DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Electronics Engineering Department
EE Technical Review**Manuscript Date: December 1985****MASTER****LAWRENCE LIVERMORE NATIONAL LABORATORY**
University of California • Livermore, California • 94550

Available from: National Technical Information Service • U.S. Department of Commerce
5285 Port Royal Road • Springfield, VA 22161 • \$11.50 per copy • (Microfiche \$4.50)

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *reb*

Preface

The EE Technical Review has two purposes—to inform readers of various activities within the Electronics Engineering Department and to promote the exchange of ideas.

The articles, by design, are brief summaries of EE work. For further details on a subject covered, please contact one of the authors. The authors are primarily responsible for the content of their articles. Inasmuch as most projects are the result of the cooperative efforts of many individuals, the person you contact will either provide the requested information directly or refer you to the appropriate person to answer your question.

EE Department personnel are encouraged to submit articles for consideration to the Editorial Board. Board members include:

H. S. Ames—Nuclear Energy Systems Division
F. Dean Lee—Fusion Energy Systems Division
M. S. Genin—Technical Editor
K. Kunz—Engineering Research Division
H. D. Francis—Field Test Systems Division
J. W. Spencer—Engineering Services Division
W. F. Thompson—EE Department Staff
P. J. Van Arsdall—Laser Engineering Division

E. A. Lafranchi
Electronics Engineering
Department Head

EE Editorial Board. From left: Bill Thompson, Paul Van Arsdall, Frank Francis, Henry Ames, Jonathan Hymer, Ann Parker, Mike Genin, Jack Spencer. Not pictured: Dean Lee and Karl Kunz.

Contents

Electronics Engineering Department

Overview	1
<i>E. Lafranchi</i>	

Laser Engineering Division

Overview	3
<i>D. L. Pehrson</i>	
A Streak Camera Readout System Using a CCD Camera	5
<i>B. A. Jones and J. D. Wiedwald</i>	

Engineering Research Division

Overview	15
<i>S. Weissenberger</i>	
Propagation of Intense Electromagnetic Pulses in the Atmosphere	17
<i>J. H. Yee and D. J. Mayhall</i>	

Fusion Energy Systems Division

Overview	25
<i>R. H. Wyman</i>	
The Magnet Power and Gas-Box Control Systems for the Tandem Mirror Experiment-Upgrade	27
<i>H. H. Bell, Jr.</i>	

Nuclear Energy Systems Division

Overview	37
<i>R. E. Twogood</i>	
Experiments with a Virtual Cathode Reflex Oscillator	39
<i>R. D. Scarpetti and S. C. Burkhart</i>	

Engineering Services Division

Overview	53
<i>R. Long</i>	
A High-Performance Communications Link between DEC's VAX and ComputerVision's Graphics Processor	55
<i>K. Blackwell</i>	

Field Test Systems Division

Overview	63
<i>L. Loquist</i>	
Subnanosecond Spectroscopy Using Stripline Microchannel Plates and Reticon 10245F Linear Arrays	65
<i>C. R. O'Brien</i>	

Index	73
-------------	----

A Ten Year Retrospective

Edward Lafranchi, Electronics Engineering Department Head

Over the past decade, one thing has remained constant: the Electronics Engineering Department's primary mission to provide quality support to the Laboratory's programs through its engineers and technical staff. A second mission, which has grown over the decade, is the development of EE's technology base. These two missions are interconnected. The technology base—with its specialized tools, equipment, knowledge, and facilities—provides a full spectrum of engineering capability that EE engineers can use in their programmatic work.

In this ten year period, the department has almost doubled in size, from 650 to 1200 people. The number of divisions has remained constant, at six. Four divisions support the Laboratory's main programs: Laser Engineering Division (Laser Program), Fusion Energy Systems Division (Magnetic Fusion Energy Program), Field Test Systems Division (Nuclear Test Program) and Nuclear Engineering Systems Division (Defense Systems Program: Nuclear Design, Military Applications, and Weaponization). The other two—Engineering Research Division and Engineering Services Division—provide special services to the department

The technology base—with its specialized tools, equipment, knowledge, and facilities—provides a full spectrum of engineering capability...

and the Laboratory. Engineering Research is home to most of the department's technology base and research and development. ESD provides general electronics-related services to both the department and the Laboratory's "institutional" areas such as Security and Computation.

The big changes in the department's organization occurred in the early '70s, when the size of LLNL's programs began to change dramatically. Since then, some of the divisions have evolved to respond to the needs of certain, rapidly

growing programs. For instance, in 1975, support for the Laser and the Magnetic Fusion Energy programs came from one division. As these two programs grew, the one division split into two, so that each program could be the focus of a single

...engineers became more involved in project management and project engineering.

division. Ten years ago, Laser Isotope Separation (LIS) was a small research effort within the overall Laser Program. Today, it is a large program unto itself, requiring almost half of the support supplied by the Laser Engineering Division.

The big, programmatic "construction" projects that have marked the last decade—projects such as Shiva, Nova, the Magnetic Fusion Test Facility (MFTF), the Flash X-ray Facility (FXR), and the Advanced Test Accelerator (ATA)—have changed how individual engineers worked as well. Since these projects required very large engineering development efforts and close coupling between engineers and scientific staff, engineers became more involved in project management and project engineering. These changes produced new career paths for engineers. An engineer could now choose to pursue a technical career or a career in project management.

The past ten years have seen evolutions in technology as well. By 1975, minicomputers were being developed at an incredible pace and were finding many applications in the programs. Small digital systems, such as microcomputers, were used to gather data and to control small, benchtop experiments. Large, computer-based control systems were developed for Shiva, Nova, and MFTF. Image processing is an example of a technology which "took off" in the mid '70s, in part due to the availability of relatively powerful minicomputers at reasonable prices. EE engineers used these

computers, particularly the PDP-11, as dedicated systems for developing their algorithms.

The increased use of computers in Electronics Engineering also changed the role of the engineer in the programs. In 1975, the department began to have many engineers who could move from one program to another with ease, thanks to their knowledge of the 16-bit, PDP-11-series computers and the RT-11 operating system. The technological breakthrough from 8-bit to 16-bit machines in the early '70s had a widespread impact in the department. Engineers became increasingly interested in digital systems and their uses as well as in software engineering and computer applications.

The increased availability of powerful computer tools also aided the department's growing involvement in computer modeling. This was particularly true in the electromagnetics area, where codes have been used to analyze circuits, electrostatics, partial discharges, and dielectric materials. Sophisticated analytical codes such as these

Sophisticated analytical codes...were used with impressive results to model things too costly to build and test.

were used with impressive results to model things too costly to build and test. For instance, engineers working on FXR in the mid '70s used modeling codes to predict electric field stress concentrations in the machine. The predictions led directly to the redesign of a crucial insulator, saving the program time and money in redesign costs.

Another important technology change is occurring in solid-state technology. For years, this technology was used to build increasingly dense solid-state circuits on silicon wafers. Now, this technology is being used to fabricate extremely small mechanical parts such as detectors, sensors, integrated optics, and microwave diagnostics.

Many of the technological changes in the department have mirrored changes in the Lab's programs. For instance, the Nuclear Test Program, which is part of the overall Defense Systems Program, has very different requirements for its underground nuclear events than it did ten years ago. EE's Field Test Systems Division, has been driven by these requirements. Events now require complex diagnostic systems to retrieve data that will aid in developing the x-ray laser, and other third-generation weapon systems. As a result of changes like these in Defense Systems and other

programs, the department is facing difficult engineering challenges.

Electronics Engineering now stands on the brink of a new era. The era of the "big project" or big machines is, if not over, at least diminished. MFTF-B is moving closer to completion, and there will most likely not be another Shiva-like laser fusion facility in the near future. The department is now moving toward more analytical work and less hardware development. The microwave world is becoming important again in engineering as several major laboratory programs begin dealing with microwave issues. Engineers are working on these issues using computer-based tools for analysis. It's a different world from the days when an engineer would use pencil, paper, and slide rule to calculate properties of a microwave circuit.

Yet, even with all these changes, EE's primary mission to the programs remains constant. Certain areas, particularly in the Engineering Services Division, continue to support the department and the programs, providing services that have been and will continue to be critical. Services such as fabrication, instrument repair, components support, and drafting and documentation are as in demand now as they were ten years ago. The EE people in these areas and others continue to provide quality services and support in areas of general use to all Laboratory programs.

This leads to the department's foundation and principal asset: its people. The past, present, and future success of the department depends upon quality people. The department, as an organization, provides the environment, the tools, and

The past, present, and future success of the department depends upon quality people.

the encouragement so that its people can complete their tasks and continue to grow.

The department has always believed in providing quality resources to its people and encouraging career and professional development. The *EE Technical Review* is, in part, a reflection of this commitment. The *Review*, in its first ten years, has provided recognition to the EE people doing the technical work. This special, anniversary issue goes a step further. Each division is represented by a technical article and an overview. The overview looks at the division's past ten years' achievements, present projects, and future challenges.

LED provides engineering and electrooptics support to the Laser Program.

David Pehrson, Laser Engineering Division Leader

Over the last decade, electronics engineers supporting the Laser Program have been an integral part of the program's efforts to explore the potential of lasers in harnessing thermonuclear fusion for energy and for defense-related physics studies and in efficiently separating fissile fuels. Ten years ago, the engineers supporting Laser's efforts were part of a division supporting both Laser and Magnetic Fusion Energy programs. LED was formed in 1977 to meet the needs of the Laser Program. LED now has 205 people and a history that reflects the changes and directions of the program it supports.

The Laser Program includes two basic applications: Inertial Confinement Fusion (ICF) and Laser Isotope Separation (LIS). LED supports each application equally and even has a deputy division leader for ICF and another for LIS. Ten years

...engineers supporting ICF...were developing the basic technology needed to build and control a neodymium glass laser.

ago, it was a different story. LIS was a relatively modest research effort; ICF required most of the engineering support.

In 1975, engineers supporting ICF were turning from the modest (by today's standards) research lasers of Cyclops and Argus to the design and construction of Shiva, a multi-arm, 10-kJ laser. In 1977, the \$25 million, 20-beam laser system was completed on schedule and within budget. For the engineers that worked on Shiva, it was the start of a new era in ICF. Before Shiva, they were developing the basic technology needed to build and control a neodymium glass laser. With Shiva, they began building large, line-item laser facilities based on that technology.

From Shiva to Novette to Nova: LED polished that technology. Each facility was larger,

more reliable, and more efficient than the previous one. The system design remained basically the same for all. The engineering challenges were in extending and refining this basic design.

The most dramatic engineering evolution in this series was in the control systems. In early systems such as Argus and Cyclops, computers were used for gathering experimental data but not for

From Shiva to Novette to Nova: LED polished that technology.

control and operation. Later, as the laser facilities grew in size and complexity, it was no longer practical to use manual control systems. Automation was necessary to achieve the required accuracy and day-to-day reliability.

The control systems evolved as computers became more effective and fiber-optics technology became more widespread. Shiva had stand-alone control systems based on the PDP-11 with fiber-optic cable connecting the front-end processors. On Nova, LSI-11/23s form the basis for distributed control systems centrally controlled by VAX super minicomputers. The Nova system contains over 10 miles of fiber-optic cable connecting over 60 LSI-11s at 170 interfaces to power supplies, diagnostics and other instrumentation.

LED also had serious safety and reliability issues to address for these enormous facilities. As the energy storage systems grew—from banks storing hundreds of kilojoules to Nova's 60-MJ bank—LED engineers incorporated features so that the energies delivered would not cause malfunctions of the sequencing and event timing, and control, diagnostic, and data acquisition systems. Reliability was a must from the standpoint of sheer numbers. Shiva alone had more than 3000 control elements and 1000 data-acquisition units operating in a severe, high-voltage, high-current

environment. For Novette and Nova, the numbers were even higher. All systems and units, from energy storage systems to flashlamps, were built and tested to the highest reliability levels.

During this decade, LIS had a complementary set of engineering challenges to explore. Whereas ICF engineers developed ways to control and monitor "one-shot" nanosecond events, LIS engineers explored ways to control and monitor a continuous process in which lasers pulse at frequencies of several kilohertz.

LIS has grown in ten years from a relatively modest research activity into a separate, significant program under the Laser Program umbrella. Early on, LIS was striving to develop an inexpensive and efficient process to provide enriched uranium fuel for the nuclear industry. In 1975, the program had just completed experiments that showed the scientific feasibility of selectively isolating desired isotopes of uranium through photoionization. Up through the early 1980s, LED engineers helped develop modest-sized laser, vaporizer, and extractor systems. Two major system demonstrations in 1984 and 1985 demonstrated the feasibility of LLNL's Atomic Vapor Laser Isotope Separation (AVLIS) process for processing uranium and other isotopes on a large scale. The program is now shifting gears into the "large-project" mode familiar to those who worked on Shiva and Nova. LIS engineers and scientists are now working with several major U.S. companies to bring the well-researched AVLIS technology to plant scale and production capability.

...engineers must also deal with problems unique to rep-rated, pulsed-power systems.

Two parts of the AVLIS system—the laser light source and the separator—have provided their own sets of challenges. The copper vapor lasers used in AVLIS have been scaled up many times from their original size and power, leading to many design challenges. And, since the lasers run continuously, engineers must also deal with problems unique to rep-rated, pulsed-power systems. For the separator, engineers have dealt with a complex set of instrumentation and control problems. The main issue has been this: How do you provide real-time control and instrumentation in a continuous process that takes place in a radio-

active, high-temperature environment? LED engineers are now automating and optimizing a system that will effectively monitor this process and feed back corrective measures in this severe physical environment.

The program is now reaching maturity. LED is turning to the challenge of enhancing and improving the reliability of the technology, as it did years ago for Shiva and Nova. As LIS moves into this large-project mode, ICF cycles back to basic research. The next generation of ICF laser systems must spring from an architecture different than

As LIS moves into this large-project mode, ICF cycles back to basic research.

that used up to now. LED is beginning to explore fundamental technologies, materials and design approaches that will enable a future generation of multimegajoule systems to reach scientific breakeven. This work, along with the research and development funded by the Defense Advanced Research Projects Agency (DARPA), will ultimately address the use of solid-state laser technology in rep-rated systems delivering high average power.

As ICF pushes toward reactor-like systems, which will run continuously, the engineering issues confronting ICF and LIS will become similar. In both programs, engineers will be working on high-average-power applications and dealing with thermal issues in both optical and power conditioning systems.

In the past ten years, LED has become adept at dealing with the engineering issues of two extreme worlds: the world of nanosecond and sub-nanosecond one-shot events, and the world of continuous process in a production environment. The following article touches on one of these worlds: the world of nanosecond events. The

in the past ten years, LED has become adept at dealing with the engineering issues of two extreme worlds...

streak camera, able to provide resolution of several hundreds of picoseconds, is an important diagnostic for providing data from these events. This article describes a lens-coupled readout system developed for the streak camera.

A Streak Camera Readout System Using a CCD Camera

B. A. Jones and J. D. Wiedwald

From the beginning of the Laser Fusion Program at Lawrence Livermore National Laboratory, we have been developing instrumentation to monitor the performance of lasers and their interaction with targets. The streak camera has become the basic diagnostic tool in this effort. We have been continually improving the technology for the recording of streak camera images in a wide variety of diagnostic applications. A new electronic readout system has been developed by the LLNL Laser Engineering Division to capture and record streak camera data. This new system, using a CCD (charge-coupled device) camera, provides a greater dynamic range, better spatial resolution, and lower noise than our previous electronic readout system. It will replace photographic film in many critical applications, thereby saving time and money.

Introduction

In the Laser Fusion Program at LLNL, streak cameras are used as the principal diagnostic instrument to monitor fast optical and x-ray phenomena associated with laser fusion experiments.¹ The visible output from the streak camera is recorded either on photographic film or by using a CCD camera. Film is used where accuracy is more important than fast turnaround time, as in the case of laser target diagnostics. For these purposes, film has provided us with good resolution, sensitivity, and a large dynamic range. However, for applications requiring fast information turnaround, such as the pulse shape adjustment of a laser, the time required to process and digitize the film is prohibitive. For several years, an LLNL-designed streak camera readout system had been used in those applications where fast information turnaround was important. This system, however, sacrificed image resolution and dynamic range when compared to photographic film. With the development of our new streak camera readout system, resolution and dynamic range are approaching that of film. As a result of this development, electronic readout systems can be used in more applications in the future.

Streak cameras in the Laser Fusion Program

Streak cameras are used to record the temporal history of a radiation flux as it relates to either the laser target heating beam or to its effects on a target.⁵ (See Fig. 1.) In some applications, multiple

optical fibers carrying independent signals are distributed along the streak camera input slit, resulting in a multi-channel transient recorder. In other cases, a microscope or spectrometer can focus spatial or chromatic information along the slit. These applications all call for high spatial resolution and dynamic range. The streak camera sweep duration is chosen to encompass the transient phenomenon being studied. The sweep duration is typically 1.5 to 10 ns, which leads to a temporal resolution of 25 to 100 ps.

Laser fusion experiments occur relatively infrequently (once or twice a day is typical) and represent a large investment per shot. Because of the uncertainty of target performance, signal levels are somewhat unpredictable. Therefore, a measuring system with a large and well-defined dynamic range is particularly beneficial. The experimenter wants to know where the limits of the dynamic range are and what happens if those limits are exceeded. In many cases the experimenter also wants to know how the spatial resolution of the system will affect the diagnostic measurement. Depending on the application, inadequate spatial resolution will result in channel crosstalk, spectral line broadening, or degradation of an input image.

The streak camera readout system

The block diagram of Fig. 2 shows the overall streak camera recording system. The system includes an LLNL-designed streak camera and a readout system consisting of a CCD camera and a computer-based camera controller. In a typical streak camera diagnostic application, a transient

Fig. 1. A schematic drawing of the LLNL streak camera. This camera has become the basic diagnostic tool for monitoring the performance of lasers and their interaction with targets. It is sensitive to visible and infrared light or, in a special configuration, to x rays. It is capable of recording single-shot events with multi-gigahertz bandwidths.

The streak camera at LLNL

The advent of the Laser Fusion Program at LLNL in the late 1960s created the need for a new family of instrumentation. The pulsed lasers developed for this program had a duration of less than a nanosecond, unprecedented at that time, but could be triggered only once every several minutes. Instrumentation was required that was sensitive to visible and infrared light and capable of recording single-shot events with multi-gigahertz bandwidths. The basic instrument that we adapted for this purpose is the streak camera (Fig. 1).

The heart of a streak camera is the streak tube. In a streak tube, the incoming light or x-ray pulse strikes a photocathode liberating electrons along the input slit. The rate at which these electrons are liberated is proportional to the intensity of the input. The resulting photoelectrons are accelerated by an electric field and deflected by a pair of plates that are driven by a very fast voltage ramp. The duration of the sweep voltage defines the duration of the data record at the output of the streak camera. The electrons are further accelerated and strike the phosphor screen, giving off light that can be recorded on film or another light-sensitive instrument. This results in a time-to-space mapping of the input intensity. The resulting image mirrors the temporal profile of the input pulse. A streak camera sweep is from less than a nanosecond to microseconds in length, resulting in temporal resolution as little as a picosecond but more typically 25 to 50 ps.

Resolution in the spatial direction along the input slit is maintained in the streak tube; as a result, one-dimensional imaging or recording of multiple simultaneous channels is possible.

The 1970s saw rapid development of a streak camera recording system for use in the Laser Fusion Program.² Breadboards led to prototypes and prototypes to laboratory instruments. Nearly 30 were built. The streak camera images were initially recorded on photographic film; and, because of the enormous information capacity of film, many still are. However, film requires processing, has a long turnaround time, and must be digitized before the data can be analyzed.

Electronic streak camera readouts that could digitize the streak camera image in a fraction of a second were developed in the late 1970s.^{3,4} However, these readouts used early CCD (charge-coupled device) technology and suffered from unstable and unreliable operation. The value of this kind of electronic readout had been proven, but the performance was inadequate for many streak camera applications. This led to the investigation described in the accompanying article and to an electronic readout with performance rivaling, and in some applications exceeding, film.

The CCD camera being described is currently used to read out optical streak cameras. In recent years streak cameras having x-ray sensitive photocathodes have become important tools for laser fusion target diagnostics. Their location, within meters of an imploding target, makes electronic readout much more difficult; so, film is still used. We plan to continue efforts to implement electronic readout in this environment as well, hopefully replacing film with a superior, instantaneous, recording system.

