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THE FAST PLASMA FROM A COAXIAL GUN*

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ABSTRACT

An investigation of the phenomena accompanying the acceleration of the fast plasma from a coaxial gun has been made using a variety of techniques including particle analysis, electric probing, space current probing by Rogowsky loops, diamagnetism as measured by external pickup loops, high speed photography both directly of the discharge between the gun electrodes and indirectly by the light of the secondary plasma produced when the fast plasma strikes a target. The gun is normally operated with an axial bias magnetic field between the electrodes. The fast plasma injected into a guide field contains $\sim 5 \times 10^{17}$ deuterons with a wide spread of energy peaking around 8 keV. It is generated over a period of slightly more than 1 μsec, beginning 2 μsec after first breakdown. When the gun is fired into a field free region, the production of the fast plasma appears to be consistent with a model based on the expansion of a fully ionized magnetized moving plasma into vacuum. Such a model would predict that a large fraction of the magnetic and streaming kinetic energy of the moving plasma between the gun electrodes would appear as kinetic energy of the front part of the plasma. The acceleration of the plasma is a gradual one over a distance of 50 cm or so beyond the gun muzzle. When the gun is fired into a 16-kG axial guide field the acceleration process is localized to a region within a few cm of the gun muzzle, the ions and electrons enter the guide field by separate processes and by different paths. The detailed acceleration mechanism is still not understood.

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* Work performed under the auspices of the U. S. Atomic Energy Commission.

DISCLAIMER

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1. Introduction

This paper is an attempt to describe and, as nearly as possible, to explain the phenomena responsible for the acceleration of the fast component of the plasma from a coaxial gun.[1,2] It must be emphasized that this is one particular gun, and that another coaxial gun may differ violently in its characteristics. The differences depend on details of design and on adjustment of easily variable parameters, which are optimized according to the immediate objectives of the experimenter. The gun discussed here is the result of a parameter search in which all gun dimensions except inner electrode diameter were optimized for the production of thermonuclear type deuterium plasma. The yield was judged by the number of neutrons produced when the fast plasma was directed against a strong magnetic mirror. Target neutrons produced when deuterons strike the walls of the system are distinguishable from these neutrons and were excluded from consideration. The reason is that optimization on target neutrons tends to lead to a different mode of gun operation and a completely different set of parameters. Contamination of the fast plasma by impurities either of other ions than deuterium or of slow deuterium plasma was not considered in the optimization procedure so long as it didn't interfere with neutron yield. Later, however, changes have been made in gun design which were intended to reduce such contamination, and which are believed to have done so. In addition the gun is now operated with an axial bias magnetic field, since this was found to improve the quality of the fast plasma. Regrettably the more inflexible gun parameters have not been reoptimized after these changes because of the large amount of effort required.

2. Gun Design and Operating Parameters

The gun design is shown in Fig. 1. The electrodes are of copper. The axial variation of the bias field is shown in Fig. 2. It is pulsed on by a large diameter coil surrounding the gun barrel. Timing is such that the bias field has soaked through the outer gun electrode, and the field external to the barrel due to the coil is small at gun firing time. The gun bank has 30-μF capacity and is normally charged to 21 kV. It is switched by 6 ignitrons through 36 low inductance cables and as seen from the terminal end of the gun electrodes has about 10 nH inductance. A purposely inductive electrolytic resistor is connected across the gun terminals to dissipate energy safely in case of an ignitron prefire, but so as not to interfere significantly with terminal voltage during approximately the first 2 μsec. The fast valve is operated by thermal expansion of a short section of mechanical transmission line, which is heated by about 50°C in 10 μsec by current from a low energy auxiliary capacitor bank. Approximately 1-cm^3 atm of deuterium gas is introduced by the valve through a labyrinth, which prevents erosion of the valve gasket by the plasma and consequent introduction of impurities, but which also slows down gas admission and therefore affects the distribution of gas density at gun firing time. This is probably the only significant mechanical design change made after parameter optimization.

3. Gun Barrel Phase

It appears that gun operation can be considered as consisting of two separate subsequent phases. The first one, the gun barrel phase, lasts from first breakdown until current appears at the muzzle. This requires about 2 μsec. Before the gun bank is triggered enough time delay has been allowed after gas admission to provide a substantial gas density throughout the gun barrel, from terminals to the space just beyond the muzzle. Apparently the gas density near the gun terminals has an optimum value, large enough so that a discharge can form in this low inductance region, dense enough so that in being driven toward the muzzle a large amount of kinetic energy of streaming plasma can result, but tenuous enough that it can be driven to high velocity and so absorb energy. The yield of fast plasma appears to depend on the amount of energy which can be stored in the first part of the discharge in the magnetized streaming plasma inside the gun barrel. The front of the radial discharge moves through the deuterium gas between the electrodes at a roughly uniform speed of about 2.5×10^7 cm/sec. The resulting plasma is not snowplowed ahead of the current front but is left behind, moving at a lower speed than the front and still carrying some radial current. The gun terminal current in the meantime is rising almost linearly (Fig. 3), so that by the time the current front reaches the muzzle the terminal current is about 2.7×10^5 A about three-fourths of which is being carried by plasma behind the front. Fast plasma is emitted by the gun only after the current front has reached the muzzle. Violent electric and magnetic phenomena take place there while it is being emitted but are not apparent in the current and voltages measured at the terminals. The fast plasma carries 1000 J or more of kinetic energy, a substantial fraction of the energy delivered electrically to the gun terminals before its emission. Its speed is much larger than the speed of the plasma behind the current front, and three or four times the speed of the current front itself. It appears then that it is accelerated by some phenomenon at the muzzle which is driven by energy stored during the gun barrel phase. Differences within reasonable limits in the gun barrel phase produce quantitative but not qualitative differences in the fast plasma acceleration phenomenon. It appears that, if conditions at the gun muzzle remain substantially the same, the speed and energy content of the fast plasma will depend on the amount of energy stored in the gun barrel phase and on the azimuthal uniformity of the gun barrel discharge when it reaches the muzzle but that the acceleration mechanism will not change essentially.

The exact role of the gun barrel bias field is not understood. It is known to affect the breakdown conditions, allowing the gun to be fired at lower gas pressures, and to have a different optimum time delay after gas admission for production of fast plasma (~ 245 μsec without B_0, ~ 330 μsec with B_0). With bias field the fast plasma is somewhat faster than without and there is considerably less late diamagnetism observed in the guide field beyond the muzzle. The most likely implication of this is that there is less slow plasma injected into the guide field. The slow plasma is assumed to be to a large extent, the streaming plasma behind the current front in the gun barrel. In the case of zero bias field it is observed to account approximately for the amount of deuterium admitted by the valve. The amount of slow plasma with bias field is unknown.

The amount and energy of fast plasma produced at the gun muzzle appears to depend on the gas density distribution in this region at gun firing time as well as on the density along the gun barrel. A high muzzle density leads to a lower particle energy in the fast plasma, perhaps simply because more mass is present to share the available energy. On the other hand it appears that a large fraction of the fast plasma is derived from gas adsorbed on the electrodes between shots. Neutron yield has been observed on shots immediately after deuterium has been pumped out of the valve system and replaced by hydrogen. Also when the system was contaminated with hydrocarbons from an imperfectly trapped diffusion pump, a much larger fraction of highly ionized carbon appeared as an impurity of the fast plasma than could be accounted for by gas phase contamination. The gas density distribution along the gun barrel and at the muzzle were optimized as well as could be by varying the position of the gas inlet, the amount of gas admitted and the delay after gas admission. Most likely a better gas distribution is possible, but it will be complicated to achieve.

4. Magnetized Plasma Expansion Model

A model which may be capable of explaining partially the generation of fast plasma at the gun muzzle is simply the expansion of the moving magnetized plasma between the electrodes of the gun barrel into the evacuated space beyond the muzzle. The presence of the azimuthal magnetic field in the plasma, which is due to the axial current along the center electrode and along the current jet extending out in front of the center electrode, tends to make the plasma behave like a continuum, and allows pressure to be transmitted from one part to another at Alfvén speed, which may be faster than ion thermal speed. Alfvén waves in the expanding parts of the plasma will be expected to have Alfvén velocity relative to the moving plasma so that expansion will not be limited to this speed. On the other hand the expansion process will be slow for speeds much greater than the Alfvén velocity. The process would be relatively simple for a one dimensional expansion (plane surface separating magnetized plasma from vacuum), and could presumably be calculated from known initial conditions. Here one would expect all magnetic and thermal energy to be transferred eventually to streaming energy with the particles near the edge of the plasma having a much larger energy than those deep inside.

