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Electrode Conditions and Their Effect on Impedance Collapse

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Changes in electrode conditions affect impedance collapse, seen in our 300 kV diode as a rapid increase in current beyond the 1 kA space charge limit. Impedance collapse comes about 100 ns later than the usual 200 ns when the diode's tantalum anode is hot (600 - 1000 K). Covering the carbon fiber ring cathode with cesium iodide delays collapse by another 100 ns. These observations might come from pre-shot removal of loosely bound adsorbates off the anode by heating, and easing electrode emission from the cathode from more but smaller, less violent explosive emission spots. We suggest modifications that implement these areas in DECADE.

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SUMMARY

The present SBIR is to check two techniques that could reduce undesirable (plasma) effects in a bremsstrahlung diode. Task 1 is to evaluate cathodes treated with cesium iodide (CsI). Task 2 is to evaluate the influence of thermally cleaned anodes, and to see whether thermal cleaning is compatible with the cathode's CsI. The final task 3 is to suggest how the two techniques, if proven to be useful, could be applied further.

Experiments show that both CsI on the cathode and heating of the anode have their desired effect. Figure 1 summarizes the conclusions. The Figure shows the current to the anode as a function of time for a particular electrical pulse (with 300 kV peak voltage: details are in the appendix) on three diode versions that differ only in treatment of the cathode and the anode. The dashed line is for a typical pulse power diode without any special attempt at cleaning. The two solid lines come from heating the anode and putting CsI on the cathode. The plateau in the current is for the space charge limited regime when the diode produces radiation. The rapid increase in current at later time is called diode collapse or impedance collapse. In this regime the voltage across the diode collapses to zero: after collapse the diode produces little or no radiation. For the baseline shot the impedance collapses after about 200 ns.

Both electrode treatments delay impedance collapse. The middle solid line is the current with a hot anode. When the anode is hot the collapse occurs after about 300 ns, a 100 ns and 50 % increase that is reproducible. Shots at different vacuum pressures and with different anode histories prove that the controlling parameter is anode temperature, and not one of these other influences.

The right-most solid line is the current when the anode is hot, and in addition there is cesium iodide on the cathode, in this case a ring of carbon fibers. Thanks to the CsI the collapse is another 100 ns later. Apparently, the CsI works well despite the 1000 K anode less than 20 mm away: the two methods to suppress plasmas from the two electrodes are clearly compatible. These observations, various additional data described in the appendix, and results from additional many shots demonstrate that parasitic plasma phenomena can be controlled to an interesting extent. Moreover, the methods are easily implemented, and compatible with each other. This fulfills the first two tasks in the Statement of Work.

The next Chapter shows how to implement the techniques on one of the modules in the DECADE Quad. The diodes being built differ slightly from the ones available on DM1 or its sister DM2, and at this time it is not clear which of these machines might be used to verify the suggestions to be given. To be specific, we have used the latest design of the diode as conveyed to us by the responsible person at then-Primex Physics International, now Maxwell Physics International (MPI). This chapter fulfills task 3.

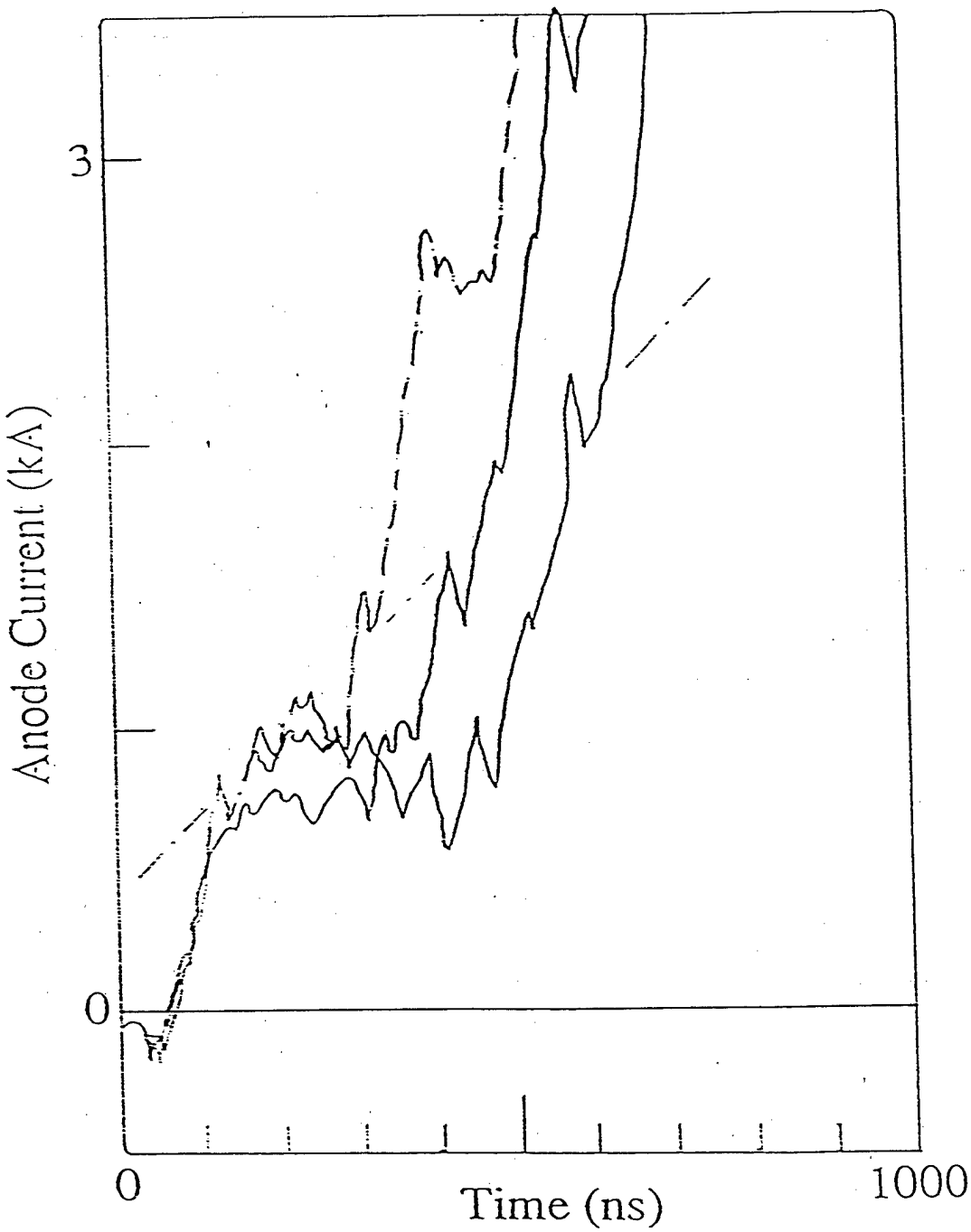

Figure 1. Summary: Diode current - for three cases: baseline (dashed), heated anode (middle), and CsI on fiber cathode

CONVERSION TABLE

Conversion factors for U.S. Customary to metric (SI) units of measurement

MULTIPLY ⟶ BY ⟶ TO GET
TO GET ⟵ BY ⟵ DIVIDE

angstrom	1.000 000	X E -10	meters (m)
atmosphere (normal)	1.013 25	X E +2	kilo pascal (kPa)
bar	1.000 000	X E +2	kilo pascal (kPa)
barn	1.000 000	X E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350	X E +3	joule (J)
calorie (thermochemical)	4.184 000		joule (J)
cal (thermochemical)/cm^2	4.184 000	X E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000	X E +1	*giga becquerel (GBq)
degree (angle)	1.745 329	X E -2	radian (rad)
degree Fahrenheit	T_K = (T °F+ 459.67)/1.8		degree kelvin (K)
electron volt	1.602 19	X E -19	joule (J)
erg	1.000 000	X E -7	joule (J)
erg/second	1.000 000	X E -7	watt (W)
foot	3.048 000	X E -1	meter (m)
foot-pound-force	1.355 818		joule (J)
gallon (U.S. liquid)	3.785 412	X E -3	meter^3 (m^3)
inch	2.540 000	X E -2	meter (m)
jerk	1.000 000	X E +9	joule (J)
joule/kilogram (J/kg) (radiation dose absorbed)	1.000 000		Gray (Gy)
kilotons	4.183		terajoules
kip (1000 lbf)	4.448 222	X E +3	newton (N)
kip/inch^2 (ksi)	6.894 757	X E +3	kilo pascal (kPa)
ktap	1.000 000	X E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000	X E -6	meter (m)
mil	2.540 000	X E -5	meter (m)
mile (international)	1.609 344	X E +3	meter (m)
ounce	2.834 952	X E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222		newton (N)
pound-force inch	1.129 848	X E -1	newton/meter (N - m)
pound-force/inch	1.751 268	X E +2	newton-meter (N/m)
pound-force/foot^2	4.788 026	X E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757		kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924	X E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011	X E -2	kilogram-meter^2 (kg·m^2)
pound-mass-foot^3	1.601 846	X E +1	kilogram/meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000	X E -2	**Gray (Gy)
roentgen	2.579 760	X E -4	coulomb/kilogram (C/kg)
shake	1.000 000	X E -8	second (s)
slug	1.459 390	X E +1	kilogram (kg)
torr (mm Hg, 0°C)	1.333 22	X E -1	kilo pascal (kPa)

* The Becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.

** The Gray (GY) is the SI unit of absorbed radiation.

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Chapter 1.

1.1: Introduction.

Heating the tantalum anode improves a standard bremsstrahlung diode, which works even better when in addition the cathode is replaced by graphite fibers that are coated with cesium iodide. Although the parameters of this diode are not identical to those in a DECADE Quad module, it seems likely that the same measures could help in achieving the machine's desired output. This Chapter shows that the two measures are compatible with the machine as it is being built: retrofitting the diode is therefore rather straightforward. Before implementing the changes based on extrapolations from the work so far, it may be prudent to do additional tests on how to suppress undesirable plasma with anode heating and graphite fibers with CsI, now exactly the desired regime.

Extraneous plasma may cause problems in the diode, but it could also have deleterious effects on the plasma-opening switch. In this switch, a well-defined amount of plasma is purposefully injected in between the discharge electrodes. The plasma is dense enough to conduct the current in a quasineutral fashion for some time, the conduction time. When all is well the conduction ends suddenly: the electrodes acquire a voltage (and what is left of the plasma develops a net space charge) through complicated processes inside the plasma that remain to be investigated. It is obvious that an unplanned plasma source could cause problems, ranging from a slightly delayed opening to instabilities in the plasma dynamics and even no opening at all. There is tantalizing but no definite evidence for such occurrences: our experiment here did not address the anode in a plasma-opening switch.

Even if unintended plasma had a minor effect on an opening switch, a variation in unintended plasma would cause changes in the opening time. Jitter, that is, (assuming the unintended plasma varies from shot to shot, since it is uncontrolled). For jitter reduction reasons alone it seems mandatory to keep disturbing plasmas to a minimum, and to keep whatever is left at the same level. Therefore, we suggest heating the anode in the plasma-opening switch together with the anode in the bremsstrahlung diode itself, so that plasmas in both devices are minimized together. Fortunately, this is not only possible but even desirable because it minimizes heat loss, see below.

Figure 1 is the diode on the DECADE Quad. The cathode in the center is a cylinder about 127 mm (5 inches) diameter about 500 mm long. On the top left side is one of the plasma injectors for the plasma opening switch. An idealized picture of the plasma flow from such an injector is suggested by the conical lines between the outside anode and the indentation in the cathode. In the upstream direction, to the left, the plasma flow is restricted by a skimmer but in the downstream direction, the plasma flow in unrestrained. Sometimes the cathode is not a solid cylinder but consists of parallel strips (and shown in the figure) so that the plasma penetrates into the cathode in part: another part of the plasma reflects back toward the anode. Just to the left of the plasma guns is a coil cooled with liquid nitrogen, intended to increase the pumping speed close to the plasma gun. The cathode is a solid stainless steel ring 6 mm (1/4 inch) wide.

The bottom part is the diode under construction, while the top part suggests the changes needed to suppress parasitic plasmas. There are two parts, the heated anode and the graphite fiber/CsI cathode.

1.2: Heated anode.

The top part of Figure 1 gives one way to implement a hot anode. In the present implementation, as being built and shown on the bottom of Figure 1, the outer vacuum envelope doubles as the anode. Its shape is slightly conical in order to accommodate the other three diodes of the DECADE Quad. The outside envelope may have current monitors attached to the side, ports for letting in argon-oxygen mixtures needed for discharge cleaning, and other small items not shown in the figure. The thin tantalum converter is stretched inside the vacuum envelope, which is closed at the end with a plate covered by the necessary electron stopper.

