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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.

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Flash x-ray accelerator

Modern nuclear weapons design involves an immense amount of computer simulation to predict the behavior of rapidly imploding objects. At some point, it becomes necessary to verify the computational model experimentally. One way to do this is to take a flash x-ray (FXR) picture (i.e., to record the imploding geometry radiographically at a given instant) and compare the result with the prediction. However, it takes a very large x-ray dose delivered in a small fraction of a microsecond to penetrate the objects involved and to form an image quickly enough to stop the rapid inward motion of the boundary surfaces.

The FXR machine is a high-current, linear-induction, electron beam accelerator for flash radiography that was designed and built at LLNL for the Department of Energy. The nominal pulsed-beam parameters are a current pulse of 2 to 4 kA, at an energy level of 20 MeV, with a 60-ns FWHM pulse width, for an x-ray dose of 500 to 1000 R at a distance of 1 m from the beam target. For tuning purposes, the machine can be pulsed at 1/3 Hz. In tuning, the solenoids are adjusted to control the magnetic field profile, which in turn, controls the beam transport from injector to target.

Although the DOE acceptance in March 1982 marked the successful and timely conclusion of the construction phase for this machine, with a measured x-ray dose of 480 R at 1 m from the beam target, this dose was achieved with less than

the full design current and without the high level of repeatability and reliability that the machine would eventually have to meet. Since then, however, much progress has been made in terms of bringing the machine to the point where it can fully assume its role as a powerful and reliable tool for radiography. This includes improvements in beam injection and transport, modifications in the pulsed power conditioning and switching system, additions to the monitoring and control system hardware and software, and characterization of the radiographic performance of the machine.

This issue of the EE Technical Review primarily addresses these changes. For additional details of the basic accelerator design, the reader is referred to the May 1981 issue of *Energy and Technology Review*,¹ as well as to other journal publications.²⁻⁷

For further information . . .

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-

Flash x-ray facility

Figure 1 shows the FXR facility, which is located at Site 300—18 miles east of the Laboratory. The FXR accelerator (Fig. 2) is housed in a massive concrete bunker for protection against the blast of the test shot on the firing table. Electron acceleration takes place through 48 modules that are each driven to 400 kV for a 90-ns FWHM pulse. Each module contains a Blumlein pulse-forming line that energizes an accelerating gap in the 146-mm-diam beam tunnel. Each gap in turn forms part of a 1-m-diam, evacuated, stainless-steel cavity (Fig. 3) with a built-in focusing solenoid capable of generating up to 2 kG on the axis of the beam tunnel. The oil-filled chamber is separated from the evacuated part of the cavity by an epoxy diaphragm. Symmetrical, 40-ohm columns of recirculated copper sulfate solution act as ballast loads. The Blumleins are switched through coaxial, midplane spark gaps that are pressurized to 40 to 60 psi with recirculating SF₆ gas. Synchroni-

zation is derived through calibrated cable lengths from two master switch gaps that trigger the Marx banks and the Blumlein switches, respectively.

The injector uses six accelerator elements acting in tandem as a 1.5-MeV voltage source driving a planar diode. The cathode is supported by a hollow steel stem that threads through four gaps and so sums their voltage contributions. Similarly, a hollow anode stem threads through two voltage modules. The mesh anode is backed by an adjustable collimator, which selects the central portion of the emitted beam for further acceleration.

Beam confinement over the 34-m-long beam tunnel is through a near-continuous array of solenoids that are positioned both internal and external to the accelerating elements. Beam transport from the last accelerating cavity to the bremsstrahlung target is achieved with discrete solenoid lenses. The original target consisted of a rotatable array of 0.75-mm-thick, tungsten platelets; more

Fig. 1. Artist rendering of the FXR facility. The FXR accelerator is housed in a concrete bunker.

Fig. 2. Plan view of the LLNL flash x-ray (FXR) facility. The FXR machine is a linear-induction accelerator used to produce an x-ray pulse intense enough and short enough to penetrate an imploding object and to capture on film its shape at a given instant.

recently, we have been using single, solid, 1-mm-thick tantalum discs. When focused to its nominal 3- to 6-mm spot size, the electron beam punctures the target in a single pulse. A new target area is then moved into position. CAMAC-based electronics provide computer-assisted monitoring and control of the FXR machine parameters, as well as rapid analysis of performance data.

