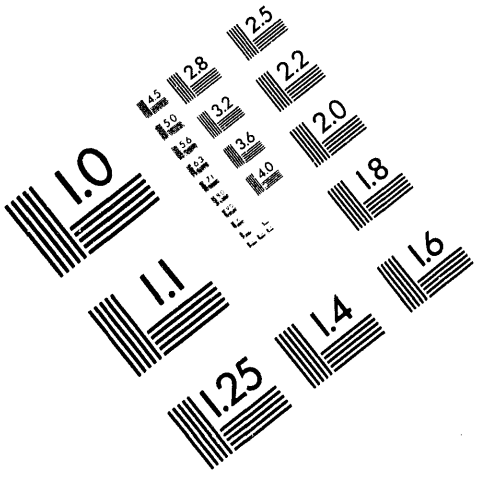

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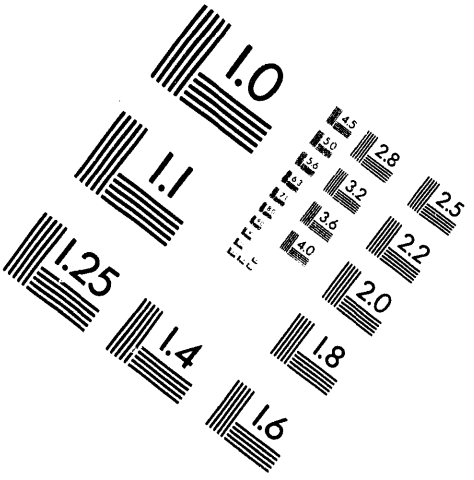

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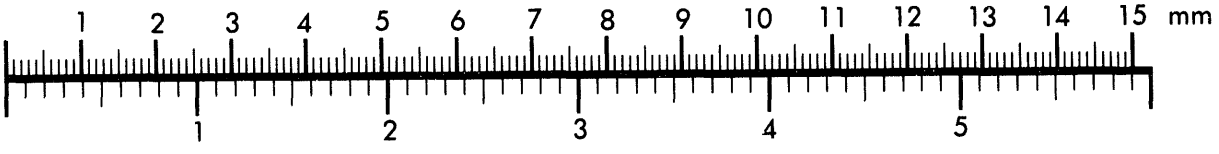

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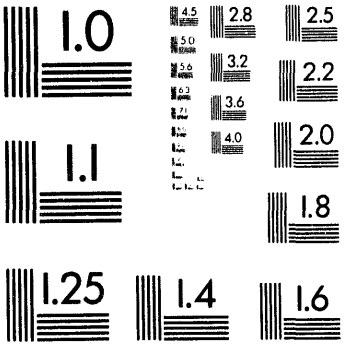

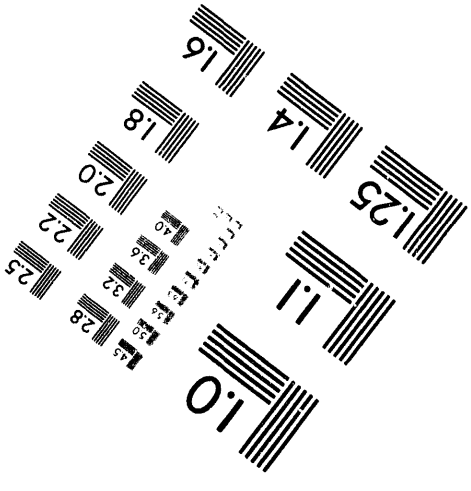

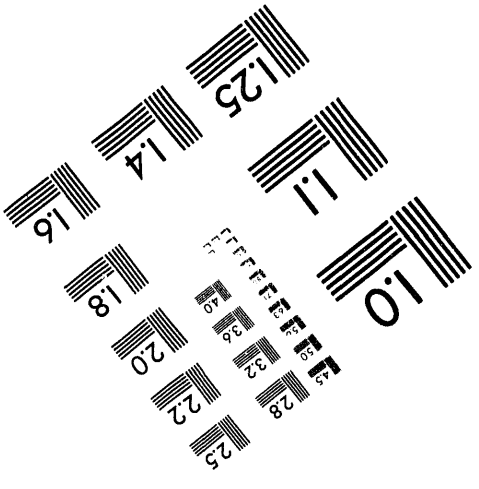

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ICRF Heating during DT Experiments on TFTR - System Improvements and Results*

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In order to carry out a program of ICRF experiments in deuterium-tritium plasmas on the TFTR device a series of technical improvements have been made to the ICRF system. These improvements allow more flexible and reliable operation of the system which is crucial for the limited number of tritium discharges available. During the last year circuitry has been installed to feedback the plasma position on antenna loading, to lock the phase between antenna elements, and to detect arcs from the second harmonic content of antenna signals.

