EUROPEAN FUSION DEVELOPMENT AGREEMENT

Control of Edge MHD instabilities in JET

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I - Identification and control of the external kink in the ELM-free regime and how this was used in the DTE1 campaign to obtain a record P_{fus}=16 MW

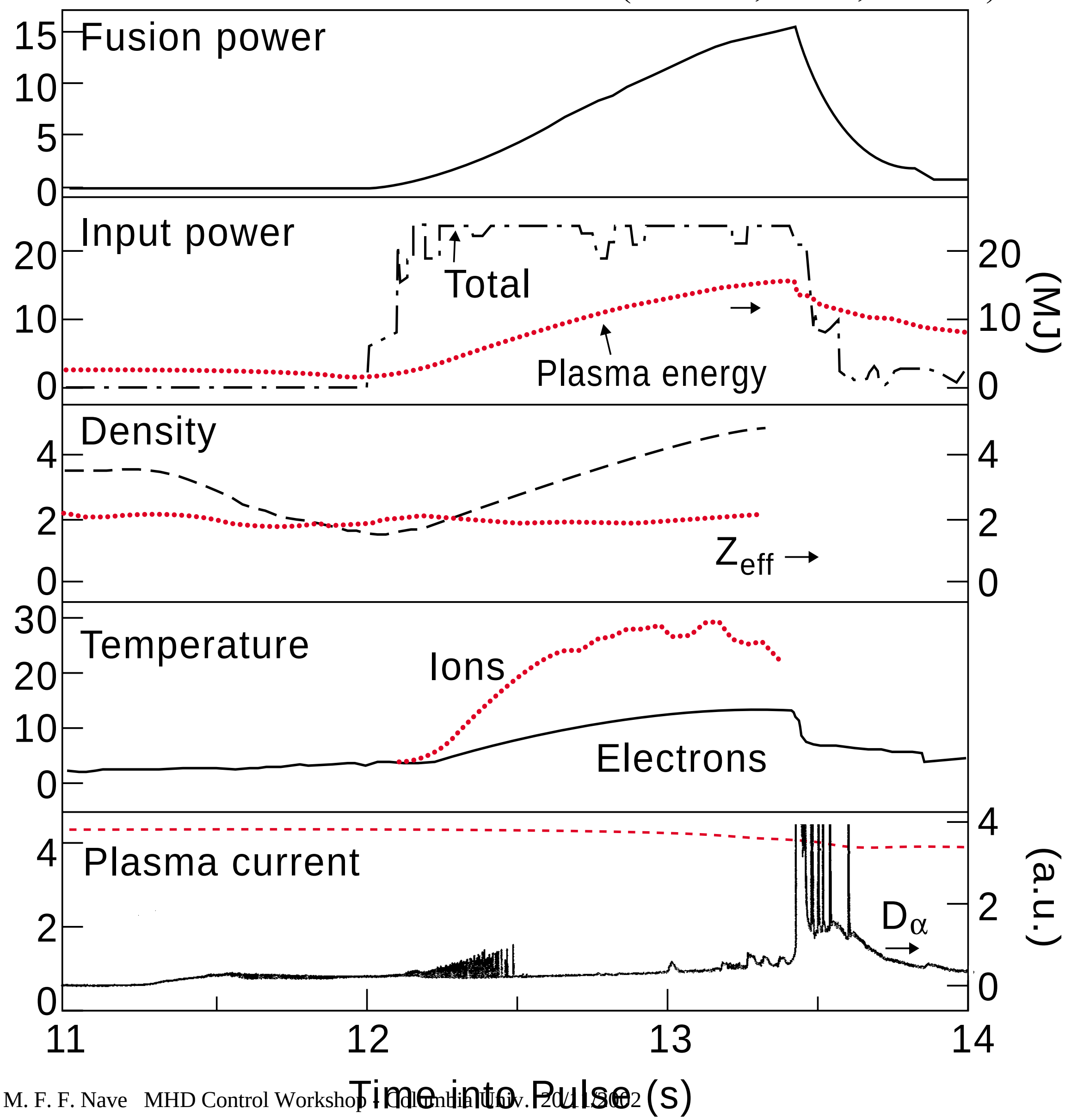
II - Control of the 1st ELM by Impurity seeding

III- ELMs and impurity seeding in recent RI-experiments

Hot-ion H-modes

16.1MW of D-T Fusion Power

(Pulse No: 42976) (4.2 MA, 3.6 T, δ~0.35)



Optimised discharge:

•W_{dia}^{max} and P_{fus}^{max} increases with the length of the ELM-free period.

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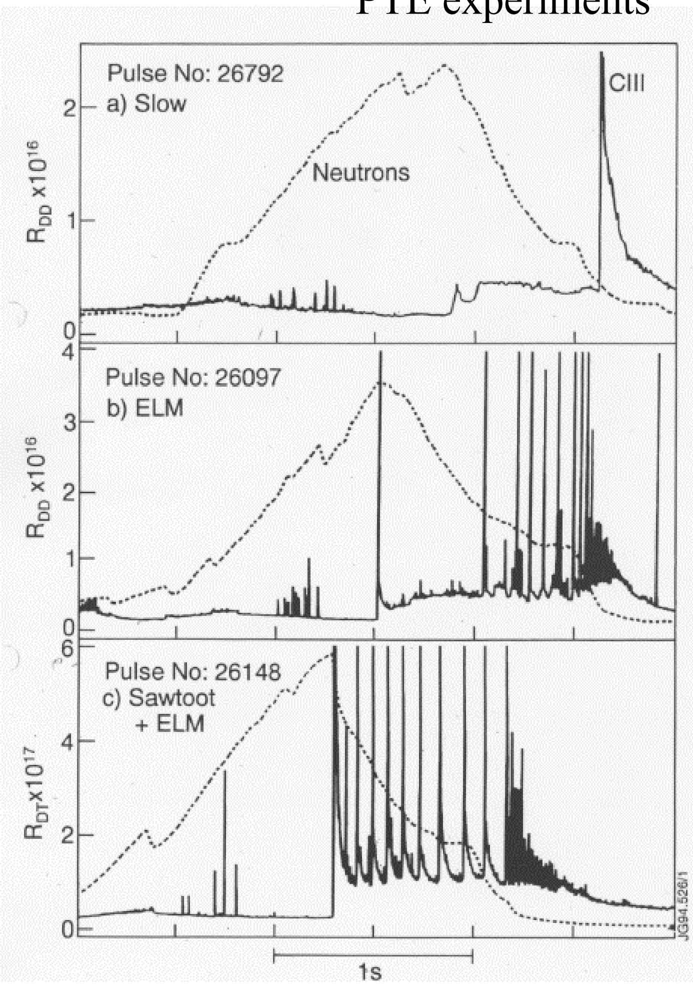
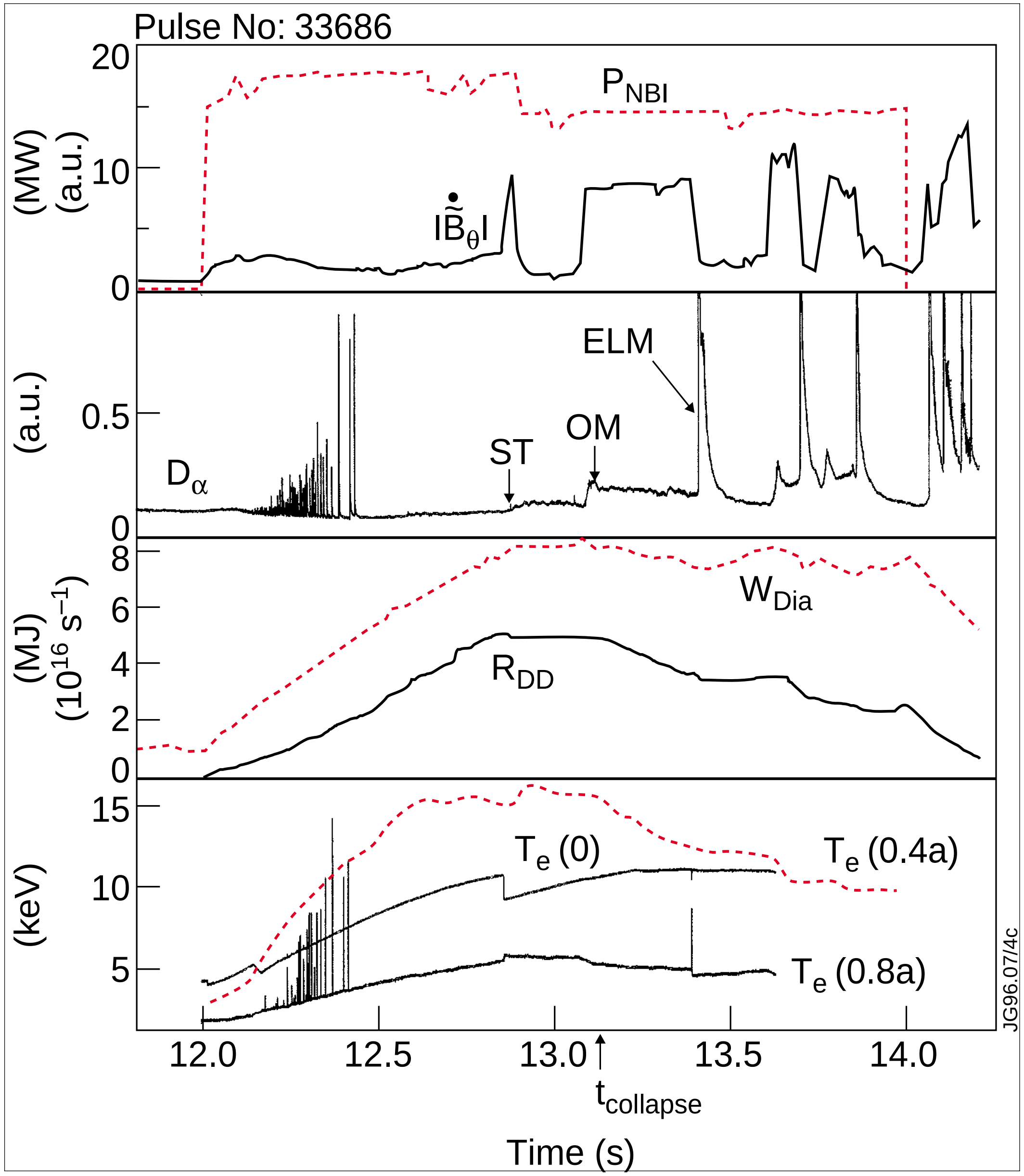
History of JET hot-ion ELM-free H-modes:

1991 PTE R_{DD} roll-over associated with Carbon-bloom
1992 Shut-down to install Divertor
1993-94 ELMy plasmas, had to re-establish ELM-free plasmas
many parameter scans done
counter-injection (not published)
1995-96 ELM-free plasmas again
No carbon-bloom, however R_{DD} roll-over still observed
Discharge optimisation: control of MHD core and edge modes essential
1997 Successful control of external kinks by current ramp-down
DTE1 record fusion power
1999 Impurity seeding experiments to control 1st ELM
1998-present ELM-free plasmas not considered for ITER because of fears of large ELMs

PTE experiments





How it use to be .

A non-optimised discharge showing a MHD nightmare

For high performance it was necessary to increase core and edge stability

MHD limitation observed at β_N~1.8

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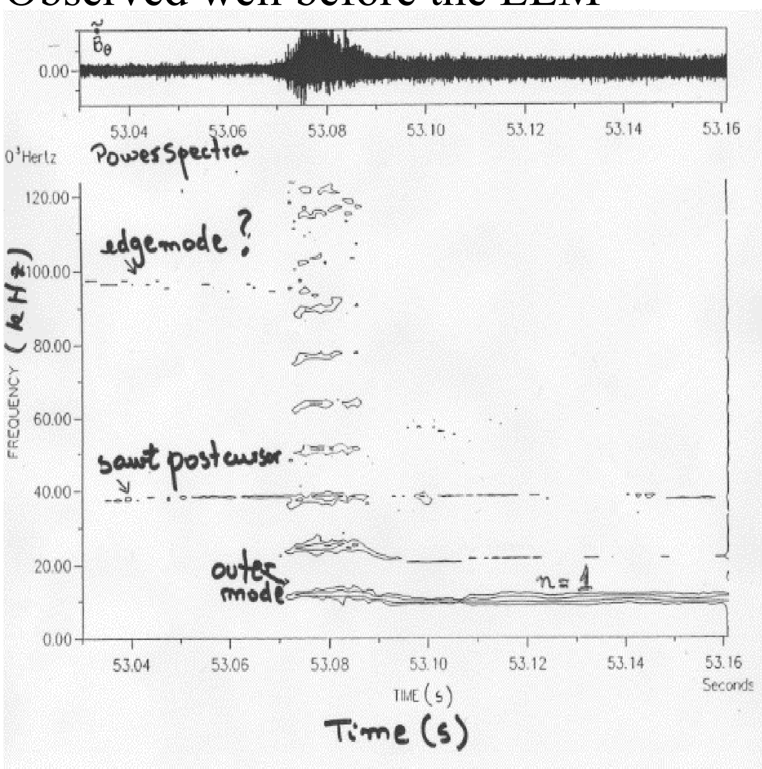
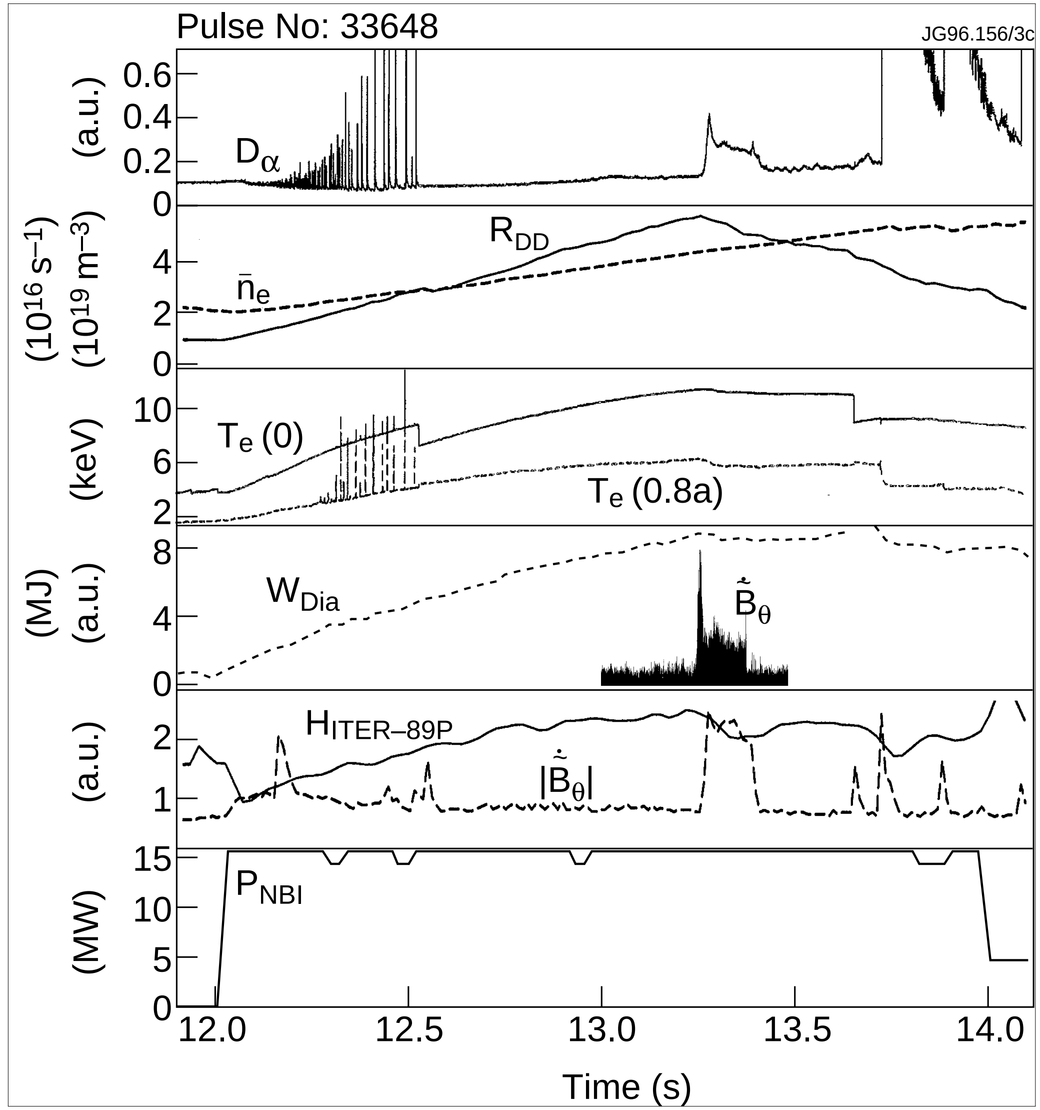
Most serious threat: to performance:

The Outer Mode

Magnetic identification:
n=1 mode, f~8-10kHz

Observed well before the ELM





M. F. F. Nave MHD Control Workshop - Columbia Univ. 20/11/2002

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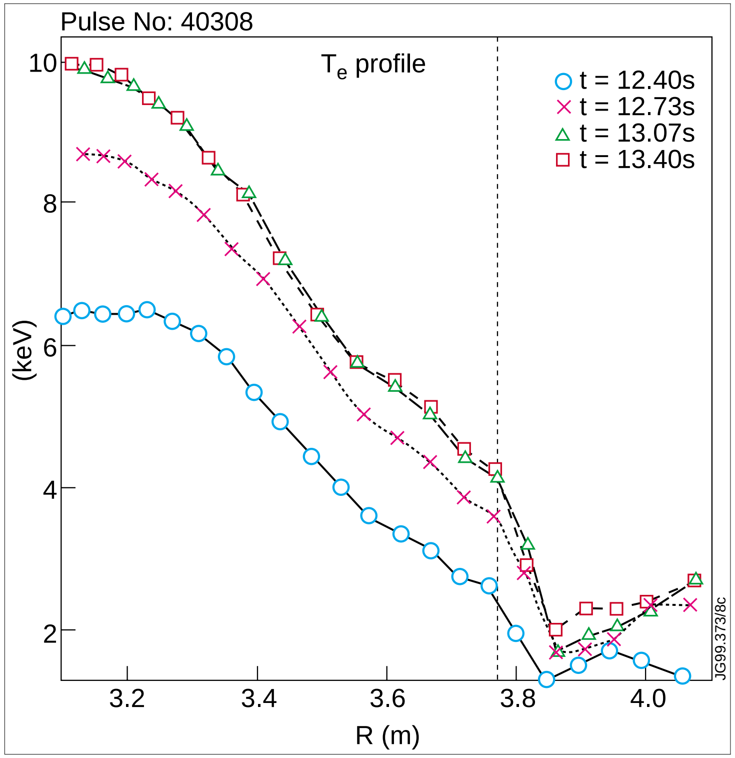
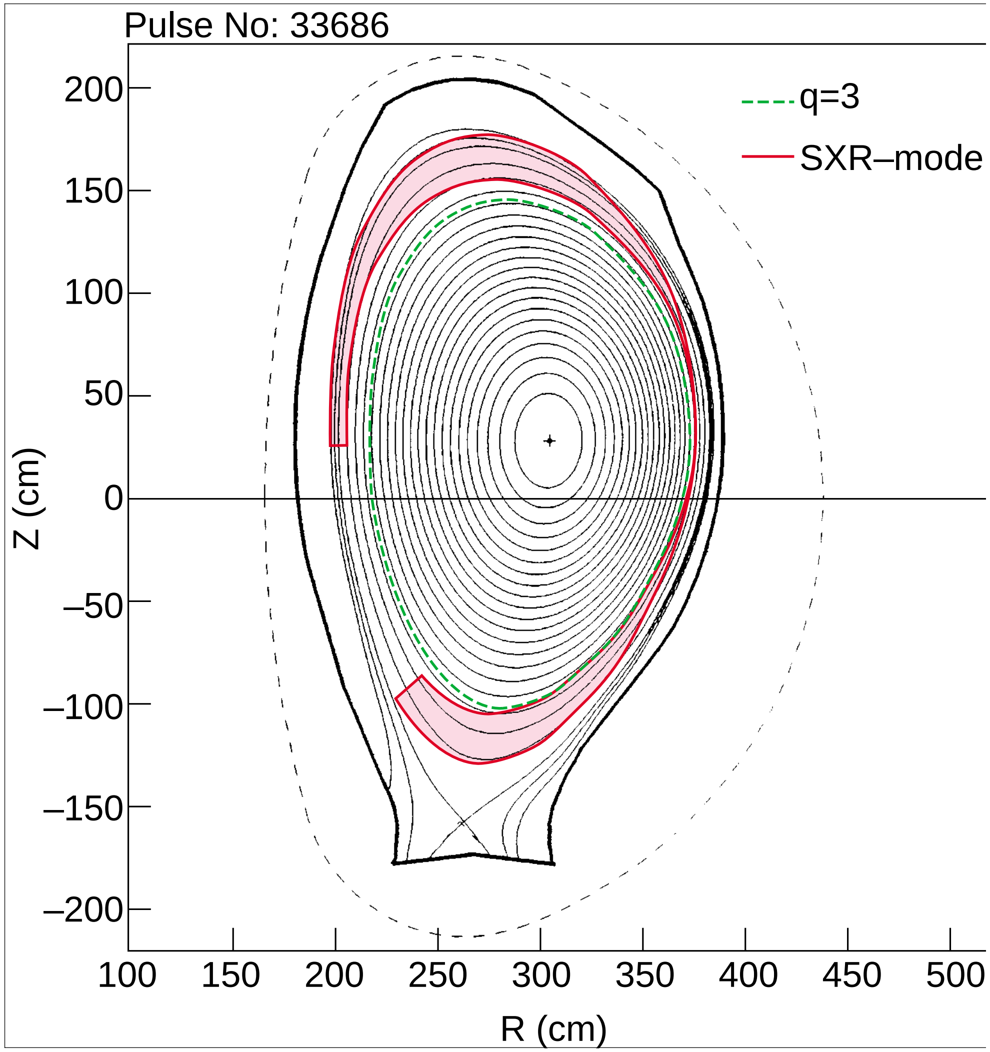
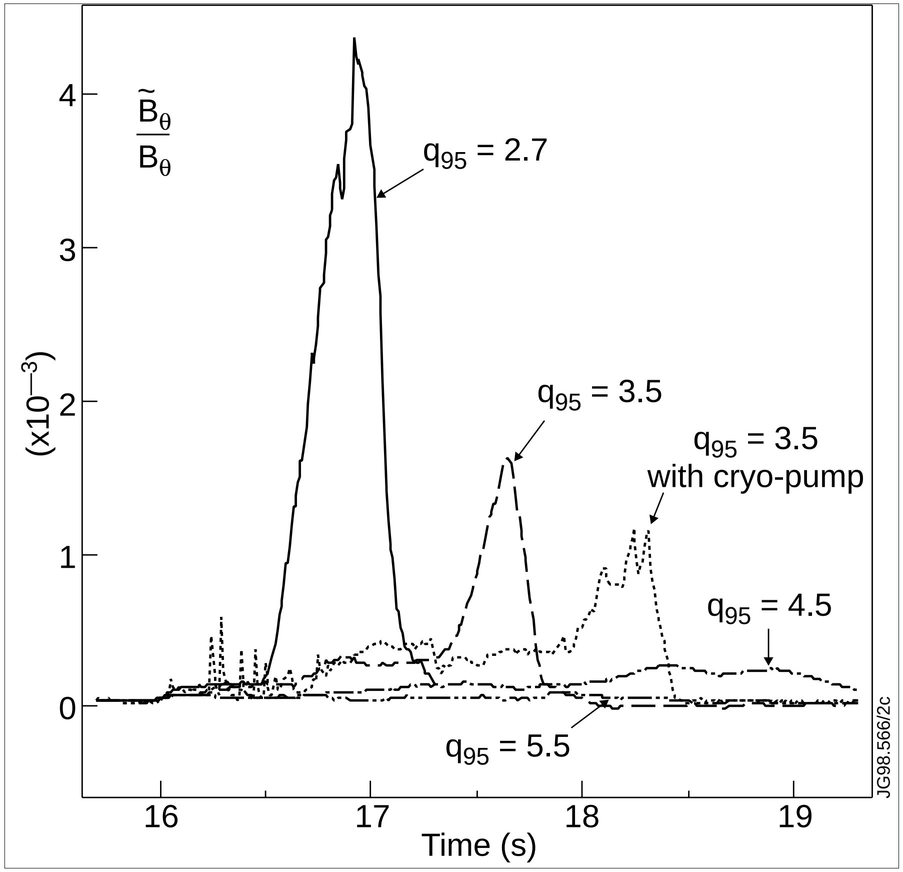
ECE, SXR and reflectometer data shows Outer Mode localised near the edge





Mode inside the H-mode edge confinement barrier.

Bt scan at fixed Ip=1.6 MA



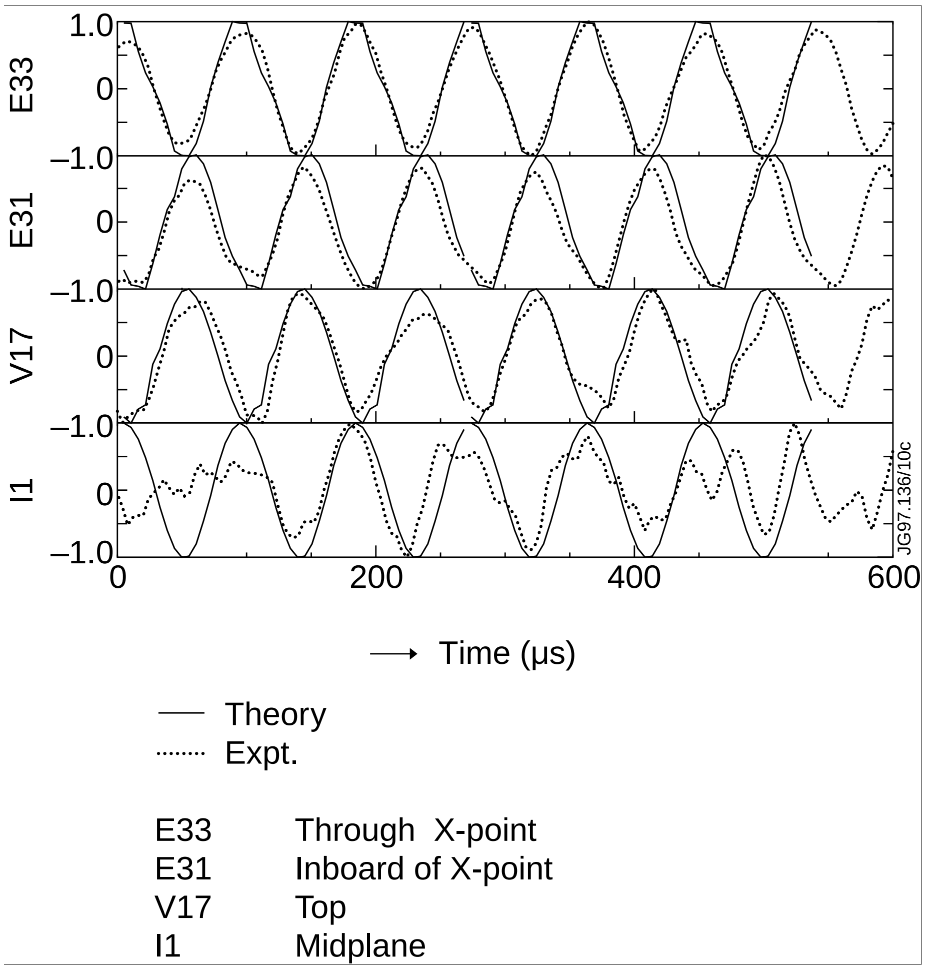
q-scans show that it is better to operate at high q-values

For q_{95}<3 outer mode locks and causes disruption

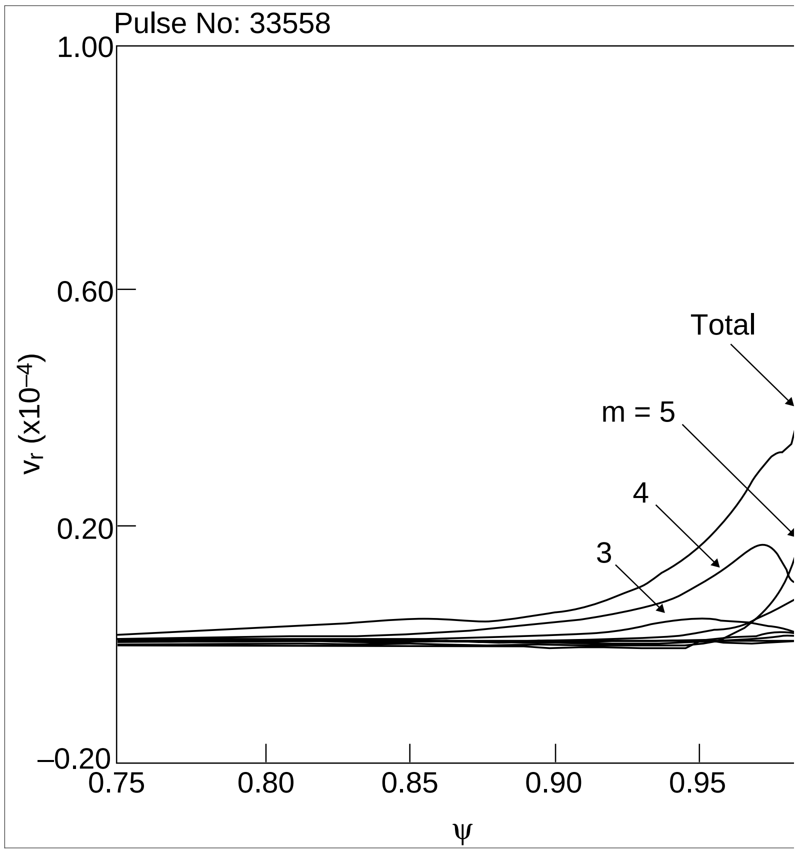
However, even the low amplitude outer-mode at q_{95}~4.5 reduces R_{DD}

