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ATA INJECTOR-GUN CALCULATIONS

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ATA INJECTOR GUN CALCULATIONS

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ABSTRACT

ATA is a pulsed, 50 ns 10 KA, 50 MeV linear induction electron accelerator at LLNL. The ETA¹ could be used as an injector for ATA. However the possibility of building a new injector gun for ATA, raised the question as to what changes from the ETA gun in electrode dimensions or potentials, if any, should be considered. In this report I will review the EBQ² code results for the four electrode configurations of Fig. 1 an attempt to determine the geometrical scaling laws appropriate to these ETA type gun geometries. Comparison of these scaling laws will be made to ETA operation. The characteristic operating curves for these geometries will also be presented and the effect of washer position determined. It will be shown that emittance growth will impose a limitation on beam current for a given anode potential before the virtual cathode limit is reached.

GEOMETRIES

The ATA injector will be similar to the ETA injector at LLNL, which has been in operation since 1979. The ETA injector consists of a cold plasma cathode from which the electrons are extracted by a planar grid, Fig. 1.

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These electrons are self-focused by their own magnetic field near the grid. External solenoid focusing is provided after the beam enters the anode.

The longitudinal coordinate origin is at the gun cathode. The beam calculations for this injector extend a sufficient distance down stream (60 cm) to allow evaluation of the beam behavior into the anode bore, approximately at 20 cm. Four geometries have been calculated over a range of anode and grid potentials so as to gain insight into the performance of the gun when the electrode potentials are varied or as these potentials change with time from nominal, fixed-flat-top conditions. In these calculations the anode potential has been chosen fixed in 1/2 MV steps while the grid voltage was varied to determine the decelerative (D) threshold and virtual cathode (VK) threshold to within a resolution in grid potential of 1 kV.

The first geometry considered is that of the ETA gun with a 10 inch diameter cathode and a cathode anode separation of 22.4 cm. The washer is midway between the cathode and anode and is at half the anode potential. The second geometry is the ETA with a 4 cm reduction in the cathode anode separation. The washer is still midway between the cathode and the anode. No other changes were made between the configurations of geometries 1 and 2. In geometries 3 and 4 the cathode diameter has been reduced to 8 inches. In geometry 3 the longitudinal dimensions have not been reduced from the ETA dimensions. In geometry 4 all dimensions have been reduced by 80% from ETA, resulting in an 8 inch cathode, and 18 cm cathode anode separation, Fig. 1.

DYNAMIC OPERATION OF GUN

The beam current anode voltage curve of the gun divides the operation into two distinct regions. Operation above the curve is in the virtual

cathode domain, operation below the curve should yield a stable beam of reasonable emittance with results predictable by computer simulations. In actual operation the voltages on the grid and anode are time dependent and the operating point of the gun, indicated as the black dot in Fig. 2A can be reached via three fundamentally different paths as shown. These paths differ only in the time the grid is fired relative to the anode. The beam current at the flat top of the anode waveform is determined by the grid voltage achieved at the flat top of the grid pulse.

Path A represents triggering the grid after the anode has achieved its flat top so that the beam current rises from zero to full value at V_a . Path B represents the path followed when the grid is triggered simultaneously with the anode, Fig. 2B. The beam current follows a $V_g^{3/2}$ power law which keeps it below the anode limiting current at all times. Path C represents the path followed when the grid is triggered before the anode. Here the beam current may exceed the acceptable anode current and consequently represent operation in the virtual cathode regime for some time.

The presence of the external focusing solenoids puts a requirement on the minimum energy the beam can have and still penetrate the catcher coil field. This requires the beam to be on the right of the vertical line shown at approximately $V_a/2$, Fig. 2A. The requirement that the beam have sufficient energy and be below the virtual cathode current limit restricts the region of operation on the current voltage diagram to the shaded area shown, and implies that the grid should be triggered after the anode, just about as the anode is to flat top.

RESIMES OF OPERATION

In the absence of beam, the potential on axis rises from that of the grid to that of the anode well inside the anode bore. If the bore of the anode is infinitesimal in comparison to the grid anode separation, the potential rises linearly with z . As the anode bore is increased the potential rise becomes more gentle, asymptotically approaching the anode value many anode bores inside the anode. When beam is present, the electric self-field of the beam depresses this axial value of the electrode potential in the grid anode space.

The beam current injected into the grid anode space is determined by the Child-Langmuir law applied to the cathode grid diode. If this current is too high, a potential drop will occur just past the grid. Onset of this potential drop defines the threshold for the deceleration regime of gun operation, Fig. 3. The limiting current is reached when a virtual cathode is formed. The threshold of the decelerative regime occurs at approximately 80% of the virtual cathode current for all geometries studied in this report, Fig. 4.

