EUROPEAN FUSION DEVELOPMENT AGREEMENT

Recent progress on JET towards the ITER Reference scenario at high density

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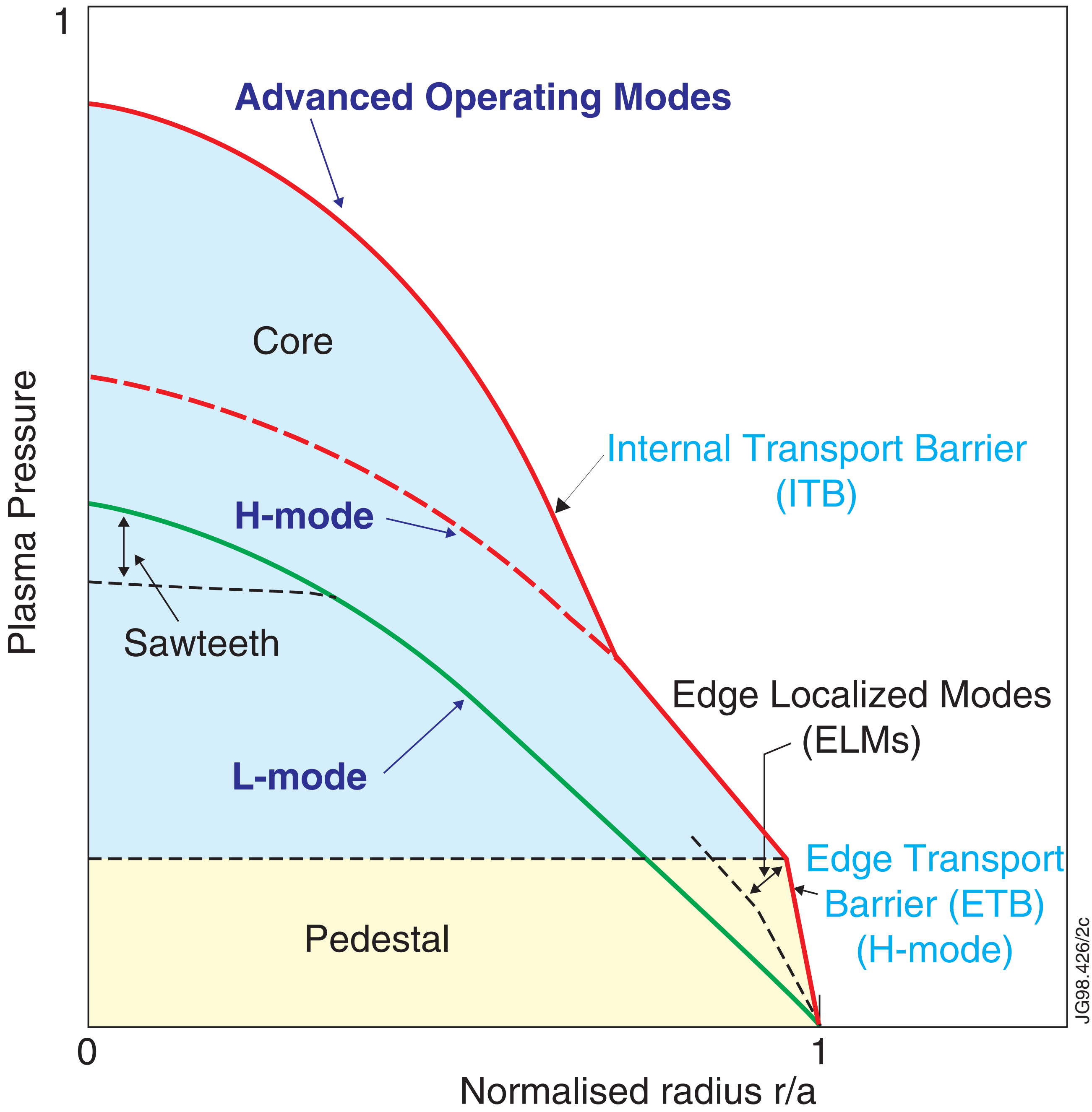
On behalf of Task Force S1 and all colleagues who contributed to the work programme of JET under EFDA

28th Conference on Controlled Fusion and Plasma Physics
Madeira, Portugal
18-22 June 2001

OUTLINE

- Introduction : Background
- Three different methods used to obtain simultaneously high density and high confinement
- ELM changes observed and hints of ELM mitigation
- MHD effects and avoidance
- Outlook

Different Operating Modes in Tokamaks



H-Mode: This Talk
For advanced operating modes: A. Becoulet, Invited Talk, 2:30pm Friday

Definitions

Greenwald Density :

- Empirical density limit
- Maximum density under normal operating conditions

H-factor :

- Characterizes energy confinement quality w.r.t. 'scaling' expressions (L-Mode/H-Mode)
- $H_{98(y,2)}$=1 ==> Plasma confinement of ELMy H-Mode

Normalized beta :

- Ratio of plasma pressure to magnetic pressure
- Normalized to a critical value for plasma stability

ITER Physics Goals

- Achieve extended burn in inductively driven plasmas with the ratio of fusion power to auxiliary power of at least 10.

- Simultaneously required in ELMy H-Mode for Q=10 :

$$n/n_{GW}=0.85,\ H_{H98(y,2)}=1,\ \beta_N = 1.8,\ Z_{eff}=1.7$$

High density high confinement discharges on JET

Three main methods used

Motivation : Maintain good H-Mode confinement at densities close to the Greenwald density

1. Plasma shaping : high triangularity
2. Impurity seeding
3. High field side pellet launch with optimized pellet fuelling cycle

First Method : Plasma Shaping

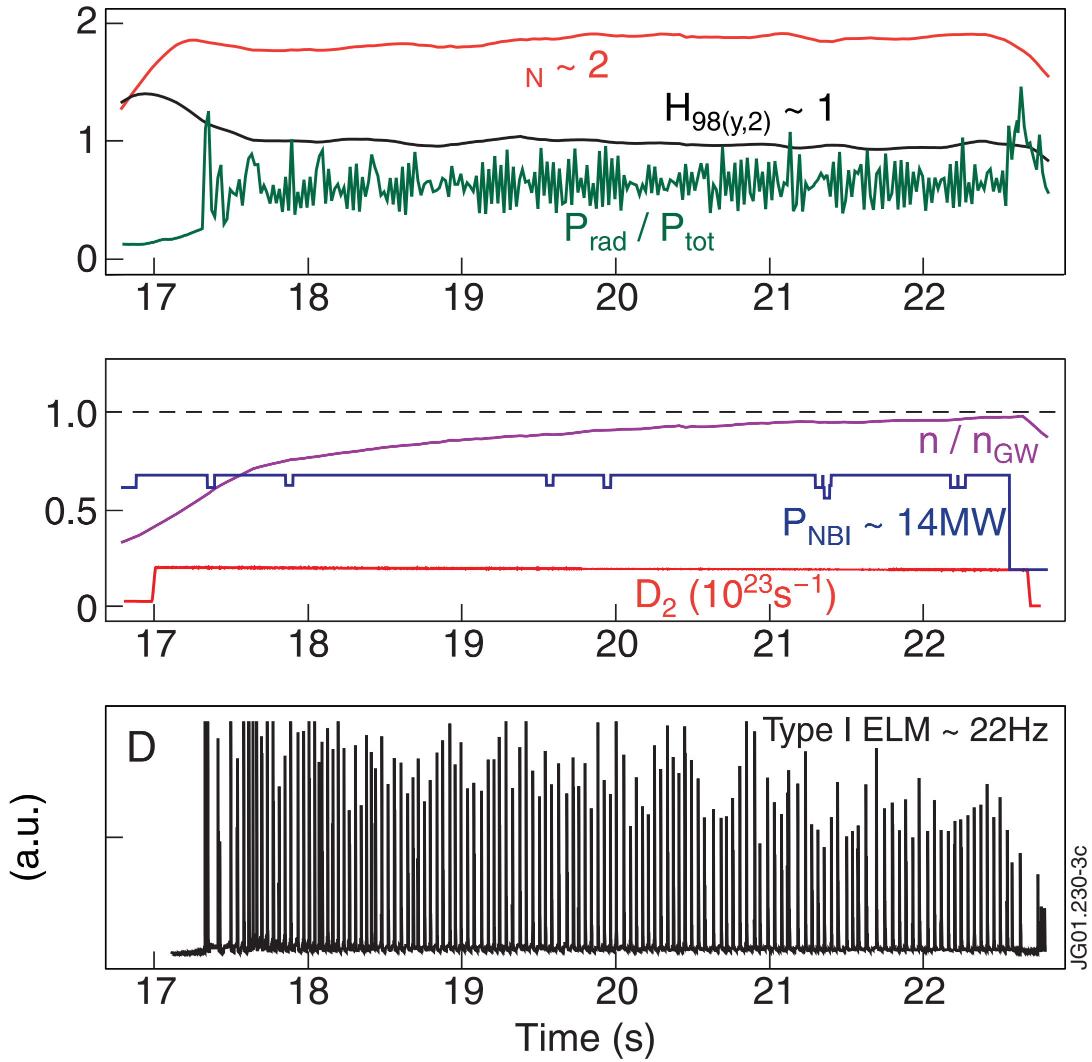
- Increase triangularity (up to δ=0.5)

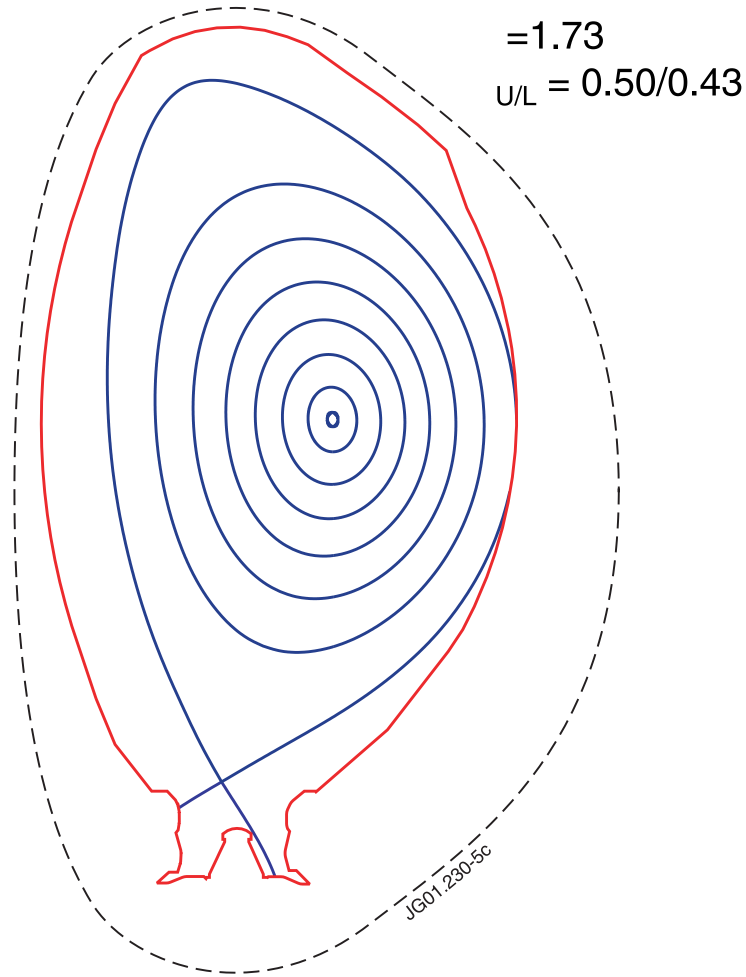
- Properties :
  - $H_{98(y,2)}$=1, β_N=2, n/n_{GW}=0.9-1.0, Z_{eff}=1.5
  - For quasi-stationary phases
  - Robust against high levels of gas puffing
  - Trade-off between heating power and δ
  - Density peaking sometimes observed

