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Calibration Source for Electron Cyclotron Emission Measurements

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Abstract

A high temperature radiation source has been developed for the absolute calibration of diagnostic instruments for measuring electron cyclotron emission from high temperature plasmas. The source has a radiation area of ϕ150 mm and can be heated up to 500 °C. The measured emissivity of the source is close to unity in the wavelength region between 0.5 and 5 mm. The grating polychromator has been calibrated using the radiation source developed. The obtained temperatures agree with those by the pulse height analysis of soft X-rays and Thomson scattering measurement within 10 %.

KEYWORDS: calibration source, electron cyclotron emission, grating polychromator, electron temperature, tokamak plasma

§ 1. Introduction

Measurements of electron cyclotron emission (ECE) are powerful diagnostics[1-4] for high temperature plasmas. When the plasma emits and absorbs the radiation as a black body, it is possible to determine the electron temperature profile simply from the measured spectrum of ECE. In order to determine the absolute values of electron temperature from the ECE spectrum measured, the normalization of the spectrum to the Thomson scattering values has widely been used. In this case, an accuracy of the electron temperature measured by ECE is inevitably limited by the error of the Thomson values. When the ECE diagnostics could be calibrated absolutely without helps of any other plasma diagnostics, they would be more useful for electron temperature measurements. However, there exists no suitable radiation source in the wavelength region of submillimeter and millimeter waves, where the main part of ECE radiated from high temperature plasmas appears.

The main characteristics of the source required for the calibration of ECE are as follows:

(1) The aperture of the source should be large enough to cover the main lobe of the antenna radiation pattern.

(2) The temperature of the source should be as high as possible.

(3) The heat capacity of the source should be large enough to give good temperature stability.

(4) The emissivity of the source should be high enough to be close to unity.

(5) The temperature of the source should be uniform across the radiative surface.

A microwave absorber (type CV Eccosorbe) at the Liq.N_2 temperature has been used for the calibration of ECE diagnostics [2,5,6], because it has a large radiative area and a high emissivity at the millimeter and submillimeter wavelengths. However, the effective temperature difference from the room temperature is quite low ($T_B \simeq 216$ K) compared with the electron temperature ($T_e \simeq 10^7$K) of the plasma, so that it is necessary to accumulate the output signals for a long time to achieve enough signal-to-noise ratio. Then, we have developed a new high temperature radiation source for the calibration of ECE measurements in the JIPP T-IIU tokamak[7]. In this paper, we describe the characteristics of the radiation source and the application to the calibration of the grating polychromator[8].

§ 2. A High Temperature Radiation Source

The radiation source is composed of a heater plate (Cu, ϕ 190 mm × t 40 mm) and a radiation plate (Macor, ϕ 150 mm × t 30 mm). We have used Macor as a radiation material from the view points of its higher absorption coefficient compared with ordinary ceramics in the far-infrared wave region and its excellent machinability. The complex optical and dielectric parameters of Corning Macor have been measured by M.N.Afsar and Kenneth J.Button[9]. Their results indicate that the absorption coefficient of the Macor increases monotonically with increasing frequency. For the wavelength region of $1/\lambda = 5 - 7\ \mathrm{cm}^{-1}$ where the second harmonic ECE appears in the JIPP T-IIU tokamak, the absorption coefficient is 2 - 3 Neper/cm.

Now, let us consider what kinds of radiation can be observed from the radiation source. When an antenna receives the radiation emitted normaly from the surface of the medium with the thickness of L, the total intensity of radiation, I_ω, is given by,

$$I_\omega = I_\omega(\mathrm{inc})e^{-\alpha_\omega L} + \int_0^L \alpha_\omega S_\omega e^{-\alpha_\omega l} d\ell \quad , \qquad (1)$$

where $I_\omega(\mathrm{inc})$, α_ω and S_ω are the incident radiation on the medium as a result of neighboring emitting bodies, the absorption coefficient and the source function of the medium, respectively. In the wavelength region of interest here, the first term of the equation is negligibly small because $\alpha_\omega L \gg 1$. Therefore, the intensity becomes the total sum of the rdiation emitted from the interior of the medium, reduced by the factor of $e^{-\alpha_\omega l}$, where ℓ is the thickness of the intervening medium which exists between the observing antenna and the radiation point. At the long wavelength limit, $\hbar\omega \ll kT$, the source function S_ω can coveniently be written by,

