Measurements of the current and hard x-ray profile and efficiency during Lower Hybrid current drive on Alcator C-Mod for simulation validation

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Study reactor relevant RF current drive now, a predictive capability is required for future devices

- Will need **efficient** current drive systems to:
  - Sustain the plasma
  - **Control** the current profile to achieve optimal confinement and stability
- Need to develop and demonstrate current drive solutions **that scale** to a tokamak fusion reactor:
  - Efficient, maintainable, steady state actuators
  - Plasma and neutron compatible
  - Minimal impact on T breeding, T inventory, gas load and regulatory envelope
- Reactor designs favor **RF systems** over NBI
- We require a predictive capability, must **validate RF models**
  - Compare to both 0D parameters and profiles
  - Quantitatively in single discharges/time slices
  - Qualitatively/quantitatively trends
- Need good diagnostics, lots of data

**ARIES-AT current profile**

<table>
<thead>
<tr>
<th>Source</th>
<th>Power [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCD</td>
<td>37.0</td>
</tr>
<tr>
<td>ICRF-FW</td>
<td>4.7</td>
</tr>
<tr>
<td>NBI</td>
<td>0.0</td>
</tr>
</tbody>
</table>

[Adapted from F. Najmabadi, FED 80 (2006)]
Talk Outline

1. Motivation: Going to need RFCD in future

2. Reactor relevant LHCD and an upgraded MSE diagnostic on Alcator C-Mod for current profile measurements

3. First systematic study of LHCD using multiple profile diagnostics for comparison to simulations:
   1. Non-inductive discharge: 0-D agreement but profiles inconsistent
   2. Strong $I_p$ dependence observed in profiles, qualitative agreement with profile trends, but over prediction of current
   3. Weak $n_\parallel$ dependence observed in both measurements and simulation but simulation profiles too broad

4. Future work and conclusions
LHCD on Alcator C-Mod: The only system on a diverted tokamak at reactor densities and fields

<table>
<thead>
<tr>
<th></th>
<th>C-Mod</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td>3-8 T</td>
<td>5 T</td>
</tr>
<tr>
<td>Density</td>
<td>5-15x10^{19} m^{-3}</td>
<td>5-10x10^{19} m^{-3}</td>
</tr>
<tr>
<td>Frequency</td>
<td>4.6 GHz</td>
<td>5 GHz</td>
</tr>
<tr>
<td>Shape</td>
<td>Diverted</td>
<td>Diverted</td>
</tr>
<tr>
<td>Launched n_{</td>
<td></td>
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- 16 column midplane launcher couples ~ 1MW
- Up to 1s long pulse ($\sim 5 \times \tau_{CR}$)
- Can create a range of current/q profiles
  - Enables studies of transport, stability

Study RF physics and validate codes in a relevant regime
Current profile diagnostics required to measure the effects of LHCD to compare to codes: Upgraded MSE

- MSE line polarization systems measure the polarized, Stark split $D\alpha$ from high energy beam neutrals
- Polarization angle is related to magnetic pitch angle and thus used to constrain magnetic reconstructions
  - Current profiles can then be compared to LHCD simulations
  - Requires $\sim 0.2^\circ$ accuracy in polarization angle
  - A challenge for high power, high density, high field, RF heated tokamaks
- Developed techniques required for measurements in future devices on C-Mod
C-Mod MSE system has made progress on many challenges that are foreseen for MSE on ITER and future devices

- Long complicated **in-vessel optical train**
  - Non-linear polarization error from mirrors
- **Dim radial diagnostic beam**, thus large optics
  - Beam-into-gas calibration insufficient
- Cryogenic environment, strong plasma heating
  - **Systematic errors** due to thermal effects
  - **In-situ calibration** inputs known polarization angles every shot
- Plasma emission **partially polarized** upon reflection from complicated, metal internal components
  - Develop compensation strategies: Multi-spectral line polarization MSE

Polarization angle uncertainty reduced from >5° to <0.1°
New reconstruction software uses MSE to obtain $J_{\text{tor}}$ profiles and runs numerical simulation code GENRAY/CQL3D

New software developed to implement MK-EFIT utilizing integrated modeling platform πScope