Suppressing unnecessary plasma from the anode with heating suggests separating the functions of vacuum envelope and anode, as shown in the upper part of Figure 1. The design here demonstrates that the anode can be kept in exactly the same position in order to keep the electrical functioning of the diode the same. The new vacuum envelope is then slightly outside the old one. The new cone is welded to the flange just inside the boltholes (these are seen only in the bottom part): to accommodate the larger vacuum envelope the bolts must become longer, use spacers, or something similar. It is cheaper to do the opposite, to keep the same vacuum envelope and to reposition the anode. A drawing to this end will be shown elsewhere.

Inside the new vacuum envelope is the old anode for the plasma opening switch. To drive off as much dirt as possible the anode must be heated to e.g. 450 Celsius (700 K, the temperature where stainless steel vacuum vessels are commonly outgassed) or a higher temperature if feasible. For heat loss estimates later we use 1000 K. Heat loss by conduction is smallest when the support is has the smallest possible cross section, and the longest length. Here the suggestion is to use six thin spacers spaced azimuthally at 120 degrees at two axial locations (as shown). This is analogous to the 4-40 bolts that held the stainless steel pipe inside another pipe in the prototype tests. The anode is connected electrically to the generator upsteam by a thin stainless steel shim (not shown).

The tantalum foil is held to the stainless steel anode by some clamping fixture. Keeping the foil taut is a major concern. Fortunately, as it gets hotter the tantalum expands about half as much as stainless steel, 0.63 % per 1000 degrees versus 1.7 % (for 304 steel: other steels may differ). On heating the steel tightens the tantalum, and nicely so if the temperature were to be uniform in the entire structure. Without heat loss, the structure's temperature must be constant throughout, and no heating is necessary. However, there is still a minor heat loss through the vacuum, and a much larger heat loss from radiation. Heat flow to maintain radiation loss might results in temperature differences and stress in the structure. Estimates show these issues to be minor.

The energy per unit area radiated by a black body is only 400 W/m^2 at room temperature (300 K) but more than 100 times higher at 1000 K, 50 kW/ m^2. From a shiny surface, the heat loss is perhaps 10 times less, but in any case still substantial. From the anode cylinder, the main heat loss is to the outside. On the inside is the cathode, which is allowed to heat up (except for plastic-insulated cables on the inside, see below). The outside anode surface with its 0.75 m circumference (10 inch diameter) and 0.4 m (15 inch) length is about 0.30 m^2, suggesting 2 kW in radiative heat losses. Vacuum furnaces struggle with the same problems, and their solutions apply here.

One way to minimize radiative heat loss in a vacuum is with one or more intermediate barriers. Usually these are made from tantalum foil because this solution is the only one that works for the highest temperatures, over 2000 K or so. Below 2000 K, there are excellent isolation materials, one of which we used in the test here. Figure 2 shows the thermal conductivity of a typical material, zirconia felt type ZYF from Zircar Products (see e.g., www.zircar.com). Its heat conductivity at 1000 K (750 Celsius) in vacuum is 0.7 W/mK. A 20 mm thick layer of ZYF surrounding the anode cuts the heat loss down to 1.5 kW. A better but more expensive material (type FBD) with conductivity 0.3 W/mK lets through only 700 W.

Additional heat is lost from the anode itself, which radiates toward the cold electron stopper, and backwards in the upstream direction. Additional loss estimates must be done on those aspects before building the hardware. Whatever the theoretical estimates, in reality the heater supplies whatever power it is designed for, and the temperature increases until the losses come up to the input power.

For conduction the losses are proportional to temperature if the heat conductivity were constant, but as seen in Figure 2 this is not the case. Instead, the heat conductivity increases linearly with temperature or perhaps even faster. Without heat insulation, the heat loss is proportional to T^4, and some equivalent heat conductivity varies as T^3. Therefore, the final temperature is not proportional to heater power but varies more slowly. Clearly, the anode heater needs no more than about 1 kW to get to an acceptable temperature.

Heating is done with standard heating elements as in your home oven (up to 600 K) or fancy versions thereof for higher temperatures. Special alloys or pure metals can also be used. Nichrome wire is used in pottery kilns that can reach over 1300 K, but for the highest temperature, tungsten is the best choice. It is conveniently available thanks to the incandescent lamp industry, and is used in the test here. A coil of such wire would be wrapped around the anode cone. This way the heating is done in a distributed way, in the same place as the heat losses. Temperature differences and mechanical stresses from differential heating are then minimal.

Figure 1's anode temperature can be measured conveniently with thermocouples, as done in our test. One of these thermocouples occupies a feed-through in the vacuum enclosure.

Unfortunately, the standard electrical diagnostics are not compatible with anode heating. Any B-dot loop embedded in the 1000 K anode must be constructed from heat-resistant materials such as ceramics: the usual plastics or epoxies are verboten. The function of the first B-dot can be taken over by looking at the voltage across the small resistor formed by the thin stainless steel foil bridge to the hot anode, but the others are not so easily replaced. How to provide the necessary diagnostics will be taken up in a hardware design phase.

The plasma opening switch anode is now hot. This hot cylinder of stainless steel supports the tantalum bremsstrahlung anode, a thin foil at about 10 mm distance from the cathode. The foil must be kept taut despite expansion from the higher temperature, and any stresses from differential expansion due to temperature gradients and differences in materials. The stainless steel anode expands 1.7 % when the temperature increases by 1000 degrees, while the tantalum expands less than half as much, only 0.63 %. Supporting the tantalum foil on a stainless steel ring will therefore stress the tantalum automatically, and keep it taut. Tantalum is ductile. As a result, the foil may stretch, and when the support shrinks on cooling the foil may crinkle. Repeated heating and cooling cycles would not be good: instead, one should heat up to the desired temperature, and then shoot the machine. After the shot, the remains of the foil are recycled, and the foil's recovery is not an issue.

It is appropriate to mention again that the beneficial effects of heating the anode foil have been observed before. The most relevant experiment was done in the late 1970's at Physics International by Dr. R. Genuario (see Appendix). Despite the apparently positive results the finding was not implemented into a standard design, perhaps in part because Dr. Genuario's failure to do more than a single shot with a hot anode, casting doubt on the finding's reproducibility. Another problem may have been that heating the tantalum made the foils crinkle, perhaps because the foil support remained cold. Wavy foils are obviously unacceptable because the varying anode-cathode gap causes variations in the space charge limited current density. Any such differential heating problems disappear by also heating the support, which in this case is the plasma opening switch anode.

1.3: Carbon fiber cathode with cesium iodide (CsI).

The cathode in Figure 1 suggests one extremely simple way to get the benefits from carbon fibers soaked in CsI: simply tape carbon fiber cloth around the existing cathode. Carbon fiber cloth with all the fibers lined up comes in 100 mm (4 inch) wide rolls. Four pieces of this cloth then cover the entire 400 mm circumference of the cathode. The fibers can be trimmed by hand with scissors, mechanically by a moustache clipper, and presumably also electrically by some special equipment.

Once the cathode is prepared, the coating with CsI is easy: dip it in a CsI solution in water. Alternatives are many, but the one we used works well enough for now. In our tests, the CsI stays on the cathode despite the nearby hot anode. On the hot diode for DECADE, the cathode is most likely much hotter, up to but not beyond the nominally 1000 K anode temperature. Since CsI melts at 900 K the cathode must either remain

below 900 K or capillary action must be sufficient to keep the molten CsI attached to the thin carbon fibers. Evaporation of CsI should not be a problem: it boils at 1553 K.

1.4: Other potential benefits of a clean anode for bremsstrahlung production.

Future enhancements of DECADE may include a small-area option and a low end point energy option. The small area bremsstrahlung source must have the same 1 Ω impedance as the baseline version. However, because the cathode must be smaller, the anode-cathode gap must be narrower. To make matters more difficult, the power density on the anode foil is also higher, and any plasma effects will be worse. Cleaning the anode before the shot seems even more necessary in this case.

In a standard bremsstrahlung diode, the softer part of the x-ray spectrum is largely absorbed by the tantalum converter itself. In a standard diode, the tantalum thickness is optimized for maximum radiated energy from the diode, perhaps for maximum dose in some absorber at a relevant place. Thinner tantalum produces fewer but softer x-rays.

Some of the lower x-ray production of the thinner tantalum foils is recovered by reflexing, i.e., forcing the electrons to come back to the tantalum from the back. One way to do this is by running the machine in positive polarity, with the cathode at ground and the anode pulsed positive. This seems to work well on Pithon at MPI. Another way is to make the electrons come back by reflecting from a virtual cathode on the far side of the tantalum. This method has also worked, most recently in tests by Dr. B. Weber and colleagues at NRL. However, reflexing electrons is not always successful because it is difficult to build up a virtual cathode, and one problem that could plague virtual cathodes is a possible current of positive ions from the tantalum. Therefore, hot, clean tantalum anode foils might well improve reflexing, and make it easier to achieve softer spectra.

