Experiment on the Focusing of High power Millimeter-Wave Beam†

Shoji MIYAKE*, Osami WADA, Masamitsu NAKAJIMA*** and Yoshiaki ARATA******

Abstract

Focusing of millimeter-wave radiation from a high power 60 GHz gyrotron is studied using a Vlasov-Nakajima type quasi-optical antenna system. Fine focusing in the E-plane of the wave with an elliptic reflector gives a sheet beam of 10 mm (FWHM) in thickness even at a high power input of about 100kW. Addition of a parabolic reflector brings a focused beam of about 10 mm in diameter in FWHM and an energy beam wit a density higher than 100kW/cm² is obtained. The beam power distribution after reflection from the elliptic mirror is compared with calculated one and a good agreement is obtained.

KEY WORDS : (Beam Focusing) (Millimeter-Wave) (Gyrotron) (Quasi-Optical Antenna) (Elliptic Reflector) (Parabolic Reflector) (High Energy Density Beam) (Materials Heating)

1. Introduction

High power gyrotrons have been utilized for ECH (electron cyclotron heating) of plasmas in nuclear fusion research. Presently an oscilator with a frequency higher than 100 GHz is available on the commercial base having an output power of 200 kW in CW or pulsed mode. Tubes still higher frequencies and outputs are now under development in various countries.

Using a high power 60 GHz gyrotron installed at JWRI, we have estudied ECR (electron cyclotron resonance) plasmas and clarified various characteristic features in the plasma production and heating in a mirror field by a millimeter-wave radiation[1,2].

We also aimed at applying this radiation as a high energy density heat source for the basic study on the heating of various materials. To perform this experiment it is necessary, first of all, to focus the radiation beam as much as possible by applying a quasi-optical antenna system[3,4], which has been developed in the fusion research to achieve local heating of electrons in the central core of the plasma column. Development of various quasi-optical antenna systems to transport and/or focus millimeter-wave ray is also important in the deiagnostics of fusion plasma parameters by the scattering method[5].

As the first experiment we applied the Vlasov-Nakajime type[4] antenna system to obtain fine focusing of the radiation from the 60 GHz gyrotron. This system consists of a half-cut circular waveguide, an elliptic reflector and a parabolic reflector.

In this report experimental reseults of ray focusing both with elliptic and parabolic reflectors are described and comparison of measured beam patterns with calculated ones is given in the case of the focusing with the elliptic mirror.

2. Experimental Apparatus and Method

Figure 1 shows the schematic diagram of the Vlasov-Nakajima type antenna system used for this experiment. Millimeter-wave rays of cylindrical TE_{02} mode radiated upwards from the output window of a 60 GHz gyrotron is transmitted through an arc-detector and a mode filter with inner-diameters of 63.5 mm, after which a circular taper waveguide is connected to diminish the inner-diameter to 25.6 mm. An antenna of a half-cut circular waveguide is directly coupled to the taper, from which rays are emitted obliquely with its electric field almost linearly polaized in y-direction. The angle between the tube z-axis and the direction of the beam emission from the half-cut antenna is calculated to be 25.80°. The beam width D_H in the direction of the wave magnetic field is about 46 mm.

Rays from the half-cut antenna are reflected by the elliptic reflector made of A1 plate to the focal point O' on O_2 axis in the figure. When the parabolic reflector of A1 plate additionally intercepts the beam as shown in (B) of the figure, it is again reflected to the focal point F.

† Received on Oct. 31, 1989

* Professor
** Research INstructor, Okayam University
*** Professor, Kyoto Universtiy
**** Professor, Kinki University

Transaction of JWRI is published by Welding Research Institute of Osaka University, Ibaraki, Osaka 567, Japan

The equation for the elliptic reflector is given by

$$\frac{(x-f_e)^2}{A^2}+\frac{y^2}{B^2}=1$$

where major axis $A=100$ mm, minor axis $B=86.6$ mm and focal length of ellipse $f_e=(A^2-B^2)^{1/2}=50$ mm were selected. The opening width D_E of the reflector is calculated to be 150 mm and its height h becomes 73 mm.