$$S_\omega = \frac{\omega^2}{8\pi^3 c^2}\ kT_r \quad , \qquad (2)$$

where ω, c, k and T_r are the frequency of the radiation, the speed of light, Boltzmann's constant and the radiation temperature of the medium, respectively. For convenience, the temperature T_r is assumed to have a linear dependence, $T_r = T_r(0) + \Delta T_r \ell$, where $T_r(0)$ and ΔT_r are the surface temperature of the medium and the temperature gradient, respectively. Since α_ω is considered to be independent of position in the medium, the equation (1) is reduced to

$$I_\omega = \frac{\omega^2}{8\pi^3 c^2}\,[kT_r(0) + k\Delta T_r/\alpha_\omega] \quad . \tag{3}$$

Therefore, the total intensity of radiation depends on the surface temperature, the temperature gradient and the absorption coefficient of the medium.

Figure 1 shows the schematic drawing of the radiation source. In order to have a large heat capacity a massive copper plate (ϕ 190 mm × t 40 mm) is used as a heater plate, which is uniformly heated up to the temperature higher than 500 ℃ by the use of a resistive heating element in a spiral shape. The copper plate is coated with chromium to prevent from oxidation of the surface at high temperature. The electric power of the heater is 2.4 kW at maximum which is determined from a rough estimation of the heat capacity of the material (~1 kcal/℃) and radiation power(~10^3kcal/hour). However, the exact estimation of the radiation power is impossible, because the radiation power strongly depends on the surrounding conditions of the material. In order to reduce the radiation loss and the convection loss by the air, the radiation source is housed in a stainless steel box (ϕ 350 mm × 300 mm in depth). The temperature of the Macor is always monitored by a chromel-alumel thermocouple embedded in the side of the Macor in the depth of 5 mm from the radiation surface. Therefore, the temperature measured by the thermocouple may be slightly different from the surface temperature. In particular, the difference is considered to be large at the high temperature operation. There are no established methods to directly measure the surface temperatue of the material. When the material is an ideal black body it is possible to determine the surface temperature from the measurement of radiation power or radiation spectrum.

A thermoviewer (JTG-IBL, JOEL LTD., Japan), which is able to measure the surface temperature of the material from the radiation power in the wavelength region of 8 - 13 μm, has been used to measure the surface temperature of the Macor. Figure 2 shows the thermogram of radiation source measured by the thermoviewer with a spatial resolution of 0.5 mm. The temperature distribution along the crossed hair are shown on the left and lower sides in the figure. The temperature scale is 3 ℃/div. It was found that the temperature variation across the surface is less than ± 3 ℃ at the temperature of 369 ℃. However, it is not so easy to obtain the exact value of the surface temperature from the measurement of the thermoviewer, because the radiation temperature depends on the emissivity of the material at the wavelength region of 8 - 12 μm. There are no data about the emissivity of the Macor in this wavelength region. Then we have compared the radiation temperature with the temperature measured by the thermocouple which is calibrated absolutely by a black body source available commercially. The result is shown in Fig.3. The radiation temperatures agree well with the values of the thermocouple in the region of $T \lesssim 200$ ℃. In the higher temperature region, the temperature gradient in the medium becomes large due to the increases of the radiation power and the convection loss by the air. These experimental results indicate that the Macor has high emissivity ($\varepsilon \simeq 1.0$) in the wavelength region of 8 -12 μm.