Fig. 2. Streak camera recording system. The system consists of an LLNL-designed streak camera and a streak camera readout system composed of a CCD camera and a camera controller with its associated components. In a typical streak camera diagnostic application, a transient optical or x-ray signal is focused onto the input slit of the streak camera. The streak camera converts this transient input signal to a two-dimensional output image. This image is then relayed through a lens to the CCD camera where the CCD sensor captures the image, digitizes it, and transfers it to the camera control system for local display, image processing, analysis, and storage.

optical or x-ray signal is focused onto the input slit of the streak camera. The streak camera converts this transient input signal to a two-dimensional output image where time is displayed vertically and spatial information is displayed horizontally. This visible output image is then relayed through a lens to the CCD camera where the CCD sensor captures the image in its matrix array of photoelements (pixels). The CCD camera digitizes the captured image and transfers it to the camera controller for local display, image processing, analysis, and storage.

Description of the CCD camera

The streak camera readout system we are using⁶ is based on a commercially available camera using a CCD as an image sensor. This CCD camera incorporates "state-of-the-art" technology to provide both analog-to-digital conversion and CCD cooling.

The CCD is an almost ideal sensing device for streak camera readout. The CCD's matrix array of pixels provides a readout sensor that is small, geometrically stable, and inherently linear to light input. The CCD we have chosen is a silicon array composed of 576 rows by 384 columns of charge-coupled pixels. Each pixel is $23\text{ }\mu\text{m}$ square resulting in an image area of 13.2 mm by 8.8 mm .

The CCD functions by absorbing visible light photons that create hole-electron pairs in the silicon. The electrons are trapped in potential wells (pixels) by gate electrodes on the surface of the CCD. The light from the phosphor of the streak camera lasts less than $100\text{ }\mu\text{s}$. During this time, a charge image corresponding to the streak camera output is built up in the CCD, thereby capturing the light image. Then, the charge in each pixel is shifted to a single output by clocking electrode voltages.⁷

The capacity of a pixel is 250,000 electrons. A three-stage thermoelectric cooler is used to cool the CCD to -30°C , reducing the CCD's noise

level to about 50 electrons (RMS). The resultant theoretical dynamic range (pixel capacity divided by RMS noise) is 5000.

This camera is compatible with many different CCD types. In the future, this will provide flexibility as CCD technology evolves.

Mechanical description

The streak camera's output image could be coupled to the CCD sensor with fiber optics or relayed with a lens. Because the CCD in our older streak camera readout system was not cooled, maximum coupling efficiency was required. For this reason, fiber-optic coupling was used. By cooling the CCD, its noise is reduced drastically, resulting in improved sensitivity. This improved sensitivity makes it possible to lens-couple the streak camera's optical output to the CCD readout system, providing ease of maintenance, mechanical reliability, and the possibility of coupling to other streak cameras.

The mechanical design of this new streak camera readout system provides for adjustment of image-size and focusing in a very stable light-tight mounting configuration. The streak camera's output is relayed through a 56-mm, f/1.2 finite-conjugate lens to the CCD array. The lens reduces the image by a factor of about 3:1 to match the size of the CCD. Figure 3 shows the overall construction of the combined streak camera and CCD camera instrument.

Electronic description

This camera readout system can be connected either in a stand-alone configuration or interfaced to the Nova laser system by means of a front-end processor.

A block diagram of the electronic system as used in the stand-alone configuration is shown in Fig. 4. The computer system uses a commercially available central processing unit and standard computer components. Commands and status signals are transferred to and from the camera controller through a parallel interface. To capture a single streaked image, the camera is commanded to enter a mode where the CCD is continually being cleared while waiting for a trigger signal. When the trigger is received the camera integrates the image from the streak camera's image-intensifier output. To capture the output image the streak camera must be triggered during the CCD's integration period. The image is then digitized with a precision of 14 bits in the camera controller using a technique known as "correlated double sampling" to reduce noise. The data is

Fig. 3. The LLNL streak camera with CCD camera attached.

then transferred by DMA (direct memory access) into video memory using a DMA interface. This configuration is capable of capturing the digitized CCD image and transferring it to memory at a data rate of 50,000 pixels per second. The captured image is immediately viewable on a color monitor through the analog processor module. The video memory and analog processor provide pseudo color, zoom, pan, and scroll features. The captured image can be manipulated while resident in video memory or, optionally, can be transferred to disk for archival. The custom interface, required to provide proper interconnection and signal levels between the camera controller and the computer system, is the only component in this imaging system that is not commercially available. This interface also provides a convenient place for test points and monitor lights indicating system status for trouble shooting.

This system has also been operated in a front-end processor configuration on the Nova laser system. In the electronic block diagram for this configuration, the disk and console are replaced with the LAN interface. The software to operate the readout system in this configuration is downloaded from a larger minicomputer to the front-end processor using an LLNL-designed 10-megabit-per-second local area network (LAN).⁸ This configuration simplifies and reduces the cost of each system by eliminating the console and attached mass-storage device. During a laser experiment, the streak camera's output image is captured in the video memory and then transferred over the LAN to the larger minicomputer for data analysis.

Readout system software

Software routines operate the camera both in a single-shot mode for streak camera readout and a repetitive-readout mode for immediate feedback while adjusting the image size and focus of the relay lens. In addition to the software devoted to system operation, a wide range of software has also been written to perform the image processing and analysis that is necessary to recover the original streak camera intensity-vs-time data. To re-

cover this image, two CCD images must be captured and processed. This image processing involves subtracting a background (dark field) image from the signal image. This background image is acquired while the CCD is in total darkness and must have the same integration (exposure) time as the signal image. This background subtraction process removes the CCD pixel dark current and results in an image containing only the data of interest.

Block diagram of camera control system.

Fig. 4. Block diagram of the camera control system. Camera commands and status signals are transferred to and from the camera controller through a parallel interface. The captured streak camera image is digitized with a precision of 14 bits in the camera controller and transferred by DMA (direct memory access) into video memory using a standard DMA interface. The captured image is viewable on a color monitor through the analog processor module and can be manipulated while resident in video memory or, optionally, can be transferred to disk for archival. This system can also be operated in a front-end processor configuration on the Nova laser system. In this configuration, the data are transferred over a local area network (LAN) to a central minicomputer for storage and analysis.

Streak camera readout system performance

The critical performance characteristics of a streak camera readout system are dynamic range, sensitivity, and resolution.

Dynamic range

Dynamic range is the ratio of the maximum signal that can be recorded to the minimum signal that can be detected (also known as sensitivity).

The important feature of our new readout system is that its dynamic range exceeds that of the streak camera. The dynamic range plot (Fig. 5) shows data for the new CCD camera/streak camera combination.

Sensitivity

The signal at the input to the streak camera is frequently very weak, limited by the laser target performance. The streak camera readout system is sensitive enough to detect individual photoelec-

Fig. 5. Dynamic range plot. The dynamic range of the readout system exceeds that of the streak camera alone. The top end of the recording system's dynamic range is limited by saturation of the streak camera. Since the readout system is capable of detecting individual photoelectrons emitted by the streak tube photocathode, the lower end of the dynamic range (A) is determined by the detection efficiency of the streak tube's photocathode.

trons generated at the photocathode of the streak camera. Therefore, the sensitivity of the system is limited only by the photocathode of the streak camera.

Resolution

The temporal and spatial resolution of the streak camera system will be degraded if the readout system has inadequate spatial resolution. An ideal readout would have a resolution much better than that of the streak camera. It is in this area that electronic readouts are likely to be the limiting factor since the number of pixels is limited by current technology to about 500×500 . (Higher resolution CCDs are available, but at very high cost.)

The resolution of an optical system is defined by the modulation transfer function (MTF). The MTF of the CCD camera alone and of the streak camera-CCD camera combination is shown in Fig. 6. The CCD camera has a resolution that is better than that of the streak camera alone. It is still not as good as film, however, and produces a

Fig. 6. Spatial resolution is described by the modulation transfer function (MTF). Here we show the MTF of the new readout system alone along with the MTF of the streak camera/readout system combination. Although the readout system has a better resolution than that of the streak camera, it is still not as good as photographic film.

noticeable degradation in the overall system resolution.

Typical application and results

This new streak camera recording system has been used to monitor the temporal profile of the master oscillator output on the Nova laser system. Experimenters desired a laser heating beam with an output pulse shape that is flat-topped (see Fig. 7). As a result of the gain saturation of the Nova amplifier chain, the output of the master oscillator that is injected into the Nova chain must be shaped in such a way as to compensate for this saturation. This pulse shaping simplifies the experimental analysis of laser target diagnostics. The need for a streak camera readout system that provided a large dynamic range and good linearity was important in this application. A typical streak camera image of the shaped master oscillator output on the Nova laser system is shown in Fig. 8. Note the low noise prior to the rise of the signal and the wide dynamic range.

Fig. 7. Nova laser system gain response. Experimenters desire a laser target heating beam with an output pulse that is flat-topped; however, the response of the Nova laser amplifier chain is non-linear. The non-linearity is the result of gain saturation effects. To provide this flat-topped heating beam, it is necessary to shape the master oscillator output, which is propagated through the laser chain, thereby compensating for these gain effects.

(a)

(b)

Typical column lineout of the shaped Nova Master Oscillator.

Fig. 8. Output pulse shaped by the Nova master oscillator as captured by the streak camera readout system. Here we show two ways of displaying data from the streak camera recording system. This data shows the shaped Nova master oscillator output: (a) both the spatial and time axis data in three-dimensional form and (b) a single lineout through the same data.

Summary

The continuing effort to develop instrumentation to monitor laser performance has resulted in this second generation streak camera readout system. We are currently using these systems in the Laser Program and several more will be implemented in the coming year. We intend to continue the characterization of this new camera system and eventually replace all of the older CCD readout systems with our new system. We also plan to explore the possibility of replacing photographic film in those applications where x-ray streak cameras are used.

Acknowledgments

The authors would like to thank Nick Selchow who provided electronic support, Chuck Petty and Don Wentworth who provided the mechanical design support, John Severyn who provided software support, and Roger Griffith who helped with details of the streak camera interface.

References

1. S. W. Thomas et al., "The LLL compact 10 ps streak camera—1974 update," 11th International Congress on High Speed Photography, London, England, 1974, p. 101.
2. S. Thomas, J. Houghton, T. Owen, and L. Coleman, "Compact Ultrafast Streak Camera," *Laser Program Annual Report—1974*, Lawrence Livermore National Laboratory, Livermore, Calif., UCRL-50021-74 (1975), pp. 292-296.
3. J. C. Cheng, "CCD Applications for Transient Digitizers," *Laser Program Annual Report—1979*, Lawrence Livermore National Laboratory, Livermore, Calif., UCRL-50021-79 (1980), pp. 5-17 to 5-21.
4. J. C. Cheng, J. T. Noonan, and G. R. Tripp, "CCD Applications in ICF Diagnostics," *1980 Laser Program Annual Report*, Lawrence Livermore National Laboratory, Livermore, Calif., UCRL-50021-80 (1981), pp. 5-62 to 5-67.
5. J. D. Wiedwald and B. A. Jones, "An Improved Approach to Characterizing and Presenting Streak Camera Performance, SPIE Conference Proceeding 569, 29th Annual Technical Symposium, San Diego, Calif., August 18-23, 1985. (Also Lawrence Livermore National Laboratory Report UCRL-92160.)
6. B. A. Jones, "A lens coupled streak camera readout system utilizing a thermoelectrically cooled CCD," SPIE Conference Proceeding 569, 29th Annual Technical Symposium, San Diego, Calif., August 18-23, 1985. (Also Lawrence Livermore National Laboratory Report UCRL-92159.)
7. C. H. Séquin and M. F. Tompsett, *Advances in Electronics and Electron Physics Supplement 8: Charge Transfer Devices* (Academic Press Inc., New York, N.Y., 1975).
8. P. Van Arsdall, "Nova Laser Alignment Control System," *EE Technical Review*, Lawrence Livermore National Laboratory, Livermore, Calif., UCRL-50025-85-2 (1985).

ERD develops new electronics and electrical engineering tools and technologies for the department and for LLNL programs.

Stein Weissenberger, Engineering Research Division Leader

ERD's charter is to research and develop engineering tools and technologies for the other EE divisions and laboratory programs. The division develops concepts and tools that are not commercially available and that provide solutions to the Laboratory's unique problems.

Over the decade, ERD's basic mission has changed little. In the past, the research was perhaps less programmatic. Ties to programmatic needs have grown, and ERD now provides more direct support to the programs than it did before. The division has grown to its present size of 165 people in its efforts to provide this added support and to maintain its primary responsibilities to the department. However, the real changes have not been in the numbers of people but in their activities.

Since research and development is the key to ERD, the division is constantly moving into state-of-the-art technologies, developing tools and facilities not available on the outside, and then moving on once those technologies become commercially available or once development is complete. For example, ten years ago ERD was developing radiation detectors and counters for Nuclear Chemistry, Biomedical Science, and various physics experiments. Once that technology matured and detectors and counters became commercial products, ERD moved on to other areas of R&D. Some of the people who worked on these problems are now

...research and development is the key to ERD...

developing solid-state devices; others are applying their knowledge to modeling problems.

Many areas that were active a decade ago are still primary foci for R&D efforts. In these cases, the projects and emphases shift over the years.

Microelectronics represents such an area. Ten years ago, ERD was exploring techniques for fabricating solid-state circuits on a silicon base. Today, the technology originally used exclusively to produce microscopic electronic circuits is also used to fabricate extremely small mechanical parts for novel physics experiments. Over the past five years, ERD has used this "micromachining" process to make x-ray diagnostic devices, x-ray laser targets, and optical components. Some of the features on these devices approach $1\ \mu\text{m}$ in size.

Other areas of microelectronics have also changed. In looking for ways to build faster circuits, ERD now researches not only silicon but also gallium arsenide. ERD is currently working on a project to develop a high-speed diagnostic device based on gallium-arsenide electronic circuits. This device will be used to measure transient phenomena, such as x rays, in downhole experiments for the Test Program. ERD's solid-state research also addresses programmatic needs for increasingly fast diagnostic instruments by developing unique, high-speed switching devices, and by beginning to explore "opto-electronic" technology.

ERD's electromagnetic (EM) studies have also expanded. For example, ten years ago, researchers studying the effects of electromagnetic pulses (EMP) were just beginning to develop simple models of how EMP couples with basic structures. Now, they are using powerful finite-element modeling programs, newly developed analytical tools, and new and improved experimental facilities to explore the complex interactions of EMP with materials, devices, and complex structures. The result of these developments has been a significantly increased understanding of basic electromagnetic coupling phenomenology, including the discovery of some essentially new coupling and re-radiation effects. ERD has also pioneered the use of electromagnetic and acoustic waves

combined with computers to "look" inside the earth. This technology, known as geotomography, is similar to computer-aided tomography, which uses x rays for medical diagnosis. Geotomography, using EM or sound waves and computer techniques to reconstruct an image, holds much promise for such uses as determining the extent of fractures in rock, exploring for oil, and predicting how well rock formations will contain nuclear and chemical wastes.

The development and application of new modeling tools were made possible by the continued improvement and availability of local computer power. The rapid evolution of powerful, highly interactive computer and graphics systems has had a tremendous influence on how ERD does business. The capabilities available in the recently developed Applied Computational Engineering (ACE) Laboratory are encouraging researchers to develop more complex computer graphic models that provide dynamic displays of EM coupling and microwave interactions.

Other areas that have benefitted from the computer boom are signal and image processing, and engineering controls. In the past ten years, ERD's Image Processing Laboratory has become a

The rapid evolution of powerful, highly interactive computer and graphics systems has had a tremendous influence on how ERD does business.

valued asset to Laboratory programs. The signal processing code SIG has found wide acceptance and use in LLNL and is the Laboratory's most widely distributed code to industry and universities. Today, ERD has moved on to consider such complex control problems as the accurate, rapid control of directed-energy weapons in space.

ERD has substantially contributed to computer-aided engineering (CAE), specifically to computer-aided design tools for circuit and logic synthesis, simulation, and printed circuit design and manufacture. In the '70s, ERD developed the DASLL code to automatically route the interconnection of electrical components on printed circuit boards. This technology has since moved to the commercial sector and is found in Tectronix/CAE Systems, Inc. In the early '80s, ERD engineers developing the S1 supercomputer wrote the SCALD logic design and timing verification software that is now at the heart of commercial CAD tools available from Valid Logic, Inc. and Case Tech-

nology, Inc. ERD also developed the Engineering Design Station in the early '80s for the capture of schematics and electronics synthesis. Design automation and drafting tools are now fast becoming commodity items.

Over the past few years, ERD has had a major hand in furthering the department's CAE capabilities through the development of the integrated computer-aided engineering network (iCAEn). This network of VAX computers, workstations, and terminals provides EE engineers easy access to an array of computer tools. Engineering divisions and groups have installed and operated VAXs and workstations and have benefitted from ERD's network development.

The last decade has brought ERD some new disciplines, including systems engineering, decision analysis, human factors, and expert systems. Systems and decision analysis is now applied in several Laboratory areas including the Nuclear Systems Safety (NSS) Program, Safeguards and Security, and Treaty Verification. ERD has also provided human factors support to NSS and LIS programs, researching how best to design man-machine interfaces in control rooms. Using the methodology of expert systems, ERD is exploring the development of computer aids for detecting and identifying seismic events. In the future, such tools could assist seismologists in monitoring treaties limiting underground nuclear tests.

To see the electronics technologies EE will be using in the future, one needs only to look at the areas ERD is just beginning to address. For example, ERD has begun work on optical devices and components that may provide the next great leap forward in high-speed devices and transient diagnostics. Computers will also play important roles in ways that cannot be clearly anticipated today. ERD's modeling capabilities will continue to improve and develop. CAE systems and engineering workstations will bring these tools and others like them to EE Department engineers wherever they may work.

Throughout ERD's history, the division has constantly examined key, emerging technical issues and has sought to ask the questions and find the answers that apply to the Laboratory's efforts. Electromagnetics—the topic of the following article—is one area where key issues have continued to emerge and develop throughout the decade. This article examines one such EM issue, the propagation of EMP through the atmosphere and its interaction with the air.

Propagation of Intense Electromagnetic Pulses in the Atmosphere

J. H. Yee and D. J. Mayhall

Under the right conditions, a significant amount of energy from a very intense electromagnetic pulse can be propagated through the atmosphere. We have developed a computer code and have conducted waveguide experiments to identify these conditions. We found that certain pulse properties, particularly frequency, intensity, and width, affect propagation characteristics. These findings will help us to predict, among other things, the vulnerability of sensitive electronic equipment to damage from intense electromagnetic pulses.

Introduction

When the voltage on a pair of electrodes reaches a critical value, the resulting field will cause the air molecules between the electrodes to break down—that is, the resistance of the gap between two electrodes abruptly changes from a practically infinite to a relatively low value. The arc in an automobile spark plug is a common example of the breakdown effect: nothing visible happens until the potential between the electrodes is high enough to cause the air to break down and the resistance between the electrodes to decrease.

A similar phenomenon occurs when an intense electromagnetic pulse in the radio, microwave, or optical frequency ranges is propagated through the atmosphere. However, if the electromagnetic energy causes air breakdown, the surrounding air becomes ionized, which, in turn, limits the amount of transmitted energy. Investigating the effects of these propagations has practical applications. For example, because solid-state devices can be damaged even by relatively small amounts of electromagnetic energy, knowledge of the extent to which these pulses are attenuated is essential in assessing the threat posed to electronic systems by high-power electromagnetic pulses, especially those at microwave frequencies.

Under the right conditions, a "sneak-through" time exists in which a significant amount of the pulse's energy will be passed through the air before being attenuated. We are examining the physics of pulse interactions with surrounding media to determine these conditions. We have developed a computer code to model intense microwave pulse propagations through the

atmosphere. We also propagated an intense pulse through a waveguide to verify the results obtained from our code. Our theoretical and experimental results show that propagation depends very strongly on certain pulse characteristics, particularly on its initial intensity, its frequency, and its pulse width.

