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Design Calculations For Soft X-Ray Electron Temperature Diagnostic System

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ABSTRACT

X-Rays emitted by a hot plasma are used for determination of electron temperature. This diagnostics is useful when electron temperature is above 100 eV and electron - ion densities are high enough ($\geqslant 10^{12} - 10^{13}$ cm^{-3}) to produce detectable X-Ray flux. Some relevant aspects of the radiation from a hot plasma are briefly discussed. The X-Ray transmission ratio technique is discussed in detail. Calculations for selecting suitable components for such a diagnostic system are presented in this note. Ratios of the transmitted X-Ray flux through different sets of beryllium and aluminium foils, as a function of electron temperature are calculated. Some aspects of the method of determining electron temperature from the pulse height analysis of the emitted X-Ray spectrum are discussed briefly.

1) Introduction

X-Ray diagnostics is now a well established technique for determination of electron temperature (kT_e) in hot plasmas, where $kT_e > 100$ eV. Many papers and reports on this diagnostics have appeared so far.$^{1-8)}$ The purpose of this report is to present some calculations essential for an experimentalist to design the diagnostic system. These calculations will be helpful in selecting the suitable detector components in a particular experiment. These calculations assume the knowledge of the expected values of electron temperature and density in the heated plasma. These values can be calculated knowing the energy input in the plasma, for heating, and the energy balance considerations. Basic principles involved in this diagnostics are well discussed in the reports mentioned earlier, and we, therefore, avoid repetition.

2) Radiation from Plasma

The radiation emitted by a plasma extends over the entire electromagnetic spectrum. There are three radiation processes in an unmagnetized plasma, viz. (i) free-free or bremsstrahlung (ii) free-bound or recombination and (iii) bound-bound or line radiation. If the atoms composing the plasma are of atomic number Z, the free-free radiation will dominate for $kT_e > 3 . V_H . Z^2$, where V_H is the ionization potential of hydrogen (= 13.6 eV). The recombination process will be effective at lower temperatures. It is to be noted that the tensity of f-f, f-b and b-b radiations are proportional Z^2, Z^4 and Z^6 respectively. In most of the plasma heating periments hydrogen ($Z = 1$) plasma is used. Impurities of gh Z values (mainly of oxygen), give rise to line radiation. esence of f-b and b-b radiations complicates the diagnostics. nce the line radiations from impurities are at higher wavengths, it can be eliminated by using suitable absorber foils. this report we will consider only the free-free radiation ocess.

Bremsstrahlung

This type of radiation arises from the interaction of ectrons with the positive ions in the plasma. In this ocess a free electron makes a transition to another free ate of lower energy, with the emission of a photon. The ectrum is continuous. Assuming the plasma electrons to llow Maxwellian distribution, the intensity of free-free diation per Angstrom is given by$^{1)}$

$$= 1.9 \times 10^{-28} N_e \; N_i \; Z^2 g (kT_e)^{-\frac{1}{2}} \; \lambda^{-2} \exp\left[-\frac{h\,c}{\lambda k T_e}\right] \frac{\text{Watt}}{\text{cm}^3 . \text{Å}} \quad . \; . \; . \; (1)$$

this equation N_e and N_i are the electron and ion densities m^{-3}) respectively, Z is the atomic number of atoms composing e plasma, g is the Gaunt factor, kT_e is the electron temrature in eV, λ is the wavelength in Å of the emitted X-Ray diation, h is Plank's constant and c is the velocity of ght. In our calculations we will assume $g = 1$, significance which has been discussed by Elton$^{4)}$. In the exponential term, hc/λ is the energy E_λ, of the photon corresponding to wavelength λ. ($E_\lambda = \frac{12.4}{\lambda}$ KeV.) When I_λ is plotted as function of λ, for a given value of kT_e, I_λ is maximum at a wavelength given by $\lambda_{max} = \frac{6200}{kT_e}$ Å. Variation of I_λ with λ for different values of kT_e, for an arbitrary value of $N_e = N_i = 10^{14}$ cm^{-3} were calculated using Eq.(1) and are plotted in Fig.1. These curves show that the short wave length (high energy) cut-off depends on kT_e. In the wavelength region $\lambda > \lambda_{max}$, the spectrum is not affected by the change in kT_e. The strong dependence of the high energy cut-off of the spectrum on kT_e, is used as the basis for measuring kT_e in hot plasma. Spectral measurements for this purpose should be made in the region $\lambda < \lambda_{max}$, where the spectrum strongly depends on kT_e 8). This diagnostics can be used only when λ_{max} is in X-Ray region and electron density is high enough ($>10^{13}$cm^{-3}) to produce detectable flux of X-Ray photons. Integration of Eq.(1), over 1 to 100 Å gives the power emitted by the unit volume of plasma in the soft X-Ray region, which is equal to

$$1.9 \times 10^{-28} \; N_e \; N_i \; Z^2 \; (kT_e)^{-\frac{1}{2}} \int_{1}^{100} \lambda^{-2} \exp\left[-\frac{hc}{\lambda \cdot kT_e}\right] d\lambda . \qquad \ldots (2)$$

This X-Ray emission from the plasma is isotropic i.e. uniform over the solid angle of 4π.

As the electron temperature increases, fraction of the power emitted in the lower wavelength region increases.

Diagnostics

For determination of electron temperature from the y measurements, two different methods are available. In first method, the intensities of X-Rays transmitted through erent metalic absorber foils of known thickness are ured[1]. Thin foils of beryllium and aluminium are generally . By knowing the ratio of the transmitted intensities ugh two foils of different thickness, electron temperature be determined. The experimental arrangement for this nique is shown in Fig.2. In the second method, the X-Ray on spectrum is recorded by a multichannel pulse height yser[9,10]. Electron temperature is then determined from slope of the differential photon spectrum. Further details hese methods are discussed in sections 9 and 10 respectively.

In most of the plasma heating experiments the plasma is in the high energy state, when the measurable X-Ray emission es place, for about few microseconds or less. Fast detectors to be used for measuring X-Rays from such plasmas. The tillator - Photomultiplier combination is mostly used for suring X-Ray flux, in both the above mentioned methods. the next three sections, calculations required for selecting table absorber foils, scintillator thickness and photomultier tube are given.

