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Alcator C-MOD ICRF Antenna and Matching Circuit

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Abstract

Alcator C-Mod will be a compact, high field, high density, divertor tokamak. Two FMIT transmitters will supply 4 MW of power in 1 sec pulses at 80 MHz for ICRF heating. Fast wave minority heating experiments are planned in D(^{3}He) at 8 T and D(H) at 5.5 T. The first antenna will have a single current strap inside a box structure, which will be movable radially. The antenna will be inserted through a side port, making the rf power density on the antenna surface ~2 kW/cm^2 at 2 MW. The antenna will be center-tapped for mechanical strength and have a double layer Faraday screen tilted along the field lines. The antenna geometry was chosen to maximize power coupling assuming voltage-limited operation. A wide antenna with slotted box sides appears the best design, and 10 Ω of loading is required to couple 2 MW of power at a voltage limit of 40 kV. Matching is achieved by choice of the drive point to a resonant circuit formed by the antenna and a loop of transmission line outside of the vacuum and by tuning elements in the transmission line to the transmitter.

I. Introduction

Alcator C-Mod is a compact (R=66 cm, a=20 cm), high field (9 T), high density ($\bar{n}$=1-10$\times10^{20}$ m^{-3}, elongated (κ=1.8-2), divertor tokamak. Up to 3 MA of toroidal current will provide a hot ($T_e \sim T_i \sim$ several keV) ohmic plasma and good confinement for high energy minority ions. Fueling will be by gas puffing and/or pellets. Fast wave heating experiments are planned in the minority heating regime for ^{3}He in a deuterium plasma at 8 T and D(H) at 5.5 T. The ICRF heating system for the Alcator C-Mod tokamak will provide 4 MW of power in 1 sec pulses at 80 MHz from two FMIT transmitters. The first antenna to be installed in Alcator C-Mod will have a single current strap and will be movable radially. The antenna will be inserted fully assembled through a side port. The goals with this antenna will be to study coupling and heating in high density, shaped, diverted discharges. The initial experiments will establish the radial location of the antenna relative to the separatrix, the best plasma shape, and the disruption speed. This knowledge will aid in designing a second, optimized antenna which will likely have two phased current straps and require internal assembly.

II. Antenna and Matching Circuit Design

The basic features of the design are a center-tapped current strap for mechanical strength, the widest current strap that can be fit through the port opening, slotted sides on the antenna box, and a double layer Faraday screen tilted along the field lines. The antenna is driven from each end 180° out of phase. The antenna is modular in design such that the box sides, current strap, Faraday screen elements, and protection limiters are separately replaceable. The antenna configuration is shown in Fig. 1. The mechanical and thermal analyses of the antenna structure are discussed in a companion paper.[1]

The requirements of the structural support against disruption forces and the narrow port opening restrict the size of the two coaxial feeds to the current strap to 5" OD. The 5" line will have a characteristic impedance of $\sim 30\Omega$. The feeds to the antenna ends are connected together outside of the vacuum region to form a closed loop which is three wavelengths long. By forming this resonant loop, the antenna can be fed at a low impedance point in the loop while maintaining the desired out of phase excitation.[2] Between the resonant loop and the transmitter, a phase shifter and stub tuner are used to match the input impedance of the loop to the 50 Ω transmission line. The resonant loop and matching circuit are shown in Fig. 2. At the tranmitters, three coaxial switches will be used to allow flexibility in operation of the ICRF system. It will be possible to connect the driver (~130 kW), the final power amplifier (Eimac X2242, ~2 MW), or a low power source or network analyzer to the antenna without any reconnecting of components. Tuning of both the driver and the final amplifier into the dummy load will also be possible.

