Field-Aligned ICRF Antenna Design for EAST

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\textbf{Abstract.} For ion cyclotron range of frequency (ICRF), a number of physics and technological challenges remain for steady state, toroidal devices. Among the most critical is maintaining good coupling and maximizing the coupled power through plasma variations including edge localized modes (ELMs) and confinement transitions. As pulse length increases, enhanced localized heat loads associated with antenna operation can challenge antenna integrity. In addition, ICRF impurity sources and contamination need to be minimized to enable effective plasma heating. Here, we report on a four strap field aligned (FA) antenna design for the EAST tokamak. A FA antenna is an antenna where the current straps and antenna side enclosure are perpendicular to the total magnetic field while the Faraday screen rods are parallel to the total magnetic field. In C-Mod, a FA antenna has been shown to be inherently load tolerant which allows for robust power delivery to the plasma. Furthermore, the RF enhanced heat flux and antenna impurity source were nearly eliminated. For both L and H-mode discharges, the core impurity contamination is 20-30\% lower but not eliminated. The emerging physics understanding is that the local RF impurity sources and RF enhanced heat flux is reduced due to the geometric alignment of the FA antenna while impurity contamination is a result of far field sheaths. An important aspect of antenna design is to identify a core absorption scenario that is characterized by strong single pass absorption for a broad range of target discharges. To maximize power coupling, the antenna spectrum needs to balance the $k_\parallel$ needed for strong single pass absorption and high coupling efficiency through evanescent layer. The latest design for a FA four strap adapted to EAST device is balance between geometrical constraints and physics requirements.

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\section*{INTRODUCTION}

Ion cyclotron range of frequency (ICRF) power is considered a good candidate to provide auxiliary heating and potential flow drive [1] for future devices[2] and fusion reactors. The core wave physics has been experimentally established including deuterium-tritium discharges in TFTR[3] and JET[4], and scales favorably to reactor plasmas without core wave penetration issues. Despite favorable core wave physics, ICRF utilization remains challenging and ICRF antenna performance is crucial for success. To reliably couple high power, good coupling is required and efficient coupling needs to be maintained despite expected load variations. To achieve good coupling, the antenna is typically situated near the plasma edge and this leads to interaction with the edge plasma, particularly impurity sources, impurity contamination and enhanced localized heat loads. Looking towards reactors and ITER, RF edge interaction will likely become more challenging with the used of high Z metallic plasma facing components (PFCs).

For EAST (superconducting, diverted tokamak ($R_0 = 1.85$ m, $a = 0.45$ m, $B_0 < 3.5$ T, $I_p \sim 1$ MA)[5], ICRF is one of the primary auxiliary heating systems and has recently demonstrated sustained H-Mode solely by ICRF heating for the first time.[6] In recent experimental campaigns, the primary heating scenario is fundamental hydrogen (H) minority heating in deuterium plasma. The source frequency range is 25-70 MHz; however, the frequencies that have been used are 27 MHz and 35 MHz. The total source power is 12 MW split between two antennas. One antenna is a two toroidal, two poloidal strap (B-port) antenna (see Figure 1) and the other is a four strap, folded strap (I-port) antenna, see Figure 2.[7] For B-port antenna, each strap is powered by one transmitter. Each poloidal pair at one toroidal location are phased at 180\degree and each toroidal pair is typically operated at [0,\pi] phasing. This corresponds to a vacuum antenna spectrum peaked at $k_\parallel=12.6$ m\(^{-1}\). For the I-port antenna, each toroidal strap is powered by a single transmitter and can be phased relative to the other straps. For [0,\pi,0,\pi] phasing, the vacuum antenna spectrum is peaked at $k_\parallel=14.4$ m\(^{-1}\).

EAST has a high level goal to couple 70\% of the ICRF source power to the plasma. For the present EAST antennas, the coupled power has been limited often by arcing in the antenna and transmission lines. This is thought to be a result of light loading at the low densities typically used for long pulse operation. The goal of this design activity is to develop a field aligned (FA) antenna for EAST.
A FA antenna has several features that make it attractive for the EAST long pulse, high coupled power mission. Perhaps foremost is the inherent load tolerance that has been observed in C-Mod over a wide range of plasma parameters.[8] The load tolerance is thought to arise from reduction in $E_||$ field in the near field of the antenna; hence, the field line pitch is an important consideration for the design. On C-Mod, we have found good load tolerance over the range routinely accessed for operations, about $\pm 3^\circ$. In addition to load tolerance, the FA antenna has low RF enhanced impurity source and heat flux at the antenna. The design implication is that the antenna can be made from robust materials that have high strength at high temperature and the antenna would not require low Z coatings that have poor thermomechanical properties and a potential to disintegrate.[9] The reduction in antenna RF enhanced impurity source and heat flux is thought to be a consequence of geometry. The local convective cell driven by the local RF fields are aligned with a FA antenna; thus do not interact with the antenna. The primary tradeoff is the power density of a FA is $\sim 27\%$ higher than classic antenna due to the helical geometry. The expected power density, however, is $\sim 4.5$ MW/m$^2$ and is well below values obtained in C-Mod[10] and Tore Supra.[11]

ANTENNA PHYSICS DESIGN REQUIREMENTS

One of the main design goals for the FA antenna is to increase the coupling efficiency. The coupling efficiency can be estimated using the following equation.

