Absolute Intensity of Synchrotron Radiation Spectrum From a Hot Electron Plasma

A.J. Lichtenberg,* S. Sesnic, and A.W. Trivelpiece

Department of Electrical Engineering
Electronics Research Laboratory
University of California, Berkeley, California

ABSTRACT

The synchrotron radiation (4.0 mm to 0.2 mm wavelength) emitted from a hot electron plasma in a strong magnetic field has been studied experimentally. The spectral distribution of this radiation is in general agreement with the theoretical predictions of Trubnikov and others, but exhibits some additional structure. The absolute intensity of the synchrotron radiation spectrum gives an independent determination for both the plasma temperature and the number of radiating electrons. Using the Fokker-Planck equation with a radiation friction term, a calculation of the cooling of the plasma due to synchrotron radiation alone predicts a rate of temperature decrease of 2.0 keV/msec; the measured decrease of the plasma temperature was greater than this.

The plasma used in this radiation study was produced in a single stage magnetic mirror compression experiment similar to "Table Top". The maximum midplane field (rise time 500 msec, mirror ratio 1.5:1) was varied between 30 and 60 kilogauss with corresponding electron temperature between 40 and 80 keV. The plasma lasts more than 1 msec

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and has a density of approximately $10^{12}/cm^3$. The time-resolved radiation was detected by means of a cryogenic InSb photodetector of the type developed by Putley. To resolve the radiation spectrally, an echelette grating monochromator was used. The calibration of the combined monochromator-detector system, which was required to determine the absolute plasma radiation intensity, was accomplished by comparison with blackbody sources.

I. INTRODUCTION

A slightly relativistic electron in a strong magnetic field radiates electromagnetic energy at its cyclotron frequency and the harmonics thereof. Trubnikov[1] pointed out that this synchrotron radiation from the electrons in the tail of a Maxwellian distribution of a magnetically confined high-temperature plasma (e. g., 50 keV) is a serious energy loss mechanism. Theoretical work of Beard and Baker[2], Rosenbluth and Drummond[3], and Hershfield, Baldwin and Brown[4] gave similar results.

Lichtenberg, Sesnic and Trivelpiece[5] reported measurements of synchroton radiation emitted by a magnetically confined "hot-electron" plasma which confirmed some of the features of the theoretical predictions concerning the relative spectral distribution of synchrotron radiation. This paper reports on additional experiments using the same "hot-electron" plasma but with the refinements of being able to determine the absolute intensity of the spectral distribution of the synchrotron radiation and thus providing additional information about the radiation properties of the plasma.

The measurements of absolute intensity of the spectral distribution of synchrotron radiation, together with the absolute radiation rate per particle which is obtained from Trubnikov's theory, can then be used to determine the total number of radiating particles. The density is determined from a measurement of the volume occupied by these radiating particles. This volume is measured by means of a "plasma camera" which determines both the size and location of the hot electron plasma.

In addition to confirming many of the features of the theoretical spectral distribution of synchrotron radiation, the measurement method is a useful means of diagnosing the properties of high-temperature, magnetically-confined plasmas. It has the advantage of being able to provide simultaneously a time-resolved measurement of both temperature and density (for a known size of plasma) of the plasma.

II. EXPERIMENT

A. PLASMA CREATION

The hot electron plasma used in these synchrotron radiation studies was created in a single-stage, magnetic-mirror compression experiment (shown schematically in Fig. 1) that is similar to the Table Top device.[6] The plasma is generated by a deuterated titanium washer stack source[7] (5 μf, 5 kV) which injects plasma into a rising field, pulsed-compression coil having a mirror ratio of 1.5:1. The field rises to its maximum midplane value (up to 100 kG) in 500 μsec and decays with a time constant of 20 msec. The high field region of the vacuum chamber (base pressure 2×10^{-7} Torr) is 4 in. diameter and 12 in. long. There is an initial, uniform dc bias magnetic field (up to 100 G) of 20 G with the same field direction as the compression field.

The experiment is usually operated with compression fields of 30 to 60 kG. At 30 kG the plasma electron temperature is 40 keV; the density is approximately $10^{12}/cm^3$ and the plasma dissipates slowly over a 15 millisecond period. At 60 kG the plasma electron temperature is 80 keV, and the plasma is stable for the first millisecond after peak compression. After this period of stability, the plasma exhibits an instability resulting in the total loss of plasma from the confinement region in about 100 μsec. For intermediate values of magnetic field, the temperature of the electrons is as expected from the adiabatic compression law. The ion temperature is not measured, but is estimated to be less than 600 eV.