The choice of a wide antenna relative to the size of the cavity was made by analyses which assumed that the power limiting factor would be the peak voltage. It may be that the limit will be the high power density on the antenna surface, but the constraint that the antenna be inserted through the port opening sets the power density independent of the particular antenna geometry. Similar codes by Mau[3] and Ryan[4] study the effects of cavity geometry both on the coupling to the plasma and on the antenna inductance. The coupled power in voltage-limited operation may be written $P = (1/2\omega^2)\ (R/L^2)\ V^2$ where R is the plasma loading on the antenna and L is the antenna inductance. Maximizing R/L^2 couples the highest power at the voltage limit. Lower inductance reduces the voltage on the antenna for a given current ($I=V/\omega L$). Typically, geometrical effects that increase R also increase L making the design a trade-off between these two parameters. Results of the Ryan code are shown in Fig. 3 for a variety of geometries. It can be seen that a wide strap and open box sides maximize R/L^2, with a deeper box having a weaker effect. In practice, opening the box sides is accomplished by slotting the sides to allow the rf magnetic flux to penetrate. The case indicated by the circled point on the top curve was chosen, with a wide current strap and the sides slotted halfway. Opening the sides completely both weakens the structure and might allow neutral gas to build up in the box.

Another code using transmission line models for the antenna and matching system determines the peak voltage and its position in the system for a given plasma loading. The most difficult part of the antenna to model is the inductance because of the complicated geometry of the current strap and box, including the radial feeds. A mock-up of the antenna geometry was constructed and laboratory measurements of the inductance were used to correct the code calculation. The correction to the code model for a bare antenna (no cavity sides or Faraday screen) were only 15-20%. Using the geometry chosen from Fig. 3 in the transmission line code gives the important prediction that for a voltage limit of 40 kV, 10 Ω of loading are required to couple 2 MW from the antenna. This loading level is consistent with predictions from the Brambilla code.[5] A voltage limit of 40 kV has been achieved in experiments but the power density at 2 MW (∼ 2 kW/cm^2) is still about a factor of two higher than was achieved experimentally in Alcator-C at high densities ($n_e \gtrsim 3 \times 10^{20} cm^{-3}$).[6] However, with divertor operation and pellet fueling in Alcator C-Mod, steeper edge profiles are expected. This may facilitate operation at higher power densities than in Alcator-C.

The transmission line analysis is also used to choose the drive point in the resonant loop. Figure 4 shows the chosen operating point, which reduces the VSWR that must be tuned out by more than a factor of two while still maintaining out-of-phase excitation of the antenna. The sensitivity of the tuning to changes in plasma loading was studied. The VSWR remains below 1.5 for changes in resistive loading of up to 40%. However, only 2% changes in the reactive loading can be tolerated. A double layer Faraday screen was chosen, in part, to reduce the sensitivity to changes in reactive loading, at the expense of some reduction in resistive loading.

A vacuum test stand with a full-scale C-Mod side port will be available for antenna testing prior to installation in C-Mod. Vacuum conditioning techniques for reaching the maximum voltage standoff will be established. The effect of bake out on the antenna structure will be tested as well as the ease with which the antenna can be tuned. The control and data acquisition system that will be used during tokamak operation will be developed and tested while the antenna is on the test stand. The results of the test stand work, along with knowledge gained from initial experiments will feed into the design of the second antenna. An antenna design incorporating two current straps fed through a single port will be pursued.[1]

III. Control and Diagnostics

The instrumentation and control requirements for the ICRF system fall into two categories. First are the control and monitoring on a shot-to-shot timescale, which will be done by a PLC (programmable logic controller). Second are diagnostics that monitor conditions during a shot through CAMAC. The PLC system will control movement of the antenna and tuning elements, moniter status, and provide safety interlocking. Diagnostics such as thermocouples on the antenna assembly and pressure in the coaxial line will be monitored by the PLC. The user interface and status display for the PLC will be an IBM PC with color monitor using commercial software. Appropriate design of the display will allow the PLC to flag problems or dangerous situations.

Data from diagnostics on a fast time scale during a shot will be acquired by CAMAC. The most important of these will the antenna loading. The loading will be measured in three different ways in the antenna system. There will be two bi-directional couplers, one between the resonant loop and the tuning elements to measure the mismatch that must be tuned out and one at the transmitters to measure the matching to the 50 Ω line. By measurement of the forward and reflected voltage and their relative phase, the complex reflection coefficient can be determined. There will also be two sets of voltage probes spaced along a half wavelength to measure the VSWR. Knowing both the VSWR and the position of the voltage maximum allows evaluation of the complex impedance at any point in the line. One probe set will be in the resonant loop to determine the input impedance of the antenna. Another will be between the resonant loop and the tuning elements to determine the input impedance of the resonant loop, supplying a redundant measure of the mismatch to be tuned out. The better this can be characterized, the fewer shots will be required to tune the antenna, a very important consideration on a device with a 20 minute shot cycle. Finally there will be magnetic pickup loops in the antenna box to measure the antenna current directly. The combination of these measurements with an appropriate antenna model will provide a measure of the load resistance.

