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Development of Gyrotrons for
Plasma Diagnostics

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ABSTRACT

Recent advances in high frequency ($>100\text{GHz}$) gyrotron technology are reviewed and application to millimeter/submillimeter wave plasma diagnostics is discussed. Gyrotrons have useful capabilities of high-power ($> 1 \text{ kW}$), long pulse/CW operation, narrow linewidth ($<100 \text{ kHz}$), and good spatial mode quality with efficient ($\sim 90\%$) mode converters. These capabilities could be used to significantly improve collective Thomson scattering diagnostics for the study of instabilities, plasma waves, turbulence, and thermal ion fluctuations. Imaging applications with many detector arrays of plasma density, field direction, and microinstabilities may be possible with gyrotrons. In a high-field compact ignition tokamak experiment a possible near-millimeter wave diagnostics window could be exploited by a gyrotron to measure a number of parameters, including alpha particle density and velocity distribution.

I. INTRODUCTION

The gyrotron is a high average power source of millimeter/submillimeter wave radiation. Recent experiments have significantly advanced gyrotron capabilities. These achievements include: operation at frequencies of up to 650 GHz at 40 kW power level for 100 μ s[1], continuously tunable 100-330 GHz operation at over 10 Watts CW[2], narrow effective linewidth of \sim 1 kHz at 137 GHz[3], and efficient (\sim 90%) mode conversion from circular TE₀₃ to TE₁₁ at 137 GHz[4]. These developments have occurred in a frequency range where microwave devices and far infrared lasers have very low power output, do not completely cover the frequency range, and are not very efficient or reliable.

Millimeter/submillimeter wave plasma diagnostics are very valuable for the study of plasmas in magnetic confinement fusion experiments. These wavelengths are longer than the plasma Debye length so the plasma can be studied through its collective properties. Low to moderate power collective Thomson scattering provides data on instabilities, plasma waves, and turbulence[5,6]. High power scattering from the ion thermal feature can provide measurements of localized ion temperature[7,8], effective Z[9], current density[10], alpha particles[11,12], and D/T fuel ratios. Interferometry and Faraday polarimetry are used to determine the electron and current densities[13]. Electron cyclotron emission (ECE) and absorption[14] are used for electron temperature and superthermal electron measurements. Recent developments in many detector arrays[15] may make it possible to image, with great detail, many of these plasma parameters over large volumes.

Many of these millimeter/submillimeter wave plasma diagnostics are now standard on most magnetic confinement fusion experiments. Some of these diagnostics have not yet been fully exploited. The availability of high-power gyrotron sources should be of benefit to most of these diagnostics.

In this paper the present status of gyrotron technology, as related to plasma diagnostics, is briefly reviewed. Next, the first plasma diagnostics making use of gyrotrons are described, followed by a discussion of other possible applications in present plasma experiments and the advantages of using gyrotrons. Finally, application to a tokamak ignition experiment is discussed.

II. GYROTRONS

In this paper we will primarily be concerned with low voltage (<100 kV) gyrotrons which have actually demonstrated parameters useful for plasma diagnostics. Relativistic gyrotrons[16] will not be covered here, but could be useful sources in the future.

A. BASIC CONFIGURATION

The basic configuration of a gyrotron[17] is illustrated in Fig. 1. The major elements are a high-field solenoid magnet, an electron gun, a millimeter/submillimeter resonator inside the solenoid, and an output collector/waveguide. The electron gun sends an electron beam guided by the magnetic field through the resonator. The electrons are launched with a velocity component perpendicular to the magnetic field which adiabatically increases as the electrons travel up the magnetic field gradient between the cathode and resonator. The millimeter/submillimeter radiation is generated inside the resonator through a weakly relativistic cyclotron resonance interaction at the fundamental or harmonic frequency. The output collector/

waveguide serves as the final anode to the electron beam and guides the millimeter/ submillimeter radiation out of the gyrotron.

Long pulse/CW gyrotrons for plasma diagnostics will tend to make use of superconducting magnets because of the high frequencies generally required. In addition, if the resonator is a waveguide cavity, mode converters[4,18,19] will be needed to transform the millimeter/submillimeter radiation into a beam which is peaked on axis and linearly polarized. These mode converters can be built in as part of the gyrotron system, as shown in Fig. 1, or added outside the vacuum window.

B. PRESENT STATUS

Fig. 2 summarizes the present availability of long pulse/CW sources and recent and projected gyrotron developments in the millimeter/submillimeter wavelength range. Backward wave oscillators (BWO's) and extended interaction oscillators (EIO's) have a rapidly decreasing power capability with increasing frequency. At about half a millimeter wavelength their projected power capability is less than 100mW, and optically pumped molecular gas lasers emerge as the more powerful sources. However, these laser sources have useful power levels on only a few discrete transitions, of which the most powerful are less than 1 Watt[20]. Besides low power, both the lasers and high-frequency microwave tubes are relatively inefficient. The BWO's and EIO's also suffer from limited lifetimes at rated power.

