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A Proposal for Study of Vacuum Adiabatic Compression of a Relativistic Electron Beam Generated by a Foilless Diode

Lester E. Thode

los alamos scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

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A PROPOSAL FOR STUDY OF

VACUUM ADIABATIC COMPRESSION OF A RELATIVISTIC ELECTRON BEAM

GENERATED BY A FOILLESS DIODE

by

Lester E. Thode

ABSTRACT

A theoretical investigation to study the generation of an intense relativistic electron beam by a foilless diode and subsequent adiabatic compression is proposed.

I. INTRODUCTION

There are a number of applications for a 5- to 50-MeV electron beam which are of interest to the Air Force, including

(1) submillimeter microwave generation,[1-8]

(2) inertially confined plasma x-ray source,[9-11] and

(3) collective ion acceleration.[12-18]

In addition to a high beam voltage, these applications ultimately require a beam energy density of 10^{19} to 10^{22} eV/cm^3. This implies a current density of 50 to 500 kA/cm^2, but not necessarily a large net current. Furthermore, the local beam momentum distribution must be sufficiently uniform in energy and well collimated, since the applications of interest depend on the development of large-amplitude, coherent waves. In this context, a measure of the beam quality is the spread in electron velocity components along a beam stream line,

$$\Delta v_{\parallel}/c \simeq \theta^2/2 + \delta\gamma/\gamma^3 \quad , \tag{1}$$

where θ and $\delta\gamma$ are the characteristic angular and energy spread of the local momentum distribution, and γ is the relativistic energy factor. The magnitude of

$\Delta v_{\parallel}$ which can be tolerated depends upon the wave spectrum associated with the particular application. For example, inertially confined plasma heating requires

$$\Delta v_{\parallel}/c < \gamma^{-1}(n_b/2n_e)^{1/3} \quad , \tag{2}$$

where n_b and n_e are the beam and plasma electron densities, respectively.

High-voltage beam generators exist (Aurora, Pulserad 1590, and Pulserad 1480), but they are generally operated with a foil diode. A foil diode suffers from shot-to-shot anode foil destruction and associated enhanced diode gap closure.[19] As a result, the initial diode gap spacing must be increased, thus lowering the current density by increasing the beam radius, in opposition to the requirements for the applications of interest. Nevertheless, the foil diode does allow the generation of a beam with a net current greatly exceeding the space charge limiting current, by isolating the vacuum diode region from the plasma or neutral gas region into which the beam is injected. This configuration is suitable for low-density CTR plasma heating experiments or collective ion acceleration experiments in which the acceleration is produced by the formation of a virtual cathode in a space charge limited beam. For the most part, past experiments investigating plasma heating[20-24] and collective ion acceleration[12-15] have been carried out in this configuration.

Foilless diodes offer the potential for overcoming the inherent disadvantages of the anode foil, including the modification of the beam momentum distribution function by classical scattering. In addition, a foilless diode is attractive from a repetitive pulsing standpoint. Foilless diodes have been used extensively in microwave generation experiments.[1-4] Beam requirements for inertially confined plasma heating[9] and collective ion acceleration produced by a train of space charge wells associated with large-amplitude Langmuir[18] or cyclotron[17] waves are also consistent with foilless diode generation. In the inertially confined plasma heating concept, the beam is propagated in vacuum to the plasma target, passes through solid end plugs, and transfers 30 to 50 percent of its energy to the 30- to 100-cm^3 plasma.

Due to the cathode shape and space charge effects, a beam generated by a foilless diode is annular with a net current determined by the space charge limit of the vacuum drift tube. For a 5- to 50-MeV electron beam the space charge limiting current is 100 to 1000 kA. Thus, for a small-radius cathode, the beam current density might be limited by the rate at which energy can be delivered through the dielectric feed to the diode. In either case, a current density of 10 to 100 kA/cm^2 appears realistic for a 5-to 50-MeV foilless diode. An alternate approach is to use a 3-to 5-MeV foilless diode as an injector for a radial pulse line accelerator.[25,26]

To achieve current densities above 10 to 100 kA/cm^2, the beam can be adiabatically compressed. To date, three experiments have been performed to investigate the adiabatic compression of a relativistic electron beam.[27-29] In order to avoid the space charge limit on the net beam current, the compression was carried out in the presence of a background gas, and rapid deterioration of beam quality and transmission occurred. As discussed in Sec. II, the adiabatic compression must be performed in vacuum if beam quality is to be preserved, consistent with foilless diode generation.

