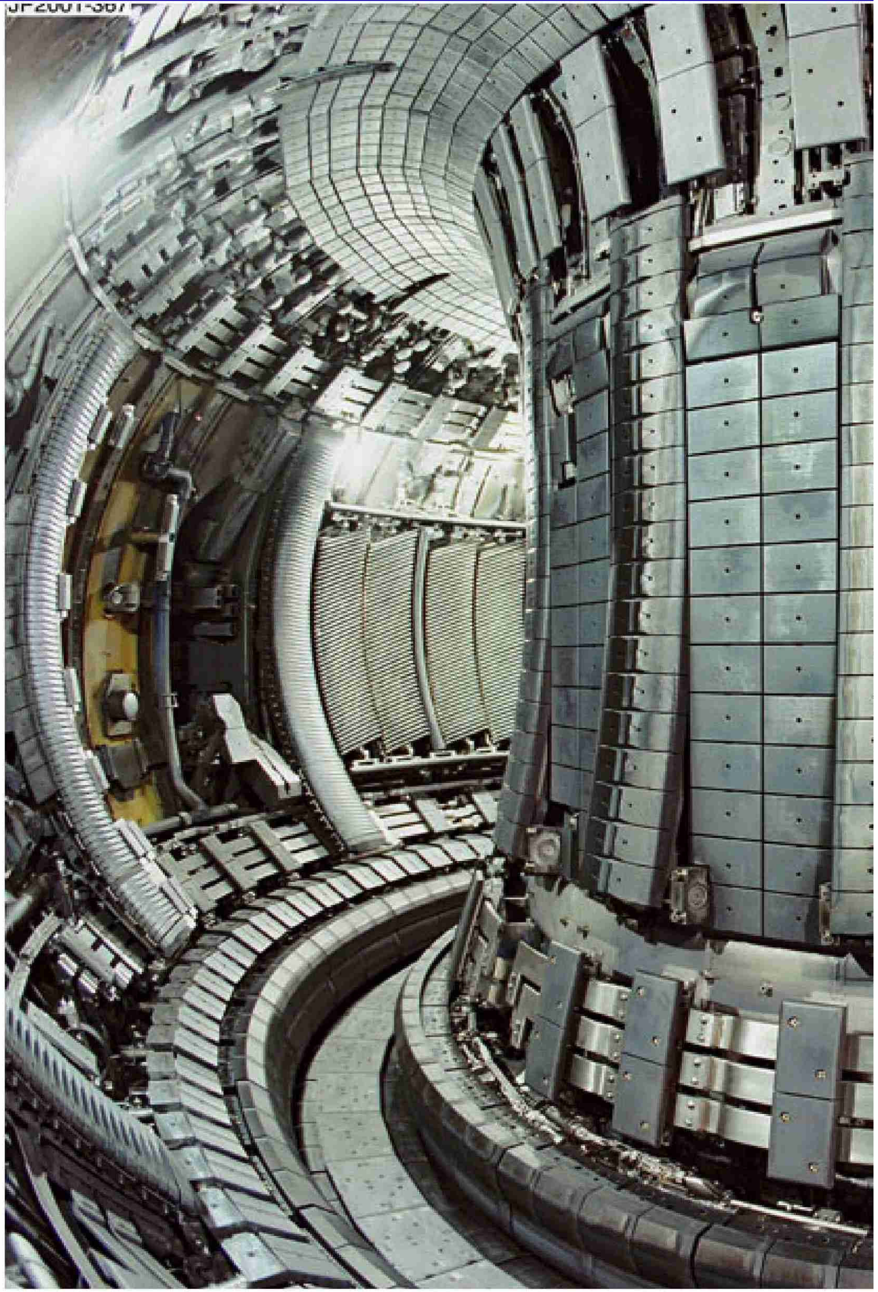
