SUPPRESSION OF ION EMISSION AND PINCHING USING HEATED TANTALUM ANODES IN HIGH-POWER ELECTRON-BEAM DIODES[†]

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Abstract Pulse-heating tantalum anodes to > 2200 K results in drastic changes to ion emission and beam dynamics. The ion current starts later, the peak ion current is reduced, and beam pinching is suppressed or eliminated. The diode current follows a single-species Child-Langmuir formula until the voltage exceeds 1 MV, then follows a critical current formula, indicating that ions have little effect on the diode impedance. The experiments indicate a definite dependence on different heating procedures. This technique can be used to improved x-ray production on high-power generators such as Decade.

Keywords ion emission, tantalum, x-ray, electron-beam, pinching

I. Pulse-Heated Tantalum

Tantalum is the conventional anode material used in x-ray diodes on high-power generators. Tantalum absorbs gases, especially at elevated temperature (maximum absorption for T = 1000-1500 K). Low-Z gases can become sources of ion (mostly proton) currents that decrease the x-ray production efficiency. Gases entrained in the tantalum may be removed by heating, ideally leaving only pure tantalum which will contribute negligible ion current. Eliminating ions should also eliminate pinching, resulting in a more distributed (more uniform) radiation pattern.

The use of heated anodes in high-power diodes has been investigated previously, primarily in 1975-80. 1),2),3),4),5) In these references, anodes were heated by various dc techniques (acetylene torch, electron emitter, heater coils) to 700 – 1300 K. Compared with anodes at room temperature, the impedance collapse was delayed significantly, low-mass ions were suppressed, and pinching was delayed (but not eliminated). Heating tantalum to only 700 K had no effect (Refs. 4 and 5), consistent with the material properties discussed below. More recent articles6),7) have revitalized interest in this area.

The work reported here differs from previous work by using slow, pulsed resistive-heating to attain much greater temperature, T > 2200 K, required for gas diffusion from the center of the tantalum to the boundary, and to break down oxides and nitrides on the tantalum surface.8),9) A capacitor bank and step-down transformer are used to drive current through a 50-μ thick, rectangular (165 mm × 180 mm) tantalum foil installed in Gamble II as illustrated in Figure 1. The foil is clamped at opposite sides and stretched

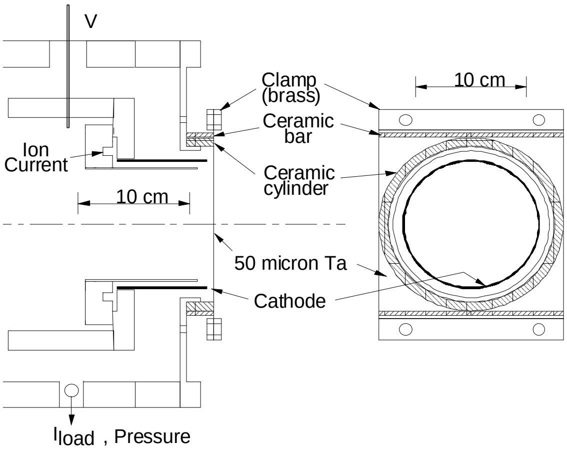

Figure 1. Tantalum heating setup on Gamble II.

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over ceramic bars and a cylinder to provide thermal and electrical isolation during the heating process. The inside surface of the ceramic cylinder flashes when Gamble II is fired.

The measured tantalum voltage, V_{Ta}, is used to calculate the temperature by numerically solving the heating equation (neglecting conduction losses):

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

where m is mass, $C_p(T)$ is heat capacity, $R(T)$ is resistance, $\varepsilon(T)$ is emissivity, A is radiating area ($A = 2lw$), σ is the Stephan-Boltzmann constant, and T_0 is the initial temperature. An example of this analysis for the heating pulse on a Gamble II shot is shown in Figure 2. The 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 not through evolved gas. A pressure gauge near the tantalum indicates a 0.5 mTorr increase at 50 ms, then a gradual decrease as the evolved gas fills the vacuum chamber. Gamble II shots were fired at t = 150 ms, a compromise timing that allows gas to disperse but maintains high temperature.

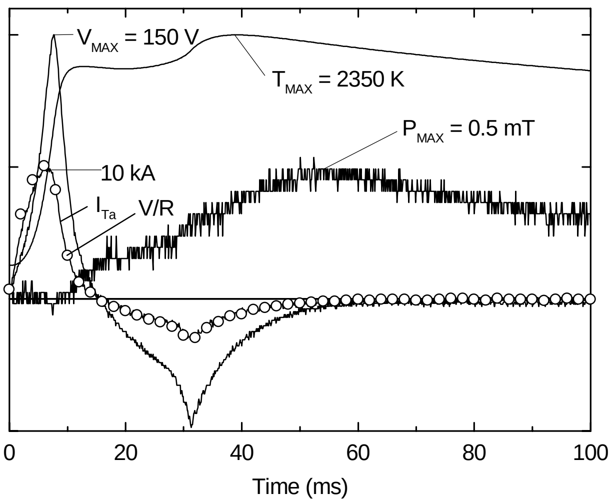

Figure 2. Heating analysis for a Gamble II shot.