B. PLASMA DIAGNOSTICS

The plasma electron temperature is measured from the energy spectrum of the x-ray bremstrahlung emitted directly from the plasma and by the x-ray emission produced by escaping electrons hitting the walls of the chamber. The end loss rate of electrons escaping from the magnetic mirror is measured by allowing them to strike a plastic crystal that is shielded for x rays. Visible and vacuum ultraviolet radiation are temporally and spectrally resolved in a grating u-v monochrometer. A narrow band, superhetrodyne receiver measures the 4 mm wavelength radiation from the plasma. To determine the size and location of the hot electron plasma, an end loss plasma camera is used. This end loss camera is a quartz flat that is coated with P 11 phosphor which has a 10 keV thick aluminum light shield vacuum evaporated on it. The quartz flat is located normal to the magnetic axis at a distance where the escaping electrons are still adiabatic so that the size of the plasma in the mirror field can be determined from the photograph of the back side of the quartz flat. At 50 kG, the plasma diameter at peak compression is approximately 3 mm diameter.

Figure 2 is a composite of the data as obtained with the various diagnostic instruments for typical operating conditions shown in relation to the magnetic field whose peak value if 50 kG.

C. SYNCHROTRON RADIATION

A complete spectrum of the synchrotron radiation provides a great deal of information about the plasma. However, it is very time-consuming to convert the raw data to a spectrum and, for certain parametric studies of plasma properties, it is more convenient to measure the total synchrotron radiation emitted in the 4 to 0.2 mm wavelength region. Typical data showing the total synchrotron radiation as a function of time are shown in Fig. 3 for several values of peak compression magnetic field.

The total synchrotron radiation provides a means of determining both the plasma electron temperature and the total number of radiating particles; however, the accuracy is less than that which is obtained from a complete spectral analysis.

The temperature is obtained by measuring the intensity of synchrotron radiation as a function of magnetic field, assuming adiabatic compression and no loss of plasma during compression.[8] The temperature measured with this method is consistent with that given by other diagnostic methods.

The total number of radiating particles can be obtained if the spectral distribution of the synchrotron radiation and the detector response as a function of frequency are known. The contribution to the radiation intensity from all the frequencies within the detector's range of sensitivity can be added together to predict the expected intensity for a given temperature as a function of density.

Early measurements made on the basis of an assumed spectrum and an approximate detector response gave results that were within a factor of two of the more accurate recent results in which both the spectrum of radiation and the detector response are known. The total number of radiating particles predicted from the measurement of total synchrotron radiation and that predicted from the detailed spectral analysis of the synchrotron radiation are in good agreement. An effect that occurs in the range of high-peak magnetic fields is that the expected intensity of the synchrotron radiation as a function of the peak magnetic field does not follow from an adiabatic compression law. This is explained as a loss of plasma at a rate that offsets the increase in intensity. Finally, it is seen that during a period after peak compression and when the plasma is otherwise quiescent, a relatively slow but nevertheless catastrophic instability develops. The period during which the plasma is quiescent and stable, decreases as the maximum magnetic field in increased.

III. ABSOLUTE SPECTRAL INTENSITY MEASUREMENT OF SYNCHROTRON RADIATION

From the absolute intensity of the spectrum of the synchrotron radiation it is possible to determine simultaneously the temperature of the hot electrons and their number. In previously reported spectral measurements[5] both of these plasma parameters were estimated using approximate techniques for system calibration. From these measurements the basic features of the theoretical predictions of the radiation spectrum from a hot electron plasma were corroborated. However, the early measurements needed improvement in two respects: 1) both variability of the properties of the plasma and unknown variations of the spectral response[9, 10] of the monochrometer-detector system can cause spurious structure to appear in the spectrum; and 2) an error in the detector frequency characteristic can cause an error in the temperature determination as determined from the tail of the frequency spectrum.

To eliminate the variability of the plasma, the number of shots for each monochrometer setting were increased and the data from different runs were averaged. In addition, the data are compared with other diagnostic signals for each shot. This latter method uses a standard shot against which all shots may be normalized. This reduces the variability of the data, but does not eliminate the need for averaging over several shots at each monochrometer setting.

The calibration of the monochrometer-detector system (spectrometer) is made by comparing the output signal from the spectrometer when it is receiving plasma radiation with the output signal from the spectrometer when it is receiving radiation from a known intensity blackbody source. This method has the advantage of obtaining a calibration of the plasma radiation of unknown amplitude, against a known standard, without calibrating the individual elements of the spectrometer. The intensity of the blackbody source is low and it is necessary to use a standard radiometer method of modulating the radiation from the blackbody source and synchronously detecting the signals using a long integration time.

