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RADIATION OF HARMONICS $n\omega_e$ AND $n\frac{\omega_e}{2}$ FROM A BEAM-GENERATED PLASMA +)

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Abstract

A short account of an experimental study on radiation from a beam-generated plasma in helium is given. Radiation at the harmonics of the electron cyclotron frequency ω_e and at half the electron cyclotron frequency $\omega_e/2$ was only found when a metallic probe was present in the beam. Both modes of these two emission spectra could be observed under characteristic experimental conditions. These conditions enable us to draw conclusions on the plasma state in which emission occurs at frequencies $\omega = n\omega_e$ or $\omega = n\omega_e/2$.

Introduction

Harmonics of the electron cyclotron frequency ω_e and half the electron cyclotron frequency $\omega_e/2$ are observed to radiate from an electron beam plasma in helium at low pressures $p \lesssim 10^{-3}$ torr. Both modes of radiation can be observed, however, only if a metallic probe is inserted in the beam. There is no radiation if the metallic probe is placed outside the beam or if a ceramic rod is introduced into the beam. It depends on the pressure and also on the homogeneity of the external magnetic field near the electron gun whether the spectra $n \cdot \omega_e$ or $n \cdot \omega_e/2$ are radiated.

The generation of electromagnetic radiation near harmonics of the electron cyclotron frequency by interaction of fast electron beams with plasmas has been investigated recently in several experiments [1-5]. The excitation of oscillations near half the electron cyclotron frequency and its harmonics has also been dealt with in the last few years [6-9].

In the experiment described here the emission of harmonics of ω_e and $\omega_e/2$ from a beam-generated plasma is measured in the X-band frequency range and with magnetic fields between 400 and 1500 gauss. Harmonics of ω_e up to the 8th order and of $\omega_e/2$ up to the 16th order are found. Each of the two spectra is observed under typical external experimental conditions. From these conditions we are able to draw conclusions about the plasma state in which microwave signals are generated at harmonics of ω_e and $\omega_e/2$.

Experimental set-up

The experimental device (Fig. 1) consists of a stainless steel tube, 160 cm long and with an inner diameter of 17 cm, which could be evacuated to a base pressure of $p_o < 3 \times 10^{-6}$ torr. At one end of the tube is an electron gun which operates at acceleration voltages up to 2 kV and with beam currents up to 120 mA. The anode of the gun is grounded. A solenoid produces a longitudinal magnetic field up to 1500 gauss. By short-circuiting some of the coils we are able to place the gun outside the homogeneous B-field so that the beam passes through an increasing B-field.

In the middle of the tube 3 cm waveguides and probes are radially inserted. The waveguides can be turned to measure polarisation $E \perp B$ and $E // B$. The probes can be moved continuously into the tube and also turned about their axes. Various types of probes are used: plane and cylindrical metallic probes and cylindrical ceramic rods. The signals are received by the waveguides and the metallic probes and measured by a Dicke-type radiometer operating in the X-band.. The receiver frequency is 9.6 kMc/sec.

Experimental results

In Fig. 2 spectra of harmonics of ω_e and $\omega_e/2$ are shown. These were recorded for various pressures of helium with varying magnetic field. The signals were received by the waveguide, which was aligned for observing polarization $E \perp B$. A plane tantalum probe (70 x 5 x 0.3 mm) was placed in the beam. The experimental conditions for receiving the $n \cdot \omega_e$ spectra in the top half of the Fig. 2 are as follows: The electron gun has to be outside the homogeneous magnetic field and the gas pressure must be relatively high.

The harmonics are found at pressures up to 2×10^{-3} torr and disappear at pressures smaller than 1×10^{-4} torr. The radiation intensity of the entire spectrum is highest at a helium pressure of about 2.5×10^{-4} torr. The floating potential of the probe is small (some 10 V) and depends on the gas pressure. Variations of the probe voltage up to 100 volts positive and negative to its floating potential have no great influence on the intensity of the radiation. With a grounded probe the intensity is a little higher. The radiation intensity increases with rising beam energy and current.

The $n \cdot \omega_e/2$ spectra in the bottom half of Fig. 2 are observed in the case of a homogeneous B-field and between the base pressure and $p < 1.5 \times 10^{-4}$ torr. When the pressure increases beyond 1×10^{-4} torr, the radiation of the harmonics disappears, first those of lower order and then, at higher pressures, those of higher order. A continuum now appears. If these spectra are observed, the floating potential of the probe is approximately equal to the acceleration voltage of the gun. No radiation is detected when a grounded probe is used. The radiation intensity grows with increasing beam energy, but attains a maximum at beam currents of about 15 mA.

The same spectra are also picked up if the metallic probes are connected with the radiometer. The signals received with probes are weaker. No differences are found, if the probes are inserted along the axis of the waveguide or perpendicular to it. No shifts of the received frequencies are found if the pressure, beam voltage or beam current is varied.

When a ceramic rod or tube is introduced into the beam instead of a metallic probe, no radiation can be detected. However, when a thin metal wire is inserted in the ceramic tube, emission of the harmonics is again observed with intensities comparable to those induced by metal probes.

Fig. 3 shows spectra of $n \cdot \omega_e$ and $n \cdot \omega_e/2$ when the angle between the normal to the probe plane and the B-field is varied. For the harmonics of ω_e the radiation is greatest when the probe plane is parallel to B and the beam. But the radiation intensity of the $\omega_e/2$ harmonics has a maximum when the probe plane is perpendicular to B, decreasing to zero when the probe is turned 90 degrees.