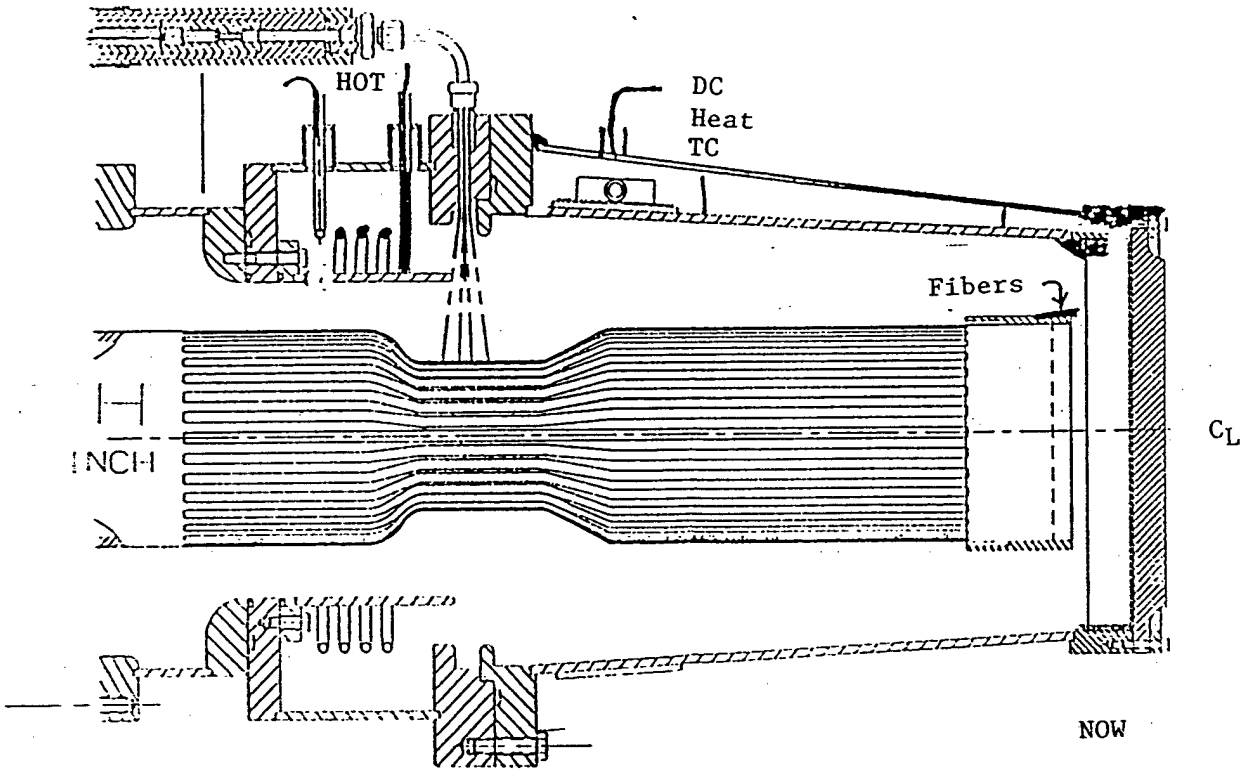

Figure 1. Diode on DECADE and possible modifications

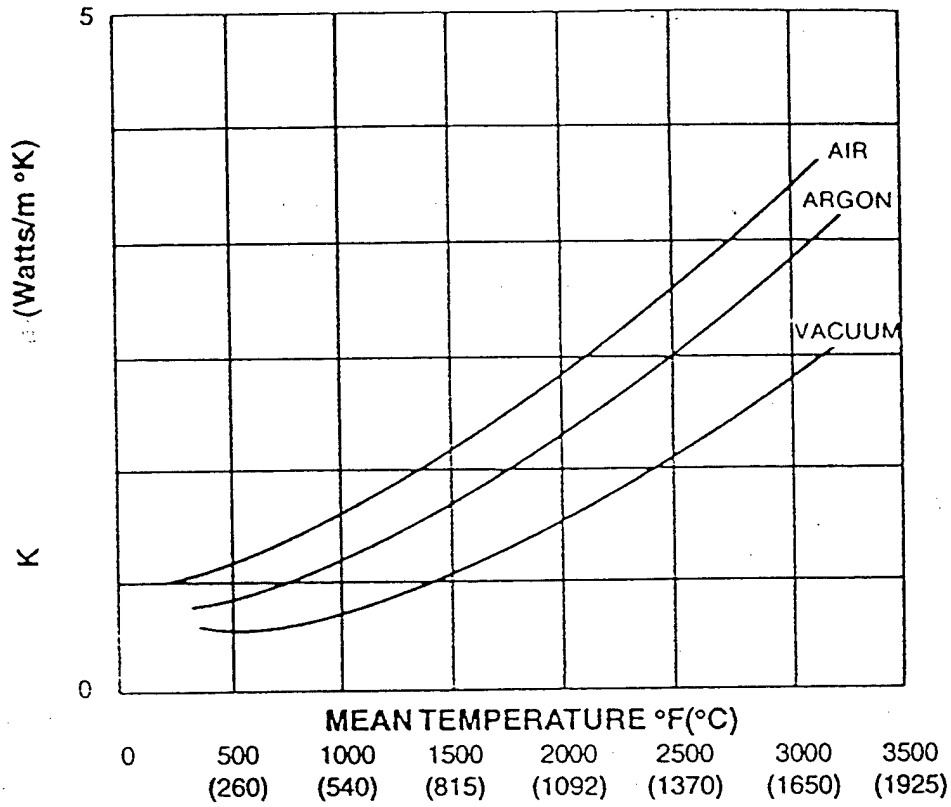

Figure 2. Thermal Conductivity of ZIRCAR Type ZYF Felt in various Atmospheres

APPENDIX

Electrode Conditions and their effect on Impedance Collapse

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Abstract: Changes in electrode conditions affect impedance collapse, seen in our 300 kV diode as a rapid increase in current beyond the 1 kA space charge limit. Impedance collapse comes about 100 ns later than the usual 200 ns when the diodes tantalum anode is hot (600 – 1000 K). Covering the carbon fiber ring cathode with cesium iodide delays collapse by another 100 ns. These observations might come from pre-shot removal of loosely bound adsorbated off the anode by heating, and easing electrode emission from the cathode from more but small, less violent explosive emission spots. We suggest modifications that implement these areas in DECADE.

Introduction:

Flash bremsstrahlung generation with pulsed power vacuum diodes[1] is often curtailed by an uncontrolled increase in current beyond the diode's space charge limit. The phenomenon, known as impedance collapse or diode collapse, is caused by plasma coming off the electrode surfaces during the discharge. The anode plasma is undoubtedly caused by electron stimulated desorption, flash heating, and similar processes. In the modest vacuum (1-10 mPa or 10^{-6}-10^{-5} Torr) typical of pulse power devices, any surface is covered with many layers of loosely adsorbed water molecules and hydrocarbons. These are knocked off by electrons or released when the surface suddenly heats up by hundreds of degrees after receiving a dose around 500 kGy to one MGy (500 J/g to 1 kJ/g) from the electrons.[2]

The cathode plasma's creation in explosive emission[3] (see also [4]) is more complicated. Explosive emission is a rapidly varying and inherently three-dimensional phenomenon with a great variety of electronic and atomic processes working together. In high power diodes, the electrons usually come from cold field emission cathodes made from stainless steel, aluminum or graphite sometimes topped with graphite fibers or other materials with many sharp points. Early on in the pulse a rapidly rising electric field pulls the electrons out of the surface in specific spots, the ones that emit electrons the easiest. These spots were at one time thought to be associated with metallic whiskers or similar field enhancement

points, but they are more likely due to subtleties in the surface that can now be found with scanning electron microscopy. The incipient current heats up the spot and its immediate surroundings. The electrons leave even easier, and the current to the spot continues to increase. Eventually the spot explodes: plasma from many different explosions ends up as a bumpy plasma cover on the cathode. Once the plasma is there it can easily supply the necessary electrons to the diode vacuum, while at the same time ions flow or diffuse back to the surface where they affect the processes further.

While microscopic processes continue close to the surface, the plasmas themselves expand from their respective surfaces into the diode. The added material causes the current I to increase, and the voltage V to decrease in response. The change in impedance $Z = V/I$ is sometimes represented by a vacuum impedance $Z(d)$ corresponding to an anode-cathode distance d that closes down with a (constant) gap closing speed v_c, as $d=d_0-v_c t$. When after the collapse time t_c the current increases rapidly the gap must have vanished, $d = 0$. In this case the impedance collapse velocity is defined by $v_c=d_0/t_c$.

Many experiments (e.g., as reviewed by Hinschelwood[5]) suggest that impedance collapse in high power diodes is not affected much by cathode material or cathode surface conditions. However, in our somewhat lower power diode the collapse can be delayed by 50% or even 100%, by two simple measures: heating the anode and covering the carbon graphite cathode with cesium iodide.

A typical example of our results is Figure 1, the current (on the vertical scale) versus time for our benchmark diode (see Figure 2). All three currents are the same early on, following the voltage increase to about 300 kV with a 50 ns rise time (see Figure 3). With the voltage at its maximum, the current almost reaches 1 kA. The remainder of the current trace depends on the electrode properties.

When the electrodes are treated as normal in a pulse power laboratory, i.e., no special care at all, the current in the diode is typically shown by the dashed line. After the initial 50 ns, the current rises in about 150 ns from about 0.7 to 1.0 kA, and the diode impedance decreases from 500 Ohm to 300 Ohm. During this time, the diode current is limited by the space charge in an apparently decreasing anode-cathode gap. Thereafter, the current rapidly increases beyond the digitizer's 3.5 kA maximum.

When the anode is hot, in this case about 900 K, the diode stays open about 100 ns longer, as shown by the left-most solid line. When in addition, the cathode has a coat of cesium iodide the collapse is another 100 ns later, the rightmost solid line. Compared to the 200 ns the diode normally remains open (dashed line), the diode with an anode at 900 K and cesium iodide on the cathode stays open twice as long, 400 ns. Some features are not significant. The 0.7 kA space charge limited current for the shot with cesium iodide on the cathode is less than the usual 0.9 kA. On this shot the generator's charging voltage was 10% lower than intended.

Measuring only the diode current is sufficient for the present purpose; a semi-quantitative

verification that the discharge has affected what is done to the electrodes. Yet the measurements contain uncontrolled variations, see examples below. However, the trends illustrated in Figure 1 are seen in the vast majority of the shots taken so far.

The results summarized in Figure 1 do not necessarily extrapolate to interesting regimes with other time scales or current densities: these might be studied later. The important point is that a simple measure as heating the anode or cesium iodide on the cathode has a desirable effect that is also more or less understandable from surface physics. In the early days of pulse power the pioneers did consider surface physics issues in designing diodes, but impedance collapse was no more than a nuisance for the short pulses and large gaps used in their radiography application.[6] The extensive work since then has not yet resulted in generally accepted to mitigate impedance collapse. Neither in very high intensity but short pulse electron diodes for flash x-rays, nor for the less intense but longer pulse diodes for pulsed microwave tubes.

For the flash x-ray application of interest here, a heated anode was tried about 20 years ago. [7] However, at that time the approach was not pursued further in part because claims to success were based only on a single successful shot. Also, because thermal expansion of the thin anode foil makes its tensioning mechanically difficult. The principal ongoing effort in improving electrode surfaces is by M. E. Cuneo and co-workers at SNL: their work has partly suppressed the so-called parasitic current that plagued ion beam diodes.[8] Related work is going on in an effort to extend pulse length in high average power microwave tubes. On the other end, heating cathodes has not worked: at least up to 1700 K the impedance collapse from a cathode plasma is the same in one experiment,[9] but hotter cathodes apparently do work better.[10]

Our interest is in improving the advanced radiation simulator DECADE. Cleaner electrodes might be desirable in its two crucial elements, the Plasma Opening Switch (POS) and the diode. As suggested below a clean diode should provide a higher radiation output from a longer pulse, and a clean POS electrode might lengthen the POS conduction time. An added benefit is the increased reproducibility that should accompany every attempt to keep hitherto floating parameters constant. A more predictable optimization: the machine's output can be optimized only by systematic variation of all relevant parameters. These must include the electrode conditions.

Further work with better diagnostics is needed to prove the two principal points suggested by additional data presented below. First, contaminants, and especially hydrogen should be removed from the anode as much as possible before the shot. Secondly, electrons should come from the maximum number of cathode spots, each with the least explosive power created by the lowest threshold fields.

Further observation on diode collapse.

Figure 2 is the diode geometry. The cathode on the left is a 13 mm diameter thin-walled stainless steel pipe topped with carbon fibers. To the right is a 3 mm thick and 50 mm

diameter tantalum anode, which is heated from behind by a coiled tungsten wire. To minimize heat loss the tungsten coil is inside a 30 mm thick zirconium oxide sponge insulator. The entire assembly is mounted on a 13 mm stainless steel tube positioned inside another stainless steel tube by three 4-40 screws at two axial positions. The temperature is measured with a chromel-constantan (type E) thermocouple junction with 0.125 mm (5 mil) thick leads, fed through a ceramic tube inside the steel tubing.

To measure the anode current the support stalk goes through the center of a ferrite core wrapped with 100 windings enclosed by an aluminum cover (found necessary against electromagnetic noise). Closing this coil with a 1 Ohm resistor gives the transformer a 100 A/V sensitivity to the anode current. The generator comes with another current monitor that measures total current with a 0.0025 Ω current viewing resistor.

With only electrons in the diode, the current is less than the Child-Langmuir space charge limit for the particular geometry. An increase in current indicates that some compensating positive charge enters the diode. If the positive charge consisted of fast ions accelerated from the anode, the diode could get into a space-charge limited bipolar regime: for a one-dimensional Child-Langmuir diode the current would then be 86% higher than without the ions. For the point-plane diode, here the increase in current from fast ions would be minimal, because most ions do not get to the cathode where their neutralizing charge would be most effective. For the diode here, which at most shows a gradual increase in current before the impedance collapses, the source of positive charge must be sought elsewhere.

Some positive charge may be left over from ionization of any remaining background gas. The maximum pressure for a bremsstrahlung discharge is usually considered about 10 mPa (10^{-4} Torr), but one typically strives for at least one order of magnitude better, 1 mPa (10^{-5} Torr). A 1 cm^3 diode filled with 10 mPa hydrogen contains about 10 pg (picogram) or 1 μ C, which carries a 1 kA current only 1 ns. Therefore, the background vacuum by itself can not cause impedance collapse.

Although the background vacuum by itself is not important, it does have an appreciable effect on the electrode surface. One single layer of atoms has approximately 10^{15} atoms/cm^2. Evaporating one such layer into the diode adds 0.4 Pa to the vacuum pressure. Therefore, an electrode is a virtually infinite reservoir of atoms. When the electrode is clean the surface atoms are tightly bound, by the same forces, that hold the metal together, and the surface atoms stay on the electrode. Surfaces remain clean only with very good vacuums, much better than the 10 mPa of a typical pulse power vacuum. Surfaces in pulse power systems are therefore always dirty, covered with water vapor, absorbed hydrogen and chemically bound oxygen (rust) for example. The dirt atoms come off the surface very easily, and destroy the diode's vacuum.

Obviously the most dangerous for destroying the discharge are the fastest ions. This is presumably hydrogen. Hydrogen is adsorbed as water or some chemically bound form of it on all surfaces in contact with air. The discharge current can loosen the hydrogen, from

the cathode in localized electron emission spots and from the anode over the entire surface. Different materials have vastly different affinities for water, so that a proper choice of electrode material should help in suppressing diode collapse.

The principal parameter of an electrode material is atomic number. For a bremsstrahlung diode, the usual material is tantalum (73) or sometimes tungsten (74). Both are refractory metals that come in a range of alloys with different properties. Each alloy's properties are further modified by fabrication processes such as heat treatments, distillation or densification in an inert or vacuum environment, and degassing. Table 10.2 in Lafferty's recent book on vacuum science and technology[11] shows tungsten and tantalum among the most adsorbing metals for all gas molecules of interest (hydrogen, nitrogen, oxygen, the carbon oxides, and the simplest hydrocarbons). Selenium and tellurium adsorb none of these, while lead and bismuth are the two high atomic number metals that adsorb only oxygen but no hydrogen.

Furthermore, each material with its specific metallurgical history may have additional parameters such as surface roughness or crystal structure. Besides these intrinsic properties, there are external parameters such as temperature. Temperature turns out to be quite influential: heating the anode to a modest 800 K or 1000 K can delay diode collapse substantially.

