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Utilization of optical image data from the Advanced Test Accelerator (ATA)

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Abstract

Extensive use is made of optical diagnostics to obtain information on the 50-MeV, 10-kA, 70-ns pulsed-electron beam produced by the Advanced Test Accelerator (ATA).¹ Light is generated by the beam striking a foil inserted in the beamline or through excitation of the gas when the beamline is filled with air. The emitted light is collected and digitized. Two-dimensional images are recorded by either a gated framing camera or a streak camera. Extraction of relevant beam parameters such as current density, current, and beam size requires an understanding of the physics of the light-generation mechanism and an ability to handle and properly exploit a large digital database of image data. We will present a brief overview of the present understanding of the light-generation mechanisms in foil and gas, with emphasis on experimental observations and trends. We will review our data management and analysis techniques and indicate successful approaches for extracting beam parameters.

Introduction: ATA and optical diagnostics

The Advanced Test Accelerator (ATA), as described in a companion paper by Chong, et al.,¹ is an induction linac that produces electron-beam pulses of 10 kA at 50 MeV for 70 ns with a pulse-repetition frequency of 1 Hz. The machine is remotely sited at the Lawrence Livermore National Laboratory's Site 300, located approximately 50 miles east of San Francisco. The ATA was funded by the Defense Advanced Research Projects Agency (DARPA) and is being used to study electron-beam transport under a variety of conditions.

Optical diagnostics are used extensively for studying the electron beam in ATA. Light is generated by the beam striking a target foil or passing through gas in the beamline. This light is transmitted to various detectors well removed from the beamline by optical lines of sight (LOS). The optical data allow experimenters to determine the electron beam position, size, profile, and intensity.

The time scales of interest for ATA LOS diagnostics are typically several nanoseconds. If optical systems can be gated to this speed, the gates can be moved on a pulse-to-pulse basis. Typical LOSs will view a field of 15-30 cm; the desired spatial resolution is 1 mm or less. The desired dynamic range on intensity for a single LOS is 100:1.

Optical diagnostics are used in two very distinct modes. The first mode is as a rapid qualitative beam diagnostic for tuning the accelerator (i.e., varying magnetic fields, gas profiles, etc.). In this mode, the data must be displayed in a convenient form (usually an image) for the selected diagnostic. The data are properly labeled at the 1-Hz repetition rate, and displayed at many locations throughout the control room and several diagnostic areas. A second complementary function for the optical diagnostics is to make quantitative measurements of beam parameters. Light measurements require a detailed understanding of the calibrations throughout the LOS and the detector. Moreover, to determine electron-beam parameters, a good understanding of the physics of light generation in the foil or gas is necessary. In this case, rapid data analysis on a 1-s time scale is not required, but sufficient data must be recorded to permit subsequent analysis of the image. The ATA optical diagnostic system has been designed to perform in both of these modes.

The ATA environment

The ATA is located in a subterranean hall and is approximately 75 m in length. Between 25 and 40 m of transport are required beyond the accelerator to bring the beam into one of the three experimental halls that are located in horizontal underground tunnels. Typical experiments are 20 m or so in length. Over the 100 to 140 m of the accelerator, transport, and experiment, about 10 LOSs are deployed; at any given time only one or several of these LOSs are in use.

The ATA presents a hostile environment in several respects. The electron beam produces copious radiation in the tunnel on each shot.² Upwards of 2000 rad may be produced on each pulse. This radiation is in the form of high-energy x rays and neutrons. The radiation is concentrated in the forward direction relative to the electron beam propagation and is often localized in a region of beam spill or at the dump where the beam is intentionally spilled. This radiation environment produces spurious signals on all signal-carrying coaxial cables in the tunnel. The radiation precludes the tunnel from being occupied by personnel during a shot. Activation of beamline components during an evening's run may render the tunnel unsafe for entry until the following morning. Hence, all diagnostics in the tunnel must be static or remotely controlled. The radiation environment can also preclude introduction of optical components into the tunnel. The electron beam and the accelerator pulse-power systems produce an electromagnetic pulse (EMP) each time the accelerator is fired. This EMP can wreak havoc with control and safety systems and contributes tens of

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millivolts to any electronic signal measured in the tunnel. The radiation and EMP in the tunnel preclude the use of solid-state electronic components unless they can be properly shielded.

The ATA tunnel presents a hostile environment in several more subtle ways. Access to the various experimental alcoves is quite limited, as the tunnels are less than 3.5 m wide at points. The beamline, vacuum lines, gas lines, water lines, and cable trays all compete for limited space. The optical LOSs, which require clear paths but do not reserve these paths with pipes or housings, are often violated by inadvertent placement of hardware. Because the ATA is a very dynamic facility with continuing beamline construction, dust is continually deposited on all optical components, changing transmission characteristics. Maintenance of alignment is difficult, as mirrors and mounts are subject to bumping by personnel and forklifts.