Radiated intensities for the polarization $E \perp B$ and $E \parallel B$ are shown in the Fig. 4 and 5. At frequencies $n \cdot \omega_e$ (Fig. 4) and at $\omega = n \cdot \omega_e/2$ (Fig. 5) the components of radiation $E \perp B$ are larger than the components $E \parallel B$ if the probe plane is $\perp B$. At the probe position $\parallel B$ no large influence of the intensities of the electron cyclotron harmonics is observed if the direction of polarization of the waveguide is varied. At this probe position no radiation is found at frequencies $\omega = n \cdot \omega_e/2$.

In Fig. 6 the signals are recorded if the metallic probe is moved into the beam at a constant B-field of 860 gauss under conditions allowing observation of the 4th harmonic of ω_e. In the top half of this figure the radiated power is shown, in the bottom half of the figure the radiometer was connected with the probe. As long as the probe is outside the beam, no radiation is detected. If the probe comes into contact with the beam, the radiation sets in abruptly. With a thin wire probe the intensities of the received signals vary while the probe is passing through the beam. The distance from peak to peak is 1.5 cm, which is equal to half the vacuum wavelength at 9.6 kMc/sec.

When larger probes are used the signal variations are not very large and may even disappear. Fig. 7 shows an example of such radiation at frequencies $n\cdot\omega_e/2$. A plane metallic probe (40 x 5 mm) perpendicular to B was used. This was moved in the upper half of the picture perpendicularly to the axis of the waveguide and in the bottom half parallel to it.

Conclusion

From the various experimental conditions (summarized in Fig. 8) we can conclude that the radiation at frequencies $n\cdot\omega_e$ and $n\cdot\omega_e/2$ may be a result of two completely different physical mechanisms.

To observe emission at frequencies $n\cdot\omega_e$, the electron beam is passed through an increasing B-field and the gas pressure has to be relatively high. A small floating potential of the probe $|U_{fl}| << |U_{gun}|$ is then observed. From this we can conclude that the beam generates a secondary plasma. After passing through the magnetic mirror the beam electrons receive a velocity component $\perp B$ and the electron velocities are randomized by collisions. The generation of the radiation might be explained as follows: Longitudinal waves $k /\!/ E$ and $E \perp B$ collide with the density gradient at the probe surface. The probe is excited and radiates transverse waves like an antenna. The most effective excitation of the probe is expected when the plasma waves collide with the maximum probe area. This is also experimentally observed when the probe plane is $/\!/ B$.

The harmonics $n\cdot\omega_e/2$ are only observed, if the magnetic field along the beam is very homogeneous and the gas pressure is smaller than 1.5×10^{-4} torr. The observed floating potential of the probe is then nearly equal to the electron acceleration voltage of the gun. Therefore, collisions and ionization processes in the gas due to the high energy electrons must be so rare that the beam is monoenergetic parallel to the field lines and the plasma density is low. We believe that in this case we have an instability mechanism due to plasma cyclotron interaction which occurs near half the cyclotron frequency. Such phenomena were observed and described by ETIÉVANT and co-workers in an interaction experiment with two counterstreaming electron beams. In our experiment we used a single beam, which is reflected by the probe if the probe voltage is sufficiently negative, and if the probe plane is perpendicular to B. When the working pressure is high enough, we observe that the signals with frequencies $n \cdot \omega_e/2$ disappear with increasing B-field.

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Figure Captions

Fig. 1 Experimental device and measuring set-up.

Fig. 2 Pressure dependence of
a) harmonics $n\omega_e$,
b) harmonics $n\omega_e/2$,
in helium, receiver frequency $f_o = 9.6$ kMc/sec. (For clarity the curves have been displaced in the ordinate.)

Fig. 3 Dependence of the angle of the probe plane (tantalum 70 x 5 x 0.3 mm)
a) harmonics $n\omega_e$,
b) harmonics $n\omega_e/2$,
probe plane $\perp B$: 0^o,
probe plane $\parallel B$: 90^o.

