Time-resolved electron temperature measurement in a multiwire Z-pinch plasma

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A simplified technique to measure the plasma temperature in multiwire Z-pinch experiments is reported. X-ray PIN, diodes fitted with different transmission filters, were employed to detect the X-radiation in different energy bands. The comparison of the relative intensities in each band gives a time-resolved measurement of the electronic temperature. The method consists in applying a simple model of the continuum spectrum that is convoluted with the filter-detector response to obtain predicted amplitude ratios. The computed ratios are then compared to the experimental ones to obtain the time-resolved temperature. When the method was applied to experiments carried out with 1-4 wire bundles, the temperature was found to be in the interval 1 to 7 keV.

Keywords: Dense plasmas; Z-pinch; X-ray sources.

Se reporta una técnica simplificada para medir la temperatura de un plasma denso tipo Z-pinch multifibra. La utilización de detectores de rayos X provistos de diferentes filtros permite detectar la radiación en varias bandas de energía. Mediante la comparación de las intensidades en las diferentes bandas se puede estimar la temperatura electrónica. El método se basa en la convolución de la respuesta de los detectores y el espectro continuo de emisión de un plasma para predecir una respuesta. Comparando las tasas de señal predichas contra las experimentales se obtiene la temperatura. Al aplicar el método propuesto a experimentos con haces de 1 a 4 fibras se demuestra que la temperatura resuelta en el tiempo varía dentro del intervalo 1 a 7 keV.

Descriptores: Plasma denso; Z-pinch; fuentes de rayos X.

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1. Introduction

Nowadays the Z-pinch plasma is considered one of the most powerful and efficient sources of pulsed, soft (<10 keV) X-rays. The understanding of its dynamics may have a considerable impact in applications such as inertial confinement fusion, semiconductor lithography, and physics of radiation hydrodynamics. The phases of the pinch are: initial ablation, melting and vaporization of the wires, coronal plasma expansion, merging of the individual plasmas, a subsequent implosion exhibiting Rayleigh-Taylor instabilities, and finally, the stagnation phase (pinch) [1]. During this latter phase most of the energy is in the kinetic energy of the ions (∼60 keV) which is then thermalized with that of the electrons.

The dense plasma in a multiwire Z-pinch experiment is produced by the application of an intense (above 100 kA), short (<100 ns duration) current pulse. This is generated by a machine ensemble comprising a marx generator, a pulse forming line, and a transfer switch. The powerful current pulse vaporizes the filaments and provides the milieu to establish the plasma. The magnetic pressure of the strong azimuth magnetic field compresses the plasma and pinches it. In single-wire pinches dense microplasma regions are observed. These are known as “hot spots”. The density and temperature achieved in the hot spots produce intense X radiation. This is made of a mixture of characteristic lines or a continuum, depending on what process is the dominating one. In multiple-wire pinches the merging of individual plasmas produces a single sheath that is imploded by the magnetic pressure.

Recent experimental results show that an increment of the number of wires accompanied by a simultaneous reduction in the individual wire diameter also increases the yield of the X-ray pulse. This increment is attributed to the combined effect of a tighter pinch compression and an improved plasma uniformity [2]. In a more recent publication, Velikovich et al investigated the variation of the electronic temperature with the wire’s atomic number [3]. Extrapolating the results reported in this last reference, it is found that for copper the electronic temperature is ∼7 keV. Also relevant is the finding that as Z increases, the X-ray yield decreases although the energy of its photons increases. From the above results clear that an optimized pinch device has to balance the interdependent variables: wire number, wire spacing, and their chemical composition.

In 1998, at Imperial College, C. Deeney obtained estimates of the electron temperature in a gas-puff Z-pinch plasma using transmission filters. He obtained his results by assuming bremsstrahlung emission only, and using a computer code to convolute the filter transmission with the predicted spectrum [4]. He reported values for T_e of 4.5 and 5.5 keV in an argon pinch; but his measurements were not time-resolved.