Identification of outer mode as an External Kink

Comparison of SXR data (dotted line) and predictions (solid line) based on the ideal kink



Mode structure from CASTOR code



Huysmans et al, NF 1998

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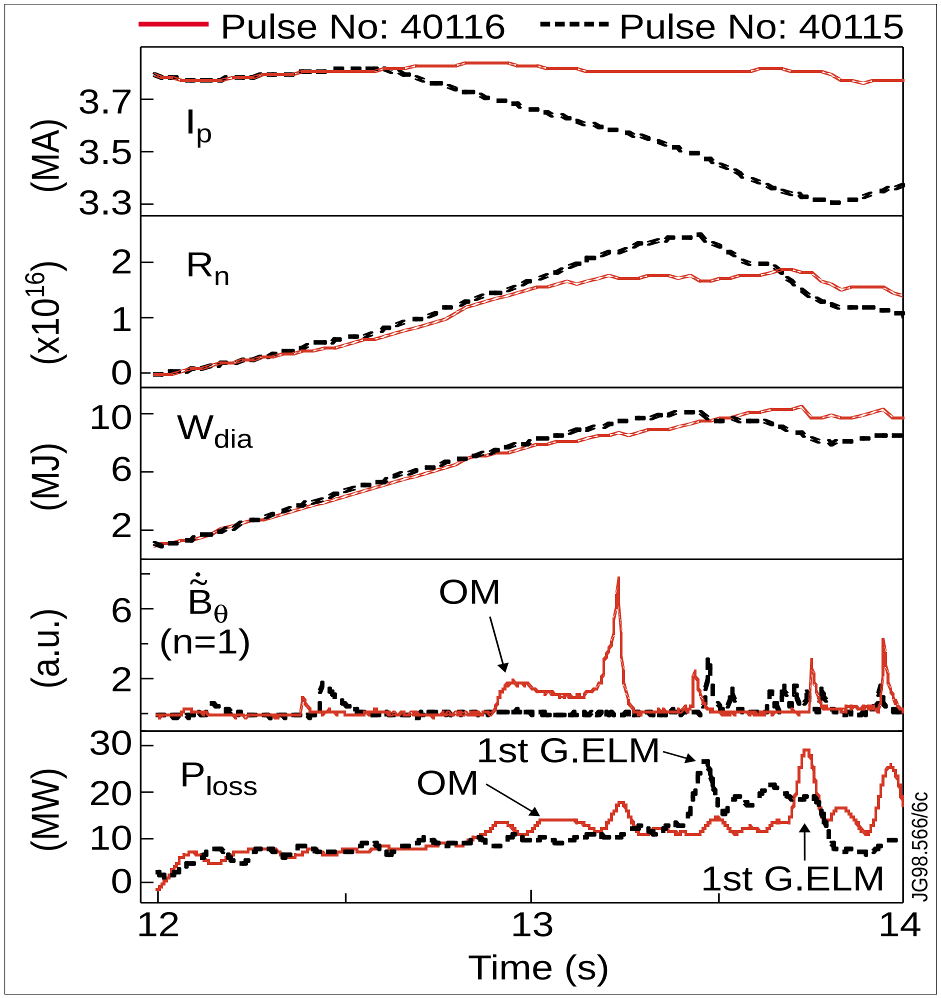
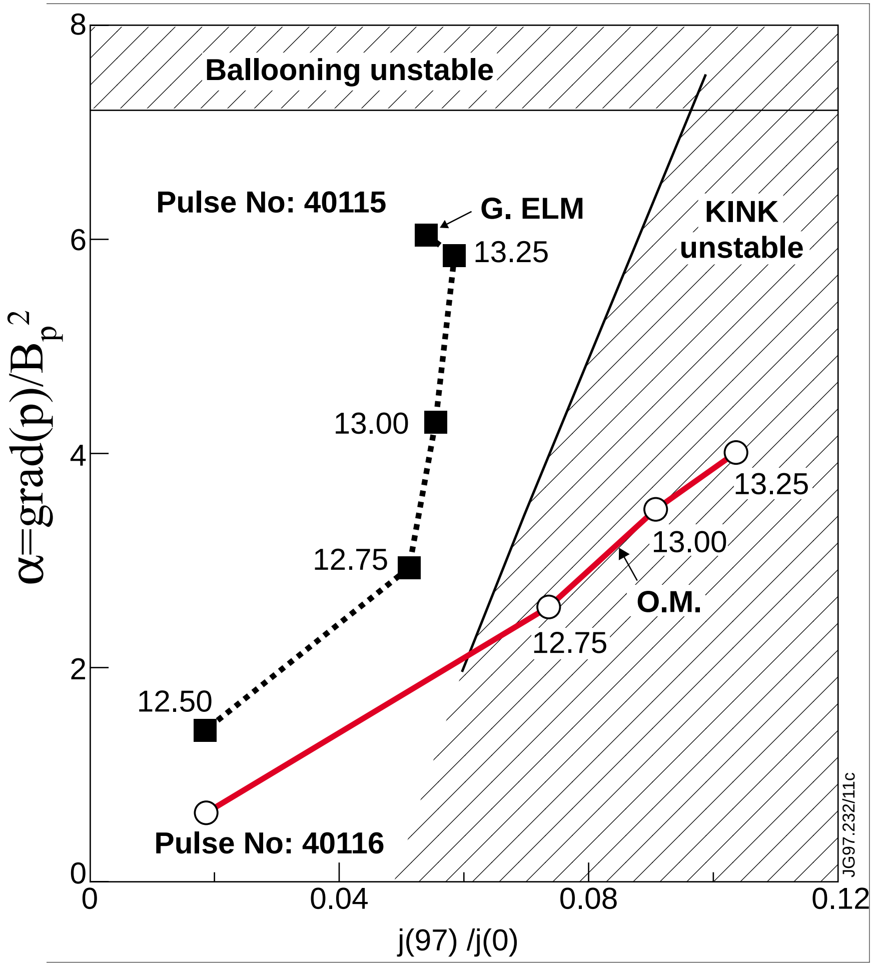
Controlling the outer mode by current ramp-down

- ❖Outer mode delayed
- ❖R_{DD} limitation delayed by 500 ms
- ❖Improved R_{DD} by 45%

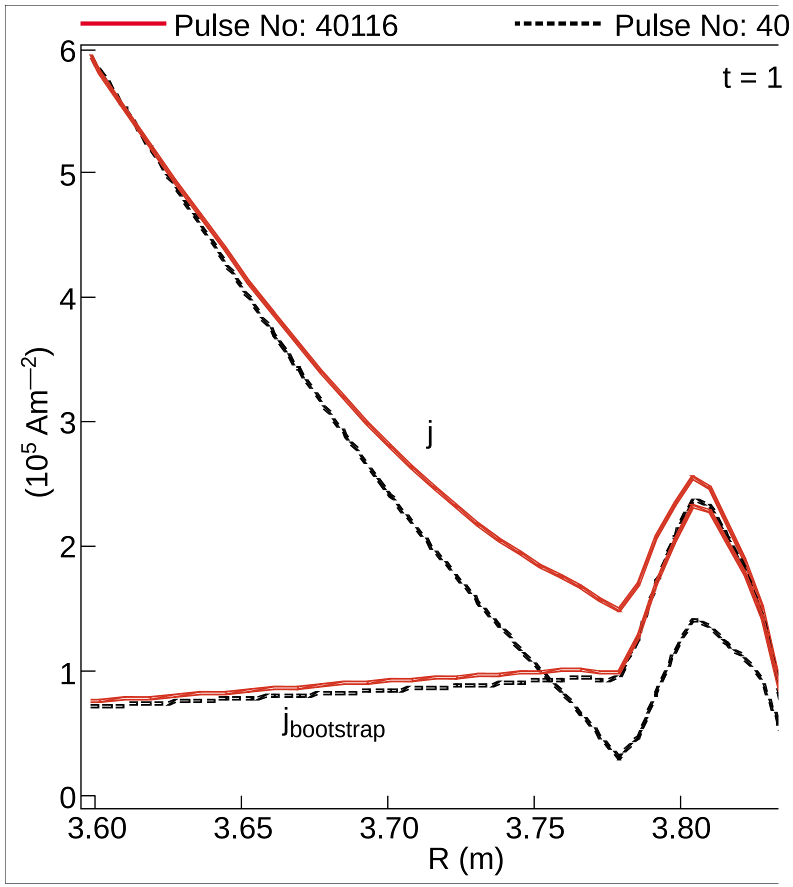


Current ramp-down experiments confirm the identification of the OM as an external kink



CASTOR code calculation

- ❖ Current ramp-down increases stability to external kink modes
- ❖ Ballooning limit reached earlier



JETTO Calculation:

- ❖Jedge lower
- ❖Grad(p) not changed
- ❖Bp decreased by 10%

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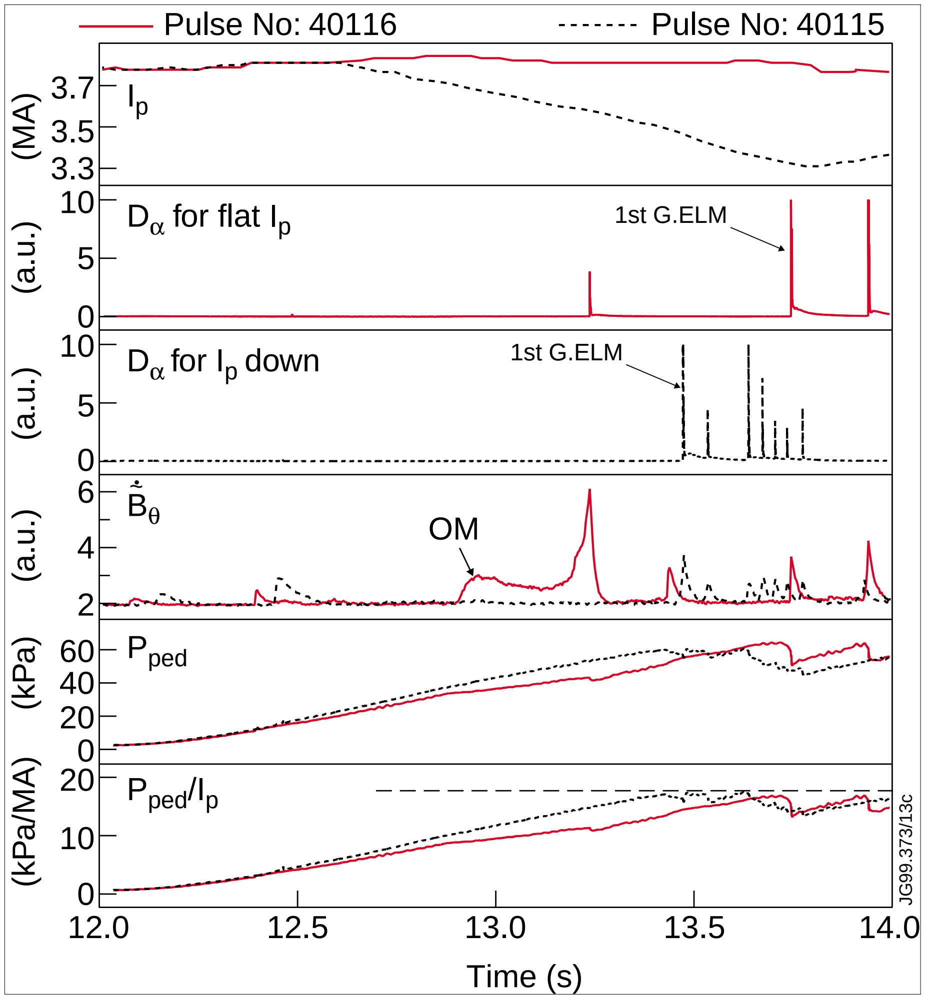
With Current ramp-down the 1st giant ELM occurs earlier