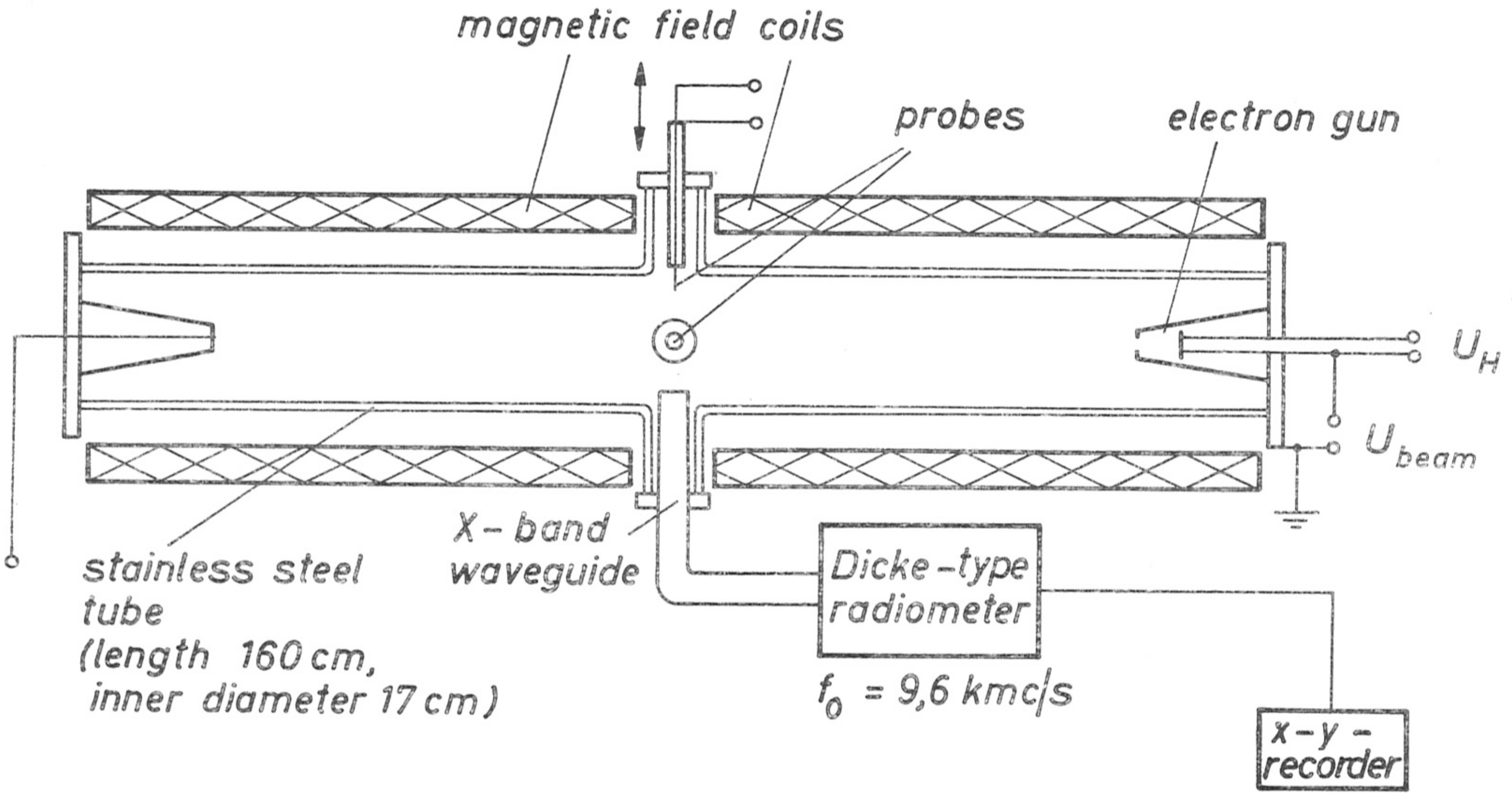
Fig. 4 Radiated power at harmonics $n\omega_e$ in dependence on the directions of polarization $E \perp B$ and $E \parallel B$ for two positions of the plane probe:
a) probe plane $\perp B$ (0^o),
b) probe plane $\parallel B$ (90^o).

Fig. 5 Radiation at frequencies $n\omega_e/2$ for directions of polarization of the waveguide $E \perp B$ and $E \parallel B$. Probe plane $\perp B$.

Fig. 6 Signals for a fixed B-field (B = 860 gauss, 4th harmonic of ω_e, receiver frequency 9.6 kMc/sec) in dependence on the radial probe position
a) radiated power ($E \perp B$),
b) signals picked up by the probe.

Fig. 7 Radiation intensities at the 8th harmonic of $\omega_e/2$ (B = 860 gauss) in dependence on the radial probe position (probes: tantalum 40 x 5 x 0.3 mm)
a) the probe is moved perpendicularly to the axis of the waveguide,
b) the probe is moved parallel to the axis of the waveguide.

Fig. 8 Table of the experimental conditions, the plasma conditions and the properties of the radiation at frequencies $n\omega_e$ and $n\omega_e/2$.



