ELECTRON ENERGY DISTRIBUTIONS FROM SOFT X-RAY BREMSSTRAHLUNG

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With increasing plasma temperatures and densities ever greater emphasis must be placed upon photon diagnostics. Of particular interest in this discussion is that spectral region of the continuum with photon energy (a) well above the ionization energy of the primary atomic species and (b) comparable to or greater than the plasma electron kinetic temperature.

Ignoring, for the moment, the possible presence of high Z impurities within the plasma, this spectral region defined above has a strong smooth photon energy dependence upon electron temperature which renders it a sensitive method for the determination of T_e . Moreover, all present day plasmas are optically thin to this spectral region.

The use of this spectral range, termed the soft x-ray region, for plasma temperatures has been discussed by several authors^{1,2} in the past decade. I wish to consider the experimental aspects of working in this spectral region whose lower limit is defined roughly by the transmission of thin beryllium foil (~ 1 keV) and whose upper region may extend to ~ 100 keV. As many plasma electron temperatures now exceed 1 keV, this lower level cutoff is not serious in terms of information loss and it gives one freedom from visible and ultraviolet light as well as the use of commercially available solid state soft x ray detectors which need be vacuum encapsulated.

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A free electron of energy E_0 undergoing a collision with an ion will give rise to electromagnetic radiation which, if the electrons is also free after the collision, is termed free-free or bremsstrahlung emission. The probability of emission or the cross section for emission of a photon is, classically, the same for all frequencies up to the energy limit $\nu = E_0/h$ and is proportional to $1/E_0$. If we multiply by the electron flux $n_e v$ we obtain the total emission per unit frequency per unit time. For a Maxwellian distribution of electron energies, this results in

$$\frac{dE_{ff}}{d\nu} = C n_e n_i Z_i^2 \left(\frac{X_H}{kT_e} \right)^{1/2} g_{ff} \exp \left(- \frac{h\nu}{kT_e} \right)$$

where $C = 1.4 \times 10^{-40}$ erg cm³, X_H is the hydrogen ionization potential and g_{ff} are the Gaunt factors which represent the quantum corrections to the classical cross section. Temperature averaged Gaunt factors are given by Karzas and Latter³ for wide ranges of photon and electron energies relative to kT_e and X_H . For $h\nu \approx kT_e \approx Z^2 X_H$ the Gaunt factors are close to unity. If on the other hand, the bulk of the radiated intensity arises from proton-electron encounters; i.e., $Z = 1$, and $kT_e \gg Z^2 X_H$. Considerable variation occurs in the Gaunt factors as $h\nu$ varies from $(1 - 10) kT_e$. As the temperature is derived from the slope of the continuum intensity vs frequency by

$$kT_e = h(\nu_2 - \nu_1) / \ln [I_1 g_{ff}(\nu_2 T_e) / I_2 g_{ff}(\nu_1 T_e)]$$

one quickly arrives at the problem of assessing the impurity concentration of the plasma to determine the primary source of the

radiation and thus the effective value of $Z^2 X_H$. As the free-free intensity is proportional to Z^2 only a small percentage of oxygen will dominate the intensity. Ten percentage oxygen additive in a theta pinch produced, for example, an order of magnitude increase in intensity.⁴ This problem is further aggravated by the fact that for $kT_e \approx Z^2 X_H$, free-bound radiation is also important and while having the same $\exp(-h\nu/kT_e)$ spectral shape, has a Z^4 intensity dependence.

Unless the plasma impurity concentration is known in detail from continuum absolute intensity measurements or other spectroscopic methods, the assumption that $g_{ff} \approx 1$ must be used which introduces something $\lesssim 10\%$ uncertainty in electron temperature determinations.

One has, in general, two basic methods for the spectral intensity determination. The first entails the use of dispersive elements for the frequency selection which then need be followed only by some detector to record the total number of photons regardless of photon energy. In this approach we include the use of foil absorbers which are energy selective devices. The second method employs photon counting by energy sensitive devices such as gas proportional counters, scintillators, and semiconductor detectors.

