LASER-GUIDING OF RELATIVISTIC ELECTRON BEAMS WITH APPLICATIONS TO FLASH X-RADIOGRAPHY*

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Abstract

The technique of guiding a relativistic electron beam by utilizing an ultraviolet-laser-ionized channel in low-pressure benzene has been demonstrated on an rf linear accelerator. Detailed measurements of the temporal behavior of the beam as it propagated a distance of 13.5 m were made as a function of laser channel parameters and accelerator conditions. Concepts and applications of this laser-guiding technique are presented as they relate to the possible improvement and simplification of the generation, transport, and focusing of relativistic electron beams used to create bremsstrahlung radiation for flash x-radiography.

Introduction

Guiding of relativistic electron beams by laser-ionized channels[1-3] and low-energy discharge channels[3,4] has been demonstrated over a wide range of currents, energies, and distances. Experiments have also demonstrated the feasibility of bending and redirecting electron beams with various combinations of magnets and ionized-channels.[3,5] We reported the first use of an ultraviolet-laser-ionized channel in benzene to guide multiple pulses from an rf accelerator.[6] In particular, two 5-ns, 750-A, 30-MeV pulses separated by 20 ns were transported a maximum distance of 13.5 m.

Relativistic electron beams are well suited for flash x-radiography due to the photon production via bremsstrahlung being well controlled by the selection of the electron beam energy, current, pulse length, angular distribution, and focused spot size. These parameters are all interactive both from the standpoint of the electron beam generator and the radiographic requirements; hence, an optimized tradeoff involving existing technologies, costs, size, and complexity must be made. The electron beam generators range from relatively simple, high-current pulsed diodes to the higher energy but lower current rf or induction type linear accelerators. The success and review of the laser-guiding experiments performed at Los Alamos with the Pulsed High-Energy Radiographic Machine Emitting X-rays (PHERMEX) electron-beam facility[7] indicate that the guiding of electron beams by ion channels may have an important application to future generation radiographic machines.

Radiographic Sources

This paper considers electron beam sources primarily used for flash x-radiography of materials explosively driven or impacted by projectiles. The beam energy is selected for maximum transmission through the object to be radiographed while minimizing the number of resultant scattered photons that degrade the contrast of the detected image. The pulse length must be short enough to "freeze" the object motion commensurate with the desired positional resolution. The detector is generally a multiple film stack whose exposure is controlled by the photon dose. Because the dose is a linear function of the beam charge and is proportional to the 2.8 power of the beam energy, a minimum current is determined. To first order, the size of the focused electron beam at the converter target linearly determines the spatial resolution for a fixed radiographic magnification (the ratio of the source-to-film-distance over the source-to-object distance). Collimators are generally used between the converter target and the object to control the cone angle of the photons as well as to reduce possible scattered photons coming from the electron beam source. The desired small (~3- to 5-mm-diam) spot at the converter target must also be stable to a fraction of this diameter to remain centered in the collimator.

There are also operational and logistical considerations for these specialized radiographic machines. These machines must employ extensive shielding from the blast, debris, etc.; they are essentially not moveable. Pulsed diode machines can readily produce high doses due to their characteristic high output current. Unfortunately, high current (greater than 25 kA) and low energy (less than 8 MeV) electron beams have large angular electron distributions that reduce the useful on-axis dose. Shielding of the unwanted radiation becomes difficult because of possible degradation of the direct-to-scattered signal of the film pack. Pulsed diode machines inherently have a low repetition rate due to the loss of the anode foil and post-shot cleanup of the cathode but are simple and inexpensive relative to linac-type accelerators. The linacs offer increased beam energy (a necessity for dense object radiography), smaller spot sizes with high on-axis dose, and repetition rates of several pulses per minute.

