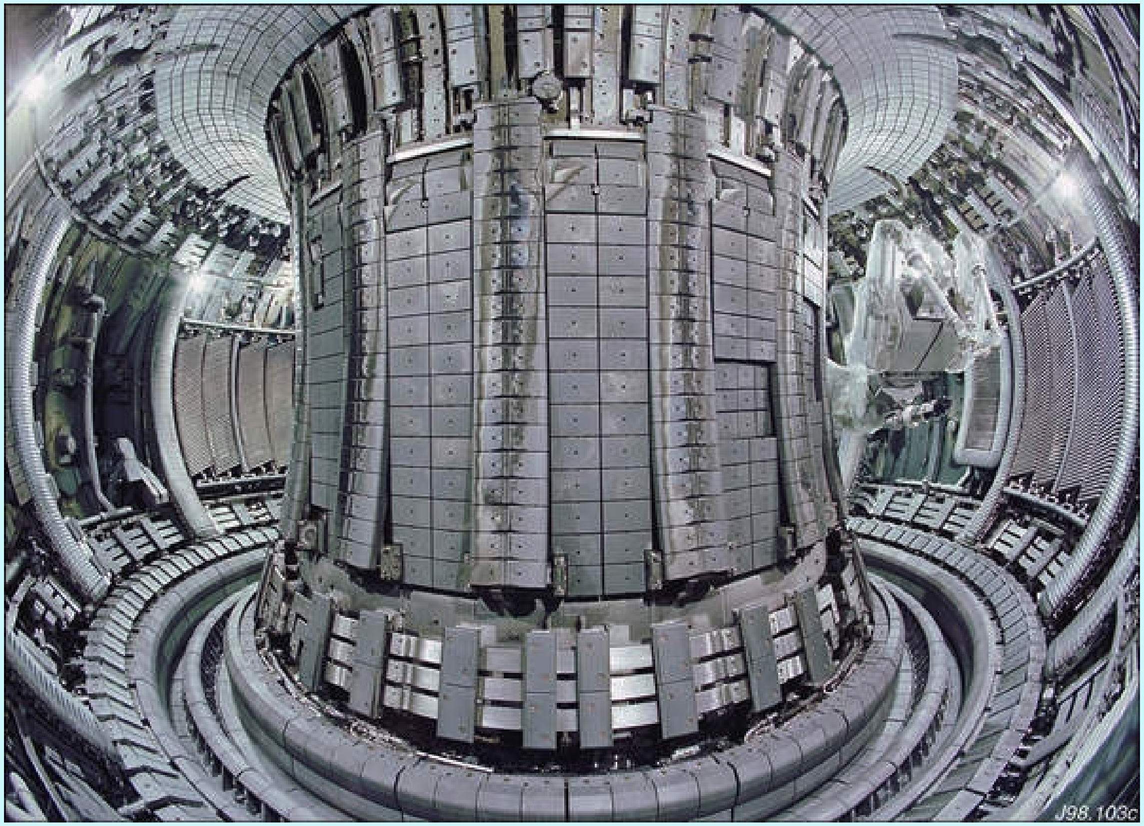
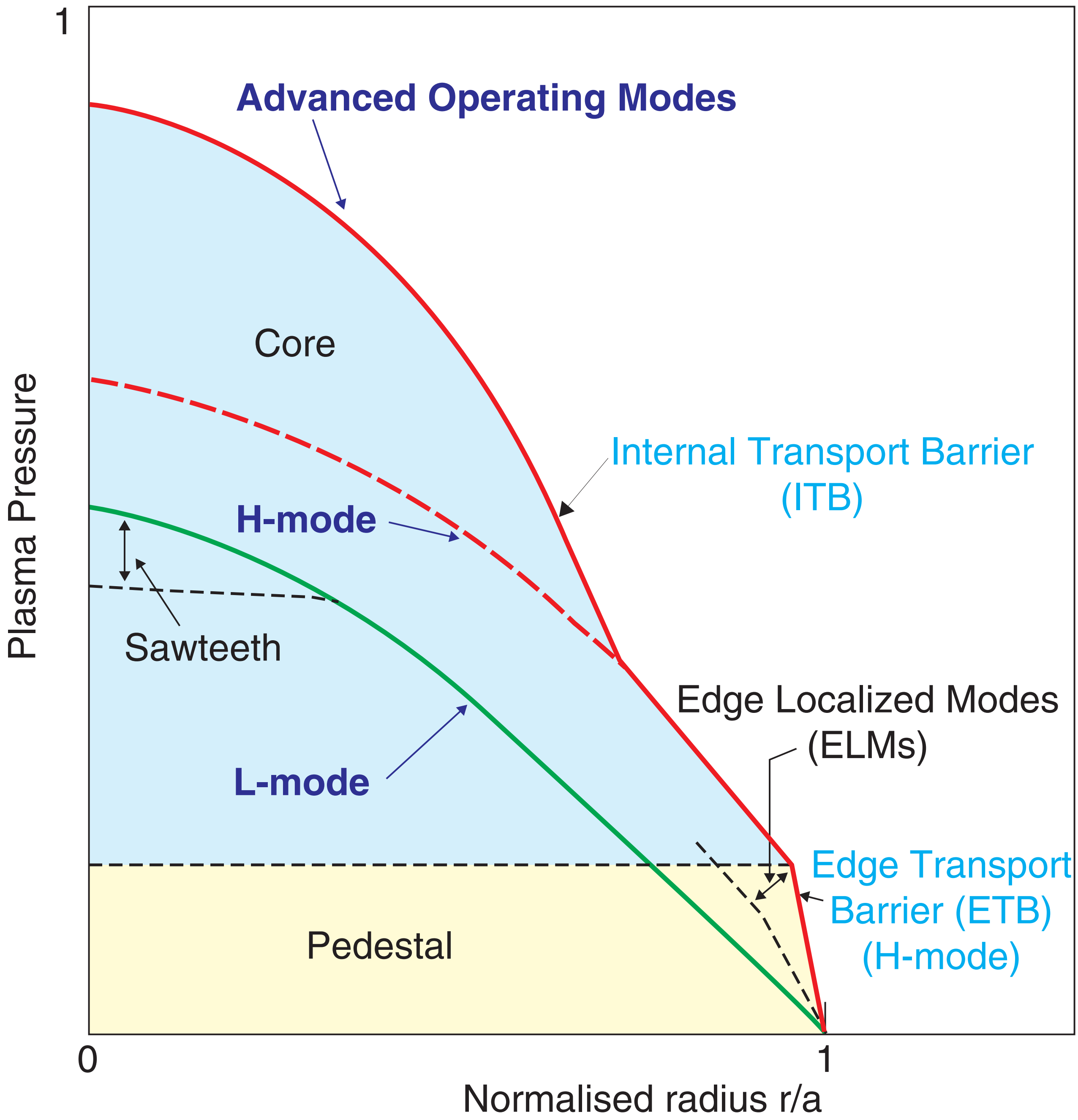
# Confinement in High Density Impurity Seeded ELMY H-mode Discharges at Low and High Triangularity on JET




