Overview of JET results

J.Pamela, J.Ongena et al.

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EFDA — EUROPEAN FUSION DEVELOPMENT AGREEMENT — JET

Acknowledging all contributors to the programme

EFDA Parties

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Morris, G.L Mort, A. Mück, M Murakami, A. Murari, D. Murdock, Y-S. Na, F. Nabais, Y Nakamura, G. Nash, V. Naulin, M.F.F. Nave, R Nazikian, I. Nedzelski, C. Negus, G.F. Neil, J.D. Neilson, B Nelson, R. Neu, W Nevins, G.J. Newbert, K. Nicholls, A. Nicolai, L. Nicolas, P. Nielsen, M. Nightingale, H. Nordman, J-M. Noterdaeme, S. Nowak, I. Nunes, M. Okabayashi, M Okabayashi, A Oleynikov, M. O'Mullane, J. Ongena, T Onjun, F. Orsitto, T Osborne, M. Ottaviani, K. Pagett, J. Paley, J. Palmer, J. Pamela, L. Panaccione, R. Panek,V. Parail, A. Parkin, B. Parsons, R. Pasqualotto, P. … G. Pereverzev, A. Perevezentsev, C Perez von Thun, V. Pericoli, Y. Perrot, S. Peruzzo, G. Petravich, L. Petri… A. Pironti, C S Pitcher, R. Pitts, A. Pizzuto, V. Plyusnin, N. Pomaro, P. Pool, S. Popovichev, C. Portafaix, G … R. Pugno, … Rainford, D Raisback, K. Rantamaki, J. Rapp, D Rasmussen, D. Reiter, G Rewoldt, T.T. Ribeiro, V. Riccardo, H L Riemerdes, F.G. Rimini, M. Riva, J. Roberts, R. Robins, D.S. 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International Collaborations

46 Laboratories Worldwide

Special thanks to Task Force Leaders and Operator (UKAEA)

JET's contribution in preparation of ITER

I- Optimising Fusion Performance

II- Preparing for Long Pulse Operation

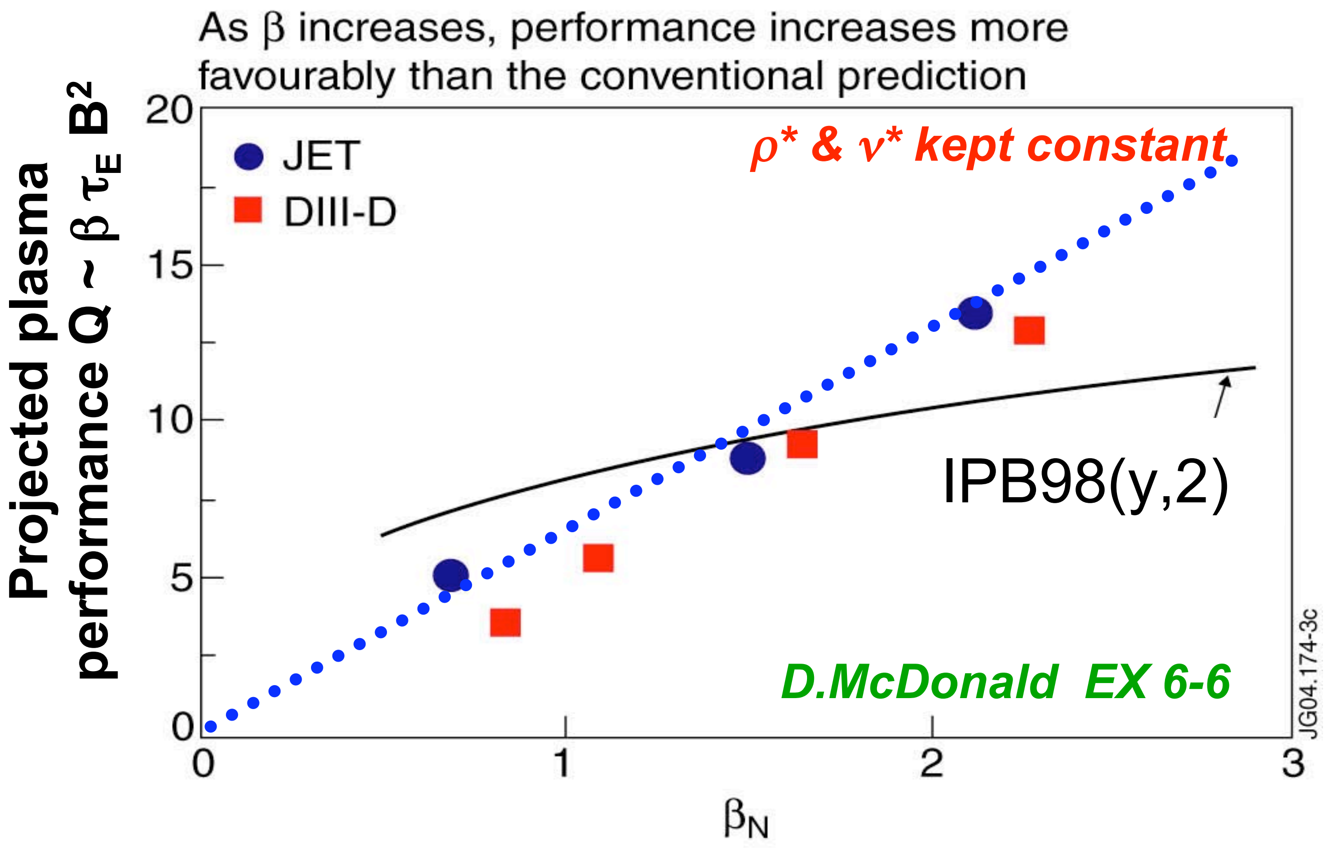
III- Optimising wall and divertor conditions (power deposition in steady and transient conditions)

IV- Controlling plasma in Real Time

V- Preparing for Burning Plasma Experiments

Trace Tritium Experiment overview by D.Stork (OV/4-1 Tuesday)

β-scaling of confinement could be more favourable than IPB98(y,2) *(joint JET/DIII-D experiment)*

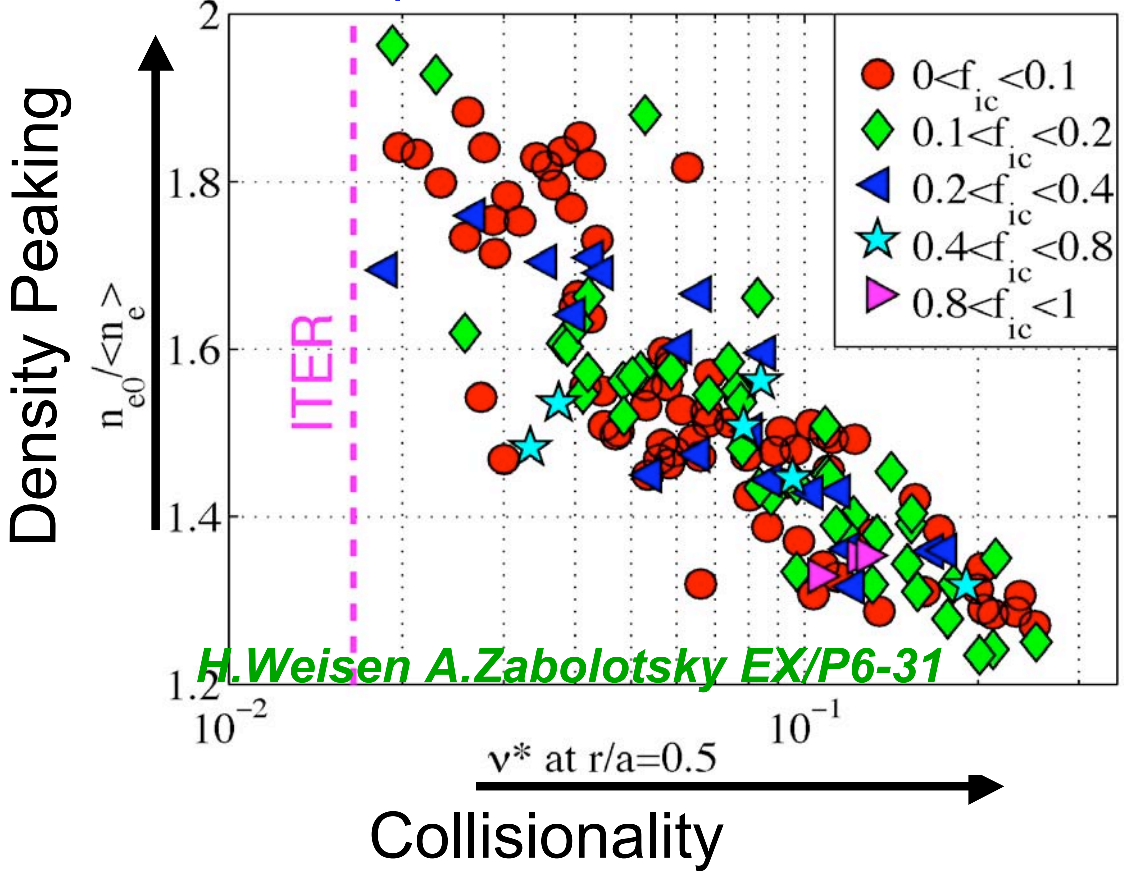


Further experiments with more heating required to reduce uncertainty and study β limit

Density profiles are peaked in H-mode at low collisionality

Peaking at low ν* independent of P_{rf}/P_{tot} (and of l_i)

=> could lead to higher fusion power in ITER



Confirmation of AUG results

Confirmation of extrapolation to ITER requires further experiments :

