FIRST STUDIES OF ATA INJECTOR

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ABSTRACT

The operational characteristics of the 10 kA, 60 ns, 2.5 MeV ATA injector are presented. Studies of beam emittance, beam profile, rf spectrum and other aspects of beam dynamics were performed, as was a detailed study of the operation and interaction of the plasma cathode and the extraction grid.

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I. INTRODUCTION

The Advanced Test Accelerator (ATA) is an experimental electron beam accelerator whose nominal parameters are a 10 kA beam current, a beam kinetic energy of 50 MeV, and a 60 ns pulse width. This accelerator is of the linear induction type and is composed of a 2.5 MeV injector followed by 190 identical 250 kV accelerating induction cores. The operating characteristics and performance of the injector are the subject of this report; special attention is given to detailed studies of the beam produced by the injector. Phenomena associated with the cathode plasma source and how this plasma interacts with the extraction grid to cause observed beam characteristics are also presented. Complete description of the ATA injector mechanical design¹ and electrical systems² are given in the references.

II. DESCRIPTION OF THE EXPERIMENTAL ARRANGEMENT

A. INJECTOR COMPONENTS

Our studies were done using the ATA injector (Fig. 1) and the transport beam line that normally connects the injector to the accelerator induction cores (Fig. 2). The injector consists essentially of a plasma cathode (K) which supplies the beam electrons, an extraction control grid (G) and an anode cone (A). An induction electric field is created by ten identical induction cores (I) the sum of which create the 2.5 MeV accelerating potential between the cathode and anode. Housed within the anode cone, and over the transport beam line are coils which focus and guide the beam. The anode voltage pulse (sum of all ten induction cores) has a ~50 ns flat top with ~30 ns rise and fall time.

Limiting beam extraction to the constant portion of the anode pulse (thereby insuring constant beam kinetic energy for all beam electrons) is the function of the control grid which "gates" current extracted from the cathode. This gating is accomplished by the sharply rising grid voltage pulse (~100 kV, 8 ns rise) that is delivered to the grid plane. Nominally the grid plane is 1.9 to 2.9 cm in front of the cathode surface and the anode plane is ~ 17 cm from the grid plane. For all studies reported here the grid was a 60% transparent heavy gauge screen. The cathode surface is a plasma surface discharge source³ that is formed by an igniter pulse (~70 kV) which is applied at a predetermined time (τ_{ig}) relative to the extraction grid pulse. Over the 500 cm² cathode plane, several thousand surface breakdowns/discharges are initiated by the igniter pulse which is resistively connected to each discharge center. These discharges quickly evolve into the cathode plasma from which electrons are extracted. A final component of the injector are the bucking coils. Since the beam electrons eventually must leave the accelerators magnetic field, conservation of angular momentum requires that they be initially extracted from a region of no axial magnetic field if the extracted beam is to have no net rotation. To accomplish this, two bucking coils (B) are located behind the plasma cathode surface and are of polarity to cancel the B_z component of the anode coils fringing field at the cathode plane.

B. INJECTOR OPERATION SEQUENCE

In bringing the injector on-line, we generally adhere to the following operational sequence which incorporates all of the functions described above:

1. The desired beam current and beam kinetic energy is chosen - this determines the settings for anode voltage, (V_A), grid voltage, (V_G), and igniter firing time (τ_{ig}).
2. A "rough tune" of the anode and transport focus coils is established.
3. The anode voltage is brought-up to operating value (i.e., all ten induction cores brought-up to full power and properly timed together).
4. The igniter-pulse and grid voltage are brought-up to operating value - this creates a beam of electrons but at low energy (V_G).
5. Timing of the grid relative to the anode is then determined and this timing adjusted until the grid pulse time is centered over the anode pulse time - this creates a full energy beam.
6. Anode and transport focus coils are tuned for optimizing current pulse amplitude and wave-shape.
7. The field values of the first four anode coils are recorded and the required settings of the two bucking coils are calculated in order to null the field on the cathode surface.
8. The bucking coils are turned on to the required value and the magnetic tune is now optimized using only coils after the first four anode focus coils.
9. Optimizing the tune entails adjusting the magnetic focus coils and slight adjustments to the power systems and timing. Always the figure-of-merit is a combination of beam current value, pulse wave shape, minimizing current loss throughout the system, and maintaining the beam current centroid on the centerline of the injector and transport line.

C. DIAGNOSTICS

We end this general description of the experimental arrangement with a listing of those diagnostics used during the injector studies. All diagnostics were deployed in order to study the injector operation and to measure various beam characteristics. Except for the emittance box which also served as a beam dump, these diagnostics are always available - thus, the total ensemble of diagnostics furnish a base on which future injector alterations/improvements can be gauged.

1. Injector Diagnostics (Fig. 1)

- a. Cathode Current Monitor: An eight-section current monitor measuring current flowing across the cathode plasma board (i.e., the igniter current) and between the cathode and grid plane (i.e., extracted beam current). The eight-sections of the monitor's circumference allow for a rough check on uniformity of emission. Igniter timing, τ_{ig} , is measured as the time difference between the igniter current and the cathode extraction current which is gated on by the grid voltage pulse.
- b. Grid Voltage Monitor: Either a resistive divider or a cable capacitor probe which measured the grid voltage pulse as it is delivered to the control grid (i.e., after the grid-magnetic-pulse-sharpener).
- c. Anode Voltage Monitor: The sum of resistive dividers across each of the ten induction cores yields this measure of anode voltage.

d. *Injector Output Current Monitor:* A four-section current monitor which furnishes measurement of total current and beam centroid location relative to centerline in two orthogonal planes. This is our standard current monitor⁴ which is duplicated throughout the rest of the accelerator.