The X-ray spectrum in the continuum has a strong dependency on the temperature of the plasma; its shape is given by Refs. 5 and 6:

$$I(E)\,\alpha\,e^{-E/T}\overline{g}\,T^{1/2} \qquad (1)$$

where *I(E)* is the radiation intensity in the energy interval *E* and *E+dE*, and $\overline{g}$ is the average Gaunt factor. The shape of

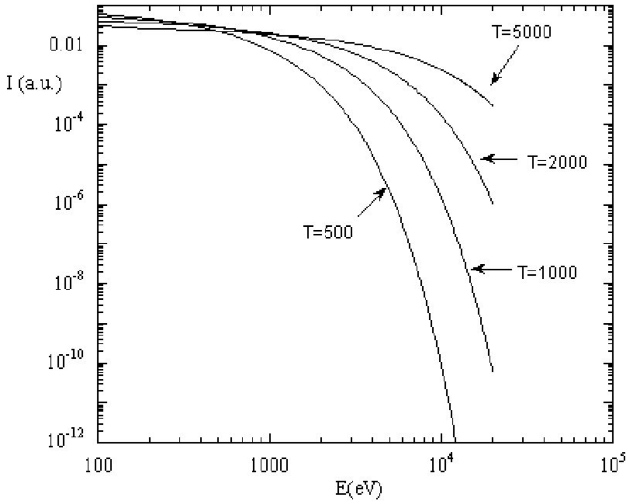

FIGURE 1. Continuum X-ray spectrum. Vertical scale in arbitrary units. Temperatures in eV.

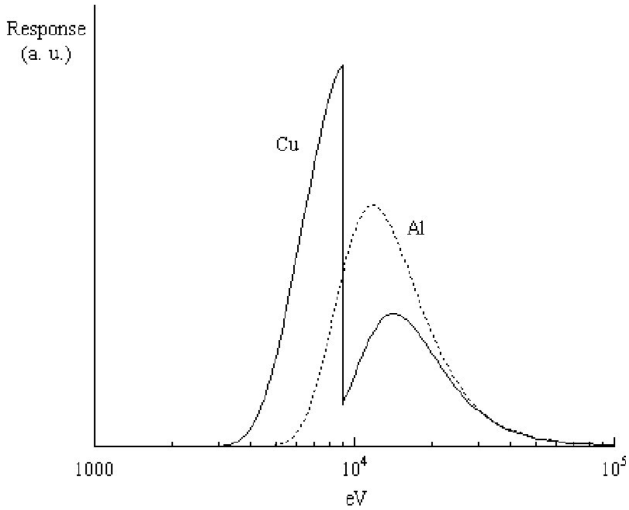

FIGURE 2. Combined response of the filter and detectors. The vertical scale is the response, in arbitrary units. The labels *Cu*, *Al* identify the filters fitted to the detectors.

the spectrum at different plasma temperatures is shown in Fig. 1. The spectra were calculated for a particular case of the parameter a=T/Z^2Ry=0.1, where *Ry* is the Rydberg constant and *Z* is the degree of ionization.

2. Experimental set-up

2.1. Apparatus

A Z-pinch generator consisting of a 36 kJ, 600 kV Marx and a 5-ohm transmission line was used in the experiments. The load consisted of an array of 3-cm long thin wires (25 μm diameter) arranged in single-wire, double-wire and four-wire bundles. The separation between wires was 2.6 mm. These were placed inside a high vacuum chamber that provided the electrical insulation between the electrodes as well as precluding a gas discharge between them to develop.

The vacuum chamber had several radial ports aimed at its center that contained the diagnostics. In 2 or 3 of the ports, X-ray detectors (identical PIN diodes from Quantrad N series, 250 μm depth) were placed. The diodes were fitted with different metallic foils to act as X-ray transmission filters and to block the light emitted by the plasma. The filters employed were: 10 μm copper, 125 μm aluminum, and 12.5 μm tungsten. The copper and tungsten filters were supplemented with an additional 4 μm aluminum foil to avoid fluorescence. In several of the experiments streak pictures of the plasma were taken simultaneously with the X-ray measurements.

2.2. Energy measurement

Figure 2 shows the combined response of the filter and PIN diodes employed. The curves in the figure represent the convolution of the filters' absorption with the response of the silicon in the detectors. The electric signal generated at the terminals of the detectors, as a function of photon energy, will be proportional to the height of the curves in Fig. 2. The predicted output of the detectors *v* is calculated as follows [7]:

$$v = \int_{E\,\min}^{E\,\max} R(E)I(E,T)W(E)dE \qquad (2)$$

where *R(E)* is the detector's response and *W(E)* is the filter transmission.