This model has serious deficiencies when applied to the coaxial gun in that the radius of the gun is about of the same size as the gyro radius of the fast plasma ions in the magnetic field of the muzzle current. This makes the behavior of the ions highly non-adiabatic, so that they cannot be considered to be attached to field lines as is required by the model. The situation is further complicated by the non-uniform azimuthal magnetic field in this case, and the three dimensional expansion to be expected. For these reasons it would appear to be a fruitless endeavor to attempt to solve the expansion problem for this case. Qualitatively the model may have some value, however, particularly since the expansion might be expected to take place mostly in the axial direction where the large field gradients might be expected to be found at the front of the current jet, and incidentally this is the direction in which the fast plasma is observed to emerge.

The expansion of magnetized plasma away from the gun is equivalent to the emergence of a jet of current together with the plasma necessary to carry it. In any case, flux is transported from between the gun electrodes into the space beyond the muzzle and a voltage between the electrodes is implied. The voltage can be thought of either as the $\vec{v} \times \vec{B}$ type generator emf of the emergent magnetized plasma stream or as the voltage required to account for the rate of flux emergence, the two pictures being equivalent. The voltage between the gun electrodes is of such a direction as to drive a plasma continuation of the axial current along the electrodes. As the magnetized plasma expands, the magnetic field decreases even in the case of a perfectly conducting plasma, and the current carried by the jet beyond the gun muzzle falls off with distance. The $E/\vec{B}$ field line or plasma speed, resulting from the crossed radial electric field and azimuthal magnetic field of the current jet, can only increase if a sample of plasma is followed in its motion away from the gun muzzle. Non-adiabatic effects having to do with large gyro radii of ions can distort this seriously so that a local $\vec{E} \times B$ direction can actually be opposite to the streaming motion of ions.

5. Experimental Observations

A number of different kinds of measurements have been made in the region beyond the gun muzzle, both with and without an axial guide field. They include electric probing, space current measurements with Rogowsky loop probes, spectroscopic measurements, particle analysis, diamagnetic measurements from outside the vacuum chamber, high-speed photography, and others. A relatively simple picture emerges in the absence of a guide field, which appears to be consistent with the magnetized plasma expansion model discussed above. In the presence of a guide field the process is much more complicated so that observations and explanations become difficult.

5.1 High-Speed Photography, Muzzle Phenomena

High speed photographs looking directly into the gun muzzle were taken at short time intervals over about 8 μsec from first breakdown (Fig. 4). During the first 2 μsec the appearance of the discharge depends on whether or not there is a bias field, but from then on the presence of bias field makes little difference, and most of the light appears to be localized on the tips of the electrodes. On the center electrode (cathode) the light appears as a bright ring with the tip of the electrode remaining dark for about another μsec. On the outer electrode it appears as a number of bright spots, a large number with bias field approximately evenly distributed around the circumference, one to three spots without bias field. Semi-quantitative considerations of ion orbits just inside the muzzle indicate that the outer surface of the cathode is probably heavily bombarded by ions, and this may be responsible for the luminescence. Inspection shows superficial melting of inner electrode near the muzzle. Lovberg has found electron emission unnecessary to explain cathode current under conditions typical of the barrel phase, but his mechanism breaks down at the muzzle, and it may be that electron emission secondary to the ion bombardment is an essential part of the phenomena observed. Recent work by Stratton [3] on low voltage d.c. coaxial guns shows that ion orbits are similar to those inferred here and that cathode current is probably due to thermionic emission of electrons.

5.2 Rogowsky Loop Volume Current Probes

The axial current jet from the muzzle of the gun was investigated with Rogowsky loops inserted into the system in appropriately bent glass tubes. The tubes were passed through teflon compression glands from the end opposite the gun and could be adjusted in axial position without breaking vacuum. The teflon glands allowed enough angular adjustment so that the loops could be centered on the axis of the system. Loops of approximately 5, 10 and 18-cm diameter were used. The glass tubing was 8-mm diameter Pyrex. The 10-cm loop was of a size just to slip over the outer gun electrode while the 18-cm loop would just slide inside the glass vacuum wall. Loops and other probes probably disturb the gun plasma at positions downstream from the tip. It is believed, however, that effects on currents and potentials at the tips are small.

In the absence of guide field a jet of negative current grows outward from the center electrode with a speed of about 6 x 10^7 cm/sec. Within 30-cm of the gun muzzle the current is pinched into a narrow enough stream that all of it passes through a 10-cm diameter circle. The return current appears to pass along the glass wall behind the large diameter Rogowsky loop. Beyond 30 cm the negative space current spreads out so that more passes through the 18 cm than through the 10-cm diameter loop. It is suspected that current and potential phenomena far from the muzzle involve wall effects and would be quite different in a larger system.

With a 16-kG guide field no current is seen with the larger loops. With a 5-cm loop, however, quite a different current system is seen. Within 10-cm of the gun muzzle a negative current jet continues in space, the current along the center electrode. Farther away the current reverses and becomes positive.

Since no current is seen with the 10-cm loop, the current through the 5-cm loop must return inside a 10-cm diameter. Presumably the positive current along the axis is due to non-adiabatic behavior of deuterons which have large enough orbits in the field to extend outward from field lines along which electrons from the cathode can accompany them. This produces a sheath of positive space charge and potential, which can then draw in electrons from the anode or from the system wall which is effectively connected to the anode (witness the return current along the wall). Space current measurements with and without guide field are summarized in Figs. 5 and 6.

5.3 Electric Probes

Plasma potentials were studied by the use of simple passive electric probes inserted through the same seals as the Rogowsky loop probes. The probes were constructed by epoxy cementing copper caps over the ends of glass tubes through which coaxial cable was led. The cable braid was left unconnected at the electrode end, but was grounded to the screen room wall and the center conductor was connected to it through a 100-ohm termination resistor on the probe side of a voltage divider network. The 100-ohm termination was found necessary to reduce noise to a tolerable level. Since probe signals were many kilovolts in amplitude, currents of up to 100 A were drawn from the plasma. The large probe currents apparently distort voltage signals, if they distort them at all, only at very early times when the plasma at the probe tip is tenuous. No difference is seen between signals obtained with 100-ohm and 50-ohm terminators within the reproducibility of the system. Summaries of potential probe observations are given in Figs. 7 and 8 for the measurements with and without guide field.

For the case of no guide field the potentials have first been smoothed by averaging a number of shots at each position, and then have been corrected for inductive voltages due to the changing axial space current. Some of the flux surrounding the current jet also surrounds the probe and should be expected to induce an emf in it which has nothing to do with the potential of the probe tip. It must be emphasized that the plotted potentials, because of the smoothing and correcting which has been necessary, are only approximate. With no guide field the potentials are negative everywhere. This is not too surprising since the anode is grounded and the potentials are measured relative to ground.

With guide field the current system is not so extended or strong as without the field and no corrections have been made for inductive emfs in the probe stems. Considerable smoothing has been necessary, however, for a disturbance at a frequency of approximately 2 Mc which rotates in the $\vec{E} \times \vec{B}$ direction. The disturbance has an amplitude of about 2 kV for probe positions near the gun muzzle, and was observed in three probes when their tips were actually touching the anode 120° apart. The inference is that it is caused by magnetic induction from a rotating current filament. The frequency of rotation is not unreasonable for the E/B speed inferred from the observed electric fields and applied guide field. The electric potential is negative close to the axis and positive away from the axis. The positive potential off axis presumably is a sheath effect having to do with the large gyro radii of the ions in the guide field, as mentioned above.