A view inside the JET Vacuum Vessel

# Different Operating Modes in Tokamaks



# 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

# 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

# Obtaining High density and high confinement discharges on JET

## methods used

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

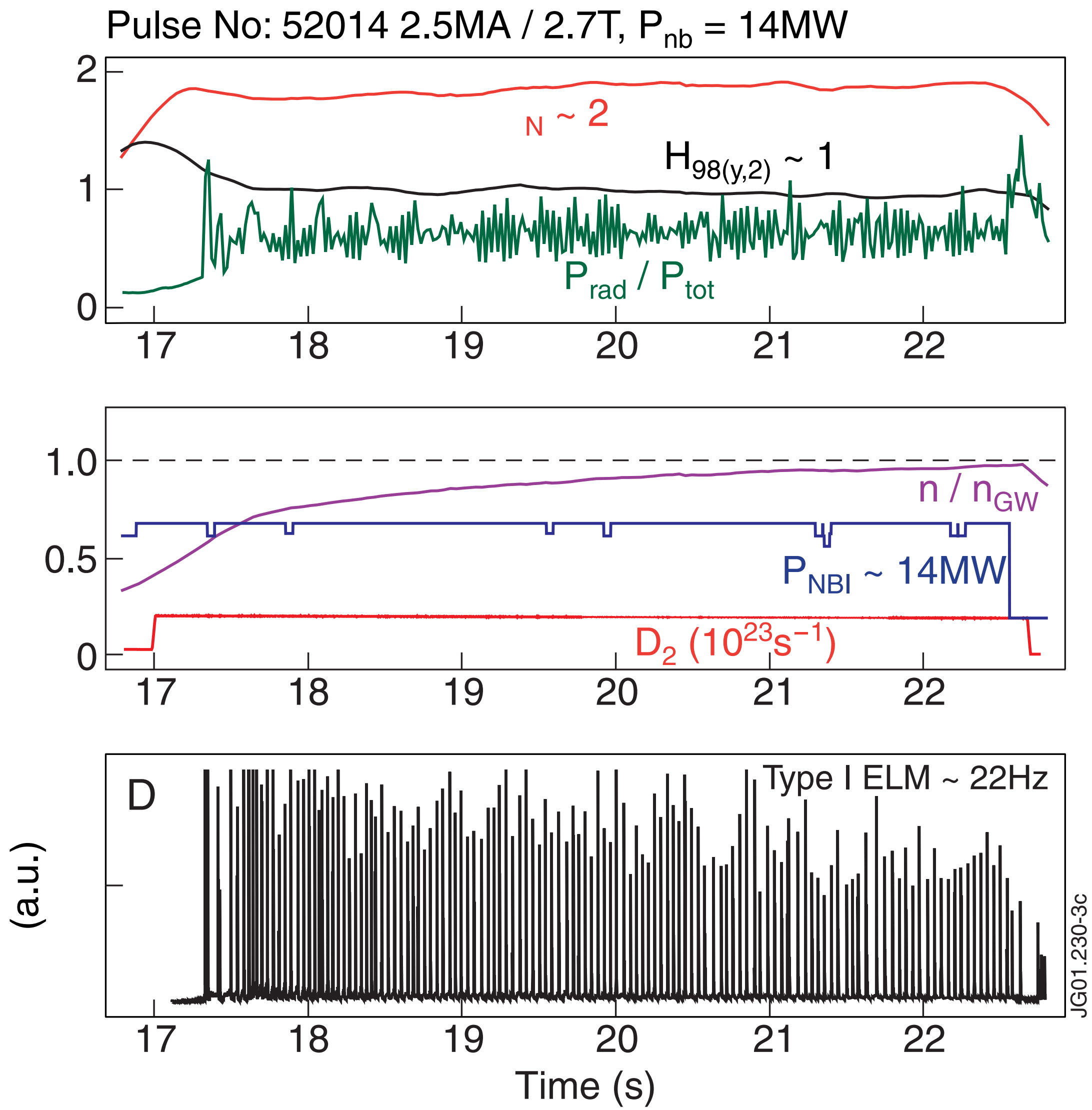
1. Plasma shaping : high triangularity
2. Impurity seeding

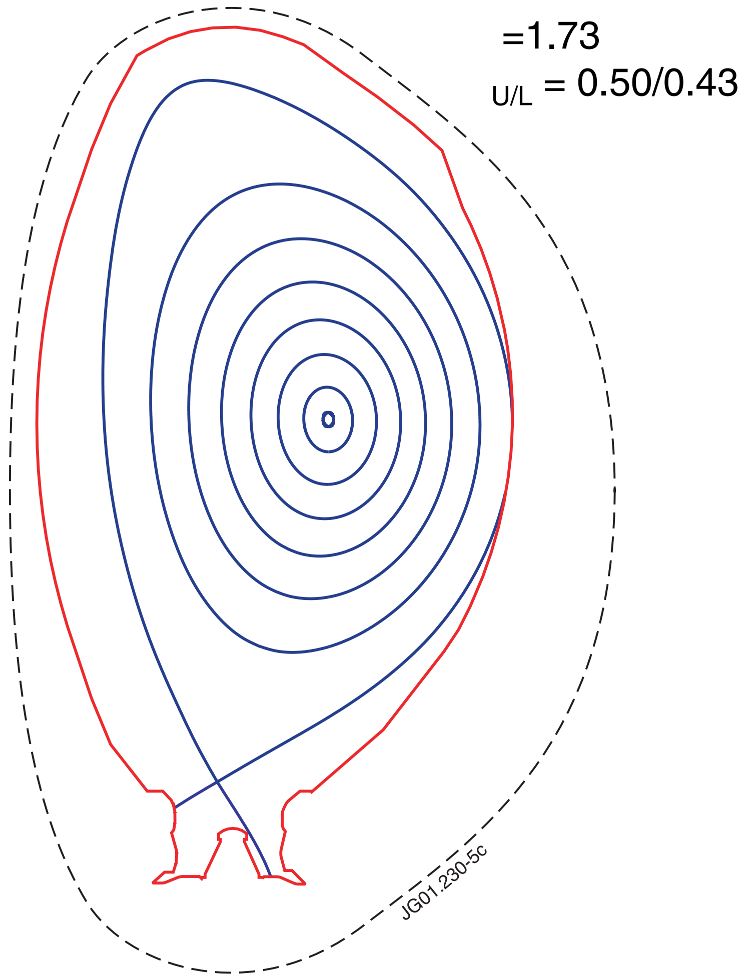
# First Method : Plasma Shaping

- Increase triangularity (up to $\delta$=0.5)

- Properties :
  - $H_{98(y,2)}$=1, $\beta_N$=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 $\delta$
  - Density peaking sometimes observed

