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X-RADIATION FROM HIGH ENERGY DENSITY  
EXPLODED WIRE DISCHARGES

David Mosher, et al

Naval Research Laboratory  
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### ABSTRACT

Exploded wire discharges of tungsten and titanium driven by a high power pulse generator have been used to produce intense X-ray continuum and line radiation. A calibrated LiF crystal spectrograph recorded the radiation spectrum in the 3 to 25 keV range. More than 20 J of X-radiation are emitted in this photon energy band by tungsten plasmas in less than 50 nsec. The source of emission is less than 1 mm in diameter and about 3.5 cm long.

### PROBLEM STATUS

One Phase of Problem, Work is Continuing

### AUTHORIZATION

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## X-RADIATION FROM HIGH ENERGY DENSITY EXPLODED WIRE DISCHARGES

It has been shown that hot, dense plasmas created in high current discharges<sup>1,2</sup> or laser heated targets<sup>3</sup> represent strong sources of soft X-radiation. Here, we characterize the X-ray emission of high energy density Z-pinch plasmas<sup>4,5</sup> produced by discharging the  $10^{12}$  W Gamble II generator through fine metal wires. It is demonstrated that these plasmas represent the most intense source of line and continuum radiation with photon energies in the range of 3 to 25 keV.

Tungsten and titanium wires about 3.5 cm long and with diameters ranging from  $0.8 \times 10^{-3}$  to  $1.0 \times 10^{-2}$  cm were mounted in vacuum between the discharge electrodes of the generator. Typical discharge currents were 1.2 MA with peak resistive voltages of about 0.6 MV across the plasma. The duration of the discharges was about  $5 \times 10^{-8}$  sec. X-ray pinhole cameras measured the time-averaged spatial distribution of the radiation from the plasma. Photodiode-scintillator combinations were used to determine the time dependence of the radiation pulse. A curved LiF crystal spectrograph<sup>6</sup> recorded the spectral distribution of X-radiation in the 3 to 25 keV photon energy band.

Figure 1 shows an X-ray pinhole photograph of a section of tungsten plasma. The radiation pattern is characteristic of the  $m = 0$  "sausage" instability to which Z-pinch plasmas are susceptible. Intense spots of radiation of less than 0.1 mm diameter are often observed to occur at the necks of the "sausage". (The 0.1 mm diameter spot in the center of the figure is the size of a point source projection of the pinhole.) The observed radial size of the plasma suggests that the average ion density, based on the initial number of atoms in the wire, is about  $10^{19} \text{ cm}^{-3}$  with the density at the necks of the sausage an order of magnitude higher. Maximum X-ray intensity occurs near the time of the current maximum. The duration of that part of the radiation pulse with photon energies in excess of 3 keV varies from about  $5 \times 10^{-9}$  to  $50 \times 10^{-9}$  sec.

Figure 2 shows continuum spectra emitted by plasmas created from  $2.5 \times 10^{-3}$  cm diameter tungsten wires for two values of peak voltage across the plasma and electrodes. The lower energy portions of the spectra (below 7 and 9 keV for the upper and lower curves respectively) are characteristic of thermal Bremsstrahlung emission<sup>7</sup> for plasmas whose maximum electron temperatures are as given in the figure. Higher radiation temperatures are associated with increased electrical energy (as indicated by increased voltage) absorbed by the plasma. Spectra covering the photon energy range of 13 to 25 keV show that the continuum spectrum above 10 keV is similar to thin target Bremsstrahlung<sup>8</sup> produced

by 20 keV electrons. Such a class of energetic "runaway" electrons is anticipated since  $10^5$  V/cm electric fields are present in the plasma. Using known crystal diffraction efficiencies and film exposure calibrations<sup>9</sup>, it has been determined that more than 10J of continuum radiation is emitted by tungsten plasmas in the 3 to 13 keV band. The intensity of emission above 10 keV is consistent with about 10% of the current being due to energetic electrons.

