FINAL REPORT

RESEARCH ON FOIL TRANSPORT
OF INTENSE ELECTRON BEAMS

LANL Contract 9-X66-W2078-1

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Tasks on LANL Contract No. 9-X66-W2078-1 were completed on December 31, 1987, ahead of schedule. Major experimental results are reported in the two publications attached as APPENDIX A and APPENDIX B. Another publication summarizing additional experiments is in preparation by C. Ekdahl of Los Alamos National Laboratory. A copy of the contract work statement is included as APPENDIX C. The following descriptions are keyed to the items in the work statement:

Theoretical Tasks

1. Extension of analytic methods to derive foil focused equilibria for annular beams

Methods were developed to predict longitudinal space charge limits and radial equilibrium of annular beams between conducting foils. Analytic expressions were derived for spatially resolved electric fields and field integrals. The expressions were evaluated with a commercial software package, SCIMATH. In addition, numerical calculations were carried out with the program LAPLACE2.5 for confirmation.

Results demonstrating the existence of a possible annular equilibrium were presented at Los Alamos in June, 1987. A summary of the theory and calculations has been sent to C. Ekdahl of LANL. A report has not been written on the results. We presently have doubts about the utility of annular beam propagation because of experimental difficulties in designing a matched beam injector and the observation of strong filamentation instabilities.

2. Derivation of envelope trajectory equations for MA beams in high gradient accelerators.

This task was not performed in detail because of our doubts about the viability of annular beam transport. Instead, an alternate task was substituted in response to experimental observations of filamentation instabilities. An analytic theory of filamentation (described in APPENDIX B) was developed and analyses of experimental results were carried out.

3. Identification of possible transverse instabilities of foil focused beams.

At the time the proposal was written, we suspected that beams transported in a foil array could be macroscopically unstable to displacement. Experiments demonstrated that the beams were strongly stabilized by self-magnetic fields. In response to the experimental observations, this task was also modified. We carried out analysis of single particle orbits and collective beam displacements in the presence of a perturbing dipole magnetic field. These results are reported in the paper by Ekdahl.

4. Investigation of methods to stabilize beams in foil focusing systems.

These methods are unnecessary (see Item 3).

Experimental Tasks

1. CHAC generator loan from Sandia.

The generator is presently in place and operational in Farris Engineering Center at the University of New Mexico.

2. Design and fabrication of output section and electron gun for CHAC.

We completely rebuilt the CHAC output section to include an integral vacuum pump and a radial vacuum insulator. We also incorporated a unique Blumlein line damping resistor to prevent prepulse emission and to remove postpulse energy quickly. Because of the design, we were able to run large numbers of shots on the machine with no damage to fine gridded anodes.

3. Laboratory set-up.

The laboratory and cable runs were completed. The oil, purified water, and forepump systems were fabricated in-house.

4. Transport system design and fabrication.

The versatile experimental design illustrated in the APPENDICES has proved successful. The approach will be used in

future high voltage experiments at LANL.

5. Diagnostic package design and fabrication.

The diagnostics operated successfully and yielded useful experimental information. See the APPENDICES for a description of the hardware.

6. Design and fabricate small shielded scintillators.

We did not produce these devices. The experiment was reproducible enough so that we could measure the progress of a beam down a transport system by assembling different length foil arrays. With this approach, we did not disturb the cylindrical symmetry of the system.

7. Perform modeling experiments

This task was greatly expanded in response to experimental observations. Results are reported in the APPENDICES and the paper by Ekdahl.

Major accomplishments include:

- a) Observation of a high-vacuum filamentation instability. Scaling studies of the instability using a planar beam.
- b) Transport of a self-pinched beam through a 16 cell foil focusing array with almost complete beam capture.
- c) Emittance measurements of foil transported beams.
- d) Transport experiments on beams from a variety of gun

geometries, including cylindrical, cylindrical with focusing electrode, annular, annular with focusing electrode, planar, planar with focusing electrode.

e) Demonstrations that beams in foil arrays are actively stabilized by image current effects.

Deliverables

This document constitutes the final report. A written progress report was submitted in April, 1987. Weekly verbal progress reports were made to C. Ekdahl of LANL.

Extensive documentation was prepared beyond the written contract requirements, including:

- a) Research paper, "Image Charge Focusing of Relativistic Electron Beams", accepted for publication, Journal of Applied Physics (APPENDIX A).
- b) Research paper, "Filamentation Instability of a Relativistic Electron Beam in a Foil Transport Channel," to be submitted to Particle Accelerators (APPENDIX B).
- c) Data and analysis for research paper, under preparation by C. Ekdahl, LANL.
- d) Graphs, line drawings, photographs and writeups supplied to C. Ekdahl for presentation at Los Alamos National Laboratory.

Image Charge Focusing of Relativistic Electron Beams

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ABSTRACT

Experimental results are reported on the transport of a relativistic electron beam by image charge effects. The transport system consisted of a cylindrical metal tube periodically interrupted by transverse conducting grids with high transparency. Partial cancellation of the beam electric fields increased the space charge limited current level, allowing propagation in a magnetically self-pinch mode. A 400 keV, 4 kA beam traveled 30 cm in high vacuum through 10 focusing foils. Capture of the beam was almost 100% efficient; beam emittance was not severely degraded during capture and transport. The radius of the self-contained beam was 1.4 cm; the beam position was centered by the image current in the transport tube to within 1 mm. The favorable results imply that image charge focusing could be considered for transport in high current linear induction accelerators.

