Investigation of ICRF Power in C-Mod SOL

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One of the primary goals of the C-Mod ICRF physics program is to:
- Develop a reliable heating and current/flow drive actuator that can be utilized to optimize overall plasma performance with minimum negative impact on plasma.

ICRF provides bulk auxiliary heating power in C-Mod thus have access to a wide variety of absorption scenarios.
- Fundamental H (strong SPA) and 3He minority (weak SPA) are primary heating scenarios.
- Mode conversion and second harmonic minority ion cyclotron scenarios are extensively investigated,
- and we have begun to evaluate Fast Wave electron heating (very weak SPA).

C-Mod ICRF share characteristics are expected to those in ITER:
- Antenna power density exceeds anticipated ITER power density.
- Strong single pass absorption (SPA).
- Metallic PFCs (Mo) that has similar sputtering characteristics as tungsten.
- Scrape off layer is opaque to neutrals.
Maintained confinement and core molybdenum is controlled for significantly increased number of RF joules.
- Radiated power is also better controlled in H-mode discharges.

Impurities and boron erosion appear linked to the active antenna.
- RF sheaths are measured on field lines connected with the active antenna.
- Impurities are controlled by “virgin“ boronized surface.

Important impurity sources are located away from antenna.
- Boron nitride RF limiter tiles did not improve plasma performance.
- Observe melt damage at strike point, top of the outer divertor, plasma and RF limiter, and upper gusset tiles.

Surface data suggests deposited Mo, W and steel on the boron film originating from melting.
- Once melting occurs, surface will be contaminated.

Films are of limited value in a steady state device unless one finds a way to continuously renew the coating.
Background: RF Impurity Physics may be More Complicated

Identify sources by vacuum plasma spray boron onto molybdenum tiles and monitor where boron is removed.
- Coated with 75-100 μm of Boron. (boronization applies ~0.2 μm)

Found no specific RF source location.
- Boron coating is not eroded except at locations with melting or spalling.

Discrete impurity events or injections appears to be related to localized melting rather than sputtering.
- Impurity injection events often limit plasma performance.
- Impurity injections are reduced/eliminated with impurity seeding.

RF impurity physics appears to be more complicated than simply an increased impurity source.
- Improved performance with impurity seeding is inconsistent with sputtering.
- Is RF power modifying the SOL to increase impurity penetration?
C-Mod ICRF Antenna and Diagnostic Configuration

<table>
<thead>
<tr>
<th></th>
<th>Frequency</th>
<th>80 MHz</th>
<th>40-80 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power</strong></td>
<td></td>
<td>2 x 2 MW</td>
<td>4 MW</td>
</tr>
<tr>
<td><strong>Antenna</strong></td>
<td></td>
<td>2 x 2 Strap</td>
<td>4 Strap</td>
</tr>
<tr>
<td><strong>Phase</strong></td>
<td></td>
<td>fixed</td>
<td>variable</td>
</tr>
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D & E Antenna

J Antenna
LH-SOL X-mode Reflectometer Provides detailed SOL Density Profiles

X-mode differential phase reflectometer is mounted on the LH coupler which is retractable.

- Frequency range is 100-146 GHz.
- Density range is $10^{16}$-$10^{20}$ at $B_0 = 5$-5.4 T.
- Differential phase mitigates issues associated with turbulence.
- Frequency is swept typically at 100 μs and Density profiles are averaged over many sweeps.

High resolution profile but uncertainty in the radial position is primary error.

- First reflection is determined experimentally but is known to within 1-2 mm.
- If B is accurately known, we would know radial position very accurately.
  - B is known to ~0.5-1% - inadequate for 1 mm resolution.
- Offset entire profile to match Langmuir probe density measurement at probe position.
- However, relative error between two density profiles is usually extremely small.

See Lau B-7 for more details.
Monitor Impurity Source from Plasma Limiter and Core Molybdenum

Local impurity line emission at the plasma limiter is monitored along a possible 24 views.

- Mo I (386.4 nm) and B I (412) lines are monitored with f/4, 0.25 m visible spectrometer.
- Monitor eight of possible 24 views.
- Time resolution is 20-50 ms depending on signal level.

Note:
- Plasma limiter maps to J antenna.
- Limiter is closer to LCFS than RF antenna limiters by ~0.8 cm.

Core Mo content is monitored at Mo XXXI (11.6 nm) using a 2.2 meter grazing-incidence Rowland circle spectrometer.
Gas Puff Imaging (GPI) is used to Monitor Edge Turbulence

Two-dimensional (2D), radial and poloidal, turbulence structure is measured using fast diode matrix.