Beam - plasma experiment

Fig.1

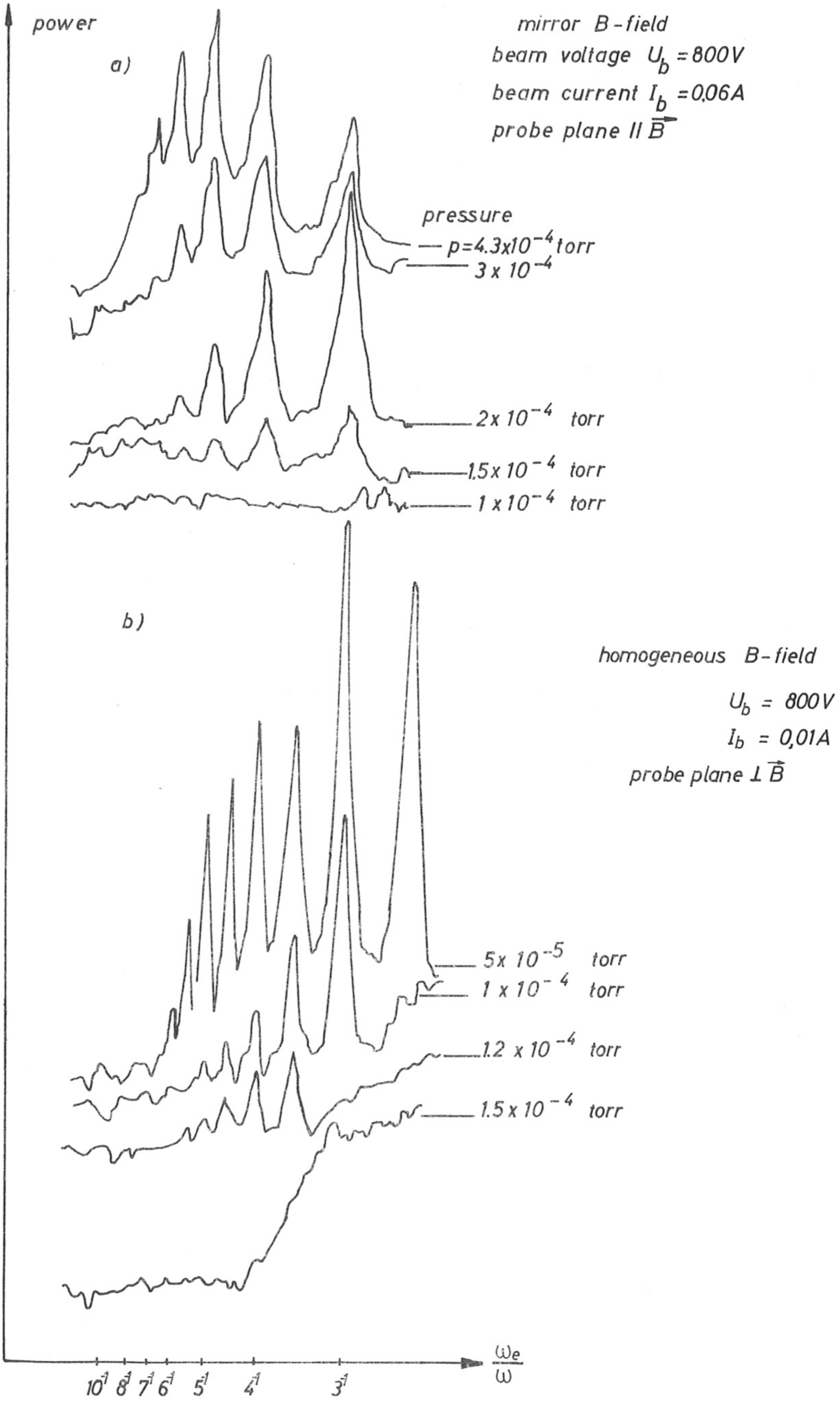

power
a)
mirror B-field
beam voltage $U_b = 800V$
beam current $I_b = 0{,}06A$
probe plane $\parallel \vec{B}$
pressure
$p = 4.3 \times 10^{-4}$ torr
3×10^{-4}
2×10^{-4} torr
1.5×10^{-4} torr
1×10^{-4} torr
b)
homogeneous B-field
$U_b = 800V$
$I_b = 0{,}01A$
probe plane $\perp \vec{B}$
5×10^{-5} torr
1×10^{-4} torr
1.2×10^{-4} torr
1.5×10^{-4} torr
10^{-1} 8^{-1} 7^{-1} 6^{-1} 5^{-1} 4^{-1} 3^{-1}
$\frac{\omega_e}{\omega}$