CHARACTERISTIC CURVES

A plot of the ETA grid voltage required to just form a virtual cathode is shown in Fig. 5. The virtual cathode threshold current injected into the grid anode space by this grid voltage is shown in Fig. 6. The virtual cathode threshold of the ETA gun has been raised by 10% from that previously reported.³ This resulted from improvements in the algorithm for calculation of the electric fields near electrodes in the EBQ code. In the previous calculations the beam energy was a few keV below the grid potential on passage through the grid. The electrons therefore had a velocity which was too low,

resulting in the deposition of too much charge on the mesh. The impulse on the beam from this charge was also too large. The net compounded effect was a 10% error in the virtual cathode threshold. Figure 5 and 6 give the virtual cathode threshold for the old and new ETA calculations as grid vs. anode voltage and beam current vs. anode voltage curves. The dashed curves are for 80% of the virtual cathode threshold current and represent the onset of the deceleration regime beyond the grid.

The virtual cathode curves for all four of the geometries studied are shown in Figs. 7 and 8. The geometries are labeled by the cathode diameter/cathode anode separation. The smaller the cathode anode separation, the higher the longitudinal axial electric field and the higher the virtual cathode threshold. For a given anode position and voltage, the larger the cathode, the higher the virtual cathode threshold, Fig. 8.

POSITIONING THE WASHER

The presence of the washer at half the anode potential approximately midway between the cathode and anode serves several purposes: 1) it increases the axial electric field on axis near the grid resulting in a higher virtual cathode threshold than possible without the washer; 2) it allows limited electrostatic focusing of the low current full energy beams. Moving the washer towards the anode provides additional electrostatic focusing for the low current beams but reduces the on axis axial electric field and therefore reduces the virtual cathode limit for a given anode potential. Figure 8 shows the effect of moving the washer from 11.2 to 13.2 cm for the 8 and 10 inch cathode characteristic curves with 22.4 cm anode cathode separation operated at 2.5 MV.

The 10-inch/22 cm curve with the washer at 11.2 cm drops from 14.5 kA to 12.5 kA when the washer is moved to 13.2 cm while the 8-inch/22 cm curve with the washer at 13.2 cm rises from 10.2 kA to 12.2 kA when the washer is moved to 11.2 cm.

The sequence of beam profiles for the ETA gun operating at 2.5 MV anode as the grid potential is increased, injecting more and more beam into the grid anode space is shown in Fig. 9. Virtual cathode formation for this washered configuration occurs at 93 kV and is 14.77 kA. Figure 10 shows the same standard ETA gun geometry without the washer. The sequence of frames is for increasing grid voltage resulting in the formation of a virtual cathode at 74 kV grid, or a current of 10.514 kA. This is a reduction in the virtual cathode limit of 29% from the washered case.

Moving a washer toward the anode provides additional electrostatic focusing for the low current beams, Fig. 11, but reduces the on-axis axial electric field and therefore reduces the virtual cathode limit for a given anode potential, Fig. 12.

ETA experience has shown that the machine works without the washer. The evidence is that beam lost on the washer may upset the voltage balance of the gun and as such does more degradation of performance than the presence of the washer helps in improving performance. Should this situation stand the test of time, it may be useful to use a washer of larger aperture, as shown in Fig. 13. Here the washer bore is 14.5 cm compared to the 12.7 bore of Fig. 9. The larger aperture should reduce beam loss on the washer while maintaining a mid point potential. The virtual cathode limit for this case occurs at 87 kV and is 13,382 amps, or 9% lower than the configuration of Fig. 9.

The position of the washer within the grid-anode space has been varied and its effect on the virtual cathode limit given in Table 1. These results are for operation at 2.5 MV anode with a grid cathode separation of 1.5 cm. The cathode is located at $z = 0$, and anode and washer position measured downstream from the cathode. In this table the virtual cathode grid voltage is expressed as V_1/V_2 giving a virtual cathode current of I_1/I_2 . V_1, I_1 is below the virtual cathode limit and V_2, I_2 is above the virtual cathode limit and represents the resolution of the calculations, namely the 1 kV increment on the grid used to identify virtual cathode formation.

GUN CONDUCTANCE

The beam current defining virtual cathode threshold can be expressed as a quadratic polynomial in the anode potential, as suggested by the shape of these characteristic curves, Fig. 8.

$$I_a = a V_a + b V_a^2 \quad (1)$$

The EBQ calculations were performed to a 1 kV resolution in the grid potential required to cross the virtual cathode line. This 1 kV grid resolution translates into an uncertainty in the beam current for a given anode potential V_a . For a given anode potential, take I_u as the current above the virtual cathode line and I_b the current below the virtual cathode line associated with this 1 kV grid resolution. Then we may define the virtual cathode current at this anode potential as

$$I_{vk} = \frac{1}{2}(I_u + I_b) \pm \frac{1}{2}(I_u - I_b) \quad (2)$$

with the uncertainty $\Delta = \frac{1}{2}(I_u - I_b)$. We solve for the coefficients a, b, of Eq. 1 by choosing two potentials $V_a = V_1$ and $V_a = V_2$ with their limiting virtual cathode currents I_{vk} of I_1 and I_2 with uncertainties Δ_1 and Δ_2 , then

$$a = \frac{I_1 V_2^2 - I_2 V_1^2}{V_1 V_2 (V_2 - V_1)} \pm \frac{\Delta_1 V_2^2 - \Delta_2 V_1^2}{V_1 V_2 (V_2 - V_1)} \quad (3)$$

$$b = \frac{V_1 I_2 - I_2 I_1}{V_1 V_2 (V_2 - V_1)} \pm \frac{\Delta_2 V_1 - \Delta_1 V_2}{V_1 V_2 (V_2 - V_1)} \quad (4)$$

The possible range in a and b introduced by these uncertainties are given by the second terms in the two preceding equations with Δ_1 and Δ_2 chosen with opposite signs.

