27
2-14-79
240 NTS

SAND78-2026
CATEGORY UC-21
UNLIMITED RELEASE

MASTER

RELATIVISTIC ELECTRON BEAM ENERGY DEPOSITION
IN THIN GOLD AND ALUMINUM TARGETS

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- NGT 101

This report was prepared by the U.S. Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Laboratory, Atlantic Ecology Division, Narragansett, Rhode Island. The authors are: Robert A. Bergquist, Robert J. Burchett, and Robert J. Farnham. The report was prepared under the supervision of Robert J. Burchett, Chief, Atlantic Ecology Division. The report was prepared under the supervision of Robert J. Burchett, Chief, Atlantic Ecology Division. The report was prepared under the supervision of Robert J. Burchett, Chief, Atlantic Ecology Division.

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AND ALUMINUM TARGETS

by

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ABSTRACT

Relativistic electron beam (REB) energy deposition in thin gold and aluminum targets has been investigated experimentally using radiation temperature measurements in the soft x-ray, vacuum ultraviolet (XUV) and optical spectral regions on two different particle accelerators. Energy deposition measurements were compared with numerical calculations utilizing particle-in-cell (PIC) diode codes, condensed history Monte-Carlo codes, and coupled radiation-hydrodynamic codes. The specific power deposited (i.e., power deposited/unit mass) was observed to be greater than that due to an average electron making a single pass through a thin target (6.4 μm thick gold foil on the Hydra accelerator and 38 and 6 μm thick aluminum foils on the Proto I accelerator). Self-magnetic field effects were primarily responsible for deposition enhancement in 6.4 μm gold foils on the Hydra accelerator ($\nu/\gamma \approx 2.5$). Reduction of electron scattering with aluminum foils on Proto I where $\nu/\gamma \approx 1$ led to deposition enhancement due to both self electric and magnetic fields.

INTRODUCTION

Interest in electron deposition by relativistic electron beams (REB) centers on possible enhancement of collisional deposition resulting from particle dynamics in strong self beam and/or diode electric and magnetic fields. The increase in deposited power per unit mass is due to an increased electron path length in a given amount of material and possibly modification of the stopping power by collective plasma phenomena. Previous papers have studied magnetic stopping or magnetic beam stagnation,¹⁻⁷ electrostatic reflexing,⁸⁻¹⁰ and plasma instabilities,^{11,12} in target and anode material.

Enhancement over classical collisional deposition by a factor of 2.3 has been reported for 40 μm thick aluminum foil by measuring the target expansion velocity on a 450 kV, 165 kA, 80 ns pulse width accelerator.² Similarly, deposition enhancement by a factor of 10 has been reported for 10 μm thick gold foil in front of 30 μm thick polyethylene foil on a 500 kV, 120 kA, 30 ns pulse width accelerator, and for 5 μm thick gold foil in front of 15 μm thick polyethylene foil on a 1 MV, 330 kA, 80 ns pulse width accelerator by measuring the target expansion velocity.⁵ Enhancement of specific power deposition (power deposited per unit mass) by a factor of 5 has been observed for 10 μm thick nickel spherical shells mounted on a stalk by measuring the line integral of the electron density as a function of radius and time from the center of the target utilizing holographic interferometry.³ Deposition enhancement factors of 100 have been claimed for aluminum, lead, and polyethylene foils by measuring the temperature, ion velocity and neutron yield of the expanding plasma on a 500 kV, 80 kA, 80 ns pulse width accelerator.¹² The role of prepulse (i.e., 10^{-7} sec or greater duration, low current, low voltage pulse;)

prior to the large main pulse (tens of nanosecond duration current and voltage) was known to play a dominant role in the results of the last case. Recently, 10 to 100 mg/cm² thick carbon, aluminum, titanium, tantalum, and gold foils were found to have no enhancement by measuring the radiation temperature with soft x-ray, vacuum ultraviolet (XUV) radiation detectors, at current densities of 0.4-1.0 MA/cm².¹³ In this last experiment, detailed theoretical modeling of the experiment was not available, and in particular, hydrodynamic foil expansion was neglected.

In this paper we present detailed theoretical and experimental results of electron number density, current density, temperature, and specific power for experiments with a variety of unbacked thin aluminum and gold foils. We also show that radiometric measurements in conjunction with detailed simulations, yield reliable energy deposition data.

The theoretical computational models include Monte Carlo codes, single particle diode codes, and a coupled radiation-hydrodynamic code. The Monte Carlo codes include effects of (a) collisions only, (b) collisions with non self-consistent magnetic fields in different versions. The Monte Carlo code was useful for studying magnetically enhanced deposition, as well as the effects of scattering, in targets of arbitrary thickness. The diode code can predict deposition in the limit of negligible beam target interaction or with a simplified scattering and energy loss model. This model was useful for computing deposition in very thin foils in realistic diode geometries. Energy deposition in the foils was determined by comparing experimentally measured temperatures with radiation temperatures predicted by the coupled radiation-hydrodynamic code

CHART D.¹⁴

In addition to the usual voltage and current monitors, diagnostics include the following: (1) quantitative x-ray pinhole photography; (2) apertured, absolutely calibrated, PIN diodes to measure the absolute x-ray flux; (3) calibrated optical photodiodes and vacuum photo-electric diodes (i.e., x-ray diodes or XRDs) to measure the thermal radiant flux and equivalent blackbody temperature; (4) time resolved optical spectra to verify the continuum emission during the power pulse and also to view the late time, low density plasma; and (5) time integrated XUV measurements to discern any line emission in this spectral region. Under appropriate assumptions, the current density as a function of radius and time, as well as the total current in the pinch was deduced from the hard x-ray data.