Theory of short, intense pulse propagations

The physical phenomena associated with a very intense electromagnetic wave propagating through any medium can be very complex.¹ To describe rigorously the physics of these interactions, one must simultaneously solve Maxwell's equations and the Boltzmann transport equation. However, solving the Boltzmann transport equation requires an enormous amount of computer time, so the Boltzmann equation is converted to a set of electron fluid equations. These fluid equations, together with Maxwell's equations, describe how the free electrons in the atmosphere behave when they interact with the passing pulse. Formally, the Maxwell-Boltzmann equations track in the atmosphere the electron number, the average electron velocity, the average electron energy, the electric field, and the magnetic field. The resulting set of nonlinear partial differential equations is still difficult to solve numerically but is more tractable than the Maxwell-Boltzmann equations. Also, by considering only one- and two-dimensional cases, we could begin to model the physics of the interaction of the pulse with its surrounding media.

To solve these equations, we needed data for the overall ionization rate, the momentum transfer

rate, and the energy transfer rate. The ionization rate determines the rate at which electrons are created through the ionization process. The momentum transfer rate determines the speed at which the electrons transfer their momentum to the air molecules through collisions. Similarly, the energy transfer rate determines the rate at which electron energy is lost to the air molecules as they are being excited by the electrons. These are, in effect, the quantities the fluid equations are designed to track. Although these parameters are not known very accurately for wide ranges of energies, the parameters have been determined experimentally within the electron energy range 10–120 eV (Refs. 2–4). We fitted these data into the one-dimensional fluid equations described above and developed a computer code to investigate how the pulse changes shape as it propagates through the atmosphere.

Most important for our purposes is the air-breakdown process described earlier. By colliding with air molecules, the free electrons in the atmosphere ionize the air and ultimately, under extreme conditions, cause the air to break down. Air breakdown changes the pulse shape and limits the amount of energy that can be transmitted. The process starts when the free electrons in air interact with both the air molecules and the electromagnetic pulse and gain enough energy to ionize the air molecules. The energy thus gained is expended in producing more electrons by impact ionization with air molecules. The avalanche process has begun. When the electric field is above the breakdown ionization threshold, the density of free electrons in the air increases rapidly, and the air becomes a plasma. Breakdown has occurred. The weak plasma is weakly conductive and dissipates energy by ohmic losses, thus dissipating energy from the electric field of the driving pulse. In this way, the pulse shape is changed and the amount of transmitted energy is reduced.

Air breakdown does not occur instantaneously because a certain amount of time will elapse before the electron density becomes sufficient to cause attenuation. The ionized plasma thus attenuates the pulse tail more than its front. The electron density varies as a function of position within the pulse: it increases as one approaches the pulse tail. Electron density can be approximated as $n = n_a e^{(z/c)v_i}$, where n_a is the ambient electron density, z is the distance measured from the front end of the pulse, and v_i is the average ionization rate. (The value of v_i depends on the electric field.) This equation shows that electron density increases as z increases. Hence, if the

field is high enough, the electron density may grow to a level on the order of 1×10^8 electrons per cm^3 , which is dense enough to cause noticeable attenuation. The pulse's front end will be relatively unattenuated, however. The amount of front-end energy that can be transmitted depends on the speed at which the electron density grows to the critical level. The elapsed time is the sneak-through time, and it determines the amount of energy that can be transmitted without severe attenuation.

Results

The electron density and sneak-through time depend on the intensity, frequency, shape, and width of the pulse. We have used our code to calculate the effects of these parameters on the final pulse shape, and hence on the amount of transmitted energy. As an example, Fig. 1 shows how a 10-GHz, 10-ns pulse changes shape as it propagates from 60 km toward the Earth's surface. Above 60 km (for this pulse), collisions between free electrons and air molecules within the pulse are virtually nonexistent. Therefore, the free electrons cannot cascade, and therefore cannot create a plasma that would absorb pulse energy. Below 60 km, if the pulse intensity exceeds the breakdown threshold, and if many electron collisions occur within the pulse, the cascade ionization process described earlier begins to occur. Figure 1 shows that, below 60 km, cascade ionization robs the pulse tail of some of its energy. At sea level, only a very small part of the pulse's front end remains; this represents the amount of energy passed through the atmosphere.

Figure 2 shows how the electric field intensity, the electron density, the electron fluid velocity, and the average electron energy vary within the square pulse of Fig. 1. We used the code to calculate these values at 49 km. As described before, the electric field intensity is high in the front portion of the pulse but diminishes quickly. The electron density, as predicted, increases toward the pulse tail. The electron fluid velocity and the electron energy also decrease at the tail. Although we chose a square pulse for simplicity, similar results have been observed for other pulse shapes.

We also found that the final pulse shape and energy are almost independent of the direction of propagation. Figure 3(a) shows how a short (10-ns) pulse changes its shape as it propagates toward the Earth's surface. Again, the tail of the pulse is eroded, as is shown in Fig. 1. Figure 3(b)

Fig. 1. Propagation of a 10-GHz, 10-ns pulse from 60 km toward the Earth's surface. We used the computer code to predict the rate at which the plasma attenuates the pulse's tail. Below 60 km, the air-molecule density is enough for an intense pulse to start the cascade ionization process. Cascade ionization robs the pulse tail of enough energy so that, at sea level, only a small part of the front end remains. This front end represents the amount of energy passed during the sneak-through time.

Fig. 2. Variation of four quantities at 49 km as a function of distance within a square pulse, as predicted by the code. The electric field intensity, electron fluid velocity, and electron energy are attenuated in the pulse tail, while the electron density is very high due to cascade ionization.

shows that a pulse propagating up from the Earth's surface changes in shape in the same manner as is shown in Fig. 3(a). The avalanche process occurs very quickly, however, because the pulse immediately sees high-density air molecules in front of it. The mean collision time between an electron and an air molecule is in the picosecond

region. An electron within the nanosecond-wide pulse undergoes many collisions before the pulse passes by the electron. Therefore, if the pulse intensity is high enough, the pulse's electrons can gain enough energy to start the ionization process. Because the process is basically the same as for a pulse propagating toward the Earth, the shapes

Fig. 3. Near independence of final pulse shape and energy with respect to direction of propagation. (a) A 1-ns pulse propagating toward the Earth's surface shows the expected tail erosion; however, erosion occurs toward the end of the pulse's journey. (b) The same pulse propagating toward outer space shows tail erosion very soon after leaving the Earth's surface. The final shape and energy, however, are nearly the same as for the pulse shown in (a).

and energies of both pulses are very similar. This near-symmetry property appears in all of our calculations regardless of pulse shape.

Although one might expect a pulse to reflect some of its energy back toward its tail, the pulses shown in Figs. 1 and 3 do not show noticeable reflections. There are two reasons for this. First, the electron density created during the ionization process is still far below the critical densities for 35 GHz and 10 GHz, which are about $10^{13}/\text{cm}^3$ and $10^{12}/\text{cm}^2$, respectively. Our calculated elec-

tron densities are about four orders of magnitude below these critical values. Second, any reflected pulse, small or large, is severely attenuated by the high electron density near the pulse tail.

Finally, with the code we predicted that, as the initial pulse energy increased, the altitude at which breakdown occurs would shift down toward the Earth's surface. The higher the intensity, the larger the downward shift. For a low-frequency, high-intensity pulse (e.g., 0.5 GHz at 30 mJ/cm^2), the electron density created due to the

avalanche process reaches near-critical density. In this case, the pulse would suffer not only tail erosion but also reflection and dispersion.

Although we have ignored air-molecule motion in our calculations, our approximation is good because the pulse widths we use are very short. Therefore, the molecules are essentially motionless during passage of the pulse. The initial electron and molecule densities we used in our calculations are the tabulated atmospheric experimental values.

Experimental results

To determine the accuracy of our theoretical model, we generated a high-power microwave pulse in a klystron and propagated the pulse through a waveguide. Previous air-breakdown experiments have used relatively low-power microwave sources, and air samples had to be placed in resonant cavities so that the fields could build up to the breakdown threshold. This build-up time effectively limited the pulse length that could be measured. Our experiment used the high-power, pulsed klystron at the LLNL linear accelerator to produce high-power, fast-risetime pulses. This experiment was designed to reduce the cavity "ring-up" time that was a necessary but limiting feature of earlier experiments. By eliminating the cavity, we were able to avoid its attendant electric-field-buildup and time requirements. We were thus able to expect breakdown in a time span an order of magnitude shorter than any experimental result developed so far.⁵

Figure 4 shows our experimental setup. We used an RCA-8568 klystron capable of generating 20 MW at 2.856 GHz with a 2- μ s maximum pulse length. The klystron was connected to a master oscillator through a PIN diode and driver klystron. The oscillator and PIN diode combination generated a 100-ns, 500-mW pulse for the driver klystron, which, in turn, produced a 200-ns, 20-kW drive pulse for the 8568 klystron. The output pulse was passed through a high-power circulator and was fed into a 5-m length of WR-284 copper waveguide that was terminated by a matched, water-cooled load to prevent reflections. Seed electrons for our plasma were provided by a 10-mCi ⁶⁰Co source placed in the collimator (Fig. 4). The pulse data were obtained from bidirectional couplers at each end of the waveguide; the shapes and amplitudes of the incident, transmitted, and reflected pulses were measured on oscilloscopes connected to the couplers.

Figure 5 shows that the agreement between our calculations for air-breakdown threshold energy and our measured data from the experiment were very good. The agreement of our measured data with data obtained by others is also good (Fig. 6).⁶⁻⁸ Threshold power density rather than threshold energy is plotted as a function of pressure because short, high-power microwave pulses with consistent widths and shapes are difficult to generate. The use of energy instead of power as a measure of air-breakdown strength takes into consideration both pulse shape and width because energy is the integral of power with respect to time.

We propagated a microwave pulse, shown in Fig. 7, through the air-filled waveguide. The electric field profile is also shown in Fig. 7. The pulse had a width of about 14 ns, a risetime of about 4 ns, and a frequency of about 3 GHz. As expected, the pulse width was shorter and its shape quite different after passage through the air section of the waveguide. A small frontal portion passed through, but the back portion was attenuated severely. This result was what we expected from our theoretical calculations.

We next determined whether our one-dimensional code would accurately predict the sneak-through behavior. Figure 8 shows our results. The calculation predicts almost exactly the waveshape and amplitude we measured for the sneakthrough wave until breakdown. However, after breakdown, the theoretical and experimental results do not agree as well. We attribute the reason for this disagreement to the use of a one-dimensional code to simulate a two-dimensional experiment. In the experiment, the electric field varied as a half sine-wave across the waveguide (Fig. 7). We believe that, although breakdown occurred at the center of the waveguide, the low amplitude parts of the wave, near the walls, propagated without suffering air breakdown and hence suffered no attenuation.

Recently, we finished developing a two-dimensional fluid code. Preliminary calculations using the 2-D code show much better agreement with the experimental data than the calculations obtained from the one-dimensional code. This result indeed indicates that the nonuniform breakdown across the waveguide plays an important role in determining the shape of the sneakthrough pulse.

Fig. 4. Schematic diagram of experimental setup. The waveguide is WR-284 (copper). The rf windows isolate the test cell from the rest of the waveguide. Seed electrons were provided by the ^{60}Co source. Pulse data were obtained from oscilloscopes connected to couplers at each end of the waveguide. The oscilloscopes displayed the shapes and amplitudes of single incident, transmitted, and reflected pulses.

Fig. 5. Comparison of experimental and calculated values for air-breakdown threshold energy. The agreement between our measured and calculated values is very good.

Fig. 7. Shape and electric-field profile of a pulse propagated through the air-filled waveguide. The electric field varied as a half-sine wave across the waveguide. The low-amplitude parts near the walls propagated with no air-breakdown and no attenuation, thus contributing to the discrepancy between experimental and theoretical results.

Fig. 6. Comparison of our measured data with data obtained by others. The agreement is also good. By measuring air-breakdown strength as energy rather than power, we considered both pulse shape and width, thus avoiding the need for short, high-power pulses with consistent widths and shapes.

Fig. 8. Comparison of code prediction and experimental result for sneak-through behavior. The disagreement after breakdown is due to the use of a one-dimensional code to simulate a two-dimensional experiment. Our recently completed two-dimensional code takes into account non-uniform breakdown across the waveguide and thus shows much better agreement with experimental data.

Conclusion

We have analyzed the dynamic behavior of a short microwave pulse as it propagates through the atmosphere. An important result, borne out by our calculations, is that a significant amount of energy can be transmitted through the atmosphere, even though a large portion of the initial energy is absorbed by electrons created by the avalanche process. In general, for a given pulse shape, the higher the frequency, the greater the amount of energy that will sneak through before breakdown. Unless the initial energy is less than the minimum threshold energy of the atmosphere, the shape of the microwave pulse that reaches the Earth's surface is quite different than that of the initial pulse and depends very strongly on the waveshape, intensity, frequency, and width of the initial microwave pulse. The final pulse width is always less than the initial pulse width. In all cases, however, the pulse tail will be attenuated in the manner we have described.

Acknowledgments

We wish to thank R. A. Alvarez and D. P. Byrne for their work on the experimental setup and for providing us with their results for use in this report.

References

1. J. H. Yee, R. A. Alvarez, D. J. Mayhall, D. P. Byrne, and J. DeGroot, *Theory of Intense Electromagnetic Pulse Propagation through Atmosphere*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-91622, Rev. 1 (1985).
2. R. J. Briggs and S. Yu, *Modeling Beam Front Dynamics on Low Gas Pressures*, Lawrence Livermore National Laboratory, Livermore, CA, UCID-19399 (1982).
3. A. G. Englehardt, A. V. Phelps, and C. G. Risk, *Phys. Rev.* **135**, A1566 (1966).
4. J. P. Bromberg, *J. Chem. Phys.* **52**, 1243 (1970).
5. D. P. Byrne, R. A. Alvarez, and R. M. Johnson, *Air-Breakdown Limits for Microwave Pulse Propagation. Part I: Experiments*, Lawrence Livermore National Laboratory, Livermore, CA UCID-19877, Part I (1983).
6. P. Felsenthal and J. M. Proud, *Phys. Rev.* **139**, A1796 (1965).
7. L. Gould and L. W. Roberts, *J. Appl. Phys.* **27**, 1162 (1956).
8. S. F. Tetenbaum, A. D. McDonald, and H. W. Bandel, *J. Appl. Phys.* **42**, 5861 (1971).

FESD's mission is to support the Magnetic Fusion Energy Program and the Beam Research Program.

Robert Wyman, Fusion Energy Systems Division Leader

Since its inception in 1977, FESD's main charter has been to support the Magnetic Fusion Energy and Beam Research work at LLNL. For most of the decade, FESD also provided engineering support to LLNL's Computation Department and the National Magnetic Fusion Energy Computer Center (NMFECC). These latter responsibilities recently switched over to the Engineering Services Division, allowing FESD to focus its attention on MFE and Beam Research requirements.

This division is unique to the department in designing high-energy, high-power systems that run for long periods of time. For instance, the power supplies for the huge magnetic fusion experiment MFTF-B will deliver 250 MW to the machine in a 30-s pulse. For machines like MFTF-B, FESD must develop high-power and computer control systems that can perform in an environment where nanowatts work next to megawatts.

At the start of the decade, one EE division provided support to both MFE and Laser program

This division is unique... in designing high-energy, high-power systems that run for long periods of time.

efforts. Most of the 35 people assigned to MFE were working on 2XII-B, a small, magnetic mirror-fusion machine. FESD now has 190 people, of which one third support the Beam Research Program. The division's growth and its history parallel that of the programs.

In 1975, efforts in magnetic fusion focused on the 2XII-B mirror machine. Using a special pair of "yin-yang" magnets developed at LLNL, 2XII-B became the first mirror experiment to create and stably confine a plasma at fusion temperatures and power plant fuel densities for many milliseconds. With the success of 2XII-B's experiments, MFE proposed building two different magnetic

fusion machines: MFTF, a big mirror machine designed along the lines of 2XII-B; and TMX, a small machine designed around the newly discovered tandem mirror concept. The proposals were accepted, and the engineering push was on.

TMX, a \$10 million test facility, was built within two years. In 1979, TMX demonstrated that the tandem mirror configuration could successfully contain plasmas at the required densities 10 times longer than could a single mirror cell at comparable temperature. With the success of TMX, the program received permission to convert MFTF into MFTF-B, a very large tandem mirror machine. However, before construction on MFTF-B began, the huge superconducting magnets had to be tested up to full energy. FESD engineers joined the push to install the vessel, magnets, and control systems in time for the 1982 test. Engineers also installed all the electronics necessary to control the cryogenic, vacuum, and magnet systems from the MFTF-B central control room.

With the success of that test, MFTF-B construction commenced in earnest. Today, even though the first phase of construction is almost finished, a lot of electronics engineering remains to be done before MFTF-B begins operation in two years. FESD engineers are working with magnetic fusion scientists to lessen "first wall" interactions between the plasma and the vessel walls. Seventy-nine gyrotrons, or radio-frequency generators, must be built and installed along with waveguides and antennas. Power supplies and cabling that will supply 240 MW to 48 magnets must

FESD engineers are working with magnetic fusion scientists to lessen "first wall" interactions between the plasma and the vessel walls.

be completed. In addition, the neutral beam systems must be installed with the necessary cabling.

In the near future, engineers will be designing, building, and installing large numbers of diagnostic systems that will help experimenters plot a plasma as it is heated and contained by the magnetic fields of MFTF-B. Such systems include laser and microwave interferometers to measure plasma density, diamagnetic loops to sense plasma conductivity, x-ray spectrometers, residual gas analyzers, and neutral flux spectrometers.

The Beam Research area has also evolved in the past ten years. The program has been principally interested in investigating the propagation of intense, self-focused beams through the atmosphere. The Advanced Test Accelerator (ATA), a linear induction accelerator first proposed in 1976, was designed for experiments in electron beam propagation through gases and the atmosphere. In 1977 the Navy funded construction of a smaller machine that was essentially the front end of ATA, the Experimental Test Accelerator (ETA). ETA had two purposes: to test some of the theories on particle beams and to generate beams for demonstration experiments. The accelerator, completed in 1978, generates beams of 10 kA and 5 MeV. At Site 300, construction started soon after on ATA, a 50-MeV, 10-kA machine capable of a 1 kHz pulse repetition rate. In November 1981, engineers got the first beam out of the injector. A year later, the entire accelerator was operating. ATA has provided the necessary beam currents and energies for exploring not only crucial propagation questions but new applications for generating high-power microwaves and laser beams.

Recently, FESD has begun work that will change ATA into a free-electron laser (FEL). FEL will use an energetic electron beam to amplify a

The Advanced Test Accelerator . . . was designed for experiments in electron beam propagation through gases and the atmosphere.

laser beam. Based on the success of future experiments on the FEL, a bigger linear induction accelerator of about 300 MeV may be a part of FESD's future engineering challenges.

For the areas it supports, FESD has taken advantage of the decade's technology changes. For instance, FESD has increasingly incorporated computers into system control and instrumenta-

tion. 2XII-B used manual control systems: push buttons, lights and meters. Both TMX and ATA are "hybrids" containing oscilloscopes, knobs, and buttons, as well as computer touch-sensitive panels and some computer-controlled systems. MFTF-B is completely computer controlled. Operators in the central control room use touch-sensitive panels to direct cryogenic, vacuum, magnet, and power supply systems.

The evolution in computer technology also changed the work done by the computer support groups in FESD. In the mid '70s, many systems were built from off-the-shelf standard cards with low levels of integration. Most of the special hardware needed by Computation and the NMFECC was designed in-house, since no industry outside the Lab was interested in designing and constructing the special equipment LLNL needed. Over the years that's changed, and now much more commercial hardware is used.

Another important evolution has occurred in the driving of the linear induction accelerator cells in machines such as ETA and ATA. The spark gap, first used ETA's big, pulse-forming Blumleins, was the beginning of this evolution. ATA's spark-gap switched Blumleins were of the same basic design as ETA's, but more reliable and better engineered. The most recent innovation in this technology has been the development of

Operators in the (MFTF-B) central control room use touch-sensitive panels to direct cryogenic, vacuum, magnet, and power supply systems.

magnetic pulse-shaping amplifiers for driving the cells. These mag-amps—passive, energy compression systems of capacitors and inductors—are smaller and more reliable than the old spark gaps. This technology, and others on the forefront of engineering, will be used when future accelerators are developed.