In this section, we have enumerated several aspects of the hostile environment presented for optical diagnostics at the ATA. In the next section, we will present the solutions we have found to achieve the measurement capabilities outlined in the introductory section, given this environment.

The ATA optical diagnostics systems

The ATA optical diagnostic system is illustrated in Fig. 1, which shows the optical path for a typical LOS. The light signal is converted to a composite video signal by a camera in the rf enclosure. The composite video signal is then manipulated, recorded on videocassette recorders (VCR), broadcast to remote viewing monitors, and passed on to digitizing systems. The digitized data are then analyzed in several locations with complementary capabilities. In the remainder of this paper, we discuss the rationale for the various components in Fig. 1.

Figure 1. Schematic diagram of the ATA optical diagnostic system.

The optical train-layout

ATA LOSs are engineered so that all optical detectors and optical components other than front surface mirrors are located outside the ATA tunnel. Light originates at a fixed foil in the beamline, an insertible foil employing a general-purpose probe (GPP), or as electron-beam-generated gas light. Light is transmitted through quartz windows on the beamline and then reflected with mirrors to penetrations or sleeves in the concrete above the tunnel. These penetrations, either originally cast in the concrete or later drilled through, have a nominal 10-in. diameter and typically limit the effective diameter of the optical system to 8 in. From the source to the detector, the optical path length of a LOS is typically 10-15 m. Thus, if the light source is isotropic and the detector has an 8-in.-diam aperture at 10 m, only 2.6×10^{-5} of the light reaches the detector. This low collection efficiency is adequate for very narrow electron beams at high currents. At lower currents, for diffuse beams, or for short time gates, this collection efficiency is too low and poor signal-to-noise levels are observed.

One way to increase light collection is to place an optical periscope in the concrete sleeve, thus reducing the distance from the source to the first optical element by several meters. In the past, periscopes have been successfully deployed at ATA. At one time, a lens was placed approximately 6 in. from the beamline to obtain a wide-angle view of the beam in the pipe. This diagnostic was extremely popular and useful, but the object lens (a standard Olympus camera lens) darkened within 1/2 to 2 h of run time; the lens had to be replaced each day. At present, the low light levels encountered with the long LOSs are partially compensated by the use of high-gain (e.g., dual microchannel plate) cameras. In cases where the beam-generated light is predicted to come out in a narrow, highly directed cone (e.g., optical transition radiation from a foil), the very narrow acceptance of the long LOS makes locating and measuring the radiation pattern quite difficult. For detecting light in narrow cone angles, alignment is done very carefully; however, beam shot-to-shot variations can often frustrate the careful alignment. At present, we are employing microchannel plate photomultipliers in the tunnel with massive amounts of shielding for x-ray measurements. In the future, we will deploy a shielded camera in the tunnel to increase light-collection efficiency.

The optical train-alignment, calibration, and documentation

Because we are typically maintaining up to ten LOSs in parallel, the alignment, calibration, and documentation must be carefully maintained. Typical LOSs may have five mirrors mounted in the tunnel, usually on stands and mirror mounts. The alignment is performed with an alignment helium-neon laser located in the rf enclosure. Calibration is achieved by imaging a 1-cm² quadrille pattern placed on the entrance port window. Special fixtures called "lighthouses" are placed at each beamline view port; these lighthouses can be manually flipped in front of the view port. The fixtures contain illuminated quadrilles that show the orientation and the label for the LOS. By viewing this lighthouse pattern, we can verify the LOS alignment each day. Given that the primary cause of loss of alignment is mirrors being bumped, all mirrors in the tunnel are labeled with their LOS number and a sequence number within the LOS. Signs in the tunnel tell workers how to report moved mirrors and strongly encourage them to do so. To document each LOS, we have developed a small computer program running on an IBM-PC. This program takes the size calibration, center location, and orientation of the image produced by the LOS and produces a sample image from the LOS for several beam diameters, as seen in Fig. 2. A line drawing of the LOS is produced and the input LOS parameters are documented. This one-page LOS description is very useful in making quantitative estimates from observed images.

The LOS documented in Fig. 2 is actually a dual LOS in which two images are combined with a partially silvered mirror and projected onto one camera. The LOS views two fixed foils in the beamline. The images from the two optical LOSs are aligned to fall to the left and right in the image plane. The ovals on the simulated image are for diameters of 2, 4, and 6 cm; the images are oval because the foils are being viewed at 45° as shown in the line drawing of the LOS.