Selection of absorber foils

When a polychromatic beam of X-Rays (containing photons of a wide energy range) passes through an absorber, the low energy photons are absorbed in it and the beam intensity is attenuated. For selecting suitable absorber thickness, the photon energies which will be cut-off (intensity attenuated to one tenth of original) by various foil thicknesses should be known. These cut-off energies for known thicknesses of different materials can be calculated as follows.

Let I_o is the intensity of a monochromatic X-Ray beam, passing through an absorber of thickness t (cm). Intensity of the transmitted beam is given by[11)]

$$I = I_o . \mathrm{Exp}\ (- \rho . K_\lambda . t) \qquad \ldots\ldots. \ (3)$$

In the above equation, ρ is the density of absorber material (gm/cm^3) and K_λ is the mass absorption coefficient (cm^2/gm), which depends on absorber material and wavelength of X-Rays. For a given absorber of thickness T (cm), the required value of K_λ to attenuate a beam of energy E_c to one tenth of its original intensity is given by

$$\ln 10 = \rho . K_\lambda T ,$$

$$\text{or} \quad K_\lambda = \ln 10 / \rho T . \qquad \ldots\ldots. \ (4)$$

Variation of K_λ with wavelength is known for most of the elements. For a given substance, the wavelength λc, corresponding to the value of K_λ given by Eq.(4) can be determined. Thus, the energy E_c of the beam corresponding to this wavelength, which will be cut-off by the foil of thickness T (cm) can be determined. For approximate calculations of E_c, the empirical relations between K_λ and λ can sed. This empirical relation is

$$K_\lambda = C\,(\lambda)^n ,$$

e C and n are constants depending on the atomic number he absorber material, and can be calculated easily. Thus, can be written as

$$\lambda_c = \left[\frac{\ln 10}{C\,\rho\,T}\right]^{1/n} \mathring{A} ;$$

$$E_c = \frac{12.4}{\lambda_c}\ \text{KeV}$$

beryllium, $\rho = 1.8$ gm/cm^3 ; C = 0.3731, n = 2.901 for 107 Å (K absorption edge) ; for aluminium $\rho = 2.7$ gm/cm^3, 13.9292, n = 2.8469 for $\lambda < 7.9$ Å. Using these values, off energies were calculated for aluminium and beryllium h are given in Table 1. Values of the cut off energies also be calculated by using Eq.(4) and the experimentally ined values of K_λ . Calculated values of E_c for aluminium beryllium using the values of K_λ given in ref. (11) were d to be almost equal to those calculated using the rical relation mentioned above.

Transmitted intensity and Scintillator

The intensity I'_λ at any wavelength λ, transmitted ugh an absorbing foil of thickness D mg/cm^2 (= t. ρ .1000) mass absorption coefficient K_λ is calculated from Eq.(1) (3) to be

$$= 1.9 \times 10^{-28} N_e\ N_i\ Z^2\ (kT_e)^{-\frac{1}{2}}\ \lambda^{-2}\ \exp\left(-\frac{hc}{\lambda k T_e} - K_\lambda \cdot D\right) \quad .. (5)$$

The total flux transmitted through a given foil can be calculated by integrating Eq.(5) over a wavelength region. The transmitted X-Rays fall on the scintillator. Plastic scintillators NE102 and NE140 (manufactured by Nuclear Enterprises Ltd) are the typical scintillators used. These scintillators have sufficient response for photon energy as low as 1 keV. The NaI crystals can not be used below 3 keV[11)]. For efficient working of the scintillator, i.e. to get maximum light output in visible range, photons with all energies in the transmitted signal should be completely absorbed in it. Knowing the expected upper limit of X-Ray photon energy, the required thickness of scintillator can be calculated. As an example, calculations for determining the required thickness of NE 102 for 90% absorption of 10 KeV photons are given here. This scintillator contains 4.78 x 10^{22} carbon atoms/cm^3 and 5.28 x 10^{22} hydrogen atoms/cm^3 as specified in its manufacturers catalogue. Using Avagadro number and atomic weights of carbon and hydrogen, it is seen that NE 102 contains 0.953 gm of carbon/cm^3 and 0.088 gm of hydrogen/cm^3. Using the formula for the mass absorption coefficient of a compound[11)], and using the values of absorption coefficients of carbon and hydrogen at 10 KeV (0.12 Å) given by Victoreen,[12)] it is found that the mass absorption coefficient of NE 102 for 10 KeV photons is 1.93 cm^2/gm. Again using Eq.(4), the required thickness of NE 102 is found to be 1.04 cm. It is advisible to use the scintillator thickness slightly more than the calculated. Proceeding in this way, the required thickness any scintillator of known composition can be calculated.

Photomultiplier Tube

Selection of the photomultiplier tube (PMT) is to be ne considering the spectral distribution of the scintillator ght out put. For example, the light output of NE102 scintiator is distributed over the range of 4000 to 5000 Å, with maximum emission at 4230 Å . The PMT should be with the otocathode of maximum response very near to 4230 Å. otomultiplier tubes with S-11 spectral response with a ximum sensitivity at 4400 Å are generally used with NE 102. PMT of the required spectral response and diameter permitted the experimental geometry should be selected. The intillator and PMT should be in perfect optical contact, that maximum number of photons from the scintillator fall the photocathode of the PMT.

Number of Photons

The number of photons emitted by the plasma and those ansmitted through an absorber foil of known thickness should so be known. Particularly, for using the method of ltichannel analysis mentioned in sec.4, the number of otons emitted between small energy intervals should be own in order to select a suitable analyser.