- **dominant electron heating**
- **extension to (high β_N, low ρ*)**

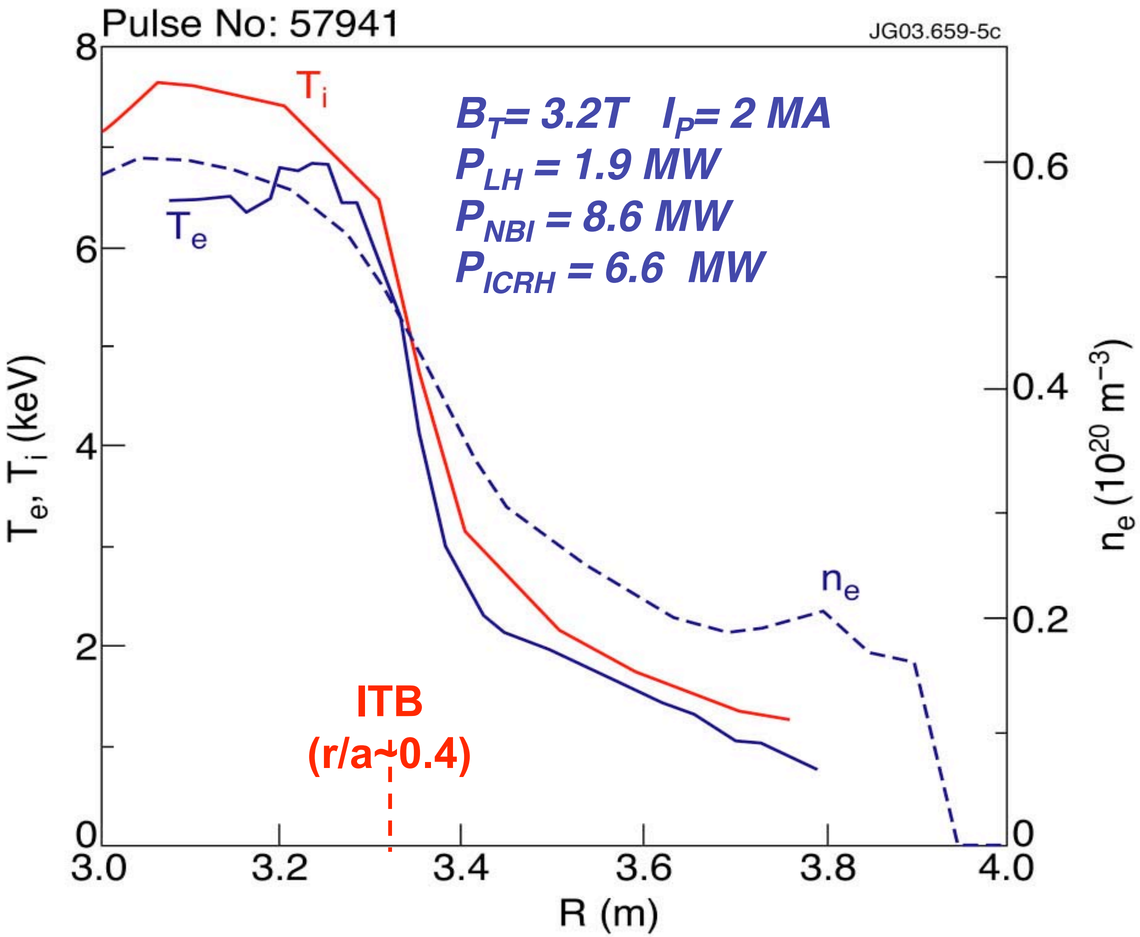
High density Internal Transport Barriers with Pellet fueling

SIGNIFICANT PROGRESS TOWARDS ITER RELEVANT CONDITIONS

⇒ ne(0) ~ 0.7 x 10^{20} m^{-3}
(~ $n_{Greenwald}$)

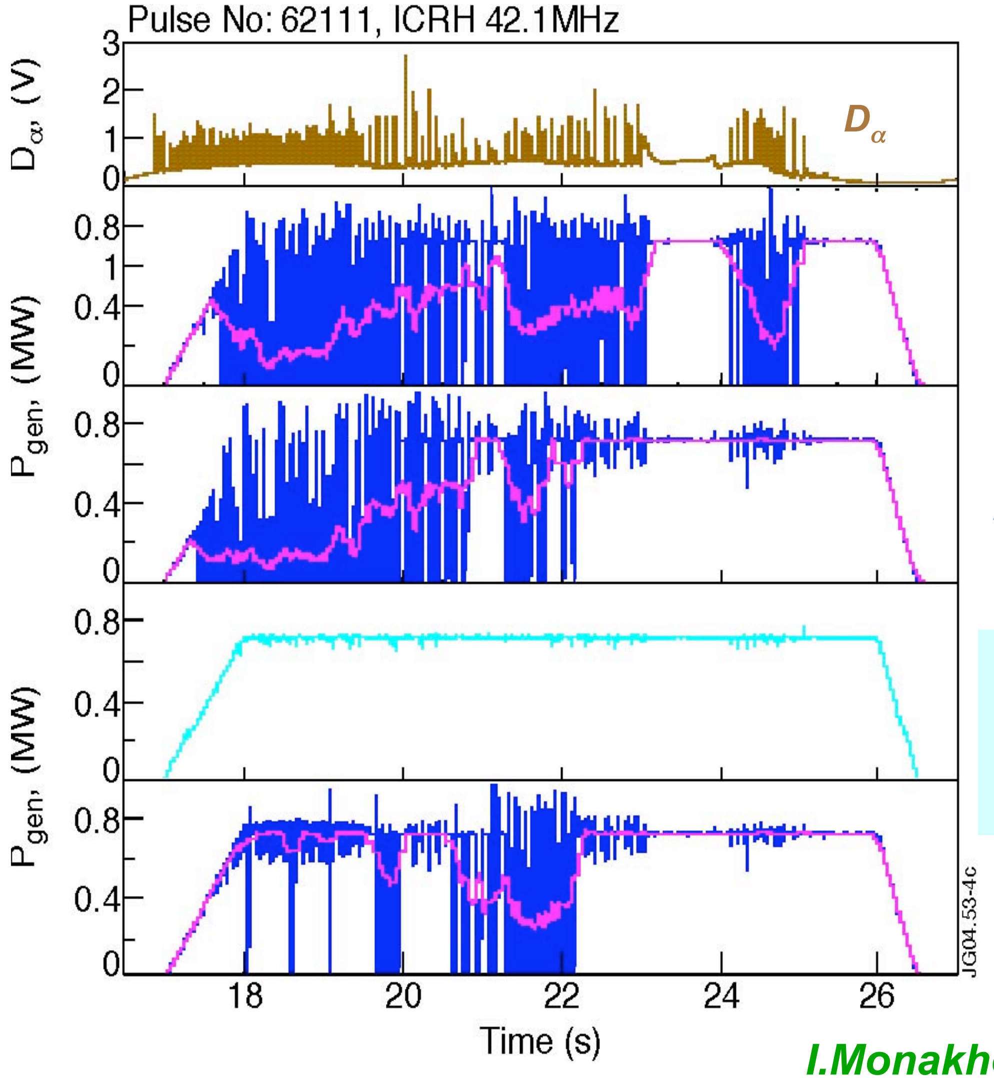
⇒ Te ~ Ti

⇒ Low toroidal rotation (4 times smaller than in standard ITB's)



A.Tuccillo, EX1-1
D. Frigione, C. Challis, M. de Baar, EPS 2003

ICRH: Proof of Principle of ELM Resilience with (External) Conjugate T Antenna Scheme



