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AN X-RAY DIAGNOSTIC FOR LIGHT-ION CURRENT MEASUREMENTS.(U)
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A technique to determine the number and current density of MeV protons in an intense beam was tested on the GAMBEL II generator. Diode current and voltage and an absolute measurement of K-line radiation emitted from a ~~6 μm~~ thick aluminum target were used to determine the number and current density of protons incident on the target. Time-dependent x-ray measurements can be used to infer variations in the ion-beam current density.

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AN X-RAY DIAGNOSTIC FOR LIGHT-ION CURRENT MEASUREMENTS

INTRODUCTION

Interest in the use of focused beams of light ions to ignite a thermonuclear target has recently led to the generation of intense proton and deuteron beams [1]. Measurements of the intensity and spatial distribution of ions are needed to characterize the beams. Nuclear activation in targets and induced currents in coils placed around the beam are techniques that have already been used for these measurements [2]. Unfortunately, they are limited in their ability to produce both time histories and separation of ion species and electrons.

An alternative technique for measuring proton currents uses characteristic K-line emission created by the interaction of beam ions with target atoms. Peak current density and number of ions in a proton beam incident on a thin aluminum target were calculated using time-integrated x-ray images of the target, known inner-shell ionization cross sections and diode electrical characteristics.

EXPERIMENT

The GAMBLE II generator at NRL was operated in a hollow-cathode, curved-anode configuration shown in Fig. 1. A geometrically-focused beam of protons struck a thin aluminum target oriented at a 45° angle to the beam propagation axis [3]. Voltage and total diode current were monitored on each shot. An x-ray pinhole camera mounted in an evacuated tube viewed the surface of the target closest to the anode (front surface) from a direction perpendicular to the beam propagation axis. This arrangement is shown schematically in Fig. 1. Images of the x-ray emission were recorded on Kodak No-Screen film. A 25 μm thick beryllium window covering the pinhole and aluminized mylar in front of

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the film prevented visible and ultraviolet radiation from exposing the film. Baffles in the tube containing the pinhole camera reduced plasma-expansion damage to the beryllium and mylar windows and reduced scattering of x-rays off [illegible] walls. Figure 1 shows an x-ray pinhole image of a special target made of 6 μm thick aluminum covered by two strips of 25 μm thick polyethylene (CH_2). The image shows x-ray emission from the uncovered aluminum is more intense than the background, indicating that most of the emission originated in the target. Where the polyethylene strips covered the aluminum, the emission was reduced. A diagonal band across the image is caused by one of several strips of aluminized mylar filters which covered the film and were used to determine the energy of the x-rays emitted by the target.

ANALYSIS

Energy of the radiation, size and uniformity of the emission region, and proton beam current density were determined from x-ray images and diode electrical characteristics. Density on film was converted to exposure using the results of Dozier et al. [4] and Brown et al. [5]. Figure 2 shows the log of the ratio of calculated to measured exposure as a function of mylar thickness. Exposure was calculated by normalizing to the measured exposure at 12.8 μm thickness of mylar and extrapolating to find the exposure through 6.8 and 25.6 μm thicknesses of mylar. This was done for photon energies of 1.0, 1.5, and 2.0 keV. Figure 2 shows that the measured data most agree with calculations at an x-ray energy of 1.5 $\pm$ 0.1 keV, implying the emission is $K\alpha$-line radiation from the aluminum target.

X-ray images show the emission region to be equal to the area of the target and to be approximately uniform. Thus, it was inferred that the beam was uniform with a cross sectional area of at least 10 cm^2.