The blackbody used in these experiments as an absolute standard was a mercury arc lamp that had previously been calibrated against 200°C cylindrical carbon coated cavity whose axis coincided with the input to the monochrometer.

In Fig. 4, a typical synchrotron radiation spectrum is presented as measured in detector output. The data has been normalized to the total number of x-ray photon counts observed during the shot, then averaged over 6 shots per spectrometer setting. Error bars indicate a standard deviation as calculated from the variability at a single frequency. The data have not been absolutely calibrated in this figure. The alternate solid and dashed lines represent successive gratings, and the jumps at the end of each grating are due to grating factors. In previous measurements a constant quantum efficiency was assumed for the detector which canceled a linear increase in bandwidth to maintain the general shape of the high frequency tail of the spectrum as given in the uncalibrated results shown here. However, in order to determine the temperature from this slope it is necessary to calibrate the system as described above.

An absolutely calibrated synchrotron radiation spectrum, using the data from Fig. 4, is presented in Fig. 5, where the small variations in the data have been smoothed out by comparison with previous data. The remaining structure represents real variation in the spectral amplitude. The experimental spectrum is compared with two theoretical spectra of the synchrotron radiation at two temperatures assuming a two-dimensional Maxwellian. Three features of the experimental spectrum differ significantly from the theory: (1) The peaks of the first and second harmonics are shifted toward low frequencies; (2) a fourth harmonic peak is more prominant than expected; and (3) the residual energy at high harmonics is considerably higher than predicted by the theory.

Attempts to explain these anomolies through improved theoretical models have not yet been successful. If the dielectric constant of the plasma is included in the computation, the first harmonic peaks shift slightly, but in the wrong direction. Interaction with quasistatic waves may account for certain phenomena at low fields but appears to be ineffective at higher field values.

In Fig. 6 the spectral distribution is compared for radiation at the peak of compression and for radiation 1 msec after peak compression. The spectrum is seen to have generally lower amplitude and be shifted to the left. The shift is accounted for by the decrease in magnetic field. The decrease in intensity over this period of time is due to several effects in addition to a decrease in the field, which results in adiabatic cooling. Loss of particles and non-adiabatic radiation cooling are two of the more important effects. The radiation cooling preferentially depletes the high energy tail of the Maxwellian electron distribution function. A calculation of this effect using a Fokker-Planck equation with a radiation damping term predicts approximately a 2 keV/msec decrease in plasma temperature with a more rapid cooling of the higher energy electrons. The calculation of the change in high harmonic radiation due to this effect predicts a 15% decrease in the eighth harmonic after 5 msec from peak compression. This decrease is less than that observed experimentally.

