Improved Bremsstrahlung From Diodes With Pulse-Heated Tantalum Anodes

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***Abstract*—Bremsstrahlung from high-power electron-beam diodes increases and becomes spatially more uniform when the tantalum anode is first pulse-heated to remove gas from the surface and interior, and then pulse-heated again to white hot just prior to and during the high-power pulse. Heating the tantalum eliminates protons, retards beam pinching, and increases the far-field X-ray dose relative to unheated tantalum. The radiation pattern becomes symmetric and hollow, producing a more uniform near-field dose distribution than for unheated tantalum. With a white-hot anode, the diode current is single-species Child–Langmuir until the voltage exceeds 1 MV, at which point it reaches critical current. These phenomena demonstrate reduced effects from ions in the diode. The increase in dose is a result of both reduced ion current and enhanced electron reflexing through the subrange tantalum foil. The heating technique is compatible with high-power generators such as Decade, whose x-radiation output would increase by as much as 30%.**

***Index Terms*—Bremsstrahlung, electron-beam, pulsed power, tantalum, X-radiation.**

I. Introduction

TANTALUM is the conventional anode material used in high-power (TW) electron-beam diodes to produce bremsstrahlung. Tantalum is appropriate because of its high atomic number and favorable mechanical properties that allow rolling of large-area thin foils. However, tantalum absorbs hydrogen and other gases. In fact, maximum absorption of hydrogen is in the range $T = 1000$–1500 K. In a bremsstrahlung diode, the electron beam deposits energy in the tantalum and heats the anode, causing the release of hydrogen and other low atomic number elements from the surface and interior. The electron beam ionizes this gas, producing an anode plasma that neutralizes the electron-beam space charge, allows the beam to pinch to the diode axis, and produces an ion current that decreases the X-ray production efficiency.

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Reducing hydrogen and other low-mass ions on or inside the tantalum should have several desirable effects for bremsstrahlung production. First, the radiation output should increase. Second, the reduced ion space charge should delay electron pinching, resulting in a more distributed radiation pattern that allows uniform irradiation closer to the diode. Finally, a diode without impurities has one less unpredictable variable to affect its behavior and should result in improved reproducibility.

Gases entrained in tantalum and adsorbed on the surface may be removed by heating, ideally leaving only pure tantalum, which contributes negligible ion current. High-power diodes with heated anodes have been investigated previously, primarily during 1975–1980 [1]–[5]. In these studies, anodes of various materials, including tantalum, were heated by dc techniques (acetylene torch, electron emitter, heater coils) to 700–1300 K. These experiments were partly successful; heating the anode delayed impedance collapse, suppressed low-mass ions, and delayed but did not eliminate pinching. However, heating tantalum to only 700 K had no effect [4], [5], presumably because tantalum retains hydrogen in its interior at elevated temperatures. More recent studies demonstrate that cleaning electrode surfaces improves the operation of ion diodes [6], high-power microwave sources [7], plasma-opening switches [8], [26], and other pulsed-power devices [9]. These successes have revitalized interest in pursuing similar improvements in bremsstrahlung diodes [10]. The work reported here differs from previous studies in that much higher anode temperatures $T > 2600$ K are used. At this temperature, the tantalum anode is white-hot. It has long been known that such high temperatures are required to clean tantalum in high-power vacuum tubes [11]–[13].

Preshot preparation of gas-free tantalum for use in a high-power diode is considered futile. In a typical pulsed-power environment, it is difficult to maintain the properties of degassed tantalum. Atomically clean tantalum surfaces react with water, hydrocarbons, and similar hydrogen-containing impurities. The reactions dissociate these impurities into atomic oxygen, carbon, and hydrogen. Carbon and oxygen stay on the surface, and [14] gives the composition of a typical tantalum surface as roughly 40% oxygen, 40% carbon, and only 20% tantalum. Hydrogen diffuses into the bulk tantalum in minutes, even at room temperature [15]. In addition, the relatively poor vacuum in a typical pulsed-power system 1–10 mPa (10^{-5}–10^{-4} torr) results in many monolayers of water vapor and other impurities deposited on the tantalum surface. For these reasons, the tantalum is cleaned *in situ*.

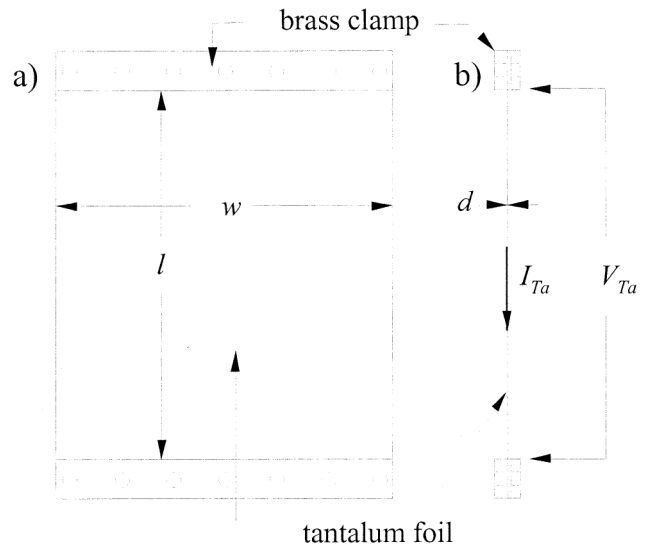

Fig. 1. (a) Front and (b) side views of a rectangular tantalum foil (length l, width w, and thickness d). Voltage V_{Ta} is applied at the brass-clamp electrodes, producing current I_{Ta} and heating the foil resistively.