For all four geometries, the quadratic coefficient, b, is small in comparison to the linear coefficient, a. Retention of only the first term is justified in the expression of I as a function of the anode potential for the ETA cathode anode separation of 22.4 cm where the quadratic term is zero within the resolution of the calculations.

$$I = a V_a \quad (5)$$

For the 18 cm cathode anode separation, neglect of the quadratic term amounts to an error of less than 10% for anode potentials to 3 MV. The range of this

uncertainty produced by the 1 kV grid resolution is shown by the error bars on Fig. 6. For the 18 cm anode cathode spacing

$$I \approx a V_a - b V_a^2 \quad (5)$$

The conductance of the gun, a , and nonlinearity, b , for these geometries are given in Table 2.

GUN GEOMETRY SCALING

For a one dimensional diode, the beam current scaling with cathode radius and anode gap is given by the Childs-Langmuir law so that for a given fixed anode voltage, the current times the square of the ratio of anode separation to cathode radius is constant. For the ETA-ATA gun dimensions, we find that the current times the ratio of the anode-grid spacing to cathode radius is constant as shown in Table 3 for the various gun configurations studied. All cases in Table 3 are for 2.5 MV anode potential and a cathode grid spacing of 1.5 cm. The virtual cathode current, I_{vk} scales directly as the ratio of the cathode radius to grid anode separation

$$I_{vk} = b \frac{r_k}{z_a - z_g} \quad (7)$$

where r_k is the cathode radius, z_a anode position, z_g grid position, and b , a numerical constant equal to 24 for ETA operation at 2.5 MV.

BEAM EMITTANCE

There are several contributions to beam emittance in the ETA-ATA gun design. The main sources are filamentation from the lens action of finite grid wires, pierce correction, spherical aberration of the anode, and coherent growth close to the virtual cathode threshold.

Simulation of the effect of the finite grid wires requires use of a fine computer mesh to allow resolution of the detail on a scale determined by the grid wire spacing.⁴ Expansion of the first few cm of the gun can be achieved by fixing an artificial boundary along some equipotential in the grid anode space. This equipotential must be calculated from a solution of Poissons equation including the space charge of the beam. Figure 14 shows these equipotentials on a coarse mesh upon which a self consistent 11 kA solution has been obtained. The 250 kV surface is used as the "anode" boundary for the expansion region around the 80 kV grid wire run shown in Fig. 15. The wire spacing is 1/2 cm. The phase plot $x - x'$ at the 250 kV surface where all particles have the same energy and therefore the same β and γ is shown in Fig. 16. The area, A , of a circumscribed figure around the individual particles is π times the product of the invariant points X_1 , X_1' shown in the figure. The normalized emittance E is defined as

$$E = \frac{A}{\pi\beta\gamma} \quad (8)$$

and can be readily found from the figure to be 580 cm-mr. This two dimensional simulation does not include the reduction of the transverse electric fields near the radial strings supporting the concentric grid wire rings. The actual emittance should be about half the value calculated from this two dimensional simulation.

$$E = 300 \text{ cm-mr}$$

SPHERICAL ABERRATION

We now investigate the contributions to beam emittance produced by the spherical aberration of the anode aperture and the beam self forces, in particular, the change in emittance as the virtual cathode threshold is approached.

For an ideal simple lens of focal length f , the angular divergence for a ray in the beam is proportional to the radial displacement r . This translates into a straight line in the phase space, Fig. 17, of slope equal to the reciprocal of the focal length. For a diverging lens, the slope is positive, for a converging lens the slope is negative.

Real lenses suffer for many nonideal screw ups. Spherical aberration, for one, contributes to the angular displacement a term cubic in the radial displacement acquired in the lens, Fig. 18.

$$r' = a r + b r^3 \quad (9)$$

For the real lenses, b is always positive as the lense strength increases the further out in the lens the rays go.

The spherical aberration of the electrostatic axially symmetric lense encountered on entrance to the ETA gun anode is characterized by the nonlinearity it introduces into the defocusing of the beam. If we express the divergence of the beam after passage through the lense as a polynomial in transverse position, then all even powers must vanish as a consequence of the assumed axial symmetry.

The value of the coefficient a , of the linear term in the expression of the radial slope on position is a measure of the strength of the lense and consists of those terms from external focusing (or defocusing) elements and self magnetic focusing. In and around the grid, the beam is self focused. Neglecting for the moment the charge build up near the grid as the beam approaches the virtual cathode limit, the higher the current, the stronger the self magnetic pinch, and therefore, the stronger the self-focusing and the more negative the value of a , that is, the stronger the self-focusing of the beam.