Previous plasma work in this spectral range has involved the use of diffraction spectrometers using various crystals of suitable lattice spacing for the desired spectral range⁵ and photon energy analysis by proportional counters.⁶ With proportional counters the average energy requirement to produce ion-electron pairs is something $\approx 30 - 35$ eV, thus a 1 keV photon which produces a

photoelectron of approximately this energy can result in at best some 30 events which produce free electrons. The statistical fluctuation in the number of events is thus $\sqrt{30}/30$ or a relatively large number. Moreover, the noise level due to thermal effects in room temperature scintillators usually precludes the resolution of such photon energies. Recent development of semiconductor detectors of silicon and germanium which operate at liquid nitrogen temperatures thus offer two advantages, namely, the reduced thermal degradations arising from low temperature operation but more importantly the inherent advantage of requiring only ~ 3.5 eV for the production of an electron-hole pair which gives a resolution a factor 3 above most other detectors. Energy resolutions of ≤ 200 eV for $h\nu = 5.9$ keV are not uncommon.

We emphasize here some recent results from the use of semiconductor detectors applied to dc plasmas and long duration pulsed plasmas as generated by Tokamaks. To count and energy resolve individual photons requires a count rate not in excess of 100 kHz which renders this approach not very suitable for plasmas of short lifetime such as generated by theta pinches or plasma focus.

The results shown in Fig. 1 are taken from an electron cyclotron produced plasma freely flowing onto a carbon target.⁷ The plasma density is low ($10^{10} - 10^{11}/\text{cm}^3$) so hydrogenic ion-electron bremsstrahlung intensity is quite small. The use of a carbon target produces copious soft x rays from which the electron temperature can be determined. The k absorption edge for carbon is only 283 eV, hence the spectral regions above this is pure continuum with the exponential dependence.¹ We record with such a

counter and pulse height analyzer not energy per unit frequency but number of photons per unit frequency. The raw data is thus multiplied by $h\nu$ and corrected at the low energy end for counter window absorption to yield the results shown in Fig. 1. The temperature deduced from the slope, assuming unity Gaunt factors, of 1.9 keV agrees reasonably well with measurements of a gridded probe intercepting the expanding plasma.

When, by such counting technique, one can show an exponential dependence spanning two orders of magnitude as exemplified by Fig. 1, one is justified in claiming the electron energy distribution Maxwellian to the extent that one can reliably employ absorption methods for temperature measurement.

The x-ray absorption coefficients of most elements are reasonably well known as a function of energy in the soft x-ray region of interest here. In the regions between absorption edges (K shell, L shell, etc.) the absorption coefficient varies approximately as $(1/\nu)^3$ and the total effect of a given absorber upon the continuum produced by a plasma at temperature T_e can be evaluated. This total reduction in intensity is thus temperature dependent affording in principle a means of measuring T_e by the use of two or more absorbers. The advantages of this method to the experimenter are that one need only record the total number of photons and they need not be resolved in pulse shape as is necessary when energy analysis by pulse height must be made. For short lifetime plasma this method is particularly appropriate.⁸ For Maxwellian electron distributions, absorption curves vs foil thickness have been calculated for several materials with electron

temperature as the parameter.^{8,9} For high density plasmas where the electron energy distribution is clearly Maxwellian, this method has been used with considerable success.³ It is essential, therefore, to determine that the electron velocity distribution is indeed Maxwellian before one can evaluate the effect of the absorber in attenuating the bremsstrahlung spectrum. For example, toroidal machines with electron density $\sim 10^{13}/\text{cm}^3$ and $T_e \sim 1$ keV are very likely to have a pronounced tail to the electron energy distribution which will give an anomalously high transmission for the thicker absorbers and thus too high a value of temperature for the main distribution.

We have employed multiple aluminum foils followed by a CsI scintillator to determine the temperature of the flowing electron cyclotron plasma discussed earlier.⁷ Shown in Fig. 2 are the calculated absorption curves of Jahoda⁸ and some extrapolated values (dashed) to bracket our experimental points. The experimental points indicate a temperature of about 1.7 keV. This compares with 1.9 keV derived from photon energy analysis and 1.5 keV as determined from a gridded probe.