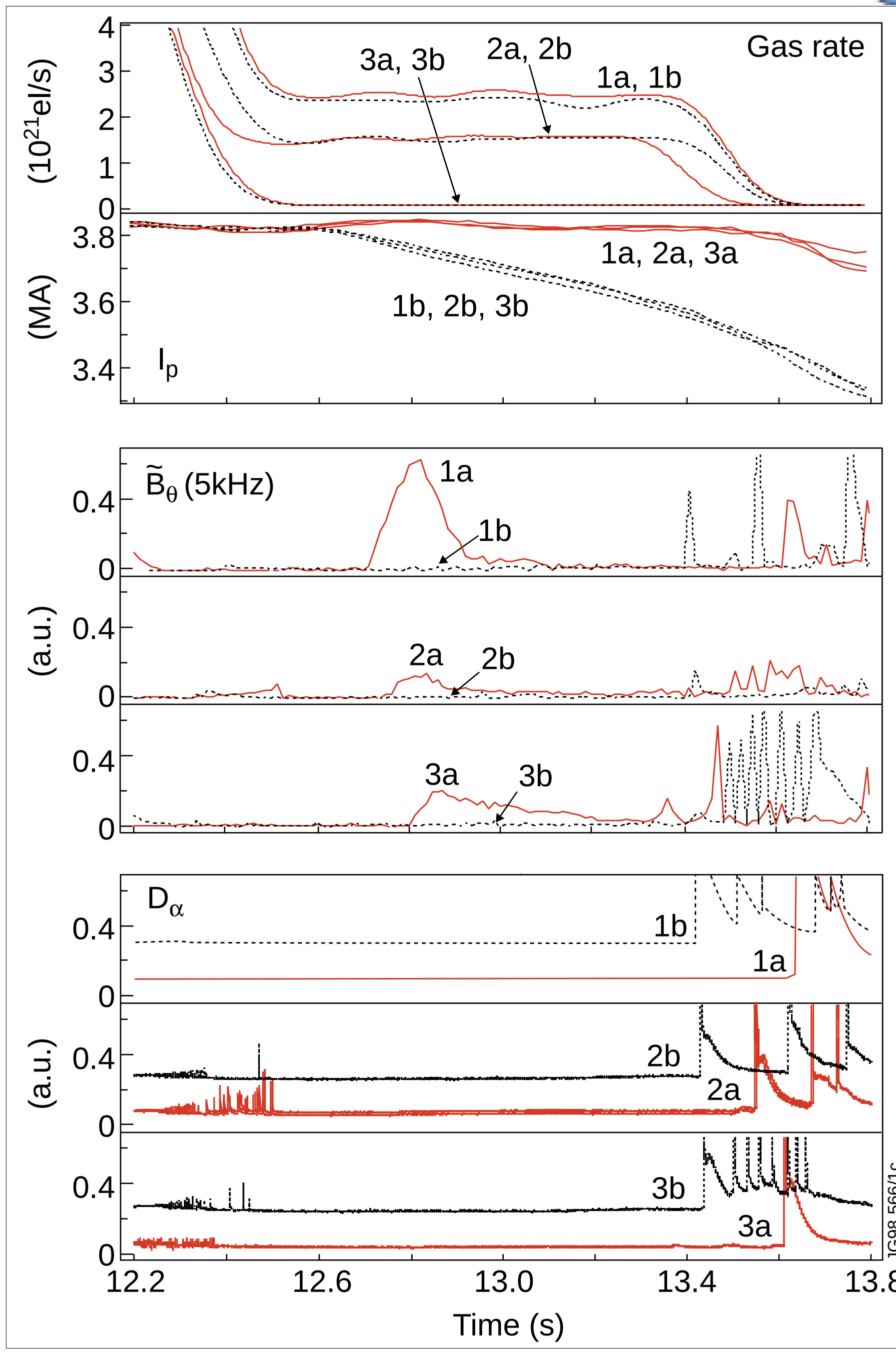


Experiments to separate
gra(p) and j effects

Vith different gas rates :
Jo effect on either ELMs or OM

Vith current ramp-down clear
esults always obtained :
)M suppressed
:LM occurs earlier

lIp/dt=-0.3-0.5 MA/s



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For discharge optimisation with respect to the 1st ELM it is better to increase IP

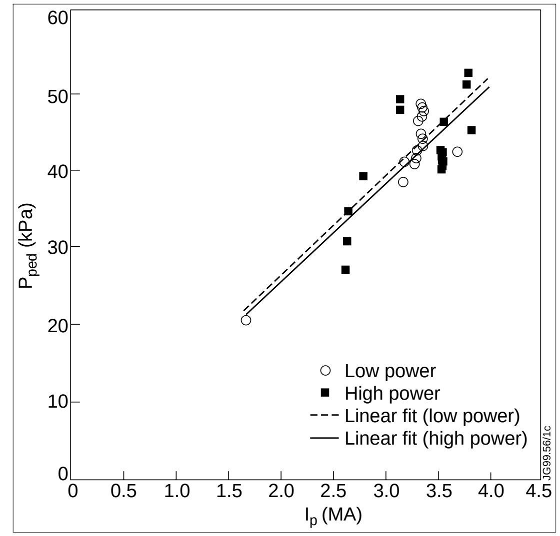
aling at fixed B_t for discharges where OM has been
ppressed

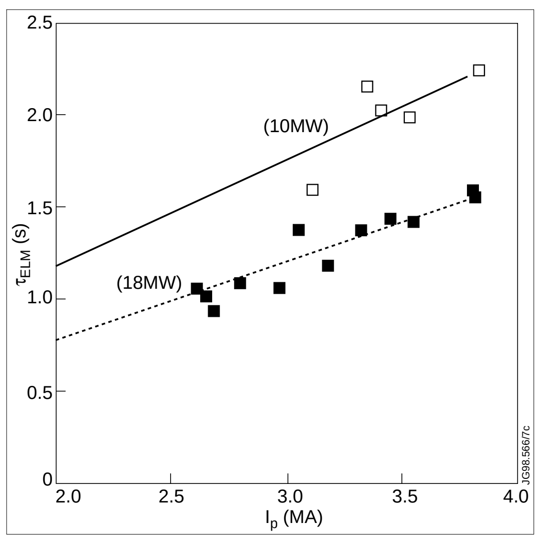
LM occurs for crit P_{ped}/I_p

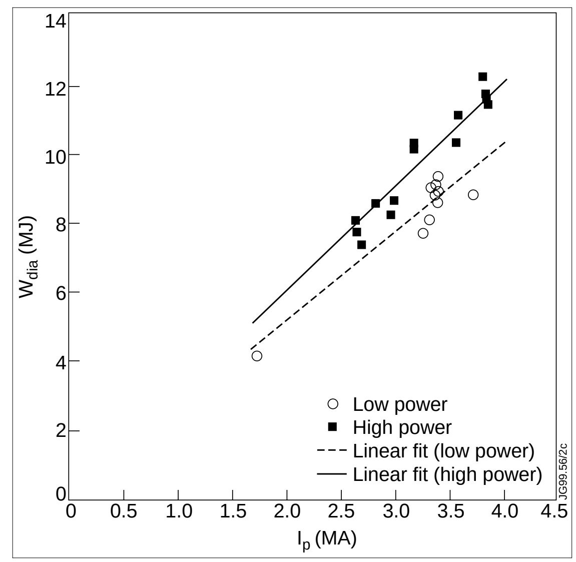
ompatible with ballooning limit if edge barrier width
$_{ar} \propto I_p^{-1}$

optimised discharges $t_{ELM} \propto I_p$
on-optimised discharges have longer ELM-Free periods

ave et al.PPCF 1999)







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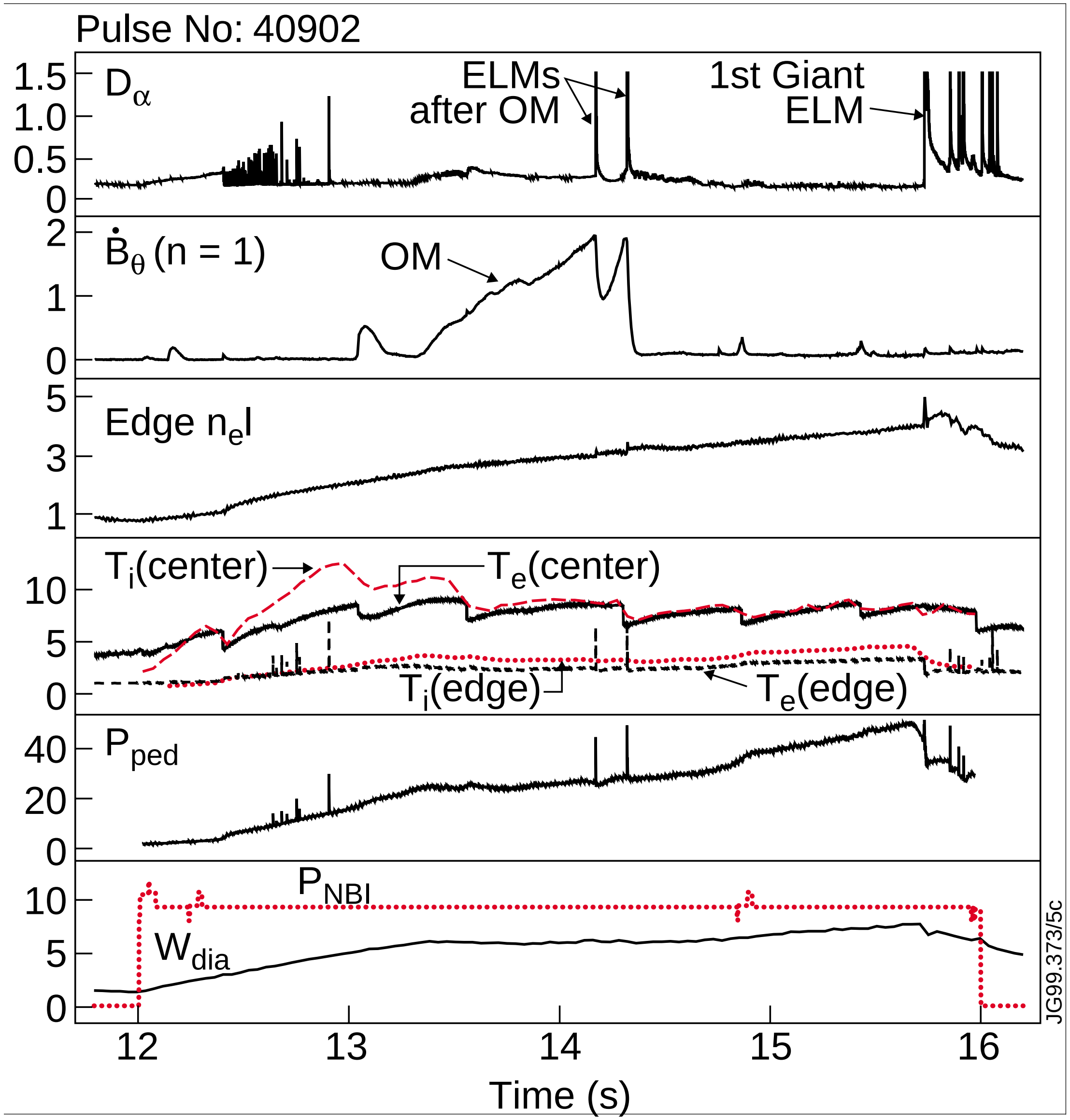

Recipe for a long ELM-free period:

❖Create a continuous External Kink

❖The mode keeps the pressure at the top of the pedestal low, delaying the first large ELM

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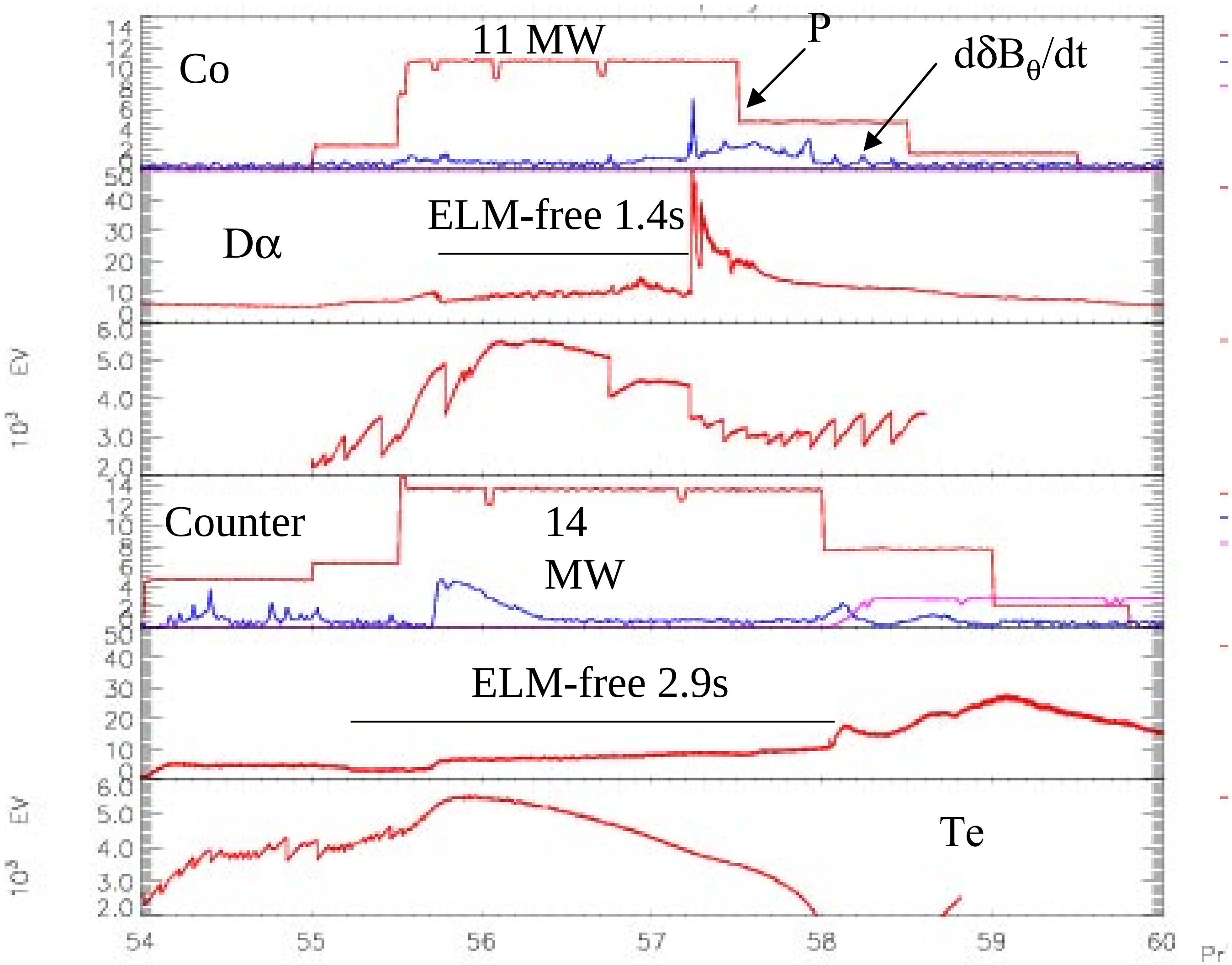
Continuous Outer-Modes and Longest ELM-free periods observed with Counter-NBI injection



JET Mk I div 1993/94 - unpublished since due to OM performance was very poor

ELM CONTROL BY ENHANCED RADIATION

At JET Impurity injection has been used to control H-mode edge conditions :

LM-free hot-ion H-modes	Argon, Krypton, Xenon Nave et al, PPCF 1995
LMy H-mode plasmas	Nitrogen, Neon .Matthews et al, PPCF 1995 .Matthews et al, NF 1999
	Argon, Neon (RI Experiments) Jachmich et al, EPS 2001/ PPCF 2002\ Rapp et al, IAEA conf. 2002
)ptimized Shear	Argon, Krypton, Neon

Hot-ion H-modes

Reducing the pressure at the top of the pedestal is expected
•to increase stability to ballooning modes (delaying 1st ELM)
•to increase stability to external kinks

