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THE EXPERIMENTAL TEST ACCELERATOR (ETA) II *

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Summary

The Experimental Test Accelerator (ETA) is designed to produce a 10 kAmp electron beam at an energy of 4.5 MeV in 40 nsec pulses at an average rate of 2 pps. The accelerator also operates in bursts of 5 pulses spaced by as little as one millisec at an average rate of 5 pps. The machine is currently operating near 80% of its design values and has accumulated over 2.5 million pulses--mostly at a rate of one pps.

Our previous paper[1] described the ETA injector and its associated pulse power system. This paper discusses the plasma cathode electron source, the remainder of the accelerator, and the operating characteristics of the machine.

System Description

The ETA injector is followed by eight accelerator cavities, a beam transport section and an experimental tank. The accelerator is shown in Fig. 1. The electron beam is powered by a total of 33 Blumlein type pulse-forming lines that were described in our earlier publications.[1,2] Of the 33, 20 are used to drive the injector; one is used to provide the grid pulse; 8 are used to drive the accelerator cavities; three are used to provide triggers for the 28 gun and accelerator drive lines; and the master trigger Blumlein is used to trigger the grid and three trigger Blumleins. All use water as a dielectric and are charged to near 200 kV by resonant transformers and discharged by identical spark gap switches as described in references 1 and 2. Because of trigger cable limitations, the output pulses of the trigger Blumleins and of the grid Blumlein are attenuated to 80 kV.

The accelerator consists of 8 units each of which adds 250 kV to the beam. The accelerating cavities are very similar to those used in the ERA accelerator.[3] As shown in Figure 2, two cavities are paired to two Blumleins, to provide a more symmetrical drive. Each accelerating gap is resistively compensated to absorb the energy in the absence of beam. At 10 kAmps and 250 kV/gap the pulse energy is evenly split between the beam and the compensation resistors. The resistors are fabricated of approximately 1000 Allen-Bradley 2 watt carbon resistors and are placed under oil in the cans above and below each accelerator cavity. The insulating oil is continuously circulated through the accelerator cavities and deionized water is circulated through the Blumlein PFN's and transmission lines. The oil-water interface is located at the accelerator cavities. These items are visible in the photograph shown in Figure 2.

From the anode to the end of the accelerator the beam is focused by a solenoidal transport system. At the cathode plane the axial component of the magnetic field is bucked to zero by a coil placed behind the cathode. From the anode to the end of the accelerator the axial magnetic field is typically 500 gauss and the beam radius is 3-5 cm. Through the beam transport the beam is focused by a system of simple lenses located approximately one meter apart. The inner radius of the accelerator and transport is 7.3 cm.

The beam current and position are monitored at nine locations along the accelerator and transport system. These monitors ("beam bugs") employ a 12.7 μm thick stainless steel foil that encircles the beam tube. The voltage developed by the beam image current passing through the foil resistor is sampled at four positions around the circumference of the

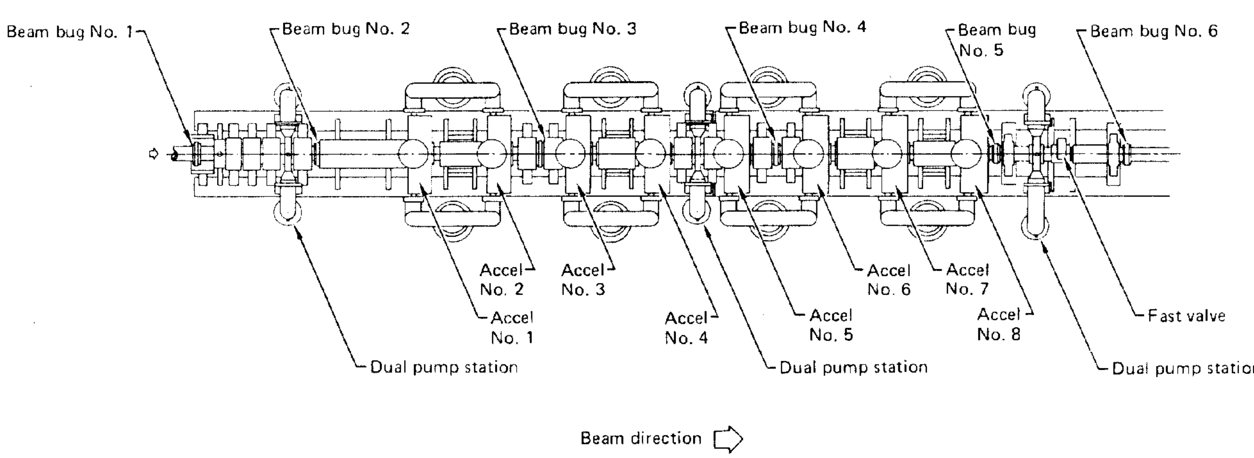

Figure 1. ETA Accelerator

*LLNL is operated by Univ. of Calif. for DOE, W-7405-Eng-48 & by LLNL for DOD/DARPA (ARPA Order 3718) monitored by NSWC N60921-80-WR-W0188.