The power emitted in $K\alpha$-line radiation per unit of beam current from the front surface of the target (S) is given by:

$$S = \frac{Nh\nu}{e} \int_0^D \sigma(E)\, Y_k \exp(-\mu\rho x)\, dx \qquad (1)$$

where

N	=	target atomic number density
ρ	=	target mass density
$h\nu$	=	energy per photon of K radiation
$\sigma(E)$	=	proton collisional ionization cross section
E	=	proton energy
Y_k	=	$K\alpha$-fluorescent yield
e	=	electronic charge
μ	=	$K\alpha$ photoelectric absorption cross section
D	=	$\sqrt{2}$ x target thickness

The exponential term in equation 1 represents photon attenuation in the target. For a 45° incidence angle used in this experiment, the distances the proton penetrates and the K-line photon traverses before exiting the target are the same and are expressed by x. The proton energy is calculated as a function of x taking into account collisional energy loss [6].

Several considerations enter into the calculation of the function S. Total K-shell proton collisional ionization cross sections from Babas et al. [7] and fluorescent yields from Bambynek et al. [8] were used since x-ray lines from target ions with multiple K-shell vacancies were not resolved in this experiment. K-line emission from electrons was negligible for electrons co-moving with 1 MeV protons because the average electron energy (down by the electron to proton mass ratio) is less than the binding energy of electrons in the aluminum K-shell. Most secondary electrons produced in the target also have kinetic energies less than K-shell binding energy and consequently contribute little to the K-line emission. At ion energies of about 4 MeV, however, co-moving protons and electrons would have collisional cross sections which are within a factor of 4 of each other. In this situation, electron induced K-line emission would have to be included in the calculation of S. The function S vs proton energy is shown in Fig. 3 for three thicknesses of aluminum target.

Peak current of the beam was calculated from exposure on the film corrected for filter attenuation, solid angle and size of the emission region. Energy (W) in $K\alpha$-line radiation, transmitted by the pinhole, is given by

$$W = \frac{\Omega}{4\pi} \int_0^T IS \, dt \tag{2}$$

where

Ω = solid angle subtended by the pinhole seen from a point on the target

I = ion current on target

The integration extends over the duration T of the voltage pulse. Measured voltage and calculated ion current shapes from shot 1997 are shown in Fig. 4. Ion current was calculated from diode electrical characteristics [9].

The $K\alpha$ energy density recorded on film from shot 1997 was 1.7×10^{-8} J/cm^2. A peak current on target of 1.5×10^5 amps was calculated using equations 1 and 2. The corresponding current density is 1.5×10^4 amps/cm^2. The number of protons which hit the target was 7.1×10^{16}. Total number of protons in the beam is uncertain because the cross sectional area of the beam was larger than that of the target area.

CONCLUSIONS

Characteristic x-ray emission from target atoms appears to be a useful diagnostic for measuring intense ion beam currents. Johnson et al. [10] at Sandia Laboratories have recently measured K-line radiation from aluminum targets to determine the peak current density of a proton beam produced in a magnetically insulated diode. The technique can be extended by measuring the time variation of K-line intensity to determine the ion current history. A suitably sensitive and shielded detector is needed for time-resolved measurements. Attempts to record the time-resolved emission were made with a PIN solid state detector in place of the film camera. The results showed that high-energy x-ray background from electron bremsstahlung produced signals in the PIN that were difficult to separate from the K-line emission. PIN's may be suitable detectors if this background can be sufficiently reduced or attenuated by shielding. Alternatively, x-ray diodes (XRD's) which are not as sensitive to high energy background as PIN's can be used if emission rates are large enough. An aluminum-cathode XRD subtending a 5×10^{-3} ster solid angle to a point source for example, could produce a one volt signal into a 50 ohm load given an 800 kV, 5×10^{4} amp proton beam incident on a 6 μm thick aluminum target. Ross filters or crystal spectrographs which can restrict the bandpass of the radiation may be useful if the K-alpha intensity is high enough and filtering of extraneous radiation is required.

