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H. A. Koehler, B. A. Jacoby, and M. Nelson

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Time-resolved tomographic images of a relativistic electron beam*

H. A. Koehler and B. A. Jacoby

Lawrence Livermore National Laboratory, University of California
P.O. Box 608, Livermore, California 94550

M. Nelson

EG&G, Inc., Santa Barbara Operations
130 Robin Hill Road, Goleta, California 93117

Abstract

We obtained a sequential series of time-resolved tomographic two-dimensional images of a 4.5-MeV, 6-kA, 30-ns electron beam. Three linear fiber-optic arrays of 30 or 60 fibers each were positioned around the beam axis at 0° , 61° , and 117° . The beam interacting with nitrogen at 20 Torr emitted light that was focused onto the fiber arrays and transmitted to a streak camera where the data were recorded on film. The film was digitized, and two-dimensional images were reconstructed using the maximum entropy tomographic technique. These images were then combined to produce an ultra-high-speed movie of the electron-beam pulse.

Introduction

We have developed a diagnostic system using optical-fiber links to monitor the propagation of relativistic electron beams in the Experimental Test Accelerator (ETA) at Lawrence Livermore National Laboratory. Our diagnostic system uses a three-view tomographic imaging scheme to observe luminescence produced by electron-beam interactions with nitrogen. Light emissions are focused onto linear arrays of optical fibers and transmitted to a streak camera where they are recorded by a solid state camera on photographic film. The data are then analyzed by computer to reconstruct a two-dimensional tomographic image from the three one-dimensional images.

By using a streak camera to record the data,¹ we were able to reconstruct a sequential series of images of the electron beam having 1-ns time resolution. Using these images, we then produced an ultra-high-speed movie of a relativistic electron-beam pulse from the ETA passing through nitrogen gas at 20 Torr.

The use of optical fibers to transmit the signals from the beam to the recording room allowed not only great flexibility in our experimental arrangements, but it enabled us to place the sensitive recording instrumentation away from the large background radiation associated with the 4.5-MeV, 6-kA ETA electron-beam pulse.

Experiment

The major components of the experimental arrangement were three linear arrays of optical fibers mounted in three sampling heads and a streak camera recording system.

Sampling heads

Three sampling heads were positioned at 0° , 61° , and 117° (0° being the top position) in a plane perpendicular to the 6-in.-diameter plastic drift tube of the ETA (Fig. 1). The mounting bracket was placed 2 ft from the entrance foil separating the accelerator section from the drift tube section and 6 ft from the beam dump. The distance of the sampling heads from the tube axis was about 3 ft. Each head observed a one-dimensional region about 4.3 in. long and oriented perpendicular to the drift tube, which corresponds to spatially resolved regions 0.07 and 0.14 in. long per fiber for the 60- and 30-fiber linear arrays, respectively.

Standard camera lenses (40-mm focal length, $f/1.8$) were used to focus the electron-beam-induced emission from the nitrogen gas onto the linear array of optical fibers. Indications are that the emission occurred at 391 nm. (At this wavelength, the lens transmission was about 0.5.)

Optical fibers

The optical fibers used in our optical electron-beam diagnostic system were selected on the basis of three criteria: 1) low attenuation in the near-UV wavelength region of the nitrogen emission lines, 2) high bandwidth for undistorted transmission of sub-nanosecond signals, and 3) minimum susceptibility to electron, gamma-, and x-ray damage. We evaluated a number of optical fiber types on the basis of these three properties (Table 1).² Test fibers were 50-ft lengths appropriate to ETA optical diagnostic systems.

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Figure 1. Configuration of the diagnostic system to monitor the propagation of relativistic electron beams in the Experimental Test Accelerator. The three sampling heads were positioned at 0°, 61°, and 117° in a plane perpendicular to the drift tube. Each head observed a one-dimensional region perpendicular to the drift tube.

Table 1. Bandwidth, attenuation, and radiation responses of selected 50-ft-long fibers at UV wavelengths.

