Integrated Plasma Simulation of Lower Hybrid Current Drive Modification of Sawtooth in Alcator C-Mod

P. T. Bonoli, J. C. Wright, PSFC-MIT,
C. E. Kessel, PPPL,
D. B. Batchelor, L. A. Berry, ORNL,
R. W. Harvey, CompX, and the CSWIM Team.

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Outline

• Review experimental results and physics issues for sawtooth modification with lower hybrid current drive (LHCD) in Alcator C-Mod.

• Time dependent analysis of sawtooth modification using TRANSP and a reduced model for LHCD (the LSC code).

• Comparison of LHCD results from LSC with a more complete ray tracing / Fokker Planck model (the GENRAY – CQL3D codes).

• Approach for time dependent simulations using the Integrated Plasma Simulator (IPS) for transport and sawtooth evolution (the TSC code) and LHCD (GENRAY – CQL3D).
Current profile control via LHCD

• **Experimental data:**
  – Sawtooth “delay” experiments from Alcator C-Mod:
    • Clear variation in the onset of sawteeth with density at fixed LH power level.
  – Data can be compared to simulation via:
    • Onset time and period of sawteeth.
    • Hard x-ray emissivity profiles due to LHRF generated fast electrons.
    • Current density profiles from Motional Stark Effect (MSE) diagnostic.
Off-axis LHCD was used to delay the onset of sawteeth during current ramp up in C-Mod.

\[ P_{\text{LH}} = 550 \text{ kW} \]

- \( n_e = 4 \times 10^{19} \text{m}^{-3} \) (red)
- \( n_e = 7 \times 10^{19} \text{m}^{-3} \) (green)
- \( n_e = 9 \times 10^{19} \text{m}^{-3} \) (blue)
- Ohmic (black) - \( 9 \times 10^{19} \text{m}^{-3} \)
Physics issues to be addressed

• Possible mechanisms for sawtooth suppression:
  – Current profile broadening due to off-axis LHCD with $q(r) > 1$ everywhere.
  – Local reduction in shear near $q=1$.

• Adequacy of ray tracing / Fokker Planck modeling to predict magnitude and location of LHCD, consistent with stabilization mechanisms, hard x-ray emission, and measured current density profiles.
Time dependent TRANSP-LSC analysis of C-Mod discharge with delay of sawteeth

• Discharge and LHRF parameters for shot 1080221014:
  - \( P_{\text{LH}} = 550 \text{ kW} \) for 0.2 – 0.7 sec.
  - \( f_0 = 4.6 \text{ GHz} \), \( n_{//}(0) = 2.33 \) (90 Deg. Phasing).
  - \( n_e(\text{line –av}) = 4 \times 10^{13} \text{ cm}^{-3} \), \( B_0 = 5.4 \text{ T} \), \( I_p = 450 \text{ kA} \)
  - Sawteeth delayed by 550 ms relative to ohmic reference case.

• Notes / caveats on analysis:
  - Analysis time starts at 0.34 sec. because good fits data for \( n_e \) and \( T_e \) not available for earlier times.
  - \( T_i(r) \) was predicted by adjusting multiplier \( (M_i) \) for \( \chi_i = M_i \chi_{i\text{-neo}} \) to yield \( T_i(r) \) consistent with the measured neutron flux.
LH model in TRANSP (the LSC code [1]) employs an adjoint solution of the Fokker Planck solution combined with a ray tracing code

- Define and solve an “Adjoint Problem” for the Spitzer-Harm function ($\chi$): [2]

\[
J_{rf} = \int d^3p \frac{\partial \chi}{\partial p} \cdot \Gamma_{rf} \quad \Gamma_{rf} = -D_{QL} \frac{\partial f_e}{\partial p_{\parallel}}
\]

- The response function $\chi$ contains all the physics effects already in the numerical 2D and 3D FP solvers such as particle trapping, DC electric field effect, and momentum conserving corrections in $C(f_e)$

- $(J_{rf} / S_{rf})$ can be found accurately, but computation of $J_{rf}$ requires separate knowledge of $\Gamma_{rf}$ and $f_e$.

- $\Gamma_{rf}$ and $f_e$ are evaluated from a 1-D ($p_{\parallel}$) solution of the FPE in LSC.
Density profiles remain in L-mode since plasma heating is only from LHRF power.
Electron temperature maintained during LHCD from direct electron heating by LHRF generated fast electrons.
TRANSP-LSC analysis of 550 kW case simulates experiment by adjusting ohmic electric field to maintain constant total current

Currents versus time

- **Total**
- **Bootstrap**
- **Ohmic**
- **Lower hybrid**

$P_{LH} = 550 \text{ kW}$
TRANSP-LSC analysis of 550 kW case: Current and q- profiles at 0.37 sec. 
Off-axis LHCD broadens the current profile to maintain $q(r) > 1$
TRANSP-LSC analysis of 550 kW case: Current and q- profiles at 0.50 sec.

Plasma Currents - 0.50 sec.

Safety factor - 0.50 sec.
TRANSP-LSC analysis of 550 kW case
Current and q- profiles at 0.60 sec.

Plasma Currents - 0.60 sec.

