Alcator C-Mod
Mini-Proposal

Subject: Improved confinement in high-density EDA H-modes via modification of the plasma boundary with Lower Hybrid RF


Group: Pedestal

Date: July 15, 2014

Approved by: Date Approved:

1. Purpose of Experiments

This MP proposes to reproduce previous discharges that showed improved confinement and suppressed edge turbulence when LHRF was injected into high-density EDA H-modes, to diagnose those plasmas with a more complete diagnostic set, and to attempt to understand the causes for the observed changes.

2. Background

Injecting Lower Hybrid (LH) power into Alcator C-Mod’s high-density H-mode plasmas has enhanced global confinement by increasing pedestal temperature gradients, modifying the edge and core rotation, and decreasing edge and SOL turbulence [1]. These experiments indicate that edge LHRF can be used as a tool to increase confinement via direct modification of boundary quantities. Ray-tracing modeling and accessibility calculations for the LH waves indicate that the LH waves do not penetrate inside the top of the pedestal and are not driving current in these plasmas; instead the LH power modifies the boundary conditions.

Fig.1 Effect of LHRF injection into high-density EDA H-mode on the QCM, broadband turbulence, and core confinement (shot 1120725009 with Ip=0.8 MA, Bt=5.44 T, NL04=1.84x10^{20} m^{-2}).
When moderate amounts of LH power ($P_{\text{LH}}/P_{\text{tot}} \sim 20\%$) are applied to high-density EDA H-modes ($n_{\text{eo}} = 3.5 \times 10^{20}\,\text{m}^{-3}$), we observe the following effects: edge/SOL fluctuation power decreases by roughly an order of magnitude; pedestal temperature gradients are increased; global energy confinement time and H-factor increase by 30-40% (H$_{98}$ from 0.7 to 1.0); co-current core and pedestal rotation velocities increase; power to the (outer) divertor target increases promptly with an increment that is roughly $1/2$ of the injected LH power, qualitatively consistent with the inaccessibility of the LH waves; and the central frequency of the edge-localized Quasi-Coherent Mode (QCM) down-shifts and becomes more coherent. Some of these changes are shown in Figs. 1-3. The H-mode confinement improvements brought about by the edge LHRF are the result of changes in the pedestal (e.g. changes in rotation/shear and increased pedestal temperature gradients), with no substantial change in peaking of core density or temperature profiles. There is not perfect correlation with turbulence suppression, indicating that the turbulence decrease may be a necessary, but not sufficient condition for the pedestal and confinement improvements. We believe edge LHRF to be a direct “actuator” for improving performance in ELM-suppressed H-mode plasmas by active modification of the boundary plasma.

![Fig. 2 Change in confinement (H$_{98}$) with LHRF power.](image)

![Fig. 3a Changes in QCM as the LHRF turns off at 1.35 s. The enhanced confinement is lost around 1.30 s. The light blue strips indicate the times for the spectra shown below.](image)

![Fig. 3b. Note the increase in coherency $\Delta f/\omega_0$ of the QCM during the period of enhanced confinement (blue) compared to a post-LHRF time (red)](image)
The observed changes in the QCM, i.e. the decrease of central frequency and the narrowing of mode width, shown in Figs. 1 and 3, are worth additional consideration. It is clear from Fig. 3a that the central frequency is modulated with the sawtooth period, so the actual frequency width of the mode must be measured over a duration significantly less than the sawtooth period. Using the polarimeter data shown in Fig. 3b, we note that $\Delta f/f_0$ is roughly a factor of 3-4 smaller with the LHRF edge modifications present compared to when the LHRF is off. It is likely that this is a result of a significant change in the $E_r$ profile and its gradient at the QCM location. Is the LHRF somehow strongly modifying the edge/SOL potentials, thus affecting the rotation and turbulence? This we wish to investigate with the edge-CXRS and especially with the Mirror Langmuir Probe (MLP).

If the LHRF can be exploited as a tool to influence the edge/SOL conditions, then one important application would be to suppress MARFEs in plasmas with densities of high Greenwald fraction. This is Idea #51 from Ian Faust from the 2014 Ideas Forum Idea #51. As part of these experiments we propose to test this Idea by producing MARFEs and observing the effects on the MARFE with the injection of LHRF.