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beam tube. Adding these signals yields a voltage that is essentially proportional to the beam current. Inverting one and adding signals from opposite sides of the pipe yields a voltage proportional to the beam current and displacement from the axis. These resistive monitors have a rise time of less than one nanosecond and are useable to frequencies beyond 500 MHz.

Beyond the accelerator is a beam transport system that contains a fast closing valve[4] that protects the accelerator in case of a foil rupture down stream; an energy analyzer[5] that was previously developed for the Astron accelerator; a beam dump and tuning aid that allows monitoring the beam size and position and protects the downstream equipment; and a final transport and experimental tank. The vacuum of the accelerator is separated from the gas in the experimental tank by a 25.4 μm Kapton foil. The length of the transport system is determined by the closure time of the fast valve.

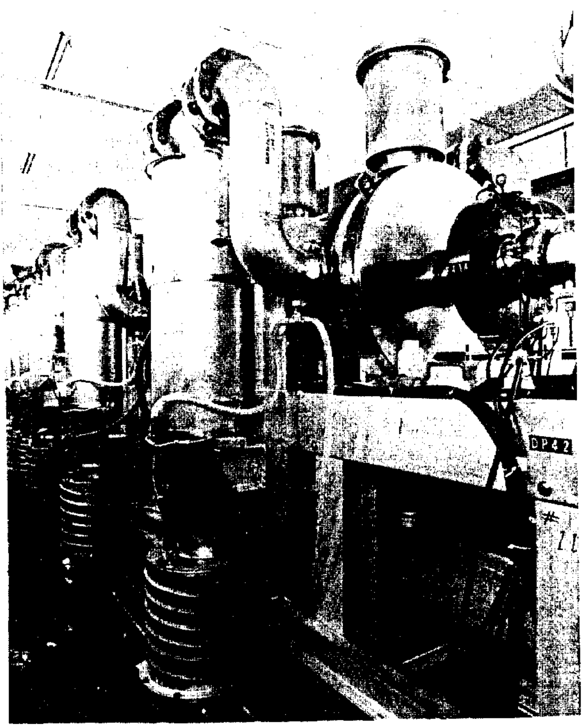

Fig. 2. A view up beam from the end of the accelerator.

The Electron Source

The ETA injector was originally designed to operate with a hot oxide cathode as the electron source. Although these cathodes demonstrated emission current densities greater than the required 20 A/cm^2 when operated in a test stand, the lifetime of the cathodes in the injector was less than satisfactory. A search for an alternative cathode design was initiated.

Previously, a plasma cathode had been developed[6] as an electron source for large area cathodes used for laser pumping. This consists of a maatrix of isolated conducting regions etched onto the surface of a metal clad dielectric. Each of these is separated from the interwoven ground plane by one or more concentric rings where the conducting metal has been etched away. The discs are connected to a common HV pulse source that ignites the surface of the plasma cathode. This connection must be made in a manner which isolates the discs from each other or the first discharge to develop will short out the high voltage source and prevent any additional discharges from forming.

This cathode was tested as a possible source for the ETA injector but showed limited lifetime because the ignitor pulse was capacitively coupled to the cathode. After a few hundred shots, the capacitors shorted and the cathode did not ignite uniformly. This lead to arcing from the cathode surface and failure of the cathode. We found that resistively coupling the igniter pulse worked more reliably and yielded cathodes with lives greater than 5 x 10^5 shots in the ETA injector.

We have developed the following model[7] for the behavior of these plasma cathodes. When an igniter pulse ($\sim$100 kV) is applied to the cathode, the large electric field in the gaps ($\sim$5 mil) generates field emission electrons from the negatively charged conducting surface. A fraction of these electrons collide with the dielectric surface both desorbing neutral gas atoms and stimulating secondary emission. Due to this secondary emission the insulator acquires a positive charge which further increases the electron bombardment of the surface. More gas is desorbed, some of which is ionized and the presence of these positive ions in the gap further enhances the field emission current. This process continues until the pressure in the gap is sufficient to allow avalanche breakdown and gas discharge forms.

Ohmic heating of this plasma by the igniter current continues to increase the plasma temperature, driving the plasma both over and away from the surface with increasing velocity. A short time later the cathode surface is completely covered by plasma and produces the predicted space charge limited current of an ideal emitting plane. At this time the grid potential is applied and electrons are drawn from the plasma sheath. This current follows the Child-Langmuir law if the movement of the plasma sheath is taken into account. At later times the plasma will close the cathode-grid spacing and finally short the grid to the cathode.

Experiments in test stands and in the ETA injector are in good agreement with this model and are discussed in detail in Ref. 7. Figure 3(a) shows oscillograms of the grid-cathode voltage and of the current obtained from a plasma cathode. The ignitor pulse was fired 100 ns before the main pulse and is barely visible in the current trace. Because of the movement of the plasma sheath the effective A-K gap is one half the geometric spacing of 3 cm. These cathodes are insensitive to vacuum conditions, show good reproducibility, and promise lifetimes of at least 5 x 10^5 pulses.