Emphasis will be placed on diagnostics of the edge plasma during ICRF. There will be at least three sets of RF probes distributed around the torus to look at surface wave excitation. Each set will include 2-3 orthogonal magnetic probes and a high frequency electrostatic probe. Sets of Langmuir probes will measure the RF perturbation of the edge temperature and density profiles. A periscope will allow observation of the front of the antenna during the plasma pulse. Impurity generaton will be studied spectroscopically both at the edge and in the core plasma. There will also be a CO_2 laser scattering diagnostic to look at RF effects in the plasma core, such as Bernstein wave excitation near the mode conversion layer.

References

[1] Y. Takase et al., this conference.

[2] J. R. Wilson et al., in *Proceedings of the 7th Topical Conference on Applications of Radio-Frequency Power to Plasmas*, Kissimmee, FL (AIP, New York, 1987), p. 294.

[3] T. K. Mau et al., *IEEE Trans. Plasma Sci.* **PS-15**, 273 (1987).

[4] P. M. Ryan et al., in *Proceedings of the 15th European Conference on Controlled Fusion and Plasma Heating*, Dubrovnik, 1987, part II, p. 795.

[5] M. Brambilla et al., *Nucl. Fusion* **28** 549 (1988).

[6] T. D. Shepard, Ph.D. Thesis, MIT, 1988.

Figure Captions

Figure 1. The side view with a partial cutaway of the ICRF antenna in an Alcator C-Mod side port.

Figure 2. The layout of the external resonant loop and matching circuit for the antenna

Figure 3. The effects of the antenna geometry on power coupling to the plasma. Plotted is the plasma load resistance over the antenna inductance squared, which is proportional to the coupled power for a fixed voltage, versus the length of the antenna box sides relative to the total depth of the box (cavity). The parameters for the curves are the current strap width S and the box depth D.

Figure 4. The effect of the choice of drive point in the resonant loop on the phase of the antenna excitation, the input impedance (resistance) of the resonant loop, and the VSWR that must be matched to 50 Ω by the phase shifter and stub tuner. The vertical line indicates the chosen drive point.