ACKNOWLEDGEMENT

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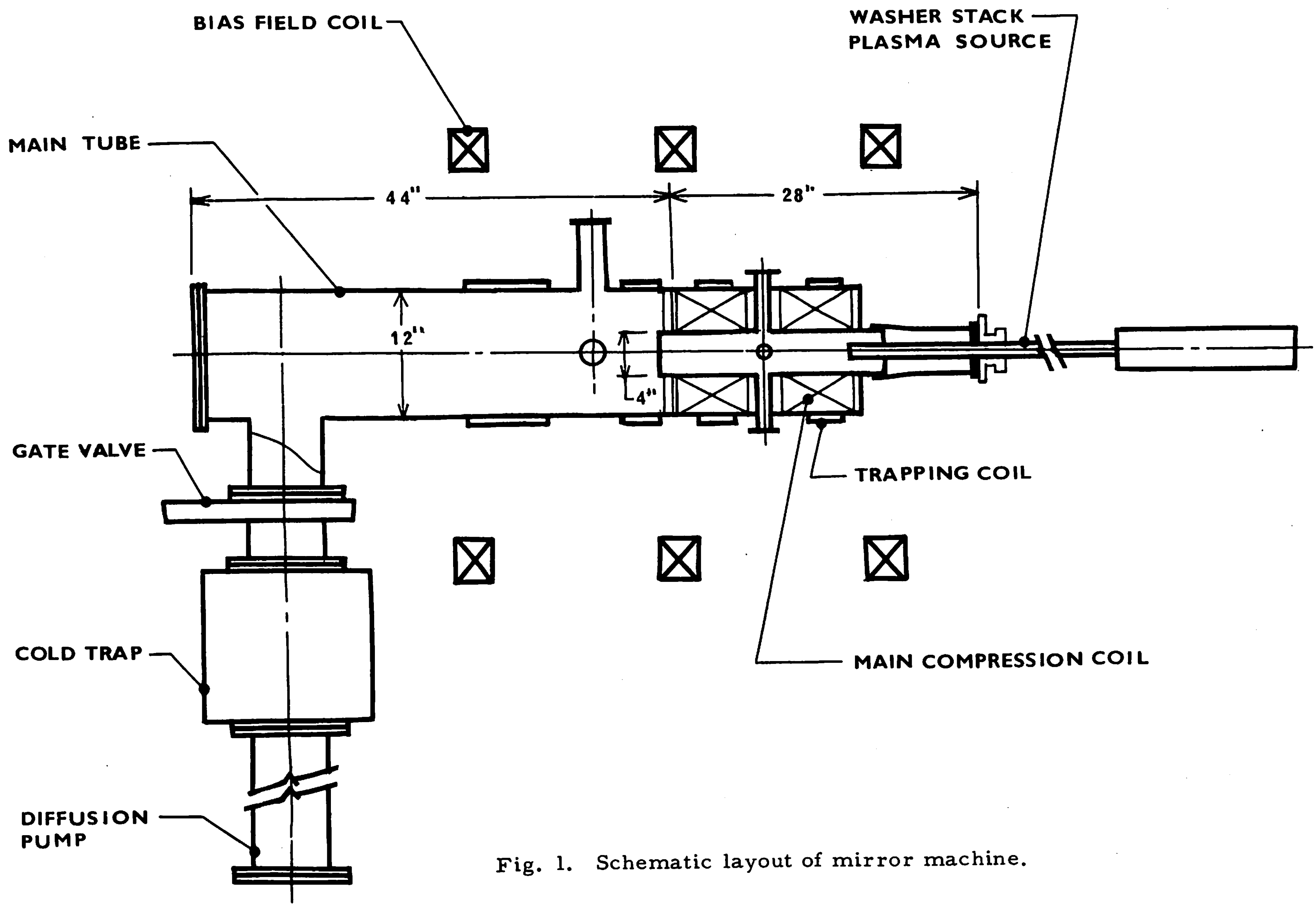

Fig. 1. Schematic layout of mirror machine.