A comparable amount of energy has been emitted in the form of tungsten L-lines. Ten of these lines with photon energies between 7.3 and 11.3 keV have been identified. Their wavelengths and relative amplitudes are indistinguishable from those of lines excited by electron bombardment of solid tungsten targets<sup>10</sup>. Assuming that the ionization levels in the plasma are determined by coronal equilibrium<sup>7</sup>, these data indicate that the plasma temperature must be under 200 eV in the region of space in which strong L-line emission occurs. These lines must then be excited by the high energy non-equilibrium class of electron responsible for continuum emission above 10 keV.

The cold target character of the tungsten L-lines is in contrast to the K-line series emitted by titanium plasmas, a densitometer trace of which is shown in Fig. 3. Lines associated with all of the highly ionized states of titanium are discernible. The structure of the 2p-1s transition lines in the wavelength region of 2.5-2.75 Å is similar to that found in vacuum spark spectra<sup>2</sup>. The shorter wavelength 3p-1s series lines have not previously been documented. The ratio of hydrogen and helium-like line intensities corresponds to a plasma temperature (based on the corona model) of about 2 keV. (Temperatures higher than those for tungsten plasmas are expected because of the lower radiation rates associated with lower atomic number materials.) Titanium K-line emission is typically an order of magnitude less intense than that of the L-lines of tungsten. Unlike tungsten line emission, titanium K-line intensities and wavelengths are consistent with excitation by thermal electrons<sup>7</sup>.

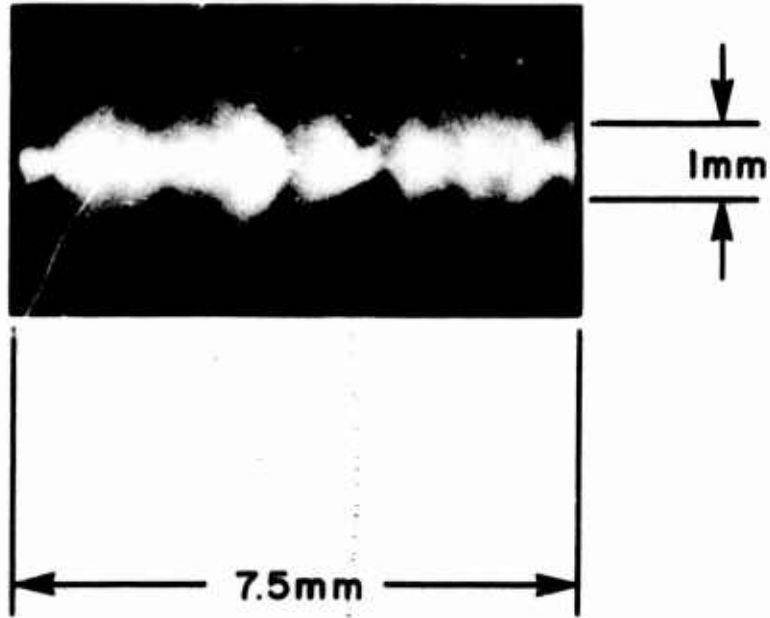
A one dimensional MHD code has been developed to interpret the radiation from exploded wire plasmas<sup>11</sup>. Generation and reabsorption rates for free-free, free-bound, and line radiation are calculated from local plasma parameters with the distribution of the ionization states determined from the corona model. The character of the low photon energy tungsten continuum is well represented by calculated time-averaged spectra. The code predicts that this radiation emanates from the tenuous ( $n \approx 10^{18} \text{cm}^{-3}$ ) exterior region of the plasma which is resistively heated to keV temperatures. The dense interior ( $n \approx 10^{19} - 10^{20} \text{cm}^{-3}$ ) is at much lower temperatures because of strong radiative cooling. Electron thermal conduction across the megagauss azimuthal magnetic field is insufficient to smooth the sharp radial temperature gradients. Although the code predicts that the interior radiates more strongly than the hot exterior, this radiation would be too soft to register on the spectrograph. Radiation due to the presence of non-equilibrium electrons cannot be treated in the existing code. Mean

temperatures predicted by the code are consistent with those inferred from observed line emission (200 eV for tungsten and 2 keV for titanium).