Fig.2

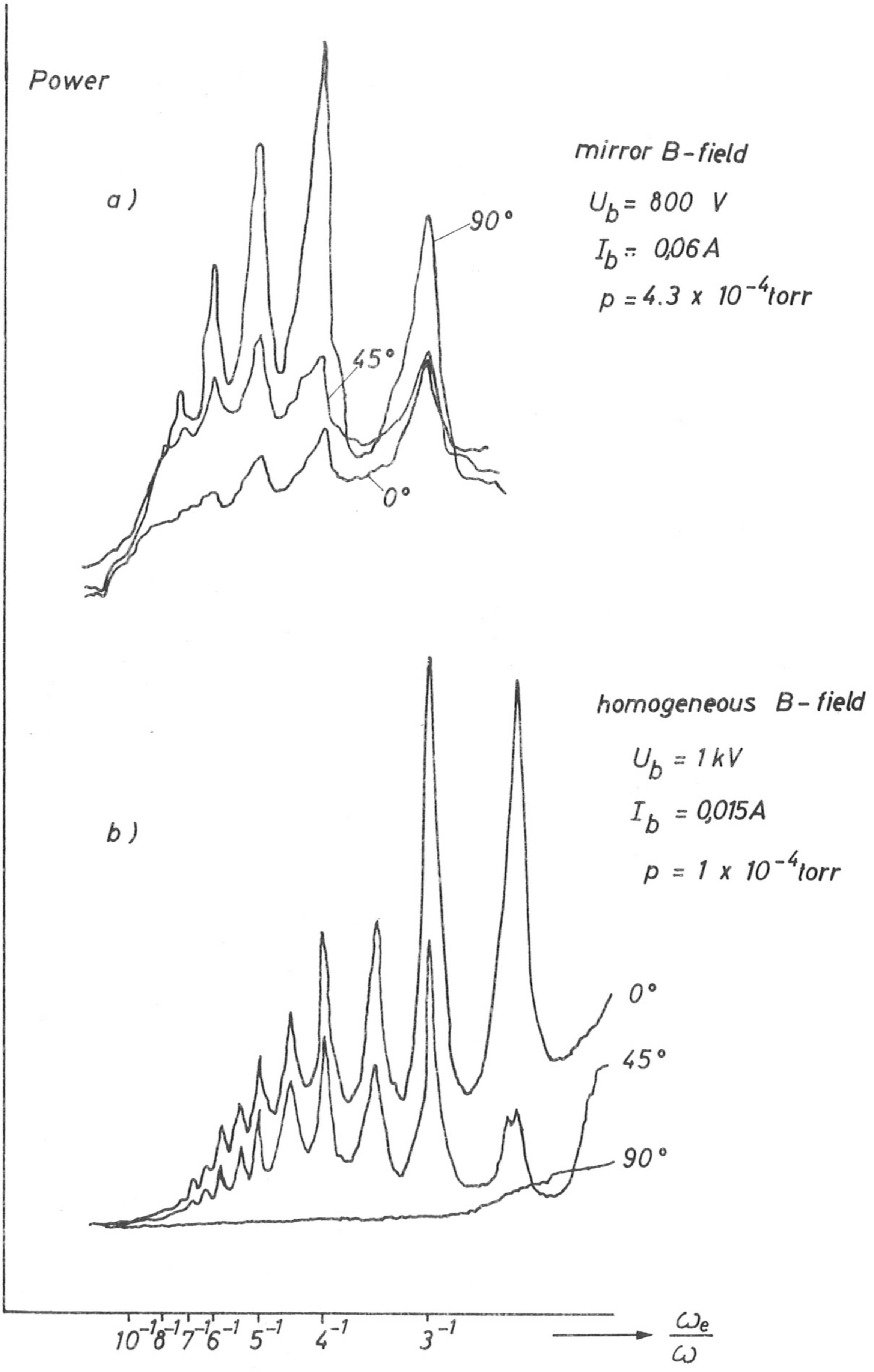
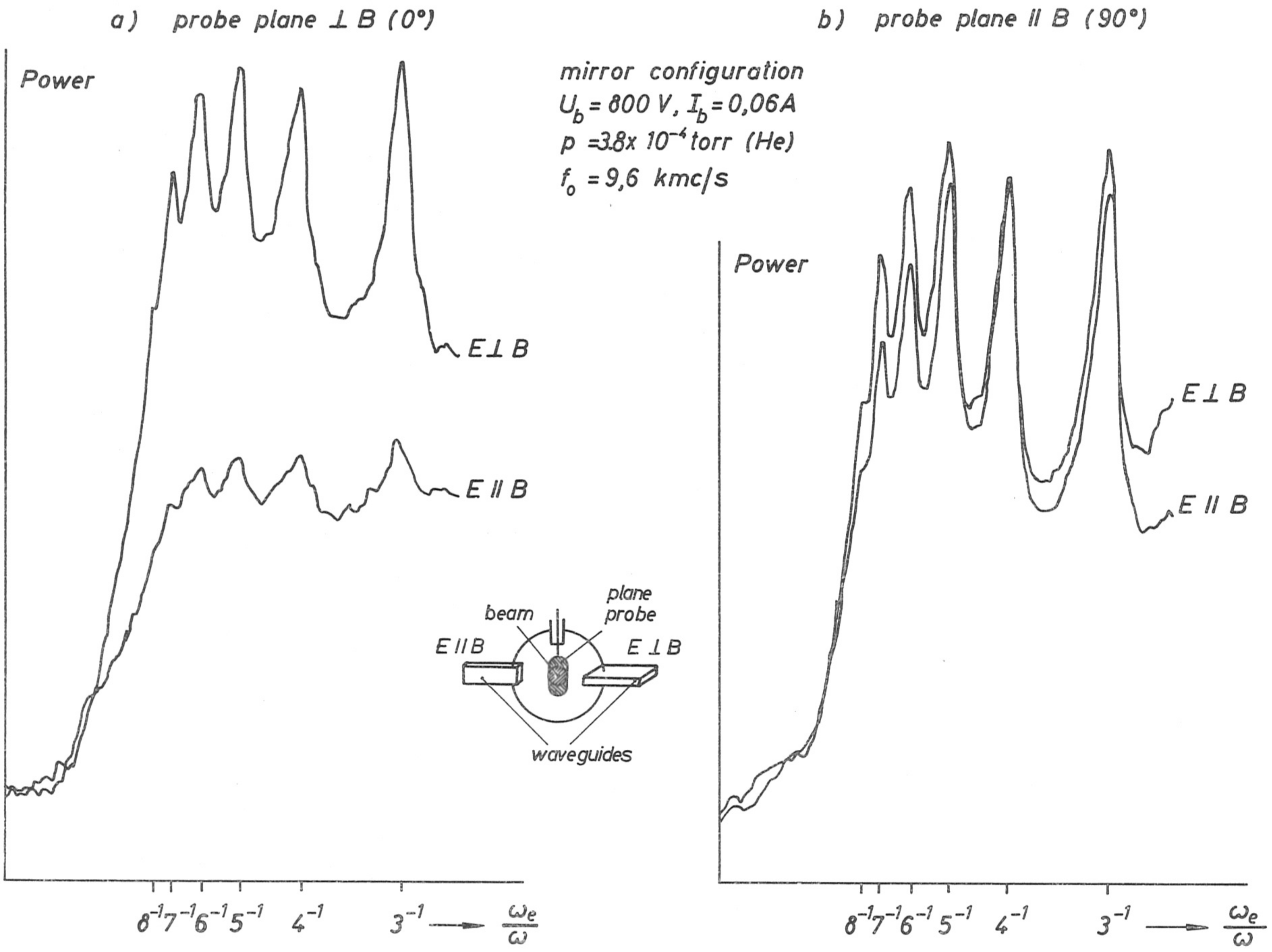