Although the approach of using a high-voltage foilless diode to generate an intense electron beam followed by vacuum adiabatic compression, to achieve an energy density of 10^{19} to 10^{22} eV/cm^3 appears attractive, there is some uncertainty about the quality of the local momentum distribution function. A theoretical study on the vacuum adiabatic compression of a 5-to 50-MeV electron beam, generated by a foilless diode, is proposed by the Los Alamos Scientific Laboratory of the Department of Energy. The aim of the study is to determine the feasibility of producing a high-quality beam by this approach. Financial support by the U. S. Air Force Office of Scientific Research is proposed. The cost of the study is estimated to be $57,000 over a one-year period.

To investigate beam generation by foilless diode and subsequent vacuum adiabatic compression, the relativistic, electromagnetic particle code CCUBE will be used. The code CCUBE obtains a time-and space-dependent solution in two spatial dimensions for any separable, orthogonal coordinate system. In conjunction with the numerical simulations, analytic studies and test particle orbit calculations will be carried out. The electric and magnetic field configuration for the orbit calculation in the diode will be guided by the simulation effort.

Results of the study will be reported in the scientific literature, if appropriate, and also in a document in a form specified by the Air Force Office of Scientific Research. It is anticipated that the results of the study will ultimately be incorporated into an experimental investigation on the AFWL Pulserad 1590.

II. BACKGROUND

For sake of discussion, it is assumed that the beam is an infinitely long, unneutralized, constant-density annular column of relativistic electrons. The radial self-electric field is E_r, and the azimuthal self-magnetic field is B_θ. Furthermore, the beam is immersed in a uniform axial magnetic field B_z, with all the electrons having a radially independent velocity v_z in the axial direction. The beam with inner radius b and outer radius a is enclosed in a cylindrical waveguide of radius R.

It is well established experimentally that a 1- to 2-MeV electron beam can be generated using a foilless diode. The maximum beam current I is determined by the space charge limit of the drift tube through which the beam must propagate,[30,31]

$$I^s = 17(\gamma^{2/3} - 1)^{3/2}/G \quad \text{kA} \quad , \tag{3}$$

where the radial beam geometry factor is

$$G = 1 - b^2/a^2 + 2\, \ln(R/a) \quad . \tag{4}$$

For these low voltages, the current density in the space charge limited beam is generally less than that due to Child Langmuir limitations associated with the effective diode gap spacing. For a 5-to 50-MeV beam, the space charge limit is greatly increased, and for a small-radius cathode the beam current density might be limited by the rate at which energy can be delivered to the diode region through the dielectric feed. In either case, a local current density of 10 to 100 kA/cm^2 appears achievable for a 5-to 50-MeV diode. As mentioned previously, an alternate technique is to use a 3-to 5-MeV foilless diode as an injector for a radial pulse line accelerator.[25,26]

To obtain current densities above 10 to 100 kA/cm^2, the beam can be adiabatically compressed. Three experiments have been performed to investigate the adiabatic compression of 1 to 2 MeV, $\nu/\gamma \approx 1$ to 10, electron beams.[27-29] In these experiments the compression was performed in the presence of a background gas in order to avoid the space charge limit on beam propagation. In addition to providing complete space charge neutralization, the background gas also provided significant current neutralization. Rapid current neutralization results in a discontinuity in the beam self-magnetic field,[32] in turn producing a velocity component perpendicular to the external magnetic guide field, in addition to that produced by anode foil scattering. As observed in the three experiments, the combination of self-magnetic field discontinuity and foil scattering leads to a large electron magnetic moment, rapid deterioration of the beam quality and, ultimately, of the transmission, even for rather modest compression ratios of M = 2 to 4.

