Simulations and Experiments on Modifying the q-Profile for Advanced Tokamak Discharges on Alcator C-Mod

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Controlling the q-Profile in Alcator C-Mod

- **Lower Hybrid** current drive provides a strong source of non-inductive current at large minor radius
- **ICRF** provides central and off-axis heating
- **Cryopump** provides density control
- **MSE/Faraday rotation** provide current profile diagnostics

- Goal is to produce **100% non-inductive plasma current** with LHCD and bootstrap current

- Goal is to **elevate the safety factor and control the q-profile evolution** in the Ip rampup and flattop
  - Divert time/heating time
  - H-mode onset time
  - Density control with crypump
  - Phasing of ICRF heating and LH heating/CD
Initial Simulations with Tokamak Simulation Code (TSC) Indicated Strong Impact of Early Heating/CD

Examine 3 Ip Rampup cases to 600 kA
  250 ms
  500 ms
  750 ms

ICRF Heating only (up to 3.5 MW)

ICRF + LH Heating/CD (up to 1.2 MW)

Examine q(0) and li(1) evolution
Plasma Boundary Growth, Density Evolution, and Profiles Assumed in TSC Simulations

**L-mode**

**H-mode**

Using up-down symmetric plasmas
Removed conducting structures
Avoid vertical instability

Density is the same for all simulations
$Z_{eff} = 1.5$
\( q(0) = 1 \) can be delayed only slightly with ICRF heating and L-mode.

**1.8 MW ICRF L-mode**

**3.5 MW ICRF H-mode**

TSC simulation

- \( q(0) \) is dropping quickly
- Slowest \( I_p \) ramp slows the drop in \( q(0) \)
ICRF Heating with Early H-mode Can More Strongly Raise $q(0)$

Difference between slowest ramp and fastest ramp is significant, due to bootstrap drive at lower $I_p$.

H-mode stops $q(0)$ drop.
ICRF and LH Heating/CD with Early H-mode Can Abruptly Elevate $q(0)$

The LHCD can be large initially as it deposits near the plasma center.

H-mode helps the CD efficiency by elevating the whole $T_e$ profile.
LHCD Can Provide a Strong Non-Inductive Current Early in the Ip Ramp

$t = 0.265 \text{ s}$
$I_{LH} = 240 \text{ kA}$

$t = 0.365 \text{ s}$
$I_{LH} = 200 \text{ kA}$

$t = 0.460 \text{ s}$
$I_{LH} = 69 \text{ kA}$

$t = 1.50 \text{ s}$
$I_{LH} = 80 \text{ kA}$
Experiments to Examine Slower Ip Rampup With ICRF and LHCD Heating/CD

- **Ip rampup** times of 500 and 1000 ms
- Ip flattop values of **600 kA**
- **ICRF heating** of up to **2.4 MW** and as early as 200 ms
- **LH heating/CD** of up to **0.4 MW** and as early as 200 ms

\[ \begin{align*}
B_T &= 5.4 \text{ T} \\
\nu_{\text{ICRF}} &= 80 \text{ MHz} \\
\nu_{\text{LH}} &= 4.6 \text{ GHz}, \ n_\| = 2.3 \\
R &= 0.67 \text{ m} \\
a &= 0.22 \text{ m} \\
\kappa &= 1.6-1.7 \\
\delta_U &= 0.25 \\
\delta_L &= 0.60 \\
\mathcal{Z}_{\text{eff}} &= 4.0-2.25
\end{align*} \]
Ohmic Reference Discharges
500 ms Ip Rampup
1000 ms Ip Rampup
Sawteeth Begin Early in Ohmic Reference Discharges with 500 and 1000 ms Rampups

Sawteeth begin on top of vertical position oscillations

Approximately 25 ms delay with slower Ip ramp
TSC Simulation of 1070711003
Ohmic, 500 ms Rampup

Sawtooth onset time is 160 ms, compared to 165 ms for the Expt.
Matching Te Peakedness
ICRF Heating Only
500 ms Ip Rampup
1000 ms Ip Rampup
Plasmas are in L-mode Most of the Pulse, Entering H-mode Late

- Ip ramp in 500 ms
- Ip ramp in 1000 ms

**ICRF heating**

**600 kA**

**L-mode**

**H-mode**

- \(0.95 \times 10^{20} /m^3\)
Ip ramp in 500 ms
Ip ramp in 1000 ms
ICRF Heating Has Delayed $q(0) = 1$ Over Ohmic, and Slower Ip Ramp Has Helped a Little

Confirms TSC result that benefit of slower Ip ramp in ICRF L-mode is not large

ICRF heating at 200 ms
Slower Ip Ramp Case Has Lower $\tau_E$ in Ramp Weakening Effects of Heating

Energy confinement clearly tracking Ip(t)

li remains higher in slower Ip ramp in spite of heating -- lower $\tau_E$

End of Ip Ramp

Ip ramp in 500 ms
Ip ramp in 1000 ms
Ohmic L-mode
Peaked Te profile leading to early sawtooth and high $l_i$

