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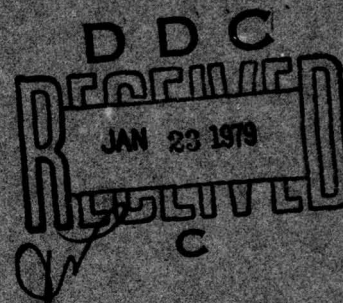
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Reflex Triode with Unidirectional Ion Flow

by Alan Bromborsky, Howard E. Brandt,
and R. Alan Kehs



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1. REPORT NUMBER HDL-TM-78-22	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Reflex Triode with Unidirectional Ion Flow	5. TYPE OF REPORT & PERIOD COVERED Technical Memorandum	
7. AUTHOR(s) Alan/Bromborsky Howard E./Brandt R. Alan/Kehs	6. PERFORMING ORG. REPORT NUMBER	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Harry Diamond Laboratories 2800 Powder Mill Road Adelphi, MD 20783	8. CONTRACT OR GRANT NUMBER(s) DA. 11L161102AH44	
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Materiel Development and Readiness Command Alexandria, VA 22333	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Ele: 6.11.02.A	
14. MONITORING AGENCY NAME & ADDRESS (If different from Controlling Office)	12. REPORT DATE October 1978	
	13. NUMBER OF PAGES 14	
	15. SECURITY CLASS. (of this report) UNCLASSIFIED	
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES HDL Project: A44823 DRCMS Code: 611102.H440011		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Intense ion beam Reflex triode Pulsed power Unidirectional ion flow		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Experimental results show that the ion beam generated by a simple reflex triode can be made almost totally unidirectional toward the virtual cathode. This flow is accomplished by constructing the triode so that a controlled surface flashover generates plasma on only one side of the dielectric anode foil.		

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1. INTRODUCTION

Experimental results are reported that show that the ion beam generated by a simple reflex triode can be made almost totally unidirectional toward the virtual cathode. This flow is accomplished by configuring the triode so that a controlled surface flashover generates plasma on only one side of the dielectric anode foil.

The reflex triode was one of the first intense pulsed ion sources developed¹ that could be adapted to the needs of plasma heating and pellet compression for controlled thermonuclear reactions. However, the triode suffers from two serious problems that reduce its ability to produce an ion beam that is efficiently generated and extracted: (1) The impedance of the triode collapsing quickly at high voltages makes it difficult to match the triode efficiently with pulse power sources.² (2) The ions emitted bidirectionally from the anode cause half the ions generated to be wasted.¹ A solution to problem (2) was first suggested by Humphries et al, "The fact that plasma production can be quenched gives hope of making a triode that emits ions from one side only by means of localized plasma production."¹ In a series of ongoing triode experiments,³ this suggestion has been implemented by controlling the side of the dielectric anode foil on which surface flashover generates a localized anode plasma. The solution of problem (2) will reduce problem (1) since excluding ions from the gap between the anode and the real cathode will greatly delay impedance collapse.⁴

Recent experiments⁴ at the Naval Research Laboratory have shown that, by operating a reflex triode in a tetrode configuration, the ion beam generated can be made almost totally unidirectional in the direction of the virtual cathode, allowing >95-percent unidirectionality of the ions generated. Here we report an alternative approach that can be used to effectively generate a unidirectional ion beam that propagates through the virtual cathode of the triode.

¹S. Humphries, J. J. Lee, and R. N. Sudan, *Appl. Phys. Lett.*, 25, (1974), 20.

²D. A. Phelps, *IEEE Trans. Plasma Sci.*, 6, (1978), 76.

³H. E. Brandt, A. Bromborsky, H. Bruns, and R. A. Kehs, *Proc. 2nd International Topical Conference on High Power Electron and Ion Beam Research and Technology* (1977), 649.

⁴J. A. Pasour, R. A. Mahaffey, J. Golden, and C. A. Kapetanikos, *Phys. Rev. Lett.*, 40, (1978), 448; *Appl. Phys. Lett.*, 32, (1978), 522.