THEORETICAL

The use of simulations codes to model the steady state behavior of REB diodes has been well documented.^{15,16,17,18} These codes employ a particle-in-cell (PIC) technique to calculate the electron and ion behavior in their self-consistent electric and magnetic fields. Gross diode behavior (such as total electron and ion current, pinch profiles, and typical particle trajectories) can be obtained with such a diode if the beam target interaction is negligible. Diode codes have been used to study diodes in which the beam target interaction was not negligible in the case of an assumed anode plasma of finite thickness.^{3,19} In order to study enhanced deposition in thin foils, a simple macroscopic model of small angle scatter and stopping power was added to the usual diode code.²⁰

The scattering model is valid for small angles of deflection. Rather than sampling from a distribution of scattering angles, as done in a Monte

Carlo model, an average scattering is computed using the formula

$$\langle \theta^2 \rangle = \ell / \gamma^2 \beta^4 L$$

where $\gamma = (1 - \beta^2)^{-1/2}$, β is v/c , v is the velocity of the electron, ℓ is the distance an electron travels in the material.²¹ Here L is a characteristic length of the material,

$$L^{-1} = 4\pi n_i Z^2 r_o^2 \ln \Lambda$$

Λ is the ratio of maximum to minimum scattering angle ($\ln \Lambda = 10$ is used in these simulations), r_o is the classical electron radius, n_i is the foil ion density, and Z is the atomic number of the foil material. The small angle approximation assumes that the velocity and path length of the electron remains constant through the foil. The assumptions are valid for sufficiently thin foils. In addition to being scattered, an electron deposits energy and slows down as it passes through the foil. The amount of energy deposited by an electron in a pass through the foil is determined from tabular stopping power values.²²

We have used several Monte-Carlo models to study electron deposition which can be divided into the following categories: (1) collisional deposition only; (2) collisional deposition in the presence of specified electric and magnetic fields and (3) collisional deposition with self-consistent magnetic fields. In all these cases either a diode code calculation or information from an experiment must be used to choose the source beam parameter.

The simplest Monte Carlo code (collisional deposition only) is represented by a 1-D model TIGER²³ and a 2-D model CYLTRAN.²⁴ These models are well-documented and are applicable for cases where fields are

not important and transport of the beam electrons are collision dominated, as would be the case for a thick high density target. A more complex code included the effects of strong electric and magnetic fields on deposition, although the choice of the fields is only representative of the true fields and are not self-consistent. This model was previously discussed in Ref. 20 and more recently documented as a more complete model called CYLEM.²⁵ The third code type represents an attempt at self-consistency. This model²⁶ uses an iterative procedure to converge on a steady-state solution that includes self-consistent beam-target interaction. One can study the effect of scattering on the self-field of the beam with this model, although the choice of the injected beam is somewhat arbitrary.

The Monte Carlo models then predicted specific power deposition for a given set of source beam parameters. This deposition was then included as an energy source term in a hydrodynamic model CHART-D to calculate the experimental observables which include material temperature and blow-off. Specific power deposited P_m (W/gm) is given by the following relation;

$$P_m = \int_{E_{\max}}^0 e F(E) \beta c S(E) dE \quad ,$$

where $e = 1.6 \times 10^{-19}$ coul, $F(E)$ = energy distribution of electrons ($\text{cm}^{-3} \text{ eV}^{-1}$), c = electron speed, $S(E)$ = electron stopping power ($\text{eV-cm}^2/\text{gm}$), and E = electron energy which ranges between $0 \leq E \leq E_{\max}$. The beam density is given as

$$n_b = \int_0^{E_{\max}} F(E) dE \quad .$$

Thus, for a monoenergetic beam, which is often approximately true for thin target deposition, we have

$$P_m = en_b \beta c S = XJS$$

where $X = \text{enhancement factor} = \beta c / \langle v_D \rangle$ where $\langle v_D \rangle$ is the normal electron drift velocity, and J the normal current density (amps/cm²).

EXPERIMENTAL

The experimental data were obtained on the Sandia Laboratories' Hydra and Proto-I accelerators. The Hydra accelerator was operated with a peak inductively corrected voltage and current of 950 kV and 600 kA. Figure 1a shows the total current and inductively corrected voltage in the diode for the Hydra experiments. The FWHM of the power pulse was 60 nsec. A 15 kV peak-to-peak prepulse with a 40 MHz oscillation was applied to the diode for 700 ns prior to the main pulse. The diode and experimental set-up used with the Hydra accelerator are shown in Fig. 2. The cathode surface was grooved brass and sprayed with Aerodag G.²⁷

The Proto-I accelerator was operated with peak voltage and current of 1.5 MV and 250 kA. The FWHM of the power pulse was 20 ns. Figure 1b shows the total diode current and inductively corrected voltage in the Proto-I experiments. The prepulse voltage and current on the Proto-I accelerator were 10 kV and 100 A for 700 ns, plus 20 ns of high frequency, less than 1 kA current and 100 kV prepulse, prior to the main pulse. The cathode surface was smooth brass and sprayed with Aerodag. Figure 3 shows the diode and experimental set-up used with the Proto I accelerator. The gold foil anode thicknesses on both accelerators were 50.8, 25.4, 12.7 and 6.4 μm . The aluminum foil anode thicknesses were 205.7, 88.9, 38.1, and 6.4 μm .

FIGURE 1

Total diode current and inductively corrected diode voltage for (a) Hydra experiments, and (b) Proto-I experiments.

FIGURE 2
Hydra diode and experimental chamber.

FIGURE 3
Proto-I diode and experimental chamber.