In general, the emissivity of the material is a function of wavelength. Now, the wavelength region of interest here is much longer, that is, 0.5 - 5 mm. Then, we have compared the radiation spectrum from the Macor with that from the Eccosorbe. The microwave absorber, Eccosorbe, is a good approximation to a black body in the millimeter and submillimeter waves. A Martin-Puplet Fourier transform spectrometer[11)] was used for the measurement of the radiation spectrum. The calibration source of the Macor was used at room temperature (T = 24 ℃) and at the temperature of 400 ℃. In order to increase the signal-to-noise ratio, signal averaging was performed by co-adding more than 20 interferograms. The difference of two interferograms of the source at different temperatures was Fourier transformed to obtain the spectrum. Hence, it is possible to eliminate the spurious signals due to the stray light from the optical components of the spectrometer. The result obtained in this way is shown in Fig.4(a). The strong absorption lines by water vapor are seen at 18.6 cm^{-1} and 25.1 cm^{-1}. The detector used here is a composite germanium bolometer which operates at a pumped liquid helium temperature. The electrical NEP of the bolometer is about 5×10^{-15} W/$\sqrt{Hz}$ with a time constant of 40 ms. The low signal level at the wavenumber lower than 4 cm^{-1} is because of the finite aperture of a light corn installed in front of the bolometer. In order to operate the bolometer with low background radiation, a glass bead low-pass filter[12] was attached to the light corn, which cuts the radiation above 20 cm^{-1}. Figure 4(b) is the radiation spectrum from the Eccosorbe at the effective blackbody temperature of T_B = 216 K, the difference between the room temperature (T = 293 K) and the liquid nitrogen temperature (T = 77 K). If the Macor emits the radiation as a blackbody, a temperature normalized ratio of the radiation spectra emitted from the Macor to that from the Eccosorbe must be unity. It is found from the result shown in Fig.5 that the Macor has the same emissivity as the Eccosorbe in the frequency range of 3.7 cm^{-1} – 20 cm^{-1}. In the wavelength regions below 3.7 cm^{-1} and over 20 cm^{-1} the measured value is unreliable due to the poor signal-to-noise ratio.

§ 3. Calibration of the Grating Polychromator

The calibration of a 10 channel grating polychromator[8] has been carried out using the developed radiation source. The experimental arrangement is schematically shown in Fig.6. The radiation source is located near the JIPP T-IIU plasma. After the end of a series of the plasma discharges, a receiving antenna part of the optical components is replaced with another receiving antenna to let the radiation enter from the calibration source. The radiation from the source was chopped at the frequency of 38 Hz and detected by Liq.He cooled indium antimonide hot electron bolometers. In order to increase the signal-to-noise ratio, the output signal was filtered through a pass-band and then amplified with a lock-in mode at a time constant of 128 s. Figure 7 shows the relation between the CH7 output signal of the polychromator and the difference between the room temperature and the temperature at 5mm depth of the Macor. The error bars in the figure mean a random noise in calibration data. The calibrated responsivity is found to be about 450 eV/V. The responsivity calibrated in this way is well consistent with the values calibrated by Thomson scattering[13] and by the soft X-ray measurement. Figure 8 shows the time evolutions of the electron temperature measured by the second harmonic extraordinary wave radiated from the centre of the plasma and by the soft X-ray pulse-height-analysis(PHA) integrated over 5 plasma discharges. The electron temperature measured by ECE at 160 ms is 1180 eV ± 100 eV with the amplitude of sawtooth oscillations $\Delta T_e \simeq 130$ eV. The electron temperature by the soft X-ray PHA at 140 – 170 ms is 1100 eV ± 60 eV. The difference between them is within 10 %, and the agreement is satisfactory considering the determination of the electron temperature by the soft X-ray PHA to be complicated by spatial profile effects.

§4. Conclusions

A new high temperature radiation source has been developed for the calibration of ECE measuring system in the JIPP T-IIU tokamak. It has an emissivity of 0.95 - 1.0 in the frequency range of 100 - 500 GHz. The temperature stability is about 0.5 %/hour at the temperature of 400 ℃, and the temperature uniformity across the surface is less than ±2 %. The accuracy of the radiation temperature depends on the radiation frequency, the temperature gradient in the material, and uncertainties in temperature measurements by the thermoviewer (±1 %) and by the thermocouple (±1 %). In the frequency region of f = 100 - 500 GHz, the uncertainty of the radiation temperature caused by the temperature gradient is ±2 % at the surface temperature of 400 ℃. The developed radiation source has been used for the calibration of the grating polychromator. It is found that the absolutely calibrated temperatures are consistent with those measured by the soft X-ray pulse-height-analysis and Thomson scattering measurement.

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Figure Captions

Fig.1 Schematic drawing of a radiation source.

Fig.2 Two-dimensional distribution of the surface temperature measured by the thermoviewer. Vertical scale of the temperature is 3 ℃/div, and the central value is 369 ℃.

