



ICRF Actuator Development at Alcator C-Mod*

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Key Results:

- 1. Field aligned ICRF antenna has characteristics that scale favorably to expected reactor environment.
 - First demonstration that an ICRF antenna can be made with reactor compatible plasma facing materials due to near elimination of antenna impurity source.
 - First demonstration of an antenna that meets the ITER design requirement for RF enhanced heat flux RF enhanced heat flux is eliminated.
 - And is inherently load tolerant.
- 2. High melting temperature, high strength materials offer a path to improved electric field and power density limits for ICRF antennas.

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25th IAEA St. Petersburg

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ICRF power readily penetrates and strongly damps in reactor plasmas using reliable, efficient and economical sources.

Antenna performance is crucial to success.

- Impurity contamination more difficult with high Z metallic PFCs.
- RF enhanced heat flux steady state operation challenge.
- Load tolerance and long distance coupling reliable steady state power delivery.
- Voltage and power handling.

Low Z solutions utilized to ameliorate unwanted consequences from ICRF antenna operation are unsuitable for expected fusion reactor conditions.



ICRF Actuator Operation Compatible with High Z Metallic PFCs Would be Significant Milestone



C-Mod is an ideal device to investigate ICRF actuator compatibility:

Same density and field as ITER.

Strong single pass absorption.

High antenna power density (10 MW/m²)

• Exceeds anticipated ITER power density.

Solid high Z metallic (Molybdenum) plasma facing components

• Similar sputtering characteristics as tungsten.

Scrape off layer is opaque to neutrals.

Similar divertor geometry as ITER.

Field Aligned Antenna is Characterized by Symmetry along Total B-Field



Field aligned antenna utilized symmetry along B-field line to reduced unwanted parallel RF electric fields.

Field aligned antenna:

 has current straps, septa, and side protection tiles that are normal to the total B-field, ~10°. Alcator

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Classic antenna:

 has straps, septa, and side protection tiles normal to the toroidal B-field and is cylindrical



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Antenna Impurity Source has been Correlated with Core Contamination

- One of the fundamental drawbacks associated with ICRF antenna operation is a strong impurity source from the antenna when the antenna is energized.
- The measured molybdenum source at the antenna scales with antenna power
- Does field alignment result in reduced antenna impurity source.



B. Lipschultz et al., NF 2001





Antenna Impurity Source Has Weak Response when Antenna is NOT Energized

Compare the response of the local Mo source at each antenna when the Classic and Field Aligned antenna are separately energized.

Reference Mo antenna source is:

- Mo antenna source at the observed antenna when the antenna is NOT energized.
- Discharge is heated by other antenna.



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Observed

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• Mo source at the Classic antenna increases with each power step.







- Mo source at the Classic antenna increases with each power step.
- Molybdenum source at the Field aligned antenna when the Field aligned antenna is energized is no higher than the reference.
 - FA antenna impurity source increases weakly with RF power.



Observed

Energized

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Strong molybdenum source at the Classic antenna when the Classic antenna is powered.

- Mo source at the Classic antenna increases with each power step.
- Molybdenum source at the Field aligned antenna when the Field aligned antenna is energized is no higher than the reference.
 - FA antenna impurity source increases weakly with RF power.

First demonstration that an antenna can be made from reactor compatible plasma facing materials.



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Field Aligned Antenna Heated Discharges have Lower Impurity Contamination

Does a reduced antenna source result in lower impurity contamination?

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

With high Z metallic PFCs, plasma response is more favorable for power from Field Aligned antenna.

Impurity contamination is lower.

- Radiated power is 25% lower for comparable injected power.
- Core molybdenum content is also reduced.







Does a reduced antenna source result in lower impurity contamination?

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

To obtain H-mode, boronization is still required.

Impurity contamination is lower but not as dramatic as reduction in antenna impurity source



• Radiated power is ~25% lower for comparable injected power.

Possible explanation: RF is increasing impurity penetration.

• Plan to investigate impact of RF on impurity transport.

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RF enhanced heat flux is the heat flux that appears on the energized ICRF antenna.

- Heat flux appears when antenna is energized.
- Universally observed but antenna design dependent.
- For ITER, the ICRF antenna design specification has specified a RF enhanced heat flux of 6 MW/m² and 0.625% injected power deposited onto the energized antenna.
 - JET has measured between 2-10% injected power on the antenna.
 - Tore Supra has found ~3.5% for their classical antennas.



Visible light image of Classic C-Mod antenna shows interaction on the top and side tiles.