Image Charge Focusing of Relativistic Electron Beams

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Linear accelerators generate electron beams of energy 10-100 MeV in the current range 1-10 kA. These accelerators have applications to particle beam weapons [1], free electron lasers [2], pulsed radiography [3] and industrial radiation processing [4]. Strong solenoidal fields are usually used for focusing high current beams in the devices. Solenoidal focusing has the disadvantage that there is no preferred axis of stability for beam propagation, leaving the beam susceptible to displacement by system perturbations or transverse instabilities. This problem can be rectified by using solenoidal lenses with alternate field polarity in a multiple cusp configuration [5]. Even so, there are technological disadvantages to magnetic lenses for some applications: they require high power input, they add to the volume and weight of the accelerator system, and presence of coils in the accelerator structure limits flexibility in high gradient design.

There has recently been interest in methods whereby relativistic electron beams are self-focused during their transit through the accelerator. Self-focusing simplifies the technology

of accelerator; furthermore, the associated non-linear force components help stabilize the beam against transverse instabilities by introducing a spread in betatron oscillation frequency. Focusing by a laser-created low-density ion channel has been demonstrated in the ATA (Advanced Test Accelerator) device at Lawrence Livermore National Laboratory [6]. Ion channel focusing has the disadvantages that the accelerator repetition-rate and beam pulselength are limited by the dynamics of the guiding plasma.

In this letter, we report experimental results on the transport of a high-current, self-focused relativistic electron beam in high vacuum. The self-focused condition is attained by partially neutralizing the electric fields with image charges on transverse conducting grids. The method was suggested for induction linac applications by Adler [7], who demonstrated the feasibility of the method in a series of experiments at 1 MeV [8]. Conditions for beam equilibria were investigated by Humphries [9]. The present experiments provide a clear demonstration of the capabilities of the method. A 400 keV, 3.2 kA electron beam was transported through a 30 cm tube with 9 grids. All electrons in the injected beam were captured, and there was no detectable radial loss of current. The beam was successfully propagated close to the longitudinal space charge limit. The self-pinched beam was precisely centered in the transport tube at the output. Beam profiles at the end of the system were in good agreement with paraxial orbit predictions. Our studies of foil scattering indicate that that beams of interest for free electron laser

applications can be transported during acceleration without foil damage and with acceptably low emittance growth.

Power to generate the beam was supplied by a CHAC generator [10] on loan from Sandia National Laboratories. The 12.5 Ω water-filled Blumlein line produced a 60 ns, 400 kV pulse. A diagram of the transport apparatus is shown in Fig. 1. The plasma emission cathode used a 5 cm diameter felt surface. The beam was extracted across a 1.7 cm acceleration gap through a fine anode mesh composed of woven 2.5×10^{-3} cm diameter wires. The cathode assembly included a polished stainless steel Pierce electrode [11] to focus the beam and to inhibit edge emission. The transport system consisted of a stack of cylindrical metal rings with an inner diameter of 9.6 cm. Some of the rings were slotted to hold the meshes that comprised cell boundaries. A variety of cell geometries could be produced by incorporating rings of different length. Meshes were fabricated by stretching 0.005 cm diameter stainless steel wire on a pattern of 39 slots cut into the supporting rings. The solid mesh geometry had an average transparency of $T = 0.975$. The width of the openings between the wires was less than 3 mm. It was also possible to fabricate iris type meshes.

Measurements of transported beam current were performed with a shielded current monitor at the end of the transport tube. Relative measurements of the current profile and angular distribution were performed with an emittance diagnostic consisting of an aperture plate with 0.05 cm diameter holes and a plastic scintillator 1.7 cm downstream from the plate. The

scintillator was coated with carbon to intercept light from the electron gun and to relieve charge accumulation. The time-integrated light emission was recorded photographically.

The properties of the injected beam were measured by locating the diagnostic package close to the anode mesh. For a gap spacing of 1.7 cm, the total current was measured to be 4 kA, within 10 per cent of the relativistic Child law prediction [12] for the Pierce geometry. Images of the beam profile showed a round beam with good uniformity over the central section, but with clear indications of a filamentation instability at the periphery. Our measurements of beam filamentation of the gridded relativistic gun with circular, blade, and annular cathodes will be reported in a separate paper. The electron divergence angle over the central portion of the beam was about 59 mrad, increasing to 130 mrad at the beam envelope, a result of the filamentation instability. The root-mean-squared emittance of the beam was about $\epsilon = 2 \times 10^{-3}$ n-m-rad.

A series of tests was performed with a transport system 30 cm in length. A current of 4 kA of 400 keV electrons was injected. By stacking various combinations of rings and mesh holders, the following cell lengths could be achieved: 3 cm, 4 cm, 5 cm, 6 cm, 10 cm and 30 cm. The transparency of the mesh array with 10 cells of length 3 cm was calculated to be 80%. When the 4 cm cell length was used, the system contained 7 full length cells and one half length cell. The current measured at the end of the 30 cm tube is plotted in Fig. 2 as a function of the cell length. The

current at cell lengths of 5, 10 and 30 cm was low and the level was relatively insensitive to the foil geometry. The transported current rose dramatically when the geometry was changed from 6 cells of 5 cm length to 7.5 cells of 4 cm length. Within the experimental accuracy, 100% current transport (corrected for the grid transparency) was achieved with 10 cells of 3 cm length.

The current monitor observations are confirmed by the beam distribution photographs of Fig. 3. The distributions were measured at the downstream end of the 30 cm transport system. For cell lengths of 5, 6 and 10 cm, the beam image was dim because of the low transported current. Electrons were distributed uniformly over the cross-section of the end plate. The divergence angle of the small fraction of particles that reached the output was small because of velocity selection and beam expansion. The nature of the changed completely with 4 cm cells. The image was much brighter (note the change in camera f/number) and the beam was confined to a small cross-section compared to the transport tube. The measured beam diameter at the end of the system was 5.0 cm. The confined particles had a higher divergence angle. When the cell length was reduced to 3 cm, the beam was more tightly pinched with a correspondingly higher divergence angle. The beam diameter in the 10 cell system was about 2.8 cm with a divergence angle of 0.21 radians (12°). The corresponding emittance, $\epsilon = 2.9 \times 10^{-3}$ n-m-rad, was not greatly degraded from the injection conditions. It is particularly noteworthy that the self-confined beams were centered in the transport tube to within ± 1 mm. The corresponding aiming accuracy of 0.2° is better than the geometry

and aligned of the system would predict. The data suggest that the confined beam was centered by interaction with image currents in the tube walls.

