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A 110 GHz, 1 MW GYROTRON WITH  
EVACUATED WAVEGUIDE SYSTEM  
ON THE DIII-D TOKAMAK**

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 **GENERAL ATOMICS**

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# INITIAL TESTS AND OPERATION OF A 110 GHz, 1 MW GYROTRON WITH EVACUATED WAVEGUIDE SYSTEM ON THE DIII-D TOKAMAK

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A gyrotron producing nominally 1 MW at 110 GHz has been installed at the DIII-D tokamak and operated in a program of initial tests with a windowless evacuated transmission line. The alignment and first test operation were performed in an air environment at atmospheric pressure. Under these conditions, the tube produced rf output in excess of 800 kW for pulse lengths greater than 10 msec and power near 500 kW for pulse lengths of about 100 msec into a free space dummy load. The gyrotron was operated into evacuated corrugated waveguide in the full power parameter regime for pulse lengths of up to 500 msec injecting greater than 0.5 MW into DIII-D for a preliminary series of experiments. Generated powers greater than 900 kW were achieved. A parasitic oscillation at various frequencies between 20 and 100 MHz, which was generated during the pulsing of the gyrotron electron beam, was suppressed somewhat by a capacitive filter attached to the gyrotron itself. Addition of a magnetic shield intended to alter the magnetic field geometry below the cathode eliminated internal tube sparks. Rework of the external power and interlock circuitry to improve the immunity to electromagnetic interference was also done in parallel so that the fast interlock circuitry could be used. The latest results of the test program, the design of the free space load and other test hardware, and the transmission line will be presented.

## **I. INTRODUCTION**

Extrapolation of size scaling for tokamak fusion reactors from the present devices to those capable of sustained net energy output has led to designs for power plants operating at high plasma currents and large magnetic fields. In the present economic equation with relatively inexpensive fossil fuels, such large and expensive installations are not as attractive as other electrical generation options with lower capital cost. The picture has been changed in the past few years by

the discovery of tokamak operating regimes with substantially improved parameters which extrapolate to smaller and less expensive system designs. These new regimes, called collectively Advanced Tokamak (AT) regimes, rely on the control of the current density profile, and hence the profile of the magnetic shear, across the plasma discharge. In particular, AT operation requires substantial off-axis current in contrast to normal tokamak operation where the current density profile is peaked in the plasma center.

Operation in the AT regimes has heretofore been achieved transiently by taking advantage of the very slow flux penetration into a hot plasma, however a power production reactor must be able to operate in the AT regime essentially continuously and therefore will rely on non-inductive current drive methods.

On DIII-D, a major effort is underway to investigate Electron Cyclotron Current Drive (ECCD) for producing and sustaining AT geometry. Initial steps in a program which could lead to installation of up to 10 MW of electron cyclotron heating and current drive power call for installation of three rf systems operating at 110 GHz, the second harmonic resonance frequency on DIII-D, each of which will generate nominally 1 MW for two seconds or longer. The three systems will use one Gycom gyrotron and two CPI (formerly Varian) gyrotrons all with windowless evacuated transmission lines. The Gycom gyrotron [1] has been installed at DIII-D and is in a test program leading to routine operation. As of July 1996 at least 500 kW rf power has been injected into DIII-D for 500 msec long pulses on a routine basis and up to 900 kW has been generated. This paper describes the system configuration and reports on the results of the tests of the Gycom Centaur gyrotron to date.

## II. RF SYSTEM OVERVIEW

The rf system is a unique combination of the gyrotron and an evacuated waveguide transmission line without any vacuum window except for the boron nitride single disk window on the gyrotron itself. The overall system is presented in Fig. 1. The 31.75 mm diameter corrugated aluminum waveguide carries the HE<sub>11</sub> mode. The waveguide diameter represents a compromise between power handling capability and the requirement that the line be somewhat insensitive to misalignment, thermal expansion and motion. The rf beam exits the gyrotron slightly off-center (about 4 mm) and slightly off perpendicular (about 0.3 degrees up tilt). The arbitrary specification that mode conversion at the entrance to the waveguide be less than 2% yields the requirement that the beam be centered at the input to the waveguide to within 0.5 mm and be coaxial to within 0.1 degree [2,3]. The beam exiting the gyrotron is phase corrected to the free space Gaussian and focused by a pair of mirrors in the evacuated Mirror Optics Unit (MOU). The MOU was aligned to the measured beam using a specially constructed and adjusted input bellows assembly and is floating on springs so