Throughout the decade, FESD has used the latest in technology to design and upgrade systems for magnetic fusion and beam-research machines. FESD is currently involved in another evolutionary upgrade, this time for TMX. The following paper discusses this upgrade, which will add computer control to TMX magnet power supplies and gas-box control system.

The Magnet Power and Gas-Box Control Systems for the Tandem Mirror Experiment—Upgrade

H. H. Bell, Jr.

The necessity for high magnet currents and precise valve operation in the Tandem Mirror Experiment—Upgrade required that control of the magnet power and gas-box control systems be automated. Computers and CAMAC modules direct the power supplies to furnish the requested currents, control the valves that provide gas to the plasma region, and monitor the performance of both systems. Accuracies of 1% of requested current are possible, and the system provides the complex waveforms needed to provide gas at the proper time during a shot.

Introduction

In the Tandem Mirror Experiment—Upgrade (TMX-U), desktop computers and computer-automated measurement and control (CAMAC) modules permit automation of the magnet power-supply and valve-control systems. An operator uses a desktop computer to direct power supplies to send any desired current to the magnet set. In addition, a computer produces the waveforms that control the valves that feed gas into the plasma region. The software can automatically develop and store the required waveforms or permit the operator to create and edit a waveform manually. Extensive use of modules and computers throughout TMX-U thus permits automation of the magnet power supplies and the gas-box control system.

The desktop computer in the magnet control system provides closed loop control, stores magnet operating cases, and displays system conditions. A set of modules in four CAMAC crates connects the computer, the power supplies, and the magnets (see Fig. 1). The necessity for a computer control system is illustrated by the size and complexity of the magnets: the 14.2-m-long, water-cooled magnet set has 24 coils weighing a total of 100 tons. The coils are connected in 17 separately controlled circuits,¹ which are energized by 36.9 MW of primary power. The circuits are operated at up to 1000 V and 5000 A (see Fig. 2). The result is a 2-Tesla field at the magnetic mirrors. The magnet set can accommodate a magnetic flux bundle diameter of 30 cm in the end plugs and up to 60 cm in the central cell.

In addition, early experimental results demonstrated the necessity for automatic control of the electronic valves that feed gas into the plasma

region. The system's eight valves must symmetrically feed gas from both ends into the plasma region at precisely controlled times. Thus, the electrical waveforms that control the valves are fairly complex. For these reasons, computer control of the gas-box system's valves became necessary. The computer system either generates the valve-control waveforms automatically or permits the operator to generate the waveforms manually.

Magnet power supply system

Each magnet power supply circuit is equipped with subsystems to measure total circuit voltage and ground fault impedance (GFZ). GFZ measurements are particularly important because they provide data about the condition of each magnet and its insulation while it is running. The GFZ subsystem measures impedance continuously with a custom, high-impedance, high-voltage (200 V) ohmmeter connected between one of the magnet leads and ground. The 200-V power supply provides excitation needed for measuring the impedance between shots, and the actual magnet power provides excitation during each shot. In the control room, a special circuit on a hardware safety module (independent of the computer) monitors the signal from the GFZ and will prevent operation of the magnet circuit if it is not within the preset limits. Most of the magnet circuits, including the dc portions of the power supplies, exhibit an insulation resistance greater than 2 M Ω .

Power supplies

The 42 power supplies are the foundation of the magnet power system. They were acquired over a period of 25 years, from 1956 to 1981. In

Fig. 1. Simplified block diagram of the TMX-U magnet power system. The four CAMAC crates connect the computer, the power supplies, and the magnets and permit the operator to control the magnets and power supplies from a remote, central location.

Fig. 2. Magnet arrangement inside TMX-U. The magnet set is 14.2-m long and has 24 coils weighing a total of 100 tons. The magnet coils can be controlled from any of 17 separate circuits and can produce a 2-Tesla field at the magnetic mirrors.

Fig. 3. The magnet power portion of the north TMX-U control room. The operator can control and observe the magnet system's performance by using the HP 9835 computer (located at left). Also located in the control room are the four CAMAC crates, a fast printer, and miscellaneous monitors. The oscilloscopes at left are used to observe the current waveforms.

spite of their age differences, the older supplies only needed minor modifications to present similar requirements to the control system. Each supply is located either on an outside pad or in a building separate from the main TMX-U experimental building at distances ranging from 25 to 125 m. (These distances result in line losses and make the control problems more difficult.) Each supply's power output ranges from 150 to 600 kW. They each have one wye and one delta transformer and two sets of full-wave, three-phase bridge rectifiers to provide 12-pulse operation, resulting in predominant ripple frequencies of 360 Hz and 720 Hz. All supplies use 480-V, three-phase, 60-Hz primary power, which is delivered from seven separate substations. All are equipped

with detectors that indicate proper phase rotation (or loss) and line voltage above a preset minimum.

Each supply has a remote-trip circuit breaker and a contactor. All use water, air fans, or both for cooling and are equipped with the appropriate flow switches. When these, as well as door and other miscellaneous interlocks are closed, the power supplies are ready to operate. In addition, 31 power supplies are equipped with silicon-controlled rectifiers (SCRs) to adjust the operating current. The SCR-controlled supplies have gate controls and require a reference signal to operate. Control power is obtained from a separate instrumentation substation and is not affected by 480-V primary power line drops when the magnets are

running. All of the supplies report dc output voltage and current to the control system; between one and five are connected in series with each magnet circuit.

Magnet computer control cycle

The control room, shown in Fig. 3, provides a convenient place for the operator to control the magnet system and to observe its performance. The control room has a computer, four CAMAC crates, a fast printer, oscilloscopes for observing current waveforms, and miscellaneous monitors.

An HP 9835 computer is the heart of the magnet control system. It controls the magnet current by sending a reference signal to the power supplies. Once this signal is sent, local analog control loops in the supplies provide the requested current. The computer reads back the actual current, and if it is not within 1% of the requested value,

the computer revises the reference signal for the next shot. The system can thus correct automatically for changes in such factors as offsets, gains, and temperatures. Data from the power supplies and magnets are displayed for the operator on a per-circuit basis, as shown in Fig. 4. A summary log (Fig. 5) is printed at the end of each shot.

Routine monitoring is handled by the computer, but matters critical to magnet safety (such as ground faults, arcs, over-voltages, over-currents, or current on too long) are also monitored by separate hardware safety circuits. The safety circuits can respond faster than the computer and continue to function if the computer fails. The computer routinely monitors the power supplies to see if they are ready and monitors the magnet temperature. For example, the computer will not permit operation if magnet temperature is less than 2 or greater than 85°C. Finally, the com-

```

Date: 10:13          TMX MAGNET POWER SYSTEM STATUS          Time: 11:27:31
Operator: SCOTT      SEQ #: 20      Configuration: Hand Entered Setup
System:              Circuits:      RCPwr: Ready      Timing: Local
Thermal Printer: 1   Set Up: Auto

      ***** Information from Last Shot#: 27 *****
Circuit Number: 3   Name: East & West   Plug Ioffe
Requested Current:  3095 Amps      Expected Voltage: 1060 Volts
Actual Current:     3074 Amps      Actual Voltage: 1011 Volts
Ground Fault Impedance: 60 Kohms   Circuit Safety Level: 0 %
Total Circuit Resistance: .329 Ohms. Res. Trip Level: 80 %

**** Power Supply Status ****
Magnet Circuit: ONLINE

PS#  Volts      Status
--  -
30   196   ON   CP ON   READY   DC OK
31    0    ON   CP ON   READY   DC OK
32   200   ON   CP ON   READY   DC OK
33   203   ON   CP ON   READY   DC OK
34   291   ON   CP ON   READY   DC OK

**** Magnet Coil Status ****
Type: Plug Ioffe
Impedance: L= 76.0 mH R=161.0 ohm
East Coil: LCM Temp= 17°C Flow: ON
West Coil: LCM Temp= 14°C Flow: ON

```

Fig. 4. Typical display screen on the TMX-U magnet control system. The display shows the performance of each power supply (lower left) and each magnet coil circuit (lower right). In addition, the display shows the operator the requested and actual currents, the ground fault impedance, the magnet resistance, and the expected and actual voltages.

Operator: ROBERT GEER

Seq #	Date	Time Error	Circuit Number	Current Rqst	Current Actl	Voltage Exp	Voltage Act	GFZ Kohms	Power 0	Supply 1	Supply 2	Voltage 3	Voltage 4
Configuration: UPHA													
	9 01:14	11:07:08											
		- .54%	1	4515	4491	647	590	8614	190	241	242		
		- .07%	2	4494	4491	293	249	9260	12	238			
		.09%	3	3095	3098	976	955	35	237	267	267	265	OFF
		- .18%	4	4494	4486	341	314	9140	24	174			
		- .10%	5	4511	4507	699	643	6094	257	146	295		
		- .22%	6	3438	3431	73	69	7039	71				
		- .10%	7	2459	2457	232	221	6660	82	148	OFF		
		- .23%	8	4408	4398	333	321	11475	127	112	107		
		.82%	9	1136	1145	90	64	8296	100				
		.79%	10	3199	3224	233	142	5226	93	147			
		.20%	11	1971	1975	165	111	6821	44	82			
		.44%	12	1450	1456	114	73	1574	41	79			
		- .28%	13	4408	4396	309	250	3765	46	125	132		
		.42%	14	2459	2469	233	209	5430	95	122	OFF		
		.38%	15	3438	3451	74	66	8414	72				
		.01%	16	4511	4512	684	621	3357	82	258	282		
		- .45%	17	4515	4495	658	579	6644	207	242	239		
T488 = 467V, T489 = 463V, T484 = 462V, T145 = 472V, T561 = 449V, T705 = 464V, T151 = 403V.													

Fig. 5. An example of the summary log printed after each shot. The values shown are those of a typical good shot. About 50% of the shots are within 1%, and about 90% are within 1.5% of the requested values.

Fig. 6. The gas-box control system in simplified form. This block diagram shows the CAMAC interfaces, with function generators and transient recorders, between the computer and the valve assemblies. The computer loads the waveforms needed to control the valves into the function generator as 2048 points.

puter synchronizes and controls the timing of the shot with the rest of the experiment through a timing computer.

All interfaces between the computer and the rest of the system are CAMAC modules. The safety modules are in CAMAC crate number 2; the analog modules, containing analog-to-digital and digital-to-analog converters are in crate 3; digital input and output modules are in crate 4; and miscellaneous monitors, display drivers, and a watch-dog timer to shut down the magnets if the computer fails are in crate 1.

Grounding and shielding

To achieve a current accuracy (and thus magnetic field accuracy) of within 1% of the desired values, it was necessary to decrease the noise and circulating currents associated with previous systems. Several techniques were used to accomplish this. For example, the power supplies and magnets float electrically. In addition, all voltage and current monitors and the GFZ monitor are isolated from the magnet circuits with isolation amplifiers, and digital signals are isolated with relays. All control cables are individually shielded, twisted-pair cables and are run in separate instrumentation conduits. In the control room all shields are grounded, and the isolated signals are referred to ground.

Gas-box control system

The first gas box had eight valves, all located on the west end of the machine between the plug and transition regions. But early results suggested that symmetrical gas feeds from both ends were desirable. In addition, fairly complex flow profiles are necessary to provide the gas at the proper time during a shot. Thus, the eight valves are located on simpler gas boxes on both the east and west ends of the machine, at the original location as well as between the transition and central cell regions.

Figures 6 and 7 show the present gas-box control system hardware. The simplified block diagram of Fig. 6 shows the CAMAC interfaces between the computer and the valve assemblies. Figure 7 is an exploded view of a valve assembly mounted inside the machine. The piezoelectric valve is at the bottom. The storage volume, with its cooling lines that keep the gas at a constant temperature, is in the center. Visible on the left side is the gas inlet, which contains a filter and a restricting orifice. Pressure transducers at the top

of the assembly report pressure drops in the storage volume back to the computer. All of these parts are made of stainless steel.

Valve computer control cycle

A desk-top computer generates, modifies, and stores the waveforms that drive the precision piezoelectric leak valves. The waveforms are output to function generators, which then control the valves. The valve pressure data are reported from Baratron pressure transducers and are analyzed, displayed if desired, and compared with the requested waveform. The computer-controlled operation of the valve-control system elements is detailed below.

Fig. 7. Exploded view of the valve/transducer assembly. The piezoelectric valve (bottom) injects the gas (obtained from the inlet, shown left center) into the vacuum chamber at the proper location with minimum conduction loss. The storage volume (center) also has cooling lines to keep the gas at a constant temperature. The pressure transducer (top) reports pressure drops in the storage volume back to the computer.

The computer, an HP 9836, uses a BASIC program called CREATE to produce the waveforms needed to control the valves. (CREATE is described below.) Because of the rapid signal speed required, the computer cannot simultaneously output the eight signals directly to the valves. Instead, the computer is connected to function generators mounted in the CAMAC crate and loads each of the eight waveforms into a function generator's memory as 2048 points. At the proper time in the shot sequence, the master timing system triggers the function generators, and the points are output through integral D-to-A converters. Because the function generators produce only ± 5 -V signals, operational power supplies are used to drive the 0- to 250-V signals to the valves. The function generators and operational power supplies both have 2-kHz bandwidths.

The valve/transducer assemblies are mounted inside the vacuum system so that the gas can be injected at the proper location with minimum conduction losses. The storage volume is 71 ml, and the supply pressure is usually controlled to between 100 and 400 Torr. The original specifications required that the computer generate one waveform for all valves, with provisions for minor variations. As the design developed, it became clear that each valve could respond to a unique waveform. Now, separate waveforms for each valve are used to produce different flow rates at different locations and to accommodate varying valve characteristics. The valves can be opened or closed in 2 ms and will respond to any arbitrary waveform with amplitudes between 70 and 250 V. (To provide a reliable seal, the valves are adjusted so that they will not open below 70 V.) They are usually operated for 65 to 80 ms.

The Baratron pressure transducers, mounted on the valves, can indicate pressure changes of less than 0.1 Torr. They use a capacitance manometer technique to produce a signal. The data from the transducers are digitized and recorded in the transient recorder while the valves are being operated. After the shot, the computer reads in the data from the transient recorder and differentiates the pressure data to produce flow-rate data. The flow-rate data are then compared with the requested flow rate and can be plotted either on the CRT screen or on the hard-copy plotter. The data from the transient recorder are also read by the TMX-U diagnostic computer and become a part of the permanent data archive.

Software system

The gas-box control computer uses two programs, both written in BASIC, to perform all control and reporting functions. The CREATE program is run at the beginning of each day to characterize the valves and produce the actual valve waveforms from the desired flow rates. The CONTROL program is then run to control the valves during actual experiments.

The CREATE Program. CREATE develops and stores the function generator waveforms needed to control the valves that feed gas into the plasma region at rates specified by the physics shot leader for a particular experiment. For example, a typical thermal barrier experiment may require a moderate initial gas feed (15 Torr-L/s) for the first 30 ms of the shot, then a high gas feed (60 Torr-L/s) for the next 20 ms, and finally a low gas feed (8 Torr-L/s) for the duration of the plasma. This gas feed needs to be distributed evenly among the valves. Since the valves do not deliver the same flow for a given voltage, they must be individually characterized and the eight waveforms stored for each requested flow configuration. A typical waveform for the thermal barrier experiment is shown in Fig. 8. The 250-V pulse for 3 ms before the shot is necessary to open the valves.

The individual waveforms were generated from the results of a series of approximations and corrections that converged to values representing the desired flow characteristics. The first step in this process was the measurement of each valve's response to two calibration voltages: 230 and 90 V. Baratron response for these two pulses was used to compute the corresponding flow rates; the first approximation at the voltage necessary for the desired flow rate was simply a linear interpolation between these two measurements. Waveforms built from these first approximations were then delivered to the valves, and the process of computing the flow rates, correcting the waveforms, and testing the results was repeated. After four to six tries, the flow converged to within 10% of the desired value. The waveforms were then stored for recall during the experiment.

A process illustrated in Fig. 9 complicated the conversion from pressure measurements made with the Baratrons to the rates of flow into TMX-U. The figure shows the Baratron pressure transducer's response when a 200-V pulse was applied to a valve for a duration of from 10 to 85 ms. The small

Fig. 8. Typical waveform used for a thermal barrier experiment. Because the valves do not deliver the same flow for a given voltage, a waveform for each valve is created and stored in the computer. The waveform will vary in amplitude depending on the gas feeds and durations needed for a particular shot.

Fig. 9. The Baratron response from a 200-V pulse applied to a valve for 10 to 85 ms. The process of converting from pressure measurements made with the Baratrons to the rates of flow into TMX-U is quite complex; however, an approximate refill rate can be compiled by fitting a second-order equation to the refill data after the valve is closed. This refill is then added to the flow measured with the valve open to obtain the actual flow into TMX-U.

Fig. 10. The CONTROL program data flow. The CONTROL program controls the valves during actual experiments and performs more general functions, including manual entry, editing, and storage of waveforms.

volume (0.071 L) where the Baratron was located had two openings. One was into the TMX-U plasma region through the piezoelectric valve, the other into the manifold that refilled the small volume. The pressure in the volume increased after the valve was closed because of refill from the manifold. The slope of the curve after the valve was closed is the refill rate. Unfortunately, the slope of the curve from 10 to 85 ms is the difference between the flow rate into the plasma region and the refill rate. An approximate refill rate can be computed by fitting a second-order equation to the refill data obtained after the valve was closed on the 230-V calibration pulse. This refill was then added to the flow measured with the valve open to obtain the actual flow into TMX-U.

The CONTROL Program. The CONTROL program controls the valves during actual experiments. It also performs the following general functions:

- Permits manual entry or creation of a waveform.
- Edits and displays a waveform.
- Stores waveforms.
- Loads the function generators.
- Operates the valves.
- Reads the transient recorder.
- Analyzes the data.
- Displays or plots raw or processed data.
- Automatically adjusts the control waveforms.

The operator can select any or all of these functions. In addition, the operator can either fire the gas box locally or have it fired by the master tim-

ing system. Figure 10 is a data-flow diagram of the program.

Conclusion

Both the magnet power control system and the gas-box control system on TMX-U have proven very reliable and work well within their design specifications. The log of Fig. 5 is that of a typical good magnet shot. About 50% of the shots are within 1%, and about 90% of the shots are within 1.5% of the requested value. The gas-box system works within 10% of the requested value.

Acknowledgments

A great deal of the credit for the performance and reliability of these systems goes to the technicians who installed them, and who now maintain, calibrate, and operate them: Scott Hulsey, Bob Geer, and Dennis Wilson. Also, thanks to Maria Lopez and C. D. Judd for their help in preparing this paper.

Reference

1. M. Calderon, A. Chargin, and T. Moore, *Construction and Operational Experience of the Tandem Mirror Experiment-Upgraded*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-88987 (1983).

NESD supports three areas of the Defense Systems Program—Nuclear Design, Military Applications, and Weaponization—and provides electronics support to substantial parts of Physics, Chemistry, and the Mechanical Engineering Department.

Richard Twogood, Nuclear Energy Systems Division Leader

NESD provides expertise in the design and construction of pulsed-power systems, computer systems, high-speed diagnostic and low-level instrumentation systems, electro-optical systems, control systems, and high-current accelerator technology. Over the past ten years, NESD's charter and customers have remained fairly constant. The division has, however, seen a number of administrative changes. It has gained three groups: one designs and develops machine control systems, the second supports Military Applications' mission simulation studies and analyses, and the third works on weapon platform studies for the strategic defense systems. The division has also gained responsibility for the EE Department's pulsed-power and microwave research and development program.

Although NESD's 185 people work on a variety of projects and programs, the division's main customer is and has been the "Weapons" (Defense Systems) Program. NESD contributes to five phases of the weapons cycle, as follows. In phases I and II, conceptual and feasibility studies, NESD works with weapons designers, studying and testing physics and engineering solutions to military problems. In Phase III, full-scale engineering development, the division helps weapons engineers test a weapon's physics package and associated support-structure hardware to verify that the design meets military requirements. During this phase, NESD engineers also participate in designing, testing, and evaluating electronic firing, safing, and control systems. When a weapon is engineered for production in Phase IV, and manufacture is initiated in Phase V, and moves into quantity production in Phase VI, NESD helps weapons engineers specify and oversee tests made during manufacturing and responds if problems occur with electronics systems in the production line. Once the weapon is in the stockpile,

NESD participates in evaluating quality assurance and reliability tests for the firing systems.

