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UNIDIRECTIONAL ION GENERATION AND GEOMETRIC FOCUSSING OF IONS IN A REFLEX TRIODE

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

Harry Diamond Laboratories
Adelphi, Maryland 20783

ABSTRACT

Experiments studying the phenomenology of the reflex triode ion accelerator have led to a simple anode design that produces an intense (5 kA average current, 1.7 MeV beam energy, 25 ns current pulse) pulsed ion beam in which greater than 95% of the ions generated are extracted through the virtual cathode. Subsequent experiments have also shown that a simple concentric-spherical anode-cathode geometry can be used to focus the ion beam and increase by an order of magnitude the on-axis ion flux to 1.1 kA/cm^2.

Introduction

The reflex triode was one of the first intense pulsed ion sources developed[1] that could be adapted to the needs of plasma heating and pellet compression for controlled thermonuclear reactions. However, the triode suffers from three serious problems that reduce its ability to produce an ion beam that has a sufficiently high power density and energy content: (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] (3) The ion flux is limited to a few hundred amperes per square centimeter at the vitual cathode. 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] A solution to problem (3) was also suggested[1] using the concept of geometric focussing to increase the ion flux.

Unidirectional Ion Beam Generation Experiment

The experimental configuration of the reflex triode[3] 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 line[3] 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 targets[5] 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, NE111 scintillators in a drift tube located below the lower ground plane.

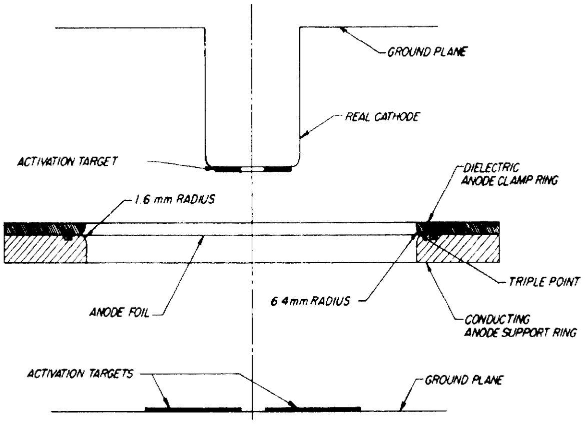

Fig. 1 Anode-cathode region of unidirectional planar reflex triode with nuclear activation targets.

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.

Analysis of Unidirectional Generation Results

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 (table 1). On these two shots, the anode holder was inverted; the inversion caused 82 percent of the protons to go up

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TABLE I. 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	-

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

[b] *Average current was computed by dividing ion yield (from nuclear activation targets) by ion pulse length.*

[c] *Maximum 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.*

[d] *Activation 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.*

[e] *Anode holder was inverted; that is, conducting support ring was placed on real cathode side of foil.*

[f] *For this shot, 0.007-mm Mylar anode foil was used. For all other shots, 0.02-mm Makrofol anode foil was used.*

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 anode[6] occurs preferentially on the side of the anode in contact with the conducting surface. This preference is to be expected in terms of 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 foil[9] 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 (figure 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, most 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.

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 that which 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.

Geometric Focussing Experiment

A cross-sectional view of the focussing geometry is shown in figure 2. The anode foil is 0.02 mm-thick polycarbonate film formed with a radius of curvature of 10 cm. The cathode is copper window screen formed with a radius of curvature of 8 cm. The on axis separation between the anode and the cathode is 2 cm and causes a concentric spherical focussing geometry.

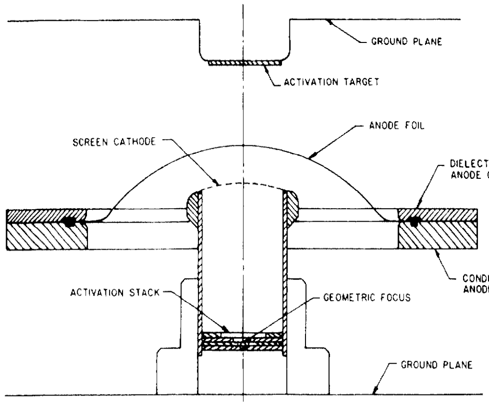

Fig. 2 Anode-cathode region of focussing reflex triode with nuclear activation targets.

The primary diagnostic tool for measuring ion current density is carbon nuclear activation targets[5] placed in the 4.76 cm diameter drift tube at varying distances behind the screen cathode.

The target stack consists of four 1.6-mm thick, 4.76-cm-diameter graphite disks. The lowest disk is solid and the disks above it are perforated with circular apertures of 0.635-cm (0.25-in.), 1.27-cm (0.50-in.), and 2.54-cm (1.00-in.) diameter. This arrangement of the targets allows mapping of the proton fluence for four adjacent radial intervals on one shot, since the targets are sufficiently thick to stop any protons that hit them.

Analysis of Geometric Focussing Results

The diagnostic results for the focussing geometry are shown in figure 3. The sum of the average currents measured by all the activation targets varies from shot to shot between 0.50 to 1.60 kA due to our inability to control the amount of plasma formed during the anode flashover process. Since comparisons between different shots must be made to determine the complete effect of the focussing geometry, all shots were normalized to a total average current of 17.8 A. This current corresponds to a current density of 1 A/cm^2 incident upon the cathode screen. In figure 3, the on axis proton flux peaks at a distance between 7 and 8 cm behind the cathode screen. This result is in good agreement with predictions since the geometric focus was 8 cm behind the cathode screen. The peak normalized proton flux on axis is 13 A/cm^2, indicating more than an order of magnitude increase in proton flux over the planar case.

Conclusions

A new technique has made the ion output of a simple planar 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 to that produced by the flashover phenomenon. In addition, geometric focussing has been demonstrated in a simple reflex triode. The focussing gain achieved was approximately 10 with a maximum average proton flux of 1.1 kA/cm^2 at 8.1 cm behind the cathode screen.

The next steps are to scale the two techniques described to much higher ion fluxes and total currents and to determine the basic limitations that alignment, self-fields, external fields, and collisions place upon geometric focussing.

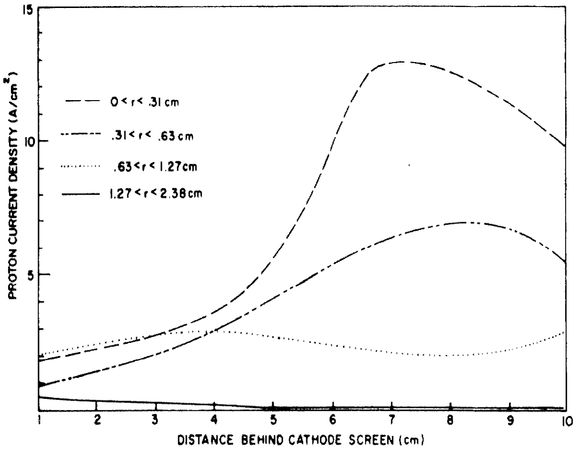

Fig. 3 Normalized proton flux map (1 A/cm^2 incident) in four adjacent annular regions for focussing reflex triode.

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