Triggered Confinement and Pedestal Temperature Enhancement in NSTX H-mode Discharges

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Enhanced Pedestal H-mode: a second transition with increased edge temperature and $\tau_E$

- Initially observed in NSTX as transient phase
- Currently being developed as long pulse advanced scenario

Maingi, JNM 390-391 (2009) 440
Common Enhanced Pedestal H-mode Characteristics

• A second transition to enhanced confinement and high pedestal $T_e, T_i \leq 700$ eV
  - Second transition after large ELM, either natural or triggered by 3D fields
  - $W_{MHD}$ ramps ~ linearly in time for ~ 0.1 s, typically $dW/dt \sim 0.4*P_{NBI}$
  - $H_{H97L} \geq 2.5$, and as high as 3.5 transiently
  - EP H-mode phase observed during $l_p$ ramp or flat-top

• Common feature: edge $v_\phi$ develops large gradient, with a large drag, often near the $q=3$ surface

• Low loop voltage, high $\beta_N$ (due partly to low pressure peaking factor)

✓ high performance, long pulse candidate
Comparison of Standard and EP H-mode evolution

- Same $I_p$, $P_{NBI}$
- Higher $W_{MHD}$ during EPH
- Higher $H_{97L}$ during EPH
- ELM trigger for EPH

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Comparison of Standard and EP H-mode profiles: Stronger T gradients, local minimum in $V_{\text{tor}}$
Enhanced Pedestal H-mode barrier width size comparable to gyro-diameter

- Edge scale lengths for both $T_i$ and $n_C$ approach the gyro-diameter during EPH-mode

- Ion gyroradius $\rho_i \sim 0.7$ cm relative to $|B|$, owing to combination of local $T_i \sim 350$ eV and $|B| \sim 0.35$ T at outer midplane
  - Approaching or at the fundamental limit on the gradient scale length?

- Minimum $v_\phi$ seems to be in center of highest $\nabla T_i$ region
Changes in $v_\phi$ accompany high $T_{e,i}^{\text{ped}}$ in Enhanced Pedestal H-mode

- First order radial force balance:
  \[ E_r + v_\theta B_\phi = v_\phi B_\theta + \nabla P_c / 6 e N_c \]

- EPH mode has $v_\phi \sim 0$ near separatrix, probably due to drag from an island, such that $\nabla P$ term dominates $v_\phi$ over large region

- Large $\nabla v_\phi$ indicative of large $E_r'$

- $v_\theta$ negligible (recent measurement)
Spontaneous EPH-mode also observed during $I_p$ flat-top

- Same $I_p$
- Lower $P_{\text{NBI}}$
- Higher $W_{\text{MHD}}$ during EPH
- Higher $H_{97L}$ during EPH
- ELM trigger for EPH
3D fields used for ELM pace making may trigger EPH during periods when 3D fields switched off.
EPH-mode phase observed for several $\tau_E$, up to $\sim 300$ msec

EP H-mode
H-mode
separatrix
Thermal and angular momentum transport reduced over outer half of plasma

**EP H-mode**

**H-mode**

\[ \chi_{\text{eff}} (\text{m}^2/\text{s}) \]

\[ \chi_{\phi} (\text{m}^2/\text{s}) \]

![Graph showing thermal and angular momentum transport](image)
Spatial extent of significant $E_r$ shear region doubled in size during EP H-mode

- $T_i$ pedestal height correlates with edge toroidal rotation shear
High $\beta_{pol}$ results in high bootstrap and non-inductive fraction ($f_{NI} \sim 0.65$ from TRANSP)

- $I_p = 0.9$ MA, $P_{NBI} = 3.8$ MW
- $\beta_p \sim 1.5$, very high for 0.9 MA
- Loop voltage low during EPH, due to high bootstrap
- Very little or no flux consumption
High bootstrap and non-inductive fractions, high thermal $\tau_E$ during EPH phase