2. Transport Diagnostics (Fig. 2)

a. *Current Monitors:* Standard beam current and centroid monitors are located between focus coils at $z = 2, 3$, and 4 meters (cathode surface is $z = 0$, injector output is $z = 2$ m).

b. *Induction Loops:*⁵ These are high frequency magnetic induction loops (B_θ) which sense the rf noise spectrum of the beam as well as lower frequency beam spatial and amplitude variation; i.e.; signal output is proportional to dI/dt of (I/r) . These monitors are located at $z = 2.5, 3.2$, and 3.8 m.

c. *Beam Profile X-ray Monitors:*^{6,7} These diagnostics, also located at $z = 2.5, 3.2$, and 3.8 m measure the time-dependent beam radial profile by passing a small high- z target through the beam and monitoring the x-rays emitted from the target. The information on beam profile is compared to computer beam-envelope simulation of injector performance.

d. *Emittance Box:*⁸ Terminating the beam line was a vacuum chamber (emittance box) which consisted of a beam intercepting target plate and an imaging plate that was viewed by a fast, gated TV. The beam was directed onto the target plate which was perforated with many holes. The beamlets streaming from the holes were casted upon an

imaging scintillation plate which was viewed by a TV monitor. The image (radial profile) that the beamlets make on the scintillation plate furnish information on beam uniformity (distribution of beamlets) and beam emittance (rate of expansion of each beamlet as determined by the size of holes in the target, the distance from the perforated target to the imaging surface, and the measured TV image profile on the imaging surface). The emittance box was in place of the first accelerator cores and hence, is not a continuous ongoing diagnostic.

e. Beam Limiter: A single-hole aperture (2 cm diameter) was for some experiments inserted immediately after the injector. The aperture limited and defined the full beam current (~ 10 kA) to a single beamlet of ~ 1 kA. With the downstream transport coils turned off, and using x-ray dot probes to measure the evolving beamlet profile, a corroborative measurement of emittance was made.

III. EXPERIMENTAL RESULTS

A. CURRENT VOLTAGE OPERATING CHARACTERISTICS

The first step in activating the injector is to establish the anode potential and then to adjust the control grid timing relative to the anode. Figure 3 documents this procedure. The anode voltage (unloaded) was 2.4 MeV, grid voltage was 110 kV and the igniter timing (τ_{ig} , the time interval that the igniter pulse precedes the grid pulse) was 80 ns. The injector output current wave form clearly shows the "gating" effect of the control grid. The current loading of the anode voltage is seen

and indicates relative timing of current and voltage. Also, the output current waveform tracks the grid voltage waveform when the grid pulse is centered on the anode pulse. When the grid timing is not centered on the anode pulse, the acceptance of the anode transport focus coils, which serve as an energy filter, truncates the output current pulse (i.e., electrons of too low an energy are not transported). Operating characteristics of the injector are dependent upon the following parameters:

- igniter timing, τ_{ig}
- grid voltage, V_g
- anode voltage, V_A
- cathode-grid gap, d_{K-G} (set at either 1.9 or 2.9 cm)
- grid-anode gap, d_{G-A} (this remained fixed at 17 cm).

For these parameters, the dependent variables are cathode current (I_K , current flowing from plasma cathode to grid) and output beam current (I_O , current leaving the base of the anode cone). These currents are neither equal in amplitude nor identical in wave form in part due to the energy selectivity of the magnetic field and also due to current extracted from the anode side of the grid surface (a topic to be covered in a later section). In Fig. 4 we show how I_K (peak) varies with τ_{ig} for various combinations of V_A , d_{K-G} , and V_g settings. Each data point represents one injector operating condition for which the anode focus coils and the relative timing of grid and anode voltage were adjusted to give optimum waveshape and amplitude on both I_K and I_O . The intrinsic difficulty in exactly duplicating injector conditions

(notably relative timing of igniter, grid and anode), causes the apparent discontinuity in the parameter scans. For example, the data showing the effect of grid voltage variation of 90, 100, 110, and 115 kV, for all other parameters fixed, does not show a successively increasing trend. However, this data, which summarizes approximately 2 months of operation with many startups, is useful in roughly indicating the interdependence of the previously listed injector parameters.

In Fig. 5 we again show the operating points of I_k versus τ_{ig} for conditions of $V_A = 2.4$ MeV, $d_{K-G} = 2.9$ cm, $V_g = 110$ and 115 kV. However, also included is the theoretical prediction based on simple Child Langmuire current, i.e.,

$$I_k = A \times P \times V_g^{3/2} / (d_o - v_p \tau_{ig})^2 \quad (1)$$

when $A = \text{cathode area} = 500 \text{ cm}^2$, $P = \text{perveance} = (4\epsilon_0/9) (2e/m_e)^{1/2} = 2.33 \times 10^{-6}$, $V_g = \text{grid voltage}$, $d_o = d_{K-g} = \text{physical spacing from cathode plasma board surface to grid surface}$, $v_p = \text{expansion velocity of the cathode plasma as it closes down the gap } d_o$, $\tau_{ig} = \text{igniter timing (time that igniter is fired before the grid voltage is applied which allows cathode plasma to expand)}$. We determine a plasma expansion velocity by normalizing to the experimental data point of $\tau_{ig} = 80$ ns, $V_g = 110$ kV, and $I_k = 10$ kA; this gives $v_p = 10.4$ cm/ μ s. Assuming this expansion velocity to be constant, Fig. 5 shows that the predicted behavior of I_k versus τ_{ig} deviates from the data. Clearly a model based on the cathode plasma would fit the observed data better, including a strong decelerating but additional phenomena, to be discussed in

susequent sections, are also involved. In Fig. 6 we show the same I_k data points but now versus the injector output current I_0 . For these experiments the grid was stainless steel mesh of 60% transparency. In contrast the data shows $I_0 \sim 86\% I_k$. The focusing due to the finite wire size of grid mesh does not significantly increase the effective transparency. Reflexing electrons (electrons reflecting between cathode surface plasma and a virtual cathode) are prevented by the grid's low transparency and hence cannot contribute to this discrepancy. This data of I_0 vs I_k suggests that as much as 26% of the beam current originates on the anode side of the extractor grid.