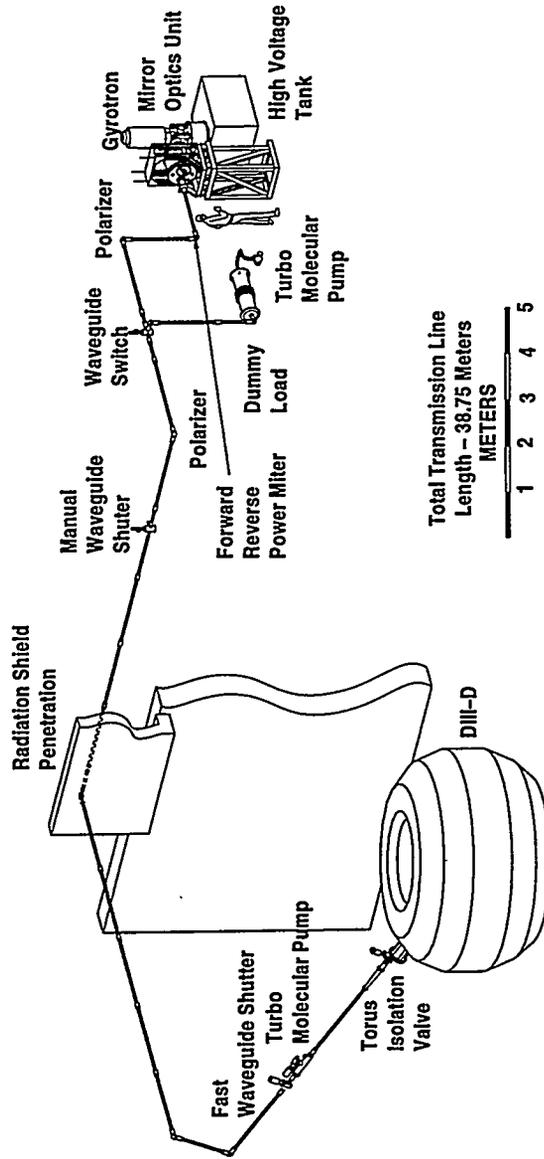


Fig. 1. Schematic diagram of the evacuated windowless waveguide system for the 110 GHz installation on the DIII-D tokamak. The line is 38.75 m long and the diameter of the corrugated circular waveguide is 31.75 mm.

that thermal expansion of the gyrotron and the waveguide assembly does not place mechanical strain on the gyrotron. Two photographs of the installation are shown in Fig. 2, one with an anechoic chamber used in initial testing, and the other with the MOU in place.

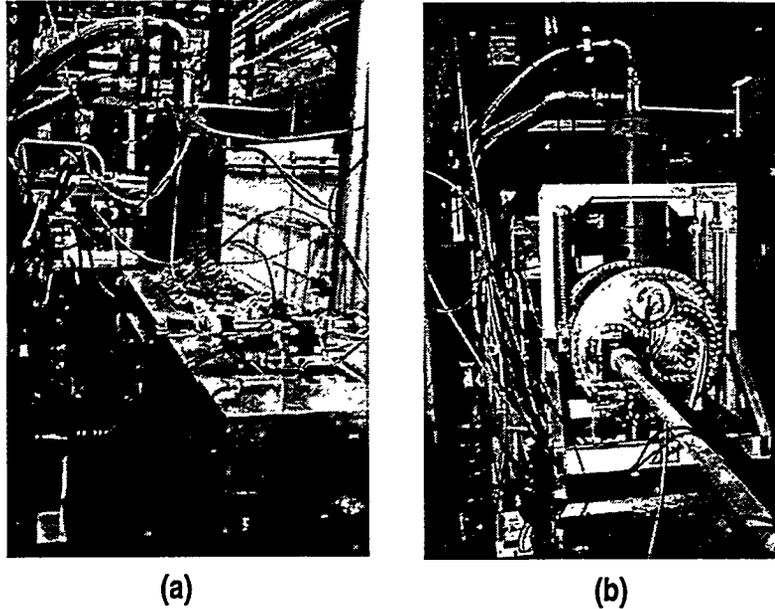


Fig. 2. Photographs of the anechoic chamber (a) used to house the planar octanol load during the initial tests of the Centaur gyrotron at DIII-D and of the final installation with the Mirror Optics Unit in place; the MOU replaced the anechoic chamber for vacuum waveguide operation, and contains the phase correction and focusing mirrors

The interface between the waveguide and the MOU is accomplished by a short section of waveguide attached to an x-y translating stage which is bolted to the MOU. This permits the actual point at which the beam enters the waveguide to be accurately positioned. The powers in the forward and reflected waves are measured at the first mitre bend located approximately 2 m past the MOU. This mitre bend has a series of several coupling holes sealed with a quartz lens which carries a fraction of the forward and reflected power to detectors. To facilitate gyrotron optimization and ECH experiments, a waveguide switch is used to shuttle the rf power between a dummy load and the DIII-D tokamak without breaking vacuum. Polarization control of the launched rf power is accomplished by a set of polarizing mirrors mounted in two of the mitre bends. By appropriate

rotation of the two mirrors, any elliptical polarization desired can be obtained. Inside the tokamak vacuum vessel is a focusing mirror and a flat turning mirror, permanently angled 19 degrees off the major radius line, which can be tilted vertically to direct the beam poloidally. This allows the power deposition region to be placed off-axis without changing the magnetic field.