The current density as a function of radius from the center of the pinch was deduced from the hard x-ray intensity of the images on a pinhole camera system located normal to the anode. On the Proto-I accelerator, pinhole photographs of the hard x-ray fluences were taken from both sides of the anode but not simultaneously on the same shot. The pinhole consisted of depleted uranium, slug, 5 cm long, with a $250\text{ }\mu\text{m}$ aperture and a cone angle of 6° . The x-ray fluences were recorded on absolutely calibrated photographic films, Kodak types M and AA. Relative calibrations of NS, NS intensified, and AA lead pack, were normalized to M and AA. Polaroid type 57 intensified was also used. The intensifying screens were Rarex BG high speed. The calibrations were performed on the Pelletron DC electron beam machine. Monoenergetic electron energies from 0.4 to 1.1 MeV can be delivered on the Pelletron with currents up to $8\text{ }\mu\text{A}$. Renormalization was obtained by comparison of the x-ray dose to the film with predictions of x-ray generation using coupled electron-photon Monte Carlo codes. The pinhole images were filtered with Lucite to provide 80 percent of the response (ten percent to ninety percent) in photons with energies of 30-160 keV. The assumptions made in deducing experimental current density were that if an electron made more than a single pass through the foil, it re-entered the foil at the same radial position it left (one-dimensional) and that the initial electron angular distribution was cosinusoidal and constant as a function of radius. This may overestimate the number density on axis by as much as 20 percent for the low Z aluminum foils.²⁸

To obtain the apparent incident current density $J(\text{amps}/\text{cm}^2)$ for a cold, cosinusoidal angular distribution with a local macroscopic electric field in the diode only, we took the current density from the pinhole

photographs except that this time we normalized to the total current as measured by the dB/dt monitors, corrected for ion current. The dB/dt monitors measure the total diode current, not just the target current. The apparent target current will be less than or equal to the target current. The ion current was calculated from the models of Creedon,²⁹ Goldstein,³⁰ and Poukey.³¹ The total current in the diode was given by the parapotential flow model as

$$I_p = I_e + I_i = 8500 (R/d) \gamma \lambda n(\nu + \sqrt{\gamma^2 - 1})$$

where R/d was taken to be the initial geometrical radius and anode-cathode separation, λ is given by $1 + eV/Mc^2$, V is the voltage in the diode and m is the rest mass of an electron. The ratio of ion (proton) current to electron current was given by

$$\frac{I_i}{I_e} = 0.033 \frac{\gamma}{\sqrt{\gamma+1}} \frac{R}{d}.$$

ν/γ for an electron beam, we define as the total current within the FWHM of the deposition profile divided by the Alfven current.³⁷ That is,

$$\frac{\nu}{\gamma} = \frac{I(\text{kA})}{17 \beta_L \gamma}$$

where I is the total current within the FWHM of the deposition profile and β_L is the component of beam velocity along the axis of symmetry. γ is $(1 - \beta^2)^{-1/2}$ where β is the beam velocity.

The total current in the pinch region was deduced from absolutely calibrated PIN detectors, apertured to view only the central 2 cm diameter area. The PINs were calibrated absolutely on the Pelletron, behind 150 μm

uranium, 250 μm erbium, 50 μm copper and 300 μm aluminum filters to allow an essentially flat response for incident radiation. The one-dimensional electron-photon transport code TIGER was used to calculate the resulting photon spectrum. Figure 4 shows the spectral and total energy response of the PINs. The PIN detector itself was surrounded with 0.5 cm thick silicon and aluminum to provide electronic equilibrium to the Compton scattered electrons, that is, a "Bragg-Gray" cavity. This is analogous to the principle of the "air-walled" ionization chamber.³² This entire package was then mounted in a lead chamber to shield against scattered x-rays. On the Hydra accelerator, a single-apertured PIN was mounted behind the photoelectric diodes or x-ray diodes (XRDs) utilizing their brass baffling system. On the Proto I accelerator, the apertured PIN was mounted in place of the pinhole assembly and utilized the lead baffled housing. On the gold foil anode shots, on Proto I, an array of apertured PINs were mounted on the image plane of the pinhole camera without their high band pass filters for relative current density measurements. The diameter of the individual PINs was 1 mm and the center-to-center distance between PINs was 4 mm. On the aluminum shots, however, the x-ray flux was insufficient to allow the array of PINs to be mounted on the image plane of the pinhole camera system.

Radiation temperature measurements were made with a triplet array of aluminum cathode XRDs which were operated windowless, with a 0.75 μm aluminum filter, and with a 0.33 μm parylene (C_8H_8) filter.³³ The XRDs viewed the source through a series of baffles to prevent scattering off of the walls of the diagnostic tubes. The XRDs gave temporal information in the energy ranges from 5 to 25 eV (unfiltered) 25 to 75 eV (0.75 μm aluminum), and 75 to 284 eV (0.33 μm parylene). Figure 5 shows the cathode

FIGURE 4

Spectral and total efficiency responses of PIN detector behind 150 micron thick Uranium, 250 micron thick erbium, 50 micron thick copper, and 300 micron aluminum filters.

FIGURE 5

Cathode response of aluminum XRD and response as a function of blackbody temperature, where

$$\bar{R} = \frac{\int_0^\infty R(E) S_{BB}(E,T) dE}{\int_0^\infty S_{BB}(E,T) dE} = \left(\frac{1}{\sigma AT^4} \right) \int_0^\infty R(E) S(E,T) dE$$

response of the XRDs as a function of blackbody temperature. Between 3 and 7 eV blackbody temperature, the response of the unfiltered XRD varies only 20 percent. The detectors are insensitive to radiation temperatures below 2 eV. The XRDs were located approximately 3 meters away from the source on Proto I to separate the radiation from the ion emission coming from the anode. Magnets were placed in the diagnostic tubes on the Hydra experiments to eliminate electron emission coming from the cathode through the anode.

Because of the small detector solid angle necessary for separation of radiation and ion emission, the Proto-I experiments required temperature measurements based on the unfiltered XRD only. For the unfiltered XRD, the response of the detector is proportional to T^4 as discussed above (see Fig. 5). For a radiating disk with a detector at normal incidence, the blackbody radiated power is given by

$$P_{BB} \cong \sigma A (T(t))^4 \left(\frac{d\Omega}{2\pi} \right) = \frac{V(t)}{50} \frac{1}{R(T)}$$

where $\left(\frac{d\Omega}{2\pi} \right)$ is the fractional solid angle radiated into 2π steradians, σ is the Stefan-Boltzmann constant, $R(T)$ is the detector response sensitivity which is approximately a constant (see Fig. 5) in units of amps/watt, $V(t)$ is the voltage as measured by the detector, and A is the source area. In estimating the minimum radiation temperature, the diameter of the radiating region was chosen to be 2 mm greater than the FWHM of the hard x-ray profile.¹³ Because of the T^4 dependence of the radiated power, the resultant temperature is insensitive to the exact area of emission.