Data capture

The light from the LOS is captured by one of three transducers.¹ A gated framing camera is typically used to capture an image with two spatial dimensions and a time gate of 3 ns or longer. A streak camera can be deployed to obtain data in time and one spatial dimension. In this case, the limit on temporal resolution has been low light levels rather than the streak sweep speed. A photomultiplier is sometimes used to obtain the time history only of the light. In this case, the signal is transmitted to the trace digitizing system (i.e., oscilloscopes) to be recorded and displayed.

Data display and recording - video

To provide rapid data display in a convenient form for eight channels of video data, each camera signal is piped through a video inserter to a video cross switch, as shown in Fig. 1. The video inserter is used to superimpose a time, date, and diagnostic identifier onto the image. This composite image can then be selected using the video cross switch and sent to one or more monitors located throughout the ATA complex. Banks of monitors are located in the control room, screen room, and diagnostic bunker to permit experimentalists to monitor the machine operation and experimental results. A special set of six monitors and a color monitor are located in the ATA conference room to accommodate visiting observers. The composite video output from our oscilloscopes is also labeled and piped around the site using this system. (One drawback is that certain

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View Description:

Name	IFR ENT.	IFR EXIT
2 (n)	21.27	33.13
2 Label:	2	2
Foil/CAS	FIX FOIL	FIX FOIL
Orient.	STNB	HTSB
View Ang.	135	45
FoIL Ang.	90	90

LOS and Camera Description:

Ap. Diam. (cm)	6	6
Optics	GLASS	GLASS
F.L (mm)	1900	1900
Obj. (n)	11.6	11.6
cm/pixel	.0385	.0385

North East South
West INJECTOR DUMP

COMMENTS:

Figure 2. Documentation for a single LOS showing the location, orientation, and size scale for a particular LOS.

Japanese streak cameras and European oscilloscopes do not follow the American standard for composite video output.) Our system has proven extremely flexible and useful for the operational phase of the experiments.

Associated with this system are six VCRs used to record any six selected video channels (either images or views of oscilloscope traces). The VCR records lack resolution and dynamic range, but they permit the convenient storage of an incredible bulk of data in a small volume at a low cost. This capability is particularly valuable for documenting machine performance and reconstructing anomalous events that may occur on shots that are not being captured by the digitizing system. Two drawbacks of the VCR system are that cataloging the tapes is very tedious and accessing the images is not straightforward.

Data display and recording - digital

Two channels of image data can be directed to LSI-11 computers and captured on "datacubes" on which the digitizer resolution is 240 pixels by 320 pixels with an 8-bit dynamic range. The digitized image is displayed at 1 Hz. A selected image can be "grabbed" and stored by the operator. The recorded image does require approximately 80 kbytes of storage; this large size is a major deterrent to accumulating large numbers of images. On a typical run day, the accelerator is pulsed approximately 20,000 times and less than 100 images are digitized. Our philosophy of data recording is to provide bulk recording with limited resolution on the VCRs and detailed recording on a limited number of shots with the digital systems.

The video cross switch allows us to loop incoming signals through 6-bit framegrabbers, which are used to freeze the image for the 1 s between pulses. These stationary images are much easier to interpret "on the fly" than the flashing image received directly from the camera.

Digitized data analysis

The goal of the image analysis work is to provide a spectrum of capabilities from rapid turnaround with little processing, to time-consuming detailed interactive processing of selected images to bulk processing of many images, without operator interaction.

The first image processing is performed by experimentalists observing the image. With a 1-Hz repetition rate, it is easy to discern systematic variations in image size, location, and intensity when accelerator parameters are changed. The ability to distribute an image to multiple monitors greatly facilitates the "instant" analysis of image data.

At the most responsive level, some data processing can take place during the 1 s between pulses. The capability exists to locate and display the centroid and "radius" of the image after each shot. Primitive algorithms must be used to obtain sufficient speed for the analysis. However, this technique of data analysis has proven very useful for studying beam shot-to-shot variation and for measuring beam temporal variations when the gating of the camera is changed.

On the next level, each acquired image is transmitted from the remote ATA site to LLNL for overnight analysis. An object-finding code locates objects in the image and computes their positions and sizes as well as documenting the image with contour and histogram plots. These data are available to experimenters the morning following the data acquisition. A typical output of the overnight analysis package is shown in Fig. 3. The code runs on a VAX computer and does not require any operator intervention.

Figure 3. Automatic data analysis of a LOS image performed overnight on a VAX computer with an object-locating code.