It might be argued that the rather negative experimental results are due to the low diode voltage and insufficient external magnetic field strength. In fact, for compression in the presence of a background gas, the quality and transmission of the center of the beam is primarily limited by collective effects. To examine this point in more detail, the required length of the compression region can be compared with the interaction length associated with the two-stream instability. If the compression is to be adiabatic, the fractional change in the magnetic field strength over a Larmor orbit must be small,

$$[\lambda_c(z)/B_z(z)][dB_z(z)/dz] \equiv f \ll 1 \quad , \tag{5}$$

where $\lambda_c(z) = 2\Pi\gamma v_z(z)/\omega_c(z)$ is the gyro-radius, $B_z(z)$ is the component of the external magnetic field in the direction of beam propagation, and $\omega_c(z) = |e|B_z(z)/mc$. A determination of how small f must be is included in the proposed study. Assuming f to be independent of z, expression (5) is integrated to give the length of the compression region

$$z_c(\mathrm{cm}) = \left[10.6\ \gamma/fB_f\ (\mathrm{kG})\right] \times \left\{M\sqrt{1-\alpha^2/M} - \sqrt{1-\alpha^2} + \alpha^2\tanh^{-1}\left(\sqrt{1-\alpha^2}\right) - \alpha^2\tanh^{-1}\left(\sqrt{1-\alpha^2/M}\right)\right\} \tag{6}$$

as a function of the compression ratio M, maximum perpendicular velocity $\alpha = v_\perp^f/c$, and the maximum magnetic field strength B_f. For a high-quality beam $\alpha \ll 1$, and thus

$$z_c(\mathrm{cm}) = 10.6\ \gamma(M-1)/fB_f(\mathrm{kG}) \quad , \tag{7}$$

which will typically be on the order of a few meters.

For comparison the nonlinear interaction length associated with the two-stream instability when $\Delta v_{\parallel}/c << \gamma^{-1}(n_b/2n_e)^{1/3}$ is[9]

$$L_N \simeq \ell n\Lambda \, \gamma(n_e/n_b)^{1/3} \, c/\omega_e \quad , \tag{8}$$

where n_e is the plasma frequency of the background gas and Λ is the plasma parameter. In the compression region, L_N would typically be on the order of tens of centimeters, or roughly an order of magnitude shorter than the compression region.

Even if the nonlinear state of the streaming instability is weak, the transmission of the beam periphery will be limited by the self-magnetic field discontinuity mentioned earlier. A rough rule of thumb for the transverse velocity component due to self-magnetic field discontinuity is that it increases linearly with the beam radius,[32]

$$v_{\perp}/c \simeq (r/a)\tan^{-1}[B_\theta(r = a)/B_z], \tag{9}$$

with $B_\theta(r = a)$ the unneutralized beam self-magnetic field at the beam edge. As the compression ratio is increased, the characteristic magnetic moment at the entrance of the compression region is increased, since the maximum magnetic field strength at the end of the compression region is limited by strength of materials considerations. (An exception to this limit might be provided by an explosive-driven flux compressor.) Thus, the presence of the background gas is the limiting factor in obtaining an intense high-quality beam. It follows that the adiabatic compression must be performed in vacuum, which implies a high-voltage diode to increase the space charge limit.

In vacuum there are a number of conditions which must be satisfied for beam equilibrium and stability in the compression region.[33,34] In the rest frame of the beam, B_z must exceed E_r;

$$\omega_{\perp}^2(1 - b^2/a^2) < \omega_c \, c/a \quad , \tag{10}$$

where $\omega_{\perp}^2 = 4\Pi n_b e^2/m\gamma$ and $\omega_c = |e|B_z/mc$. In addition, the centrifugal force associated with the $\vec{E} \times \vec{B}$ rotation plus the radial self-field force $E_r - v_z B_\theta$ must be less than the $v_\theta B_z$ restoring force;

$$\omega_\perp^2(1 - b^2/a^2) < 0.5\ \omega_c^2 \quad , \tag{11}$$

where $v_\theta = r\omega_\theta(r)$ and $\omega_\theta(r) = 0.5\ \gamma^{-1}\omega_\perp^2(1 - b^2/r^2)\omega_c$.