ELMy Plasma

⇐ *module 'A' - conventional matching*

⇐ *module 'B' - conventional matching*

⇐ *amplifier 'C' - conjugate-T matching*

Higher average power, lesser strain on generators

⇐ *module 'D' - conventional matching*

I.Monakhov, SOFT 2004 J-M.Noterdaeme SOFT 2004

Advanced scenarios with ITBs: progress towards ITER Steady State scenarios

V_{loop} close to 0

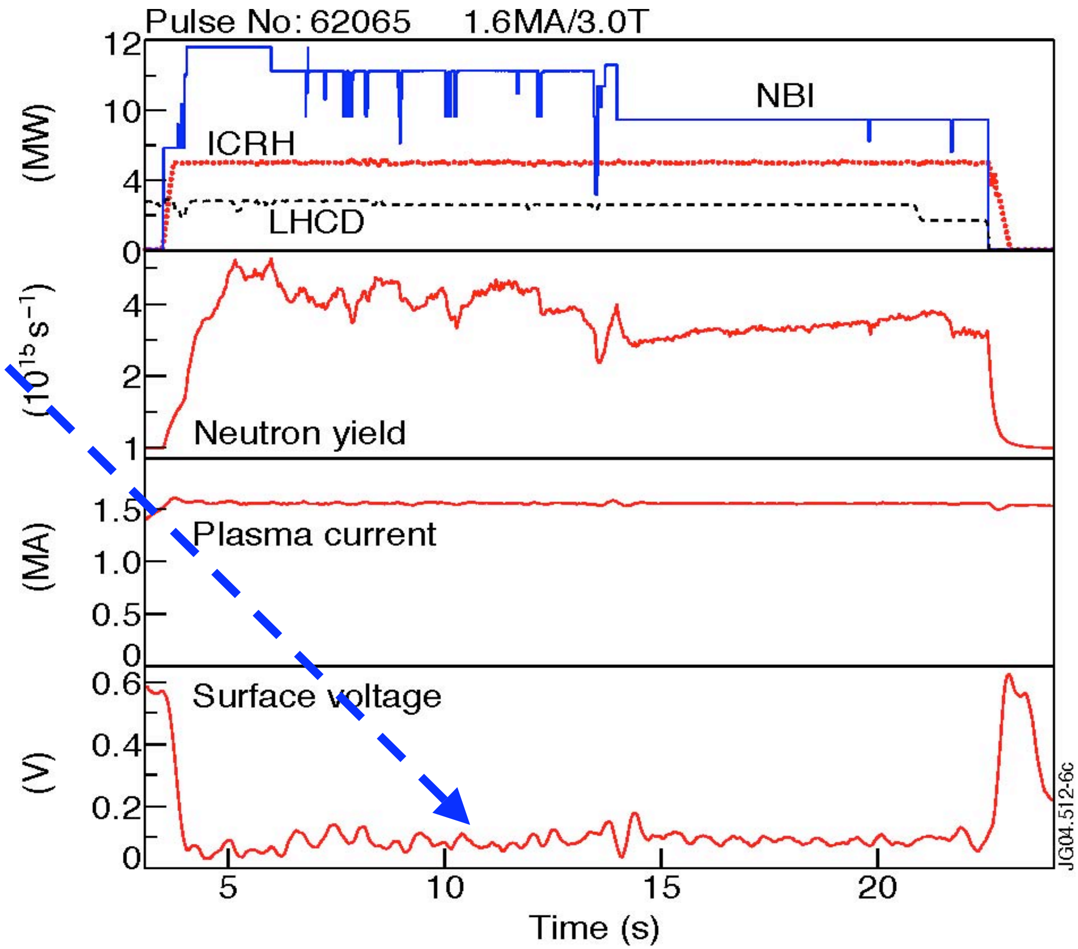
for 20 seconds

~1.6 MA

mostly current driven by heating systems and bootstrap current

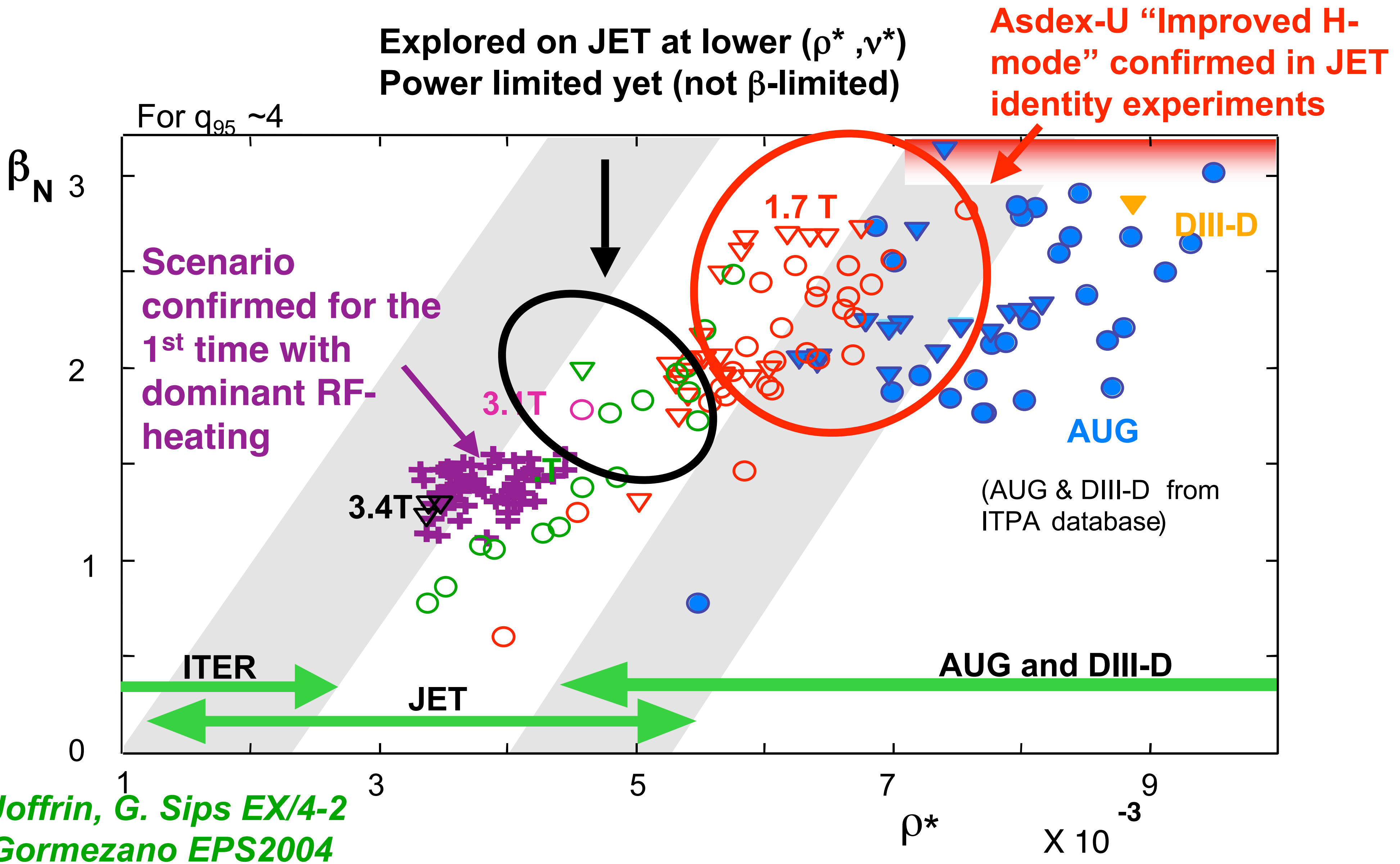
Record injected energy for JET : 326 MJ

(Full CD also obtained in other pulses, 1.8MA during 6-7 s periods)



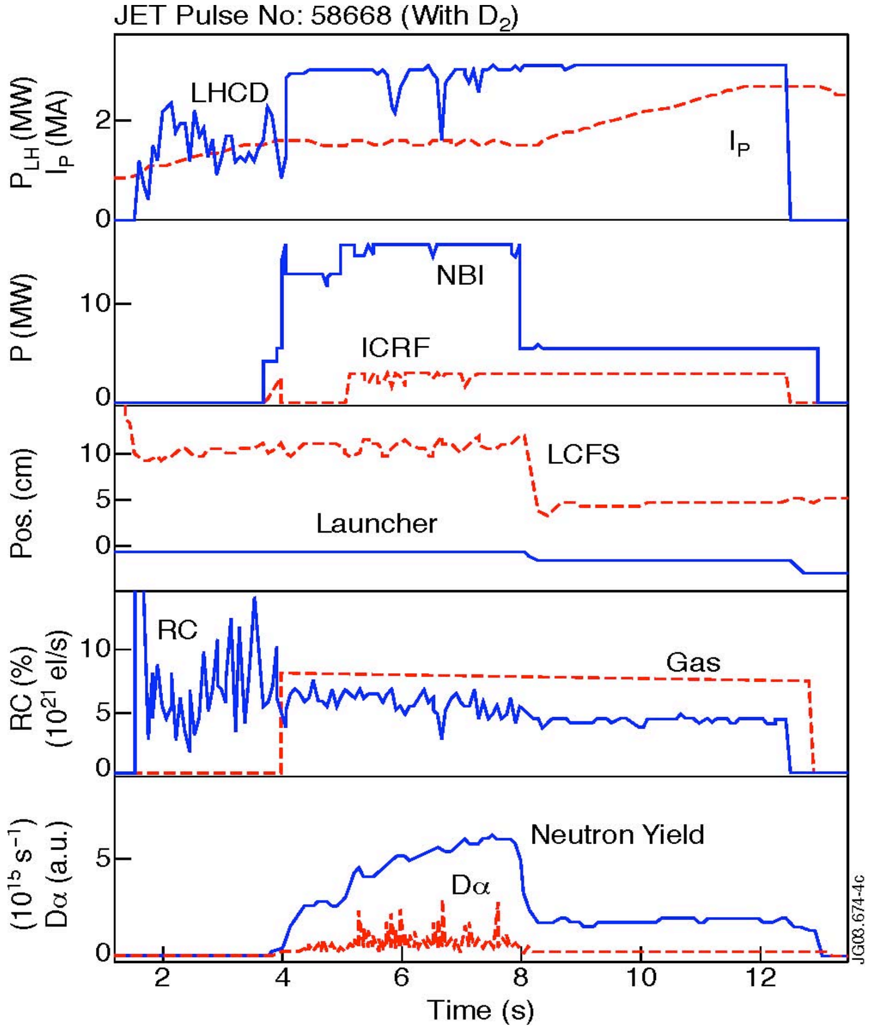
A.Tuccillo, EX1-1
V.Pericoli, EPS2003

Confirmation of "hybrid" scenarios on JET



E. Joffrin, G. Sips EX/4-2
C. Gormezano EPS2004

LHCD: ITER-relevant large distance coupling



3MW LHCD coupled

at 10-11cm distance between LCFS and launcher

with D_2 injection (8×10^{21}el/s) near the coupler

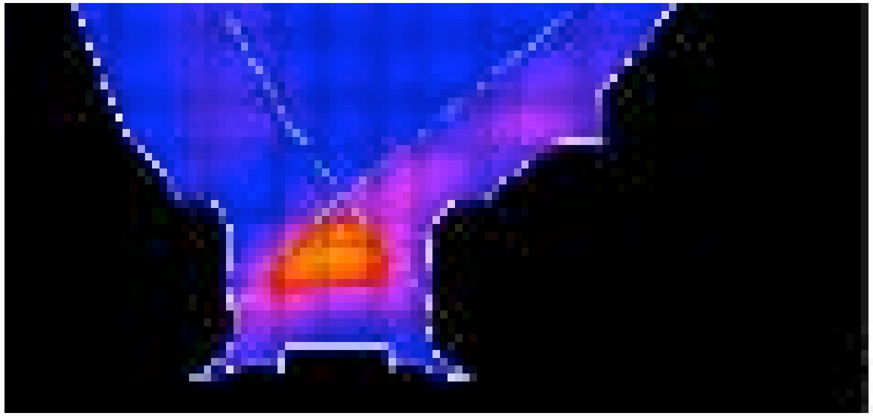
in ELMy plasma

Together with the successful test of the PAM coupler on FTU: important milestone achieved for LHCD towards ITER

