Improved confinement in high-density H-modes at the ITER field via modification of the plasma boundary with Lower Hybrid RF

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Motivation & Background

- We search for external actuators that positively affect performance or facilitate study & understanding.

LHCD works on C-Mod, but this is NOT a talk about LH as a current-drive actuator [see Mumgaard: Fri. Y11.00002]
Motivation & Background

• Search for external actuators that positively affect performance or facilitate study & understanding

• Changes in the boundary plasma can have profound effects on the core plasma
  – recycling affecting core performance – striking example is the effect of Li wall-conditioning in TFTR & NSTX
  – boundary turbulence as likely mechanism for the density limit

• Pedestal as boundary condition for the core

LHCD works on C-Mod, but this is NOT a talk about LH as a current-drive actuator [see Mumgaard: Fri. Y11.00002]

- rather about LHRF as actuator for improving high-$n_e$ H-modes
Confinement Improves with moderate-power LH injection into high-$n_e$ H-modes

Following work on C-Mod by Hughes, et al. [NF 50 (2010)], where the pedestal was significantly affected by LH into H-modes, we observe pedestal modification & confinement improvement by putting LH power into *high-density* H-modes

- the LHRF is *not* accessible to the core and is *not* driving current in these cases

We will show LHRF to be an actuator for affecting the edge
Confinement improvement due to pedestal improvement with core responding via profile stiffness

Core profiles maintain $a/L_{Te}$, $a/L_{Ti}$, $a/L_{ne}$

$LHRF$ - ON
$LHRF$ - OFF

$n_e$

$T_e$

$T_i$

$\nabla p^{ped}_e \uparrow$

$T_e$, $p_e$, $T_i$ increase

$n_e$ at sepx decreases
Scaling of confinement changes
– $\Delta H_{98}$ increases with $P_{\text{LHRF}}$

up to 35% change in $H_{98}$
for 16% increase in $P_{\text{tot}}$
Scaling of confinement changes – $\Delta H_{98}$ tends to decrease as confinement of target improves.
Changes in pedestal $E_r$ profile consistent with confinement improvement

Better confinement correlated with a deeper $E_r$-well is a general trend on C-Mod

L-mode -
EDA H-mode -
I-mode -
ELMy H-mode -
Changes in pedestal $E_r$ profile consistent with confinement improvement

better confinement correlated with a deeper $E_r$-well is a general trend on C-Mod
LH waves are launched from outboard phased wave-guide array with dominant $n_{||} = 1.9$

(nominal $n_e$ for accessibility is $n_e < 0.8 \times 10^{20} \text{ m}^{-3}$)

- no evidence of fast-electrons & no evidence for significant current drive

Ray-tracing modeling (GENRAY) shows SOL and pedestal deposition

non-linear effects are not included in ray-tracing calculation → precise deposition profile relative to LCFS is uncertain
Large fraction of LH power shows up promptly on outer target

PDF of $P_{LH RF}$ fraction on outer target

- Total power to outer target
- LH power
- ICRF power /10

PDF: # of occurrences

Fraction ($\Delta P_{out. target}^{prompt}/P_{LH}$)
Large fraction of LH power shows up promptly on outer target.
Heat flux footprint onto outer target

Heat flux to outer target increases with LHRF, but profile shape remains similar.

Normalized footprint profiles:

LHRF - ON
LHRF - OFF

implies LHRF power increment to target comes from at or inside the sepx.
Edge-localized Quasi-Coherent Mode (QCM) affected by LHRF-improved confinement

fluctuation spectra (PCI)

LHRF - ON
LHRF - OFF
Edge-localized Quasi-Coherent Mode (QCM) affected by LHRF-improved confinement

QCM is an edge mode
- its exact location relative to pedestal, $E_r$-well, and sepx is still uncertain in these plasmas

Effects of LHRF-improved confinement on QCM
- $f^{QCM}$ downshift, with small reduction or no change in $k^{QCM}_{pol}$
- less variation in $f^{QCM}$ vs time
- QCM amplitude decreases

These effects larger for larger $\Delta H_{98}$
Turbulence suppressed with LHRF-improved confinement

fluctuation spectra (PCI)

LHRF - ON
LHRF - OFF

QC-mode subtracted
integration powers
in this band & compare change with $\Delta H_{98}$
Mid-frequency density-fluctuation-decrease is well-correlated with $H_{98}$ improvement.

