Conversion of gyrotron output into Gaussian beam and its application to plasma diagnostics

I.Ogawa, T. Idehara, Y.Itakura, T.Hori[1], D.Wagner[2] and M.Thumm[3]
Research Center for Development of Far-Infrared Region, Fukui University,
3-9-1 Bunkyo, Fukui 910-8507, Japan
[1]Basic Research Center, Communications Research Laboratory, 4-2-1, Nukui-Kita, Koganei, 184-8795, Japan
[2]Max-Planck-Institut für Plasmaphysik, Garching, D-85748, Germany
[3]Institut für Hochleistungsimpuls- und Mikrowellentechnik, Forschungszentrum Karlsruhe
P.O. Box 3640, D-76021 Karlsruhe, Germany

Abstract
Gyrotron FU II is applied as a submillimeter wave radiation source to plasma scattering measurement for the Compact Helical System (CHS) in National Institute for Fusion Science (NIFS) in Japan. The conversion of the output radiation into a well-collimated beam is necessary for improving the performance of the measurements. A carefully designed cavity resonator with nonlinear up-taper has been developed and implemented in Gyrotron FU VA. The measurements of the radiation patterns have confirmed high-purity mode operations. The output radiation of TE_{03} and TE_{13} modes are converted into bi-Gaussian beams by a quasi-optical system.

1. Introduction
Plasma scattering measurement is effective technique to observe low frequency density fluctuations (f<1MHz, k~10cm^{-1}) excited in plasma. The spatial and wave number resolutions and the S/N ratio of measurement depend on the wavelength range, the size and the intensity of a probe beam. A well-collimated, submillimeter wave beam to offer small scattering volume and relatively large scattering angle is suitable for improving the spatial and wave number resolutions.

Up to the present, molecular vapor lasers [1, 2] and backward-wave oscillators have been used as the principal power sources. However, their output powers are lower than 0.5W. Application of high frequency gyrotron is effective in improving the S/N ratio of the measurement because of its capacity to deliver high power [3, 4]. We have already carried out plasma scattering measurements using a submillimeter wave gyrotron (Gyrotron FU II). It turns out that the stabilization of gyrotron output and high quality probe beam are required to improve the performance of the measurement.

In order to apply the gyrotron to plasma scattering measurement, we have stabilized the output (P=20W, f=301GHz) of gyrotron up to the level ($\Delta P/P<10^{-2}$, Δf<10kHz) established by molecular vapor lasers. The gyrotron output can be stabilized by decreasing the fluctuations of the cathode potential and the anode potential. Because a gyrotron is characterized by voltage controlled oscillator, phase lock technique is effective in stabilizing the frequency. Using a phase-lock control, stability of the frequency of radiation increases up to $\Delta f/f<3.3\times10^{-9}$.

Unlike the molecular vapor lasers, the gyrotrons generate diverging beam of radiation with TE_{mn} mode structure. It is therefore necessary to convert the output radiation into a Gaussian beam (TEM_{00} mode), which is suitable for an effective transmission and can be used as a well-collimated probe beam. In this respect, a high purity mode operation is a prerequisite for effective conversion of the output radiation into the Gaussian beam. A carefully designed cavity resonator with nonlinear up-taper has been developed and implemented in Gyrotron FU VA. The measurements of the radiation patterns have confirmed a high-purity mode operation.

A quasi-optical antenna is a suitable element for the conversion system under consideration since it is applicable to several TE_{0n} and TE_{1n} modes. It should be noted, however, that the far-field of the linearly-polarized beam produced by the antenna consists of side lobes and a main beam, which is similar to a bi-Gaussian beam. A Gaussian beam can be obtained by converting the main beam. A con-focal mirror system with different focal lengths in different directions is used for the conversion.