The equation for the parabolic reflector is given in terms of (x', y, z') coordinates in Fig. 1 (B) with the origin at O'.

$$z' = -\frac{1}{4f_p}(x' + x'_f)^2 - f_p$$

where the focal length of the parabola f_p was selected to be 74 mm and x_f' was given to be 122.5 mm.

Experiments were performed by measuring the power distributions of the beam at various x-positions on the y-z plane. The millimeter-wave radiation is injected on the microwave absorber sheet (Eccosorb AN, Emerson & Coming) set at various x-positions in parallel with the y-z plane. Change of the temperature distribution on the sheet, which corresponds to that of the beam power, is measured by a thermal video system (TV-300 Nippon Avionics). This system has the the maximum time resolution of 50 ms/frame. While the millimeter-wave is radiated in a pulsed mode and its maximum pulse width is 100 ms, by which data by the thermal video system is essentially time-integrated one.

3. Calculated Beam Patterns by Elliptic Reflecter

We performed the calculation of the beam power distribution using the code developed by Wada and Nakajima[4]. The 60 GHz TE_{02} mode millimeter-wave beam emitted from the half-cut circular waveguide antenna and reflected from the elliptic reflector is treated as if it comes from an image radiation source lying behind the reflector. As the focusing point was designed to be positioned at $x = 100$ mm on the y-z plane, we obtained beam patterns on the y-z plane at various x-positions, whose results are shown in **Figure 2.** As described already the electric field vector is parallel to y-direction. We find from the figure that the position giving the peak intensity is shifted towards the higher values of z as the beam propagates obliquely from z-axis, but the beam width in this direction is neary the same at each value of x. It is clear that the beam is focused only in y-direction towards the focusing position and a thin beam pattern with a width Δy (FWHM) of about 8 mm is obtained at $x=100$ mm. At positions far from the focusing point the power distribution has a broad and gentle peak in y-direction as we can find in the case of $x=50$ mm and 150 mm.

4. Experimental results and discussion

To test the mode purity of the gyrotron first we measured the power distribution of the radiation emitted just after the taper waveguide. The absorber plate was set 100 mm apart above the taper normal to z-axis and the output power P_i of the gyrotoron was selected to be 70 kW with a pulse duration τ_μ of 1 ms. The result is shown in **Fig. 3.** A cylindrically symmetric temperature distribution corresponding to the beam pattern of TE_{02} mode is clearly found and it keeps almost the same profile even when Pi is varied from several kW to more than 100 kW. We note that in the figure a part of the pattern is cut away and this is because the edge of the taper obstructs the view of the thermal video detector.

Next by fitting the output power P_i to 20 kW and the pulse width τ_μ to 1 ms we measured the distribution of the beam power after the reflection from the elliptic mirror at various x-positions on the y-z plane. The result is shown in **Fig. 4.** On the upper-left part of each figure drawings of each pattern are sketched and the measured range of the temperature is also shown.

At $x = 50$ mm for instance, the beam is widely distributed with a low peak temperature of about 45°C, which is in agreement with the calculated one as we can see in Fig. 2. When the beam approaches to the focusing plane its width Δy (FWHM) in y-direction becomes thinner as the theory predicts and at x=100 mm the width is about 10 mm, which is in fair agreement with the calculated profile in Fig. 2. The peak temperature rises to a value of about 95°C. While at $x = 150$ mm the experimental data and the calculated one has a remakable