Los Alamos has proposed a new flash x-radiographic facility consisting of two electron beam sources oriented with respect to one another at 135° to provide two views with minimal cross-exposure of each film pack. The arrangement is shown in Fig. 1. The final focusing element, converter target, and associated collimators must be readily movable because variable magnification is an important requirement for one machine. An intriguing dual benefit of laser-guiding would be transport of the beam from the accelerator source through a long (5-10 m) drift tube as well as highly accurate final focus on the target. Because there would be no magnetic elements in such a scheme, alignment would be simple and essentially independent of the electron beam source. Magnification could be easily changed by adding or removing sections of drift tube. An effort to demonstrate the feasibility of this approach is being experimentally investigated using a newly designed 5-MeV, 10-kA, 45-ns, pulsed, foilless-diode machine.

Laser-Guiding Concepts

A KrF laser operating at 248 nm is directed into and partially ionizes benzene gas in the drift tube.

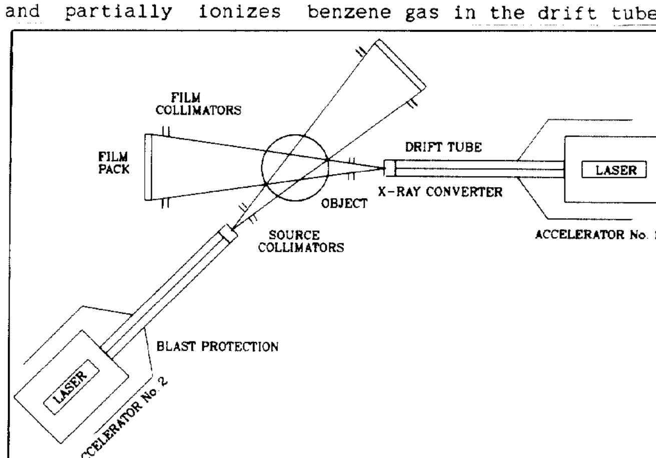

Fig. 1. Schematic representation of two electron beam generators arranged for dual-axis flash x-radiography.

*Work performed under the auspices of the U.S. Department of Energy by Los Alamos National Laboratory under W-7405-ENG-36.

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PAC 1987

An electron beam entering this plasma channel expels the plasma electrons, creating a positive path of ions that the main body of the electron beam will electrostatically track. Benzene gas pressure must be sufficiently low that it will neither inhibit the expulsion of plasma electrons nor allow self-ionization by the electron beam. Conversely, the gas pressure must be high enough given the available laser energy so that there will be enough ions in the channel for successful neutralization of the electron beam. The beam propagates with an equilibrium radius behind the beam head determined by the balance of the pinching self-magnetic field and the expansive forces due to finite beam emittance and the partially neutralized, self-radial electric field. If the equilibrium size attained by the electron beam is larger than the laser channel, phase-mix damping of transverse beam motion can occur at the expense of increased beam emittance.[1] This is not desirable for radiographic applications where small spot size and low divergence of the electrons at the converter target are necessary. Conversely, a laser channel larger than the beam equilibrium size has a harmonic nature; radial oscillations of the beam are not damped.

The laser-guiding experiments at PHERMEX indicated that greater than 95% of the beam current and charge can be transported over distances greater than 10 m by careful matching of the injected electron beam into a larger laser-ionized channel. Failure to match the electron beam to the channel at injection causes the electron beam to lose current until a new, effective neutralization and beam equilibrium are established. Propagation then occurs with little additional loss of current or charge. At neutralizations greater than unity (more initial plasma electrons in the channel than beam electrons), two-stream instability and loss of channel tracking were evident. The equilibrium radius attained by the beam was as predicted, and transverse motion of the beam centroid was about 20% of the beam diameter during the pulse. After all parameters were optimized, beam propagation was relatively insensitive to accelerator tuning, laser channel conditions, and several degrees of misalignment between the injected beam and channel axes.