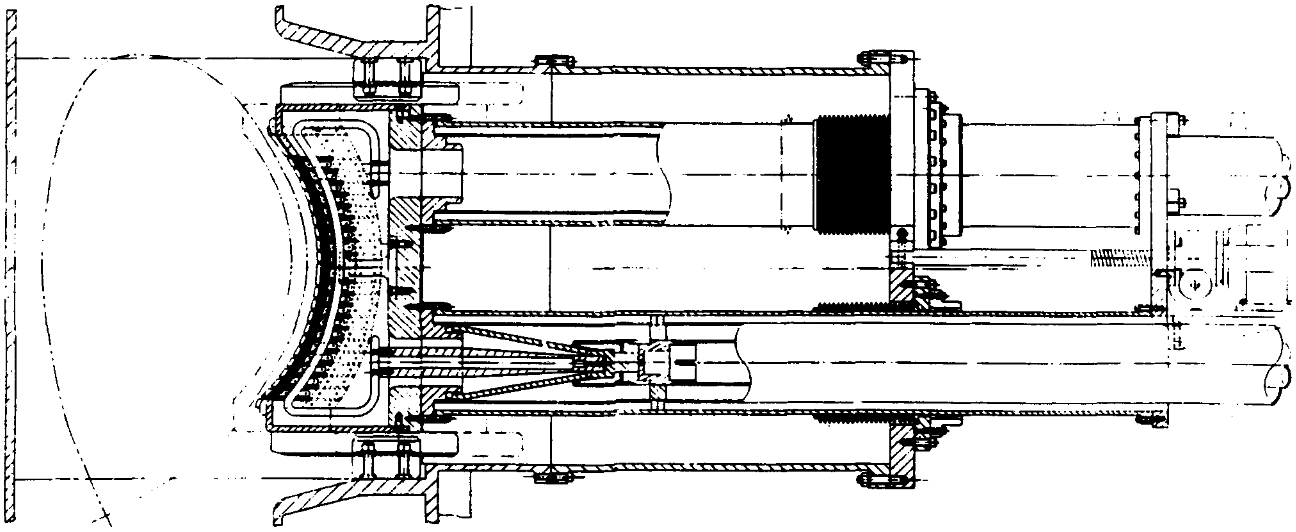

Figure 1

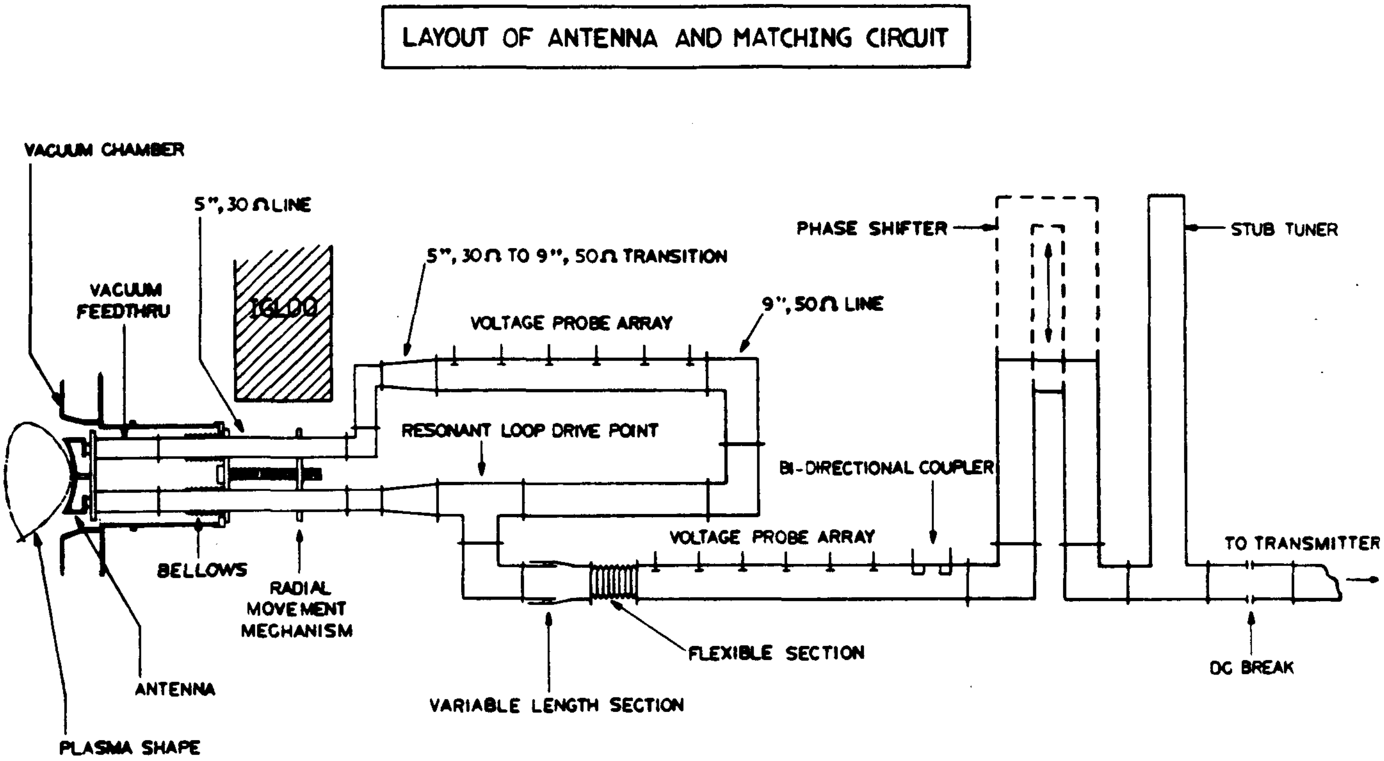
LAYOUT OF ANTENNA AND MATCHING CIRCUIT
VACUUM CHAMBER
5", 30 Ω LINE
VACUUM FEEDTHRU
IGLOO
5", 30 Ω TO 9", 50 Ω TRANSITION
VOLTAGE PROBE ARRAY
9", 50 Ω LINE
PHASE SHIFTER
STUB TUNER
RESONANT LOOP DRIVE POINT
BI-DIRECTIONAL COUPLER
VOLTAGE PROBE ARRAY
TO TRANSMITTER
BELLOWS
RADIAL MOVEMENT MECHANISM
ANTENNA
PLASMA SHAPE
FLEXIBLE SECTION
VARIABLE LENGTH SECTION
DC BREAK

