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Reflex Tetrode with Unidirectional Ion Flow

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Experimental results are reported which show that the backward-directed (and unusable) ion current in a reflex triode can be almost completely suppressed by adding a second anode, made of aluminized Mylar, 0.5 cm from the existing polyethylene anode. Proton-generation efficiencies in excess of 50% have been obtained.

During the last few years, remarkable progress has been made on the development of pulsed, high-current, ion sources.[1-9] Presently, pulsed ion sources are available[1,3] at power levels in excess of 0.2 TW, and even higher power levels are anticipated in the near future. Among the various ion sources the reflex triode has several attractive features. For example, it can operate in the presence of a magnetic field and its ion current can be considerably higher than that predicted for bipolar flow. However, the reflex triode has the undesirable feature that about one-half of the ion current flows toward the cathode of the device and thus is wasted. Therefore, under the best conditions, the optimum efficiency of an ordinary reflex triode cannot exceed 50%. For any practical device the efficiency is less than 30%.

In this Letter we report results which demonstrate that by adding a second anode to an ordinary reflex triode the wasted ion current can be reduced to $\lesssim 5\%$, i.e., $\gtrsim 95\%$ of the ion current propagates toward the virtual cathode and thus can be extracted out of the source and utilized. So far, ion-generation efficiencies in excess of 50% have been obtained.

The reflex-tetrode configuration with double anode is illustrated schematically in Fig. 1(a). A 5-cm-diam graphite cathode, maintained at ground potential, is located ~1.5 cm from the first anode, A_1. This anode consists of a 6-μm-thick aluminized Mylar foil. The second anode, A_2, is placed ≈0.5 cm from A_1 toward the virtual cathode and is made of a 13-μm-thick polyethylene foil which is the primary source of protons. The anodes are mounted on the edges of a 12.7-cm i.d. aluminum ring that is connected to the seven-ohm line (SOL) generator, which is operated in positive polarity. Typical peak output voltage of this generator is ~500 kV with a pulse width of ~50 nsec (full width at half-maximum). The experiments are performed with an axial magnetic field of ~5.6 kG.

The motivation for using this double-anode geometry was to obtain an electric potential profile in which protons from the anode plasma would be preferentially accelerated in the forward direction, i.e., toward the virtual cathode. In an ordinary reflex triode, the potential is more or less symmetric in the vicinity of the anode, so protons are emitted in both the forward and backward directions in approximately equal numbers. The addition of the second anode modifies the potential in such a way that most of the ions emitted at A_2 are unable to reach A_1, as may be seen

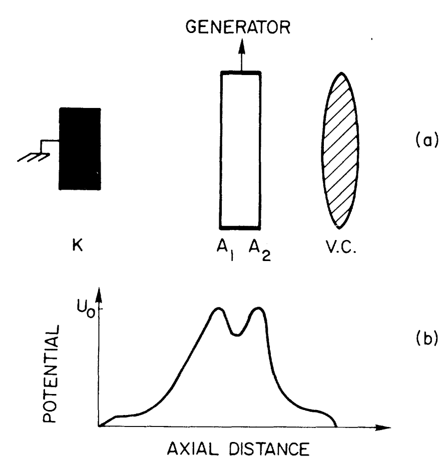

FIG. 1. (a) Schematic of reflex tetrode. (b) Qualitative electric potential profile of this configuration.

from the hypothesized potential profile shown in Fig. 1(b). The number of protons emitted from A_1 toward the cathode K is small because, as has been observed in previous experiments,[10] aluminized Mylar anodes are poor sources of protons.

The number of protons emitted in either direction is determined by nuclear-activation techniques.[11] Thick graphite or boron nitride targets are placed ~7 cm from A_2 to measure the forward-directed number of protons. The number of back-directed protons is determined by measuring the activity induced in the graphite cathode and on BN or carbon targets placed around the cathode. In cases where the proton flux is intense enough to cause substantial target blowoff, a 33% transparent screen is placed in front of the target to reduce the number of protons striking the target.

Since nuclear activation gives only the time-integrated proton yield, the proton current is inferred from the total yield together with the duration of the proton pulse. The duration of the proton pulse is assumed to be equal to the time interval from plasma formation until the diode voltage drops below the threshold for target activation [277 kV for the reaction $^{14}N(p,\gamma)^{15}O$ on BN, 430 kV for the reaction $^{12}C(p,\gamma)^{13}N$ on graphite]. To determine the proton efficiency, the resulting average proton current is then divided by the average value of the total current during this time (as measured with a resistive shunt in the outer conductor of the SOL diode).

