Advanced Tokamak regimes at JET :

what are the changes when operating at high triangularity ?

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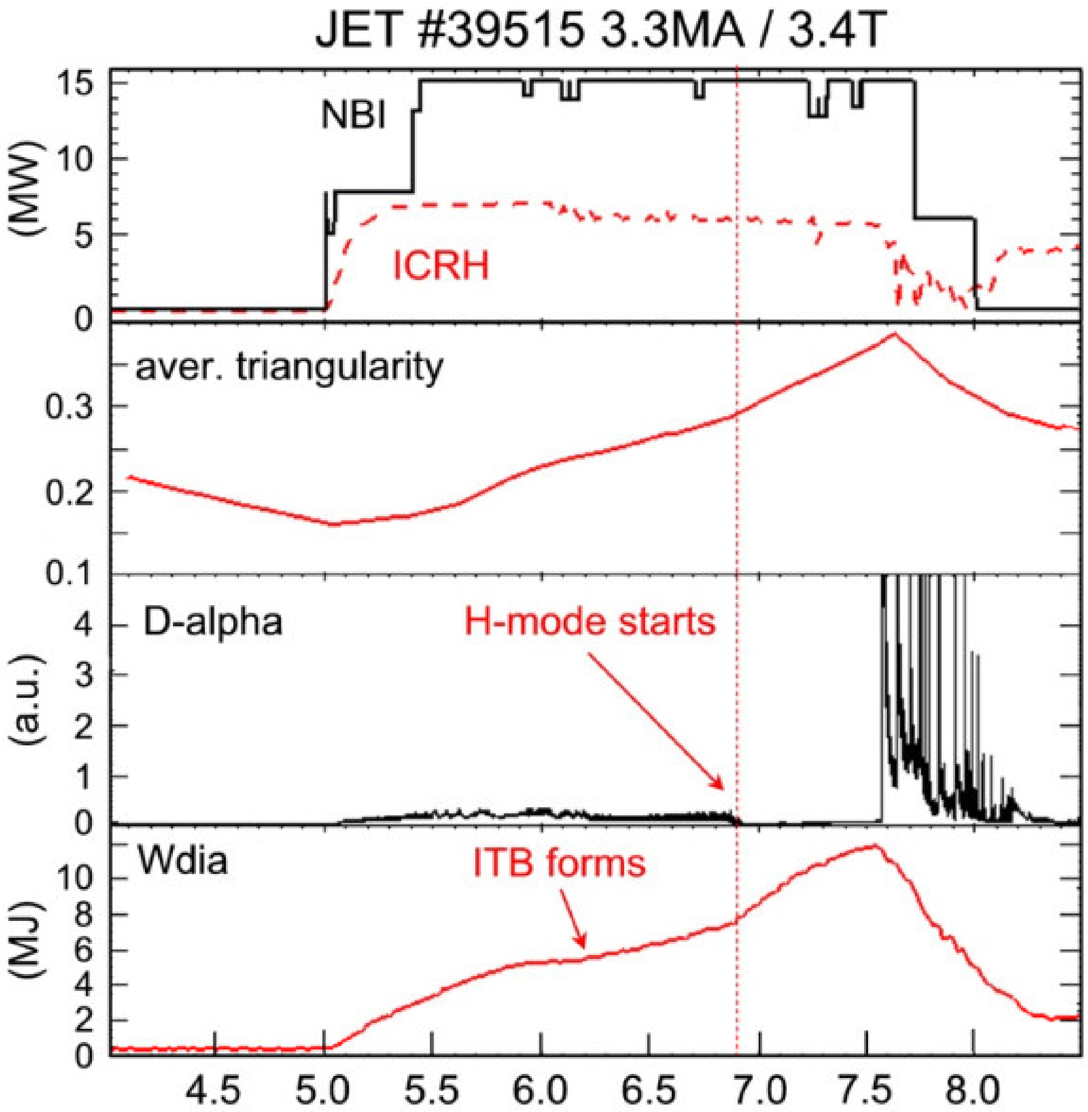
shooting at a moving target (I)

mkIIa divertor - early ITB studies - δ~0.2-0.35 - not really aiming at Steady-state yet (Sips NF2001) :

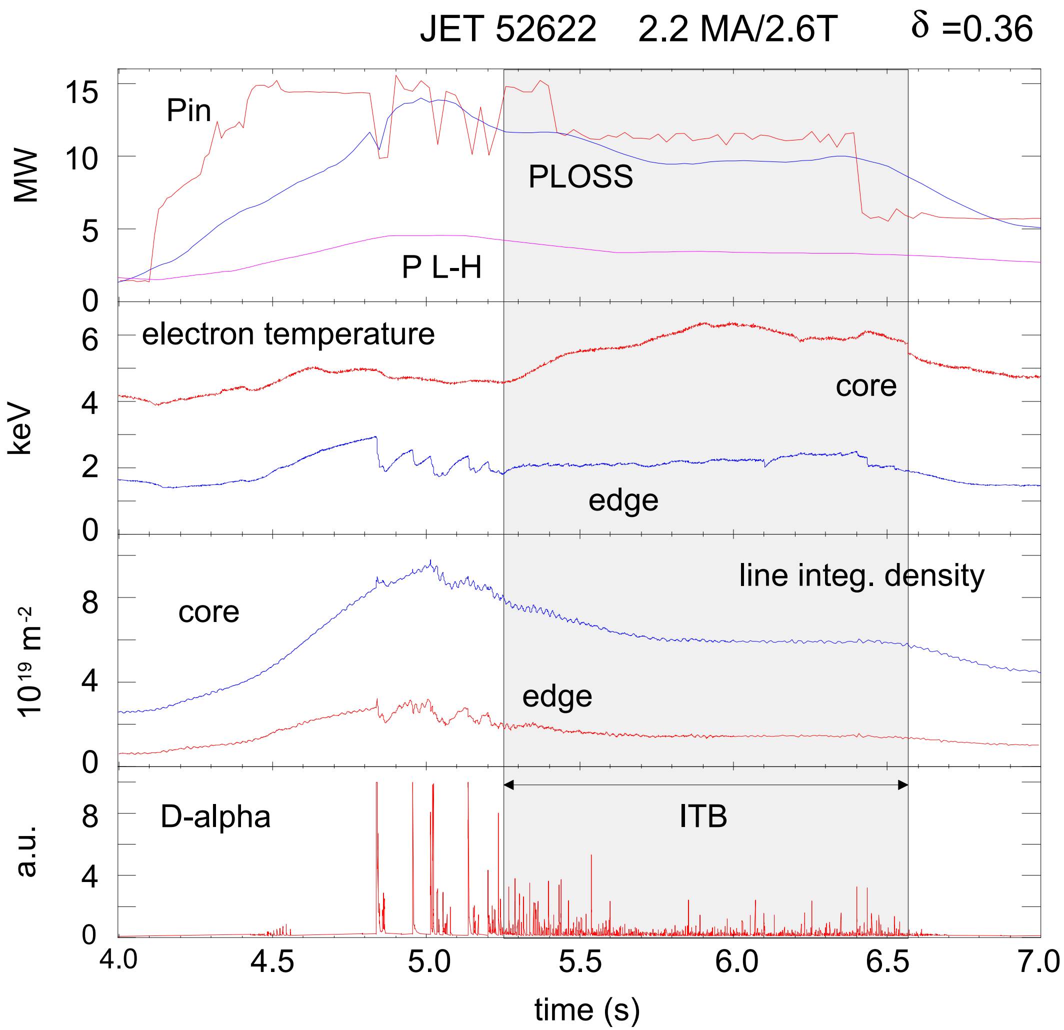
- edge was L-mode then long ELM-free (but OS current profile !?)

- ITB weakened but *survives* ELM-free but not type I



shooting at a moving target (II)

mkII gasbox (closer divertor)



- almost all Xps at low δ~0.2 & low f_{GDL} (<< 50%)
- edge is naturally ELMy - i.e. no long L-mode phase anymore
- impurity inj. used to control edge (Argon) at δ~0.2
- D_2 dosing not successful - gives high density + type I
- at higher δ ≈ 0.35 – 0.45 edge becomes type I with strong pedestal incompatible with ITB (Crisanti PPCF2003)

explore ITB scenarios in high δ configs
close to what is planned for ITER-FEAT

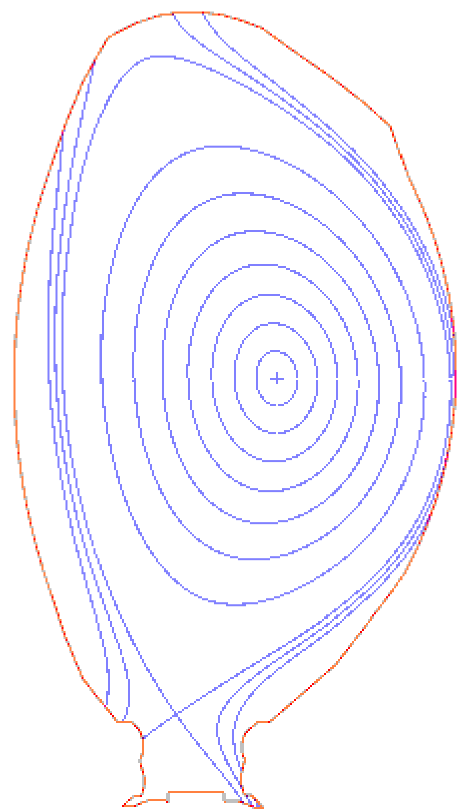
combine high performance ITB + ETB
(ITPA steady-state scenario)

- avoid large type I ELMs (so far <u>not</u> compatible with ITB)
- use ITB to compensate for lower confinement with type III ELMs

or

- explore high density regime of high confinement type II + good confinement + ITB

needs simultaneous optimisation of
core (ITB) and edge (ELMs control)