IV. DETAILS OF BEAM CHARACTERISTICS AND INJECTOR OPERATION

A. BEAM PROFILE

The radial distribution of the beam was studied by two different techniques. At discrete locations along the magnetic transport we used "x-ray probes" which had radial movement to scan across the beam profile. The emittance box which terminated the transport line also gave a TV image of the beam profile. As both these diagnostics and their results are detailed in additional reports,^{7, 8} we will only summarize the findings here. In Figs. 7 and 8 we show radial profiles of beam current density at three times during the beam pulse. These curves are smoothed data from the actual x-ray probe signals whose output is proportional to beam current density. For both data sets the beam profiles have current density variations that cause the profiles to be asymmetric and non-monotonic. In Fig. 9 we show the corresponding

cathode current, anode voltage, beam output current and magnetic topology (axial magnetic field in the anode and transport) that correspond to Figs. 7 and 8. Obviously, for the condition of Fig. 7 the final magnetic field was weaker so that the beam profile was broader and the 0.3 cm diameter x-ray target could better resolve the details of the beam profile. Also, for Fig. 7 the higher beam current, and late timing of the current pulse relative to the anode voltage (note the "loading" of current pulse on the anode voltage), all contributed to hollowing of the head and tail of the beam pulse. For both examples the grid voltage was 110 kV, but the igniter timing was 80 ns (100 ns) for Fig. 7 (Fig. 8).

The emittance box TV systems, when used as a beam profile monitor, affords better spatial resolution than the x-ray probe technique. In Fig. 10 we show a 3-d plot of beam current density profile for a 7.5 kA/2.5 MeV beam whose beam radius was pinched (by increasing magnetic field strength in the transport coils) to ~ 0.5 cm. However, again the details of the beam profile show significant fine-scale structure (a current density variation of $\sim 25\%$ within a beam FWHM radius). Even when the emittance box's TV systems was used to measure emittance, fine scale, non-reproducible beam asymmetries were apparent.

Summarizing these studies, we measured beam profiles and observed their sensitivity to operating parameters. As detailed in the x-ray probe report,⁷ these measured profiles are in good agreement with computational predictions of beam envelope codes. However, we have observed that the beam has asymmetry and fine-scale structure that is preserved through at least the length of the transport section

(3.8 meters). Non-azimuthally symmetric profiles with the current centroid on axis, can produce a non-uniform wall return current which could excite unwanted cavity modes. A final observation, not illustrated by the data profiles presented here, is that the head of the beam (i.e., first ~ 12 ns, does not have a well-structured profile. By both the TV imaging and the x-ray probes the beam head was observed to be a diffuse, blotchy blob of charge nearly filling the pipe.

B. BEAM EMITTANCE

Terminating the injector transport line was the emittance diagnostic box.⁸ In Fig. 11 we summarize the findings; over a parameter range of 6 to 10 kA. For many experimental operating conditions (V_g , V_A , τ_{ig} , and various magnetic tunes including strength of the bucking coil), the beam emittance was relatively invariant with a value of 0.3 radian centimeters. This value is in excellent agreement with theoretical predictions of Neil and Paul.⁹ A dominant contribution to the predicted emittance is the field perturbation caused by the finite grid wire spacing. To test this sensitivity, the injector was equipped and operated with two different grid materials of identical transparency but with wire spacing varied by a factor ~ 4 . Within the bounds of experimental uncertainty, emittance measurements of the beam extracted from these grids did not deviate from the 0.3 radian centimeters. Because of this null experimental result, we presently are uncertain as to what is the dominant contribution to the beam emittance.

In order to cross-check the measurements made by the emittance box, a second determination of emittance was used. Again, these experimental

results are described in detail in the x-ray beam profile report.⁷ An aperture plate with a single 2 cm diameter hole on axis was installed immediately after the injector output current monitor (see Fig. 2). Magnet coils downstream of this (i.e., the transport beam line coils) were turned off and x-ray probe scans determined the profile of the beamlet expansion at discrete axial locations. The purpose of the aperture was to define a hard-edge to the beam and to limit the total current so that space charge was less a dominant factor governing envelope expansion. Computational predictions of the beamlet profile expansion were fit to the measured profiles, the beam emittance being a free parameter. This procedure yields an emittance of 0.48 radian-cm. Given the experimental limitations of this technique, its results substantiate the emittance box measurement of 0.3 radian cm.

A second use of the aperture plate was to enable confirmation that the bucking coils do effect total beam emittance, ϵ_T , defined as $\epsilon_T^2 = \epsilon_I^2 + P_\theta^2$. Here, ϵ_I is the intrinsic emittance due to random motion (temperature) and P_θ is in the canonical angular momentum. P_θ includes kinetic plus field momentum, i.e., $P_\theta = \gamma m r^2 \dot{\theta} + q \frac{r}{c} A_\theta$ where the angular vector potential is $A_\theta = \frac{1}{r} \int r B_z(r) dr$, which for uniform B_{z0} gives $A_\theta = \frac{1}{2} r B_{z0}$. To minimize ϵ_T implies $P_\theta = 0$ requiring that the beam be created with no particle rotation ($\delta m r^2 \dot{\theta} = 0$, i.e., beam extracted purely by E_z from the grid) and that no external B_z thread the cathode plane ($A_\theta = B_z = 0$ across the cathode surface). The purpose of the bucking coil is to null the leakage B_z field from the anode focus coils, and thereby insure $P_\theta = 0$. The required current in the two bucking coils

(Bucking Coils A and B) is related to the currents in the first four anode focus coils (1 through 4) by

$$3.56 I_A + 11 I_B = 3.65 I_1 + I_2 + 0.4 I_3 + 0.1726 I_4 \quad . \quad (2)$$

$$2.97 I_A + 11.51 I_B = 3.23 I_1 + 0.89 I_2 + 0.375 I_3 + .1745 I_4 \quad . \quad (3)$$