- Gaussian process regression of pressure and pitch angle profile constraints

Increases robustness of reconstruction and uncertainty estimation

Provides total $J_{\text{tor}}$ profile using MSE

Same environment runs simulations for validation effort: GENRAY/CQL3D:

- Ray tracing + bounce average 3D Fokker Planck solver w/ SOL model
- Calculates distribution function on each flux surface
  - Including background electric field
- Calculates total plasma current, also run with $P_{\text{LH}} = 0$, $E_{\text{DC}} = 0$ to get contributions
- Total current profile for comparison to MSE constrained reconstruction

[Shiraiwa TP8 Thurs am] [A. Smirnov, Bull. APS, 1995] [R. Harvey, GA Tech Report, 1992]
Hard X-ray camera measures fast electron bremsstrahlung profiles, providing a complementary diagnostic to MSE

- 32 sightline poloidally viewing HXR camera
  - Measures Bremsstrahlung $> 40$keV (high energy tail) from fast electrons
  - Provides information about energy distribution and spatial location of fast electrons
  - Included as synthetic diagnostic in RF codes for quantitative comparisons
MSE shows current profile modification by LHCD

+0.15s LHCD, $J_{\text{tor}}$ picks up in edge, current density in core starts to decrease
MSE shows current profile modification by LHCD

+0.25s LHCD, Edge has small changes but core continues evolving
MSE shows current profile modification by LHCD

+0.35s LHCD, Edge stabilized, core is still evolving a bit
MSE shows current profile modification by LHCD

+0.45s LHCD, Everything stationary for 0.1s
MSE shows current profile modification by LHCD

+0.55s LHCD, Stationary for 0.2s
MSE shows current profile modification by LHCD

LHCD off +0.15s, Profile start to return to pre-LHCD state
MSE shows current profile modification by LHCD

LHCD off +0.25s, nearly back to Ohmic starting profile
A note about where the current is driven

Eye is drawn here But most of the current is out here due to larger area
Current profile takes time to reach stationary state while HXR profile is promptly established at the start of LHCD

- Equilibrium reaches stationary state < 300ms after the turn on of LHCD.
- The **hard X-rays are prompt** and the profile is **stationary** from the very beginning of LHCD
  - No significant feedback of the fast electrons on the equilibrium
- Use late, stationary, times for further study

Hard X-Ray profile self-similar for all time slices
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4. Future work and conclusions
LHCD efficiency is density independent in regime of this study, limit study to strongly driven LHCD discharges

Current drive efficiency: $\eta \equiv \frac{I_{LH}n_e R}{P_{LH}}$

For points away from non-inductive adopt a convention:

$\eta^* \equiv \frac{(I_{\text{Plasma}} - I_{\text{Inductive}})n_e R}{P_{LH}}$

Where $I_{\text{Inductive}}$ is estimated from a Spitzer conductivity argument using the change in temperature and loop voltage due to LHCD:

$I_{\text{Inductive}} \equiv I_{\text{PreLHCD}}^\text{Plasma} \left( \frac{V_{\text{LHCD}}}{V_{\text{loop}}^\text{PreLHCD}} \right) \left( \frac{T_{\text{eLHCD}}}{T_{\text{ePreLHCD}}} \right)^{3/2}$

$\eta^*$ takes credit for any effect of DC field on fast electrons, shown to be small on C-Mod [Bonoli POP 2008] focus on strongly driven plasmas

- Much of the previous work on C-Mod was to determine cause of anomalous loss of current drive at high density

- Concentrate on where LHCD drives substantial current, low density on C-Mod but relevant for future machines [Scott TP8 Thurs am]
Unlike a reactor, C-Mod operates in the multi-pass regime, where the bounces at the edge of the plasma are important.