Ten years ago, the division was busy working on five weapons systems that were in development and production: the B-77 bomb, the W-84 cruise missile warhead, the W-70 Lance warhead, the W-79 8-in. artillery shell and the W-82 155-mm artillery shell. It was also working on a project to design a non-nuclear, hard-structure munition for the Department of Defense. In general, the past eight years have seen a strong emphasis on full-scale engineering and development, with less emphasis on developing new ideas or concepts. This was a time to deliver ideas in concrete form.

As a part of this emphasis, NESD was developing and upgrading facilities that would help weapons designers test high-explosives assemblies of devices. In Phase III, mechanical assemblies are tested at Site 300's environmental test facilities, which include thermal chambers, a vibration testing facility, and a mechanical shock testing facility. The Site also has facilities for testing the hydrodynamic design of high-explosive

... the past eight years have seen a strong emphasis on full-scale engineering and development ... This was a time to deliver ideas in concrete form.

assemblies. NESD is responsible for the design, fabrication, and maintenance of the instrumentation, controls, and computerization of two complex bunker facilities used to make hydrodynamic measurements of the high-explosive systems of devices. One of these bunkers, Bunker 801, was marked as the site for the Flash X-ray Facility (FXR): a large, pulsed, radiographic system. FXR is based on a 20-MeV linear-induction electron accelerator that produces up to 500 R of Bremsstrahlung.

lung x rays 1 m from the machine's front end. Ten years ago, FXR was in the planning and funding stages. The facility was funded as a congressional line item at \$11.8 million in 1977 and was completed in 1982. FXR is now operating and providing weapons designers with more insight into the hydrodynamic performance of high-explosives assemblies.

The upgrade of Bunker 801 continued through 1985 as NESD engineers added advanced diagnostic instrumentation and a sophisticated computer control system. NESD designed and installed Fabry-Perot laser interferometers to measure material velocities, raster-oscilloscope pin systems to measure material positions with nanosecond resolution, and other systems to gather

... engineers have used these (computer) tools ... to model complex pulsed-power and detonator firing systems.

high-speed timing information. The computer control system is a state-of-the-art distributed LSI-11 system that controls the bunker countdown and provides personnel safety. When possible, the division took advantage of commercially available systems; however, much of the hydrodiagnostic equipment was specialized and was designed and produced in-house.

NESD has also supported critical technologies that contribute to the Defense Systems Program, such as materials testing and analysis, precision machining, and chemistry. Within the last ten years, the division has worked with mechanical engineers to develop improved high-precision machines, such as the Precision Engineering Research Lathe (PERL 2), the Large Optics Diamond Turning Machine (LODTM), and the Diamond Turning Machine 3 (DTM-3). Other projects have included providing electronics support to the design and development of the Ultrasonic Test Bed (UTB), and providing tools to conduct computerized testing of materials.

NESD, as other EE divisions, has been influenced by the computer revolution. From the MCS-4 in 1971, to the present LSI-11, to the upcoming microVax, the division has integrated state-of-the-art computers into the systems it de-

signs. NESD used computers to make "smart" instruments, to automate chemistry labs, to provide computer-aided testing of materials, and to control precision machines. The division has also taken advantage of sophisticated computer tools to ease the tasks of its engineers. NESD engineers have used these tools—including two- and three-dimensional static and dynamic electromagnetic field codes, particle and field codes, and electronic

NESD is now working on ... conceptual studies on "Star Wars" systems ... and testing new ideas for nuclear directed-effects weapons.

circuit codes—to model complex pulsed-power and detonator firing systems.

When we look at NESD's present and future tasks, we find that the emphasis has shifted from what it was at the decade's start. Most Phase III projects are completed. In the Defense Systems Program, it is a time of ideas. NESD is now working on Phase I and II projects such as conceptual studies on "Star Wars" systems for the Strategic Defense Initiative (SDI), and is testing new ideas for nuclear directed-effects weapons. The division is exploring new technologies, such as the microwave technology exemplified by MGX, a high-powered microwave source that generates 300 MW at 7.5 GHz. Also nearing completion is a 2-MV, 0.5-TW accelerator that will be used in plasma physics and high-power microwave experiments.

It is a time for expanding the frontiers of research and applications. NESD is helping to design and construct the High Explosives Applications Facility (HEAF) which will be used to apply explosives technology to nuclear weapons problems. NESD is responsible for HEAF's "special (electronic) facilities" which include flash x-ray machines, laser interferometers, and high-speed cameras. NESD will also specify and integrate computer systems to control the high-explosives inventory and provide data acquisition and reduction functions.

The article that follows is an example of the division's current work in microwaves. The VIRCATOR (Virtual Cathode Oscillator) is a laboratory-scale microwave generator used to study the generation of high-power microwaves.

Experiments with a Virtual Cathode Reflex Oscillator

R. D. Scarpetti and S. C. Burkhart

At LLNL we have been experimenting with a VIRCATOR (virtual cathode oscillator), a device for generating high-power microwaves. Potentially, a VIRCATOR can produce microwave output power in the multimegawatt range at frequencies of a few to tens of gigahertz for short periods of time (typically ten to several hundred nanoseconds). We are presently producing 200 to 300 MW at frequencies of 6 to 9 GHz for 40 to 60 ns. We have extensively modeled the performance of the VIRCATOR with CONDOR, a particle-in-cell computer code and have found good agreement between model and experiment.

Principles of operation

The VIRCATOR microwave generator is a reflex triode oscillator that includes both a real and a virtual cathode (Fig. 1). Electrons emitted from the real cathode pass through a wire-mesh or thin-foil anode into a waveguide. As the electrons pass into the waveguide, their kinetic energy is converted into field energy. The space charge of the injected electron beam forms a potential (voltage) well in the waveguide that grows in magnitude as the space charge accumulates. When the magnitude of the potential well exceeds the energy of the electron beam, a virtual cathode forms in the waveguide, reflecting electrons back toward the real cathode.¹ As the virtual cathode loses electrons, its potential declines until it drops below the energy level of the injected electrons, enabling them to pass the potential barrier. The fresh injection of electrons once again causes the potential well to develop into a virtual cathode, thereby repeating the cycle.

Microwaves are generated in the waveguide both by the virtual cathode as it oscillates in space and time and by the reflected electrons as they oscillate between the real and virtual cathodes. The frequency oscillation of the virtual cathode is proportional to the square root of the electron density. The frequency of the reflected electrons is roughly determined by their round-trip transit time between the real and virtual cathodes. These two frequencies may be quite distinct, and can be observed independently.

VIRCATOR system

Figure 2 shows the VIRCATOR's diode-waveguide assembly and its pulsed power source. The power source consists of a 10.8- Ω , water-dielectric Blumlein pulse-forming line that produces a 90-ns voltage pulse. The Blumlein is resonantly charged in 1 μ s by a Marx generator (a voltage multiplier) that can be charged to 100 kV per stage and can store 14 kJ of electrical energy. A series water gap suppresses the charging prepulse and reduces the rise time of the output voltage pulse. At peak charge, the Blumlein is command-triggered through a coaxial spark-gap switch pressurized with SF₆ gas. An energy diverter switch consisting of several self-breaking water switches reduces late-arriving energy to prevent damage to the diode. The water is isolated from the vacuum in the diode (typically 2.66×10^{-3} Pa) by a machined epoxy insulator that is shaped to give optimal hold-off voltage. A stainless steel cathode is used for most experiments. To enhance the electric field at the emitter surface and ensure a uniform density of electron emissions, the 38-mm-diam cathode has been machined with circular grooves 5 mm apart (Fig. 3). Anodes of stainless steel mesh (with transparencies of 60 and 84%) and pure aluminum foil (7.6, 12.7, and 25.4 μ m thick) have been tested. Most of our tests have been done at an anode-cathode gap spacing of 8.6 mm.

Peak diode voltage and current are 500 kV and 44 kA, respectively, with a 25-ns rise time.

Fig. 1. Operating principles of a VIRCATOR. The darkness of the pattern here represents relative electron density. (a) Electrons emitted by the cathode pass through the anode into a drift region. (b) The electron-beam current is greater than the space-charge-limiting current, and a potential well begins to grow as the kinetic energy of the electrons is transformed into field energy. (c) When the well potential exceeds the energy of the injected electron beam, a virtual cathode forms, and the electrons are reflected back toward the anode as their kinetic energy becomes zero at the virtual cathode. (d) The virtual cathode diminishes, once again permitting electron transport. The potential well again begins to grow and the cycle repeats.

Figures 4a and b show typical waveforms. Voltage is monitored with a capacitive probe located near the diode in the water-filled transmission line,

and current is measured with a resistor band located on the anode.

The cylindrical waveguide is 85 mm in diameter and could be made as long as 8.5 m. The microwave power is extracted axially from the waveguide. We considered, but rejected, transverse extraction, because it requires three-dimensional computer modeling. Axial extraction, in contrast, lends itself well to two-dimensional modeling. A terminator at the end of the waveguide minimizes microwave reflections during an experiment.

Diagnostics

The primary diagnostic instruments for measuring microwave output are a series of electric field probes, which are recessed in the waveguide wall about 1.6 m from the diode (Fig. 5). The probes measure the strength and frequency of the radial electric field of the passing microwave pulse. (A dispersive line to measure frequency and a microwave calorimeter to measure total microwave energy were tried with limited success.) The probes extract microwave energy from the waveguide and send it to a directional coupler, which diverts 10% of the microwave pulse. The signal is then rectified by a diode detector and recorded on fast digitizers. By examining that record, we can determine the strength of the waveguide pulse; however, the frequency of the pulse is lost during the diagnostic process. To determine the frequency, we pass the undiverted 90% of the original pulse through several other directional couplers, each diverting a further 10% of the pulse. Each diverted signal is then fed through a bandpass filter 0.5 GHz wide. The filter passes only those frequencies that match the bandpass filter frequencies. The filtered output is then fed to a diode detector to be rectified and then is once again recorded by digitizers. By examining that record, we can determine the frequency of the waveguide pulse.

The system is calibrated using a low-power continuous microwave source and the coupling is measured for 6 to 9 GHz. A pulser puts a 2-ns-wide time marker on the diode voltage and current traces, as well as on the microwave output traces, making cross timing possible.

Modeling the VIRCATOR

We have done extensive simulations of the reflex triode oscillator using CONDOR, a time-dependent, relativistic, particle-in-cell computer

Fig. 2. VIRCATOR assembly. In the VIRCATOR microwave generator, a water-filled Blumlein provides a 450-kV, 90-ns pulse to the diode, producing a 38-kA electron beam. A virtual cathode forms in the waveguide beyond the anode, generating microwaves that propagate down the waveguide. A carbon cone at the end of the waveguide acts as a terminator to absorb the microwaves during experiments.

Fig. 3. Circular grooves in the stainless steel VIRCATOR cathode, machined about 5 mm apart. The grooves enhance the electric field at the surface and ensure that electrons are emitted with a more uniform density. The radius of the cathode is 38 mm.

Fig. 4. Typical waveforms generated by the VIRCATOR. The voltage waveform (Fig. 4a) rapidly reaches -500 kV and then returns to zero, resulting in a pulse width of 70 ns. The associated current waveform (Fig. 4b) increases more slowly than the voltage due to diode inductance. The current remains flat for 60 ns before going to zero. Figure 4c shows the microwave output for frequencies ranging from 3 to 15 GHz. To determine the specific frequency of a pulse, the microwave signal is passed through several 0.5-GHz-wide bandpass filters. Figure 4d shows the output from a filter that only passes those pulses whose frequencies range from 7.25 to 7.75 GHz. The single peak shown in the figure corresponds in time to the larger of the two peaks in Fig. 4c. The smaller peak in Fig. 4c corresponds to microwave output between 6.75 and 7.25 GHz. All traces are aligned in time using the time marker signal seen at 140 ns.

Fig. 5. Microwave diagnostics system for the VIRCATOR. Probes mounted in the waveguide wall are used to measure the radial electric field generated by the microwave pulse. The signal passes through attenuators that decrease the signals to useable levels. Directional couplers are used to divert fractions of the signal, which are then sent through bandpass filters and diode detectors. The bandpass filters determine the frequency while the diode detectors change the oscillatory signal to dc so that it can be recorded on fast digitizers. A 2-ns pulser provides the time marker to all digitizers.

code. CONDOR, which is two-dimensional, performs calculations in three-dimensional momentum space.² Figure 6 is a radial section of the problem's geometry. A transverse electromagnetic wave with a 1-ns rise time is introduced from the left to drive the cathode negative. The dimensions of the input port define an impedance of $10.8\ \Omega$ to match that of the experiment. The 500-kV/cm electric field produces space-charged-limited emission from the cathode toward the anode. The code specifies the cathode face as the only emitting surface.

The electrons pass through the anode into the waveguide and establish a virtual cathode. The oscillating electric fields propagate down the waveguide and are absorbed by a lossy medium to prevent reflections from perturbing either the microwaves generated or measurements of the electric field. The lossy medium, shown as a resistor block in Fig. 6, is modeled as a low-conductivity block that simulates a standard, low-reflection microwave terminator. In the code, the electric and magnetic fields are measured by probes in the waveguide wall just before the terminator. The output power is the Poynting flux integrated over the Poynting surface (cross-sectional area) of the waveguide. A dielectric surface is positioned upstream of the Poynting surface to prevent electrons from passing through and adding to the measured microwave power. Results of the simulations are in good agreement with the experiment.

Experiments with the VIRCATOR

We have conducted a series of experiments with the VIRCATOR, the results of which are in

good agreement with our computer simulations. The microwave output shown in Fig. 4 is typical of the performance of the VIRCATOR. The output signal is passed through a wideband filter to detect frequencies from 3.5 to 15 GHz (Fig. 4c) and through a bandpass filter with a 7.25- to 7.75-GHz bandwidth (Fig. 4d). All signals are correlated in time. The output in Fig. 4c shows that oscillation frequency increases with time, a result of the slow rise time of the current (Fig. 4b). As the current rises and the voltage falls, the electron beam converges toward the axis, increasing the electron density, which, in turn, increases the oscillation frequency of the virtual cathode (recall that the frequency of the virtual cathode is proportional to the square root of electron density). Cathode plasma propagation may also increase the oscillation frequency by effectively decreasing the cathode-anode gap and thereby increasing the electron current density.

The output in Fig. 4c also shows that power peaks at 225 MW between 7.25 and 7.75 GHz. Our computer simulations (Fig. 7) are in good agreement with the experimental results: power peaks at 220 MW at 7.2 GHz. The symmetry of the microwave mode is checked by comparing the microwave output from two probes located 90° apart (Fig. 8). As can be seen from the figure, the two tracks are similar, meaning that the microwave mode is symmetric about the azimuth.

Electron beam trajectory study

To better understand the cathode and virtual cathode behavior, we have measured the trajectory of the electron beam as it converges toward the axis (pinches) with a technique that measures emittance.³ A tantalum plate greater than one

Fig. 6. Geometry of the calculational model used to simulate VIRCATOR operation. The electron absorber stops electrons from reaching the Poynting surface and affecting measurement of microwave power.

Fig. 7. Output from the computer simulation code, CONDOR. The code predicts that the microwave output will peak at 7.2 GHz. This is in good agreement with experimental results.

Fig. 8. Output signals from two probes that form a 90° angle with respect to each other. The overlaid signals show that the microwaves are symmetric about the azimuth.

electron range thick is riddled with a pattern of small holes that allows only those electrons through that are converging toward the axis. The plate is then placed at or immediately behind the anode. The electrons that pass through the holes strike a phosphor screen and cause it to fluoresce, and the resulting light is recorded on film. By noting the radial position of the electron beam at the phosphor, and comparing it to the radial position of the hole on the plate, we have determined that the angle of the trajectories is 30 to 35°. We have also used the computer simulation code, EBQ (Ref. 4), to determine the angle of convergence. The results are shown in Fig. 9 and are in good agreement with our experiment.

Application of an external axial magnetic field

In the VIRCATOR experiments, as the electrons oscillate between the real and virtual cath-

odes, some escape from the oscillation region and move toward the wall of the waveguide. In an attempt to increase the microwave output power of the VIRCATOR (by keeping the electrons in the oscillation region), we applied an axial magnetic field. While the field forces the electrons to remain in the oscillation region, it has a detrimental effect: the microwave output decreases as the magnetic field strength increases from 0 to 1200 G. Specifically, when a 1-kG magnetic field is applied, microwave power drops 25 to 40% (Fig. 10). We therefore conclude that our attempt to keep the electrons in the problem by applying a magnetic field actually degrades the virtual cathode and lowers its ability to generate microwaves.

Angular scattering of electrons

As an electron passes through the anode, it experiences a change in momentum normal to its incident direction. By degrading the quality of the

Fig. 9. Model of the behavior of VIRCATOR diode. The model was constructed using the simulation code, EBQ, a time-independent code that predicts the electron beam behavior. The figure shows the electron beam pinching as the electrons travel from the cathode to the anode.

Fig. 10. Effect of an axial magnetic field on microwave output power. When the field has been applied, the power decreases because the field keeps electrons, which would normally hit the waveguide wall, in the problem. These electrons degrade the operation of the virtual cathode, which decreases microwave production.

electron beam, such angular scattering can affect microwave production. We performed a study to determine the magnitude of this effect. We used two methods of estimating scattering: calculation from the appropriate scattering equations and computer simulation. The anodes used in both the calculations and the simulations were pure aluminum foils 25, 13, and 7.6 μm thick and stainless steel meshes with 84 and 60% transparency. Table 1 shows the results. The two methods produced similar values of scattering angle up to about 300 mrad, beyond which the equations are no longer valid.

In Fig. 11 the results of simulating microwave production with the same anodes listed in Table 1

are compared with experiments using similar anodes in the VIRCATOR. It is apparent that microwave power falls off as electron scatter increases. We demonstrated that loss of output efficiency is due to electron scattering and not to energy loss in the foil. Others, using anode foils of comparable thickness, have found little or no effect on output efficiency.⁵ However, the configurations used in such studies generate microwaves more by reflected electrons than by virtual cathode oscillation.

Finally, we attempted, unsuccessfully, to improve microwave output by applying an axial magnetic field. This result indicates that, at least in this configuration, the loss of microwave production is strongly tied to virtual cathode performance and not to the loss of reflected electrons. Because the virtual cathode is dramatically degraded by electron scattering, we conclude that a high-quality electron beam is necessary to efficient microwave production.

Table 1. Calculated and computer-simulated mean scattering angles for 500-kV electrons passing through various anode materials.

Anode characteristics	Calculated angle, mrad	Simulated angle, mrad
84% transparent mesh	44	— ^a
60% transparent mesh	87	— ^a
7.6- μm Al foil	166	163
13- μm Al foil	224	211
25- μm Al foil	336	297

^a Not simulated.

Reflected electrons vs virtual cathode

We have also performed computer simulations to isolate the respective contribution of reflected electrons and virtual cathode to microwave production. By varying the thickness of the anode, we were able to change the oscillation frequency of the reflected electrons without significantly affecting the oscillation frequency of the virtual

Fig. 11. Results of computer simulations (circles) compared with data from VIRCATOR experiments (triangles). The trends are clearly consistent, showing a decline in microwave power with increasing scattering angle.

cathode (although the virtual cathode is affected to some degree by coupling with the reflected electrons). Our study assumed a real cathode with a radius of 23.4 mm, a cathode-anode spacing of 5.6 mm, and an input voltage of 500 kV.

Figure 12 shows the microwave frequencies produced by a simulation using an anode 4.68 mm thick. Two distinct frequency peaks can be discerned, one at 9.8 GHz and the other, of greater amplitude, at 16.3 GHz. The oscillation frequency of the reflected electrons is crudely estimated by the inverse of the round-trip time of the electrons between real and virtual cathode. Assuming that the distance between real cathode and anode is the same as that between virtual cathode and anode, and that electrons travel at nearly the speed of light, c , the oscillation frequency is c/d_r , where d_r is the round-trip distance, equal to $2[(2 \times 5.6 \text{ mm}) + 4.68 \text{ mm}]$, or 9.43 GHz. This value corresponds nicely to the 9.8-GHz peak in Fig. 12.