Safety factor - 0.60 sec.
TRANSP-LSC analysis of 550 kW case
Current and q- profiles at 0.69 sec.
Effect of LHCD at higher densities was estimated by fixing the density, lowering $P_{LH}$, and repeating the TRANSP-LSC analysis.
TRANSP – LSC analysis results

- At $P_{\text{LH}} > 500$ kW, off-axis LHCD broadens the current density profile enough to keep $q(r) > 1$ for the entire LHRF pulse, with $q_0 \approx 1.5-2$.
- At $P_{\text{LH}} < 500$ kW the elevation of $q(r)$ above 1.0 is reduced significantly with $q_0 \approx 1.2-1.4$.
- These trends agree qualitatively with the experimental results, although $q(0) < 1$ is not seen in the simulations:
  - TRANSP-LSC analysis should be redone using constant LH power and increasing density to be consistent with how the actual experiment was done.
  - Note that as $n_e$ is increased at constant $P_{\text{LH}}$, the LH current will also decrease because the LHCD efficiency drops at higher $n_e$. 


Improving physics fidelity of the time dependent TRANSP-LSC analysis

• **Motivation:**
  – Would like to test the predictive capability of sawtooth models such as that due to Porcelli [3] that are employed in the time dependent transport code TSC [4].
  – It is known that the LSC code can underpredict the LH driven current by as much as 50-60% [5]:
    • Need to self-consistently combine a 2D or 3D Fokker Planck calculation with a ray tracing code [6,7].
3-D\( (p_\perp, p_{\parallel}, r) \) Fokker Planck – Ray Tracing Model: CQL3D-GENRAY [6,7]

- Codes compute the steady state solution of FPE, neglecting the radial diffusion operator:

\[
\frac{\partial}{\partial p_{\parallel}} D_{rf} (p_{\parallel}) \frac{\partial f_e}{\partial p_{\parallel}} + C(f_e, p_{\parallel}, p_\perp) + eE_{\parallel} \frac{\partial f_e}{\partial p_{\parallel}} \\
+ \Gamma_s \delta(p_{\parallel}) + \frac{1}{r} \frac{\partial}{\partial r} r \chi_F \frac{\partial f_e}{\partial r} = \frac{\partial f_e}{\partial t}
\]

- Ray tracing and FP solver iterate until a self-consistent \( D_{rf} \) and \( f_e \) are obtained.
- CQL3D employs numerical bounce averages for \( C(f_e) \) and \( D_{rf} \).
Parameters for TSC/LSC and CQL3D comparison taken from a TSC “gedanken” simulation of Alcator C-Mod

- **Plasma parameters – corresponding to an advanced tokamak target discharge:**
  - \( R_0 = 0.67 \text{ m}, a = 0.21 \text{ m} \)
  - \( B_0 = 5.3 \text{ T}, I_p = 0.61 \text{ MA} \)
  - \( I_{BS} = 0.37 \text{ MA}, I_{LH} = 0.24 \text{ MA} \)
  - \( T_e(0) = 7.94 \text{ keV}, T_i(0) = 6.35 \text{ keV} \) (i=D)
  - \( n_e(0) = 2.17 \times 10^{20} \text{ m}^{-3}, Z_{\text{eff}} = 1.50 \) (constant)

- **LHRF:**
  - \( f_o = 4.6 \text{ GHz}, P_{LH} = 2.5 \text{ MW} \)
  - \( P_{LH}(+) / P_{LH} = 1.0 \)
  - \( n_{\parallel 0}(+) = 2.35, \Delta n_{\parallel} = 0.2 \)
Alcator C-Mod: LHCD Prediction is 70% higher from CQL3D (relative to LSC), but damping locations are in qualitative agreement

**LSC:** \( P_{\text{LH}} = 2.5 \text{ MW}, I_{\text{LH}} = 0.236 \text{ MA} \)

**CQL3D:** \( P_{\text{LH}} = 2.5 \text{ MW}, I_{\text{LH}} = 0.403 \text{ MA} \)
Time dependent simulations of LHCD in Alcator C-Mod can be done using a parallel framework - the Integrated Plasma Simulator (IPS [8, 9])

• TSC for time dependent transport and sawtooth evolution [3,4].
• GENRAY/CQL3D for LH current drive [6,7].
• All physics components communicate through the “Plasma State” [8].
Advantages of the IPS Framework and Approach

- Each code or “component” is implemented in a way that does not require that the original code be changed:
  - Fortran “wrapper” is written to read data from the Plasma State and “prepares” an input file in the format expected by the component.
  - Fortran “wrapper” is also used to “process” output from the component and write data to the Plasma State in the format expected by the State File.
  - Prepare and process operations are controlled by a Python driver script, along with an “initiate” step if necessary.
- Wrapper codes and drivers are all open source.
- Approach facilitates the use of both serial and parallel components.
Current status of IPS simulation using TSC + LHCD modules

• TSC + LSC has been implemented as a component of the IPS and is now being tested:
  • Using this component a standalone simulation of LHCD in C-Mod using TSC+LSC by C. Kessel will first be reproduced.
  • Wrapper and Python drivers have been written for GENRAY – LH and have been successfully tested using the IPS.
  • Wrapper and Python driver for CQL3D – LH are now being written and tested.

• Next Steps:
  • Replace TSC with GENRAY / CQL3D components and compare levels of LH current drive.
  • Possible approach for future may also be to produce Plasma State files from TRANSP-LSC simulations and execute GENRAY / CQL3D on selected time slices.
Summary

• Preliminary analysis of sawtooth modification experiments using off-axis LHCD in Alcator C-Mod indicate a possible stabilization mechanism by increasing $q(r) > 1$.

• Analysis was carried out using TRANSP-LSC:
  – Only lowest density discharged has been analyzed thus far and further analysis must be done for discharges at higher density using TRANSP-LSC.

• Entire analysis will be repeated using the Integrated Plasma Simulator (IPS):
  – Use of TSC to simulate discharge evolution will make it possible to test the onset of sawteeth as predicted by the Porcelli sawtooth model.
  – Use of GENRAY-CQL3D will provide more realistic simulation of LHCD effect.
References