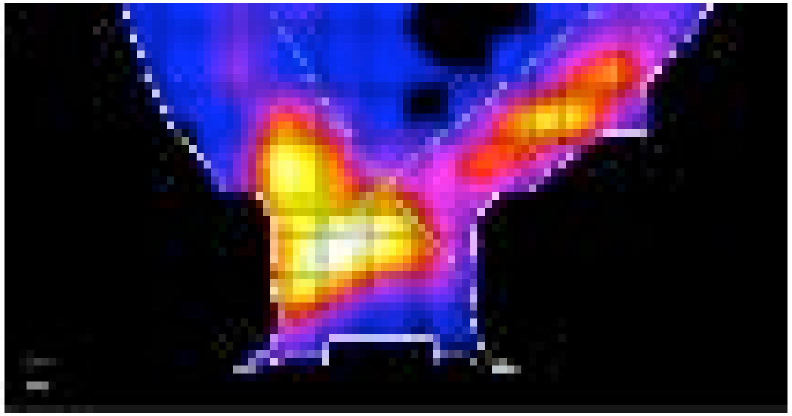
J.Mailloux EX/P4-28   A. Ekedahl, EPS 2004

Radiation in Divertor (bolometry)

Before ELM



After 1 MJoule type-I ELM



Divertor target ablation must be avoided

The quest for mild ELM regimes

- *Mixed Type-I-Type-II at n_e~n_G δ>0.4 up to 3MA*
  encouraging, but Type-I ELMs still there...*(Stober, EX/P1-4 and Sartori EX/6.3)*

- *N_2 seeded high radiation type-III ELMy H-mode 2.5MA* *(see later)*

***At lower current** (further from ITER ρ* and ν*): (Stober, EX/P1-4)*

- No controlled EDA modes found on JET (Alcator C-mod shape, 0.65MA)
- Type II ELM phases "à la AUG" found at ~0.9 MA
- grassy ELMy H-mode obtained under restrictive conditions *(see later)*

=> unfavourable ν (or ρ*) dependence for EDA and type II ?*
=> strong edge shear needed ?

ELM MITIGATION REMAINS TOP PRIORITY

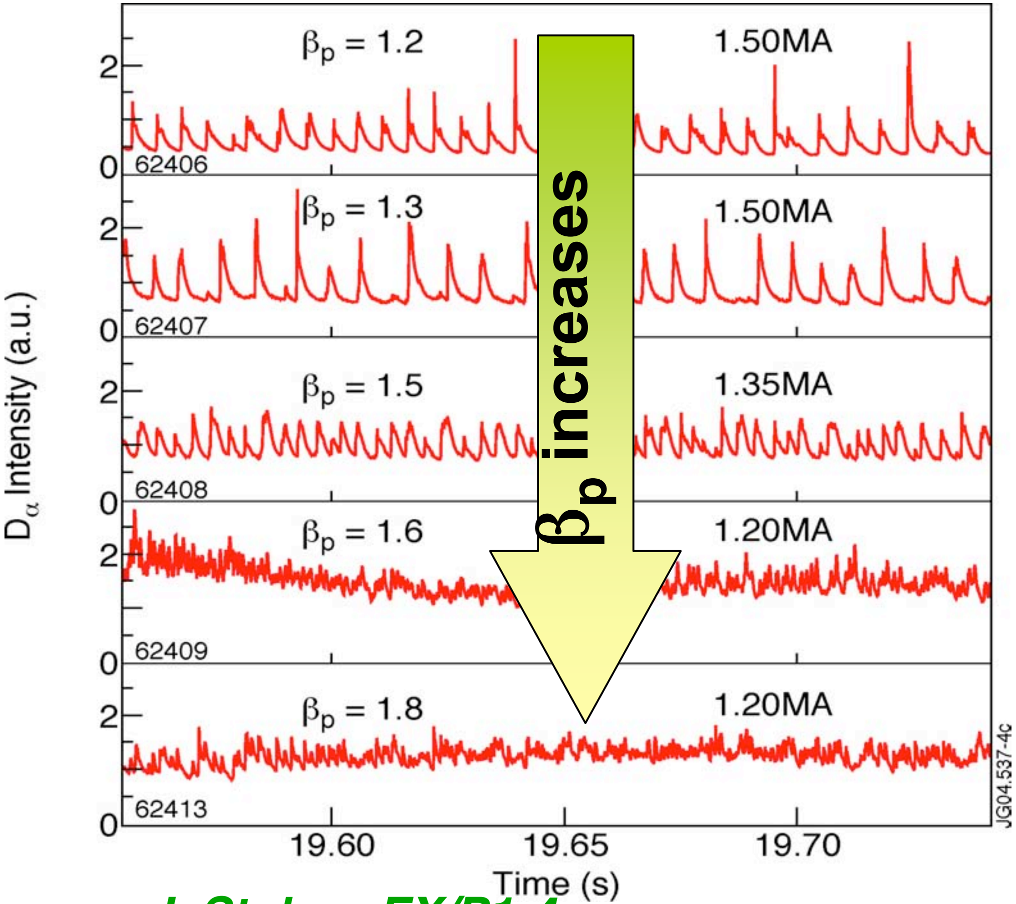
Impurity seeding / Edge ergodisation, see DIII-D / Pellet ELM-pacing, see AUG

+ MORE MODELLING EFFORTS and ELMs PHYSICS

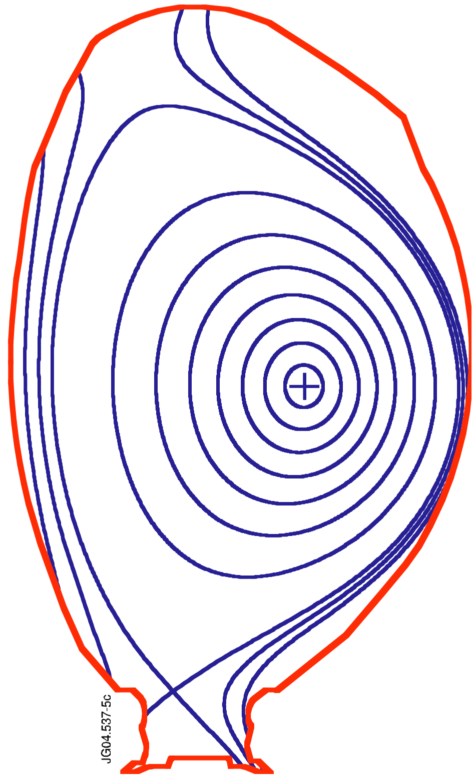
The quest for mild ELM regimes (ctd)

Grassy ELMs *(similar to JT60-U)*

low I_p~1.2MA, q_{95}~6-7, QDN, $\beta_p \geq 1.6$



J. Stober EX/P1-4
G. Saibene EPS2004



so far quite restrictive conditions / further exploration needed

The quest for mild ELM regimes (ctd)

Type III ELMy H-mode with N_2 seeding

	ITER Q=10 17MA	JET #59029
I_p	17MA	2.5MA
B_t	5.3T	2.0T
H_{98}	0.75	0.73
f_{GDL}	1.0	1.05
β_N	1.5	1.7
q_{95}	2.6	2.6
T_i/T_e	1.1	1.2
δ	0.5	0.44
f_{rad}	0.75	0.8
Z_{eff}	1.7	2.2
$\Delta W_{ELM}/W_{tot}$	≤1%	0.7%

J.Rapp et al.

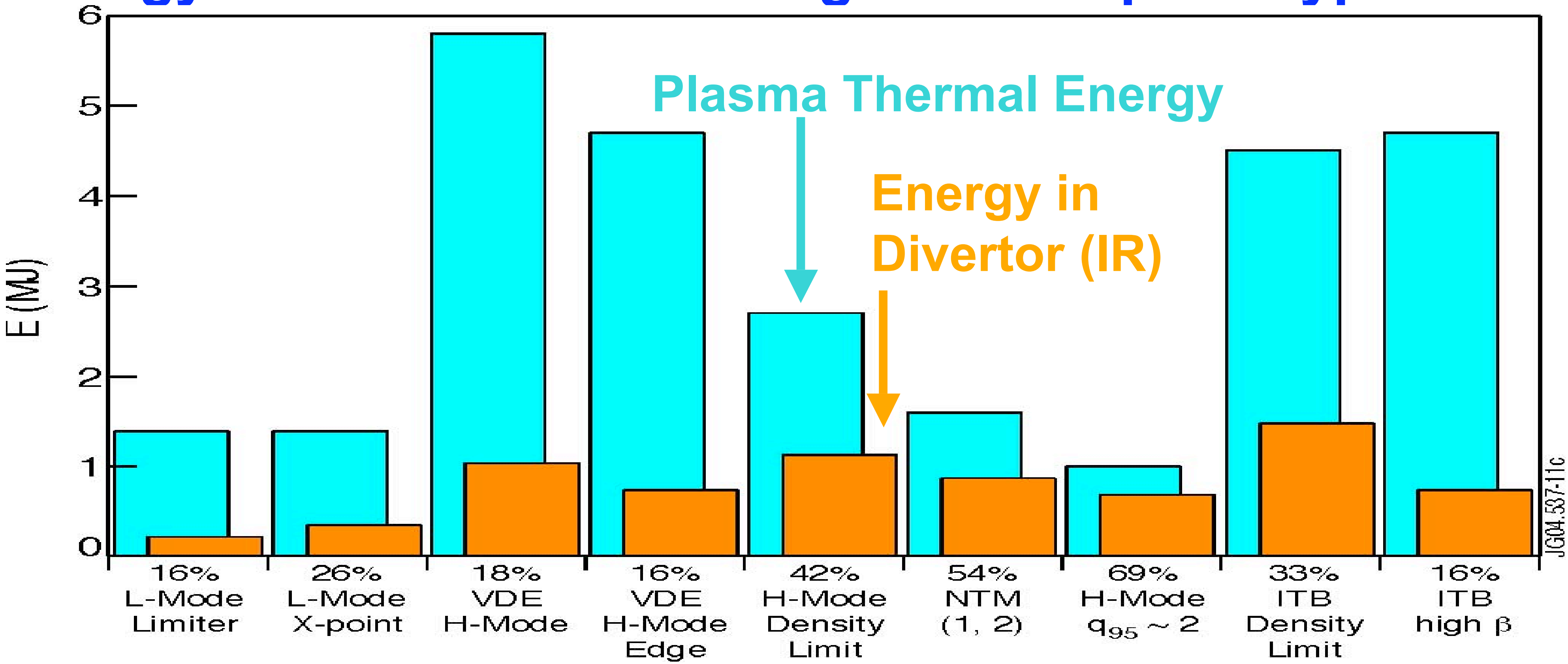
NF44 (2004)312

confinement degradation could be a price to pay to achieve very mild edge conditions (radiation up to 95%)