The few representative gyrotron results plotted in Fig. 2 have exceeded previously available power levels by several orders of magnitude. They are also the most efficient (up to 40%) of sources in this wavelength range.

The tunable Sydney gyrotron[2] and solid points[3,21] are for operation at the fundamental cyclotron resonance frequency. The open points are second harmonic results[21-23]. Lines projecting gyrotron performance correspond to a frequency scaling of $-5/2$ power which is based on resonator wall loading considerations for a given mode. These gyrotron projections extend only to frequencies of about 400 and 800 GHz for fundamental and 2nd harmonic operation, respectively. These frequency limits correspond to the maximum field of 16 Tesla available from present commercial superconducting magnets.

The gyrotron projections should not be rigidly interpreted. Operation on different resonator modes can move these curves up or down along the power axis. Also, higher frequency operation is possible with pulsed conventional magnets[1,24] or by operating on higher harmonics of the cyclotron resonance[25,26].

High-power and efficiency are not the only advantages of gyrotrons. The quality of the millimeter/submillimeter emission in terms of frequency stability, linewidth, and spatial mode quality can also be superior to other sources. The frequency stability is mainly affected by the magnetic field which is very stable in superconducting magnets. Electron beam voltage and current variations influence the gyrotron frequency only indirectly[27], unlike BWO's and EIO's which require very well regulated power supplies.

The linewidth of gyrotron emission may be narrower than any other unlocked high-frequency microwave device. For example, heterodyne receiver measurements of the 137 GHz gyrotron shown in Fig. 1 were unable to determine the narrowness of the gyrotron spectrum because of the limiting 100 kHz

linewidth of the tripled Gunn local oscillator. Using a receiver with frequency tracking[28] to cancel out the fast and slow frequency drift of the Gunn oscillator relative to the gyrotron resulted in the spectrum shown in Fig. 3. The linewidth in this case was again instrumentally limited to about 1 kHz full width at half maximum (FWHM) by the crystal reference oscillator in this receiver.

The spatial mode quality of the gyrotron beam for diagnostics can also be excellent with the use of mode converters. The far field pattern of the 137 GHz gyrotron is shown in Fig. 4 after conversion to the circular TE_{11} mode[4]. The overall conversion efficiency from TE_{03} to TE_{11} was about 90%. The linearly polarized TE_{11} mode can be used directly or further converted to an HE_{11} mode which couples to a free space Gaussian beam.

These results demonstrate that gyrotrons can be excellent sources for plasma diagnostics. The future trend will be to push this technology to higher frequencies, filling in a void in high-power millimeter/submillimeter sources.

III. PLASMA DIAGNOSTIC APPLICATIONS

A. Present Experiments

The first plasma diagnostic application of a gyrotron was carried out at Kyoto University[29]. A 70 GHz, ~ 10 kW, 5 ms pulsed gyrotron was used to scatter from low frequency (< 1 MHz) drift wave fluctuations in the WT-2 toroidal device. Less than 1% of the gyrotron power was usable at the plasma because a -20dB directional coupler was used to convert from the circular TE_{02} to a rectangular TE_{10} mode. However, available

power level was not a problem. The linewidth of this gyrotron was measured to be about 9 kHz FWHM with a Gunn oscillator heterodyne receiver. Drift wave fluctuations were readily studied without the need to frequency lock the gyrotron and receiver local oscillator. A drift in the electron diamagnetic direction was detected during ohmic discharges but not during lower hybrid current drive.

The second plasma diagnostic using a gyrotron is being implemented on the TARA tandem mirror experiment at M.I.T. The goal of this diagnostic[3] will be to study instability driven fluctuations in the thermal barrier plug. These instabilities include the drift cyclotron loss cone (DCLC)[30], the axial loss cone (ALC), harmonics of the DCLC and ALC, and the ion two stream instability. The gyrotron developed specifically for this diagnostic is shown in Fig. 1 and has the excellent linewidth and spatial mode qualities previously described. Its power output can be varied from 10W to 3 kW in pulses exceeding the TARA plasma pulse length of 30 ms.

The DCLC and ALC fluctuations occur at the ion cyclotron frequency with a perpendicular wavenumber (k_{\perp}) approximately equal to the inverse of the ion Larmor radius. Scattering measurements will be made in the plug region where the magnetic field is 1 Tesla. The frequency and k_{\perp} therefore will be about 7 MHz and $1-3\text{cm}^{-1}$, respectively, for a deuterium plasma.

