Taming the ICRF antenna - plasma edge interaction using novel field-aligned ICRF antenna on Alcator C-Mod

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A solution for two major issues of ICRF application: transients and impurity

ICRF (ion cyclotron range of frequencies) heating is attractive in heating fusion reactor-grade plasmas (20 MW on ITER):
– reliable power source, readily penetrates and strong absorption.

Two of the remaining major issues:
• Maintain reliable antenna operation during transients, including L→ H transitions and ELMs;
• Minimize impurity generation and impurity flux associated with ICRF heating.

We have discovered a solution for both issues on Alcator C-Mod: Field Aligned (FA) antenna

Y. Lin et al, YI1.00003, “Field-aligned ICRF antenna on Alcator C-Mod”
Outline of the talk

1. Introducing the field-aligned antenna

2. Dealing with transients: antenna loading resilience of the FA antenna

3. Impurities reduction: near elimination of the FA antenna itself as an impurity source

4. Summary
1. Introducing the field-aligned (FA) antenna
Replaced a 4-strap traditional antenna with a 4-strap FA antenna in 2012

Color coding for data representation

Red

Blue
Rationale behind FA: geometrical symmetry may help lower impurities

Motivation: minimize impurity contamination associated with ICRF heating

Background:
- Oscillating $E_{||}$ leads to voltage rectification on the field lines (because ions and electrons respond differently) and produces a sheath region.
- Ions accelerated by the RF sheath can generate sputtering and increase impurity source.

Thought process:
- Field alignment $\rightarrow$ reduce integrated $E_{||}$ $\rightarrow$ lower RF sheath $\rightarrow$ less sputtering $\rightarrow$ fewer impurity sources $\rightarrow$ lower impurities in the plasma
Field Aligned (FA) antenna seeks geometrical symmetry along field lines.

Field Aligned Antenna
Antenna current straps are perpendicular to the total magnetic field (5.4 T, 1.0 MA plasmas)
Antenna shape conforms to typical plasma shape.
Source power 4 MW@78 MHz

Traditional Antenna
Antenna current straps are perpendicular to the toroidal field.
Antenna shape is cylindrical.
Source power 4 MW@80 MHz
2. Dealing with transients: loading resilience of the FA antenna
ICRF system prefers adequate and resilient antenna loading

- There is always an unmatched transmission line section where voltage can be very high.
- Plasma transients can cause significant changes in antenna loading.
- An ideal antenna:
  - Adequate loading so that high RF power can go through the transmission line without breaching the voltage limit (typically ~40 kV);
  - Resilient loading under various plasma conditions.
Antenna loading is sensitive to plasma edge and plasma transients

- The resistive part of the antenna loading is determined by the edge plasma density profile
  - Sets the distance to propagation;
  - Determines the transmission impedance.

- The capacitive part of antenna loading (reactance) is mostly determined by antenna geometry.

Edge density profile of a typical H-mode plasma is shown. SOL and pedestal both affect the antenna loading.
FA antenna loading is resilient during L-H transitions

- Complex reflection coefficient on the un-matched transmission line:
- Equivalent resistive loading:

\[
\Gamma = \sqrt{\frac{P_{\text{ref}}}{P_{\text{forw}}}} = |\Gamma|e^{i\theta}
\]

\[
R(\Omega) = 50 \left( \frac{1 - |\Gamma|}{1 + |\Gamma|} \right)
\]

- After a L-mode to H-mode transition, SOL density is reduced and pedestal is steeper \(\rightarrow\) typically lower antenna loading, as seen in rising \(|\Gamma|\) in both antennas
- Nearly zero change in \(\theta\) for the FA antenna \(\rightarrow\) little change in antenna reactance

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FA antenna loading is also less sensitive to ELMs

- ELMs typically increase antenna loading (smaller $|\Gamma|$)
- FA antenna is less sensitive to ELMs, shown in both $|\Gamma|$ and $\theta$. 

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The loading of the FA antenna has similar dependence vs. plasma parameters, but it is contained within a much tighter range.
The phase variation of the FA antenna is closer to zero.
Loading variation of the FA Antenna is largely only resistive (in $|\Gamma|$ only)

- The FA antenna loading variation is mostly resistive, while the traditional antenna is both resistive and capacitive.
- The insensitivity to ELMs may be due to the fact that the effect of “common-mode” plasma variation on a field line is canceled on the FA antenna.
- Antenna impedance matrix may have become 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 $E_{||}$

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

Detailed measurement of the antenna impedance matrix with plasma will be carried out next campaign.
Loading resilience makes possible a simple solution for pre-matching
Lower transmission line voltage increases reliability and RF power

Installing pre-match stubs greatly reduced the voltage in the transmission line for ALL plasma conditions.

\[ V_{\text{max}}(kV) = \sqrt{100P_{\text{net}}(MW) \left( \frac{1 - |\Gamma|}{1 + |\Gamma|} \right)} \]

Before FA antenna power up to 3.7 MW \( \rightarrow \) 11 MW/m\(^2\), much higher than ITER ICRF antenna.