In Fig. 12 we show data indicating how beam expansion rate (and hence ϵ_T) is effected when the bucling coils are off and then turned on to values prescribed by the above relation. For both conditions the injector output current monitor recorded current and centroid location immediately preceding the 2 cm diameter aperture plate. Bucking coils being on or off did not affect the beam at this location. Again, the transport coils are off after the aperture. The second current monitor, located 0.7 meters downstream of the aperture records the amount of transported current. As the data indicate, for bucking coils off (on) the peak current was 1.1 (1.6) kA. In both cases the x-ray profile monitors indicated the beam was hitting the walls. For each condition the initial 1.0 cm radius beam expanded to some radius, a , larger than the pipe radius, a_p ; therefore the pipe acts as a second aperture. Ignoring the dominant space charge contribution to beam expansion, one can estimate P_θ by using the relation for emittance dominated beam envelope expansion

$$a^2(z) = a_0^2 + \frac{(\epsilon_I^2 + P_\theta^2)}{\gamma^2 a_0^2} z^2 \quad . \quad (4)$$

The ratio of transported current is measured for bucking coils on and off is

$$\frac{I \text{ (coils on)}}{I \text{ (coils off)}} = \frac{a_0^2 + \frac{\epsilon_I^2 + P_0^2 z^2}{\gamma^2 a_0^2}}{a_0^2 + \frac{\epsilon_I^2 z^2}{\gamma^2 a_0^2}} \quad (5)$$

Using the experimental measurements and recognizing $a_0^2 \ll \frac{2}{\gamma} z^2 / a_0^2 \gamma^2$ yields $\frac{P_0}{\epsilon_I} \sim .7$. The magnetic field strength at the cathode without bucking coils was ~ 38 gauss; projecting the ratio of current transmitted through the aperture to current incident upon the aperture as a ratio of areas, then approximately $(1/\sqrt{7})$ of the 12.7 cm cathode radius was sampled. For these values, $P_0 = eBr^2/2 mc \gamma \sim .250$ rad-cm, and using $\epsilon_I \sim .3$, $P_0/\epsilon_I \sim 0.8$, consistent with the experimental value thus indicating the necessity and efficiency of the bucking coil cancellation. Finally, note that the centroid offset beyond the aperture did change for the conditions of bucking coil on/off. This variation suggests non-uniform current density being extracted from the cathode-grid region.

C. NOISE SPECTRA MEASUREMENTS

The Beam-Break-Up (BBU) instability, a beam cavity interaction with a peak growth rate at 800 MHz, is only one of many possible beam-driven cavity oscillations which occur at frequencies less than the 1.2 GHz

cut-off limit imposed by the 5.25 inch diameter accelerator pipe size. Magnetic induction probes positioned to sense the B_0 field of the beam current are an extremely useful and simple diagnostic giving information on beam behavior over this rf band.¹⁰

For the BBU instability, what matters is the frequency spectrum of the dipole excitation, $I\delta$, where I is the beam current and δ is the amount of spatial off-set of the magnetic centroid relative to the geometric axis. Measurements of the dipole-excitation frequency spectrum have been performed.¹¹ The sum of the signals from a pair of rf loops located on a pipe diameter with opposing orientations cancels the monopole contribution but adds the dipole contribution. The result is an output signal given by

$$V_{\text{cut}} (\text{difference}) = \frac{\omega k |I\delta|^2}{r_0^2} \quad (6)$$

where k is a geometric factor which included rf probe dimensions and orientation relative to the plane of transverse beam motion, ω is the radian frequency of the driving dipole excitation, $I\delta$, and r_0 is the beam pipe size. These measurements indicate that the upper bound of the beam's dipole excitation noise level (1.7×10^{-4} cm) is slightly less than that experienced on the ETA injector. Theoretical/computational analysis this initial BBU excitation noise level suggests that attaining a full 10 kA current through the entire accelerator will require some damping of transverse beam motion. The output signal from a single

rf loop also gives the spectrum of the fields that exist within the vicinity of the probe. These fields can either be intrinsic to the beam, or indicative of the localized field structure (i.e., a beam can induce a field structure within a cavity, but this field structure might not couple back onto the beam). Figure 13a shows the frequency spectrum over the range 100 to 1100 MHz. The first three spectra in Fig. (13a) are for 8, 9 and 10 kA of beam current respectively. Here the rf probes are simply mounted on ports that penetrate through the accelerator pipe. The cause of the broad, low Q, resonance at 500 to 600 MHz is not understood - and as the other spectrum indicate, is not reproducible. The remaining spectra shown in Fig. (13b) are for two different runs at 8 kA. Here, two differently located rf probes were used. The first, located on accelerator pipe ports, did not show discernible resonant structure. The second set of rf probes, located in vacuum pump boxes that exist periodically along the beamline, showed a 500 MHz resonance. We presently do not understand why such structure in the frequency spectra exist, why it is non-reproducible, or even if it adversely affects the beam.

D. CATHODE GRID STUDIES

Four phenomena motivated a detailed study of the plasma cathode and the control grid. The beam emerges from the injector with non-uniform (in time and space) current density. A sizeable fraction of the current is from an unaccounted for current source (Fig. 6). The emittance is invariant over a wide range of operating conditions (Fig. 11), and the precursor current which precedes the main current wave form. In Fig. (14)

we show that for full 10 kA operation the precursor current exceeds 1 kA for 30 ns; furthermore, even when the main current centroid is well centered at one axial location, the precursor current centroid is far offset (>4 cm).