1.5-2.5 MA / **3.45T**

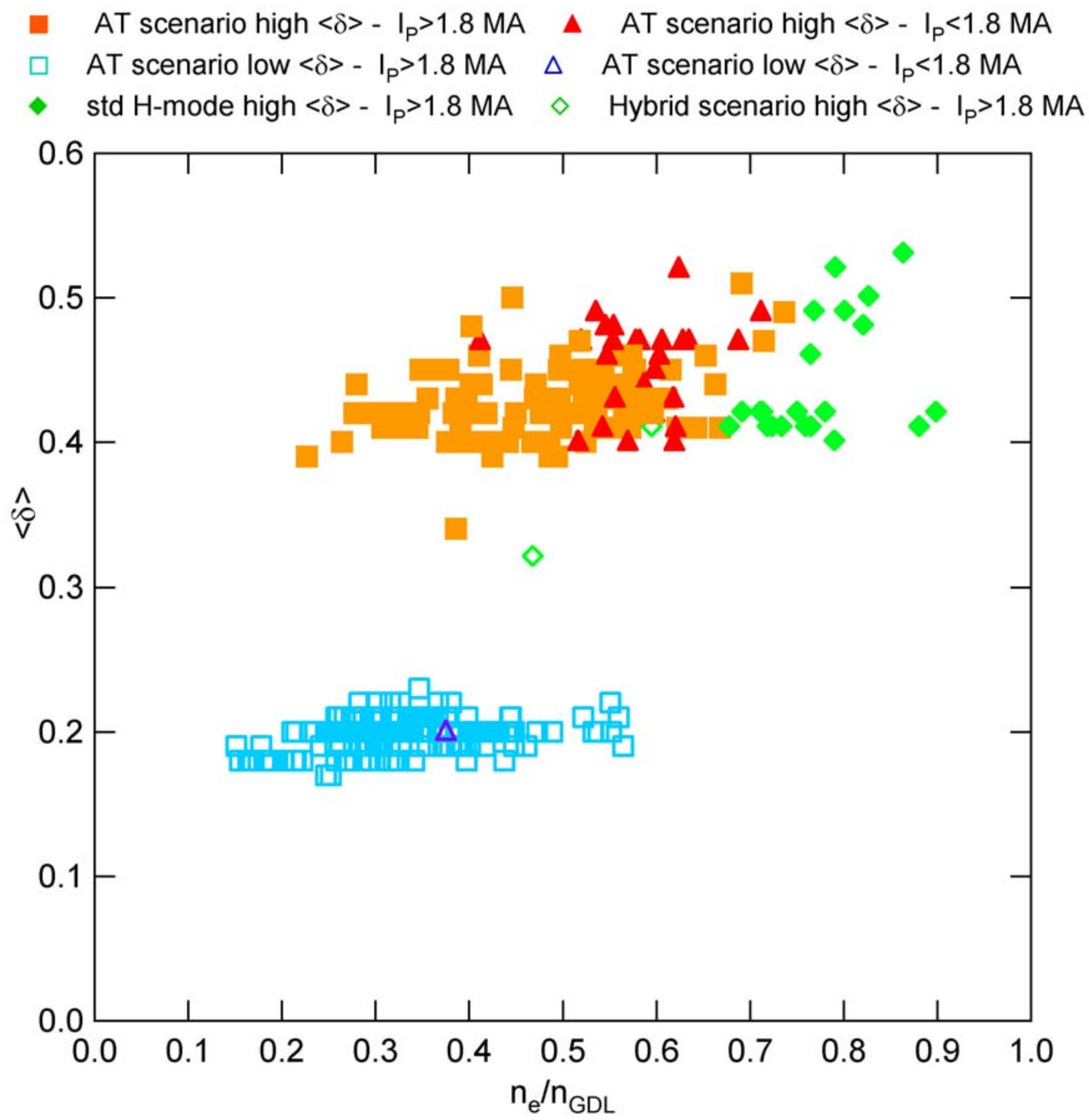
q_{95}=4.5-7.5

$\beta_p \approx 0.6$ (2 MA) $l_i \approx 0.9$

$< \delta > \approx 0.40 – 0.44$

Note : in mkII SRP AT scenarios at low δ

- almost all Xps at low δ~0.2, low f_{GDL} and deeply reversed q profiles
- edge is naturally type III
- sometimes very localised D_2 / CD_4 injection used to improve LHCD coupling (< 1.2 10^{22} el/s)
- *inner* ITB triggered very reliably
- *outer* ITB only observed at high power



pure Deuterium injection

gas scan at high δ

increasing gas :

long ELM-free +type I

⇓

coumpound type I/III

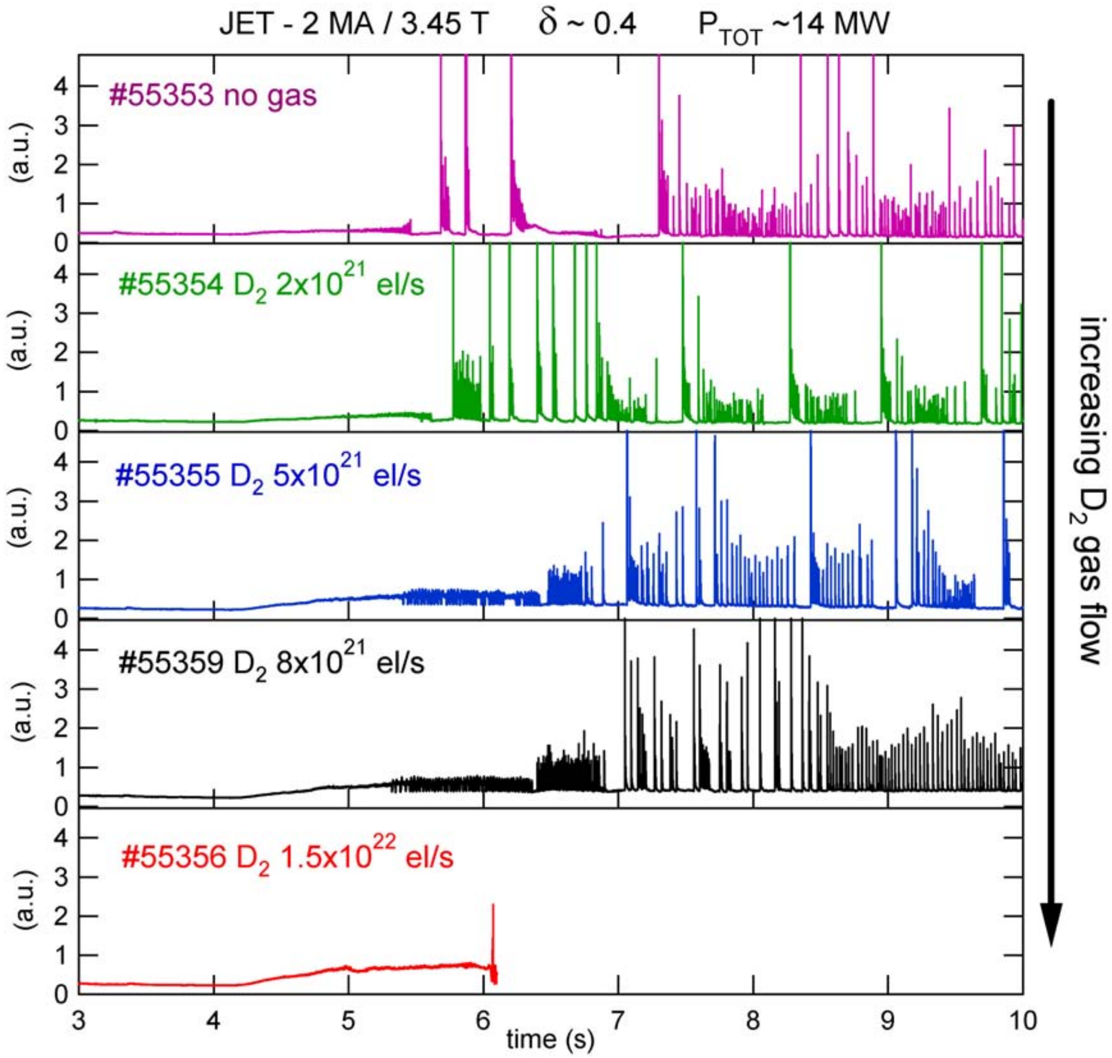
⇓

long dithering + type III

+ frequent type I

⇓

L-mode

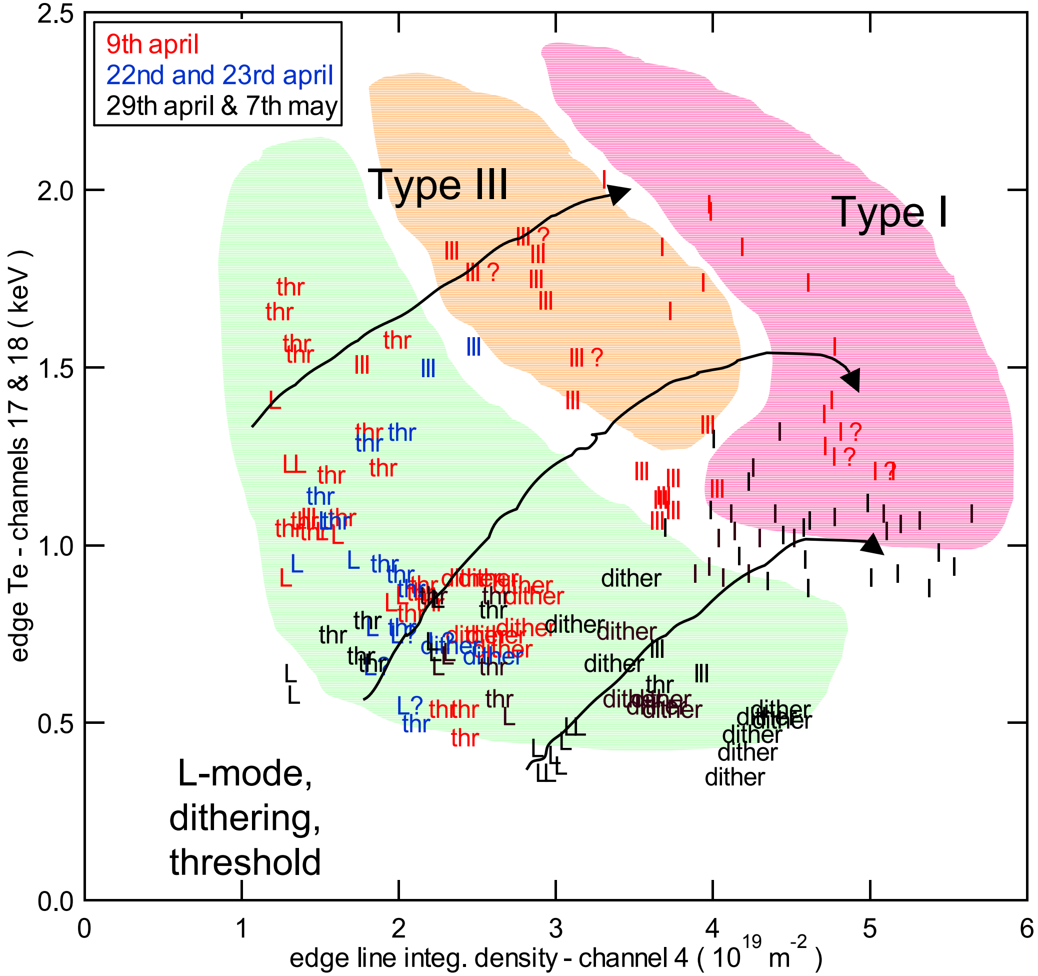


pure D_2 injection

confirmed :

! colours indicate different exp. sessions

- higher L-H thresh. than in conventional H-mode
- tendency towards type I ELMS at low or no gas fuelling
- narrow ITB present during small ELMs or L-mode phases, collapses when type I appear



new :