Complex \( \Gamma \)

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3. Impurities reduction: near elimination of the FA antenna itself as an impurity source
Elevated impurities associated with ICRF heating remains a challenge

- ICRF antennas have to be installed quite close to the plasma. As a result, elevated impurities have always been associated with ICRF heating on tokamaks, especially in machines with high-Z wall material.

- Two separate aspects for impurity problem:
  - Where do the impurities come from? Impurity sources: from the antenna and also from the wall.
  - How do the impurities get in? Impurity transport: the ICRF field in front the antenna and RF sheath may play a role in affecting the transport.
ICRF power causes boron coating erosion and degrade performance

- C-Mod is a all solid high-Z metal (Mo) wall tokamak.
- Plasma performance with pure Mo wall was not great and low-Z coating is regularly applied.
- Boron coating can improve performance, but the effect starts degrading after about 40 MJ energy from ICRF.

ICRF power erodes the low-Z wall coating, and then increases impurity sources

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Impurities originated from the antenna are correlated with core impurity level

- Strong impurity source from the antenna when the antenna is energized is observed.
- The measured molybdenum source at the antenna scales with antenna power.

- Does FA antenna result in reduced impurity source from the antenna? [Yes, greatly]
- Does it result in reduced core impurity level? [Yes, but not as dramatic]

B. Lipschultz et al., NF 2001
Local antenna impurity source is nearly eliminated for the FA antenna

- Strong molybdenum source at the traditional (classic) antenna when the antenna is powered.
- Mo source at the FA antenna when the FA antenna is energized is no higher than the reference level* (increasing weakly with the RF power).
- Elimination of the antenna itself as an impurity source $\rightarrow$ ICRF antennas can be made from reactor compatible plasma facing materials.

*Reference level: Mo source level measured from the FA antenna while the classic antenna is powered.
FA antenna generates lower impurity in L-mode (before boronization)

- L-mode plasmas at same $n_e$, $B_t$, $I_p$ and $P_{RF}$.
- FA antenna produces much lower total radiated power and higher $T_e$ and stored energy.

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Performance enhancement is also seen in H-mode plasmas

- More slowly rise in $P_{\text{rad}}$ for FA antenna;
- Consistent with a lower impurity source.

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In I-mode plasmas, FA antenna also shows lower $P_{\text{rad}}$.

- I-mode plasmas: same target density, $B_t$, $I_p$ and $P_{\text{RF}}$.

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However, RF sheath seems NOT to have been reduced in FA antenna

The FA antenna has reduced the impurity source and impurity level, but the RF sheath is not reduced.

→ RF sheath is probably not the main reason of the impurity reduction.

Question: what are other possible mechanisms?

The FA antenna appears to have the same RF sheath potential as the classic antenna.
ICRF induced convective cells

- Potential is higher in from the antenna and top and bottom.
- Convective cells increase density flux to the antenna, and can affect both impurity source AND impurity transport.
Alignment of convective cells with the antenna may be a key

- Thinking the picture in 3-D, FA antenna is also aligned with the convective cells. A key in explaining the reduced impurity?
- Intentionally creating cases where the FA antenna does not perform as well → preliminary evidence supporting this picture
Plasma shape alignment appears to be important

Intentionally move plasma lower vertically
→ the FA antenna does not conform to this plasma shape
→ Significant increase of $P_{rad}$ and core Mo is observed
→ Result in poorer plasma performance than traditional antenna.

Red, FA shape aligned

Green, FA Shape mis-aligned

Blue, shape misaligned

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ICRF induced convective cells have been directly measured

- Gas puff imaging measurement near the edge.
- Dramatic change in $E_r$ with application of RF.
- In the far SOL, turbulence is at the local $E \times B$ velocity.
- Data so far are from classic antenna.
- We plan to do more detailed study next campaign.
4. Summary
Field-aligned antenna has been a great success on Alcator C-Mod

FA antenna has helped resolve two important ICRF issues:

1. Maintain reliable antenna operation during transients, including L→H transitions and ELMs;
2. Minimize impurity generation associated with ICRF heating.

Based on what we have learned so far, we are seriously considering a second field-aligned antenna on Alcator C-Mod (to be ready for the 2016 campaign).
Supplemental Slides
Near term plan

• Antenna impedance matrix evaluation
  – Installed more current and voltage probes on the antenna.

• Antenna and impurities
  – Experiment on impurity penetrations.

• 2\textsuperscript{nd} FA antenna
  – Based on the good performance of the first FA antenna
  – Move ICRF antenna away from the lower hybrid launcher (and reduce interaction).
Small field-line misalignment is tolerable in terms of performance

- At different plasma currents, the field-alignments are slightly different;
- FA antenna is slightly better in all cases.

\[ I_p = 0.6 \text{ MA} \]
\[ I_p = 0.8 \text{ MA} \]
\[ I_p = 1.0 \text{ MA} \]

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Former 4-strap antenna is typically slightly worse than the 2x2-strap antenna.