Optical temperature measurements were made with an absolutely calibrated silicon photodiode. The optical photodiode was filtered to a 70 nm bandwidth at 507 nm, and had a calculated response proportional to $T^{1.9}$ for a blackbody radiation source in the temperature region of interest.

Because of the weaker temperature dependence, the accuracy of the emitting area becomes more critical. A Questar telescope was used to image the central 0.05 cm^2 of the deposition region through a pinhole to the optical photodiode. The entire optical system was absolutely calibrated with a tungsten lamp at 507 nm. Optical photodiode measurements were taken simultaneously with XUV measurements with XRDs on the Hydra experiments. The diode geometry prevented simultaneous measurements on the Proto-I experiments.

Validity of the blackbody assumption was a critical question in the analysis of these experiments. To this end, the foil heating and expansion was simulated with the CHART D¹⁴ radiation-hydrodynamic code and compared with opacity calculations.³⁴ The results of a typical case are displayed in Fig. 6 for a $25 \mu\text{m}$ thick gold foil with a 1 TW/gm deposition rate. The temperature and density profiles, measured from the foil center plane, are given as simulated at the end of the power pulse with values corresponding to the left-hand ordinate. Photon escape functions.

$$\exp\left(-\int_x^\infty K(\rho, T) dx\right)$$

on the right-hand scale, describe the percentage of optical (2.5 eV) or average XUV (20 eV) photons escaping from a given depth. It is clear that the expanded foil is still opaque for these photons and that both systems see into regions of the same temperature, although differing densities. These simulations also allow an estimate of the interior temperature to be made based on surface temperature measurements.

Time integrated XUV spectra were obtained with a 300 line/mm concave diffraction grating mounted on a 2.2 m Rowland circle, grazing incidence spectrograph. The spectrograph was mounted in place of the optical photodiode on the Hydra accelerator for the gold foil experiments. The

FIGURE 6

Temperature, density, and photon escape functions vs. distance into a $25\text{ }\mu\text{m}$ thick gold with a 1 TW/gm deposition rate utilizing the radiation-hydrodynamic code CHART D.

spectrograph was located approximately 1 m away from the source. The sensitivity of the spectrograph, photographic plate combination was not sufficient to observe continuum emission on a single shot. In particular, this instrument was used to check the validity of the blackbody radiation assumption. If any gold N or O plasma line emission were observed, the assumption would be invalid. The energy region of 10 eV to 1 keV observed with this instrument was coincident with the spectral region of the time resolved XRD measurements from which temperature measurements were deduced.

Similarly, time resolved optical spectral measurements were made on the Hydra, gold foil experiments. The spectrometer system consisted of a Cerny-Turner optical spectrograph coupled to an image converter camera. The optical spectrometer was capable of viewing 70 nm between 245 and 700 nm on a given shot. This system was employed to verify the blackbody radiation assumption at 507 nm where the optical photodiode temperature measurements were made. In addition, different spectral measurements in other parts of the spectrum were utilized to determine the effective ionization species of the expanding plasma.

HYDRA EXPERIMENT

A. Experimental Results

Figure 7 shows the apparent incident current density based on pinhole photographs on the Hydra experiments. The total incident current was normalized to the dB/dt monitors corrected for ion current as discussed in the last section. The curves to the left give the apparent incident current density as a function of radius, while the curves to the right give the total apparent incident current in the pinch region as a function of radius. The term "apparent incident" current was used to denote the fact

FIGURE 7

Current density and total current vs. radius for 0.32 cm carbon 50, 25, 12.7, and $6.4 \mu\text{m}$ thick gold on the Hydra experiments.

that the x-ray flux was normalized to single electron passes through the foil from the dB/dt monitors and did not consider two-dimensional effects. The apparent current densities were for 0.32 cm thick ATJ graphite, 50 μm , 25 μm , 12.7 μm , and 6.35 μm thick gold foils. Apparent peak current densities as high as 0.9 MA/cm² were observed for graphite, while apparent peak current densities as low as 0.2 MA/cm² were observed for 6.35 μm thick gold. The trend appeared to be that the thinner the foil, the greater the FWHM of the hard x-ray deposition profile, and the lower the apparent peak current density for a given incident current.

Figure 8 shows the total current in the diode inferred from dB/dt measurements (as a function of time) as compared to the calculated current in the pinch from the apertured PIN detector. The signal strength is integrated assuming a cosinusoidal (average angle of 45°) angular distribution and a single pass electron beam. The total current measurements were for the Hydra experiments with 50, 25, 12.7, 6.4 μm thick gold foils. The general trend appeared to be that the thinner the foil, the greater the calculated pinch current for a given incident current. In the cases where the calculated current was less than the total diode current, we conclude that not all the current in the diode got to the center pinch region. However, the possibility of some multiple passes or recirculation of electrons cannot be ruled out. In the case of the 6.4 μm thick gold, though, the calculated current in the pinch region exceeds the net total diode current. Therefore, in the case of 6.4 μm thick gold, each beam electron makes more than a single pass through the foil. Since the bremsstrahlung coming from the foil is very much peaked in the observer's direction, we infer that electrons re-enter the foil from the diode side

FIGURE 8

Total current in the diode and effective current in the pinch for single pass electrons vs. time for 50, 25, 12.7, and 6.4 μm thick gold on the Hydra experiments.

roughly two times on the average. This evidence for enhanced x-ray flux is also evidence for enhanced deposition for $6.4\text{ }\mu\text{m}$ thick gold.

