Divertor detachment and radiated power control developments on DIII-D and EAST

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presented at the
28th IAEA Fusion Energy Conference

2021-05-11
Divertor detachment and radiated power control developments on DIII-D and EAST

- Detachment control systems using Langmuir probe (LP) feedback added at DIII-D and EAST
- Stable divertor $T_e$ (new, using EAST’s triple LPs) or $J_{sat}$ (based on JET\(^{(1)}\)) and can follow dynamic targets (new, aggressive demonstration of control capability)
- Integrated with core scenario to allow up to $H_{98, \gamma 2} \approx 1.5$ (DIII-D), 1.1 (EAST); $\beta_p \approx 2.3$ (DIII-D), 1.5 (EAST) while detached\(^A\)
- Similar outcomes despite differences in divertor material, geometry, impurity species (first successful use of Ar for control at EAST), and heating method
- Radiated power control deployed in super-H mode


\(^A\) Based on DIII-D#180257, EAST#85293
Related presentations

- Liang Wang, High $\beta_p$, talk #892 May 14
  - Poster #1497 May 11

- Theresa Wilks, Super H-mode, talk #863 May 12
  - Poster #1443 May 11
Introduction and motivation

Detachment control system

High $\beta_p$ scenario core performance with detachment control

Radiated power control near super H-mode

Conclusions
ITER requires heat exhaust mitigation such as divertor detachment to protect plasma facing components \(^{(3, 2)}\)

- Detach = dissipate energy and momentum along the open field lines
- \(T_e(R, Z)\) sets where dissipation processes turn on \(^{(2)}\)
- Reduce \(Q_{SOL}\) until tolerable by PFCs \((\lesssim 10–15 \text{ MW m}^{-2})\) \(^{(3, 4)}\)
- Reduce \(T_e\) at the plate to avoid sputtering
Divertor control is an optimization problem

- Detach by increasing $n_e$ or $P_{rad}$
  - Prevent divertor melting & sputtering
- Can cause problems for core
  - Lower confinement
  - MARFE
  - H-L transition
  - Radiative collapse
  - Density limit
- Optimum set point is not static
  - Control must adapt


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Not all scenarios allow successful integration studies on present devices

- Open divertor: higher $n_e$ required for detachment
- RMP or ECH in DIII-D: low $n_e$ required
- High performance DIII-D scenarios typically do not tolerate detachment
- Detachment studied in low performance scenarios

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The high $\beta_p$ scenario was able to maintain confinement in detachment

**Motivation:** $\beta_p \propto I_{bs}/I_p$
- Steady-state relevant
- First development on JT-60U$^6$
- Pedestal is degraded by detachment
- ITB maintains confinement
- Supports core-edge integration studies on DIII-D and EAST

$\beta_p = 2\mu_0 \langle p \rangle_A / \langle B_{pol} \rangle^2$

$\langle p \rangle_A$ = pressure averaged over poloidal cross section
$\langle B_{pol} \rangle$ = average poloidal magnetic field on the boundary

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Similar high $\beta_p$ scenarios developed in DIII-D and EAST

<table>
<thead>
<tr>
<th></th>
<th>DIII-D</th>
<th>EAST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target material</td>
<td>C</td>
<td>W</td>
</tr>
<tr>
<td>Target geometry</td>
<td>horiz</td>
<td>vert</td>
</tr>
<tr>
<td>PF coils</td>
<td>Cu</td>
<td>SC</td>
</tr>
<tr>
<td>$P_{beam}$ / MW</td>
<td>6.8</td>
<td>0.0</td>
</tr>
<tr>
<td>$P_{RF}$ / MW</td>
<td>0.0</td>
<td>2.9</td>
</tr>
<tr>
<td>$P_{total}$ / MW</td>
<td>6.9</td>
<td>3.0</td>
</tr>
<tr>
<td>$q_{95}$</td>
<td>7.9</td>
<td>6.5</td>
</tr>
<tr>
<td>$\beta_p$</td>
<td>2.3</td>
<td>1.5</td>
</tr>
<tr>
<td>$\beta_N$</td>
<td>3.0</td>
<td>1.2</td>
</tr>
<tr>
<td>$H_{98,y2}$</td>
<td>1.8</td>
<td>1.1</td>
</tr>
<tr>
<td>$\langle n_e \rangle$ / $10^{19}$ m$^{-3}$</td>
<td>6.2</td>
<td>5.3</td>
</tr>
<tr>
<td>$I_p$ / MA</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Impurity species</td>
<td>$N_2$</td>
<td>Ne</td>
</tr>
</tbody>
</table>