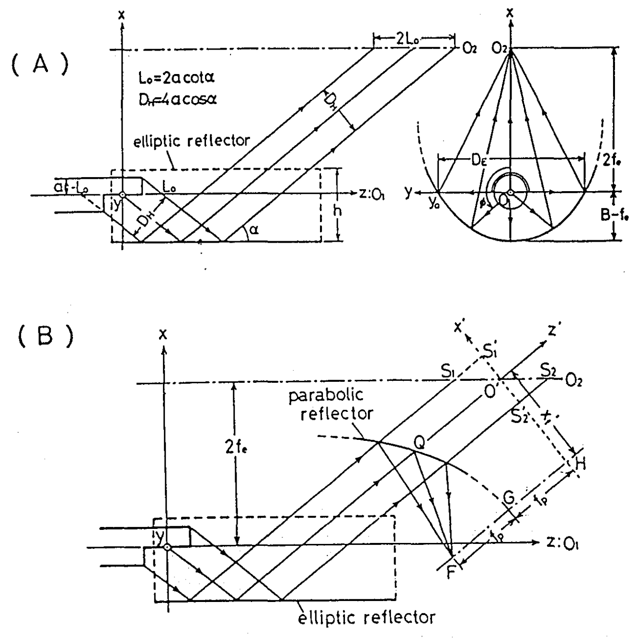

Fig. 1 Schematic diagram of Vlasov-Nakajima type quasi-optical antenna system.