Expression for the number of photons emitted by the lasma, can be derived from Eq.(1). Energy emitted between avelengths λ and $\lambda+d\lambda$ due to free-free radiation is given by

$$I_\lambda d\lambda = 1.9 \times 10^{-28} N_e N_i Z^2 (kT_e)^{-\frac{1}{2}} \lambda^{-2} \exp\left[-\frac{E_\lambda}{kT_e}\right] \frac{\text{Watt}}{\text{Cm}^3}$$

OR

$$I_\lambda d\lambda = 1.9 \times 10^{-28} \times 6.24 \times 10^{18} N_e N_i Z^2 (kT_e)^{-\frac{1}{2}} \lambda^{-2} \exp\left[\frac{-E}{kT_e}\right] \frac{\text{eV}}{\text{Sec.cm}^3} . \quad (6)$$

We have the relation

$$E_\lambda = \frac{12400}{\lambda} \text{ eV}$$

$$\text{or} \quad dE_\lambda = -12400 \lambda^{-2} d\lambda . \quad \ldots\ldots \quad (7)$$

Number of photons emitted within energy E_λ and $E_\lambda + dE_\lambda$ is now given by

$$dN = \frac{I_\lambda \, d\lambda \ (\text{eV})}{E_\lambda \ (\text{eV})} ,$$

or $dN = 1.9 \times 6.24 \times 10^{-10} N_e N_i Z^2 (kT_e)^{-\frac{1}{2}} 1/E \ \lambda^{-2} \exp\left(\frac{-E}{kT_e}\right) d\lambda .$

Using relation (7), we get

$$dN = 9.56 \times 10^{-14} N_e N_i Z^2 (kT_e)^{-\frac{1}{2}} \frac{1}{E} \exp\left(-\frac{E}{kT_e}\right) dE . \ \frac{\text{Photons}}{\text{sec.cm}^3\text{.eV}} \ldots\ldots (8)$$

Using above expression, the number of photons emitted by the plasma in given energy interval can be calculated. To get the number of photons from unit plasma volume emitted in unit solid angle, Eq.(8) is to be divided by 4 π. Number of photons passing through an absorber of thickness D (mg/cm^2) and between energy E and E + dE can be written from equns. (8) and (3) as

$$dN = 9.56 \times 10^{-14} N_e N_i Z^2 (kT_e)^{-\frac{1}{2}} \frac{1}{E} \exp\left(-\frac{E}{kT_e} - K_E D\right) dE \ldots\ldots \quad (9)$$

In above expression, K_E is the mass absorption coefficient as a function of photon energy.

9) Transmission Ratio Technique

As mentioned in sec. (4), further details of the smission ratio technique are discussed here. Knowing expected values of kT_e and N_e, the expected X-Ray trum can be plotted using Eq.(1), and λmax can be rmined. For selecting the absorber thickness, the ndence of only the high energy side of the spectrum on should be remembered. Foil thickness with cut-off energy ter than $\frac{12.4}{\lambda \text{max}}$ KeV, and with sufficient intermidiate gap of 1 KeV) should be selected. Consideration for cting the scintillator and photomultiplier are already ussed in secs. 6 and 7. Signal of the photomultiplier mplified by suitable preamplifier, amplifiers and finally rded on an oscilloscope.

For actual design of the X-Ray detector, the plasma netry and relative position of detector are to be considered. solid angle ω subtended at the scintillator should be culated. This solid angle gives the volume of the plasma n by the detector. Multiplying Eq.(5) by the plasma ume seen by the detector, life time of heated plasma and $\omega/4\pi$, we get the transmitted flux. In plasma heating eriments, when the plasma parameters are to be determined one shot, the transmitted X-Ray flux through two or more orbers are to be measured in one shot. In this situation, photomultiplier tubes can be placed in one diagnostic t, and using two ports, flux transmitted through four orbers can be measured in one shot. An alternative angement using light guides in one port, is described by 13)

Ratio of the integrated X-Rays transmitted through absorber, to the total incident X-Ray flux is to be calculated for different absorbers, for determining kT_e. This ratio can be written from Eq.(1) and (5) as

$$\frac{\int \lambda^{-2} \exp\left[- \frac{hc}{kT_e} - K_\lambda \cdot D \right] d\lambda}{\int \lambda^{-2} \exp\left[- \frac{hc}{kT_e} \right] d\lambda} , \quad . \; . \; . \; . \qquad (10)$$

limits of these integrations depend on the range of kT_e. For values of kT_e of the order of 500 eV, this integration should be done over 1 to 100 A. At still higher temperatures of the order of 1 KeV and above, the lower limit should be 0.1 Å. This ratio should be calculated for different values of kT_e and the selected values of absorber thickness. This ratio was calculated for beryllium and aluminium foils of different thickness, and its variations with absorber thickness, for different values of kT_e are shown in Fig.3. High purity beryllium foils of thickness ranging between 0.001" and 0.02" are available from Brush Wellman Inc. (17876 St.Clair Avenue, Cleveland, Ohio 44110, USA), and these thicknesses are used in present calculations. These standard thicknesses given in inches have been converted into mg/cm^2 and are given in Table 1 (B). Mass absorption coefficients for beryllium were taken from ref. (14). Aluminium foils of different thickness ranging from 2.7 to 864 mg/cm^2 are available from Electronic Corp. of India Ltd., and some of these standard thicknesses are used in these calculations.

off wavelengths and cut-off energies of aluminium foils lable from ECIL were calculated as stated in sec.5 and given in Table 2. Mass absorption coefficients for inium were taken from ref. (15). The integrals were rically calculated using the IBM 360 Computer and the os were automatically plotted by the plotter of the uter system. From these calculations, ratio of the smitted flux through two selected absorbers, for different es of kT_e were calculated. These results are shown in 4. Thus, using the experimentally obtained values of these os, and the curves plotted in Fig.4, kT_e can be determined.

Multichannel Analysis

For finding the suitability of this method, selecting analyser and number of channels to be used, the number of ons emitted between small energy intervals are to be ulated. A thin filter in the form of metalic foil is to avoid the ultraviolet and long wavelength radiation. llustrating these calculations, we take an example of ogen plasma in which $kT_e = 500$ eV and $N_e = 10^{14} cm^{-3}$. The n energy from 0.12 KeV ($\lambda = 100$ Å) to 10 KeV is divided etween 100 channels, each channel of width of 0.0988 KeV. er of photons emitted in these energy channels per unit angle were calculated using Eq.(9). The graph between umber of photons and the energy interval for the two bers is shown in Fig.5. The linear portion of the

The essential condition for using this technique is that, sufficient number of photons should be emitted in each energy channel which can be measured within the statistical error of measurements. In Fig.5, we see that number of photons emitted in the useful energy range is very small and thus, this technique should not be used in present case. This method can be used at still higher temperatures.