That heating of the anode affects the discharge's electrical behavior is consistent with desorption of loosely attached gas molecules. High vacuum systems are baked out for the same reason, to desorb all the gas that can be removed easily to prevent excessive outgassing. Cryopumps do the opposite: these pumps remove gas from a system by attaching it on a cryogenically cold surface. Just as heating the anode improves the discharge, cooling the anode should be expected to make the discharge worse. We have not tried to verify this interesting but irrelevant prediction. However, it should not hold for cases where the anode can be cooled so deeply that heating by the discharge does not desorb the gas.[12]

The following cases show in some detail how heating the tantalum anode delays diode collapse. For the baseline anode current shown in Figures 3 the diode is handled with the care characteristic of many pulse power laboratories. After leaving the setup open overnight the vacuum vessel is evacuated first thing in the morning by an oil-filled roughing pump. After reaching about 50 Pa (50 mTorr) the system is pumped to high vacuum with an 8 inch cryopump at the end of a 2 m long and 200 mm diameter conduit. From an initial high vacuum pressure of around 100 mPa, the pressure decreases to around 5 mPa (50 microTorr) after 2 hours, when the shot takes place.
The solid trace in Figure 3 is the anode current on the first shot using a carbon graphite cathode. It was freshly coated with cesium iodide by dipping it into a CsI solution in distilled water, and a room-temperature tantalum anode 50 mm diameter and 3 mm thick. In the first 50 ns the current rises to about 0.6 kA together with the voltage. For the next 250 ns, the current is then substantially constant, increasing slowly to about 0.9 kA. Three hundred ns into the discharge the diode collapses, and the current increases rapidly until it

runs off screen (at 7 kA). During the first 300 ns while the diode has not yet collapsed the total current is roughly constant at about 10 kA, but after collapse the generator current increase also, to about 25 kA at 900 ns into the discharge.

The dashed line in Figure 3 is the anode current for the same diode (without refurbishing the cathode with new CsI) on the next day. The currents are basically the same up to 400 ns or so before collapse. Additional shots on the same diode a few minutes later give very much the same traces. After the collapse begins the currents increase somewhat differently, as might be expected if collapse is caused by moving plasmas from anode and cathode. Whether the anode plasma is more important than the cathode plasma can not be determined by measuring only the diode current. In future experiments we hope to supplement the diagnostics with direct plasma measurements to clarify this question.

Figure 5 compares shots before and after the series of discharges that follow (Figures 6 and 7). The solid line is the first shot with a hot anode (at about 1000 K) and CsI on that cathode. The current is fairly constant around 1 kA, with impedance collapse starting after 400 ns or so. The dashed line is the last shot in this series, taken with a cold anode after letting the diode up to air for 1 hour and re-evacuating. The current remains constant only for about 100 or 200 ns before the impedance collapses, slightly longer than on a similar but completely fresh diodes in other shot series taken earlier (not directly comparable). In addition, a fresh diode never has the current plateau around 3.5 kA. Figures 4 and 5 together demonstrate that anode heating has a reproducible and important effect on diode behavior.

High power diodes are notoriously hard to control. In this experiment, the purpose is to identify parameters that cause the variability. The premise is that high power diodes are just as reproducible as other physical devices if all the relevant parameters are actually kept constant on each shot. Variability between shots then implies variability in the relevant shot parameters. Freely floating parameters in pulse power practice rarely reflect irresponsible behavior or sloth on the part of the experimenter but is mostly because the important parameters are unknown. Figure 5 shows that temperature is relevant because its change has a predictable effect: anode temperature delays impedance collapse irrespective of the diode's history, before and after a series of shots. Despite the quite-acceptable reproducibility in Figure 4, and the predictable effect of anode heating in Figure 5, lots of variation remains in the diode's behavior.

Conditioning refers to improving performance of many high voltage devices due to gradual changes from a series of shots or exposure to gradually increasing voltages. A hot anode with a carbon fiber cathode without CsI shows little conditioning: repeated shots are largely reproducible. However, a hot anode and a carbon fiber cathode with cesium iodide suggests some conditioning hidden behind erratic behavior. Without opening the vacuum after the first shot (Figure 5, solid line), the current for the next shot in Figure 6a does not show collapse until about 700 ns into the discharge. The shots thereafter, Figures 6b and 6c are more erratic than usual, but even here, collapse seems to occur only after the same 700 ns. Subsequent shots revert to about 500 ns for the collapse-free time.

With the limited diagnostics available in this experiment, it was not possible to identify the reasons behind the gradual change in diode behavior. A possible cause is a gradual change to the cathode. The first shot in Figure 5 has a graphite fiber cathode freshly coated by dipping it into water with CsI. The normally black fibers end up with a whitish sheen that is presumably CsI but with unknown amounts of water. Evacuating the diode must dry out the CsI, and its position opposite a 1000 K anode dries it out even more, but there may well be some loosely bound water remaining on the cathode. The first shot might evaporate any such material into the diode to cause impedance collapse after only 400 ns.

After the first shot, the loosest atoms are gone. Presumably, therefore, on the next shot the impedance collapses later. Subsequent shots are more erratic perhaps because of a competition between cathode cleaning by the discharge on the one hand, and the cathode's catching whatever plasma comes off the anode on the other hand. An eventual equilibrium between these two processes is consistent with the eventual settling down of the diode impedance illustrated in Figure 7. The last shots in this series have settled down around the solid line. For comparison, the dashed line is one shot later. It was taken while the anode was cooling from a relatively hot 1100 K during all the shots of Figure 6 until about 750 K. A colder anode brings with it earlier diode collapse.

Base pressure has its expected influence, namely a worsening diode behavior as the base pressure increases. Figure 8 is an example of the standard diode with a 19 mm gap and 1200 K anode temperature (without CsI on the cathode) but a larger base pressure, 30 mPa (3×10^{-4} Torr). With the higher pressure, the current has no rigorously constant region. Instead, the current increases slowly until the collapse proper starts. The gradual increase in current is absent on the other shots, which are all taken at the pressures (typically 2 mPa, more than an order of magnitude lower). The observation is consistent with higher coverage of adsorbates that are more loosely bound.

The current density on the anode is another important variable. As an example, Figure 9a is the current in a diode with a much smaller diode gap, only 9.5 mm. Presumably the current density is now much larger than before, perhaps four times larger, and the anode heats more rapidly. The solid line is the current with a heated anode, the dashed line when the anode is cool. A constant impedance region is not visible in this case, and more surprisingly, the current during impedance collapse rises faster when the anode is hot. Figure 9b is for a slightly larger diode gap, 11 mm. This diode stays open for the same time irrespective of the anode temperature, and the current during the impedance collapse is again more rapid for the hot anode. One reason could be that with a higher current density the anode gets hot enough to dislodge more tightly bound adsorbates, which might safely remain attached to the anode in a diode with a larger gap. This matter deserves further study; in particular because in the DECADE machine the current densities may tend toward the higher current density regime explored here. Theoretically, there is no problem: simply compensate the higher heating rate during the discharge with better cleaning of the surfaces before the discharge. Do so by heating to a higher temperature, using a lower base pressure, and perhaps waiting longer before the shot. Resolution of

these important aspects must await further experimentation with additional diagnostics that can see plasma coming off the individual electrodes.

Theoretical considerations.

To a surface physicist a vacuum discharge mixes electron stimulated desorption (ESD) and temperature programmed desorption (TPD). In ESD each species of molecules desorbed from the anode surface is measured as a function of the electron incident angle and direction from a surface of a well-defined crystal or a typical polycrystalline surface. It has been exposed to a well-defined vacuum environment for a known time. In TPD, the surface heats up with a few degrees per second, and the specific pressure of each molecular species is monitored. The pressure peaks as function of temperature give information about how much material is bound to the surface with what energy. The mixture of ESD and TPD in a typical bremsstrahlung diode, insufficient characterization of the anode surface, and the lack of diagnostics on the desorbed gases makes a high power density bremsstrahlung discharge a particularly poor assessment of surface contamination.

In pulse power work, the surface is usually considered as a mysterious black box with uncontrollable characteristics that must be designed around. This is done using phenomenological concepts such as a typical closing velocity v. The distance between anode and cathode d is then chosen such that the diode gap does not close during the pulse time t (namely d larger than $v)t$. In the early days of pulse power the existing knowledge of surface physics was indeed not yet good enough to be helpful (and other pulse power problems were vastly more important). So much new information has become available over the last decade or so that surface physics insights can become very helpful in designing high power vacuum devices. The best-known example is the Nobel-prize winning development of the scanning tunneling microscope, and its derivatives. Other techniques such as ESD do spectroscopy with particles impinging and departing the surface. A list of acronyms with short descriptions for the various techniques needs five pages.[13] Some of the results, namely the surface structure of the adsorbates on the various substrates, stretch over 135 pages in a table (2.5 in Reference [14]). Most of this information is not directly relevant, while some has already found its way into the newest books on vacuum techniques.[15]

With all these data, it should be possible to make a reasonable model for plasma generation from the anode in high power diodes. On a crystal surface with a particular orientation, the most tightly bound molecules have a specific binding energy E, which determines how rapidly the molecules leave the surface by thermal processes. For the simplest case as $d\theta/dt = - A \exp -(E/RT)$, where $A = 10^{13}$/s is a typical collision rate and R= 8.3 J/K-mol is the gas constant. The coverage fraction θ is unity for full coverage, when each lattice site carries an adsorbed atom and the density of adsorbed atoms is roughly 10^{19} atoms/m^2). The vacuum pressure determines how many molecules go back onto the surface, and the equilibrium between the two determines the actual coverage.

A typical anode surface is not a single crystal but polycrystalline. A single binding energy

no longer exists, but the same formula might still apply with some effective binding energy that increases as fewer molecule remain on the surface. A binding energy around $E = 100$ kJ/mol (or 25 kcal/mol or 1 eV/molecule) is typical for hydrogen atoms on metals, but on the metals that bind hydrogen most the binding energy may be three times higher. Unfortunately, tantalum binds hydrogen strongly, so that tantalum must be heated to more than 2500 K before it loses its hydrogen. These high desorption temperatures used to be well known. Langmuir, in 1913 already degassed tungsten filaments at over 3000 K.

Bremsstrahlung diodes are typically not cleaned at all. Even when they are cleaned by an argon or argon/oxygen discharge, the vacuum contacts the metal long enough. Leftover water and other noxious molecules readsorb during the hundreds of seconds of pumpdown from the 100 Pa (1 Torr) pressure needed for discharge cleaning to the 10 mPa (100 micron) needed for shooting. Therefore, the electrodes are covered with adsorbates. The results of our experiment suggest that heating removed only the weakly bound adsorbates, and that the remainder was sufficiently plentiful to cause continuing impedance collapse at the higher power density.

There would be little problem if the newly injected ions stayed close to the surface, but apparently, they travel into the diode. A single layer of hydrogen desorbed from the anode, at about 10^{19} molecules/m^2: when the surface is has many nooks, crannies or ink bottle pores the surface density might be an order of magnitude more. Desorbing all this material gives a density around 10^{15}/cm^3 (or an order of magnitude more) if all the hydrogen's were to spread out equally over a 1 cm wide anode-cathode gap. For the background vacuum, such a high density corresponds to 5 Pa, much higher than shooting vacuum. Cold desorbed hydrogen would be innocuous, unable to expand beyond a 1 mm boundary layer if the temperature were only 10,000 K or 1 eV. Then the expansion velocity (three times the thermal velocity) is about 0.03 mm/ns, or 3 mm in a typical 100 ns pulse.

The numbers mentioned here are consistent with the observed diode collapse. In Figure 1, the diode stays open for 200 when the plasma can come from both the cathode and that anode. However, the diode stays open maybe 300 ns, when the anode plasma is reduced by heating while the cathode plasma is not changed. When in addition the cathode's cesium iodide has modified the cathode plasma, the diode stays open even longer, 400 ns. Eventually the impedance collapses in all the diode versions, presumably because as the discharge continues the surfaces generate more and more gas until there is enough to fill the diode.

From a surface adsorption standpoint tantalum and tungsten are among the worst, and stainless steel seems no better. Table 1 (Table 10.2 in Ref. 14, based on data from 1962) shows that these usual materials absorb everything left in the vacuum. The table's data also suggests that a surface coat of tellurium or selenium applied under vacuum to the tantalum might reduce the amount of desorbable material. For a high intensity diode where the anode evaporates completely, a good alternative to tantalum or tungsten might be bismuth (if coating can not be done). Bismuth (and lead) adsorbs only oxygen, which might be chemically removable in situ by heating in a background of hydrogen. It is also a

good radiation converter because its atomic number (Z = 83) is the highest of all the radioactively stable elements.