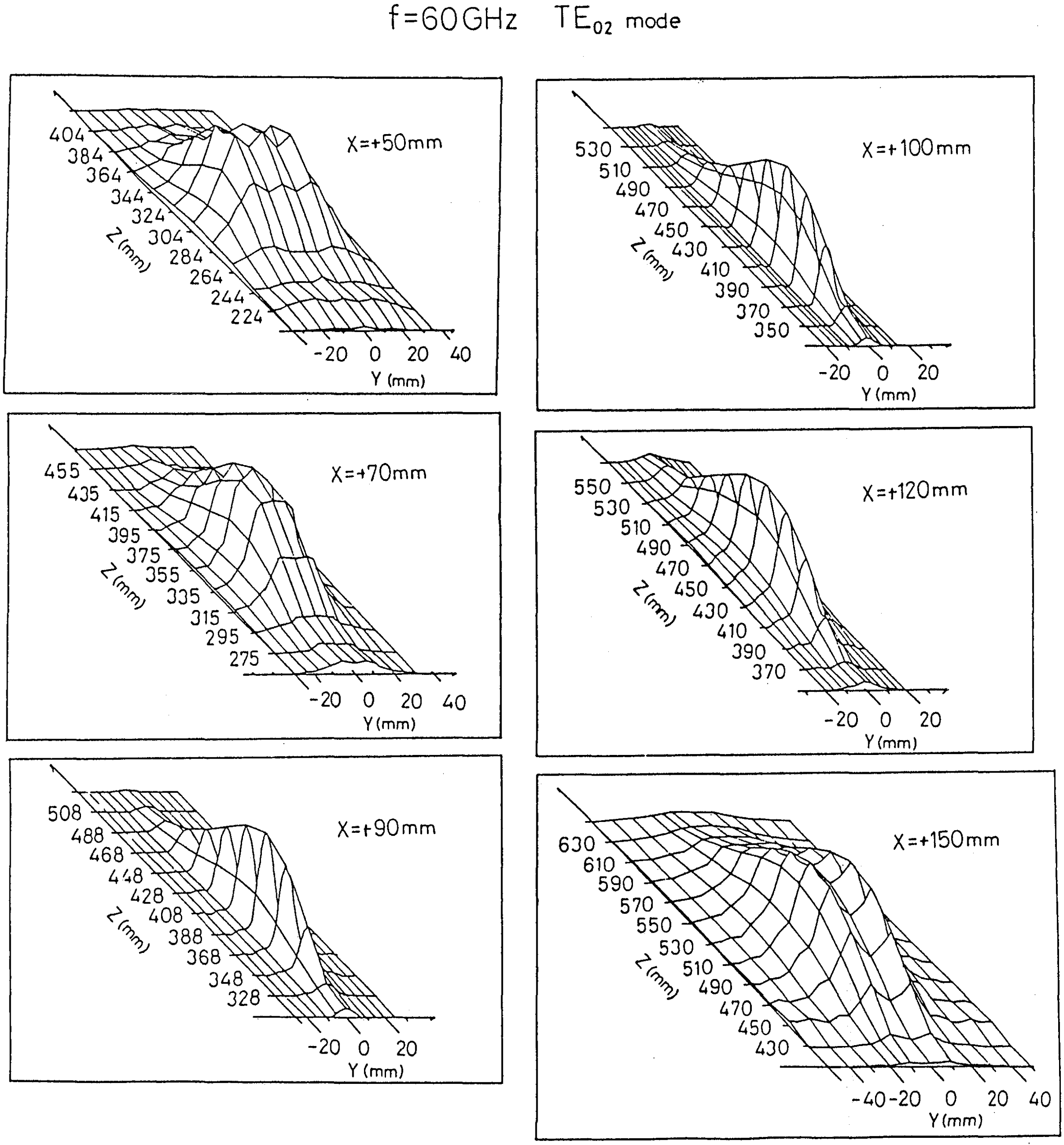

Fig. 2 Calculated profiles of the beam reflected from elliptic mirror.

difference. In the calculation there appear two peaks in the distribution (Fig. 2), while in the experiment we have only one peak. This result mainly comes from the limited spatial resolution of the detector of about 5mm.

To know the applicability of this focusing system to a higher output power we obtained the power dependence of the beam profile on the focusing plane at $x = 100$ mm, whose result is shown in **Fig. 5.** The output power is varied from 20kW to 75kW but the distributions have the same shape and a further increase of the power was apt to bring about burning of the absorber.

From these results we can conclude that the beam focusing in the E-plane of the millimeter-wave radiation is very efficient when we use an elliptic reflector in good agreement with the thoretical prediction.

We further made an experiment of the beam focusing by additionally intercepting a parabollic reflector as shown in (B) of Fig. 1. The focusing point F is positioned around $x = -70$ mm. We again measured the temperature distributuion on the y-z plane at various x-positions. In this case the temperature was increased drastically and burning and/or removal of the absorber at the beam injection point was easily observed, by which the beam power was lowered to 10 kW and the pulse width to 0.5 ms. **Figure 6** shows the beam power distribution at $x = -55$ mm, -70 mm and -120 mm. We can clearly find that at $x = -70$ mm a well focused nearly Gaussian beam is obtained with a width (FWHM) of about 10 mm. The peak temperature reaches to a value of 120°C. This result suggests that a high energy density millimeter-wave radiation of 100 kW/cm^2 is easily obtained, when the beam power is increased to 100 kW.

5. Conculsion

Using the Vlasov-Nakajima type quasi-optical antenna system and a high power 60 GHz gyrotron, experiments on the focusing of millimeter-wave radiation was performed to obtain a high energy density beam of radiation. and following results were clarified.

(1) Combination of elliptic and parabolic reflectors made us obtain a well focused beam having a nearly Gaussian profile, which was verified by the measurement of the temperature distribution on the absorber plate where the wave was injected.

(2) By focusing the beam with the elliptic mirror a thin sheet beam was obtained and the beam profiles had a good agreement with calculated ones.

(3) Additional focusing by the parabolic reflector gave a finely focused cylindrical beam with a diameter (FWHM) of about 10 mm, by which a high energy density beam of 100kW/cm^2 was obtained at a power input of 100kW.

Acknowledgement

The authors would like to express their gratitude to Prof. M. Sato and Mr. M. Iima of Kyoto University for their interest and strong support to this work. They also thank to Mr. A. Arahori for his technical help in the experiments.

This research was partly supported by the Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture.