Large Te values at the top of the H-mode pedestal:
Te (edge) ~ 2-5 keV

Pressure at the top of the pedestal may be reduced by reducing Te

- D_2 puff
- An impurity puff

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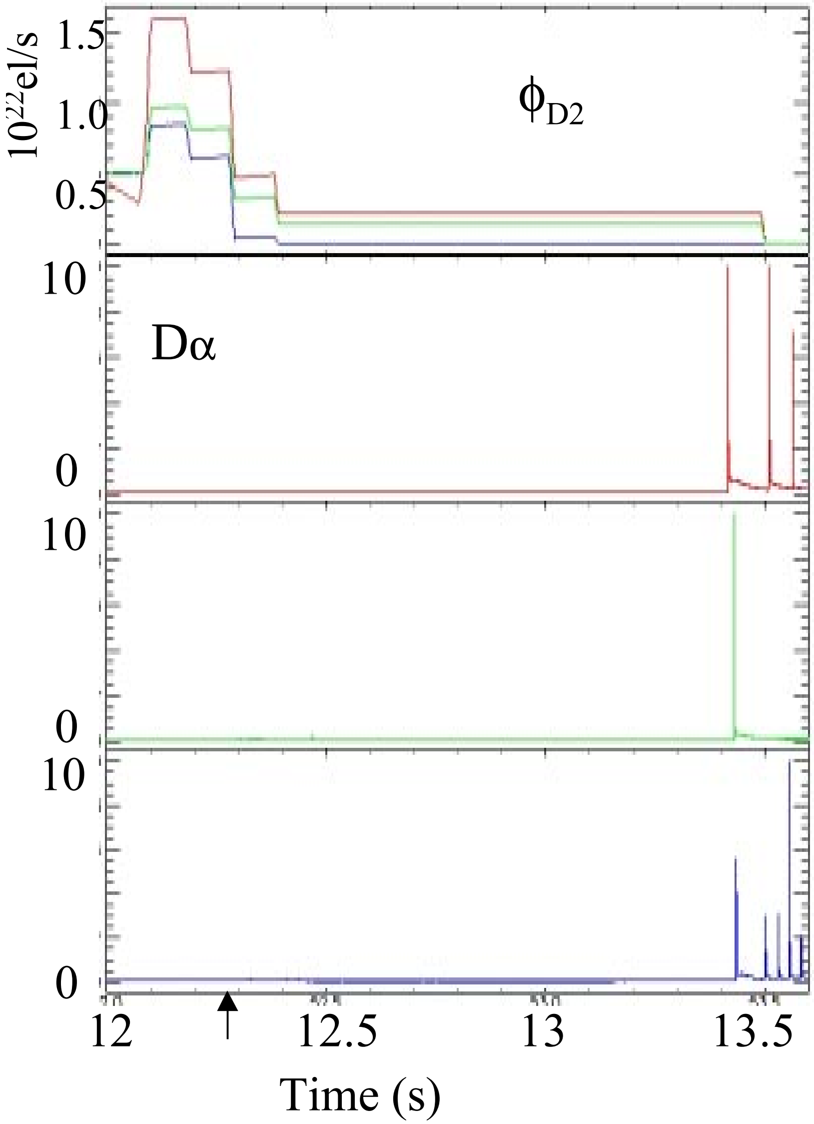
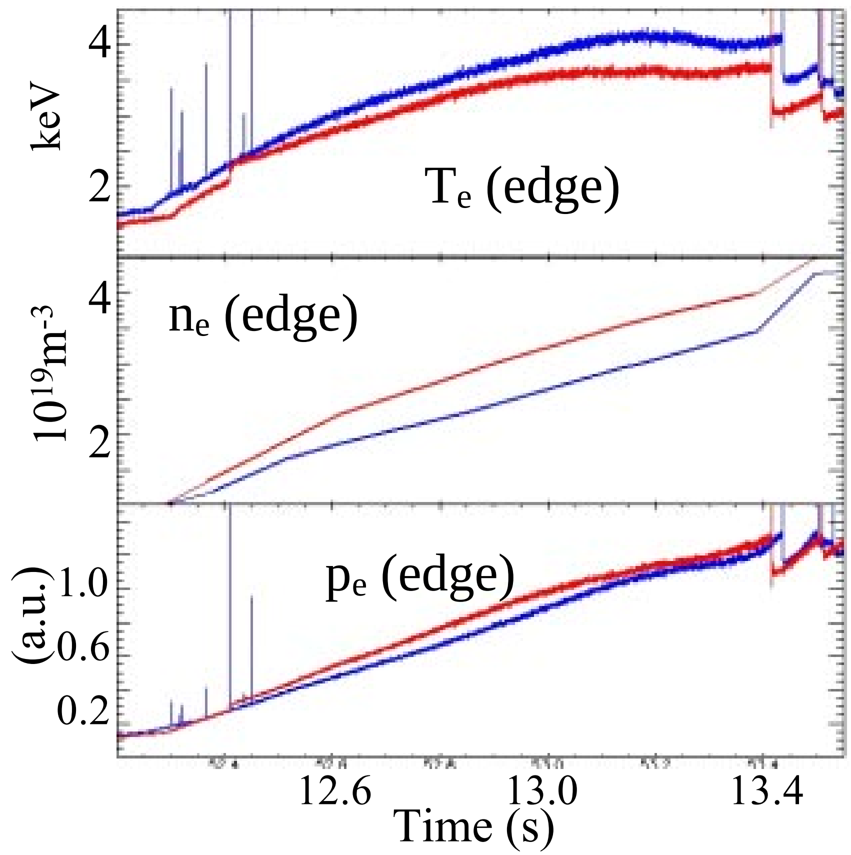
Hot-ion H-modes



Increasing D_2 rate has not delayed the 1st ELM



Experiments with impurity injection

Objective : To limit the edge pressure gradient by controlling the power flowing through the H-mode confinement barrier

Impurities used : Ar, Kr and Xe

Chosen to radiate effective at values of Te typical of the top of pedestal ,

Te ~ 2-5 keV

Impurity injected from the main chamber (either from top or mid-plane) in short puffs lasting ~100 ms.

Experimental set up:

P_{NBI} =10 MW, I_p=2.5 MA, B_t=2.5-2.8 T, δ~0.37

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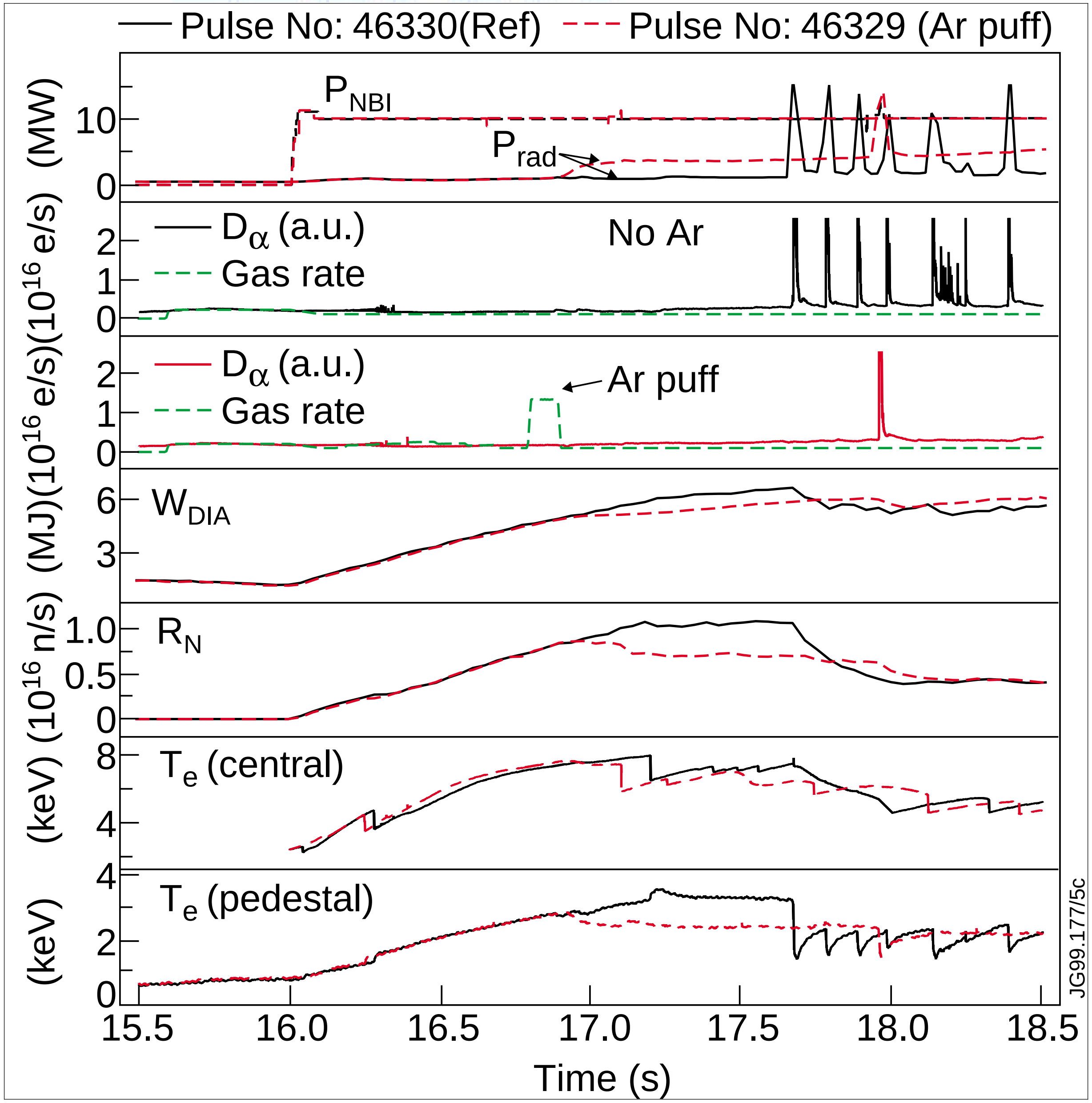
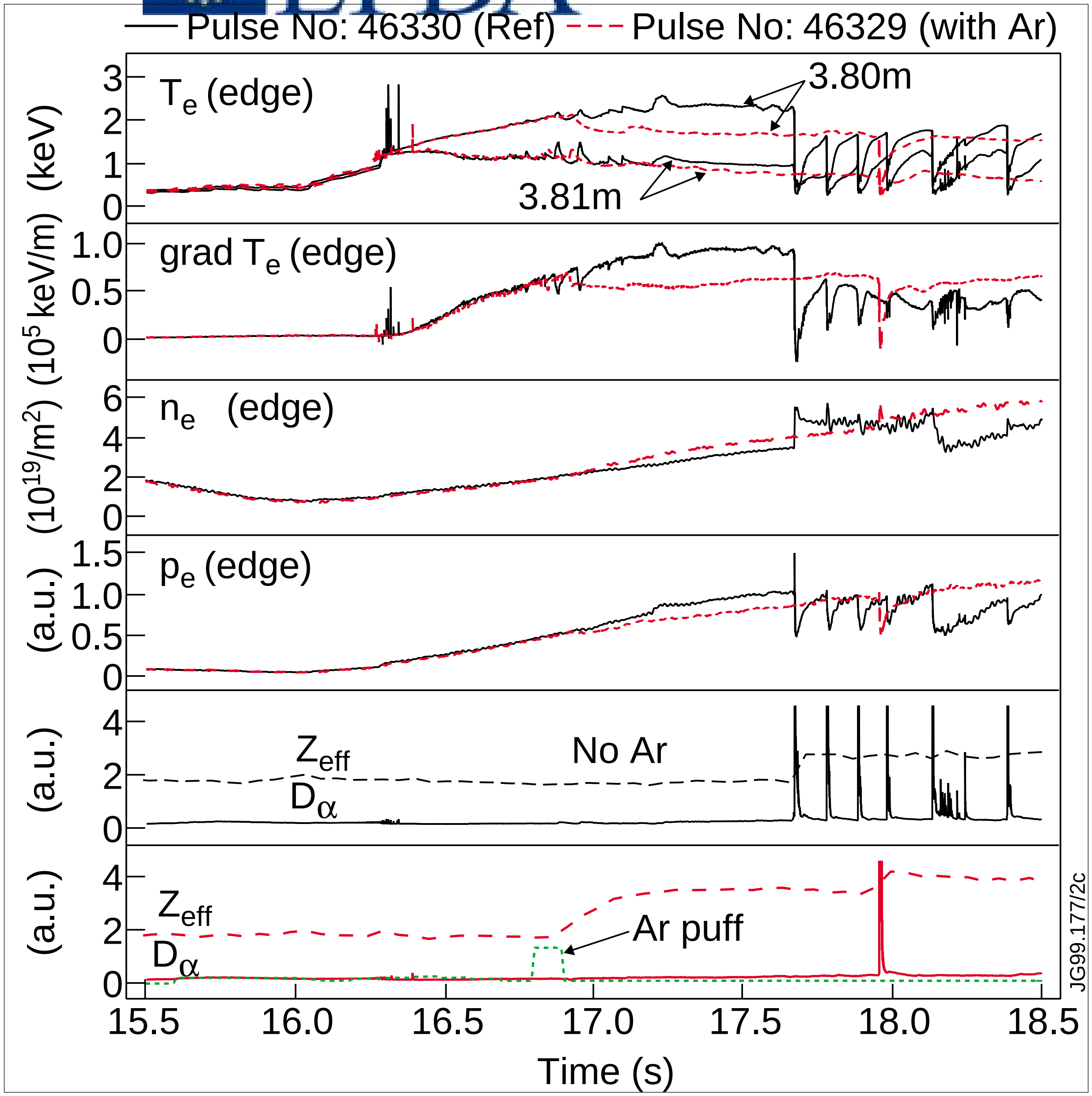
Hot-ion H-modes



- *1st ELM delayed*
- *ELM frequency decreased*
- *Similar observations fo Ar, Kr and Xe*

Hot-ion H-modes



Observations at the edge

With the impurity:

- *T_e pedestal decreases,*
- *∇T_e (edge) decreases,*
- *Z_{eff} increases producing a small increase of the edge density.*
- *There is a net decrease of p_e*