Fig.3 Comparison between the radiation temperature (T_r) measured by the thermoviewer and the temperature ($T_{t.c}$) at 5 mm depth of the Macor measured by thermocouple.

Fig.4 Raw spectra of Fourier transform spectrometer for the Macor heated up to 400 ℃(a) and for Liq.N_2 cooled microwave absorber (b). The apodized spectral resolution of the spectrometer is 0.25 cm^{-1}. The deep dips at 18.6 cm^{-1} and 25.1 cm^{-1} are due to absorption by water vapor.

Fig.5 The ratio of raw spectrum from Fig.4(a), to that from Fig.4(b).
The vertical scale is normalized by the temperature difference.

Fig.6 Schematic diagram of the experimental arrangement for the calibration of ECE. GPC: Grating polychromator.

Fig.7 Dependence of the CH7 ECE intensity on the difference between the room temperature and the Macor temperature at 5 mm in depth.

Fig.8 Time behaviors of plasma current, loop voltage (a), and electron temperatures measured by the second harmonic ECE (b) and by soft X-ray PHA (c). The intensity of ECE is absolutely calibrated by the use of the radiation source developed.

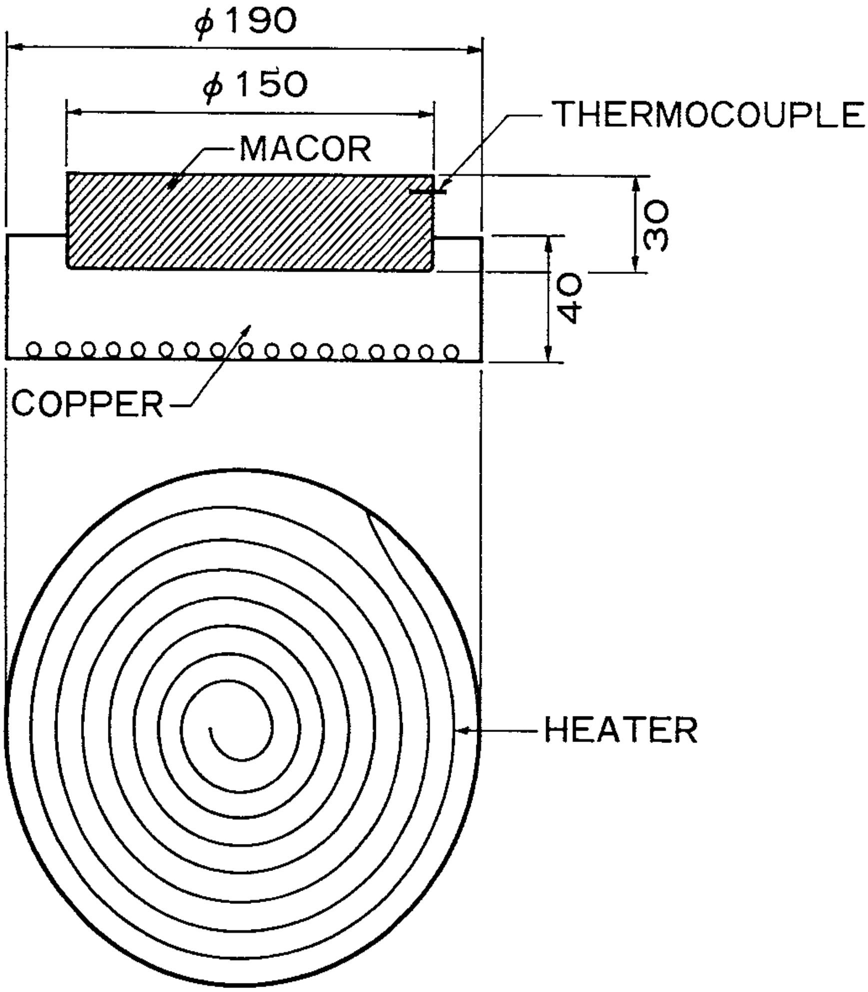


Fig. 1

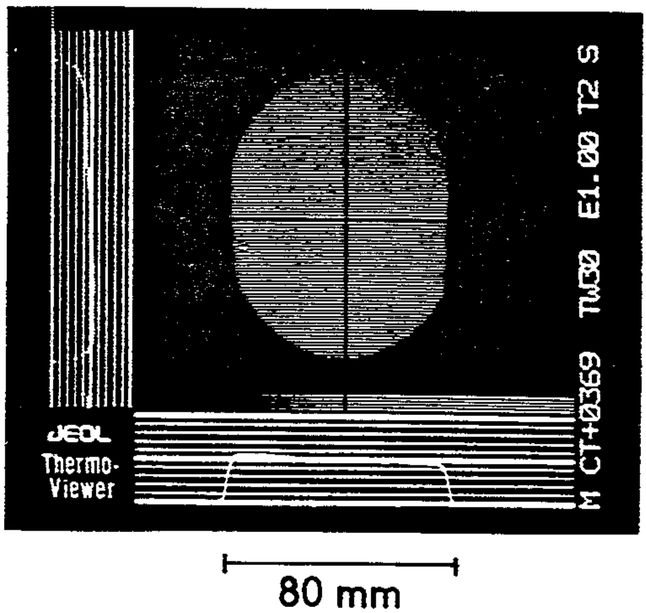


Fig. 2

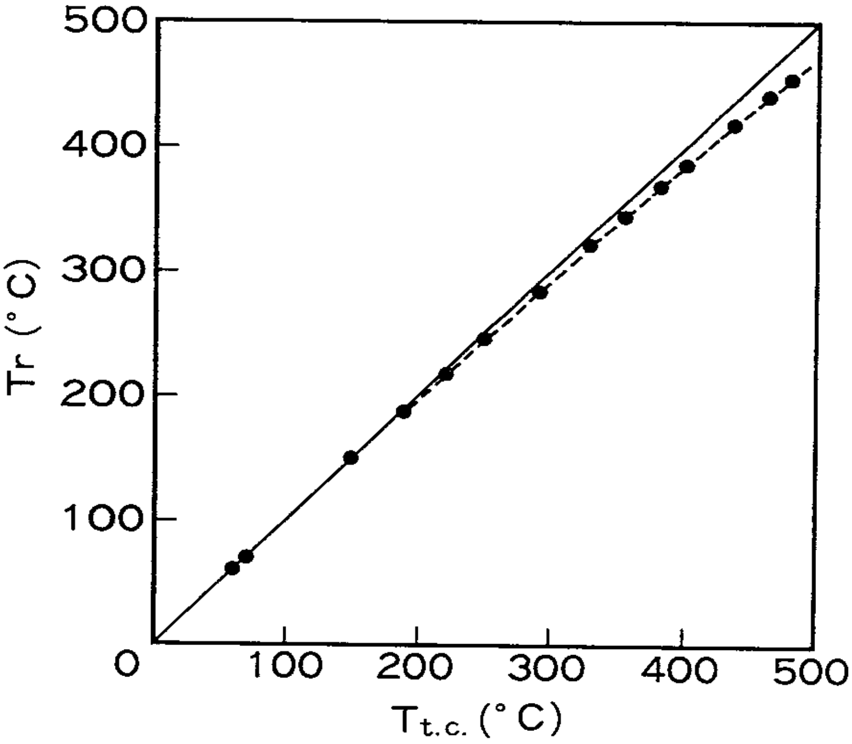


Fig. 3

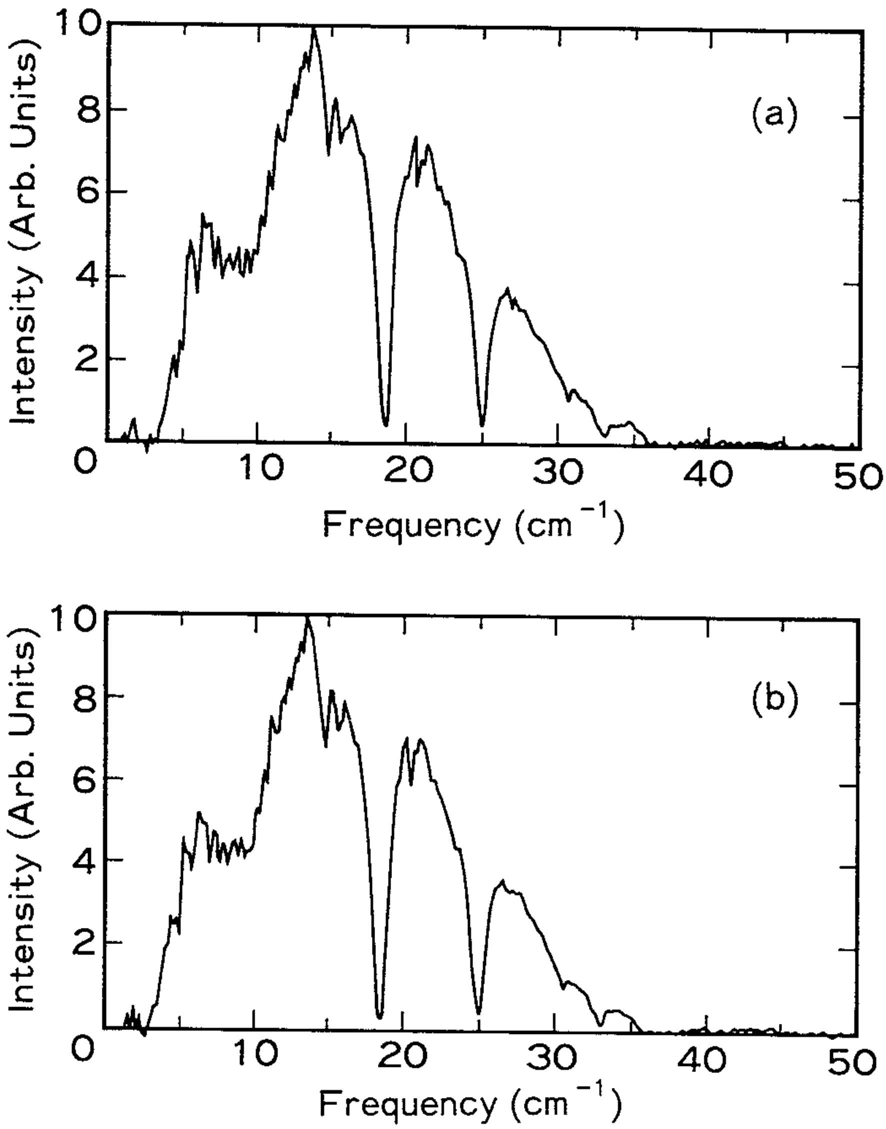


Fig. 4

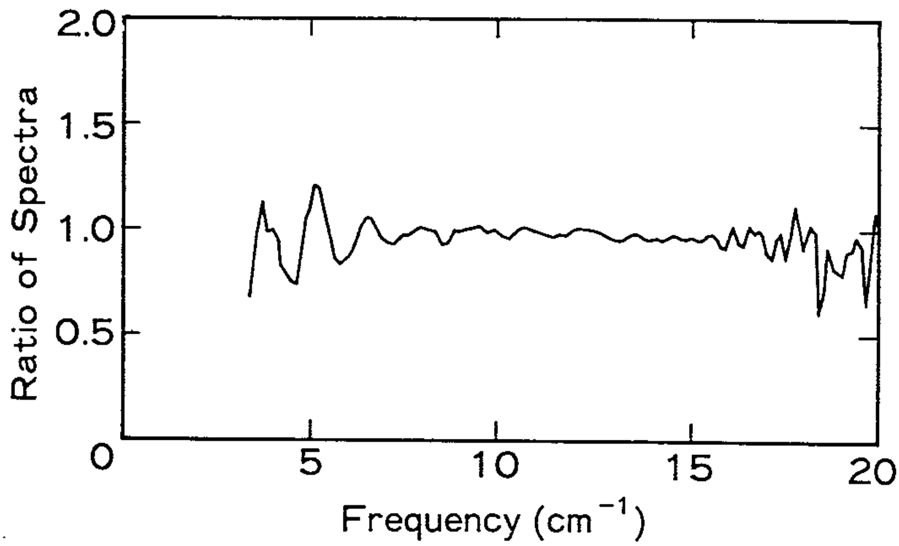
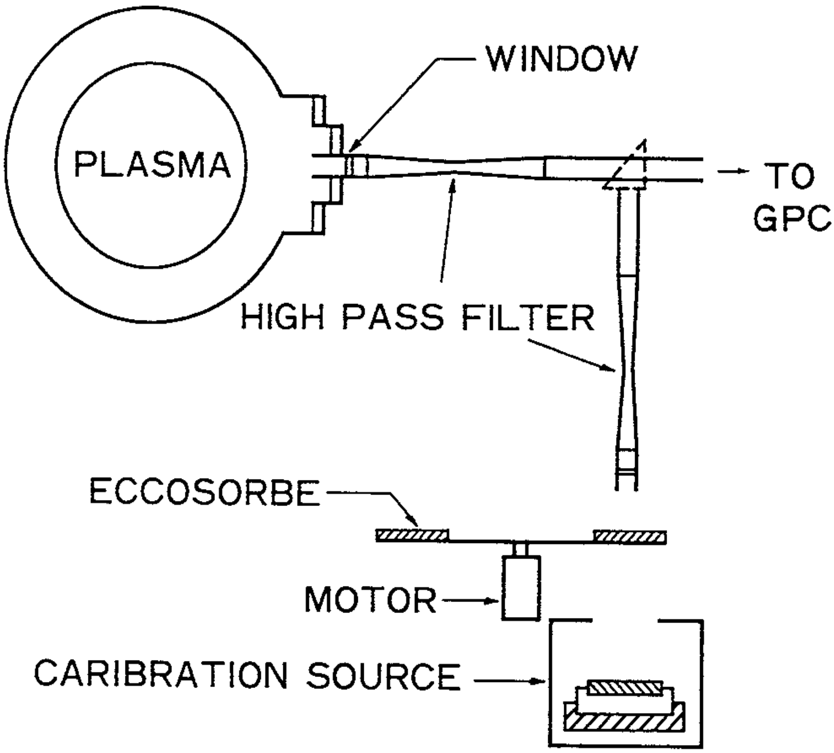