Figure 9 shows the temporal history of the hard x-ray, XUV and optical radiation diagnostics for experiments on Hydra. The hard x-ray signal given by the PIN detector is coincident with the power pulse in the diode. The streak time is that given by the optical spectrometer and image converter camera system. The temperature at 507 nm is that given by an absolutely calibrated photodiode behind an interference filter. The XUV temperature is that given by the absolutely calibrated XRD utilizing no filter and assuming a source area of 1 cm^2 . This particular shot on the Hydra accelerator was for a $6\text{ }\mu\text{m}$ thick gold foil anode. Also shown is a comparison with a calculation utilizing the radiation-hydrodynamic, Lagrangian code, CHART D.¹⁴ The code used the average deposition given by the electron-photon, condensed history Monte-Carlo code TIGER,²³ including the time integrated electron spectrum for the particular shot. The average electron deposition in $6.4\text{ }\mu\text{m}$ gold for this particular shot was $3.6\text{ MeV/cm}^2/\text{g}$ for a cosinusoidal angular distribution of incident electrons and a local macroscopic electric field in the diode given by the corrected voltage. The closest fit to the experimentally measured temperature was a peak specific power of 1 TW/g . This corresponds to a peak current density of approximately 0.28 MA/cm^2 as compared to an apparent incident current density of 0.21 MA/cm^2 (see Fig. 7). Equivalently, 9.9 percent of an average electron's energy was deposited in the foil compared with an expected 7.6 percent for a single electron pass.

Figure 10 shows the temporal history of the radiation temperatures for three shots with 50, 25, and $12.7\text{ }\mu\text{m}$ thick gold foil anodes on the

FIGURE 9

Temporal history of the hard x-ray flux, optical streak spectrum, XUV and optical temperature, and theoretical CHART D prediction for $6 \mu\text{m}$ thick gold on the Hydra accelerator.

FIGURE 10

Temporal history of the XUV radiation temperature compared with theoretical CHART D predictions for 50, 25, and 12.7 μm thick gold foils on the Hydra accelerator,

with no filter, and source areas of approximately 0.5 cm^2 . The temperatures were compared with the calculations from the code CHART D¹⁴ as described above. The average deposition per electron was 4.8, 5.1, and $4.2 \text{ MeV/cm}^2/\text{g}$ for the above thickness foils, based on the respective electron spectra for these shots. The closest fit to the experimentally measured temperatures were peak specific powers of 1.3, 3.1, and 1.3 TW/g , respectively. These peak specific powers correspond to peak current densities of 0.25, 0.62, and 0.3 MA/cm^2 , respectively. No special significance should be attached to the $25 \text{ }\mu\text{m}$ thick gold shot other than that the total impedance in the diode was lower for this particular shot and consequently the total current in the pinch was higher. These experimentally deduced peak current densities were equal to or less than the apparent incident peak current densities as measured from the hard x-ray fluences (see Fig. 7). Since the peak specific powers and x-ray flux from the pinch were less than or equal to the apparent incident current density on 50, 25, and $12.7 \text{ }\mu\text{m}$ thick gold, we can only conclude that less than 100 percent of the current in the diode made it to the pinch region. The peak current densities are consistent with the x-ray pinhole profiles, where the total current in the pinch was normalized to the results of the PIN measurements (see Fig. 8).

Figure 11 compares the temporal response of the unfiltered XRD, the $0.75 \text{ }\mu\text{m}$ thick aluminum filtered XRD, and the $0.33 \text{ }\mu\text{m}$ thick C_6H_6 filtered XRD for $6 \text{ }\mu\text{m}$ thick gold foil on the Hydra experiment. The intensity ratios between any pair of XRDs were consistent with the 3-6 eV temperatures measured from the unfiltered XRD. However, these ratios are very sensitive to the thicknesses of the XRD filtering foils as well as their photon absorption cross sections. The aluminum foil thicknesses varied anywhere from 0.5 to $1 \text{ }\mu\text{m}$ in thickness. Each foil was weighed prior to

FIGURE 11

Temporal history of the XUV radiation diagnostics for 8-30 eV (bare XRD), 30-73 eV (0.75 micron Al), and 73-284 eV (0.33 micron C_6H_6) for 6 μm gold foils on the Hydra accelerator.

use and foil uniformity was assumed. Roughly, the ratios between the unfiltered XRD and the $0.75\text{ }\mu\text{m}$ aluminum filtered XRD was 100:1 and the ratio between the $0.75\text{ }\mu\text{m}$ aluminum XRD and the $0.33\text{ }\mu\text{m}$ parylene (C_8H_8) XRD was 3:1 in the temperature region of interest and were consistent with a single blackbody temperature.

Table I lists the XUV line emission taken with a $300\text{ }\text{\AA}/\text{mm}$ grating in a grazing incidence spectrograph for the Hydra experiments with a $6.4\text{ }\mu\text{m}$ foil anode. The spectra were obtained between 10 and 80 nm. No emission lines from gold were observed on any of the gold foil shots. Only contaminant lines from primarily oxygen were present. On this particular shot, these lines were coincident in energy with the aluminum and parylene filtered XRDs which appeared, in time, at the collapse of the diode impedance at the end of the power pulse. Therefore, we can be reasonably sure that the spectrum is dominated by continuum earlier in time. Unfortunately, we did not have sufficient intensity to observe the continuum directly, since the entrance slit to the spectrograph was located more than a meter away from the source.

Figure 12 shows the time resolved optical spectra observed in the spectral region between 245 and 315 nm for 6.4, 12.7, and $50\text{ }\mu\text{m}$ thick gold on the Hydra experiments. Only continuum was observed during the time of the power pulse (see Fig. 8). However, after the power pulse was turned off, numerous absorption lines from neutral and single ionized gold were observed. No absorption lines were observed in the spectral region around 507 nm. However, this does suggest that the blackbody assumption was breaking down in some parts of the spectrum after the power pulse was turned off. We have no evidence to suggest that the blackbody assumption was not valid during the power pulse. The late time plasma, however,

TABLE I

Contaminant XUV line emission . Au targets

<u>Wavelength (nm)</u>	<u>Ionic Species</u>
16.4	OV
18.3	OIV
19.8	OV
23.7	OIII
27.2	OIV
30.0	OIV
37.4	OIII
55.3	OIV
61.6	OIII
74.1	OII
74.8	OI

FIGURE 1.