At 20 cm, just inside the anode bore, the beam has passed through a waist and is now diverging. Figure 19 shows the phase space at this location for a 2.5 MV anode potential as the grid potential is varied. At 70 kV grid, the beam current is quite low for this anode potential. Note the inner portion of the plot is linear and deviates from the straight reference line in the outer portion only, Fig. 20. This is the spherical aberration of the anode bore. Observe that the outer portion of the higher current phase plots have progressively larger negative slopes resulting from the stronger self-focusing of these beams near the grid. As one approaches closer and closer to the

virtual cathode limit, the central portion of the beam experiences a stronger and stronger radially defocusing force from the accumulating charge near the axis close to the grid. Observe the inner portion of the high current phase plots, Fig. 19 and 20, with progressively larger positive slopes. The defocusing of the inner portion of the beam comes from the charge buildup on axis near the grid as the virtual cathode limit is approached.

Writing the slope of the phase space contribution for coherent virtual cathode approach as a polynomial in radial position

$$r' = a r + b r^3 \quad (10)$$

In the proximity of the grid, operated far from the virtual cathode limit, $a < 0$ and $b = 0$. Close to the virtual cathode limit, $a > 0$ and $b < 0$. Thus the coherent effects just beyond the grid contribute effective emittance to the beam and appear as negative spherical aberration, e.g., $b < 0$.

As we extend operation from the accelerative regime further and further into the decelerative regime, the defocusing of the central portion of the beam increases, resulting in a hollowing of the radial beam profile. The humping of the phase space here, results in an increase of the beam emittance. As an attempt to parameterize the gun operation we should note that this coherent emittance growth occurs on the characteristic curves between the decelerative and virtual cathode thresholds.

The combined effect of emittance growth close to the virtual cathode formation and spherical aberration on the emittance of the beam is shown in Fig. 21. The emittance has been normalized and plotted against longitudinal position. The grid is at 1.5 cm and the anode is at 18 cm. At small currents

the emittance grows after entry into the anode as a result of spherical aberration. At currents just below virtual cathode formation the emittance is spoiled by the coherent growth just passed the grid. At intermediate currents, the emittance is best from partial cancellation of the coherent growth and the anode spherical aberration. Note particularly the minimum emittance at 95 kV operation.

Beams of good emittance will be easier to tune and transport through external magnets and acceleration cells. This combined with the desire to have the largest possible current will probably lead to operation of the gun at a grid potential which minimizes the emittance, Fig. 22. Higher grid voltage increases the beam current but this brings about a rapid growth in emittance. It appears therefore, that optimum operation occurs above the decelerative threshold, but considerably below the virtual cathode threshold. From Figs. 7, 8, and 22 for ETA at 2.5 MV we have the results given in Table 4.

COMPARISON OF ETA OPERATION WITH VIRTUAL CATHODE CALCULATIONS

Combining the scaling laws Eq. 5 with $a = 5.85 \pm .25$ kA/MV and Eq. 7 with $b = 24$ with the effect of the washer position measured by the parameter r , we obtain

$$i_{vk} = 9.60 \frac{r_k}{z_a - z_g} f V_a \quad (11)$$

i_{vk} in kA and V_a in MV. For a gun without a washer, $f = 0.7$. For the ETA gun with the washer at 1/2 anode potential, midway between the cathode and anode, $f = 1$. For other washer positions f spans the range $0.7 \rightarrow 1$.

At 80% of the virtual cathode threshold, the beam begins to decelerate after passage through the grid. The calculations indicate that minimum beam emittance should occur somewhere between the onset of deceleration and virtual cathode formation. The resulting range of gun current for the ETA experimental conditions (2 MV anode, $z_a = 22.4$ cm, $z_g = 1.5$ cm) then should be given by Eq. 11, as $i_D = 9.33$ kA $< i < i_{vk} = 11.7$ kA.

This range of operating currents has been marked on a modified version of viewgraph 40.F.-13, Fig. 24 depicting the experimental operation for the indicated parameters. The label VK designates the virtual cathode threshold and the label D designates the decelerative threshold.

Comparison between the calculated currents and the operationally observed currents for these three cases will have to be subject to interpretation.

- o The washered configuration may have been subject to beam loss on the washer, lowering its potential and consequently lowering the virtual cathode threshold.
- x The cathode current for this case appears to be at or near the virtual cathode limit where emittance growth would be large. Note the poor transmission down the accelerator.
- The cathode current for this case appears to be near the virtual cathode limit, however the good transmission down the accelerator

precludes this as a virtual cathode example. The explanation may be that the anode voltage was higher than the 2 MV quoted in the figure (measurement). Note that at an anode potential of 2.2 MV, 10% above that quoted in the figure, the virtual cathode limit for this case would be 6.3 kA rather than 5.7 kA.

FIGURE 1. The four geometries considered in this report:

- A) Original ETA geometry with 10 inch cathode and anode at 22.4 cm indicated as 10/22.
- B) ETA with anode at 18 cm 10/18.
- C) Eight-inch diameter cathode with anode at 22.4 cm, 8/22 and
- D) Eight-inch cathode with anode at 18 cm 8/18.

FIGURE 2.