Power
a)
mirror B-field
U_b = 800 V
I_b = 0,06 A
p = 4.3 x 10^{-4} torr
90°
45°
0°
b)
homogeneous B-field
U_b = 1 kV
I_b = 0,015A
p = 1 x 10^{-4} torr
0°
45°
90°
10^{-1} 8^{-1} 7^{-1} 6^{-1} 5^{-1} 4^{-1} 3^{-1}
$\frac{\omega_e}{\omega}$

Fig.3

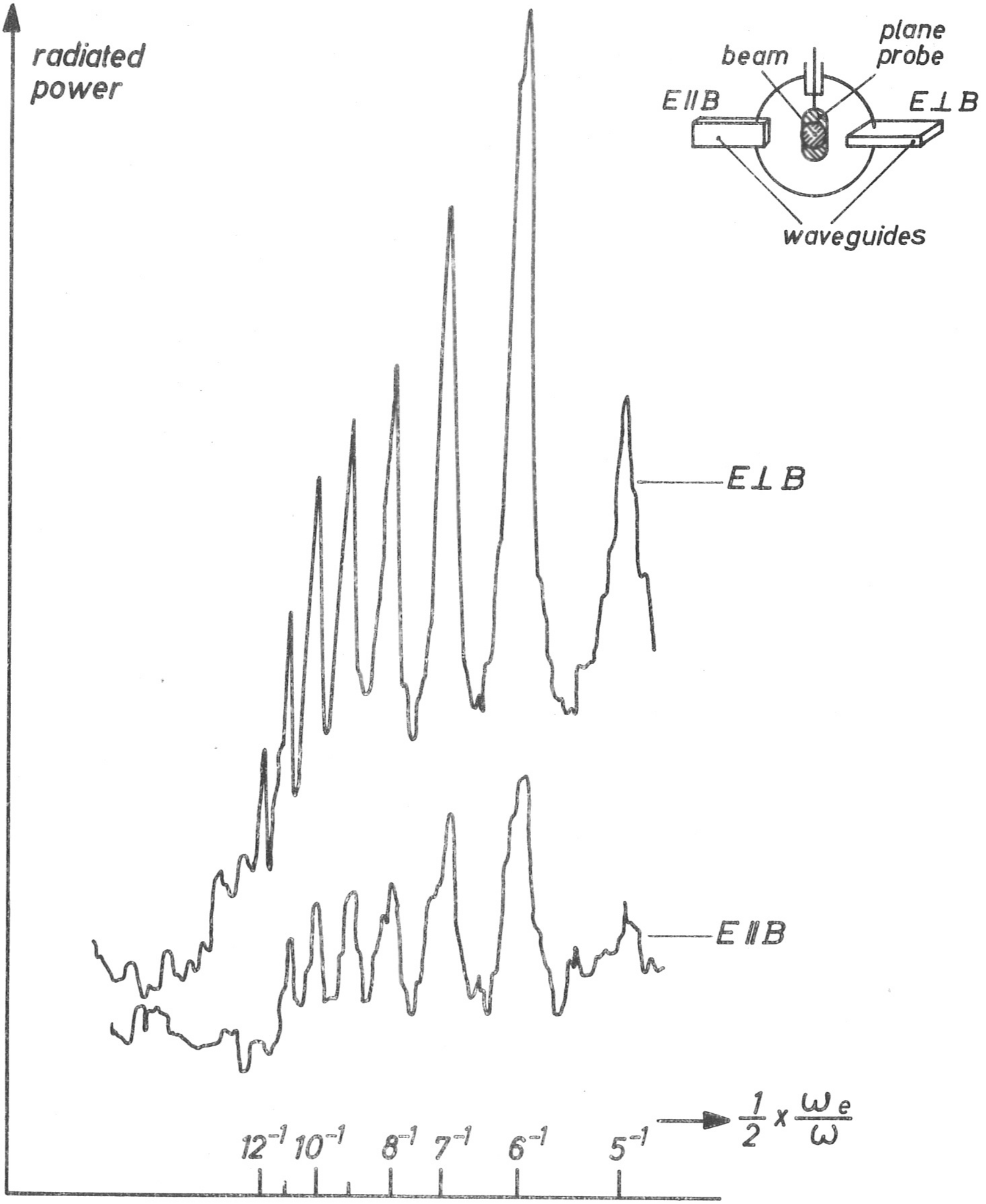


a) probe plane ⊥ B (0°)

b) probe plane ∥ B (90°)