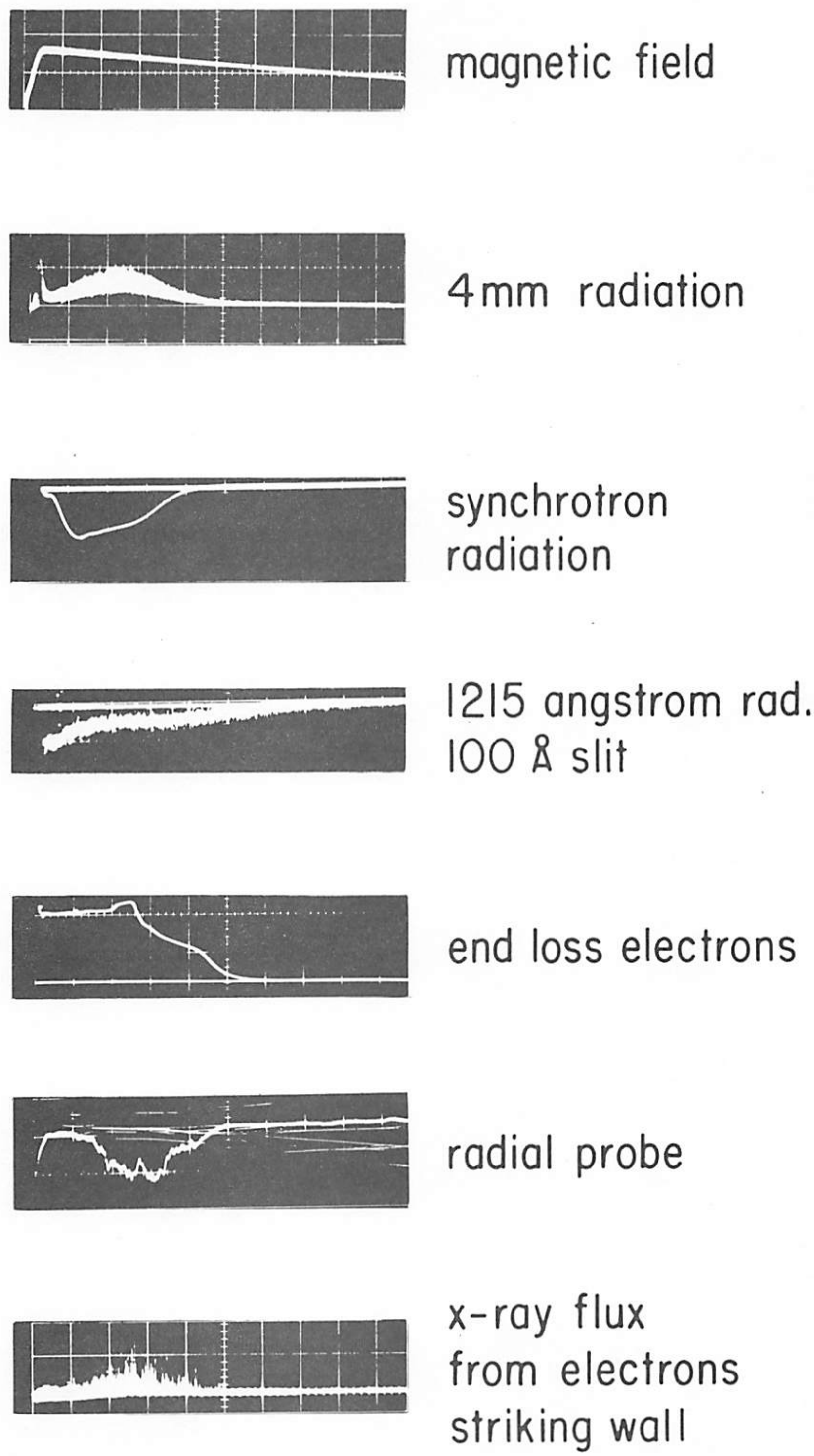

Fig. 2. Composite of diagnostic measurements on hot electron plasma for maximum midplane magnetic field of 50 kilogauss; first two traces 1 msec/div.; other traces 0.5 msec/div.