2. EXPERIMENT

The experimental configuration of the reflex triode³ is shown in figure 1. A 5-cm-diameter grounded carbon cathode is located 3 cm above the anode foil. Ten centimeters below the anode foil (the virtual cathode side) is a copper ground plane. The anode foil used was either 0.02-mm (0.8-mil) Makrofol (polycarbonate film) or 0.007-mm (0.3-mil) Mylar. The foil was tensioned and clamped to a conducting anode support ring by a dielectric anode clamp ring. An O-ring and a groove further tensioned the anode foil and ensured that the foil was in close contact with the conducting support ring. Both the dielectric clamp ring and the conducting support ring were machined from FR-4 epoxy fiberglass, and the conducting support ring was electroplated with a 0.05-mm (2-mil) thickness of copper. The conducting anode support ring was attached to the Ion Physics Corp. FX-45 Flash X-Ray Machine 60-ohm pulse line³ operated in a positive polarity mode. Typical FX-45 operating characteristics with the triode attached are peak applied voltages of 1.9 to 2.4 MV with a pulse width of 15 to 20 ns (full width at half maximum). All data shots were taken with an applied axial magnetic field of 3.0 to 3.5 kG. The proton fluence emerging from the anode was measured by using nuclear activation targets⁵ with a threshold of 430 keV for the reaction $C^{12}(p, \gamma)N^{13}(\beta^+)$. The targets were graphite disks (2 mm thick and 5 cm in diameter) placed on the cathode (to measure the upward component of the proton fluence) and below the virtual cathode on the copper ground plane (to measure the downward component of the proton fluence). Proton energies were measured by using a time of flight system consisting of four fast quenched Nuclear Enterprises, Inc., NE 111 scintillators in a drift tube located below the lower ground plane. Plasma near the anode structure was photographed with an open shutter camera. The results of the 13 shots shown in table I indicate that the configuration of figure 1 produces a proton beam in which 91 to 99 percent of the ions detected (>430 keV) flow downward through the virtual cathode and, hence, can be extracted from the triode.

The unidirectionality of the reflex triode was computed on the basis of those protons that were intercepted by the carbon activation targets. The actual ion currents would be slightly greater than the value measured. However, these differences are probably small because the intercepted downward current did not significantly increase when the number of activation targets was increased from one to three. The

³H. E. Brandt, A. Bromborsky, H. Bruns, and R. A. Kehs, *Proc. 2nd International Topical Conference on High Power Electron and Ion Beam Research and Technology* (1977), 649.

⁵F. C. Young, J. Golden, and C. A. Kapetanakis, *Rev. Sci. Instrum.*, **48** (1977), 432.

difference between actual and measured upward proton current would be smaller than the difference between actual and measured downward proton current since the activation target on the cathode is closer to the anode foil than the activation targets on the lower ground plane.

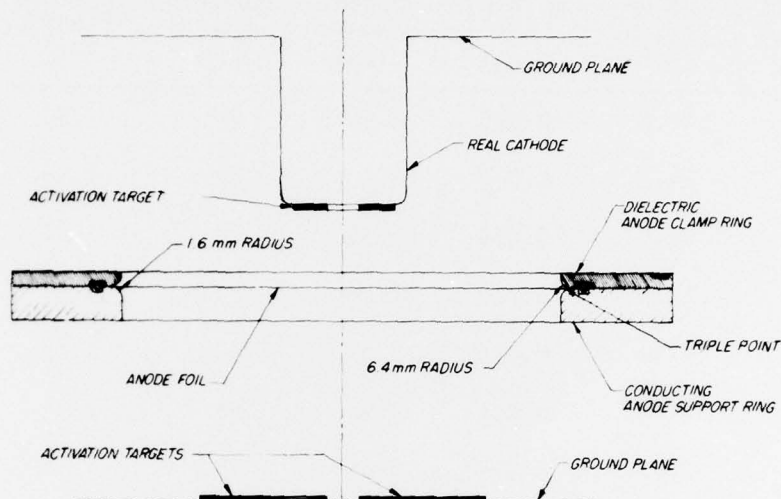


Figure 1. Reflex triode anode-cathode region.

3. DISCUSSION

The reason that the anode shown in figure 1 produces a unidirectional beam is made clear by considering the results of shots 23 and 25. On these two shots, the anode holder was inverted; the inversion caused >82 percent of the protons to go up instead of down. Clearly, the figure 1 anode structure produces a significant amount of plasma only on the side of the foil that touches the conducting support ring. This conclusion agrees with open shutter photographs of the anode region, which show a bright blue plasma glow on the conducting support ring side of the anode, whereas little blue glow is seen on the dielectric clamp ring side. Thus, the flashover phenomenon that generates the anode plasma in a reflex triode using a dielectric anode⁶ occurs preferentially on the side of the anode in contact with the conducting surface. This preference is to be expected in terms of

⁶S. Humphries, Jr., J. J. Lee, and R. N. Sudan, *Advances in the Efficient Generation of Intense Pulsed Ion Beams*, Cornell University LPS154 (1974), 7.