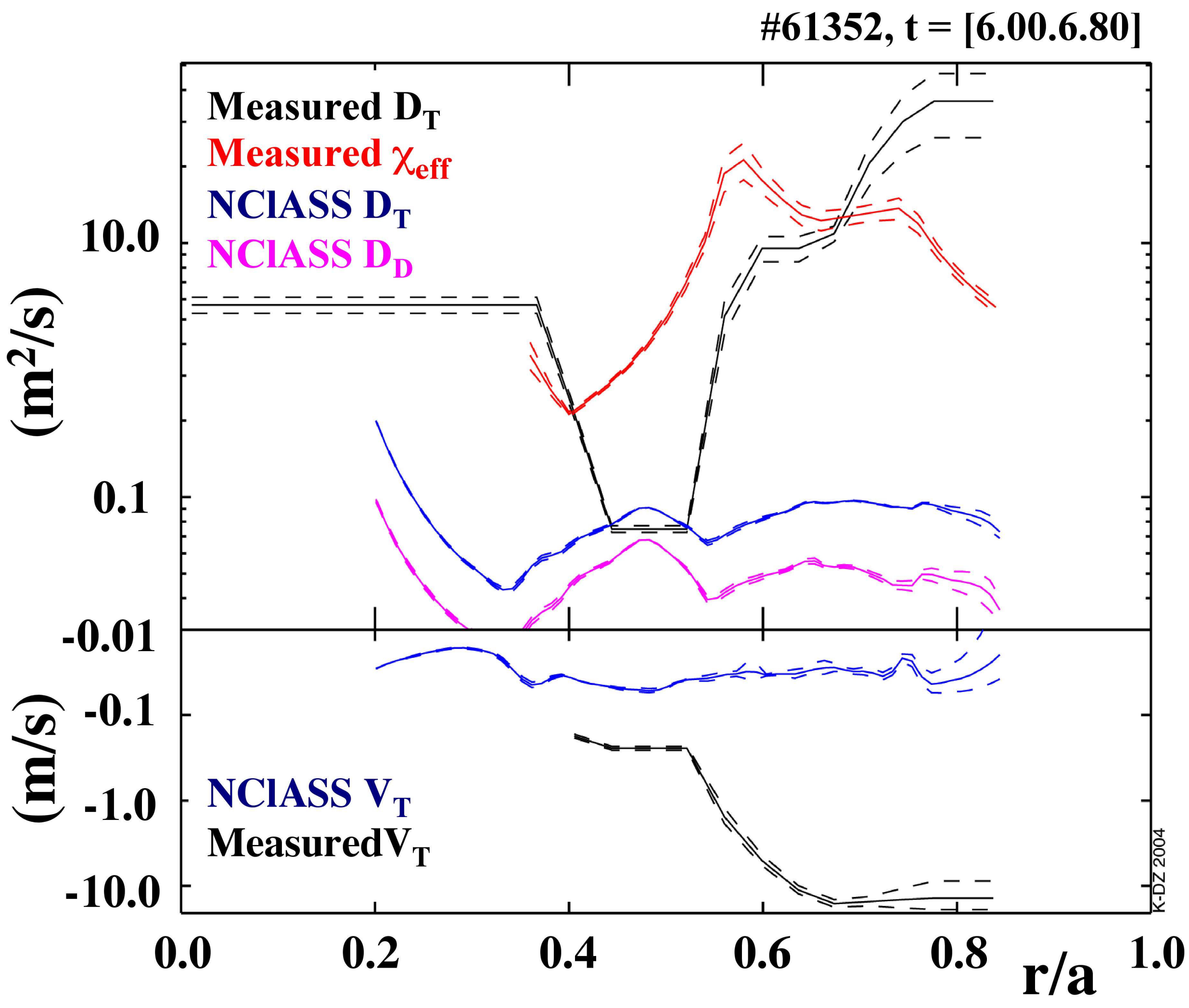