Figure 2

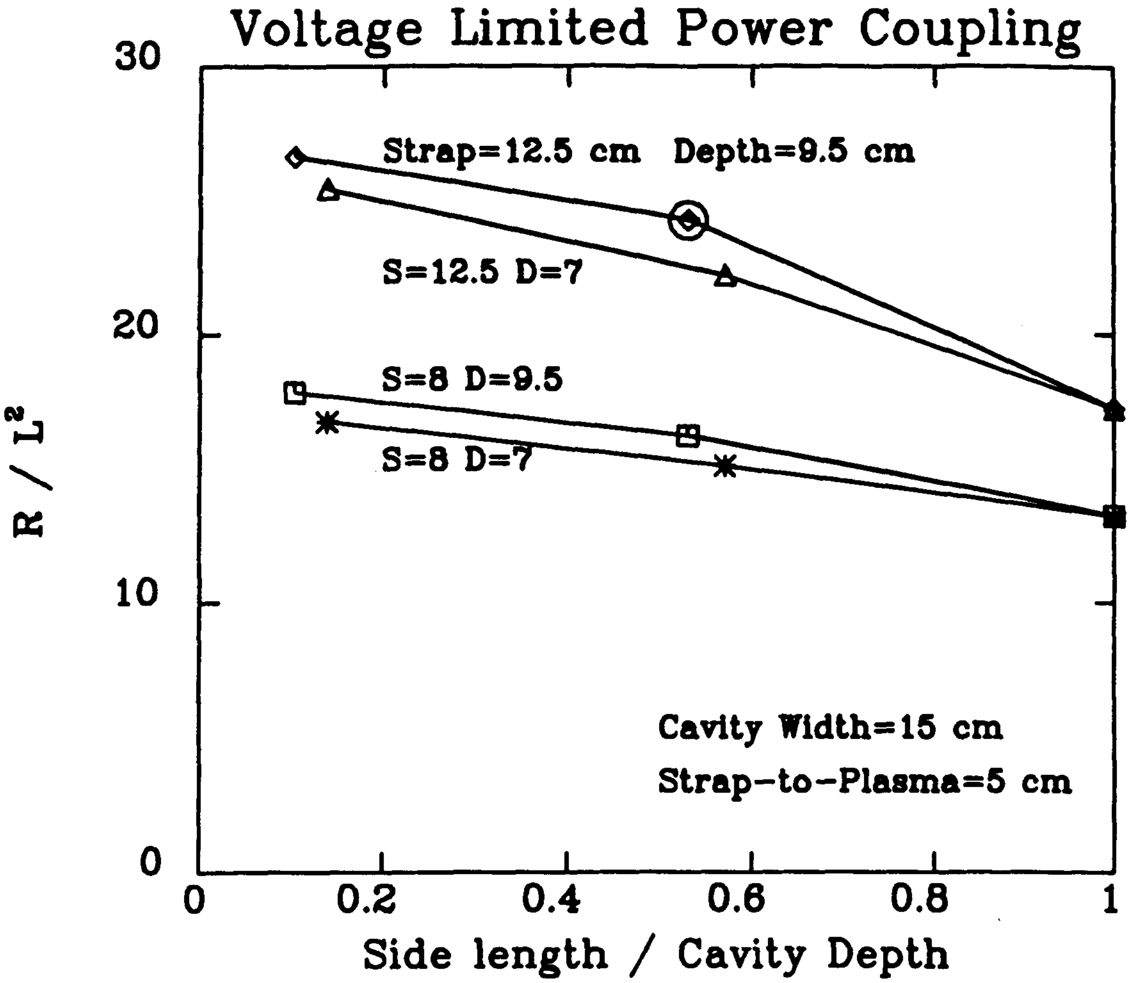
Voltage Limited Power Coupling
Strap=12.5 cm Depth=9.5 cm
S=12.5 D=7
S=8 D=9.5
S=8 D=7
Cavity Width=15 cm
Strap-to-Plasma=5 cm
R / L²
Side length / Cavity Depth
0
10
20
30
0
0.2
0.4
0.6
0.8
1