3. **Approach**

Our approach is to

1. reproduce the shots of 1120725 (see Fig. 3a) that exhibited the LHRF confinement enhancement (there were ~5 of these shots 1120725007-012) and diagnose that condition with a more complete set of diagnostics, specifically all turbulence diagnostics, CXRS, rotation diagnostics, divertor heat-flux diagnostics, and PDI probes;
2. to scan the LH power to extend the range shown in Fig. 2 to ~900 kW;
3. to reduce the density in order to make contact with the results seen by Hughes et al [2] at $n_e^{bar}=1.8-2.1\times10^{20}$ m$^{-3}$ and $n_e^{ped}=1.4-1.8\times10^{20}$ m$^{-3}$;
4. perform a current “scan” (0.8 and 1.0 MA) to observe the effects at higher current;
5. to test our present hypotheses about cause(s) of this effect, i.e.;
   - It is a result of modification of edge neutral density/fueling via increased ionization in the SOL. This is supported by the observation that the effect is much reduced later in the 1120725 run for which the neutral pressure was significantly higher than for the shots earlier in the day which showed a strong effect (neutral pressure =0.27 mTorr for “trophy” shot 1120725009 and 0.37-0.9 mTorr for 1120725026-029). It is also supported by the observation that the He emission profile from the GPI gas puff is moved out in the SOL by the LHRF – We will test this hypothesis by performing a density scan and additionally by strong puffing during the enhanced confinement period thereby raising the edge neutral pressure. We will continue to observe the He(D$_2$) puff profiles with GPI (CXRS) under these conditions.
   - It is a LH-wave effect other than LHRF simply depositing power into the edge – We will test this hypothesis by varying the LH phase while still...
maintaining the inaccessibility of the waves. This would allow a scan for peak-\n\n_{||} at 1.7, 1.9 (1120725), and 2.3. The radial profile of the critical \n_{||}, for which LH waves of lower \n_{||} are inaccessible inside of a given r/a, is shown in Fig. 4, which is based on the measured edge profiles from the “trophy” shot 1120725009. The dashed lines show that for \n{\textit{s}} of 1.7, 1.9, and 2.3 the waves are inaccessible inside of r/a~1.02,1.0, and 0.99 respectively, i.e. all outside of the top of the pedestal. Of course the full launched \n_{||} spectrum will have to be taken into account.

- It is a result of a strong perturbation of the edge/SOL \(E_r\), as discussed above. We will test this by measuring changes in the LHRF-induced \(E_r\) profile with CXRS and especially in the SOL with the MLP dwelling in the far-SOL (just in the limiter shadow). (The MLP would also measure changes in the turbulence spectra there.) A more exacting test of this hypothesis will be performed by achieving the observed effects in high-density Ohmic EDA H-mode and scanning the MLP through the SOL before and during LHRF injection. The possibility of making an Ohmic EDA H-mode as a target for the LHRF is examined in Fig. 5, where \(I_p, q_{95}\) and density of an Ohmic H-mode are seen to be matched to the “trophy” ICRF-heated EDA H-mode shot 1120725009. The \(H_{98}\) values during the H-mode phase (no LHRF) are essentially the same. The neutral pressure is actually lower in the Ohmic H-mode. The LHRF accessibility is changed due to the lower field (see the red curve in Fig. 4), moving the absorption outward into the SOL for the same density profile, and of course the pre-LHRF input powers are different – 4.2 MW compared to 1.0 MW. Reproducing the same effects in Ohmic EDA H-mode and interrogating the SOL with the MLP would yield a wealth of important data, including detailed \(E_r\) profile changes.
6th to test the LHRF as an actuator to suppress the MARFE in plasmas with high Greenwald fraction.

4. **Resources**

As required to be similar to 1120725009 (ICRF EDA H-mode) and to be similar to 1120712027 whose parameters are shown in Fig. 5:

4.1 Machine and Plasma Parameters

Give values or range for:

- **Toroidal Field:** 5.4 T as well as the Bt waveform as in 1120712027
- **Plasma Current:** 0.6, 0.8, and 1.0 MA
- **Working Gas Species:** D
- **Density:** similar to 1120725009 i.e. NL04\_target=0.9x10^{20}, NL04\_H-mode=1.9x10^{20}. With density reduced during the density shot-to-shot density scan to NL04\_H-mode=1.1x10^{20}. The target density for the Ohmic H-Mode is NL04\_target=0.8x10^{20}
- **Boronization Requested:** Yes – a well boronized machine is critical
- **Equilibrium configuration (if possible, refer to database equilibria):** reference 1120725009 and 1120712027 (Ohmic)

