Recent ICRF Results in Alcator C-Mod

33rd EPS Conference on Plasma Physics and Controlled Fusion
Rome, Italy June 17-22, 2006


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Recent ICRF Results in Alcator C-Mod

Key Results
RF sheaths on the top of the outer divertor are likely responsible for core Mo and boronization erosion.
L-Mode D(\(^3\)He) minority heating scenario is as effective as D(H) minority heating scenario.
Identified coaxial multipactor as leading explanation for observed ICRF antenna neutral pressure limit.

Outline
1. Overview of ICRF system on C-Mod
2. Comparison of D(H) and D(\(^3\)He) minority heated plasmas
3. Discuss RF impurity source and boronization erosion experiments.
5. Present physics of antenna operational neutral pressure limit.
Motivation

The antenna is the most critical element to the success of ITER’s initial 20 MW of ICRF heating power.

- Understand the underlying physics that limits antenna power and voltage handling.
- Develop an understanding of the RF-plasma edge interactions to minimize impurity production, enhanced sputtering, and localized hot spots.

C-Mod discharges can simulate ITER ICRF situation.

- Antenna power density and
- Wave absorption are similar.
- PFCs are metallic.

More practically we would like reliable, robust operation.
Three ICRF Antennas Provide only Auxiliary Heating on C-Mod

Flexible ICRF system:
- Two similar fast wave antennas separated toroidally by ~180°.
- D and E-antennas are dipole antennas
- J antenna is a 4-strap antenna
- +90º(-90º) launches waves co-(counter) plasma current.

Flexible boronization technique.
- Boronization is localized around the resonance location allowing for control over areas to be boronized.
- Can be applied between discharges.

Metallic PFCs allow relatively easy removal of boronization coating.

Antennas and LH coupler have private protection Mo limiters located ~1 cm behind plasma limiters (GH, AB, and K).
- K midplane limiter is ~0.3 cm proud of other plasma limiters.
- K has most melt damage of any limiter.
Two 2-strap, fast wave antennas couple power at 80 MHz.

- Vacuum transmission includes short coaxial feedthru and stripline.
- Operated with field aligned Faraday screens and ~27% transparent.
- Vacuum peak $n_{\phi} = 10$.
- Operated with strap currents out of phase $(0, \pi)$.
- Maximum voltage $\leq 50$ kV.

Matching network utilizes:
- Phase shifter/stub tuner network and
- Antennas are excited using resonant loop configuration.
J Antenna is 4-strap, Fast wave Antenna

4-strap, fast wave antenna couples power through single horizontal port.

- Sources are variable 40-80 MHz.
- Standard matching network with decoupling stub.
- Vacuum transmission line (VTL) is a combination of coaxial and parallel plate transmission line.
- Faraday screen rods are horizontal and 50% transparent.
- Operated with strap currents out of phase.
- Peak $n_\phi = 13$ in vacuum spectrum.
- Operating $\leq 35$ kV in plasma.
Controlling impurities is key to high performance discharges.

- Radiated power from Mo dominates radiated power.

Radiation cools edge resulting in lower central temperature due to profile stiffness.
Experiments to Identify RF Impurity/Erosion Location: Background

Core Mo content increases with RF power.
  - Antenna Mo source increases with power.

RF impurity source is a result of RF sheaths.
  - Measured enhanced plasma potential on field lines connected to powered antenna.

B. Lipschultz et al., NF 2001

S. Wukitch et al., 33rd EPS, Rome Italy 2006
Experiments to Identify RF Impurity/Erosion Location: Background

Performed series of H-mode discharges to compare duration of boronization of Ohmic versus ICRF discharges.

- Integrated injected power is similar in the discharges (~2 MW)
- RF heated discharges show faster boronization erosion rate than ohmic H-modes.
- ICRF erosion rate is ~3-4 times that of Ohmic heated discharges.
Each antenna maps to different toroidal location.

Open field lines passing near the antenna terminate on divertor shelf.

Field lines to top of outer divertor are 2-3 m compared to 13-18 m for upper gussets and inner wall.
Limiters and RF Protection Tiles are Secondary Sources

Eliminate sheaths by utilizing insulating limiters.
Installed BN tiles on antennas.
  • All field lines intersecting antenna would be free of RF sheath effects.
  • Lower impurity production and boronization erosion.
  • Field lines passing near the antenna could still have RF sheath.

Plasma performance was unimproved.
  • Impurity sources still required extensive boronization to control.

Eliminates RF antenna and plasma limiters as primary contributing source to core Mo and radiation.