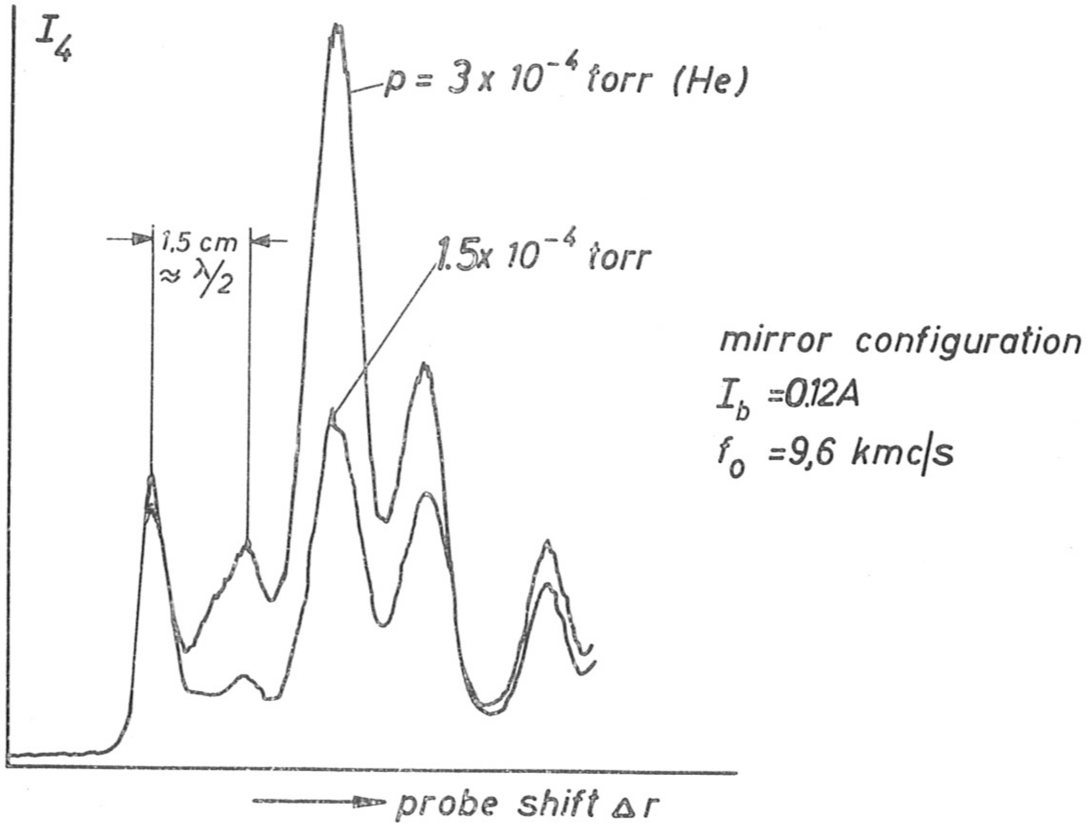
mirror configuration
$U_b = 800\ V,\ I_b = 0{,}06A$
$p = 3{,}8 \times 10^{-4}$ torr (He)
$f_o = 9{,}6$ kmc/s

Fig.4

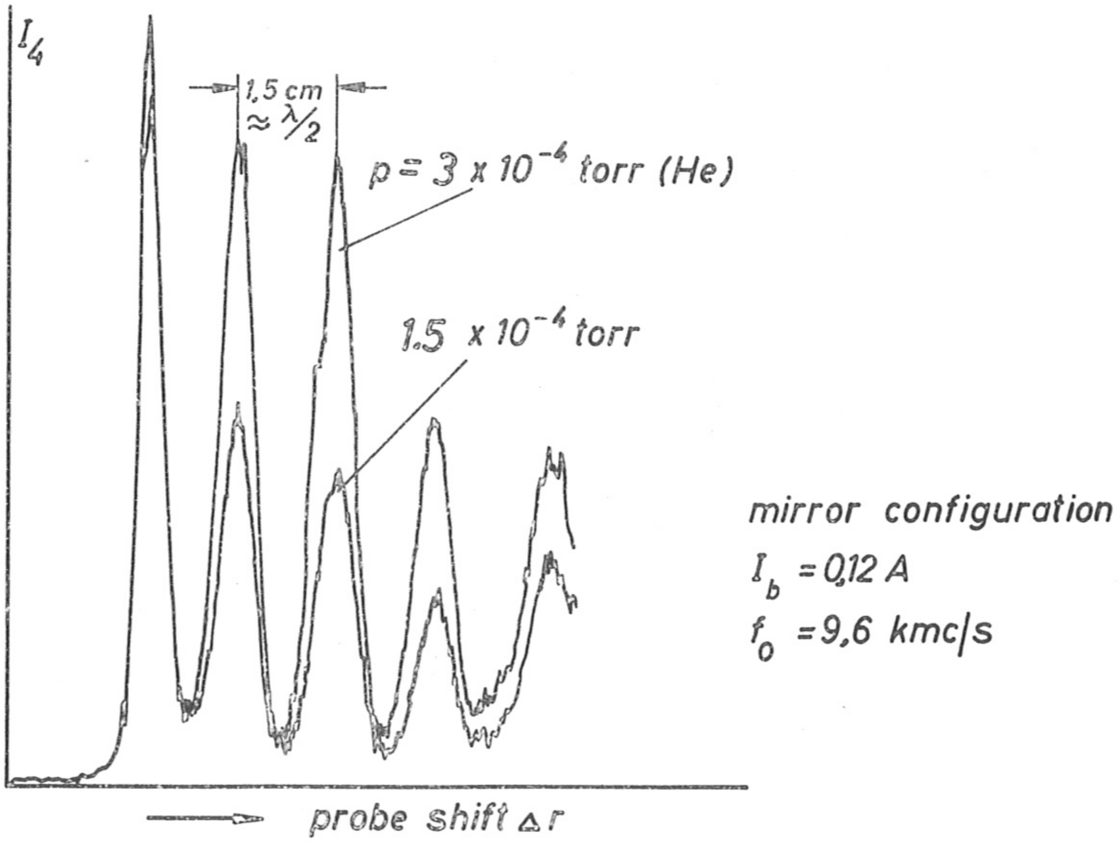


Radiation at frequencies $n\frac{\omega_e}{2}$ (homogeneous B-field, $P_{He}=1 \times 10^{-4}$ torr) at polarisation E⊥B and E∥B. Probe plane ⊥ B.