2. Application of submillimeter wave gyrotron (Gyrotron FU II) to plasma scattering
The gyrotron FU II is one of high frequency, medium power gyrotrons included in Gyrotron FU Series developed in Fukui University. In the gyrotron, as well as other gyrotrons included in the series, a narrow resonant cavity with high Q value is installed for achieving high separation between the cavity modes. Such a situation is important for high harmonic operation of high frequency gyrotrons. Because of this narrow cavity, our gyrotrons could be operated in many single modes at the fundamental and the second and third harmonics of electron cyclotron resonance. The Gyrotrn FU II consists of an 8T superconducting magnet, water-cooled gun coils and sealed-off gyrotron tube. The electromagnetic wave generated

in the cavity transmits in a circular waveguide and emitted from the vacuum window. We used TE_{161} mode operation at the second harmonic (*n*=2) resonance for plasma scattering measurement. The frequency is 354GHz (the corresponding wavelength is 0.85mm). For the application, we tried long pulse operation. Fig.1 shows the results. The pulse width is about 600ms, the output power is 110 watt and the electron beam energy and current are 28keV and 240mA, respectively. This pulse length and the output power are both enough for plasma scattering measurement.

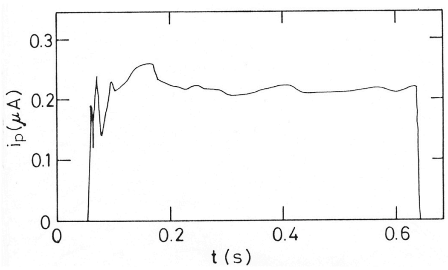


Fig.1 Time evolution of output power measured by a pyro-electric detector.

In order to observe low frequency density fluctuations in the CHS (Compact Helical System) plasma, a plasma scattering measurement system with a gyrotron as a power source is installed (Fig.2). The gyrotron output (*f*=354GHz, *P*=110W) is transmitted to a quasi-optical antenna through circular waveguides and two miter bends and then converted into a linearly-polarized beam. It is injected into the plasma as O-mode. The quasi-optical antenna plays two important roles. One is the mode conversion of the circular waveguide mode into a linearly-polarized mode and the other the focusing of the gyrotron output. The waves scattered by plasma density fluctuations are received by horn antennae installed in the plasma vessel and are converted into low frequency signals by a homodyne detection system. A compact Schottky barrier diode mounted in a corner cube is used as the mixer.

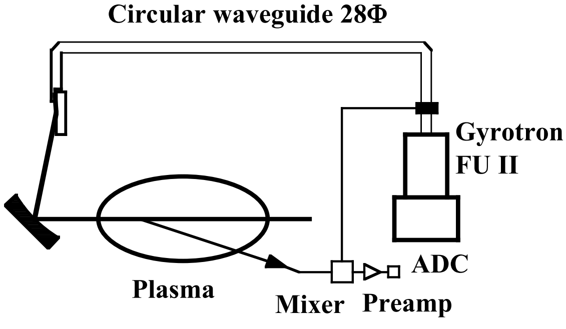


Fig.2 Block diagram of the submillimeter wave scattering measurement.

The frequency spectrum of the signal is obtained by FFT. The scattering measurements with scattering angles of 4.4° and 8.8° are carried out for ICRF (*f*=26MHz, *P*=250kW) heated plasmas. The scattering angle is determined by the configuration of the probe beam and the scattered wave (horn antennae). Target plasmas are produced by electron cyclotron resonance heating (*f*=53.2GHz, *P*=200kW, *t*=13~43ms) and heated further during the ICRF pulse (*t*=40~90ms). After the ICRF pulse, the energy stored in the plasma abruptly decreases and the plasma density becomes zero around *t*=150ms. Figure 3(a) shows time evolutions of scattered wave power for respective frequency intervals. This scattering angle of 8.8° corresponds to wavenumber of $11.4cm^{-1}$. The increase in scattered wave power is observed in the ICRF heating phase (*t*=40~90ms). However, no significant increase in scattered power is observed in high frequency range (*f*>50kHz). Reflectmetry at the frequency of 39GHz gives similar results (Fig.3(b)). This measurement system gives a S/N ratio high enough in the higher frequency range.

