Assessment of a Field-Aligned ICRF Antenna*

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Key Results:

1. Novel, Field aligned ICRF antenna has reduced impurity contamination, impurity sources, and RF enhanced heat flux.

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.

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Outline

Description of field aligned antenna.

Impurity contamination and sources

RF enhanced heat flux to antenna and PFCs

Characterize RF enhanced plasma potentials.

Comparison of Dipole and Monopole heating effectiveness
Field Aligned Antenna

Antenna straps, septa, and side protection tiles are normal to the \textbf{total} magnetic field, $\sim 10^\circ$. 
Guiding Design Principle is Field Line Symmetry

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C-Mod ICRF has Similar Characteristics as ITER

Antenna power density exceeds anticipated ITER power density.
Strong single pass absorption (SPA).
Metallic PFCs (Mo) that has similar sputtering characteristics as tungsten.
Scrape off layer is opaque to neutrals.
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 dipole, estimated integrated $E_\|$ is reduced particularly at the peaks.
- For monopole, integrated $E_\|$ is significantly reduced.
  - Lower than dipole– a surprising prediction.
High Z metallic materials are favored for plasma facing components (PFCs).

- Impurity sources and contamination are more difficult to manage.
- Plasma tolerance of high Z materials is much lower than low Z materials.

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

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

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ICRF compatibility with high Z PFC has extensively investigated at C-Mod.
  • ICRF heated H-mode performance with high Z PFCs is insufficient.
  • ICRF impurity contamination has been 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).
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) sources are monitored with visible spectrometer:

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

Prior to boronization in L-mode discharges, 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 significantly reduced.
Core Mo is significantly lower for Field Aligned antenna compared to Toroidally Aligned antennas.

- Rise time on the core Mo content is significantly slower for the Field Aligned antenna than the Toroidally Aligned antennas.

Field Aligned antenna has lower radiated power.

- Radiated power is ~20-30% lower than for the Toroidally Aligned antennas in EDA H-mode.
Compare the response of the local Mo source for each antenna view when the Toroidally Aligned and Field Aligned antenna are powered separately.

Strong Molybdenum source response at the Toroidally Aligned antenna when the Toroidally Aligned antenna is powered.

• Mo source at the Toroidally Aligned antenna increases with each power step.
Compare the response of the local Mo source for each antenna view when the Toroidally Aligned and Field Aligned antenna are powered separately.

Strong Molybdenum source response at the Toroidally Aligned antenna when the Toroidally Aligned antenna is powered.

- Mo source at the Toroidally Aligned antenna increases with each power step.

Weak Molybdenum source response at the Toroidally Aligned antenna when Field Aligned antenna is powered.
Field Aligned Antenna Molybdenum Source Correlates with Toroidally Aligned Antenna Power

Measurable Mo source response at Field Aligned antenna when Toroidally Aligned antenna is powered.
Field Aligned Antenna Molybdenum Source has Weaker Response to Field Aligned Power

Measurable Mo source response at Field Aligned antenna when Toroidally Aligned antenna is powered.

Mo source response is lower at Field Aligned antenna when Field Aligned antenna is active.
Challenges for ICRF Utilization: RF Enhanced Heat Flux

RF enhanced heat flux needs to be managed to prevent exceeding the power handling capability of the antenna and other PFCs.

• Steady state operation becomes challenging.

Enhanced RF sheaths are thought to be the underlying physics

• Sheaths increase the energy per ion
• Radial profile results in convective cells that increase the particle flux.

In ITER, the ICRF antenna design assumes an RF enhanced heat flux of 6 MW/m².

• ~125 kW out of 20 MW or 0.625%
• JET has measured between 2-10% is found on the septum and antenna limiters
• Tore Supra has found ~3.5% for their classical antennas.
Field Aligned Antenna is Instrumented with Thermocouples

In 5 out of 9 protection tiles, the TZM tiles are instrumented with thermocouples.

- Thermojunction is pressed in direct contact with the TZM tile.
- Thermocouple response time is insufficient to calculate the surface temperature or heat flux.
- Use before and after shot temperatures with the tile mass and surface area to calculate the energy flux for each instrumented tile.