- combination of gas and/or Ipla variations can suppress type I

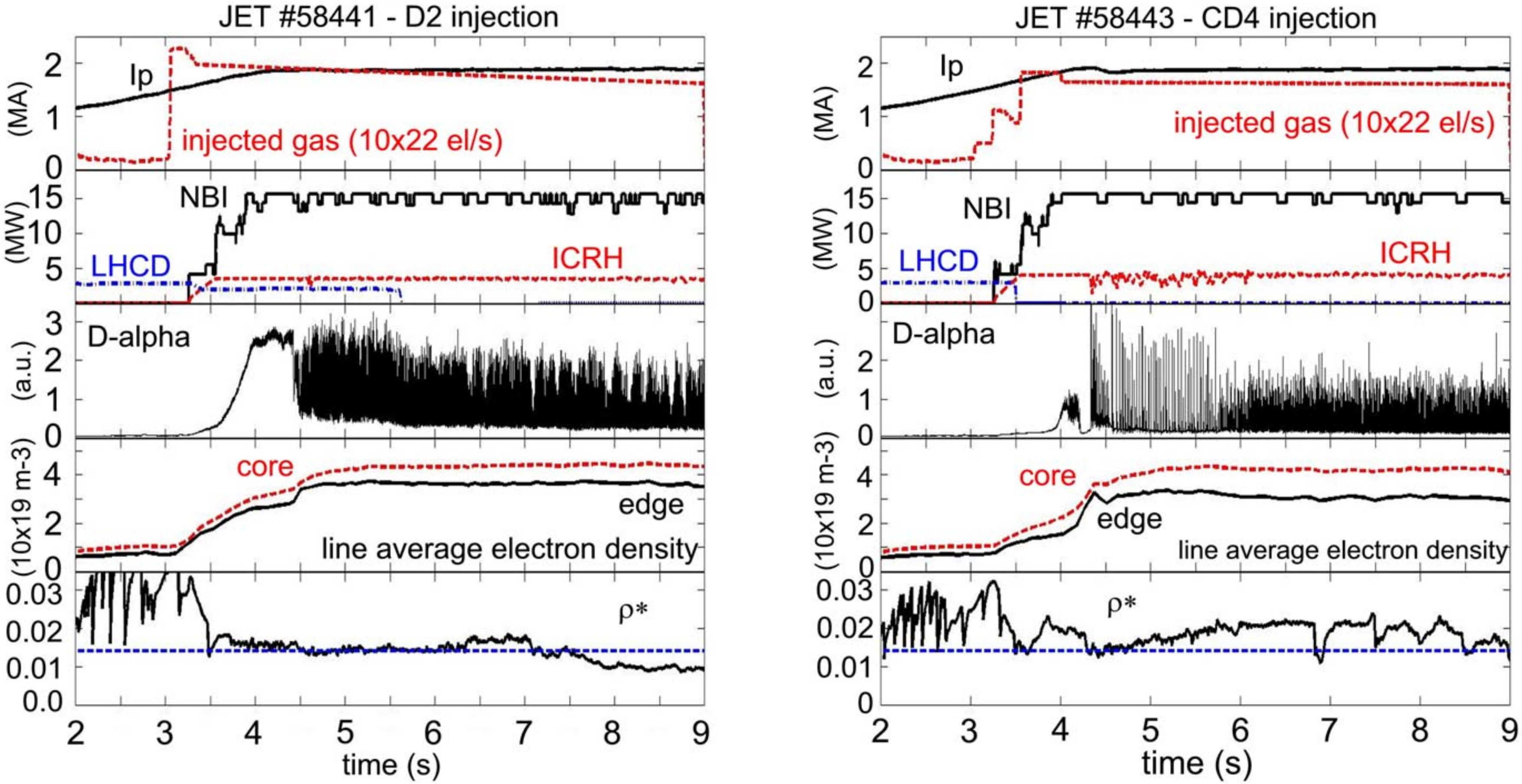
but : type III domain is small & depends on input power / recycling …

alternative route : light impurity injection

both D_2 and CD_4 give frequent/small type I or type III ELMs

inner ITB sustained in CD_4 case

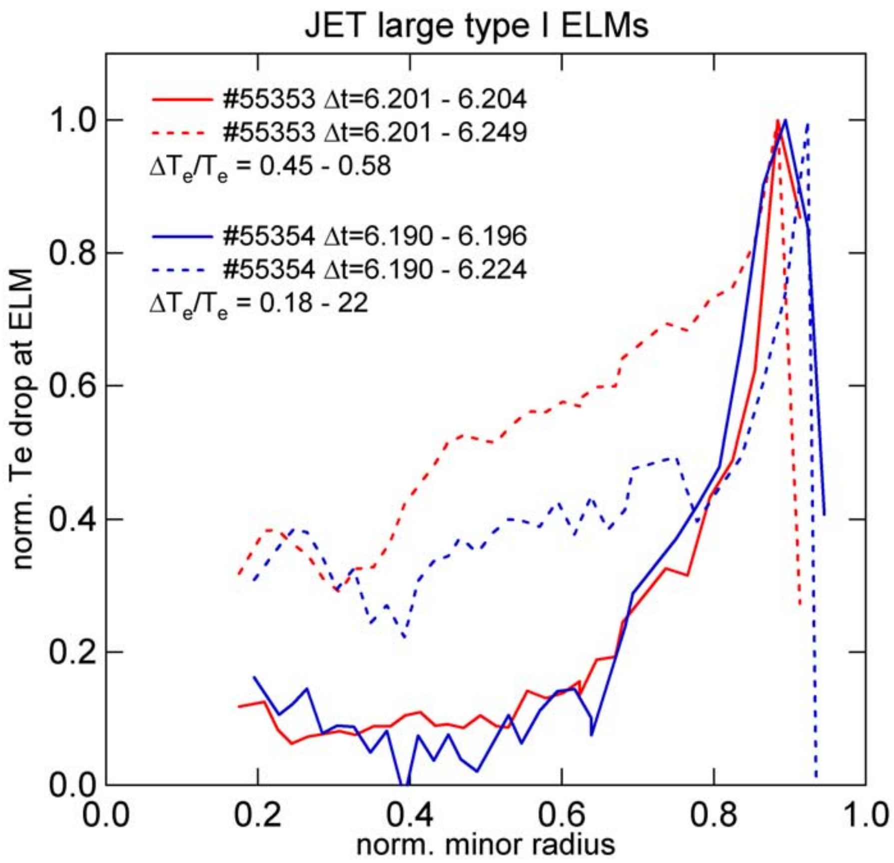
! P_{TOT} < 20 MW – NBI ~15 MW : marginal for *inner* ITB - too low *outer* ITB ?

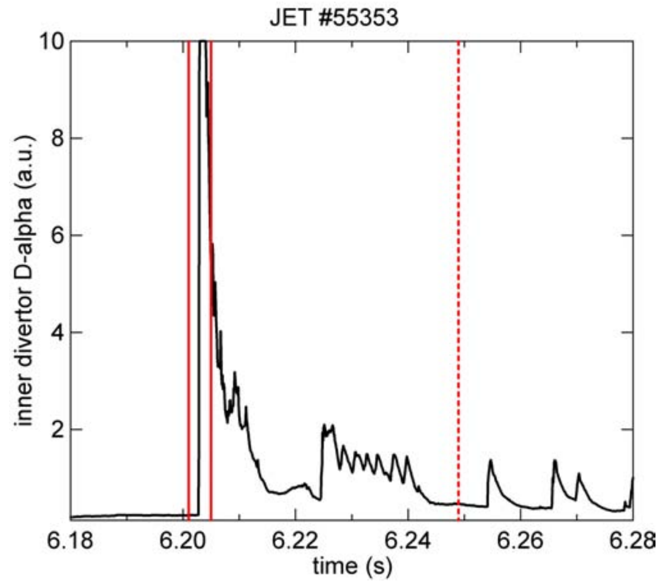


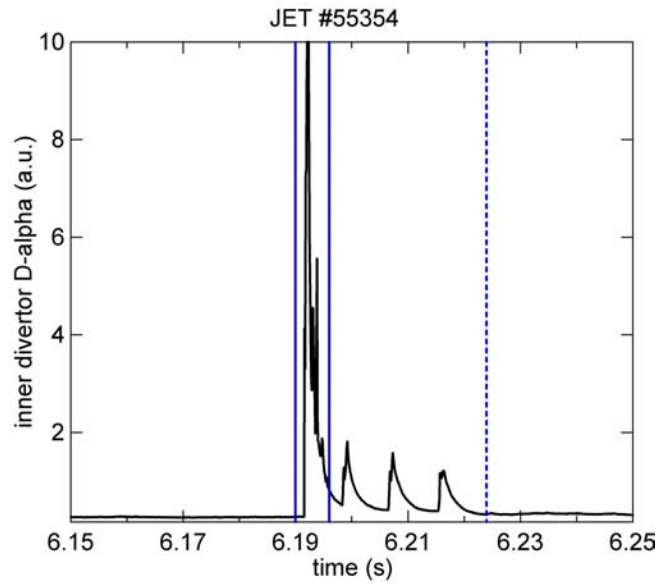
note : target q profiles : deeply reversed & q_{min}~3 (initially)

ELM size (I)

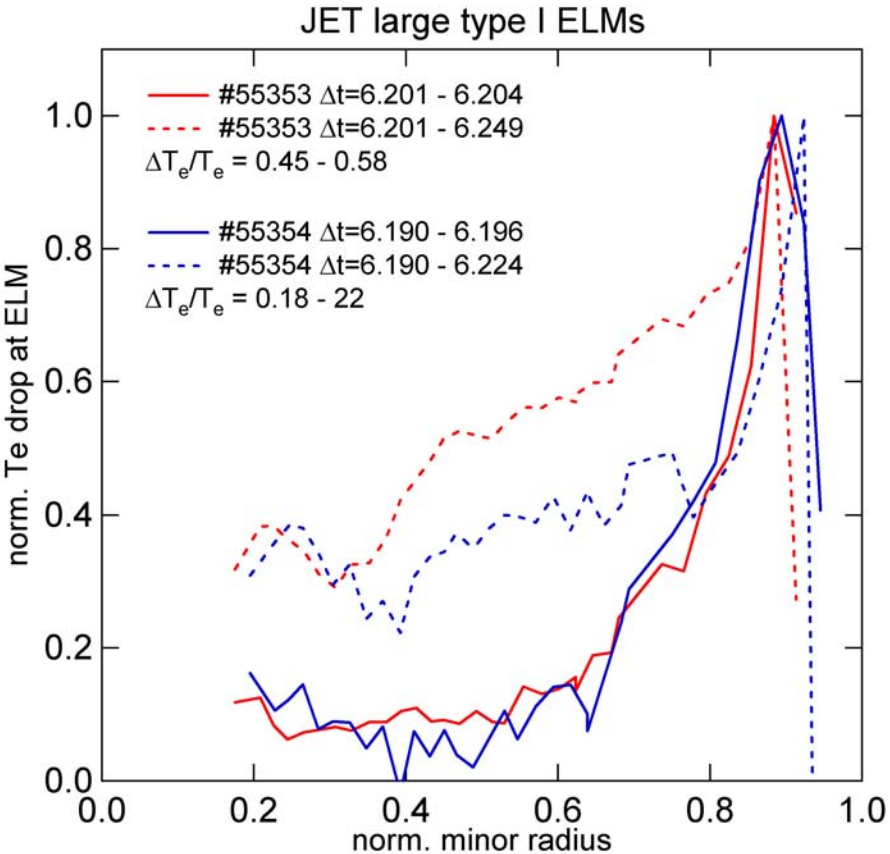
Te drop at ELMs <u>in high δ AT</u> scenarios (mk2_SRP)