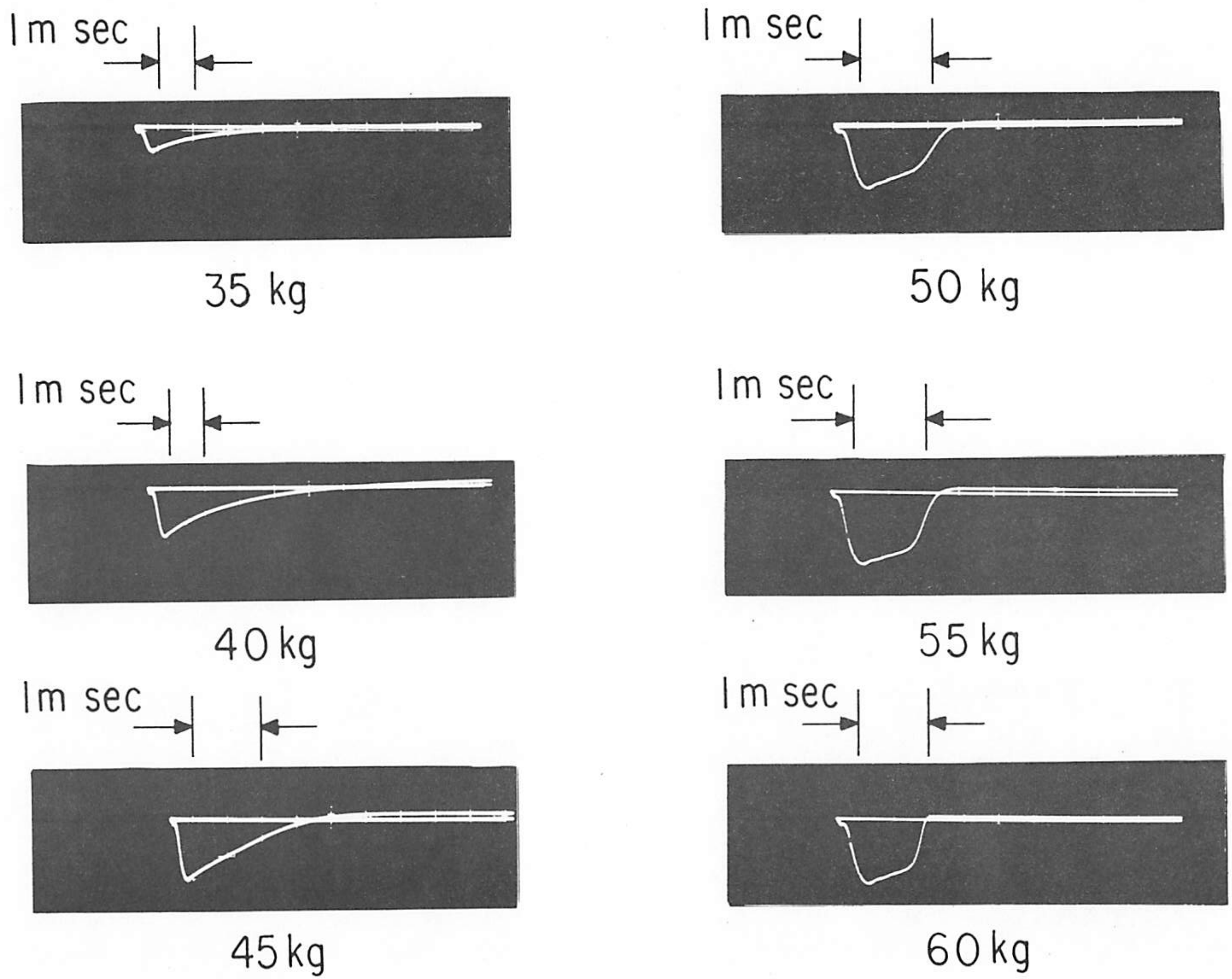

Fig. 3. Variation of synchrotron radiation with peak magnetic field, B.