The observations were consistent with the theory of foil transport. For cell lengths of 5 cm and greater, the beam created an electrostatic potential energy between the foils that was greater than the beam kinetic energy. In the absence of foils, the space charge limited current for a 2.8 cm diameter beam is predicted to be about 1.4 kA [13]. The injected beam exceeded the longitudinal space charge limit. For the 30 cm cell length (no foils), the beam generated a virtual cathode in the transport region. The reduced energy electrons were either reflected or driven radially outward to the wall. Only a small fraction (2%) of the electrons passed this barrier to reach the far end of the system. With widely spaced foils (5, 6 and 10 cm), a virtual cathode still formed but the radial space charge fields were reduced, allowing a higher fraction to propagate (≤6%). When the cell length was reduced to 4 cm, the maximum space charge potential was reduced to a value below the electron injection voltage, allowing all particles to propagate. The 4 cm critical cell length is in good agreement with theoretical predictions. For a 400 keV injection energy, the maximum space charge potential must be reduced by about a factor of three to propagate a 4 kA beam. Assuming a cylindrical beam of radius of 2.5 cm, solution of the Poisson equation implies that the maximum potential in the presence of foils spaced 4 cm apart was reduced by a factor 0.3 from that of an infinite length beam.

radius of the beam was about 80% larger. The observed radius, $r_0 \cong 2.5$ cm, overlapped the inner radius of the iris. We did not observe evidence of beam interaction with slow waves in the iris-loaded waveguide, even though the cells were predicted to have a Q value in excess of 100. We attribute the absence of longitudinal instabilities to the fact there was a significant longitudinal velocity spread since the beam propagated close to the longitudinal space charge limit. The beam equilibrium at injection was already close to the saturation state that would result from a longitudinal instability.

Acknowledgments

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FIGURE CAPTIONS

1. Transport experiment. a) Felt surface cathode. b) Pierce focusing electrode. c) Mesh anode. d) Transport mesh. e) Vacuum chamber. f) Spacing ring. g) Aperture plate. h) Graphite covered scintillator. i) Shielded current monitor. j) Viewport.

2. Net transported current as a function of cell length for a 30 cm system length. Reduced current level (dotted line) is based on the transparency factor for nine meshes. Aperture radius of iris grid: 2.2 cm.

3. Beam distribution measurements at the exit of the 30 cm transport system; time-integrated photographs. (Injected beam: 4 kA of 400 keV electrons, 5 cm diameter circular cathode, solid meshes.) a) 10 cm cell length, $f/16$. b) 6 cm cell length, $f/16$. c) 5 cm cell length, $f/22$. d) 4 cm cell length, $f/45$. e) 3 cm cell length, $f/45$. f) Scale drawing of transport tube cross-section, 9.8 cm inside diameter.

APPENDIX

Filamentation Instability of a Relativistic Electron Beam
in a Foil Transport Channel

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ABSTRACT

High-current relativistic electron beams can be focused in vacuum by arrays of transverse conducting foils. The foils reduce defocusing space charge electric fields, allowing self-pinched propagation. Beams in such a transport channel may be subject to a filamentation instability caused by local magnetic pinching; similar processes are observed when high current electron beams pass through a neutralizing plasma. The instability leads to a growth of the beam emittance. We report observations of the filamentation of a 4 kA, 280 keV electron beam propagating in a transport array of fine wire meshes. Strong modulation of the beam density was observed with propagation lengths of only a few centimeters. Observations of the filamentation of a sheet beam are compared to a theoretical model, which accurately predicts the instability growth length and saturation values of beam angular divergence. The filamentation instability is not expected to be a serious problem for paraxial beam transport. On the other hand, the present results indicate that filamentation may seriously degrade the quality of intense relativistic electron beams generated by high perveance guns with an anode foil.

Filamentation Instability of a Relativistic Electron Beam in a Foil Transport Channel

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I. Introduction

Filamentation instabilities are a familiar phenomenon in the transport of intense relativistic electron beams in plasmas [1-9]. When the space-charge electric field of a relativistic beam is canceled, transverse non-uniformities of current density can grow because of local pinching by the strong beam-generated magnetic fields. In this paper, we report observations of transverse filamentation of 280 keV electron beams propagating in high vacuum. The beams were transported in a self-focused mode using transverse conducting foils [10-13]. In retrospect, the presence of magnetic filamentation is not surprising since the purpose of the foils is to reduce space charge electric fields to allow a self-contained equilibrium. Foil transport achieves space charge neutralization with image charges, while plasma neutralization results from free charges. With regard to the filamentation instability, the final state is not strongly affected by the method by which neutralization is achieved.

The magnetic filamentation instability reaches saturation when

the beam gains sufficient dispersion in transverse velocity. Ultimately, the transverse beam pressure force becomes large enough to resist magnetic pinching. The end result of filamentation is growth of the beam emittance. The results reported in this paper suggest limitations on the quality of beams in space-charge neutralized transport systems and optimal approaches to transport that limit emittance growth. The results also bear on the feasibility of relativistic electron guns with anode grids or foils. We observed strong filamentation of beams in a variety of gun geometries within a few centimeters of an anode mesh.

