Field-Aligned ICRF Antenna Characterization and Performance in Alcator C-Mod*

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Goal:

Test whether a field aligned (FA) antenna can improve antenna operation, particularly impurity contamination and impurity sources.

Key Results:

1. Novel, Field aligned ICRF antenna has reduced impurity contamination and impurity sources.
2. Field aligned antenna has greater load tolerance.
3. Measured plasma potentials for Field Aligned antenna are not remarkably different from plasma potentials associated with toroidally aligned (TA) antenna.
4. Low heating effectiveness with monopole phasing is a result of poor wave penetration.

*Work supported by US DoE awards
Outline

1. Motivation
2. Field Aligned Antenna description
3. Impurity contamination and source characterization.
4. Antenna load tolerance.
5. Characterization of plasma SOL potential with power from the Field Aligned and Toroidally Aligned antennas.
Renewed interest in metallic plasma facing components (PFCs) for fusion devices including ITER.

- Metallic PFCs have significantly better erosion resistance.
- Concerns about tritium retention in machines with carbon PFCs.

ICRF compatibility with high Z PFC has extensively investigated at C-Mod.

- ICRF heated H-mode performance with high Z PFCs is insufficient.

Greenwald et al., Nucl. Fusion 37, 793 (1997).
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- ICRF heated H-mode performance with high Z PFCs is insufficient.
- ICRF impurity contamination has been can be controlled by boron coatings.
- Low Z film lifetime is limited and does not scale to reactor
- Seek to develop ICRF antennas without needing to resort to boronization.

Adapted from Greenwald et al., Nucl. Fusion 37, 793 (1997).
For High Z PFC Devices, A New Approach to Limit Impurities is Required

Although detailed phenomenology differs, recent experiments from ASDEX-U\(^1\) and JET\(^2\) confirms previous C-Mod results.

- ICRF impurity contamination is too large in the case of high Z PFCs.

‘Jacquinot rules’\(^3\) (developed for devices with Carbon PFCs) to minimize ICRF impurity contamination are:
  - Utilize dipole phasing.
  - Align the Faraday screen with total magnetic field.
  - Antenna armor use low Z materials.
  - Utilize high single pass absorption.

Can a Field Aligned antenna reduce ICRF impurity contamination?

G. Matthews et al., 20\(^{th}\) Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen (2012).

1. R. Neu et al., 20\(^{th}\) Int. Conf. on Plasma-Surface Interactions, Aachen (2012).
2. V. Bobkov et al., 20\(^{th}\) Int. Conf. on Plasma-Surface Interactions, Aachen (2012).
Underlying Physics of ICRF Contamination is RF Enhanced Sheaths

Oscillating \( E_\parallel \) leads to DC sheath rectification.

I-V curve is highly non-linear and leads to excess electron collection in presence of RF.
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I-V curve is highly non-linear and leads to excess electron collection in presence of RF.

DC bias voltage is established on conducting surfaces to maintain ambipolarity.

Bias voltage accelerates ions and leads to enhanced sputtering of surfaces.
RF Enhanced Sheaths Can Lead to Both Source and Transport Enhancement

Impurity source is enhanced by accelerated ions due to RF sheaths.¹

- Impurity influx is sensitive to sheath voltage where plasma potentials ∼ 100 V will result in steep increases in sputtering yield.
- RF sheath enhancement is proportional to \( \int E_{\|} \cdot dl \) and will be proportional to square root of RF power.

Transport can be modified by convective cells driven by spatial gradients in the RF enhanced sheaths.²

Reduce integrated \( E_{\|} \) and impurity contamination should be reduced.

- Analysis of dipole versus monopole operation of Toroidally Aligned antennas supports this hypothesis.³

Guiding Design Principle is Field Line Symmetry

Field Aligned Antenna

Antenna straps, septa, and side protection tiles are normal to the total magnetic field, $\sim 10^\circ$. 
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Antenna straps, septa, and side protection tiles are normal to the total magnetic field, \( \sim 10^\circ \).

Antenna is helical to conform to plasma shape.
Field Aligned Antenna is Normal and Conformal

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<thead>
<tr>
<th>Field Aligned Antenna</th>
<th>Toroidally Aligned Antenna</th>
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<td>Antenna straps, septa, and side protection tiles are normal to the <strong>total</strong> magnetic field, ~10°.</td>
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Field Aligned Antenna

Antenna straps, septa, and side protection tiles are normal to the total magnetic field, \( \sim 10^\circ \).

Antenna is helical to conform to plasma shape.

Faraday rods are parallel to the total magnetic field.

Toroidally Aligned Antenna

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### Field Aligned Antenna

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### Toroidally Aligned Antenna

- Antenna straps, septa, and side protection tiles are normal to the **toroidal** magnetic field.
- Antenna is **cylindrical**.
- Faraday rods are parallel to the total magnetic field.
Field Aligned Antenna has Achieved Electrical Performance Similar to Toroidally Aligned Antenna

Electrically the Field Aligned antenna has performed well.

- Antennas conditioned very quickly in plasmas (~15 discharges) to 2 MW (~6 MW/m²).
- Operation over wide range of $q_{95}$ (3-5.5) has seen little variation in performance.
  - Misalignment to magnetic field is <5%.

Achieved 45 kV into plasma compared to 40 kV for the Toroidally Aligned antennas.

Power densities are similar to Toroidally Aligned antennas and exceed ITER requirements.

- In L-mode, 3 MW have been coupled (~9 MW/m²).
- I-mode and EDA H-mode, 2.5 MW has been coupled (~7.6 MW/m²).
- ELM free H-mode, 2 MW has been coupled (6 MW/m²).
FEM Simulation Utilizes Detailed Antenna Geometry and Simplified Core Wave Propagation

Finite Element Method:
- 3-D toroidal FEM
- Antenna CAD model is utilized.
- Cold plasma permittivity tensor rotated along magnetic field.
- Use artificial collisional damping to model minority absorption.
- C-Mod plasma and magnetic data are used in the model.

Limitations of the model:
- RF sheath boundary conditions are not implemented.
- Plasma density and temperature do not evolve with application of RF power.
- RF potentials are calculated in vacuum region ~1 cm in front of the Faraday screen.

FEM Simulation show Reduced Integrated $E_\parallel$ for the Field Aligned Antenna

For Field Aligned antenna, the integrated $E_\parallel$ fields are reduced for all antenna phases.

- For dipole, estimated integrated $E_\parallel$ is reduced particularly at the peaks.
- For monopole, integrated $E_\parallel$ is significantly reduced.
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- For monopole, integrated $E_\parallel$ is significantly reduced.
  - Lower than dipole— a surprising prediction.
Compare Measurements of Core Impurity Contamination, Local Impurity Sources

Compare antenna performance between toroidally and field aligned antenna in near axis minority H absorption scenario with RF power up to 3 MW.

- Magnetic field 5.2-5.4 T with currents 0.6-1.3 MA.

Core impurity content is monitored using VUV spectroscopy Mo XXXI.

Local impurity (Mo I, Ti I, and B I) sources are monitored with visible spectrometer:

- Multiple views of each antenna and poloidal protection limiter.
In L-mode, FA Antenna has Lower Impurity Contamination

Prior to boronization in L-mode discharges, plasma response is more favorable for power from FA-antenna.

Impurity contamination is lower.

- Radiated power is 25% lower for comparable injected power.
- Core molybdenum content is significantly reduced.
Core Mo is significantly lower for FA antenna compared to TA antennas.

• Rise time on the core Mo content is significantly slower for the FA antenna than the TA-antennas.

FA antenna has lower radiated power.

• Radiated power is ~20-30% lower than for the TA antennas in EDA H-mode.
TA Antenna Mo Source Correlates with TA Power

Compare the response of the local Mo source for each antenna view when the TA and FA antenna are powered separately.

Strong Mo source response at the TA antenna when the TA antenna is powered.

- Mo source at the TA antenna increases with each power step.
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**Strong Mo source response at the TA antenna when the TA antenna is powered.**
- Mo source at the TA antenna increases with each power step.

**Weak Mo source response at the TA antenna when FA antenna is powered.**
FA Antenna Mo Source Correlates with TA Power

Measurable Mo source response at FA antenna when TA antenna is powered.
Measurable Mo source response at FA antenna when TA antenna is powered.

Mo source response is lower at FA antenna when FA antenna is active.

- Plasma limiter views show similar behavior to FA antenna view.
Antenna Impedance is Determined by the Density Profile in Plasma Edge

Edge plasma density profile determines the antenna resistive loading.

- Sets the distance to propagation and
- Determines the propagation characteristics or transmission impedance.

Antenna geometry determines antenna reactance.
Load tolerance is important for antenna reliability and efficiency.

- Sensitivity to load variation leads to large reflected power.

Field aligned antenna has improved load tolerance.

- Reflection coefficient from Field Aligned antenna occupies less area than Toroidally Aligned antenna.
- Impedance variation is reduced.
- Q of the antenna, ratio of reactance to resistance, is approximately constant.
- Impedance variation depends primarily on the real part of the antenna load.
ELMs Loading Perturbation is Largely Resistive for Field Aligned Antenna

During an ELM:

Field Aligned antenna has impedance change is due only to changes in the resistive load.

• Resistance and reactance have a defined relationship.

Toroidally Aligned antenna Q and impedance both vary.

• Resistance and reactance have a more complicated relationship.

Antenna model needs properly include antenna geometry with respect to magnetic field.

• Models using lossy dielectric to model the plasma, often used in antenna design, will fail to accurately reproduce or predict antenna behavior in a tokamak plasma.
Reciprocating Emissive Probe and Gas Puff Imaging
Monitor Plasma Potential

Hot emissive probe monitors measures the plasma potential directly.

- Can be plunged to about radius of antenna protection tiles.
- Maps to middle region of Field Aligned antenna – where integrated E|| is expected to be lower than the stap ends of the antenna.

GPI diagnostic measures the poloidal velocity of the SOL turbulence.

- Monitors the radial region between ~1 cm behind the antenna tile radius to the last closed flux surface.
- Maps to the corners of both the Field Aligned and Toroidally Aligned antennas where the integrated E|| is expected to peak.
- Vertical resolution of ~4 cm and radial resolution of ~0.4 cm.
GPI measures emission fluctuations resulting from the local plasma turbulence.

Measure poloidal propagation from fluctuation spectra.

- Example fluctuation power spectrum versus $k_\theta$
- Color scale for power is normalized at each frequency so that higher frequency features are resolved.
- Slope is the poloidal phase velocity.
- Negative slope $\Rightarrow$ ion diamagnetic drift direction.
- Positive slope $\Rightarrow$ electron diamagnetic drift direction.
SOL Potential Profile Estimated from GPI Measurements

In the far SOL, turbulence is convected at the local ExB velocity.

- Poloidal velocity and corresponding $E_r$ are small in ohmic discharge.
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- Dramatic change in $E_r$ with application of RF.

Integrate $E_r$ profile to deduce potential profile with profile referenced to $3T_e/e$.

- Plasma potential is conserved on a field line.
Emissive probe and GPI indicate Strong Change in $E_r$ at the Antenna Limiter Radius

Emissive probe and GPI $E_r$ profiles are consistent – strongest change in $E_r$ is at RF limiter radius.

Profiles also scale with RF power, $\sim P_{RF}^{1/2}$, and vary with mapping to antenna.
Impurity contamination differs between the antennas with the Field Aligned having lower sources and contamination.

- Challenge to hypothesis that lower integrated E|| will lower RF enhanced sheaths.
Monopole Phasing does not Perform as well as Dipole

Recall Field Aligned antenna in monopole phasing was predicted to have the lowest integrated $E_{\parallel}$ fields.

Plasma response to monopole is significantly lower than dipole phasing.
Monopole Phasing does not Perform as well as Dipole

Recall field aligned antenna in monopole phasing was predicted to have the lowest integrated $E_{||}$ fields.

Heating effectiveness with monopole is significantly lower than dipole phasing.

Measured plasma potential is higher for monopole operation than that measured during dipole operation.

- Suggests antenna-plasma model is missing some key physics.
Field line symmetry was to reduce integrated $E_{||}$ resulting in lower RF enhanced plasma potential and impurity contamination/sources.

Further monopole phasing was to have lower integrated $E_{||}$.

Low Z seeding has a strong influence on measured potentials with same injected ICRF power.

- Are there additional plasma effects that can be used to modify the plasma potential in the presence of ICRF?

- Model will need to include sheath boundary conditions and impurities.
Wave spectrum is peaked at long wavelength if one only considers the antenna straps as the excitation structure (analytic approximation).

- Good for coupling at long distances.
- Dipole has peak at shorter wavelength – $n_\parallel \sim 13$.

Explanation for poor performance has been a combination of impurity contamination, higher RF enhanced sheaths, and poor absorption.
Hypothesis is that Monopole Spectrum Peaks at Short Wavelength

FEM antenna-plasma model indicates monopole wave spectrum is peaked at very short wavelength.

- Wavelength is about half dipole resulting in high $n_{\phi}$.
- Image currents on antenna box including the septa significantly modify the launched wave spectrum.
- Dipole phasing image currents on septa cancel – little modification of the analytic wave spectrum.

Monopole Currents Add

Dipole Currents Cancel
Mode conversion heating scenario enables measurement of core waves with phase contrast imaging (PCI).

- Monopole and dipole should have similar single pass absorption.

Dipole plasma heating effectiveness is higher than monopole.

Radiated power and core impurity contamination are similar.

- Suggests difference between monopole and dipole is not dominated by impurity contamination.

Carbon II responds strongly to monopole phasing.

- Indicates RF power is interacting with the SOL.
Monopole Spectrum is Inaccessible

PCI measures no waves in the plasma core during monopole phasing.

Full wave modeling shows that the monopole spectrum including the image currents launches waves that remain in the plasma periphery.
Future Directions

Add plasma response to antenna – plasma model.
  • Sheath boundary conditions are next physics to be included.
  • Antenna-plasma model capable of calculating scattering matrix for field aligned antenna geometry.

Investigate relationship between ICRF antenna and plasma potential.
  • Characterize plasma potential with additional emissive probes - same mapping as GPI and over wider set of plasma conditions.
  • Increase poloidal coverage to characterize poloidal profile of plasma potentials.
  • Does the tile geometry and orientation to the magnetic field play a role?
  • Can the antenna structure be biased to reduce RF enhanced plasma potential?

Establish relationship between SOL plasma potential and impurity contamination and sputtering.
  • Identify impurity source locations.
  • Is SOL impurity transport modified with RF?
A field aligned ICRF antenna has reduced impurity contamination and impurity sources.

Field aligned antenna is more resilient to load variations than toroidally aligned antennas.

Our physics understanding of Field Aligned antenna is incomplete.

- Plasma potentials associated with field aligned antenna operation are similar to toroidally aligned antenna operation.
- Monopole phasing has higher impurity contamination and plasma potentials than dipole phasing.
- Clarification of the underlying physics that influences the SOL plasma potential in the presence of ICRF is required.

Monopole antenna phasing has poor heating effectiveness due to poor wave penetration in the plasma core.

- Launched wave spectrum is modified by image currents.