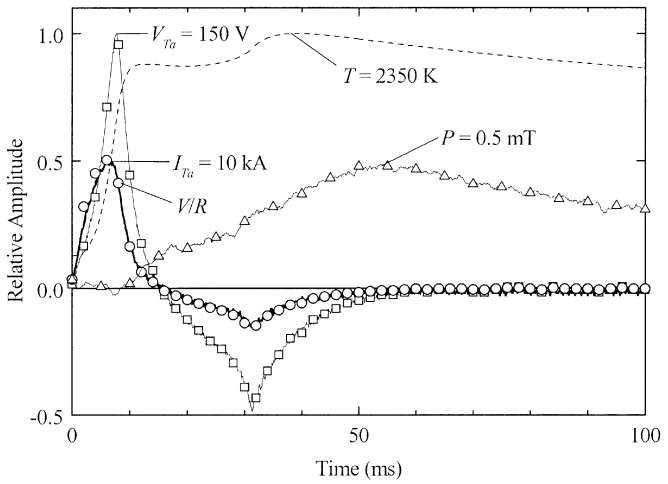

Fig. 2. Heating analysis based on measured voltage (V_{Ta}, squares) and current (I_{Ta}, thick line) for a 16.5 cm × 18 cm × 50 μm tantalum foil driven by a capacitor-bank discharge. Calculated temperature (T, broken line) determines resistance R used to compare V/R (circles) with measured current. Pressure (P, triangles) increases after the foil is heated.

Pulsed-resistive heating is used to clean the tantalum. In this procedure, the tantalum is a variable resistor in a low-voltage electrical circuit. The circuit is activated for up to one second, long enough to heat the tantalum but short enough to avoid melting or desorbing gases from the surrounding materials. The tantalum must be at 2300 K or higher long enough for hydrogen to diffuse out from the interior of the foil and for oxides and nitrides to decompose, but must remain below 3258 K, the melting point of tantalum. At sufficiently high temperature (2000 K), hydrogen diffusion is rather fast, a few times 10^{-4} cm^2/s [15]. However, below about 1500 K, hydrogen tends to diffuse into the tantalum, while above about 2000 K hydrogen diffuses out. At 2300 K, most light ions attached to the surface of tantalum are desorbed. When the main discharge heats the tantalum to melting and evaporation, the only remaining ions come from the tantalum itself. The heavy tantalum ions are necessarily slow (even though they could be multiply ionized) and should not affect diode operation during the 100-ns pulse duration for typical high-power bremsstrahlung diodes.

The paper is organized as follows. Section II describes the heating technique. Section III presents results obtained on Gamble II during the technique's development and its eventual implementation on a Decade Module. Section IV summarizes the beneficial effects of anode heating and potential applications for other generators.

II. Heating Technique and Protocol

The resistive pulse-heating technique chosen for these experiments is simple to implement and provides uniform heating. A rectangular foil (length l, width w, and thickness d) with electrodes attached along opposite sides (Fig. 1) is connected to the pulsed-current source. As the temperature rises, the resistivity increases, providing feedback that redistributes the current to cooler regions, resulting in uniform heating in the foil.

When gas evolves from the metal, a gas discharge can occur if the voltage between the electrodes is too large. Such discharges divert heating current from the metal and limit the temperature. These discharges are avoided by using a long-duration pulse at low voltage, releasing gas without striking a gas discharge.

The measured voltage between the electrodes, V_{Ta}, is used to calculate the foil temperature by numerically solving the heating equation

$$mC_p \frac{dT}{dt} = \frac{V_{Ta}^2}{R} - \varepsilon A\sigma \left(T^4 - T_0^4\right) \tag{1}$$

where m is the tantalum mass, T is temperature, C_p is heat capacity, R is resistance ($R = \eta l/wd$ where η is the resistivity), ε is emissivity, A is the radiating area ($A = 2lw$, where l and w are the length and width of the foil), σ is the Stephan–Boltzmann constant, and T_0 is the initial temperature. The temperature-dependent $C_p(T)$, $\eta(T)$ and $\varepsilon(T)$ are modeled using polynomial fits to published values between 300 K and 3250 K. Here, conduction loss to the electrodes is along the thin foil and is therefore negligible.

Fig. 2 shows an example of this analysis for the heating pulse used on a Gamble II shot. Current from an ignitron-switched capacitor bank (3.7 mF, 12 kV, 20 mH) and a 5 : 1 step-down transformer heats the tantalum foil. The tantalum dimensions are $w = 16.5$ cm, $l = 18$ cm, and $d = 50$ μm. The maximum voltage between the electrodes is 150 V and changes polarity during the 50-ms heating pulse. The maximum current is 10 kA, and the current waveform differs from the voltage waveform because the tantalum resistance increases during the pulse. (The tantalum resistance is 3 mΩ at 300 K and 30 mΩ at 3000 K.) The calculated tantalum temperature reaches 2350 K in 40 ms, then slowly decreases. The voltage divided by the inferred resistance V/R compares well with the measured current I_{Ta}, verifying that the current flows through the metal and supports the validity of the heating model.

The time required for hydrogen to diffuse from the center of the tantalum to the surface can be estimated using diffusion coefficients, δ, extrapolated from data in [13]. At $T = 2000$ K, $\delta \approx 2 \times 10^{-4}$ cm^2/s for hydrogen diffusion in tantalum. The

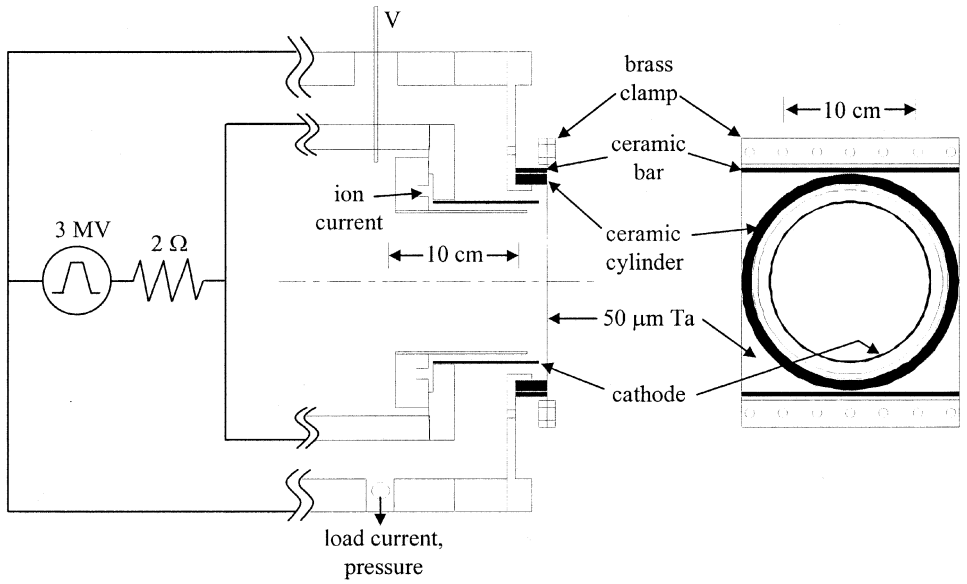

Fig. 3. Tantalum heating setup on Gamble II. The generator is represented by its characteristic impedance (2 Ω) and open-circuit voltage waveform (maximum 3 MV). The vacuum diode consists of a hollow cylindrical cathode and a rectangular tantalum foil stretched over ceramic structures for thermal and electrical isolation during heating. The locations of voltage, current, ion current, and pressure measurements are indicated.

