Results from ICRF Heating and Current Drive

G. Schilling, P. T. Bonoli, A. Hubbard, L. Lin, Y. Lin, A. Parisot, M. Porkolab, J. R. Wilson, S. J. Wukitch, and the C-Mod Team

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MIT Plasma Science and Fusion Center, Cambridge, MA 02139
Princeton Plasma Physics Laboratory, Princeton NJ 08543

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Abstract

On C-Mod, ion cyclotron range of frequencies (ICRF) is the only auxiliary heating. To inject high power, the antennas need to be able to withstand high RF voltages. To maximize voltage handling, the antennas have been modified to avoid or minimize the RF E-field in regions where the RF E-field is parallel to the tokamak B-field. For 0.5 second pulses, the ICRF antennas have now delivered up to 5 MW with minimum density and impurity generation in H-mode. Furthermore, initial tests of the 4-strap antenna in non-symmetric phasing were begun. In minority H heating scenario, the 4-strap antenna has coupled 2.7 MW with both counter and co-current phasing without significant negative impact on the plasma. The sawtooth period was observed to lengthen with co-current phase and shorten with counter-current phase. In addition, initial mode conversion current drive experiments were begun. Direct electron heating was observed, independent of phase, for a D($^3$He) mode conversion scenario. An analysis of the antenna performance and plasma response will be presented.
Physics achievements
- Mode conversion studies
- Current drive initiation
- Mode conversion studies

ICRF antenna upgrades
- Power
- Phased operation
- ICRF system technical achievements

Outline
C-Mod ICRF resonance location at 78 MHz
ICRF Mode Conversion

Narrow deposition may provide tool for modifying or controlling pressure and current profiles.

Mode conversion can compete with other damping mechanisms.

Detailed measurements provide test for ICRF code predictions.

More complicated than expected.

Absorption details could affect current and flow drive predictions.

Unique combination of diagnostics, codes, and RF system to study various scenarios (D(3He), H(3He), and D(H)).

PCI measures chord-integrated fluctuation level.

High resolution (~0.7 cm) ECE radiometer measures power deposition profile.

First principle 2-D full-wave calculation using ICRF code TORIC.

TORIC GpCh GpCexp D(3He) discharge.

D(3He) = 0.14, BT = 8 T, Ip = 0.8.

High resolution (~0.7 cm) ECE radiometer measures power deposition profile.

First principle 2-D full-wave calculation using ICRF code TORIC.
Phase Contrast Imaging diagnostic measures

- Electron density fluctuations

RF ANTENNA

PCI Chords

Wide spectrum of wavenumbers are measured simultaneously; spatial structure is probed over wide area

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- May allow direct measure of wave damping rate.

Increase memory.

Upgrade from 12 to 32 channels.

- Effective spacing is set by magnification optics

Sensitivity

Utilize 100 W CO2 laser ($\lambda = 10.6 \mu m$)

- Poor spatial localization results from line integration

$0.5 < \frac{|k_R|}{\sqrt{R}} < 1.0 \text{ cm}^{-1}$

$60 \text{ cm} < R < 79 \text{ cm}$ ($R^0 = 0.66 \text{ m}, a = 0.22 \text{ m}$)

Planned upgrade:

- 2-500 KHz

- $10^{12} \text{ m}^{-2} \text{ Hz}^{-1/2}$

- 2-500 KHz

Utilize field alignment of scattered wave to provide localization.

- 12 vertical chords:

Simultaneously: spatial structure is probed over wide area
Detected mode converted Ion Cyclotron wave

Contour Plot of Fourier Analyzed PCI Data

-10
-5
0
5
10
kR, cm⁻¹

320
340
360
380
Df [kHz]

80.47
80.50
80.53
fRF [MHz]

-6 -4 -2 0 2 4 6
PCI chords

5 < k < 10 cm⁻¹

Measured wavenumbers are in good agreement with dispersion relation.

First experimental observation of D(H) mode conversion.
Experimental fraction of absorbed power is 0.16 and TORIC predicts 0.14.

Experimental deposition profiles during D(H) MC
Comparison of measured and predicted power

Y. Lin et al., PPCF (accepted) 2003.
Off-axis \( \text{D(H)} \) mode conversion

\( \text{D}(\text{H}) \) mode conversion is an opportunity to compare simulation with experiment. Direct monitor of \( \text{H}\) minority is routine.

Experimental absorbed power is 0.2 and TORIC predicts 0.18.

Simulation indicates a complicated mode conversion region. IBW and ICW are both present.

Y. Lin et al., PPCF (accepted) 2003. Simulation indicates a complex mode conversion region. IBW and ICW are both present.

\( S_\text{eldFW} = \frac{\text{Power}}{\text{S}_\text{FW}} \)
On-axis current drive initiation

- Sawtooth period increased x3 (co vs counter phasing)
Off-axis current drive initiation

- First off-axis current drive experiments
- Observed both shortening and lengthening of the sawtooth period depending upon phase, deposition location, and power level.
- Further analysis required to determine driven current.

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IP=0.8 MA, BT=8.0 T

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ICRF system technical achievements

- Operated ICRF antennas to maximum achievable voltage in their 12/2002 configurations and evaluated voltage and power limits.
- Evaluated and implemented changes to increase the voltage and power handling capabilities of all three antennas.
- Began high-power heating experiments with the modified antenna systems and identified candidate target plasma conditions likely to lead to high temperature and low collisionality.
- Produced high temperature plasma with 5 MW ICRF power for 0.5 sec.

12/2002 configurations and evaluated voltage and power limits.
Operated ICRF antennas to maximum achievable voltage in their
5 MW ICRF H-mode discharges

- Antenna modifications significantly improved power handling of D, E, and J-port antennas.
- D and E-port power limit increased to 3 MW.
- J-port power limit increased to 3 MW.
- Full assessment requires more operation time and an inspection (Jan 2004).
Demonstrated flexible antenna phasing

- In L-mode discharge, 2.7 MW is coupled through J-port in co-current phasing for ~0.4 sec.
- Comparable plasma response for D and E-port antennas (heating phasing).
- Impurity and density production are similar.
- Antenna heating efficiencies are independent of phase.

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- Impurity and density production are similar.
- Comparable plasma response to D and E-port antennas (heating phasing).
- Current phasing for ~0.4 sec.
- Coupled through J-port in co-
- In L-mode discharge, 2.7 MW is coupled through J-port in co-

Also use for flow drive experiments.

Very encouraging results for future FWCD and MCCD experiments.
Antenna performance

- Power limits now up to ~1.5, 1.5, 1.5 MW for D, E, and J-port.
- Have now achieved 35 kV on all antennas.
- Further antenna upgrades were carried out 12/2002 - 3/2003.
- Power limits in 12/2002 were ~1.0, 1.0, 1.5 MW for D, E, and J-port.
- Voltage limits in 12/2002 were ~30, 30, 35 kV for D, E, and J-port.
ICRF antenna upgrades

Performance limits dominated by antenna voltage.

Antenna front surface - plasma interactions have been largely eliminated by covering exposed metal with boron nitride.

The empirical rf voltage holding limit of $E \parallel B \approx 15 \text{ kV/cm}$ has required redesign of internal antenna elements to reduce local rf electric fields.

Interactions.

Holding limits and antenna front surface - plasma interactions.

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C. Modor

Actor
D- and E-port fast wave ICRF antennas

D-port:
- Arc damage on #4 feedthrough center conductor at 20 ohm section.
- D-port: Arc damage on #4 feedthrough center conductor at 20 ohm section.
- Replaced feedthroughs #2 and #4.
- Modified center conductor diameter to 50 ohm dimension.
- Replaced feedthroughs #2, #3, and #4.
- Modified center conductor diameter to 50 ohm dimension.
- Replaced feedthroughs #2, #3, #4, and #2,
- Arc damage on #4 feedthrough center.
- Arc damage on #4 feedthrough center.
- Upper left thermocouple was melted.

E-port:
- Arc damage on #4 feedthrough center at 20 ohm section.
- Arc damage on #4 feedthrough center at 20 ohm section.
- Replaced feedthroughs #2 and #4.
- Arc damage on #4 feedthrough center.
- Arc damage on #4 feedthrough center.
- Arc damage on #4 feedthrough center.
Damage suggests arcing is where $E \parallel B$.