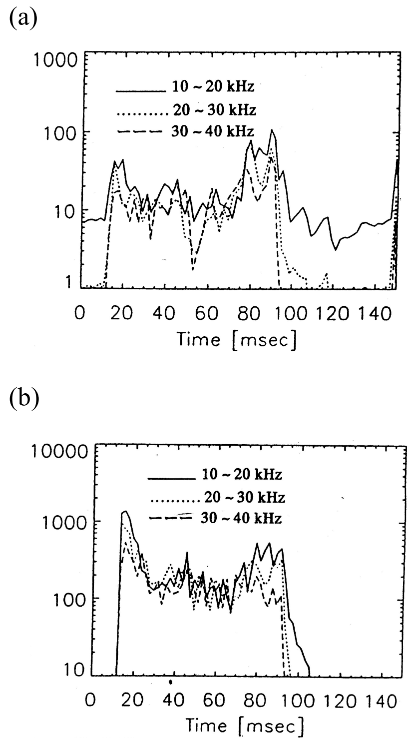


Fig.3 Time evolution of (a) scattered wave power and (b) signal of reflectmetery at the frequency of 39 GHz.

3. High purity mode operation of a gyrotron

Gyrotron FU VA (Fig.4) consists of a gyrotron tube and a helium-free superconducting magnet. This magnet can produce a magnetic field up to 8T without using liquid helium. The tube is demountable, because we will try to optimize all components, the cavity, the transmission waveguide and the output window. The window is made of quartz plate with the thickness of 3.175mm and relative dielectric constant of 3.83.

In order to avoid conversion of the cavity mode to spurious modes, the cavity (Fig.5) has an optimized design with nonlinear up-tapers and a rounded iris at the output. The resonance calculation using a scattering matrix formalism (SM-code) was performed taking into account the complete gyrotron geometry including the pumping sections (slots) and the window [5].

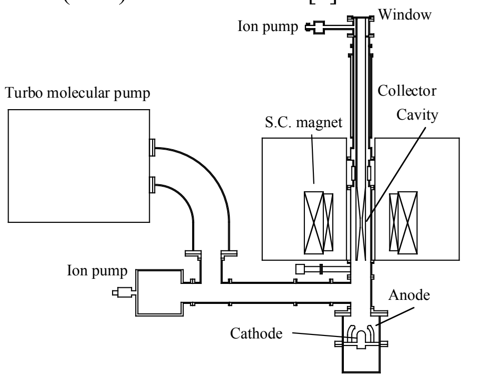


Fig.4 Schematic drawing of Gyrotron FU VA.

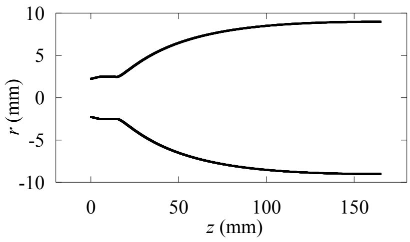
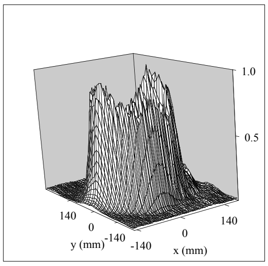


Fig.5 Configuration of the cavity and up-taper.

The radiation patterns are measured by two-dimensionally (x-y plane) moving pyro-electric detector array over the gyrotron window. The intensity profiles of radiation pattern for TE_{03} mode and TE_{13} mode are shown in Fig.6. These patterns are not so affected by the diffraction at the output aperture of waveguide because they are measured in the far-field region ($z > z_f = ka_w^2$~200mm).

The patterns for these modes agree well with the intensity profiles calculated. This demonstrates that Gyrotron FU VA can produce outputs of high purity mode. Such a feature is favorable for converting a gyrotron output into a Gaussian beam.