The entire waveguide system contains six miter bends and is 38.75 meters long with estimated loss of 2% in the waveguide and 0.6% in each miter bend. The miter bend losses are from mode conversion, 0.5%, and from ohmic loss, 0.1%. The line is evacuated to a pressure of approximately  $1 \times 10^{-5}$  torr by a turbomolecular pump at the MOU, by a turbopump pumping through small holes in the waveguide in the final section leading to the tokamak and by the tokamak itself. The dummy load also has a pumping port with turbo pump which maintains its base pressure at  $1 \times 10^{-6}$  torr. Vacuum protection for the tokamak is provided by a fast shutter system installed in the waveguide three meters in front of the tokamak. The pressure sensor for this shutter is at the MOU, and any increase in pressure above  $1 \times 10^{-3}$  torr there results in closure of the fast shutter in less than 10 msec. The fast shutter was primarily intended to protect the tokamak from the coolant in the case of fracture of a double disk gyrotron window, not the situation in the case of the Centaur gyrotron, which has a single disk window. Two complete waveguide lines have now been installed on DIII-D and the launchers for four systems are in place inside DIII-D.

### III. INITIAL OPERATION

The initial testing of the gyrotron at DIII-D was done at atmospheric pressure into a specially constructed free space dummy load, shown in Fig. 3, capable of absorbing the full gyrotron output power for 50 msec. The load is about 35 cm square and consists of two parallel sheets of dielectric filled with 1-octanol [ $\text{CH}_3(\text{CH}_2)_7\text{OH}$ ]. The entrance surface is teflon with pyramidal facets presenting a 60 degree conical absorber, which is ten free space wavelengths deep, to the incoming beam. The circulating octanol has an attenuation of 13 dB/cm [4] and the attenuation of the entire load is about 40 dB. The back surface of the teflon is also faceted to a depth of five wavelengths in octanol. The back surface of the load is made from a flat sheet of TPX (polymethylpentene). The teflon and TPX sheets were mounted on an aluminum spacer which contained the flow fittings and calorimetry block. The load was scribed with fiducials so that detailed measurements of the beam could be made using thermally sensitive paper mounted directly on the load.

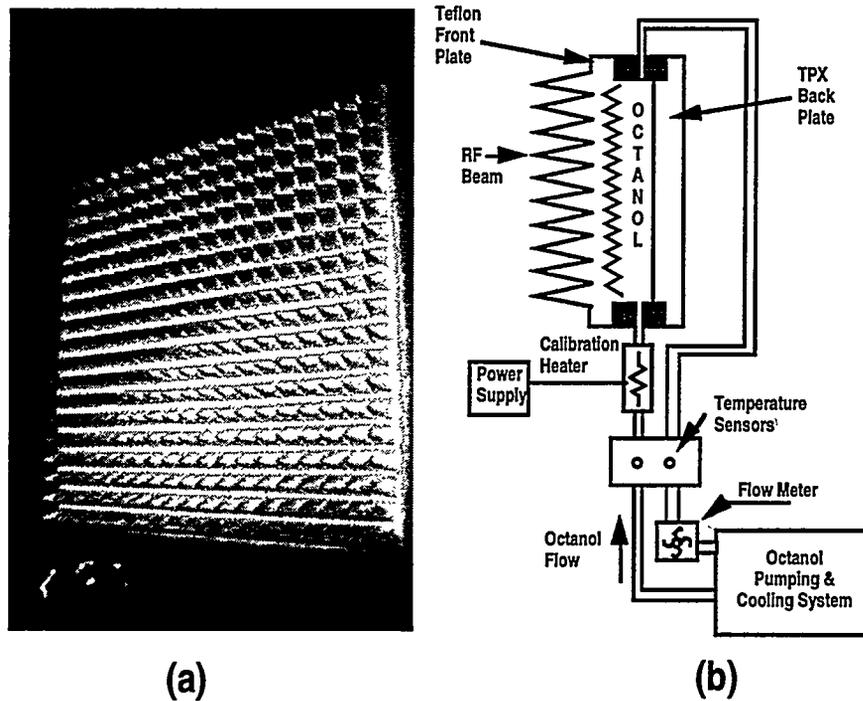


Fig. 3. Photograph (a) and sketch (b) of the planar octanol load used for free space calorimetry and beam quality measurements at atmospheric pressure. The load can withstand the full 1 MW gyrotron output power for about 50 msec. The load is 35 cm square and provides about 40 dB attenuation.