The oscillation frequency of the virtual cathode can be derived from the nonrelativistic beam plasma frequency, which depends on the square

root of the electron number density. In the present simulation, this gives a virtual cathode frequency of between 6.5 and 16.3 GHz, corresponding to the second peak in Fig. 12.

As we reduce the thickness of the anode, the gap between the two frequencies narrows until they merge at about 12 GHz. At that point, the two oscillations lock and are indistinguishable from each other. The locking process appears to produce a microwave power spectrum that is purer and of higher power than either of the two frequencies alone.

In an actual VIRCATOR experiment, we used a cathode-anode gap of 8.6 mm to produce a reflected-electron frequency of 8.5 GHz. Assuming an electron density of $3 \times 10^{11}/\text{cm}^2$, the virtual cathode produces an oscillation frequency of 8.74 GHz, in close agreement with the reflected-electron frequency of 8.5 GHz. The two effects can be separated experimentally by using a honeycomb anode, which changes the transit time of the reflected electrons without changing the virtual-cathode frequency.

Fig. 12. Virtual-cathode oscillation frequency (16.3 GHz) and the reflected-electron oscillation frequency (9.8 GHz). The two frequencies are the result of a thick (4.68 mm) anode (Fig. 12a). As the thickness of the anode is reduced, the two frequencies move closer together and finally merge into a single frequency at 12 GHz (Fig. 12b), producing a purer and more powerful microwave spectrum than either measured separately.

Fig. 12. (Continued).

Summary

Our experiments with a VIRCATOR (virtual cathode oscillator) have shown that it can produce high-power microwaves (200 to 300 MW) at 500 kV for 40 to 60 ns. Our models of VIRCATOR performance are in good agreement with these experimental results.

In the experiments we have done using the VIRCATOR we have found that:

- An axial magnetic field degrades microwave output production.
- Microwaves are symmetrical about the azimuth.
- A high-quality electron beam is necessary if high microwave efficiencies are to be obtained.
- When the oscillation frequencies of the reflected electrons and the virtual cathode merge ("lock"), a microwave power spectrum is produced that is purer and of higher power than either of the two frequencies alone.

Acknowledgment

The VIRCATOR project is supported by Defense Sciences as part of its high-power microwave program.

Notes and references

1. D. J. Sullivan and E. A. Coutias, "Virtual Cathode Formation in an Electron Beam as a Bifurcation Phenomenon," in *Proceedings of the 4th Annual International Topical Conference on High-Power Electron and Ion Beam Research and Technology*, June 29-July 3, 1981, H. J. Doucet and J. M. Buzzi, Eds. (Palaiseau, France, 1981), vol. 1, p. 371.
2. The code is a derivative of one developed to study relativistic magnetrons; see A. Palevsky, G. Berkefi, and A. T. Drobot, *J. Appl. Phys.* 52, 4938 (1981).
3. A. Septier, *Focusing of Charged Particles* (Academic Press, New York, NY, 1967), vol. 2, p. 150.
4. A. C. Paul, *EBQ Code Transport of Space Charge Beams in Axially Symmetric Devices*, Lawrence Livermore National Laboratory, Livermore, CA, UCID-8005 (1978).
5. Private communications; M. C. Clark, Air Force Weapons Laboratory, Albuquerque, NM (July 1983), and J. Benford, Physics International, San Leandro, CA (March 1984).

Engineering Services Division

ESD is a diverse organization that provides general electronics services and support to the entire EE Department and to Lab-wide institutional areas.

Robert Long, Engineering Services Division Leader

ESD's charter is and always has been *service*. The division provides electronics-related services to both the EE Department and Laboratory "institutional" areas such as Security and Computation. ESD is unique in the department. Whereas most other divisions primarily support a given Laboratory program, ESD provides the expertise and services that "smooth the road" for all of EE. This is a common theme found at the heart of all ESD activities, whether fixing instruments and systems; building electronics equipment; developing electronics and computer systems; setting Lab-wide standards; evaluating components, units, and software systems; or providing publications support. No matter what the task, ESD's people are experts at delivering general solutions to electronics engineering problems. It is the largest EE division, with 239 employees and about 30 contract drafters and technicians.

Over the years ESD has tried various approaches to address the needs of its customers. At

... ESD provides the expertise and services that "smooth the road" for all of EE.

the start of the decade, ESD subscribed to the concept of "centralized engineering" in which requests came in and completed projects went out. Today that's changed. Along with its traditional "centralized" focus, ESD now proudly houses people with "concentrated, rentable expertise" who are loaned to areas or projects that need their special skills. For example, six fabrication technicians recently spent two months with an outside company helping the company build power supplies for the Laser Isotope Separation Program. In other areas, ESD staff members are "on loan" to help plot the future of the Laboratory's telephone and security systems.

Given all the areas and technologies it must support, ESD is, by necessity, very diverse. A look at the history of ESD's two arms—production services and engineering services—offers some examples of how ESD has been an integral part of many of the electronics engineering efforts in the department and throughout the Laboratory.

Production services provides services that are as in demand now as they were ten years ago, including drafting and documentation, fabrication, instrument services, parts inspection, and

ESD now proudly houses people with "concentrated, rentable expertise" . . .

manufacturing engineering. The jobs and tasks it has taken on reflect the changes in programmatic requirements during this time. In 1975, fabrication technicians were building units for the Shiva laser facility and power supplies for magnetic fusion. Later in the decade, they provided components for the electric roadway vehicle project, targets for the Rotating Target Neutron Source, and subsystems for the S1 computer project. Today, many of their jobs reflect LLNL's push to upgrade communications and security.

In instrument services, techniques changed and new skills evolved as programmatic requirements for complex computer systems and instruments increased. Technicians in 1975 used voltmeters and single- or dual-channel oscilloscopes to calibrate instruments and repair analog devices. Now, much of what comes in for service is "computerized" instrumentation. Technicians working on these complex systems diagnose system failures using logic analyzers that can sample and display up to 64 different signals at once. In the mid to late '70s, fabrication technicians used manually generated printed-circuit artwork to fabricate single- or double-sided boards with traditional components. Today, drafters design

complex pc artwork using the sophisticated ComputerVision design and drafting system, and technicians use this computer-generated artwork to fabricate multi-layered boards using surface-mounted components. Connections between components are made not with wires but by using the electrical characteristics of the board's various substrate materials to provide the necessary resistance, inductance, and capacitance.

Over the decade, the engineering services area of ESD has expanded the types of services it extends to others. This part of the division includes components engineering, institutional systems engineering (which supports LLNL's security and telecommunications efforts), design and manufacturing integration, systems development engineering, technical publications, and two recently added groups that provide computer support to LLNL's Computation Department and National Magnetic Fusion Energy Computer Center.

Today, drafters design complex pc artwork using the sophisticated ComputerVision design and drafting system . . .

Ten years ago, ESD engineers were working on a variety of projects, including the design of the MCS-8, and later, the MCS-80 microcomputer. These modular, general-purpose, 8-bit microcomputers were among the very first microcomputer "systems" and represented a radical departure from previous, nonmodular designs. ESD also was designing state-of-the-art security systems: an automated personnel-access control system called CAIN, which is still in use at the Laboratory, and a television intrusion-surveillance system for Site 300. Engineers were finishing the design of the first color TV recording studio for the Lab's Continuing Education program and developing electronic systems to increase the precision of numerically controlled machine tools, such as an "electronic corrector bar" used to machine mirrors for

(The MCS-8 and the MCS-80) were among the very first microcomputer "systems" and represented a radical departure from previous, nonmodular designs.

the Laser Program. ESD also started the Technology Transfer Program, an early technology trans-

fer that taught people outside LLNL about microcomputers.

As engineering technologies evolved, ESD evolved as well so that it could keep up with increasing demands. Much of ESD's engineering work reflected the growing dependence of the Laboratory on computers and their attendant technologies. Ten years ago, micro- and mini-computers were establishing a niche in the Laboratory's programmatic work, so ESD provided support and service for their use. The division primarily supported logic systems and discrete components as Stores-stock computer-related items. Then, with the coming of the microcomputer, the modular MCS-8 and -80 systems were added. Today, ESD supports Stores-stock computer systems—from personal computers to VAX systems—and their operating systems, software, and hardware. ESD personnel also work in the PC Store, which provides comprehensive support to all LLNL personal computer users. In the communications field, ESD recently specified and installed two satellite dishes, which will provide up-to-date communication links between LLNL and the world for education and televised seminars. ESD engineers are also assisting on OPMODEL, a communications link, which will permit LLNL and others in the DOE

Computer technology plays an ever-increasing role in almost every aspect of ESD's very diverse organization.

Weapons Complex to exchange information electronically.

Computer technology plays an ever-increasing role in almost every aspect of ESD's very diverse organization. Much of ESD's efforts are now aimed at servicing computers or computerized instruments, providing computer expertise to others, and installing computer-aided engineering and computer-enhanced tools for the division, the department, and the Laboratory.

The article that follows is one example of how the division is bringing the power and networking capabilities of computers into the daily work of the division and the department. ESD engineers developed a communications link between widely-used DEC systems and ESD's ComputerVision system. This link allows EE engineers using computer-aided engineering work-stations to exchange data with ESD designers.

A High-Performance Communications Link Between DEC's VAX and ComputerVision's Graphics Processor

K. Blackwell

A three-way venture in technology transfer has succeeded in forging a communications link between engineers and designers at LLNL. The link allows users of Digital Equipment Corporation computers to exchange engineering data rapidly with designers using ComputerVision's systems. The three organizations that agreed to share the technology are:

- ComputerVision, which shared proprietary information and computer hardware.
- LLNL's Engineering Services Division, which designed the communications link.
- The Department of Energy, which set up a unique way to transfer the technology to the private and public sectors—a way that could serve as a model for future cooperative ventures.

Introduction

At LLNL, engineers and designers spend an ever larger share of their time in front of their CAE (computer-aided engineering) or CAD (computer-aided design) workstations. Because of their need to exchange data rapidly between their workstations, a rapid data-exchange system, called VAX-CV FASTLINK, has been developed. The system, developed under the technology transfer umbrella, consists of hardware and software that enable engineers on DEC's VAXs to exchange data quickly with designers using ComputerVision's (CV) graphics processors.

Computer-aided drafting in the EE Department

The EE Department has been using CAD systems since 1978 to design and draft printed wiring boards (PWBs). As work called for increasingly complex designs, the Department installed CV's CADDs 4X system, which augmented our ability to draft schematics, PWBs, and circuit designs electronically.

Communications with other systems became more of an issue after CADDs was installed because it gave us the opportunity to move designs between systems electronically (by magnetic tape) rather than by paper pushing. (Magnetic tape was used because it was the only common thread among the various systems.) The two systems

"talked" to via tape were the electron beam recorder (EBR) and the Gerber photoplotter. The EBR read data from the magnetic tape and wrote directly onto 105-mm film. The photoplotter was used to prepare photo-tools, such as PWB artwork and front panel silk screens.

Computer-aided engineering

At the same time as the CAD system became a tool for drafting, engineers began to use computers more frequently in their designs. To meet the increased need for computers, the Department acquired more VAX systems, placing computing power directly in the hands of the engineers.

Concurrent with CAD and CAE growth was the growth of personal computers, which gave engineers and technicians even greater access to computing power. The PCs enabled engineers to design a system, simulate and model it, and, when it functioned to satisfaction, send design data to a CAD system to be turned into a real product. Sharing information by magnetic tape was now hindering communications because users needed to move data from PCs that did not have magnetic tape to systems that accepted only that medium.

Another communication problem arose because the PC workstations required a library of component parts that was compatible with the library that already existed on the CAD system. Thus, there was a possibility that each workstation would use its own unique library,

which would duplicate work already done and cause additional work to maintain compatibility with other workstations.

It was obvious that an efficient communication strategy was needed to complement the advances in both computer-aided engineering and drafting, and that magnetic tape was no longer satisfactory. We wanted to give users on either the VAX computers or the CAD systems the ability to send and receive data files, exchange messages, determine whether the communications link was error-free, and control the link. The next step, then, was to link the various systems so that it would be easier for designers to communicate with each other.

Cooperation with ComputerVision

Previous requests to private industry for help in developing a high-speed link among various computer systems had been unsuccessful for two reasons:

- Private industry was reluctant to participate, suggesting that such a venture might encroach on proprietary information.
- The Laboratory could develop the link, but had no interest in maintaining the software once the research phase was completed.

In the spring of 1984, the ESD's Design and Manufacturing Integration group agreed with ComputerVision's Communications Development group that we would jointly benefit by developing a fast link between CV computer graphics processors (CGP) and VAX computers. CV agreed to allow access to their FASTLINK detailed design data and to supply their CGP hardware and software. LLNL agreed to adapt the CV FASTLINK code to the VAX and to prepare data flow diagrams and structure charts for the code. This exchange indicated full commitment on both sides, and, after review by the DOE SAN office and legal departments from CV and LLNL, the project was under way.

Developing VAX-FASTLINK

To complete the project rapidly, we adopted the YOURDON structured approach for analyzing the CV-FASTLINK code. From this we were able to design, implement, code, and test the VAX-FASTLINK hardware and software (Fig. 1). Two design constraints were imposed on us: CV-FASTLINK software could not be modified, and

the VAX-FASTLINK software had to run on a VAX-750 or -780 computer, with a VMS operating system, version 3.6 (or more current versions). Our completed product met the requirements.

Analysis

The CV-FASTLINK software consists of approximately 10,000 lines of code written in FORTRAN/S, TPL, and Assembly languages. The communication code does not have the seven layers common to modern communications systems, where each layer is dedicated to a particular task; however, it does have an upper layer that runs on the CV processor and a link (communications) layer that runs on the programmable control unit (PCU) board. Our first challenge was to analyze both layers of the CV-FASTLINK software so that we could develop a design that would fit the VAX environment. We divided this task into four parts:

- First, we analyzed the CV-FASTLINK code line by line and produced structure charts, data dictionaries, and diagrams.
- Next, we developed a physical model for a generic fast link that was not dependent on any hardware or operating system.
- Then, we participated in analysis walk-throughs with CV engineers.
- Finally, we experimented with various software approaches to specific tasks on the VAX/VMS system. The approaches included:
 - Global sections [partitioning the code into pieces ("sections") and allowing data sharing between the pieces. The process is "global" because many sections can share the same piece of information].
 - Queueing input/output functions (lining up information in the right order to do a specific task).
 - Mailboxes for interprocess communication.

Hardware selection

So far we had created a physical model on paper of the CV-FASTLINK code and we knew that we wanted to run the code on the VAX computer. The next step was to choose a communications board. We eventually selected a communications board similar to the CV PCU board in that it:

- Provided speeds ranging from 9.6 to 460 kbits/s.
- Was based on a Z-80 microprocessor. This allowed us to move most of CV's PCU code with moderate modifications.

Fig. 1. Development of the VAX-FASTLINK code. The first step was to analyze what the CV code was supposed to do (specifications) and then analyze the code listings to figure out how the code accomplished its tasks. The analysis consisted of breaking down the source listings into structure charts, data dictionaries, and data flow diagrams so as to understand how the CV code was designed. Next we diagrammed the code's tasks and the logical sequence of those tasks. We ended up with a FASTLINK model that was independent of both the hardware and software used by ComputerVision; i.e., it could theoretically run on any system. In the next step, we examined the operating system (VMS) on the VAX and the code that controlled communications of the VAX (ACC-UMC) and combined that with our logical model in order to derive structure charts, data flow diagrams, and a data dictionary for the VAX system. Based on those charts and diagrams, we wrote and tested ("implemented") the VAX-FASTLINK code. The code consisted of a library of software routines and three communication layers (application, session, and link). As part of the process we also prepared manuals for users and programmers.

- Interfaced to the VAX-UNIBUS backplanes (the connectors that the PCBs plug into).
- Had an RS-449 hardware interface.
- Supported the CV-SDLC communications protocol.

The only board that met these requirements was the UNIBUS Micro-Communications (UMC) board from Advanced Computer Communications (ACC). This board allowed us to link a VAX and a CV that were as much as 2000 ft apart.

Design phase

We developed a physical design that would take advantage of the VAX/VMS environment. Four goals influenced our design approach:

- To provide a layered communications environment. This was difficult because we were starting from an environment with only a few indistinct layers.
- To use a language that is portable and that has system-dependent features that are isolated.
- To make the code as modular as possible so that when a change needed to be made, it could be made to one specific part of the code without forcing changes throughout the code.
- To use as much of CV's PCU code as possible.

Figure 2 shows the protocol layers for the VAX code. We were able to identify three layers in the communications protocol: application, session, and link. Normally, we would have had to substantially alter the CV code to coordinate and run

the three layers; however, we took advantage of the multiprocessing ability of the VAX/VMS operating system to design a layered code for the VAX that would still be compatible with the CV code.

Application layer. Figure 3 shows the VAX-FASTLINK architecture. The application layer starts the process by handling all user interactions, such as accepting commands and displaying errors. The layer also conducts the VAX-to-CV communications sessions: it initializes the process and manages the multiple-communication channels and subprocesses. The application layer communicates with the session layer via one-way mailboxes.

Session layer. The session layer sends and receives all bi-directional messages and files for the VAX. The layer consists of several subprocesses that are activated as they are needed by the application layer. The session layer also sends status information back to the application layer.

Fig. 2. Comparison of the structure of CV's version of FASTLINK to LLNL's version of VAX-FASTLINK. In the CV version, the FASTLINK code is so tightly coupled to the driver and the communications code (which operates in the PCU) that it is difficult to know where one code leaves off and the other begins. On the other hand, the VAX design has a number of distinct layers that are dedicated to particular tasks. This layered approach had two advantages when we were writing and testing the VAX code. First, it saved time in developing the code because, since we could treat each layer separately, we could modify one layer without having to modify the whole code. The second advantage was that the VMS operating system on the VAX already had the ability to coordinate and run the layers, so we did not have to create a new sub-operating system. These advantages contributed to our success in writing VAX codes that were functionally compatible with the CV-FASTLINK.

Fig. 3. Architecture of VAX-FASTLINK. The VAX user communicates with the rest of the system through the applications layer. The layer also retrieves configuration information from the static files and then logs status information to the dynamic files. The application layer is linked to the session layer subprocesses (which transmit messages and data files between the VAX and CV systems) by the VMS mailboxes. The mailboxes contain the status of each of the logical data streams. The final layer in the system, the link layer, receives data from the applications layer, via mailboxes and the session layer, and sends it to the CV system. It also receives data from the CV system and passes it, by the reverse route, to the application layer. The UMC driver is a software interface between the link layer code, which runs on the hardware interface board, and the session layer.

Link layer. The link layer receives data buffers (units of information) from the application and session layers and breaks them into 1-kbyte packets. These packets are then routed between the VAX and CV using the CV-SDLC protocol. By the same token, the link layer receives data packets from CV, reassembles them into an appropriate buffer, and sends them on to the session and application layers. These upper layers must be ready to receive the data at any time on all eight communication channels (streams).

Implementing FASTLINK

During the implementation phase we wrote, tested, and documented the code. In writing the software, we adopted a "top-down" approach, wherein we developed codes for both the link and upper layers simultaneously, using structure charts as a guide.

To test the software, we used a Hewlett Packard protocol analyzer and a RELMS in-circuit emulator. We originally tested the upper layers under the VAX/VMS operating system, version

3.6; however, the final tests were done with the more current versions, VMS 4.0 and 4.1. ComputerVision has since developed a complete test plan that is followed whenever any changes are made to the VAX-FASTLINK code.

Performance

To determine the speed with which data were transferred from one system to the other, we examined the log entries from "start of transfer" to "transfer complete." The log recorded the elapsed time, which included the protocol overhead, time-to-print on the console terminal, and any process times on either computer system caused by interruption from other users. The tests were performed at different times of the day so that user loads varied, and no attempt was made to control the usage or types of processes executing during the test.

The test results included block file sizes of 4, 96, 240, 496, and 2176 (1 block = 512 characters). All file sizes were run at four different speeds: 9.6, 70.9, 230.4, and 460.8 kbps. The effective transfer rate of the smaller files was lower due to the ratio of data bytes to system overhead.

With a file size of 2176 blocks running at 460.8 kbps, the effective transfer rate was approximately 9 kbytes/s.