Experimental observations of the filamentation of a high perveance beam from a 4 kA, 280 kV electron gun are described in Section II. In addition to voltage and current diagnostics, we measured time-integrated output beam profiles and emittance. Circular and annular cathodes were used with a fine mesh anode. Filamentation of annular beams was particularly violent; beam electrons developed an azimuthal divergence angle of $\pm 15^\circ$ within 2-4 cm of the anode. Measurements of the transverse distribution of current density showed complex structure for both guns. In order to compare experimental results with theoretical predictions, we designed a cathode to generate a well-confined thin sheet beam. Experimental results on filamentation of the sheet are reported in Section IV; a simplified theoretical treatment for the beam geometry is developed in Section III. Measured values of the instability growth length, instability wavenumber, and saturation angular divergence are in good

agreement with the theory. Implications of the results for foil transport are discussed in Section V.

II. Observations of filamentation instabilities in cylindrically symmetric beams

The pulsed electron gun was driven by a CHAC generator [14]. The water-filled Blumlein line produced a 60 ns (full width at half-maximum) pulse with a good 40 ns flattop. The pulseline, electron gun, and transport volume are illustrated in Fig. 1. We modified the output section of the pulseline, incorporating a large output resistor and radial vacuum insulator. The resistor was used in place of an inductor to relieve charge from the Blumlein line center conductor during pulsed energy transfer from the Marx. Although the resistor caused a relatively high value of positive prepulse voltage (~ 60 kV) on the gun cathode, we encountered no problem with premature emission. In contrast to the situation with an inductor, the prepulse voltage waveform with a resistor was monopolar; the positive cathode prepulse voltage inhibited electron emission. The output voltage waveform was optimized by adjusting the output resistor to match the net load impedance. The resistor also served to absorb postpulse energy, so that we were able to accumulate a large number of shots on the gun with no damage to the fine anode mesh.

The gun voltage was measured using a balanced probe in the output resistor (Fig. 1). The monitor was cross-calibrated against a magnetic spectrometer that measured the output energy of electrons. The slow risetime of the beam current in the diode

contributed an inductive correction of less than 10 kV to the voltage monitor signal, or less than 5 per cent. The current of the extracted electron beams was typically 4 kA or less. Beam current extracted through the anode and transported in vacuum by foil arrays was measured with calibrated in-vacuum current monitors. The monitors (Fig. 1) contained a toroidal multi-turn Rogowski coil [15,16] in a re-entrant shield. The coil was potted in low vapor pressure epoxy. The predicted risetime of the current monitors was 5 ns [17]. An oscillograph of cathode voltage and extracted electron current for the planar gun described in Section IV is shown in Fig. 2. Although the voltage was constant over the pulselength, the current exhibited a long term increase. Variation of the current was probably a consequence of plasma expansion from the cathode.

Electrons were generated from an explosive plasma cathode activated by the extraction voltage pulse. We used velvet cloth as the active surface. The material has been shown to ignite rapidly and to produce a uniform electron beam [18,19]. We used a variety of cathode geometries. In most cases, the velvet surface was surrounded by a modified Pierce focusing electrode [20], as shown in Fig. 1. The polished stainless steel electrode inhibited edge emission and aided in the creation of well-directed beams. Measurements of the extracted beam profiles confirmed that when the field stress on the focusing electrode was less than 300 kV/m, electrons were emitted only from the velvet surface. The anode consisted of a planar mesh composed of 0.0025 diameter stainless steel wires with a transparency of 80 per cent. The

current at the end of the voltage pulse was about double the space charge limit [21], implying that the width of the extraction gap was reduced by a factor of 0.7 at the end of the pulse. This figure implies a plasma expansion velocity of about 10 cm/ μ s, a typical value for surface plasma cathodes operated at high current density (100-200 A/cm²) [22].

The time-integrated beam profile was measured by taking open shutter photographs of a scintillator that intercepted the beam. The scintillator surface was coated with graphite. Multiple layers of fine mesh were compressed against the entrance surface to attenuate the beam and relieve charge accumulation. The time-integrated beam emittance was measured using the "pepperpot" [23] illustrated in Fig. 1. For these measurements, the scintillator sheet was located 1.4 cm behind an aperture plate. The 0.05 thick stainless steel aperture plate had an array of 0.04 cm diameter holes separated by a distance 0.5 cm.

Electron beams were transported through removable foil assemblies inserted into a 20.3 cm diameter cylindrical vacuum chamber. In order to propagate the 280 keV electron beam through large numbers of focusing cells, wire meshes were used instead of foils. The meshes, constructed from 0.005 cm diameter wires mounted on a mandrel, had 98 per cent transparency. As shown in Fig. 1, a variety of cell geometries could be achieved by stacking spacers and meshes. The removable transport assembly had an inner diameter of 9.6 cm. The current monitor and emittance diagnostics were usually mounted at the end of the system.

We first observed evidence of filamentation using the high perveance cylindrical cathode with focusing electrode illustrated in Fig. 3(a). The active cathode surface was 5.1 cm in diameter. The initial width of the cathode-anode gap was 2.0 cm. The extracted current reached a value of 2.6 kA at the end of the voltage pulse, corresponding to 3.3 kA of electron flow in the cathode-anode gap. The final current was about 1.8 times the space charge limit, implying a final effective gap width of 1.5 cm. Beam profile measurements were performed with a detector 4.5 cm from the anode mesh.

The measured beam profile is illustrated in Fig. 4(a). The time-integrated photograph shows a clear indication of beam filamentation; the beam edge is strongly feathered, the result of local electron pinches and orbit crossings. The observed beam radius was substantially larger than the cathode radius. There are three potential causes for enlargement of the beam:

1. The exposure of the profile photograph is strongest at the end of the pulse, when the beam current is enhanced by plasma closure. The higher current causes increased space charge expansion in the propagation region.
2. Plasma expansion moves the emission surface away from the physical cathode surface, degrading the gun optics.
3. Filamentation results in significant disordered transverse motions of electrons.

