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Analysis of double stub tuner control stability in a phased array antenna with strong cross-coupling

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HIGHLIGHTS

- A novel method for reducing reflection coefficients for LHCD launchers is proposed and evaluated.
- Numerical models of antenna behavior with stub tuning are analyzed.
- The system is found to be stable under most realistic operating conditions.

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ABSTRACT

Active stub tuning with a fast ferrite tuner (FFT) has greatly increased the effectiveness of fusion ion cyclotron range of frequency (ICRF) systems (50–100 MHz) by allowing for the antenna system to respond dynamically to changes in the plasma load impedance such as during the L–H transition or edge localized modes (ELMs). A high power waveguide double-stub tuner is under development for use with the Alcator C-Mod lower hybrid current drive (LHCD) system at 4.6 GHz. The amplitude and relative phase shift between adjacent columns of an LHCD antenna are critical for control of the launched $n_{||}$ spectrum. Adding a double-stub tuning network will perturb the phase and amplitude of the forward wave particularly if the unmatched reflection coefficient is high. This effect can be compensated by adjusting the phase of the low power microwave drive for each klystron amplifier. Cross-coupling of the reflected power between columns of the launcher must also be considered. The problem is simulated by cascading a scattering matrix for the plasma provided by a linear coupling model with the measured launcher scattering matrix and that of the FFTs. The solution is advanced in an iterative manner similar to the time-dependent behavior of the real system. System performance is presented under a range of edge density conditions from under-dense to over-dense and a range of launched $n_{||}$. Simulations predict power reflection coefficients (Γ^2) of less than 1% with no contamination of the $n_{||}$ spectrum. Instability of the FFT tuning network can be problematic for certain plasma conditions and relative phasings, but reducing the control gain of the FFT network stabilizes the system.

1. Introduction

Stub tuning networks have been used to reduce power reflected from the plasma on many fusion experiments in the ion cyclotron range of frequencies (<~100 MHz) [1,2] but have not yet been deployed at higher frequencies. A double stub matching network with electronically controlled tuning stubs is under development for the lower hybrid current drive (LHCD) system on Alcator C-Mod [3,4]. The multijunction concept employed in many LHCD experiments [5–9] reduces reflected power passively through destructive interference of the reflected waves, but at the cost of $n_{||}$ spectrum control. The peak $n_{||}$ of a multijunction antenna is adjustable over a small range ($n_{||,peak} = n_{||,0} \pm \delta n_{||}$ where $\delta n_{||} \sim 0.1$ for ITER and $\delta n_{||} \sim 0.3$ for Tore Supra), but is not capable of larger changes in $n_{||}$ or use in reverse current operation. Furthermore, side lobes in the $n_{||}$ spectrum of a multijunction antenna tend to grow when the reflection coefficient at the waveguide mouth is large. An active matching network like a double stub tuner allows for complete control of the $n_{||}$ spectrum, in either the co- or counter-current direction, while reducing reflection coefficients to near zero.

The behavior of a double-stub tuner connected in series with a single mismatched load, Z_L, is a well known problem in microwave

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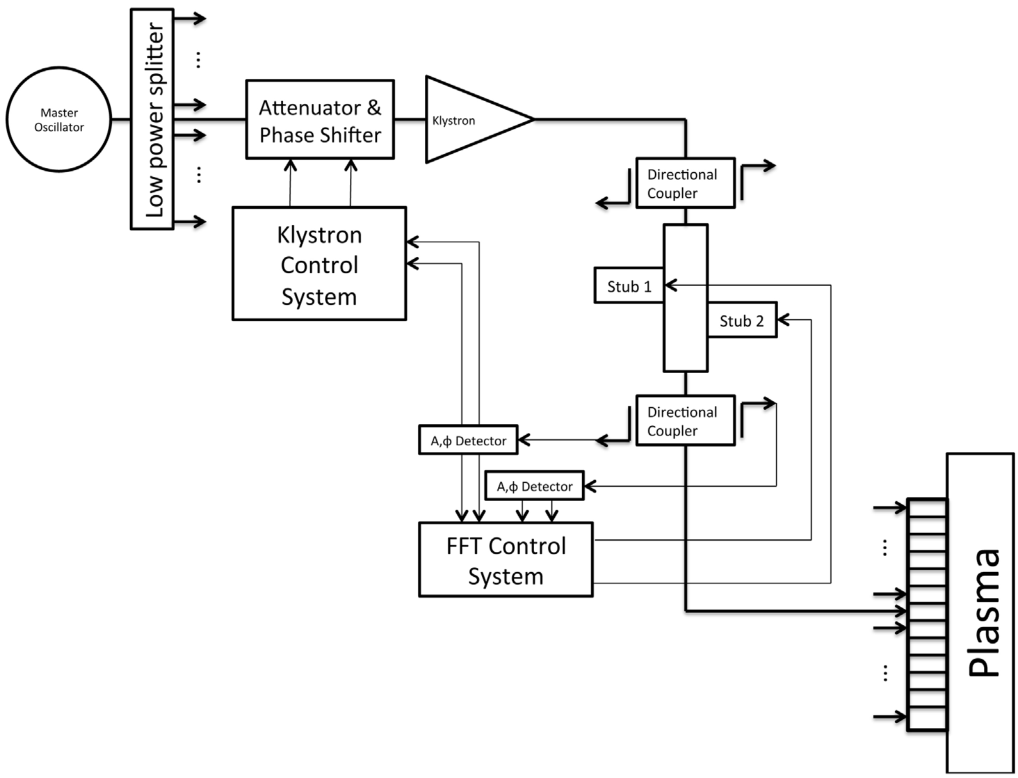