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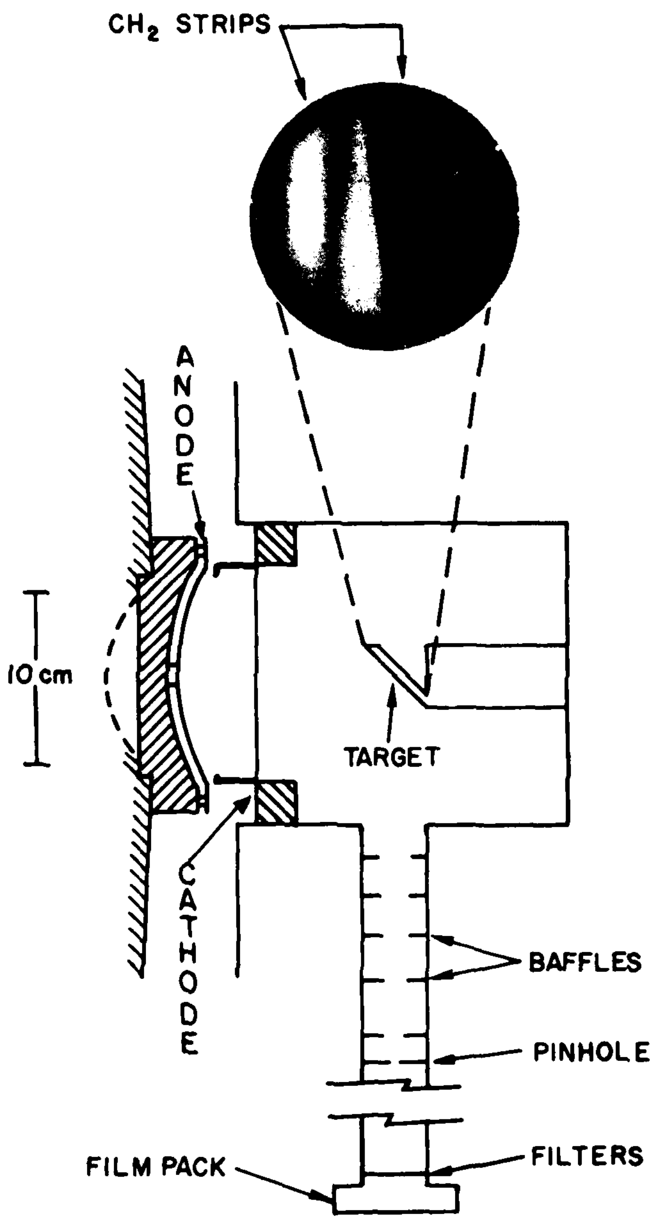

Fig. 1 — Schematic of the GAMBLE II ion beam diode, and x-ray diagnostic arrangement and an x-ray image from shot 1997. A 1.8 μm thick KIMFOL transmission foil (shown as a line between cathode surfaces) provides partial current neutralization of the beam. The x-ray pinhole photograph shows $K\alpha$-line emission from a 6 μm thick aluminum target. No emission is visible where two CH_2 strips cover the target. The dark diagonal band across the image is due to a layer of aluminized mylar placed over the film. Uniform 6 μm thick aluminum targets were used on other shots.