The probes indicate high potentials out in front of the current system measured with the Rogowsky loops. The first signal in the absence of guide field moves with a speed of about 2×10^8 cm/sec. With guide field the early signals tend to be noisy and no reliable front velocity has been obtained from the probe data. Another measurement, however, has been made from outside the vacuum vessel by using capacitive pickup electrodes on the surface of the glass. This shows that a positive potential front propagates along the tube with a speed of 4×10^8 cm/sec. The impedance of this measurement is high while the probe results are with low impedance, so there may be no significance to the difference of the front velocities in the two cases.

5.4 Particle Analysis

An ion energy, momentum analyzer using a slit collimator with electrostatic and magnetic deflection was constructed and used on the system with the object of studying impurities. We do not wish to discuss the impurities here beyond the statement that they form a very minor part of the fast plasma with the present system. However, the particle analyzer made it possible to identify deuterons, measure their energies, and determine at what time they arrived at the Faraday cup collector 4.9-m from the gun muzzle. From the known velocities associated with the measured deuteron energies it was then possible to infer the time at which they left the gun muzzle. The results of these measurements, made with a 16-kG guide field, are displayed in Fig. 9. It will be observed that the first deuterons appear to leave the muzzle 2 μsec after first breakdown, in agreement with the measurements discussed above. The first deuterons are of low energy but the maximum energy observed increases over about the next μsec and then decreases again. The gun muzzle appears to be a source of fast plasma over about the time that a strong current sheath flows between the electrodes. These measurements were made with an instrument capable of detecting only particles on the axis of the system and moving at angles of less than a few degrees from the axis. The deuterons have a broad energy distribution peaking at about 8 keV and extending above 14 keV. It can be seen from the figure that the first deuterons observed by this method to pass the diamagnetic loops are roughly coincident with the beginning of the diamagnetic signals. What appears to be excessive diamagnetic signal at late times is largely due to particles moving with a large fraction of their velocities in the transverse direction where they are outside the analyzer collimation limits. Some particles are stopped and reflected in what amounts to a mirror field produced by plasma diamagnetism in the guide field. The diamagnetism being larger near the gun, the guide field is reduced by a larger amount there than it is farther away, and the resulting field rises with distance. Particles so reflected spend a relatively long time at their reflection points and contribute large amounts to late diamagnetism. Peak diamagnetism in the two loop signals plotted corresponds to about 5 and 2.5-J per cm of transverse particle energy, assuming the plasma to be of low β.

5.5 High Speed Photography of Fast Plasma by Secondary Luminescence

High speed photographs were taken of the secondary light produced when the fast plasma is allowed to bombard a glass plate. Under the large energy fluxes involved ($\sim 10^7$ W/cm^2) the surface of the glass evaporates and forms a luminous plasma. The duration of the light following a pulse of fast plasma depends on the presence or absence of a magnetic field, and light production is certainly non-linear with energy delivered, so altogether the method is good only for qualitative information. It will indicate, however, when an energetic plasma first arrives and where. The camera was a fast three-frame image converter unit, the exposures being of 2 x 10^{-8}-sec duration at 10^{-7}-sec intervals. The amount of light was so large that even at this short exposure it was necessary to stop down the lens to f/70 with a factor 100 neutral filter. A Pyrex disk was used as a target. The side away from the gun was frosted and the disk was viewed from the frosted side so that the gun could not be seen by the camera. Typical results are seen in Fig. 10. First luminescence with a guide field appears on axis, with later light reaching out approximately to the radius of the gun muzzle. The size of the fast plasma column appears to be almost independent of guide field strength except that below 5 kG some of the plasma seems to flute outward producing irregular patterns. Some of the photographs show sickle shaped patterns which are probably associated with the $\vec{E} \times B$ rotation discussed above under electric probing. The first plasma to arrive is distinctly faster with large guide field strength than it is when the guide field is small or absent.

6. Summary and Conclusions

The picture of the fast plasma acceleration mechanism which emerges from the measurements described here is quite different with and without guide field. With no guide field the magnetized plasma expansion model discussed above appears to apply at least qualitatively. Certainly at least the $\vec{j} \times \vec{B}$ forces in the gun muzzle current system must be applied to some reaction force, and there appears to be nothing available for the role except ion inertia. Since current and magnetic field are extended over a large volume in front of the gun muzzle the acceleration must be a gradual one as it would be in the expansion model. According to the expansion model, the streaming velocity of the plasma should everywhere be in the $\vec{E} \times \vec{B}$ direction and its speed should be E/B. Inspection of Fig. 8 shows that the $\vec{E} \times \vec{B}$ direction is substantially forward with almost a constant value of radial electric field and a transverse magnetic field which decreases with increasing distance from the gun. The expanding plasma, moving in the $\vec{E} \times \vec{B}$ direction should then accelerate gradually parallel to the electric equipotentials. The model breaks down badly in regions where the particles behave non-adiabatically. This is so particularly at the gun muzzle where estimates of particle trajectories show that deuterons starting at rest on the inner surface of the outer electrode pass very close to the surface of the inner electrode so that in fact many of them might be expected to strike it. Bombardment of the inner electrode tip may well be responsible for luminescence observed there during the time of emission of fast plasma and may also account for the large electron currents which probably originate there. The inward trajectories of the deuterons together with the magnetic deflection of their orbits in the forward direction probably account for the apparent small size of the plasma source beyond the tip of the center electrode.

With a 16-kG guide field the magnetized plasma expansion model appears not to apply to the situation at all. The continuation beyond the electrode tips of the currents established along them during the gun barrel phase never reaches out more than about 12 cm. Beyond this the measured current is actually in the opposite direction from the electrode current. This positive current in the neighborhood of the axis might be expected to be present when fast plasma from any laboratory source whatever impinges against the end of an axial guide field. It arises from the relatively large magnetic rigidity of the ions in the end of the guide field which allows them to cross appreciable amounts of field while the electrons cannot do so. Plasma electrons can stream into the field along the axial line, but to the side, where the ions can penetrate because of their large orbits, the electrons cannot come directly from the plasma and a positive space charge results, which can pull electrons in from any available conducting surface along the field lines in question. A mechanism of this sort has been inferred by Ashby [4] from somewhat different measurements of the currents involved and at much smaller plasma densities. In a situation like this, where the ions and electrons of a plasma actually come from different sources, it would be meaningless even to think of the process as describable by the behavior of a plasma continuum. Instead one must think of the mechanism as involving interdependent but separate non-adiabatic behavior of electrons and ions. Under such conditions there is no difficulty in understanding the thorough mixing of fast plasma and field which first appeared rather mysterious when the plasma was considered from a hydromagnetic viewpoint.

When the gun is fired into the guide field nearly all of the fast plasma acceleration occurs at the gun muzzle or very close to it. This follows from the direct observation that the entire current from anode to cathode closes close to the muzzle. The $\vec{j} \times \vec{B}$ forces which must be responsible for the acceleration occur only in this region. In the positive current whorl inside the guide field there is probably a further acceleration of a part of the plasma to higher speeds at the expense of some of the ions which get slowed down or turned back. The basis for this statement is not very solid and in any case the effect is probably not a large one. The acceleration process with the guide field is obviously more complicated than without it, and many details are not yet understood.

7. Acknowledgments

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[4] ASHBY, D. E. T. F., Bull. Am. Phys. Soc. 9 3 (1964) 331.

FIGURE CAPTIONS

Fig. 1. 1. Gas inlet. 2. 16 Rex 4 cables to valve driver capacitor bank (240 μF, 2 kV). 3. Driver section (2 coaxial 0.25-mm wall inconel-x tubes). 4. Glass insulator. 5. Lucite clamping ring. 6. 36 B.I.C.C. type 20 cables to gun capacitor bank (30 μF, 21 kV). 7. Sonic line. 8. Copper outer electrode. 9. Copper inner electrode. 10. Gas outlet holes (15 holes, 3-mm diameter). 11. Valve spring. 12. Valve plenum. 13. Teflon bumper washer. 14. Polyethylene insulation. 15. Phenolic insulator. 16. Cooling air inlet. 17. Small holes for air outlet.

Fig. 2. Experimental arrangement and axial magnetic field strength.

Fig. 3. Time variation of gun current and voltages. Gun muzzle voltage measured with probe touching tip of center electrode.