ELM activity not completely removed since ne is not controlled

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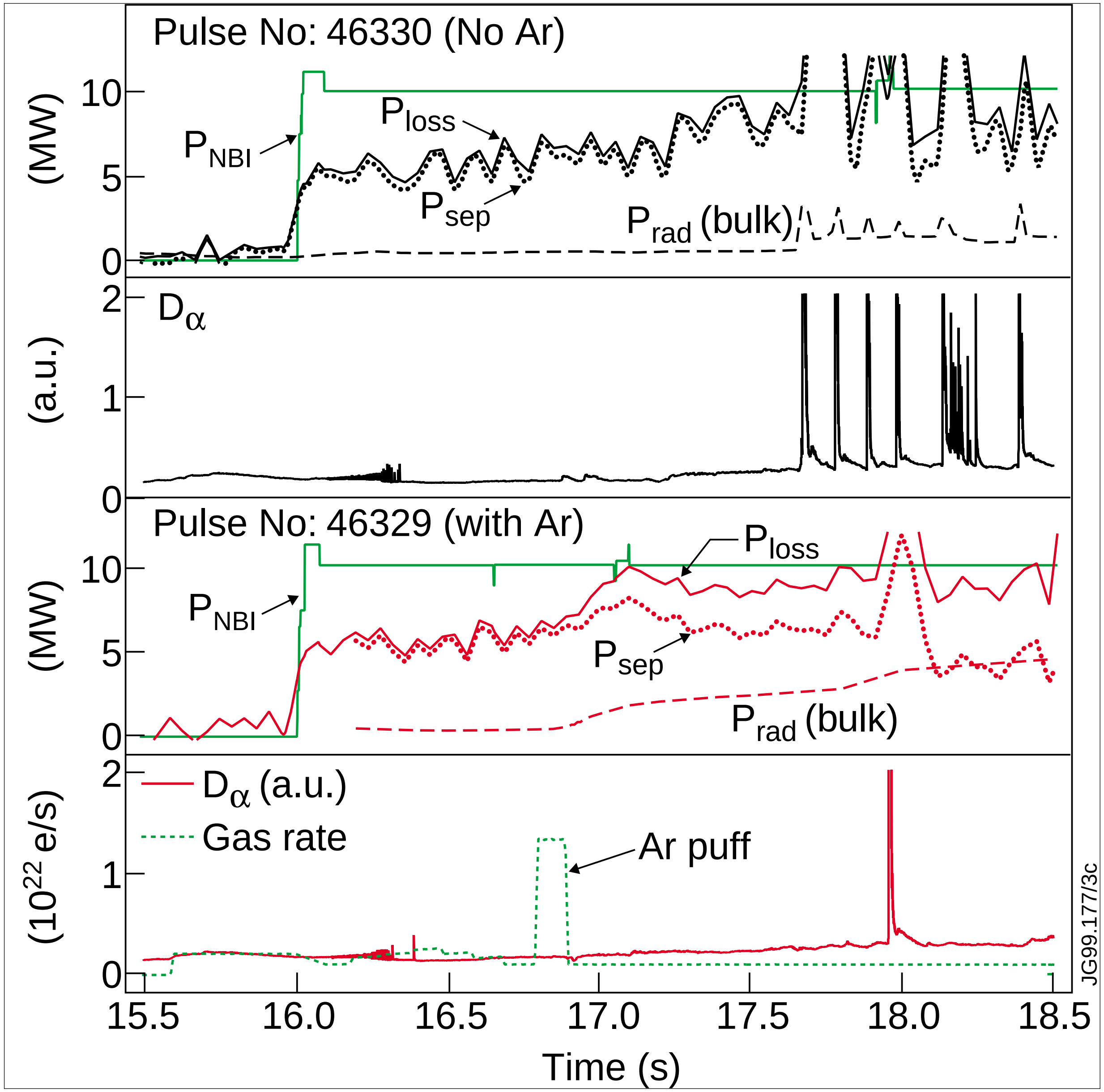
Hot-ion H-modes



Observations at the edge

The power flowing to the H-mode barrier decreases

Power loss:

$P_{loss}=P_{NBI}-dW_{Dia}/dt$

Bulk radiated power:

P_{rad} *within the flux surfac*

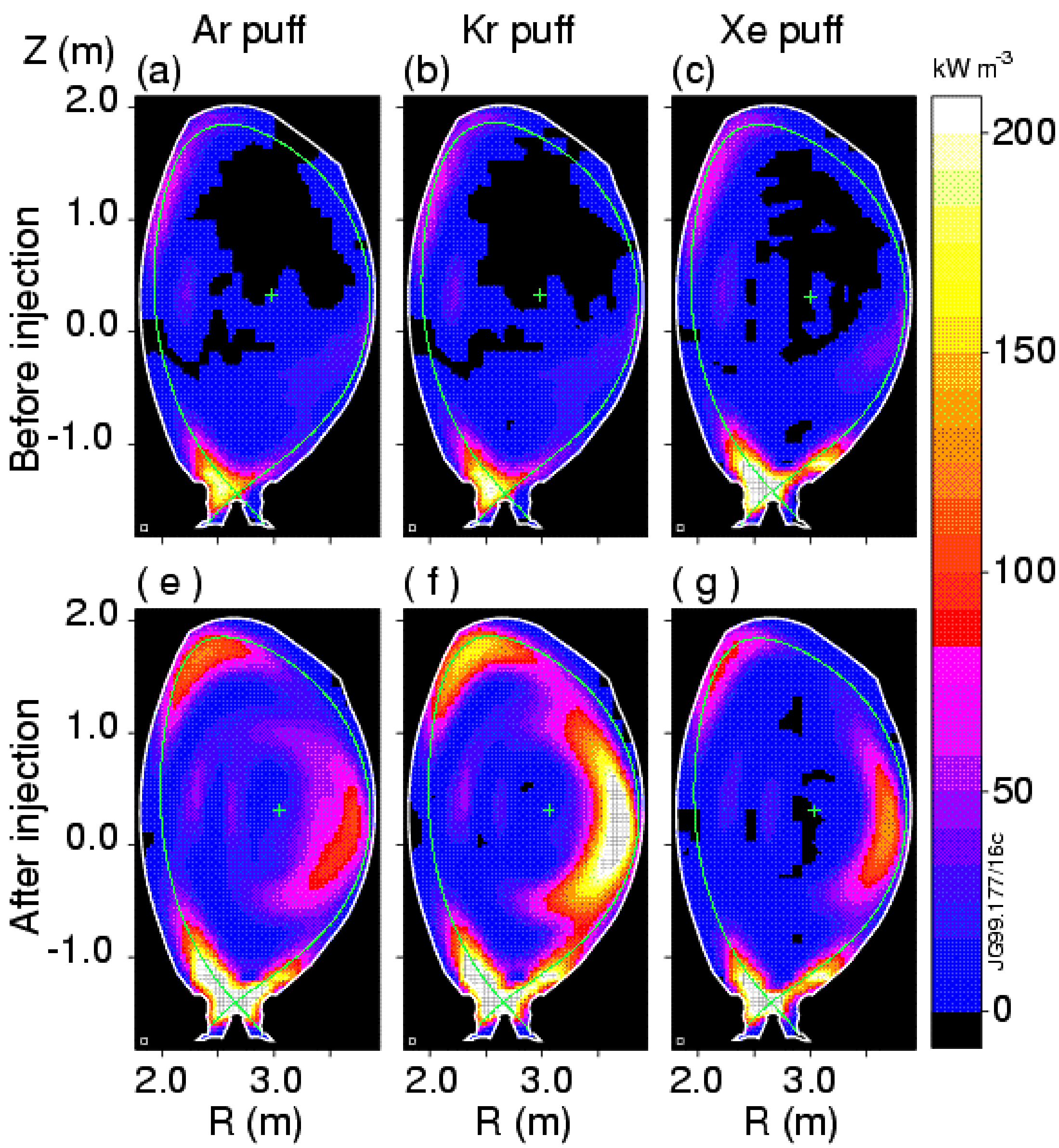
$\rho=0.95$

Power flowing through th

H-mode barrier:

P   =P   -P   .

Hot-ion H-modes



Contour plots of Pra

a wide radiating region is observed r>0.4

Largest accumulati with Kr

Recent experiments:

Current ramps

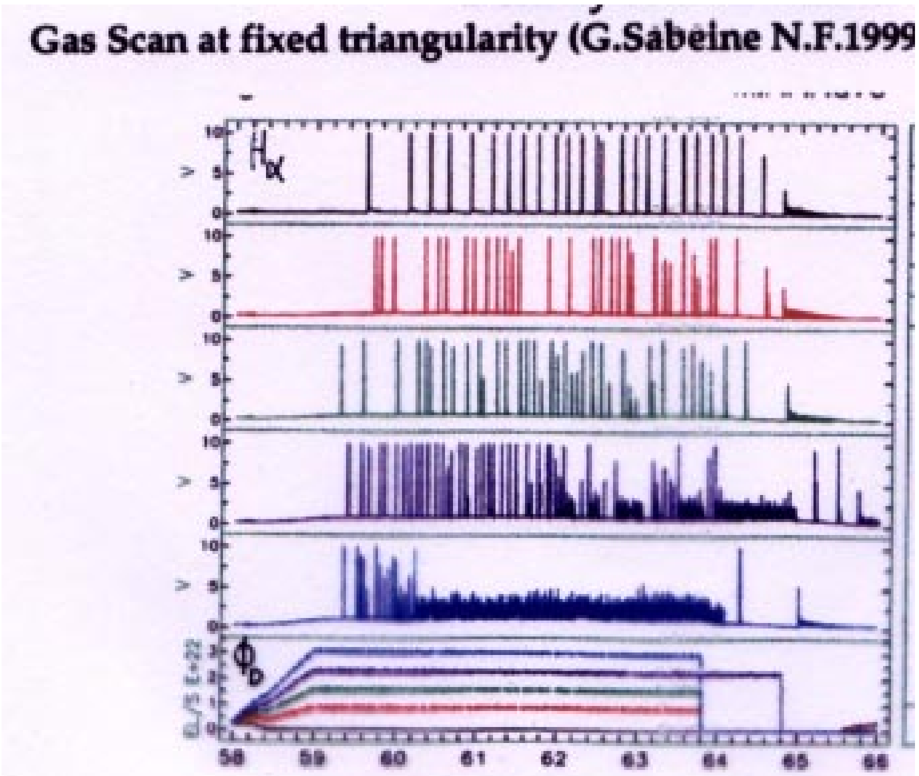
used in Optimised shear to affect ELMs

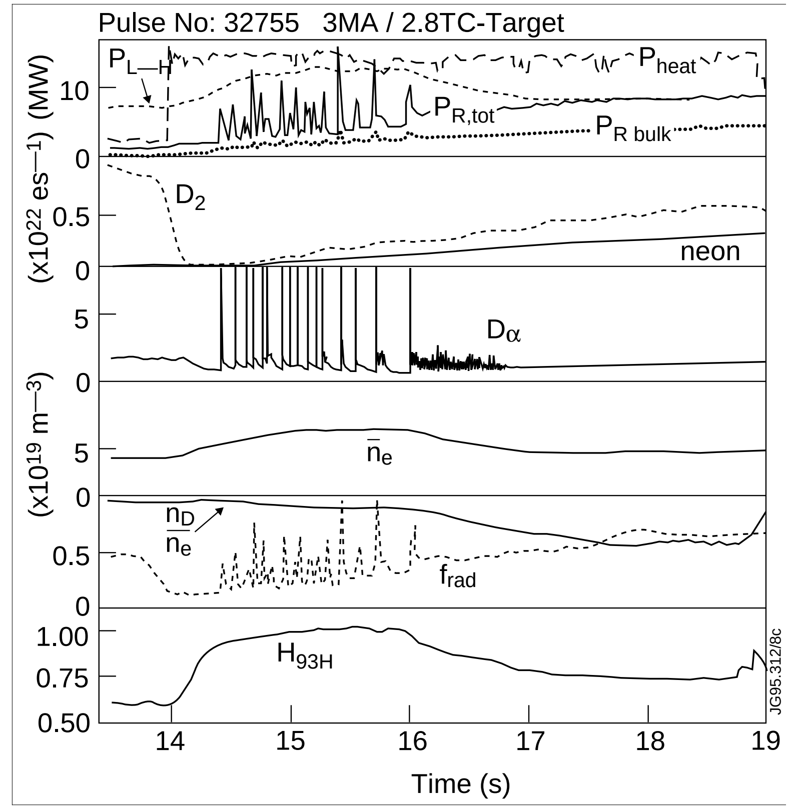
Radiation effecst on ELMs

studied in RI experiments

ELM mitigation by impurity seeding is at present an important subject

ELMy H-modes





With D_2

f_{ELM} increases with D_2 rate

With large D_2 rate:

Transition to Type III occurs.

Experiments with Ni, Ne and Ar

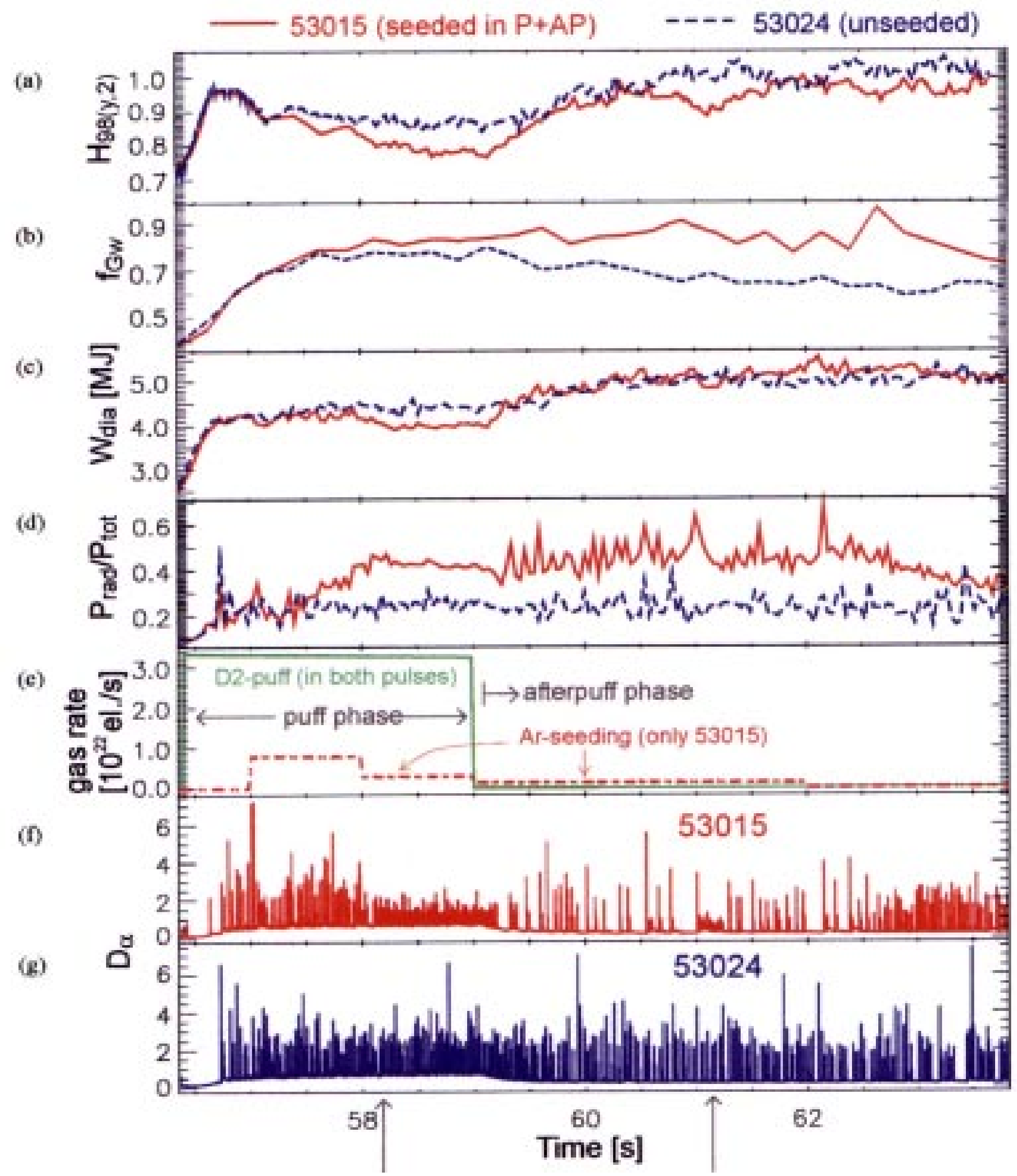
f_{ELM} decreases with Impurity rate/ Prad/Ptot

However, for large impurity injection

Transition to Type III occurs.