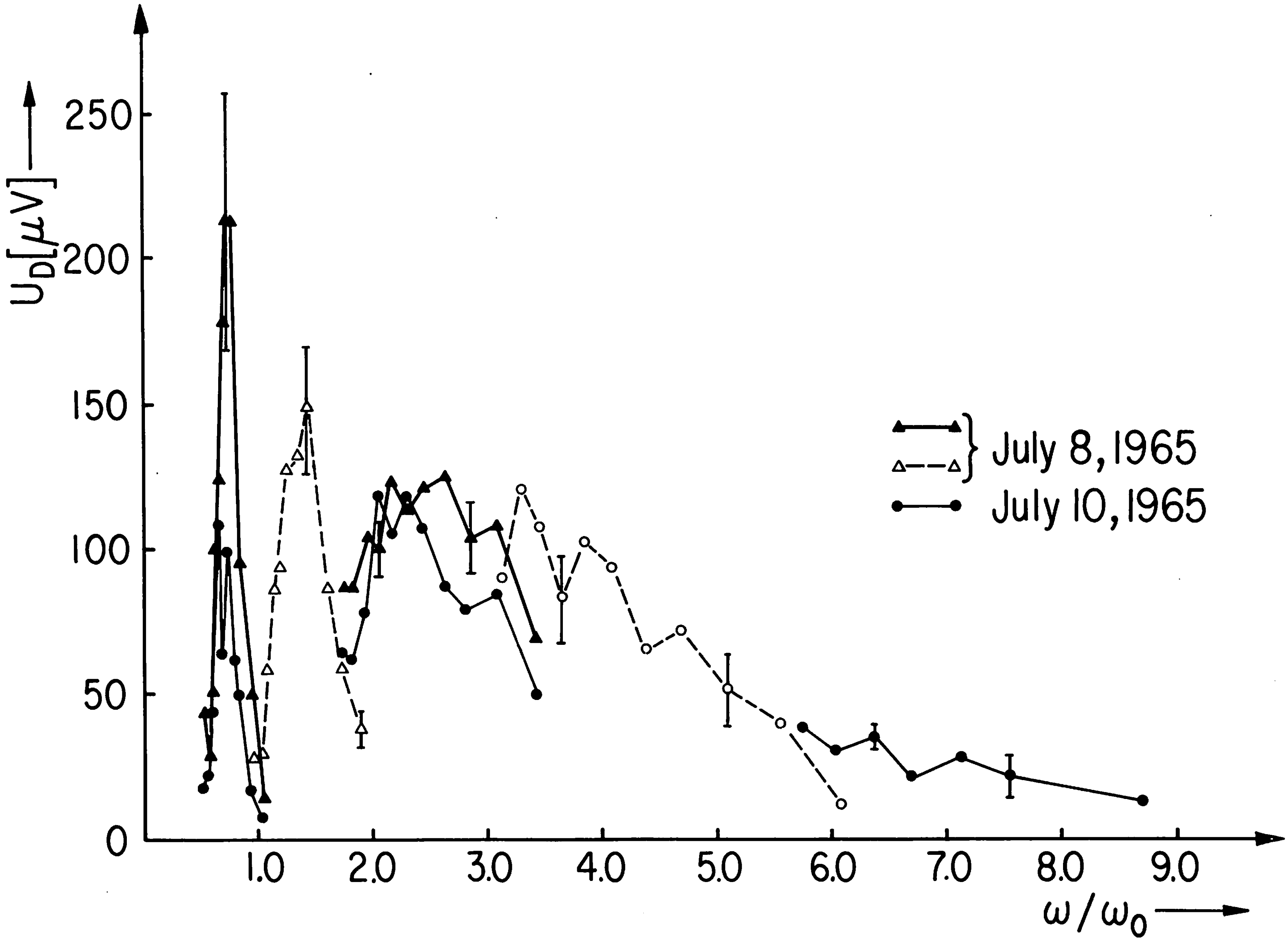

Fig. 4. Synchrotron radiation spectrum as measured in the detector output.

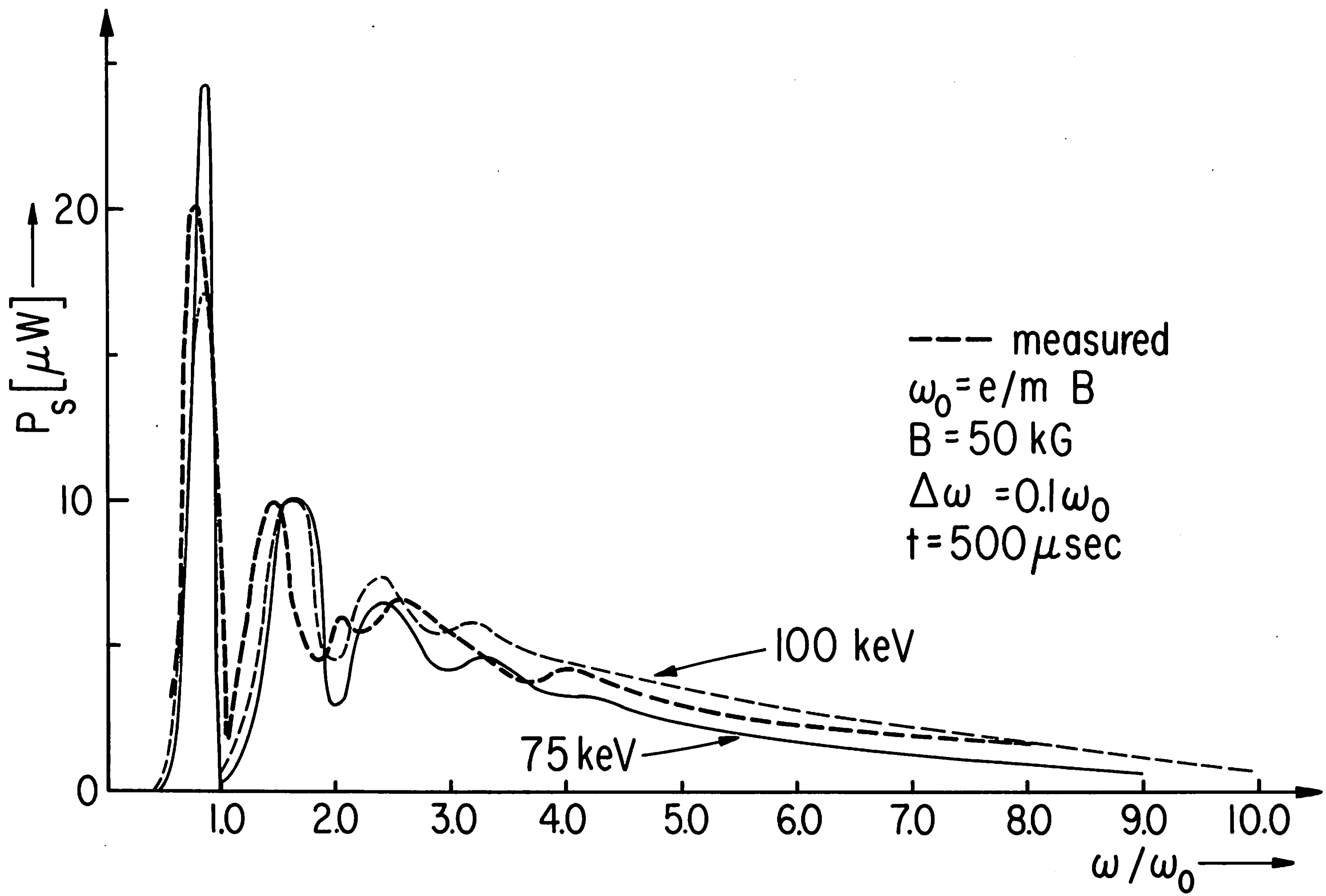

Fig. 5. Absolute power spectrum of synchrotron radiation emitted by a hot electron plasma.