In obtaining expressions (10) and (11), the beam diamagnetic field due to the $\vec{E} \times \vec{B}$ rotation has been neglected. The neglect of the diamagnetic field B_z^s is valid if

$$B_z^s/B_z \simeq \left[0.5(\omega_\perp/\omega_c)(a\omega_\perp/c)(1 - b^2/a^2)\right]^2 << 1 \quad . \tag{12}$$

Expression (12) is also related to the condition that the relativistic factor $\gamma = \gamma_o(1 - \beta_\theta\gamma_o^2)^{-1/2}$ is approximately independent of the beam radius and thus represents a beam quality condition. The radially independent relativistic factor is $\gamma_o = (1 - \beta_z^2)^{-1/2}$ and $\beta_\theta\gamma$ is given by the term in brackets in Eq. (12).

In the high-voltage regime, the equilibrium conditions can be satisfied within strength of materials limitations on the external magnetic field. For example, if $\gamma_o = 60$, $n_b = 10^{14}\ cm^{-3}$, $a = 1$ cm, and $B_z = 200$ kG, the most stringent condition (12) yields $\beta_\theta\gamma_o = 2 \times 10^{-2}$. Also, if the compression is adiabatic, Eqs. (10) through (12) remain constant throughout the compression region.

The preceeding annular beam equilibrium is not stable. Due to the presence of a shear in angular velocity $v_\theta(r) = r\omega_\theta(r)$ for $b \neq 0$, flute perturbations $\exp(im\theta)$ on the beam surface are found to be unstable. The growth rate of this so-called Diocotron instability is[34]

$$\delta \simeq 0.5\gamma^{-1}(\omega_\perp^2/\omega_c)P_m(b/R,a/R) \quad , \tag{13}$$

where P_m is a geometric factor depending on the beam profile. Thick annular beams are only unstable to the m = 2 mode, with $P_{m=2}^{max} \simeq 0.2$. For $(a - b)/R << 1$, the higher modes are also unstable with $P_{m>>1}^{max} \simeq O(1)$. Comparing the instability e-folding time $t \simeq 1/\delta \simeq 10^{-7}$ to 10^{-6} sec with the characteristic transit time for beam compression $t \simeq z_c/c \simeq 10^{-8}$ sec, the instability has a negligible effect on the beam profile. On a longer time scale, such as needed for collective ion acceleration, the instability may have sufficient time to slightly modify the beam profile, however.

Due to the time-dependent, relativistic character of the electron dynamics, the primary technique to be used in the investigation will be numerical simulation. Specifically, the relativistic, electromagnetic particle code CCUBE will be used.[35] The code CCUBE obtains a time-and space-dependent solution in two dimensions for any separable, orthogonal coordinate system. The local field strength in each cell can be specified, if desired. Thus, it is possible to have a boundary which is periodic or irregular, with a fixed or floating potential.

A large number of specialized time-integrated numerical measurements such as beam inductance, local electric and magnetic field probes, diamagnetic loops, Faraday cups, and calorimeters are implemented in the code. In addition, local beam distribution functions and particle density profiles in both dimensions are available.

The code has been successfully used to study space charge limited flow,[36] collective ion acceleration,[37] and beam injection into a plasma with subsequent heating due to the streaming instabilities.[11] To date, the distribution function at injection has been assumed to be of the form

$$f(\theta,\gamma,r) \propto \delta(\gamma - \gamma_o)\exp[-(\theta - \theta_r)^2/\theta_s^2] \quad , \tag{14}$$

where θ_s is the anode foil scattering angle, $\theta_r = rB_\theta(r = a)/aB_z$, and a is the beam radius. The only code development required to carry out the proposed study is the implementation of an electron emission[38,39] algorithm in CCUBE.