R.Sartori, P3.003
G.Saibene, Oral 28, Poster P3.002
V.Parail, P5.027
M.Valovic, P.3.008
J.G.Cordey, P.3011

High Confinement at High Density with High Triangularity

Pulse No: 52014 2.5MA / 2.7T, P_{nb} = 14MW





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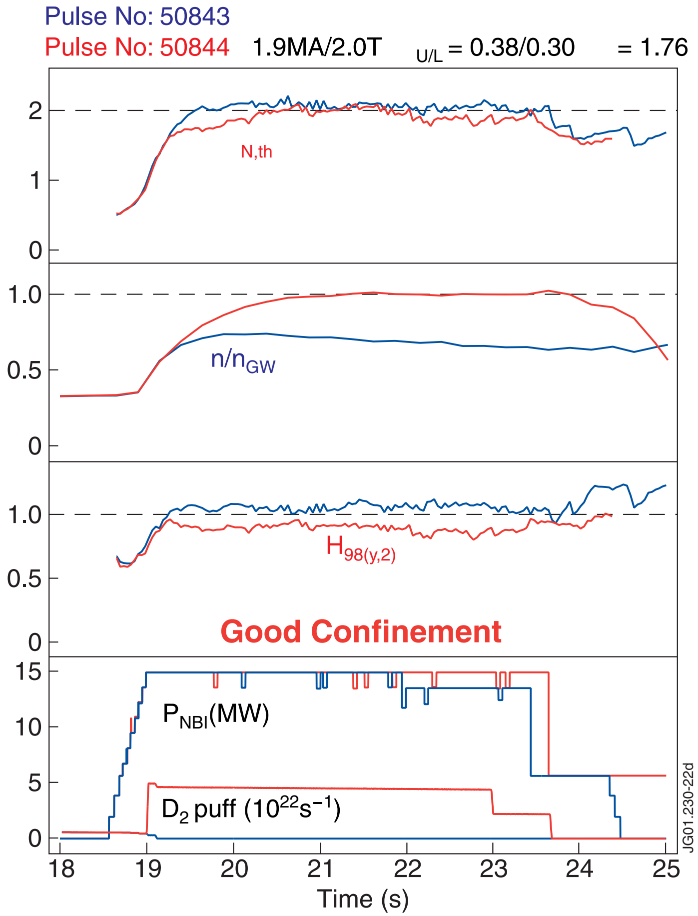
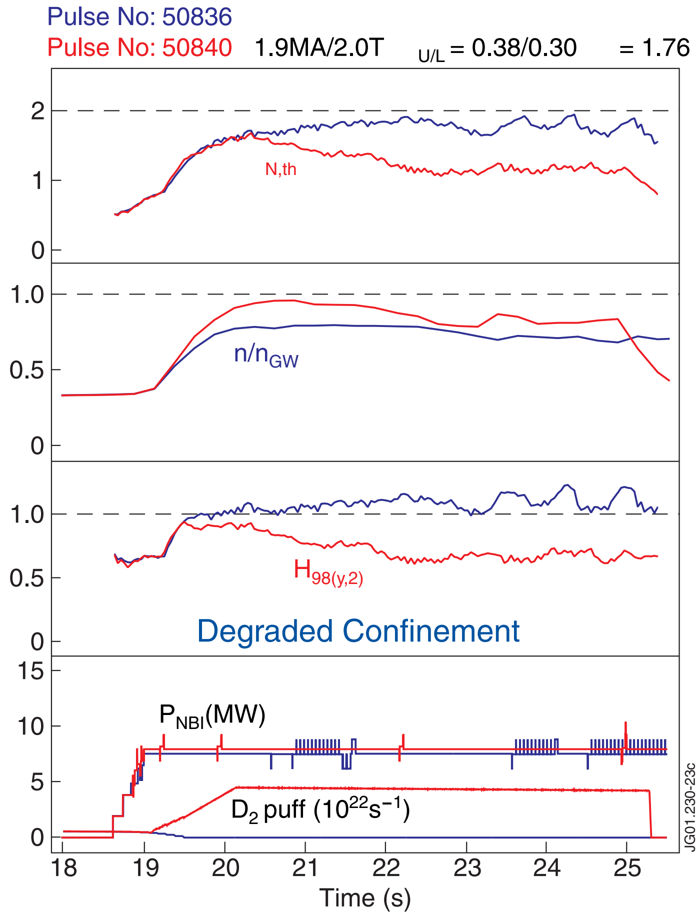
Extension of Good Confinement Results to Lower Triangularities





Increase power level to keep Type I ELMs
Quantified with ratio $P_{in}/P_{L\text{-}H}$

High power level

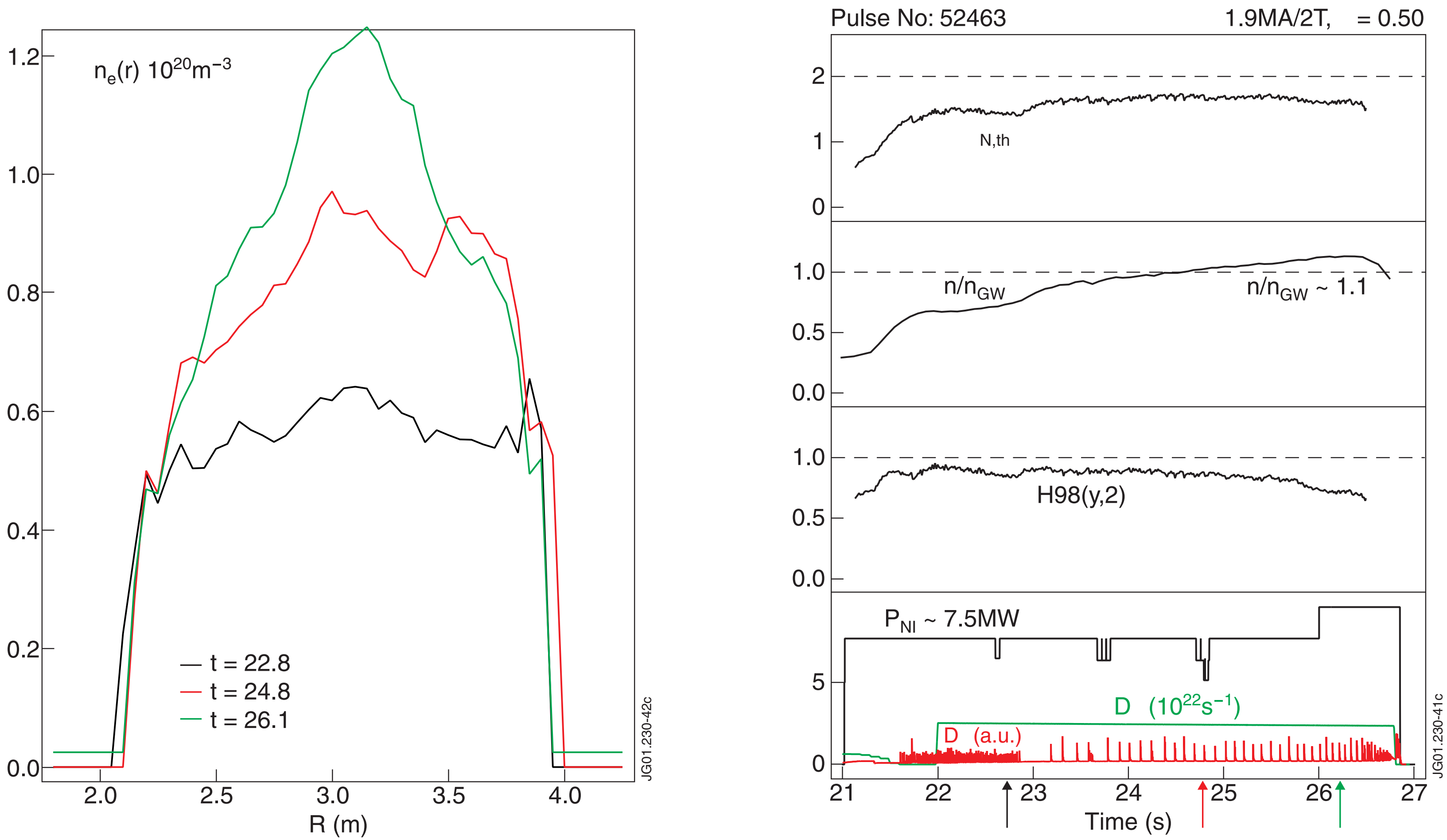
- **P_{NBI} = 15MW**
- **$2.7 < P_{in} / P_{L-H} < 3.5$**