The dummy load was housed in a wooden anechoic chamber with dimensions  $1 \times 1 \times 2$  meters which was lined with microwave absorber and purged with dry nitrogen as protection against fire. The load could be moved axially within the box, and this capability was used to determine the direction and position of the beam as it propagated out from the gyrotron window. Thermally sensitive paper was used to diagnose the beam and in Fig. 4 the free space beam patterns are shown for the near field close to the window and the far field 1.7 m past the window. There was good qualitative agreement with calculations [5].

The anechoic chamber was used both with the gyrotron launching into free space and with the phase correction and focusing mirrors in the MOU. The

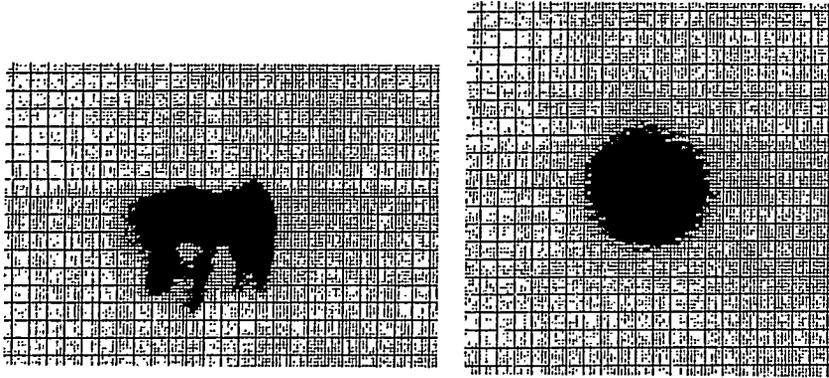


Fig. 4. Free space power profile measurements using thermally sensitive paper in the near field at 31 cm from the gyrotron window and the far field at 173 cm from the window. The beam exiting the gyrotron window is a flattened Gaussian to spread the power more uniformly over the window surface. The major divisions on the paper are 1 cm apart.

initial measurements with the gyrotron only were used to build an adapter flange to connect the MOU to the gyrotron so that the beam propagated through the MOU on the designed path. The MOU output waveguide, a section of 31.75 mm diameter guide with x-y translation and tilt capability, was then installed on the MOU and was adjusted slightly to center the beam.

The beam was accurately centered on the waveguide following the MOU as indicated by the thermal paper patterns in Fig. 5. The MOU output waveguide is 70 cm long and the beam is seen to be well centered both at the input and the output of this section of waveguide. The power measured following the output waveguide was approximately the same as the free space measurements. Tuning mechanically to eliminate possible tilt of the beam axis with respect to the waveguide axis has not yet been done.

Power measurements were performed calorimetrically using the octanol load, either by pulsing repetitively at constant frequency but for different duty cycles (to eliminate uncertainty from the turn-on of the gyrotron), or by analyzing the octanol response to a single pulse. The calorimetry was calibrated using a heater immersed in the flow which delivered a known power to the octanol.

Following the initial tests, the output waveguide was connected to a vacuum dummy load capable of absorbing the full gyrotron output power for 1 second. This experimental arrangement was used to verify the coupling of the power to the dummy load using approximately 4 meters of corrugated evacuated waveguide and two miter bends. Calibrated calorimetry was performed on the water cooling for the gyrotron output window, the MOU mirror and housing and



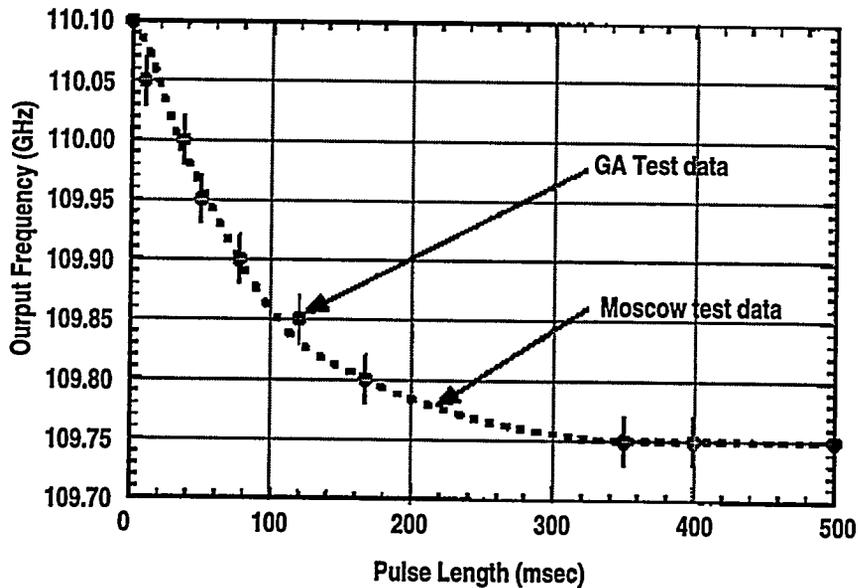


Fig. 6. Gyrotron output frequency as a function of pulse length. The measurements at DIII-D agreed with the tests performed in Moscow.