(a)



(b)

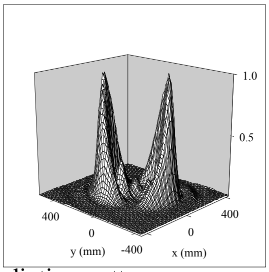


Fig.6 Intensity profiles of radiation pattern.
(a) for TE_{03} mode and (b) for TE_{13} mode.

4. Production of intense, well-collimated beam

The first element in the quasi-optical system is the quasi-optical Vlasov antenna which consists of stepped-cut launcher with radius 9mm and length of the step 100mm and a parabolic reflector whose focal length is 21.75mm. This is followed by an ellipsoidal mirror (Fig.7).

The quasi-optical antenna converts the gyrotron output into a linearly-polarized beam. While the mirror collimates it. In order to observe the intensity profiles, we have constructed an array of 7 pyroelectric detectors. The measured intensity profiles are shown in Fig.8. The quasi-optical system can convert the gyrotron output into bi-Gaussian beam.

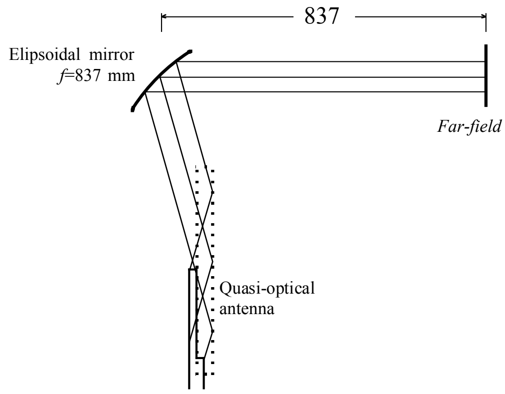
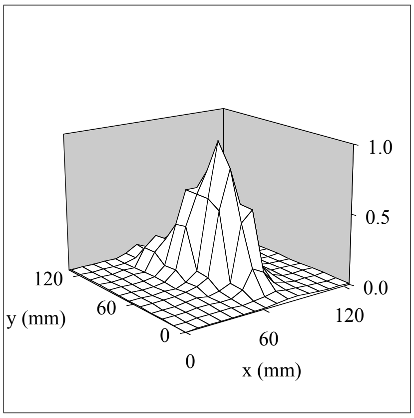


Fig.7 Quasi-optical system.

(a)



(b)

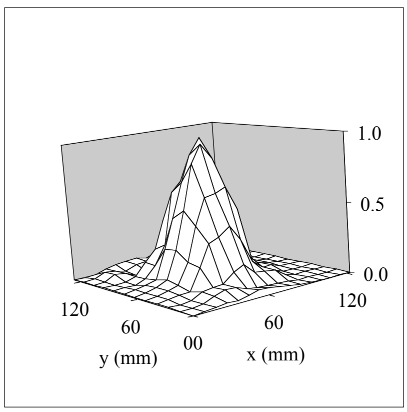


Fig.8 Measured intensity profiles of output beam.
(a) for TE_{03} mode and (b) for TE_{13} mode.

5. Conclusion

The GYROTRON FUII delivers long pulses (*t*=0.6s) of suitably high power (*P*~110W) in submillimeter wavelength range. Output power is steady for long time interval (0.45s), which is long enough to carry out scattering measurements in the CHS plasma (plasma duration~0.1s). The scattered signal from the CHS plasma is picked up by the horn antenna installed inside the plasma vessel and analyzed by a homodyne detection system. During NBI or ICR heating, the scattered signal in the frequency range from several tens to several hundred kHz is observed in a frequency spectrum. It is possibly explained as a manifestation of spontaneous excitation of a drift wave instability in CHS.

To produce high purity mode outputs, a carefully designed cavity is installed in Gyrotron FU VA. The measurement of radiation patterns demonstrates high purity non-rotating mode operations.

The quasi-optical system consisting of a Vlasov antenna and a focusing mirror can convert the high purity mode outputs of TE_{03} and TE_{13} modes into bi-Gaussian beams.

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