Not sufficient power

- P_{NBI} = 8MW
- $1.5 < P_{in} / P_{L-H} < 1.7$

R. Sartori, Poster P3.003

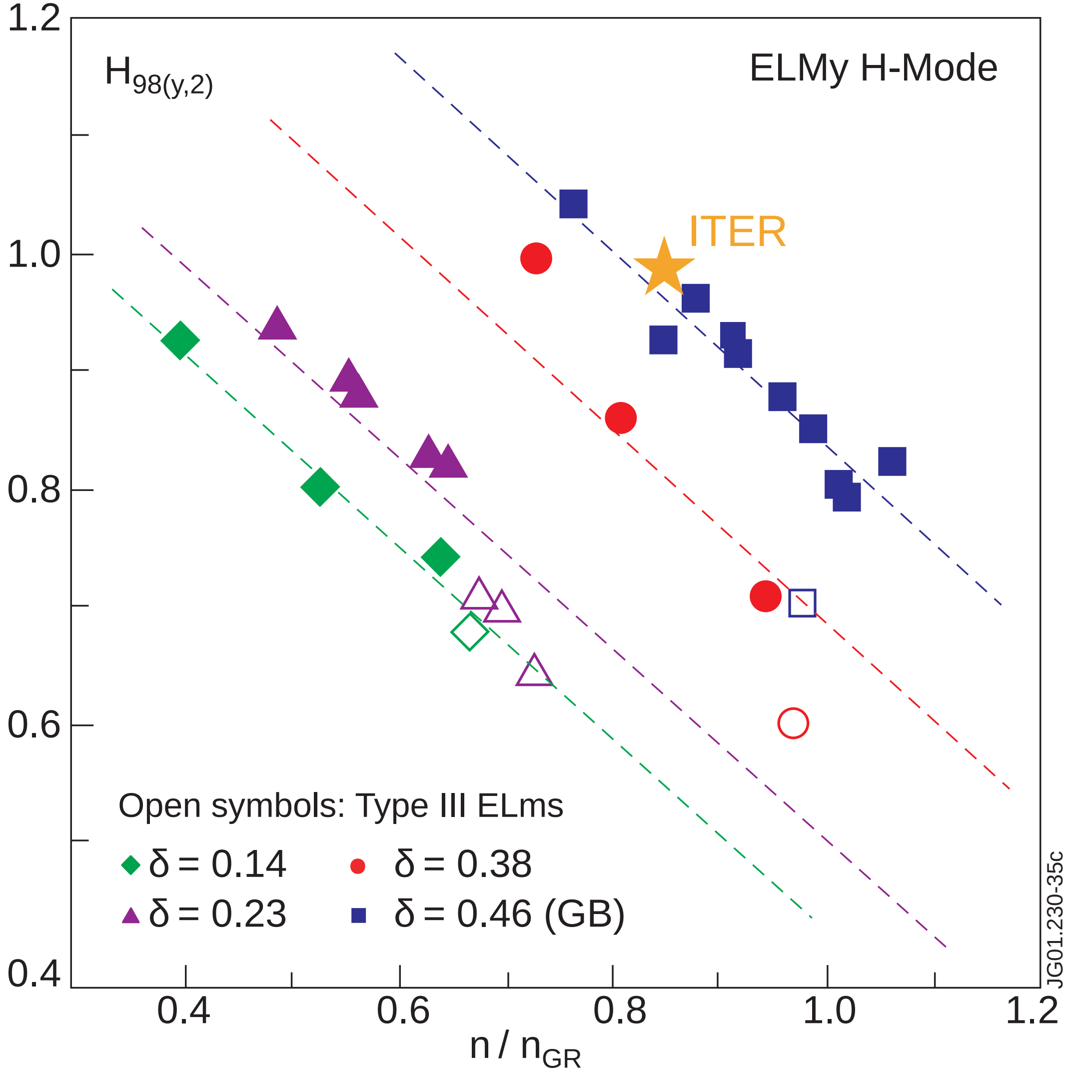
Density Peaking in ITER like ELMy H-Mode Plasmas



- Fuelling below a certain limit, and long time scales
- High Greenwald factor $\cong$ 1.1
- Similarities with regimes found on DIII-D, ASDEX-U

M. Valovic, Poster P3.008

JET Confinement Depends on Triangularity and ELM Type



- Higher triangularity allows higher densities at high confinement
- For all triangularities: Confinement degrades with density
- Simultaneously obtained n/n_{GW} ~ 0.9 and $H_{98(y,2)}$ ~ 1at high δ = 0.5
- Trade-off between triangularity and heating power: lower δ discharges need higher P_{in}/P_{L-H}

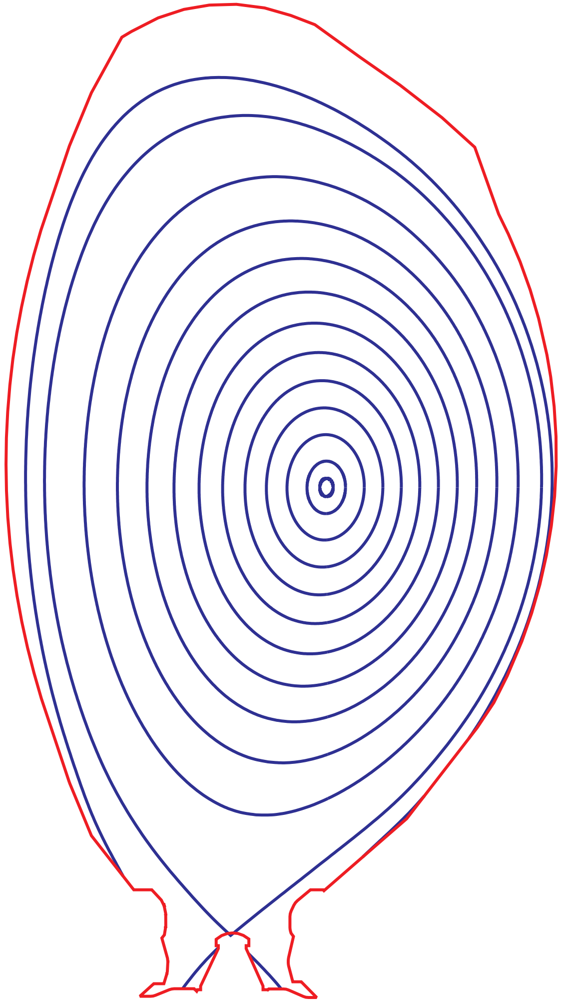
G. Saibene, Oral 28, Poster P3.002   R.Sartori, Poster P3.003

Second Method : Radiative mantle discharges

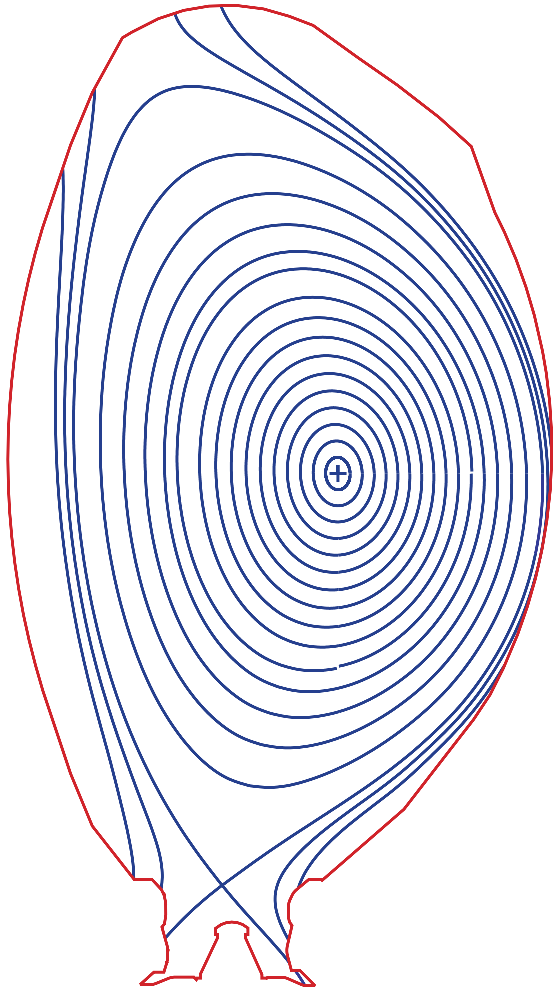
- Aim : Realization of integrated operational scenario combining
  - High density
  - High confinement
  - Acceptable power density on first wall
- Using Ar and Ne as seeding impurity
- Using cautious D dosing
- Low and high δ, with and without septum

P.Dumortier, P3.004
M.E.Puiatti, P3.007
S.Jachmich, P3.013
G.Jackson, P3.017
M.Z.Tokar, P3.032