S. Wukitch et al., 33rd EPS, Rome Italy 2006
Identified Critical Erosion Region

Boronize by scanning ECDC resonance location over 10 cm region.
Identified location that resulted in best reduction and control of radiated power.
Location corresponds to top of outer divertor shelf – same region RF sheaths are likely.

S. Wukitch et al., 33rd EPS, Rome Italy 2006
Boronization Erosion is Toroidally Localized

<table>
<thead>
<tr>
<th>Control Series</th>
<th>D+E heated discharge</th>
<th>D+E heated discharge</th>
<th>Increased Prad and lower stored energy</th>
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<tr>
<td>Test Series</td>
<td>D+E heated discharge</td>
<td>J heated discharge</td>
<td>Prad and stored energy</td>
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Test toroidal localization by running series of consecutive discharges.
- Monitor radiated power and plasma confinement.

Test series has good performance for both discharges whereas control shows performance degradation.

Evidence that the primary RF erosion is RF enhanced sputtering on the top of the outer shelf.
RF Sheath Erosion of Mo and Boronization Summary

RF sheaths are likely responsible for significant core Mo and boronization erosion.

Important location is on the top of the outer divertor (outside the divertor and away from the antenna!)

- Important consideration for ITER divertor design.

Antennas map to separate toroidal locations on the outer divertor.

ICRF and Plasma limiters appear to be secondary sources.
D\(^{(3}\text{He})\) Heating is Primary ICRH Scenario for 8 T Discharges

Previous experimental data indicated the heating efficiency is more sensitive to \(^3\text{He}\) concentration than D(H).

May anticipate greater density and impurity production due to lower single pass absorption for D\(^{(3}\text{He})\) than D(H).

- Directly compare L- and H-mode discharges heated by D\(^{(3}\text{He})\) to D(H) at ~5 T.
- Investigate the effect of higher power density and plasma temperature.
In L-mode, Similar Plasma Response for D\(^{(3}\text{He})\) and D(H)

For L-mode comparison, RF power is ramped to 1.5 MW to avoid H-mode.
- J antenna utilizes D\(^{(3}\text{He})\) minority and
- E antenna utilizes D(H).

Stored energy and central temperature response are similar.
Density and impurity production are similar as well.
- No significant density increase with either heating scenario.
- Radiation remains low for both scenarios.

![Graph showing comparison of different plasma response parameters for J and E antennas.](image)
H-mode Threshold Power Appears nearly Identical

Using slow RF ramp up to \(~1.4\) MW, power threshold is similar for both D(\(^3\)He) heating (J antenna) and D(H) heating (E antenna).

- Response in L-mode is also quite similar.
Plasma Response Varies with Antenna Phasing

Series of power ramp discharges using D(³He) minority consistently showed:

- Modest increase in stored energy for heating and -90°, compared with +90°,
- Temperature response is largest with -90°, and
- Obtain H-mode with -90°.

May suggest interaction with K limiter.
Initial $D(^3He)$ heated H-modes have Moderate Confinement

Although data set is small, additional indications suggest performance is below that obtained with $D(H)$ heating.

- Boronization effect appeared to erode more quickly.
- Between shot boronization did not improve discharge performance unlike $D(H)$ discharges.

S. Wukitch et al., 33rd EPS, Rome Italy 2006
Parasitic Absorption could reduce H-Mode Performance

H-mode performance can be greatly affected by radiated power fraction.

- Power absorbed by parasitic mechanism could result in increased impurity production.
- Impurity production could have larger affect on plasma performance than parasitic power fraction.

D(\(^{3}\)He) scenario has additional cyclotron resonances including minority \(^{11}\)B and fundamental majority D.

- \(^{11}\)B can reach 1-2% post boronization.
- Additional resonances are not present in D(H) minority.

RF fields fill the torus for D(\(^{3}\)He) compared to D(H).
- Far field sheaths could become more important than in the case of D(H).
Experiments to Investigate Faraday Screen-less Operation

Mixed results from operation without Faraday screen.
  • Successful operation without FS on TEXTOR and Phaedrus-T.
  • ASDEX-U had reported reasonable operation in L-mode but 10% degraded heating efficiency in H-mode.
  • Operation was unsuccessful without FS on DIII-D

Purpose of FS is thought to be two fold:
  • Prevent plasma from entering antenna box.
    » DIII-D observed significant voltage degradation with FS removed.
    » Lower sputtering from antenna by material selection.
  • Set wave polarization.
    » Difficult to imagine that electron response along a field line cannot perform as well as FS.

Faraday screen is subject to significant thermal and disruption loads.
  • In C-Mod, active cooling inside cryostat is difficult.
  • In ITER, heating of the Faraday screen could result in failure of antenna structure.