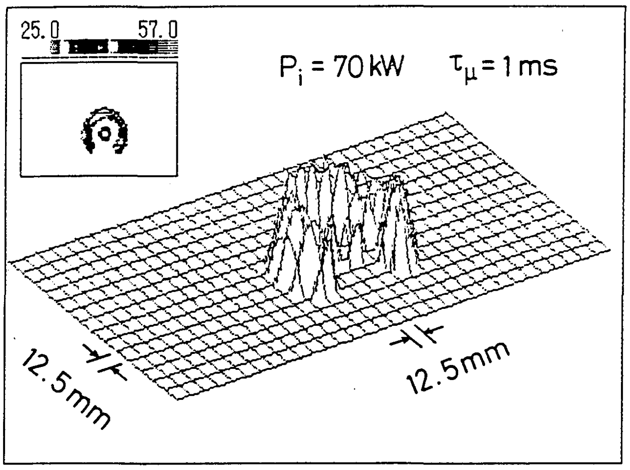

Fig. 3 Beam pattern of millimeter-wave radiation from the 60 GHz gyrotron with TE_{02} mode.

References

1) Y. Arata, S. Miyake, H. Kishimoto, N. Abe and Y. Kawai, Jpn. J. Appl. Phys. Vol. 27, No. 7, (1988) pp. 1281-1286.
2) Y. Arata, S. Miyake and H. kishimoto, Jpn. J. Appl. Phys. Vol. 28, No. 2, (1989) pp. 234-239.
3) S. N. Vlasov and I. M. Orlova, Radiophysics and Quantum Electronics, Vol. 17, No. 1, (1974) pp. 148-154.
4) O. Wada and M. Nakajima, Space Power, Vol. 6, (1986) pp. 3-8.
5) M. H. Bowden, P. F. Fekete, M. J. Ballico, G. F. Brand, I. S. Falconer, B. W. James, K. J. Moore and T. Idehara, Proc. 13th Int. Conf. on Infrared and Millimeter Wave, (1988) pp. 150-151.