Septum discharge, δ~0.2

ELMy H-modes
RI with Ar



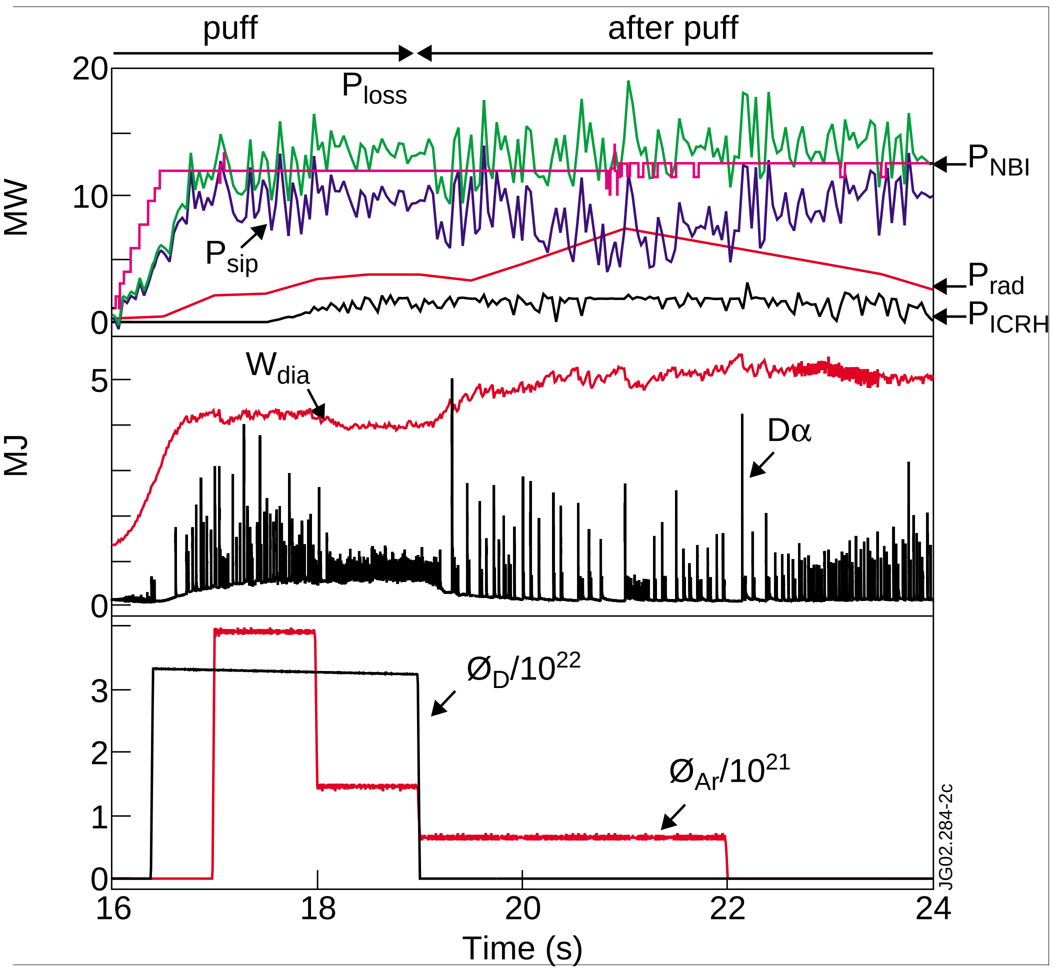
Two Phases:

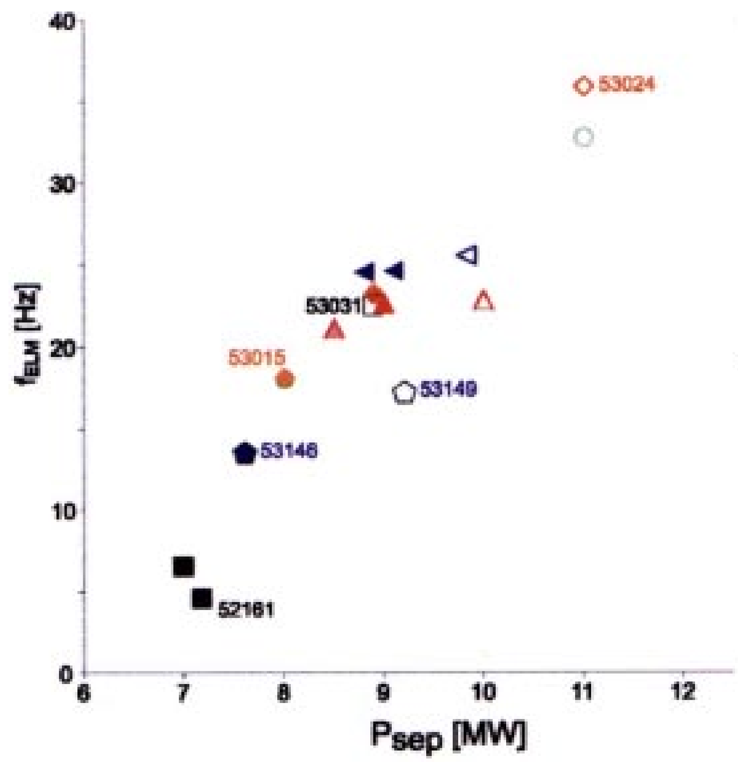
- Puff phase: with Ar Type III ELMs
- After-puff phase: with Ar Type I ELM frequency is reduced

ELMy H-modes

RI with Ar

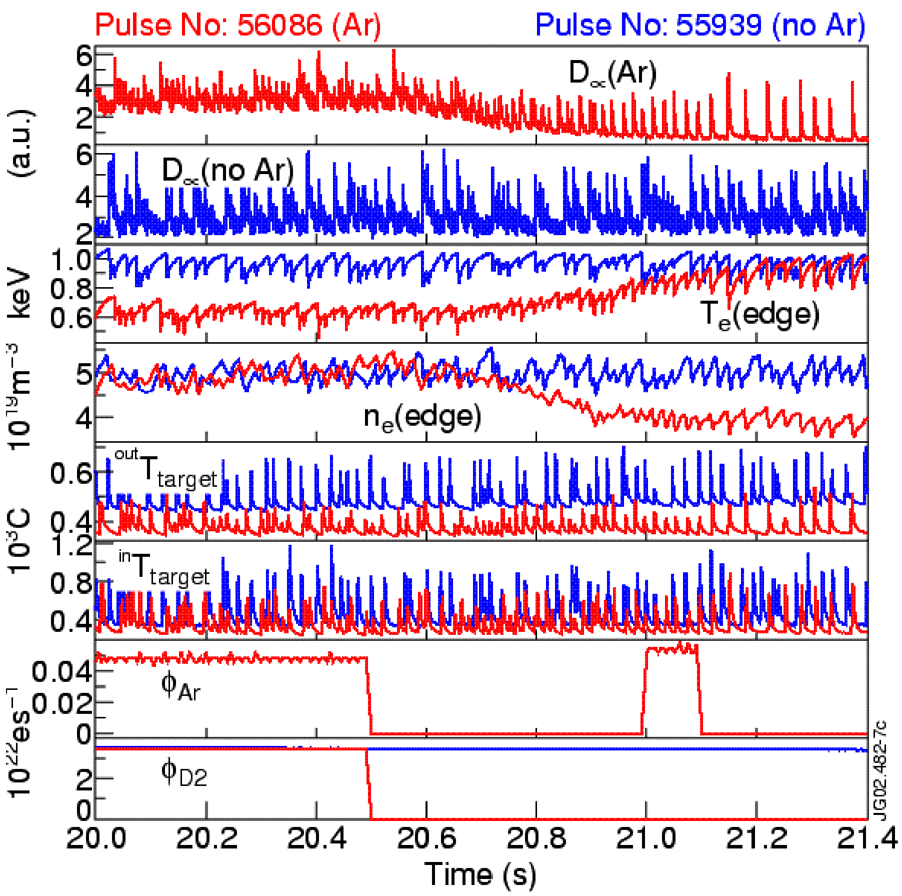
With Argon
Lower Type I f_{ELM}
observed with reduced P_{sep}





Open symbols: no Ar
Closed symbols: with Ar

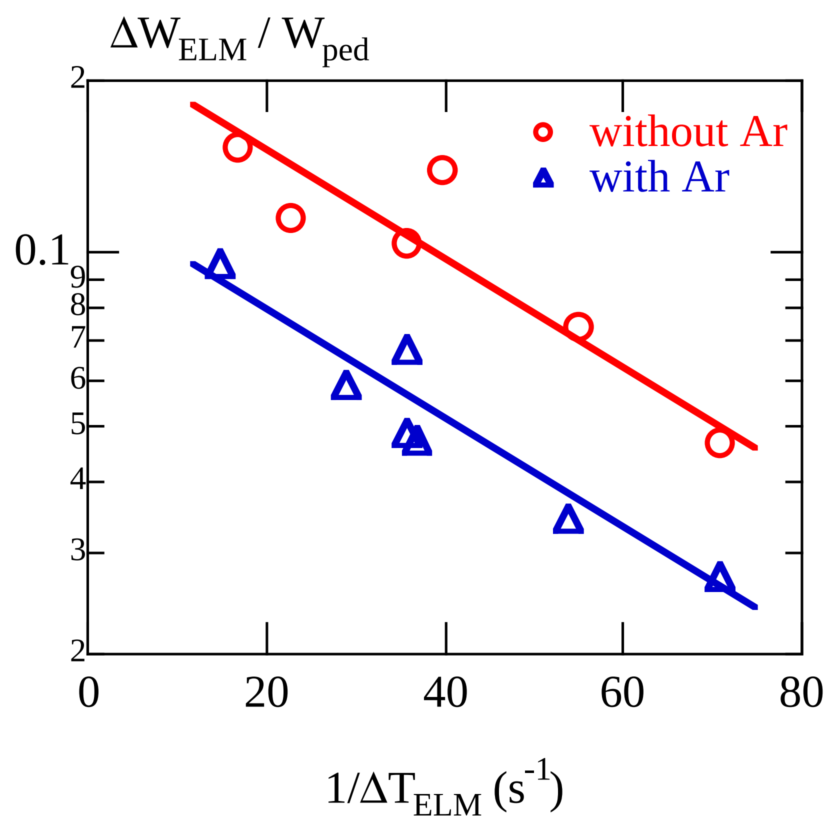
ELM Mitigation with Impurity Seeding



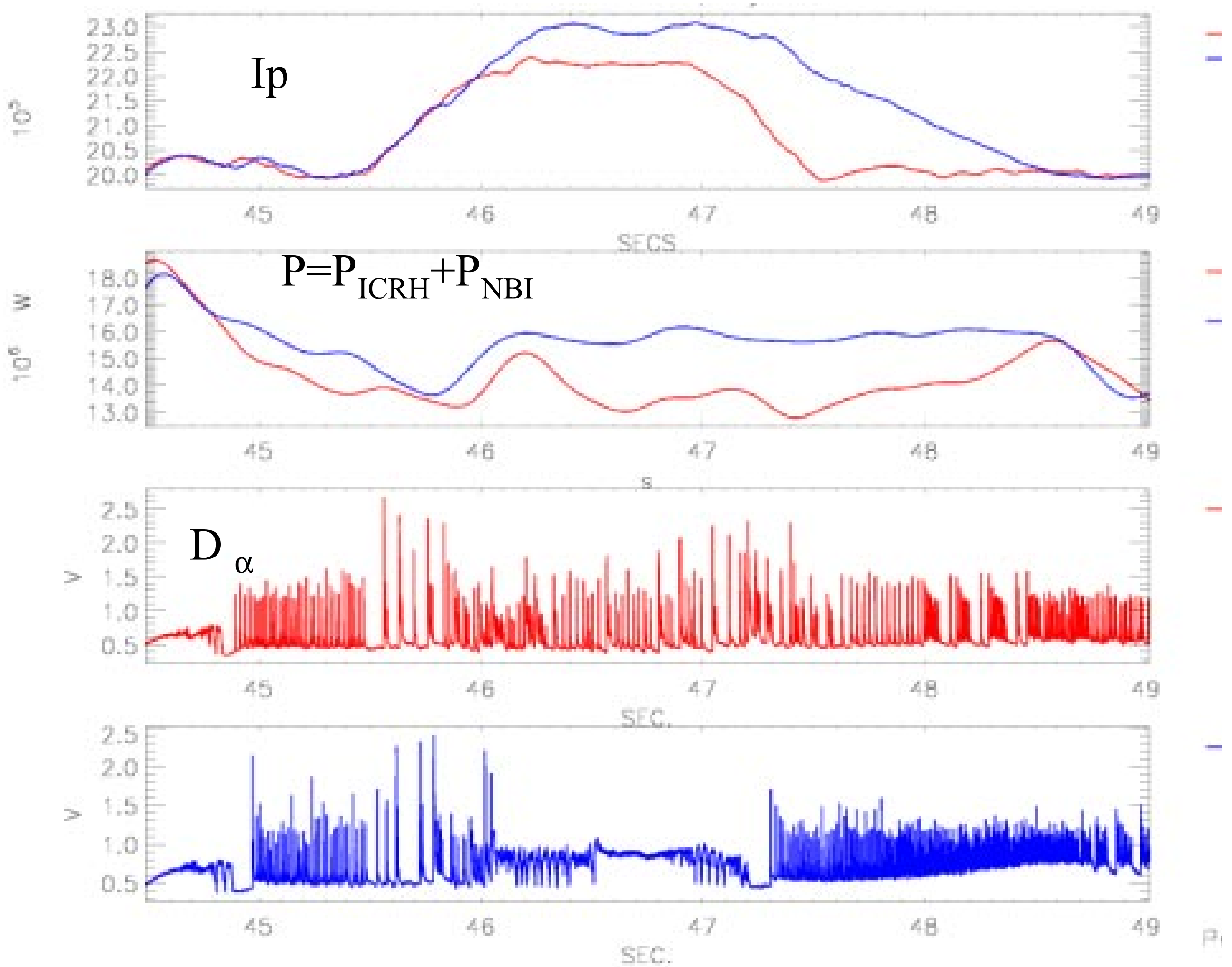
Reduced target surface temperature with Ar

Pedestal energy is reduced with Ar

$\Delta W_{ELM}/W_{PED}$ is reduced.



