Recent ICRF Results in Alcator C-Mod


MIT Plasma Science and Fusion Center, Cambridge MA

48th Annual Meeting of the APS Division of Plasma Physics
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(³He) 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(³He) 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.
- +90°(-90°) launches waves co-(counter) plasma current.

Flexible boronation technique.
- Use electron cyclotron power to create plasma.
- Boronation is localized around the electron cyclotron resonance location allowing for control of deposition.
- Can be applied between discharges.

Metallic PFCs allow relatively easy removal of boronation coating. Antennas and LH coupler have private protection Mo limiters located ~1 cm behind plasma limiters (GH, AB, and K).
D and E Fast Wave Antennas

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:
- Standard 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.
- Peak $n_{\phi} = 13(\pm 7)$ in vacuum for $\Delta\phi = 180^\circ(\pm 90^\circ)$ phasing.
- Operating $\leq 35$ kV in plasma.
RF has Strong Impact on Plasma Edge

Primary physical mechanism is RF sheaths.

- Open field lines connect conducting surfaces and enclose RF flux.
- Electrons are lost preferentially and field lines charge positive.
- Voltage is dropped across the sheath at limiters, walls, and divertor.

Sheaths result in increased impurity and gas production with RF power.

- Enhanced sputtering from ions are accelerated by the RF sheaths (100-500V).
- Focus has been on sputtering from Faraday screen and antenna limiters.
Sheaths on RF Limiters are not Primary Source of Core Mo

Observed clear correlation between RF limiter Mo source rate and core Mo content.

Utilized insulating BN tiles to eliminated sheaths and Mo source local to the antenna.

Plasma performance was unimproved despite lowering the local RF source.

B. Lipschultz et al., NF 2001

M. Porkolab et al., APS-DPP 2006
RF Heated Discharges show Accelerated Erosion

For H-modes with similar input energy, the RF heated discharges show faster erosion rate than ohmic H-mode.

- Reduced plasma performance is associated with high plasma radiation.

Erosion rate is \(\sim 15-20\) nm/s with RF heating.

- Corresponds to 20-30 high RF power plasmas for \(\sim 200\) nm coating and
- typically one discharge for thin \((\sim 20\) nm) coating.

Additional experiments suggest erosion and subsequent Mo source is away divertor strike point.

- Localized boronization is optimized plasma performance when applied in the region of the top of the outer divertor.
- Post-campaign inspection confirmed B layer did not survive on tiles between 0.65-0.7 m.
Observe Elevated Plasma Potential on Field Lines Connected to Active Antenna

Measured potentials are typically 100-400 V.
- Above threshold for D sputtering of Mo.
If RF enhanced sheaths are responsible for accelerated erosion,
- The erosion should be localized to the active antenna.
- The field lines with the enhanced sheaths should be unaffected by insulating limiters and
- Erosion is localized to the top of the outer divertor.

Low plasma radiation can be maintained for consecutive discharges following a light boronization by:
- heating the first discharge with Ant 1 and
- the second discharge with Ant 2.

M. Porkolab et al., APS-DPP 2006
Erosion is Linked to Active Antenna

Radiated power significantly increased for second discharge in consecutive discharges heated by single antenna (Ant 1).

Maintained low radiated power for second discharge in consecutive discharges when heated by second antenna (Ant 2).
Open Field Lines Passing Near the Antenna Terminate on Outer Divertor

Open field lines that terminate on top of the outer divertor pass near the antenna will have RF enhanced sheaths.
Antennas have unique toroidal shadow.
  - Ironically nearly in front of the other antenna.
Antenna Characteristics are Strong Influence on Erosion/Impurity Generation

J antenna erosion and subsequent impurity generation appears to be slower than D+E antenna.

- Suggests details of antenna design impact erosion/impurity generation rate.

Erosion rate unaffected by weak single pass absorption scenario, D(³He).
RF Sheaths are Responsible for Accelerated Erosion

Measured potentials are typically 100-400 V above the threshold for D sputtering of Mo.

Demonstrated erosion is local to active antenna.
- The field lines with the enhanced sheaths would be unaffected by insulating limiters and
- Field lines terminate on the top of the outer divertor.

Low plasma radiation maintained for consecutive discharges following a light boronization by:
- heating the first discharge with D+E antenna and
- the second discharge with J antenna.

Near field effects dominate sheaths resulting from low single pass absorption.

Antenna configuration may have strong effect on E|| associated with the antenna.

Sheaths have a double impact on erosion and impurity generation.
- Sheaths increase sputtering.
- Convective cells increase impurity penetration.
D(3He) Heating is Primary ICRH Scenario for 8 T Discharges

Previous experimental data indicated the heating efficiency is more sensitive to 3He concentration than D(H).
May anticipate greater density and impurity production due to lower single pass absorption for D(³He) (10-20%) than D(H) (80-90%).

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

For L-mode comparison, RF power is ramped to 1.5 MW to avoid H-mode.
- J antenna utilizes D(\(^3\)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.
H-mode Threshold Power Appears nearly Identical

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

- Response in L-mode is also quite similar before the H-mode transition.