The transmission line operated with no sign of any waveguide arcing and with transmission loss of less than 5%, which was at the limit of the accuracy of the calorimetry. Although pulse length was initially limited by rf interference from a parasitic oscillation, pulses of 500 msec in length, the administrative limit, were produced reliably with dummy load power greater than 500 kW, approximately 150 kW absorbed in the MOU cooling circuit, and generally good power accountability.

#### IV. LOW FREQUENCY PARASITE

The operation of the gyrotron has been accompanied by a low frequency parasitic oscillation which caused severe problems for the protective interlock circuitry despite the fact that the basic operation of the gyrotron at 110 GHz was relatively unaffected. Several measures which collectively made it possible to operate were undertaken to obviate the effects of this parasite.

The initial operation of the gyrotron during acceptance testing in Moscow was without a strong parasitic oscillation. After some days of operation in San Diego, a parasitic oscillation began to be observed first on the calorimetry signals and then on virtually all signals. The parasite frequency initially was in the 20 MHz range with harmonics out to 150 MHz. The parasite had the

characteristics that it was about 5 MHz wide at -3 dB, did not appear to be connected with the external circuit parameters, and was present whenever the beam was present in the tube (independent of rf generation at 110 GHz).

Several direct measures were undertaken on the gyrotron in an attempt to reduce the amplitude of this parasite. A capacitive filter, Fig. 7, was connected across the gyrotron accelerating gap. This filter provided a 1 nF short across the tube insulator, with uniform electric field gradient maintained by a voltage divider chain. An iron collar was installed at the top of the tube insulator to eliminate the possibility of a magnetic well with a trapped electron population below the cathode, which might be causing the parasite. The actual effect produced by this collar was to eliminate small internal gyrotron sparks which had been observed during operation in the presence of the parasite, however its effect on the parasite itself was minimal. Additional work on understanding the parasite is in progress [6].

The tube filter installation resulted in a substantial change in the character of the instability. The new spectrum has a small peak at 4.7 MHz with a satellite at 5.7 MHz, plus a strong peak at 96 MHz with sidebands and structure between 88 and 106 MHz. Harmonics out to the third are observed. The 96 MHz peak had not been observed before the installation of the gyrotron filter. The rf spectrum, estimated to have a total power of several kW, is shown in Fig. 8.

This parasite is still observed during normal operation of the gyrotron. There has not been any evidence that the amplitude of the parasite has decreased during the course of gyrotron operation to date. Despite the installation of the tube filters, it continued to be impossible to run the gyrotron without spurious interlock trips and other control and monitoring problems. Therefore a comprehensive program of rf interference suppression, both in the gyrotron system and in other DIII-D systems, was undertaken, which enabled operation in the presence of the parasite.

It has occasionally happened that during normal gyrotron operation the parasite suddenly has become more severe. Reducing the gun coil current by about 10% has permitted return to normal operation and following conditioning the normal operating regime can be restored. The present situation is that the parasite is a serious but generally manageable problem.

## V. INITIAL OPERATION INTO DIII-D

Although thus far experimental time has been limited, the gyrotron and transmission line system have been operated into DIII-D plasmas and the principal features of the systems have been checked. The launcher injects the rf power at a fixed angle of 19 degrees off perpendicular to the toroidal field and can be scanned poloidally, as indicated in Fig. 9. Calculations of the spot size in the plasma predict that 98% of the rf power will be distributed across an area