# High Confinement at High Density with High Triangularity

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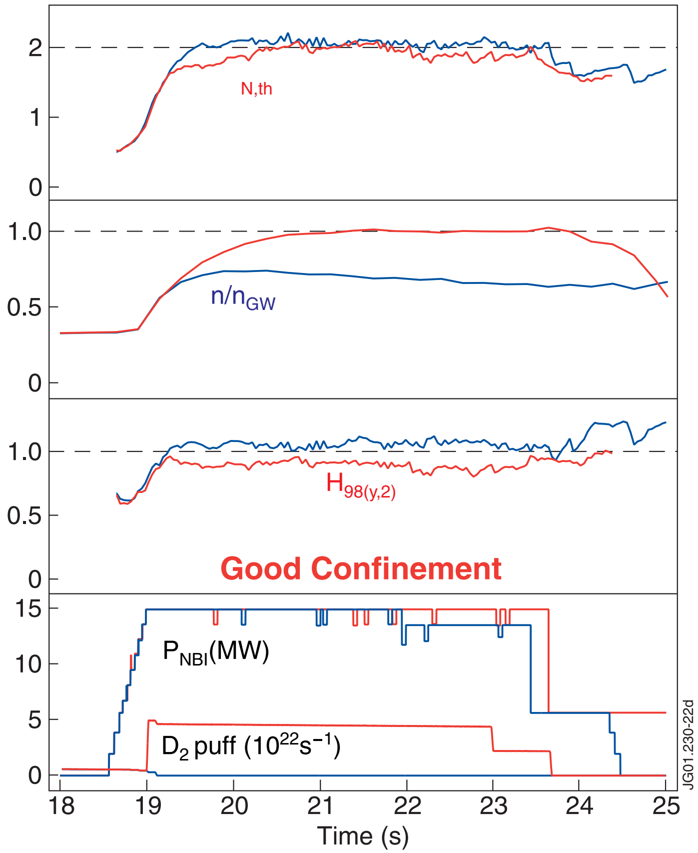
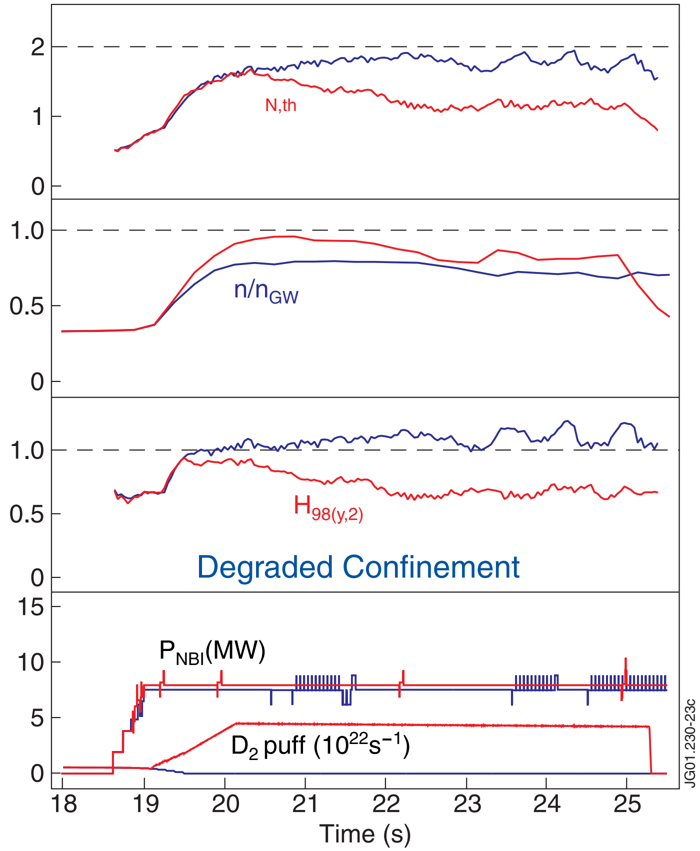
# Extension of Good Confinement Results to Lower Triangularities

Pulse No: 50843
Pulse No: 50844   1.9MA/2.0T   $_{U/L}$ = 0.38/0.30   = 1.76




Pulse No: 50836
Pulse No: 50840   1.9MA/2.0T   $_{U/L}$ = 0.38/0.30   = 1.76




**High power level**

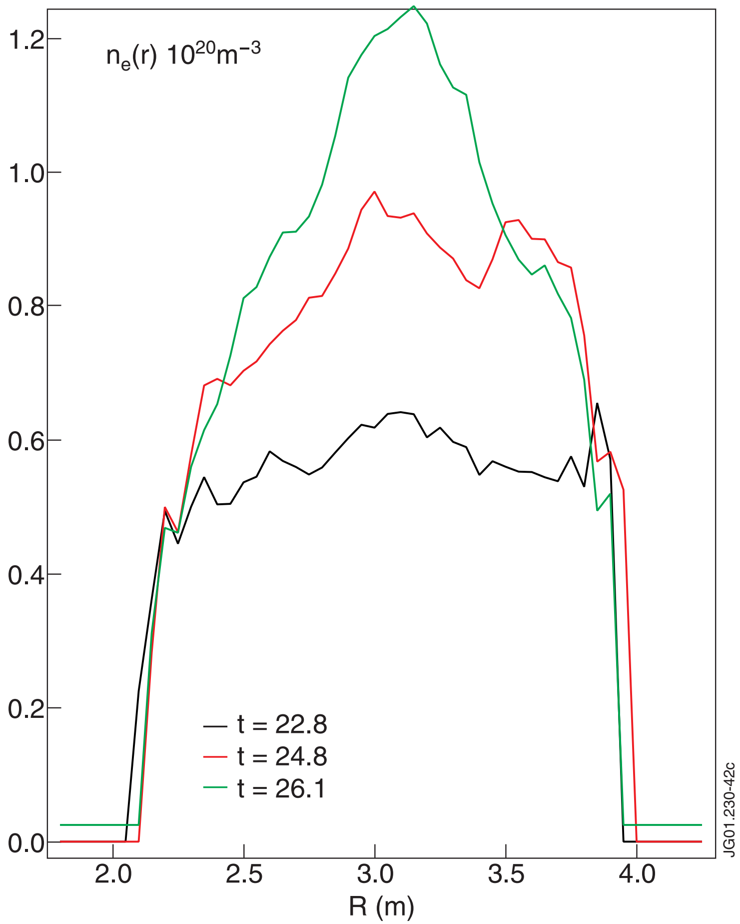
- $P_{NBI}$ = 15MW
- 2.7 < $P_{in}$ / $P_{L-H}$ < 3.5

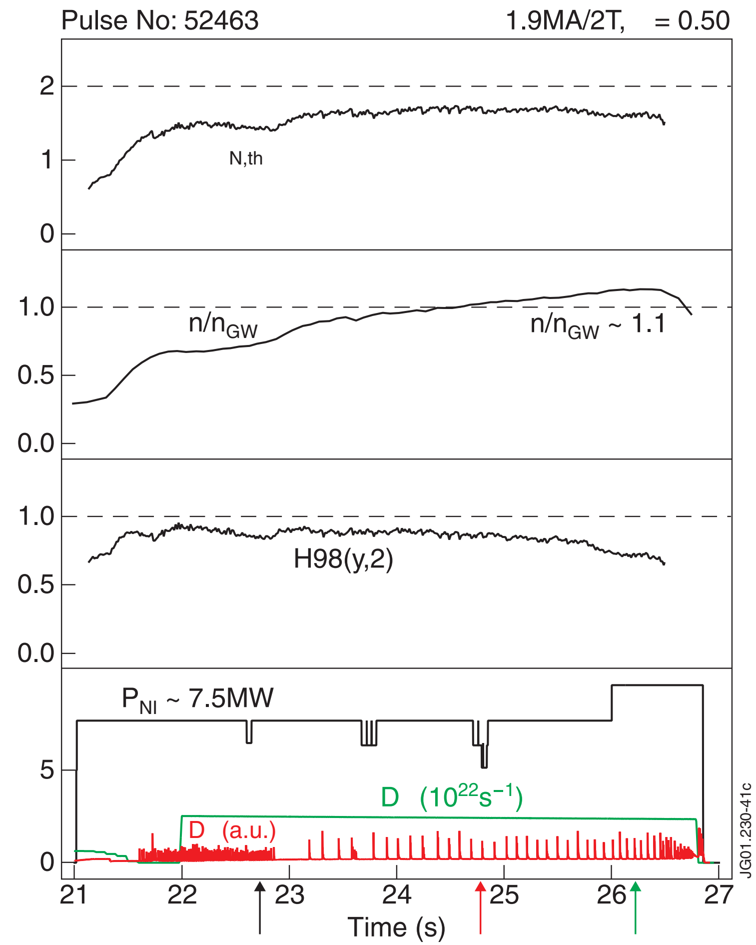
Increase power level to keep Type I ELMs
Quantified with ratio $P_{in}/P_{L-H}$

