Design Concepts For A Long Pulse Upgrade For The DIII-D Fast Wave Antenna Array

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Abstract. A goal in the 5-year plan for the fast wave program on DIII-D is to couple a total of 3.6 MW of RF power into a long pulse, H-mode plasma for central electron heating. The present short-pulse 285/300 antenna array would need to be replaced with one capable of at least 1.2 MW, 10 s operation at 60 MHz into an H-mode (low resistive loading) plasma condition. The primary design under consideration uses a poloidally-segmented strap (3 sections) for reduced strap voltage near the plasma/Faraday screen region. Internal capacitance makes the antenna structure self-resonant at 60 MHz, strongly reducing peak E-fields in the vacuum coax and feed throughs.

Keywords: DIII-D, RF Heating, Fast Wave Antenna
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INTRODUCTION

The Fast Wave heating system on DIII-D consists of three 4-strap antenna arrays, each powered by a 2 MW transmitter. The 0° and 180° arrays are long-pulse (nominal 10 s) antennas capable of operating over a 60-120 MHz frequency range. The 285°/300° array is an uncooled, short pulse (~ 2s) system presently operating at 60 MHz [1]. The DIII-D 5-year plan has a fast wave goal of coupling a total of 3.6 MW into a long pulse, H-mode plasma for central electron heating [2]. To accomplish this, the present 285°/300° antenna will need to be upgraded for long pulse and high power operation into the low electrical loads presented by ELMing H-mode plasmas. Due to thermal concerns, DIII-D requires the gap between the first wall and the last closed flux surface to be 6 cm or greater for high power NBI-driven H-mode plasmas. The electrical load presented by such plasmas to the 285°/300° antenna is a relatively low 0.3-0.5 Ω (specific loading of 2-3.5 Ω/m) [3]. Developing reactor-relevant antenna technology is not a primary goal of the DIII-D program. This allows for simplified fixed-frequency designs and relaxed material constraints compared to broadband systems designed to operate in a remote-maintenance, high flux neutron environment.

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ANTENNA DESIGN APPROACH

The general design philosophy for robust, reliable operation is to minimize both the E-fields and the voltages in the structure, particularly in the immediate vicinity of the plasma. All antennas are fairly high-Q resonators that must be matched to the relatively high characteristic impedance of the transmission system to minimize the reflected power to the transmitter and the VSWR on the lines. High currents are needed near the plasma to generate the requisite B-field for power coupling, but the charge (and associated surface E-field) required to provide this current should be stored in a controlled, protected environment, shielded as much as possible from the plasma. Charge stored more than $\lambda/2$ from the strap ground is not useful since it does not contribute to the antenna currents.

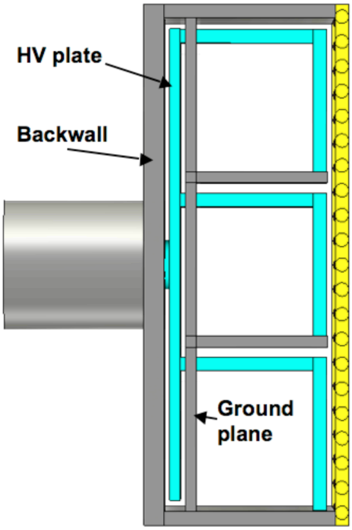
The approach taken to minimize strap voltage is to break the reference strap into N short segments fed in parallel. For the same strap current and inductance per unit length, the peak voltage on the straps in the vicinity of the plasma would be reduced by approximately a factor of N. N = 3 was chosen as an acceptable compromise between reduced voltage ($\propto 1/N$) and space wasted by the breaks ($\propto N$). The E-field was further reduced by increasing the 7 mm minimum gaps in the reference design to 10 mm in the upgrade. Positioning the capacitance needed for charge storage as close to the straps as possible was a goal for reducing the system voltage to a minimum. This capacitance would resonate the structure at the design frequency (60 MHz in the cases studied here). This clamps V_{max} to a value close to the strap voltage and presents a real terminating impedance so that the voltage elsewhere in the unmatched section of transmission line would not exceed the value on the capacitor.

The antenna designs were evaluated with the 3D, finite integral electromagnetic code CST Microwave Studio. Two straps of the 4-element array were modeled; one was the existing 110 mm wide, 450 mm high strap used as a reference. Wherever possible, the new antenna design was constrained to fit within the envelope of the existing array enclosure. The plasma load was simulated by a lossy dielectric with its conductivity adjusted to give a terminating impedance of ~ 0.5 Ω to the reference strap (σ = 0.2 S/m). In all cases the evaluation was made at the maximum transmitter capability of 2 MW.

CHARGE STORAGE OPTIONS

Parallel Plate Vacuum Capacitance

The most basic charge storage option is a parallel plate capacitor located behind the current strap. Figure 1 shows the basic segmented strap configuration. The capacitor consists of a high voltage plate sandwiched between two ground planes and fed by the coax line. For 110 mm wide straps, capacitance of around 360 pF is needed to resonate at 60 MHz, resulting in 2.8 mm capacitor gaps for a 440 mm x 174 mm plate. These gaps can be increased to 5 mm by decreasing the strap width to 40 mm; however, this higher inductance increases the peak voltage on the segments from 35% of the voltage on the reference strap to 49%. These gaps are considered too small to be practical, particularly since high vacuum cannot easily be maintained in this region.