=> this scenario could extrapolate to ITER (Q=10 at 17MA)

=> scaling needs to be determined

Energy balance in a wide range of disruption types



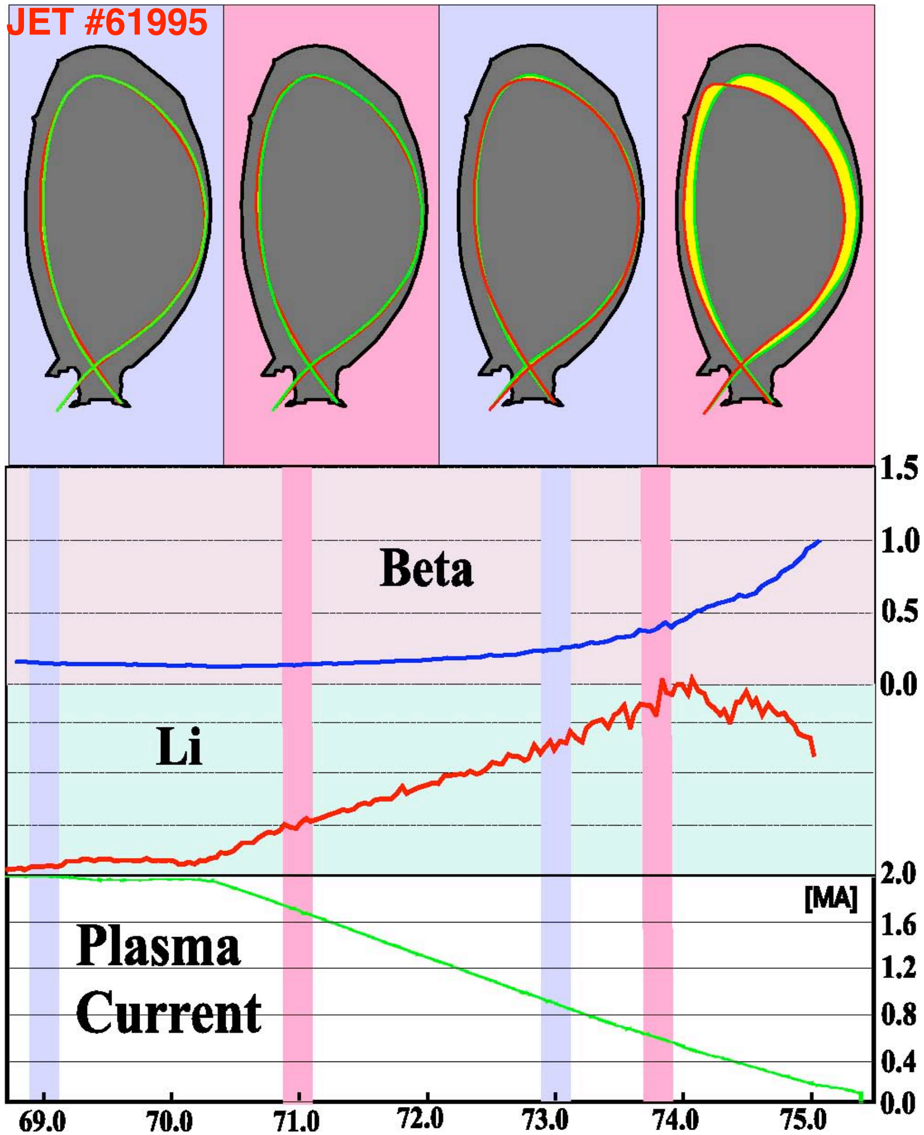
• ***Only a fraction of $W_{thermal}$ measured into the divertor (<u>similar results with large ELMs power deposition</u>)***

=> ITER divertor specifications wrt transients might be relaxed

=> Consequences for ITER first wall to be assessed

A.Loarte IT/P3-34 V.Riccardo, submitted to PPCF and NF

Real Time Control of the Plasma Shape with the Extreme Shape Controller (XSC)



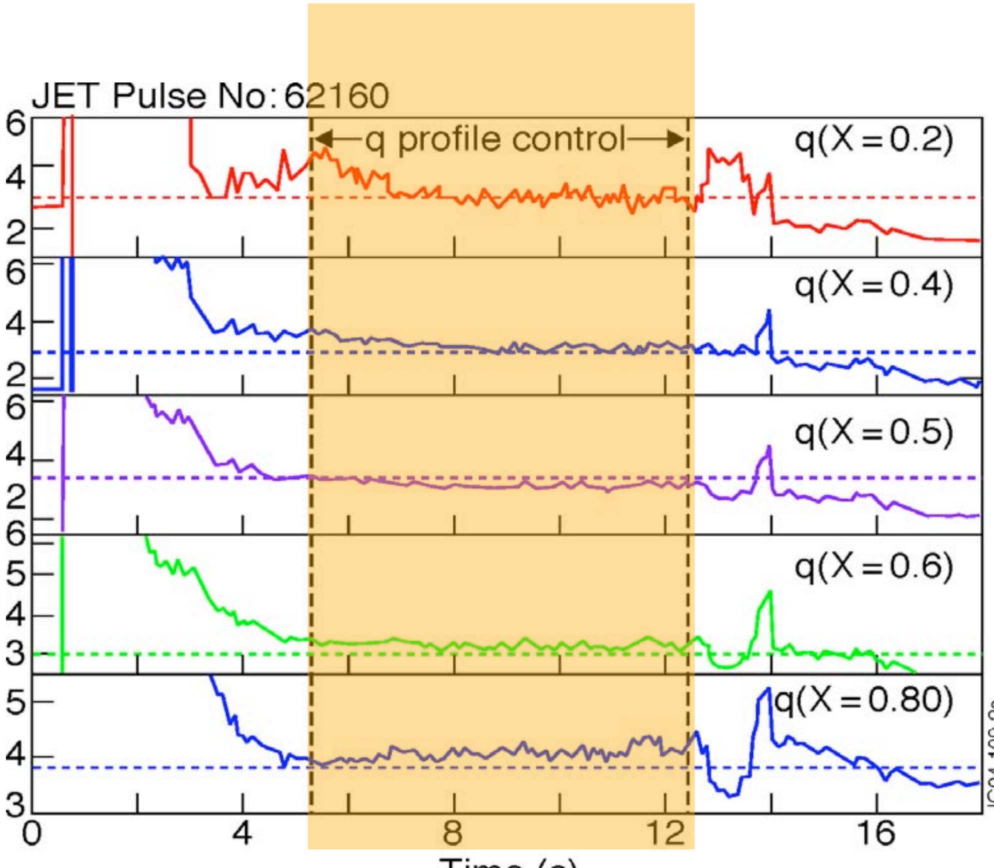
Plasma shape kept as constant as possible even in the presence of large variations of β_p and l_i

=> safe operation of highly shaped ITER-like configurations

F.Sartori, Albanese, De Tommasi/UKAEA, Ambrosini/ENEA, SOFT 2004

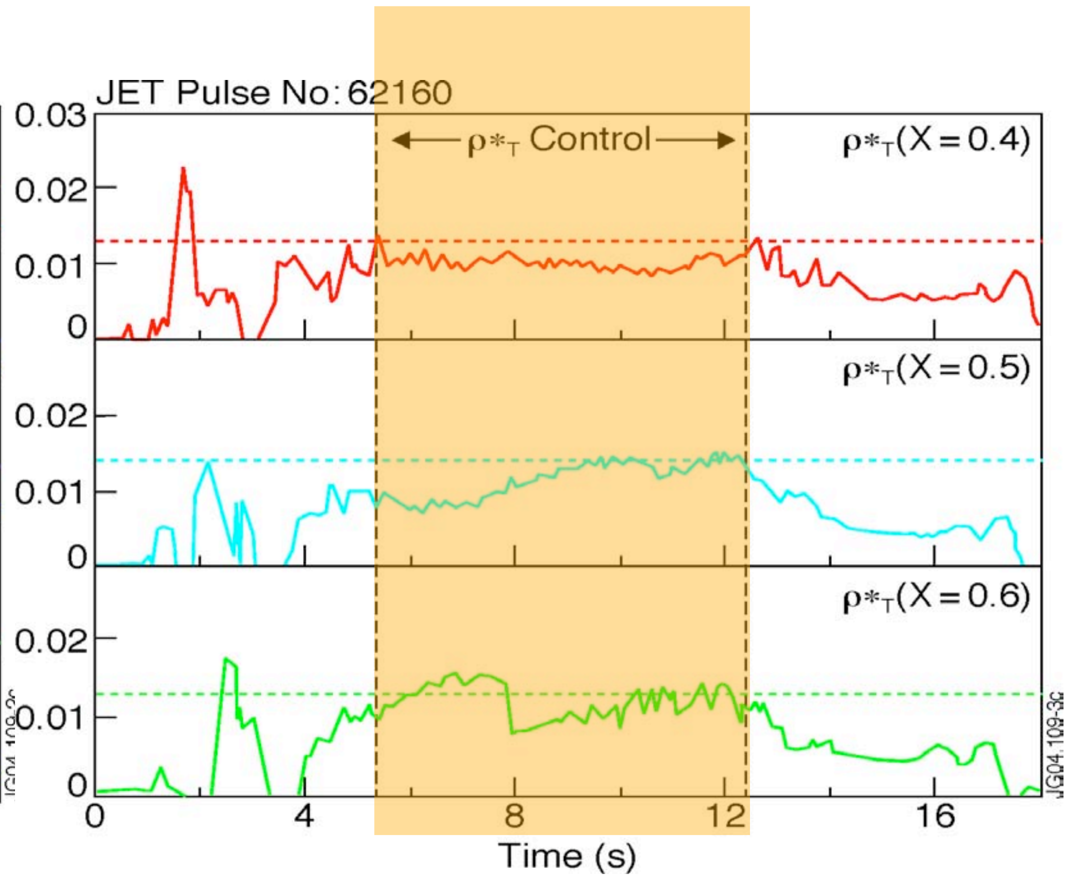
First simultaneous control of q-profile and ITB strength