4.2 Auxiliary Systems
ICRF Power, pulse length, phasing: 3.5 MW (E and J antennas only), dipole phasing, 0.8 s pulse. Will need max available from J; E at lower power

LHCD Power, pulse length, phasing: up to 900 kW 0.3 s flattop, n|| of 1.7, 1.9, and 2.3

Pellet Injection (species): None
Impurity blow-off injection: None
Diagnostic Neutral Beam: May piggy
Special gas puffing: minimal Ne for quiet ICRF & divertor seeding, NINJA with 10 PSI He in C-port plenum for GPI and 8 PSI D2 in the F-port plenum for CXRS
Ar for HiREX Sr

Cryopump: Yes
Non-axisymmetric Coils (Connections, Current): Standard compensation
Other:

4.3 Diagnostics
List required diagnostics, and any special setup or configuration, e.g. non-standard digitization rate.

Critical diagnostics: TS, ETS, GPI, gas-puff charge exchange, IR Thermography, ECE, reflectometer, FTCI, PCI, fast magnetics, MLP, divertor probes, HiREX, PDI probes
Desired diagnostics: Toroidally-viewing Lyα array, radially-viewing Lyα array

5. Experimental Plan
5.1 Run sequence Plan
2 run days

5.2 Shot sequence plan

Day 1
shots 1-10: Load 1120725009, establish steady EDA H-mode for LHRF target. Apply LHRF at 600kW (n||=1.9). Reproduce effects seen on shots 1120725007-012. Monitor edge neutral pressure. Document effects on turbulence, pedestal, and confinement diagnostics. Dwell MLP in limiter shadow.

shots 9-10: “LHRF power scan” – repeat above, but at PLH=850 kW.

shots 11-14: “Ip scan” – repeat above, but at Ip=1.0 MA (q95=3.7) – if necessary raise the field to 5.8 T (q95=3.95). If LHRF effect is still present, then document with full diagnostics.

shots 15-20: “LHRF phase scan” – repeat 0.8 MA condition, but with LH phasing at n||=1.7 and then n||=2.3 – PLH=600 kW.
Shots 21-30: “Ohmic EDA H-modes” - Load 1120712027, establish steady EDA H-mode for LHRF target. Apply LHRF at 600kW ($n_\parallel$ to be decided depending on the results of the “LHRF phase scan”; $n_\parallel = 1.9$ if effect is not seen to be dependent on LHRF phase). See if effects are similar to those in ICRF-heating H-modes. Use MLP to diagnose the SOL of these plasmas with probe scans in both the pre-LHRF and LHRF phases.

Day 2 – scheduled allowing time to digest the experience/data from Day 1

shots 1-5: Load best shot from Day 1, establish steady EDA H-mode for LHRF target. Apply LHRF at 600kW ($n_\parallel = 1.9$), and puff gas into edge during enhanced confinement period in order to raise the neutral pressure.

shots 6-16: “density scan” - repeat above condition, but with lowest ICRF-target density ($NL04_{\text{target}} \approx 0.5 \times 10^{20}$) and no added puff, observe effect of LHRF on H-mode. Repeat, but with higher ICRF-target density ($NL04_{\text{target}} \approx 1.5 \times 10^{20}$), observe effect of LHRF on H-mode.

shots 17-22: “connect with Hughes’ observations” - Reduce the current to 0.6 MA and $NL04_{\text{target}} \approx 0.6 \times 10^{20}$ in order to connect with the results of [2], where quite different effects were seen in discharges where $Ip=0.6$ MA and $NL04_{\text{H-mode}} = 1.1 \times 10^{20}$, observe effect of LHRF on H-mode. Increase density until $NL04_{\text{H-mode}} \approx 2 \times 10^{20}$, observe effect of LHRF on H-mode.

Shots 23-30: “use LHRF as actuator for MARFE suppression” – Reload the best shot from Day 1, turn off the ICRF and LHRF. Ramp the density during the shot to reach $n/n_{GW} \approx 0.6$ ($NL04_{\text{target}} \approx 1.9 \times 10^{20}$) at which time a MARFE should occur. On subsequent shots inject LHRF ($\sim 600$ kW) to observe the effects on the MARFE.

6. Anticipated Results

This work will be the basis for a 2014 APS-DPP Invited talk and publication. If it is a robust result, it opens up an entire area of edge/SOL physics that is amenable to study using LHRF as an edge “actuator”.