e-folding time for diffusion is $\tau \approx x^2/2\delta$, where x is the diffusion scale length, or in this case, the distance from the center to the surface of the tantalum. For $2x = 50$ μm, $\tau \approx 16$ ms. Gamble II shots are fired at $t = 150$ ms, a compromise timing that allows gas to diffuse (nine e-folds) and disperse, but maintains high temperature (1900 K) to avoid hydrogen re-absorption.

A promising protocol consists of two heating pulses without breaking vacuum, one heating pulse to evolve gas from the interior of the foil followed by a second heating pulse simultaneous with the high-power generator shot. Fig. 2 shows data from a fast pressure gauge near the tantalum that indicates a 0.5 mtorr increase at 50 ms, then a gradual decrease as evolved gas expands into the vacuum chamber. For the second heating pulse the pressure increase is less than for the first pulse, probably because the first pulse removes most of the entrained gas and the interior remains degassed when the second heating pulse is applied. The second heating pulse then provides a clean surface, and less total gas evolves into the vacuum chamber. A third heating pulse does not give further improvement. This two-heating-pulse protocol resulted in substantial improvements in X-ray production from diodes tested on Gamble II.

III. Experimental Results

Pulse-heated anodes were investigated in three experimental series on the Gamble II generator at the Naval Research Laboratory, Washington, DC, and one series on the Decade Module 2 (DM2) generator at Titan Pulse Sciences Division, San Leandro, CA. The first tantalum heating experiments [16] on Gamble II (1.5 MV, 0.7 MA, 60 ns) used a 50-ms current pulse from a capacitor bank and stepdown transformer to resistively pulse-heat 50-μm-thick foils to $T > 2200$ K. These experiments demonstrate increased dose, reduced ion current and reduced pinching. A second set of Gamble II experiments used a 1-s current pulse provided by a battery bank to heat 100-μm-thick, larger-area tantalum foils to $T > 2600$ K. Additional diagnostics in these experiments demonstrate orders-of-magnitude proton reduction and increased X-ray production due in part to electron reflexing. A third set of experiments incorporated a foil-stretching mechanism to keep the foil taut during heating, greatly improving the azimuthal symmetry of the X-ray source, resulting in a hollow source distribution. All three Gamble II series indicate a 20% increase in far-field dose. This final diode arrangement and heating procedure proved successful on DM2, increasing the X-ray output and pulse duration, resulting in a dose increase of up to 30%. The results of these experiments are presented in the following sections.

A. First Gamble II Experiment

Fig. 3 illustrates the diode arrangement for testing pulse-heated tantalum foils on Gamble II. The generator drives a hollow cylindrical cathode with a 6-cm radius and 3-mm cylindrical wall thickness. The tantalum anode is a rectangular (165 mm $\times$ 180 mm) 50-μm-thick foil. Clamps hold the foil at opposite sides. The foil is stretched over ceramic bars and a ceramic cylinder to provide thermal and electrical isolation from the diode electrodes during the heating process. The inside surface of the ceramic cylinder flashes when Gamble II is pulsed.

A resistive divider (Pulse Sciences, Inc., Model PSI-VVM-16) measures the voltage V close to the diode anode–cathode (A–K) gap of the diode. B-dot loops measure the load–current time-derivative dI/dt. The load voltage is calculated using $V_{\text{load}} = V - LdI/dt$, where L is the inductance between the voltage measurement and the diode A–K gap. A Rogowski loop inside the center conductor measures ion current, assuming negligible electron emission from the cylinder concentric with, and inside the cathode. Several diagnostics measure the bremsstrahlung emission including time-resolved

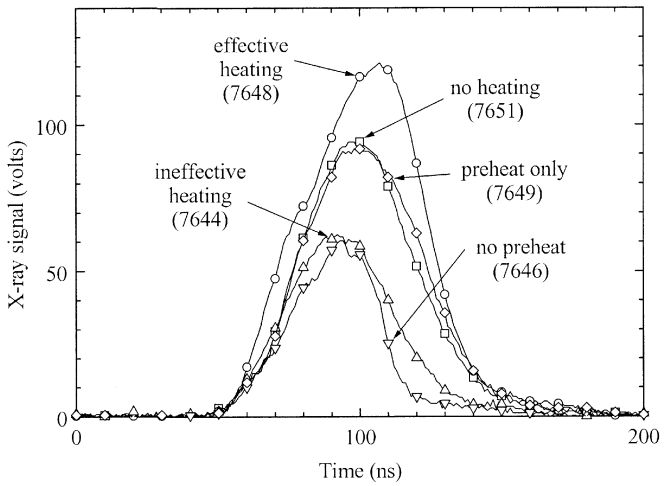

Fig. 4. X-ray (PD) signals using different heating procedures: no heating (squares), effective heating (circles), ineffective heating (up triangles), no preheat (down triangles), and preheat only (diamonds).

scintillator-photodiode (PD) and silicon PIN detectors, CaF_2 thermoluminescent dosimeters (TLDs) at different distances to determine the absolute dose, and a time-integrated pinhole camera to image the tantalum anode.

Different heating procedures were tested on 12 Gamble II shots. Three shots had no heating. For six shots, the tantalum was preheated to remove the bulk of the gas, then heated again starting 150 ms prior to the Gamble II shot. These six shots included four "effective-heating" shots, where the temperature was $\geq$2200 K on both the preheat and Gamble II shots, and two "ineffective-heating" shots, where gas breakdown limited the temperature to about 1500 K on the Gamble II shots. Two shots with no preheating and one shot with just preheating verified the need for the two-pulse heating protocol.