- view He emission fluctuations in a plane $\perp B$
- Gas puff injects neutral He, sensitive to $n_e$ and $T_e$
- toroidal localization via local gas puff
- 90 channel array $\sim$5 cm x 5 cm
- Views coupled to APD arrays sampled at 2 MHz
Limiter Thermocouples Provide Measure of Thermal Heat Load

Concentrate thermocouples in the plasma midplane where melting has been observed in the past.

- Thermocouple response time is insufficient to calculate the surface temperature or heat flux.
- Use before and after shot temperatures with the tile mass and surface area to calculate the energy flux for each instrumented tile.
- The color limiter plots at a 2D spline interpolation/extrapolation of the instrumented tiles.
- The inferred deposited energies were found to vary by less than 10%.
Example fluctuation power spectrum versus $k_{pol}$ and frequency is shown in figure at right.

- Color scale for power is normalized at each frequency so that higher frequency features are resolved.
- Slope (white lines) is the poloidal phase velocity.
- Negative slope corresponds to ion diamagnetic drift direction.
  - $V_{pol} \approx -1.6 \text{ km/s}$ for spectra shown.
- Positive slope corresponds to electron diamagnetic drift direction.
  - $V_{pol} \approx 2.8 \text{ km/s}$ for spectra shown.
For ohmic discharges, the radial profile of the turbulence phase velocities is typically:

- Directed in the electron-diamagnetic direction inside LCFS.
  - GPI data in blue.
  - Estimated electron diamagnetic flow velocity is also shown.
- Directed in the ion- diamagnetic direction in the SOL.
  - GPI data in red and probe measurement of ExB is in green.

**EDD propagation in the edge is close to the electron diamagnetic flow velocity estimated from measured electron temperature and density profiles.**

Poloidal velocity in the far SOL, where blobs are seen, matches ExB velocity from probe measurements.

Plot on right is the radial profile of the poloidal velocities with color coding indicating the velocity distribution.
Radial Phase Velocity Profiles are Significantly Modified in SOL

In the ~3 cm region beyond the separatrix, the steady-state dominant propagation direction for $V_{\text{pol}}$ reverses up to four times.

Based on previous measurements showing the poloidal phase velocity matched the measured ExB, the RF is strongly modifying the $E_r$ profile.

- Velocity magnitudes imply $E_r$ up to 25 kV/m.
Structure is Modified with Higher RF Power

Antennas have unique signature that may be related to magnetic mapping along field lines.
Modified Phase Profiles are in Region where Fast Wave is Propagating

- Fast wave begins propagating between 91-91.5 cm.
- Near fields are limited to radial region beyond 91.5 cm.
- Antenna protection tiles are 91.3 cm.
- Faraday screen is at 92 cm.

Suggests effect is not a consequence of near fields.
Radial Profile varies with Plasma Current – Implies Mapping is Important

$q_{95}=5.5$

D ant power ramped

E ant power ramped

$q_{95}=3.5$

D ant power ramped

E ant power ramped
Radial Profile is dependent on Magnetic Configuration

D antenna is ramped from 0.5-1.5 MW from 1.05 s - 1.3 s.
Radial Profile Varies with Magnetic Field Direction

Forward field case has:
- Two EDD features: Near LCFS and another in the far SOL (near the limiter radial position).
- One peak in poloidal flow velocity in the IDD near a radius of 89.5 cm.

Reverse field case has:
- Two EDD features: near LCFS and another peaked near a radius of 90 cm.
- One IDD feature near 91 cm.

Reversing the toroidal field and current directions yields approximately mirrored profiles (up-down transformed) in the far SOL but perhaps not in the near SOL.
- An -1.5 km/s offset would make perfect symmetry.
Radial Profile is Unaffected by Confinement Mode

The presence of fine-scaled radial structure in $E_r$ is not affected by confinement mode (L-mode or H-mode),

Independent of RF frequency (50, 78, or 80 MHz)

ICRF Modification of SOL Density Profile is Limited to Far SOL

Most robust observation with applied ICRF power is a reduction in the density in the far SOL.

- Underlying physics is under investigation.
- Need to characterize far SOL density decrease with RF power, phasing, edge $q$, and target density.

See Lau B-7 for more details.
SOL Density Profile is Reduced with Application of LH Power

SOL density profile is reduced up to the LCFS:

- Decrease is observed in L, I, and H-modes with ICRF+LH as opposed to just ICRF.

In H-mode, plasma performance is improved due to increase in edge electron temperature.

- Core plasma density decreases and temperature increases.
ELMs Present Challenging Load Variations

SOL density profile has strong impact on ICRF antenna loading.
- Loading can be influenced by the distance to cutoff or density gradients.
- C-Mod loading is dominated by changes in density gradients except perhaps during ELMs.