Fig. 1. LH FFT system-level block diagram for a single klystron channel, or column. Each column is equipped with an identical system. Two tuning stubs are located between each klystron and the antenna.

engineering [10]. The matching network will reduce the input reflection coefficient, Γ_{in}, to zero for any load impedance outside the "forbidden region", and from Γ_{in} to Γ_{in}^2 for load impedances inside the forbidden region. The problem is more complicated for a phased array LHCD antenna with strong cross-coupling between elements. The effective reflection coefficient for each element, Γ_n, is a function not only of the plasma density profile but also of the relative phase and amplitude of other nearby radiating elements. Mathematically, this can be expressed in terms of a series of matrix multiplication operations involving the scattering parameters of the plasma, antenna, and individual FFT elements. The mathematical system description is discussed in the next section of this paper, followed by simulation results of the FFT system behavior with realistic plasma profiles.

2. System description

Fig. 1 shows a block diagram for a single klystron channel of the LH FFT system. For the simulations presented in this paper, each klystron feeds a single column of a fully active "grill" antenna. The two stubs are located between the klystron and the antenna, with the stubs as close to the plasma as practical to minimize the region of recirculating power. Directional couplers for monitoring the forward and reflected power are located on either side of the LH FFT.

The plasma scattering matrix, S_p, can be calculated based on the linear coupling theory first developed by Brambilla [11]. The scattering matrix is determined by the geometry of the antenna (primarily the waveguide height and septum thickness) and the plasma profiles in front of the LH antenna (electron density, density gradient, and thickness of evanescent region). S_p is an $n \times n$ matrix, where n is the number of radiating elements in the antenna. The (n, n) elements are of order 0.3, while the $(n, n \pm 1)$ elements are of order 0.5. The magnitude of matrix elements decreases farther away from the diagonal since radiating elements spaced farther apart have weaker cross-coupling. The magnitude and phase of S_p for the fundamental mode as calculated by the ALOHA code [12] for a plasma with $n_0 = 2.7 \times 10^{17}\ \mathrm{m}^{-3}$ and $\nabla n = 4.7 \times 10^{20}\ \mathrm{m}^{-4}$ are plotted in Fig. 2. The pitch-angle of the magnetic field is not included in this calculation of S_p. Finite pitch angle will introduce non-reciprocity to the S_p matrix.

The 2-port scattering matrix for a single FFT can be calculated given the reactive admittance of the two stubs, B_1 and B_2, the wave propagation constant of the waveguide, β, and the distance between the stubs, l. The most straightforward way to determine this scattering matrix is to convert from a series of three cascaded ABCD matrices

$$ABCD_{FFT} = ABCD_{stub2} ABCD_{interstub} ABCD_{stub1} \tag{1}$$

where

$$\begin{aligned} ABCD_{stub2} &= \begin{bmatrix} 1 & 0 \\ iB_2 & 1 \end{bmatrix} \\ ABCD_{interstub} &= \begin{bmatrix} \cos(\beta l) & iZ_0 \sin(\beta l) \\ iY_0 \sin(\beta l) & \cos(\beta l) \end{bmatrix} \\ ABCD_{stub1} &= \begin{bmatrix} 1 & 0 \\ iB_1 & 1 \end{bmatrix} \end{aligned} \tag{2}$$

For simplicity we will assume $Z_0 = Y_0 = 1$. From this ABCD matrix the S-matrix for the kth FFT can be calculated as follows:

$$S_{FFTk} = \begin{bmatrix} \dfrac{A + B/Z_0 - CZ_0 - D}{A + B/Z_0 + CZ_0 + D} & \dfrac{2(AD - BC)}{A + B/Z_0 + CZ_0 + D} \\ \dfrac{2}{A + B/Z_0 + CZ_0 + D} & \dfrac{-A + B/Z_0 - CZ_0 + D}{A + B/Z_0 + CZ_0 + D} \end{bmatrix} \tag{3}$$

where A, B, C, D are the four elements of the matrix $ABCD_{FFT}$.