The delay in diode collapse from anode heating in Figure 1 suggests that heating the anode reduces the amount of material coming from the anode, and also, that the anode plasma is not solely responsible for impedance collapse. At least for the carbon fiber cathode in this experiment the collapse must come partly from cathode plasmas. While anode plasmas are expected to form a more or less uniform layer of anode plasma that expands perpendicular to the anode, the cathode plasmas should be more complicated, e.g., in the form of plumes that may point in arbitrary directions.

Emission of electrons from a cold cathode is localized. Through the presence of macroscopic whiskers or dielectric inclusions, certain spots on the cathode emit electrons more easily than other spots. The resulting current heats the spot's surroundings, which makes further electron emission even easier and causes the current to increase further. Material adsorbed in or near the hot spots ionize, the ions stream back to the same hot spot, and add to the heating: likewise, impact of individual ions causes runaway problems in field emission and field ion microscopy. All this and maybe more leads to an explosive increase in current and heating in the spot.

For explosive emission, the result might be plumes of ejected plasma. If the plasma is not uniform the current density might follow the variations and cause additional instabilities related to plasma heating and injection of plasma into the diode where it (presumably) contributes to impedance collapse. A uniform layer of desorbed gas or plasma might retard the instability, and cause the collapse to occur later. A plasma of heavy ions might also retard the collapse.

Inspired by these arguments we tried to reduce the amount of plasma on the cathode by maximizing the number of emission spots, so that each spot would explode with less violence. More emission spots come from a faster voltage rate of rise, but in our experiment the rise time a given, 50 ns. Instead, we coated the carbon fibers with a layer of cesium iodide because cesium iodide emits electrons easily, especially when helped by photoemission due to the flash of light that precedes the x-ray flash. Surface physicists would measure these phenomena in detail, as in optically stimulated electron emission (OSEE) for electrons or photostimulated desorption (PSD) for ions. As on the anode, a cathode in a flash x-ray machine, all the various processes occur simultaneously and remain undiagnosed.

In our experiment, the cesium iodide on the cathode usually delays diode collapse. Figures 1, 6, and 7 are good examples. Characteristic of all shots with cesium iodide on the cathode is lots of fluctuation in the current trace. A fluctuating current is quite reasonable when plasma jets shoot into the diode. If such plasmas were dense, they could carry lots of current, but if they are tenuous, the plasma might behave as in a plasma-opening switch. The result could be a current that rises rapidly and falls just as fast.

How relevant are the present results to DECADE, DSWA's advanced radiation simulator. This machine uses a plasma-opening switch to convert a nominally 500 ns long and 1.5 MA peak current at 1.5 MV into a much shorter (50 ns) pulse across a bremsstrahlung diode. The switch' conduction time is hundreds of ns, as in this experiment. In DECADE, the 1500 kA switch current is carried by two approximately 30 cm diameter cylinders over their 100 cm circumference. The width of the current contact on the anode and cathode is not known, but it should be on the order of the distance between anode and cathode, a few cm. Then, the peak current density on the switch electrode surfaces may be a few kA/cm^2, with a charge density around 1 mC/cm^2. The experiments here are with a somewhat smaller charge density perhaps 0.3 mC/cm^2. It is hard to extrapolate what would happen for higher charge densities compensated by higher voltages: maybe the relevant parameter is not the charge density but the increase in surface temperature during the pulse. Thanks to the lower stopping power of higher energy electrons, the increase in anode surface temperature in DECADE is comparable to the one in this experiment, and consistent with a minimal melting of the surface.

The pulse time in DECADE's diode is 50 ns, the linear current density is 20 kA/cm (1 MA from a 50 cm circumference cathode), and the linear charge density is 1 mC/cm. In this experiment the pulse is an order of magnitude more, 500 ns, and the linear current density is two orders of magnitude less, so that the linear charge density is a single order of magnitude lower. Still, replacing DECADE's stainless steel cathode by changing to graphite fibers coated with cesium iodide should have a positive effect on the diode, for the same reasons that cesium iodide coated graphite fibers work so well in the test here.

The extrapolations from this experiment to DECADE by one order of magnitude are tempting, but of course not conclusive. Unfortunately, with the available equipment it was not possible to get a closer match to DECADE's parameters in the available time. For this reason, it might be very interesting to explore anode heating and cesium-iodided graphite fiber cathodes in a regime closer to DECADE. If the results obtained here do transfer to DECADE, as expected, DECADE should reach its specifications with no other changes than a heated anode and a graphite fiber cathode with cesium iodide.

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[1] e.g., R. B. Miller, *An Introduction to the Physics of Intense Charged particle Beams*, Plenum, 1982.

[2] Recent results are in T. W. L. Sanford, J. Appl. Phys., early results in A. E. Blaugrund, G. Cooperstein, and S. A. Goldstein, Phys Fluids 20, 1185 (1977).

[3] G. A. Mesyats and D. I. Proskurovskii, Pulsed Electrical Discharges in Vacuum, Springer, Berlin 1989.

[4] Particularly helpful is D. Hinshelwood, Explosive Emission Cathode Plasmas in Intense Relativistic Electron Beam Diodes, NRL Memorandum Report 5492 (1985).

[5] Besides original work, Ref. 4 includes over 250 references.

[6] J. C. Martin

[7] R. Genuario, *Characterization of electron and ion current flow in very large aspect-ratio terawatt diodes employing heated and unheated anodes*, Appl. Phys. Lett. 33 694 (1978)

[8] M. E. Cuneo et al, Proc. Pulse Power Conf. 1995, p640, summarizes his work.

[9] R. B. Baksht, S. P. Bugayev, V. I. Koshelev, G. A. Mesyats, V. P. Stasev, K. N. Sukhulin, M. A. Timofeev, Sov. Tech. Phys. Lett 3, 243 (1977).

[10] Another Russian group has reportedly used a white-hot anode in a pulsed microwave tube, but this was apparently not corroborated elsewhere (M. Friedman, private communication).

[11] J. M. Lafferty, ed, *Foundations of vacuum science and technology*, John Wiley, New York, 1998.

[12] D. R. Welch and M. E. Cuneo, *Simulations of hydrogen layers in applied-B diodes*, Proc. 1995 IEEE Pulse Power Conference, p 969.
[13] See e.g., A. W. Adamson and A. P. Gast, *Physical Chemistry of Surfaces*, 6th edition, John Wiley, 1997, p 313-318.
[14] G. A. Somorjai, *Introduction to surface chemistry and catalysis*, John Wiley, New York, 1994.
[15] J. M. Lafferty, ed., *Foundations of vacuum science and technology*, John Wiley, New York, 1998.

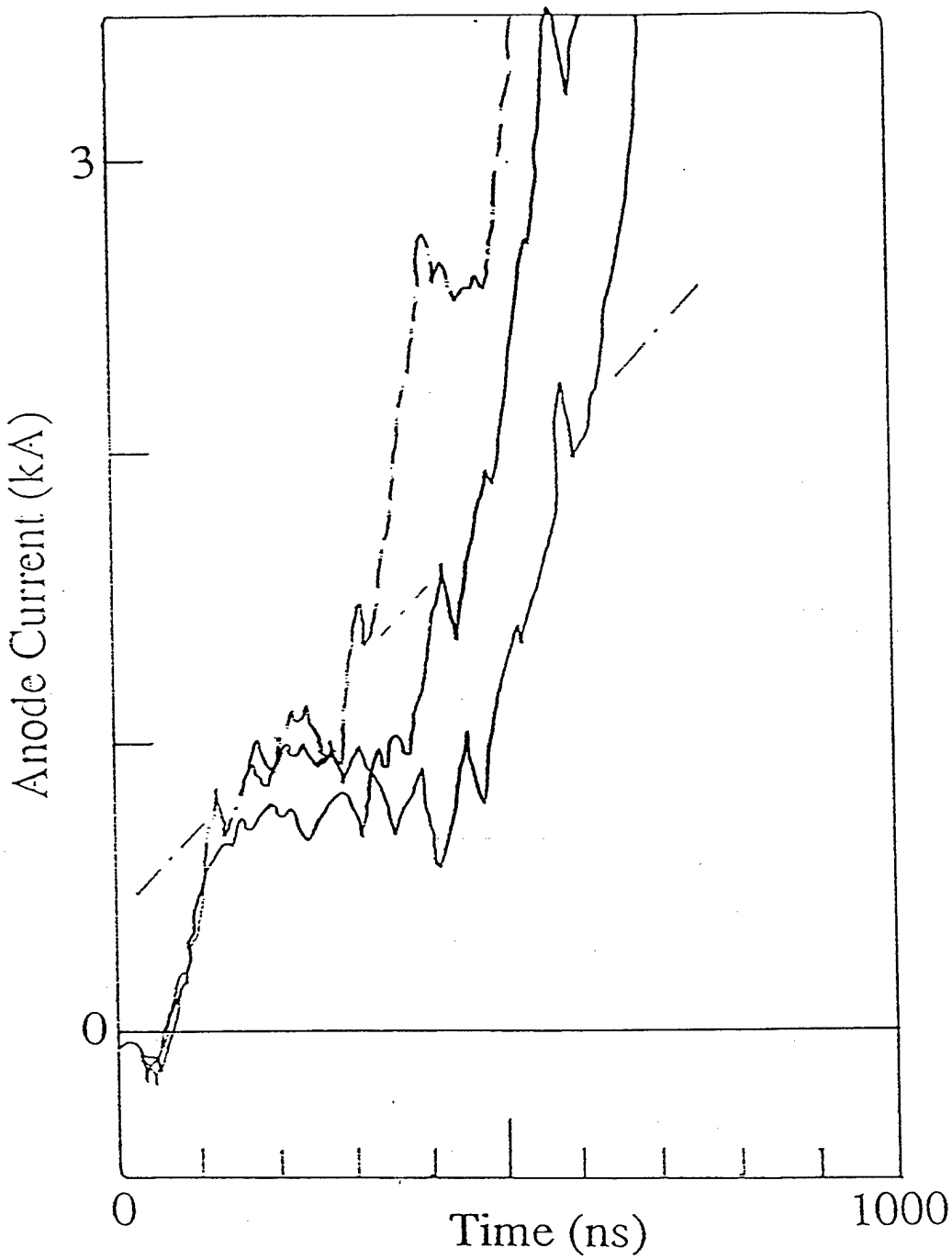

Figure 1-1. Summary: Diode current - for three cases: baseline (dashed), heated anode (middle), and CsI on fiber cathode

