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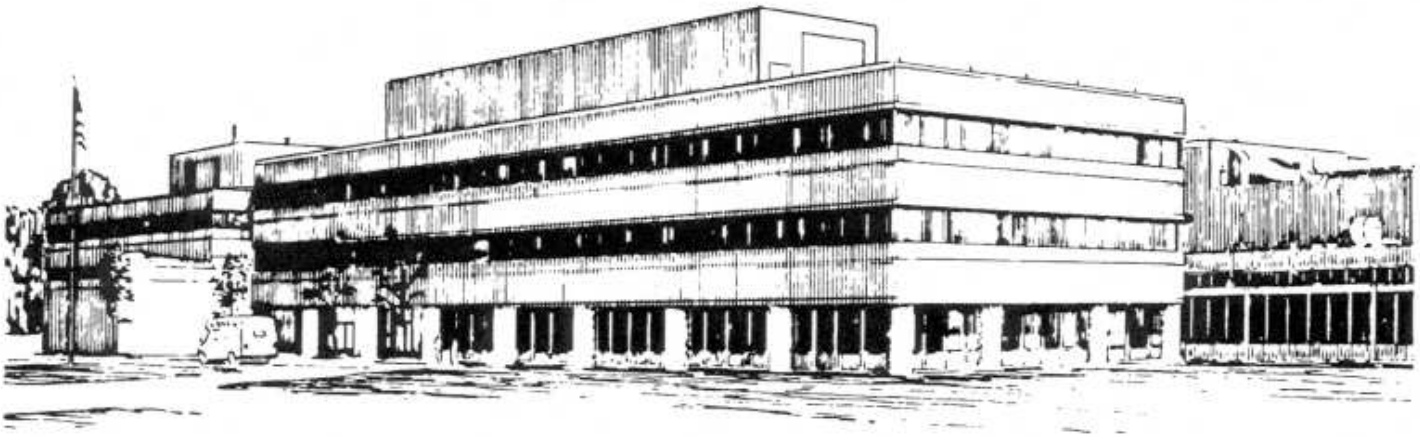

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A Lower Hybrid Current Drive System for Alcator C-Mod.

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Abstract. A Lower Hybrid Current Drive system is being constructed jointly by PSFC and PPPL for installation on the Alcator C-Mod tokamak, with the primary goal of driving plasma current in the outer region of the plasma. The LH system consists of 3 MW power at 4.6 GHz with a maximum pulse length of 5 seconds. 12 Klystrons will feed an array of 4-vertical and 24-horizontal waveguides mounted in one equatorial port. The coupler will incorporate some compact characteristics of the multijunction power splitting while retaining full control of the toroidal phase. In addition a dynamic phase control system will allow feedback stabilization of MHD modes. The desire to avoid possible waveguide breakdown and the need for compactness have resulted in some innovative technical solution, which will be presented.

ARIES studies show the remarkable improvement in the attractiveness of a tokamak reactor that results from AT physics operation: ARIES-AT requires LHCD for off-axis seed current [1]. In Alcator C-Mod, the LHCD experiment is designed to aid in the achievement of AT regimes with high bootstrap fraction (~70%), high β_n ($\geq$3) and high confinement (H~2-3) under quasi-steady-state conditions. LHCD current in the range of 150-270 kA is expected to be driven at $0.6<r/a<0.8$: this, in conjunction with the heating obtained by 8 MW of ICRF power, will allow the development and study of Advanced Tokamak Regimes under quasi-steady-state conditions [2]. The high electron temperature predicted with 5 MW of ICRF (T_{eo}~5-7 keV) insures first-pass damping of the LH waves, and therefore very good localization of the damping [3].

The RF power generation will utilize 12 high-power C-band klystrons. The klystrons, CPI (formally Varian) model VKC-7849, were originally purchased over 20 years ago for the Alcator-C Lower Hybrid experiment. The klystrons are cathode switched (no control connection) and are rated at an output of 250 kW CW at 4.6 GHz. The transmitters are arranged in carts with 4 klystrons each. For system flexibility, each cart is controlled semi-independently of the others with its own fast-off Transmitter Protection System (TPS) and PLC controller. Critical protection, control, and status lines are shared for coordination.