The measurement of the temperature was performed using a simple method that can be implemented in any scientific spreadsheet. First, the Gaunt factor is fitted to an analytical formula, second using this fit the spectrum is calculated at several energies using Eq. (1) for fixed *T*. A new curve-fit is then applied to the resulting spectrum column. This is next convoluted with the combined diode-filter response using Eq. (2); this is the predicted detector output for a given *T*. The process is repeated for several temperatures and a table of detector output versus temperature is generated for every diode-filter combination. The routine is repeated for the other combinations. The tables thus obtained are then used to calculate the signal ratio of differently-filtered detectors as a function of temperature. Figure 3 shows the calculated ratio as a function of temperature for copper and aluminum filters; this constitutes a temperature calibration curve. This curve can then be compared with the experimental signal ratios, and from the comparison the temperature is figured out. Note that the absolute values of both the spectrum and the theoretical detector response are not indispensable: on calculation of the ratios all constants cancel out, leaving only the functional dependency on energy and temperature.

The intensity of line radiation varies substantially over a narrow energy interval. The continuum spectrum, by contrast, depends almost equally on the energy and the temperature over wide intervals. For a fixed temperature 2,000 eV, for example, a variation in energy from 2 to 5 keV reduces the yield by 79%, as shown in Fig. 1. Similarly, for a fixed

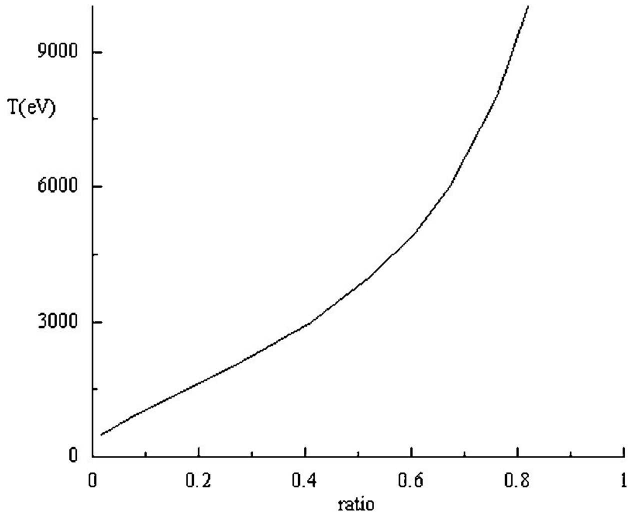

FIGURE 3. Calibration curve for temperature measurement. The curve represents the ratio of calculated detector signals as a function of temperature.

5 keV photon energy a variation from 5 to 2 keV in the temperature reduces the yield by 68%.

An ideal monoenergetic line will produce dissimilar signals in two differently-filtered detectors since their responses are different functions of photon energy. So the comparison of two signals can be a useful tool to discriminate between characteristic and continuous radiation at any instant of time. As the integral in Eq. (2) for the continuum is assumed to extend over a wide energy interval, line emission does not cover this span; for this reason the present method ought not to be applied when characteristic radiation is suspected.

3. Experimental results and discussion

Figures 4 to 6 show examples of the determination of the electronic plasma temperature, with time resolution. In Fig. 4 the results obtained with a pair of Al-filtered and Cu-filtered detectors are particulary shown for a shot on a single 25-μm copper fiber. The trace of the copper-filtered diode clearly has two peaks while that of the aluminum-filtered shows the first one strongly attenuated while the second one is clearly observed. This is interpreted as the first peak being due to copper characteristic radiation (8 keV) that is transmitted by the copper filter but partly blocked by the Aluminum one. Both detectors see the second peak although with different amplitudes. When the method described in the previous section was applied to the determination of the temperature, the results shown in the upper frame of Fig. 4 were obtained. This shows that the temperature steadily increases from 1.5 keV to a peak value of 4 keV and then decreases again. The present method does apply to the second peak but not to the first one; the time-resolved temperatures obtained under the first peak are not valid since one of the premises of the method is that it cannot be applied to characteristic radiation.