Reference [8] shows the derivation of a number of useful equations describing the transport of electron beams in ionized benzene channels for various combinations of flat and gaussian profiles. The simplest case relevant to the present application is the solution for the equilibrium radius of an electron beam propagating within a larger radius laser channel under the conditions that the respective charge distributions are flat, collisional ionization of the benzene by the electron beam is negligible, and $\gamma \gg 1$. Equation (36) of Ref. [8] is

$$R_b = \frac{R_c}{R_b}\,\frac{E_N}{\gamma}\left(\frac{I_A}{I_b f}\right)^{1/2}, \quad R_c \geq R_b \quad , \qquad (1)$$

where R_b and R_c are the RMS radii of the electron beam and laser channels, E_N is the RMS normalized emittance, I_b is the beam current, $I_A \approx 17{,}000\ \beta\gamma$ is the Alfven current, and $f = N_i/N_b$ is the neutralization fraction expressed as the ratio of channel ion line density to electron beam line density. The beam may need to propagate several betatron wavelengths to become stabilized at this equilibrium radius; the betatron wavelength λ_β from Eq. (25) of Ref. [8] is given by

$$\lambda_\beta = 2\pi\, R_c \left(\frac{I_A}{I_b f}\right)^{1/2} . \qquad (2)$$

Using Eq. (1) and the conservation of normalized emittance, the angular RMS divergence, θ, at the converter target expressed as a radian angle is

$$\theta = \frac{R_b}{R_c}\left(\frac{I_b f}{I_A}\right)^{1/2} \quad \text{for } \theta \ll 1 \ . \qquad (3)$$

A figure of merit for radiographic machines is the dose divided by the source area under the assumption that the beam energy has been selected. Using the expressions for R_b, θ, and dose scaling, it can be shown that an injector or pulsed diode having a large ratio of beam current to emittance is desired. Because the on-axis dose is decreased by increasing angular divergence of the electrons at the converter, Eq. (3) indicates f should be low; however, f near unity is also necessary for channel tracking and small spot size.

A Laser-Guiding Application

A baseline example illustrating the numerical feasibility of combining laser guiding with an electron beam source at an energy of 8 MeV is now presented. The electron beam is created by a large area diode (> 10-cm diam) similar to the velvet injector used on Lawrence Livermore National Laboratory's Advanced Test Accelerator (ATA), which can deliver 8 kA with an emittance E_N of 0.25 rad-cm at a voltage of 2.5 MV.[9] The laser is directed from behind and through a hole in the cathode down the drift tube toward the converter target. The electron beam is focused onto the laser channel via a transport magnet external to the diode region. Benzene gas injected at the converter region fills the drift tube to an aperture downstream of the transport magnet, creating a differential benzene pressure profile between the aperture and the diode region. Careful matching of the beam from the magnet focus region onto the laser channel must be accomplished to limit emittance growth of the beam from the diode, a feature that has been demonstrated on ATA.[2] The laser channel has been selected to be larger than the electron beam to facilitate beam matching and capture at injection as well as to reduce the required benzene pressure and laser energy as discussed below. The nominal parameters for the present example are:

$\gamma = 16$, ($V \approx 8$ MeV), $\theta \sim 5°$, $f \sim 0.5$,

$R_b = (5\text{-mm diam})/2$, $R_c/R_b = 1.75$, $E_N \approx 0.25$ rad-cm

Equation (1) yields a minimum beam current of $I_b = 6500$ A to achieve the desired spot size with an angular divergence of $\theta \sim 4°$, from Eq. (3), for electrons incident on the converter. A higher beam energy (available from induction linacs) would allow for some emittance growth and achieve the same or smaller spot size with lower beam currents.

The laser requirements for the above ionized channel can be estimated by the photoionization model[10], with the restriction that the laser intensity must be less than 5 MW/cm^2 to avoid significant fragmentation of benzene.[11] Equation (10) of Ref. [7] gives the fractional ionization, f_1, of benzene versus laser intensity, I, for a nominal 25-ns laser pulse as

$$f_1 = 6.6 \times 10^{-4} I^2,\ N_i = f_1 n_g PA,\ N_b = I_b/\beta ce, \text{ and}$$

$$f = \frac{N_i}{N_b} \approx 100\ I^2 \frac{AP}{I_b} \ , \qquad (4)$$

where A is the laser cross-sectional area in cm^2, P the benzene pressure in μm, n_g the benzene gas ion-density (3.22×10^{13}/cm^3-μm at 300°K), and I the laser intensity in MW/cm^2.