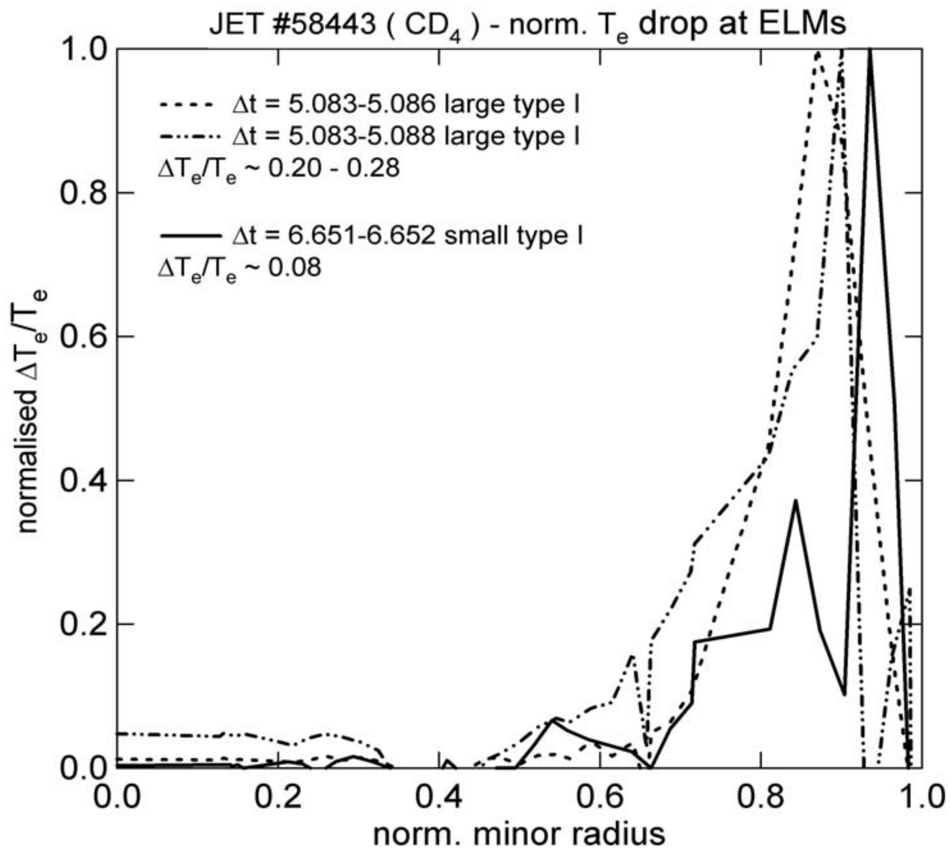






ELM size (II)

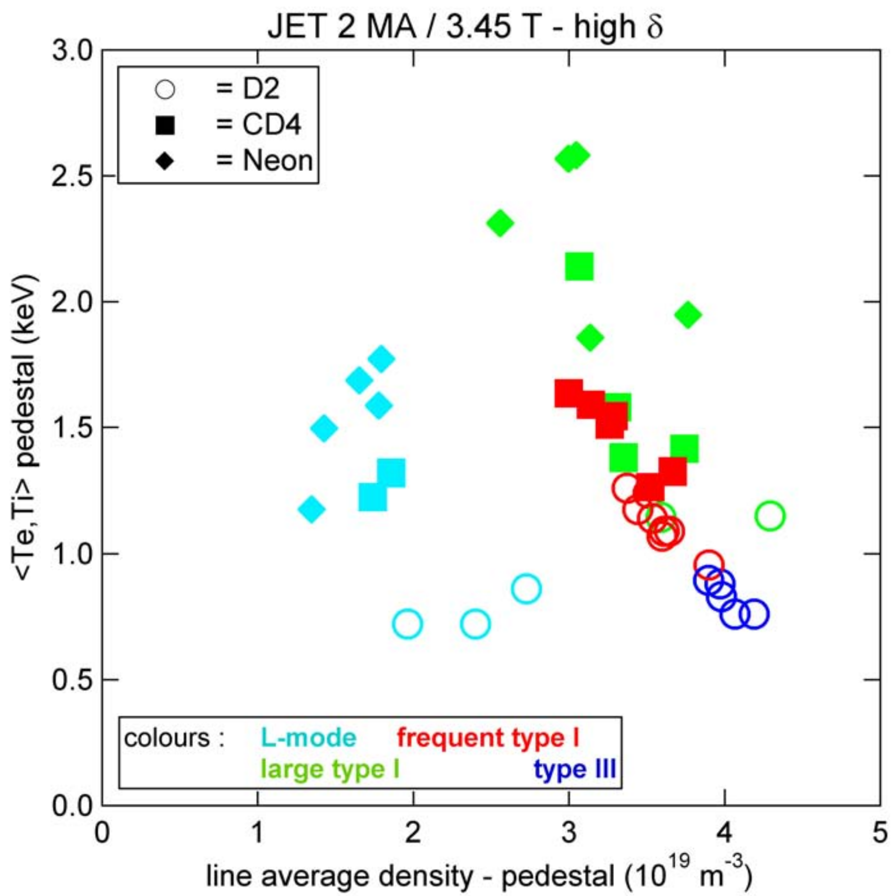


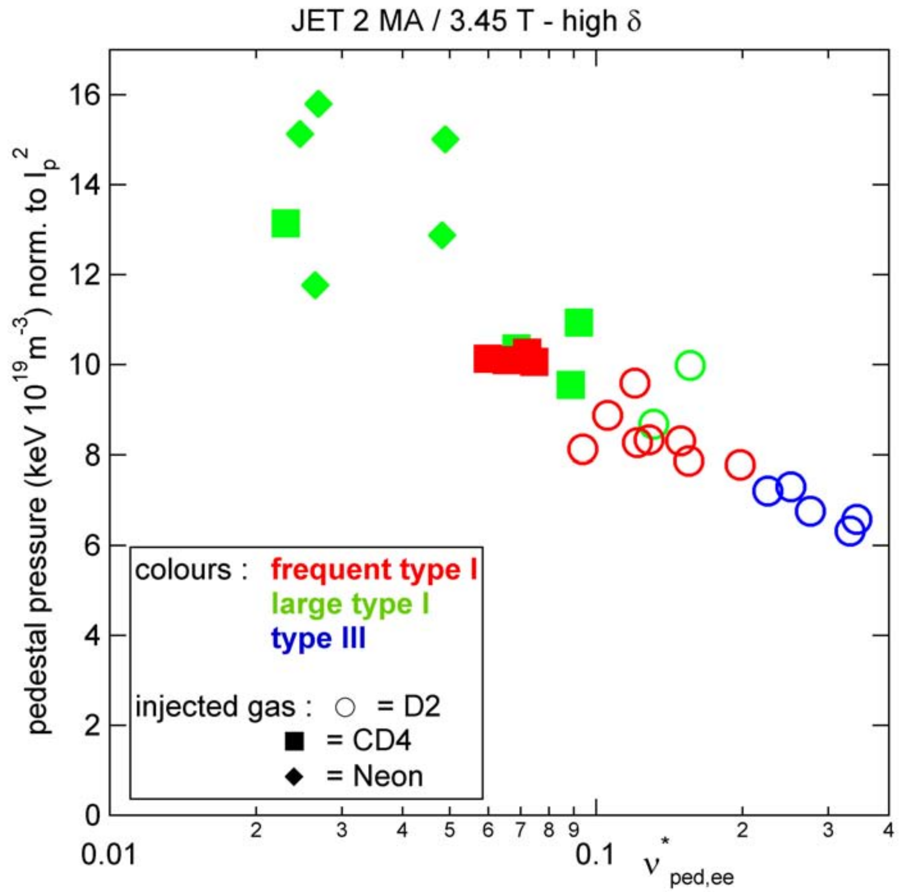


no gas / D_2 only : ELM perturbation extends to mid-radius

CD4 : much reduced ELM perturbation (amplitude & radial extent)

D_2 / CD_4 / Ne : edge parameters - 1.9MA





edge parameters *similar* for D_2 and CD_4 injection (but $n_{e,D2}$ higher)

higher Carbon, P_{RAD} and Zeff (core & edge) with CD_4 ⇒ edge current ?

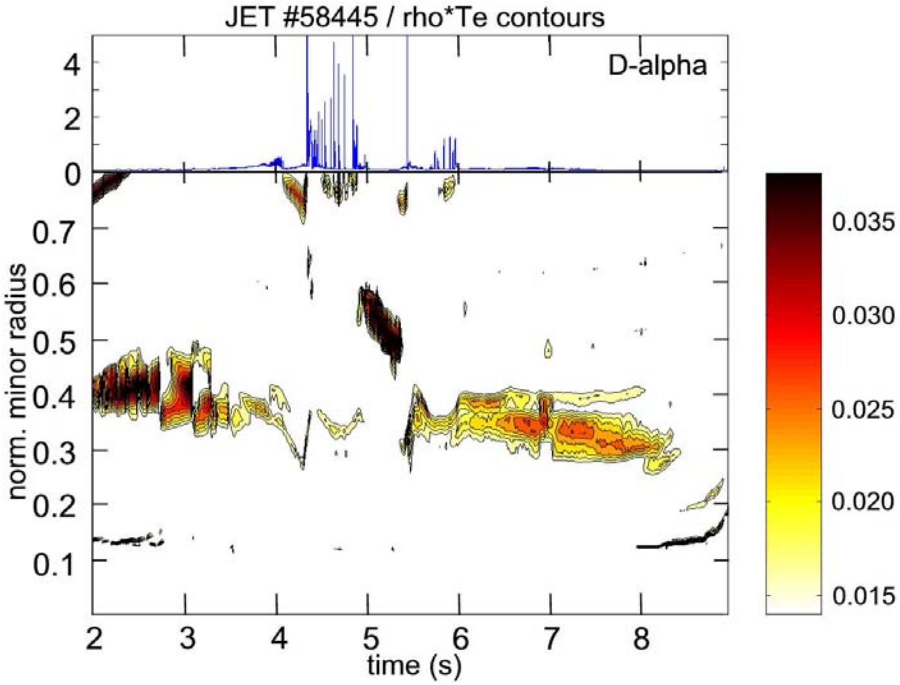
is decrease in the edge pressure enough to allow *inner* ITB sustainment ?