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Table 1 - (A) Cut off Wavelengths and Energies for Aluminium Foils

Thickness Inches	Thickness cm	Thickness mg/cm^2	Cut off Wavelength Angstroms	Cut off Energy KeV
0.001	0.00254	6.858	3.058	4.061
0.002	0.00508	13.716	2.397	5.181
0.003	0.00762	20.574	2.079	5.974
0.004	0.01016	27.432	1.879	6.609
0.005	0.01270	34.290	1.738	7.148
0.006	0.01524	41.148	1.630	7.620
0.007	0.01778	48.006	1.544	8.044
0.008	0.02032	54.864	1.473	8.431
0.009	0.02286	61.722	1.413	8.787
0.010	0.02540	68.580	1.362	9.118
0.011	0.02794	75.438	1.317	9.429
0.012	0.03048	82.296	1.278	9.721
0.013	0.03302	89.154	1.242	9.998
0.014	0.03556	96.012	1.210	10.262
0.015	0.03810	102.870	1.181	10.514
0.016	0.04064	109.728	1.155	10.755
0.017	0.04318	116.586	1.130	10.986

Table - 1 (B) Cut-Off Wavelengths and Energies for Beryllium Foils

Thickness inches	Thickness cm	Thickness mg/cm^2	Cut Off Wave-length Angstroms	Cut-Off energy KeV
0.001	0.00254	4.699	11.883	1.045
0.002	0.00508	9.358	9.358	1.327
0.003	0.00762	14.097	8.137	1.526
0.004	0.01016	18.796	7.369	1.685
0.005	0.01270	23.495	6.823	1.820
0.006	0.01524	28.194	6.408	1.938
0.007	0.01778	32.893	6.076	2.044
0.008	0.02032	37.592	5.803	2.140
0.009	0.02286	42.291	5.572	2.229
0.010	0.02540	46.990	5.373	2.312
0.011	0.02794	51.689	5.199	2.389
0.012	0.03048	56.388	5.046	2.461
0.013	0.03302	61.087	4.908	2.530
0.014	0.03556	65.786	4.785	2.596
0.015	0.03810	70.485	4.672	2.658
0.016	0.04064	75.184	4.569	2.718
0.017	0.04318	79.883	4.475	2.775
0.018	0.04572	84.582	4.388	2.831
0.019	0.04826	89.281	4.307	2.884
0.020	0.05080	93.980	4.231	2.935

Table - 2 Aluminium Foils Available from ECIL

S.No.	Thickness in mg/cm^2	Thickness in cm.	Cut-off wavelength in Augstrom	Cut-Off energy in KeV
1	2.7	0.001	4.2428	2.9273
2	5.4	0.002	3.3259	3.7343
3	13.4	0.0049	2.4278	5.1157
4	27.0	0.010	1.8897	6.5724
5	40.5	0.015	1.6389	7.5782
6	84.5	0.0312	1.2671	9.8019
7	219	0.0811	0.9059	13.7101
8	243	0.090	0.8734	14.2202
9	324	0.120	0.7894	15.7334
10	432	0.160	0.7136	17.4047
11	540	0-200	0.6598	18.8238
12	709	0.262	0.6001	20.6965
13	864	0.320	0.5594	22.2023