The larger the decrease in mid-freq fluct., the larger $\Delta H_{98}$.
Broadband-fluctuation-decrease observed by many diagnostics

<table>
<thead>
<tr>
<th>n_e-sensitive diagnostic</th>
<th>Fluct. quantity</th>
<th>Meas. region</th>
<th>mid-freq decrease correlated with ΔH98</th>
<th>low &amp; mid-freq decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPI</td>
<td>î/⟨l⟩</td>
<td>pedestal</td>
<td>yes</td>
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<tr>
<td>reflectometer</td>
<td>ñ_e</td>
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<td>Phase Contrast Imaging (PCI)</td>
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<td>chord thru core &amp; edge</td>
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<tr>
<td>polarimeter</td>
<td>ñ_e, ï</td>
<td>chord thru core &amp; edge</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>GPI</td>
<td>î/⟨l⟩</td>
<td>SOL</td>
<td>yes ~x10 (*)</td>
<td></td>
</tr>
<tr>
<td>Mirror-Langmuir Probe (MLP)</td>
<td>ñ_e, î, φ</td>
<td>far-SOL in limiter shad.</td>
<td>no</td>
<td></td>
</tr>
</tbody>
</table>

* possible local effect from launcher

unfolded outer wall of C-Mod with mapped field-lines
Loarte, et al. [PoP 2011] & Hughes, et al. [NF 2011] have shown C-Mod confinement ordering with $P_{\text{net}} = P_{\text{core}} - P_{\text{rad core}} - dW/dt$, normalized by L-H power threshold, $P_{\text{th,ITER}}$ (ITER-scaling relation) [Martin et al., J. Phys. 2008]

EDA H-modes exhibit confinement ordering with $P_{\text{net}}/P_{\text{th,ITER}}$

well conditioned data set of impurity-seeded & unseeded H-modes (no LHRF actuator!) selected for $\frac{n_{e,sep}}{\bar{n}_e} < 0.5$ burgundy

“...the drop in confinement below the linear trend is strongly correlated with increased $n_{e,sep}$, which considerably degrades the $T_e$ pedestal.” [Hughes, NF 2011]
EDA H-modes exhibit confinement ordering with

\[ \frac{P_{\text{net}}}{P_{\text{th}}} \]

Loarte, et al. [PoP 2011] & Hughes, et al. [NF 2011] have shown C-Mod confinement ordering with

\[ P_{\text{net}} = P_{\text{core}} - P_{\text{rad core}} - \frac{dW}{dt}, \]

normalized by L-H power threshold, \( P_{\text{th}}^{\text{ITER}} \) (ITER-scaling relation) [Martin et al., J. Phys. 2008]

well conditioned data set of impurity-seeded & unseeded H-modes (no LHRF actuator!)

selected for \( \frac{n_{e,\text{sep}}}{\bar{n}_e} < 0.5 \) burgundy

\( \frac{n_{e,\text{sep}}}{\bar{n}_e} > 0.5 \) grey

“…the drop in confinement below the linear trend is strongly correlated with increased \( n_{e,\text{sep}} \), which considerably degrades the \( T_e \) pedestal.” [Hughes, NF 2011]
EDA H-mode confinement is better when \( \frac{n_{e,sep}}{\overline{n}_e} < 0.5 \).

Similar change is being actuated by LHRF for these cases – no LHRF actuator.
LHRF-actuated H-modes show a similar confinement improvement with a decrease in $\frac{n_{e,sep}}{\bar{n}_e}$

- difference between these cases and those of the previous H-mode database is that these changes are actuated by the LHRF!
Open Questions & Summary

- Understanding of how the LHRF is actuating the observed changes is still a work in progress – see Orals by S.G Baek on role of LH Parametric-Decay-Instability (Wed. aft. PO3-010) and I. Faust (PO3-011) on LH power accounting

- Untangle the roles of edge quantities that are being modified by LHRF injection (e.g. turbulence, rotation, electric field, …)

- Role of changes in fueling & neutral profiles?

- Role of critical-gradients in boundary?

- Significant increase in confinement by adding LHRF to high-\(n_e\) H-mode
  – correlated with suppressed edge turbulence (100-300 kHz)
  – correlated with drop in \(n_{e,sep}/\overline{n}_e\), consistent with previous non-LHRF results

- LHRF power deposited in boundary, with large fraction appearing promptly on outer target, but with a profile shape that is unchanged

- Strong evidence that LHRF can be used in these plasmas as an actuator to affect global confinement via modification of quantities at the plasma edge
Additional slides
Additional physics at play for cases when $H_{98}$ improved to values well above 1

In these cases, something occurs during LHRF pulse, affecting QCM & resulting in density, stored energy, & confinement increases