Fuel Transport in ITB discharges



Spatial and temporal neutron emissivity fitted by UTC/Sanco code:

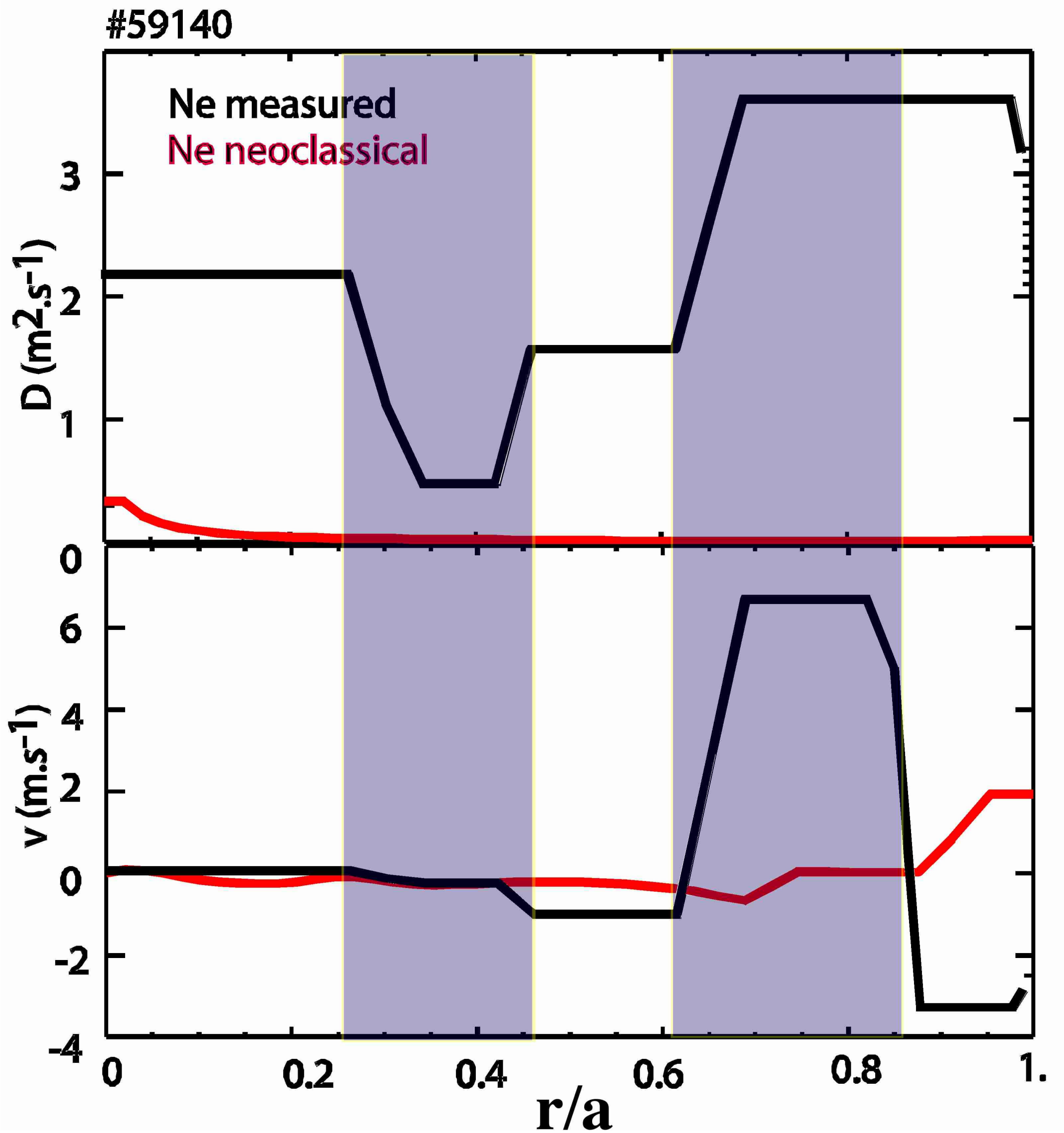
Tritium diffusivity decreases to neoclassical value at barrier location

Convection decrease too but higher than neoclassical

Again barrier seems a narrow layer of reduced diffusivity

J. Mailloux, C. Challis, K-D. Zastrow (UKAEA)

Impurity Transport in double barrier scenario



Best Fitting with UTC/SANCO Ne^{10+} density (CXS) and Ne^{7+} line intensity (VUV)

Double barrier structure evident on inferred transport coefficients of injected Ne

Comparable behaviour on stronger barrier, $C_s/\omega_{ci}*L_{Te}$>> 1.410^{-2}

Step down of diffusivity at inner ITB location but remains always higher than NC

Strong outward convection at outer ITB otherwise close to NC

C. Giroud (UKAEA, United Kingdom)

CONCLUSIONS

Integrate optimisation of core and plasma edge allowed AT research at JET progressing towards wide ITBs

Real Time Control techniques have contributed to this progress. Simultaneous RTC of pressure and current profile has also been achieved.

Wide barriers with foot close to H pedestal have been obtained at ITER relevant triangularity, $\delta \sim 0.45$, with edge MHD moderate by Ne injection

ITBs scenarios suitable for steady state operations have been developed bringing to a JET record of ~330 MJ of injected energy.

CONCLUSIONS

Hybrid regimes have been extended to ρ^* values close to ITER domain. Development of the regime with dominant Electron heating also started

Transport analysis of injected impurities, T fuel or heat wave induced by ICRF modulated power indicate that the ITBs behave as a layer of reduced diffusivity

Exploitation of developed scenarios at higher performance will progress in future JET campaigns accordingly with increasing power availability

Related Papers

Wednesday November 3rd

EX/4-2) E. Joffrin "The Hybrid scenario in JET: towards its validation for ITER"

EX/P2-1) F. Crisanti "JET RF Dominated Scenarios and Ion ITB Experiments with Low External Momentum Input"

EX/P2-5) D. Moreau "Development of Integrated Real-Time Control of ITB in Advanced Operation Scenarios on JET"

Thursday November 4th

EX/P3-11) F. Rimini "Development of ITB scenarios at ITER relevant high triangularity in JET"

EX/P4-28) J. Mailloux "ITER relevant coupling of Lower Hybrid Waves in JET"

Friday November 5th

EX/P6-18) P. Mantica "Progress in understanding heat transport at JET"