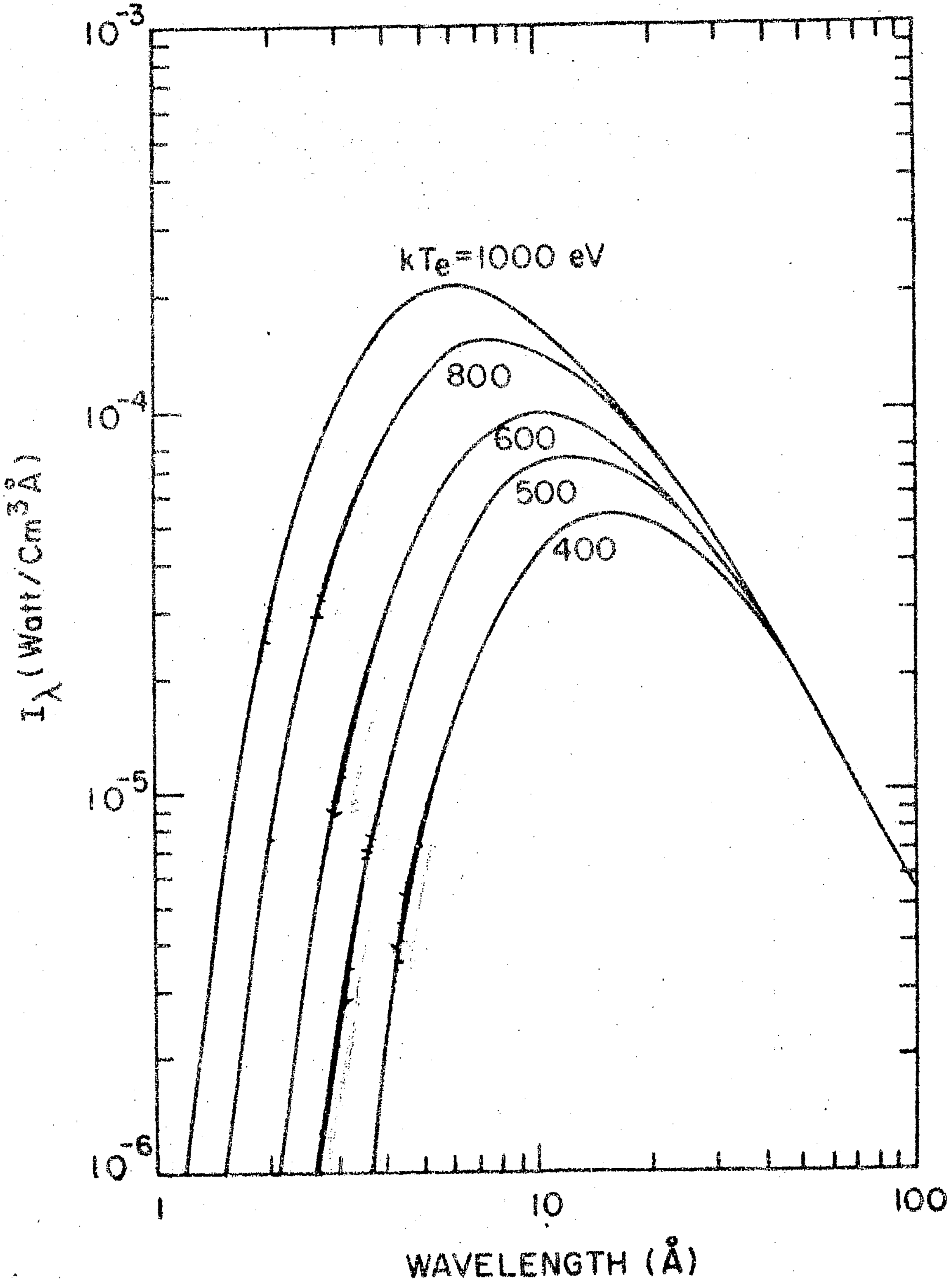

Fig.1. Calculated bremsstrahlung emission per cm^3, for Hydrogen Plasma. $N_e = 10^{14}$ cm^{-3}.

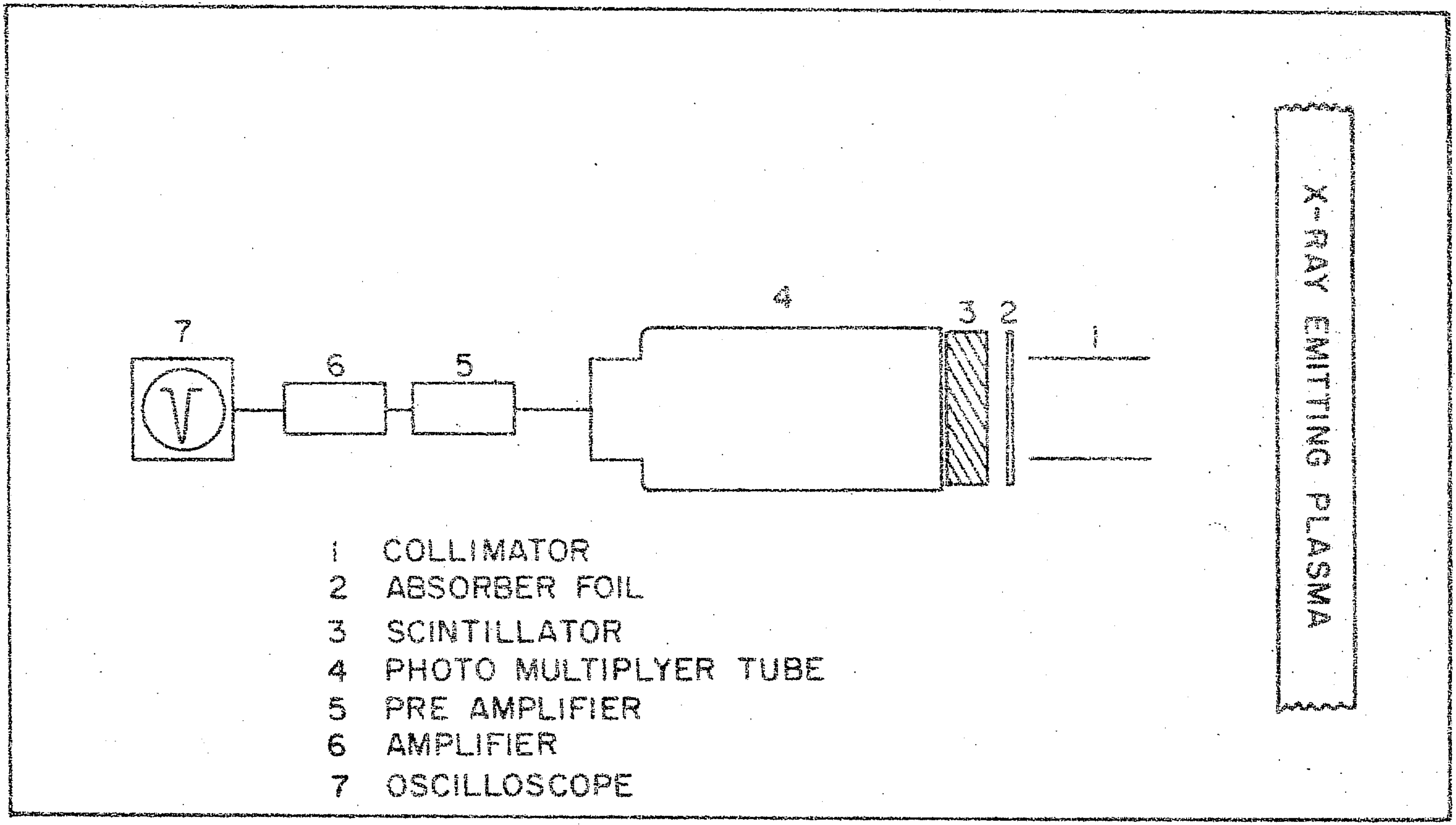

Fig.2. Experimental arrangement for determination of electron temperature by transmission ratio technique.