Two Basic Plasma Shapes Used for Impurity Seeding



Low Triangularity
X-Point on Septum



High Triangularity

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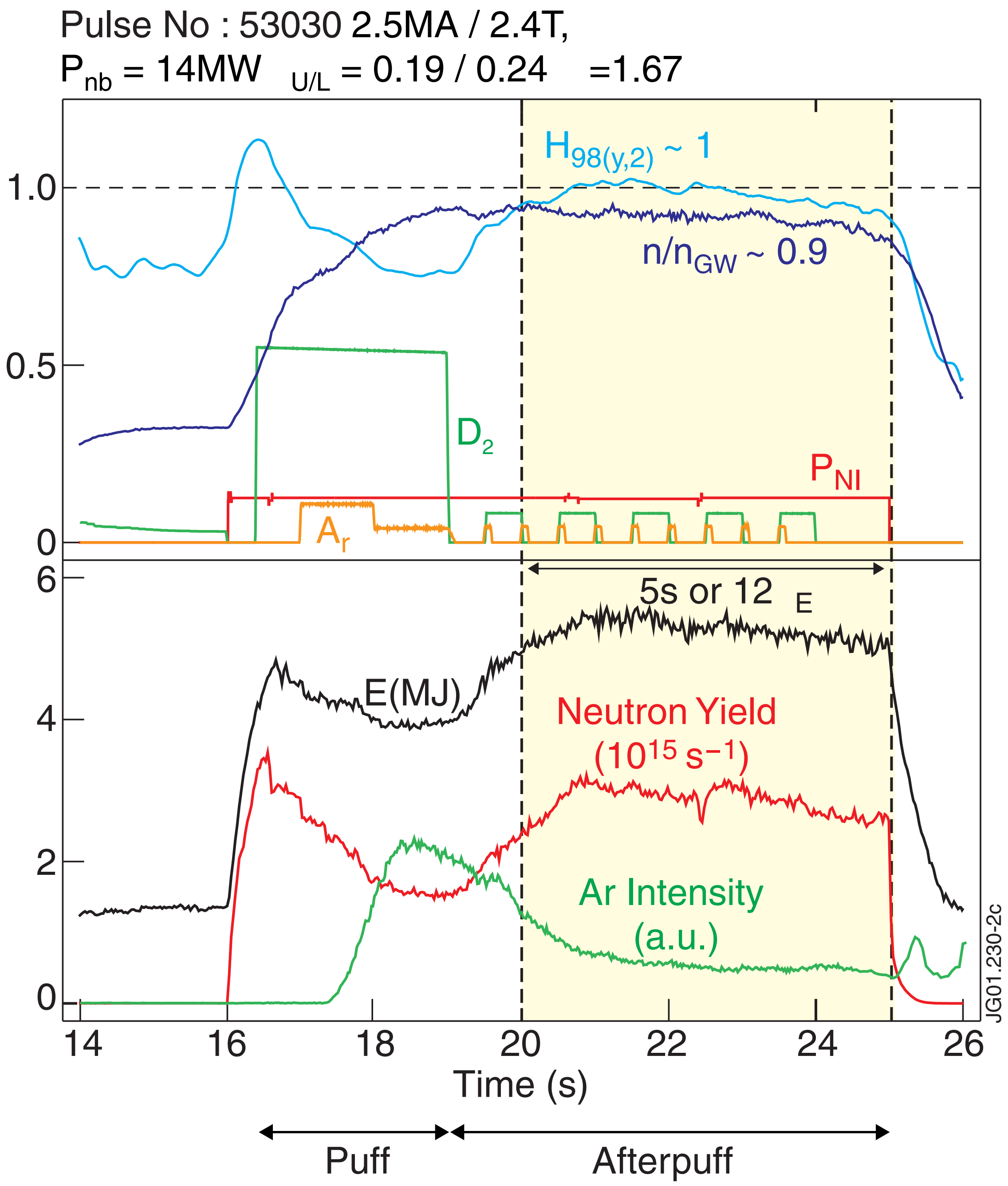
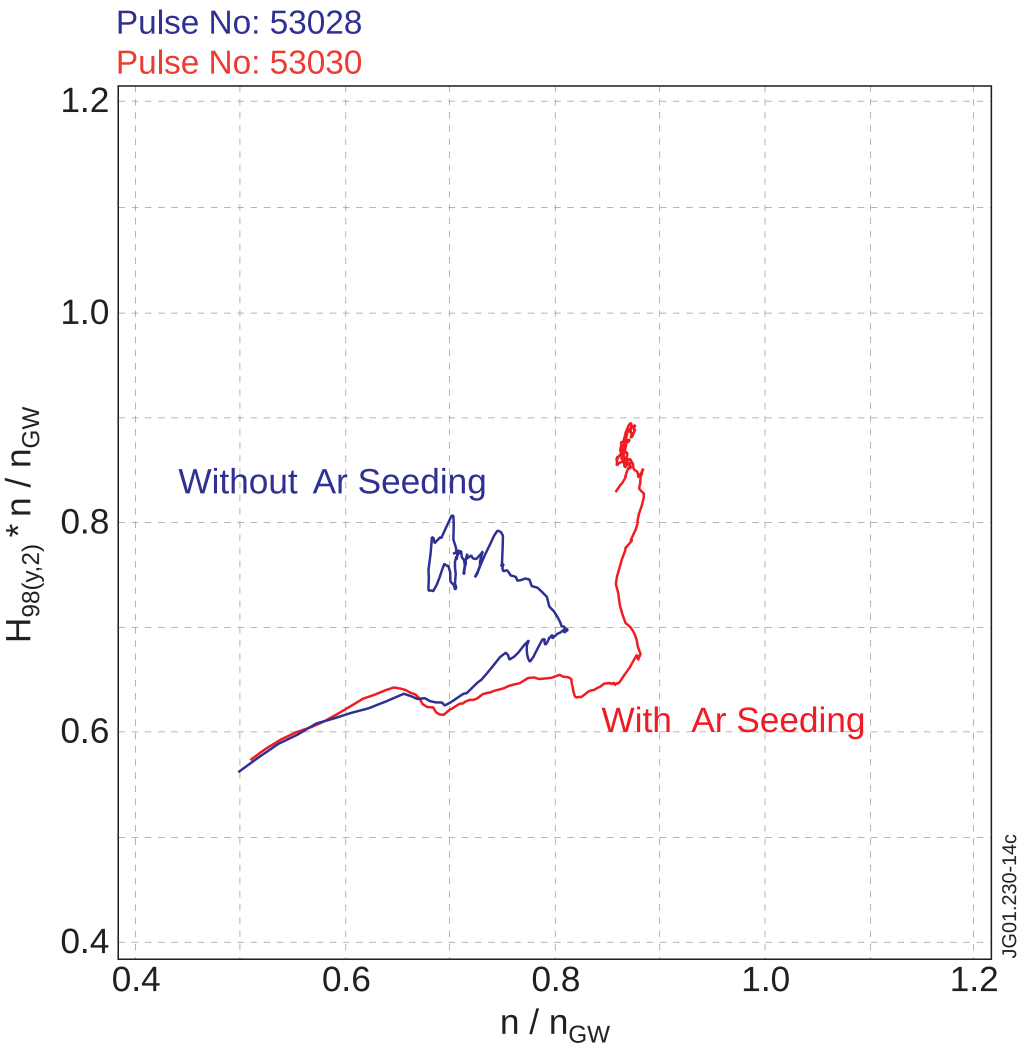
Impurity Seeding in ELMy H-mode (Low Triangularity, X-Point on Septum)

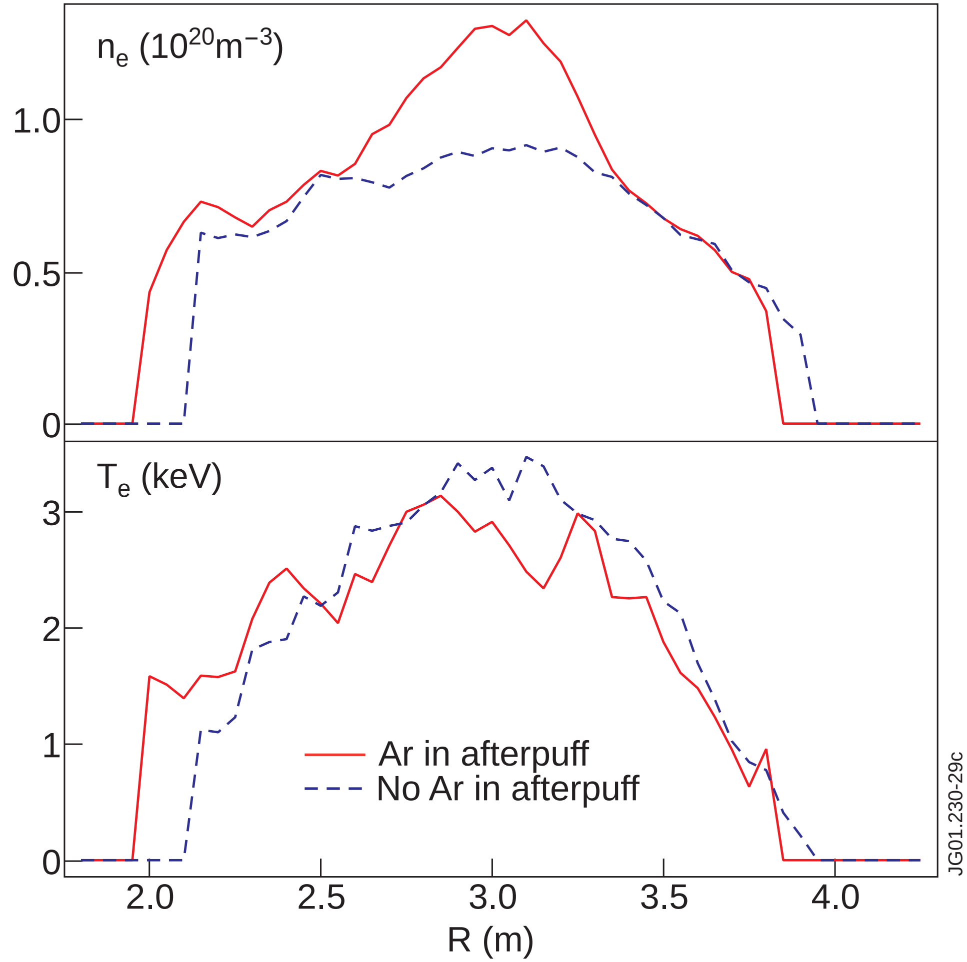


- **Strong D and Ar puff to increase density**
- **Afterpuff with gentle D and Ar puff**
- **Long quasi-steady phase of high H and n/n_{GW}**

P. Dumortier, Poster P3.004

Impurity Seeding Dramatically Improves Plasma Performance (Low Triangularity, X-Point on Septum)





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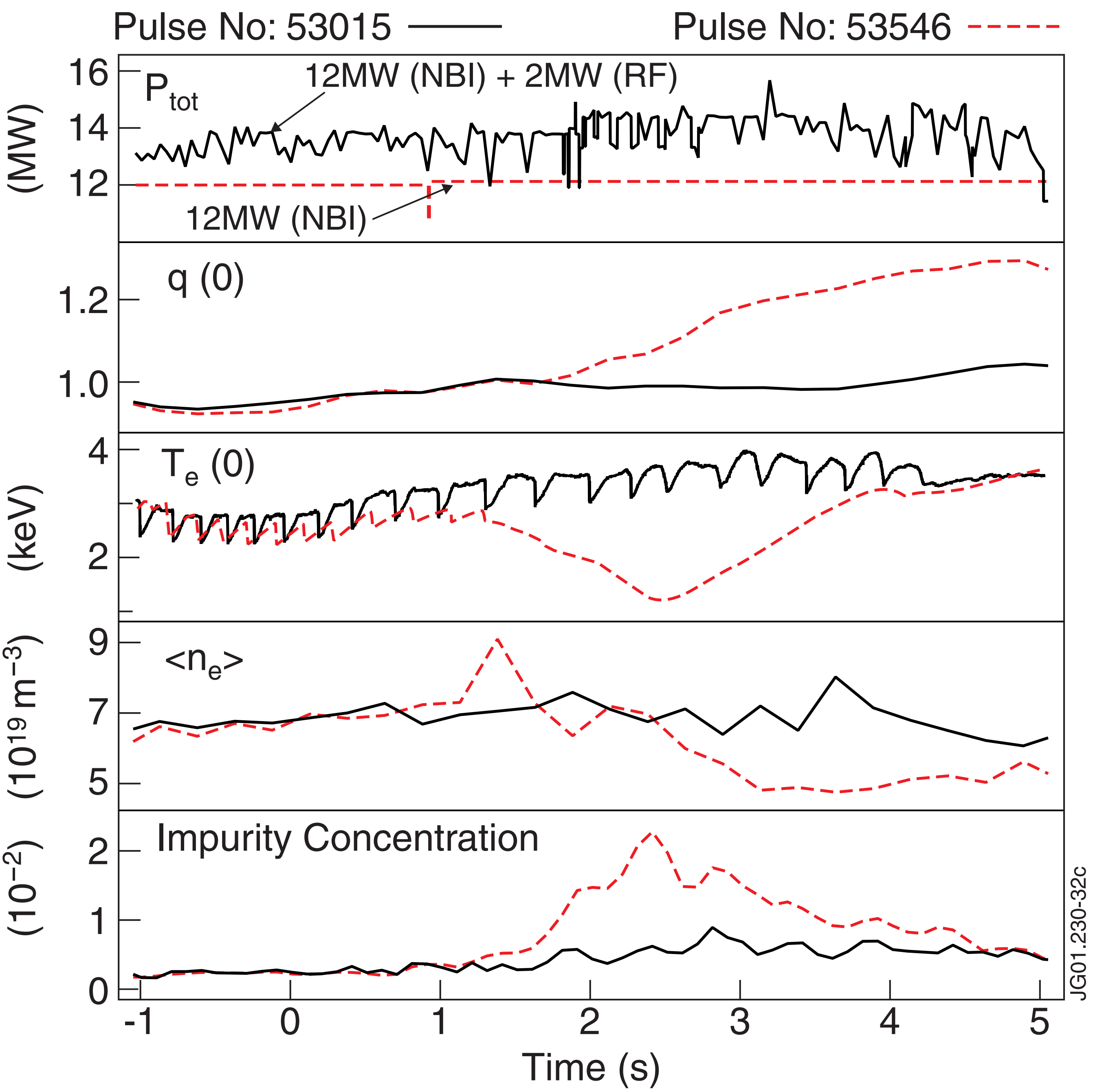
ICRH with Central Deposition Avoids Impurity Accumulation