M. Porkolab et al., APS-DPP 2006
Initial $D(^3\text{He})$ 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.
H-Mode Performance Could be Degraded via Impurities or Parasitic Loss

$D(^3He)$ scenario has competing absorption mechanisms:

- minority cyclotron resonances including $^{11}B$ (1-2%) and majority D.
- absorption by Alfvén wave mode conversion near $R \sim 0.5$ m.
- Due to weak single pass absorption, far field sheaths could become more important than in the case of D(H).

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

- Power absorbed by parasitic mechanism could result in increased impurity production and radiation.
Experiments to Investigate Operation without FS

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.
- Eliminate $E_{||}$ to B-field.

Mixed experimental results from operation without Faraday screen.

- Successful operation without FS on TEXTOR and Phaedrus-T (limiter devices).
- ASDEX-U had reported reasonable operation in L-mode but 10% degraded heating efficiency in H-mode with D(H) minority heating.
- Operation was unsuccessful without FS on DIII-D with high harmonic heating.
- C-Mod results presented below.

Operation without FS has several advantages:

- Simpler antenna design and significant cost savings.
- 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.

Address an ITER need to evaluate whether ICRF operation without FS is compatible with high performance plasmas.

M. Porkolab et al., APS-DPP 2006
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.
Heating Effectiveness was Significantly Decreased without FS

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

Loading, voltage and power handling were unchanged.

Relative Cu density shows strong correlation with antenna without a FS.
- Interaction was observed where near the middle of the antenna.
- Cu source is from the current straps.

Sheath rectified fields near antenna strap midplane are likely cause of Cu sputtering.

Need to modify antenna strap to minimize sheath fields.

Note: Previously demonstrated similar heating effectiveness with Faraday screen on D+E and J antennas.

M. Porkolab et al., APS-DPP 2006
Present antenna 2 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.

Neutral pressure limit is where the voltage handling degrades at high neutral pressure.

- Earlier reports from PLT indicated reduced voltage handling as a result of increased neutral pressure.
- Our research indicates multipactor initiated discharge 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-
  » 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.
Current Understanding of Neutral Pressure Limits

CMX demonstrated multipactor induced discharge limits the RF voltage/power for neutral pressures ~10x less than the Paschen limit. Magnetic field significantly increases the antenna’s multipactor susceptibility.

- Measured limits in CMX are remarkably similar to observed limits in C-Mod. Demonstrated we could raise J antenna’s neutral limit by multipactor assisted discharge cleaning from 0.4 mTorr to 1 mTorr.
- Consistent with CMX, surfaces free of impurities have higher thresholds for striking multipactor discharge.

Confirmed that the decreasing the secondary electron coefficient can be 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.
Observe a neutral pressure limit (~ 1 mtorr) at which voltage and power handling degrade abruptly and unable to recover. Impacts machine operation at high density. Phenomenon may be the underlying physical explanation for antenna voltage and power handling degradation with ELM’s.

- Despite increased plasma loading and lower antenna voltage, an antenna often faults during ELMs.
A multipactor discharge is a resonant condition for electrons in an alternating E field where

- Vacuum conditions required and
- Electron multiplication from secondary electrons – $\delta(E) > 1$.

Find coaxial geometry is more susceptible to multipactor.

For neutral pressure > 1 mTorr, a discharge is formed.

- This pressure is ~100x less than minimum in the Paschen curve.

Find magnetic field further reduces the pressure at which discharge forms.
Modified Multipactor Discharge is Responsible for Voltage Degradation at High Neutral Pressure

Find neutral pressure at which discharge forms is the same as the neutral pressure limit.

- Both antenna operational limits agree with onset of modified multipactor discharge.

Tests indicate reducing secondary electron coefficient ($\delta(E)$) can raise or eliminate this limit.

- Simulations suggests both inner and outer conductor need to have $\delta(E)<1$ for coaxial case.
- For parallel plate geometry, only one surface needs to have $\delta(E)<1$. 

M. Porkolab et al., APS-DPP 2006
Summary

Achieved antenna performance compatible with high performance plasmas with all metal PFCs post boronization.

RF Mo source and erosion location:
- 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.

Screen-less operation:
- Present screen-less antenna configuration is incompatible with high performance plasmas.
- Reducing RF sheaths by antenna design change is logical next experiment.

Modified multipactor discharge is responsible for voltage degradation at high neutral pressure.
RF sheaths are likely responsible for significant core Mo and boronization erosion.

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

\[ \text{D}^{(3}\text{He}) \] and \[ \text{D}(\text{H}) \] minority heated L-mode plasmas have similar heating effectiveness.

- H-mode threshold appears to be similar and
- Initial H-mode performance data suggests confinement in \[ \text{D}(^3\text{He}) \] discharges is reduced compared to \[ \text{D}(\text{H}) \] → impact of weak single pass absorption.

Screen-less antenna configuration deteriorates plasma performance in C-Mod; fix may be available but yet untested.

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

Identified coaxial multipactor as the leading explanation for voltage handling degradation at high neutral pressure.
Reprints

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