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Alcator C-Mod





Analyzed the thermocouple data over a three month operational period.

- Define reference discharges as discharges where the Classic antenna power >90% of total injected RF joules (blue squares).
- Compare with discharges where the FA antenna power injects >70% of injected RF joules (red squares).
- Discharges heated with the FA antenna have lower total energy deposited on FA antenna.









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- Estimated total RF enhanced heat flux energy is ~6 kJ per 1.5 MW injected or ~0.4%.
- First demonstration of an antenna that meets the ITER antenna design specifications.





- To maintain coupled power to the plasma, an ICRF antenna needs to be load tolerant
 - either intrinsically
 - or through external matching.
- Edge plasma density profile determines the antenna resistive loading.
 - Sets the distance to propagation and
 - Determines the transmission impedance.

Antenna geometry determines antenna reactance.

- Modified by plasma which breaks symmetry of the off diagonal terms in the impedance matrix.
- Plasma load variations are encountered during confinement transitions and edge localized mode (ELMs) activity.



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Reflection coefficient from Classic antenna occupies a large phase and amplitude range.

- Reflection coefficient is the square root of reflected power to forward power.
- Discharge has confinement transitions and ELMs.
- Variations are rapid (<100 μs)
- Impedance variation is both in magnitude and phase.



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- Field Aligned antenna reflection coefficient occupies less area than Classic antenna.
 - Impedance variation is reduced.
 - Impedance variation depends primarily on the real part of the antenna load.



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Antenna Impedance Matrix

$$Z_{ant} = \begin{bmatrix} a_{11} + jL_{11} & b_{12} + jM_{12} \\ b_{21} + jM_{21} & a_{22} + jL_{22} \end{bmatrix}$$

Generic antenna impedance matrix:

• a₁₁ and a₂₂ are the plasma resistive load





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Field alignment significantly reduces asymmetry in impedance matrix.

- b₁₂ and b₂₁ become negligible.
- Density profile changes should only result in changes in resistive load.





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ELMs Loading Perturbation is Largely Resistive for Field Aligned Antenna

- Edge density profile evolution with ELMs provides opportunity to hypothesis.
 - Changes distance to cutoff and propagation in SOL.
 - Expect field aligned antenna to have only resistive change in reflection coefficient.



- Refle Edge density profile evolution with ELMs 1.0 provides opportunity to hypothesis.
 - Changes distance to cutoff and propagation in SOL.
 - Expect field aligned antenna to have only resistive change in reflection coefficient.
- Field aligned antenna impedance change is due resistive change.
 - Classic antenna reflection coefficient phase and amplitude both vary.
- Plan to measure field aligned antenna impedance with and without plasma.
 - Measure load tolerance as function of plasma current – determine sensitivity of load tolerance to misalignment.



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Demonstrate Low Reflected Power for Plasma Discharges



Fixed matching stub was installed to lower reflected power in unmatched line.

- Prior to installation of stub average reflected power is 65%.
- Average reflected power after installation is ~17%.
- Maximum achieved power increased to 3.7 MW (4 MW source).

Plan to utilize active matching to maintain reflected power below 5%.





Materials offer Potential Path to Higher Breakdown Limits

- For reliable antenna operation, antenna needs to have high breakdown limits.
- Breakdown models suggest high melting temperature, high strength materials could offer path to higher breakdown limits.
- DC spark test experiments suggests candidate materials.



Advances in manufacturing open possibility to utilize materials that improve breakdown limits.





Refractory Materials have Higher Breakdown Voltage

RF breakdown can be different process from DC breakdown

- Examined range of materials utilizing 3λ/4 resonant line to produce high RF voltages.
 - Investigated bulk oxygen free, high purity copper, Inconel 625, tungsten and molybdenum.
 - Tungsten coated Inconel were also examined.

bulk tungsten and molybdenum show Both increase of ~40% over copper.

- Copper limit ~5.8 MV/m.
- Inconel achieved ~7.2 MV/m.
- Tungsten achieved 8.4 MV/m
- Molybdenum breakdown limit exceeds 8.4 MV/m.

40% improvement in field = doubling of power.







Tungsten Coating with Highest Density had Best Performance



Obtained highest voltage and conditioned quickly.

Voltage limit exceeded copper when surface condition was similar.

• Suggest higher density material would result in higher breakdown limit.

Plan to investigate high density (~99%) tungsten and molybdenum coatings.



Visible image of tungsten coating at breakdown





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