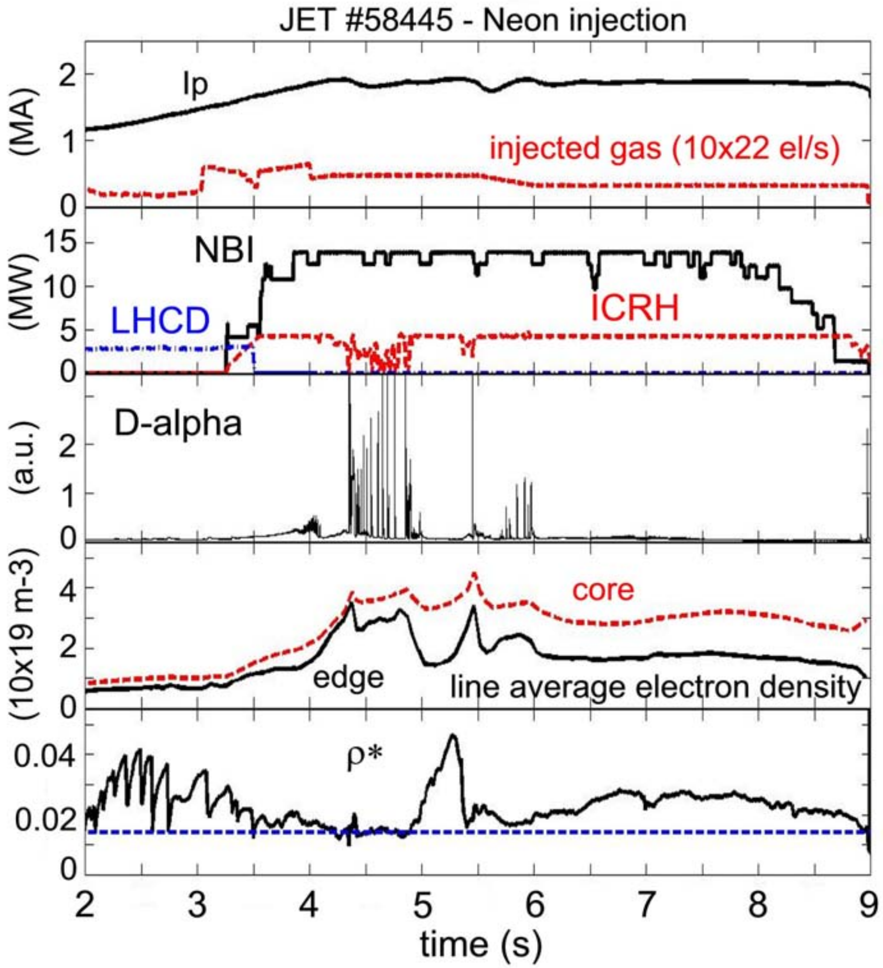
aside : Ne injection at 1.9MA

successive Elm-free – L-mode phases

inner ITB sustained throughout

outer ITB triggered but not sustained

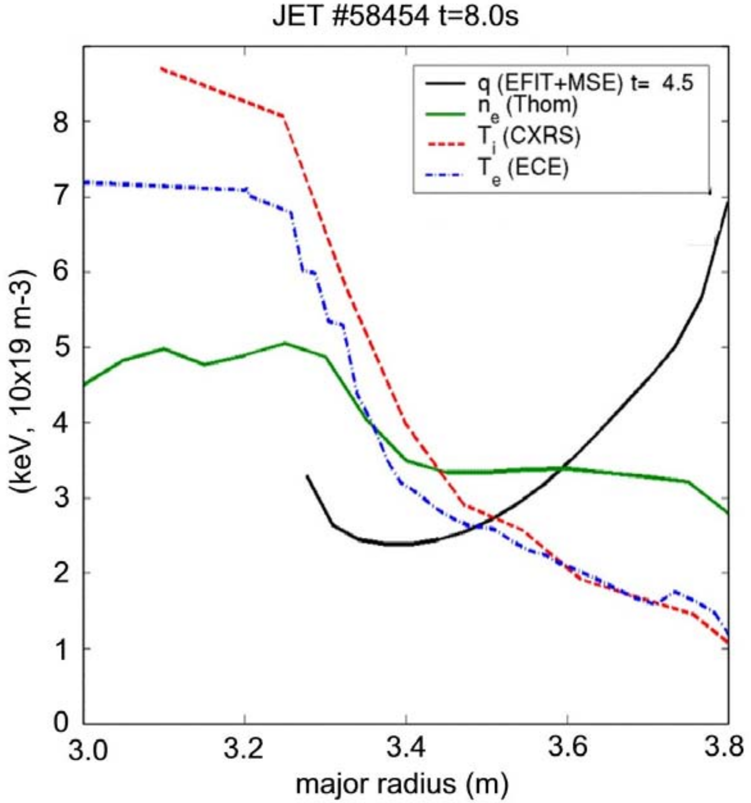


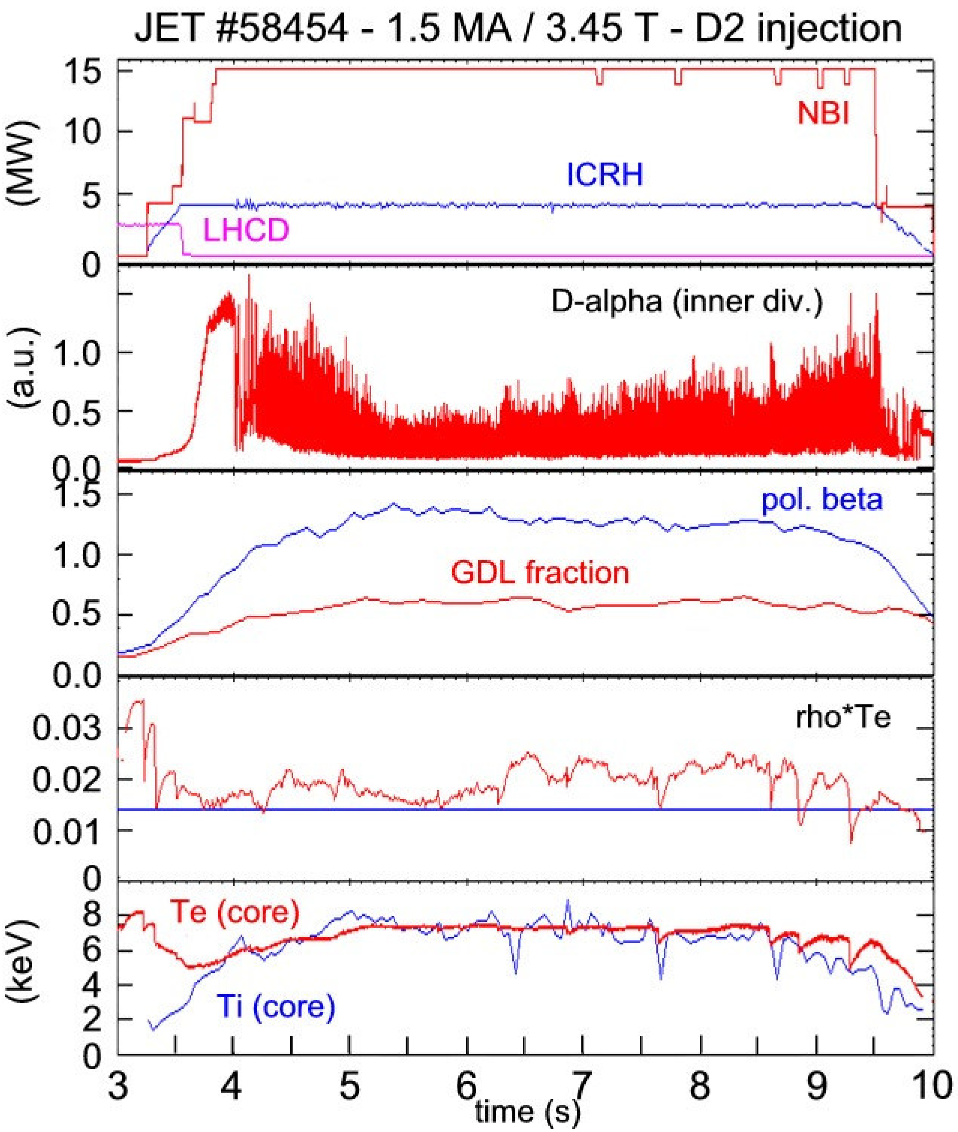


… more later …

1.5 MA : can sustain *inner* ITB with D_2

note : EFIT+MSE q profiles essentially the same for 1.5 and 2 MA