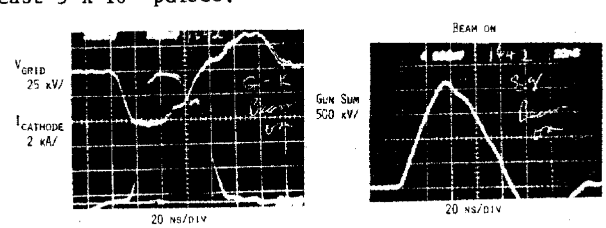

Fig. 3. Four trace overlays of (a) Grid voltage and cathode current and b) Injector anode-cathode voltage.

ETA Operating Characteristics

The operating characteristics of the injector are shown in Fig. 4. These curves represent the maximum good quality current that can be extracted from the injector as a function of the anode-cathode voltage for various size cathodes. Although operation above the lines is possible, a virtual cathode forms just beyond the grid that greatly increases the beam emittance. The "EBQ" code was used to compute these curves. This code is an axisymmetric particle simulation code that self-consistantly solves for the trajectories of cylindrical beamlets taking account of external boundaries and the electrostatic and magnetic fields of the beam. A more thorough discussion of these phenomena and a comparison of theory and experiment is presented in Ref. 8.

As described in (1), the injector accelerating voltage is obtained by firing 20 40 ns Blumleins into ten gun gaps. These Blumleins have a 10-90% rise time of approximately 22 ns. The pulse rise time is further lengthened by the capacitance of the gun gaps with the result that the anode-cathode voltage pulse is as shown in Fig. 3(b). This oscillogram was obtained by electronically summing outputs of capacitive probes that monitor the voltage across each of the ten gun gaps. This oscillogram represents four sequential firings of the injector at 1 pps.

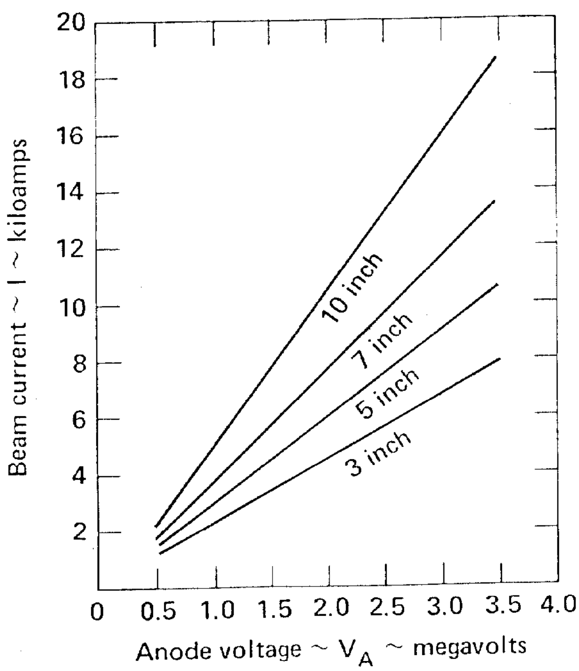

Fig. 4. Current limits of the ETA injector for various diameter cathodes

Figure 5 shows oscillograms of the beam current at the injector output and at the accelerator output. For these data the beam energy was 1.8 MeV at the gun output and 3.5 MeV at the accelerator output. Each of these oscillograms also represent four firings of the injector and accelerator units. The beam at the accelerator output shows evidence of the beam breakup instability. These phenomena are covered in more detail by Briggs[9] et al. in a companion paper.

Conclusions and Further Comments

The ETA accelerator produces current pulses from 5 to 8 kA in amplitude with FWHM of approximately 30 ns. Over this period the beam energy varies approximately 25%. The energy variation causes a shortening of the beam current pulse to approximately

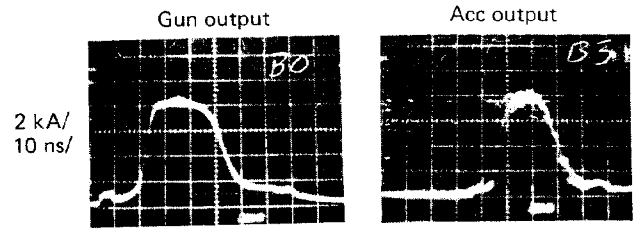

Fig. 5. Four trace overlays of the beam current at the injector output and at the accelerator output.

one half the width of the gun voltage pulse. Calculations of the beam envelope show that an optimum adjustment of the focusing field for peak energy results in large oscillations of the beam envelope at lower energies. As a result low energy electrons at large radii are lost in and just beyond the injector at the position of the second envelope maximum.

The jitter of the sparkgap firing is typically 2 to 3 ns which is acceptable for operation. However, the lifetime of the tantalum sparkgap electrodes is often less than 500,000 shots and as the electrodes approach their end of life the firing jitter and the firing delay increases. This affects the gun voltage waveform and causes asymmetrical drive currents in the injector and accelerator cavities. For these reasons the spark gap trigger pulses which are currently 80 kV will be increased to 150 kV and the tantalum spark gap electrodes will be replaced in brass or inconel in the near future. On the basis of development tests[10] performed in support of the ATA accelerator, we expect a significant improvement in sparkgap firing jitter and electrode life after these changes.

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