Not sufficient power

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

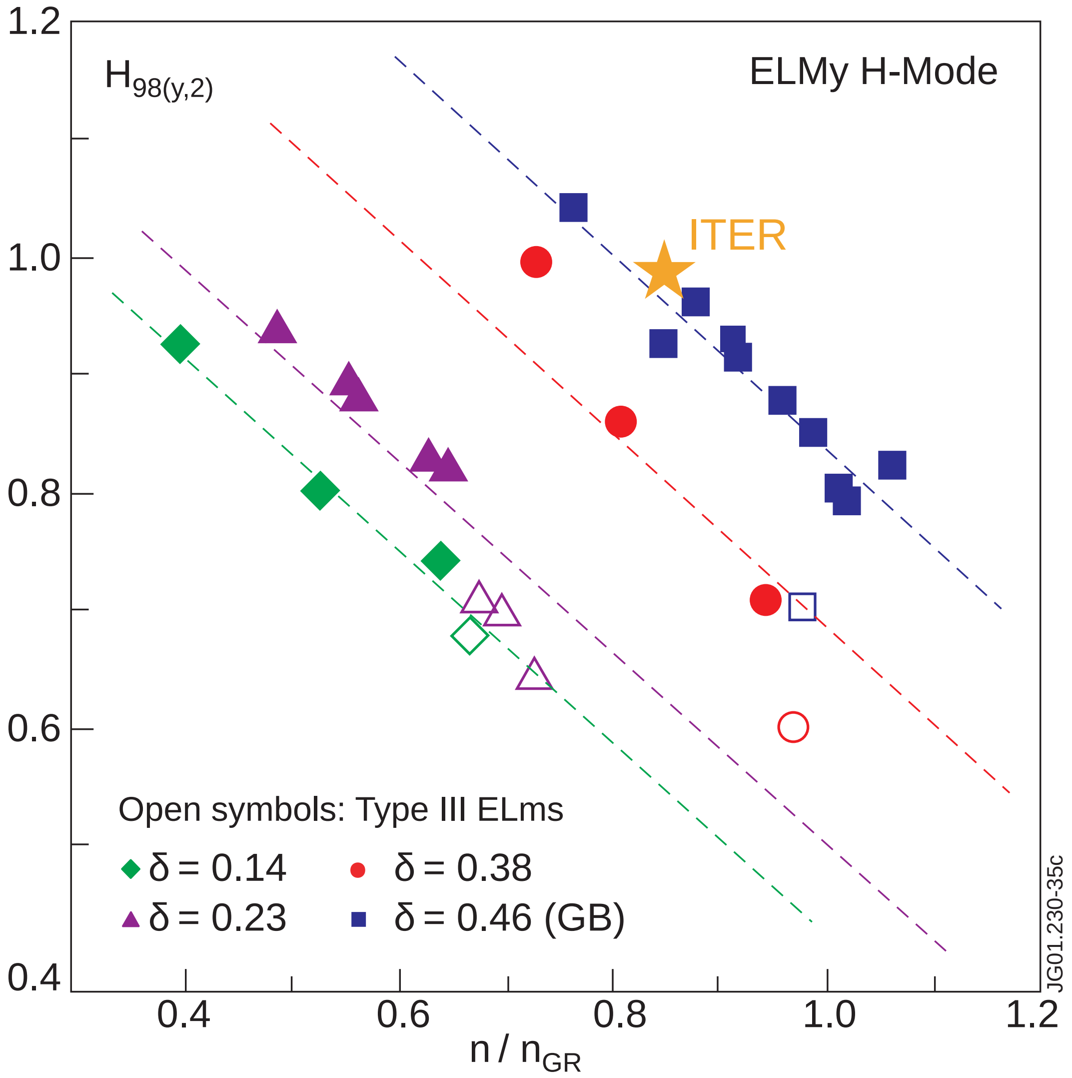
# Density Peaking in ITER-like ELMy H-Mode Plasmas