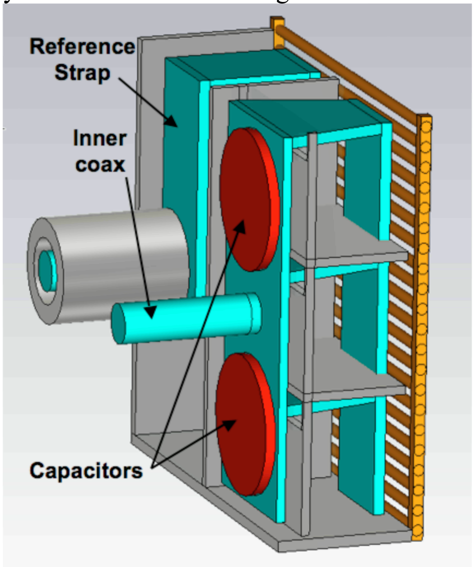


FIGURE 1 Double-parallel plate vacuum capacitor formed by HV plate between two ground planes.

FIGURE 2 Ceramic capacitors placed between HV plate and back wall (not shown)

Ceramic Disk Capacitors

The parallel plate capacitors can be replaced with ceramic disk capacitors; Figure 2 shows two disks made of 99.5% alumina (ε=9.9), 160 mm in diameter and 11.5 mm thick, with a capacitance of ~155 pF each. Additional capacitance is provided by the gap between the HV plate and the ground plane. The ground plane is intended to shield the HV plate from breakdowns due to line of sight influence from the plasma; it can be eliminated with no significant effect on plasma loading should it pose a problem. A plasma that gives a 0.5 Ω load to the reference strap feed gives a 2.2 Ω load to the upgrade. To deliver 2 MW total power, the peak voltages on the upper and lower capacitors are 12.9 and 14.5 kV, respectively. The rms currents are 545 and 610 A, for a power dissipation of 500-600 W each. The peak strap voltages are 10.3 to 12.3 kV with rms ground currents of 586 to 620 A. For comparison, the reference strap has V_{peak} = 30.3 kV, I_{rms} = 584 A for the same power and load.

Commercial Vacuum Capacitors

Commercially available, sealed vacuum capacitors have the advantage of operating in a controlled environment and having been well tested in the field. Comet makes a 50 pF Mini-Cap (CFMN-50EAC/35-DH-G) with a working voltage of 21 kV. With 50 W conduction cooling, it can handle 185 A (rms) for 10 s pulses with a 2% duty cycle.

The primary drawback of this capacitor is its 87 mm length, which when placed in the present antenna enclosure degrades plasma coupling due to the small area of the resulting current loops. Relaxing the constraints on maintaining the existing enclosure geometry would make this a more promising option, allowing 7-8 of them (depending on geometry details) to resonate each array element.

Low Impedance Transmission Line

Another option is to store the charge in a section of low impedance (high capacitance per unit length) transmission line feeding the straps. This approach allows a ceramic cylinder to be placed between the inner and outer conductors to act as a vacuum seal. Differential pumping would permit a high quality private vacuum to be maintained in the high electric field region of the line. Figure 3 shows a 200 mm length of $Z_0 = 7\ \Omega$ line; $V_{max} = 18.9$ kV at the end of the line ($E_{max} = 3.9$ kV/mm). The maximum E-field may be reduced by using higher impedance line, at the expense of higher voltages in the unmatched line and longer sections for resonance.

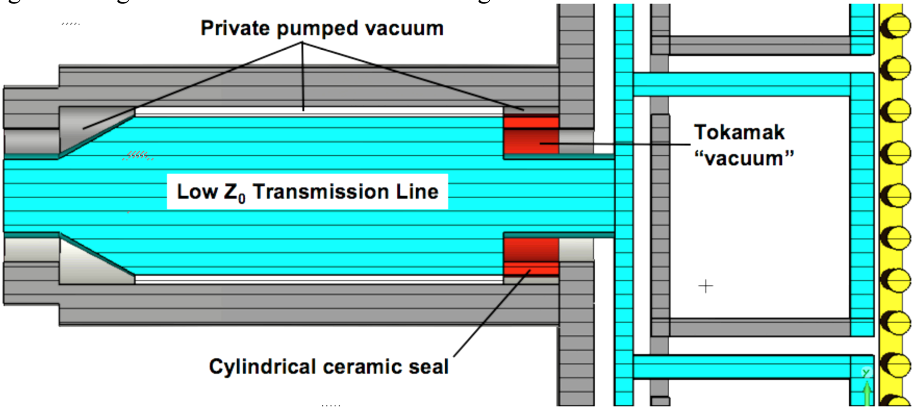


FIGURE 3. Ceramic vacuum seal separates the tokamak environment from the private vacuum of the low Z0 transmission line section.

ACKNOWLEDGMENTS

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