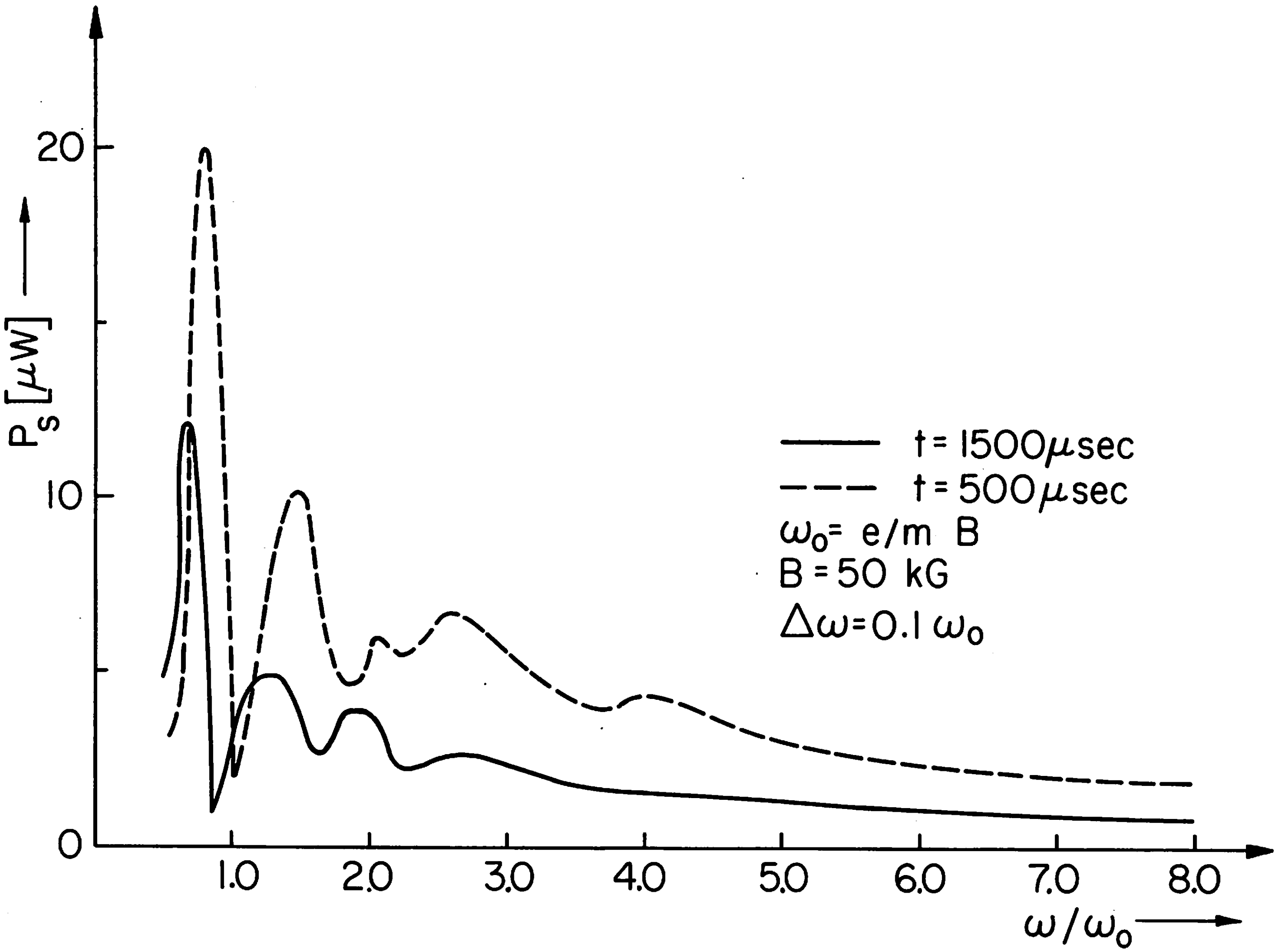

Fig. 6. Comparison of absolute power spectra of synchrotron radiation at two different times.