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Conclusions
Detachment is characterized by low $T_e \& J_{sat}$ rollover

- **Attached:** $J_{sat} \propto \langle n_e \rangle^2$ (more particles hit divertor)
- **Detached:** momentum loss reduces $J_{sat}$
- $J_{sat}$ “rolls over” as density increases
- **Degree of detachment** \( \propto \langle n_e \rangle^2 / J_{sat} \)

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DIII-D data

\[
J_{sat} = 1.01 \langle n_e \rangle^2
\]

DIII-D #180257 1250-5000 ms

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DIII-D & EAST studies in similar scenarios using sensors in the divertor and nearby gas inlets

DIII-D probes:


EAST probes: (8)

DIII-D demonstrates ability to follow dynamic $J_{\text{sat}}$ targets with PID loop between LP & N$_2$ puff.
Dynamic target following performance is probably not overly sensitive to scenario details.

Neon control on DIII-D can be challenging; may be easier in this scenario.

DIII-D data
First use of triple-tip Langmuir probes for $T_{e,\text{div}}$ control

- EAST $J_{\text{sat}}$ control has been documented previously


- Fast & simple $T_e$ from triple probes

EAST demonstrated ability to meet a range of targets using feedback of $T_e$ from 3LP

* $\Gamma Z$ is the flow of impurity gas out of the tank
$T_e$ and $J_{sat}$ are reduced across the whole divertor target plate.
Tangential TV\textsuperscript{(11)} shows CIII emission moving from target to X-point, consistent with detachment.

Control limitations and considerations

- So far: rely on fixed strike point instead of RT analysis of profiles from multiple LPs $\rightarrow$ vulnerable to strike point drift
  - Some EAST data thrown out after strike point drifted
  - Longer EAST pulse $\rightarrow$ more drift $\rightarrow$ improvement needed
- LPs might have trouble measuring low $T_e$
  - EAST: 200 V external voltage makes calculations easy, but reduces sensitivity to low $T_e$
  - Probes might overestimate $T_e$ at low $T_e^{(12)}$
- $T_e$ sensitivity decreases with further progress into detachment; for example:
  - Detachment onset: $\gtrsim 10$ eV to $\approx 5$ eV
  - DOD=2 to DOD=4: $\approx 5$ eV to $\approx 4$ eV

$J_{sat}$ can be a more sensitive indicator of progress deeper into detachment than $T_e$.
High $\beta_p$ scenario core performance with detachment control

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Conclusions
Maintained $H_{98}$ and $\beta$ during detachment in DIII-D high $\beta_p$ scenario

DIII-D data

$J_{\text{sat}} / J_{\text{roll}}$
Target

$N_2$
$\Gamma_{N_2} / 10^{21} \text{ el s}^{-1}$

$\beta_N$, $\beta_p$, $H_{98,Y_2}$, $\tau_E / 100 \text{ ms}$
ITB retains confinement even as the pedestal degrades due to heavy puffing

- High fuel or impurity puffing can degrade pedestal
  - By $\approx 20\%$ in this case

- ITB growth compensates for pedestal degradation
  - By $\approx 30\%$

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DIII-D data

EAST high $\beta_p$ scenario has significant core gradients that could compensate for weakened pedestal.
EAST retains $H_{98} \geq 1$ unless heavy argon puff ($\approx 10\%$ loss) or depleted Li coating ($\approx 20\%$ loss).
EAST retains $H_{98} \geq 1$ unless heavy argon puff ($\approx 10\%$ loss) or depleted Li coating ($\approx 20\%$ loss)

![Graphs showing EAST data for 50% Ne+50% D₂ and 50% Ar+50% D₂](image-url)
Although confinement quality remained good, disruption risk increased during neon seeding in DIII-D high $\beta_p$. 