The heterodyne receiver for this diagnostic has been installed on TARA. Background ECE levels during initial ECRH operation in the plug have been measured to be equivalent to 73 and 450 eV blackbodies for ordinary and extraordinary emission, respectively. Also, fifth harmonic emission at 140 GHz has

been detected from the ECRH gyrotrons. The advantage of high-power gyrotron scattering will be realized in this noisy environment. In order to achieve a fluctuation sensitivity of $\frac{\tilde{n}_e}{n_e} = 10^{-6}$ in the plug where $n_e \approx 8 \times 10^{12} \text{ cm}^{-3}$, kilowatt power levels will be needed to overcome the background noise.

The gyrotron developed for this diagnostic has the unique combined capabilities of high-power, to overcome background noise; long pulse length, to study the fluctuations as a function of time; narrow linewidth, to frequency resolve the fluctuations; and good spatial mode quality, for well defined scattering volumes and to minimize stray radiation. No other single source could duplicate all of these capabilities in the millimeter/submillimeter wavelength range.

B. Future Applications

Of the millimeter/submillimeter diagnostics listed in the introduction, scattering and imaging applications will probably benefit most from the availability of high average power gyrotron sources. The first applications of gyrotrons to plasma diagnostics, as described above, have been to scattering from non-thermal plasma fluctuations where high-power, narrow linewidth sources are a definite advantage.

Non-thermal scattering to study instabilities, plasma waves, and turbulence will continue to be an important application of gyrotrons. For example, in present tokamak experiments gyrotron scattering at about one millimeter wavelength would allow for good plasma propagation and fluctuation k resolution down to about 1 cm^{-1} (Bragg scattering). High-power capability would allow good sensitivity even in the presence of strong ECE. Scattering in the Raman-Nath regime[31,32] could be used to further improve k

resolution at a millimeter scattering wavelength while maintaining high sensitivity to fluctuations.

Thermal scattering from ion fluctuations may be a diagnostic application where gyrotrons could have a significant future impact. Such a diagnostic has been shown experimentally to provide measurements of localized ion temperature[7,8], effective Z[9], and current density[10]. It has also been proposed for alpha particle measurements[11,12] in fusion ignition experiments. So far this diagnostic has not been fully exploited because of the difficulties of achieving adequate signal to noise ratios. The use of gyrotron sources could significantly increase achievable signal to noise ratios and make this diagnostic practical in major magnetic confinement experiments.

When signals are noise like, as in thermal scattering, the signal to noise ratio (where noise is defined as r.m.s. fluctuation in the signal and noise) is given by[33]

$$S = \frac{a}{1 + a} \sqrt{1 + \Delta f \tau}$$

where S is the post-detection signal to noise ratio, $a = P_s/P_n$ the predetection signal to noise ratio, Δf is the predetection bandwidth, and τ is the integration time.

The time bandwidth product, $\Delta f \tau$, is the limiting factor in achievable signal to noise ratio. Fig. 5 illustrates this. High-power CO₂ and FIR lasers which have been used for this diagnostic have pulse lengths which limit the integration time to about 1 μ s. Frequency resolution for an ion temperature measurement would be on the order of 100 MHz for typical fusion plasma parameters. Consequently, laser thermal scattering diagnostics are limited to maximum signal to noise ratios of about 10. In practice this limit can be easily degraded (and has been) by stray light and other problems which reduce P_s/P_n .

However, gyrotron sources are long pulse. Increasing the pulse length to 10ms would increase the limiting signal to noise ratio to about 1000 (and even higher for longer pulse lengths). With this kind of limit there is significant room for degradation and still have useful signal to noise ratios. Peak power level requirements could be reduced, and even in the presence of strong ECE it may be practical to implement such a diagnostic.

Plasma imaging is another application where gyrotron sources may be of great value. Up to now density interferometry and Faraday polarimetry have been applied to only one or a few plasma chords. Scattering diagnostics generally look at only one localized volume. The development of many detector (>10) microbolometer[15] and heterodyne[34] arrays can greatly increase the mapping of plasma density, magnetic field direction[35], and fluctuations. It may also become possible to apply holographic interferometry techniques[36,37] to obtain detailed volume information about localized plasma densities and microinstabilities.

To fully implement millimeter/submillimeter plasma imaging diagnostics sources with power levels greater than 1 Watt will be needed. Good

spatial mode quality and frequency stability are also important. The gyrotron can fill these requirements.

C. Tokamak Ignition Experiment

The study of ignited fusion plasmas is an important future goal. Present studies[38] show that a high-field compact ignition tokamak (CIT) is a low uncertainty, cost effective way of achieving ignition. Toroidal fields greater than 10 Tesla are being considered.

In an ignition experiment the high electron temperatures ($\geq 10\text{keV}$) will make the first 5 ECE harmonics optically thick in the extraordinary polarization. Many more harmonics above this will be very strong sources of background noise. Emission in the ordinary polarization will also be very strong due in part to internal wall reflections.