The klystrons are powered by a single high-voltage power supply/modulator which was specified and procured custom for this application from Thomcast AG of Switzerland. The HVPS is based on Pulse Step Modulation (PSM) technology using 68 individual solid-state modules. The HVPS also acts as the modulator since the klystrons conduct with the application of high voltage. The supply is rated for an output of 50 kV at 208 A for a 5 second maximum pulse width. The supply will be housed in a custom outdoor two-story container with the high voltage routed to the transmitter carts via a special high-voltage tri-axial cable. The supply has its own fault sensing and protection system and is linked via fiber-optic cable to the TPS and the Allen-Bradley“ PLC controller associated with each klystron cart.

The output RF from each klystron is routed to the coupler by TE_{10} rectangular waveguide (WR 187). The initial plan is to pressurize the waveguide with 2-bar nitrogen or dry air with a backup plan of using SF_6 if necessary. The klystrons are protected from reflected power by a 4-port ferrite circulator specified custom for this application and procured from Advanced Ferrite Technology of Germany. The circulator is rated to handle full reflection at full power over the entire 5-second pulse width with a forward insertion loss of less than 0.2 dB.

The coupler is protected from potentially damaging high VSWR or waveguide arcs by the Coupler Protection System (CPS). The CPS monitors a total of 60 forward and 156 reverse power sample points to generate 156 possible high VSWR fault conditions. The CPS is linked to the transmitter TPS by fiber optic links to provide fast shutoff of the input RF to the appropriate klystron in the event of a fault. A digital controller is used to provide active phase and amplitude control of the twelve klystrons with a 1 ms response time. Fast solid-state I-Q vector modulators are used as the phase and amplitude control elements for the low-level microwave drive signals to the klystrons. Phase and amplitude feedback information is provided to the controller by twelve I-Q detectors.

Fig. 1 Front coupler

The dimensions of the port and the power density achievable at this frequency dictate the configuration of the front coupler: it will consist of 4 rows of 24 waveguides each (Fig. 1). The dimension of each waveguide is 6x0.55 cm^2; for 2 MW source power the expected power density at the coupler mouth is $\leq$ 5 kW/cm^2, which is below the empirical limit for breakdown.

The design principles of the coupler have been maximum flexibility in the control of the $n_{||}$ spectrum and maximum reliability, together with the desire of compactness because of the tight configuration of C-Mod.

The elevation view is shown in figure 2. The construction of the 4 arrays of waveguides is obtained by

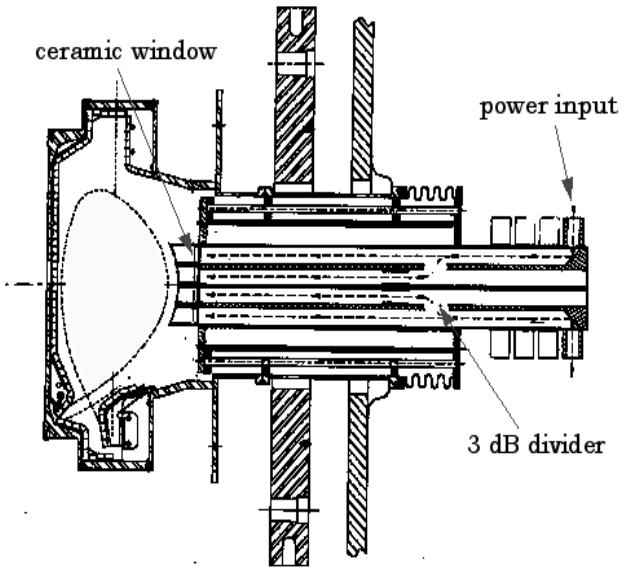

Fig. 2 Elevation view of the LH coupler

milling the waveguide patterns on metal plates and by stacking and bolting them. Each Klystron feeds a total of 8 waveguides, two adjacent vertical columns. The stacked plates array includes a vertical 3 dB divider. A fixed phase shifter compensates for the difference in phase due to the splitter and to the different length of the channels, so that at the mouth vertically the phase is constant. The schematic in figure 3 shows how the phase across the arrays is fully controlled: a high power phase shifter adjusts the phase between the two adjacent columns to the desired value, while a low power phase shifter before each Klystron adjusts the phase between the modules of two waveguides. This second phase shifter is a ferrite device capable of changing the phase in microseconds: this allows the very high degree of $n_{||}$ spectrum control in real time needed for feedback stabilization of MHD modes.