The striking feature of the double-anode configuration is its undirectionality. Nearly all (> 95%) of the protons are emitted in the forward direction. When A_1 and A_2 are interchaged (i.e., the proton source is located at A_1), most (> 95%) of the proton current flows toward the cathode. With a 2-μm-thick A_1 foil (this thickness is small compared to the 8-μm range of 500-keV protons), no radioactivity from backstreaming protons is detected on the cathode nor on BN targets placed around the cathode. Thus, the unidirectionality of the proton current is evidently due solely to the potential distribution and not to stopping by the aluminized Mylar anode.

The performance of the tetrode is found to depend strongly on the A_1-A_2 spacing. If A_1-A_2 is too small ($\lesssim 2$ mm with the present operating conditions), the tetrode's electric potential is similar to that of a reflex triode and no improvement over triode operation is observed. When A_1-A_2 is too large ($\gtrsim 1$ cm in these experiments), the proton yield and generation efficiency begin to decrease. This has tentatively been attributed to the formation of a virtual cathode between the two anodes.[12]

As a result of its unidirectionality, the efficiency of the double-anode configuration is considerably higher than that of an ordinary reflex triode. Proton to total current ratios of $\gtrsim 50\%$ are obtained with this configuration compared to maximum efficiencies of $\lesssim 30\%$ previously observed with reflex triodes under the same conditions. About 9×10^{14} protons per pulse are detected (E > 277 keV), i.e., about twice that generated with ordinary reflex triodes under similar conditions. These results may not represent the maximum efficiency, since a systematic optimization of parameters has not yet been performed.

The performance of the double-anode device is characterized by a substantial delay in impedance collapse when compared to a reflex triode with the same anode-cathode spacing. This phenomenon is illustrated in Fig. 2, which shows voltage and current traces for each case. The anode voltage is initially the same in both the reflex triode and the reflex tetrode. However, about 30 nsec after the initiation of the voltage pulse, the impedance drops sharply in the reflex triode (dashed curves), resulting in a considerably shorter voltage pulse. The total current of the reflex tetrode is about $\frac{1}{3}$ that of the simple reflex triode. This suggests

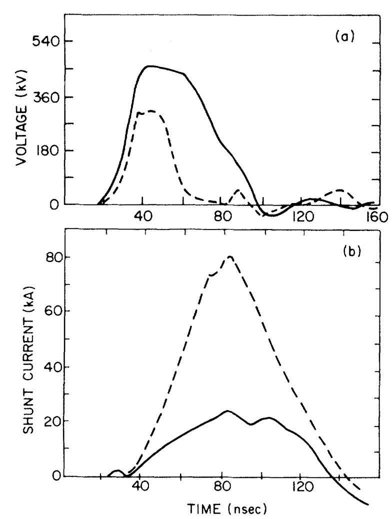

FIG. 2. (a) Inductively corrected anode voltage traces for the reflex tetrode (solid curve) and reflex triode (dashed curve). (b) Corresponding shunt currents for the two cases. For the reflex tetrode A_1-$K \simeq 1.1$ cm and A_2-$K \simeq 1.6$ cm while for the reflex triode A-$K \simeq 1.6$ cm.

that the plasma formed at A_1 is not dense enough to provide sufficient numbers of protons to neutralize the electron space charge in the cathode-A_1 region. Thus, the cathode emission is substantially reduced.

Framing photography is used to compare plasma formation and propagation in the reflex-tetrode configuration to that in a conventional reflex triode (i.e., with polyethylene foil on A_1 or A_2 and the second anode removed). An image-converter camera photographs the anode assembly from the side in three 10-nsec exposures on each shot. In Fig. 3, a microdensitometer analysis of a typical set of framing photographs illustrates the operation of the reflex tetrode. Bright areas corresponding to the two anode plasmas and the cathode plasma can be seen. The important feature is that the plasma formed at A_1 (from the aluminized Mylar) remains essentially stationary, while the A_2 plasma (formed from the polyethylene) moves downstream. The absence of A_1 plasma motion is consistent with previous reflex-triode observations that both the electron and ion currents are appreciably reduced and the impedance of the device remains practically constant when the polyethylene foil anode is replaced with aluminized Mylar.[10]

By incorporating photographs from several shots, it is possible to examine the time history of the plasma expansion. In Fig. 4, data are plotted for three cases: (a) the reflex tetrode, (b) a reflex triode with polyethylene anode at A_2, and (c) a reflex triode with polyethylene anode at A_1. In the reflex triodes, the emitted light is dim, and it is difficult to see the plasma expansion inside the aluminum anode ring, even though a 1-cm-long section of it has been removed to allow photographing between A_1 and A_2. It is clear from these results that the A_1 plasma expands toward the cathode in the reflex-triode case [Fig. 3(c)], but not in the reflex-tetrode configuration. In general, the plasma expansion velocity away from the polyethylene anode is ~1.7 cm/μsec.