1. INTRODUCTION

The TFTR ICRF system consists of four antennas in adjacent midplane ports fed by six rf transmitters. Each antenna contains two radiating elements [1]. The outer two antennas are each powered by a single transmitter that operates at a fixed frequency of 43 MHz and with a maximum power rating of 3 MW for 3 seconds. The inner two antennas are each powered by two transmitters and are designed to operate at both 43 and 63.6 MHz. The transmitters are capable of operation from 40 to 80 MHz with a maximum output power of 2.5 MW for 3 seconds. Total power levels of up to 11.3 MW have been injected into TFTR. The use of separate transmitters on each strap of the inner two antennas allows for operation with arbitrary phasing between the antenna elements. As a result of the design of these antennas a large mutual inductance exists between the elements making the antennas difficult to operate at phases other than 0 and π.

Many of the experiments on TFTR involve operation in conjunction with NBI fueled "supershot" plasmas [2]. These plasmas feature a low target density (n_{el}~$1x10^{19}$) which is rapidly increased by NBI. In order to maximize the power level and pulse length of ICRF heating applied to these plasmas a number of techniques have been employed. These include: Plasma position and shaping control, careful programming of the rf power waveform amplitude, reapplying power after high VSWR interrupts, and a novel arc protection scheme that distinguishes between rapid changes in VSWR due to changes in the surface plasma impedance and changes due to breakdown in the antenna structure. These techniques have allowed us to achieve essentially 100% reliability in applying rf power to tritium discharges.

In order to investigate ICRF current drive, either directly via the fast wave or through the mode converted ion Bernstein wave, active phase control of the antenna currents is essential. Circuitry has been implemented that takes signals directly from the antenna elements and locks the phase between them by varying the phase of the rf drive signals to the transmitters.

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2. POSITION AND SHAPE CONTROL

The TFTR plasma is bounded by a toroidally symmetric inner limiter which extends $\pm 60^0$ from the midplane and a series of toroidally local poloidal limiters which extend around the outer part of the plasma. These limiters do not have the same curvature or axis of curvature. The rf antennas are located just outboard of the outer limiters and have the same curvature. Most TFTR plasma operation is for plasmas with a major radius such that the plasma touches the inner limiter in the midplane and misses the outer limiter by at least 20 cm. This geometry leads to a low level of radiation resistance for the rf antennas and is not conducive to high power operation. For ICRF heated plasmas the plasma major radius is increased so that while the plasma is still nominally limited on the inner midplane it approaches closely (~1 cm) the outer midplane limiters and nearly touches the poloidal limiters all around the cross section. Nominally the plasma is circular. However low beta plasmas are typically slightly elongated ($\kappa \sim 1.05$) and hence may actually touch not at the midplane but at the top or bottom.