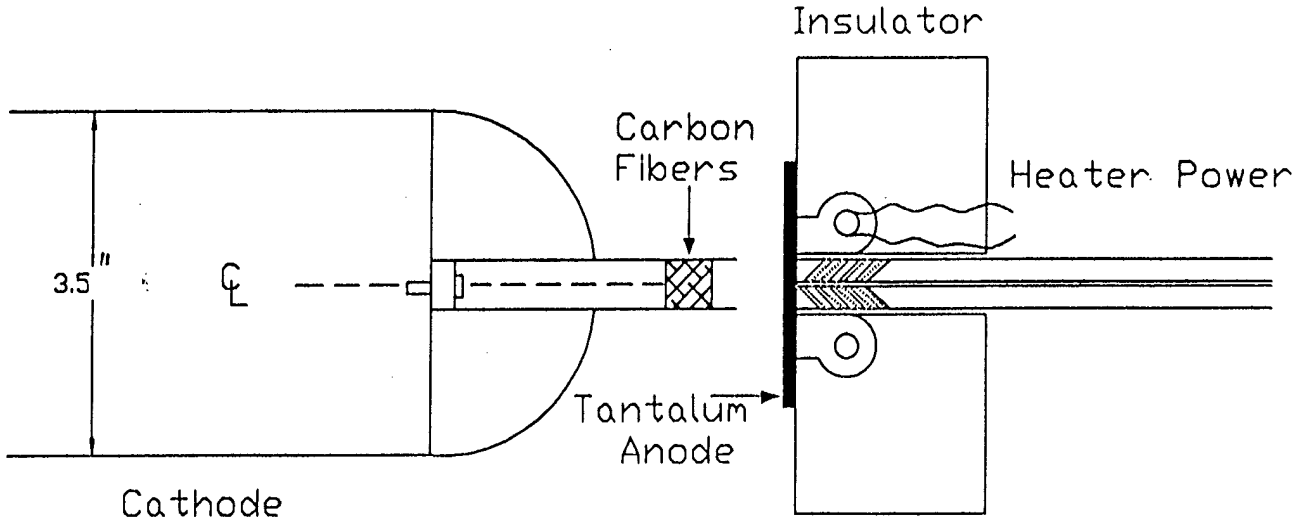

Figure 1-2. Diode geometry

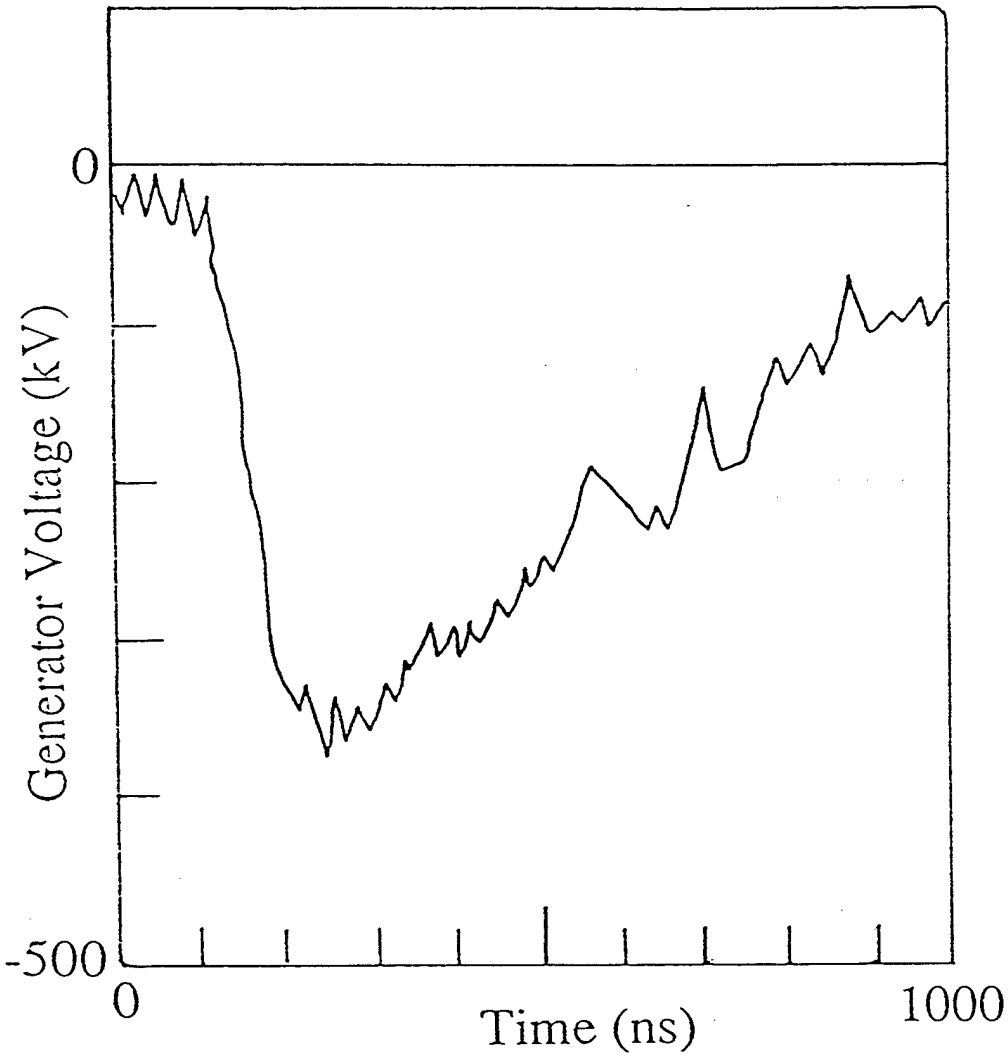

Figure 1-3. Nominal voltage pulse for all shots

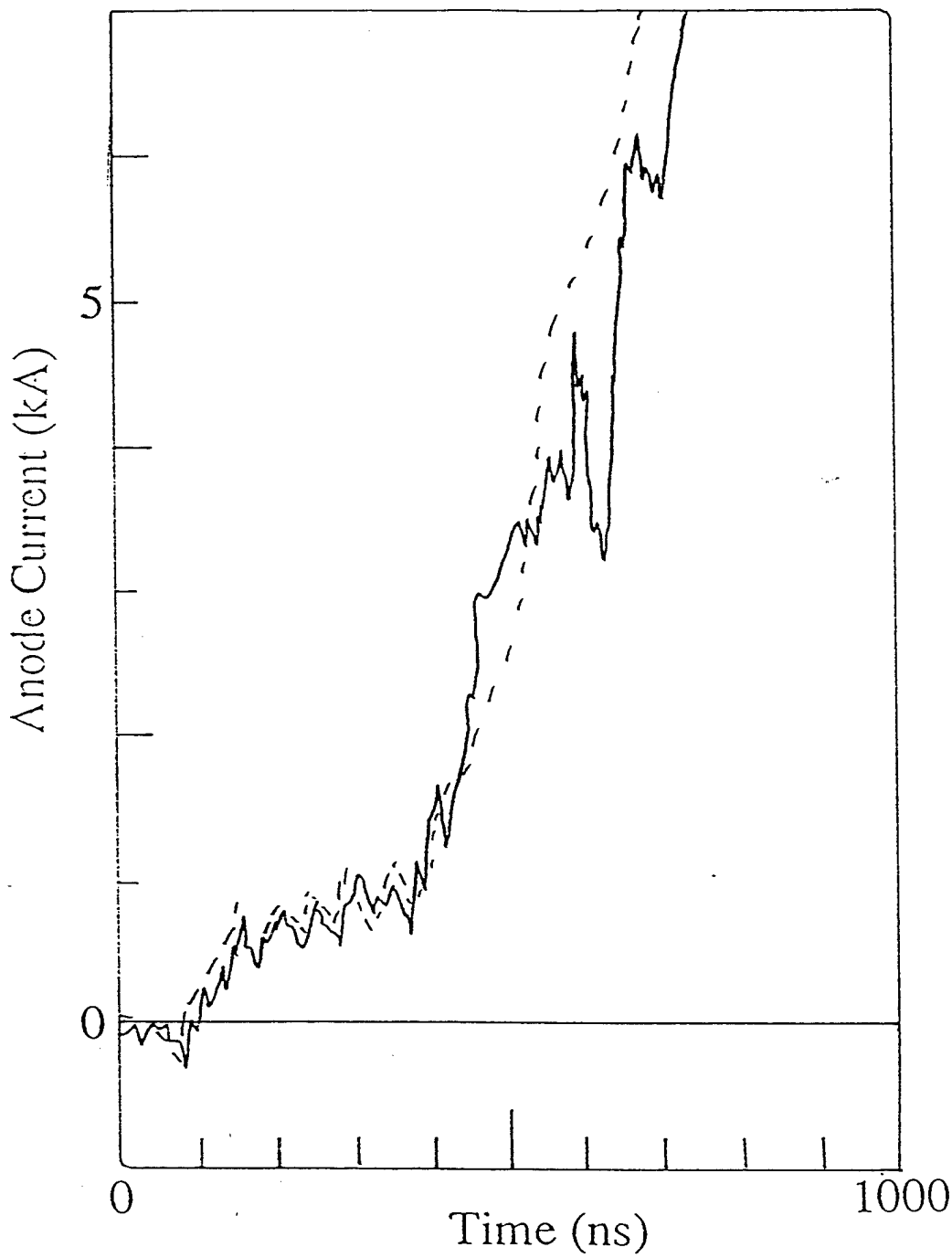

Figure 1-4. Reproducibility of two nominally identical shots

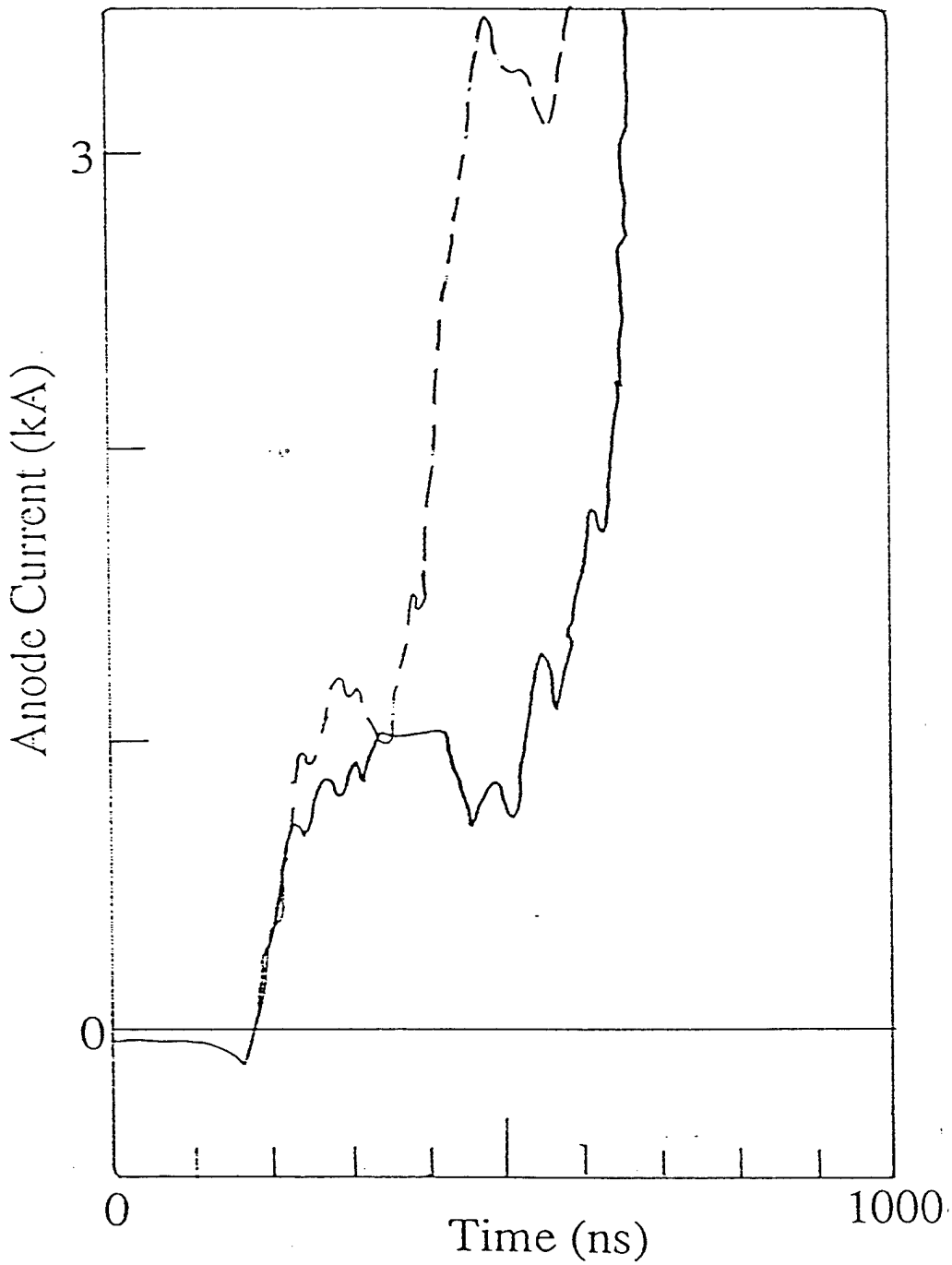

Figure 1-5. Anode temperature effect

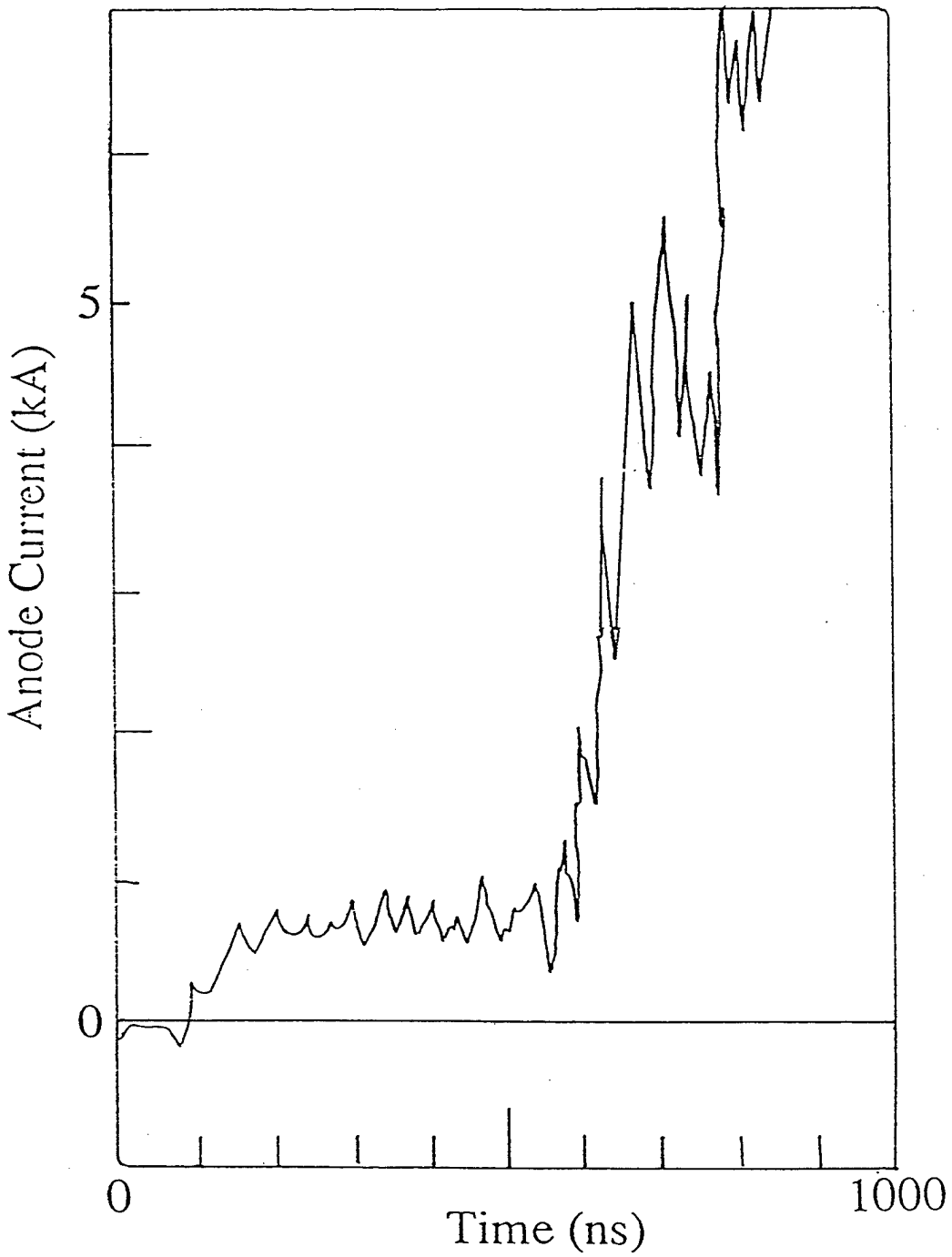