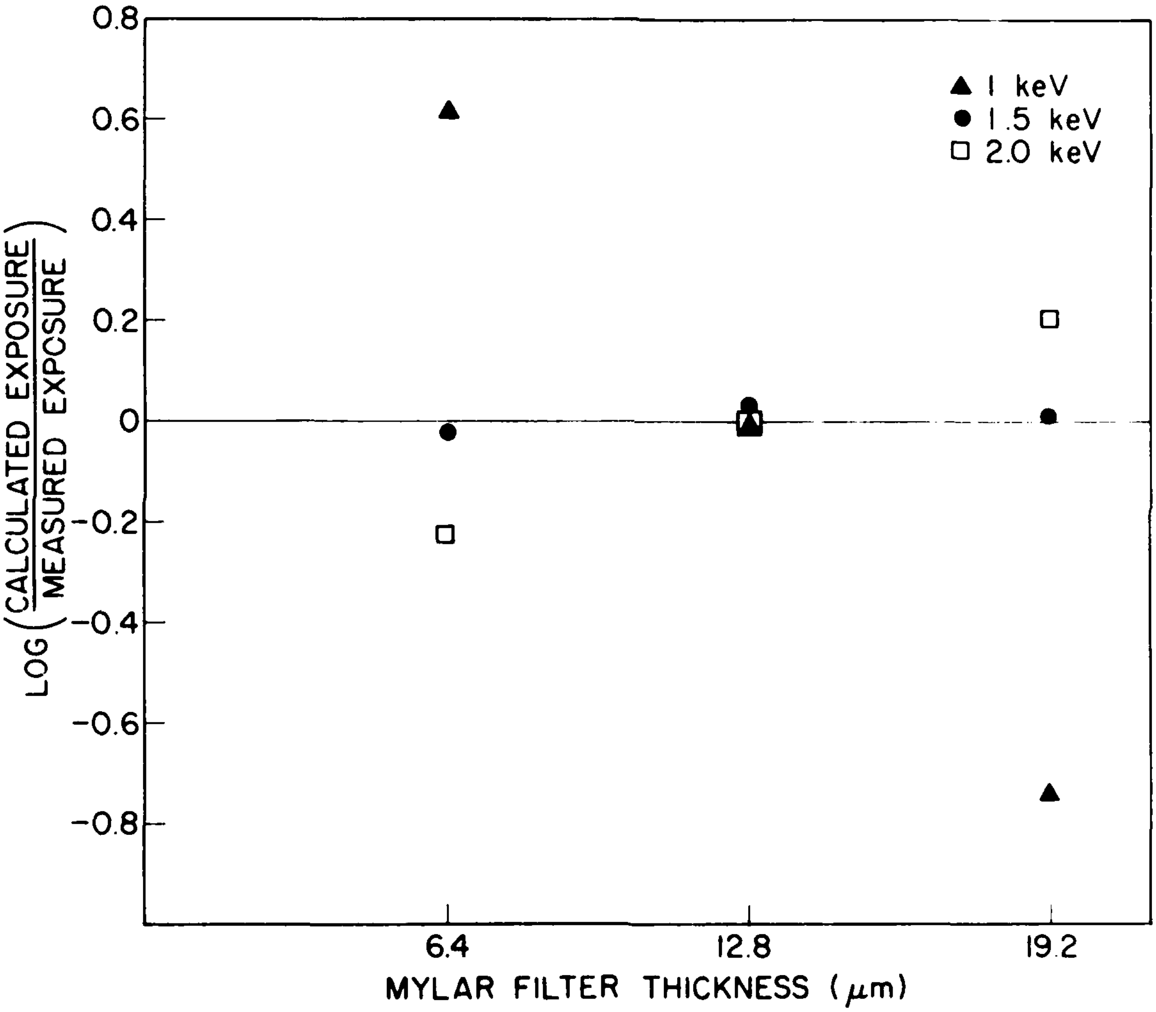

Fig. 2 — The ratio of calculated to measured exposure on Kodak No-Screen x-ray film vs aluminized mylar filter thickness. A photon energy of 1.5 keV best fits data obtained using three thicknesses of mylar covering the film