The simulations will provide information on the electric and magnetic field configuration in the diode for a limited number of parameter variations. Using these fields, test particle orbit calculations can be carried out to extend the parameter variation. In addition, the test particle orbit calculations will provide additional detail of the local beam distribution function, such as local Larmor radius and temperature. From the simulations, the local distribution functions will be coarse grain in character, typically 100-150 particles (3 × 3 or 3 × 4 cells). It is expected that five to ten local distributions across the beam profile can be obtained. Comparison between summed test particle orbits and the coarse-grain simulation distribution will provide the check on the test particle technique.

III. OBJECTIVE

The investigation of the foilless diode generation of a 5- to 50-MeV electron beam and the vacuum adiabatic compression of such a beam is proposed. The objective is to determine the feasibility of obtaining a beam with a local energy density of 10^{19} to 10^{22} eV/cm^3, with sufficient microscopic quality to be applicable to

(1) submillimeter microwave generation,[1-9]

(2) inertially confined plasma x-ray source,[9-11] and

(3) collective ion acceleration.[12-18]

IV. PROPOSED RESEARCH PROGRAM

The proposed program is not intended to be a detailed design effort. Rather, a number of features of high-voltage foilless diode operation and vacuum adiabatic compression will be clarified, which can be ultimately incorporated into an experimental study. The investigation is split into two parts.

A. Foilless Diode in Cylindrical Coordinates

The first part of the study considers the basic aspects of a simple foilless diode in cylindrical coordinates, assuming spatial azimuthal symmetry. The proposed geometry of the diode is shown in Fig. 1. Four parameters are expected to be important in determining the beam quality and intensity:

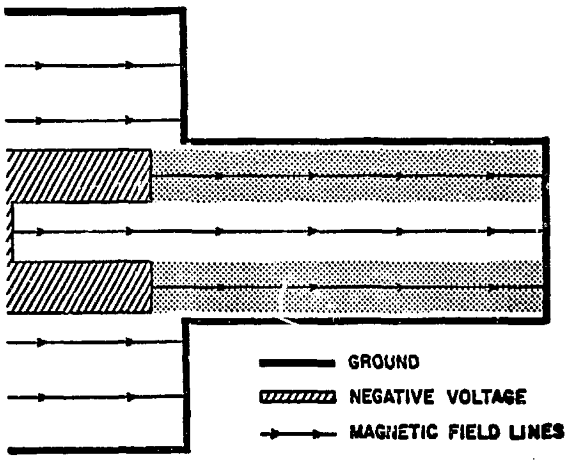

Fig. 1. Proposed geometry for part A (Cylindrical Coordinates).

(1) the relativistic factor

$$\gamma = (1 - \beta_z^2 - \beta_\theta^2)^{-1/2} \quad , \qquad (15)$$

(2) the effective diode gap spacing d through the ratio

$$I(d)/I^s \quad , \qquad (16)$$

(3) the diamagnetic and radially dependent parameter

$$\beta_\theta \gamma_o = 0.5(\omega_\perp/\omega_c)(a\omega_\perp/c)(1 - b^2/a^2) \quad , \tag{17}$$

and (4) the geometry factor

$$G = 1 - b^2/a^2 + 2\,\ell n(R/a) \quad . \tag{18}$$

It is planned to obtain a consistent set of simulations, which contain significant changes in beam quality as γ, I/I^s, $\beta_\theta\gamma$, and G are varied. It is not proposed to obtain simulations involving all combinations of the parameters. For example, since $\beta_\theta\gamma_o << 1$ can always be satisfied physically, the effect of increasing this parameter can be limited to the high-voltage case with only variations in I/I^s. Also, extensive variation in the geometry factor G, which depends primarily on the ratio b/a since $(R - a)/r << 1$, is not anticipated. Finally, a small number of simulations to investigate the effect of the emission temperature are planned.

To provide additional insight into the sensitivity of the beam quality on the various parameters, test particle orbit calculations will be carried out in conjunction with the simulations. In turn, the electric and magnetic field configuration for the test particle calculations will be guided by the simulations.

B. Foilless Diode and Vacuum Adiabatic Compression in Spherical Coordinates

The second part of the study considers the combination of high-voltage foilless operation and adiabatic compression. In addition to the four parameters associated with the diode, the effect of the fractional change in the compression ratio must be considered. If the beam quality is preserved during the adiabatic compression, the parameters I/I^s, G, and $\beta_\theta\gamma_o$ determined at the diode remain constant. The parameters chosen for the simulations will depend to a great extent on the results of the cylindrical diode studies, part A. The proposed geometry for part B is shown in Fig. 2.

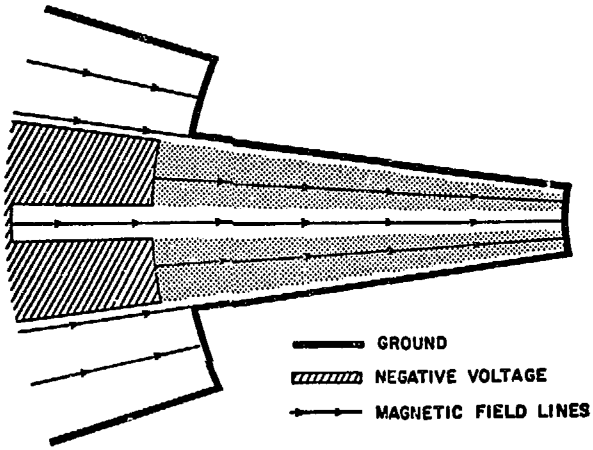

Fig. 2. Proposed geometry for part B (Spherical Coordinates).

A small number of simulations are planned to consider the magnitude of f, which can be tolerated for high-voltage beam compression. The primary aim of these simulations is to determine a practical upper bound for f.

It is expected that the primary effort will be to determine the trade-off in beam quality between diode current density and the compression ratio, for a fixed-beam energy density at the exit of the compression region.

V. WORK STATEMENT

Implement an electron emission alogrithm in the two-dimensional particle code CCUBE.

Study the basic aspects of high-and low-voltage foilless diode operation in cylindrical coordinates using CCUBE. Obtain a consistent set of simulations which contain significant changes in the beam quality as a function of the 1) ratio of the beam current to the space charge limiting current, 2) diamagnetic factor, and 3) geometry factor. It is not proposed to obtain simulations involving all combinations of the preceding parameters.

Solve the relativistic equations of motion using an electric and magnetic field configuration guided by the simulation effort.

Study the basic aspects of high-voltage foilless diode operation and vacuum adiabatic compression in spherical coordinates using CCUBE. Determine an upper bound on the fractional change in the external magnetic field strength over a Larmor orbit to insure adiabatic compression. Determine the trade-off in beam quality between current density at the diode and the adiabatic compression ratio for a fixed-beam energy density at the exit of the compression region.

VI. TERM

The work will be initiated on October 1, 1977, or upon receipt of authorization from the Department of Energy to proceed, whichever is later. The duration of the proposed study is one year. If authorization is not received by January 1, 1978, it may become necessary to modify this proposal.

VII. REPORTING

Results of the study will be reported as required by the U. S. Air Force Office of Scientific Research. If appropriate, the results of the study will also be reported in the scientific literature.

VIII. PERSONNEL

L. E. Thode of Group T-15 (LASL) will be the manager of the proposed study. He will have the general responsibility for the performance and reporting of the proposed work, and for liaison with the Air Force representatives as required. A major portion of the work will be performed by a LASL postdoctoral fellow under Thode's direction.

In addition to Thode, B. Godfrey, F. Faehl, B. Newberger, and R. Shanahan of Group T-15 (LASL) will act as technical consultants for the proposed study.

IX. COSTS

The costs to the Department of Energy for the performance of the proposed study are itemized in the following table.

TABLE I

COST FOR PROPOSED RESEARCH PROGRAM

Proposed starting date: October 1, 1977

Proposed ending date : October 1, 1978

Man-years	
Scientific	1
Other	0
Costs	
Salaries	$21 000
Indirect Costs	13 000
Materials and Services	4 000
Computer Services	19 000
Total	$57 000

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