ECE in a high-field CIT experiment, on first inspection, would appear to force all collective plasma diagnostics to wavelengths less than about $100\mu\text{m}$. However, the high-field of a CIT experiment coupled with the Mruakami limit on plasma density may open up a near-millimeter wave window for diagnostics. This window occurs because the electron cyclotron frequency increases faster than the electron plasma frequency with increasing magnetic field in a tokamak.

The electron plasma frequency ($f_p = 8.97 \sqrt{n[\text{m}^{-3}]} \text{ Hz}$) scales as the square root of electron density which in turn is proportional to magnetic field. The electron cyclotron frequency ($f_c = 28B [\text{Tesla}] \text{ GHz}$) varies linearly with magnetic field. At high enough toroidal fields these frequencies could be separated enough to create a low background noise window for diagnostics.

For example, in the 10.2 Tesla CIT proposal[38] peak densities of $7 \times 10^{14} \text{ cm}^{-3}$ are expected. This results in f_p and f_c frequencies of 237 and 286 GHz at the plasma center. The possible diagnostic window between these frequencies becomes wider with increasing magnetic field. (For a "super high field" 21 Tesla device[39] these frequencies increase to 347 and 588 GHz.) This window is even wider if one considers only the extraordinary polarization. According to the Appleton-Hartree dispersion relation[40], the lower cut off frequency is given by:

$$f = [(f_c/2)^2 + f_p^2]^{1/2} - f_c/2$$

The lower limit in the 10.2 Tesla CIT experiments would therefore be down shifted to 134 GHz.

There will be some filling in of this window by lower frequency ECE due to the magnetic field gradient in a tokamak, but a vertical viewing geometry may minimize this component. Another possible mechanism for filling in this window would be relativistic down shifted ECE or Cerenkov emission[41] by superthermal electrons, but high density and low RF heating requirements (a super high field device could be ohmically heated to ignition) for a CIT experiment may make such a hot electron component negligible. However, more study is in need of these possible superthermal electron emission mechanisms. Bremsstrahlung radiation[42] at these frequencies and plasma conditions would be less than $10^{-19} \text{ WHz}^{-1}$ (about the noise temperature of the best submillimeter wave receivers).

Refractive effects would be important for diagnostics so close to the plasma frequency, but this disadvantage would not outweigh the advantages of long wavelength, low noise diagnostics.

Examination of Fig. 2 shows that this diagnostic window occurs in a frequency range where the capabilities of BWO's, EIO's, and lasers are at

a minimum. Gyrotrons, on the other hand, can have excellent capabilities at these frequencies to fully exploit collective diagnostics in a CIT experiment.

A unique gyrotron diagnostic capability at these frequencies would be the localized measurement of D/T fuel ratios and alpha particle burn products. This information is contained in the ion thermal feature. As shown in Fig. 5, gyrotrons have an advantage over laser sources because of their long pulse capability. Another significant advantage is being able to do this diagnostic at much longer wavelengths than possible with lasers.

For example, it has been recently proposed to use a 100 MW, 1 μ s, 10 μ m CO₂ laser for scattering at a 1° angle to measure alpha particles in an ignition experiment[11,12]. Thermal scattered signal levels per unit frequency scale as wavelength to the three halves power ($\lambda^{3/2}$) and inversely as scattering angle to three halves power ($\theta^{-3/2}$)[43]. This scaling combined with longer pulse lengths makes gyrotrons attractive for this diagnostic. A 90 kW, 10ms, 1mm gyrotron at a 20° scattering angle could in principle achieve the same signal to noise ratio as the 100 MW laser. The gyrotron, however, could be operated CW and provide time dependent plasma burn information, or even higher signal to noise ratios for longer integration times. The larger scattering angle would help reduce stray source radiation reaching the receiver and improve plasma spatial resolution. In addition, receivers at 1mm wavelengths have lower noise temperatures and larger bandwidths than available at 10 μ m.

IV. CONCLUSIONS

Gyrotrons have the important combined capabilities of high-power in long pulse/CW operation, narrow linewidth, and good spatial beam quality with mode converters. These capabilities are being extended into the millimeter/submillimeter wavelength range where other long pulse/CW high-frequency microwave devices and lasers have power levels orders of magnitude weaker at much lower efficiencies.

Plasma diagnostics in the millimeter/submillimeter wavelength range are valuable for the measurement of a wide range of plasma parameters including density, electron and ion temperatures, magnetic field direction, and non-thermal fluctuations. Gyrotrons can make an important contribution to the advancement of these diagnostics. In particular, scattering applications where higher-power, narrow-linewidth sources offer improved measurement capabilities and in imaging applications with many detector arrays for which higher power sources are required, will benefit most from the availability of gyrotrons.

An important new application may be to exploit a possible near-millimeter wave window in a proposed high-field ignition tokamak experiment. Parameters important to ignited plasmas such as alpha particle density and velocity distribution could be measured much more reliably with gyrotrons than with present high-power molecular lasers.