Time resolved optical spectra observed in the Hyman experiments for the 6-18 foils between 260 and 240 nm.

suggest a low density, low temperature plasma which is absorbing radiation from a hotter, denser plasma located behind it.

B. Theoretical Results

The diode code was used to simulate the deposition in 6 μm gold with the Hydra diode geometry for: (1) in the limit of negligible beam target interaction; (2) with a simplified scattering and energy loss model; and (3) with and without space charge neutralization behind the foil (i.e., with and without ion emission from the back side of the foil). The average specific power within a 1.0 cm diameter focal volume (i.e., roughly the FWHM of the radiation spacial profile) was 0.96 TW/g compared with 1 TW/g experimentally measured. The average number of passes through the foil was approximately 1.8, comparing well with the experimentally measured values of 1.3 to 2 based on radiation temperature measurements and hard x-ray emission, respectively. The following qualitative facts were observed from the calculation: (1) scattering in the foil reduced the maximum current density on axis approximately 18 percent over the case of no beam foil interaction; (2) space charge neutralization lowered the average specific power by a factor of 2. Agreement with experiment was poor, however, in the shape of the radial deposition profile and for the case of a totally absorbing target.

In an attempt to understand the x-ray pinhole data for three planar Hydra anodes; 6 μm Au, 50 μm Au, and 0.32 cm thick carbon, the CYLEM²⁵ Monte Carlo code was employed to study coupled electron/photon transport in the presence of certain assumed electromagnetic fields. The radial distribution of the source-electron current density was taken to be identical to the x-ray deposition profile for thick carbon as shown in Fig. 7. This radial profile was chosen because of the small collisional albedo of

carbon, and tacitly assumes that transport of primary electrons from cathode to anode is not affected by the composition and thickness of that anode. When non-zero, the externally simulated self-magnetic field of the beam was obtained from this current density profile.

Fifteen calculations are summarized in Table 1. The three subgroups are distinguished by the angular distribution of the source current. A qualitative explanation for the measured x-ray profiles can be obtained from the isotropic results shown in Fig. 13 where the radial profiles, normalized to their peak values of the forward bremsstrahlung emission are compared. The relatively sharply peaked profile for carbon is a consequence of the relatively small collisional albedos. The more broadly peaked profile observed in the case of the $50\text{ }\mu\text{m}$ Au anode can be explained by the radial diffusion (i.e., surface migration⁷) of the large number of collisionally reflected electrons. The even broader profile observed for the $6\text{ }\mu\text{m}$ Au anode, when the magnetic field is present on both sides, can be attributed to a more general radial diffusion resulting from the large number of re-entries. Thus, the trend of the results can be accounted for by calculations 1, 2, and 4, respectively. Note, however, that the absence of the magnetic field from the transmission side of the $6\text{ }\mu\text{m}$ Au anode leads to a much more sharply peaked profile, because the large number of transmitted electrons escape (the mean number of re-entries, next to last column of Table 1 for calculations 4 and 5 differ by an order of magnitude). Thus, should the magnetic field not penetrate through the $6\text{ }\mu\text{m}$ Au anode, some other mechanism (e.g., space charge reflexing⁴) would be necessary to account for the broad profile in Fig. 7.

The normal incidence results are only of academic interest and are not relevant for superpinched beams. However, we have considered in

FIGURE 13

Theoretical prediction of forward bremsstrahlung as a function of anode escape radius for the 2π isotropic source calculations listed in Table I, for comparison with x-ray pinhole measurements on the Hydra experiments.

calculation 6 vs. calculation 7, the effect of the presence of the magnetic field within the carbon anode. The maximum magnetic field is about 65 kG. This is not large enough for field effects to compete with collisional effects within normal density Au, but it is large enough in the case of normal density carbon.³⁵ The peak in the radial power deposition profile (last column of Table I) is more than a factor of two larger when the field exists within the carbon, and the mean number of re-entries is an order of magnitude greater. Since the peak depositions are averaged over a thickness of carbon that is greater than the range of the source electrons, the increase in the true differential deposition when the field is present could be much greater than a factor of two. It is appropriate here to emphasize that none of these calculations account for the possibility of additional enhancement of deposition resulting from anode expansion.^{2,4} A cosine law angular distribution for the source current was used in the third group of calculations. This is probably more realistic than either normal incidence or the isotropic distribution. Still, the basic trends in the results are the same. The peak power depositions in Table II for calculations 12 and 13 indicate that the presence of the magnetic field within the carbon anode sustains the pinch against collisional scattering.

Comparison of peak powers in Table II with experimentally measured peak powers in Figs. 9 and 10 show very close agreement. In the case of the 6 μm Au, the number of electron passes was estimated to 1.3 to 2 passes compared with over 3 passes theoretically. It appears that the case of a magnetic field on both sides of the foil, more closely correlates with the experimental data.

TABLE II

Summary of model calculations. The second to last column is the average number of times that a source electron re-enters (would be zero without macroscopic electromagnetic fields) the anode. The last column is the peak value of the radial specific power deposition profile (0.1 cm resolution) for the given source current, averaged over the anode thickness; it always occurs in either the central circular zone or the adjacent annular ring.

Source-Current Angular Distribution	Anode	Magnetic Field	Source Current	Mean No. of Re-entries	Peak Deposition TW/g	
1.	.32 cm C	both sides	I_o	0.386	0.7619	6%
2.	50 Au	both sides	I_o	2.402	2.2508	3%
3.	50 Au	diode only	I_o	1.332	1.564	5%
4.	6 Au	both sides	I_o	3.744	2.460	4%
5.	6 Au	diode only	I_o	0.363	1.303	7%
6.	.32 cm C	everywhere	I_o	0.223	2.240	5%
7.	.32 cm C	both sides	I_o	0.023	0.9207	4%
8.	50 Au	both sides	I_o	1.985	2.2.3	5%
9.	50 Au	diode only	I_o	0.967	1.722	6%
10.	6 Au	both sides	I_o	4.259	2.184	8%
11.	6 Au	diode only	I_o	0.029	0.5358	10%
12.	.32 cm C	everywhere	$0.74I_o$	0.295	1.015	4%
13.	.32 cm C	both sides	$0.74I_o$	0.179	0.6059	5%
14.	50 Au	both sides	$0.74I_o$	2.007	1.433	4%
15.	6 Au	both sides	$0.74I_o$	2.286	1.363	10%