II. Gamble II Experimental Results

Twelve Gamble II shots were fired with different heating procedures. Three shots were taken with no heating. Six shots were taken where 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 2200 K or greater on both the preheat and Gamble II shots, and two “ineffective-heating” shots, where gas breakdowns limited the temperature to about 1500 K on the Gamble II shots. Two shots were taken with no preheating, and one shot was taken with preheating only.

The load voltage is determined by a resistive divider (see Fig. 1). Load current is measured using two B-dot loops. The ion current is measured with a rogowski inside the center conductor. X-rays are diagnosed with several time-resolved detectors, TLDs at different distances, and a time-integrated pinhole camera.

Pinhole camera images illustrate the dramatic effect heating has on the electron beam dynamics. Figure 3 compares end-on images from typical shots with no heating (left) and with effective heating (right). Both images are the same exposure and spatial scale. The unheated anode image shows an intense pinch in the center of the tantalum; the heated anode shows emission from a larger area with little emission from the center. The filamentary structures in the heated case may be partly the result of wrinkling that results from the heating pulse.

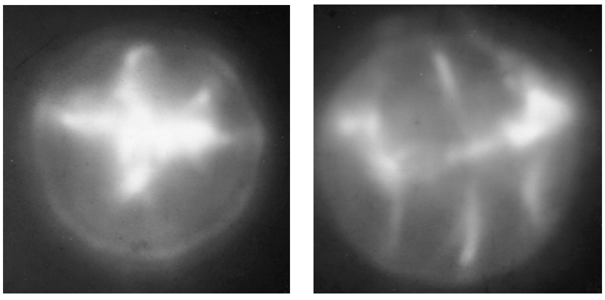

Figure 3. X-ray pinhole camera images for an unheated shot (left) and an effective-heating shot (right).

X-ray signals for four different heating procedures are compared in Fig. 4. The largest signal for each heating procedure is shown. The "ineffective heating" (T = 1500 K) and "no preheat" shots produce much less radiation than the "no heating" shots. This can be attributed to gas in the diode gap that becomes ionized and prematurely shorts the diode. The "effective heating" shot produced more radiation than the "no heating" shot and shows no evidence of premature impedance collapse.

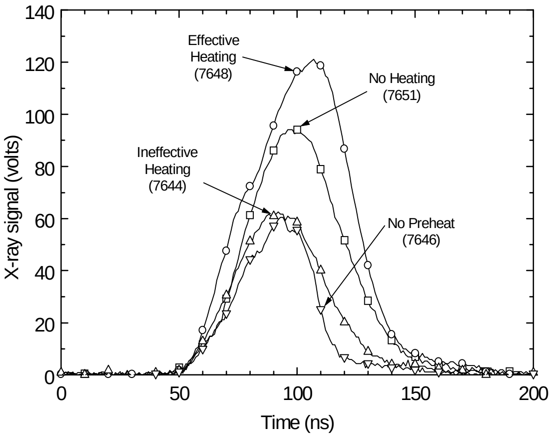

Figure 4. X-ray signals for different heating procedures.

Electrical data for a no-heating shot are plotted on the left in Fig. 5. The ion current begins 30-40 ns later than the load current, 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. Ion current measurements are compared on the right in Figure for the no-heating and effective-heating shots. Heating results in 10-20 ns delay and about 50% decrease in the ion current, part of the reason that the x-ray production increases with effective heating. The effective heating shots produce more radiation even after accounting for ion currents, voltage and electron beam energy. This suggests that the heated anodes are more efficient x-ray targets than unheated targets, possibly a result of ion reduction that allows virtual cathode formation and reflexing of electrons back into the tantalum, increasing the x-ray production efficiency.