ICRF L-mode
Significant broadening of Te profile

ICRF H-mode
500 eV pedestal and broad Te with high $n$
TSC Simulation of 1070711010
ICRF Heating Only

Model L-mode for entire simulation
Sawtooth onset $t = 310$ ms compared to 220 ms in Expt
$q(0)$ drops below 1 at 200 ms, but Porcelli model does not trigger the sawtooth until later
Early Te Profile Peaking is Important in q-Profile Evolution

\[ \sqrt{\frac{\phi}{\phi_b}} \]

\[ t = 250 \text{ ms} \]

\[ t = 750 \text{ ms} \]
Te and n Profiles Are Critical to Getting q-Profile Evolution

- Te(R) and n(R) profiles at different times:
  - t = 278 ms
  - t = 705 ms
LH Heating/CD Only
500 ms Ip Rampup
$V_{surf}$ Lower in Ip Ramp with LH Compared to Ohmic

Appears CD is responsible

End of Ip Ramp

1070711003 ohmic
1070711012 LH only
1070711013 LH only
1070711015 LH only
$P_{\text{LH}} = 0.4 \text{ MW Does Not Affect Stored Energy Much, CD is Important}$

Weak effect on stored energy since low power

Fast electron component in GPC measurement which means LHCD

Relaxes with $T_e(0) \approx 0.5 \text{ keV}$ above ohmic case
Sawteeth Are Delayed by up to 175 ms with Only 0.4 MW of LH

Sawtooth onset delayed by > 150 ms compared to ohmic

ICRF only heated cases delay sawtooth onset time by about 50 ms
Ohmic L-mode

LH L-mode, early

Non-thermal component from LH on GPC measurement

LH L-mode, late

1070711015

0.4 MW LH on at 200 ms

Te(R)

n(R)
TSC Simulation of 1070711015
LH Only, 500 ms Rampup

Sawtooth onset at 450 ms, versus 350 ms in Expt
ICRF (2.4 MW) and LH (0.4 MW)
Heating and CD
500 ms Ip Rampup
1000 ms Ip Rampup
Combined ICRF Heating ($\approx 2.4 \text{ MW}$) and LH Heating/CD ($\approx 0.4 \text{ MW}$)
Ip Rampup in 500 ms

Ip Rampup in 1000 ms
Combined ICRF and LH Delay Sawteeth up to 250-375 ms With Slower Ip Ramp

Ip Rampup in 500 ms
Ip Rampup in 1000 ms
Ip Rampup in 1000 ms

Te(0), keV

Sawtooth onset time

Ohmic reference cases,
500 ms ramp
1000 ms ramp
\[ \Delta f \text{ (kHz)} = 0.31 \]
\[ \Delta t \text{ (ms)} = 3.28 \]

J. Snipes
TSC/LSC Simulation of 1070711020
ICRF + LH

Driving ≈ 100 kA of LHCD, with only $P_{LH} = 0.4$ MW
$P_{ICRF} = 2.3$ MW
Sawtooth Onset Time NOT Matched Well in Spite of Good Te Profile Match

ICRF+LH elevates \( q(0) > 1 \), barely

\( q(0) \) drops below 1 at 650 ms, but Porcelli model does not trigger a sawtooth

Expt had sawtooth delayed until 350 ms
LHCD Profiles Fairly Consistent Deposition Over Time

$t = 301$ ms

$L_{NH} = 109$ kA

$t = 389$ ms

$L_{NH} = 132$ kA

$t = 780$ ms

$L_{NH} = 109$ kA

$t = 1000$ ms

$L_{NH} = 99$ kA

total LHCD BS $t = 550$ ms
Conclusions

• Initial TSC simulations indicated that Ip ramp and heating/CD can influence the q-profile evolution in C-Mod significantly

• Experiments show that
  – Slower Ip ramp does delay sawtooth by 25 ms for ohmic discharges
  – ICRF (2.4 MW) heating delays sawtooth onset by about 50 ms over ohmic discharges
  – LH heating/CD alone can delay the sawtooth onset by 150 ms (with only 0.4 MW)
  – ICRF (2.4 MW) and LH heating/CD (0.4 MW) can delay sawtooth onset by
    • 175 ms for the 500 ms Ip ramp
    • 375 ms for the 1000 ms Ip ramp

• Experiments confirm TSC results that slower Ip ramps are only effective for modifying q with sufficiently early heating/CD
  – Early H-modes should be even more effective

• TSC simulations of these discharges produce reasonable agreement, but numerous improvements can be made
Future Work

- Improve early front-end of discharges to smooth transition in Ip waveform
- Push to earlier divert and heating times, < 200 ms
- Inject more LH power
- Establish methods for entering H-mode on demand in ramp or otherwise
- Continue TSC simulations to improve discharge modeling, and project to larger powers