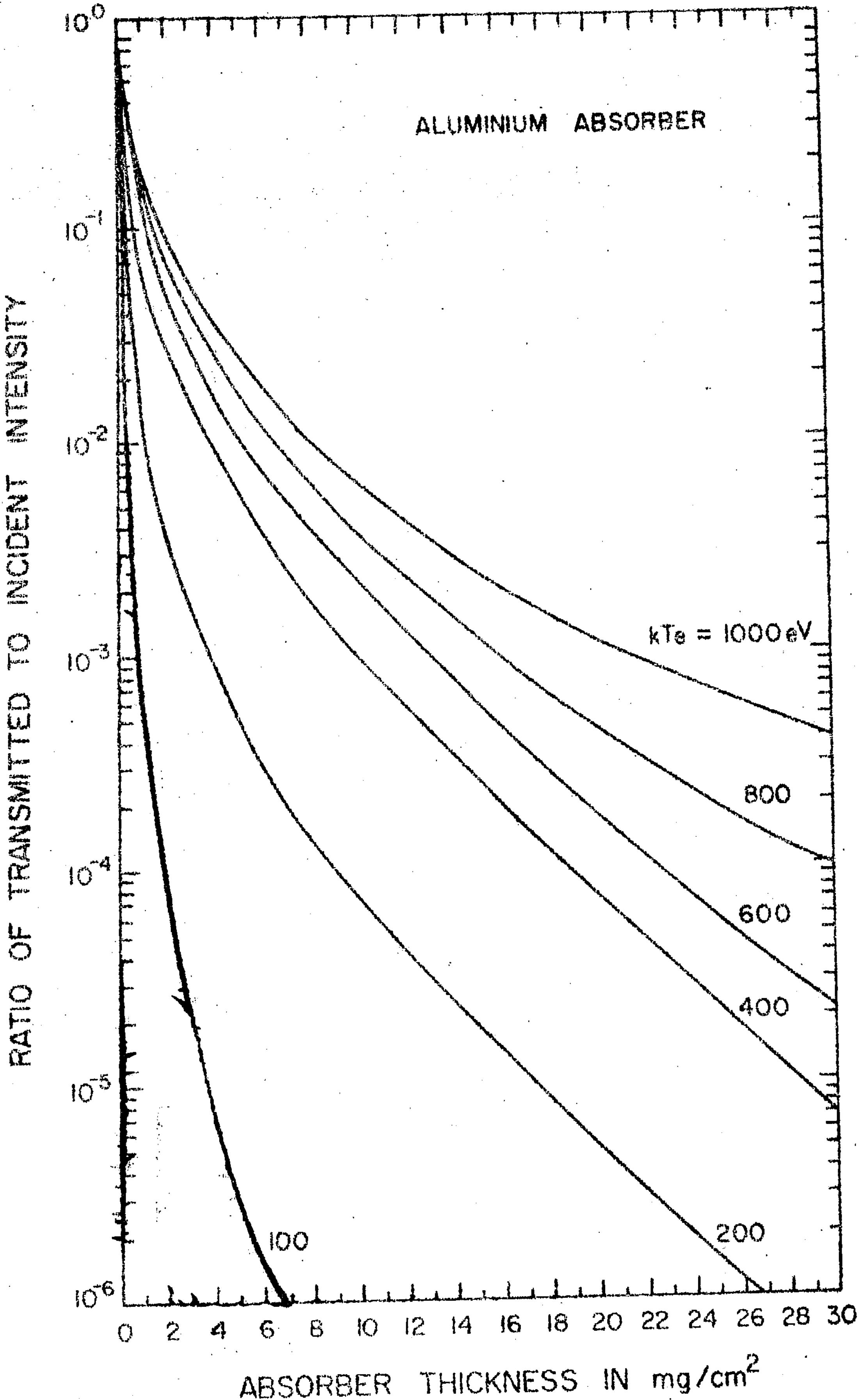

Fig. 3 (a) Ratio of X-Rays transmitted through Aluminium foils to the total incident

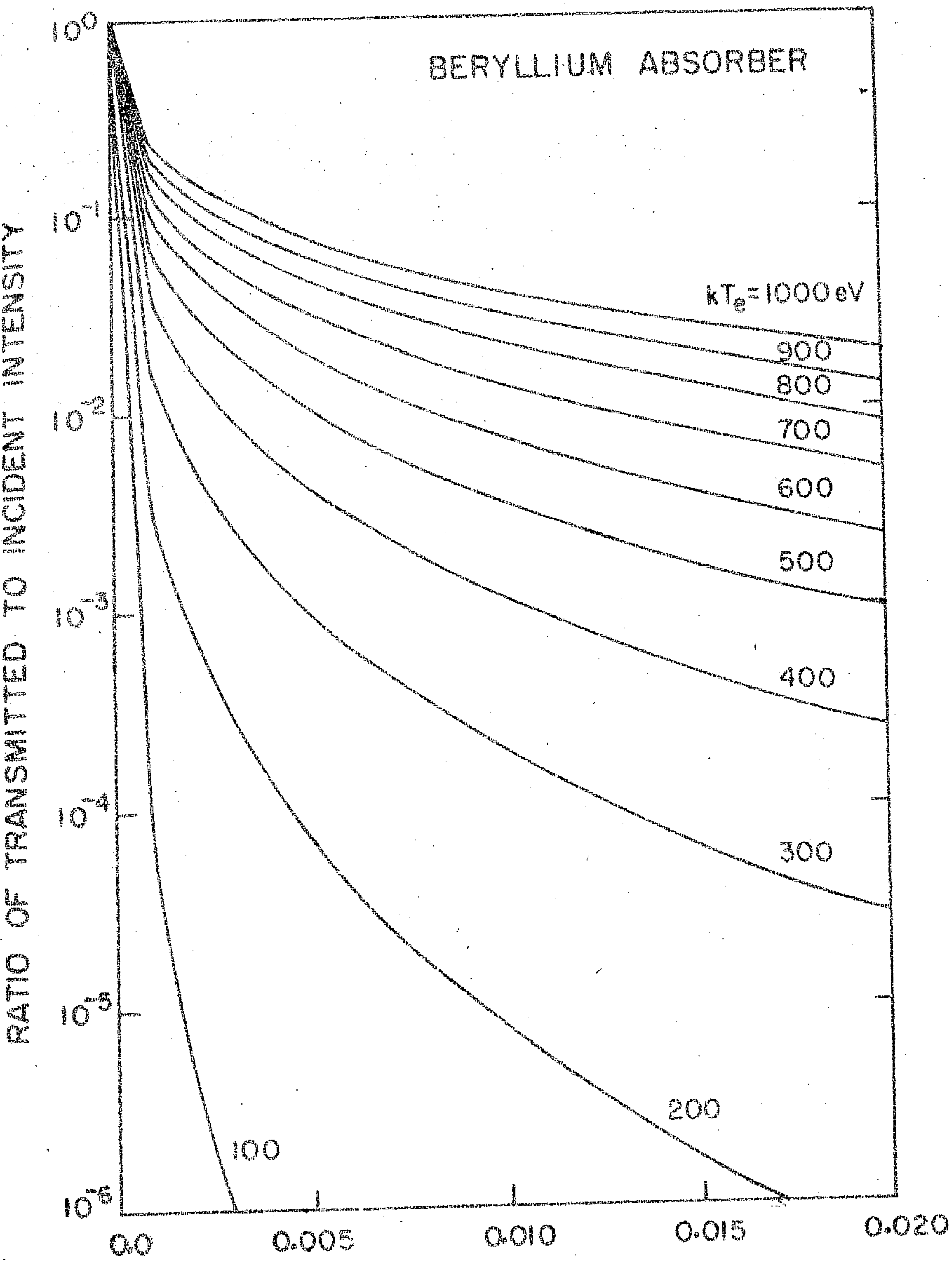

Fig. 3 (b) Ratio of X-Rays transmitted through beryllium foils to the total incident flux versus foil thickness.