Figure 3

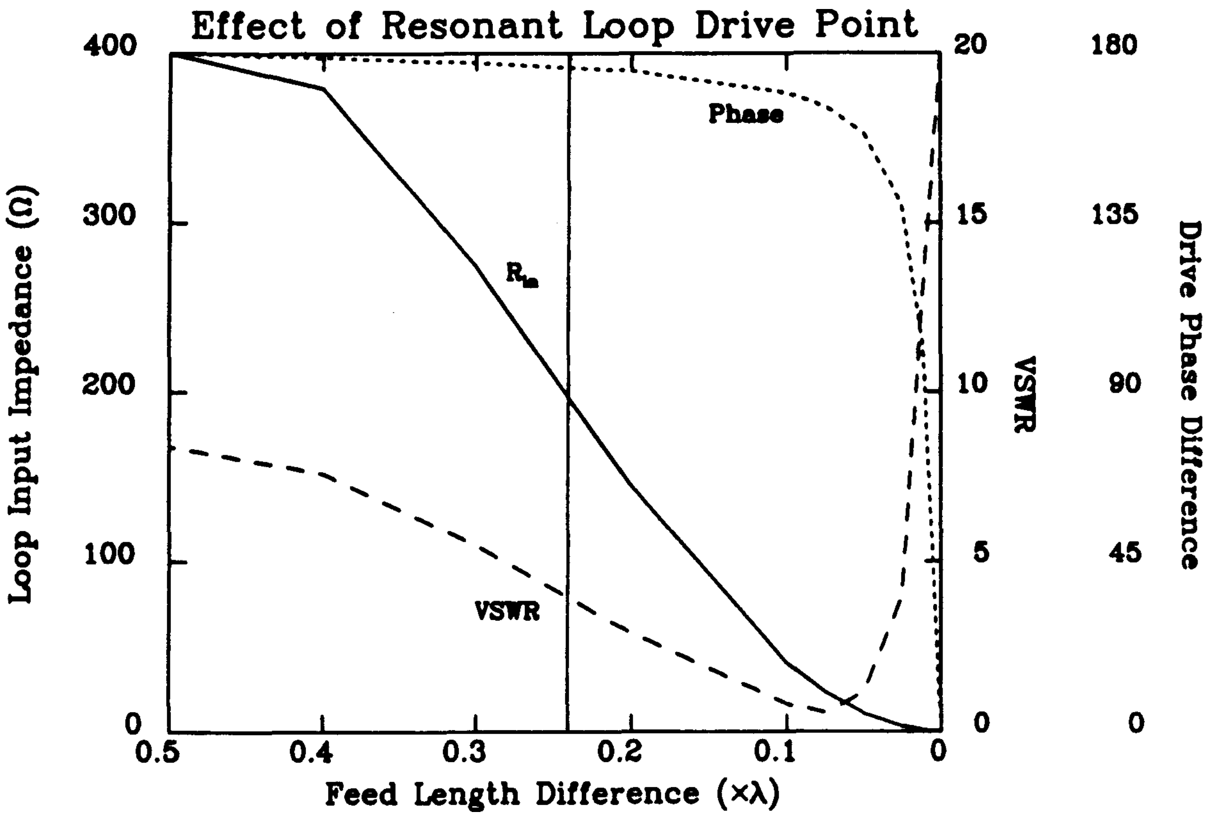
Effect of Resonant Loop Drive Point
Loop Input Impedance (Ω)
400
300
200
100
0
0.5
0.4
0.3
0.2
0.1
0
Feed Length Difference (×λ)
20
15
10
5
0
VSWR
180
135
90
45
0
Drive Phase Difference
Phase
R_{in}
VSWR

Figure 4