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

# JET Confinement Depends on Triangularity and ELM Type

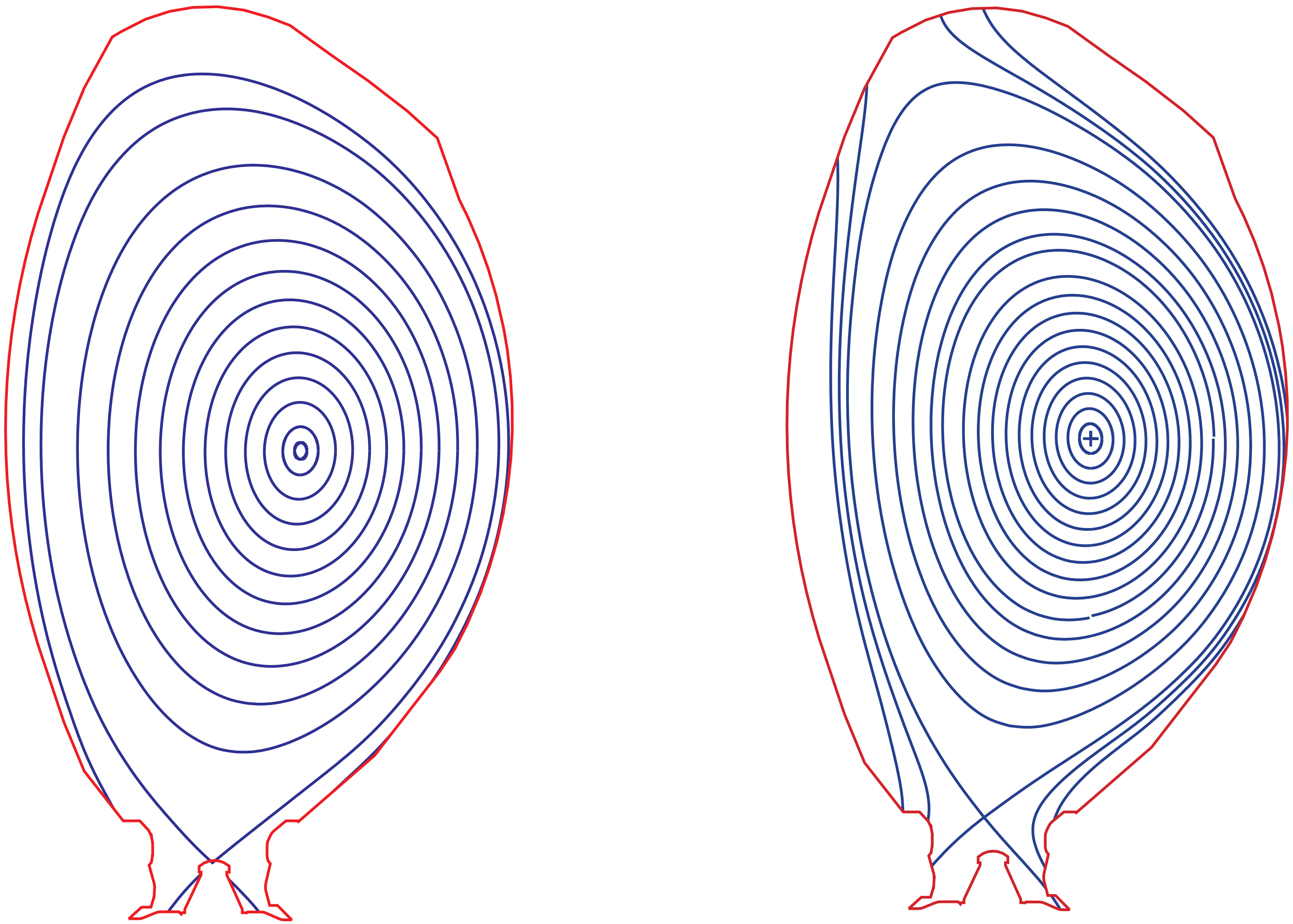



- Higher triangularity allows higher densities at high confinement
- For all triangularities: Confinement degrades with density
- Simultaneously obtained $n/n_{GW}$ ~ 0.9 and $H_{98(y,2)}$ ~ 1at high δ = 0.5
- Trade-off between triangularity and heating power: lower δ discharges need higher $P_{in}/P_{L-H}$

# 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 $\delta$, with and without septum

# Two Basic Plasma Shapes Used for Impurity Seeding



Low Triangularity
X-Point on Septum

High Triangularity

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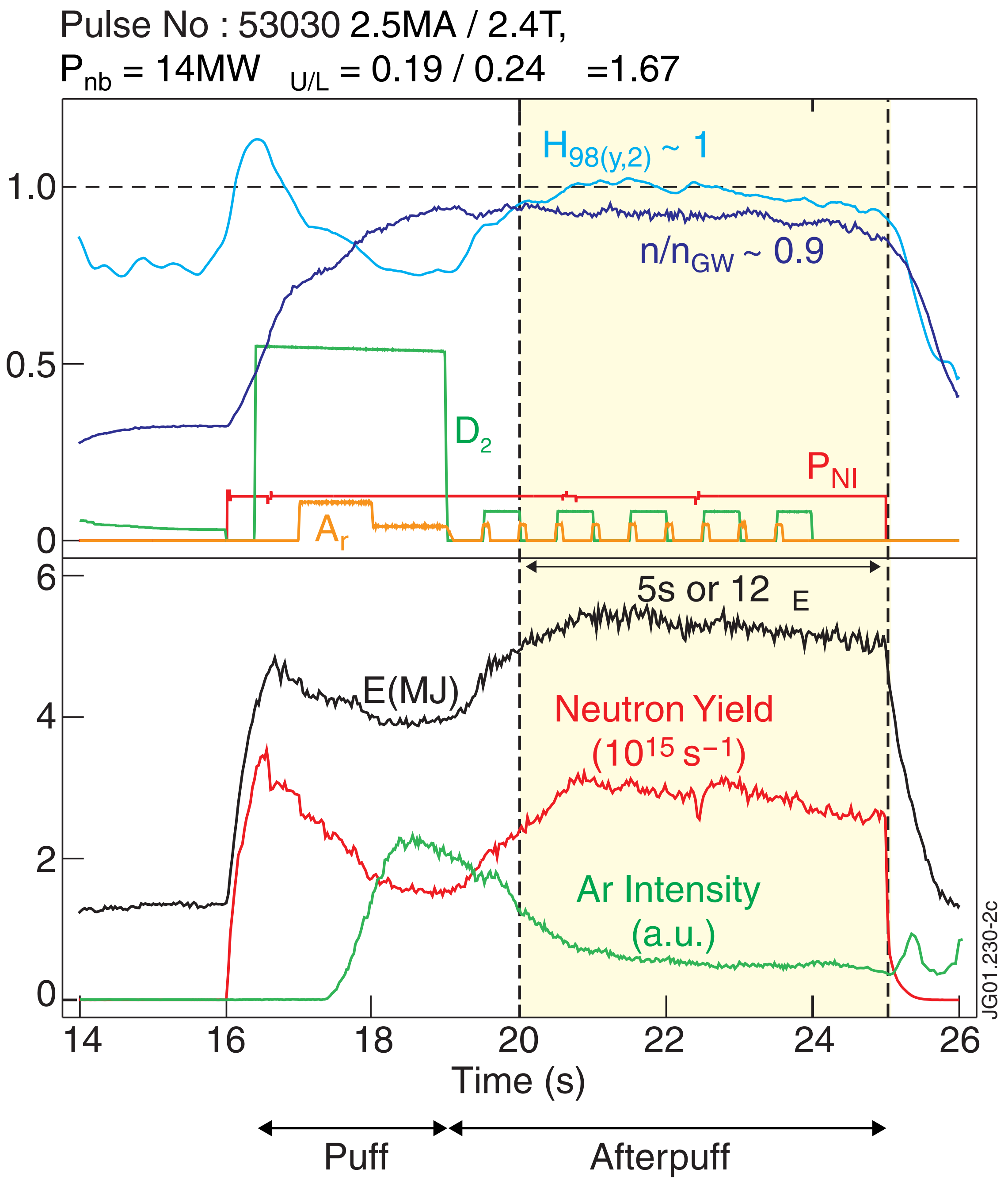
# Impurity Seeding in ELMy H-mode (Low Triangularity, X-Point on Septum)