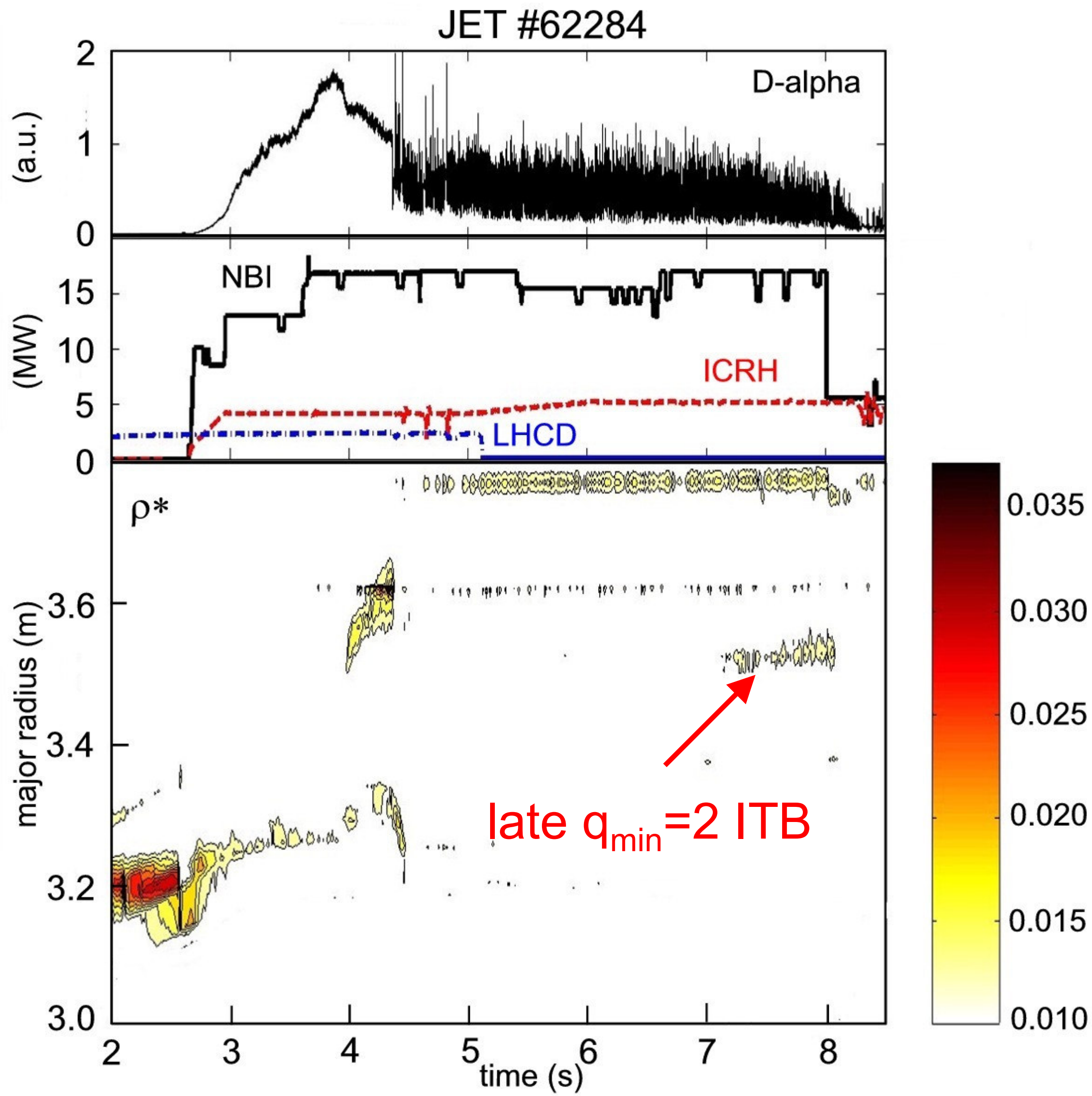




… at higher input power …

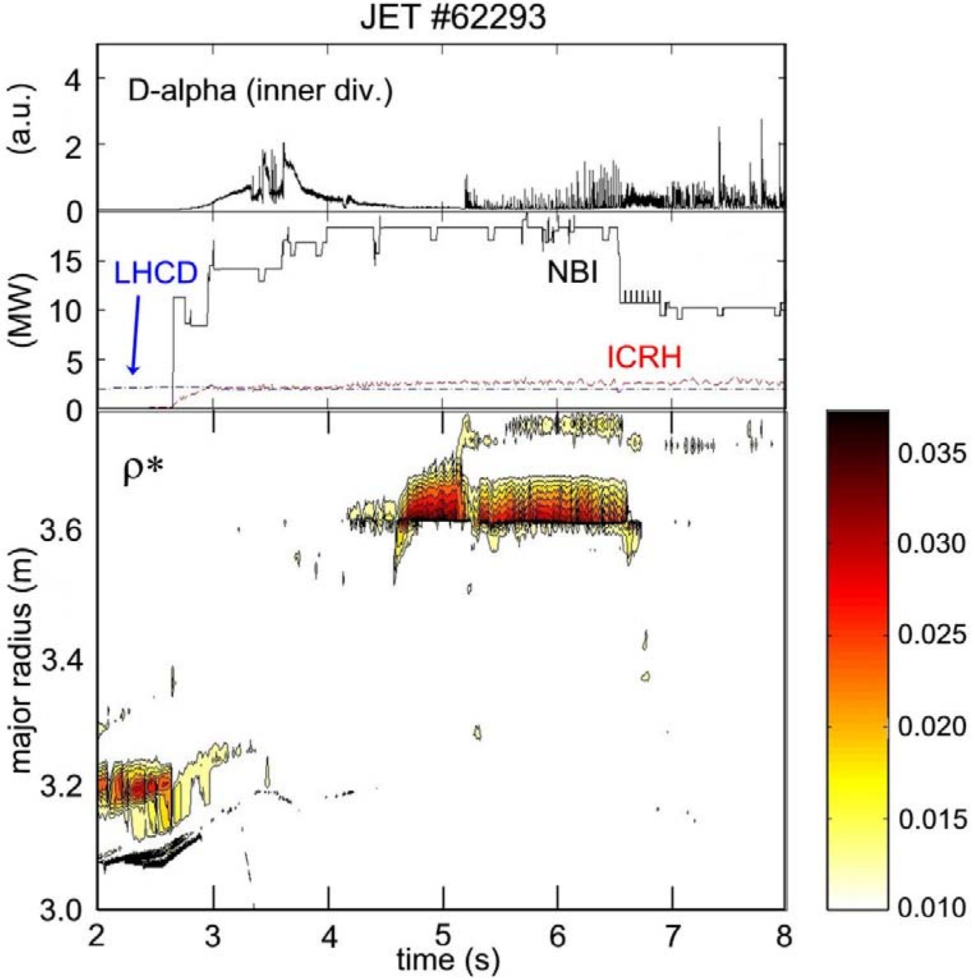
with D_2 injection :

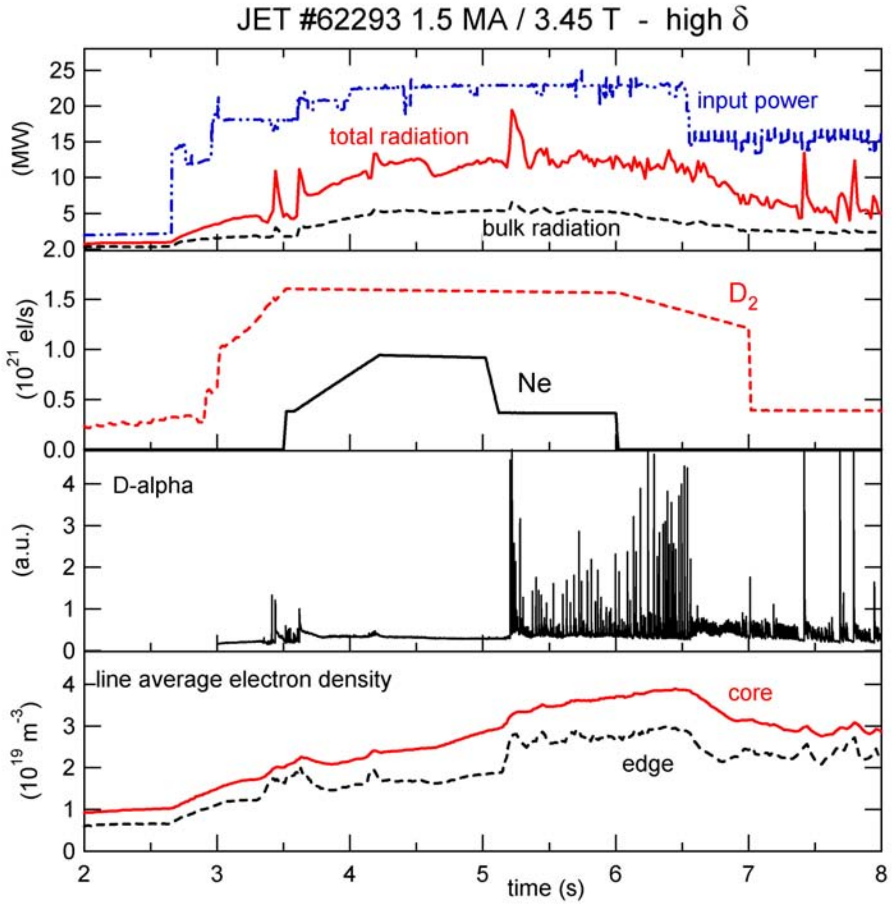
- edge control still works ⇒ short L-mode followed by frequent/small type I
- *outer* ITBs are reproducibly triggered in L-mode phase
- but do not survive transition into H-mode