- A) For a given flat top anode potential V_a , gun operation must be at a current below the virtual cathode line VK and at a potential above the focusing coil cutoff line FC. This should restrict operation of the gun at all times to the shaded area, even when the anode deviates from the desired value V_a .
- B) In actual operation, the anode is turned on at time $T = 0$. The potential rises from zero to the sum flat top value V_a . The grid can be turned on after the anode has reached the flat top A, simultaneously with the anode B, or before the anode C. The operating point in the current anode voltage space moves with time for these three grid turn-on times as indicated by curves A, B, and C in A.

FIGURE 3.

The axial potential in these guns varies with longitudinal position. This variation can be used to define a declarative and virtual cathode threshold in the gun operation. For sufficiently small beam currents, the potential rises everywhere, starting at zero at the cathode and finally approaches that of the anode. This defines operation in the accelerative regime. As the beam current is increased, the potential drops from the grid value to a minimum before beginning its rise. This drop to a minimum decelerates the beam and operation here is in the decelerative regime. When the beam current is sufficiently high, a virtual cathode may form just beyond the grid. Any current above the virtual cathode threshold will result in the formation of a virtual cathode.

FIGURE 4.

Ratio of minimum axial potential V_{min} , to the grid potential V_{grid} vs the ratio of the beam current I , to virtual cathode threshold current I_{vk} . Different curves are for different geometries and different anode potentials. The decelerative threshold, $V_{min}/V_{grid} = 1$ occurs at approximately 80% of the virtual cathode threshold current for all geometries considered.

FIGURE 5.

Characteristic grid anode voltage curves for the ETA gun with 10-inch cathode and 22.3 cm anode position. The results of a previous calculation (8/22/79) and the new improved calculations (3/26/82) are shown. These curves represent the threshold for virtual cathode formation in the grid-anode space. The dashed curve is the decelerative threshold.

FIGURE 6.

Characteristic beam current anode voltage curves for the ETA gun showing the results of a previous calculation (8/22/79) and the new improved calculations (3/26/81). These curves represent the threshold for virtual cathode formation in the grid-anode space. The dashed curve is the decelerative threshold and is at 80% of the virtual cathode threshold current.

FIGURE 7.
Characteristic virtual cathode threshold grid anode voltage curves for the four geometries shown in Fig. 1. These geometries are labeled as the cathode diameter (inches) slash the anode position (cm).

FIGURE 8.

Characteristic virtual cathode threshold beam current anode voltage curves for the four geometries shown in Fig. 1. The effect on virtual cathode threshold by changes in the washer position as indicated for the 10-inch/22 cm and 8-inch/22 cm guns.

2.5 MV 86 kV 13.151 kA

Just inside
decelerative
regime.

2.5 MV 92 kV 14.479 kA

Just below
virtual cathode
formation.

2.5 MV 93 kV 14.768 kA

Just above
virtual cathode
formation.

FIGURE 9.
2.5 MV ETA configuration with 12.7 cm radius washer at 11.2 cm. Runs are at 86, 92 and 93 kV on the grid.

2.5 MV 70 kV 9.683 kA

2.5 MV 73 kV 10.304 kA

Just below
virtual cathode
limit.

2.5 MV 74 kV 10.514 kA

Just above
virtual cathode
formation.

FIGURE 10.

2.5 MV ETA configuration of Fig. 1 without the washer. Runs are at 70, 73 and 74 kV on the grid.

FIGURE 11.

1 ampere 2.5 MV anode ETA gun a) washer centered, b) washer 1-inch toward anode, c) washer 2-inches toward anode.

11.8 kA beam in
acceleration regime.
Washer centered

11.8 kA beam
below virtual
cathode limit.

11.8 kA beam
above virtual
cathode limit.

FIGURE 12.
11.8 k amp 2.5 MV anode ETA gun a) washer centered, b) washer 1-inch toward
anode, c) washer 2-inches toward anode.

FIGURE 13.
2.5 MV ETA configuration with 14.5 cm washer at $z = 11.2$ cm. Runs are for 85, 86, and 87 kV on the grid.

FIGURE 14.

The equipotential surfaces in the ETA geometry in the presence of the charge resulting from the passage of 11 kA beam. The anode potential was 2.5 MV and the grid is at 80 kV. The 250 kV equipotential is indicated for use as a boundary condition in the expansion of the first few cm of the gun.

FIGURE 15.

The expanded cathode 250 kV boundary region showing the grid simulated by concentric wire rings spaced every half cm. The focusing of the electron beam by the lens action of the grid wires is evident. The grid wires are infinitesimal in diameter and do not intersect the beam. They are plotted as diamonds centered at the wire location.

FIGURE 16.

The beam phase space at the 250 kV equipotential surface showing the filamentation introduced by the lens action of the grid wires spaced on half cm intervals. The normalized beam emittance is 580 cm-mr.

FIGURE 17.

Ideal lens, A diverging and B converging. The angular slope is proportional to the radial position inside the lens and results in a linear phase plot as shown.

FIGURE 18.

Real lenses are stronger at their perimeter and contribute a cubic spherical nonlinearity to the phase plane A). Approach to the virtual cathode limit results in the defocusing of the inner portion of the beam B) and results in a cubic nonlinearity of the opposite sign to that of spherical aberration.

FIGURE 19.

2.5 MV anode, 10-inch/18 cm ETA phase space for the various grid potentials indicated. The different curves within each frame are the $x - x'$ phase space projections at the indicated longitudinal positions.

FIGURE 20.

2.5 MV anode 10-inch/18 cm ETA phase space frame at longitudinal position of 20 cm. This is just inside the anode entrance. Note the increase slope at large r value for the 70 kV curve relative to the linear extrapolation from the slope at small r . This is the result of the anode spherical aberration. At the higher grid voltages (higher beam currents) the phase space is bowed by the beam coherent effects close to the virtual cathode formation.

FIGURE 21.

Normalize beam emittance for the 2.5 MV anode 10-inch/18 cm ETA gun along the first 32 cm of the gun for various grid potentials and their associated beam currents. At small currents the emittance grows after entry into the anode as a result of spherical aberration. At current just below virtual cathode formation the emittance is spoiled by the coherent effects just past the grid. At intermediate currents, the emittance is best from partial cancellation of the coherent growth and the anode spherical aberration. Note particularly the 95 kV operation.

FIGURE 22.

The Normalized emittance of Fig. 21 plotted against grid potential at 10, 20 and 30 cm longitudinal positions. The minimum reached at 95 kV results from the partial cancellation of the coherent growth and anode spherical aberration. The virtual cathode threshold is at 107 kV. Note the large emittance growth as this limit is approached.

FIGURE 23.

2.5 MV anode, 80 kV ETA 10-inch/18 cm geometry phase space. The circumscribed ellipses about phase points are shown for the indicated longitudinal positions. These ellipses can be used for match into transport runs. Note the waist at 19 and 32 cm, bracketting the catcher coil position.

FIGURE 24.
Comparison of calculated deceleration and virtual cathode thresholds and ETA operation for three different operating geometries. The theoretical points are derived from Eq. 11 and presented in Table 5.

Beam profiles for the four geometries of Fig. 1 are presented in the following four figures. Each figure consists of a set of three profiles for each of six anode potentials of 0.5, 2.0, 1.5, 2.0, 2.5 and 3.0 MV. The set of three profiles at each anode potential are for different grid voltages, the first being well below the virtual cathode threshold, the second just below the virtual cathode threshold, and the third just above the virtual cathode threshold. In these figures the boxes with the crosses are the cross sections of the focusing coils and the bell shaped curve passing through the origin, rising to a peak at the first coil is the plot of the axial external focusing magnetic field. Electron trajectories are basically the horizontal lines and the equipotentials are basically the vertical lines on these plots. The dashed line visible in some of the plots is the beam envelope on the previous iteration and indicates the degree of convergence of the solution.

<u>ANODE (MV)</u>	<u>10-in/22 cm</u> <u>FIGURE 25</u>	<u>8-in/18 cm</u> <u>FIGURE 26</u>	<u>8-in/22 cm</u> <u>FIGURE 27</u>	<u>8-in/18 cm</u> <u>FIGURE 28</u>
0.5	A	A	A	A
1.0	B	B	B	B
1.5	C	C	C	C
2.0	D	D	D	D
2.5	E	E	E	E
3.0	F	F	F	F
0.1			G	
0.25			H	

The data for EBQ from which these runs we made is given in Table 6.

Figure 25 A

0.5 MV 25 kV
2.086 kA

0.5 MV 28 kV
2.469 kA

0.5 MV 29 kV
2.602 kA

Figure 25 B

1.0 MV 44 kV
4.848 kA

1.0 MV 49 kV
5.692 kA

1.0 MV 50 kV
5.866 kA

Figure 25 C

1.5 MV 60 kV
7.703 kA

1.5 MV 65 kV
8.674 kA

1.5 MV 66 kV
8.873 kA

FIGURE 25 A, B & C. Standard ETA gun geometry. Ten inch cathode with 22.4 cm anode cathode separation. Washer is at 11.2 cm.

Figure 25 D

2.0 MV 73 kV
10.314 kA

2.0 MV 79 kV
11.591 kA

2.0 MV 80 kV
11.809 kA

Figure 25 E

2.5 MV 86 kV
13.151 kA

2.5 MV 92 kV
14.479 kA

2.5 MV 93 kV
14.768 kA

Figure 25 F

3.0 MV 95 kV
15.248 kA

3.0 MV 102 kV
16.942 kA

3.0 MV 104 kV
17.436 kA

FIGURE 25 D, E & F. Standard ETA gun geometry. Ten inch cathode with 22.4 cm anode cathode separation. Washer is at 11.2 cm.

Figure 26 A

Figure 26 B

Figure 26 C

0.5 MV 33 kV
2.927 kA

0.5 MV 37 kV
3.471 kA

1.0 MV 57 kV
6.615 kA

1.0 MV 58 kV
6.789 kA

1.5 MV 70 kV
9.684 kA

1.5 MV 76 kV
10.150 kA

1.5 MV 77 kV
10.344 kA

FIGURE 26 A, B & C. Ten inch cathode gun with 18 cm anode cathode separation. Washer is at 9.8 cm.

Figure 26 D

2.0 MV 88 kV
12.619 kA

2.0 MV 92 kV
13.479 kA

2.0 MV 93 kV
13.697 kA

Figure 26 E

2.5 MV 100 kV
15.251 kA

2.5 MV 106 kV
16.626 kA

2.5 MV 107 kV
16.859 kA

Figure 26 F

3.0 MV 118 kV
18.474 kA

3.0 MV 119 kV
19.719 kA

3.0 MV 120 kV
19.964 kA

FIGURE 26 D, E & F. Ten inch cathode gun with 18 cm anode cathode separation. Washer is at 9.8 cm.

Figure 27 A

0.5 MV 25 kV 1.342 kA

0.5 MV 31 kV 1.852 kA

0.5 MV 32 kV 1.942 kA

Figure 27 B

1.0 MV 54 kV 4.242 kA

1.0 MV 55 kV 4.359 kA

Figure 27 C

1.8 MV 55 kV 4.36 kA

1.5 MV 73 kV 6.644 kA

1.5 MV 74 kV

FIGURE 27 A, B & C. Eight inch cathode gun. The anode is 22.4 cm from the cathode with the washer at 11.2 cm.

Figure 27 D

2.0 MV 80 kV 7.612 kA

2.0 MV 87 kV 8.622 kA

2.0 MV 88 kV 8.769 kA

Figure 27 E

2.5 MV Grid 97 kV 10.12 kA

2.5 MV 101 kV 10.76 kA

2.5 MV 102 kV 10.92 kA

Figure 27 F

3.0 MV 110 kV 12.2 kA

3.0 MV 114 kV 12.87 kA

3.0 MV 115 kV 13.04 kA

FIGURE 27 D, E & F. Eight inch cathode gun. The anode is 22.4 cm from the cathode with the washer at 11.2 cm.

Figure 27 G

0.1 MV 5 kV 120 amps

0.1 MV 7 kV 199 amps

0.1 MV 8 kV 243 amps

Figure 27 H

0.25 MV 15 kV 625 amps

0.25 MV 17 kV 754 amps

0.25 MV 18 kV 821 amps

FIGURE 27 G & H. Eight inch cathode gun. The anode is 22.4 cm from the cathode with the washer at 11.2 cm.

Figure 28 A

0.5 MV 30 kV 1.764 kA

0.5 MV 42 kV 2.915 kA

0.5 MV 43 kV 3.019 kA

Figure 28 B

1.0 MV 65 kV 5.589 kA

1.0 MV 70 kV 6.242 kA

1.0 MV 71 kV 6.375 kA

Figure 28 C

1.5 MV 75 kV 6.916 kA

1.5 MV 92 kV 9.367 kA

1.5 MV 93 kV 9.519 kA

FIGURE 28 A, B & C. Eight inch cathode gun with anode cathode separation of 18 cm. The washer is placed midway between the cathode and anode.

Figure 28 D

2.0 MV 105 kV 11.394 kA

2.0 MV 111 kV 12.371 kA

2.0 MV 112 kV 12.536 kA

Figure 28 E

2.5 MV 110 kV 12.187 kA

2.5 MV 127 kV 15.079 kA

2.5 MV 128 kV 15.273 kA

Figure 28 F

3.0 MV 136 kV 16.702 kA

3.0 MV 141 kV 17.616 kA

3.0 MV 142 kV 17.801 kA

FIGURE 28 D & E. Eight inch cathode gun with anode cathode separation of 18 cm. The washer is placed midway between the cathode and anode.

TABLE 1

Cathode diameter (inches)	Anode position (cm)	Washer radius (cm)	Washer position (cm)	Virtual cathode grid voltage	Virtual cathode current (kAmp)
8	18	10.16	9.82	127/128	15.097/15.273
-	-	-	none	110/111	12.207/12.372
8	22.38	10.16	11.2	110/111	12.206/12.371
-	-	-	13.2	101/102	10.76/10.92
-	-	-	none	90/91	9.067/9.216
10	18	12.7	9.82	106/107	16.626/16.859
-	-	-	11.2	101/102	15.475/15.706
-	-	-	none	92/93	13.478/13.696
10	22.38	12.7	11.2	92/93	14.478/14.768
-	-	-	13.2	83/84	12.474/12.704
-	-	-	none	73/74	10.304/10.514
10	22.38	14.5	11.2	86/87	13.115/13.382

TABLE 2

Cathode diameter inches	Cathode anode separation cm	Washer position cm	Conductance a kA/MV	Nonlinearity b kA/MV ²
10	22.4	11.2	5.85 $\pm$.25	0 $\pm$.125
10	18	9.82	7.03 $\pm$.23	-.134 $\pm$.11
8	22.4	13.2	4.46 $\pm$.16	-.048 $\pm$.077
8	18	9.82	6.63 $\pm$.18	-.221 $\pm$.086

TABLE 3

Cathode diameter inches	r _k radius cm	Z _a anode position cm	Radius cm	i _{KV} virtual cathode threshold	i _{VK} $\frac{Z_a - Z_g}{r_k}$	i _{KV} Normalized
8	10.16	22.4	10.16	10.7	22.01	1.023
8	10.16	18	10.16	15.2	24.68	1.147
10	12.7	22.4	12.7	13.12	21.59	1.003
7	8.89	22.4	12.7	9.29	21.84	1.015
5	6.35	22.4	12.7	6.89	22.68	1.054
3	3.81	22.4	12.7	4.79	26.27	1.221
10	12.7	22.4	13.2	14.62	24.06	1.118
10	12.7	18	13.2	16.56	21.51	1

TABLE 4

Anode at 18 cm	Grid (kV)	Current (kA)
Decelerative threshold	91	13.28
Minimum emittance	95	14.43
Virtual cathode threshold	106	16.6

Anode at 22.4 cm	Grid (kV)	Current (kA)
Decelerative threshold	79	11.8
Minimum emittance	-	-
Virtual cathode threshold	92	14.6

TABLE 5

	Decelerative threshold	Virtual cathode threshold
Ten inch (10") cathode, washer	9.33 kA	11.7 kA
Ten inch (10") cathode, no washer	6.53	8.17
Seven inch (7") cathode, no washer	4.57	5.72

TABLE 6

```

CHILD'S LAW, OLD ETA DATA .5 X .1 CM
TITLE 2.5 MV ANODE AT 18 CM      ETA GUN      100 KV GRID
$ 100.105. 110.120
MAP OFF
BOUNDARY $ CATHODE DIAMETER CHANGED TO 12.5 CM
31 36 0 15 0 3.5
1 0 0 5 12.7 0 5 15 1.67 5
$ 1 0 0 5 12.7 0 5 15 1.67 5
$ 2 0 1.5 2 12.7 1.5 2 15 3.17 5
2 0 1.5 2 12.7 1.5 2 15 3.17 5
2 0 1.5 2 0 3.5 2 15 3.5 2 15 3.17 5
5
POT
0 100.0E3 1350.0E3 2600.0E3 0 0 0 0 0
0 105.0E3 1355.0E3 2605.0E3 0 0 0 0 0
0 110.0E3 1360.0E3 2610.0E3 0 0 0 0 0
0 120.0E3 1370.0E3 2620.0E3 0 0 0 0 0
0 97.0E3 1347.0E3 2597.0E3 0 0 0 0 0
5
CONST
*16 1 100 $ POISSON EQUATION ERROR, VOLTS
*22 1.0E-4 $ CURRENT CONVERGENCE AMPS
*26 1.5 $ STOP AT GRID
5
COLLGEN 2 0 0 15.5 0 0
0 3.5 .5 .5
-328.38 1662.56 27583 700R3 5
20.18 20.18 1 -31.232 -16.998 1.0E5
16.51 16.51 1. 28.57 51.43 2.54
16.51 16.51 1. 56.26 79.12 2.54
16.51 16.51 1. 83.88 106.94 2.54
16.51 16.51 1. 111.51 134.37 2.54
16.51 16.51 1. 139.13 161.99 2.54
16.51 16.51 1. 166.75 189.61 2.54
16.51 16.51 1. 194.37 217.23 2.54
5
PUNCHB 1.5 5
RAYGEN 3 25 1 .49 -10300.
TRACK X 10
END
5
2.5 MV ANODE AT 18 CM WASHER 9.82CM ETA GUN
MAP OFF
BOUNDARY
31 121 0 15 0 60
1 0 0 5 12.7 0 5 15 0 5
2 0 1.5 2 12.7 1.5 2 15 2.667 5 $ GRID
3 12.7 9.82 3 15 9.82 5 $ WASHER
$ 3 12.7 11.2 3 15 11.2 5 $ WASHER
4 15 18 4 14.25 18
FIT 4 13.5427 18.2927 4 13.25 1' 4 13.25 22.38 5
4 15 22.38 4 13.25 22.38 4 13.25 80
4 15 80 4 15 22.38 5
5
COLLGEN 2 0 0 15.5 0 0
0 80 1 1
-328.38 1662.56 27583 700R3 5
20.18 20.18 1 -31.232 -16.998 1.0E5
16.51 16.51 1. 28.57 51.43 2.54
16.51 16.51 1. 56.26 79.12 2.54
16.51 16.51 1. 83.88 106.94 2.54
16.51 16.51 1. 111.51 134.37 2.54
16.51 16.51 1. 139.13 161.99 2.54
16.51 16.51 1. 166.75 189.61 2.54
16.51 16.51 1. 194.37 217.23 2.54
CONST
*3 0
*9 1.5 $ 1 RAY START
*16 100 150
*22 .001
*25 30 $ RAY CONVERGENCE 2
*35 -7.5 -15 $ CALCCOMP PLOT SIZE
*37 01 $ CALCCOMP PHASE PLOT
*47 50 $ EQUIPOTENTIAL LINES
5
PLOT SCALES BFIELD 0 1000
LAPLACE
MAP SECTION 1 TO 1
MAP SECTION 1 121 5
RKSTEP .1 5 .25 7 .5 80 5
RAYS 8 1
DENSITY OFF
TRACK 5 5
DENSITY ON
PLOT TRAJ 5
PLOT PHASE 30 5
$ MOMENT 2.5 5 10 20 30 5
TRACK CONTINUE 5
MAP 2 $ UI1
END
END

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