Fig. 4 compares X-ray signals for five different heating procedures. The largest signal is shown for each case. The "ineffective heating" ($T = 2200$ K on preshot, 1500 K on shot) and "no preheat" (no preshot pulse, $T = 2200$ K on shot) shots produce less radiation and have shorter pulses than the "no heating" shot. In both cases, this is attributed to excessive gas in the diode gap that becomes ionized and prematurely shorts the diode, but for different reasons. For the "ineffective heating" shot, the tantalum adsorption from the vacuum ambient is enhanced. For the "no preheat" shot, the evolved gas from the tantalum has not been removed sufficiently from the A–K gap. The "effective heating" ($T > 2200$ K on both preshot and shot) shot produces more radiation than the "no heating" shot and shows no evidence of premature impedance collapse. The shot with preheating only is indistinguishable from the no-heating shot. This suggests that surface readsorption from the vacuum ambient just prior to the shot is sufficient to supply the ion flow that produces pinching and pulse-length shortening. The double-pulse heating procedure consisting of one preheat pulse followed by a heating pulse simultaneous with the Gamble II shot is superior for X-ray production for this diode arrangement.

Pinhole camera images from typical shots with no heating [Fig. 5(a)] and with effective heating [Fig. 5(b)] illustrate the dramatic effect heating has on the electron beam dynamics.

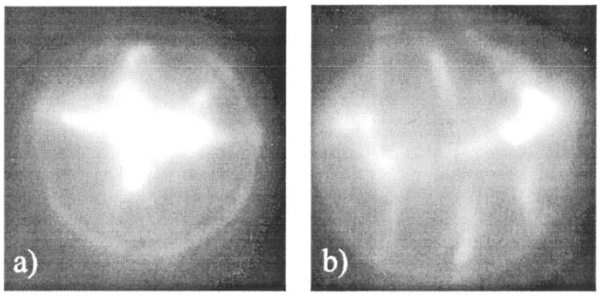

Fig. 5. X-ray images for (a) unheated shot (7651) and (b) effective-heating shot (7648).

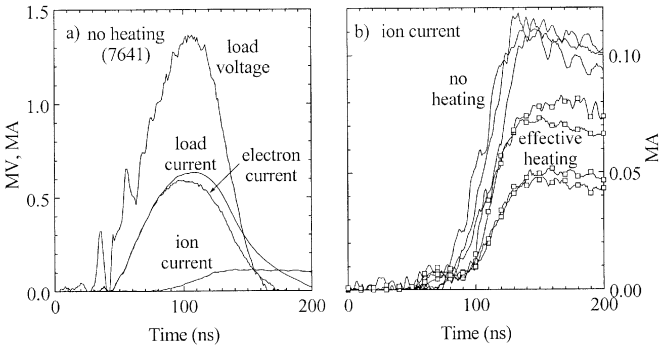

Fig. 6. Electrical data for (a) a shot with no heating and (b) ion current signals for shots with heating (squares) and without heating (lines). Electron current is the difference between the measured load current and ion current.

These two images are made with the same exposure and spatial scale. The unheated anode image has an intense pinch in the center of the tantalum, while the heated anode shows emission from a larger area with little emission from near the center. The filamentary structures in the heated case may result from wrinkling of the tantalum foil that results from thermal expansion during the heating pulse.

Electrical signals indicate that the ion current is reduced as a result of effective heating. Fig. 6(a) shows electrical data for a no-heating shot. The ion current begins 30–40 ns later than the load current (integral of the dI/dt signal), consistent with the formation time for an anode plasma on the tantalum surface. The ion current increases to 116 kA just after the maximum load voltage (1.36 MV) is reached. The maximum load current is 635 kA. The electron current, responsible for bremsstrahlung production, is calculated as the difference between the load current and the ion current. Fig. 6(b) compares ion current measurements for the three "no-heating" and four "effective-heating" shots. Heating results in a 10–20 ns delay and about a 50% decrease in the ion current. The remaining ion current indicated by the Rogowski signal could represent the current of ions that are not removed by the heating procedure or it could be a current of electrons emitted from the inner cylinder.

Reduced ion current (and therefore increased electron current) is one reason for the increased X-ray emission, but effective heating shots produce more radiation even after accounting for this, suggesting that heated anodes are more efficient X-ray targets than unheated targets. The reduced ion current may allow virtual cathode formation and reflexing of electrons back into

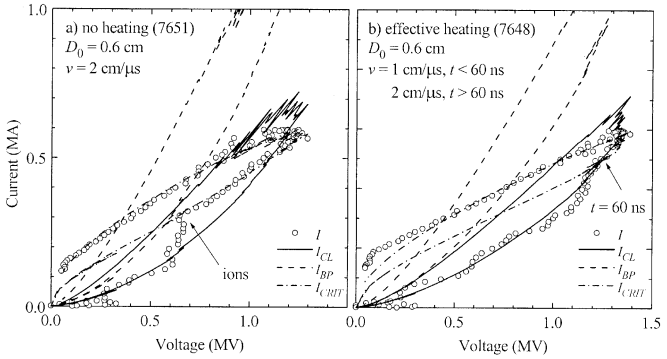

Fig. 7. Current–voltage characteristics (circles, 1 ns/point) compared with diode models (lines) for (a) unheated and (b) heated anodes. Model parameters are $r = 6$ cm, $\Delta r = 3$ mm, initial A–K gap D_0, and gap-closure velocity v.

the tantalum, increasing the X-ray production efficiency. This is discussed further in the following section.