In a small number of shots, we have investigated the presence of high-energy protons in the double-anode configuration. Using the reaction $^{63}Cu(p, n)^{63}Zn$, it has been concluded from the activation induced on stacked copper-foil targets that ~$2-5\times10^9$ protons with energy $\gtrsim 5$ MeV are generated. The presence of these high-energy protons suggests a time-dependent potential profile. This aspect of the double-anode configuration is evidently similar to that of an ordinary reflex triode, in which we measured similar numbers of 5–6-MeV protons.

In conclusion, a new tetrode configuration has been developed that is characterized by a unidirectional proton beam and high proton-generation efficiency ($\gtrsim 50\%$). At least 95% of the 10^{15} protons produced propagate in the desired direction. The impedance-collapse problem which characterized reflex triodes is greatly reduced in the

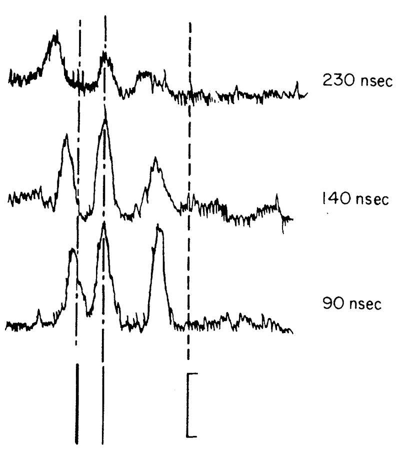

FIG. 3. Microdensitometer analysis of a set of framing photographs, taken in three 10-nsec exposures at various times after initiation of the voltage pulse, for the reflex tetrode. A_1-K gap is 1.5 cm.

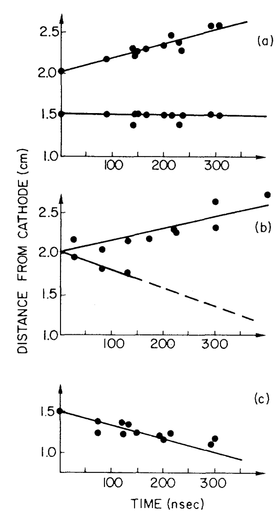

FIG. 4. Position of anode plasma fronts at various times as determined by framing photography in three configurations: (a) reflex tetrode, (b) reflex triode with polyethylene at A_2, and (c) reflex triode with polyethylene at A_1.

reflex tetrode. With this device, it might be possible to exceed significantly the 200-kA usable proton current produced with a coaxial reflex triode on the Gamble II generator.[1]

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Anomalous Electron-Ion Energy Transfer in a Relativistic-Electron-Beam-Heated Plasma

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Studies at Cornell University show experimental evidence for an anomalous electron-ion energy transfer in a relativistic-electron-beam–heated plasma that is 10^3 times faster than can be predicted by classical processes. Electron cooling, ion heating, and a constant total plasma perpendicular energy on a time scale of ~ 1 μsec after electron-beam injection are consistent with an empirically derived electron-ion energy equipartition time in the presence of current-driven instabilities.

In recent years, several experimental programs have been implemented to study the potential application of intense relativistic-electron beams to controlled thermonuclear fusion research.[1] With the capability of delivering several megajoules of energy in times of the order of 1 μsec or less, one of the more promising applications of a relativistic-electron beam is the rapid heating of a magnetically confined linear plasma.[2] Experimental results to date indicate the beam-to-plasma energy transfer is far faster than can be explained by classical processes. While several theoretical mechanisms have been suggested,[3] that which is believed to be responsible for the beam-plasma coupling in most experiments is the electron-electron two-stream instability.[3,4] Unfortunately, this mechanism has the undesirable characteristic for application to controlled fusion that it heats primarily plasma electrons instead of ions. Ion heating is possible via other mechanisms, such as excitation of the ion-acoustic instability[3,5] or generation of large-amplitude magnetosonic waves.[6,7] However, it is probable that these mechanisms alone cannot provide the ion heating required by a high-density linear reactor system.[2] In this Letter, experimental evidence is presented for an observed anomalous electron-ion energy transfer in a magnetized beam-heated plasma that is approximately 10^3 times faster than classical (1–2 μsec at an initial electron temperature and density of $T_{e\perp} = 300$ eV and $n_p = 4.5 \times 10^{13}$ cm^{-3}, respectively).

The Cornell University experimental facility used in the present study is shown in Fig. 1, and