- **In the multi-pass regime**, waves make a bounce off the inner/outer wall.
  - Ray $n_{||}$ downshifts and upshifts as it propagates, including through SOL.
  - Eventually absorbs when $n_{||}$ matches the damping condition.
- **No indications of PDI, non-linear processes**, but bounce/SOL propagation still likely important.
  - Can ray-tracing codes correctly account for this?
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Fully non-inductive shots at low current show broad current profile, but still significant current on axis.
GENRAY/CQL3D predicts correct total current, but has broader current and HXR profiles than experiment

- Simulation predicts nearly the correct total current and HXR count rate
- But profiles are both too broad
  - Under predicts central current density
  - Corresponding to too high of predicted $q_0$

**IP [kA]**

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<td>521</td>
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<td><strong>Simulation</strong></td>
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Higher efficiency observed at higher plasma current, not due solely to residual loop voltage

- Increased efficiency correlates with higher plasma current
  - Effect still present at similar loop voltages in power scan
Higher efficiency observed at higher plasma current, not due solely to residual loop voltage

- Increased efficiency correlates with higher plasma current
- Effect still present at similar loop voltages in power scan
- Older, Pre-MSE, data shows similar effect even at V_{loop} near 0
- Effect also seen in Tore Supra during current scan at V_{loop} = 0

\[ \eta = I_{\text{LH}} \bullet \bar{n}_e \bullet R/P_{\text{LH}} \]

Near non-inductive (V_{loop} < 0.1V)
\[ \bar{n}_e < 8 \times 10^{19} \text{ m}^{-3} \]

Tore Supra result at 0 V_{loop}

\[ \eta_0 \left[ Z = 1.0 \right] \sim 1.0 \times 10^{-2} \text{ m}^2 \text{A/W} \]

[Peysson, NF 2001]
Profiles broaden significantly and HXR increases at higher current with a significant contribution at large minor radius

- Magnetic reconstructions and HXR measurements indicate a broader fast-electron profile at higher plasma current
  - Both diagnostics show a broadening effect
  - Significant contribution outside of $r/a=0.8$
- Total HXR rate increases at higher $I_p$
- Is this a $T_e(r)$ effect? Or from wave trajectories?

At fixed $P_{\text{LH}}$, $n_e$

- **Total $<j_{\text{tor}}>$ [MA/m$^2$]**

\[
\begin{array}{c|c|c|c}
\text{Total $<j_{\text{tor}}>$ [MA/m$^2$]} & \text{530 kA} & \text{680 kA} & \text{800 kA} \\
\hline
5 & 5 & 5 & 5 \\
4 & 4 & 4 & 4 \\
3 & 3 & 3 & 3 \\
2 & 2 & 2 & 2 \\
1 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 \\
\end{array}
\]

- **LHCD contribution to $<j_{\text{tor}}>$ [MA/m$^2$]**

\[
\begin{array}{c|c|c|c}
\sqrt{\psi_{\text{tor}}} \sim r/a & 0.0 & 0.2 & 0.4 \\
\hline
530 kA & 5 & 4 & 3 \\
680 kA & 4 & 3 & 2 \\
800 kA & 3 & 2 & 1 \\
\end{array}
\]

- **HXR $I_p$ dependence, 800kW**

\[
\begin{array}{c|c|c|c}
\text{Counts [s$^{-1}$]} & 530 kA & 680 kA & 800 kA \\
\hline
0 & 0 & 0 & 0 \\
10 & 1 & 1 & 1 \\
20 & 2 & 2 & 2 \\
30 & 3 & 3 & 3 \\
\end{array}
\]
Simulation shows same qualitative trend: Broader at higher current, but doesn’t match profiles or total current

- GENRAY/CQL3D using experimental profiles, no diffusion or pinch, shows a broadening of the current and HXR profiles as plasma current is increased
  - Predicts large amount of current at r/a~0.7, resulting is a very broad HXR profile
  - Much of the simulated current is from the residual DC field acting on the fast electrons
• GENRAY/CQL3D using experimental profiles, no diffusion or pinch, shows a broadening of the current and HXR profiles as plasma current is increased
  • Predicts large amount of current at \( r/a \sim 0.7 \), resulting is a very broad HXR profile
  • Much of the simulated current is from the residual DC field acting on the fast electrons
• Significantly over predicts both total HXR and total current
• Measured profiles significantly narrower than simulation

Simulation shows same qualitative trend: Broader at higher current, but doesn’t match profiles or total current
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   3. $n_\parallel$ dependence

4. Future work and conclusions
Experiment: Launched $n_{\parallel}$ has little effect on current drive efficiency

- Very well controlled scan of $n_{\parallel}$ into L-mode targets
- All $n_{\parallel}$ are accessible
- No trend in inferred current drive efficiency
  - Reaches similar loop voltages
  - $\sim$50-60% non-inductive
Very little profile dependence in either profile

Increases confidence in two complementary diagnostics

Larger $n_{||}$ results in slightly narrower profiles??