Fitting the experimental results to simple diode models [17] shows that heating significantly reduces the effects of ions on the diode I–V characteristics. The familiar Child–Langmuir current $I_{\rm CL}$ describes space–charge-limited flow without ions

$$I_{\rm CL}(kA) = 2.32A\,\frac{V_{\rm MV}^{3/2}}{D^2} \tag{2}$$

where A is the effective emission area from a hollow cylinder to a plane, given approximately by

$$A \approx 2\pi r\,(\Delta r + 2D) \tag{3}$$

where r is the cathode radius, Δr is the thickness of the cylindrical wall and the gap D decreases with time as dense electrode plasmas expand with velocity v

$$D = D_0 - vt. \tag{4}$$

When sufficient ion space charge is present in the diode gap, the current increases to the bipolar value

$$I_{\rm BP} = 1.86 I_{\rm CL}. \tag{5}$$

When the electron orbits are bent sufficiently by the magnetic field associated with the diode current so that the electrons strike the anode at grazing incidence, the current and voltage are related by the critical current formula

$$I_{\rm CRIT}\,(kA) = 1.6 \times 8.5\sqrt{\gamma^2 - 1}\,\frac{r}{D} \tag{6}$$

where γ is the standard relativistic factor related to the voltage by $\gamma = 1 + eV/m_e c^2$. The factor 1.6 accounts for geometrical and space–charge effects, determined from particle-in-cell simulations [18].

In principle, the diode current I should be space–charge limited ($I = I_{\rm CL}$ or $I_{\rm BP}$ depending on whether ions are present) until it reaches $I_{\rm CRIT}$. Then the current should be magnetically limited ($I = I_{\rm CRIT}$). The influence of ions on the diode impedance is demonstrated by comparing $I(V)$ data with these models.

Fig. 7 compares $I(V)$ data from typical shots with the diode models for cases with and without heating. The measurements (circles) are plotted every ns, starting at $I = V = 0$. The diode models [(2)–(6)] are evaluated using the measured voltage and the actual diode parameters $(r,\ \Delta r,\ D_0)$; the only adjustable parameter is the effective gap closure velocity v. For the unheated shot with $v = 2$ cm/μs [Fig. 7(a)], the current initially follows

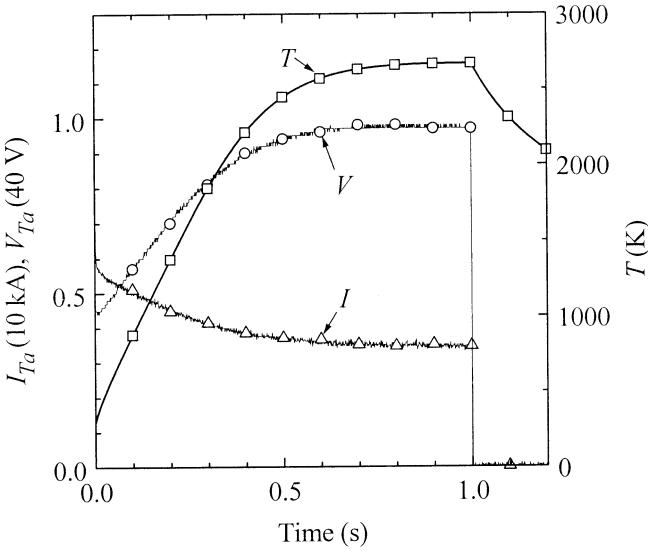

Fig. 8. Measured voltage (circles) and current (triangles) for heating a 28 cm × 30 cm × 100 μm tantalum foil with a battery bank. The calculated temperature (squares) exceeds 2600 K.

$I_{\rm CL}$, then rapidly increases to $I_{\rm CRIT}$ when V exceeds 0.6 MV. The fact that I exceeds $I_{\rm CL}$ when $V > 0.6$ MV is strong evidence for the presence of ion space charge in the diode gap at that time. The $I(V)$ data follow $I_{\rm CRIT}$ for the remainder of the pulse. For the shot with effective heating [Fig. 7(b)], the current initially matches $I_{\rm CL}$, then transitions to $I_{\rm CRIT}$ when V exceeds 1.2 MV with no evidence of ion space–charge effects. Here, a good fit to the diode models requires $v = 1$ cm/μs until the current reaches $I_{\rm CRIT}$, then $v = 2$ cm/μs for the remainder of the pulse.

B. Second Gamble II Experiment

A second experiment on Gamble II used the same configuration as in Fig. 2, but with 100-μm-thick tantalum, as appropriate for optimum bremsstrahlung on the Decade generator [19]. The 16-ms hydrogen-diffusion time for $2x = 50$ μm at $T = 2000$ K increases to $\tau \approx 64$ ms for $2x = 100$ μm. The pulse duration of the capacitor-bank circuit (50 ms) is too short for this tantalum thickness. A battery-bank heating circuit was constructed to provide a longer heating pulse.

The battery bank consists of 24 lead–acid batteries (each 12-V, 2 kA) arranged in three series strings of eight so that the maximum voltage is limited to about 100 V. Each of the series strings is switched on and off using two insulated gate bipolar transistor (IGBT) modules rated at 1000 A and 600 V each. The system is de-energized 100 ms before the shot to prevent damage to the system.

Fig. 8 shows current and voltage waveforms measured for a 28 cm × 30 cm × 100 μm foil driven by the battery bank, and the tantalum temperature derived using (1). A 1-s-long heating pulse allows about 15 e-folding times for hydrogen to diffuse from the interior of the 100-μm-thick tantalum. Several minutes prior to a shot, one heating pulse cleans the tantalum *in situ*. The voltage is low enough (<40 V) to prevent gas discharges that would reduce the heating. The heating pulse is repeated immediately before a shot to further clean the tantalum and keep the

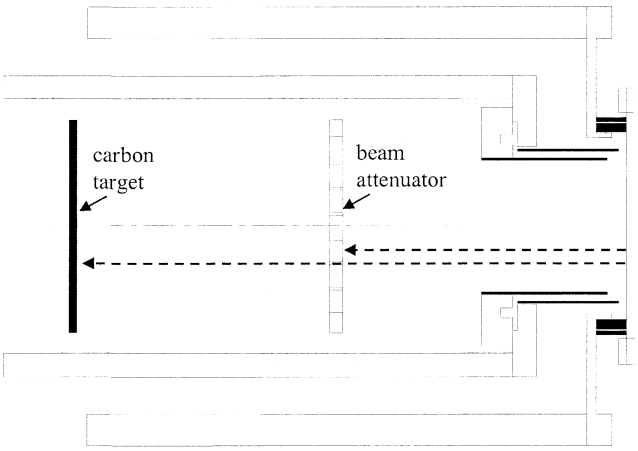

Fig. 9. Setup used to detect high-energy protons by carbon activation. The attenuator is located 22 cm from the tantalum anode and the carbon target is located 44 cm from the tantalum anode. Dashed lines indicate typical proton trajectories.

surface hot enough to prevent further adsorption. The generator current begins 200 ms after the end of the one-second heating pulse, when the temperature is 2100 K.