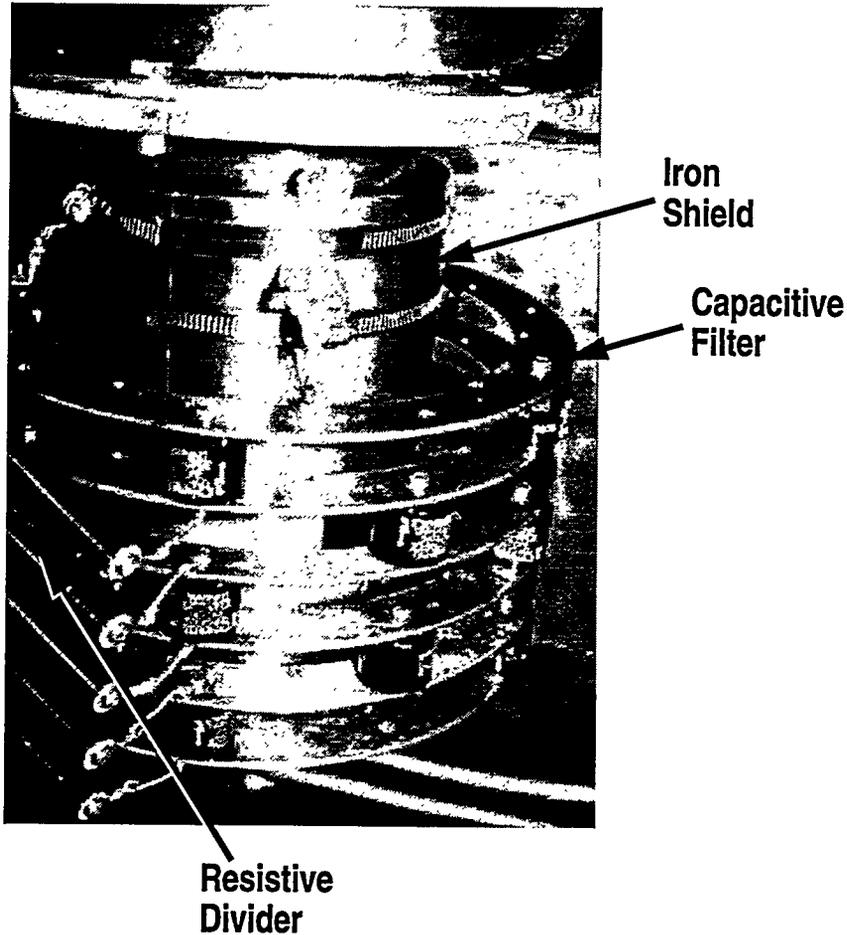


Fig 7. Photograph of the capacitive filter and magnetic collar mounted on the gyrotron inside the high voltage tank. Five planes connected with 5 nF are arranged in series for a total 1 nF filter. The iron collar is mounted on the upper, anode, portion of the gyrotron.

with diameter 12.8 cm at a distance of 1.00 m from the final poloidally scanning mirror. The calculated spot size increases to 16.3 cm diameter at a distance of 1.25 m from the final mirror. The actual power deposition profile was estimated from the change in the time derivative in the ECE  $T_e$  signals at the termination of the rf pulse. These measurements are summarized in Fig. 10, where the power deposition profile is seen to be broader than expected and with substantial

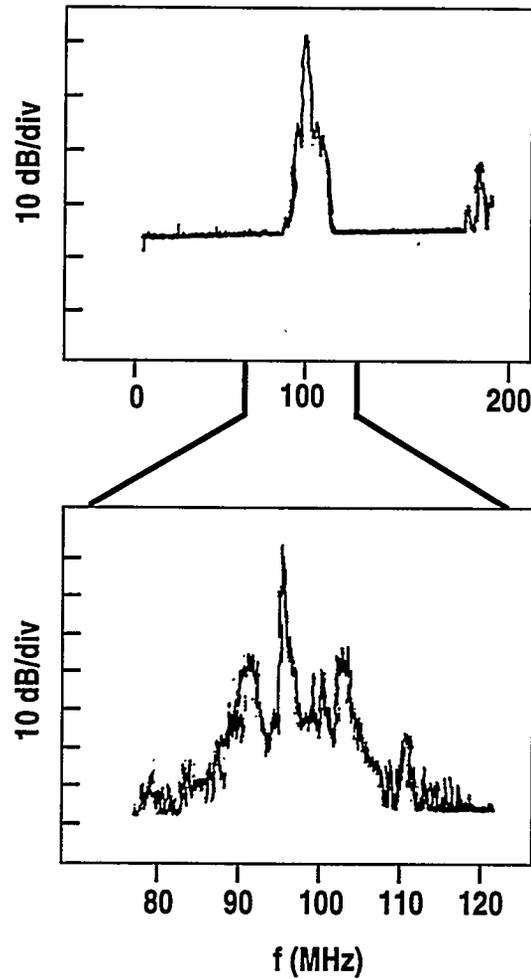


Fig. 8. Spectrum of the low frequency parasitic oscillation after installation of the filter and collar. The center frequency is about 96 MHz and sidebands are visible. The second harmonic is 35 dB below the fundamental.

wings. The FWHM is 14 cm but appreciable power is absorbed within a broader region with 30 cm radius, for absorption centered about 10 cm off the magnetic axis. Fourier analysis of modulated rf injection indicated an even broader power