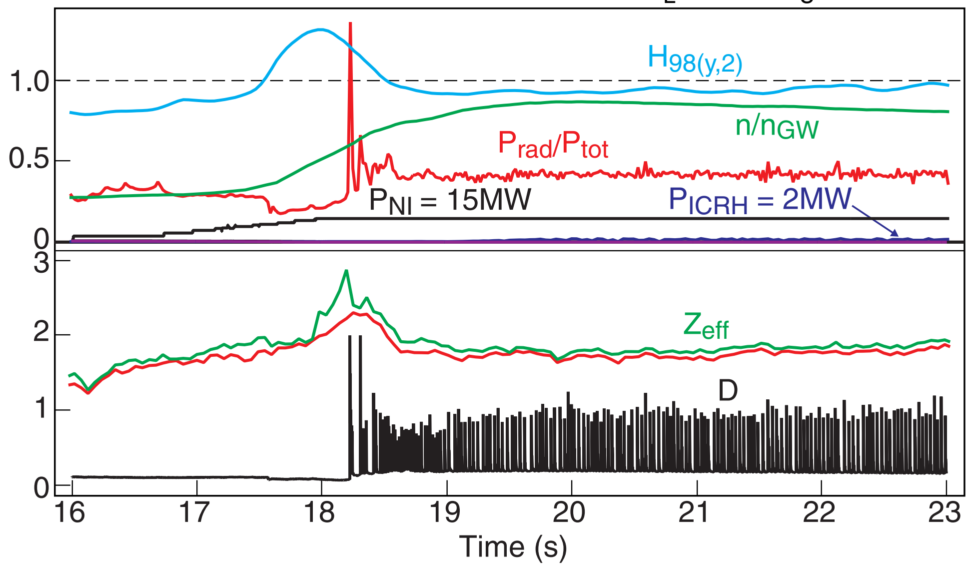


M. Nave, Poster P.3009 **M. E. Puiatti, Poster P.3007**

High Confinement, Density and Radiation in Impurity Seeded High Triangularity Plasmas

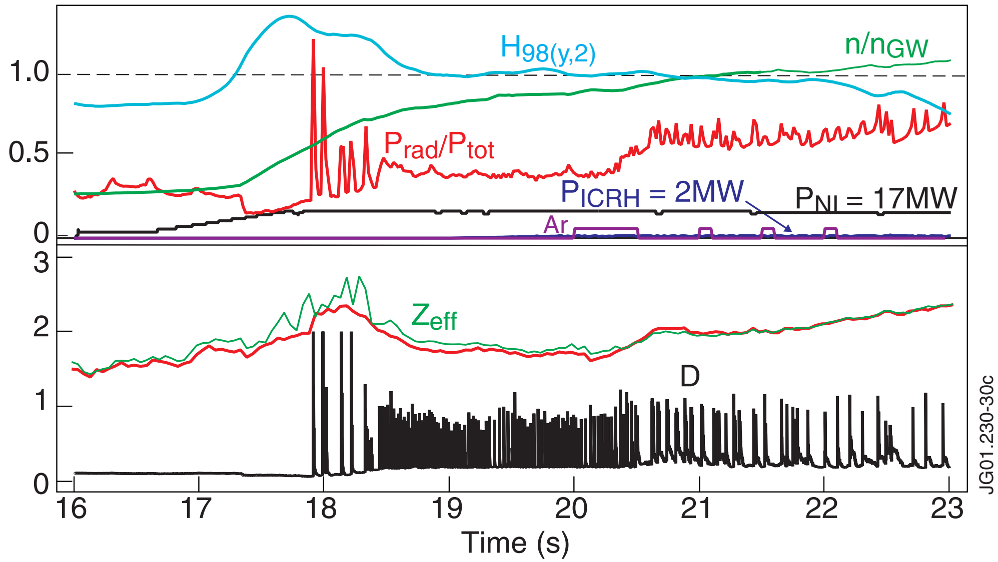
Reference plasma without Argon Seeding

Pulse No: 53549   2.3MA/2.4T   =1.7, $_{L}$ = 0.35, $_{U}$ = 0.48



Argon Seeded plasma

Pulse No: 53550   2.3MA/2.4T   =1.7, $_{L}$ = 0.35, $_{U}$ = 0.48



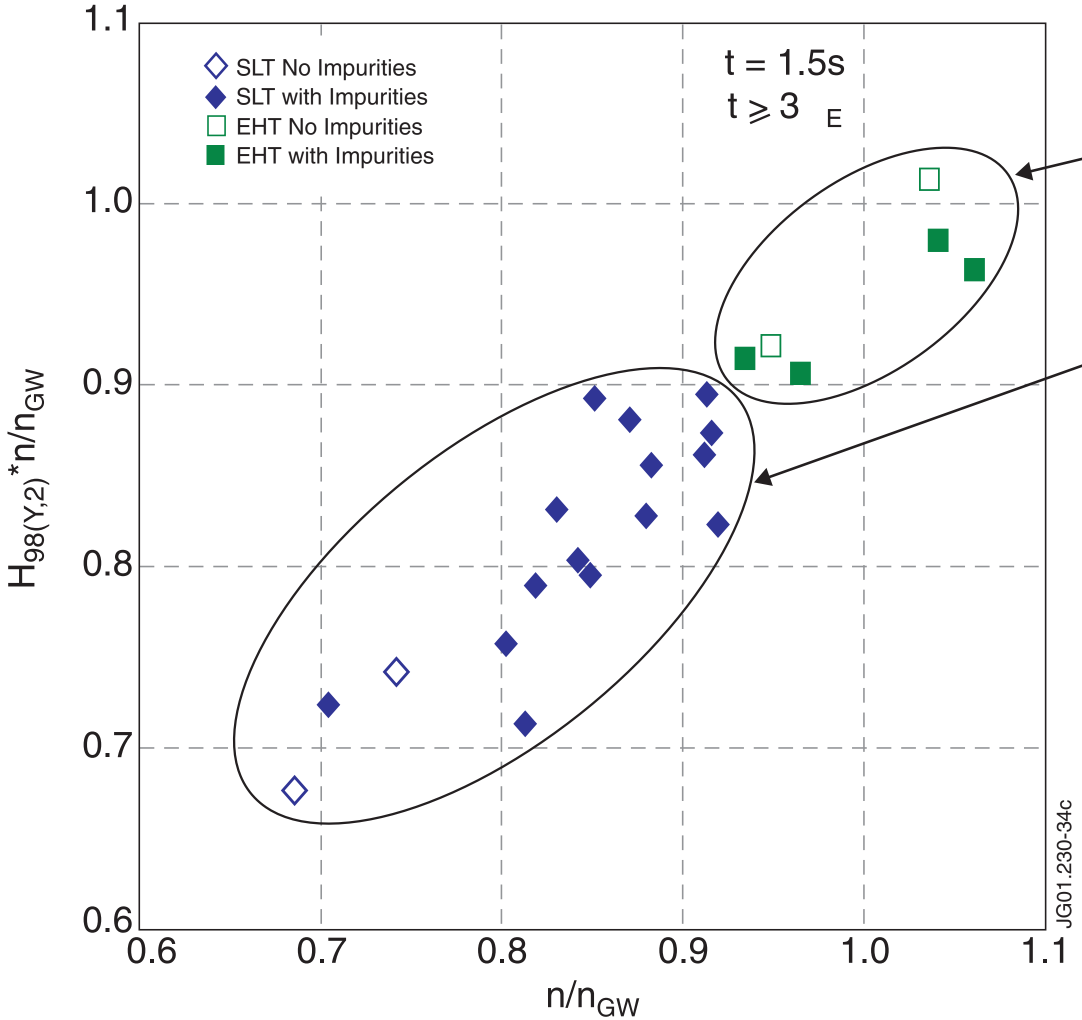
Argon seeding with high triangularity plasmas:

- Combines $H_{98(y,2)}$ ~ 1 and n/n_{GW} ~ 1
- Higher densities due to Ar (increase in $_{p}$)
- High radiation (but somewhat higher Zeff)
- q(0) < 1 with ICRH and Ar seeding

P. Dumortier, Poster P3.004   M. E. Puiatti, Poster P3.007   H. R. Koslowski, Poster P.3010   M. Nave, Poster P.3009

Radiative mantle discharges

Present Results



On top of the good confinement properties, mantle radiation is added by Ar seeding in high   discharges

Ar improves performance of low delta discharges

- Low and medium   with and without X-Point on Septum
- High   , ITER-like
- Stationary phases up to 10 $_E$ (~ 5s)