The sample image in Fig. 3 shows data taken from the LOS documented in Fig. 2. In the upper-left corner (a), a contour plot of the light level vs x and y is displayed. Comparing Figs. 2 and 3, one can observe that either the beam is far from centered on the foil or the LOS alignment for the exit spot is off. The oval nature of the beam image is clearly shown. The beam radius appears to be less than a centimeter at the exit. The cross hairs on the contour plot indicate where one object was located by the image analysis code (the code did locate both beam images). Slices through the contour plot in x and y appear in the upper-

right (b) and lower-left (c) plot positions. The histogram in the lower right (d) is valuable for determining system performance. The number of pixels is displayed on a logarithmic scale vs intensity. The highest observed amplitude is 50, so only 20% of the dynamic range is being utilized. There is a large "background" signal around 12 or so in intensity. The source of this background is at present unknown.

For a more detailed study of a single image, we employ an interactive image manipulation code. Users can perform various operations such as background subtraction, normalization, smoothing, row and column extraction, etc., to obtain quantitative data from the recorded images. This is very satisfactory for analyzing single images, but more rapid and automated techniques are required for the bulk processing of data.

At the last level of image processing, a routine is maintained on the Cray computers at LLNL to perform bulk processing of image data. This code documents each frame of optical data by producing a contour plot of the image, a histogram of the pixel intensities, and a set of slices of the image in the x and y planes. This documentary output is produced on paper and fiche. Throughput is around one frame per second of computer time, but there is limited interactivity. Analysis is on a single frame only; it is up to physicists to develop the frame-to-frame correlations (e.g., radius vs time for several shots with differing time gate locations). Because several file transfers are required to move the data to the Cray computer network, the bulk analysis is not available for days to weeks after the data are acquired.

Future enhancements of optical diagnostics

To better the performance of our optical LOSs, a first step is to understand the mechanisms of light generation. Simply from a phenomenological point of view, measurements are being made to determine if the light has the same spatial and temporal behavior as the beam current density. In a gas, the light arises from the excitation of the molecules by collisions with beam electrons or by breakdown in the electric field associated with the beam. In some cases with well-behaved beams, the light is directly proportional to beam-current generation. When a foil is present, the light may be Cherenkov radiation or optical transition radiation (among other possibilities). Experiments are being conducted to determine the time history, angular distribution, and polarization of light from various foils for comparison with theoretical predictions. An understanding of the light-generation mechanism may allow us to optimize the emission intensity and angular distribution to increase the intensity of collectable light.

To enhance light-collection efficiency, we are exploring three options. A camera with extensive shielding will be placed in the tunnel to reduce the object distance by factors of several. In the past, periscopes have been used with interferometers; we are studying the advisability of using a standard periscope in conjunction with the first surface mirrors. Optical elements in the tunnel could be shielded, manually replaced, or automatically replaced. Fiber-optic bundles are being considered for image transmission, as discussed in the companion paper.¹ However, fluorescence, transient darkening, and permanent darkening appear to be serious problems. Moreover, the relatively small-diameter bundles are expensive, and coupling the image to the bundle is a nontrivial task.

To improve light-detection efficiency, we are deploying camera upgrades as they become available. Recently, we have begun employing cameras with dual microchannel plates for low-current applications.

The data acquisition software is undergoing a major upgrade. The primary computer for image acquisition will be a microVAX II. This computer has memory and speed advantages over the LSI-11s now employed. Moreover, the microVAX will reside on a network that will allow convenient transfer of experimental data to the various computers where processing occurs. Data transfer by magnetic tape will thus be eliminated. The video inserter can then be controlled by the same system that captures video images so calibrations, etc., can be included in the image data file. One goal of this new system will be the display of pertinent calibration information with the image in real time. Another priority will be to develop acquisition systems in which the image data are preprocessed to extract relevant lines or slices for storage. This will greatly reduce the bulk of information to be stored, thereby allowing many more pulses to be recorded. Data from picture "slices" will be stored in the same format in which the "traces" from oscilloscope data are stored. Thus, much of the analysis software used for trace analysis will be usable. This tradeoff allowing data from the image to be discarded will permit the number of images recorded and analyzed to be greatly increased.

Conclusions

Optical diagnostics will continue to play a major role in operations and experimentation at the Advanced Test Accelerator. The design and performance of the system are greatly influenced by several elements of the hostile environment in which the system must operate. The design must also accommodate the several very different uses made of the diagnostic information. Future expansions of the ATA optical diagnostics will be made in light of the operational needs, realistic environment, and past experiences described in this report.

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