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

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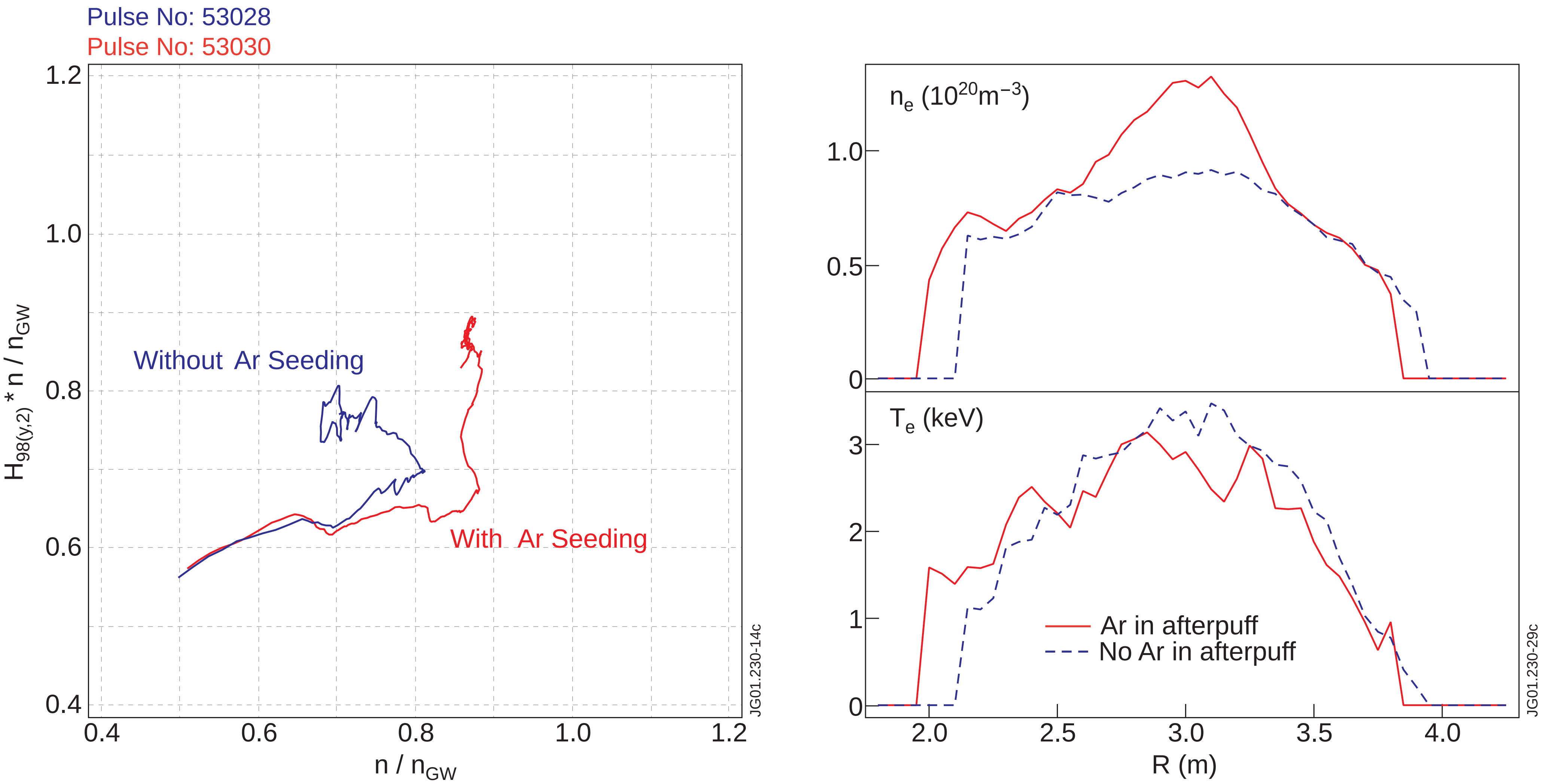
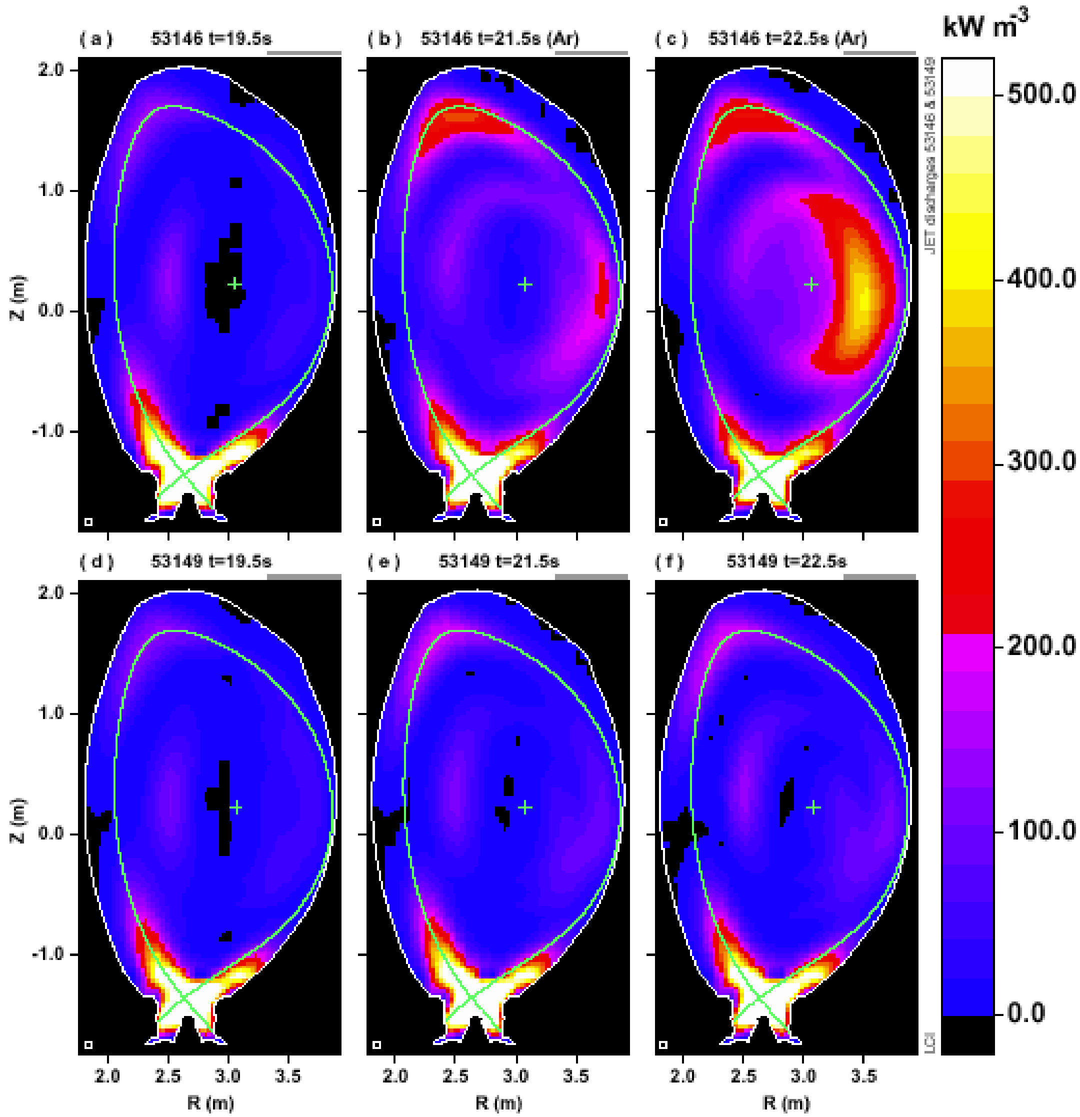
# Impurity Seeding Dramatically Improves Plasma Performance
# (Low Triangularity, X-Point on Septum)



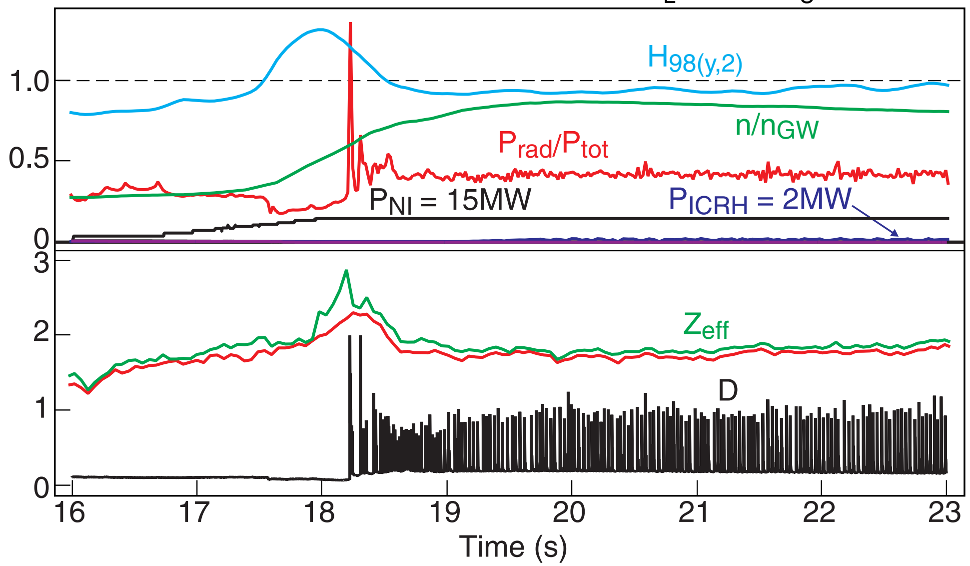
# Mantle Radiation Produced by Ar Impurity Seeding