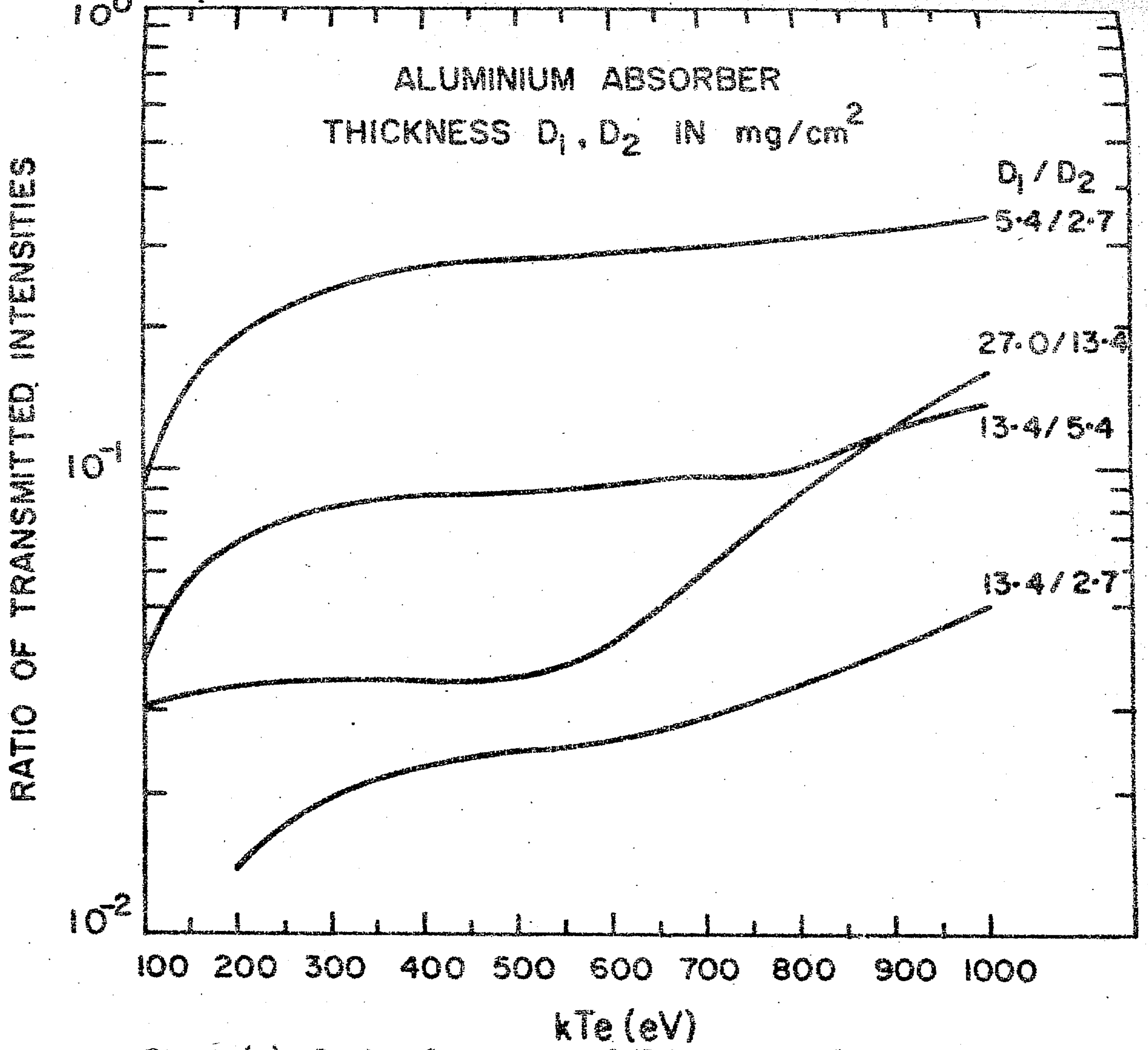

Fig.4 (a). Ratio of transmitted X-Rays through combinations of two aluminium foils versus electron temperature.