PROTO I

A. Experimental Results

Figure 14 shows the apparent incident current density based on x-ray pinhole photographs assuming a single pass through 50, 12.7 and 6.4 μm thick gold foils on the Proto I experiments. The total current in the pinch was normalized to absolutely calibrated photographic film, Type M x-ray film. The radius of the foil was 0.5 cm. Peak apparent current densities for 50, 12.7 and 6.4 μm thick gold foils were 2.5, 1.8, and 1.2 MA/cm^2 , respectively. We see again that the apparent current density is lowered for thinner foils. For these particular shots, approximately 60, 50, and 50 percent, respectively, of the total diode current was found in the pinch region. Relative PIN diode measurements behind the photographic film on the image plane of the pinhole camera system verified the x-ray flux profile. The pinhole camera viewed the forward going bremsstrahlung and was very insensitive to bremsstrahlung from electrons coming from the side of the foil away from the diode.

Figure 15 shows the apparent incident current density for aluminum foils of 206, 89, 38 and 6.4 μm thickness on the Proto-I accelerator. The pinhole camera assembly was mounted behind the cathode and was therefore most sensitive to backward going bremsstrahlung. However, if electrons re-enter the foil from the back side, then the pinhole camera system would be most sensitive to the bremsstrahlung coming from these electrons. To account for the fluence of x-rays from these aluminum shots, the electrons must have made a second pass through the anode foil, entering the foil from the back side. Based on the x-ray fluence, the apparent incident peak current densities for the above thickness foils were 2.0, 1.7, 1.7, and 1.3 MA/cm^2 . These foils had a 1 cm radius. The percentage of current

FIGURE 14
Current density vs. radius for 50, 12.7, and 6.4 μm thick gold on the Proto-I accelerator from absolutely calibrated x-ray film on the image plane of a Uranium pinhole camera.

FIGURE 15

Current density and total current vs. radius for 6.4 μm thick aluminum on the Proto-I accelerator.

in the pinch region out of the total electron current available were 50, 63, 100, and 100 percent, respectively, for the above thicknesses.

Figure 16 shows the apparent incident current density for 6.4 μm thick aluminum with a 0.5 cm radius. Based on absolute calibration of x-ray film located on the image plane of a pinhole camera, the apparent peak current density was 3.8 MA/cm². In this case, the pinhole camera system was primarily sensitive to forward going bremsstrahlung from the anode. Based on the x-ray fluence, 100 percent of the total diode current was incident on the pinch region. Only a single pass of an electron was required for this x-ray fluence.

Figure 17 shows the temporal history of the radiation temperature measurements for 25, 12.7 and 6.4 μm thick gold foils on the Proto-I experiments based on unfiltered XRD measurements. The source area was chosen from the hard x-ray measurements as discussed before. The average deposition per electron with a local macroscopic electric field in the diode, and including the electron spectra for the respective shots were 3.8, 3.5, and 2.7 MeV-cm²/g. The temperatures were compared with calculations from the code CHART D¹⁴ as previously described. The closest fit to the experimental measured temperatures were peak specific powers of 6.8, 6.4, and 2.7 TW/g, respectively. These peak specific powers correspond to peak current densities of 1.8, 1.8, and 1.0 MA/cm², respectively. These peak current densities are consistent with the x-ray fluence measurements, assuming only a single pass of the electrons through the gold foils.

Figure 18 shows the temporal history of the unfiltered XRD radiation temperature measurements for 38 and 6.4 μm thick aluminum foils on the Proto I experiments. The average deposition per electron for a single pass-through the foil with a local macroscopic electric field in the diode, and

FIGURE 16

Current density and total current vs. radius for 6.4 μm thick aluminum with 0.5 cm radius.

FIGURE 17

Temporal history of the radiation temperature measurements on the Proto-I experiments for 25, 12.7, and 6.34 μm thick gold foils based on the bare XRD, XUV measurements.

FIGURE 18

Temporal history of the radiation temperature measurements on the Proto-I experiments for 38 and $6.4 \mu\text{m}$ thick aluminum based on bare XRD, XUV measurements.

including the electron spectra for the respective shots, were 3.0 and 3.7 MeV-cm²/g. The experimentally measured temperatures from the unfiltered XRDs were compared with temperatures calculated from the code CHART D.¹⁴ The closest fit to the experimentally measured temperatures were peak specific powers of 9.4 and 20 TW/g. This would correspond to apparent peak current densities on a single electron pass of 3.1 and 5.3 MA/cm². However, from quantitative x-ray fluence measurements (see Figs. 16 and 17), for two passes through the aluminum foils, the apparent peak current densities, were 1.7 and 3.8 MA/cm². These measured peak current densities imply effective depositions of 5.5 and 5.2 MeV-cm²/g as opposed to 3.0 and 3.7 MeV-cm²/g for 38 and 6.4 μ m thick aluminum foils for a single electron pass, respectively. Equivalently, an average electron deposits 4.9 and 1.7 percent of its energy as compared with 2.7 and 1.2 percent of its energy with a single pass through the above respective foils.