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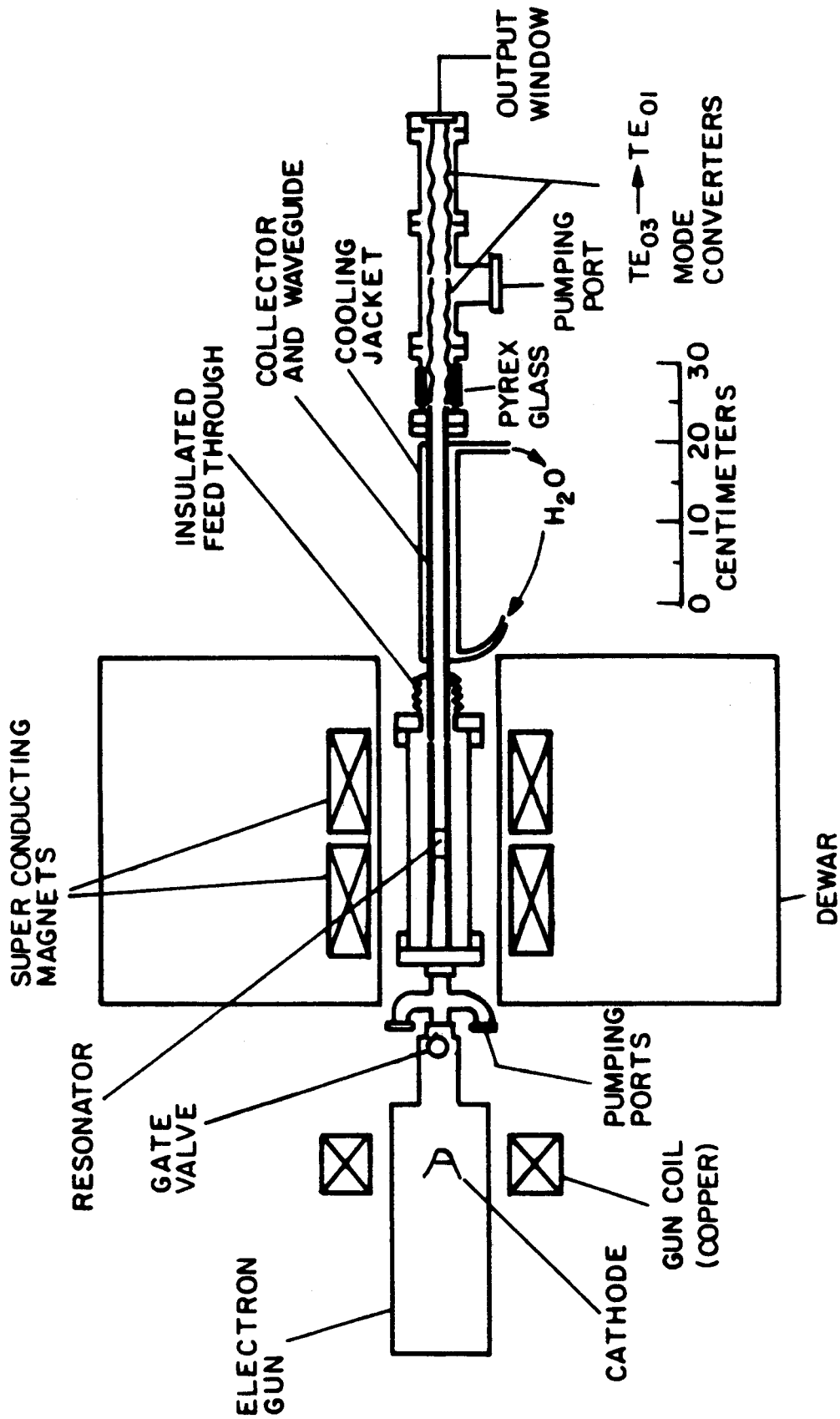
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FIGURE CAPTIONS

1. Illustration of major features of a gyrotron developed for plasma diagnostics. This particular gyrotron is being used for scattering diagnostics to study instability driven fluctuations in the plug of the TARA tandem mirror.
2. Comparison of the power capabilities of long pulse/CW, millimeter/submillimeter wave sources. Gyrotron power is scaled as frequency to the $-5/2$ power.
3. Linewidth measurement of the 137 GHz output of the gyrotron illustrated in Fig. 1. Signal level is displayed on a linear scale. A heterodyne receiver with frequency tracking[28] to cancel out relative drift between the tripled Gunn local oscillator and gyrotron was used.
4. Far field pattern after mode conversion to the circular TE_{11} mode of the output of 137 GHz gyrotron illustrated in Fig. 1. Overall mode conversion efficiency from TE_{03} including ohmic losses, was approximately 90%.
5. The advantages of sources with long pulse length for increasing signal to noise ratio are illustrated.