Several observations indicate that the beam leaves the cathode-grid with a time-varying asymmetrical and non-uniform radial profile. Shown in Fig. 15 are data from the first two current monitors in the transport beam line. The data in Fig. 15a show that between the two current monitors (I_0 and I_1) no beam current is lost but that the centroid of the beam both rotated and increased its displacement. Since the transport is very nearly a continuous solenoid these data imply that the beam entered the transport off axis. To prove that the beam enters asymmetrically we increased the current of the first anode focus coil by 50%. This change caused the beam current centroid at injector output (Fig. 15b) to vary significantly in the y-plane. Extreme care was taken in injector assembly and check-out to ensure the orthogonality and concentricity of the cathode/grid with respect to the co-linear magnetic and geometric axis. Thus, only if the beam emerges from the grid surface asymmetrically, or at least with its magnetic centroid off-axis, can the first anode focus coil (a symmetric magnetic lens) cause steering of the beam's centroid.

A second indication that a cathode-grid interaction causes beam non-uniformity is shown in Fig. 16. The beam line immediately after the injector was removed, the injector was capped with a lucite plate, and a high resolution gated TV was installed to view up axis and focused to monitor the cathode-grid region. No anode voltage was applied so that no

beam was extracted. Since the grid was 60% transmissive the effect of reflexing electrons was minimal. Fig. (16a) shows the light recorded by the TV (gated to a 10 ns window) 120 ns after just the igniter pulse was applied (no grid voltage applied). The light from just the ignited dots in the cathode board is spatially non-uniform, and if the 10 ns gate was moved in time, temporal variation on a pulse-to-pulse basis was also apparent. Figure (16b) shows the same arrangement but now the 100 kV grid voltage was applied at 80 ns (at $t = 0$ the igniter was pulsed, at $t = 80$ ns the grid was pulsed and at $t = 120$ ns the 10 ns TV was turned on). To avoid saturation the TV gain had to be significantly reduced and as shown the degree of light intensity modulation was extreme. Again, moving the 10 ns gate in time showed the intense light emission to be temporarily and spatially non-uniform. These observations only indicate that emitted white light is non-uniform - no attempt at spectroscopic resolution was made so the source of this light is unknown (excitation, recombination, etc?). However, the observed non-uniformity is consistent with other observations which suggest that the beam's spatial and temporal variations stem from the plasma cathode source and its interaction with the extraction grid.

The following experimental observations were performed in attempts to define the cause of the extra current source (refer to Fig. 6). It was initially thought that grid wire field emission would alone account for the additional current. In the absence of beam current (beam space charge will depress the local potential near the grid) the electric field stress of the anode voltage is sufficient to extract very large field

emission current if there is no emission limit - i.e.,

$$J \sim K \frac{V_A^{3/2}}{d^2} \sim \frac{2.33 \times 10^{-6}}{17^2} \frac{2.5 \times 10^6}{3/2} \sim 32 \text{ A/cm} \quad (7)$$

where K is the perveance assuming space charge limited flow from the grid (no emission limitation), V_A is the anode voltage seen by the grid, and d is the 17 cm grid-to-anode spacing. In Fig. (17a) we show the injector output current when the anode voltage is 2.2 MV, no grid voltage is applied and no igniter voltage applied to the plasma cathode. The scale is 200 A/div and ~20 ns/div. We know this current is extracted from the grid wires for numerous reasons, 1) the cathode current monitor which measures current flowing in the cathode-to-grid gap shows no current is flowing in that circuit, 2) the grid wire weave is sufficiently close such that there is no anode field leakage into the cathode-grid gap, 3) when the aspect ratio of the grid wires was increased by 4 (aspect ratio = s/d where s = wire spacing and d is wire diameter) which increases field enhancement on the grid wires, the extracted grid field emissions current increased accordingly (see Fig. (17b), scale is now 1 kA/div, 10 ns/div but again $V_A = 2.2$ MV, igniter and grid voltage = 0). For the extracted grid field emission currents of Fig. (17a, b) the falling edge of the current is characteristic of the γ selectivity of the anode focus coils magnetic acceptance. However, for Fig. 17a, the magnitude of the current is more than an order-of-magnitude less than is possible if there is no emission limit. Moreover, the linear increase in

extracted current during the constant voltage time suggests that the emission limit is gradually being overcome. Low transparency grids whose field emission characteristics are shown in Fig. 15a were used for this report.

Finally, to obtain Fig. (17c), we return to the same configuration as for Fig. (17a), but now the plasma cathode igniter board is pulsed 50 ns before the anode voltage is applied. Again grid voltage is zero and no cathode current is measured. The amplitude of the extracted field emission current is increased but still appears emission-limited, however, a precursor current now appears. The characteristic of this additional precursor current is a rapid spike that is quickly depleted followed by an approximately constant-in-time lower current value that finally gives way to the normal grid field emission current. Our interpretation of this current signature is that as the plasma cathode is ignited it ejects a fast, ($\sim 1 \times 10^8$ cm/sec - see Fig. 19) tenuous plasma through the grid mesh. When the anode voltage is applied the tenuous plasma is rapidly drained of electrons causing the initial current spike, i.e., the plasma is eroded back down to the grid surface. The persistent lower level of current is the emission-limit of the plasma-grid interface. Based on this model the plasma properties can be deduced for the conditions shown in Fig. 17c, where $\tau_{ig} = 50$ ns. The initial current spike is ~ 300 A with a 4 ns duration, and the approximately constant emission-limited current is ~ 100 A. The tenuous plasma's characteristics are

$$n_p = \frac{\int i_{\text{spike}} dt / q}{A \times (v \tau_{ig} - 2.9 \text{ cm})} = 3.6 \times 10^9 \text{ cm}^{-3} \quad (8)$$

(where $A = 500 \text{ cm}^2$ cathode area, $v = 1 \times 10^8 \text{ cm/sec}$ plasma frontal speed, $\tau_{ig} = 50 \text{ ns}$, and 2.9 cm is the cathode-to-grid gap) and

$$\left(\frac{J_p}{qn_p} \right)^2 \left(\frac{m_e}{q} \right) = T_e \sim 70 \text{ eV} \quad (9)$$

(where $J_p = 100 \text{ A/500 cm}^2$).