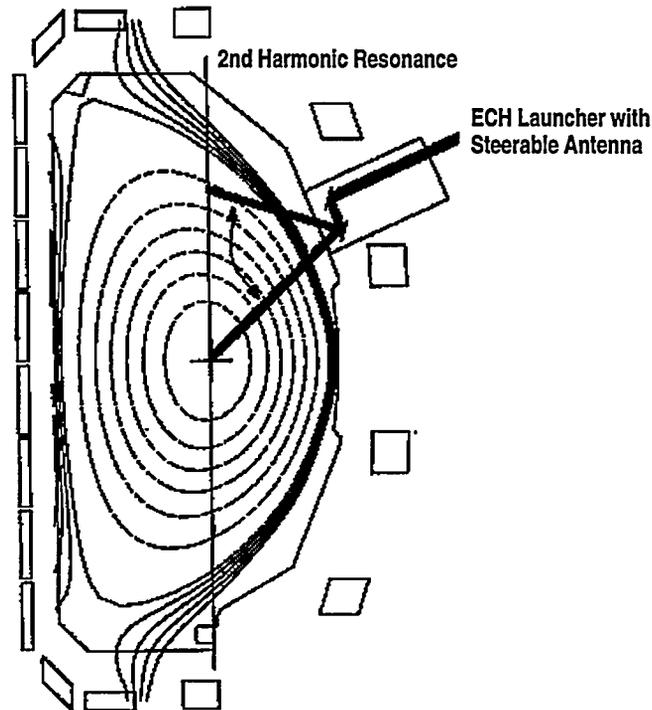


Fig. 9. Cross section of the DIII-D chamber showing the poloidal scan of the injected rf power.

deposition profile. Presently, measurements of the elliptical polarization of the beam launched into DIII-D are being performed under the assumption that an admixture of O-mode is present.

It is characteristic of the operation of this system that there is some reflected power measured at the first miter bend during the first 100 msec of the rf pulse. The forward power measurement has a maximum value during this part of the pulse and then drops, reaching a steady value after about 200 msec. The reflected power decreases to unmeasurable levels after the first 100 msec. An rf monitor on the MOU is also available to indicate the rf power reflecting in the MOU and not a part of the Gaussian beam. These rf monitor traces are shown in Fig. 11, both for an unmodulated and a modulated case. For the modulated case, the high voltage, the collector sweep coil current and the window arc detector

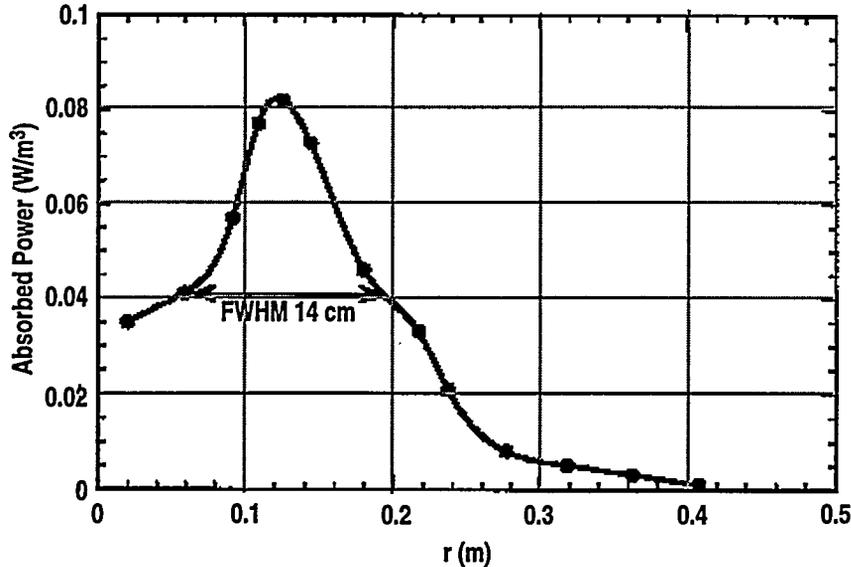


Fig. 10. Power deposition profile measured from the time derivative of the ECE  $T_e$  signal upon termination of the rf pulse. The profile is broader than calculated from the optics of the launcher.

signal are also displayed. The beam voltage is modulated approximately 13% to obtain greater than 60% modulation of the generated rf power. These traces were for injection into DIII-D plasmas for the full 500 msec long pulses.

Injection of approximately 500 kW into DIII-D plasmas at low density has resulted in electron temperatures as high as 12 keV. Traces of the discharge with the highest  $T_e$  are shown in Fig. 12 along with the electron temperature profile from the Michelson interferometer, the heterodyne radiometer and Thomson scattering. The radiometer data show a suprathermal electron population at these low densities.

## VI. CONCLUSION

The Gycom Centaur gyrotron is now running routinely at DIII-D with generated power in all modes at 110 GHz of approximately 900 kW, pulse lengths up to 500 msec and good power accountability. The efficiency is 35% for 110 GHz rf power generation and better than 95% for the evacuated windowless transmission line to the tokamak. Approximately 15%–25% of the power generated by the gyrotron, as inferred from window calorimetry, appears in the MOU.