Transfer rate after VAX and CV improvements

Several improvements on the VAX side increased the effective transfer rates. Routines that handled data transfer were optimized by eliminating unnecessary initialization loops, reducing VMS mailbox overhead, and allowing variable record length transfers at the link layer. In addition, data buffer sizes were increased from 1 to 8 kbytes, providing an effective transfer rate of approximately 19 kbytes/s. Improving the software on the CV side increased the effective transfer rate to 23.7 kbytes/s (Fig. 4).

Summary and conclusions

The success of the VAX-FASTLINK code has made our CADDs 4X system an integral part of computer-aided engineering, and has moved us closer to our goal of having a fully computer-integrated system. Because of the code's high

Fig. 4. VAX-FASTLINK performance. The initial performance tests were run using 1-kbyte packets and yielded an effective transfer rate of about 9 kbytes/s with large files. The next tests were run after reducing mailbox overhead, allowing variable packet sizes, and increasing data buffer sizes from 1 to 8 kbytes. The changes increased the effective transfer rate to about 19 kbytes/s. The final improvements (made to the CV code) raised the rate to about 24 kbytes/s.

speed and its ability to correct errors, we can now move large files between the VAX and CV systems reliably, thereby speeding up communication between the design and fabrication groups. Furthermore, the code's attributes have attracted attention outside of Engineering, notably in the Magnetic Fusion Energy and Nuclear Test Programs, which are now using the code on their systems.

However, creating VAX-FASTLINK is only a beginning. We are now writing programs that move ASCII files between systems, converting from one native format to another. Because different CAD systems use different formats to represent the same schematic parts in their database, we are working on neutral formats to increase compatibility. Another project involves moving schematic parts between CADDs 4X and PC-based workstations. In addition, now that VAX-FASTLINK is part of EE's integrated computer-aided engineering network (iCAEn, Fig. 5), we are expanding the network to include the fabrication shops. The next challenge will be to integrate the

Fig. 5. The integrated computer-aided engineering network (iCAEn) in which VAX-FASTLINK functions. The network connects a growing number of VAX and microVAX computers and engineering workstations. Engineers taking advantage of the network can now transfer product designs between drafting and fabrication groups, and contribute to advances in such disciplines as microelectronics, image and signal processing, electromagnetic and circuit modeling, and electronic circuit design. The network also stretches to other networks at the Laboratory, allowing closer communication between members of EE and their colleagues throughout the Laboratory.

Fig. 6. Flow of data in a design project. The process starts with the engineer designing and simulating a new product on a CAE workstation. This design data is then moved to the CAD system where the design is transformed into the tools needed to build the product. The design package then moves to the computer-aided manufacturing (CAM) system, which builds the product, and then to the computer-aided testing (CAT) system, which tests it and compares the results to the original simulation data. We are now working on integrating this whole process electronically.

various computer-aided manufacturing machines and workstations (Fig. 6).

It should be noted in closing that only the close cooperation of ComputerVision, LLNL, and both DOE and CV's legal departments made the CV-VAX FASTLINK project possible. Future projects that transfer technology will benefit by following the legal procedures set up in this venture.

Acknowledgments

I would like to extend my gratitude to Faith Shimamoto, the system architect on the project, who designed all of the link layer code; and to Ivan R. Corey and Jim Kucala, who designed the application and session layer codes. VAX-FASTLINK is a success because of their contributions.

Field Test Systems Division

FTSD develops electronic systems to gather experimental data, often in non-laboratory environments, for the Nuclear Test Program, several energy-related programs, plus a variety of other scientific organizations.

Leland Loquist, Field Test Systems Division Leader

In the past ten years, FTSD's main mission has remained constant: to support the Laboratory's Nuclear Test Program, which conducts underground nuclear experiments at the Nevada Test Site (NTS). Ten years ago, about half of the division's 100 personnel supported the Test Program; today, two-thirds of the division's 160 people support it. These people are responsible for

Ten years ago... state-of-the-art systems included traveling-wave oscilloscopes and coaxial cable for high-bandwidth data.

designing, developing, and building electrical and electronic systems required by the program's scientific organizations. The other third of the division supports Earth Sciences, Biomedical and Environmental Sciences, E-Division Physics, and Hazards Control. They also provide electronics engineering expertise for the Liquid Gaseous Fuel (LGF) and Coal Gasification programs. Although FTSD's overall mission has remained the same, the technology used has changed radically.

Throughout the decade, FTSD has constantly strived to field state-of-the-art systems in the areas of data acquisition, command, and control for its customers. Ten years ago, such state-of-the-art systems included traveling-wave oscilloscopes and coaxial cable for high-bandwidth data. The highest resolution available from these oscilloscope systems was a few hundred megahertz. Engineers and scientists might retrieve 20 or 30 channels of data from a standard underground nuclear event at NTS in 1975, with data from each channel coming up on its own cable. In addition to fielding each of the Nevada events, the division was working on a centralized, NTS-based computing facility known as NADS (Nevada Automated Data System).

Now, all that's changed. There are oscilloscopes with bandwidths up to 3 GHz. Physics data from NTS events are gathered by distributed computer and networked communications systems. With the advent of fiber-optics technology, eight multiplexed channels of data can be transmitted on a single, 1/2-in.-diam fiber-optics cable, allowing scientists and engineers to gather thousands of channels of data. Both data density and bandwidth have increased tremendously.

Two key developments for the support of the Test Program occurred in this decade: the Pinhole Imaging Neutron Experiment (PINEX) and the streak camera. The PINEX is essentially a "pin-hole camera" that takes a two-dimensional picture of the radiation pulse from an imploding device. The first PINEX developed in the late '60s was mechanical; current ones are electronic and record phenomena that last only a few nanoseconds. The electronic PINEX has been a standard measurement system for the last five years.

A streak camera data-acquisition system was successfully fielded in a downhole configuration in 1983. On the "Cottage Event" of March 1985, eight streak camera systems were fielded downhole, the first time this complex configuration had ever been tried. The Cottage Event was notable for the division in another way: it was the first time that such a complete "downhole laboratory" had been fielded on an event. Thousands of

On the "Cottage Event" of March 1985, eight streak camera systems were fielded downhole...

channels of data were retrieved, more than is usually recorded on four or five average events.

The technology and tools have changed no less dramatically for those in FTSD supporting Livermore-based projects and organizations. Ten

Field Test Systems Division

years ago, these engineers were developing specialized instrumentation that could survive the harsh environment of coal gasification or oil shale retorts. There was also on-going work on large array systems to monitor seismic events. The second generation of a portable gamma ray spectrometer was developed in that time. An infrared CO₂ analyzer was developed for environmental monitoring and used in the Liquefied Natural Gas (LNG) Program to monitor the airborne products of propane spills. The experimental physics support area was developing high-purity germanium detector systems and exploring ways to deal with

... engineers were developing specialized instrumentation that could survive the harsh environment of coal gasification or oil shale retorts.

abnormal pulse shapes in detectors. New exotic detector materials like CdTe and HgI₂ were just beginning to be developed. CAMAC—a standardized digital logic system—was finally becoming standard and useful.

Now, high-purity detectors have been perfected and have become extremely reliable. Several types of charged particle detectors have been developed, such as ion-implanted Si detectors, which can operate at room temperature. CAMAC-based systems are now used extensively for data-acquisition and control systems. Digital telemetry is also routinely used in the Seismic Research Program and will be used in the LGF's new spill facility at NTS.

Today's projects depend on stand-alone computer-based systems that have a sophistication in control and analysis not available ten years ago when LSI-11 minicomputers were becoming available. Microprocessors have evolved and division personnel now use a powerful computer network based on the VAX computer technology to run complex data-reduction codes. In addition, the personal computer has increased the ease with which engineers and other division staff members do their daily work.

In this ten year period, the division has also taken on more responsibilities. Eight FTSD people now act as "technical contacts" to EG&G, which supplies about 300 people to support the division in its operational responsibilities at NTS. The division has increased its developmental role in supporting the Test Program, as well. Over the past

few years, two groups have been added in support of the Test Program: one in support of Nuclear Chemistry, the other in support of diagnostic development for prompt diagnostics. This increase in the diagnostic development effort for underground

... eight multiplexed channels of data can be transmitted on a single, 1/2-in.-diam fiber-optics cable ...

testing is due to the recent revitalization of the entire weapons development complex.

While support for the Test Program has grown, support for the energy programs has declined. The division currently supports the coal gasification and LGF programs—programs it has supported for years—but the levels of support are now lower: Early in the decade, FTSD also supported other alternate energy programs, including the Geothermal, Oil Shale, and In-Situ Copper Leaching projects.

The future promises continued change and growth in technology. Microwave experiments are requiring a new expertise in FTSD as well as new detector technology and fielding capabilities. FTSD engineers will find increased uses for computer-aided engineering tools and distributed networking systems. The division plans to develop electrooptic data acquisition systems and to standardize hardware, calibration techniques, and facilities. Engineers will be perfecting high-rate data acquisition systems for spectroscopy and mass spectrometry, developing techniques for improved real-time corrections, and continuing the search for solid-state detector systems for photon spectroscopy.

The following article discusses a Spectroscopy Array Camera (SPAC) system, which has a

Microwave experiments are requiring a new expertise ... as well as new detector technology and fielding capabilities.

design that owes much to past and present technologies. The linear arrays that form the SPAC have been a powerful spectroscopy tool since the mid '70s. In this design, a SPAC with seven linear arrays was coupled to a specially gated stripline microchannel plate to form a subnanosecond spectroscopy system.

Subnanosecond Spectroscopy Using Stripline Microchannel Plates and Reticon 1024SF Linear Arrays

C. R. O'Brien

In a new approach to subnanosecond spectroscopy we use a Spectroscopy Array Camera (SPAC) consisting of a stack of seven Reticon 1024SF linear arrays coupled to a specially gated stripline microchannel plate. The advantage of this approach is that we can read out seven subnanosecond time slices of the spectrum on a single cable with a frame time of 1 ms. Each time slice is capable of 1024 channels of spectral data, and each channel has a dynamic range of 1000. In this paper we discuss the design considerations of the SPAC; the characteristics of the Reticon 1024SF linear array; the array driver circuitry; and the amplification, digitization, multiplexing, and serialization of the analog data.

Introduction

The Reticon 1024SF linear array (EG&G Reticon Corporation, Mountain View, CA) is a highly viable choice for spectroscopy because each of its 1024 pixels has a 100-to-1 aspect ratio and wide dynamic range.¹⁻³ Furthermore, it has good electrooptical characteristics (Table 1). Recently, 14 of these Reticon linear arrays were integrated into a spectroscopy array camera. Because of the camera's modular design, the user can select the number of arrays he needs up to 14. We used a SPAC consisting of seven Reticon 1024SF linear arrays coupled to a specially gated stripline

microchannel plate (MCP). The result was a system capable of taking seven individual subnanosecond time slices of the input spectrum, each of which had a dynamic range* of 1000 and a spatial resolution of 12.5 line pairs/mm. The resolution of the system was determined by the physical characteristics of the stripline MCP, and each Reticon linear array had a limiting resolution of 20 line pairs/mm, as shown by the contrast transfer function (CTF) curve in Fig. 1. The camera's output consisted of a single digital serial bitstream of nonreturn-to-zero (NRZ) data with a total frame time of 1 ms.

Spectrometer readout system

Figure 2 is a schematic representation of the spectrometer readout system developed for the SPAC with seven Reticon linear arrays. The major components of this system are the spectral gating section, the optical coupling section, and the optical-to-electrical signal conversion section. The gated stripline MCPs act as the x-ray detectors for the readout system. The spectral integration time for each individual Reticon linear array is a function of the time of the array's associated stripline. The striplines can be gated independently. The user determines the time between the channels and the order in which each stripline is gated. The output of the optical coupling section of the spectrometer readout system is seven channels of yellow-green light (P-46) that is 2.54 cm wide ×

Table 1. Electrooptical characteristics of the Reticon 1024SF linear arrays (25°C).^a

Center-to-center spacing	25 μm
Aperture width	2.5 mm
Responsivity ^{b,c}	2.8×10^{-4} C/J/cm ²
Nonuniformity of response ^b	$\pm 10\%$
Saturation exposure ^{b,c}	50 nJ/cm ²
Saturation charge	14 pC
Average dark current	5 pA
Quantum efficiency ^{b,c}	75%
Spectral response peak ^c	750 nm
Spectral response range ^{c,d}	250-1000 nm

^a This table is a courtesy of EG&G Reticon.

^b Typical value specified at a 750-nm wavelength.

^c Specified for quartz-windowed devices. The fiber-optic faceplate may modify response characteristics.

^d Greater than 20% of peak responsivity.

* Here we define dynamic range as peak signal divided by peak-to-peak noise.

Fig. 1. Contrast transfer function curve showing the 20-line pair/mm limiting resolution of each Reticon linear array.

Fig. 2. Schematic representation of the spectrometer readout system developed for the SPAC with seven Reticon linear arrays. The major components of this system are the spectral gating section, the optical coupling section, and the optical-to-electrical signal conversion section.

0.3 cm high and capable of handling 12.5 line pairs/mm of input spectral information.

To couple the optical signal from the output fiber-optic faceplates of the MCPs to the input fiber-optic faceplates of the seven Reticon 1024SF linear arrays, we used the fiber-optic coupling array shown in Fig. 3. The coherent array had 12- μ m fibers to maintain the 12.5-line pair/mm resolution of the stripline MCPs. If we had coupled the linear arrays directly to the fiber-optic faceplates of the MCPs, we would have encountered two problems when trying to read the output of the stripline MCPs. First, because of the size of the arrays and the size of the supporting electronics, it is not possible to mount more than three arrays against the back of an MCP. We could couple four arrays directly against the back of an MCP by using short cables, but this would introduce noise into the video system and decrease its dynamic range by an order of magnitude.

In Fig. 4 we show the calibration curve for 50-nm-wide pulsed light going from the fiber-optic coupling array to the Reticon 1024SF linear array. In Fig. 5, for the sake of comparison, we show the calibration curve for the same light going directly to the Reticon 1024SF linear array.

Electronic readout

The Reticon 1024SF linear array

As mentioned previously, we chose to use the Reticon 1024SF linear array in our SPAC because

of its high dynamic range. Specifically, this array offers a dynamic range of at least 1000 at a 1-ms frame time and it does not have to be cooled. We can obtain a higher dynamic range (theoretically up to 10,000) by using a slower frame time and cooling the array. The 1-ms frame time of the SPAC with the seven Reticon 1024/SF linear arrays was mandated by the conditions of the test measurement.

Figure 6 illustrates the sensor geometry of the Reticon 1024SF linear array. Each diode consists of diffused P-type bars on an N-type substrate. The diode's sensing area generates a charge when it is struck by incident light. The charge is collected and stored on the P-type bars during integration and then sequentially switched onto the active video line for readout. Both the N-type and P-type areas are photosensitive. Light incident on a P-type bar will generate a charge that is stored on diode P. Figure 7 shows the distribution of charge for light falling on N-type material between two P-type bars. These diodes are sequentially selected by MOS (metal oxide silicon) multiplex switches and sent to their respective video lines for readout.

Video Chain

Figure 8 shows a simplified model of a typical amplifier chain for an active/dummy video line pair. Since each array has two video line pairs—one for even data and one for odd data—there are 28 video chains in each 14-linear array SPAC. The switches S_1 and S_2 represent the MOS switches that send the individual photosites to the video

Fig. 3. Fiber-optic coupling array used to couple the optical signal from an MCP to a stack of seven linear arrays.

Fig. 4. Calibration curve for 50-nm-wide pulsed light going from the fiber-optic coupling array to the Reticon 1024SF linear array.

Fig. 5. Calibration curve for 50-nm-wide pulsed light going directly to the Reticon 1024SF linear array.

Fig. 6. Sensor geometry of the Reticon 1024SF linear array. Each diode consists of diffused P-type bars on an N-type substrate. The diode's sensing area generates a charge when it is struck by incident light. The charge is collected and stored on the P-type bars during integration and then sequentially switched onto the active video line for readout. Both the N- and P-type areas are photosensitive.

Fig. 7. Distribution of charge for light falling on N-type material between two P-type bars. These diodes are sequentially selected by MOS multiplex switches and sent to their respective video lines for readout.

Fig. 8. Simplified model of a typical amplifier chain for an active/dummy video line pair. Since each array has two video line pairs—one for even data and one for odd data—there are 28 video chains in each 14-linear array SPAC. S_1 and S_2 are MOS switches that send the individual photosites to the video line. C_{VA} is the active video line capacitance, and C_{VD} is the dummy video line capacitance. Switches S_3 , S_4 , S_5 ; capacitor C_i ; and charge integrator U1 make up the integrator section. The output signal from the integrator section is amplified in the line driver, which delivers a 5-V signal to the 50- Ω output of the sample and hold section. The sample and hold section takes a 200-ns sample of the pixel and holds it for 1.8 μ s.

line. C_{VA} represents the active video line capacitance, and C_{VD} represents the dummy video line capacitance.

Let us assume that switches S_1 , S_2 , S_3 , S_4 , and S_5 have been closed for a long time. C_{VA} , C_{VD} , C_{DA} , and C_{DD} will charge up to the substrate voltage (V_0). The five switches will then open. The incident light on the photodiode creates electron hole pairs that turn the diode on, partially discharging C_{DA} and C_{DD} . When the photosite is

accessed for data readout, switches S_1 and S_2 are closed and the remaining charge in C_{DA} and C_{DD} is redistributed by C_{VA} and C_{VD} . Acting as a differential charge integrator, U1 then delivers a signal to the output line driver. Because clocking noise is common to both active and dummy video lines, such noise is not passed by the integrator section of the amplifier—switches S_3 , S_4 , S_5 ; capacitor C_i ; and charge integrator U1.

The integrator section of the amplifier has three modes of operation: reset, integrate, and hold. In the reset mode, we establish initial conditions by closing switches S_3 , S_4 , and S_5 . This puts an initial zero charge across C_1 . When these three switches are opened, the integrator section goes into the integrate mode. During this time, the difference of the charge across C_{VA} and C_{VD} appears across the input of U1, allowing C_1 to charge up to a value that corresponds to the amount of light that appeared at the photosite. The differential input to U1 nulls clocking noise and substrate noise on the active video line with the assumption that both types of noise will also appear on the dummy video line. When the input charge is transferred to C_1 , the integrator section goes into the hold mode. In this mode, the discharge of the capacitor results from the bias current of the amplifier, the dielectric leakage of the capacitor, and the leakage current in the FET (field effect transistor) switches S_3 , S_4 , and S_5 .

The next section of the amplifier, the line driver, amplifies the output signal from the integrator section. The line driver delivers a 5-V signal (0 V = no signal; -5 V = saturation) to the 50- Ω

input of the sample and hold section. When the pixel video information stabilizes (i.e., when the integrator is in the hold mode), the sample and hold section takes a 200-ns sample of the pixel and holds it for 1.8 μ s. A successive approximation analog-to-digital converter then converts the video line to 10-bit parallel data. These data are then put into a d-type flip-flop where they are held until they are latched onto the data bus line.

The amplifier is temperature compensated to give a maximum swing of 30 mV (out of a 5-V maximum signal) over a temperature range of 70-120°F.

Analog Chain

In a complete SPAC (i.e., one with 14 linear arrays) there are two amplifier stacks, each of which houses 7 1024SF linear arrays and 14 individual amplifier-array driver sections. Figure 9, a typical amplifier stack (Xedar Corporation, Boulder, CO) is made up of seven modules, each of which has its own drive circuitry, for driving its own array; its own power regulation; and two differential amplifier/line driver sections. The individual modules are shielded to prevent crosstalk

Fig. 9. Typical amplifier stack housing 7 Reticon 1024SF linear arrays and 14 individual amplifier/array driver sections. It consists of seven modules, each of which has its own drive circuitry, its own power regulation, and two differential amplifier/line driver sections.

The clock generator card generates all of the timing signals used in the SPAC, including the three clock lines and the start pulse required by each linear array. To cut down on system crosstalk and noise, the clock lines and the start pulse are optically coupled to each of the 14 array drivers. The Reticon 1024SF linear array does not have a reset line; so, as soon as the charge is removed from the pixel (i.e., as the array is being read out), the pixel begins to integrate.

The pixel will integrate all the optical energy that falls on it from the time that it is first accessed and read out to the time that it is reaccessed and read out again. The SPAC receives three trigger pulses that are 10 ms apart. The first two pulses clear the arrays of any unwanted information. Between the second and third pulse, the spectrometer is activated. A third scan is then taken to read out the system information.

eter is not activated between the second and third pulse. A computer system subtracts the background scan from the raw data scan to remove (1) any pattern noise and (2) the signal introduced by the dark current in the arrays.