Trend is a good test for numerical simulation

Simulate with GENRAY/CQL3D and compare non-trend and profiles

Current

Experiment: Launched $n_{||}$ also has little effect on profiles

Quantitative, no scaling!
Predicts nearly stationary $J_{\text{tor}}$ profile and similarly stationary HXR profiles

- HXR total decreasing at higher $n_{||}$
- Predicts constant current drive efficiency (ie constant total current) but RF driven current decreases
Predicts nearly stationary $J_{\text{tor}}$ profile and similarly stationary HXR profiles

- HXR total decreasing at higher $n_{\parallel}$
- Predicts constant current drive efficiency (ie constant total current) but RF driven current decreases
- Simulation over predicts total current
Simulations are broader than the measured profiles

- Agreement between simulation and experiment better at high $n_{||}$

\[
\text{\% of Experimental } I_p
\]

\[
\begin{array}{|c|c|}
\hline
n_{||}=1.6 & n_{||}=2.5 \\
159\% & 146\% \\
\hline
\end{array}
\]
Profile sensitivity study: No single scale factor reproduces profiles and total current

- Sensitivity to scaling density, but not to scaling temperature
  - Profiles move outward at higher density
  - But always have large spike in $J_{\text{tor}}$ and peaks in HXR

| $n_{||}$ | Experimental $I_p$ | $1.0*n_\text{c}$ | $0.9*n_\text{c}$ | $1.1*n_\text{c}$ |
|---------|--------------------|-------------------|-------------------|-------------------|
| 1.6     | 159%               | 146%              |                   |                   |
| 2.5     | 193%               | 158%              |                   |                   |
| 1.1*n_\text{c} | 132%               | 127%              |                   |                   |
Including fast electron diffusion provides a better match to total current and profiles, but shape still differs

- Fast electron spatially diffusivity: \( D = D_0 \times \frac{v_{\parallel}}{v_{th} \gamma^3} \)
- Adding diffusion results in wing at \( r/a = 0.7 \) being lost, flattening of the HXR profile, better agreement on total current, but central HXR too low
  - Need convection of fast electrons?
- Previous low power LHCD modulation experiments indicate \( D_0 < 0.02 \text{ m}^2/\text{s} \) and low convection [Schmidt, MIT PhD 2011]
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4. Conclusions and future work
Conclusions

- First systematic study of the current profile during LHCD using a MSE diagnostic in the density, field and magnetic configuration envisioned for a reactor
- \( J_{\text{tor}} \) and hard X-ray profile measured for comparisons to GENRAY/CQL3D simulations across relevant parameters to look for trends
- Results:
  - Predicts the correct total current in 0-\( V_{\text{loop}} \) discharges but profiles much too broad
  - Qualitatively reproduces experimental profile and 0-D trends in plasma current and launched \( n_{||} \)
  - But over predicts the total driven current when residual electric field is present
  - Always predicts too broad of a current and HXR profile
  - Diffusion helps on shape and total current. But would it need to be \( V_{\text{loop}} \) dependent to correct for over-dependence on residual electric field
- What is the importance of multi-pass? How sensitive are these results to the details of the ray bounce at the edge?
Future work: multi-spectral MSE, new HXR detector, tests of single pass regime, more LHCD power, continue validation

Experiment

- Try to obtain a single pass regime
  - High temperature I-modes (FY15)
- Scans of $P_{\text{LH}}$, $V_{\text{loop}}$ to determine influence of residual electric field
- Revisit higher current operation, expand parameters
- Second off axis launcher, $\sim2x$ total power
  - Single pass absorption
  - Synergetic effect with existing launcher

Simulation

- Continue sensitivity study with GENRAY/CQL3D
  - Profiles, $n_{||}$ spectral widths, SOL profiles, fast electron diffusion, pinch
- Simulate with full-wave codes