FS can be significant source of impurities.
  • Impurity production decreased on Phaedrus-T without FS.
  • JET employs low self-sputtering, low Z material Be on FS to decrease production and limit impact on plasma.

Address an ITER need to evaluate whether screen-less ICRF operation is compatible with high performance plasmas.
Replaced FS with Slotted Mo Septums

- Mo septums added to prevent plasma from entering the antenna box.
  - Plasma is scraped off and has short decay length (~3 mm) in shadow of limiter.
  - Septum design balanced RF transparency against plasma streaming along field lines.
  - All field lines are intercepted due to B-field line pitch.
Results are Mixed

Loading, voltage and power handling were unchanged.

Heating effectiveness was decreased:
  • ~10% in L-mode and
  • 15-20% in H-mode discharges.

Relative Cu density shows strong correlation with Ant 2 operation.
  • Interaction was observed where near the middle of the antenna.
  • Cu source is from the current straps.
Assessment of Screen-less ICRF Operation

Present antenna configuration is incompatible with high performance (good confinement) plasmas.
- Cu impurities degraded plasma performance.
- Sheath rectified fields near antenna strap midplane are likely cause of Cu sputtering.

Eliminate folded strap design to minimize sheath fields near antenna midplane.
Antenna Performance can be Limited by Number of Factors

Voltage handling of an antenna often sets the ultimate antenna power limits. Impurity production is the primary concern on C-Mod where as density production is typically low. Neutral pressure limits is where the voltage handling degrades at high neutral pressure.

- Earlier reports from PLT indicated reduced voltage handling as a result of neutral pressure.
- New research indicates multipactor initiated discharge is responsible for this limit.

- Multipactor occurs in an alternating E-field for a given geometry when:
  - $e^{-}$ traverses distance between surfaces in half a period,
  - $e^{-}$ impacts with sufficient energy to release more than one secondary $e^{-}$ and
  - These $e^{-}$'s are born at a correct phase and energy to traverse gap between surfaces.
- Coaxial geometry is more susceptible to multipactor than parallel plate.
- Requires secondary electron coefficient to be greater than 1.
A neutral pressure limit is observed on all antennas.
- Neutral pressure limit for J antenna is \(~0.4\) mTorr.
- Limit increases with plasma current.
- D and E antenna neutral limit is \(~1\) mtorr.

Impacts machine operation:
- Limits initial target densities,
- And slows boronization recovery.
  » Neutral pressure is higher following boronization for a given target density.
At 1-2 mtorr, multipactor-induced glow discharge in coaxial geometry is observed and is well below nominal Paschen pressure.* Once discharge is established, power must be removed to quench discharge.

*See T. Graves et al.,
Magnetic Field Modifies Antenna Multipactor Susceptibility

Voltage handling decreases with increasing pressure.
Total loss of power at glow onset
- Magnetized J-antenna multipactor-induced glow discharge at 0.5 mtorr
- Magnetized E-antenna multipactor-induced glow discharge at 1 mtorr.
Remarkable agreement with experimentally observed neutral pressure limits.
Current Understanding of Neutral Pressure Limits

CMX demonstrated multipactor induced discharge limits the RF voltage/power for neutral pressures ~10x less than the Paschen pressure limit.

Magnetic field significantly modifies the antenna’s multipactor susceptibility.

• Measured limits are remarkably similar to operationally observed limits.

Demonstrated we could raise J antenna’s by striking a multipactor discharge from 0.4 mTorr to 1 mTorr.

• Consistent with CMX results suggesting plates free of impurities have higher thresholds for striking multipactor discharge.

Confirmed that the secondary electron coefficient can be modified to eliminate this limit.

Outstanding issues include:

• Neutral pressure limit variation with plasma current.
• Understanding of initial RF trip.
• Role of magnetic field in lowering the onset of multipactor induced discharge.
Summary

RF sheaths are likely responsible for significant core Mo and boronization erosion.

• Important location is on the top of the outer divertor (outside the divertor and away from the antenna!).
• Important consideration for ITER divertor design.

$D(\text{He})$ and $D(H)$ minority heated L-mode plasmas have similar heating effectiveness.

• H-mode threshold appears to be similar and
• Initial H-mode performance data suggests H-mode performance was reduced compared to D(H).

Present screen-less antenna configuration is incompatible with high performance plasmas.

• Reducing RF sheaths by antenna design change is logical next experiment.

Identified coaxial multipactor is leading explanation for observed neutral pressure limit.
Reprints

Links to C-Mod EPS contributions can be found at: