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AUTHOR(S): R. B. Feldman
A. H. Lumpkin
D. W. Rule
R. B. Fiorito

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DEVELOPMENTS IN ON-LINE, ELECTRON-BEAM EMITTANCE MEASUREMENTS USING OPTICAL TRANSITION RADIATION TECHNIQUES*

R. B. FELDMAN and A. H. LUMPKIN

Los Alamos National Laboratory
Los Alamos, New Mexico 87545, USA

D. W. RULE and R. B. FIORITO

Naval Surface Warfare Center
Silver Spring, Maryland USA

Abstract

We have developed image analysis software to facilitate the analysis of optical transition radiation (OTR) patterns generated by the electron beam from the Los Alamos free-electron laser facility. The software can be used for beam alignment, beam profile and angular divergence measurements, and the programs run on an IBM AT microcomputer. The programs and their use are described and some results shown.

Introduction

An important aspect of optimizing the performance of a free-electron laser (FEL) is ensuring the spatial and temporal overlap of the electron beam and optical beam in the wiggler. Generally, the spatial overlap issue is characterized by the requirement that the emittance of the electron beam be small enough that the beam size matches the optical mode. Thus, the on-line monitoring of electron beam emittance can facilitate the optimization of the FEL performance and provide critical input data for FEL simulation programs. We are in the process of developing such a capability on the Los Alamos FEL, using gated, intensified television cameras to give

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input to the data acquisition system. We simultaneously record information on the beam spot waist size and divergence of a single macropulse (or a few micropulses) generated by optical transition radiation (OTR). The software we have developed uses a set of medium level routines from ITEX, written in C. We have developed a set of menu-driven routines to perform the functions we will describe below.

We will discuss in this paper OTR, the IBM AT clone and the associated computer hardware, and the software aspects of our project. We will also show results.

Optical Transition Radiation

Optical transition radiation¹ occurs when an electron crosses a boundary between materials of different dielectric constants. Notice in fig. 1 the lobes that result when the e-beam hits the boundary of a single foil. The upper left pattern shows the OTR radiation from a single interface with the e-beam at normal incidence. It is useful, however, to make observations at right angles to the e-beam. The upper right portion shows the OTR radiation patterns from that same interface, when it is at an angle to the beam. In our experiments, the foil is oriented at 45° to the electron beam and we can observe the radiation at 90° to the beam. As a comparison, the lower pattern is that made by Cherenkov radiation incident on a fused silica screen. Its cone angle of $\sim 40^\circ$ is much larger than the OTR cone for $\gamma = 40$.

Interference fringe patterns are obtained by using two parallel foils in tandem, also oriented at 45° . The interference of the light emitted from the two foils produces fringes that are more sensitive to beam divergence than the pattern from a single foil, as is shown in fig. 2. The characteristic pattern drawn below is of a horizontal cut across the minimum of the interferogram pattern. The separation of the fringes is a

measure of the electron-beam energy, and the height-to-peak ratio is a measure of the divergence of the beam.

The layout of the Los Alamos measurement system is shown in fig. 3.² The light from the OTR screen is split and goes to two intensified CID cameras. One camera is focused onto the OTR foil and displays the beam spot. The other is focused at infinity and displays the angular distribution of the light and, hence, of the electron beam.

Computer Hardware

The hardware consists of an IBM AT clone, Imaging Technology's (ITEX) 1024×512 ($\times 12$ bit) pixel frame-grabber and its display, a Sony 512×512 monitor. A polaroid camera is attached to the Sony monitor, and a Tektronix hard copier is connected to the computer monitor.

Fig. 4 is a schematic of the computer hardware. The freeze frames hold the images for about a half-second from each of the two CID cameras for each shot of the laser, which occurs at a 1-Hz repetition rate. Under the control of the Everex JS-286 (IBM AT clone), Imaging Technology's fg-100-at/2 frame-grabber is able to grab the image at near television rates and display it on the Sony monitor. The use of the extra 4 Mbyte memory permits a ram disk for faster archiving; the Bernoulli Box II, with its two 21-Mbyte removable disks, allows an infinite amount of storage. The PC mouse allows easy input of the point or area under consideration.

The system was limited by storage of the image files, which takes both space and time. The data is now stored as 8-bit intensity files, using 1/8 Mbyte each where before, using 12-bit images, each file used 1/4 Mbyte. It was limited by time of storage onto the Bernoulli disk; we have shortened the time by using a ram disk and copying onto the Bernoulli floppy. The system could be improved by the use of a

frame-grabber with four 512×512 quadrants, 1024×1024 pixels in all, in a faster machine also with a ram disk. The use of the Bernoulli Box improved the system immeasurably, as it was no longer limited by the 40 Mbytes of hard disk storage. The cost for microcomputer architecture is much less than for minicomputer architecture. The cost of the computer with burnt-in frame-grabber and color image display monitor was \$10k, that of the Bernoulli Box under \$2k.

Computer Software

The data acquisition programs described below can process data and display the results in the real time of the experiment, except for archival storage. Fig. 5 is a schematic of the video data acquisition software. It consists of three main routines: XHAIRS, REALTIME, and ONLINE.

XHAIRS is an on-line pointing routine that, at about half television rates, snaps an image and displays it in pseudocolor (intensity contours) with movable crosshairs superimposed. In practice, it is used routinely to center an alignment laser signal on the angular distribution and beam spot cameras. We then can align the e-beam on the same laser axes. The color tables can be changed and the crosshairs can be moved. Fig. 6 is an illustration of XHAIRS in use.

REALTIME is an on-line analysis routine. It allows the snapping of a camera image and a camera background, which could be either from the OTR camera or from an electron spectrometer camera. One selects with a mouse a specific point on the image. Then, at a carriage return, REALTIME generates a background-subtracted intensity profile of the image taken vertically and horizontally through the selected point. REALTIME is designed to run at the same rate as the experiment. REALTIME allows observation of beam profiles and/or energy spread "on the fly."

ONLINE, fig. 5c, is a routine that adds to REALTIME numerical operations and archival storage and retrieval of images or sections of images. A full page of 8-bit-intensity data takes 8 seconds to store on a ram disk; the file can then be copied to the appropriate Bernoulli diskette for permanent storage. The program allows two-dimensional integration and some image processing. It also plots and archives ASCII files of the horizontal and vertical profiles or profiles taken at an angle. Because of the added features, it runs more slowly than the experiment.

The application of XHAIRS is illustrated in fig. 6. The routine sees daily use in the laser alignment. The figure to the left shows the use of XHAIRS to align the OTR cameras with the HeNe alignment laser. The figure to the right shows the use of XHAIRS to align the e-beam using the OTR signal. These figures illustrate that, in a single shot at the same position, XHAIRS can be used with the two OTR cameras. One then measures simultaneously the position and the direction of the e-beam at the same point.

Fig. 7 illustrates the use of ONLINE with single-foil OTR. On the top left is an image, intensity bitcolored, from the angular distribution camera in a one-foil experiment. Notice the characteristic "cat's eyes" shape of the image. Top right is the corresponding image of the e-beam focused on the OTR foil. It is at an x waist and is therefore narrow in the horizontal direction. Below each image is an intensity profile: one from the angular distribution camera taken through its minimum and one from the beam spot camera taken through its maximum. Both are from raw, unsmoothed data.

The radiation from the OTR foil is radially polarized and appears cylindrically symmetric if there is no polarizer, but a polarizer picks out a preferred plane. In both figs. 7 and 8, a horizontal polarizer was used.

The use of ONLINE with double-foil OTR is shown in fig. 8. The upper left section shows the polarized two-dimensional interferogram from the angular

distribution camera, intensity bitcolored. In the upper right is the beam spot of the same shot, focused on the front of the second foil. Below each is its profile, the interferogram taken through the point of minimum intensity, the beam spot taken through the point of maximum intensity.

Finally, fig. 9 shows the results of comparisons between theory³ and experiment of the angular distributions for both single and double foils. In the theory, beam energy and divergence were adjusted to give the best fit. The theoretical interferogram calculating routine illustrates the theoretical profiles of the normalized intensity of the light from the OTR foil(s) in the camera, which is focused at infinity. The two-foil calculation includes energy spread, the single-foil calculation does not.