Effects of the filamentation instability on the beam distribution

are illustrated in the pepperpot data of Fig. 4(b). Analysis of the centroid locations showed that the beam was diverging with an angle of about 8° at a 2.5 cm radius. An inspection of the shape of the spots shows a complex angular structure. The divergence angle of electron orbits was approximately isotropic in the radial and azimuthal directions. The approximate boundary value of the divergence angle is plotted in Fig. 5 as a function of radial position. The greatest increase in angular divergence occurred on the periphery of the beam; the average divergence angle was about 7.5° .

We observed interesting filamentary behavior using the annular cathode illustrated in Fig. 3(b). The cathode was a simple velvet annulus with no focusing electrode. The cathode proved useless for propagation experiments because emission was dominated by edge effects; the resulting beam has strong divergence radially inward and outward from the initial annulus. The most significant result from experiments with the ring cathode was the occurrence of an extremely strong filamentation instability. The initially thin sheet beam pinched into a number of bunches, resulting in a large increase in disordered azimuthal velocity.

Because of edge emission, the net current from the 20 cm^2 cathode was substantially higher than the planar space charge limit prediction at all times. With a 1.7 cm gap, the peak current was typically 4.5 kA. A beam profile measured 1.7 cm downstream from the anode is shown in Fig. 6(a). A scale drawing of the cathode dimensions is included as Fig. 6(c). The effects

of azimuthal filamentation superimposed radial expansion of the beam are evident. The emittance plot of Fig. 6(b) shows strong angular beam clumping in the azimuthal direction. While the average beam divergence angle in the radial direction is only $\pm 5.7^\circ$, the azimuthal divergence is $\pm 15.4^\circ$. This angular divergence is acquired within a propagation distance of less than 3 cm.

III. Scaling laws for sheet beam filamentation

Although the beam filamentation described in Section II resulted from straightforward magnetic pinching, analysis of the process is difficult because of the three-dimensional geometries involved. In order to carry out a quantitative investigation of the factors affecting the growth of filaments, we designed a cathode to generate a parallel sheet beam. Experimental results on the thin one-dimensional beam geometry are described in Section IV. The linear theory of thin beam filamentation in a foil focusing system is reviewed in this section. The theory gives first order estimates of growth rates and saturation values of beam divergence that are in good agreement with experimental observations.

A thin sheet beam is illustrated in Fig. 7. The beam propagates in the z-direction; it is assumed that the beam has infinite extent and uniform properties in the direction of propagation. In equilibrium, the beam has infinite extent in the x-direction; we shall investigate conditions under which perturbations in the x-direction lead to magnetic pinching. In

the experiments, the beam propagates through a number of closely spaced transverse meshes. The meshes reduce space charge effects but have little effect on magnetic fields. The experimental geometry with its axial variations, is difficult to describe analytically. Instead, we shall concentrate on the simplified geometry of Fig. 7. The beam is contained between symmetric planar boundaries. To model the effect of partial space charge neutralization by transverse foils, the image charge boundary is located at a different position than the image current boundary. The image charge boundary at position y_e with respect to the beam axis defines a surface of constant electrostatic potential, ϕ , where $E_x = 0$. The return current boundary at position $y_m \geq y_e$ defines a surface of constant vector potential, A_z , where $B_y = 0$.

In order to facilitate a linear analysis of beam stability, we assume that the relativistic sheet beam satisfies the paraxial approximation, $v_x, v_y \ll v_z$. This condition implies that all beam electrons have about the same kinetic energy, $(\gamma-1)m_0c^2$, and longitudinal velocity, $v_z \cong \beta c$. Motion in transverse direction can be described by non-relativistic type equations with an adjusted particle mass, γm_0 . Unspecified equilibrium forces act to confine the beam in the y -direction; we shall consider only the possibility of motion in the x -direction. In the equilibrium state, the beam is taken to have uniform charge density ρ_0 distributed over a half-thickness Δy . The thin beam limit is described by the condition $\Delta y \ll y_e, y_m$. Perturbations in the x -direction are taken to have a scale length long compared to the beam thickness. In terms of the spatial wavenumber, k , this

condition can be expressed $k \leq 1/\Delta y$. The quasi-static approximation is to estimate the electric and magnetic fields; this limit is valid if instability growth times are long compared to $1/kc$.

In equilibrium, the electric and magnetic fields have the following values at the beam boundaries:

$$E_{y0} = \pm \rho_0 \Delta y / \epsilon_0, \quad (1)$$

$$B_{x0} = \pm \mu_0 \rho_0 \Delta y \beta c. \quad (2)$$

We assume a perturbation of beam charge density in x-direction with wavenumber k :

$$\rho(x) = \rho_0 + \Delta \rho \cos kx. \quad (3)$$

The density variation gives rise to an associated perturbation of beam current density:

$$j_z(x) = \rho_0 \beta c + \Delta \rho \beta c \cos kx. \quad (4)$$

To begin, we shall calculate the electrostatic potential associated with the perturbed density. The solution that satisfies Laplace's equation outside the beam and meets the boundary condition at the conducting boundary is

$$\Delta \phi(x, y) = \Delta \phi_k \cos(kx) [\exp(ky) \exp(-ky_e) - \exp(-ky) \exp(ky_e)]. \quad (5)$$

There is an additional matching condition for electric field at the beam boundary. In the limit that $\Delta y \rightarrow 0$, the normal component of electric field approaches the value:

$$\Delta E_y(0^+) = -\partial \phi(x, 0)/\partial y = \Delta \rho \Delta y \cos(kx)/\epsilon_0. \quad (6)$$