q profile control



<- 7 seconds ->

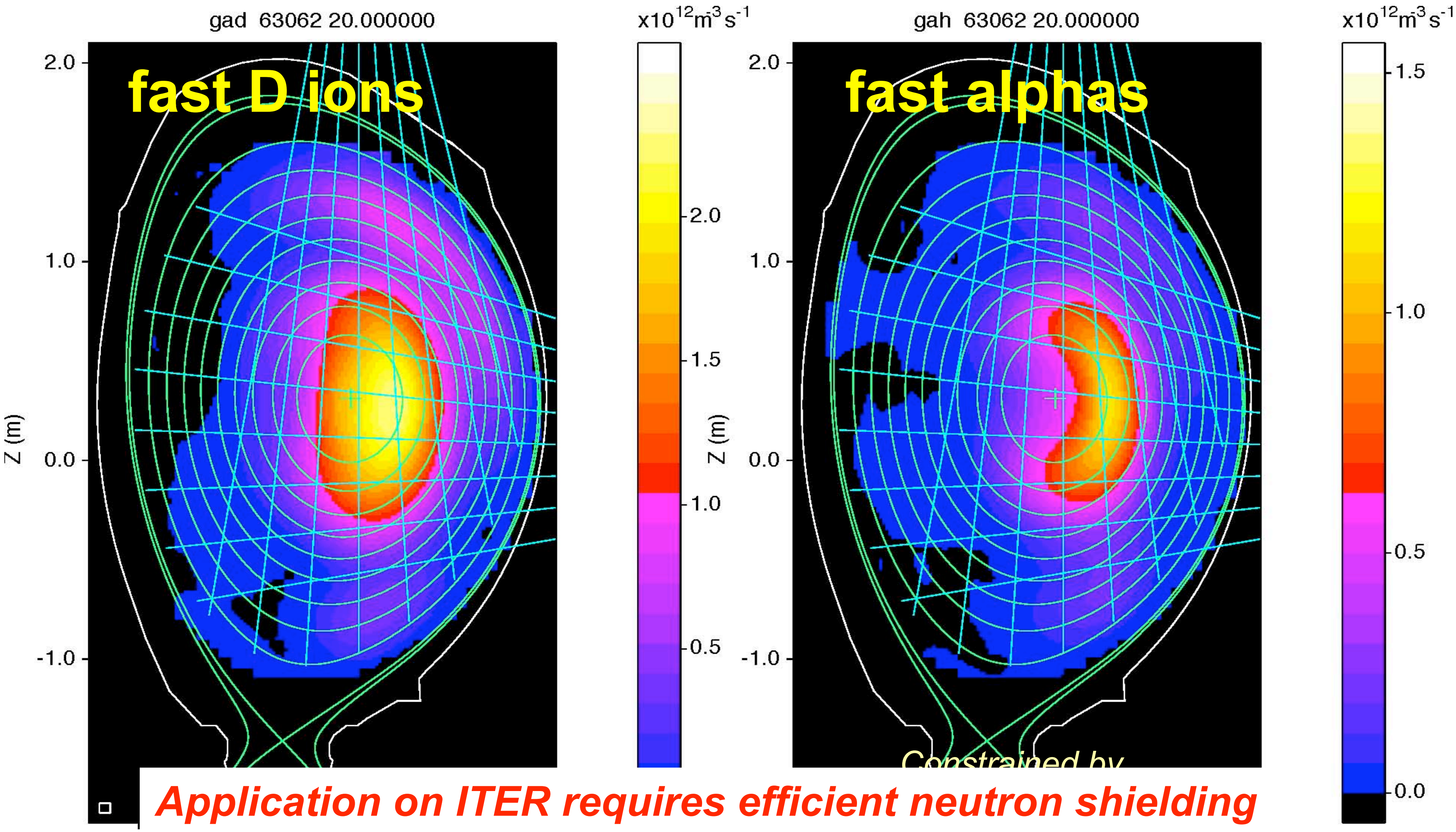
ρ^*_{Te} control



- 3T/1.7MA $H_{89} \times \beta_N \sim 3.4$

D.Moreau EX/P2-5, T.Tala TH/P2-9
A.Tuccillo EX/1-1

Progress towards ITER Burning Plasma diagnostics Fast particle γ-Tomography

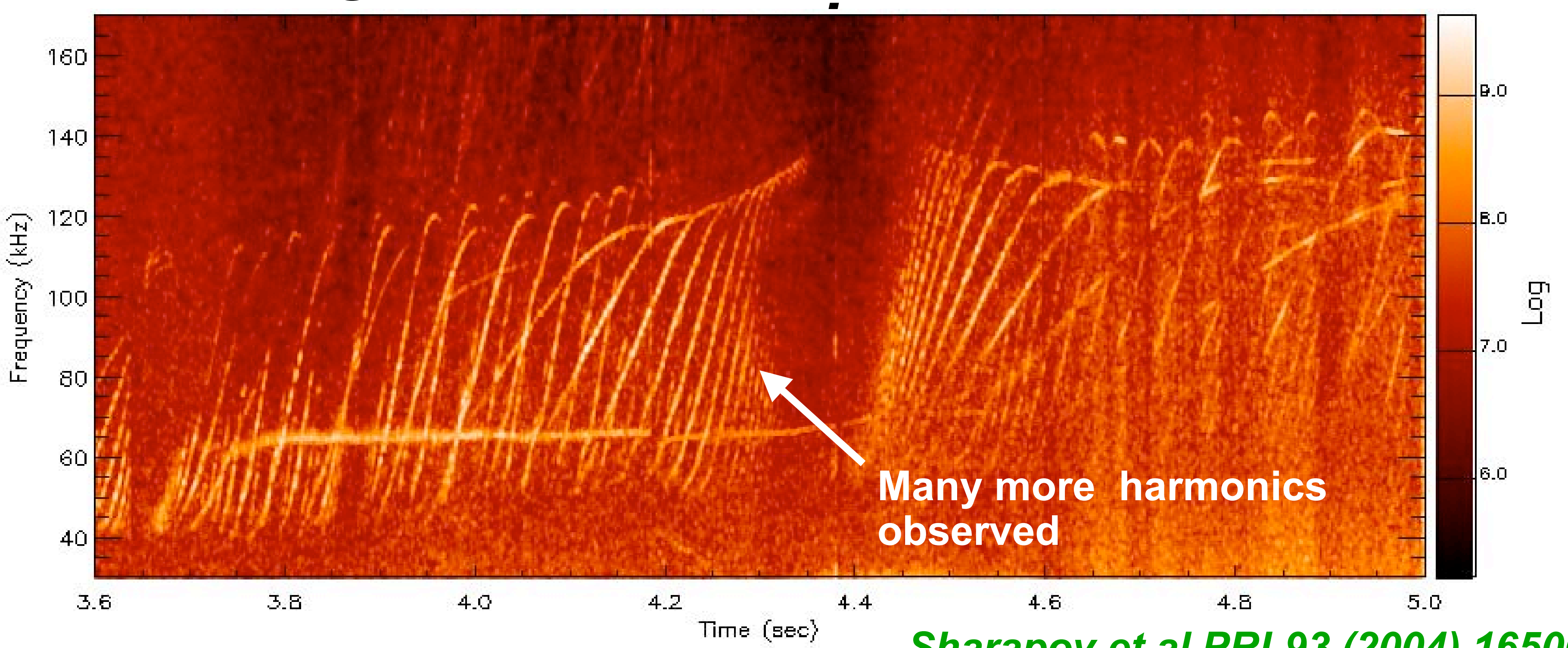


Application on ITER requires efficient neutron shielding

(on-going work with Russian Federation)

Alfvén Cascades

Reflectometer in interferometric mode reveals unprecedented cascade evolution details showing modes up to n=16:

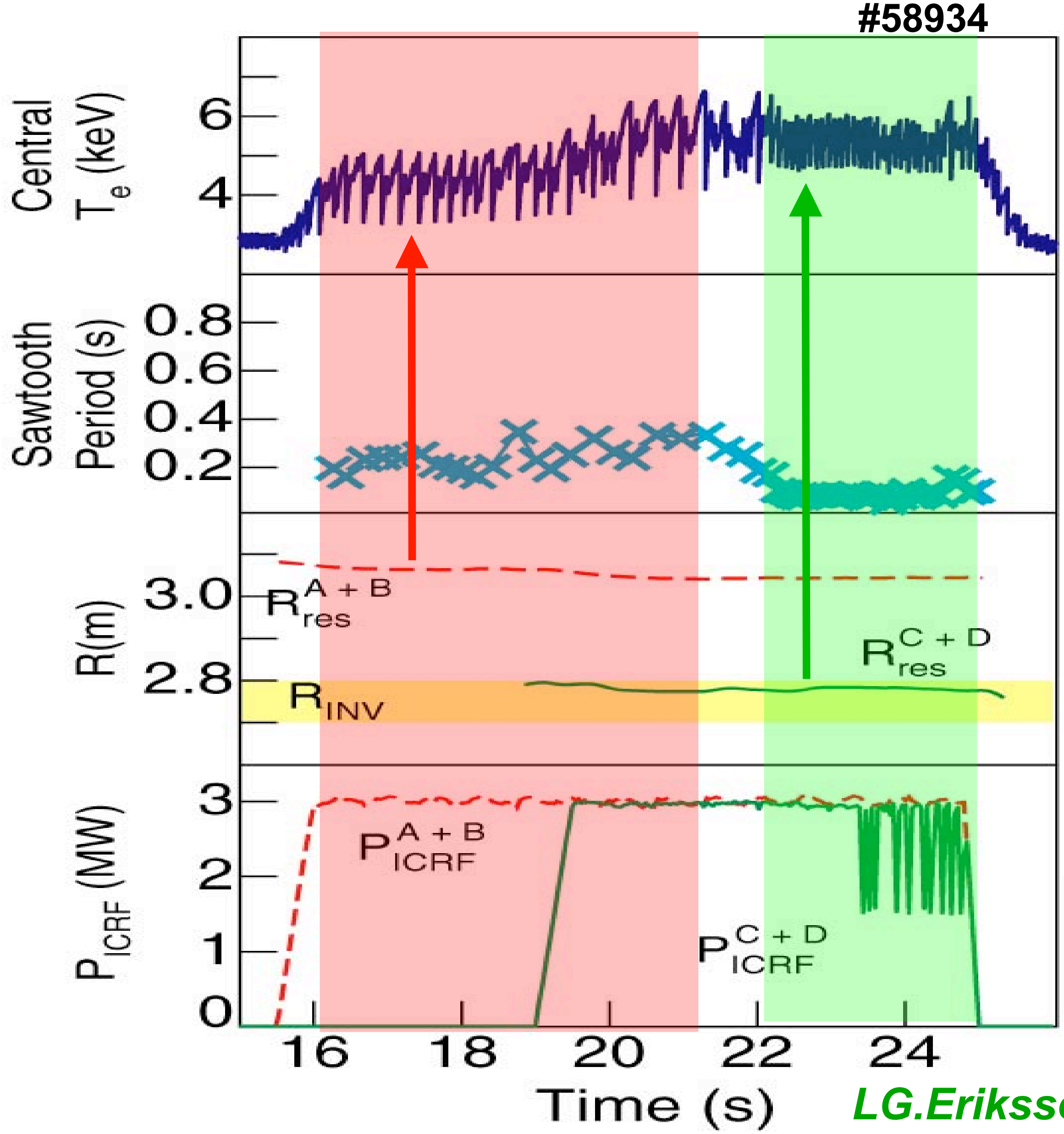


Sharapov et al PRL93 (2004) 165001

see also R.Nazikian EX / 5-1

Key tool for fast particle studies, in particular in advanced modes

'Monster' sawtooth control



core +90º phasing ICRH to make fast particles and large sawteeth (period up to 0.4s)

q=1 -90º phasing ICRH for current drive sawtooth destabilisation

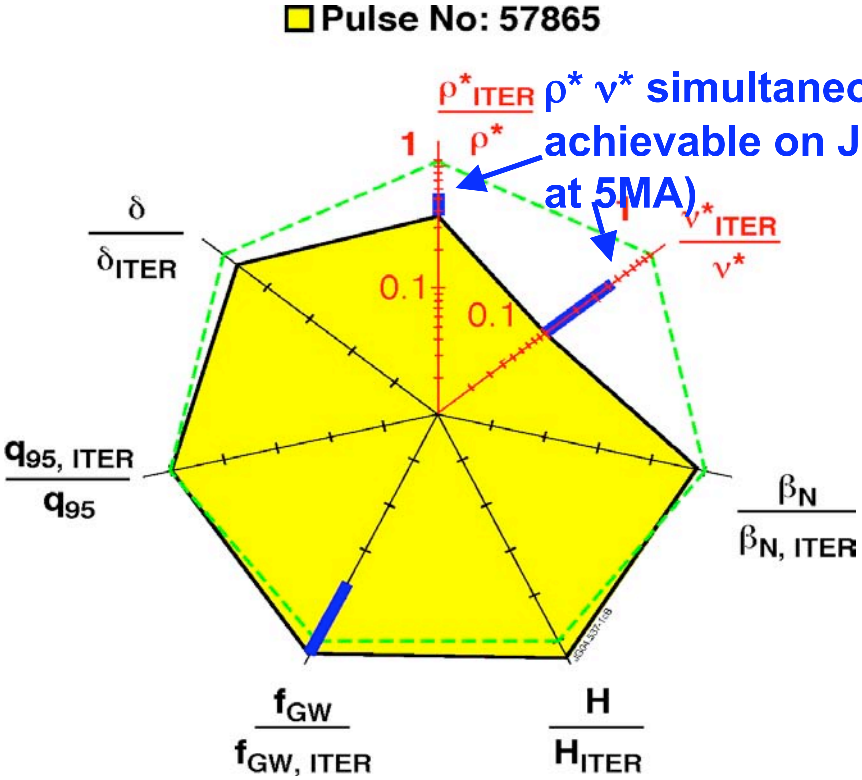
Essential technique for ITER to control fast alphas stabilised sawteeth

R.Buttery, EX/7-1
LG.Eriksson et al PRL92 (2004)235004

EUROPEAN FUSION DEVELOPMENT AGREEMENT

Summary of ELMy H-Mode Development

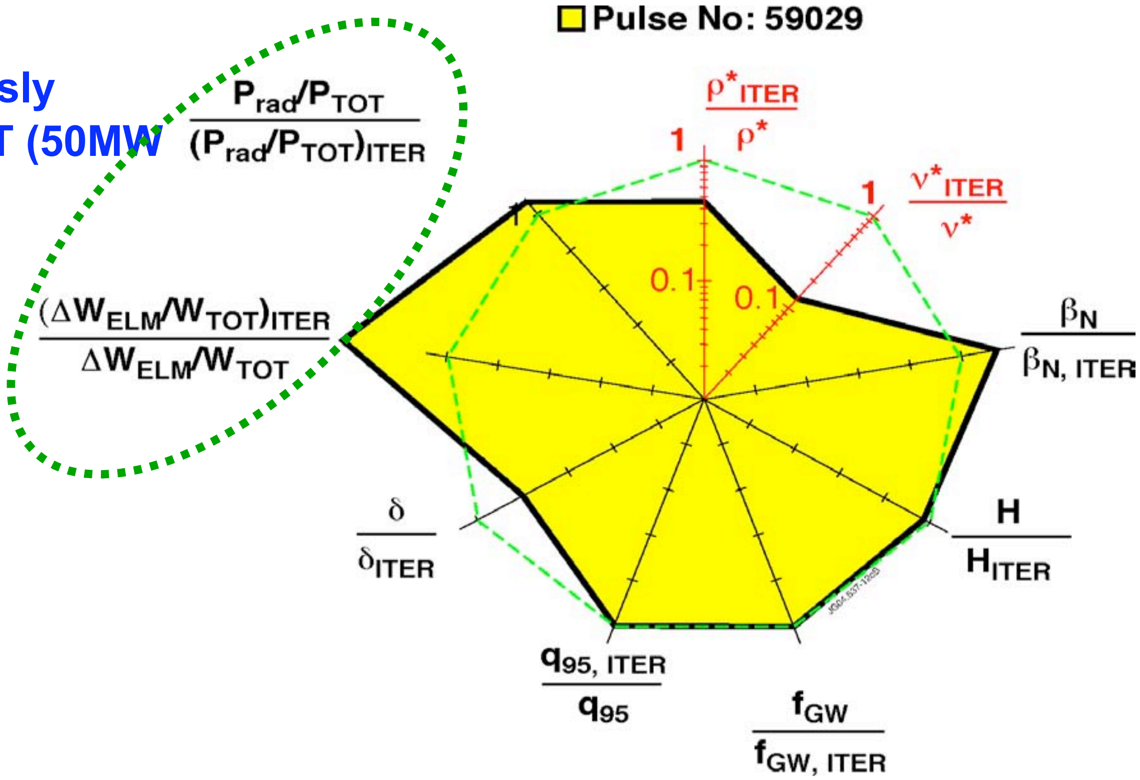
Type I ELMs



ITER (Q=10, Ip= 15 MA, inductive):
δ=0.49 q_{95}= 3 f_{GW}= 0.85 H=1
β_N=1.8

Type III ELMs, N_2 seeding

(new development)

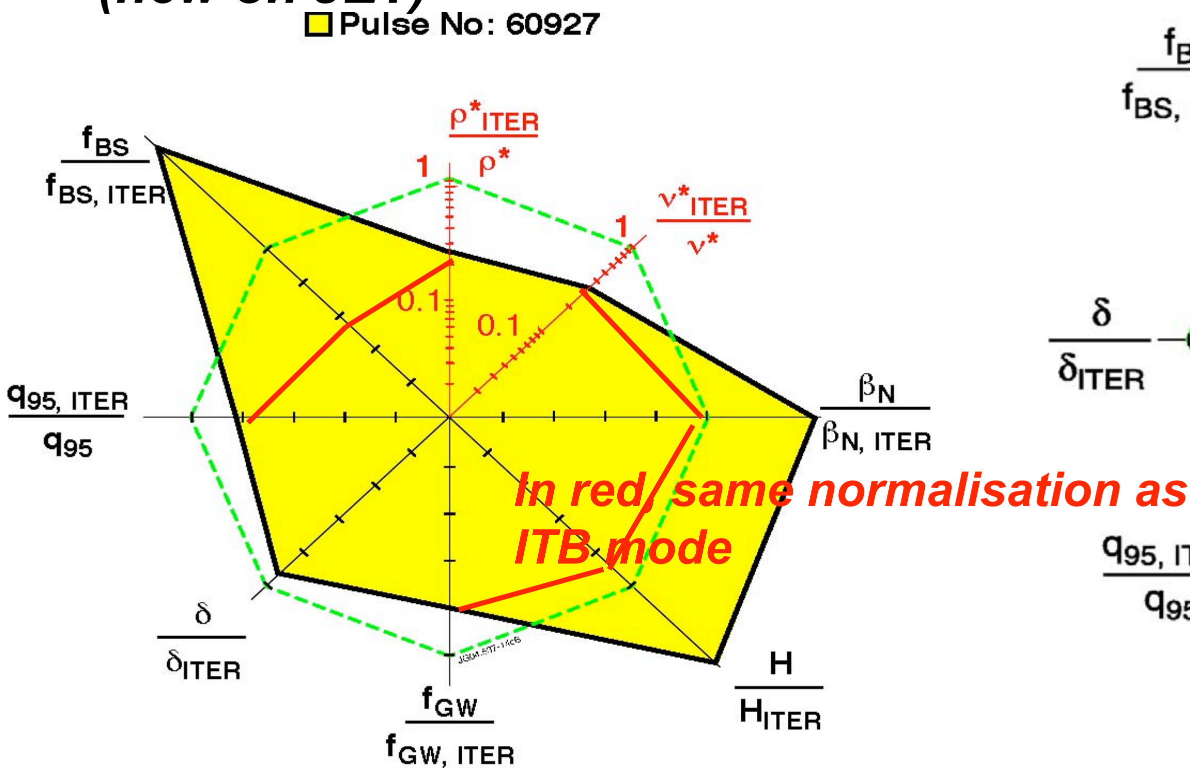


ITER (Q=10, Ip=17 MA, inductive) :
δ=0.49 q_{95}=2.6 f_{GW}= 1 H=0.75 β_N=1.5
$\Delta W_{ELM}/W_{TOT}$= 1% P_{rad}/P_{TOT}=75%