The upper pattern and comparison are for the OTR using a single-foil, the lower interferogram is the fit to a two-foil experiment. The angular spacing between the two peaks is inversely proportional to the energy of the e-beam, and the contrast between the peaks and the valley is a measure of the e-beam divergence. The fit is quite good.

The lower figure is the calculated pattern and experimental fit from a double foil. The fringe contrast is more sensitive to e-beam divergence than the contrast in the single-foil experiment. The peak-to-valley ratio is dependent upon the divergence, the fringe spacing is proportional to the energy. The fit is not as good as the upper pattern, but the fringe spacing and the peak-to-valley ratio fit is good. We are modifying the REALTIME and the ONLINE software to include the display of the measured profile and several profiles with different divergence.

Conclusions

We have developed hardware and software for analyzing optical transition radiation for electron-beam diagnostics. The hardware is simple and inexpensive. The menu-driven software is convenient to use and modify. It performs the necessary image processing and numerical analysis in the real time of the Los Alamos free-electron laser.

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Figure Captions

Fig. 1. Optical transition radiation patterns, single foil.

Fig. 2. Optical transition radiation patterns, double foil.

Fig. 3. Schematic of OTR experiment (Los Alamos).

Fig. 4. Image-processing hardware.

Fig. 5. Video data acquisition software.

Fig. 6. The code XHAIRS in use.

Fig. 7. Single-foil OTR data and single-line cut.

Fig. 8. Double-foil OTR data and single-line cut.

Fig. 9. Comparison between theory and observation:

Single-foil divergence results and double-foil divergence results.

OPTICAL TRANSITION RADIATION PATTERNS SINGLE FOIL

CHERENKOV RADIATION PATTERN ($\theta \sim 46^\circ$)

OPTICAL TRANSITION RADIATION PATTERNS DOUBLE FOIL

PARALLEL FOILS

Schematic of OTR Experiment (Los Alamos)

IMAGE PROCESSING HARDWARE

VIDEO DATA ACQUISITION SOFTWARE

**XHAIRS.....AN ONLINE ALIGNMENT ROUTINE:
SUPERIMPOSES CROSSHAIRS
ON AN IMAGE CAPTURED
FROM THE FREEZE FRAME.
USED FOR BEAM ALIGNMENT
REPETITION RATE: 15 HZ**

**REALTIME.....AN ONLINE, REALTIME
ANALYSIS ROUTINE.
SNAPS IMAGE AND BACKGROUND
ALLOWS CHOICE OF POINT AT
WHICH X AND Y INTENSITY
PROFILES ARE TAKEN. AND
PLOTS EACH PROFILE
(BACKGROUND SUBTRACTED).
MAXIMA AND HALFWIDTHS
ARE INDICATED.
REPETITION RATE: 1 HZ.**

**ONLINE.....1-D OR 2-D PROFILE ANALYSIS
WITH IMAGE FILE ARCHIVING
& RETRIEVAL, LINEAR
INTENSITY FILE ARCHIVING,
(HORIZONTAL & VERTICAL
OR AT A DEFINED ANGLE)
2-D IMAGE PROCESSING.
CAN BE USED ON OR OFF LINE.**

**ITEX-100 software is used for
the low level routines.**

Beam Spot Camera

OTR Camera

Fig 6a

Fig 6b

Single Foil OTR Data

ANGULAR DISTRIBUTION
(HORIZONTAL POLARIZATION)

BEAM SPOT (x-waist)

Fig 7

Double Foil OTR Data

ANGULAR DISTRIBUTION
(HORIZONTAL POLARIZATION)

BEAM SPOT (x-waist)

Fig 8

SINGLE FOIL DIVERGENCE RESULTS
20 MeV, 4.9 mrad, x-waist,

DOUBLE FOIL DIVERGENCE RESULTS
horiz. waist: horiz. - vert. polariz., 20 MeV, 4.0 mrad