$$\eta = e^{-1.1k_||x}$$

where $k_||$ is the parallel wavenumber and $x$ is the width of the evanescent layer.[12] For EAST, the last closed flux surface (LCFS) is typically at $2.3$ m with the plasma limiter and antenna strap at 2.35 m and 2.38 m respectively. The corresponding cutoff densities for each antenna operated in $\pi$ phasing are $6.4 \times 10^{18}$ m$^{-3}$ and $9.8 \times 10^{18}$ m$^{-3}$, respectively. For a typical discharge, the cutoff density is near or inside the LCFS; thus the evanescent region is $\sim 8$ cm. This corresponds to a rather low coupling efficiency of 0.33 and 0.28 for the B and I antennas, respectively. For context, the C-Mod coupling efficiency is $\sim 0.75$ for dipole phasing and strong loading is routinely obtained even in H-mode. If we consider current drive $[0, \pi/2, \pi, 3\pi/2]$ and $\pi/3$ phase $[0, \pi/3, 2\pi/3, \pi]$, the vacuum $k_||$ is 7.2 m$^{-1}$ and 4.8 m$^{-1}$, respectively. If we assume the evanescent width remains 8 cm, the coupling efficiencies increase to 0.56 and 0.65 which would be significant improvement over dipole phasing. From a typical H-mode density profile (Figure 3), the cutoff density for the current B and I-antennas is near the top of the pedestal, located near the LCFS. For current drive and $\pi/3$ phase operation, the cutoff densities are $2.2 \times 10^{18}$ m$^{-3}$ and $1 \times 10^{18}$ m$^{-3}$, respectively, and are near the bottom of the pedestal. This results in a reduction in the evanescent width of order 2 cm and the corresponding coupling efficiencies increase to 0.73 and 0.62, respectively. This highlights that reducing the $k_||$ improves the coupling efficiency directly through $k_||$ and indirectly by reducing the evanescent width. For the FA antenna, we would like to
target ~5 m⁻¹ from a coupling perspective but the port spacing limits the antenna strap spacing for a rotated antenna to ~9 m⁻¹, 35 cm on center strap separation.

An important physics requirement for efficient ICRF heating is to have strong single pass absorption. Far field sheaths are thought to play an important role in impurity production and impurity contamination associated with ICRF power. To minimize far-field sheaths and have effective heating, one would like to have high single pass absorption in thermal plasmas. However, energetic minority ions have a strong impact on single pass absorption. As the minority ion energy increases, the Doppler broadened cyclotron resonance becomes wider and overlaps more strongly with the fast wave with favorable polarization. Using analytic formula for minority absorption[13], one can readily observe the impact a modest increase in minority temperature has on the single pass absorption. From experience on C-Mod, efficient H minority heating is observed for H concentrations in the range of 2-8% where the estimated total absorbed power is >90%.[10] The dashed blue curve in Figure 4 shows the single pass absorption for a typical C-Mod discharge with a minority temperature of 1 keV, 5 keV, 10 keV and 100 keV. The 1 keV and 5 keV curves represent thermal plasma single pass absorption. The 10 keV curve shows how quickly the minority energy impacts single pass absorption. The 100 keV curve shows the single pass absorption for a minority ion temperature typically achieved in C-Mod.

**FIGURE 3:** EAST core density profile from a typical H-mode discharge where the edge density profile is based on a connecting the top of the pedestal to the edge with a standard tanh function. The cutoff density is near the top of the pedestal.

**FIGURE 4:** Analytically calculated single pass absorption for minority H heating scenario for C-Mod and EAST parameters. The 1 and 5 keV curves represent thermal plasma conditions and the 10 keV shows how strongly increased minority temperature increases single pass absorption. The 100 keV curve shows the single pass absorption for a minority ion temperature typically achieved in C-Mod.

**ANTENNA CONCEPTUAL DESIGN**

Since the source power for the antenna is 6 MW, the target antenna power to be delivered is 4.2 MW which corresponds to 4.5 MW/m² power density. Although the transmitters have a 25-70 MHz bandwidth, this antenna will be optimized over a narrower range, 30-60 MHz, which allows for H minority ion heating over the accessible EAST magnetic fields. The maximum average electric field is not to exceed 15 kV/cm where the RF electric field is parallel to the equilibrium magnetic field[14] and the maximum voltage is limited to 45 kV. The mechanical stress is analyzed based upon a 0.2 MA/s disruption and bake out temperature of 300°C. The antenna is to operate effectively continuously; thus, the current straps, Faraday shield and protection tiles are to have the capability to be cooled with water.

The antenna is to be normal to the total magnetic field where the field line pitch is 7° as shown in Figure 5. The current strap is an end fed center grounded strap with a folded strap as a contingent design configuration. The strap length is ~70 cm which is similar to the present I-port antenna. The current straps are 35 cm on center which corresponds to a vacuum kₗ = 9 m⁻¹ for [0,π,0,π] phasing and kₗ = 4.5 m⁻¹ for current drive phasing. The coupling efficiency, assuming the evanescent width is unchanged, is 0.45 and the cutoff density is 4x10¹⁸ m⁻³ which is expected.
to be near the bottom of the pedestal. The FA antenna is to replace the I-port antenna and will occupy the vacuum vessel wall space between H and J ports. This geometrical limitation effectively sets the strap width; hence, the coupling efficiency.

For an end fed/center grounded antenna strap, the coaxial to vacuum strip line are a challenge. We plan to utilize standard 6" coaxial feedthrus mounted onto the flange cover plate and minimize the vacuum transmission line length. We also plan to run the vacuum transmission line behind the back plate of the antenna (see Error! Reference source not found.) and the network is shown in Error! Reference source not found..

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