Fig. 4. Image converter camera photographs of gun muzzle. Gun bias field, B_o = 1.4 kV. The time scale is the same as in Fig. 3. Exposure time 0.05 μsec.

Fig. 5. Plasma current measured with 5-cm diameter Rogowsky loop. Bias field, B_o = 1.4 kG. Guide field, B_z = 16 kG.

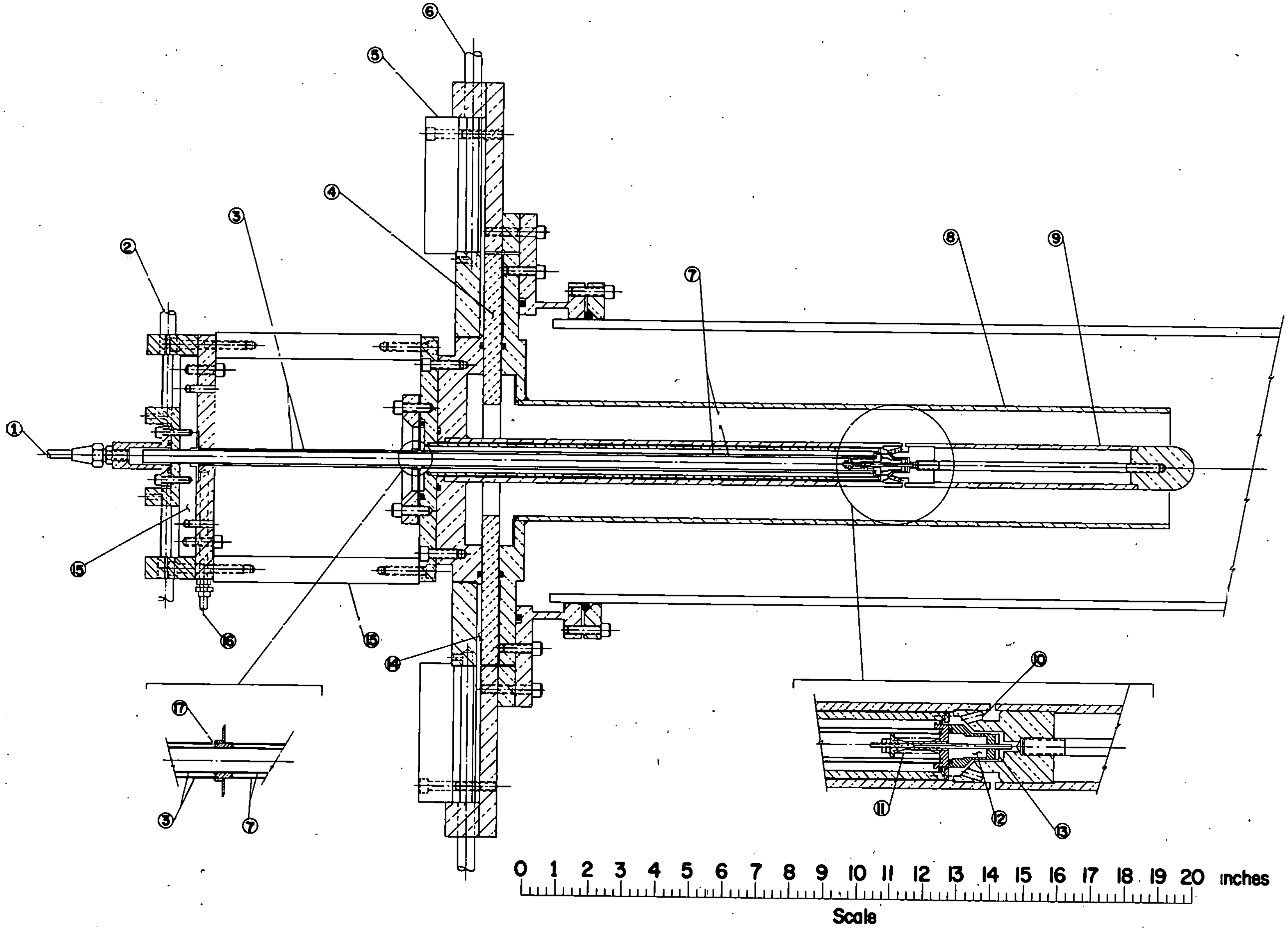
Fig. 6. Plasma current measured with 10-cm and 18-cm diameter Rogowsky loops. Bias field, B_o = 1.4 kG. Guide field, B_z = 16 kG.

Fig. 7. Potential and current distributions at various times. Bias field, B_o = 1.4 kG. Guide field, B_z = 16 kG. Note that these represent smoothed data from a large number of shots, and that a considerable amount of imagination has been employed in drawing the current streamlines.

Fig. 8. Potential and current distributions at various times. Bias field, B_o = 1.4 kG. Guide field, B_z = 0.

Fig. 9. Axial distance vs time of deuterons of various energies observed by particle analyzer. Diamagnetic signals at two loop positions plotted on same time and distance scale.

Fig. 10. Image converter camera photographs of secondary luminescence produced by fast plasma bombardment of glass plate 48 cm from gun muzzle. Bias field, B_o = 0. Guide field, B_z = 16 kG. Three gun shots; three 20-nsec exposures per shot at indicated times.



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0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 inches
Scale

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Fig. 1. 1. Gas inlet. 2. 16 Rex 4 cables to valve driver capacitor bank (240 μF, 2 kV). 3. Driver section (2 coaxial 0.25-mm wall inconel - x tubes). 4. Glass insulator. 5. Lucite clamping ring. 6. 36 B.I.C.C. type 20 cables to gun capacitor bank (30 μF, 21 kV). 7. Sonic line. 8. Copper outer electrode. 9. Copper inner electrode. 10. Gas outlet holes (15 holes, 3-mm diameter). 11. Valve spring. 12. Valve plenum. 13. Teflon bumper washer. 14. Polyethylene insulation. 15. Phenolic insulator. 16. Cooling air inlet. 17. Small holes for air outlet.

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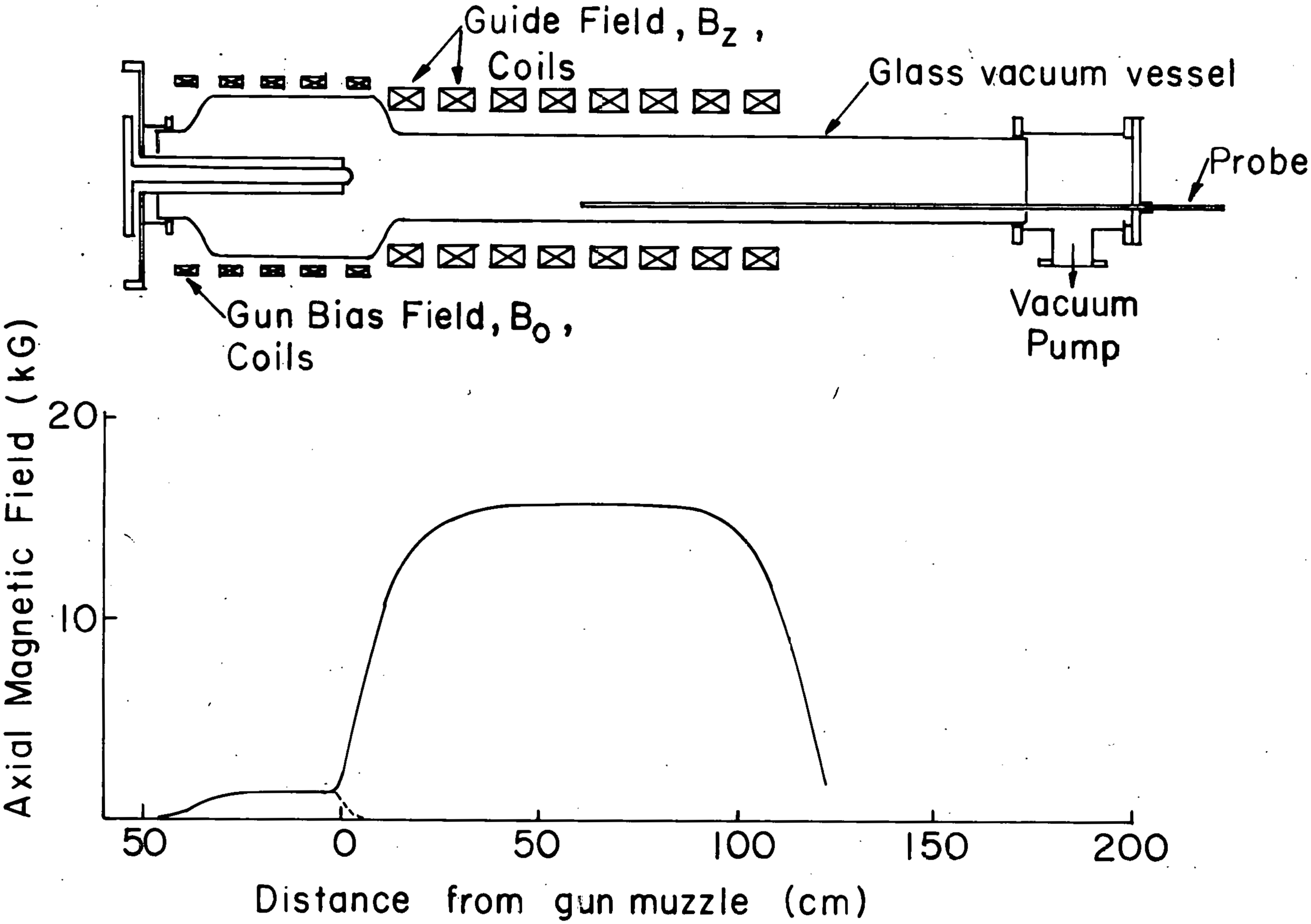
Guide Field, B_z, Coils
Glass vacuum vessel
Probe
Gun Bias Field, B_o, Coils
Vacuum Pump
Axial Magnetic Field (kG)
20
10
50
0
50
100
150
200
Distance from gun muzzle (cm)