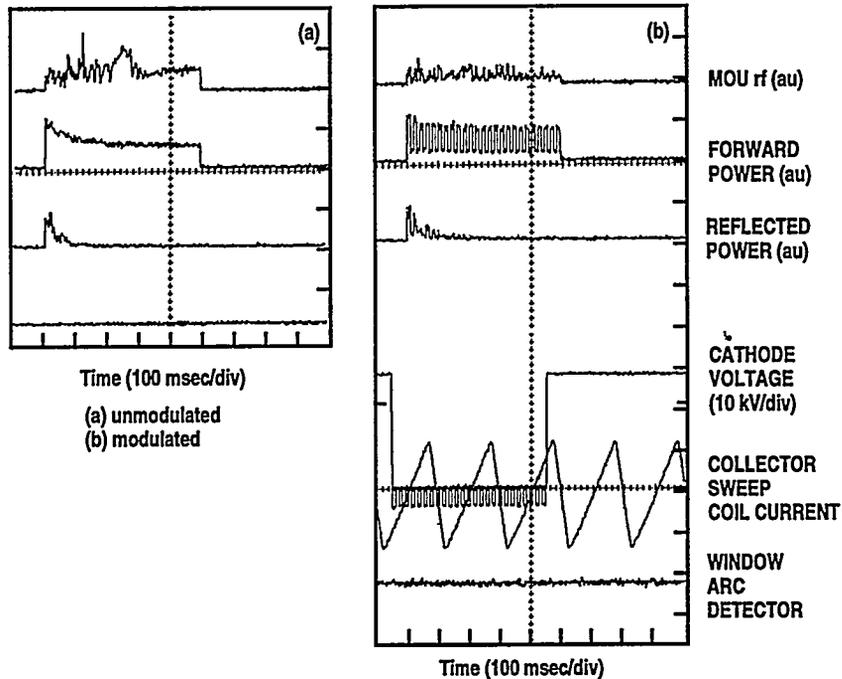


Fig. 11. The rf monitor signals for unmodulated and modulated 500 msec long pulses. The sawtooth signal is the collector sweep coil current. A 13% modulation of the cathode high voltage yields a 60% rf output modulation for transport studies.

Initial injection into DIII-D plasmas has been performed for 500 msec pulses. The MHD measurements of plasma energy indicated that about 550 kW was absorbed in the plasma for about 800 kW generated. Initial transport experiments using modulation of the 110 GHz rf have been performed and ECH synergy for fast wave current drive was investigated.

#### ACKNOWLEDGMENT

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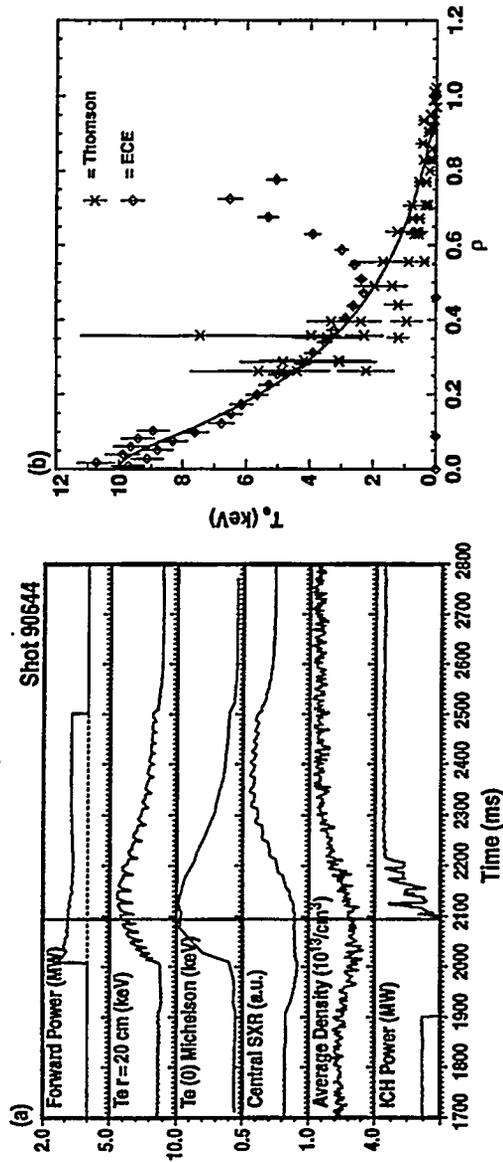


Fig. 12. Time dependence of the forward rf power and several diagnostic traces during ECH/fast wave synergy experiments: (a) the electron temperature profile (b) from ECE and Thomson scattering is shown at the time indicated by the vertical line on the time plots. The density increase associated with the injection of ICH power at 2100 msec decreases the value. Comparison of the ECE and Thomson data at indicates a superthermal electron velocity distribution function during the low density portion of the discharge.

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