137 GHz DIAGNOSTICS GYROTRON

Figure 1

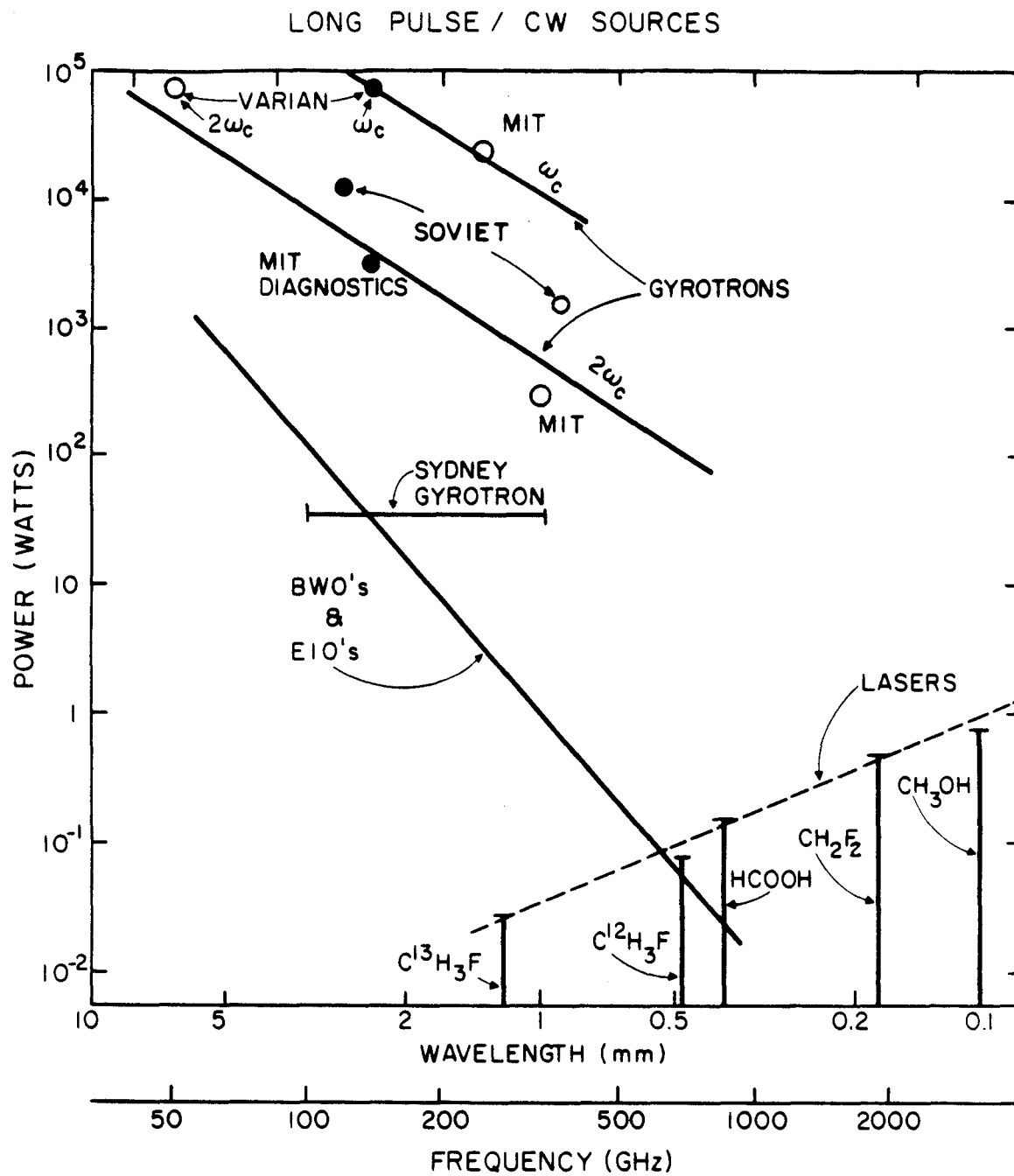
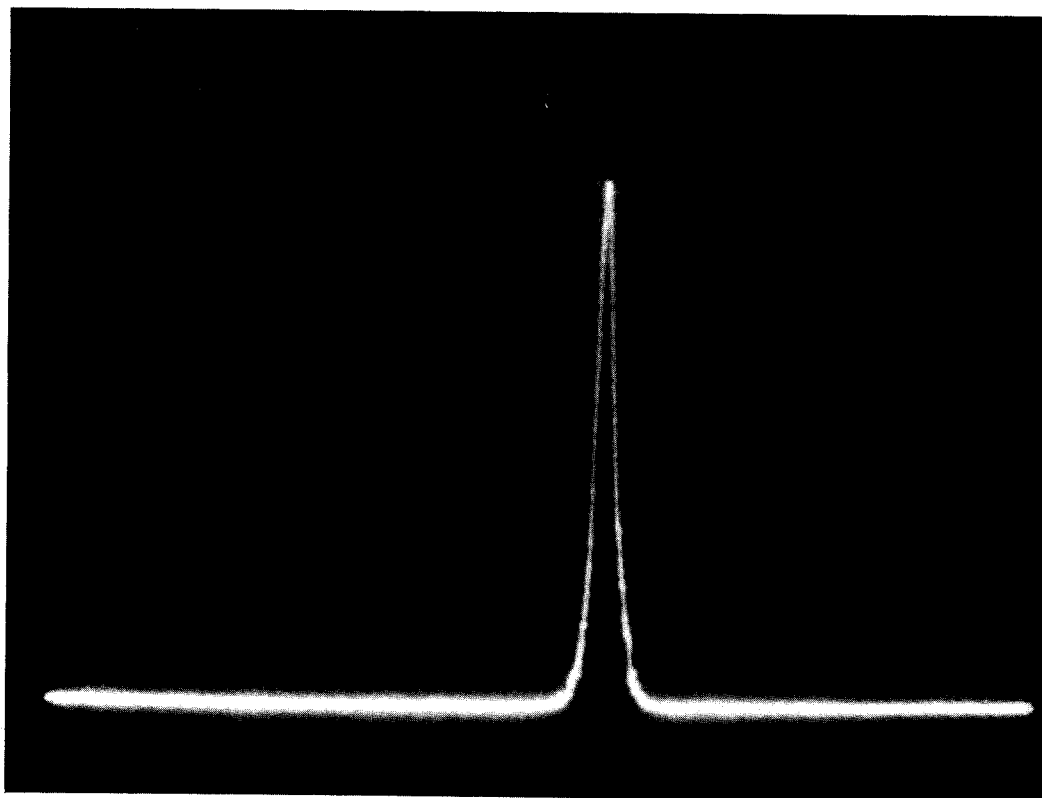