Eq. 6 implies that

$$\Delta \phi_k = -(\Delta \rho \Delta y / 4\epsilon_0) \cosh(ky_e). \quad (7)$$

The electric field component E_x affects the growth of filamentation instabilities. Taking $\Delta E_x = -\partial \phi(x, y)/\partial x$, yields the following expression:

$$\Delta E_x(x, y) = (\Delta \rho \Delta y / 2\epsilon_0) \tanh(ky_e) \sin(kx). \quad (8)$$

A similar treatment can be applied to calculate the perturbed magnetic field. A solution for the vector potential $A_z(x, y)$ yields the result:

$$\Delta B_y(x, y) = (\Delta \rho \Delta y \beta / 2\epsilon_0 c) \tanh(ky_m) \sin(kx). \quad (9)$$

The net force in the x-direction resulting from perturbed beam-generated fields is

$$F_x = (e \Delta \rho \Delta y / 2\epsilon_0) \sin(kx) [\tanh(ky_e) - \beta^2 \tanh(ky_m)]. \quad (10)$$

The linearized moment equations for beam motion in the x-direction are:

$$\frac{\partial \Delta \rho}{\partial t} + \frac{\partial}{\partial x} (\rho_0 \Delta v_x) = 0. \quad (11)$$

and

$$\begin{aligned}
\gamma m_0 \rho_0 \frac{\partial \Delta v_x}{\partial t} + \gamma m_0 \langle \delta v_x^2 \rangle \frac{\partial \Delta \rho}{\partial x} &= \quad (12) \\
= \frac{\rho_0 e \Delta y}{2 \epsilon_0} \Delta \rho \sin(kx) [\tanh(ky_e) - \beta^2 \tanh(ky_m)]
\end{aligned}$$

The quantity Δv_x is the perturbed directed velocity, while $\langle \delta v_x^2 \rangle$ represents a random velocity dispersion in the x-direction. With the assumption that all quantities vary as $\exp(\alpha t) \sin(kx)$, Eq. 12 reduces to following expression for the linear growth rate of perturbations:

$$\begin{aligned}
\alpha^2 = -k^2 \langle \delta v_x^2 \rangle - (e J_z / 2 \gamma m_0 \beta c \epsilon_0) k \tanh(ky_e) + \\
+ \beta^2 (e J_z / 2 \gamma m_0 \beta c \epsilon_0) k \tanh(ky_m), \quad (13)
\end{aligned}$$

The quantity J_z is the net current of the equilibrium beam per unit length along x:

$$J_z = en_0 \Delta y \beta c. \quad (14)$$

The beam pressure and space charge force have a stabilizing effect, while the beam-generated magnetic force leads to growth of perturbations. The beam is stable if $y_e = y_m$; in this case, the repulsive electric forces dominate. The effect of adding transverse foils for focusing can be simulated by taking $y_e < y_m$. In this case, the transverse electric field is reduced more than the magnetic field and a low emittance beam may be subject to a

pinching instability. The result of the instability is to increase the transverse emittance of the beam. Ultimate, the transverse beam velocity dispersion grows to a level that stabilizes pinching. The root mean squared beam angular dispersion for stable propagation given by

$$\Delta\theta \cong \frac{(\langle \delta v_x^2 \rangle)^{1/2}}{\beta c} = \left[\frac{(qJ_z) [\beta^2 \tanh(ky_m) - \tanh(ky_e)]}{(2\epsilon_0 \gamma m_0 \beta^3 c^3) k} \right]^{1/2} \quad (15)$$

IV. Observations of sheet beam filamentation

We conducted experiments using a sheet beam cathode to clarify the nature of the high vacuum filamentation instability and to verify the theoretical predictions of Section III. The plasma emission cathode had an active emission area with dimensions 0.5 cm width by 8.5 cm length. Along the length, the emission area was bordered by polished stainless steel focusing electrodes. A cross section of the gun and a simulation of sheet beam extraction using the EGUN code [24] are shown in Fig. 8. For a 1.5 cm gap, the simulation predicts a linear current density of 8.5 kA/m in the anode-cathode gap. For propagation experiments, we could assemble a wide variety of foil transport geometries, such as the three cell system illustrated. Most instability measurements were performed with the diagnostic package as close as possible to the anode, typically 2 to 3 cm.

Voltage and extracted current traces for the gun are

illustrated in Fig. 2. The current was initiated immediately after application of the gap voltage. The current quickly rose to a level consistent with EGUN predictions, confirming that emission was predominantly from the velvet surface. Over the succeeding 40 ns voltage pulse, the total current reached a value approximately double the space charge limit. For comparison to the time-integrated measurements, instability analyses were based on the linear current density at the end of the pulse, since the gun had the highest power density at this time and the instability growth rate was predicted to have a maximum value. We measured a linear current density of $J \cong 2 \times 10^4$ A/m at the end of the pulse.

Fig. 9(a) shows a time-integrated beam profile with the scintillator detector located 1.1 cm downstream from the anode mesh. Note the well defined planar beam with a clear induction of incipient filaments. The full width of the beam is about 0.78 cm, in good agreement with the EGUN prediction. The beam profile indicates that emission took place primary from the velvet surface, although there are indications of peripheral electrons, probably generated by emission from the focusing electrode. Profiles taken at 3.8 and 6.6 cm from the anode mesh are shown in Figs 9(b) and (c). Measurements of the beam width shown an envelope divergence angle of 7° , considerably larger than the EGUN prediction. The increased divergence reflects the combined results of optics mismatch from the cathode plasma expansion and emittance growth from the filamentation instability.