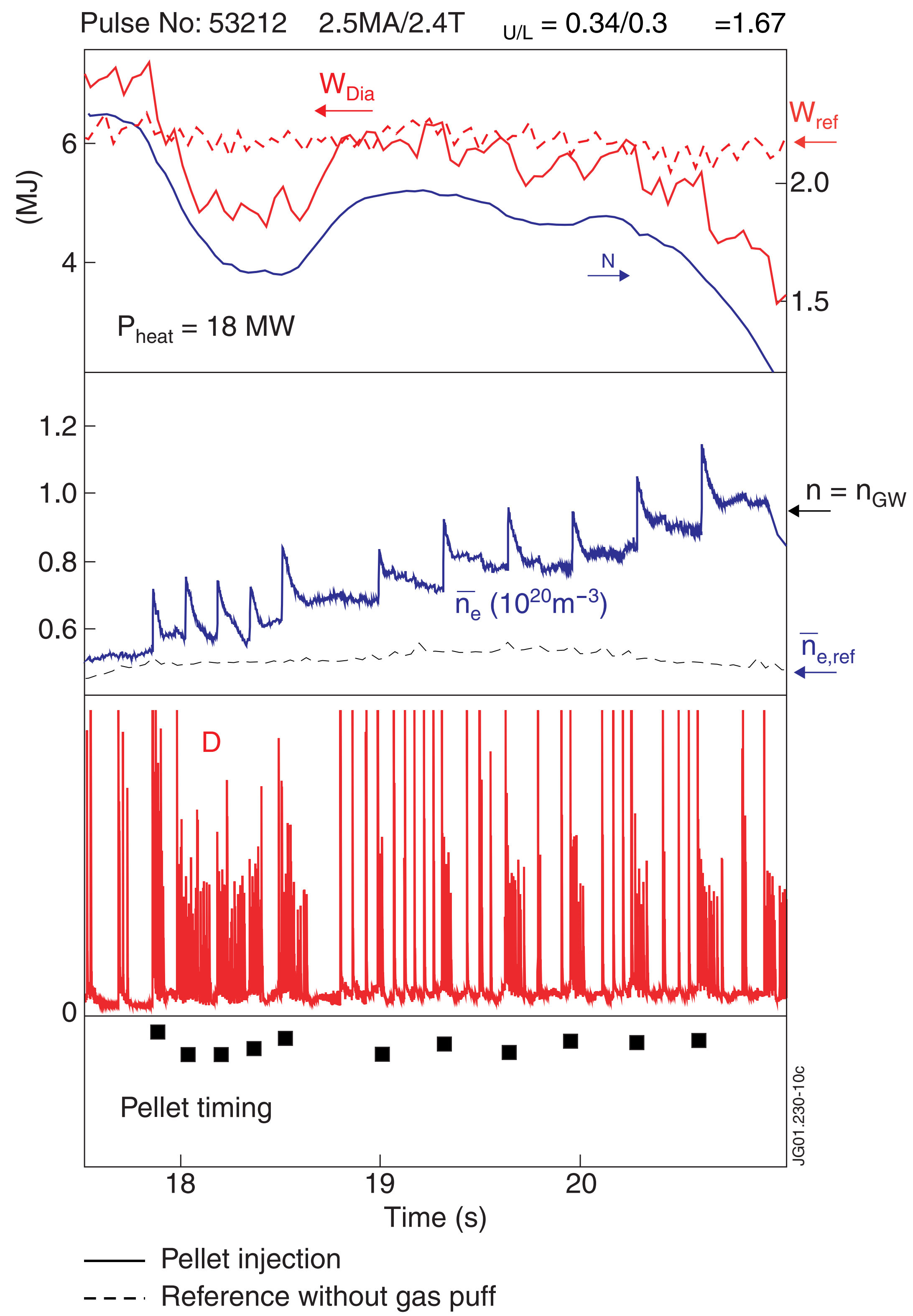
P Dumortier, Poster P3.004

Third Method : High Field Side Pellet Injection

- Pellet injection in medium triangularity plasmas
- Optimised pellet injection cycle
- High confinement and high densities reached

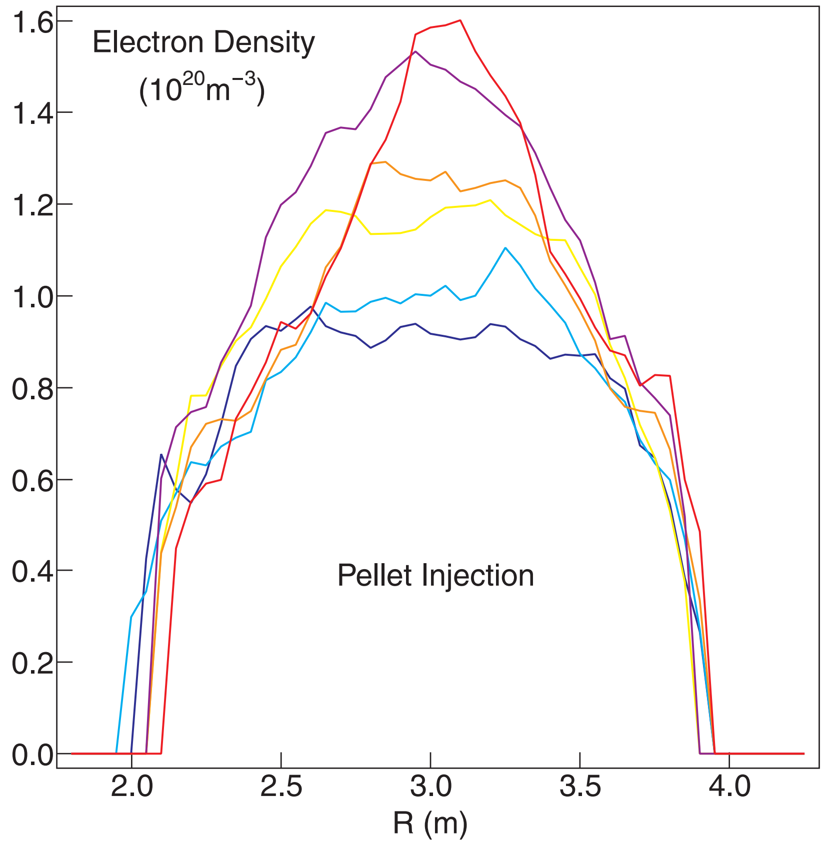
P.T.Lang, P3.012

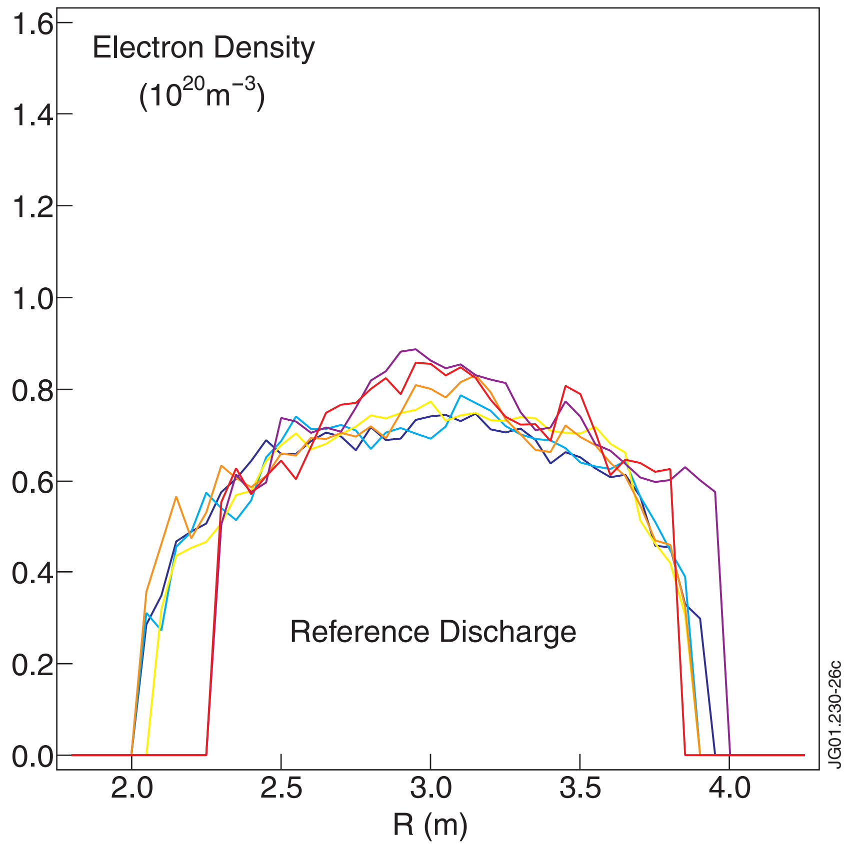
High Density and High Confinement with Inboard Pellet Injection



P. T. Lang, Poster P3.012

High Density Peaking with Pellet Injection





P, T. Lang, Poster P3.012

Different ways to obtain density peaking in JET

- With pellets : central fuelling
- Also seen with :
  - Highly triangular discharges
  - Impurity seeding in high AND low δ discharges
  - Possible physical mechanisms:
    - Stabilization of microturbulence, v/D changes
    - Beam fuelling

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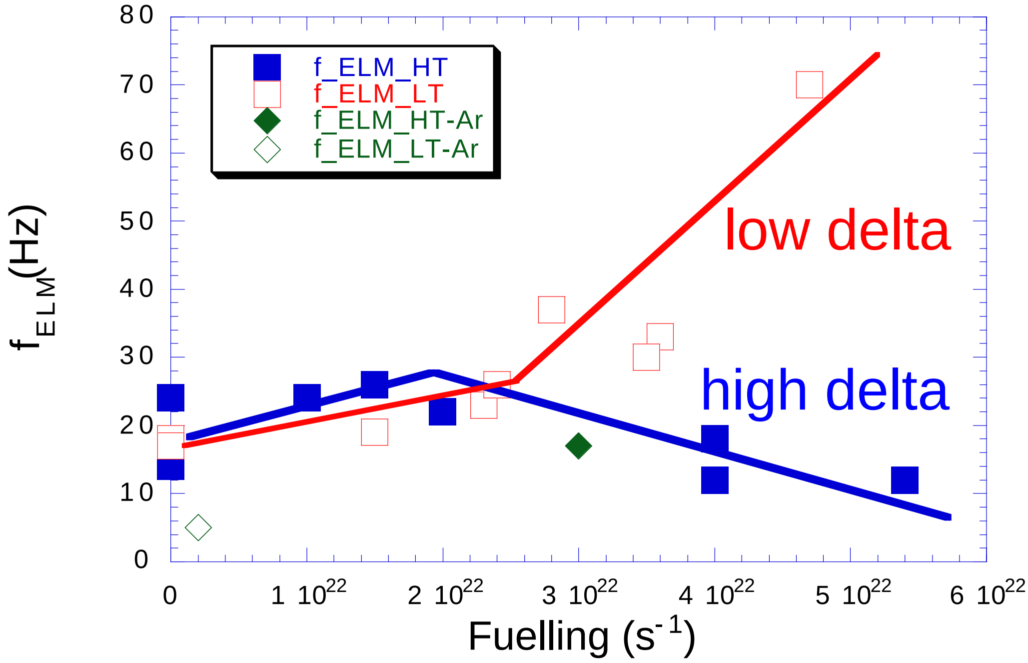
ELM changes observed using different techniques