An interesting and straightforward use of the threshold detector such as represented by the semiconductor devices with thin Be foil windows or any such detector with a fairly sharp low energy cutoff has been discussed by Halverson.¹⁰ If the plasma temperature is low compared to the photon energy threshold of the detector e.g., if $T_e < 100$ eV and the threshold E_0 is 1 keV, all the photons passed by the detector window are very close to E_0 in energy because of the rapidly decreasing exponential tail of the Maxwellian electron energy distribution. Energy resolution by the

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the detector is no longer required and the electron temperature can be rather accurately related to the total number of photons above E_0 . This method is particularly suitable for high density low temperature plasmas such as might be produced by laser irradiation of solid or high density gas targets.¹⁰ If the target is of high Z material such that the continuum contains line spectra in the x ray region, then one does have to avoid cases where a spectral line falls in the vicinity of the threshold energy.

To illustrate the nature of the low energy cutoff as produced by thin foils of beryllium and aluminum we show some sample attenuation curves vs photon energy in Fig. 3. Notice the strong K absorption edge in aluminum at 1.6 keV. If aluminum alone is used as an absorber an appreciable low energy window thus exists from about 1 keV to 1.6 keV which can be used for energy selection. If on the other hand, one desires large attenuation of low energy photons (1 - 3 keV) then aluminum should be used in conjunction with beryllium to block this low energy window.

With a combination of various size apertures and foil absorbers and the use of a silicon semiconductor detector in conjunction with a beryllium window encapsulated thin sodium iodide crystal von Goeler et al.¹¹ have examined the electron energy distribution of the ST tokamak in the photon range 1 - 100 keV. These results are shown in Fig. 4. There exists, in general, a pronounced tail to the distribution which would render the use of foil absorbers in the manner employed for the data of Fig. 2 somewhat risky. Specifically one would have to insure that the total photon population in the tail was small compared to the main thermal photon flux passed by the thickest of the

absorbers. One sees, however, data taken at relatively high pressure in which a single exponential photon flux is obtained for 5 orders of magnitude in intensity. Clearly the use of absorber attenuations based on a Maxwellian electron velocity distribution is well justified and should yield the time resolved electron temperature throughout the machine pulse.

Finally in Figs. 5 and 6 we show some recent data taken on the compression tokamak ATO. Figure 5 is data from uncompressed plasma where 1.25×10^{-2} cm beryllium foil is used to reduce the count rate to manageable levels. The reduction occurs primarily at the low energy end of the spectrum where large correction factors are necessary to correct for the true spectrum. Multiplying the corrected spectrum by $h\nu$ and using unity Gaunt factors one gets a temperature of 585 eV. If the radiation were entirely from a $Z = 1$ plasma, the correct Gaunt factors would give 645 eV, so the uncertainty in temperature is not large.

Figure 6 contains data taken from the compressed plasma where T_e is increased by somewhat more than a factor of 2 and the density is up by about a factor of 5. The increased flux requires a greater attenuation which one achieves with a combination of 2.5×10^{-2} cm Be and 2.5×10^{-3} cm Al. With unity Gaunt factors a temperature of 1230 eV results and for a $Z = 1$ plasma with appropriate Gaunt factors, 1430 eV.

In comparison with Thomson scattering data, we find bremsstrahlung temperatures about 20% lower than the average of $n_e^2(r) T_e(r)$ obtained from the laser scattering. If high Z impurities are concentrated more to the outside where T_e is lower,

this could clearly account for the difference. At present we do not have much overlapping laser data for comparison so the discrepancy does not seem at all serious.

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FIGURE CAPTIONS

Fig. 1. Semiconductor detector-pulse height data corrected for window absorption and converted to energy per unit frequency dE/dv .

Fig. 2. Integrated photon flux vs aluminum absorber thickness (points) superimposed on calculated transmission curves from Jahoda.⁸

Fig. 3. Attenuation curves vs photon energy for foils of beryllium and aluminum. The K edge for aluminum occurs at 1.6 keV.

Fig. 4. Electron energy distributions of the ST tokamak obtained by photon counting for various machine filling pressures.

Fig. 5. Photon intensity vs energy (dN/dv) from uncompressed ATC plasma. Raw data and absorber corrected data are shown.

Fig. 6. Photon intensity vs energy, corrected and uncorrected for absorber, of compressed ATC plasma.