New diagnostics for this Gamble II experiment included nuclear activation of carbon placed inside the center conductor to detect energetic protons and a differentially-filtered silicon PIN diode array [20] to determine the electron energy and current. Both diagnostics yielded new information about the effects of heating.

The proton component of the beam was measured with the $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}$ nuclear reaction on graphite samples [21] located upstream of the hollow cathode using the configuration illustrated in Fig. 9. With unheated anodes, the ion beam ablates the carbon samples unless a stainless steel plate with an array of small holes (1.5% transparency) is used to attenuate the ion beam. With hot anodes, the activity detected using the attenuating plate was marginally larger than the background. With the plate removed, statistically significant $^{13}\mathrm{N}$ activity was obtained. A portion of this activity is produced by the $^{12}\mathrm{C}(d,n)^{13}\mathrm{N}$ reaction, depending on the ion voltage. The measured voltage and ion current were used to account for the deuteron contribution, which ranged from 8% to 53% depending on the shot. This analysis indicated a 450× reduction in the proton intensity for shots with a heated anode. The pulse-heating therefore removes hydrogen-containing materials from the tantalum.

Measurements with an array of five PIN diodes with different filters (material and thickness) are used to determine the electron current and voltage based on Cyltran [22] modeling for an assumed Gaussian distribution of electron-incidence angles on the tantalum anode. Typical results for unheated and hot anodes are compared in Fig. 10. For the unheated anode, the inferred electron current equals the measured electron current (determined by subtracting the measured ion current from the total load current), and the inferred electron energy is in good agreement with the measured voltage. For the hot anode, the inferred electron current is 30% larger (730 kA versus 550 kA) than the measured electron current and the inferred electron energy is about 100 kV larger than the measured voltage. This analysis indicates

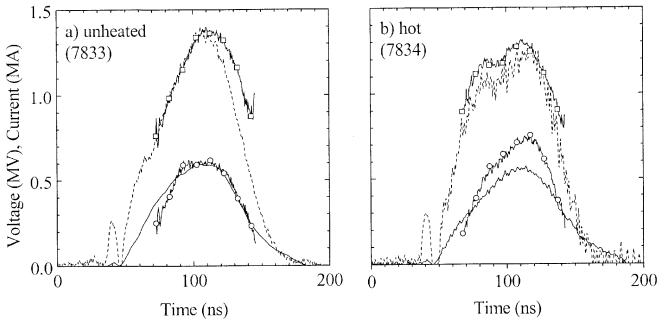

Fig. 10. Electron–current (solid line) and voltage (dashed line) waveforms for shots (a) with an unheated anode and (b) with a hot anode compared with electron current (circles) and voltage (squares) computed from filtered X-ray PIN diode signals.

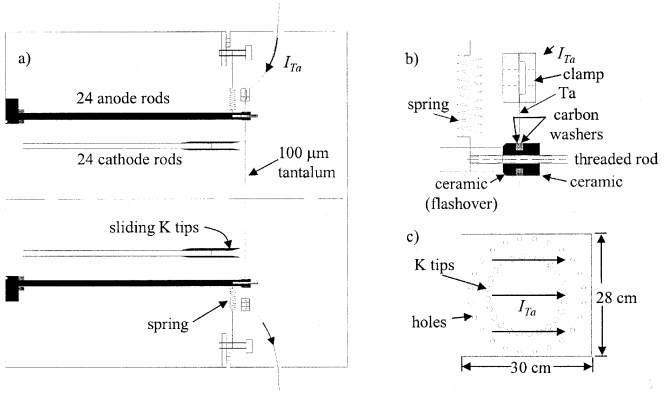

Fig. 11. Sketch of the tantalum-stretching mechanism. (a) Top view cross section, (b) close up of clamping assembly, and (c) front view of tantalum foil.

that the electron-beam assumptions used to interpret the filtered X-ray signals are appropriate for the unheated case, but the radiation is larger than expected, given the measured current and voltage, for the heated case. Overestimation of the electron current and voltage could be a consequence of electron reflexing, where transmitted electrons are reflected (reflexed) back to the tantalum by a virtual cathode formed by electron space charge downstream of the anode. For unheated anodes, the presence of ion space charge prevents virtual cathode formation. This kind of reflexing mechanism has been inferred from experiments [23] with similar diode configurations and is being pursued as a way to efficiently produce "warm" (10–100 keV) X-rays [24].

C. Third Gamble II Experiment

The third Gamble II experiment tested a mechanism for stretching the tantalum *in situ*, keeping it flat while it is being heated (similar to the technique used in [3]). Fig. 11 is a sketch of the clamping and stretching mechanisms. Here, the cathode is a cylindrical array of 24 rods on a 16-cm diameter with sliding hollow-cylinder tips on each rod (this cathode is similar to one investigated during the development of Decade modules [19], and produces reproducible centering of the beam on the anode.). The outer conductor consists of 24 33-cm-long rods on a 26-cm diameter. The tantalum foil is connected to the free ends of the anode rods where springs pull radially outward to tension the foil. A ring of 24 holes is punched in the tantalum foil at the diameter of the anode rods. A small threaded rod

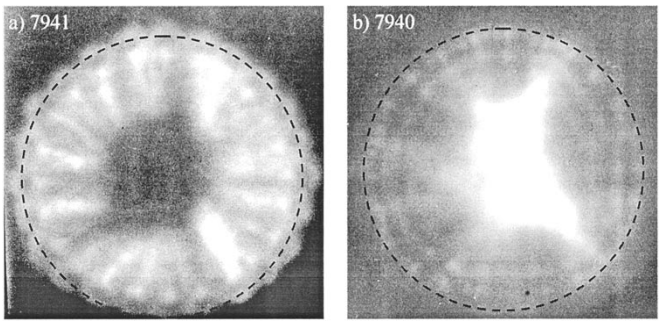

Fig. 12. Time-integrated X-ray pinhole photographs of (a) hot and (b) unheated tantalum anodes using the stretching mechanism. The axes of the cathode tips lie on the dashed circles [see Fig. 11(c)].