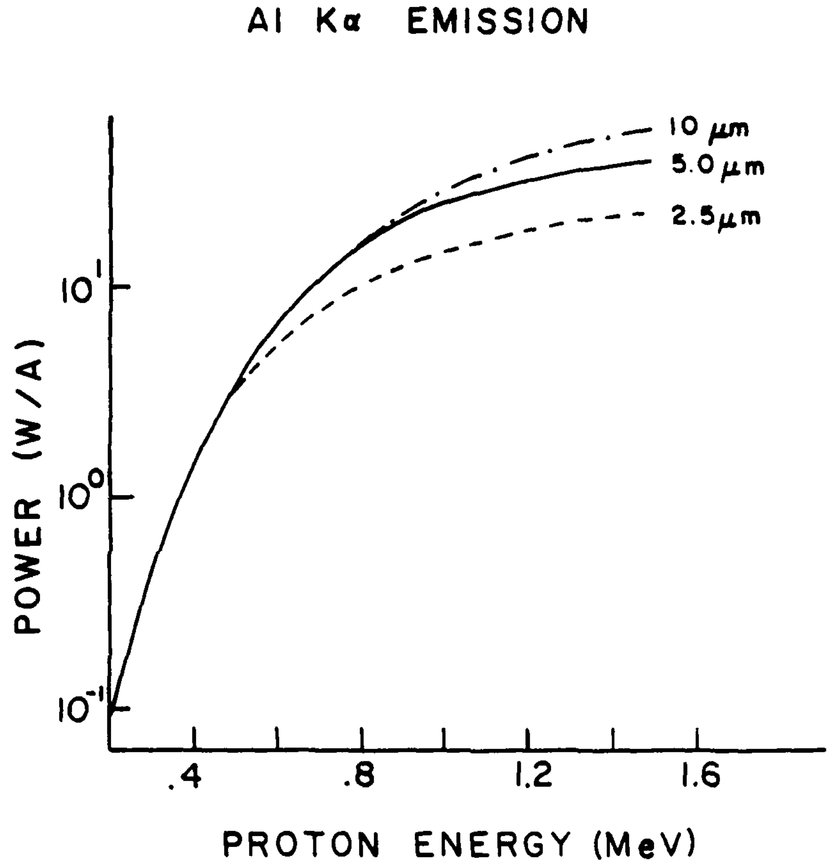

Fig. 3 — The power radiated in Kα emission from the front surface of an aluminum target per unit proton beam current vs proton energy. Curves for three target thicknesses are shown. Kα emission from the front and rear surfaces is comparable for the thicknesses shown.

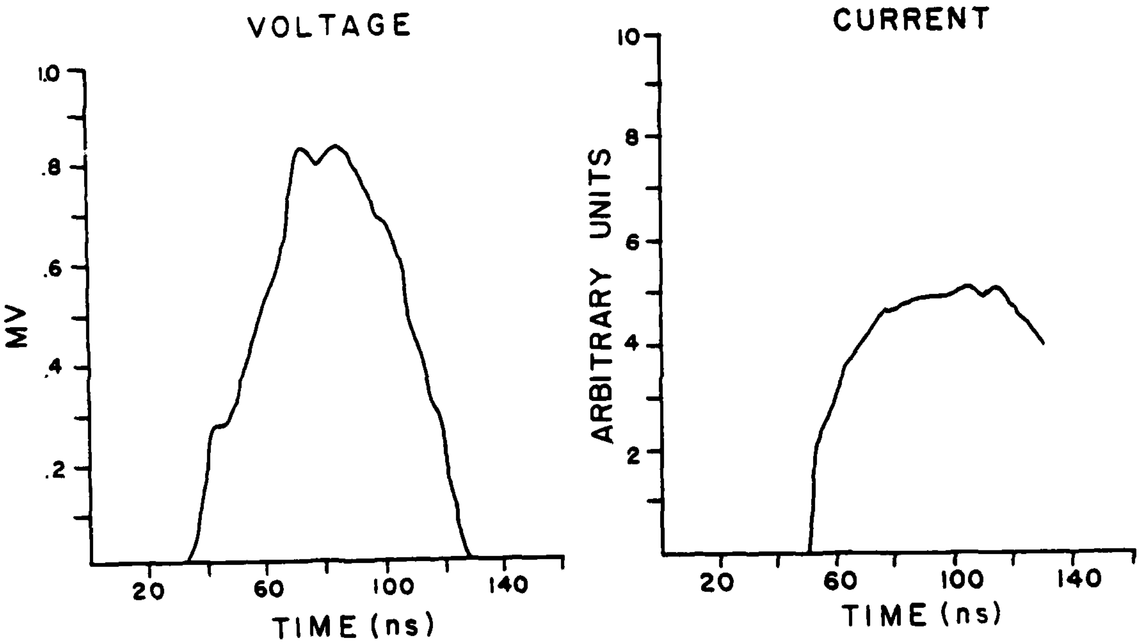

Fig. 4 — Time histories of the GAMBLE II measured voltage and calculated ion current shape on shot 1977.

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