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

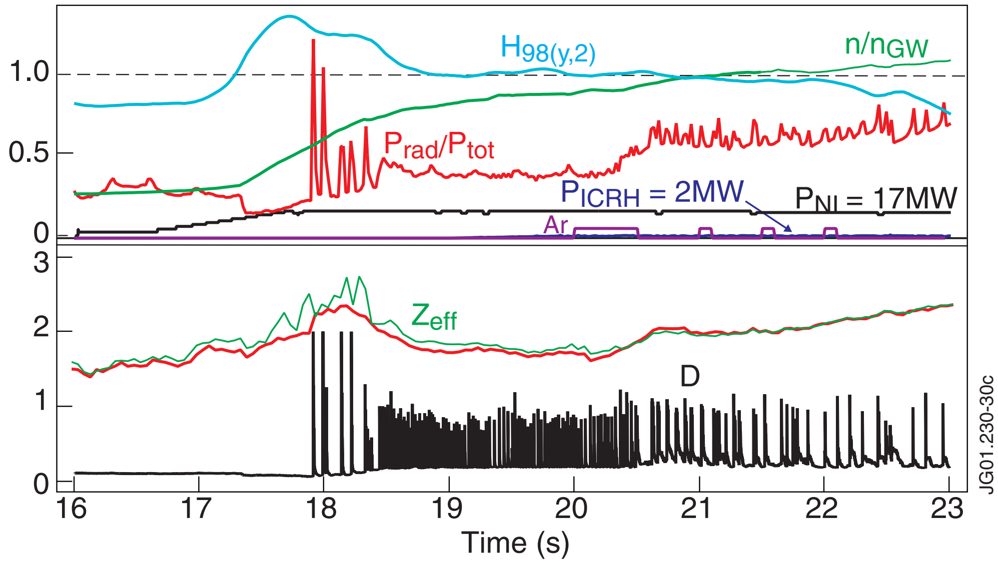
**Reference plasma without Argon Seeding**

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

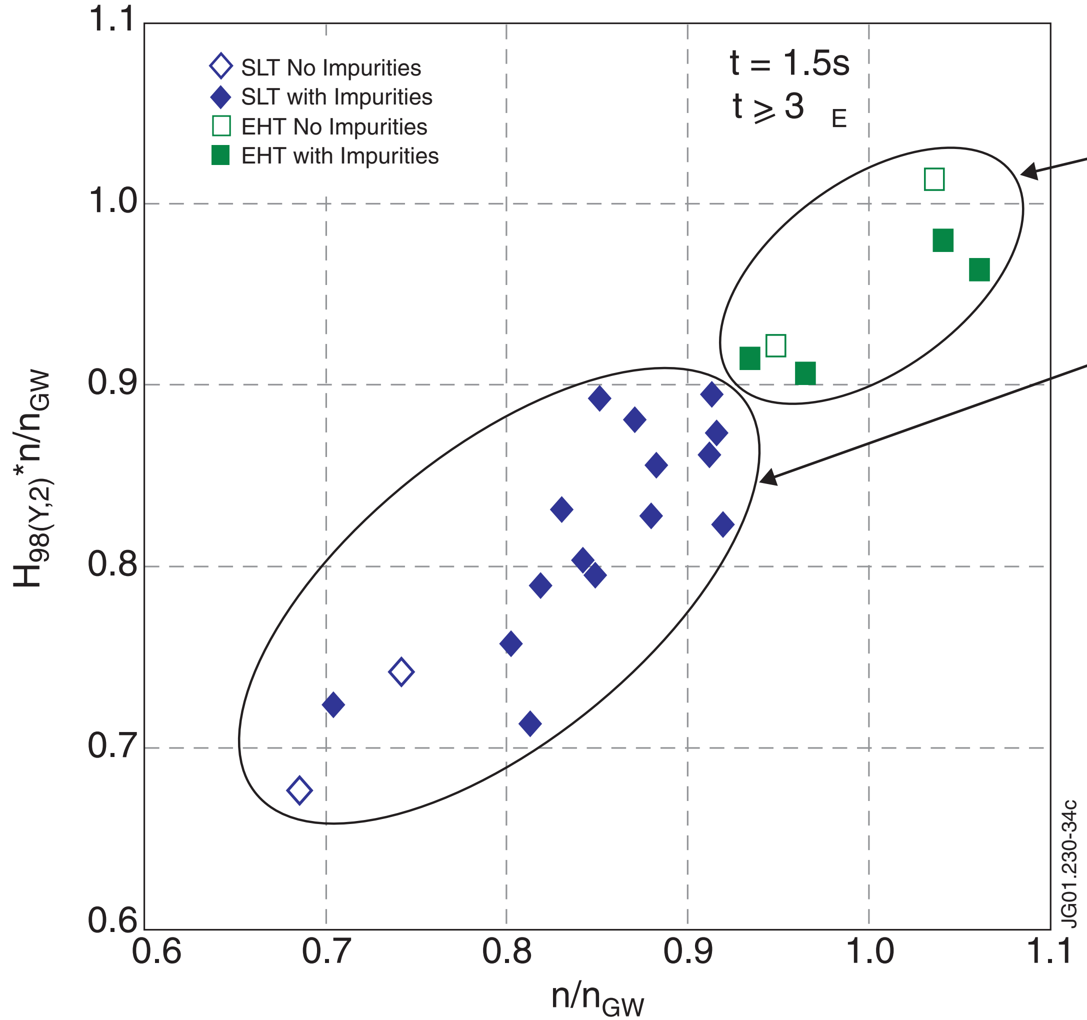



Argon seeding with high triangularity plasmas:

- 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

# 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)

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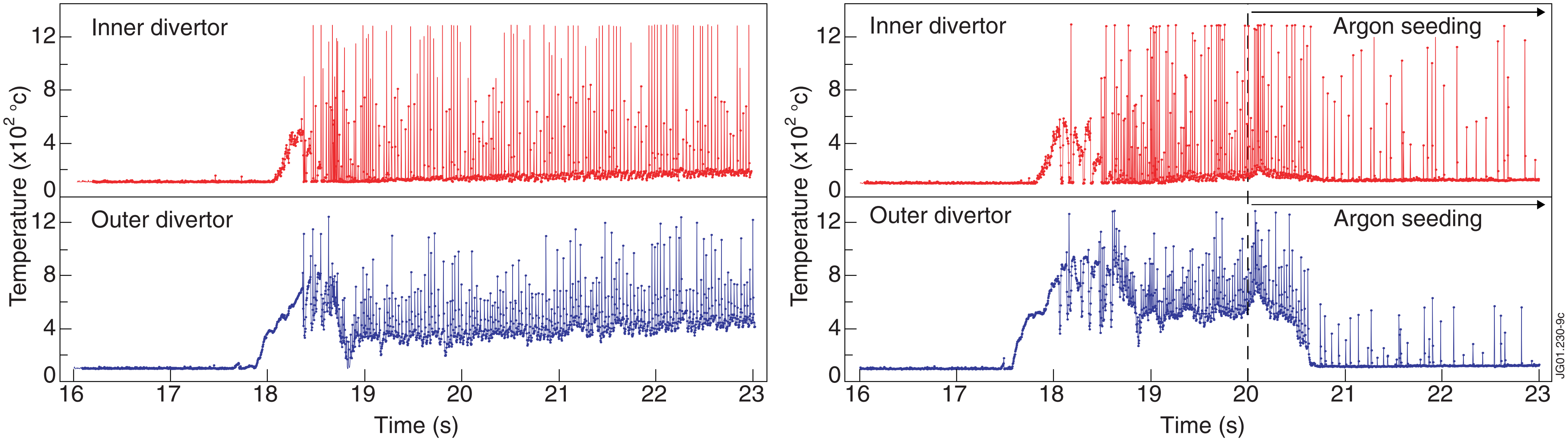
# Strong Reduction of Divertor Target Temperature During Argon Seeding