(6 × 32) and nut at the end of each anode rod support two nested ceramic cylinders that clamp the tantalum foil between two carbon washers. The ceramic pieces provide electrical and thermal isolation from the generator during the heating pulse, then flash over when the generator is pulsed providing a current path to complete the diode circuit. The carbon washer thickness is chosen to provide an appropriate resistance in the current path near the holes in the tantalum. Without these washers, the heating current would concentrate at the edges of the holes in the tantalum, increasing the temperature there and either melting the foil or limiting the central temperature to a lower value than desired. The heating circuit is connected to the tantalum with brass clamps that connect along the length of the shorter (28 cm) sides of the tantalum foil, as in Fig. 1, outside the ring of anode rods.

The springs are stretched about 10 mm to allow the tantalum to expand during heating. The linear expansion of tantalum at 3000 K is 2%, corresponding to a 3-mm increase in the radial position of the anode rods. After a heating pulse, the tantalum is flat and smooth inside the circle formed by the anode rods, and wrinkled outside the rods because the brass clamps prevent expansion there.

The time-integrated pinhole photographs in Fig. 12 illustrate the difference between unheated and hot tantalum anodes obtained using this configuration. With the unheated anode, the beam undergoes a rapid pinch, and the X-ray emission is concentrated on axis. With the hot anode, pinching is reduced resulting in a hollow annular X-ray distribution. Electron emission from the individual cathode tips results in a set of 24 circles at the cathode diameter, indicating that the beam dwells at this large radius much longer than it does with an unheated anode. Each of the 24 cathode rods produces a local pinch at the inner edge of the cathode, which then propagates inward. The velocity of propagation is significantly slower for the hot anode, presumably because the time required to form anode plasma is longer for the hot anode than for the unheated anode. The stretching mechanism is responsible for the improved symmetry of the X-ray distribution with heated anodes. In contrast, previous experiments, even using the rod-cathode technique, always result in asymmetric images, similar to those in Fig. 5, probably because thermal expansion results in wrinkling of the tantalum.

The dose in the far field was measured with CaF_2 TLDs that record the time-integrated dose at 1 m from the tantalum, and

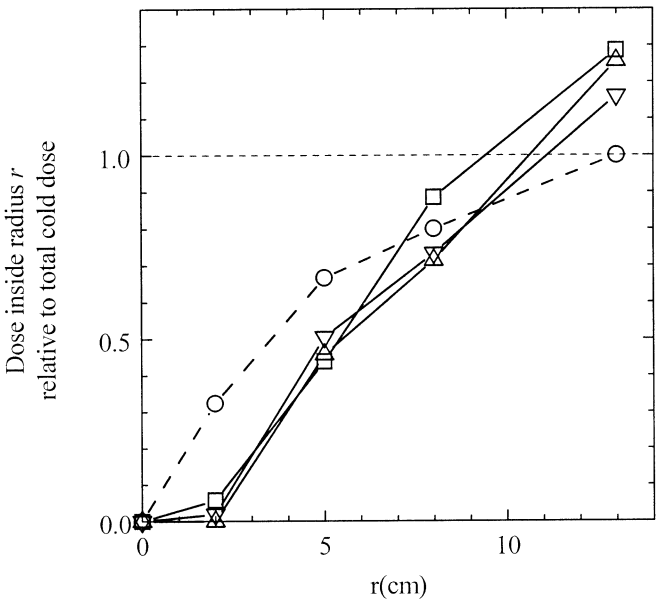

Fig. 13. Dose distributions measured with collimated PD detectors relative to the total dose for a shot with an unheated anode (circles). The cathode tip axes are located at $r = 8$ cm, and the anode rods are at $r = 13$ cm. Data for three shots with hot anodes are indicated by squares and triangles.

scintillator-photodiode (PD) detectors that measure the time-dependent X-ray emission. The integrated PD signals for different shots measure the relative dose in the scintillator. Comparable data were obtained for three shots with unheated anodes and four shots with hot anodes. This set of shots used the same anode–cathode gap (9 mm) and had almost identical electrical power waveforms (0.5 TW peak, 60 ns FWHM) and total energy (30 kJ). The maximum current and voltage values were 0.4–0.5 MA and 1.0–1.2 MV. Both the TLDs and integrated PDs averaged over the data sets indicated a 20% increase in dose with the hot anode. This result is similar to the dose increase observed in the previous two Gamble II experiments without the stretching mechanism.

Four PDs, collimated to detect the radiation inside circles with $r = 2,\ 5,\ 8$ and 13 cm, were used to measure the X-ray distribution from the tantalum. Radial dose distributions for three heated anode shots and one unheated shot (determined by integrating and normalizing the PDs to the total integrated signal for the unheated anode shot) are compared in Fig. 13. The unheated shot in this Figure had the largest dose of the three unheated shots, based on TLD and PD measurements. For the unheated shot, more than 60% of the X-ray emission is inside $r = 5$ cm, and more than 30% is inside $r = 2$ cm. The three shots with hot anodes have a very different radial distribution. With hot anodes, the emission inside $r = 2$ cm is negligible, and the emission from the entire tantalum area ($r = 13$ cm) is 22% larger, on average. These source distribution measurements are consistent with the pinhole photographs in Fig. 12 and the TLD measurements.