- $f_{bs}$ between 0.5-0.6, and $f_{NI}$ between 0.6-0.7

- $H98y2$ between 1.6 and 1.8, with $\tau_E^{th}$ between 90-100 msec

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Effort underway to develop EPH-mode as a high performance, long pulse target

• Initiating EPH-mode:
  - Lithium conditioning for ELM-free conditions
  - RMP trigger of a large ELM
  - Since density profile control may be important, *supersonic gas injection (SGI) may provide easier access (longest pulse EPH had SGI)*

• Sustaining EPH-mode:
  - Use $\beta$ feedback + $n=1$ feedback to avoid $\beta$ limit
  - Pre-program NBI reduction, if needed
  - Raise $B_t$ or drop $I_p$ or more shaping to delay $q_0=1$ crossing
The Enhanced Pedestal H-mode has favorable characteristics and improved long pulse prospects

- EP H-mode is characterized by high pedestal temperature, increased edge $v_\phi$, improved confinement
- EP H-modes occur naturally following large ELMs, or can be triggered with 3D fields
- Recently, EPH phases were obtained during $I_p$ flat-top for several $\tau_E$
- With the advent of $\beta$ feedback on NBI and good n=1 feedback, extending the pulse length and using EPH as a high-performance target will be attempted in FY10 in NSTX
Backup
The Enhanced Pedestal H-mode (EPH) has favorable characteristics and improved long pulse prospects

- Energy confinement in NSTX H-modes is generally 0.8-1.2* ITER98y2 scaling
  - Note that $\tau_E$ increases stronger with $B_t$ and weaker with $I_p$ than 98y2
  - Several next step ST designs based on ~ 50% higher $\tau_E$

- A transition to a (transiently) improved confinement with enhanced H-mode pedestal $T_e, T_i$ observed a few years ago

- Characteristics of EP H-mode
  - Highest normalized energy confinement of any regime in NSTX, with $H89P \leq 3.5$ and $H98y2 \leq 1.8$

- Prospects for increasing pulse length
  - Can be triggered by large ELM or RMP-triggered ELM(!), with pulse length $\leq 3 \tau_E$ (up to 300 msec) observed in 2009
EP H-mode profiles evolved continuously during $I_p$ ramp

$T_e$ [keV]

$T_i$ [keV]

$n_e$ [$10^{19}$ m$^{-3}$]

$V_{tor}$ [km/sec]

R [m]
EPH-mode phases up to several hundred msec observed recently (more common with lithium?)

- $I_p = 0.9$ MA, $P_{\text{NBI}} = 3.8$ MW
- $W_{\text{MHD}} \leq 350$ kJ
- $\beta_n > 6.5$
- $\tau_E \geq 80$ msec for 225 msec
- $H_{97L} \leq 3$

- Natural ELM trigger for EPH
- Not sure of termination event

Maingi, PRL (2010) at press

Maingi, PRL (2010) at press
High $\beta_N$ phase maintained for 2 $\tau_E$

- $I_p = 0.9$ MA,
  $P_{NBI} = 3.8$ MW
- $W_{MHD} \sim 325$ kJ
- $\beta_N \sim 6.5$
- $\tau_E \geq 80$ msec for 225 msec
- $H97L \geq 2.5$
- EPH phase is ELM-free
Long pulse EPH – density still evolving slowly, $Z_{\text{eff}}$ rising, but $P_{\text{rad}}$ seems reasonable

![Graph showing $I_p$, $n_e$, $P_{\text{rad}}$, and $Z_{\text{eff}}$ over time.](image)
EPH may occur naturally in recovery period following ELM/braking triggers.
EP H-mode profiles evolve continuously, although recovery from trigger takes a little time.

- Discharge had Li evaporation to improve performance in regular H-mode.
EPH-mode can have transient H89P up to 4

134987: $t_1=0.75$
134991: $t_2=1.0$ (EPH)