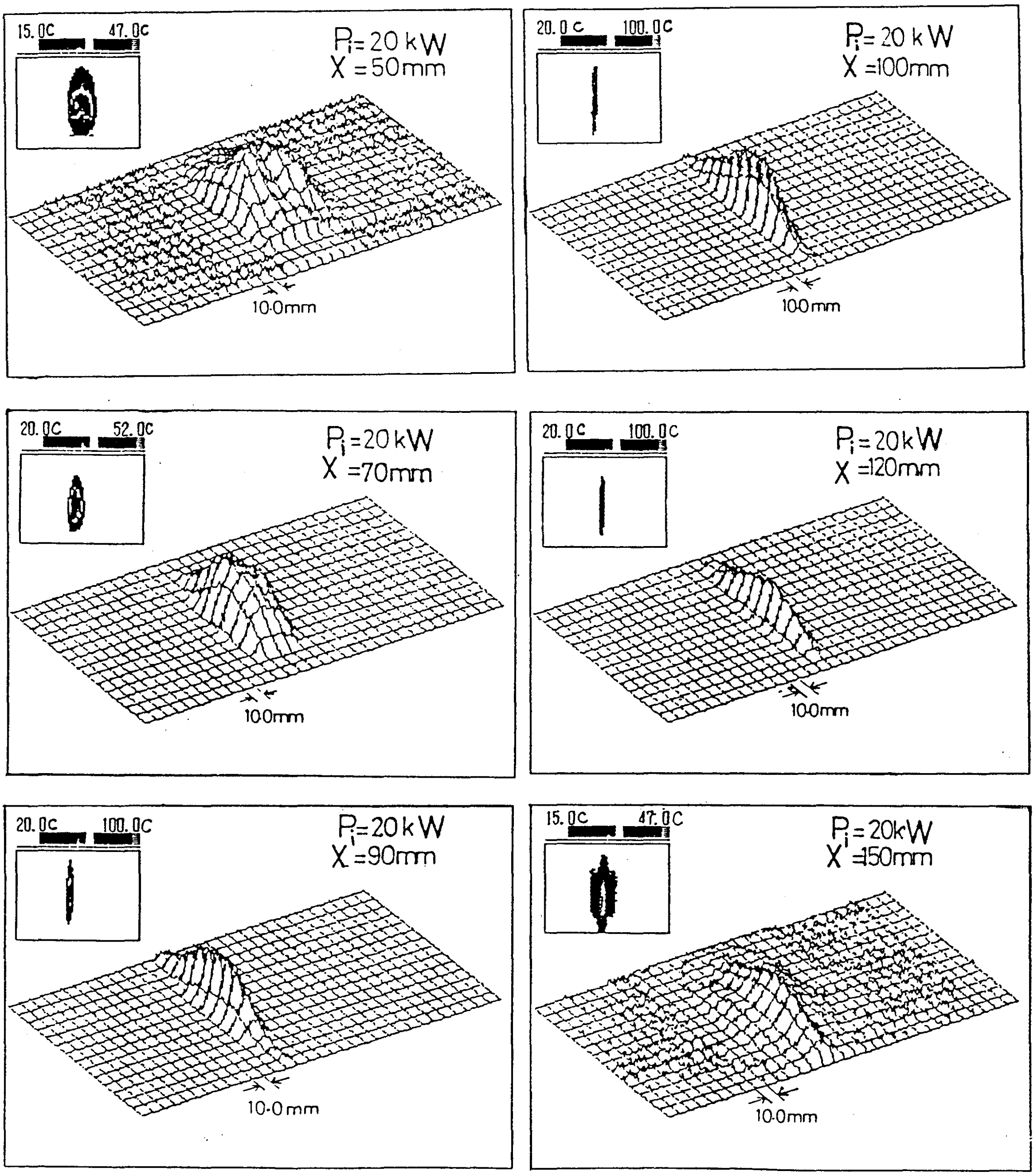

Fig. 4 Beam profiles at various positions measured by thermal video detector reflected from elliptic mirror.