We can look upon a complete SPAC as 28 separate camera channels that are all mixed together to give a single data output line. Each channel has 512 pixels, and each pixel is $2\ \mu\text{s}$ long; therefore, it takes 1.024 ms to read out a single array. To read out a SPAC, we take a sample from each pixel of each channel and multiplex it into a single data stream. Consider mixing together the first pixel from each of the 28 separate channels. We will call this the first row of data of a 40×512 array. The 10-bit words from the arrays will be rearranged into 8-bit words before serialization to accommodate the memory system used. Each word in the memory will be 8 bits plus 1 parity bit (generated by the serializer section). Each row will be made up of 40 words. The first 5 words in each row will be housekeeping information; the next 35 words will contain the 10-bit data from the 28 separate channels. The first row will look like this:

FRAME SYNC
FRAME SYNC
STATUS
8 LSB's OF ROW COUNT
2 MSB's OF ROW COUNT
8 MSB's OF ARRAY 1, PIXEL 1
8 MSB's OF ARRAY 1, PIXEL 2
8 MSB's OF ARRAY 2, PIXEL 1
8 MSB's OF ARRAY 2, PIXEL 2
BIT 8 = BIT 2 FROM ARRAY 1, PIXEL 1
BIT 7 = BIT 1 FROM ARRAY 1, PIXEL 1
BIT 6 = BIT 2 FROM ARRAY 1, PIXEL 2
BIT 5 = BIT 1 FROM ARRAY 1, PIXEL 2
BIT 4 = BIT 2 FROM ARRAY 2, PIXEL 1
BIT 3 = BIT 1 FROM ARRAY 2, PIXEL 1
BIT 2 = BIT 2 FROM ARRAY 2, PIXEL 2
BIT 1 = BIT 1 FROM ARRAY 2, PIXEL 2

```

8 MSB's OF ARRAY 14, PIXEL 1
8 MSB's OF ARRAY 14, PIXEL 2
BIT 8 = BIT 2 FROM ARRAY 13, PIXEL 1
BIT 7 = BIT 1 FROM ARRAY 13, PIXEL 1
BIT 6 = BIT 2 FROM ARRAY 13, PIXEL 2
BIT 5 = BIT 1 FROM ARRAY 13, PIXEL 2
BIT 4 = BIT 2 FROM ARRAY 13, PIXEL 1
BIT 3 = BIT 1 FROM ARRAY 13, PIXEL 1
BIT 2 = BIT 2 FROM ARRAY 13, PIXEL 2
BIT 2 = BIT 1 FROM ARRAY 13, PIXEL 2

```

71

Fig. 10. The SPAC consisting of an amplifier stack of seven linear arrays. A full SPAC would be twice this size.

There are 512 rows like the one we just described in which the pixel counts increase by one each time the row increases by one. The pixel counts shown here would increase by one.

We serialized the 8-bit plus parity parallel data using a nine-to-one multiplexer. The order of transmission was bit 8, bit 7, bit 6, bit 5, bit 4, bit 3, bit 2, bit 1, parity, bit 8, etc.

Conclusion

The Reticon 1024SF linear array has been a very powerful spectroscopy tool since its introduction in the mid-1970's. The SPAC demonstrates that the Reticon linear array can become even more powerful when it is used with several other Reticon 1024SF linear arrays: for example, we have multiplexed 14 of them into a 1024 system. We are now refining this approach by reducing the SPAC to half its size but maintaining its 14-channel capability. We have increased its dynamic range by reducing video noise to a point where a 12-bit system now appears to be practical. This means that we will not have to cool the arrays.

In addition to its use as a spectroscopy read-out device, the SPAC may also be a candidate tool for tomographic work.

Acknowledgments

My thanks to J. M. Zumstein, M. J. Eckart, M. E. McGee, H. Schulte, and W. R. Edwards for all their help and assistance on this project.

References

1. R. W. Simpson, "Noise in Large-Aperture Self-Scanned Diode Arrays," *Rev. Sci. Instrum.* **50**, 6 (1979).
2. R. E. Bell, M. Finkenthal, and H. W. Moos, "Time-Resolving Extreme Ultraviolet Spectrograph for Fusion Diagnostics," *Rev. Sci. Instrum.* **52**, 12 (1981).
3. E. H. Snow and R. K. Hopwood, *Spectral Response of Reticon Linear Photodiode Arrays*, EG&G Reticon, Sunnyvale, CA, Application Note No. 121.

Index

This index lists the subjects and authors to be found in published EE Quarterlies and EE Technical Reviews (including this issue). The number after an item indicates the year and issue in which the item was published. For example: *Cross-borehole*, 79-1, 81-3 means the subject is in the first issue of 1979 (report No. UCRL-50025-79-1) and in the third issue of 1981 (report No. UCRL-50025-81-3).

A

Ables, E., 80-1
Alexander, E., 75-1
Alpha emitters, long-lived, 80-1
Alick, K., 75-1
Aluminum-air battery, 82-1
Ames, H. S., 76-2, 79-3
Analyses, automated
 chemical, 75-3
 geological, 78-3
Analysis and management, 79-3
Analyzer,
 chlorine, 79-1
 Dunegan 920, 77-1
 radioisotope, 76-3
Anesthesia, 80-2
Antenna, unique directional, 81-3
Argus laser, 77-2
Arming, 77-3
Armstrong, G. H., 79-3
Artificial people, 80-3
Axelrod, M. C., 78-3

B

Baker, J., 76-1, 78-3
Balch, J. W., 75-2, 81-1
Barlow, O. M., 75-3
Barton, V., 75-3
Baseball-II, 76-1
Battery, aluminum-air, 82-1
Behrin, E., 82-1
Bell, H. H., 79-2, 85-3
Benge, W. L., 75-3
Bishop, S. R., 78-2
Blackwell, K., 85-3
Bogdanoff, A., 76-1
Bourret, S., 75-3
Bozogamesh, H., 81-1
Bradley, R. T., 75-4, 76-2
Braille, 82-1
Brase, J., 84-3
Brazing furnace, induction, 75-1
Breitenbucher, P., 84-1
Brown, B. J., 79-1
Brown, D. R., 81-1
Bryant, R., 84-2
Buettner, H. M., 81-3
Burgess, T. J., 77-2
Bus, general purpose interface, 80-1
Bus structure, 76-2
Butner, D. N., 77-3

C

CAIN, 76-2
CAMAC, 80-3, 83-3
CATV, 78-1
CDC camera, 85-3
CMOS, 77-2
CTR, see Controlled thermonuclear
Calibration, automatic, 74-4
Candy, J., 82-2
Carbon dioxide sensor, 79-2
Casterson, R., 77-1, 83-1
Castleton, R. N., 84-1
Chau, H. H., 79-2
Chlorine analyzer, 79-1
Christie, D., 84-2
Ciarlo, D., 75-1, 81-1
Circuit diagnostics, 84-2
Clark, J. C., 77-2
Cleland, L. L., 77-1
Clendenen, L. D., 77-2
Coal, high speed spectroscopy
 for process control, 81-1
Coffield, F. E., 84-3
Communications cards, LSI-11, 84-2
Communications link, fiber optics, 80-2
Computer model, 77-2
Control system, isolation, 78-1
Control systems, MFTF, 83-1
Controlled thermonuclear research, 76-1
Copper resistivity, 77-2
Coradetti, T., 84-1
Coutts, G. W., 75-1
Crates, CAMAC, 80-3
Criminal diversion of
 nuclear materials, 77-1
Criticality false alarm, 76-1
Cross-borehole, 79-1, 81-3
Cruise missile, computer-based
 testing of, 82-3

D

DASLL, 80-3
Danielli, F., 80-1
Data
 acquisition, 77-1, 80-1
 collection, 76-1
 gathering, 76-1
 handling, 79-3
 low-level signal, 82-3
Davis, G. E., 81-2
DeGroot, T., 85-2

Deadrick, F. J., 75-2
 Delay generator, 78-3
 Detectors, time-resolved radiation, 75-2
 Diagnostics, 77-1, 79-2
 2XIIB, 76-1
 Digital techniques, high speed, 78-2
 Distributed instrumentation control, 83-1
 Drill press, 79-1
 Druce, R., 84-2
 Dye lasers, 78-2

E

Electron Cyclotron Resonant
 Heating, 84-3
 EPA lab, 76-2
 Editing, text, 77-3
 Effluent characteristics, 75-3
 Ekstrom, M. P., 75-1
 Electro-optics, 76-3, 79-2
 Electromagnetic
 cross-borehole, 79-1
 railgun, 80-1
 Energy storage, 77-3
 Equations-of-state, 79-2
 Ewins, J. H., 75-2
 Explosive, 79-2, 79-1

F

FASTLINK, 85-3
 Fiber optics, 77-2, 80-2, 83-3
 Fiber-optic data links, 81-2
 Fiber-test facility, 77-1
 Field-compression devices, 77-2
 Fisher, E. R., 75-3
 Flow cell analyzer, 75-1
 Fluorometric, 78-2
 Follow-up systems design, 82-3
 Framing camera, 75-4
 tube, 78-3
 Francis, F. D., 80-3
 Friesen, R. D., 76-1
 Fuels, alternative transportation, 75-4
 Fusion, laser, 77-2
 Fuzing, 77-3

G

Gadd, T. J., 76-3
 Gages, talking, 83-1
 Gas-pressure diagnostic system, 81-2
 General Purpose Interface Bus, see GPIB
 Geologic, 78-3
 Geology, 79-1
 Geophysical probing, 75-2
 Goerz, D., 79-1
 Gordon, L., 84-2
 Gozani, T., 81-1
 GPIB, 80-1
 Graphics, computer, 79-2
 Gunn, R. C., 81-1, 82-3

H

Hasbrouck, R. T., 85-1
 Hawke, R. S., 80-1
 Herget, C., 80-2, 82-2
 Hersey, R. J., 76-1
 High voltage test stand, 78-2
 High-speed photography, 75-4
 High-speed radiation camera, 75-1
 Hill, C., 79-3
 Holloway, F. W., 75-2
 Hollstein, R. B., 77-2
 Huebel, J. R., 75-4
 Huen, T., 75-2
 Hunt, D. N., 83-1
 Hunt, G. F., 80-2
 Hydrodiagnostic, 77-3
 Hydrodynamic test data, 79-3
 Hydrogen, compressed, 80-1

I

IC, 81-1
 ICRF, 84-3
 Image intensifiers, pulsed, 75-4
 Image processing, digital, 75-1
 Imaging, 77-1
 Imaging gamma-ray cameras, tumor, 75-2
 Imperial Valley, California, 78-3
 Induction brazing furnace, 75-1
 Interferometer phase detection, 78-2
 Interferometer, microwave, 75-1
 Interlocks, CAMAC-based, 83-3
 Ion-implantation, 81-1
 Isocon camera, 80-3

J

Jaroska, M. F., 75-4, 77-3, 82-1
 Jensen, C. W., 75-3
 Johnson, B. C., 76-3
 Johnson, G. W., 84-1

K

Kalibjian, R., 75-4, 78-3
 Kaser, J. B., 78-3
 Kaufman, A. M., 81-2
 Koo, J. C., 84-3
 Krammen, J., 85-2
 Krausse, G. J., 85-1
 Kuramoto, A., 79-3

L

LGF data acquisition system, 84-1
 LSI development, 75-2
 LSI-11, 84-2
 Lager, D. L., 75-2, 80-2
 Laine, E. F., 81-3
 Language aids, 77-2

Large optics diamond turning machine, 84-1
 Laser, 75-2, 75-4, 76-3, 77-2, 78-1, 79-2, 78-2, 80-2
 optics, 83-1
 Lathe LeBlond, 79-1
 Latorre, V. R., 80-1
 Lawson, J. C., 77-3
 LeBlond lathe, 79-1
 Lee, F. D., 75-3, 79-2
 Leighton, J., 77-1
 Lightning vulnerability of nuclear explosive test systems, 85-1
 Liston, D., 77-1
 Long, J. R., 76-2
 Low-level signal data acquisition, 82-3
 Lytle, R. J., 75-2, 79-1

M

MACRO2, 81-1
 MFECC, see NMFECC
 MFTF, 81-2, 81-3, 82-1, 82-3, 83-3
 MFTF-B power supply, computer model, 85-1
 MGX, 83-3
 MOS fast-switching techniques, 85-1
 MOS time-resolved radiation detectors, 75-2
 MOS/LSI facility, 75-1
 Machine-control system, programmable, 75-3
 Macro, structured, 77-2
 Magnet, superconducting, 82-3
 Magnetic fusion, 76-1
 energy, 78-3
 Magnetic mirror fusion, 78-1
 Magnets, 79-1
 Magnuson, W. G., 80-3
 Maiten, M. S., 80-3
 Maples, M. D., 75-3
 Mass storage, 78-3
 McConaghy, C., 75-1, 75-2, 81-1
 McCue, H. K., 84-1
 McGibbon, A. L., 76-3
 McQuaid, J. H., 75-2, 79-2, 81-1
 Meeker, D. J., 75-1
 Mendell, D. S., 78-2
 Message processing system, automated, 75-3
 Microchannel plate x-ray spectrometer, ultrafast gating, 85-1
 Microcomputer, 77-2, 78-2, 79-1, 82-3
 Microcomputer, special issue, 75-3
 Microcomputer system, modular, 75-3
 Micropellet guidance, 76-1
 Microprocessor, 79-2
 LSI-11, 77-1
 Microstructure fabrication, 81-1
 Microwave propagation, 85-3
 Mihalka, A. M., 81-3
 Miller, E. K., 75-2
 Minicomputer, 77-3
 bus structure, 76-2
 D112, 77-1

Minor, E. G., 82-3
 Monitor, fast scan, 78-1
 Montoya, C., 82-3
 Mooney, L. J., 78-1
 Moore, T. L., 84-3
 Morrison, J., 75-1
 Mullenhoff, D., 81-3
 Multiprocessor, debugging, 81-2
 Myers, D., 85-2

N

NAL' system, 75-1
 NC machine tool, see Numerically controlled
 NC, see Numerically controlled
 NMFECC, 77-1
 NTS diagnostics, 75-1
 NURE program, 78-3
 National MFE computer network, see NMFECC
 Networking microcomputers, 80-1
 Neutral beam, 82-1
 injectors, 76-1
 ion-density profile, 78-1
 power supply, 78-1, 81-3
 protection circuits, 83-3
 Neutron monitoring, 76-1
 Neutron, portable spectrometer, 80-2
 Neutron-gamma field, 80-2
 Newton, L. E., 76-2, 79-1
 Niven, W. A., 82-1
 Nova
 Alignment control, 85-2
 Beam diagnostics, 85-2
 Central controls, 85-2
 Pulse power control, 85-2
 Target diagnostics, 85-2
 Shot scheduler, 85-2
 Nova laser, 80-2, 84-2
 Nuclear science data production facility, 83-1
 Nuclear test, underground, 77-1
 Nuclear waste repository, 81-2
 Numerically controlled machine tool, 76-2, 76-3

O

O'Brien, C. R., 85-3
 O'Brien, D. W., 83-1
 Octopus, line switching, 83-3
 Oicles, J. A., 85-1
 Oil shale, 82-1
 Olk, L. B., 75-1
 Olken, H., 75-3
 Optics, high power laser, 83-1
 Oscilloscope, dual raster, 77-3
 fast-transient, 75-3
 Oxidants, photochemical, 78-3
 Ozarski, R., 85-2

P

Pavel, G., 84-2
People, artificial, 80-3
Peratt, A. L., 75-2
Phase detection interferometer, 78-2
Photochemical oxidants, 78-3
Photodetector, 79-2
Photometer, a scanning reflection
transmission, 83-1
Plasma diagnostics, 82-1
Pocha, M., 81-1, 84-3
Pockels cell, 76-3
Pollock, G. G., 76-1
Pomernacki, C. L., 79-1, 80-1
Portnoff, M., 82-2
Power supplies, 82-1
Pressure switch, subnanosecond
MOS, 75-4
Printed circuit board, 77-1
layout, 80-3
Pulse generator, 84-2
Pulse height analyzer, high speed, 82-1
Pulse-power, 78-1
Pulsed image intensifiers, 75-4

R

Rabbit, 75-3
Radiation camera, high-speed, 75-1
Radiation detectors, time-resolved, 75-2
Radioisotope analyzer, 76-3
Rail-gap switch, 84-2
Railgun, 80-1
Reactors, 80-1
Recorder, on-board, 82-1
Recording, high-velocity, impact, 82-1
Rectifier transformer, 81-3
Relativistic beam, 77-2
Retorts, 82-1
Ring seating, 84-1
Robinson, W. F., 83-1
Ronchetto, J. J., 82-1
Rotating turbine camera controller, 84-1
Rotter, M. D., 81-2, 83-3
Route profile analysis, 81-3
Rufer, R. P., 78-1
Rupert, P. R., 78-1

S

Safety, machining 79-1
Safing, 77-3
Scarafiotti, J. J., 83-3
Scarpetti, R. D., 83-3, 85-3
Sensor, carbon dioxide, 79-2
Severyn, J. R., 77-2, 80-2, 85-2
Sewall, N. R., 75-4, 77-1
Shaker control, 75-2
Shiva, 78-1
Shock-wave-velocity measurements, 75-4
Signal and Control Engineering, 82-2
Smart, J., 85-2
Smith, B. H., 76-1

Smith, M. E., 78-2
Smith, R. J., 77-1
Software debugging tool, 81-2
Solder-joint reliability, 76-1
failures, 76-1
Spann, J. M., 75-3, 81-2
Sparks, D. F., 80-3
Spectrometer,
gamma ray, 76-3
portable neutron, 80-2
x-ray, 76-3
Spectroscopy, 81-1, 85-3
Sphere-winding machine, 75-4
Spracklen, H. P., 82-1
St. Leger-Barter, G., 75-1, 75-4
Steinmetz, L. L., 75-1, 78-2, 79-2
Strauch, M. S., 83-3
Streak camera,
isocon, 80-3
x-ray, 75-1
Substation, 230-kV, 81-3
Superconducting cable, 79-3
Surgery, 80-2
Switches, high speed, 84-3
Switching, high power, 76-2
Synthesizer, voice, 83-1

T

T. IX, see Tandem Mirror Experiment
Tandem Mirror Experiment,
79-1, 81-2, 84-3, 85-3
Technology transfer, 75-3
Temperature control, 75-1
Test, nuclear, 79-2
Testing, short circuit, 81-3
Text editing, 77-3
Thermometry, 82-1
Thomson scattering, 75-2
Three-dimensional images, 75-4
Thrust area, 82-2
Time-resolved radiation detectors, 75-2
Transient
electromagnetics measurement, 75-2
high-speed recording of, 81-1
output current, 82-3
recorder, 79-3
Transportation, alternative fuels, 75-4
Transuranics, 80-1
Tumor, 75-2
Twogood, R., 82-2
Tyler, G. C., 76-1

U

U.S. Postal Service, 81-3
Ultrasonic, 82-1
inspection of superconducting
cable, 79-3
test bed, 84-3
Underground caverns and tunnels, 81-3

V

Van Arsdall, P., 85-2
Van Ness, H., 82-3
Victor, R. A., 76-2, 79-3
Video playback facility, 81-1
VIRCATOR, 85-3
Vogtlin, G., 84-2
Voice synthesizer, 83-1

W

Warhus, J., 82-3
Water samples, 79-3
Waugh, A. F., 78-1
Weapon control, 75-2
Weiskamp, T., 75-3
Wentz, D. L., 78-3
Werner, R. E., 82-1
Whelan, H. A., 76-3
Whitham, K., 77-3
Wiedwald, J. D., 85-1, 85-3
Willows, J. L., Jr., 82-1
Wilson, J. H., 81-3
Wind calculations, NTS, 75-3
Woodruff, J., 82-1

X

X-ray
 medical, 75-4
 monitor and control, 79-3
 pulse calorimeter, 75-2
 spectrometer, 76-3, 85-1
 streak camera, 75-1

Y

Yee, J., 85-3
Young, R. H., 75-3

Z

Zoret, R. E., 75-4

Numeric

2XIIIB diagnostics, 76-1