Summary of advanced modes development

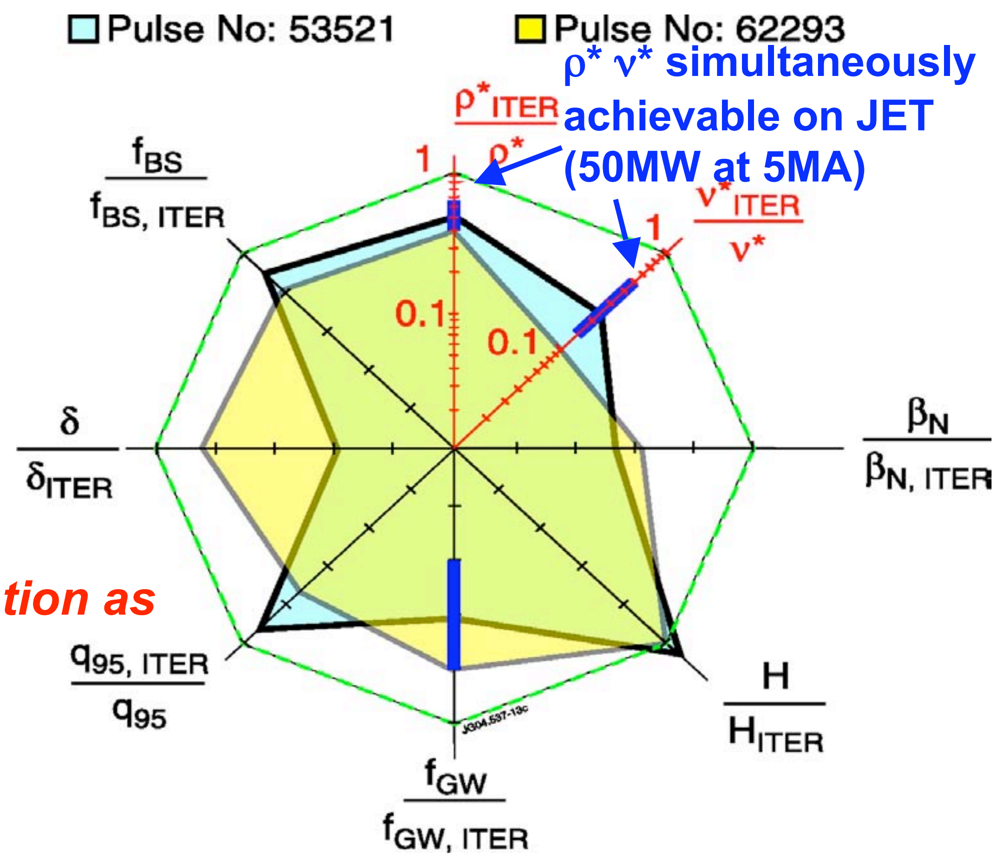
Hybrid Mode or improved H-mode

(new on JET)



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



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%

Nota Bene: much milder requirements used in the normalisation for Hybrid Mode

Conclusion: progress towards ITER

- High confidence in ELMy H-mode performance for ITER (Q=10 reference)
- More favourable β_N scaling and density peaking at low collisionality

Likely to increase margins for high fusion performance on ITER

- ITB Plasmas extended towards high performance, high density, long pulses
- Hybrid modes confirmed on JET and extended towards ITER conditions

Long Pulse modes and their control progressing well / scaling to be determined

- steady mild ELM regimes achieved with loss of confinement (N2 seeded Type III) or in restrictive conditions (grassy ELMs)

Encouraging results on mild ELMs / Mitigation of ELMs remains top priority

- Lower power fraction than foreseen in Divertor during transients (disruptions, ELMs) *ITER Divertor and First Wall specifications may need revision*

- Erosion, SOL flows and deposition studies (results not shown, see PSI 2004)

Favourable for T-retention / *Be wall lifetime to be assessed*

- ITER-relevant ICRH (conjugate T) and LHCD coupling (large distance)
- Real Time Control Demonstrations (highly shape plasmas; j(r) and T(r) profiles in ITB plasmas)
- Advances in Burning Plasma Diagnostics (fast particles γ-tomography, Alfvèn cascades, neutrons)

Support to defining ITER auxiliaries progressing well

EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

ORAL PRESENTATIONS reporting JET related results

Tuesday 2 November

OV4/1 Derek STORK Overview of Transport, Fast Particle and Heating and Current Drive Physics using Tritium in JET plasmas
EX1/1 Angelo TUCCILLO Development on JET of Advanced Tokamak operations for ITER
EX1/4 Wolfgang SUTTROP Studies of the "Quiescent H-mode" regime in ASDEX Upgrade and JET
EX2/4-Ra Wojczek FUNDAMENSKI Power Exhaust on JET: an Overview of Dedicated Experiments
FT1/3 Richard GOULDING Results and Implications of the JET ITER-Like ICRF Antenna High Power Prototype Tests

Wednesday 3 November

TH2/1 Yueqiang Liu Feedback and Rotational Stabilization of Resistive Wall Modes in ITER
EX4/2 Emmanuel JOFFRIN The "hybrid" scenario in JET: towards its validation for ITER
IT1/2 Gabriella SAIBENE Dimensionless identity experiments in JT-60U and JET

Thursday 4 November

EX5/1 Raffi NAZIKIAN Energetic Particle Driven Modes in Advanced Tokamak Regimes on JET, DIII-D, Alcator C-MOD and TFTR
EX5/2-Ra Sergei SHARAPOV Experimental studies of instabilities and confinement of energetic particles on JET and on MAST
EX6/3 Roberta SARTORI Scaling Study of ELMy H-Mode Global and Pedestal Confinement at high triangularity in JET
EX6/6 Darren McDONALD Particle and Energy Transport in Dedicated ρ^*, β and ν^* Scans in JET ELMy H-modes
TH5/3 F NABAIS Cross-machine NTM physics studies and implications for ITER
EX5/1 Richard BUTTERY Cross-machine NTM physics studies and implications for ITER

Saturday 6 November

EX10/1 Volker PHILIPPS Overview of recent work on material erosion, migration and long-term fuel retention in the EU-fusion programme and conclusions for ITER

EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

POSTER Contributions with JET related results

OV/P4-9 A.Murari ·New developments in JET Neutron, Alpha Particle and Fuel Mixture Diagnostics with potential relevance to ITER
EX/P1-2 P.Monier-Garbet Impurity-seeded ELMy H-modes in JET, with high density and sustainable heat load
EX/P1-3 E.Solano ELMs, strike point jumps and SOL currents
EX/P1-4 J.Stober Small ELM regimes with good confinement on JET and comparison to those on ASDEX Upgrade, Alcator C-mod, and JT-60U
EX/P2-1 F.Crisanti JET RF dominated scenarios and Ion ITB experiments with no external momentum input
EX/P2-5 D.Moreau Development of Integrated Real-Time Control of ITBs in Advanced Operation Scenarios on JET.
EX/P2-22 T.Hender Resistive Wall Mode Studies in JET
EX/P2-27 V.Plyusnin Study of runaway electron generation process during major disruptions in JET
EX/P3-11 F.Rimini Development of Internal Transport Barrier scenarios at ITER-relevant high triangularity in JET
EX/P4-5 B.Gonçalves On the momentum re-distribution via turbulence in fusion plasmas: experiments in JET and TJ-II
EX/P4-26 P.Lamalle Expanding the operating space of ICRF on JET with a view to ITER
EX/P4-28 J.Mailloux ITER Relevant Coupling of Lower Hybrid Waves in JET
EX/P4-45 D.Testa Experimental Studies of Alfven Mode Stability in the JET Tokamak
EX/P5-22 T.Loarer Overview of gas balance in plasma fusion devices
EX/P6-18 P.Mantica Progress in understanding heat transport at JET
EX/P6-31 H.Weisen Anomalous particle and impurity transport in JET
TH/P2-9 T.Tala Progress in Transport Modelling of Internal Transport Barrier and Hybrid Scenario Plasmas in JET
TH/P4-49 V.Yavorskij Confinement of Charged Fusion Products in Reversed Shear Tokamak Plasma
TH/5-2Rb K.Gorelenkov Fast ion effects on fishbones and n=1 kinks in JET simulated by a nonperturbative NOVA-KN code
TH/P5-18 D.Coster Integrated modelling of material migration and target plate power handling at JET
IT/P3-32 G.Cordey The scaling of confinement in ITER with β and collisionality
IT/P3-34 A.Loarte Expected energy fluxes onto ITER Plasma Facing Components during disruption thermal quenches from multi-machine data comparisons