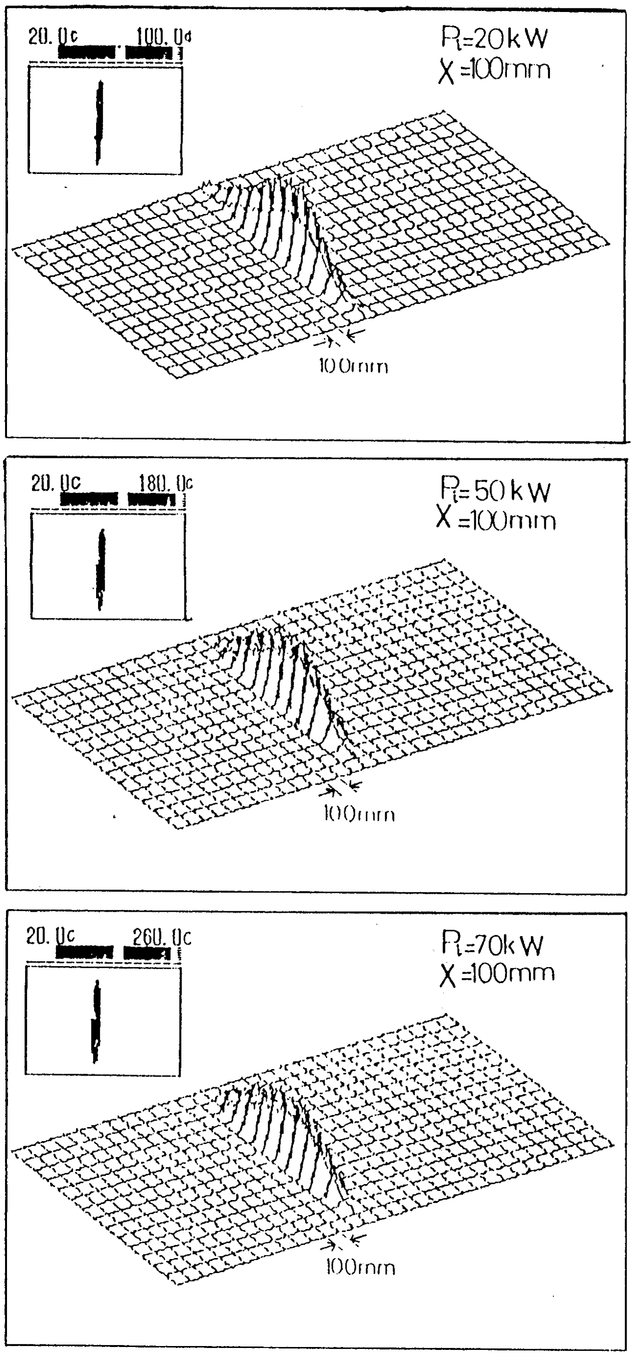

Fig. 5 Power dependence of beam patterns onthe focusing axis in case of reflection by elliptic mirror.

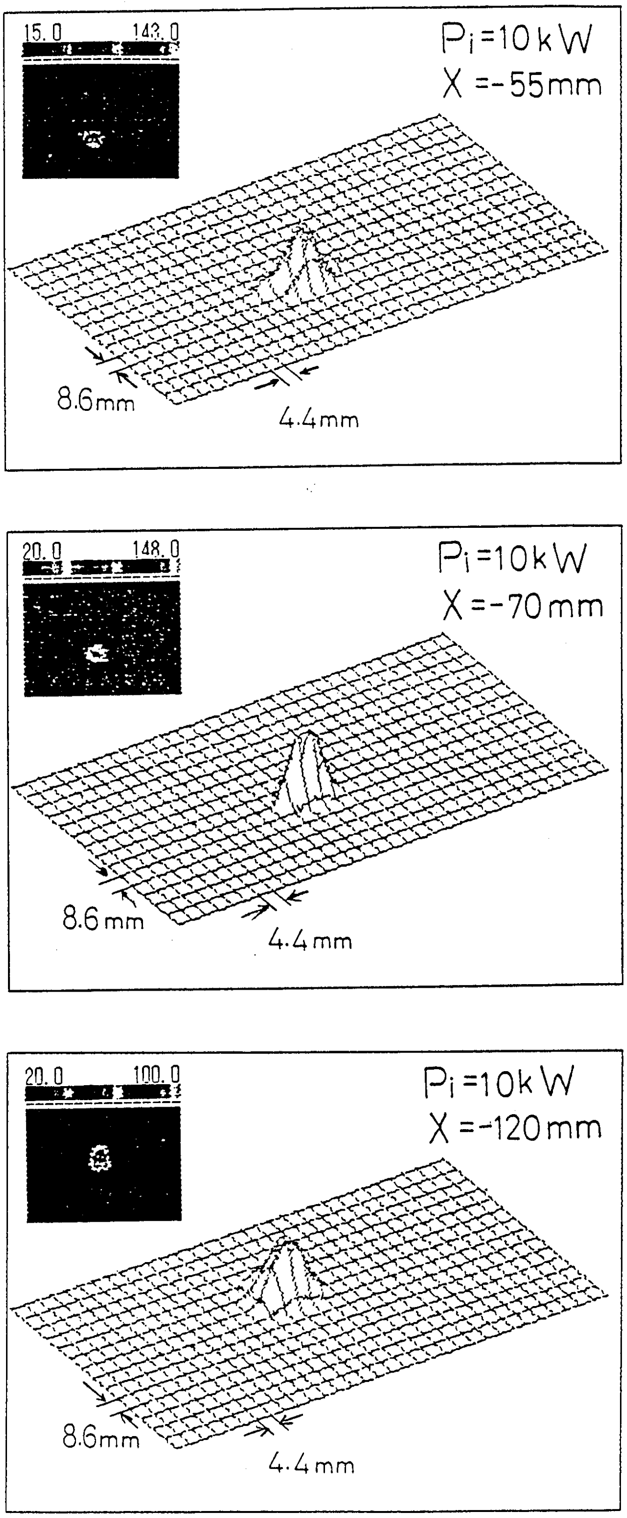

Fig. 6 Measured beam pofiles at various posisions reflected by parabolic mirror.