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Fig. 2. Experimental arrangement and axial magnetic field strength.

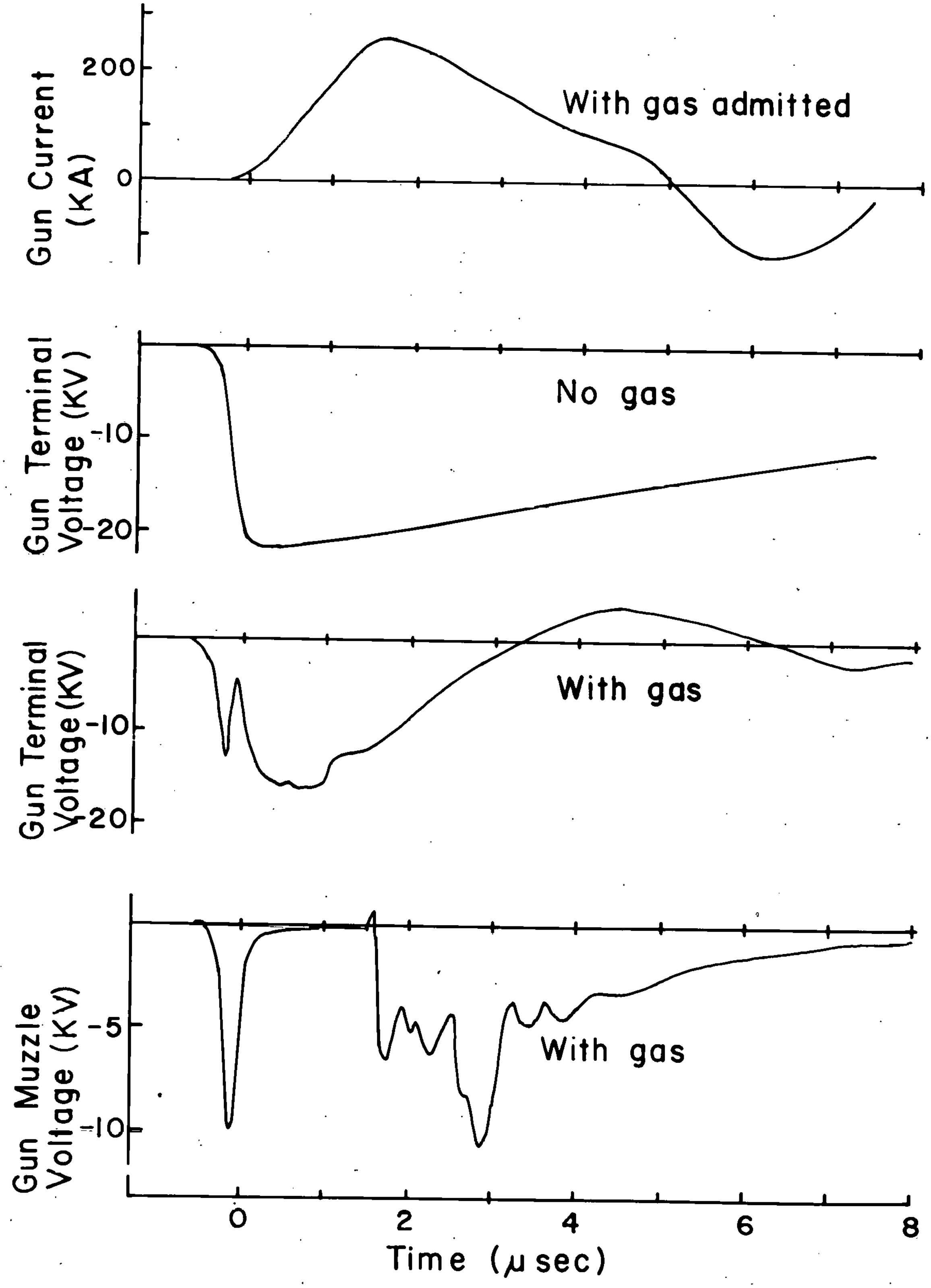
Gun Current (KA)
200
0
With gas admitted
Gun Terminal Voltage (KV)
-10
-20
No gas
Gun Terminal Voltage (KV)
-10
-20
With gas
Gun Muzzle Voltage (KV)
-5
-10
With gas
0
2
4
6
8
Time (μsec)

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Fig. 3. Time variation of gun current and voltages. Gun muzzle voltage measured with probe touching tip of center electrode.