Fig. 9(a) shows a well developed filamentary structure parallel to the cathode direction noted at very short distances from the anode mesh. The predicted propagation length for the growth of the filamentation instability from Sect. III is short enough to account for the structure observed. Given the instability growth rate, α , the growth length is approximately:

$$L_g \sim \beta c / \alpha. \quad (16)$$

To estimate L_g , assume that neutralization of transverse electric fields was almost complete near the anode mesh and that the initial emittance of the beam was negligibly small. In the experimental geometry, the return currents flow on a surface a large distance from the beam compared to the beam width and observed wavelengths for filamentation. In this limit, we can take $\tanh(ky_m) \cong 1$ in Eq. 13. With the above approximations, the predicted growth length is,

$$L_g \geq (2\gamma m_0 \beta c^3 \epsilon_0 / e J_z k)^{1/2}. \quad (17)$$

Measured values of parameters in Eq. 17 are $\gamma = 1.55$, $\beta = 0.764$ and $J \cong 2 \times 10^4$ A/m. The only other input required is k , the instability wavenumber. This quantity can be estimated from the beam profile data. A digitization of the intensity profile of Fig. 9(a) on a line parallel to the cathode surface is shown in Fig. 10. A Fourier analysis shows the strongest variation occurs with a wavelength of $\lambda = 0.8$ cm. This is a physically reasonable result; in the thin beam limit, Eq. 17 predicts the strongest filamentation growth occurs at the shortest wavelength. The thin beam approximation is invalid if the pinching scale length is

less than or comparable to the width of the sheet beam near anode. The growth rate for filamentary structures smaller than the beam width is reduced. In consequence, the fastest growing filaments should have a dimension comparable to or larger than the average beam width, on the order of $\Delta y \sim 0.6$ cm. If we take $k = 2\pi/(0.008) = 785 \text{ m}^{-1}$, Eq. 17 predicts a growth length, L_g , of only 1.4 cm. It is therefore not surprising to observe significant filamentary structure over the total beam transport length of 2.6 cm.

Emittance data taken 2.4 cm from anode mesh is illustrated in Fig. 11. The enhancement of the beam angular divergence occurs mainly in the direction parallel to the cathode length, consistent with the observed profile (Fig. 10). The divergence in the parallel direction is about 0.11 radians (6.3°), twice the divergence in the normal direction. The downstream divergence has about the same magnitude and becomes more isotropic. The divergence figure can be compared to predictions of Eq. 15 for the saturation angular divergence resulting from filamentation. Inserting parameters for the sheet beam and again assuming complete electrical neutralization and neglecting return current effects, Eq. 15 gives a divergence of 0.10 radians (5.7°), in agreement with the observations.

V. Conclusions

Although foil focusing has been demonstrated as an effective method for high current electron beam transport [10-13], filamentation instabilities set limits on the range of

application. To understand the implications of the present results, we must note that transverse conducting foils can serve two functions for beam transport:

1. By reducing transverse electric fields, conducting foils allow a relativistic electron beam to propagate in a self-pinched equilibrium.
2. By lowering longitudinal electric fields and the beam-generated electrostatic potential, conducting foils may facilitate transport of beams at levels beyond the conventional space charge limiting current [25].

Transverse focusing by foils is effectively applied to paraxial electron beams propagating below the longitudinal space charge limit. As an example, the electron beams from linear induction accelerators envisioned for free electron laser applications [26,27] satisfy the paraxial approximation. If the beams are highly relativistic, the required electric field reduction factor is small and the foils can be widely spaced. The best foil transport strategy for such beams is to focus the electrons to an emittance limited spot size at the entrance of the foil transport array and to arrange the foil geometry so that the beam propagates with a small radius and relatively high angular divergence. The filamentation instability is avoided because the radial force balance in the foil transport system is dominated by emittance and magnetic forces. Reduction of the beam dimension to a small diameter also minimizes emittance growth from foil scattering. Our studies of foil scattering indicate

that high brightness electron beams can be generated by induction accelerators with foil focusing.

The second potential application of foil focusing, propagation of very high current (>100 kA) electron beams by the reduction of longitudinal space charge effects, may be affected by filamentation instabilities. Generation of such beams calls for a high perveance gun with a grid or foil anode. The present results indicate that there are two related problems associated with this transport geometry:

1. Foils must be closely spaced to achieve a significant reduction in the beam-generated electrostatic potential.

Beams entering such a foil array from a high perveance gun are inevitably over-focused. The resulting non-linear envelope oscillations lead to emittance growth until radial force equilibrium is attained.

2. High perveance beams with initially low angular divergence will be subject to the filamentation instability, further increasing the emittance.

If beam brightness is a concern, alternate approaches may be required for very high current electron beam transport, such as an annular beam geometry.

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FIGURE CAPTIONS

1. Experimental system. A) Pulser output insulator. B) High voltage output terminal, 300 kV pulser. C) Blumlein line shunt resistor, aqueous resistive solution. D) Flexible contacts. E) Balanced voltage monitor. F) Radial vacuum insulator. G) Vacuum chamber. H) High voltage terminal. I) Adjustable cathode carrier. J) Surface plasma cathode with focusing electrode. K) Transport tube. L) To vacuum pump. M) Mesh anode. N) Transport system spacer rings. O) Transport system support flange. P) Shielded current monitor. Q) Pepperpot aperture plate. R) Coated scintillator sheet.

2. Cathode voltage and extracted current, planar gun with focusing electrode, 1.3 cm cathode-anode gap spacing. Top: Gun voltage, 120 kV/div, 20 ns/div. Bottom: Beam current 1.5 cm from anode grid, 1.22 kA/div, 20 ns/div.

3. Electron gun geometries. a) High perveance circular cathode with focusing electrode. b) Simple annular cathode.

4. Output beam properties, high perveance circular cathode. a) Beam spatial profile, 2 cm cathode-anode gap, scintillator 4.5 cm downstream from anode mesh b) Emittance measurement, 1.7 cm cathode-anode gap, aperture plate 3.8 cm downstream from anode mesh. c) Scale drawing of cathode and transport tube cross-sections.