The calculated plasma parameters of $n_p \sim 3.6 \times 10^9$ and $T_e \sim 70 \text{ eV}$ also imply a Debye length of $\lambda_D = \sqrt{\frac{\epsilon k T_e}{q^2 n_p}} \sim 0.1 \text{ cm}$, which is comparable to grid wire spacing and thus consistent with the observation that the plasma does not "shield" the grid from anode fields causing field emission. The slight increase in emission (Fig. 15c compared to 15a) may result from plasma ion back bombardment causing secondary electron emission from the grid wires i.e.

$$I_e = \text{secondary electron emission current} = \gamma I_i = \gamma (n_p v_i q) A \sim 322 \text{ Amps}$$

where we have used $\sim 25 \text{ keV}$ protons (anode stress on the grid is $\sim 125 \text{ kV/cm}$ and we estimate that the plasma protrudes several Debye lengths) and secondary emission coefficient of $\gamma = 5$ (no enhancement due to acute angle of incidence is included).

Up to this point we have examined grid and plasma-cathode effects only for the condition of no applied grid voltage and an early $\tau_{ig} = 50 \text{ ns}$ time. We now look in more detail at data for when the grid

voltage was applied and the igniter timing was varied. In Fig. (18) we show the grid voltage (20 kV/div, 20 ns/div), the cathode current (2 kA/div, 20 ns/div; due to signal cable lengths this signal is displayed 9 ns late with respect to the grid voltage trace), and the injector output current (2 kA/div, 20 ns/div). The first negative going current on the cathode current trace is the igniter current which was set for $\tau_{ig} = 80$ ns. The cathode current monitor shows a small rising precursor current (-1kA) that results from the grid magnetic drive having a small leakage voltage that precedes the main pulse before the magnetics saturate. Also shown in Fig. (18) is the signal from the injector output current monitor which still shows the rapid step in the precursor current that is not seen on the cathode monitor. For these operating conditions, in order to estimate the characteristics of the plasma that envelops the grid before the main current is extracted we need the behavior of $(I_o(t) - T I_k(t))$ where I_o is the output current, and T is the grid 60% transmission which attenuates the cathode current I_k . We are only interested in the time of the precursor current which precedes the main pulse. Plotted at the bottom of Fig. 18 is $I_o(t) - T I_k(t)$ for the $\tau_{ig} = 80$ ns condition. As in the condition of no applied grid voltage, there is still a first spike, I-1, followed by a lower current plateau, I-2.

The influence of τ_{ig} on the precursor current is shown by the oscilloscope traces of Fig. 19. We also plot how the characteristic value for I-1 and I-2 vary with τ_{ig} . From the characteristic of I-1 versus τ_{ig} we interpret as the arrival time of the plasma front at the grid surface. The time-of-flight across the ~ 3 cm K - G gap determines

the frontal speed to be $\sim 1.0 \times 10^8$ cm/sec. The spike characteristic of I-1 continues to indicate plasma having penetrated beyond the grid and then being eroded back due to application of the anode voltage. Saturation of I-1 indicates that plasma does not freely expand into the volume past the grid but rather that its velocity is arrested. Such behavior is to be anticipated since the bucking and anode coils form a very sharp cusp field which would stagnate forward plasma motion. Simple pressure balance ($B^2/2\mu \sim nkT$ where T is the equivalent temperature of the forward plasma ion velocity of 10^8 cm/sec) indicates that ~ 50 gauss of B_r magnetic flux would stagnate the forward motion. Magnetic field plots of the bucking and anode coils indicates this occurs ~ 4 cm beyond the grid and the behavior of I-1 (i_{ig}) suggests this stagnation is complete in a time interval $\tau \sim 130$ ns. A simple algebraic approximation for the decelerating plasma velocity that satisfies the criteria of $v_p(t) = v_0 = 10^8$ with $L(t) = 0$ at $t = 0$ and $v_p(t) = 0$ with $L(t) = 4$ cm at $t = \tau = 1.3 \times 10^{-7}$ (where $t = 0$ implies the grid crossing and L is the distance from the grid) is

$$v_p(t) = v_0 - 2.15 \left(\frac{v_0}{\tau} \right) t + 1.15 \left(\frac{v_0}{\tau^2} \right) t^2 \quad . \quad (10)$$

with $L(t) = \int_0^t v_p(t) dt$. Now, again using the definitions

$$n_p = \frac{\int (I-1) dt/q}{A \times L(t)} \quad . \quad (11)$$

$$T_e = \frac{(I-2/A)^2}{(q n_p)^2} \frac{m_e}{q} \quad . \quad (12)$$

we can estimate how the plasma which envelops the grid prior to main beam current extraction evolves with increasing τ_{ig} . In Fig. 20 we show these estimates of n_p and T_e . The T_e values increase to a level too high to be actual (~ 700 eV) and indicates a breakdown of our simplistic model - probably since these precursor currents come from a thermal tail component and not a bulk plasma. However, the n_p value of $\sim 5 \times 10^9$ gives an explanation to some of our operational characteristics. First, with the grid voltage applied, ion back bombardment of the grid structure (note the grid always shows a blueing indicative of surface heating due to ion bombardment) will now create a secondary electron emission current of ~ 1.5 kA ($\gamma = 5$, $n_i = 5 \times 10^9$, and assume 300 KeV average ion energy). We assume that due to intense ion back bombardment the grid no longer has emission limitations (Fig. 15) so that once the grid starts emitting current, the beam inductance will maintain the total current value. Simulations done by A. Paul on current emitted from the grid plane show that ~ 1.5 kA from this surface will dominate the total beam emittance. Second, ion dynamics are not included in our present codes which model injector operation, but ions clearly would influence perveance, virtual cathode formation and most notably the formation of the beam waist (first ~ 12 ns). Third, the possibility of beam-plasma interaction does exist in the vicinity of the grid where $n_p \sim n_b$.

