Advanced Tokamak regimes at JET:
what are the changes when operating at high triangularity?

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mklA divertor - early ITB studies - $\delta \sim 0.2$-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
mkII gasbox (closer divertor)

- almost all Xps at low $\delta \sim 0.2$ & low $f_{\text{GDL}}$ (<< 50%)
- edge is naturally ELMy - i.e. no long L-mode phase anymore
- impurity inj. used to control edge (Argon) at $\delta \sim 0.2$
- $D_2$ dosing not successful - gives high density + type I

- at higher $\delta \approx 0.35 - 0.45$ edge becomes type I with strong pedestal incompatible with ITB (Crisanti PPCF2003)
explore ITB scenarios in high $\delta$ 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 not 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) $l_1 \approx 0.9$
$\langle \delta \rangle \approx 0.40 - 0.44$
Note: in MkII SRP AT scenarios at low $\delta$

- almost all Xps at low $\delta \sim 0.2$, 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 ($< 1.2 \times 10^{22} \text{ el/s}$)
- *inner* ITB triggered very reliably
- *outer* ITB only observed at high power
gas scan at high $\delta$

increasing gas:

- long ELM-free + type I
- compound type I/III
- long dithering + type III
- frequent type I
- L-mode
confirmed:

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

\textit{inner} ITB sustained in CD$_4$ case

! $P_{\text{TOT}} < 20$ MW – NBI $\sim 15$ MW : marginal for \textit{inner} ITB - too low \textit{outer} ITB?

\textbf{note : target q profiles : deeply reversed & $q_{\text{min}} \sim 3$ (initially)}
Te drop at ELMs in high $\delta$ AT scenarios (mk2_SRP)
no gas / $D_2$ only: ELM perturbation extends to mid-radius
CD4: much reduced ELM perturbation (amplitude & radial extent)
edge parameters *similar* for D₂ and CD₄ injection (but nₑ,D₂ higher)
higher Carbon, P_{RAD} and Zeff (core & edge) with CD₄ ⇒ edge current?
is decrease in the edge pressure enough to allow *inner* ITB sustainment?
successive Elm-free – L-mode phases
inner ITB sustained throughout
outer ITB triggered but not sustained
note: EFIT+MSE q profiles essentially the same for 1.5 and 2 MA
with D\textsubscript{2} injection:

- edge control still works $\Rightarrow$ short L-mode followed by frequent/small type I
- \textit{outer} ITBs are reproducibly triggered in L-mode phase
- but do not survive transition into H-mode
outer ITB survives into the H-mode phase for ~2s, ~10 $\tau_E$ 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 $q_{95} \sim 7.5 \Rightarrow$ rather low $H_{89} \beta_N / q_{95}$
$I_p$ ramp-up

⇒ directly driving edge current
⇒ initially increase $\Delta$
pressure during ELM cycle
+ decrease of ELM frequency
subsequently ( when edge
current approaches kink limit
) type III ELMs could appear
JETTO-MISHKA codes analysis consistent with experimental results

Note: probably no access to $2^{nd}$ stability (but low $\beta_{pol}$ ... )
small set of Xps at lower $I_p \sim 1.0$-$1.2$ MA max NBI+ICRH to get high $\beta_{pol}$

compare:
- AT scenario with $q > 1$
- AT scenario with $q > 2$
- *std*. H-modes scenario in QDN configuration
- at similar $\delta$
- but different current profiles & equilibria
- some $n_e$ range overlap

(see G. Saibene's talk for edge parameters analysis)
In AT scenarios $\beta_{\text{pol}} \sim 2$ 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 $\beta_{\text{pol}} \sim 2$ 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

\[ l_i = 0.8 - \beta_p = 0.55 \]

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

low deltaUP - high deltaLOW

\[ \delta_{up} = 0.21 \]
\[ \delta_{low} = 0.48 \]
\[ q_{95} = 4.95 \]
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 $\nabla p$ + 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.
at high $\delta$ 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 $\delta$ scenario developed: controlled edge (Ne inj.) + long lasting outer ITBs + high performance at higher $f_{\text{GDL}}$ than low $\delta$ scenario
- at high $\beta_{\text{pol}} \sim 2$ high q95: no evidence of type II or grassy ELMs (see G. Saibene's talk) - effect of edge current?
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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**
ge ( light impurities better ) needed to get small type I / type III
'though with D₂ outer ITB does not survive transition into H-mode
but scenarios developed where :

- CD₄ : reduced ELM size/amplitude & inner ITB sustained ( but no Xps at max. power )
- Neon : at max. power outer ITB survives transition into H-mode
in forthcoming mk2-LBSRP divertor:

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

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