Fiber	Core/clad diameters (μm)	Type ^a	Numerical aperture ^b	Impulse response ^c (ps)	Attenuation ^d (dB)	Radiation response ^e (dB/cm · krad)	Comments
QPC QSF-AS	163/200	G-G	0.2	460	4.8	0.007	1200 ppm OH
QPC QSF-AS	135/200	G-G	0.2	560	16.9	—	1200 ppm OH
QPC QSF-UV	200/380	PCS	0.4	600	2.4	0.008	—
QPC QSF-UV	400/550	PCS	0.4	620	2.4	—	—
QPC QSF-UV	600/750	PCS	0.4	680	2.2	—	—
QPC QSF-A	200/380	PCS	0.4	600	2.6	0.008	—
ITT PS-05	125/300	PCS	0.3	900	2.9	—	—
ITT T-1210	—	PCS	—	540	11.8	—	—
Dupont Pifax S-120	200/600	PCS	0.42	1400	3.8	—	—
Times	—	PCS	—	460	8.7	—	—

^a G-G is glass-on-glass; PCS is plastic-clad silica.

^b Numerical apertures were not measured, and the values given are those supplied by the manufacturer.

^c Measured response to a 300-ps full width at half-maximum 337-nm laser pulse. The system response was 460 ps.

^d Attenuation was measured at 340 nm.

^e Radiation response was measured at 350 nm.

Attenuation measurements were made at 340 nm using a white light source, a narrowband filter, and a radiometer. The standard measure-and-cutback technique was used.

Bandwidth evaluations were made at 337 nm using a nitrogen laser emitting 300-ps pulses and a vacuum photodiode/oscilloscope recording system with a 400-ps impulse response.

Radiation-induced attenuation was measured with a Febetron Model 706. A coil of the optical fiber was arranged so that about 2 cm of each loop was positioned in the beam path. The loops were large enough so that the 2-cm sections were separated by a 10-ns optical transit time. When the fiber loops were irradiated, the Cerenkov pulses (one generated in each loop and spaced 10 ns apart) were observed using a photomultiplier/monochromator. Figure 2 shows the experimental arrangement. The Cerenkov pulse generated in the first loop was attenuated the most because it passed through irradiated sections of the subsequent loops of the fiber. The pulse generated in the last loop served as reference for the other pulses (since it did not pass through irradiated glass). The radiation-induced attenuation was determined by comparing the relative attenuation of the pulses. The dose measurement was made using radiochromic film.

Table 1 also lists the core diameter/cladding diameter ratios, which establish the effective light collection area of the fiber and affect the size of a resolution element in the fiber array configuration, and the numerical apertures (NA) of the fibers. The NA values were not measured, and the values listed are those of the manufacturer.

On the basis of these measurements, two types of fibers were selected: QSF-AS and QSF-UV. The QSF-AS fiber has 4.8-dB attenuation at 340 nm, <450-ps impulse response, 0.007-dB/cm·krad radiation response at 350 nm, core/cladding diameters of 163 and 200 μm , respectively, and a nominal NA of 0.2. The QSF-UV fiber has a 2.4-dB attenuation at 340 nm, 600-ps impulse response, core/cladding diameters of 200 and 380 μm , respectively, and a nominal NA of 0.4. The QSF-AS fibers were arranged into one 12-mm-long linear array of 60 fibers, and the QSF-UV fibers were arranged into two 12-mm-long linear arrays of 30 fibers each. Both ends of each linear array were mounted into plastic blocks.

Streak camera recording system

A streak camera recording system was used to record time-resolved beam profiles. The three linear fiber arrays were aligned perpendicular to the streak direction and focused with 3:1 reduction onto the slit area of a 675 Hadland streak camera. The microchannel plate intensifier output of the streak camera was recorded with a Reticon 100 $\times$ 100 photodiode array and stored on a floppy disk or, when greater resolution was desired, the intensifier output was recorded on Kodak 2484 film. When film was used, the spatial resolution was 1.6 in. of the beam/mm of film, and the temporal resolution was 3.6 ns/mm of film. The streak camera photocathode with 7 line pair/mm limited the system's resolution. The corresponding resolution was about 45 elements per fiber optic array (using a 12-mm-wide slit).