Fig. 5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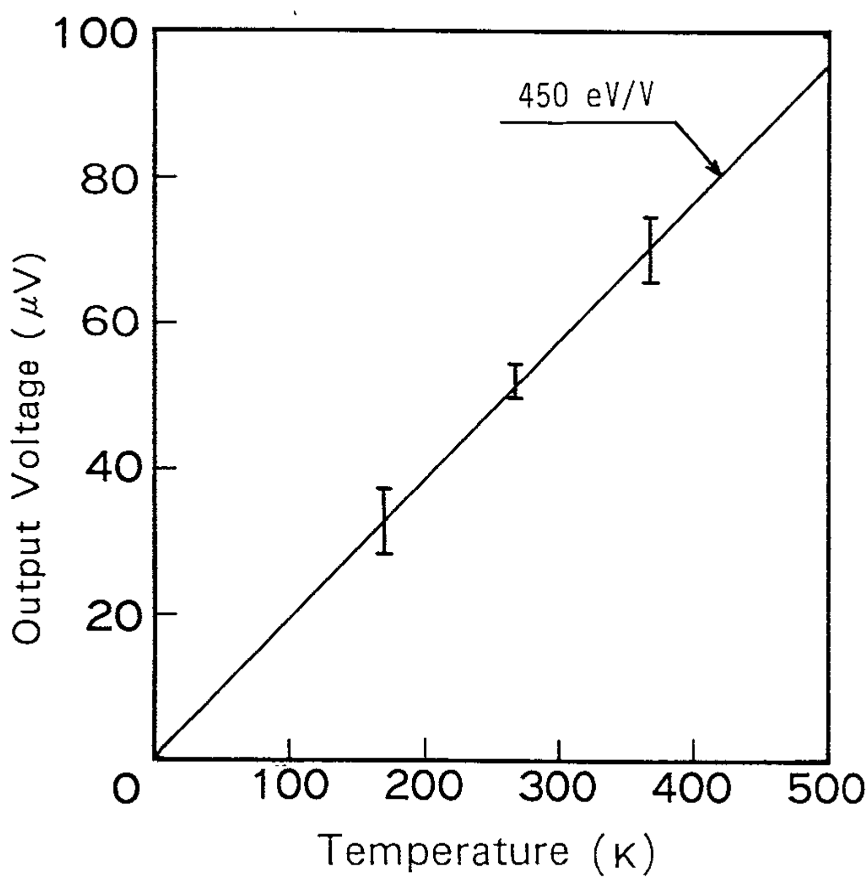
PLASMA
TO
GPC
HIGH PASS FILTER
ECCOSORBE
MOTOR
CARIBRATION SOURCE