As a final observation we return to Fig. (18) and examine the "turn-on" characteristics of the main beam, i.e., the cathode-grid behavior immediately before and after the grid voltage rapid turn-on (at $t = \tau_0$ as indicated in Fig. 18). The table below indicates the measurements and the calculated value for the effective K-G gap base on both unipolar and bipolar (including ions) Child-Langmuire formulation.

Turn-on Characteristics of Cathode-Grid

time	V_{grid}	I_k	d_{eff} (K-G) (unipolar)	d_{eff} (K-G) (bipolar)
∞	0	0	2.9	2.9
τ_0	10 kV	1.1 kA	1.03	1.40
$\tau_0 + 10 \text{ ns}$	80 kV	7 kA	1.94	2.65

We conclude that the original 2.9 cm gap was initially filled with plasma. The plasma then partially eroded back due to the precursor current, and finally further eroded open due to main current extraction. Obviously, at least the beam head is being emitted and propagated through a dynamic plasma where $n_B \sim n_P$.

What has emerged from this detailed study of the operating characteristics of the plasma-cathode/grid/output current is as follows. The plasma produced by igniting the plasma-cathode is not a well-defined plasma sheath, but rather a diffusing plasma cloud whose leading edge is fast and tenuous and extends past the grid. The spatial distribution of this plasma depends critically upon the igniter firing time, τ_{ig} . The penetration of this plasma past the grid gives rise to a precursor current. Application of the main grid pulse rapidly erodes this plasma, but the ions back-bombarding the grid wires release secondary electrons and cause the apparent field emission limitations to be overcome. Thus, the grid becomes an extra current source and possibly the dominant source of beam emittance. The dynamic phase that the beam head experiences (i.e., plasma erosion with density gradients,

grid interaction with ion back bombardment, and transient ion dynamics) must seriously complicate the formation of the beam head and may cause the observed poor quality early time profiles.

V. SUMMARY

The ATA injector fully meets or exceeds its design specifications. Operational characteristics of 10 kA, 2.5 MeV, 300 milliradian-cm emittance and 50 ns pulse duration are easily attainable; capability of 3 MeV operation has been demonstrated. The operational characteristics for a range of grid-voltage, igniter-timing, anode-voltage, cathode and output current, and magnetic field topology (including effects of a cathode bucking coil) have been investigated. Detailed studies have been performed on various features of the beam as it exits the 2.5 MeV injector. Measurements of the rf spectrum show the ATA beam's intrinsic noise level to be comparable to its ETA predecessor. Beam profile measurements show the beam to have spatial and temporal asymmetries and non-uniformities in current density. If the magnetic centroid of the beam is stable and centered, these deviations from ideal will only contribute higher order non-uniformities in the wall return current. The beam emittance was found to be acceptable but resistant to control. Studies of the cathode-grid operations show that the cathode-igniter plasma couples to and interacts with the grid in a manner that can account for the details of beam profile, extra current source, and emittance invariance. To avoid these complications may require refinements of the cathode plasma source. Another possibility is that if the cathode plasma were two components (i.e., if the troublesome fast/tenuous plasma was

separable from the cold-dense-quasi-stationary bulk plasma), then a strong grid prepulse (no anode voltage) fired early enough might sweep away all low density electrons and ions and expose the cold bulk plasma.

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FIGURE CAPTIONS

- Fig. 1. Schematic of the ATA Injector. The various components cited in the text are cathode surface (K), control grid (G), inductive acceleration cores (I), anode focus coils (AC), anodes (A), bucking coils (BC), cathode current monitors (I_K), output current monitor (I_O).
- Fig. 2. Schematic of the beam transport with diagnostics. The various components are the injector output current monitor I_O , I_1 and I_2 located at $z = 2, 3$ and 4 meters from cathode surface, rf monitors RF-0, RF-1 and RF-2, x-ray probe monitors XR-0, XR-1 and XR-2, the emittance box (EB), the beam attenuator plate (BA), and the transport coils (C).
- Fig. 3. Depicted are reproductions of wave forms for grid voltage, anode voltage, and injector output current as the grid timing is adjusted relative to the anode voltage pulse - the gating of the control grid on the output current is apparent. All traces are 20 ns/div with V_{grid} on 50 kV/div, V_{anode} on 500 kV/div and I_O on 2 kA/div.
- Fig. 4. Operational parameter dependence of cathode current, I_K , versus igniter timing, τ_{ig} , for several different grid voltages, anode voltages, and grid-to-cathode spacings.

- Fig. 5. The data points of I_k versus τ_{ig} are duplicates of those shown in Fig. (4); the solid curve is a theoretical prediction based on Child-Langmuire limitations where the gap spacing is determined by $d = d_0 - v_p t$ where d_0 is the initial 2.9 cm gap and v_p is the plasma velocity given by normalizing to the operating point of $I_k = 10$ kA, $\tau_{ig} = 80$ ns. The lack of correlation between prediction and data indicates that a model of constant plasma closure velocity is overly simplistic.
- Fig. 6. For a fixed grid transparency of 60%, we show the experimental data of cathode current I_k , versus injector output current, I_0 for numerous settings of the other variables (τ_{ig} , V_g and V_a). This data indicates an additional current source that is proportional to cathode current exists on the anode side of the extraction grid.
- Fig. 7. Beam radial profile at three different times in the beam pulse taken by an x-ray "dot" probe located at 3.8 meters. The operating conditions and magnetic field tune are shown in Fig. 9.
- Fig. 8. A second set of beam radial profile at three different times in the beam pulse taken by an x-ray "dot" probe located at 3.8 meters. The different operating conditions and magnetic field time are also shown in Fig. 9.
- Fig. 9. Experimental operating conditions for data of Figs. (7) and (8).
- Fig. 10. Shown is a 3-d plot of beam current density profile (7.5 kA, 2.5 MeV) as determined by the emittance box diagnostic system. Apparent is the fine scale structure and asymmetry in the beam current density radial distribution.