Figure 2



→ | ← 30 kHz

Figure 3

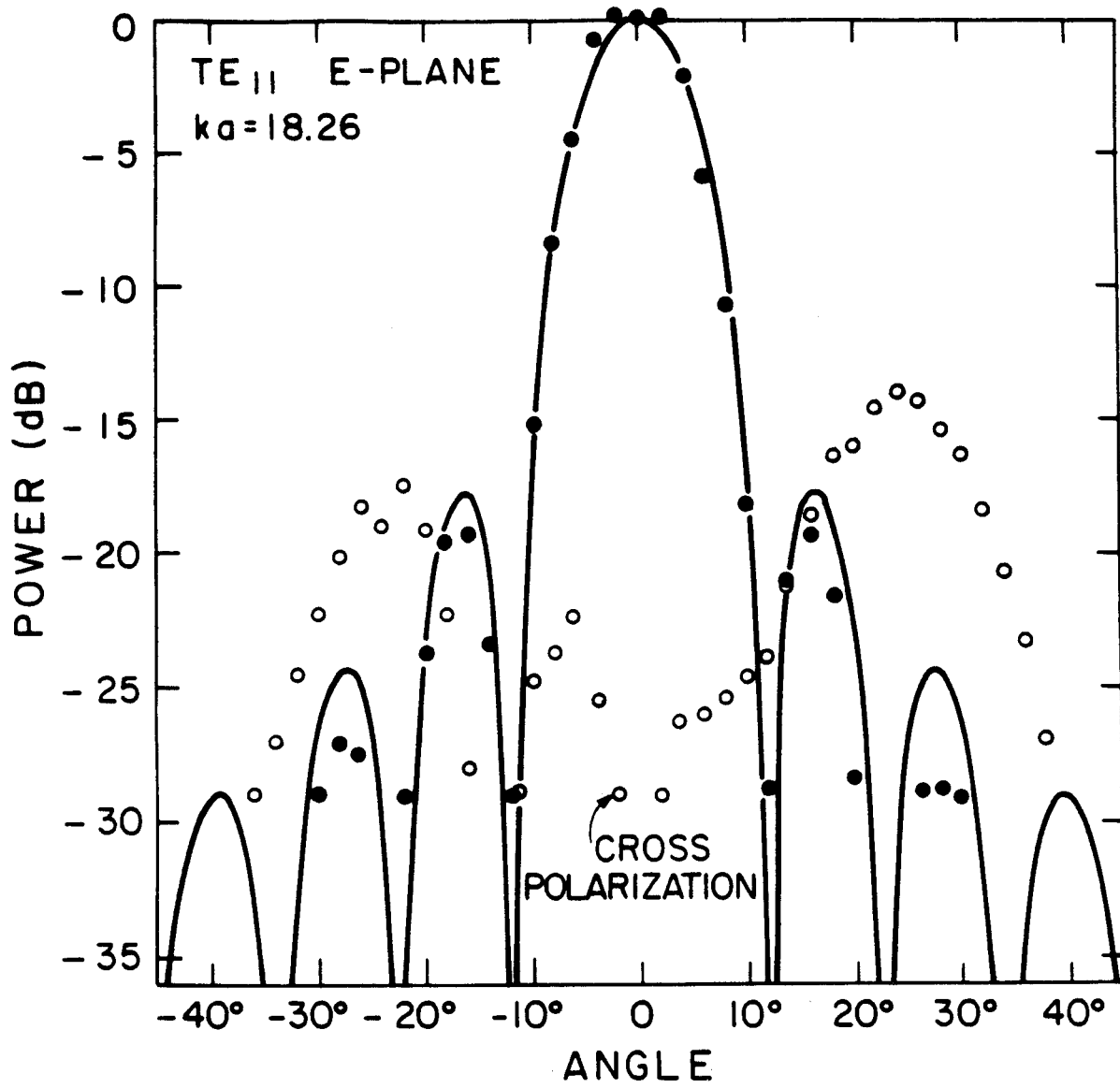