For the hot-anode annular distribution, the dose distribution in the near field (i.e., less than one cathode radius away from the anode) will be more uniform than for the unheated anode which has a point-like distribution. An array of four such diodes on

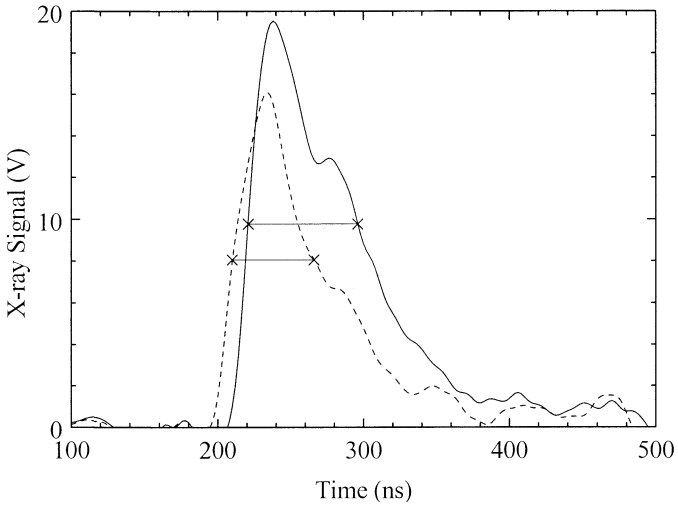

Fig. 14. Comparison of X-ray signals from DM2 for shots with hot (shot 839, solid line) and unheated (shot 838, dashed line) anodes. Horizontal lines with crosses indicate the FWHM. Time zero corresponds to the start of the generator current, upstream of the POS.

Decade would then produce a more uniform exposure than four unheated anodes.

D. DM2 Experiment

Decade uses a plasma-opening switch (POS) to generate a fast (50 ns), high-voltage (1–2 MV) pulse [19]. Pinch-beam diodes are the only demonstrated technique to efficiently produce bremsstrahlung from this generator. Other diodes that would produce more uniform dose distributions, such as ring diodes, require vacuum convolutes on the downstream side of the POS that probably will result in power flow losses and reduced X-ray production. Using the heated tantalum anode is an alternate approach to both increase the dose and make a more uniform dose distribution in the near field.

A brief experiment (six shots) on DM2 at Titan Pulse Sciences Division, verifies that the hot tantalum system works in the Decade environment. The diode configuration was identical to that tested on Gamble II (Fig. 11) except for a smaller A–K gap (7 mm). Electrical diagnostics determine the current on the upstream side of the POS and the voltage, inductively corrected to the POS location. The radiation measurements include the array of four collimated PDs used on Gamble II, an array of LiF TLDs located 7.5 cm from the tantalum, and a time-integrated pinhole camera.

Two shots with almost identical POS voltage and upstream current demonstrate the potential improvement heating provides for this system. Fig. 14 compares PD signals for these two DM2 shots. The PD amplitude is larger (by 20%) and the FWHM is larger (75 ns versus 56 ns) for the shot with heated tantalum. Enhanced reflexing and greatly reduced hydrogen in the diode can account for both the increased X-ray amplitude and longer X-ray pulse. The integrated PD signal is about 40% larger for the heated tantalum shot. The array of LiF TLDs at the vacuum window indicated 30% larger dose, on average, for the heated case. However, the X-ray distribution indicated pinching of the electron beam near the axis for both shots, based on pinhole camera images, TLD maps and time-dependent, collimated-PD signals. This result differs from the Gamble II experience and may indicate that space charge from the POS plasma is reaching the diode and allowing the beam to pinch.

A practical advantage of the heated tantalum anode on Decade is greatly reduced activation of the electrodes. Normally, the stainless steel cathode tips become activated by nuclear reactions induced by high-energy protons [25]. If the activity is too large, the vacuum chamber must remain closed until the activity decays to an acceptable level, substantially increasing the time between shots. The DM2 experiment demonstrates that heated tantalum anodes reduce the activity to only slightly above background, significantly less than measured on shots without heating. This reduction in activation is attributed to eliminating hydrogen in the tantalum. Also, these results imply that the high-energy protons that activate the electrodes on shots without heating come from the tantalum anode, not the POS plasma.

IV. Conclusion

A simple technique to pulse-heat tantalum anodes to white-hot temperature results in improved bremsstrahlung from high-power electron-beam diodes. A resistive-heating procedure, consisting of one preheat pulse to 2200 K or larger followed by a second heating pulse simultaneous with the shot, is sufficient to produce several beneficial effects, even in the relatively dirty vacuum environment of typical pulsed-power generators. Heating to only 1500 K results in premature impedance collapse, as does heating to 2200 K without a preheat shot. Preheating alone makes no noticeable difference compared with shots with no heating.

Experiments on Gamble II demonstrate that heating reduces the proton component of the beam by more than two orders of magnitude. With heated anodes, beam pinching is reduced, resulting in a hollow radiation source that will produce a more uniform dose distribution in the near field compared with an intense pinch (point source). The dose is about 20% larger with heated anodes, a result of reduced ion current and enhanced electron reflexing by a virtual cathode mechanism. A foil-stretching mechanism keeps the tantalum taut and flat during heating, greatly improving the symmetry of the radiation source compared with shots without active stretching. Heating reduces tantalum contaminants and should therefore eliminate an uncontrolled variable, improving shot-to-shot reproducibility.

In an experiment on a Decade module (DM2) where a POS generates a fast, high-voltage pulse, the heated tantalum anode results in 30% increase in dose. Both the amplitude of the radiation and its pulse width increase, consistent with reduced ion current and enhanced reflexing. An additional practical advantage of heating the tantalum is nearly eliminating nuclear activation of the electrodes.

At least two other applications could benefit from heating the tantalum anode. Reflex diodes intended to improve the efficiency of warm (10–100 keV) X-ray production use very thin tantalum foils, typically 13 μm or less, as the bremsstrahlung converter. The challenge is to force electrons to reflex through the foil many times and eventually lose their energy there. This scheme is limited by the enhanced ion current drawn out of

the anode by the electron space charge. Heating the tantalum could significantly reduce the ion current and improve the efficiency of the reflex diode. A second application is operation of bremsstrahlung diodes at very small radius and A–K gap in order to increase the electron current density, pushing the near-field dose rate to its practical limit. Electrode plasma closure traditionally limits the A–K gap in high-power diodes to no less than 2–3 mm. Heating the anode may increase the anode plasma formation time enough to extend diode operation to smaller gap sizes. Changes would also be needed to delay or reduce the expansion of plasma from the cathode.

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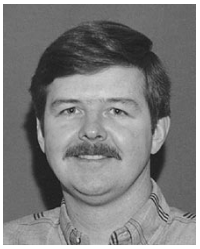

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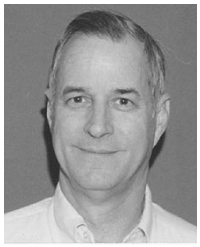

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