The corresponding results obtained for a shot in a two-wire bundle of copper fibers are shown in Fig. 5. The graph shows that both detectors see the single peak and that they have similar shapes. Frame (b) in this figure shows that the estimated temperature rises quickly at the beginning of the pulse and then stays fairly constant at a value of $\sim$3.5 keV almost until the end of the pulse. A streak photo taken in this shot is shown in Fig. 5(d). The sweep time employed was 100 ns. The streak shown is a radial one, *i.e.* the entrance slit of the camera was perpendicular to the wires. The photo shows that plasma initially develops separately in the 2 wires, and then some 30 ns later they merge and the plasma implodes. The speed of collapse measured was 0.3 km/s. This is a representative streak of most shots and, as in Fig. 5(d), all of them also showed that the plasma corona expanded immediately after the collapse.

The results obtained for a 4-copper-wire bundle are shown in Fig. 6. In this case the two signals are similar in shape, except for the small peak labeled *a* in the aluminum-filtered signal. The temperature remains fairly constant at a value of about 3,570 eV. The sharp increase in the temperature, up to 7 keV, in coincidence with the peak *a* is spurious. This small peak, which is not seen by the copper-filtered detector is attributed to an electron beam, and is certainly not due to continuum emission, as the main pulse is.

Similar shots made with bundles from 1 to 4 metallic fibers made of copper and Tungsten showed that the temperature fell mostly in the range of 1-7 keV. In the majority of the cases the temperature reached a peak value in coincidence with the peak of the X-ray pulse. It was also noted that the yield decreased as the number of wires in the bundle increased. This was attributed to the fact that the current per wire was reduced and that the individual plasmas did not merge satisfactorily to collapse. The different charging voltages employed and, consequently, the applied current i also had an effect on the yield Y; this scaled as $Y \alpha i^4$, as predicted in Ref. 8.

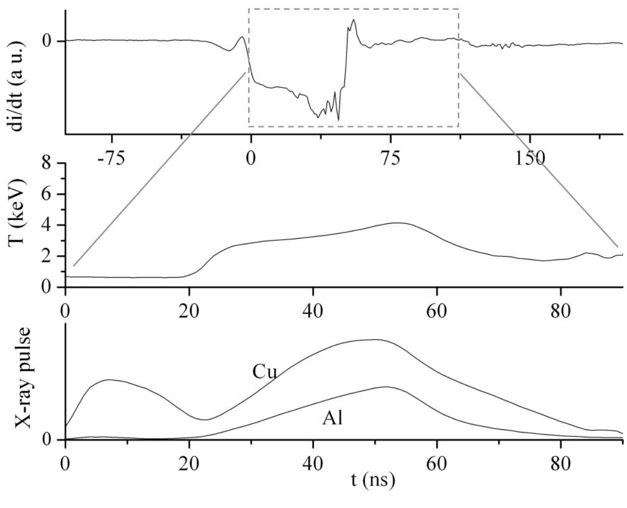

FIGURE 4. Single copper wire shot. Upper frame: di/dt signal, the rectangle shows the time scale of the other frames. Middle frame: time-resolved measurement of the temperature. Bottom frame: PIN detectors' traces identified by the filter fitted.