Fig. 6


450 eV/V
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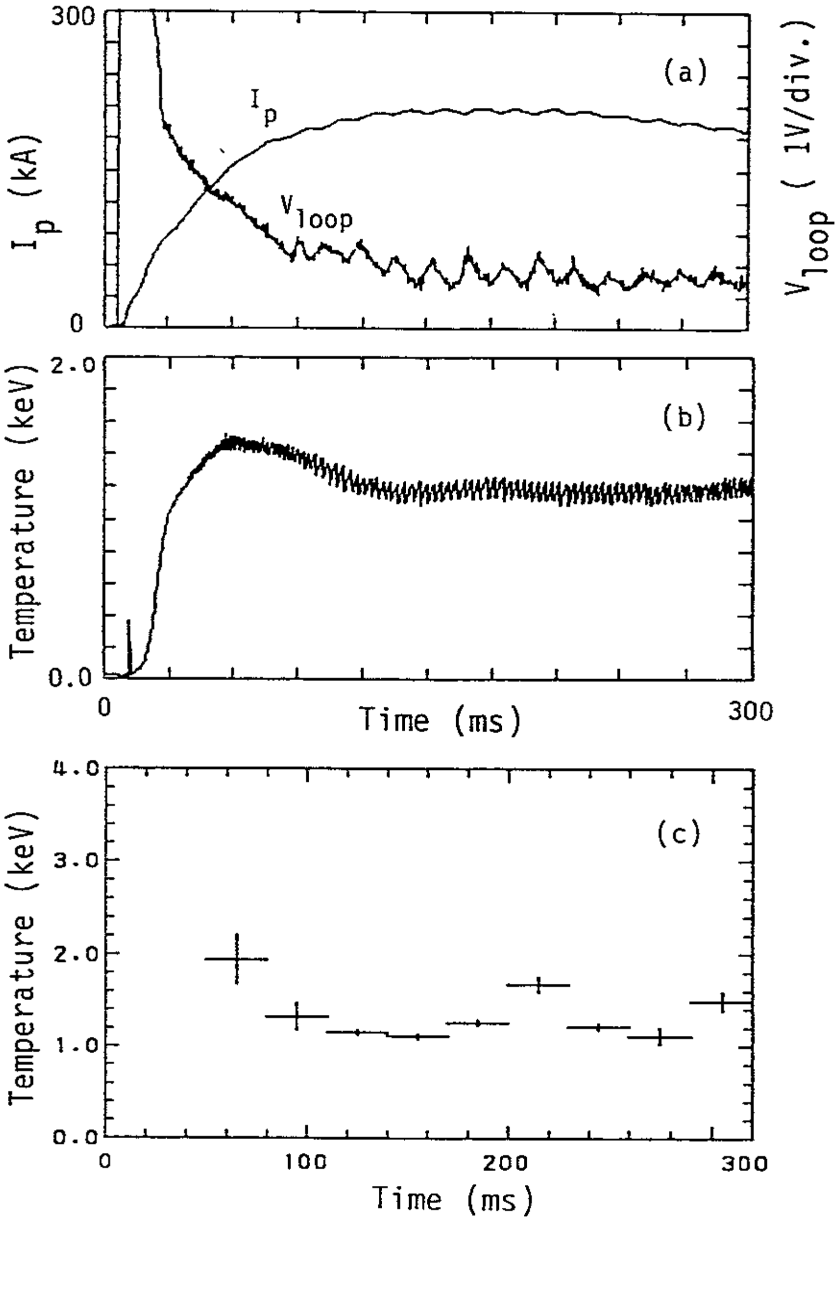
100
80
60
40
20
0
100
200
300
400
500
Temperature (K)

Fig. 7



300
0
(a)
Ip
Vloop
Ip (kA)
Vloop (1V/div.)
2.0
0.0
(b)
Temperature (keV)
0
300
Time (ms)
4.0
3.0
2.0
1.0
0.0
(c)
Temperature (keV)
0
100
200
300
Time (ms)

Fig. 8