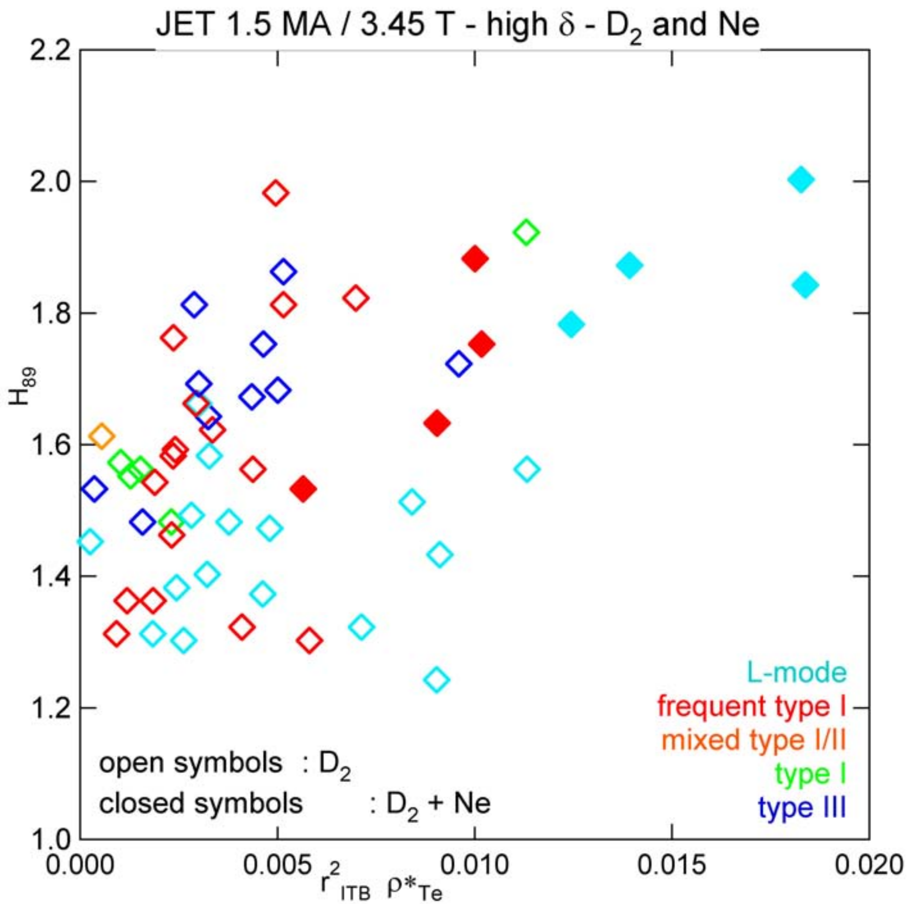
… but with D_2+Ne injection …

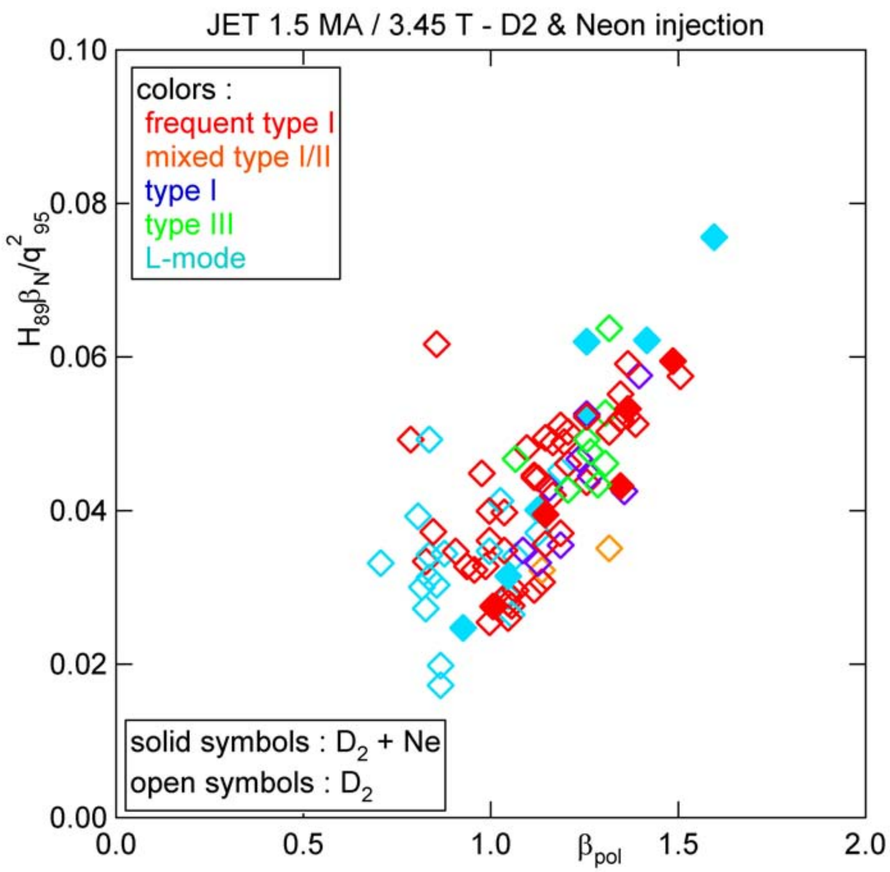
outer ITB survives into the H-mode phase for ~2s, ~10 τ_E at ~ 60-70% n_{GDL}





Prad~ 50-55 % of Pin (divertor and X-point ~ 30-35% Pin) in our Xps : only discharges with outer ITBs provide the high performance required for viable AT operation





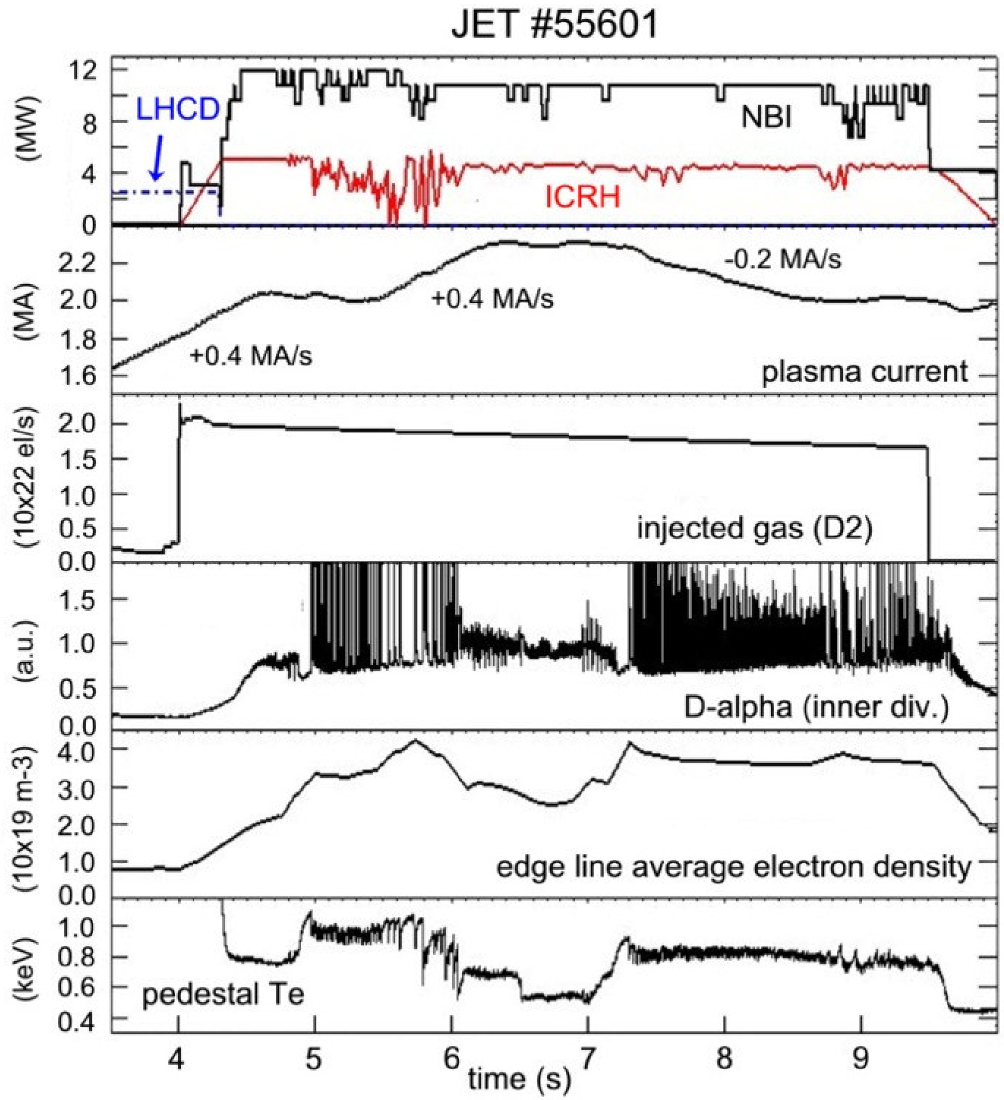
but high q_{95} ~ 7.5 ⇒ rather low $H_{89}\beta_N/q_{95}$

additional topic : edge current studies (I)

I_P ramp-up

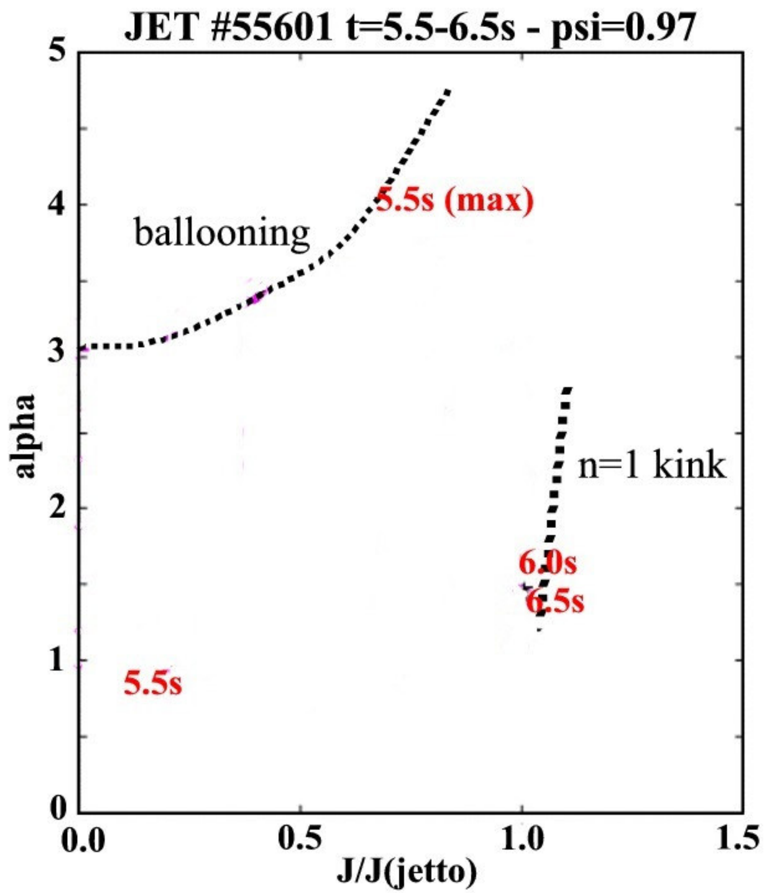
⇒ directly driving edge current

⇒ initially increase Δ pressure during ELM cycle + decrease of ELM frequency subsequently (when edge current approaches kink limit) type III ELMs could appear



additional topic : edge current studies (II)

JETTO-MISHKA codes analysis consistent with experimental results



Note : probably no access to 2nd stability (but low β_{pol} …)

additional topic : high β_{pol} discharges (I)

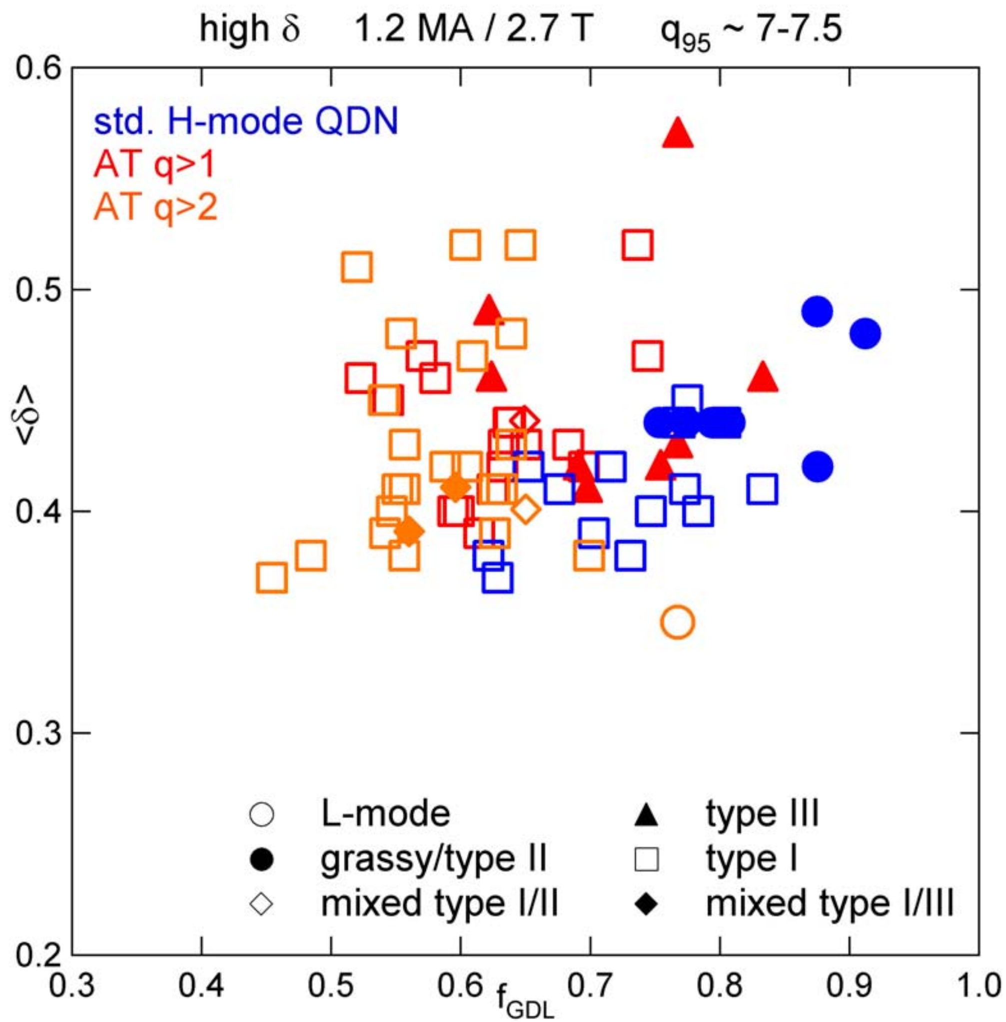
small set of Xps at lower I_P~1.0-1.2 MA max NBI+ICRH to get high β_{pol}

compare :