- Damage in D and E feedthroughs.
- Modified FS resulted in longer antenna electrical length.
- Moved higher voltage to this section of transmission line.
- Estimated impedance is $\approx 20$ ohms.
- $D$-port had damage on feedthrough #2, #3, and #4.
- $E$-port had heavy damage localized to #4 with minor damage to #2.

50 ohm line has maximum voltage handling capability.
Modification will lower electric field by ~30\%.

- Coupled power should also double but will be limited by breakdown.
- Should require about 2 times the circulating power to reach

\[ \text{Modification will lower electric field by } \sim 30\% \]
20

J-port fast wave antenna

Installed new nose tiles replacing the failed BN cover tiles.
Replaced septum spine because of severe damage.
Refurbished feedthroughs:
- #2 and #4 vacuum side ceramic was cleaned before re-installation.
- #4 vacuum side ceramic was replaced.
- Refurbished #2 and #4 feedthrough center conductors.

Modified antenna mounting plate to improve contact and reduce E-fields. Center conductor connection to vacuum strip line and spool piece contact with strip line.

Did not install RF contact along side plate (capacitors).

Coaxial line center conductors were damaged.

Found arc damage across field lines on #4 near back plate feedthrough.
Vacuum coaxial line center conductors were damaged.

J-port fast wave antenna
BN cover tiles failed

Fastening system moved with the BN tiles instead of being hard fastened.

- BN performs poorly under tensile stress.
- Compressive and tensile stress.
- The BN experiences both compressive and tensile stress.
- The BN experiences both torque.
- The plate the BN tile rests upon and the rail experience this torque.
- Disruption force results in a torque applied to the BN tile.

- Disruption torque induced.
- BN cover tiles failed.
- Tiles top #2 and #3 and bottom #7 failed completely.
- Tiles bottom #5 partially failed.
BN tile redesign

- BN tile.

- MO tile modified to accommodate thicker.

- All tile is over bearing.

- Metal.

- Preload flange to ~200 G so

- BN tile moves with metal tile.

- Preload bevel washers to 200 G so

- Shield fasteners from plasma.

- Failed fasteners suggest ~200 G loads.

- Test indicates the tile failed ~1000 G.

- Previous nose tiles have not failed to

- Front tile.

- Replace front and cover tiles with single.

- Tile strength is not compromised.
Septum sustained significant damage.

Observations:
- Melt damage is most severe where there is no probe.
- Probes appeared to weld to the spine.
- Injections from J-port ~ at cross over.
- BN tile facilitates breakdown.
- For (0,0,0,0) phasing, large flux through slots results in voltage across slot.

Mechanism:
- High power for ~ 8 discharges.
- For (0,0,0,0) phasing, large flux through slots results in voltage across slot.

Made new spine without slots.
- BN tile facilitates breakdown.
- Slot.

Antenna ran in (0,0,0,0) phasing from 1020628-1020802.
- Antenna ran in (0,0,0,0) phasing from 1020723.
- Injections from J-port ~ at cross over.
- Probes appeared to weld to the spine.
- There is no probe. Melt damage is most severe where
Mounting plate modifications

Address arc damage found in vacuum coax.

Basic problem is reliable contact.
Possible to have poor contact due to multiple connections.

Increased diameter of opening and added full radius.
Increased the bolt pattern from 4 bolts to 8 bolts.
Relieved the plate to allow the plate to rest only around the openings.
Plated the flange face with copper to improve contact.

To improve reliable contact and reduce E-fields.

- Plated the flange face with openings.
- Relieved the plate to allow the plate to rest only around the openings.
- Increased the bolt pattern from 4 bolts to 8 bolts.
- Increased diameter of opening and added full radius.
- Relieved the plate to allow the plate to rest only around the openings.
- Plated the flange face with copper to improve contact.
Modified all junctions to improve contact

Number of junctions showed signs of series arcing.

Improved contact by relieving the flat section leaving a shoulder.
Antenna performance summary

- Improvements will continue as we learn more about antenna behavior.
- Plasma: with good heating efficiency and no deleterious effects on the plasma.
- We have been able to bring the total antenna power up to above 5 MW, with good heating efficiency and no deleterious effects on the plasma.
- Careful analyses of antenna fault modes together with thorough antenna inspection following each run period have allowed us to raise antenna performance systematically during use on C-Mod.
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