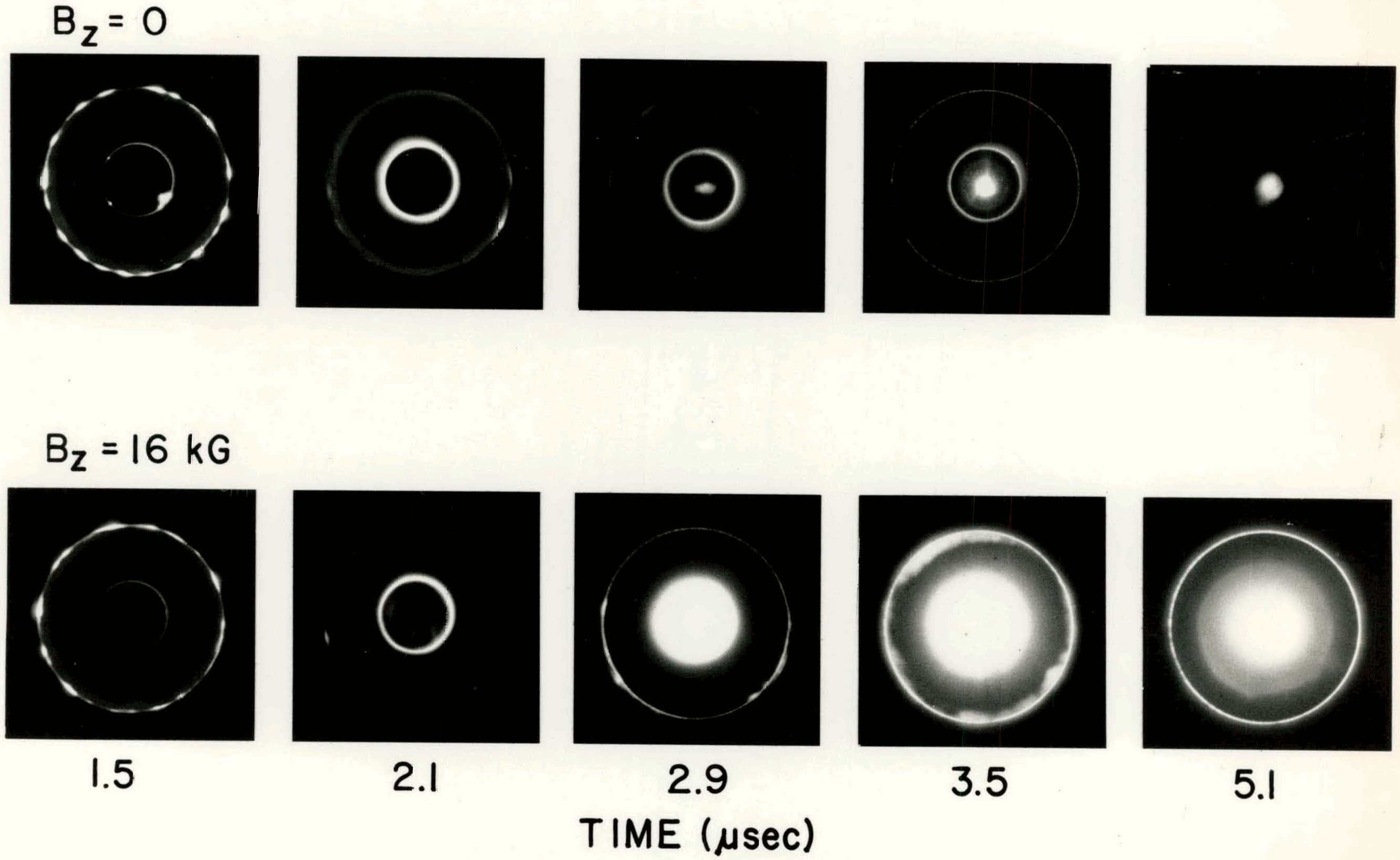
$B_Z = 0$
$B_Z = 16$ kG
1.5
2.1
2.9
3.5
5.1
TIME (μsec)

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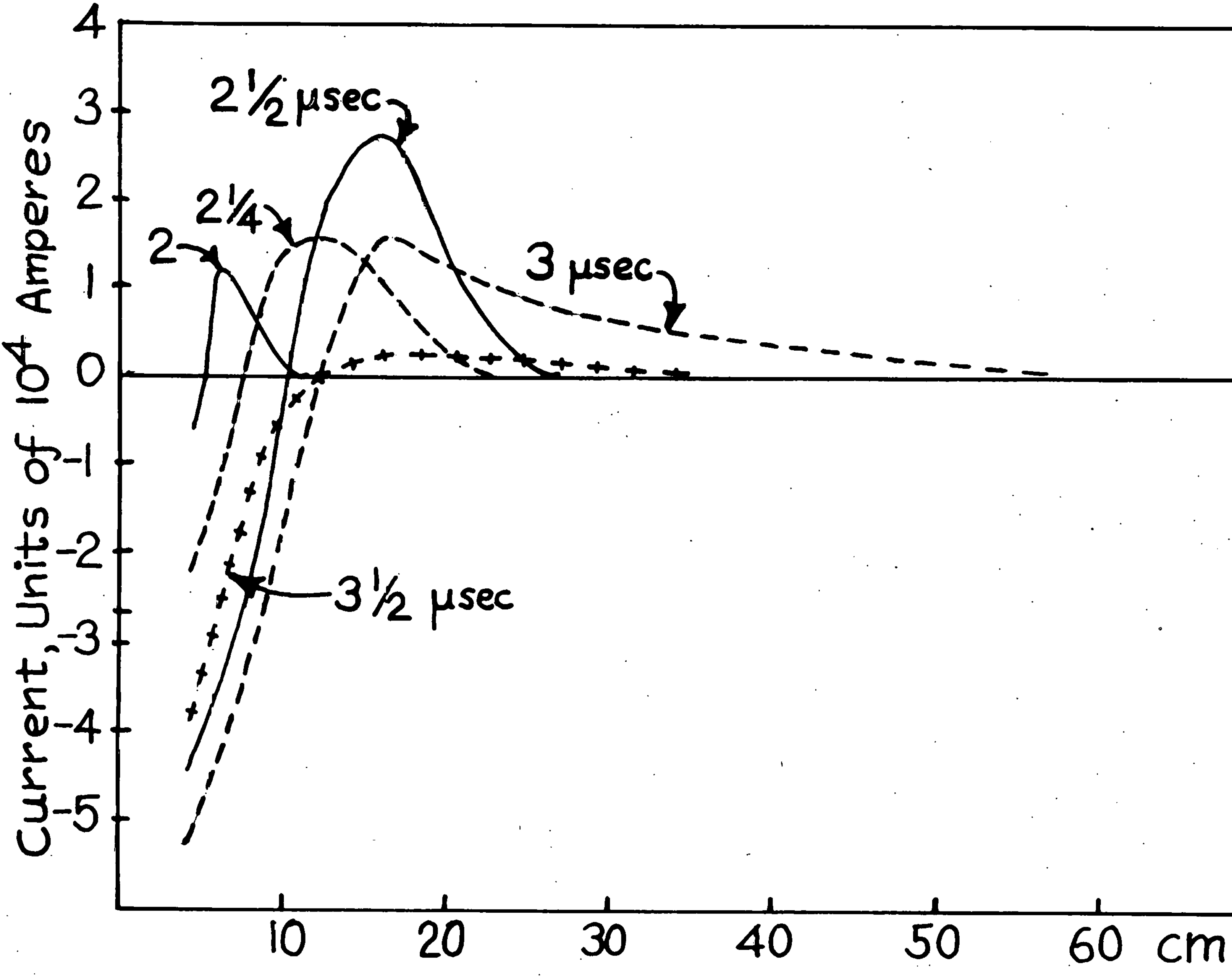
Fig. 4. Image converter camera photographs of gun muzzle. Gun bias field, B_o = 1.4 kV. The time scale is the same as in Fig. 3. Exposure time 0.05 μsec.



Current, Units of 10⁴ Amperes
4
3
2
1
0
-1
-2
-3
-4
-5
10
20
30
40
50
60 cm
2
2¼
2½ μsec
3 μsec
3½ μsec