Equation (4), with $f = 0.5$, $I_b = 6.5$ kA, $I = 5$ MW/cm^2, and $A = 1.2$ cm^2 ($R_c = 0.44$-cm RMS), gives the required benzene pressure of ~1.1 μm with a laser energy of 150 mJ. This energy is well within the

750-mJ capability of a Lambda Physik EMG-150ES KrF excimer laser. From Eqs. (8) and (9) of Ref. [8], an estimate of the ratio of the electron beam collisionally induced ion density to the beam density can be obtained. This ratio is the neutralization, f, at the end of the beam pulse in the absence of any laser ionization and is given by

$$f = (T\,P)/(7.52\,T_N) \quad , \qquad (5)$$

where T is the beam pulse length and T_N is about 30 ns for beams of energy 5-15 MeV. This equation is consistent with the results of Ref. [6] where self-induced beam ionization was observed with 10 μm of benzene pressure and an effective pulse width of 10 ns. For a beam pulse length of 75 ns and the determined benzene pressure of 1.1 μm, Eq. (5) gives a value of $f = 0.36$. Because the initial laser ionization is set at $f \sim 0.5$ and the beam experiences only an additional average $f = 0.36/2$, the effect of this collisional beam ionization should not be detrimental to transport and, in fact, will reduce the beam spot size toward the end of the beam pulse.

The drift tube must be at least several betatron wavelengths long to allow the beam to attain a stable equilibrium radius before impinging on the converter. Equation (2) gives a $\lambda_\beta \sim 25$ cm that is easily satisfied by the desire to use a 5- to 10-m drift tube. Although a simplified example has been presented, Ref. [8] provides the necessary expressions to more accurately model the parameters affecting the laser ionized benzene transport process.

An experimental effort is underway to construct a prototype of a pulsed, foilless-diode machine employing laser guiding for transport and focusing. The design utilizes a velvet cloth cathode similar to the low emittance injector at ATA except that a higher voltage (5 MV) is applied across the anode-cathode gap. The voltage is derived from a pulsed transmission line source utilizing a novel radial insulator. Computer simulations using a 2-D electrodynamic, self-consistent, particle-in-cell, field code are shown in Fig. 2. The diode voltage is 5 MV, and a beam current of 5.4 kA is generated with a normalized RMS emittance of 0.15 rad-cm from an 11-cm-diam emission surface. The re-entrant anode will contain a magnet for focusing and transporting the beam onto the laser channel.

The experimental program is intended to demonstrate the successful generation of low emittance 5- to 10-kA beams with beam transport and focusing utilizing an ion channel. A theoretical effort will provide the direction for the ongoing experiments and the scaling laws for machines of greater energy. The scalability of the prototype pulsed voltage source will be addressed as it relates to a simple radiographic machine or to an injector for a series of induction linac modules.

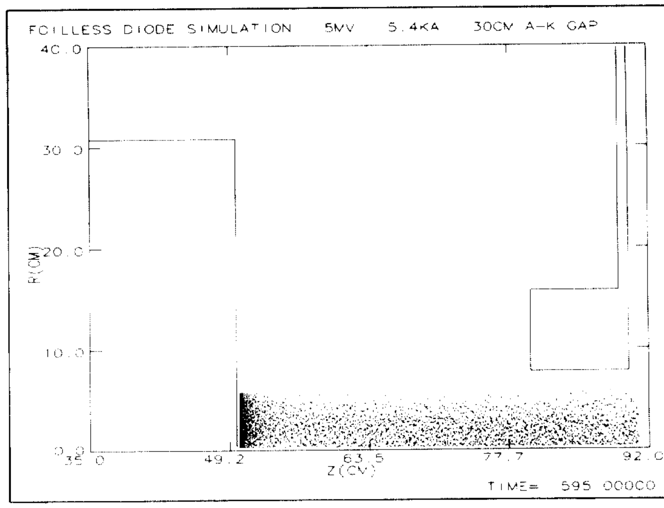

Fig. 2. Diode simulation of the generation of a 5-MeV, low-emittance, 5.4-kA beam.

Acknowledgments

The author would like to thank J. M. Mack for the diode simulations; R. B. Miller and J. W. Poukey of Sandia National Laboratories for their many suggestions; and B. B. Godfrey of Mission Research Corporation/Albuquerque for his continued technical support.

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