5. Linear scan of angular divergence across beam, 3.8 cm from anode mesh (reduction of Fig. 4(b)). High perveance circular

cathode, 1.7 cm cathode-anode gap.

6. Output beam properties, annular cathode. a) Beam spatial profile, 1.7 cm cathode-anode gap, scintillator 1.7 cm downstream from anode grid. b) Emittance measurement, 1.7 cm cathode-anode gap, aperture plate 1 cm downstream from anode mesh. c) Scale drawing of annular cathode.

7. Geometric parameters, filamentation of a thin sheet beam.

8. EGUN simulation, sheet beam gun with focusing electrode, 1.5 cm cathode-anode spacing, three transport cells of length 2 cm. Predicted linear current density: 8.5 kA/m.

9. Output beam profiles as a function of distance from anode, sheet beam gun with focusing electrode, 1.5 cm cathode-anode gap. a) Single transport cell, distance from anode mesh, 1.1 cm b) Dual cell, distance from anode mesh, 3.8 cm c) Triple cell, distance from anode mesh, 6.6 cm.

10. Photodensitometer scan of intensity profile of Figure 9(a), parallel to long axis of cathode.

11. Emittance data, sheet beam cathode with focusing electrode. 1.3 cm cathode-anode spacing, aperture plate 2.4 cm downstream from anode mesh.

Figure 1

FIGURE 2

Figure 3(a)

Figure 3(b)

Figure 5

A

B

C

Figure 7

SHEET01. 300 kV CHAC sheet beam injector, 1.5 cm gap spacing
Zscale: 1.40 Rscale: 1.40

A

B

C

APPENDIX C

"FOIL TRANSPORT OF INTENSE ELECTRON BEAMS RESEARCH"

STATEMENT OF WORK

AUGUST 5, 1986

The University of New Mexico (UNM) shall establish an experimental beam transport facility in the Institute for Accelerator and Plasma Beam Technology, UNM campus. Further, UNM will carry out certain studies of foil focused relativistic electron beams in support of Los Alamos National Laboratory (LANL). The following theoretical and experimental tasks shall be performed between October 1986 and September 1988.

Theoretical Tasks

1. Extension of analytic methods to derive foil focused equilibria for annular beams.

The foil focusing theory *of S. Humphries, Jr. will be extended to address the problems of very high current beam transport by annular beams. Envelope equations will be derived at the inside and outside of annular beams with sharp boundaries. A search will be made for conditions under which equilibrium conditions can be satisfied at both boundaries.

2. Derivation of envelope trajectory equations for MA beams in high gradient accelerators.

The results of Task 1 will be applied to determine average radial force acting on annular beams as a function of radial beam geometry, foil geometry, beam current, and beam gamma. The force expression will be applied to the calculation of the beam trace through a high gradient accelerator.

3. Identification of possible transverse instabilities of foil focused beams.

Neglecting the effects of radial boundaries, a foil focused beam is in an equilibrium state of neutral stability. The space charge lens effect moves with the beam. Therefore, the inclusion of image charge and image current forces could lead to transverse instability. This may be a particular problem in disc accelerators where the image charge is at a smaller average radius than the image current. UNM will carry out a qualitative analysis of the nature of transverse instabilities.

4. Investigation of methods to stabilize beams in foil focusing systems.

There are potential methods to stabilize beams if transverse

Reference

*S. Humphries, Jr. Particle Accelerators 13, 249 (1983)

instabilities present a serious problem. The concept is to modify the system so that the centered beam is at an energy minimum. Two potential methods are shaping of the focusing foils (i.e., truncated cones) or addition of non-linear focusing forces provided by permanent magnet multipoles.

Experimental Tasks

The goals of the experimental work are to perform modeling studies with a relativistic electron beam to confirm the equilibrium models and to assess the severity of transverse and longitudinal instabilities. An existing pulsed power equipment and a versatile transport chamber assembly will be used to obtain relevant data in a short time scale. The following Tasks shall be performed.

1. Arrange loan of thyatron triggered CHAC generator from Sandia National Laboratories. Electrical properties: 12 ohm, 50 ns, Matched pulse: 300 kV matched at 36 kA, unmatched pulse: 500 kV at 12 kA. Features: High shot rate, low jitter and high reproducibility.
2. Fabricate electron beam diode chamber and annular gridded gun using design of present IAPBT betatron injector.
3. Set up experiments and diagnostics in existing screenroom complex (radiation shielding already in place). Construct charging supplies and systems for oil handling and water purification.
4. Design and fabricate versatile transport system consisting of commercial stainless steel vacuum sections, diagnostic ports, and movable modular mesh holders.
5. Design and fabricate diagnostic package, consisting of a net current Rogowski loop, a charge collecting probe array, and a beam distribution diagnostic. The package is mounted to replace a particular foil to measure time resolved beam current and the time-integrated beam distribution. Because of the nature of foil focusing, the conducting boundary of the diagnostic package does not perturb the beam distribution. The package has already been tested on the IAPBT Betatron Injector.
6. Design and fabricate small shielded scintillators (pilot B) to be inserted transversely at a number of axial locations. Photograph of the scintillator assemblies from the end of the system will give information on the axially resolved radial beam profile.
7. Perform modeling experiments with the primary goals of a) confirming the equilibrium theory for annular beam at high current density, 2) determining if there are any macroscopic transverse

instabilities, and 3) measuring emittance growth in the non-linear focusing channel. The secondary goal is to carry out detailed parameter studies of foil focusing and its applicability to a variety of applications.

Deliverables

UNM shall provide quarterly progress reports for LANL review. Additionally, UNM shall provide a final report to LANL within 30 days of project completion.

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