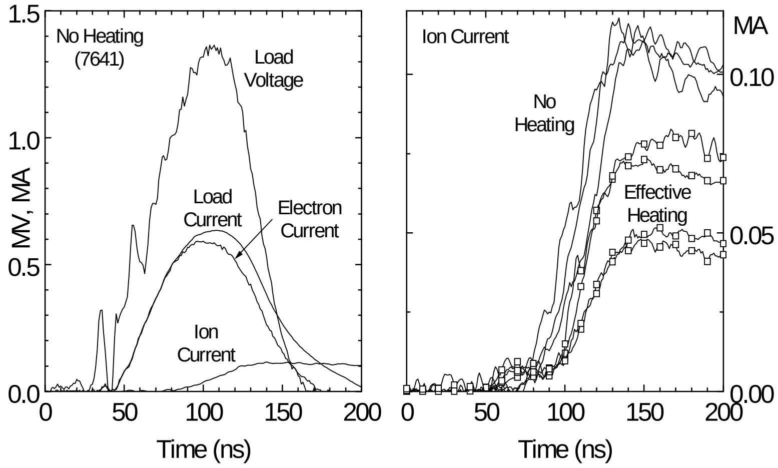

Figure 5. Electrical data (left) and ion currents (right).

The $I(V)$ dependence can be compared with simple models. Space-charge limited emission without ions is described by a Child-Langmuir current, I_{CL}:

$$I_{CL}(kA) = 2.32A\frac{V_{MV}^{3/2}}{D^2}\text{, where } A \approx 2\pi r(\Delta r + 2D) \text{ and } D = D_0 - vt\,.$$

A is the effective emission area from a cylinder and the gap, D, decreases with velocity v. When ions are present in the gap, the current increases to the bipolar value, $I_{BP} = 1.86 I_{CL}$. When the electron orbits are bent in the magnetic field and strike the anode at grazing incidence, the current and voltage are related by the critical current formula:

$$I_{crit}(kA) = 1.6\times 8.5\sqrt{\gamma^2 - 1}\,\frac{r}{D}\text{, where } \gamma = 1 + eV/m_e c^2\,.$$

In principle, I should be space-charge limited (I_{CL} or I_{BP} depending on whether ions are present) until I_{crit} becomes smaller, then the current is magnetically limited. Comparing the $I(V)$ data with these models is an indication of the influence of ions on the diode impedance.

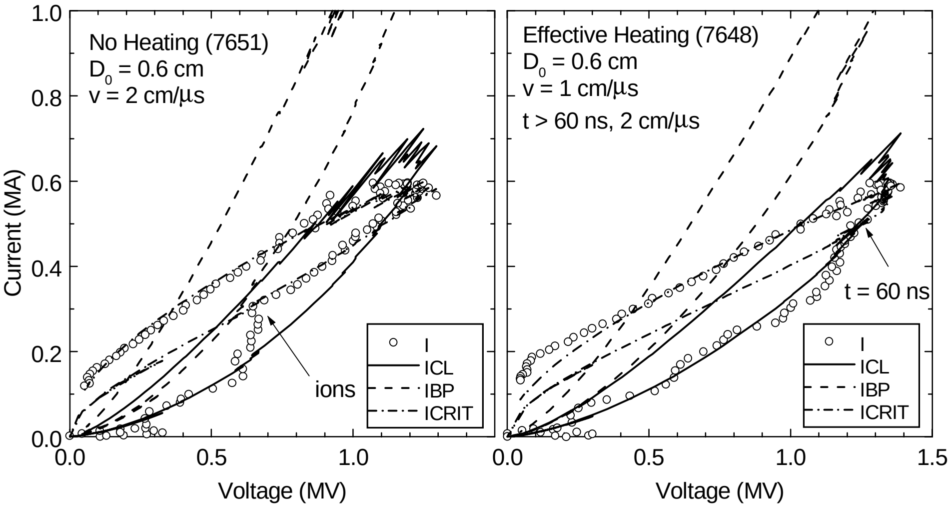

Figure 4. $I(V)$ for unheated (left) and heated (right) tantalum.

Data from typical shots with and without heating are compared with the diode models in Figure 4. For the unheated shot (left) the current (circles) initially follows I_{CL}, then rapidly increases to the point where I_{BP} and I_{CRIT} intersect, when $V > 0.6$ MV. This is strong evidence for the presence of ion space charge in the diode gap. The $I(V)$ data follows I_{CRIT} for the remainder of the pulse. The shot with effective heating (right) transitions to I_{CRIT} at 1.2 MV with no evidence of ion effects.

III. Conclusions

Pulsed resistive heating of the tantalum converter can change the condition of the x-ray target in ways that may be beneficial for high-power generators, such as Decade. Three potential advantages are: increased x-ray production from reduced ion currents and possibly increased reflexing; reduced pinching to produce a more uniform x-ray distribution; and more control of tantalum contaminants to improve shot-to-shot reproducibility.

A simple heating procedure consisting of one preheat shot to 2200 K or greater followed by a second heating pulse beginning 150 ms prior to the shot is sufficient to produce the desired effects. 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. Heating to higher temperatures for longer times may further reduce ion currents and make greater improvements in x-ray production.

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