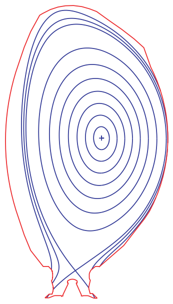
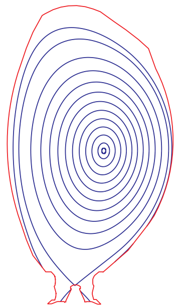
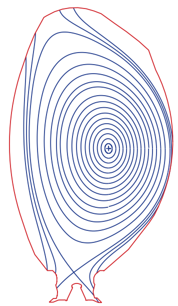
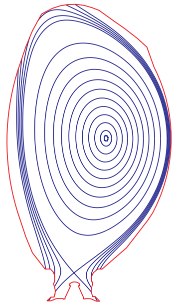
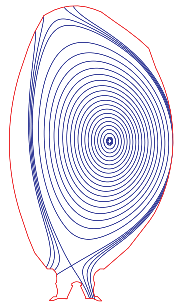
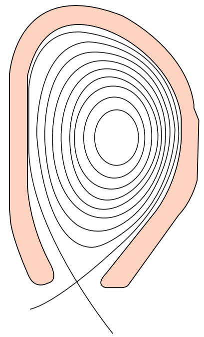



- IR thermography measurements show:
  Baseline temperature reduced by factor of ~5
  ELM effects are also reduced
- Further studies needed: comparison to thermocouple and divertor probes

# 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

# Three Different Methods used to match ITER Requirements

| | PELLETS | IMPURITY SEEDING | | SHAPING | | |
|---|---|---|---|---|---|---|
| |  |  |  |  |  |  |
| | **JET**<br>HT HFS Pellets<br>Pulse No: 53212,<br>2.5MA/2.4T | **JET**<br>LT Ar seeded<br>Pulse No: 53030,<br>2.5MA/2.4T | **JET**<br>EHT Ar seeded<br>Pulse No: 53550,<br>2.3MA/2.4T | **JET**<br>HT High power<br>Pulse No: 50844,<br>1.9MA/1.9T | **JET**<br>"ITER shape"<br>Pulse No: 53299,<br>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** |

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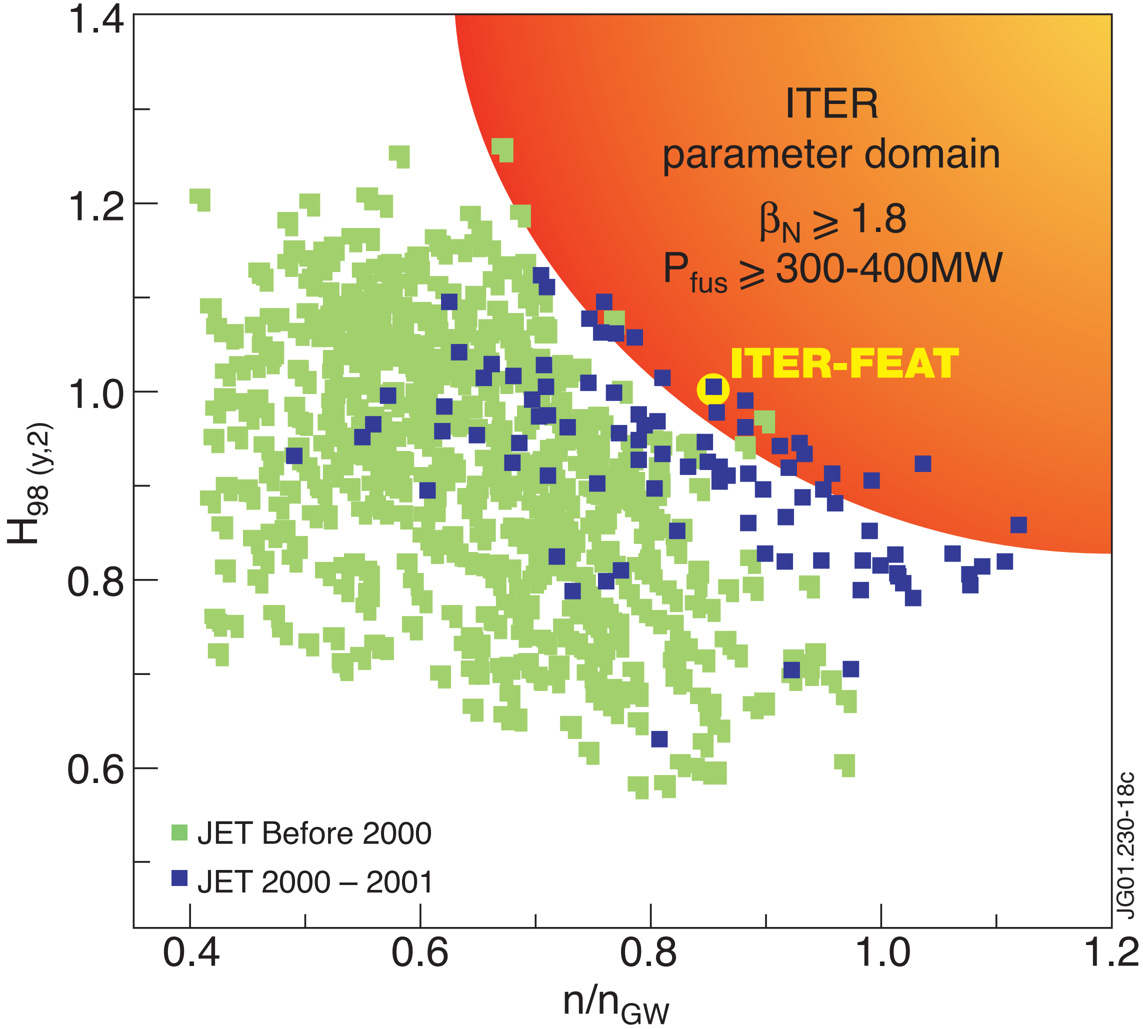
# Methods Used to Obtain $H_{98(y,2)}$ = 1, $n/n_{GW}$ > 0.9 for ITER




- Extension of parameter domain leading to simultaneous realization of $H_{98(y,2)} = 1$, $n/n_{GW} > 0.9$ and $\beta_N \geqslant 1.8$ 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**

# OUTLOOK AND FURTHER WORK

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

Narrow the gap to ITER-like 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

## *This research performed by:*

**ORNL** & EFDA-JET 2000 workprogramme contributors*

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