Figure 1-6a. Delayed collapse - shot 2 with CsI

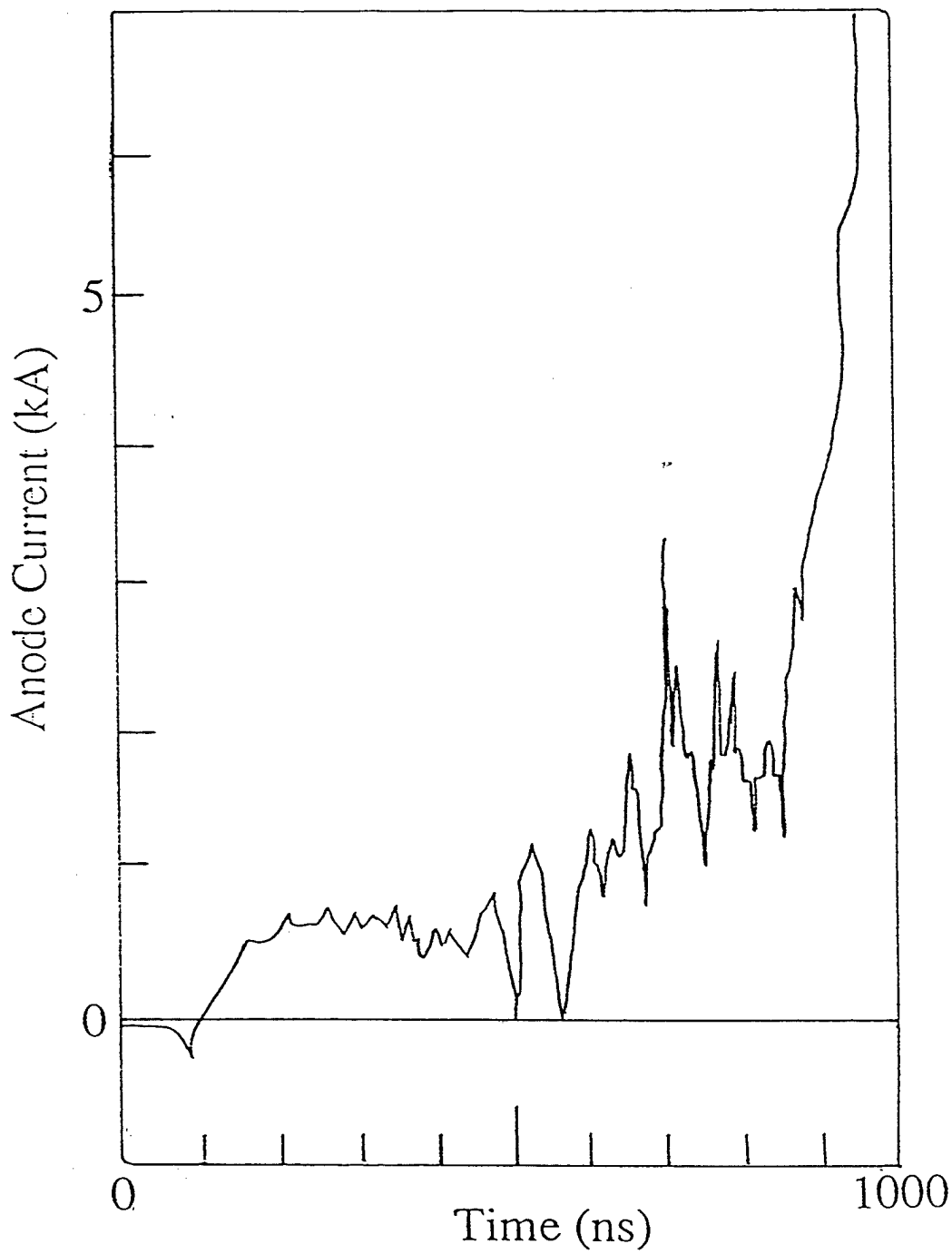

Figure 1-6b. Delayed collapse - shot 3 with CsI

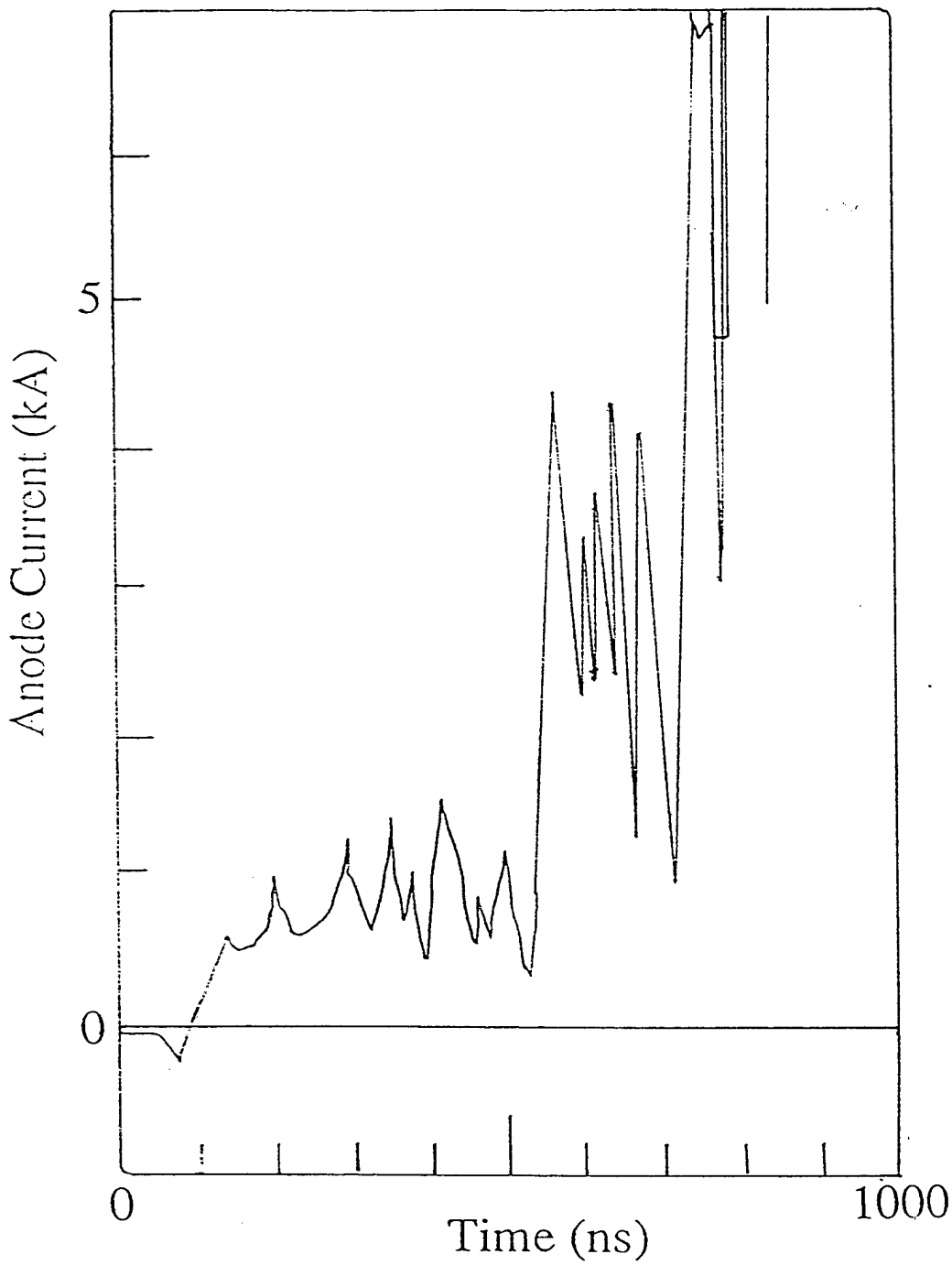

Figure 1-6c. Delayed collapse - shot 4 with CsI

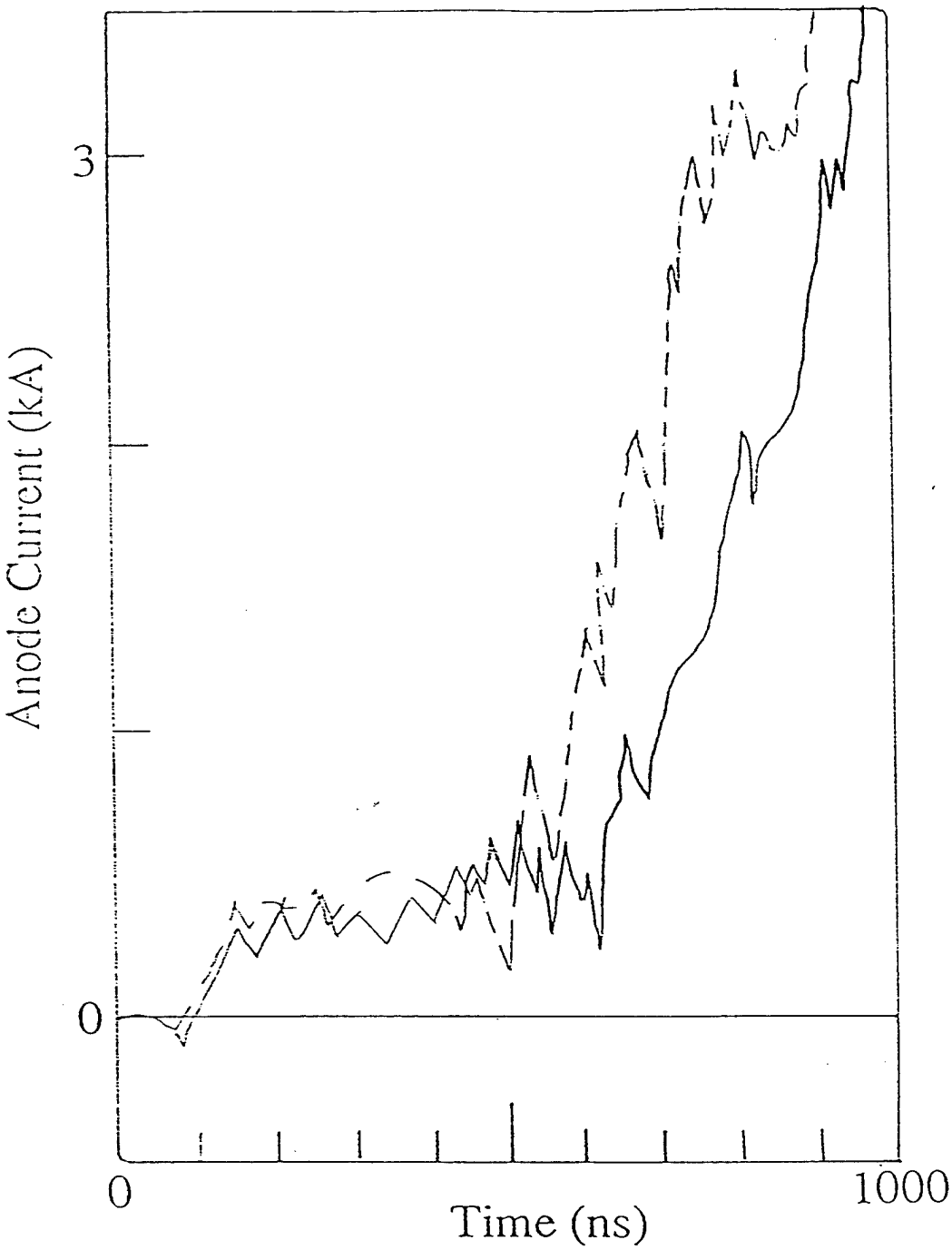

Figure 1-7. Delayed collapse for last 2 shots: hot (solid) & cooling (dashed)