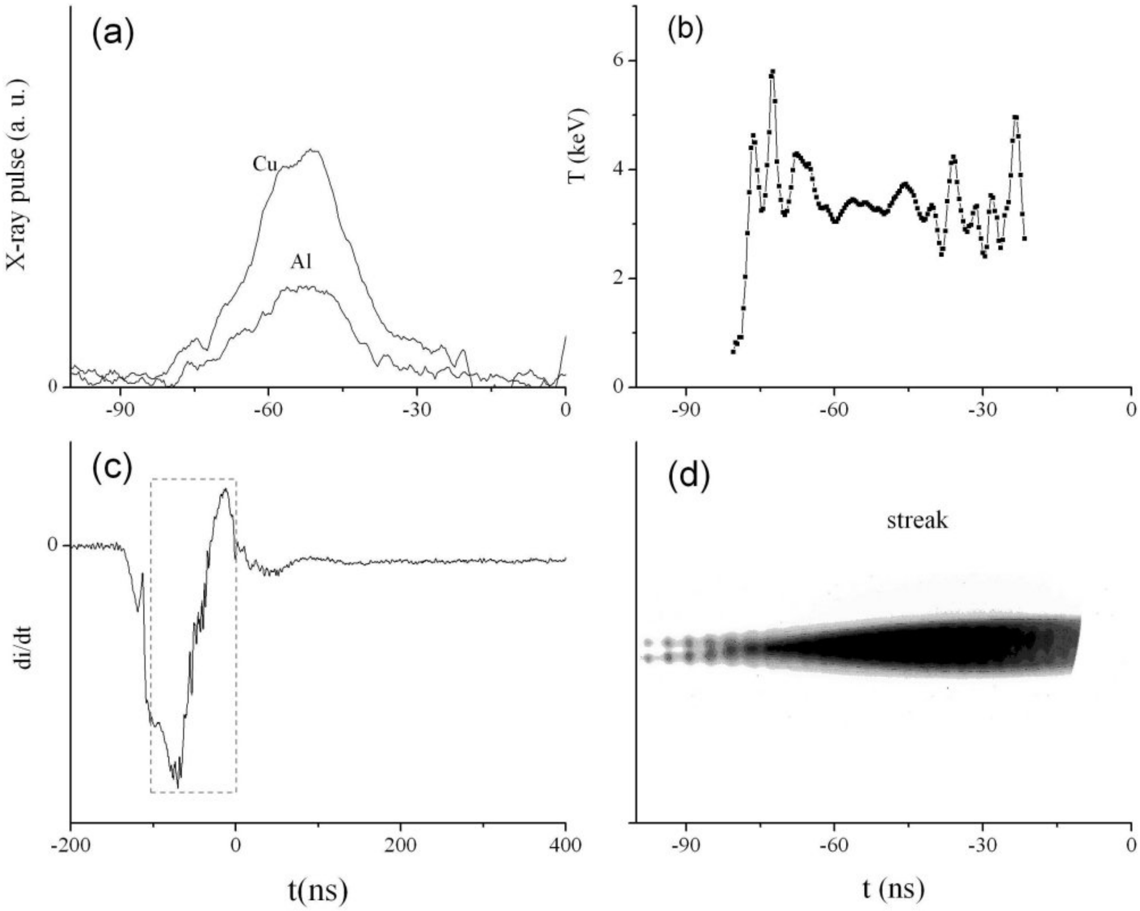

FIGURE 5. Experimental signals and electron temperature measurement for a 2 Cu-fiber bundle. The rectangle in the di/dt signal, frame (c), indicates the time span of the other 3 frames.

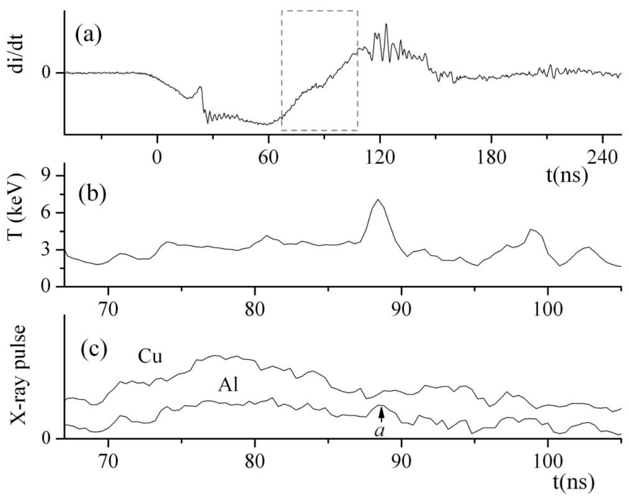

FIGURE 6. Experimental signals and temperature estimation for a 4 Cu-fiber bundle.

4. Conclusions

The bases for a simple method to determine the temperature in a Z-pinch plasma were presented. The method relies on the comparison of the calculated and experimental signal ratios for different filters. The results show that the temperatures are in the range 1 to 7 keV. The temperatures obtained, when characteristic radiation is present, have to be weeded manually by inspection of the signals, as in peak *a* in Fig. 6. The presence of line or e-beam radiation can be spotted when one of the detectors misses a radiation peak that is clearly visible in the other.

The results obtained agree reasonably with the results obtained with bigger Z-pinch machines, such as Z [3]. This gives hope that the work carried out in small machines, like the one used for the present research, can be scaled to more powerful machines. It is very likely that the underlying physics in both cases is the same. Future work will expand on this scalability issue.

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