Hints for ELM mitigation

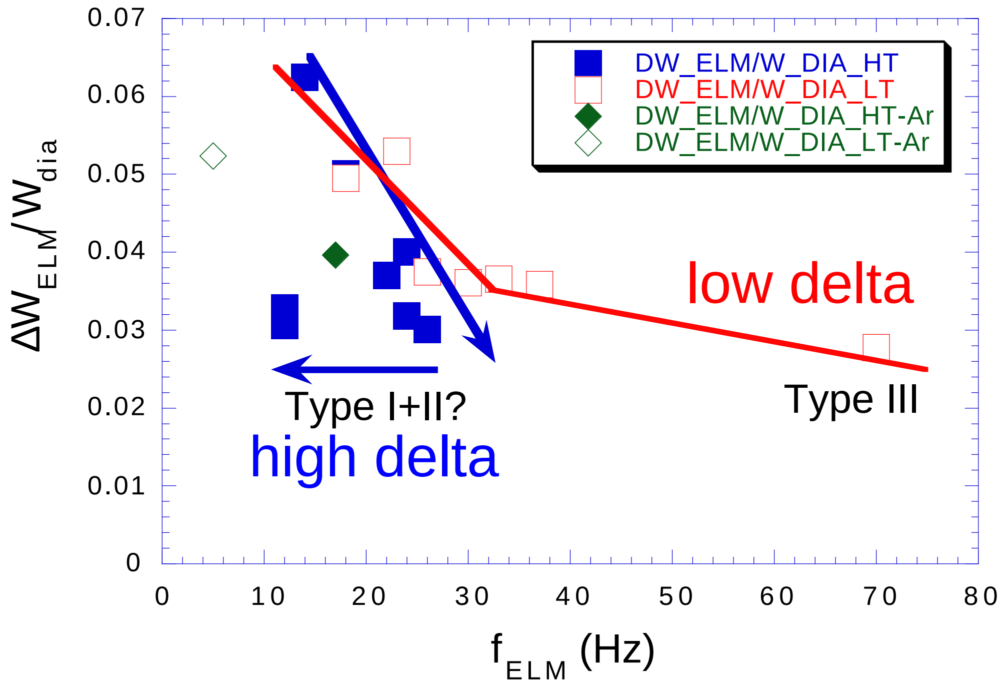
- In high density, high δ discharges :
  - low power losses / ELM
  - lower frequency
- With impurity seeding :
  - impurity radiation reduces heat load

G.Saibene, Oral 28 and P3.002
R.Sartori, P3.003
A.Loarte, P3.005
Th. Eich, P5.010
S.Jachmich, P3.013
G.Maddison, P3.018
M.Becoulet, P4.076
W.Fundamenski, Oral 13, P4.073

'Anomalous' ELM behaviour observed at high density and triangularity



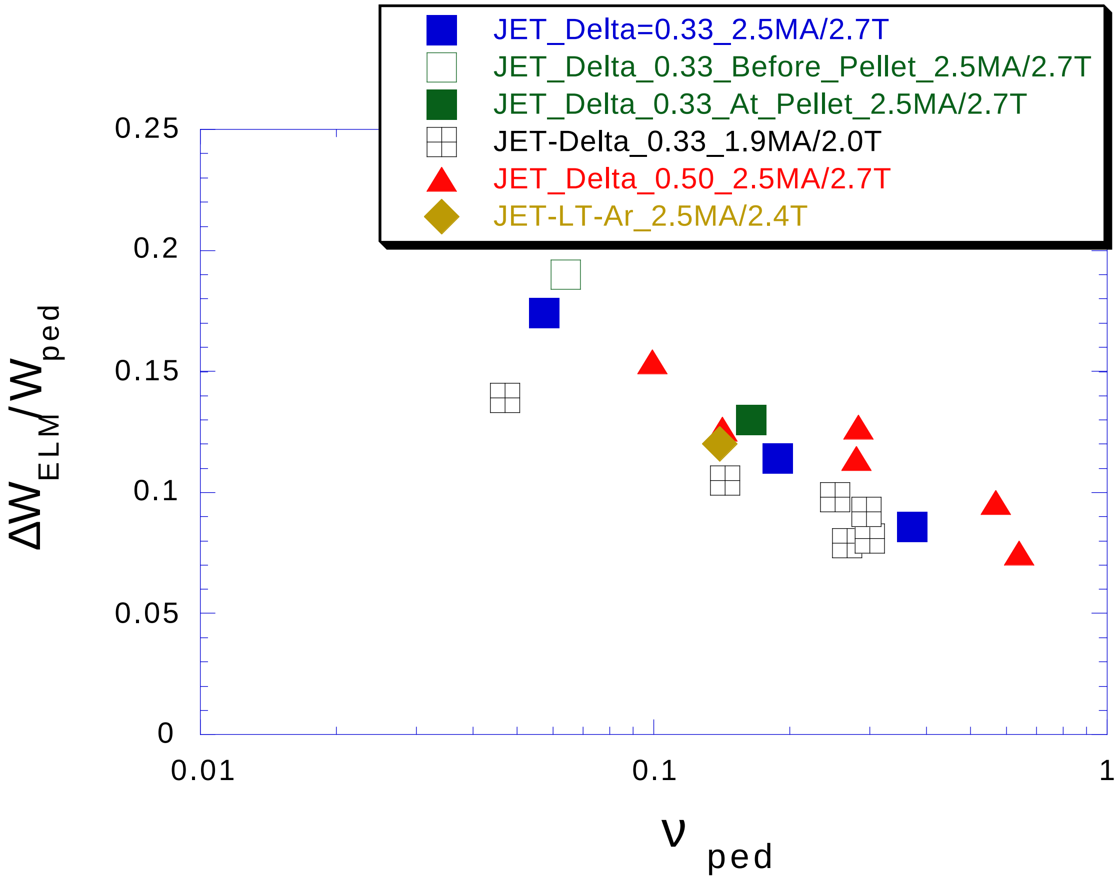
Frequency of Type I ELMs stays low at high density



Losses per ELM stay low at high density
ELMs have a low frequency !

A.Loarte, Poster P3.005

Correlation between ELM size and pedestal collisionality (Loarte scaling)



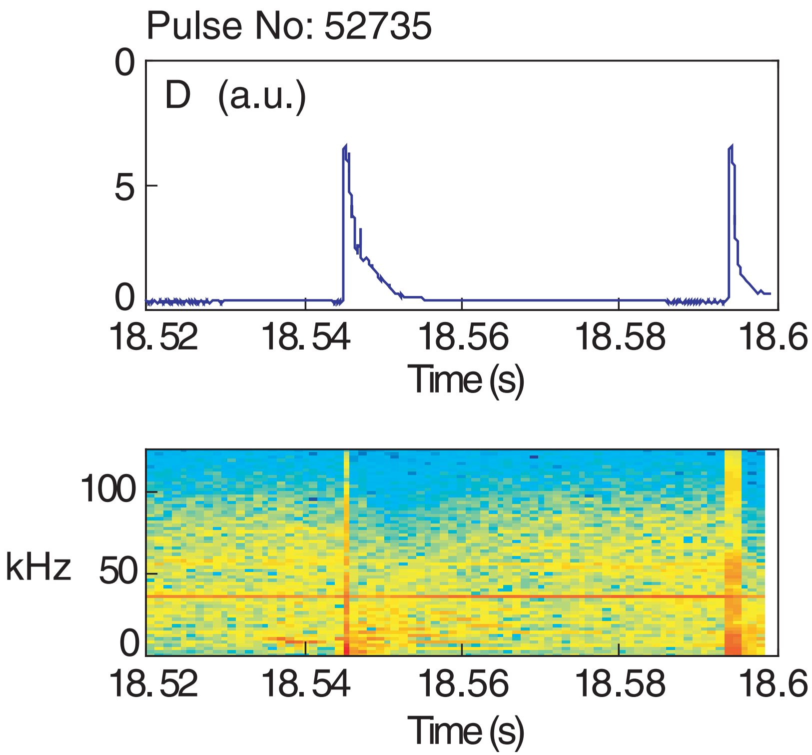
Independent of magnetic field
plasma current
heating power
...

ELM size prediction on the basis of edge parameters

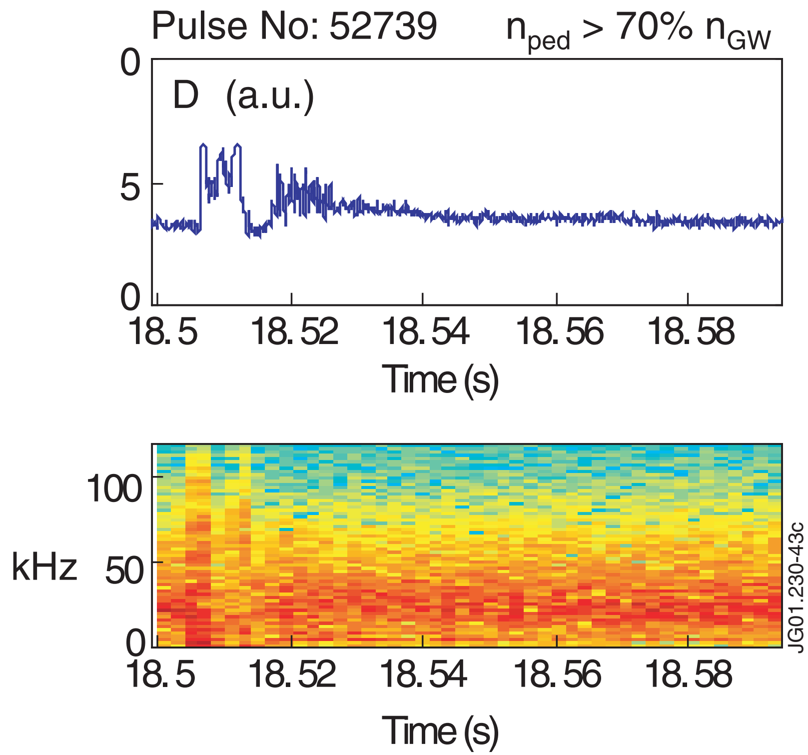
A.Loarte, Poster P3.005

Broadband Turbulence Between ELMs at High Density
High Triangularity Plasmas ~ 0.47

LOW Density



HIGH Density



- Is broadband turbulence involved in extra losses?
- Type II ELMs??
- Can be used for mitigation?

G. Saibene, Oral 28, Poster P.3002 A. Loarte, Poster P3.005 R. Sartori, Poster P3.003

EFDA

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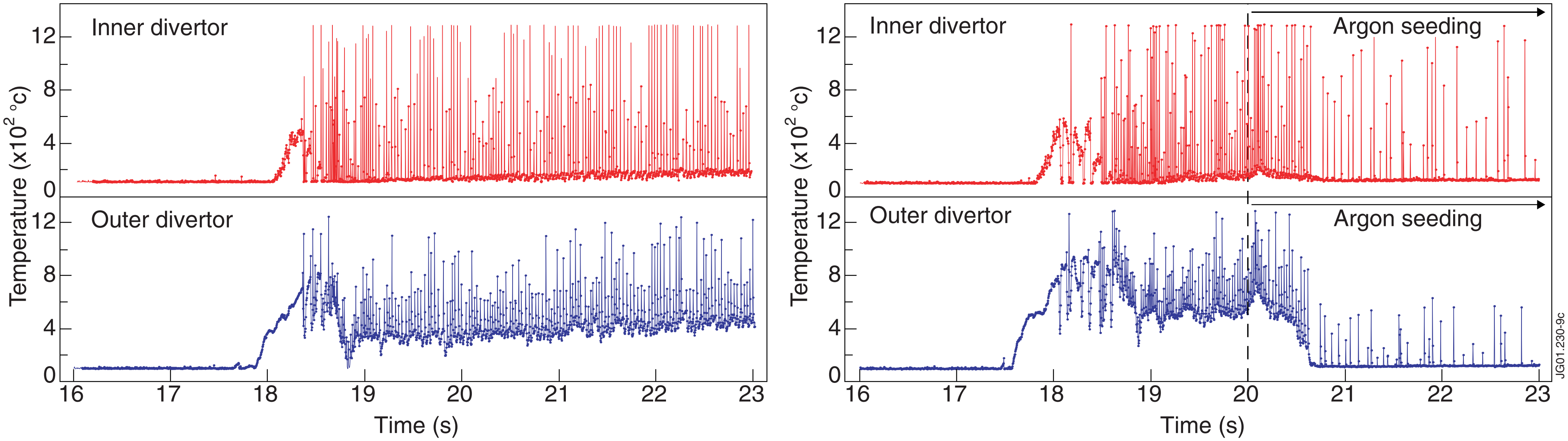
JET

Strong Reduction of Divertor Target Temperature During Argon Seeding



- IR thermography measurements show:
  Baseline temperature reduced by factor of ~5
  ELM effects are also reduced
- Further studies needed: comparison to thermocouple and divertor probes

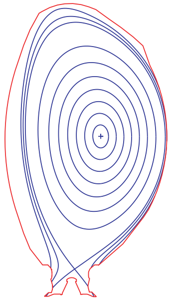
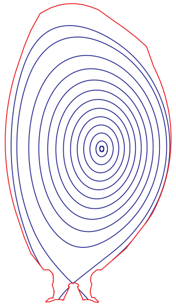
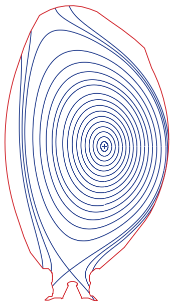
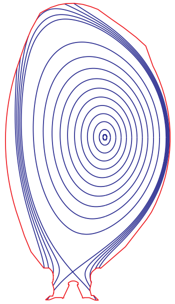
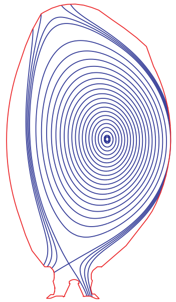
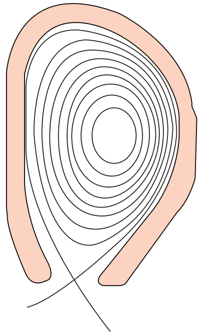
P. Dumortier, Poster P3.004   A. Loarte, Poster P3.005   T. Eich, Poster P5.010   W, Fundamenski, Poster P.4.073

Performance often limited by MHD

- Appearance of MHD modes correlated with high β
    - 2/1 NTM disrupts
    - 3/2 NTM correlates to confinement degradation
    - 5/4 and 4/3 NTM more central, but destroy density peaking
    - destabilize sawteeth using ICRH
- Also correlated with impurity accumulation :
    - avoid with central heating ICRH

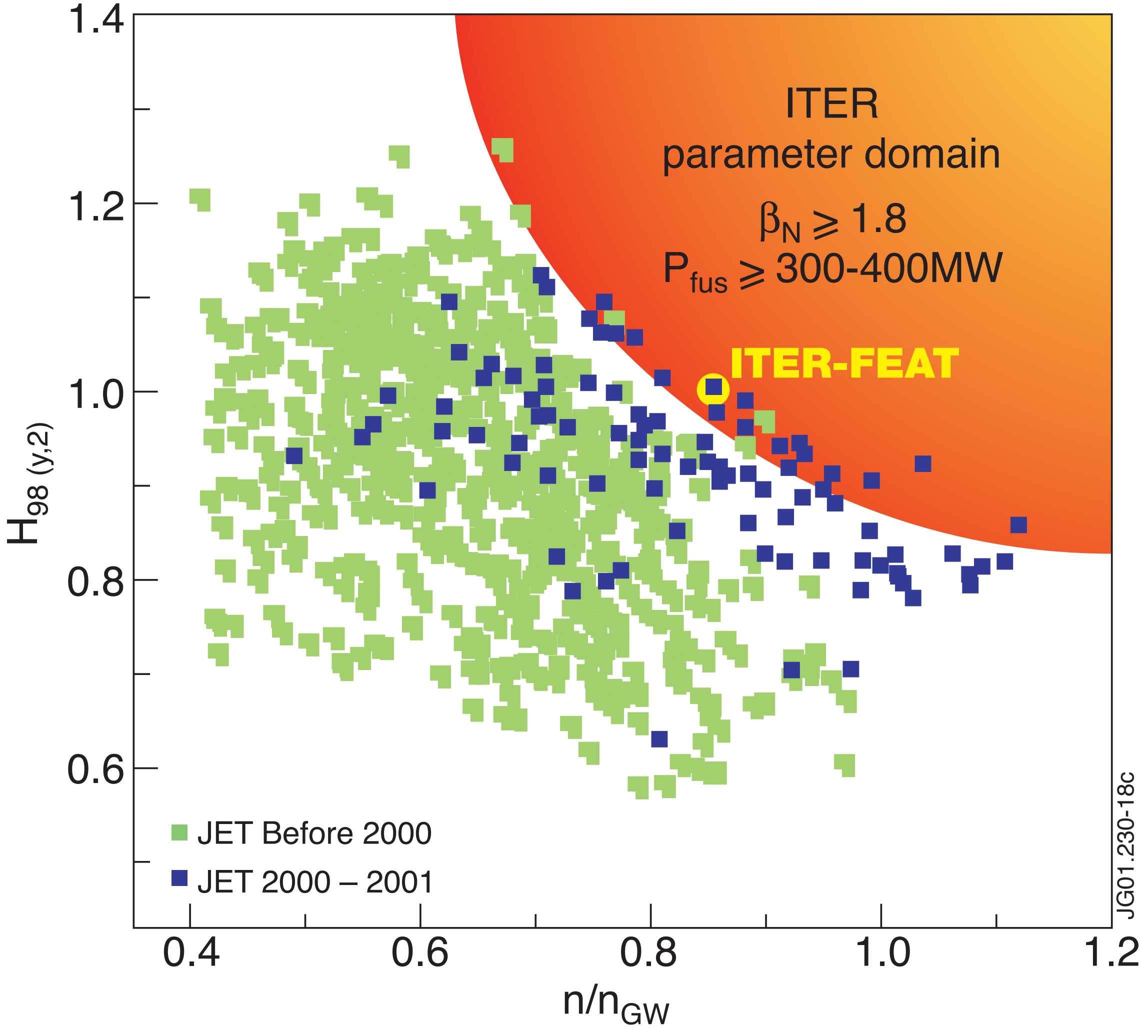
O.Sauter, Oral 8, P5.001
H.R.Koslowski, P3.010, P3.011, P5.005
M.F.F.Nave, P3.009

Three Different Methods used to match ITER Requirements

	PELLETS	IMPURITY SEEDING		SHAPING		
						
	JET HT HFS Pellets Pulse No: 53212, 2.5MA/2.4T	**JET** LT Ar seeded Pulse No: 53030, 2.5MA/2.4T	**JET** EHT Ar seeded Pulse No: 53550, 2.3MA/2.4T	**JET** HT High power Pulse No: 50844, 1.9MA/1.9T	**JET** "ITER shape" Pulse No: 53299, 2.5MA/2.7T	**ITER**
$H_{98\,(y,2)}$	0.8 – 0.95	1.00	0.96	0.91	0.91	**1.0**
$_{N,th}$	1.7 – 1.8	1.75	2.00	2.00	1.90	**1.81**
n_e / n_{GW}	1.0 – 1.1	0.86	0.9 – 1.1	1.00	1.1	**0.85**
Z_{eff}	1.8 – 2.0	1.9	2.2	1.4	1.5	**1.7**
P_{rad} / P_{tot}	0.50	0.50	0.7	0.44	0.40	**0.58**
,	1.7, 0.32	1.66, 0.22	1.7, 0.4	1.74, 0.34	1.74, 0.48	**1.84,0.5**
q_{95}	3.0	3.0	3.1	3.4	3.2	**3.0**
$_{pulse} / \ _E$	~5	12	10	17	15	**110**

JG01.230-39c

Three Methods Used to Obtain $H_{98(y,2)}$ = 1, n/n_{GW} > 0.9 for ITER



- Extension of parameter domain leading to simultaneous realization of $H_{98(y,2)} = 1$, $n/n_{GW} > 0.9$ and $\beta_N \geq 1.8$ using different approaches and
- In addition Plasma purity as required for ITER: Zeff ~ 1.5
- For quasi-stationary phases of several seconds
- **Consolidation of ITER Q = 10 Reference scenario**

Summary of JET ELMy H-Mode results this year

Simultaneously achieved projected ITER Q=10 parameters

$$n/n_{GW} \geq 0.9,\ H_{H98(y,2)} \sim 1,\ Z_{eff} \leq 1.7,\ \beta_N \geq 1.8$$

- For quasi-stationary durations up to several seconds
- Using different methods
- Promising ELM mitigation techniques
- MHD avoidance techniques successfully applied

OUTLOOK AND FURTHER WORK

- Extend good confinement results to higher current, density and field

Narrow the gap to ITER plasmas

  - Higher densities : fuelling with high confinement (pellets, advanced gas fuelling control)
  - Reduce core impurity content while keeping high edge radiation
  - Control of MHD
- ELM Mitigation studies

Preparing a solid basis for
future JET experiments and possible D-T campaigns