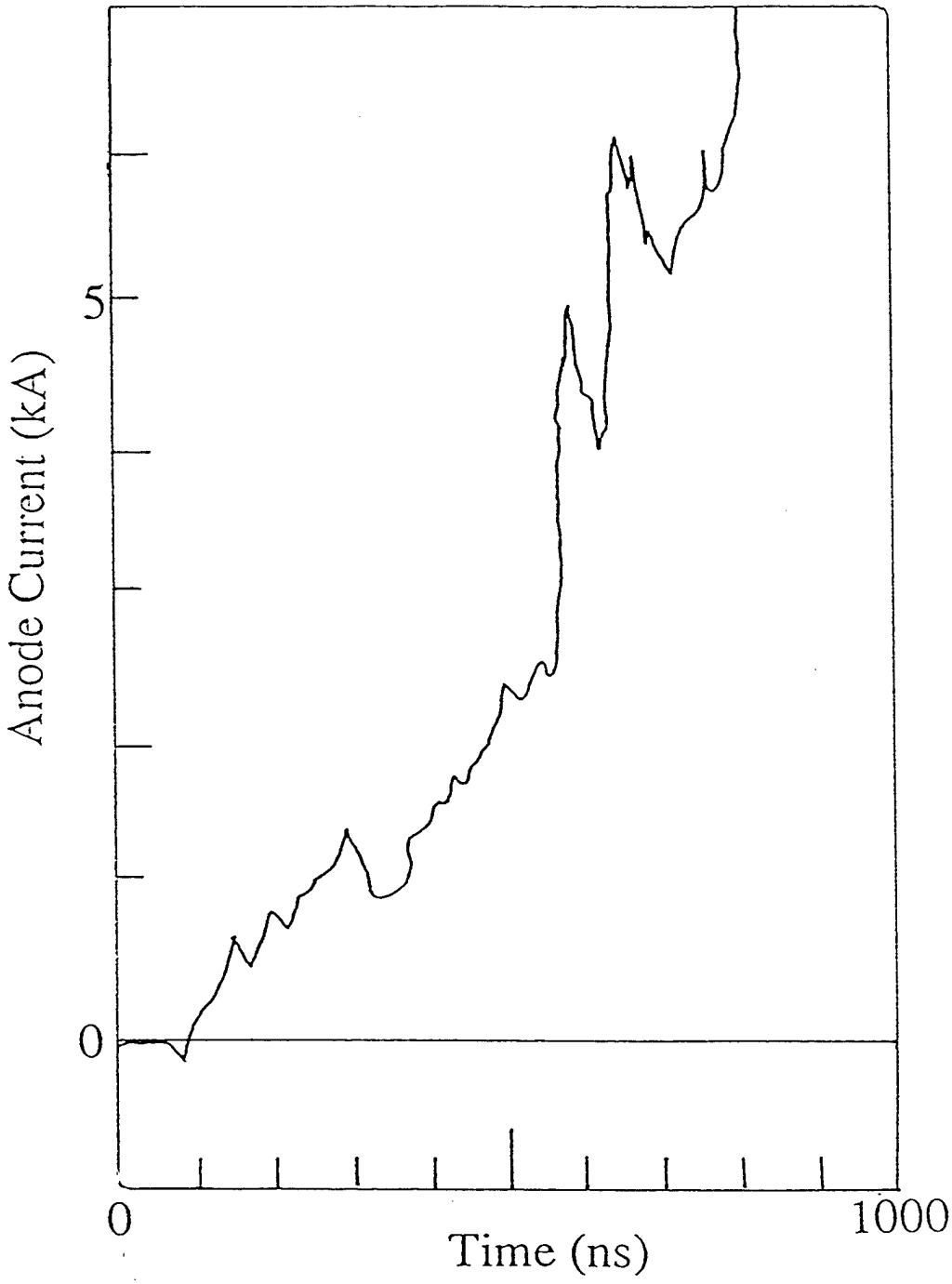

Figure 1-8. Effect of base pressure on standard diode with hot anode

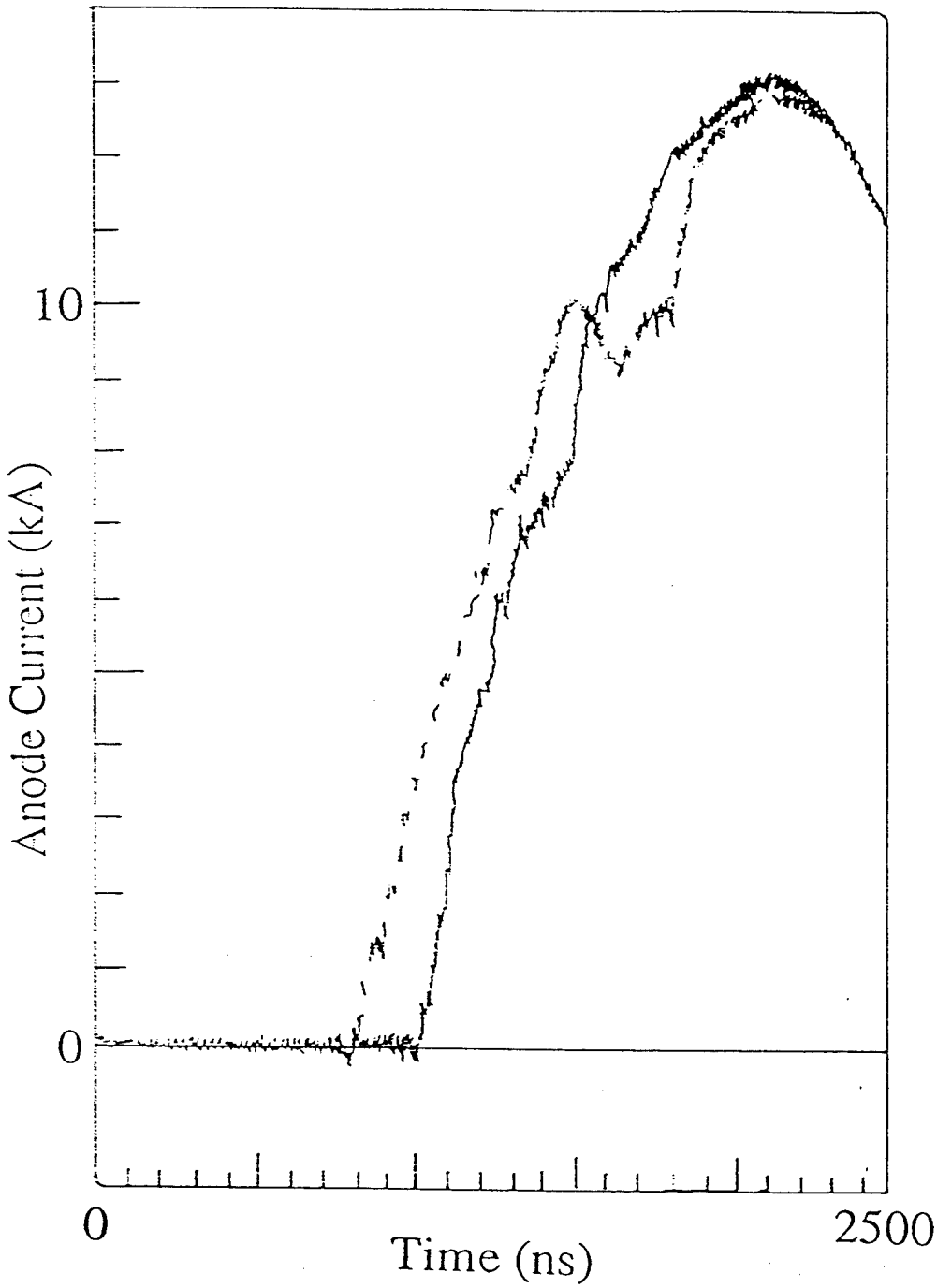

Figure 1-9a. Current density with small diode gap

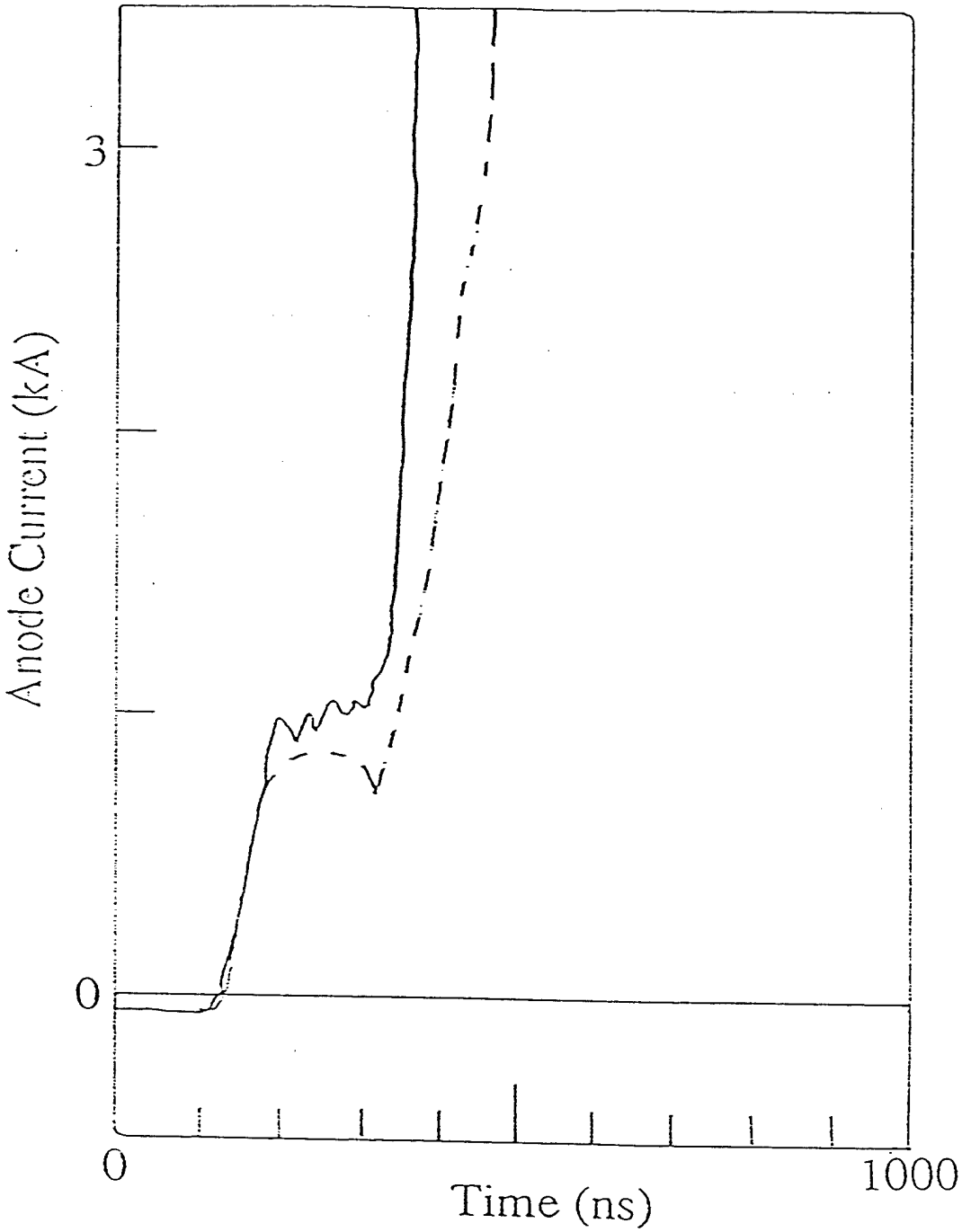

Figure 1-9b. Current density with slightly larger diode gap