DIII-D data

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In DIII-D, neon was associated with more disruptions than nitrogen when used for detachment control in high $\beta_p$.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Safe rampdown</th>
<th>Disruption in rampdown</th>
<th>Disruption in $I_p$ flattop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>11</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Neon</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

DIII-D data, from the same run as #180257
Radiated power control near super H-mode

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Conclusions
Super H-mode enables higher pedestal height and fusion performance than for H-mode

- Super H-mode exists in narrow region of parameter space, first predicted by EPED\textsuperscript{(16)}

- Performance boost is all from pedestal
  - In contrast to high $\beta_p$, where performance depends more on ITB & pedestal can be sacrificed

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**EPED Predictions for Medium Seeded Case**

<table>
<thead>
<tr>
<th>Pedestal Pressure [kPa]</th>
<th>Pedestal Density [$n_{e,ped}(Z_{eff}/2)^{1/2}, 10^{19}m^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>35.0</td>
<td>8.0</td>
</tr>
<tr>
<td>30.0</td>
<td>7.0</td>
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<tr>
<td>25.0</td>
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<td>20.0</td>
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<tr>
<td>15.0</td>
<td>4.0</td>
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<tr>
<td>10.0</td>
<td>3.0</td>
</tr>
<tr>
<td>5.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

See Talk #863 by T. Wilks, May 12

DIII-D DATA
DIII-D’s radiated power control system\textsuperscript{(17)} uses foil bolometers\textsuperscript{(18)}

- Voltage on the foils ($\Delta V_{bol,j}$) converted into estimate for radiated power from lower divertor ($P_{rad,div,L}$)

- Plasma region can be changed ($P_{rad,core}, P_{rad,div,U}, P_{rad,\Sigma}$) by selecting different bolometer channels

\begin{align*}
P_{d,j} &= \left( A_j \cdot \Delta V_{bol,j} + B_j \cdot \frac{d}{dt} \Delta V_{bol,j} \right) \quad (1) \\
P_{rad,j} &= 2\pi R_j r_j \Delta \theta_j K_j P_{d,j} \quad (2) \\
P_{rad,div,L} &= \sum_j C_j P_{rad,j} \quad (3)
\end{align*}
Radiated power control works in super-H mode, but degrades confinement quality.

- **Nitrogen injection** → up to 70% $P_{rad}$
- **ITER needs** $\approx 70\% P_{rad}$ (19, 20, 21)
- **Confinement ($H_{98}$)** degraded by 25% at highest $P_{rad}$
- **Super H is lost at higher $P_{rad}$**
  - 60% $P_{rad}$: super H lost partway through (marginal)
  - 70% $P_{rad}$: not super H
Conclusions

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Conclusions
Summary: LP detachment control integrated with core scenario while maintaining confinement

- DIII-D\textsuperscript{(22)} & EAST\textsuperscript{(9)} added $J_{sat}$ control similar to JET\textsuperscript{(1)}
- EAST added triple Langmuir probe $T_e$ control
- Control avoids excess puffing, while high $\beta_p$ scenario tolerates detachment w/ high confinement (ITB ...)
- Achieved $H_{98} \approx 1.5$ and $\beta_p \approx 2.3$ in controlled detachment in DIII-D
- Achieved $H_{98} \approx 1.1$ and $\beta_p \approx 1.5$ in controlled detachment in EAST
- Radiated power control added to super-H mode for up to 70% $P_{rad}$