Historically a weak point in terms of waveguide arcing in LH couplers have been

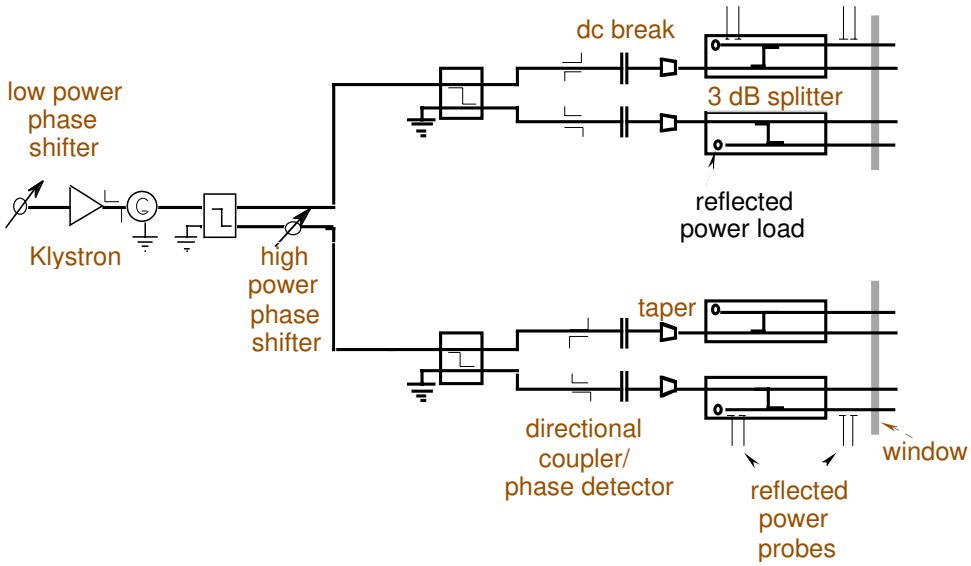

Fig.3 Schematic of the transmission line

the existence in vacuum of the layer where $\omega = \omega_{ce}$, which is somewhere near the magnetic field coil location. Other weak points have been the vacuum joints of the waveguide lines: we decided to eliminate both types of potential problems by incorporating the microwave vacuum window in the nose coupler. We already have achieved a high degree of reliability in brazing multiple alumina windows on a Titanium alloy frame [4], for C-Mod we plan to braze the 24 alumina breaks inside the 24 channels, each cut 10 cm deep in a Titanium alloy block via EDM-wire. Not only the electron cyclotron resonance layer will be in a pressurized area, but all the waveguide joint will be as well. Because Titanium absorbs Hydrogen gas, which could cause breakdown if it escapes from the wall, care will be taken to coat the waveguide channels with a metal, which has also a low secondary electron emission to minimize multipacting, such as Copper or Silver. The coupler nose will be protected by Boron-Nitride tiles (see figure 1). The radial position of the entire launcher can be adjusted in order to optimize coupling.

In ideal conditions, the reflection on vertically placed waveguides will be in phase and the power will be directed toward the generator and dissipated in the circulator. In practice we should expect the density in front of the coupler to vary somewhat vertically, in part because of the geometry of the machine and in part due to the ponderomotive force applied by the LH waves. In this case some of the reflected power will be directed toward the " fourth arm" of the 3 dB divider (see figure 2). The obvious solution would be to insert a load in each channel to dissipate this reflected power; for most of the waveguides this could be possible, but depending on the particular phasing chosen, some waveguides will receive a very high percentage of the power, in some cases even close to 100% because of cross-coupling. It is very difficult to insert a load in the narrow space of the waveguides (0.55 cm width). It would be also very cumbersome and expensive to transition to standard waveguide in order to have a full size load. There would be the possibility of leaving the "fourth arm" shorted, but in this case the reflection would alter the phase of the forward wave. Therefore we plan to unite all 24 loads of each array into one, by inserting dielectric pipes perpendicular to the stack plates and run water through them: this will achieve two things, absorb the reflected power and transport away the heat generated. It turns out that a single broad pipe, carrying enough water to absorb up to ~20% of the total power causes unwanted reflections. Using models obtained from the HFSS™ simulator we found that the best configuration is to have 4 5/16" o. d. Teflon pipes appropriately placed. They will be mounted on a separate stack of plates, with a flange which allows the attachment to the rear of the coupler assembly. This way, different configurations and even a simple short can be tested.

Rf probes of the kind described in [5] inserted on the narrow sides of the top and bottom arrays will allow measurement of the power flow in each waveguide. In figure 2, taper refers to the transition from standard WR187 waveguide to a reduced size: up to that point all the components are standard.

Aside from the movement for coupling optimization, the coupler assembly can be separated from the machine and rolled out either for inspection or for replacement of one of the front components, which are the one more likely to sustain damage. The rest are standard components and readily reachable.

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