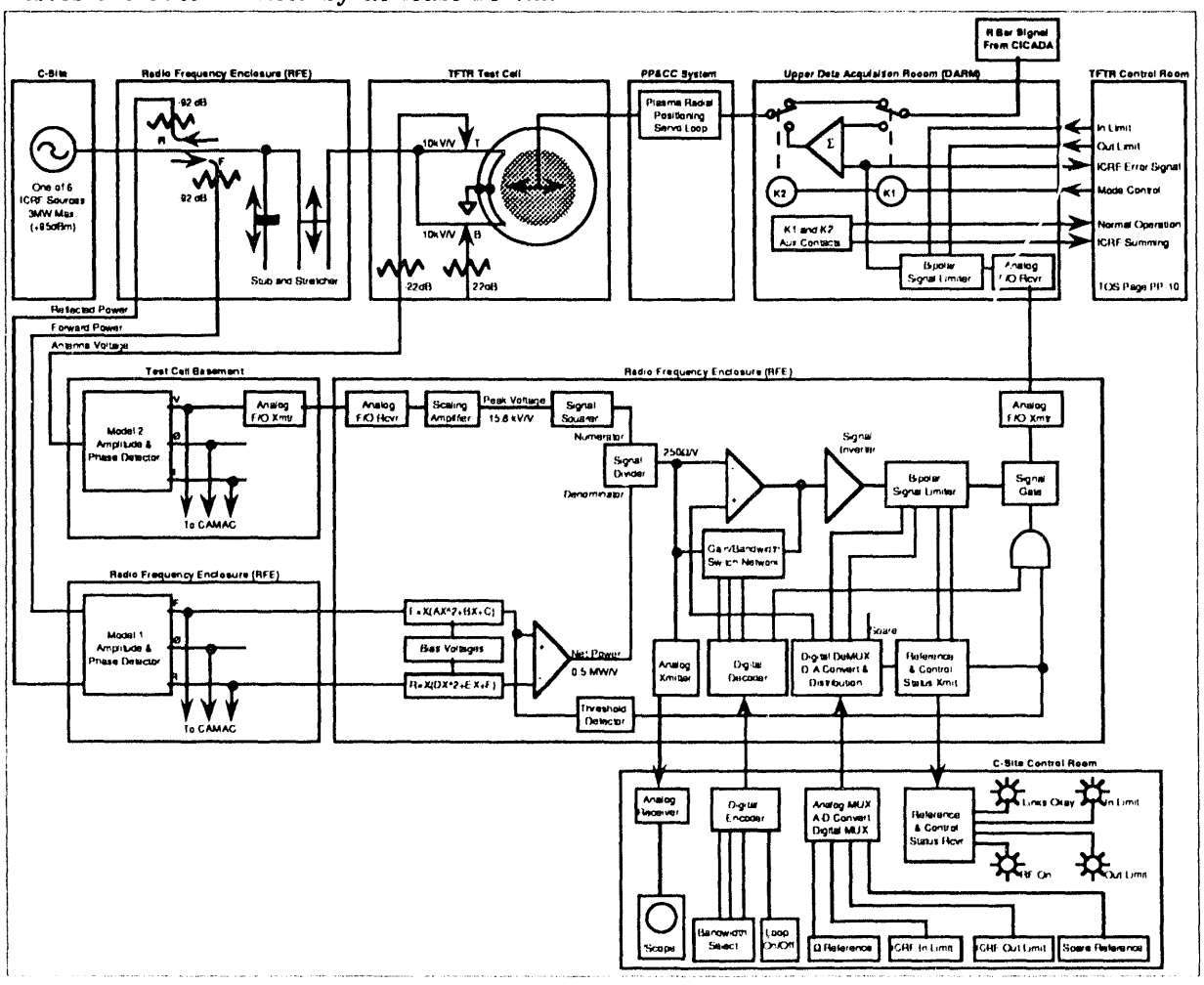

Figure 1 Block diagram of postion feedback system

When this happens the outer edge of the plasma pulls away from the antenna and its position does not move for small variations in major radius. As the plasma beta is increased

the plasma elongation shrinks and kappa may become less than unity. To insure a target plasma with kappa less than unity a separate variable curvature power supply can be energized. This supply changes the shape of the equilibrium field and decreases the plasma elongation. The effect of the supply decreases with increasing plasma current.

Control of the plasma radial position can be used to smooth out variations in the antenna loading. This has been successfully implemented on JET and D-IIID [3,4]. Such a circuit has also been constructed for TFTR. In Figure 1 we show a block diagram of the TFTR system. A parallel resonant resistance is derived from the net antenna power and a signal proportional to antenna peak voltage via the formula $R= V^2/P$. The value of R is compared to a reference signal and the error signal is applied via a summing amplifier to the normal error signal in the plasma position control system. The system gain requirement was determined by measuring the antenna loading as a function of plasma position. The bandwidth was determined by applying a triangle wave step in the requested plasma position and measuring the plasma response. In order to not cause an oscillation in the regular position control system a zero at 40 Hz was installed. The system response is shown in figure 2.

3. PHASE CONTROL

The inner two ICRF antennas with one transmitter per strap have been utilized for current drive experiments. To hold the 90^0 phasing between straps required a phase locking circuit has been built. This greatly simplifies the impedance matching problem as it locks the phase at the antennas between the elements. Powers of greater than 3 MW have been coupled to the plasma at 90^0 phasing with this technique. The circuit also has a track and hold feature that allows it to remain locked during an arc and between pulses. Figure 3 shows a block diagram of the circuit.