B. Theoretical Results

The diode code was used to simulate the deposition in 6 μ m gold and 6 μ m aluminum foils with the Proto-I diode geometry: (1) in the limit of negligible beam target interaction; (2) with a simplified scattering and energy loss model; (3) varying the ion species of the ion component of total current, and (4) with and without space charge neutralization behind the foil. The average specific power within a 0.16 cm radius local volume (i.e., roughly the FWHM of the radiation spacial profile) was 4.7 TW/gm for 6 μ m gold and 9.0 TW/gm for 6 μ m aluminum for the data shown in Fig. 14 and data similar to that in Fig. 16, except with a peak specific power of 10 TW/g.³⁶ The experimentally measured peak specific power for the 6 μ m gold shot was 2.7 TW/g (see Fig. 17). However, whereas a 100 percent of the current was incident in the case of the 6 μ m aluminum

target (see Fig. 16), only 50 percent was incident on the 6 μm gold target, the rest being lost at large radii. Experimentally, we find that a single electron pass is sufficient to account for the deposition in the gold foils on the Proto I accelerator, whereas the diode calculation predicts an incident current of 100 percent and a deposition consistent with 3.2 passes by a given electron. However, if the current were reduced theoretically, the deposition levels would be roughly consistent. In the case of the 6 μm aluminum, the 9 to 10 TW/gm is consistent with an average of 1.3 passes for a *cosinusoidal angular distribution of electrons compared with 2.9 passes with the diode calculation.* The discrepancy could be caused by an electron angular distribution that is more nearly normal, with the deposition requiring a larger number of experimental electron passes. In the case of the 6 μm gold calculation, the scattering model may be too simple as manifested by a predicted spatial deposition profile that is much too narrow and the lack of time dependence.

Coupled electron-photon Monte Carlo calculations were performed to look at the effect of scattering on the deposition in planar 6 μm , 12 μm and 50 μm gold targets on the Proto I accelerator. Both one-dimensional (TIGER) and two-dimensional (CYLEM) calculations were performed. For all calculations, a *cosinusoidal angular distribution for the incident electrons and a radial distribution consistent with the diode calculations were assumed for each bin of the diode simulation in order to smooth the discontinuities in the profile.* The two-dimensional calculations included magnetic fields consistent with the current profile and electric fields which were roughly equal to the self-consistent fields calculated in the diode simulations. Variation in the electric field in the diode by factors of 2-3 in the CYLEM calculation resulted in negligible changes

(~ 10 percent) in the energy deposited in a radius of $\lesssim 0.75$ mm. However, diode calculations with ion emission coming from the back of $6\text{ }\mu\text{m}$ thick gold and aluminum foils resulting in space charge neutralization behind the foil, predicted energy deposition that was a factor of two lower than that obtained for the case of no ion emission from the back side of the foil.

The two-dimensional calculations, with 51 percent of the incident electrons striking the target region, indicate that 0.8 percent, 2.2 percent and 10.4 percent of the incident energy will be deposited for 6, 12, and $50\text{ }\mu\text{m}$ thick gold foils, respectively. One dimensional calculations were performed with the Monte Carlo code TIGER for the case of $6\text{ }\mu\text{m}$ and $50\text{ }\mu\text{m}$ gold targets and compared with two-dimensional calculations in which the fields at the rear of the anode were space charge neutralized. The TIGER calculations were performed both by allowing all transmitted and reflected particles to escape and by allowing specular reflection of the reflected particles at the front surface of the target. The arithmetic mean of the two-calculations predicted 0.8 and 9.2 percent compared with 0.8 and 9.7 percent for the two-dimensional calculations.

The good agreement between the 1 and 2-dimensional codes in the case where half the back-scattered electrons are reintroduced indicate a relatively small enhancement due to recirculation in the diode field; about 80 percent of the dose is obtained if no recirculation occurs. The lack of recirculation is apparently a result of the relatively low value of beam v/γ , namely, of order 1. The observed lack of reflexing in the sub-millimeter radius pinch region does not imply that no reflexing occurs, but only that the reflexing electrons tend to strike the anode at radii larger than the pinch region. This is consistent with experiment, whereby

no recirculation of electrons in gold foils was necessary to account for the energy deposition (see Fig. 18).

CONCLUSION

The important point to stress from this work is that electromagnetic effects associated with self-electric and magnetic fields, as well as macroscopic fields in the diode, strongly interact with foils of thicknesses less than 50 microns. A great many assumptions went into the analysis, both theoretically and experimentally. The qualitative agreement between both seems remarkable. Experimentally, an isotropic angular distribution of electrons averaged over the focal volume was assumed. The good agreement on specific depositions as obtained from the hard x-ray flux and radiation temperature measurements testify to its validity. Second, a blackbody photon spectrum was assumed and justified by the good agreement between optical and XUV measurements, as well by the lack of line emission during the power pulse. Theoretically, the diode calculations assumed a time independent electron spectrum, as well as no interaction with the foils. This was justified by the good agreement with experiment for the average specific deposition in the focal volume. The Monte Carlo calculations assumed an incident electron spatial profile given by either x-ray pinhole profiles, from a low-Z (i.e., carbon) target or by the diode calculation, and ignored hydrodynamic motion of the foils. The good agreement with the peak specific depositions for the radiation temperatures testifies to its validity.

We have shown that, on the average, an electron makes more than a single pass in a 6 μm thick gold foil for a $\mu/\gamma = 2.5$ electron beam (800 kV, 100 kA) within a focal radius of 0.5 cm. This was manifested by enhanced bremsstrahlung and by specific power deduced from radiation temperature

measurements that could not have been accounted for by a single electron pass. On the basis of the Monte Carlo calculations, a 6 μm gold foil with a magnetic field on the both sides of the foil could account for the deposition. It was not necessary to appeal to electrostatic reflexing to account for the deposition.

In the case 38 and 6 μm thick aluminum foils, more than a single electron pass was necessary to account for the deposition. In the case of the 6 μm aluminum foil, enhanced deposition was observed for a $v/\gamma \sim 2.2$, but not for $v/\gamma \sim 1.1$ suggesting agreement with magnetic stopping and space-charge neutralization behind the foil. The 38 μm aluminum data suggests possible electrostatic reflexing, since v/γ of the incident beam was about 1.1. No enhancement was observed for the gold foils, for an incident beam with a v/γ of about 1.1.

At present, although enhancements of a factor of 2 have been observed, only a small amount of the incident electron's energy (1 - 10 percent) has been deposited in the foil. A much greater fraction of the electron's energy must be deposited before thin foils may be utilized in electron beam fusion targets. This will require either substantially higher current densities than achieved in these experiments or externally applied magnetic fields.*

*Results obtained after the completion of this work tend to confirm this expectation.³⁷

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