An ELM presents a dynamic load that results in a fast change.
- Real loading changes more slowly than change in forward or reflected power.
- Suggests load mismatch is a result of reactive power changes.
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- Real loading changes more slowly than change in forward or reflected power.
- Suggests load mismatch is a result of reactive power changes.
- SOL profile gradient decreases while distance to cutoff moves little.
- SOL profile recovers as quickly as antenna loading.

Caveat: profiles are more difficult during non-stationary events and the relative error between profiles is larger.
Impurity Seeding Offers Path to Improved Antenna and Plasma Performance

Found nitrogen or neon seeded discharges provided much improved ICRF performance.
- Molybdenum radiation is well controlled.
- Injections from antenna and divertor are eliminated.
- Antenna faulting greatly reduced.
- $Z_{\text{eff}}$ increased to $\sim 2$.

Seeding appears to be compatible with discharges with moderate impurity confinement and good energy confinement.
- I-mode, EDA H-mode, and ELMing H-mode seeding is compatible with high performance.
- ELM free H-mode appears to have limit tolerance for seeding.
Impurity control with seeding is counter intuitive:

- One might expect sputtering to increase with light impurity species.

Measured RF loading and voltages differ little between unseeded and seeded discharges
- SOL density profiles are also very similar consistent with the loading observation.

Other possible explanations are speculative.
- From optical monitoring, injections local to the antenna structure decrease.
- Possible explanation is reduction of the local heat flux to critical location.
Discrete Injections can Inconveniently Limit Plasma Performance

Distinguish discrete injections from core impurity content.
- Post boronization the core impurity content is well controlled but discrete events often limit plasma performance.
- Boronization is generally done when the core impurity content is too high.

Molybdenum is potentially contributed from number of sources.
- K-limiter center tiles.
- Leading edges from J Antenna protection tiles.
- Leading and trailing edges of upper divertor tiles.
- Leading edges from misaligned outer divertor tiles.
- Inner divertor strike point tiles (may explain injections during I-mode.)

Tungsten seems to be sourced from probe tips and remnants of melted divertor tungsten tiles.

J antenna Faraday screen has melt damage that likely contributes Nickel and Titanium.
- These injections were reduced/eliminated via impurity seeding.
- Injections from Faraday screen were dependent on magnetic geometry.
Energy flux to limiter scales with ICRF power normalized by plasma density.

- Without normalization the data is scattered.
- Data is from campaign from 7/2009-3/2010.
- Heat flux of 40 MJ/m² uniformly deposited over a single title for 1 sec will result in surface melting.

Power per particle is reminiscent of energetic ions.
Increased Energy Flux to Limiter with Operation

Melting threshold is reached with less power per particle over the course of the campaign.

- Damage begets more damage.
- Number of discharges reaching the melting threshold (or higher limiter energy flux) increases for a given power per particle.
Energy Flux Pattern is Modified with ICRF Power

Energy flux pattern to the limiter is variable.

Three example L-mode discharges are shown at right.

- Limited amount of heat flux reaches the limiter during the ohmic discharge and is centered about the midplane.

High density, ICRF heated discharge has a energy flux pattern that:

- extends the width of the limiter at the midplane,
- Higher energy flux above the midplane and on the right side.

Low density, ICRF heated discharge has a energy flux pattern centered on the midplane and in the middle of the limiter.

- at low density, low current discharges.
Mode Conversion Heating Reduces Limiter Heat Load

Observed energy flux to the limiter becomes centrally peaked at low density, low current discharges.

- Reduce limiter heating by raising plasma current or density - reminiscent of energetic ions scaling.

Replacing 2 MW H minority with 2.5 MW He³ mode conversion reduced limiter energy flux.

- No energetic He³ ions are expected.
Found that the turbulence radial phase velocity profiles in the SOL were significantly modified with the application of ICRF power.

- Over 3 cm radial region between the limiter and the LCFS, the propagation direction reverses up to four times.
- Profile was dependent on RF power, edge q, magnetic configuration, and magnetic field direction.
- Profile structure was unaffected by confinement mode.

SOL density profile is modified by RF power.

- Density is reduced in the far SOL with ICRF alone.
- Density is reduced across the entire profile with addition of LHRF.

Measured SOL density profile during an ELM event evolution.

- SOL profile gradient relaxes while radial cut-off position varies little.
- SOL profile recovers as quickly as the antenna loading.

Impurity seeding offers path towards improved antenna and plasma performance.

- Improvement does not appear to be a result of improved coupling or reduction in antenna voltages.

Energy flux to the limiter is modified with the presence of ICRF power.

- Energy flux scaling is suggestive that energetic ions are the source of high energy flux at the limiter midplane.