Figure 2. Experimental arrangement used to measure the susceptibility of optical fibers to radiation-induced attenuation. Cerenkov pulses generated by electron-beam irradiation of sections of the fiber passed through similarly irradiated sections further down the fiber. The extent of the fiber's attenuation was determined by comparing the relative attenuation of the pulses. Radiochromic film was used to measure the radiation dose.

The beam profiles recorded on film by each fiber optic array were digitized for computer processing. Digitization was done using a 20 μm -wide slit to give 50 digitized points/mm of film. The resulting image contained 1151 rows and 601 columns, which corresponds to 25 digitized points/fiber (for a 60-fiber array).

Tomographic reconstruction

The data were reconstructed using the maximum-entropy method developed by G. Muerbo.³ This method uses an algorithm that can be described as follows: the projection of a two-dimensional object onto a line rotated an angle θ_i away from the x -axis is written as

$$p(\theta_i, s) = p_i(s) = \int dt f(x, y), \quad (1)$$

where s is the variable along the line and t is a variable perpendicular to s (Fig. 3). The variables (x, y) and (s, t) are related through

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} \cos \theta_i & \sin \theta_i \\ \sin \theta_i & \cos \theta_i \end{pmatrix} \begin{pmatrix} s \\ t \end{pmatrix} \quad (2)$$

and

$$\begin{pmatrix} s \\ t \end{pmatrix} = \begin{pmatrix} \cos \theta_i & \sin \theta_i \\ -\sin \theta_i & \cos \theta_i \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}. \quad (3)$$

The entropy of the image is defined as^{1,3}

$$H(f) = - \int dx \int dy f(x, y) \ln f(x, y). \quad (4)$$

The algorithm attempts to maximize Eq. (4), subject to the constraints imposed by Eq. (1). This can be done through the use of La Grange multipliers. Thus the following equation needs to be maximized:

$$\Psi(f, \lambda) = H(f) + \sum_i \int ds [p_i(s) - \int dt f(x, y) \lambda_i(s)]. \quad (5)$$

Taking the variation of Ψ with respect to λ_i reproduces the constraints of Eq. (1). Taking the variation of Ψ with respect to f gives

$$\delta \Psi = \left\{ - \int dx \int dy [1 + \ln f] - \sum_i \int ds dt \lambda_i(s) \right\} \delta f = 0 \quad (6)$$

or

$$0 = \int dx \int dy \left[1 + \ln f + \sum_i \lambda_i (x \cos \theta_i + y \sin \theta_i) \right], \quad (7)$$

which reduces to

$$f = e^{-1} \exp \left[- \sum_i \lambda_i (x \cos \theta_i + y \sin \theta_i) \right]. \quad (8)$$

This can be redefined as

$$f(x, y) = \prod_i h_i (x \cos \theta_i + y \sin \theta_i). \quad (9)$$

Returning now to Eq. (1) and substituting in Eq. (9) produces

$$p_i(s) = \int dt \prod_j h_j (x \cos \theta_j + y \sin \theta_j). \quad (10)$$

and using Eq. (2) gives

$$p_i(s) = \int dt \prod_j h_j [s \cos(\theta_j - \theta_i) + t \sin(\theta_j - \theta_i)]. \quad (11)$$

Let $\theta = \theta_k$. Eq. (11) can be rewritten as

$$p_k(s) = h_k(s) \left[dt \int_{-\infty}^{\infty} h_k(s) \cos(\theta_i - \theta_k) + t \sin(\theta_i - \theta_k) \right] \quad (12)$$

Equation (12) forms the basis of the maximum entropy routine. Each $h_k(s)$ can now be updated using the measured projection data, $p_k(s)$, and the old values of h_k as

$$h_k(s) = p_k(s) / \left[dt \int_{-\infty}^{\infty} h_k(s) \cos(\theta_i - \theta_k) + t \sin(\theta_i - \theta_k) \right]. \quad (13)$$

The values of $h_k(s)$ that are so determined are then used in Eq. (9) to reconstruct the image.