Fig. 11. Measurements of beam emittance for numerous experimental parameters and experimental conditions. The relative invariance of emittance, especially for changes in grid wire spacing, indicates that the dominant contribution to total beam emittance was not varied in these experiments.

Fig. 12. How the bucking coil effects the beam by cancelling angular momentum is illustrated by this data. Two experimental conditions are shown, the bucking coil off and then on. The current and centroid data oscillograms indicate that total current delivered to the aperture plate is unaltered, but the slight increase in transmitted current indicates the cancellation of angular momentum. Analysis of the data is included in the text.

Fig. 13a. Displayed are the rf spectrums from 0.1 to 1.1 GHz of the beam as it leaves the injector. The beam current level is (i) 8kA, (ii) 9 kA, and (iii) 10 kA. These measurements were taken at the 3.2 meter location. The low Q like peak which shifts in frequency as the current is varied is not understood. Scale is 10 db/div and 100 MHz/div.

Fig. 13b. Two examples of rf spectrum taken at two locations on the beam transport section for 8 kA beam current are shown. In each case the spectrum taken at the 3.2 meter location (which is a pump box cavity) shows a resonance peak which may indicate a cavity mode that could couple back onto the beam.

Fig. 14a. Oscilloscope trace showing 10 kA injector output current but also demonstrating the level of precursor current (scale 2 kA/div, 20 ns/div).

Fig. 14b. Oscilloscope traces of a nearly ideal 9 kA beam current except for the precursor current. The centroid location in the x (y) plane is found by the relationship $(V_x/2V_I) R_p$ where V_x is the x (y) signal, V_I is the current signal and R_p is the pipe radius. From this we see that the body of the beam is very well centered but the precursor is 4 cm off axis. Scale: for current, 2 kA/div; for x and y off set at time of peak current, 0.37 cm/div.

Fig. 15. Indication that beam asymmetry exist and originates from the cathode/grid source is shown in this data. The top two current and centroid measurements made at the injector output (I_0 , at $z = 2$ m) and the next downstream current monitor (I_1 , at $z = 3$ m) show that the maximum current portion of the beam leaves the injector almost centered, but is significantly off-axis 1 m downstream - i.e., the beam is spiraling and exiting the injector with an angle. However, a 50% variation in the first anode focus coil changes the offset at injector output (bottom oscilloscope indicating centroid location) which can only occur if the beam is created with the centroid off-axis.

Fig. 16. As described in the text, a gated TV - looking at the cathode-grid also suggests that beam non-uniformity and asymmetry originates there. The first photograph (A) is of just the cathode igniter board, where as (B), which is approximately one order of magnitude down in recording sensitivity (to avoid saturation), is with the grid also on.

Fig. 17. Studies of grid field emission. (a) No grid or igniter pulse is applied and the injector output current shows field emission current occurs when anode voltage is applied. Scale 200 A/div, 20 ns/div. The slow increase in current is apparently due to emission limitations. (b) Same as (a) except the grid wire size and spacing was changed to increase field enhancement which resulted in appropriate increase in current, scale 1 kA/div, 10 ns/div. (c) Same as (a) with exact same grid except now the igniter was pulsed 50 ns before anode. The characteristic signature of the prepulse current identifies the source of the current as originating from the igniter cathode plasma.

Fig. 18. Top: Negative going trace is grid voltage on 20 kV/div, 20 ns/div. Positive going trace is cathode current showing igniter current 80 ns before grid voltage turn on, scale is 2 kA/div, 20 ns. Bottom: Injector output current on 1 kA/div, 20 ns/div. Plot: For the time of the precursor (τ_p) we determine the current contribution coming from the anode side of the grid by subtracting ($I_0 - TI_k$) where I_0 is the output current, I_k is the cathode current drain due to the grid voltage leakage and T is the 50% transparency factor.

Fig. 19. Oscilloscope traces showing how the output current, especially the precursor current, varies with igniter timing. Scales are 1 kA/div and 10 ns/div. Plot indicates how precursor characteristics I-1 and I-2 vary with igniter timing. The zero crossing of I-1 indicates a plasma frontal speed of $\sim 10^8$ cm/sec.

Fig. 20. Estimates of the density and temperature of the plasma responsible for the precursor current as a function of igniter timing.

Fig. 1

Anode focus coils f-3 through f-9
transport focus coils 10a through 10h

Fig. 2

Effect of Control Grid

- Injector output current gating by relative timing $V_G \rightarrow V_A$
- Beam current loading of anode voltage is apparent

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Operating
data for
Figure 7

Top anode volt 500 kV/
Bottom cathode 12 KA/

Injector output 2 KA/
current

- 42 -

Operating
data for
Figure 8

Top anode V 400 kV/
Bottom cathode 12 KA/

Injector output 1 KA/
current

Magnetic profiles

Fig. 9

Fig. 10

Fig. 11a

Fig. 11b

(a)

No bucking coils on

(b)

With bucking coils on (note scale change of 2.5 on I_1 , x_1 and y_1 from previous)

Fig. 12

(i)

(ii)

(iii)

Fig. 13a

(i)

(ii)

Fig. 13b

(a)

(b)

Fig. 14

(a)

(b)

Fig. 15

Fig. 16a

Fig. 16b

(a)

(b)

(c)

Fig. 17

Fig. 18

$\tau_{ig} = 50 \text{ ns}$

$\tau_{ig} \approx 80 \text{ ns}$

$\tau_{ig} = 110 \text{ ns}$

Fig. 19

Fig. 20