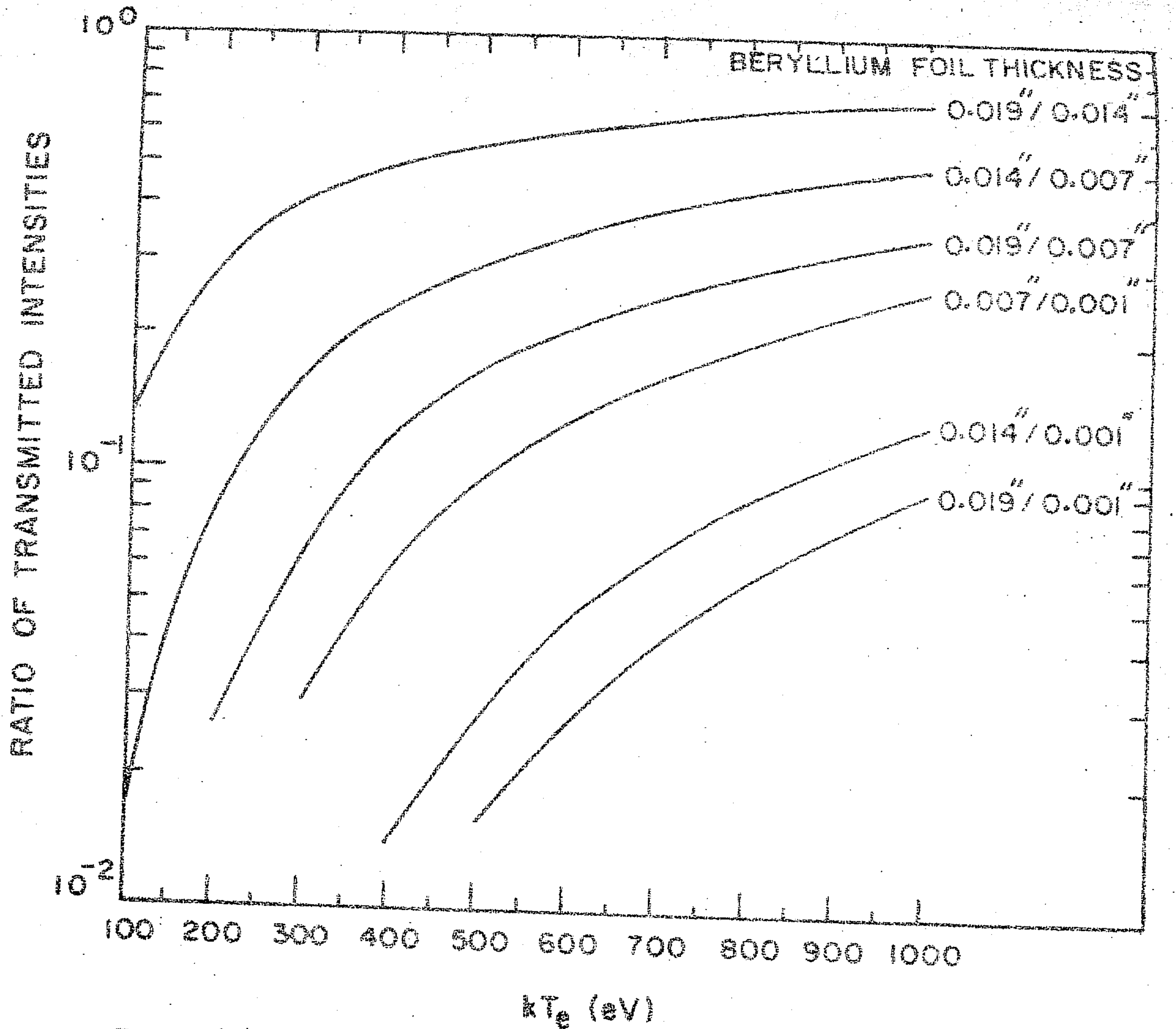

Fig.4 (b). Ratio of transmitted X-Rays through combinations of two beryllium foils versus electron temperature.

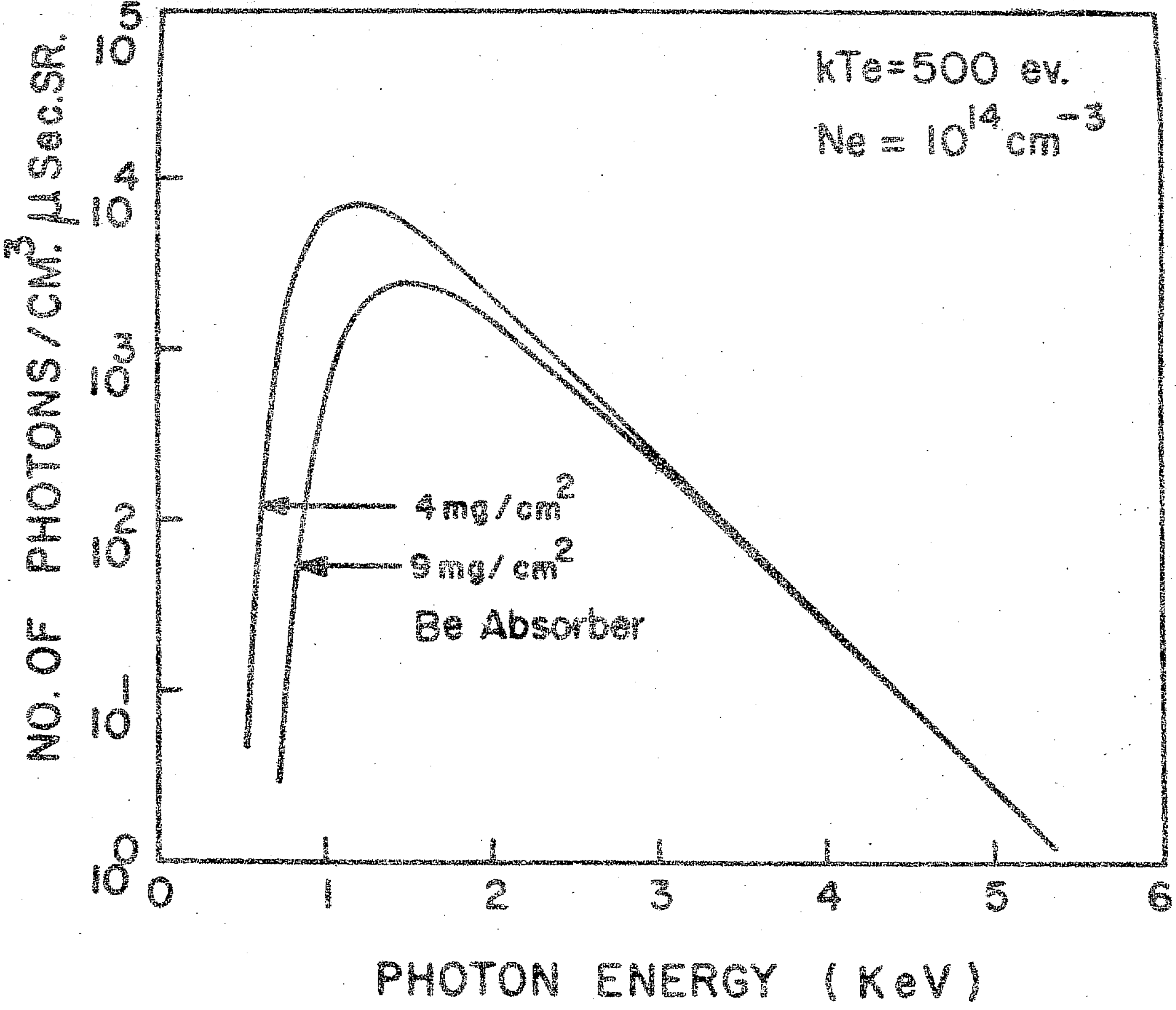

Fig.5 Calculated photon spectrum