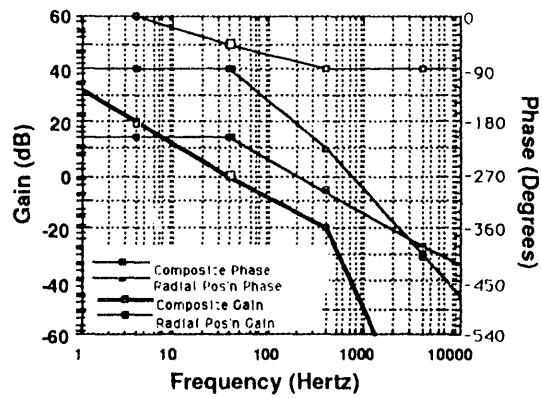

Figure 2 Bode plot analysis of position feedback circuit

4. ARC PROTECTION CIRCUITRY

Arc protection circuits protect both the antennas and the transmitters. The most common form of arc protection circuitry in use relies on a simple comparison of the ratio of the reflected power to the forward power to a reference level. If a given transmitter feeds only one antenna element than this is a relatively simple and effective way to perform antenna and transmitter protection. If a transmitter feeds a more complicated set of antenna elements then an arc in one of the elements may not produce a large change in the VSWR as seen by the transmitter. In this case the circuit will not perform its function and the antenna can be damaged. In addition changes in the plasma surface impedance can produce large excursions in the VSWR that are not arcs but will be interpreted as arcs and shut off the rf power. A circuit has been developed that looks at the second harmonic content of the rf power. Due to the non-linear nature of an rf arc, a large second harmonic component can be generated by an arc. Changes in the plasma surface impedance (such as those due to eigenmodes or ELMs) do not induce a second harmonic component and will not trip the new circuit.

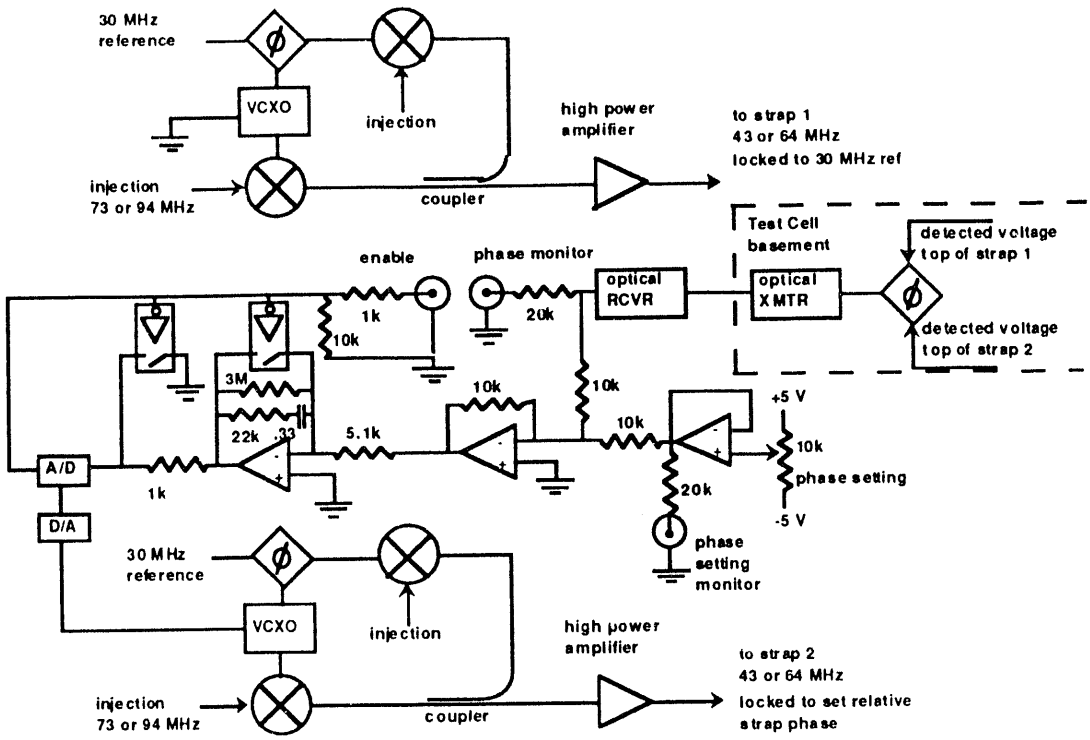

Figure 3 Block diagram of phase locking circuitry

The ability to retry after an arc has proven to be quite valuable. After an arc is sensed the rf drive is removed for an adjustable time period (~30 ms is adequate) and then reapplied. It was found that the retry was most successful if the power was ramped back on with a time constant of ~20 ms. It was also found that a step up to ~30% of maximum power followed by a ramp (~ 100 - 200 ms) to maximum power facilitated rf turning without having an antenna voltage peak at the beginning of the rf pulse.

5. SUMMARY

The institution of a variety of additional circuits for phase locking, plasma position control, arc protection, pulse shaping coupled with plasma shape control has allowed the TFTR ICRF system to operate reliably into a variety of plasmas at power levels up to 11.3 MW with phase control of the antenna currents.

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