Halo current measurements using Langmuir ‘rail’ probes in Alcator C-Mod

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Outline

• Motivation
• Langmuir ‘rail’ probes
• Edge safety factor
• Halo flux width
• Halo region resistivity
• Summary
Motivation: Accurate predictive modeling of halo currents is needed for future devices like ITER

Simulation inputs:
• Halo region resistivity/temperature
• Halo flux width
• Edge safety factor $q_{\text{edge}}$ “triggers”

Sayer NF 1993
Bandyopadhyay IAEA FEC 2008
Paccagnella NF 2009
Measurements from a new poloidal array of Langmuir ‘rail’ probes in C-Mod can help guide simulation efforts.

Kuang NME 2016
Kuang RSI 2017 (in progress)
Rail probes measure plasma “sliding” down the divertor during downward Vertical Displacement Events (VDEs)
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Blue/Red = current flowing into/out of probe
Magnetic reconstructions of the plasma boundary match the plasma-divertor contact point with experiment.

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Halo current measurements from reproducible VDEs can be used to estimate the halo region/sheath resistance.
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Rail probe measurements:
- Current: \( \sim 16 \, \text{A} \)
- Voltage: \( \sim 11 \, \text{V} \)
The effective resistance of the halo region is calculated to be \(\sim 0.5-2\ \Omega\)

\[
V_{\text{eff}} = I_{\text{measured}} \times R_{\text{eff}} + V_{\text{measured}}
\]

\[-L_h \frac{d}{dt} (I_{\text{measured}})\]
The effective resistance of the halo region is calculated to be $\sim 0.5-2 \, \Omega$

\[ V_{\text{eff}} = I_{\text{measured}} \times R_{\text{eff}} + V_{\text{measured}} \]

\[ -L_h \frac{d}{dt} (I_{\text{measured}}) \]
The effective resistance of the halo region is calculated to be \( \sim 0.5-2 \, \Omega \)

\[
V_{\text{eff}} = I_{\text{measured}} \times R_{\text{eff}} + V_{\text{measured}} - L_h \frac{d}{dt}(I_{\text{measured}})
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V_{\text{eff}} = I_{\text{measured}} \times R_{\text{eff}} + V_{\text{measured}}
\]

\[-L_h \frac{d}{dt} (I_{\text{measured}})\]

<table>
<thead>
<tr>
<th>Rail Probe</th>
<th>Resistance ( R_{\text{eff}} ) (( \Omega ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>RP50</td>
<td>0.8 ± 0.7</td>
</tr>
<tr>
<td>RP52</td>
<td>1.3 ± 0.9</td>
</tr>
</tbody>
</table>
Cross-field current sharing dominates at the rail probe, so we find an upper bound for the sheath resistance.
Spitzer resistivity predicts a halo region temperature around 47-75 eV

\[ \eta_{\text{halo}} = R_{\text{halo}} A_{\text{cs}} / L_c \]

\[ \approx (13.7 \ \Omega - 2 \times 0.8 \ \Omega) \times (5 \ \text{mm}^2) / (2\pi R_0 q_{\text{edge}}) \]

\[ \sim 6.3 \ \mu\Omega\cdot\text{m} \]

\[ \rightarrow \text{For } Z_{\text{eff}} = 1-2, \text{ Spitzer temperature } T_e \sim 47-75 \text{ eV} \]

On the upper end of typical simulation values of 1-50 eV
• A poloidal array of Langmuir ‘rail’ probes measures halo current on C-Mod

• The edge safety factor decreases to approximately rational values (~1 and 3/2) before plasma termination

• The halo flux width varies between ~15-60%

• An upper bound for the sheath resistance of ~1 Ω is measured

• The temperature of the halo flux region is estimated to be ~47-75 eV
Backup slides
Measurements from a new poloidal array of Langmuir ‘rail’ probes in C-Mod can help guide simulation efforts.

Kuang NME 2016
Kuang RSI 2017 (in progress)
Edge safety factor is found to decrease to approximately rational values (~1 and 3/2) before plasma termination.
For a perfectly-grounded rail probe...
A more realistic picture...

halo flux tubes
sheaths
divertor & vacuum vessel

voltage measurement

rail probe

current measurement

vacuum vessel

vacuum vessel

20 Ω
5 Ω
0 Ω

0.5 Ω
Cross-field current sharing dominates at the rail probe, so we find an upper bound for the sheath resistance.
Halo current measurements from reproducible VDEs can be used to estimate the halo region/sheath resistance.

\[ V_{\text{loop}} = V_{\text{pol}} + q \cdot V_{\text{tor}} \approx - \left( B_0 \frac{dA}{dt} + q \cdot L \frac{dI_P}{dt} \right) \]

<table>
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<tr>
<th>Discharge No.</th>
<th>RP Resistor (Ω)</th>
<th>(V_{\text{loop}}) (V)</th>
</tr>
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<tbody>
<tr>
<td>1160628003</td>
<td>20</td>
<td>251</td>
</tr>
<tr>
<td>1160628004</td>
<td>20</td>
<td>211</td>
</tr>
<tr>
<td>1160628005</td>
<td>5</td>
<td>238</td>
</tr>
<tr>
<td>1160628006</td>
<td>5</td>
<td>251</td>
</tr>
<tr>
<td>1160628007</td>
<td>0</td>
<td>217</td>
</tr>
<tr>
<td>1160628008</td>
<td>0</td>
<td>245</td>
</tr>
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The effective resistance of the halo region is calculated to be \( \sim 0.5-2 \, \Omega \)

\[
V_{\text{eff}} = I_{\text{measured}} \times R_{\text{eff}} + V_{\text{measured}} - L_h \frac{d}{dt} (I_{\text{measured}})
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\[ 230 \, V = 16 \, A \times R_{\text{halo}} + 11 \, V \]
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\[ 230 \text{ V} = 16 \text{ A} \times R_{\text{halo}} + 11 \text{ V} \]

\[ \rightarrow R_{\text{halo}} = 13.7 \Omega \neq R_{\text{eff}} \sim 1 \Omega \]
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\[ 230 \, \text{V} = 16 \, \text{A} \times R_{\text{halo}} + 11 \, \text{V} \]

\[ \Rightarrow R_{\text{halo}} = 13.7 \, \Omega \neq R_{\text{eff}} \sim 1 \, \Omega \]

\[ \Rightarrow R_{\text{sheath}} \leq 1 \, \Omega \]