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**Fig. 1 - X-ray ( $h\nu > 2$  keV) pinhole photograph of tungsten plasma. Spatial resolution is about 0.1 mm.**

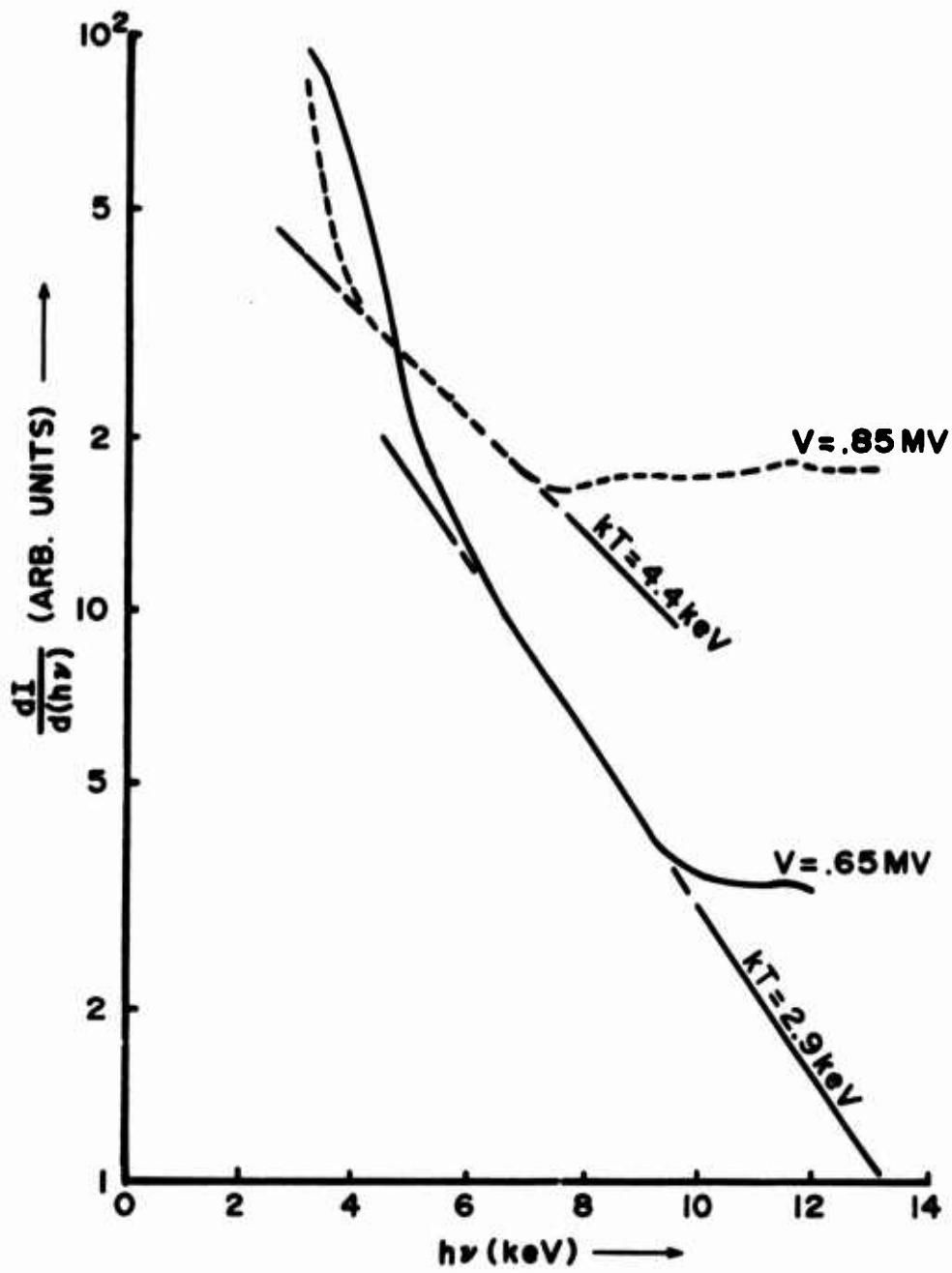


Fig. 2 - Continuum spectra of  $2.5 \times 10^{-3}$  diameter tungsten exploded wire plasmas.