- AT scenario with q > 1
- AT scenario with q > 2
- *std.* H-modes scenario in QDN configuration

- at similar δ
- but different current profiles & equilibria
- some n_e range overlap

(see G. Saibene's talk for edge parameters analysis)

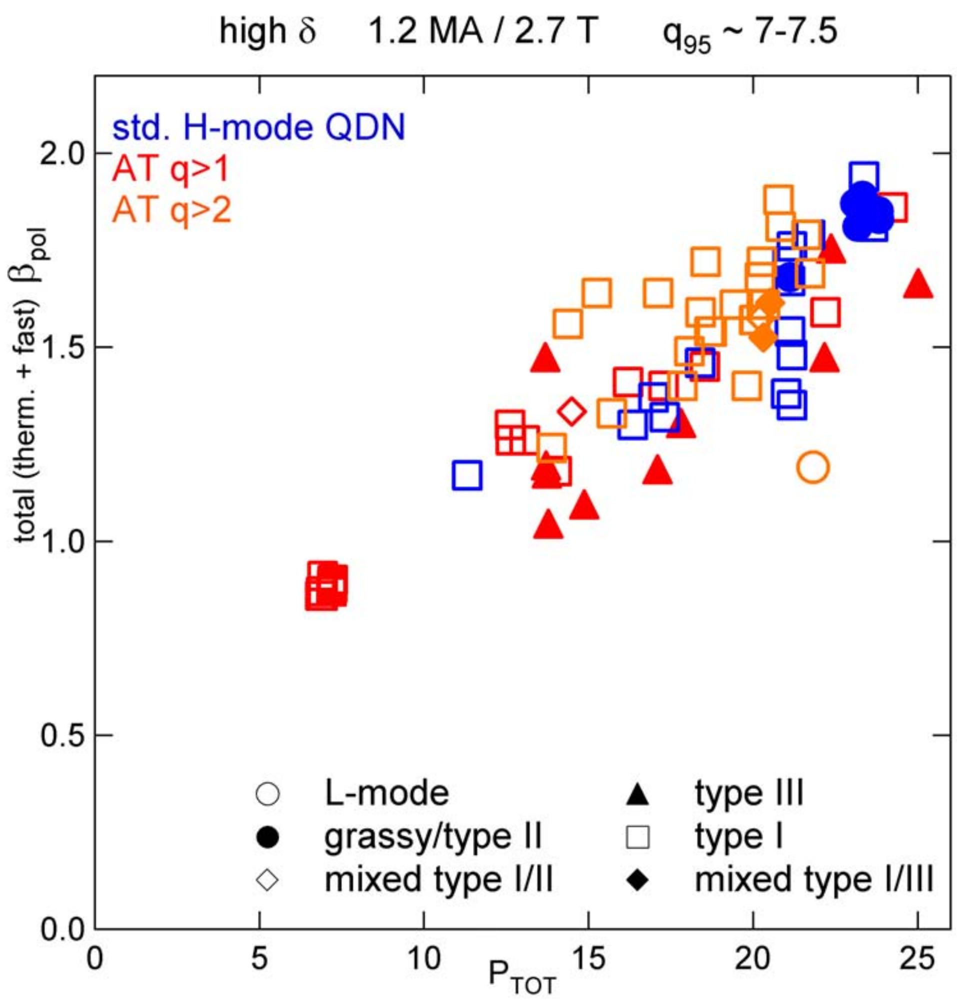


additional topic : high β_{pol} discharges (II)

In AT scenarios β_{pol} ~2 obtained transiently with 25 MW of NBI + ICRH

q>1 : no ITBs (deliberately)

q>2 : signs of weak ITBs at mid-radius (lack of power ?) - ITBs compatible with small type I ELMs ?



¡ control of configs. at β_{pol} ~2 a problem (despite use of new XSC controller) - unwanted interaction with walls - L-mode + impurity influxes !

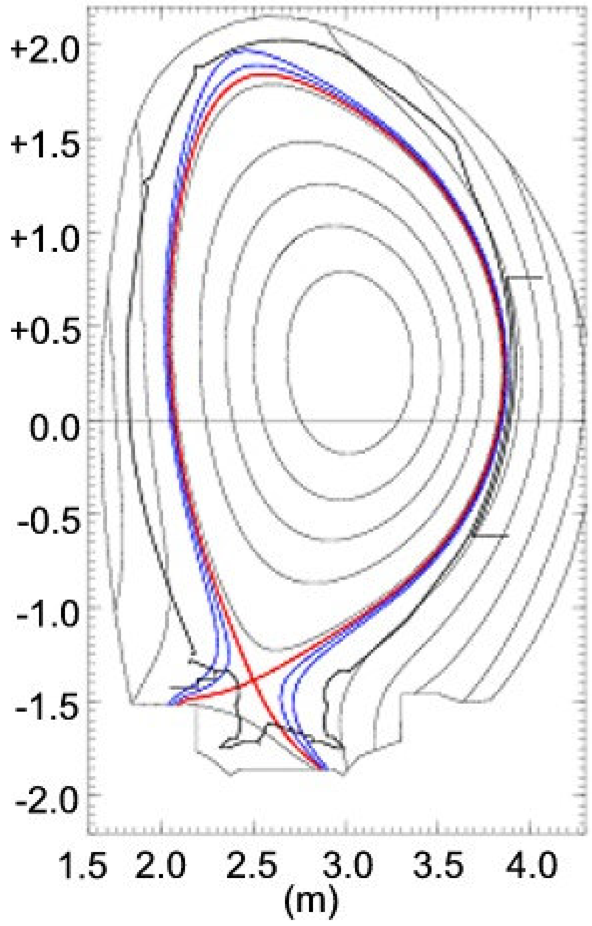
promising & intriguing results but need further experimental time

possible directions for future Xps (I)

independent variation of upper and lower triangularity

preliminary equilibrium studies

high deltaUP - high deltaLOW



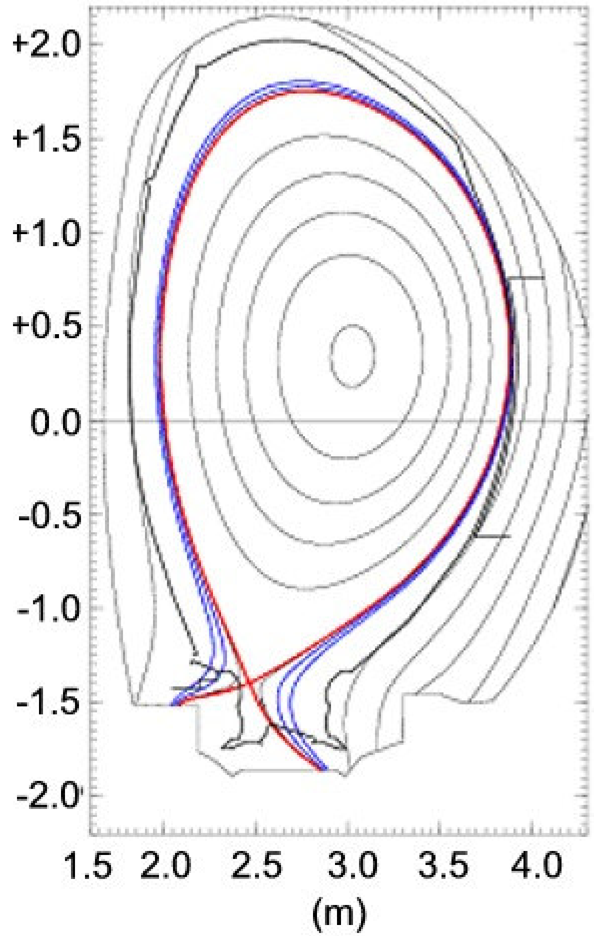
2 MA

$l_i = 0.8 - \beta_p = 0.55$

$\delta_{up} = 0.47$
$\delta_{low} = 0.51$
$q_{95} = 5.02$

$\delta_{up} = 0.21$
$\delta_{low} = 0.48$
$q_{95} = 4.95$

low deltaUP - high deltaLOW



possible directions for future Xps (II)

exploit different current profiles

revisit *Optimise Shear* scenario - low shear - $1.5 < q < 2$ in the core

in JET deeply reversed shear scenario :

- low power threshold for *inner* ITB
- but performance low ? steep $\nabla p \Rightarrow$ low beta limit ?
- and question on fast ion confinement in current hole …
- power threshold for *outer* ITB is higher

OS current profiles can give ITBs located at large radii (*outer* ITB) $\Rightarrow$ potentially higher performance + less steep ∇p + higher beta limit

in addition : use LHCD for tailoring of the current profile (target q - ITB location) + approach to steady-state condition during main heating phase.

summary / conclusions

at high δ in recent JET AT scenarios :

previous xps (mk2GB) :

- type I ELM and ELM-free phases dominant - only marginal inner ITBs

in mk2SRP :

- extensive set integrated studies of edge & core conditions (gas injection + edge current variations) - not always full power available …
- a high δ scenario developed : controlled edge (Ne inj.) + long lasting *outer* ITBs + high performance at higher f_{GDL} than low δ scenario
- at high β_{pol} ~ 2 high q95 : no evidence of type II or grassy ELMs (see G. Saibene's talk) - effect of edge current ?

Advanced Tokamak regimes at JET :

what are the changes when operating at high triangularity ?

as expected (w.r.t. lower δ)

unfuelled / low gas input : preferentially long ELM-free + large type I

and in general in JET AT scenarios (high or low δ):

ITBs not compatible with large type I ELMs

gas (light impurities better) needed to get small type I / type III

'though with D_2 *outer* ITB does not survive transition into H-mode

but scenarios developed where :

- CD_4 : reduced ELM size/amplitude & *inner* ITB sustained (but no Xps at max. power)
- Neon : at max. power *outer* ITB survives transition into H-mode

plans

in forthcoming mk2-LBSRP divertor :

- more freedom in configs choice at high δ
- better control (new XSC controller) with varying l_i & β_{pol}
- explore different configurations (vary lower and upper δ)
- explore different current profiles (OS rather than deeply reversed)
- decrease q_{95}

- revisit high β_{pol} > 1.7 scenarios and connect with std. H-modes with grassy ELMs (higher density , QDN equilibrium) - decrease q_{95}
- revisit high β_{pol} > 1.7 scenarios at sufficient power to give *good* ITBs