TABLE 1. RESULTS OF UNIDIRECTIONAL ION SHOTS FOR REFLEX TRIODE

Shot (No.)	Ion pulse length ^a (ns)	Ion current up ^b (kA)	Ion current down ^b (kA)	Ion current down (%)	Peak voltage (MV)	Peak energy ^c (MeV)
16 ^d	20.8	0.220	2.75	92	1.93	-
18 ^d	24.8	0.080	4.39	98	1.98	1.65
19 ^d	26.0	0.015	5.30	99	1.92	-
20	24.4	0.100	6.09	98	1.92	1.50
21	22.0	0.018	3.81	99	1.88	1.73
22	25.6	0.031	7.50	99	2.00	1.47
23 ^e	21.2	0.324	0.070	18	1.78	-
25 ^e	20.0	0.290	0.059	17	1.97	-
26 ^f	23.2	0.021	2.81	99	1.97	1.95
28 ^{e,f}	21.2	0.268	2.84	91	1.93	-
29	32.8	0.020	4.56	99	2.62	-
30	30.0	0.018	5.00	99	1.96	-
31	31	0.016	3.60	99	1.81	-

^aTime during which applied voltage exceeded 0.43 MV, which corresponds to kinetic energy threshold of $C^{12}(p, \gamma)N^{13}(\beta^+)$ reaction.

^bAverage current was computed by dividing ion yield (from nuclear activation targets) by ion pulse length.

^cMaximum ion energy was determined from time of flight data from at least three scintillators. Data on all shots were not obtained because of oscilloscope malfunctions.

^dActivation target on lower ground plane consisted of one disk located on axis. On all other shots, three disks with edges tangent to one another were placed symmetrically around axis on lower ground plane.

^eAnode holder was inverted; that is, conducting support ring was placed on real cathode side of foil.

^fFor this shot, 0.007-mm Mylar anode foil was used. For all other shots, 0.02-mm Makrofol anode foil was used.

the "triple point" phenomenon^{7, 8} at vacuum-metal-dielectric interfaces. The location where surface flashover is usually initiated in a vacuum is at the junction of the negative electrode, the dielectric, and the vacuum.⁸ For the triode, since no negatively charged conductor is contacting the anode foil, breakdown initiates at the junction of the positive conductor, the dielectric, and the vacuum. It is likely that flashover proceeds in the following manner:

(1) Electrons are field emitted from the dielectric anode foil⁹ in the region of the highest electric field; due to dielectric polarization and field intensification, this field is at the triple point where the anode foil, the vacuum, and the conducting support ring come together (fig. 1).

(2) Electrons flow into the conducting part of the anode ring; this flow leaves a section of the anode foil surface positively charged.

(3) The intense fields between positively charged and uncharged regions of the nonconducting anode foil cause field emitted electrons to hop along the dielectric surface from the uncharged region into the charged region.

(4) This electron hopping from uncharged to charged regions leads to the creation of more free electrons via the avalanche process of impact ionization in the presence of large electric fields.

(5) At the same time, the impact ionization process produces ions that form the anode plasma and makes the anode foil effectively a conductor. Since the process described is a surface phenomenon, the plasma stays on the side of the anode at which flashover is initiated during the time frame of the ion pulse. This localized formation of plasma results in a unidirectional ion beam.

All data are consistent with the flashover model, except for shot 28, which used an inverted Mylar anode. In this shot, the majority of the current went down even though the conducting support ring was above the anode foil. Since Mylar was used only twice as an anode material during the experiment, one cannot tell if shot 28 is a statistical fluke or if the results are consistent with the use of thin Mylar anodes. For the current densities used in the experiment, the Makrofol anode was discolored, but not punctured; however, the Mylar anode was always punctured, and the region in the center melted. Future experiments will include test sequences to determine the effect of anode material and thickness upon the formation of an anode plasma on both sides of the anode foil.

⁷O. Milton, *IEEE Trans. Electr. Insul.*, EI-7 (1972), 9.

⁸M. J. Kofoid, *AIEE Trans.*, 79, part III (1960), 991.

⁹A. Watson, *JAP*, 38 (1967), 2019.

A major reason why triode efficiencies (ratio of average ion current to average total current) did not exceed 50 percent was the limited duration of the applied voltage (~20 ns). The voltage pulse was too short for the ions traversing the 10-cm gap to acquire energies consistent with the applied voltage; the shortness lowered the average ion current and energy below what would be obtained with an applied voltage pulse of the same maximum value, but longer duration.

Finally, the efficiency of ion generation varied greatly from shot to shot with values between 18 and 50 percent. This variation results from an inability to control the amount of plasma formed by the flashover process. If a large amount of plasma is formed, the triode efficiency increases, but the average ion energy decreases due to a lowering of the gap impedance. One possible technique for reproducible plasma formation is to locate sharp conducting points about the inner circumference of the anode support ring. These points should provide well-defined locations for initiation of the flashover process, thus improving the reproducibility of the plasma generated.

4. CONCLUSION

In conclusion, a new technique has made the ion output of a simple reflex triode almost totally unidirectional. This technique should be scalable to larger ion currents as long as the energy deposited in the anode foil by the oscillating electrons does not generate an anode plasma comparable in density with that produced by the flashover phenomenon. Future experiments on lower impedance machines will determine if the controlled surface flashover anode can be used to tailor the impedance of the triode and substantially delay impedance collapse.

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