Side protection tiles are expected to receive the majority of the heat flux.

- FS rods, top and bottom tiles are shadowed by 5 mm and 3 mm, respectively.
Total Energy Deposited is Lower with FA Antenna Powered

Analyze the thermocouple data over a three month operational period.
  - Includes L-mode, H-mode
  - Current scan Ip=0.6-1.3 MA
  - Various outer gaps, 0.5-2 cm.
  - Primarily dipole phase with few monopole discharges.

Isolated discharges where the FA antenna power (63 discharges) is greater than 0.7 on injected RF joules (red squares).

Compare with discharges where TA antenna power > 0.9 of the injected power (111 discharges).

Discharges heated with the FA antenna have lower total energy deposited.
  - Monopole phasing has elevated energy deposited – about 3x that of dipole.
Spatial Distribution of Deposited Energy is Similar

Profile is similar regardless of which antenna is powered.
  - Top (#1) and bottom (#9) tiles have majority of deposited energy.

When field aligned antenna is powered, tile #9 has less the 0.8 kJ deposited energy.
  - Data above 0.8 kJ are discharges with lower hybrid power, locked mode discharges, or increasing power from TA antenna.

Monopole phasing causes increased deposited energy on top tile.

Estimate the total power deposited as a fraction of the coupled RF energy
  - linearly interpolate the energy deposited on tiles #2, #3, #7, and #8 ~ roughly doubles the measured deposited energy.
  - Assuming an equal amount on the right set of side protection tiles
  - the total deposited energy is ~6 kJ for 1.5 MJ injected or 0.4%.
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.
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.
Field aligned antenna impedance change is due resistive change.

- Toroidally aligned antenna Q and impedance both vary.

Speculation: antenna impedance matrix becomes symmetric due to field alignment.

Generic antenna impedance matrix:

- $a_{11}$ and $a_{22}$ are the plasma resistive load
- $L_{11}$ and $L_{22}$ are the strap self inductance
- $M_{12}$ and $M_{21}$ are mutual coupling
- $b_{12}$ and $b_{21}$ represent the coupling through the plasma – particularly $E_{||}$

Coupling variation through plasma results in large changes in reflection coefficient.

$$Z_{ant} = \begin{bmatrix} a_{11} + jL_{11} & b_{12} + jM_{12} \\ b_{21} + jM_{21} & a_{22} + jL_{22} \end{bmatrix}$$
ICRF interaction with SOL: What is $E_{||}$ Role?

Oscillating $E_{||}$ leads to DC sheath rectification.

- I-V curve is highly non-linear and leads to excess electron collection in presence of RF.
ICRF interaction with SOL: What is $E_\parallel$ Role?

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

Radial profile of RF enhanced sheaths leads to convection.

$E_\parallel$ interacts with SOL results in variation in off diagonal terms in the antenna impedance matrix.

Does a field aligned antenna reduce RF enhanced sheaths?
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.
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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- Poloidal velocity and corresponding $E_r$ are small in ohmic discharge.
- 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.
Measured Potential for Field Aligned and Toroidally Aligned Antennas are Similar

- 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.
  - Furthermore, difficult to reconcile lower impurity sources and contamination with E|| unchanged.

\[ \phi_{\text{max}} (V) \quad \text{vs.} \quad P_{\text{ICRF}} \text{ (MW)} \]
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.
What is Underlying Physics of Poor Performance with Monopole Phasing

Wave spectrum is peaked at long wavelength if one only considers the antenna straps.

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

![Power Spectrum Graph](image)
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.

Re(E+) (kV/m)

Monopole

Dipole

Currents Add

Currents Cancel
Test Hypothesis with Mode Conversion Absorption Scenario

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.
- Reconstruct antenna impedance matrix from antenna-plasma model to investigate role of magnetic field and off diagonal terms.

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?
Hypothesis: does a field aligned antenna improve ICRF antenna performance?

- reduced impurity contamination and impurity sources,
- has low RF enhanced heat flux, and
- is more resilient to load variations than toroidally aligned antennas.

However, our physics understanding of Field Aligned antenna is incomplete.

- Plasma potentials associated with field aligned antenna operation are similar to toroidally aligned antenna operation.
- 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.