Evaluation of a Field Aligned ICRF Antenna in Alcator C-Mod

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Goal:

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

Key Results:

1. Field aligned ICRF antenna has reduced impurity contamination and impurity sources.

2. Operational characteristics of this novel, high power ICRF antenna are favorable.

3. Measured plasma potentials for FA antenna are not remarkably different from plasma potentials associated with toroidally aligned (TA) antenna.
Outline

1. Motivation
2. Antenna and Diagnostic description
3. Impurity contamination and source characterization.
5. Characterization of plasma potential with FA and TA antennas.

Field Aligned Antenna

Toroidally Aligned (TA) Antenna
For High Z PFC Devices, A New Approach to Limit Impurities is Required

Impurity contamination with ICRF antenna operation has been universally observed.

‘Jacquinot rules’* to minimize ICRF impurity contamination are:

• Operate in so-called dipole phasing.
• Align the Faraday screen with total magnetic field.
• Antenna armor should use low Z materials.
• Utilize high single pass absorption.

Despite applying ‘Jacquinot rules’, experience from JET, ASDEX-U, C-Mod has shown that this prescription is insufficient in devices with high Z PFCs.

Can a FA antenna reduce ICRF impurity contamination?

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

Underlying Physics of Impurity Contamination is Thought to be RF-Sheaths

TA antennas were found to have less impurity contamination in dipole phasing rather than monopole.

Reduction in $E_\parallel$ was used to explain results.$^1$

- Significant reduction in integrated $E_\parallel$ is shown in recent FEM simulations.

Reduce $E_\parallel$ and impurity contamination should be reduced.

Guiding Design Principle is Field Line Symmetry

Rotate antenna straps and structure 10° to be perpendicular to total B field.
- Along a field line, integrated $E_\parallel$ will be minimized due to symmetry.
Guiding Design Principle is Field Line Symmetry

Rotate antenna straps and structure 10° to be perpendicular to total B field.
   • Along a field line, integrated $E_{||}$ will be minimized due to symmetry.

For a FA antenna, the integrated $E_{||}$ fields are reduced for all antenna phases.
   • For dipole, estimated sheath field is reduced ~2-3.
   • For monopole, sheath field is negligible – a surprising prediction.
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:

- Views of FA antenna (shown as white circles),
- TA antennas, and
- plasma limiter.

Plasma potential is monitored by gas puff imaging (GPI) and reciprocating emissive probe.
SOL Plasma Potential Profile Estimated from GPI Measurements

2D GPI measures emission fluctuations resulting from the turbulence in the local background plasma.

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

Measure the radial profile of dominant poloidal phase velocities and deduce the Er profile.

Plasma potential is estimated as $\phi = \lambda_\perp Er$ where is $\lambda_\perp$ penetration depth of the rectified potential.

- Er profile (top figure) yields a plasma potential profile shown in bottom figure

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Field Aligned Antenna Evaluation: Experimental Overview

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.
- Experiments have been done prior and post boronization.

Experimental parameters are similar to expected ITER conditions:

- Antenna power density exceeds anticipated ITER power density.
- Experiments are performed at the ITER magnetic field and plasma density.
- Strong single pass absorption.
- Metallic PFCs (Mo) that has similar sputtering characteristics as tungsten.
- Scrape off layer is opaque to neutrals.
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.
In H-mode, FA Antenna has Lower Impurity Contamination

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.
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.
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.

Weak Mo source response at the TA antenna when the FA antenna is powered.
Measurable Mo source response at FA antenna when TA antenna is powered.
FA Antenna Mo Source has Weaker Response to FA Power

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.
Engineering Performance has met or Exceeded Expectations

TA antenna $\Gamma$ and phase of $\Gamma$ ($\phi_\Gamma$) varies over wide range.

- From matching perspective, would like less variation in $\Gamma$ and little or no variation in $\phi_\Gamma$. 

\[ \Gamma = \left( \frac{p_{\text{refl}}}{p_{\text{forw}}} \right)^{1/2} \]

\[ \phi_\Gamma [\pi] \]
FA antenna has improved load tolerance.

- \( \Gamma \) and \( \phi_\Gamma \) variation is significantly reduced.
- From matching perspective, antenna is effectively load tolerant.
Engineering Performance has met or Exceeded Expectations

FA antenna has improved load tolerance.

- $\Gamma$ and $\phi_{\Gamma}$ variation is significantly reduced.
- From matching perspective, antenna is effectively load tolerant.

Achieved 45 kV and 9 MW/m$^2$ into plasma (meets ITER requirement).

- Antenna power is limited by voltage handling – injected power effectively is dictated by antenna loading.
- In L-mode, 3 MW have been coupled (~9 MW/m$^2$) high loading.
- In ELM free H-mode, 2 MW has been coupled (6 MW/m$^2$) low loading.
Measured Plasma Potential However is NOT Reduced

Plasma potential associated with the FA antenna is very similar to potentials observed from the TA antennas.

- GPI and emissive probe measurements are in agreement.

Integrated $E_\parallel$ does not set the plasma potentials.

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Monopole Phasing does not Perform as well as Dipole

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

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

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

Plasma response to monopole is significantly lower than dipole phasing.

Measured plasma potential is higher for monopole operation than that measured during dipole operation.
What Physics Influences the Plasma Potential?

Integrated $E_{||}$ is does not set SOL plasma potentials.

Plasma potential scales as $P_{RF}^{1/2}$.

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?

Investigate role of the ICRF antenna in setting plasma potential.

- Antenna protection tiles have been shown to draw electron current (ASDEX-U and TEXTOR).
- Does the tile geometry and orientation to the magnetic field play a role.
A field aligned ICRF antenna has reduced impurity contamination and impurity sources.

FA antenna operational characteristics are favorable.

- Antenna is more resilient to load variations than TA-antennas.
- Antenna has achieved voltages up to 45 kV and power density ~9 MW/m². (similar to expected ITER values).

Our physics understanding of FA antenna is incomplete.

- Plasma potentials associated with FA antenna operation are not remarkably different from TA 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.
Impurity influx during ICRF operation can limit plasma performance, particularly high performance discharges.

- ICRF heated H-mode performance with high Z PFCs is insufficient.
- Seek to develop ICRF antennas compatible with high performance discharges without needing to resort to boronization.

Detailed phenomenology often differs from device to device.

- In C-Mod, an impurity source at antenna is present but is not dominant and non-antenna sources are important.
- ASDEX-U data indicates primary RF source is the RF limiters.\(^1\)
- JET has identified the FS and sources away from antenna as important impurity sources.\(^2\)
- T-10 1985 field aligned antenna – need to find

1. R. Neu et al., 20\(^{th}\) Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen (2012).
2. V. Bobkov et al., 20\(^{th}\) Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen (2012).