In recent JET Optimised Shear discharges current ramps used to attempt to change ELM behaviour by changing discharge trajectory in the α vs j diagram.



Summary

JET ELM-free H-modes are limited by edge MHD instabilities

Stability analysis shows that outer modes and ELMs occur close to both the external kink and the ballooning marginal stability boundaries

Theory indicated severtal paths to increase stability: $j_{edge}(\nabla p)$, li, q_{edge}, $\alpha(\nabla p, B_p)$, s_{edge}

Experiments- shape scans
Bt and Ip scans
Edge j (current ramp down)
Edge ∇p (cryo-pump/ gas fuelling/ radiation control)

Current ramp-down experiments confirmed identification of outer mode as an external kink, while indicates that giant ELM occurred at the ballooning limit (with Pped$\propto$Ip)

The different responses of ELMs and outer modes to decreasing Ip suggest that these are independent edge phenomena

Control of one mode should not be in detriment to the control of other types of modes and overal confinement properties

Compromise used in DT: used current ramp-down while working at max Ip

ELM Control by increased radiation

HOT ION H-MODES

· **Increased Type I edge stability in ELM-free hot-ion H-modes obtained in discharges whe her Ar, Kr or Xe were injected into the plasma during the heating phase.**

The first giant ELM delayed.

· **The edge grad T_e was kept low, by creating a wide radiating region and decreasing the pow ducted to the H-mode confinement barrier.**

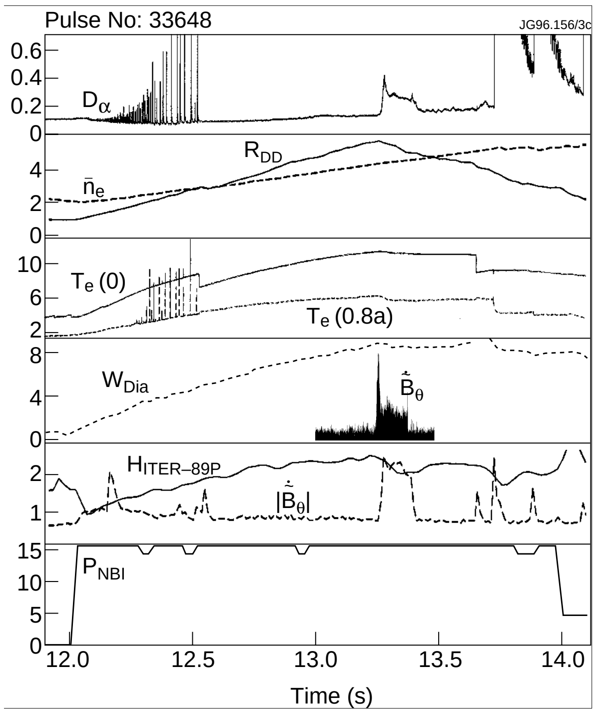
· Since n_e continues to increase, the discharges are still limited by a giant ELM. Further increase e stability leading to a steady state regime could be envisaged by control of the edge density

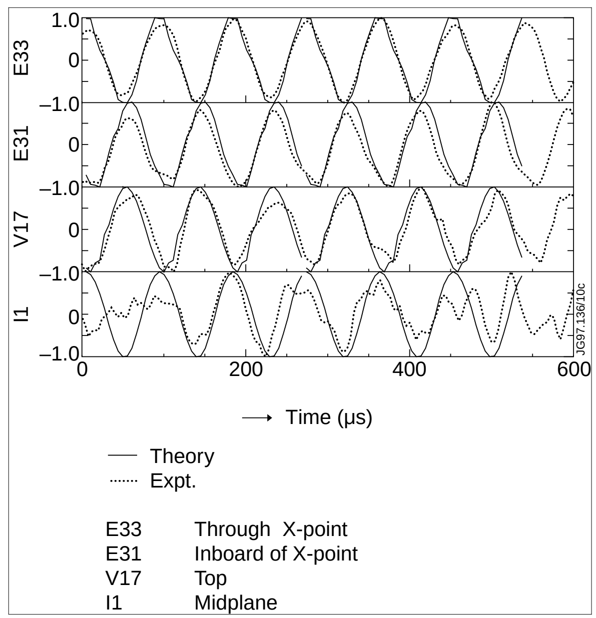
ELMy H-MODES

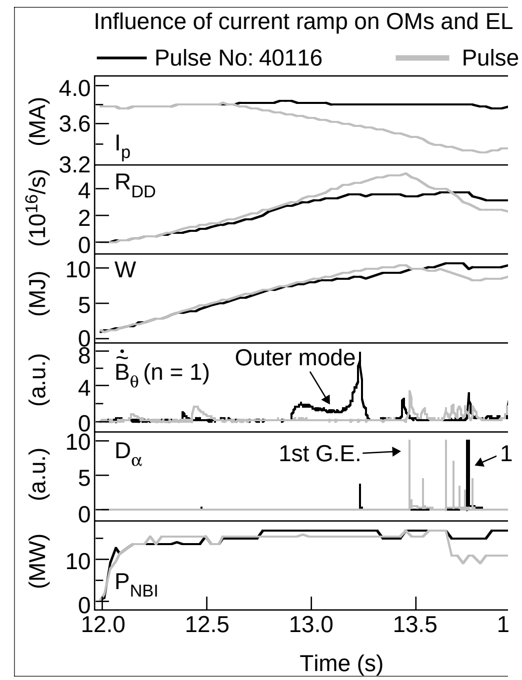
· **Impurity injection (Ne, Ni, Ar) has also lead to increased type-I ELM stability in ELMy H de regimes.**

lose co-operation of MHD studies with the High Performance Task Force lead to control of Out
[ode and helped to obtain 16 MW of fusion power

Experiment → Model compared with data OM identified as External Kink → Experiment Current ramp-down



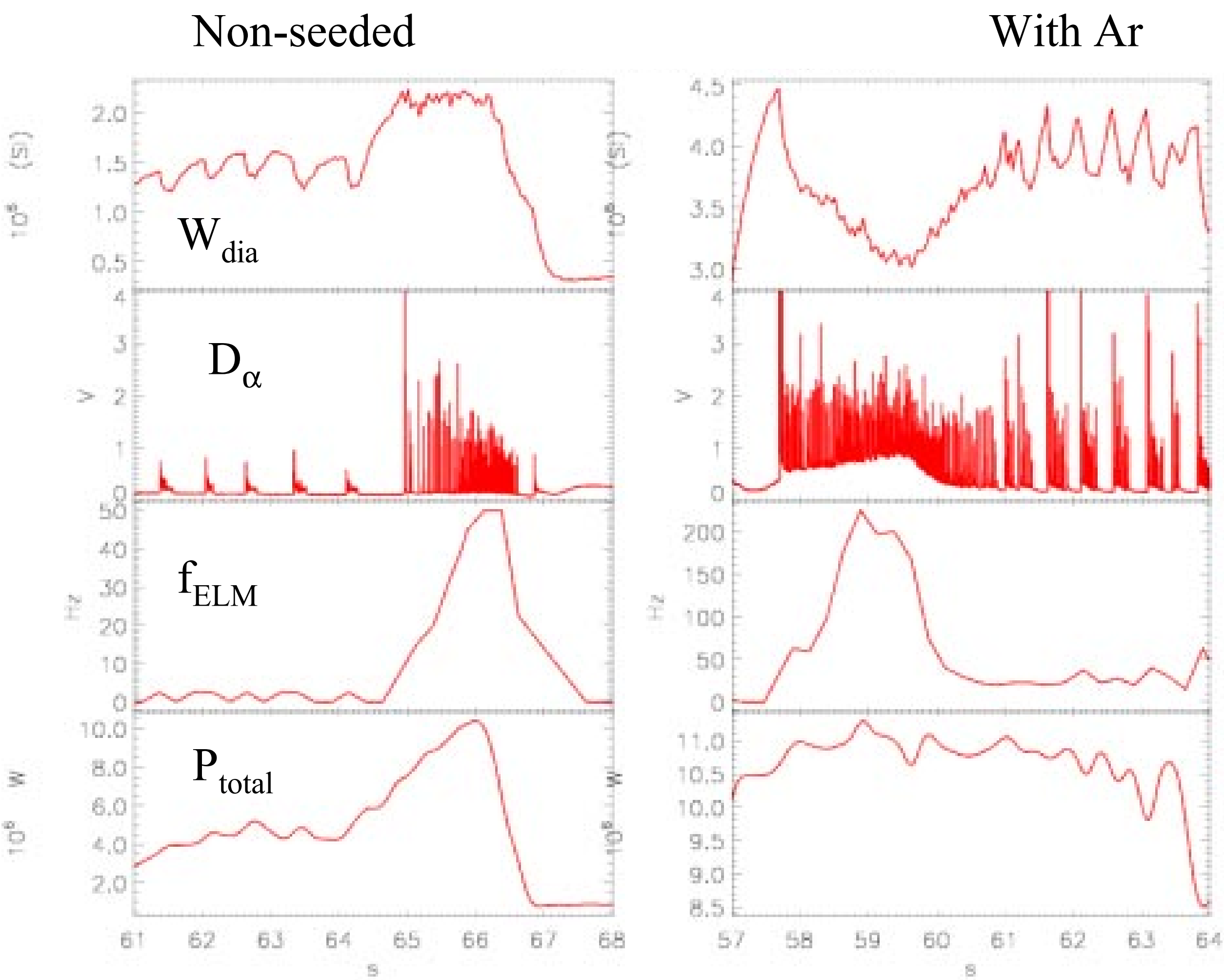




Nave et al NF 97

Huysmans, Hender NF 98

Nave et al NF 99



Low Type I ELM frequency with Ar similar to observations in non-seeded discharges with low input power

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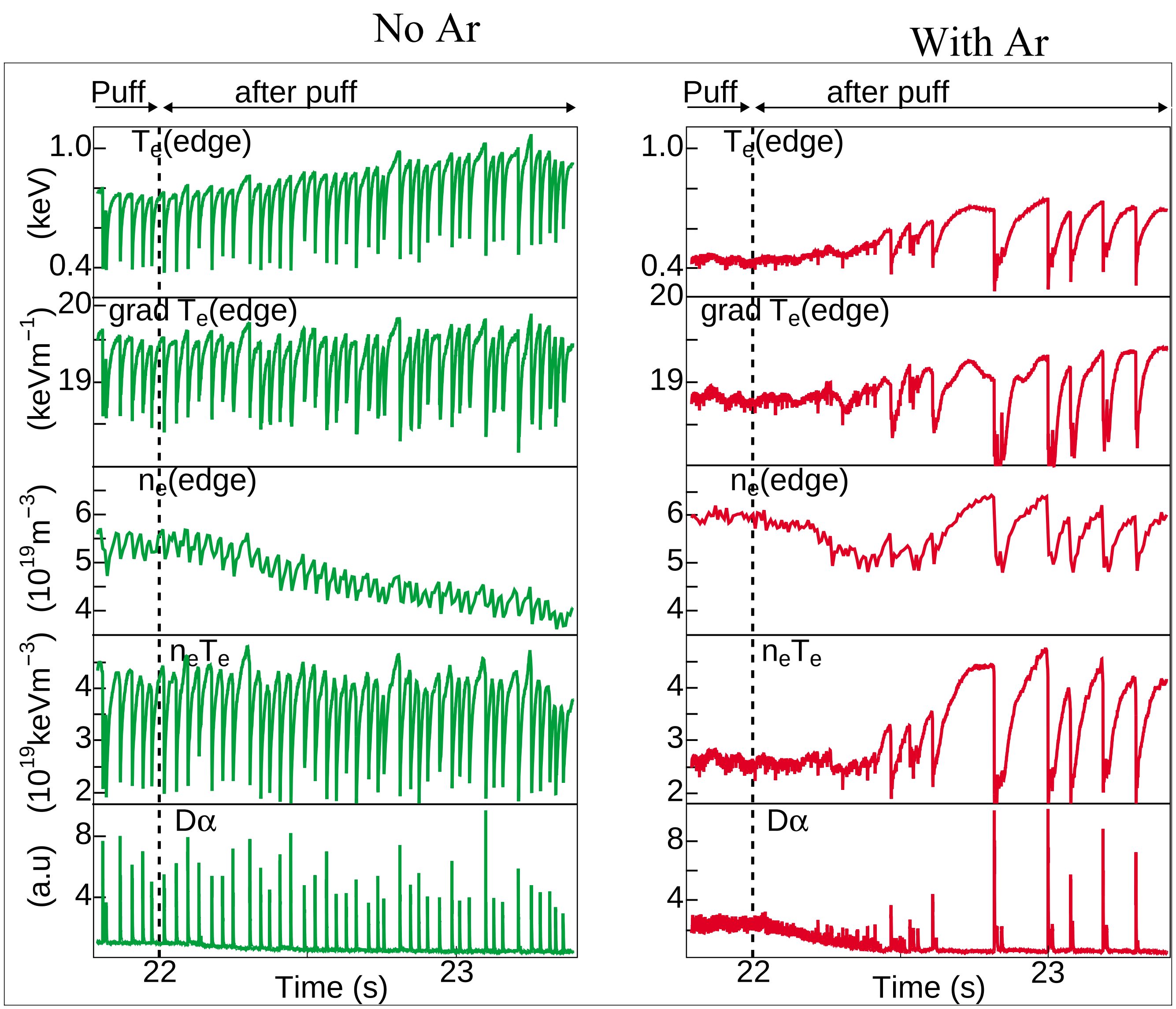
ELMy H-mod

RI with Ar

MKII-GB, δ~0.33



MKII-GB, δ~0.33

ELMy H-modes