Fig.5

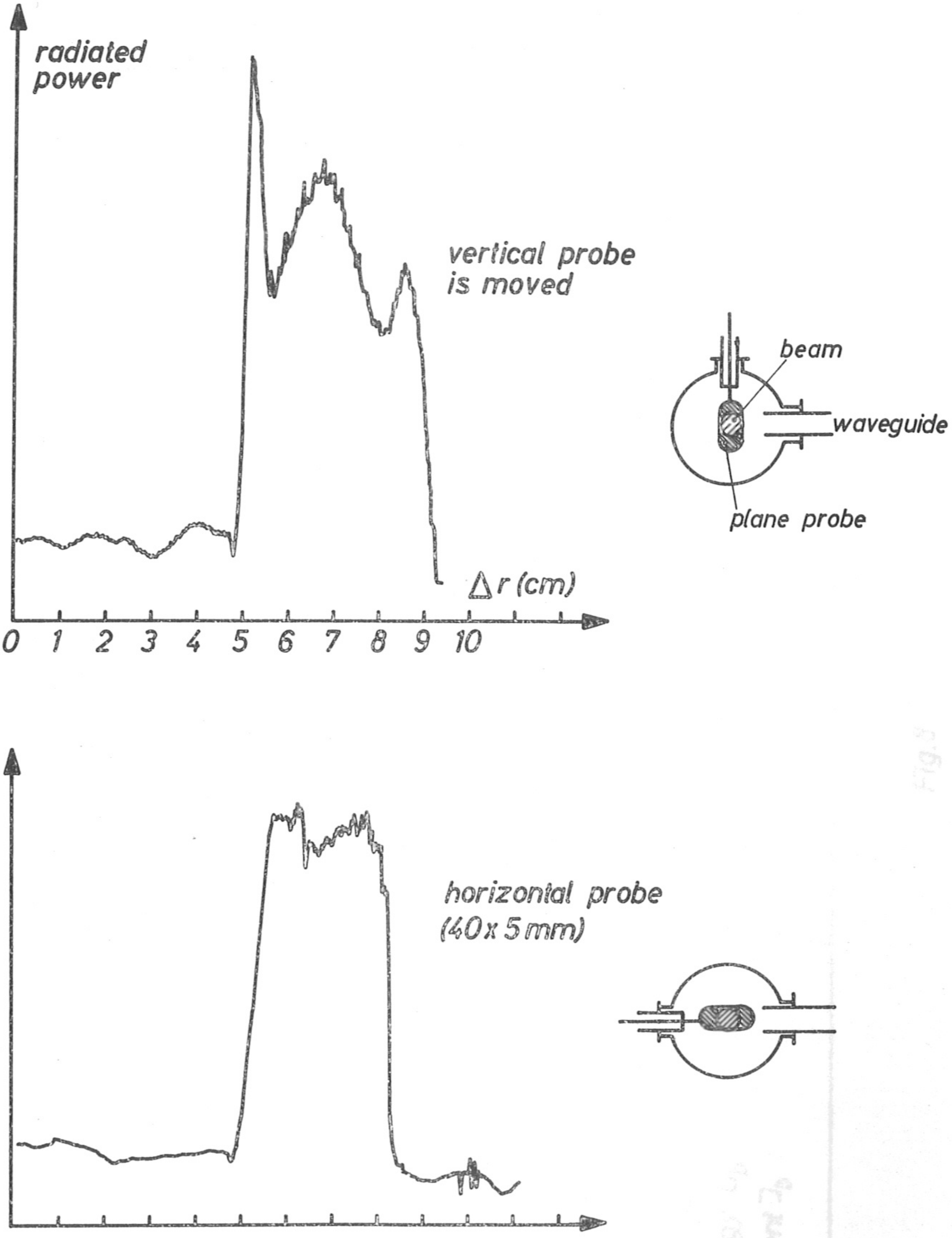


Radiated power of the 4th harmonic



Power of the 4th harmonic picked up by the probe

Fig.6



Radiation of the 8 harmonic of $\frac{\omega_e}{2}$ picked up by the waveguide (He, $P= 1\cdot 10^{-4}$, homogeneous B-field, $U_b=1\,kV$, $I_b=15\,mA$, plane probe position=0°).

Fig.7

	radiation at frequencies:	
	$\omega = n\omega_e$	$\omega = n \frac{\omega_e}{2}$
1) experimental conditions		
gun position:	outside the B-field	inside the homogeneous B-field
gas pressure:	high, $P_{He} > 2x10^{-5}$torr	low, $P_{He} < 3x10^{-5}$ torr
2) plasma conditions		
floating potential of the probe:	$\lvert U_{fl}\rvert \ll \lvert U_{gun}\rvert$	$\lvert U_{fl}\rvert \approx \lvert U_{gun}\rvert$
density :	high(secondary plasma)	low
velocities of beam electrons:	distributed over different directions	monoenergetic, $\parallel$ to B
3) conditions for maximum intensity		
orientation of the plane probe:	$\parallel$ B, $\parallel$ beam	$\perp$ B and $\perp$ beam
probe potential U_{fl} :	no large influence	$\lvert U_{fl}\rvert \lesssim \lvert U_{gun}\rvert$
beam energy U_b :	increases with U_b	increases with U_b
beam current J_b :	J_b high	J_b low

Fig.8