Figure 4

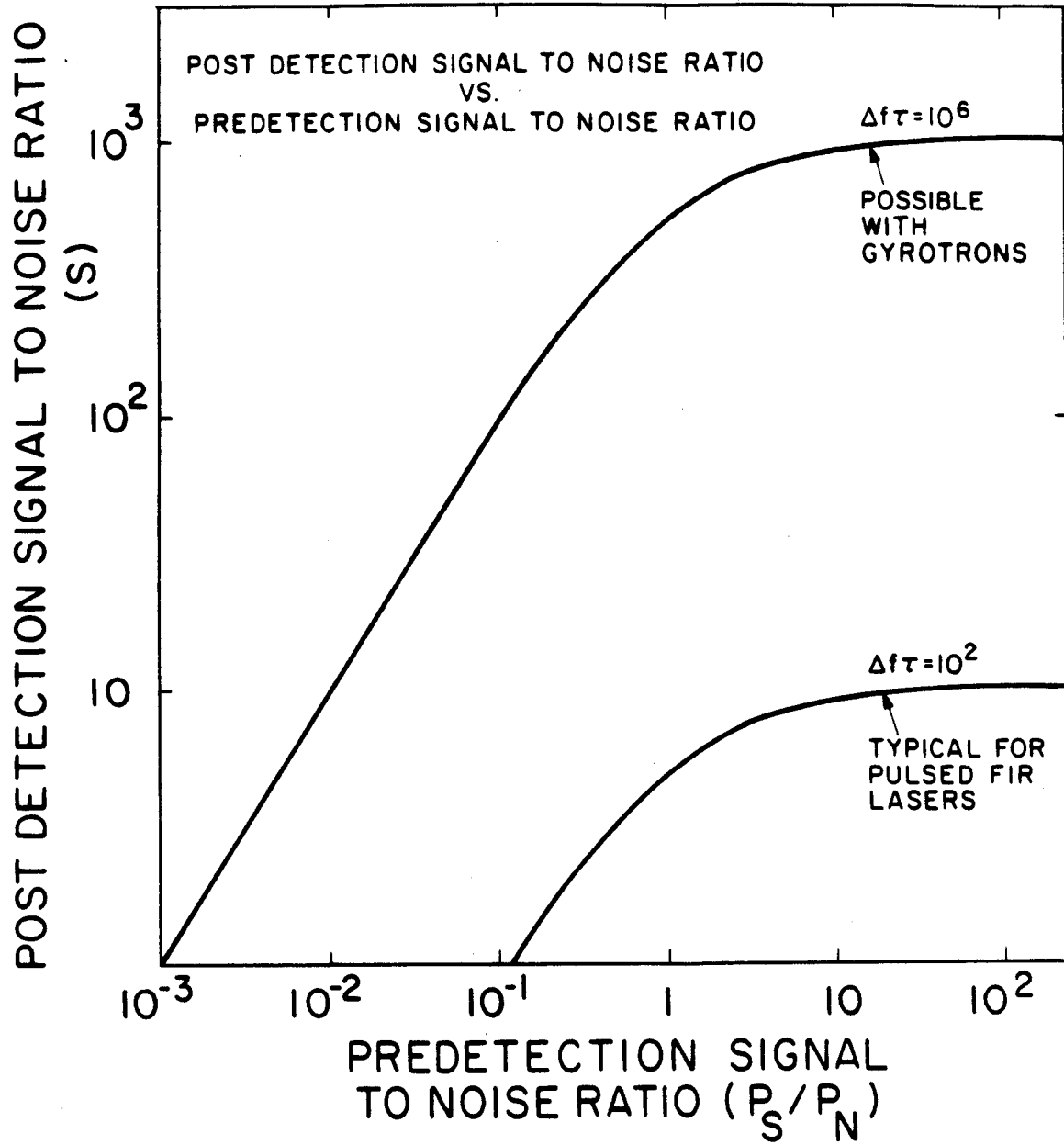


Figure 5