Data manipulations before reconstructing

While Eqs. (9) and (13) form the backbone of the maximum entropy reconstruction, two aspects of the projection data must be treated before the data is handed over the tomographic portion of the code. The first such aspect is conservation of energy. The "energy" in the image is given by

$$I = \int dx \int dy f(x, y). \quad (14)$$

This energy should also be the same as that contained in any projection or

$$I = \int ds p_k(s). \quad (15)$$

This can be easily seen as a consequence of Eq. (1) or

$$I = \int ds p_k(s) = \int ds \int dt f(x, y) = \int dx \int dy f(x, y) \quad (16)$$

since both integrals are over all space. Thus, the code finds I using Eq. (15) on the first set of projection data and then normalizes each subsequent set of projection data so that it too produces the same value of I .

The second aspect is that the back projection of the separate centers of mass of each set of projection data needs to meet at the center of mass (cm) of the image (Fig. 4). That this is indeed the case can be seen from the definition of the center of mass of a projection

$$S_{cm_i} = \frac{1}{I} \int ds s p_i(t) = \frac{1}{I} \int ds s \int dt f(x, y). \quad (17)$$

Figure 3. Relationship of reference coordinate system (x, y) to rotated coordinate system (s, t). The (s, t) system was rotated by the projection angle θ_k , which, in this experiment, was 0° , 61° , or 117° .

Figure 4. Back projection of the separate centers of mass of each set of projection data, which must meet at the center of mass of the image.

Using Eq. (3) gives

$$S_{cm} = \frac{1}{I} \int d\gamma \int du (X \cos \theta_k + u \sin \theta_k) f(X, u) \quad (18)$$

$$S_{cm} = \frac{\cos \theta_k}{I} \int d\gamma \int du (X) f(X, u) + \frac{\sin \theta_k}{I} \int d\gamma \int du (u) f(X, u) \quad (19)$$

and finally

$$S_{cm} = X_{cm} \cos \theta_k + Y_{cm} \sin \theta_k \quad (20)$$

This is the fact that the projection of the center of mass of the image on the angle θ_k is the center of mass of the projection. Thus, the code ensures that this occurs by calculating each S_{cm} and then forcing the various back projections to meet at one point. This one point or image center of mass is found by using a least-squares fit to Eq. (14) to determine X_{cm} and Y_{cm} . A new S_{cm} is then calculated from Eq. (14), and the projection data is slid left or right according to the offset between new S_{cm} and the originally calculated S_{cm} .

Results

Figure 5 shows contour plots of three digitized beam profiles from a film recording of a 4.5-MeV, 6-kA, 30-ns FTA electron-beam pulse through nitrogen gas at 20 Torr. The plots show that the beam wandered off the drift-tube axis during the 55-ns recording time. This motion was very clear in a movie of 70 reconstructed images, recorded during 55 ns. (This off-axis propagation was also observed by two wall-current monitors placed in front and behind the tomographic arrangement along the drift tube.)

The raw data file shown in Fig. 5 was reconstructed as follows. First, data in the y direction below 28.8 ns and above 79.2 ns were ignored, thus producing a new file of 701 rows and 596 columns. Second, 70 time cuts were reconstructed to form a 70-frame movie showing the evolution of the electron beam. To produce these 70 images, the file was reduced by averaging 10 rows to produce one row and averaging two columns to produce one column, thus forming a smaller file containing 70 rows and 298 columns. Third, each file was processed through the tomographic reconstruction to produce the sequence of contour images and pseudo three-dimensional images shown in Fig. 6.

Figure 5. Contour plots of three digitized beam profiles from a film recording of a 4.5-MeV, 6-kA, 30-ns FTA electron-beam pulse through nitrogen gas at 20 Torr. The plots show that the beam wandered off the drift-tube axis during the 55-ns recording time. The maximum region that the fibers could record was 4.3 in.

Figure 6. Sequence of contour images and pseudo three-dimensional images tomographically reconstructed from the data shown in Fig. 5.

Conclusions

We successfully tracked the position and intensity of a relativistic electron beam from the FFA. The beam was visualized by passing it through nitrogen, the emitted light was focused onto the fiber arrays, transmitted to a streak camera, and recorded on film. The film was digitized, two-dimensional images were reconstructed using the maximum-entropy tomographic technique, and these images were combined to produce an ultra-high-speed movie of the electron-beam pulse.

The use of optical fibers allowed the recording instruments to be placed away from the large background radiation associated with the electron beam.

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