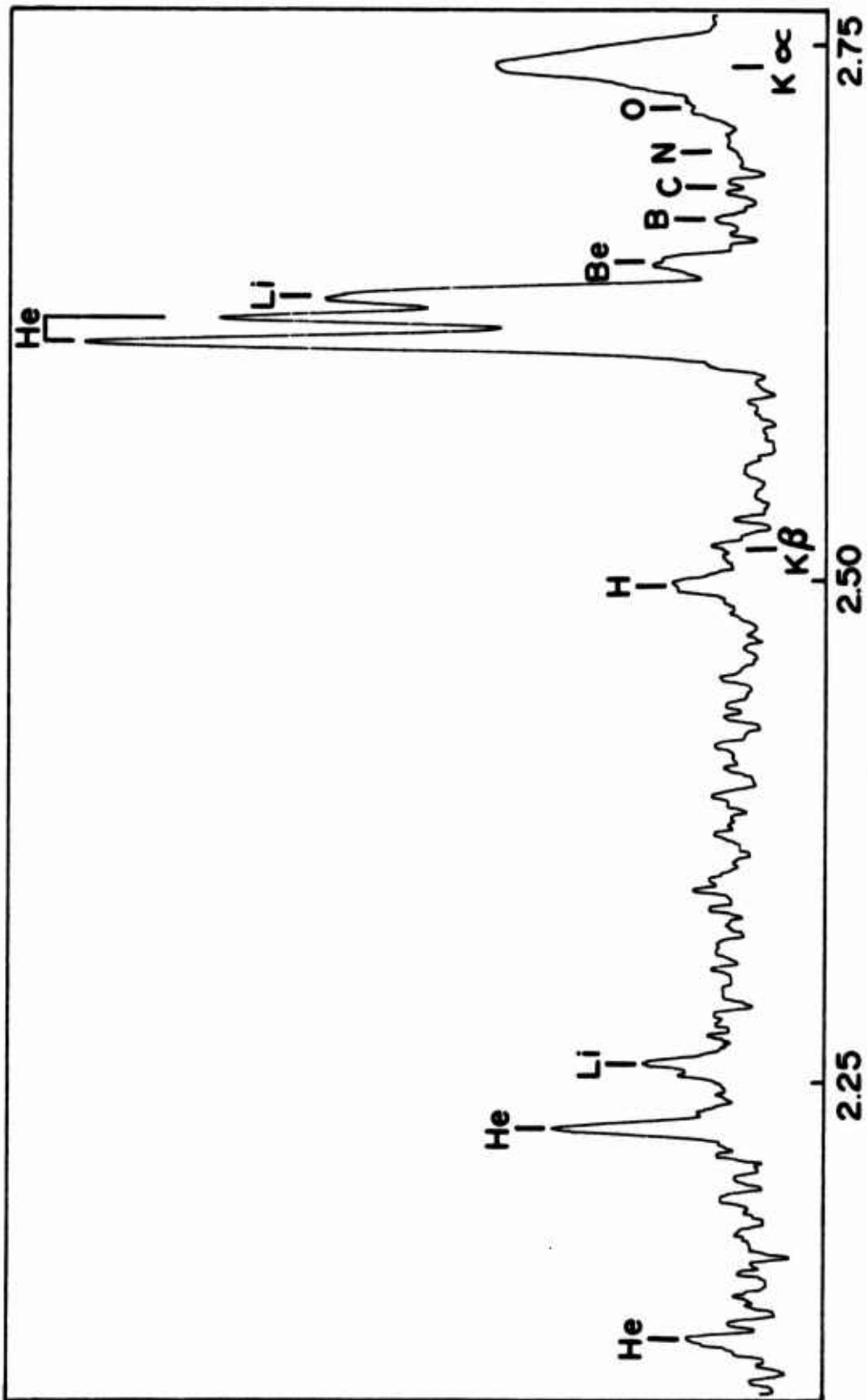


Fig. 3 - K-line spectrum of a titanium exploded wire plasma.