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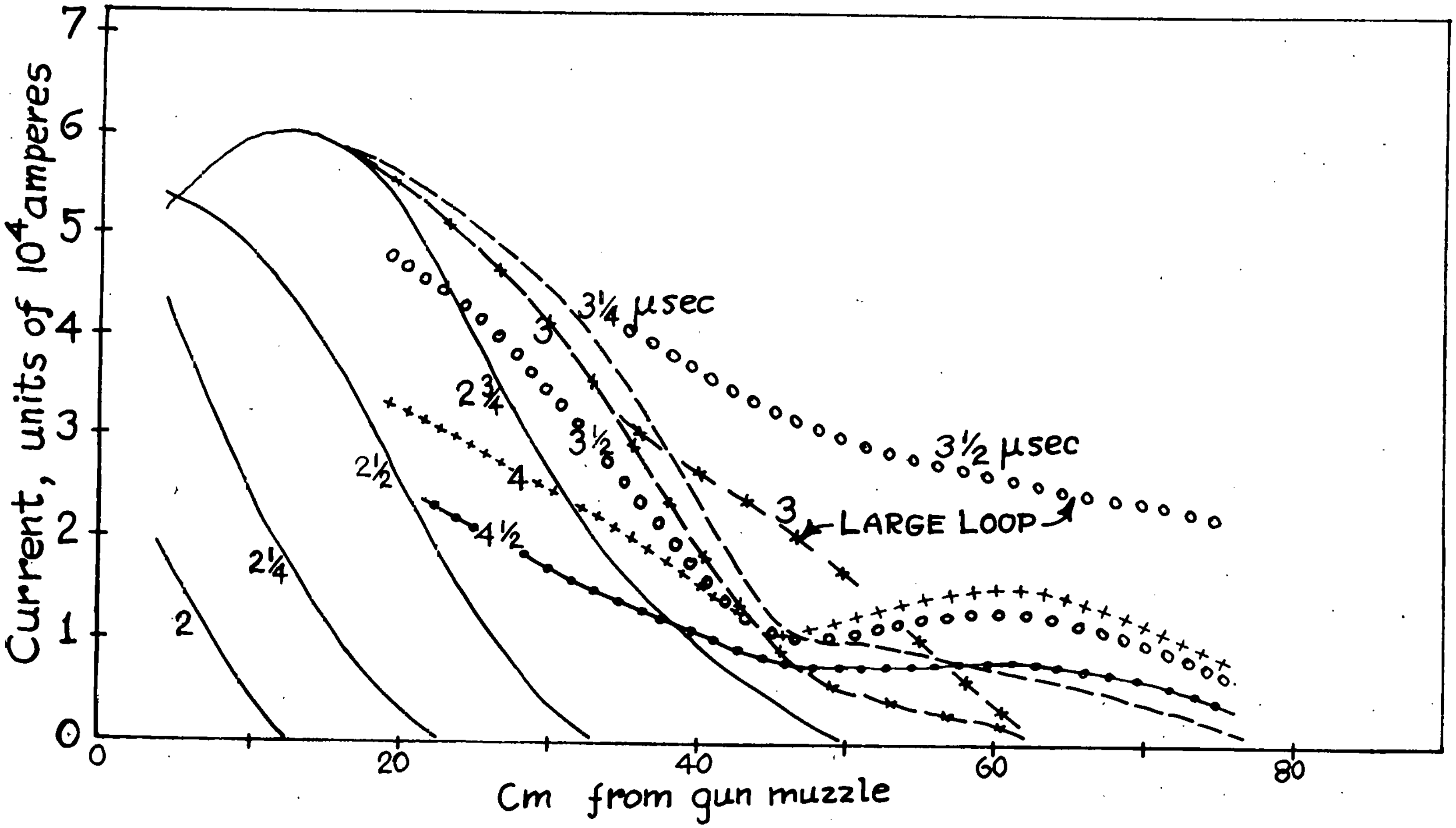
Fig. 5. Plasma current measured with 5-cm diameter Rogowsky loop. Bias field, B_0 = 1.4 kG. Guide field, B_z = 16 kG.



Current, units of 10^4 amperes
0
1
2
3
4
5
6
7
0
20
40
60
80
Cm from gun muzzle
2
2¼
2½
2¾
3
3¼ μsec
3½
4
4½
3
LARGE LOOP
3½ μsec

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Fig. 6. Plasma current measured with 10-cm and 18-cm diameter Rogowsky loops. Bias field, $B_o = 1.4$ kG. Guide field, $B_z = 16$ kG.

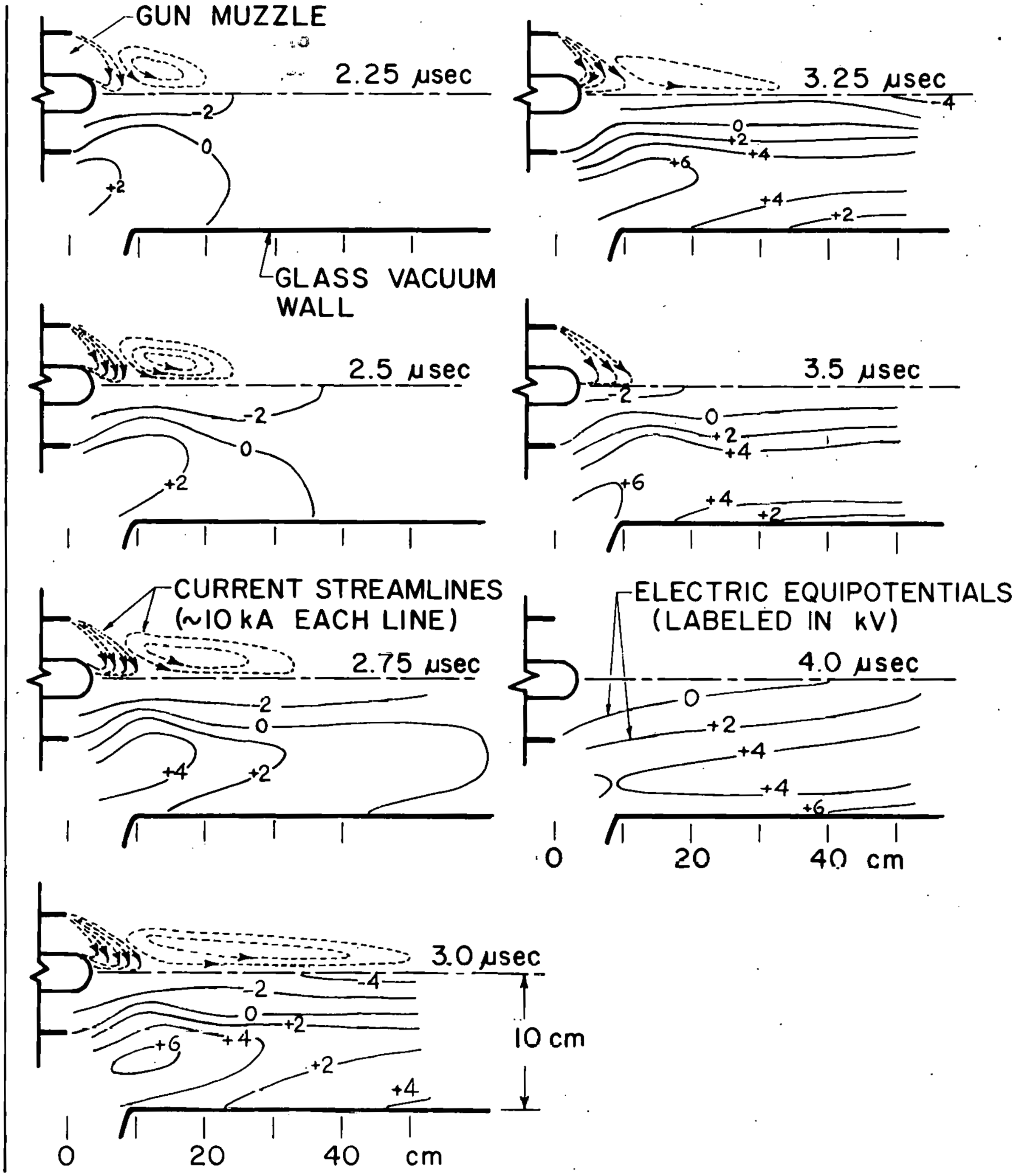
GUN MUZZLE
2.25 μsec
-2
0
+2
GLASS VACUUM WALL
3.25 μsec
-4
0
+2
+4
+6
+4
+2
2.5 μsec
-2
0
+2
3.5 μsec
-2
0
+2
+4
+6
+4
+2
CURRENT STREAMLINES (~10 kA EACH LINE)
2.75 μsec
-2
0
+4
+2
ELECTRIC EQUIPOTENTIALS (LABELED IN kV)
4.0 μsec
0
+2
+4
+4
+6
0
20
40 cm
3.0 μsec
-2
-4
0
+2
+6
+4
+2
+4
10 cm
0
20
40
cm

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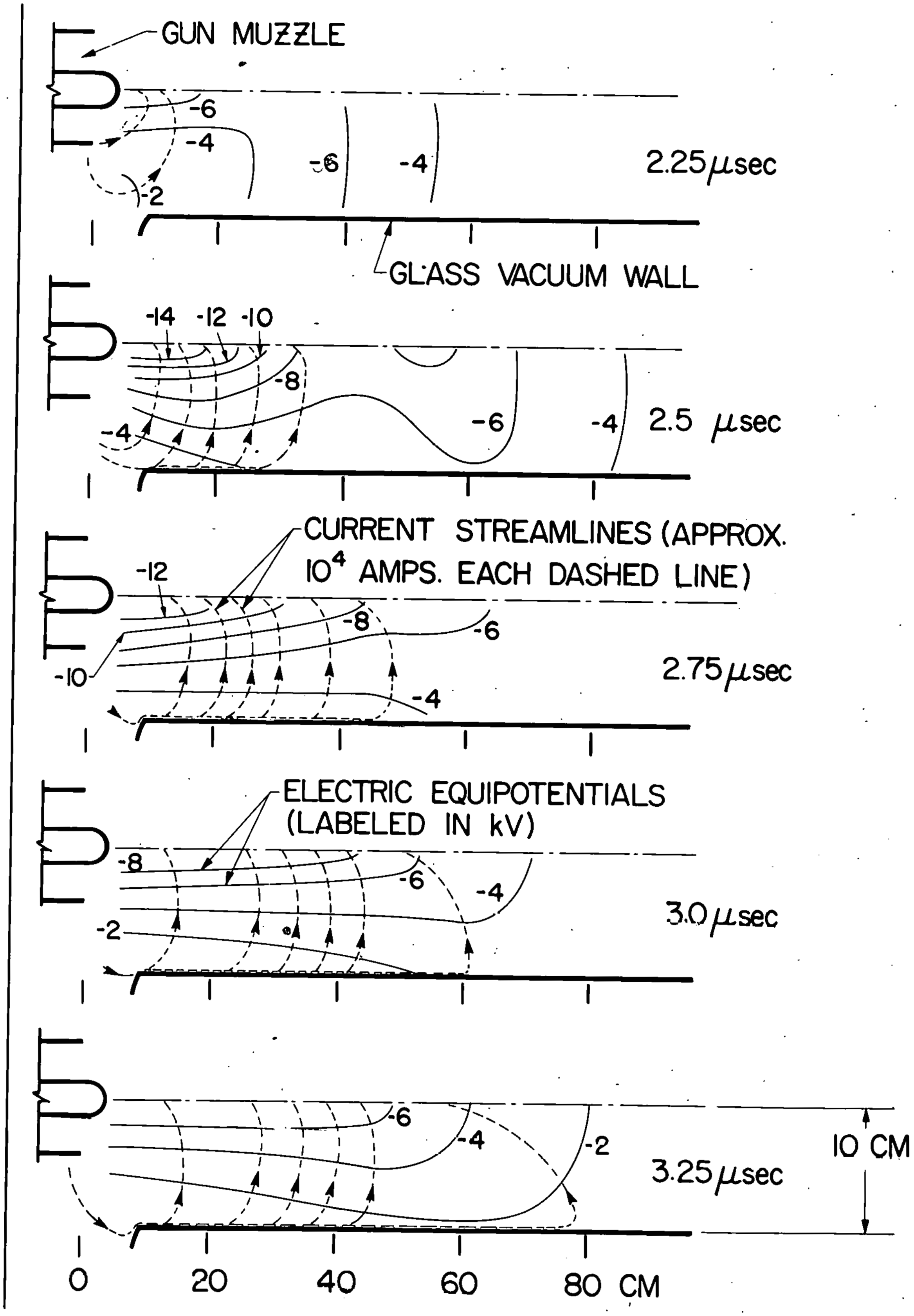
Fig. 7. Potential and current distributions at various times. Bias field, $B_o = 1.4$ kG. Guide field, $B_z = 16$ kG. Note that these represent smoothed data from a large number of shots, and that a considerable amount of imagination has been employed in drawing the current streamlines.



GUN MUZZLE
-6
-4
-2
-6
-4
2.25 μsec
GLASS VACUUM WALL
-14
-12
-10
-8
-4
-6
-4
2.5 μsec
CURRENT STREAMLINES (APPROX. 10⁴ AMPS. EACH DASHED LINE)
-12
-8
-6
-10
-4
2.75 μsec
ELECTRIC EQUIPOTENTIALS (LABELED IN kV)
-8
-6
-4
-2
3.0 μsec
-6
-4
-2
3.25 μsec
10 CM
0
20
40
60
80 CM

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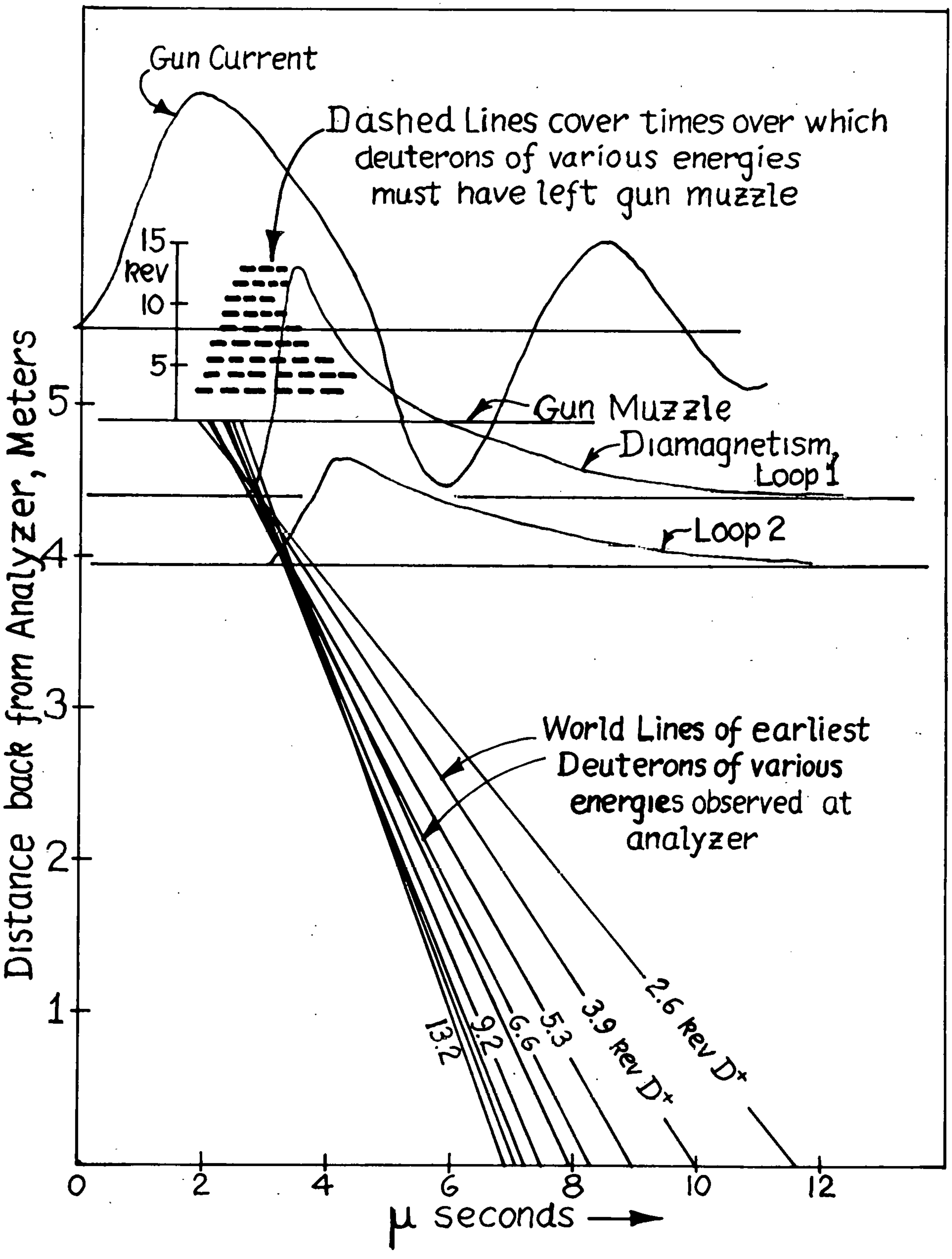
Fig. 8. Potential and current distributions at various times. Bias field, $B_o = 1.4$ kG. Guide field, $B_z = 0$.



Gun Current
Dashed Lines cover times over which deuterons of various energies must have left gun muzzle
15
Kev
10
5
Gun Muzzle
Diamagnetism, Loop 1
Loop 2
World Lines of earliest Deuterons of various energies observed at analyzer
2.6 Kev D+
3.9 Kev D+
5.3
6.6
9.2
13.2
Distance back from Analyzer, Meters
5
4
3
2
1
0
2
4
6
8
10
12
μ seconds →