The Marx banks: a trouble spot in the pulsed-power train

The FXR pulsed-power system converts ac line power into high voltage pulses that ultimately result in the 5-kJ beam pulse. The basic pulse power train is shown in Fig. 4. A 100-nF Marx bank is bipolar-charged to ± 35 kV and discharged into four (or for the injector, six) Blumlein pulse-forming lines in parallel, over a 1.8- μ s interval. The 10-ohm, 18-nF, water-filled Blumleins are then triggered to energize the accelerator cavities.

The system contains 15 Marx banks: 12 banks to power 48 accelerator cavities (1 bank powers 4 accelerator cavities), 1 bank to drive the injector, and 2 banks to charge calibrated, high-voltage cable sections that are used to synchronously trigger the different machine components. A sample Marx bank, which had been bought earlier for test and evaluation, had performed well for more than

100,000 pulses, but unfortunately, this performance was not duplicated by any of the production units delivered later. Modifications we made included both the spark gaps and the charging resistors; a part of the energy storage capacitors had already been replaced by us during the construction period with longer-lived units from a different manufacturer. The two modifications are now discussed.

Marx spark gap switches

The Marx spark gap switches (six switches per Marx bank) are planar midplane gaps, with the three electrodes spaced by short segments of 5-in. o.d. Lucite tubing. The assembly is held together by 1/2-in., threaded rods and pressurized to 30 to 60 psi (air). When it became apparent that in the original design, Lexan rods would crack and eventually break from the stress of a few thousand shots, we replaced them all with stronger, epoxy-fiberglass material (G10).

The midplane electrodes on all Marx switches carry illuminator pins that produce a small spark along the inner diameter before application of the main trigger pulse. The resulting ultraviolet light generates some free electrons that serve to initiate the switching arc and so help to minimize the jitter. These electrodes are held on the end of thin

Fig. 3. (a) End view of an accelerator cavity with its driver module. (b) Simplified cross section (side view) of the accelerator cavity.

brass rods that traverse the midplane electrode body radially. The original, split rods were connected by a spring contact that would fail randomly, thus preventing the gap from firing. All illuminator electrodes were redesigned for better seals and with a thread-free configuration.

A modest amount of air pressure is maintained continuously in the Marx switch gaps in order to prevent insulating oil from leaking into the gaps. In order to forestall inadvertent loss of air pressure due to a power outage, we installed an automatic crossover valve that connects the system to a compressed-air bottle farm. During our all-too-frequent Marx generator failures, safety considerations required that the insulating oil be pumped from the tank and all capacitor terminals ground-hooked and strapped to ground

before any repairs were attempted. This procedure has become much more efficient since the installation of special safing terminals on the capacitors, and of an oil supply and return manifold to which all Marx tanks are permanently connected.

Marx charging resistors

As delivered, all Marx charging resistors (50- to 500-ohm range, 1 in. in diameter) were of the uncoated, carborundum variety. These resistors caused much difficulty as they would disintegrate, sometimes after only a few pulses, contaminating the oil volume in the Marx tank and necessitating tedious pumping, filtering, and cleaning operations. Apparently, oil penetration into the uncoated resistors is not always uniform, leaving

Fig. 4. Pulsed-power conditioning for FXR.

voids that arc over and cause local overpressure, leading to gradual breakage and sometimes to spectacular explosions. We also found that arcing in partially failed resistors could cause false triggering of nearby spark gap switches, leading to early erection of the Marx bank or to prefires in the Blumlein or Stage II (intermediate triggering) gaps. All these resistors have now been replaced with a more trouble-free, epoxy-sealed variety, where oil is excluded from the conducting volume.

Pairs of 15-ohm, carborundum resistors were used at one point for damping two Marx banks after charging and firing the two sets of 13 cables that trigger and synchronize the charging Marxes and the Blumlein switches. Here it was found that even the epoxy-coated variety of resistor did not stand up under the stress, and new, wirewound resistors were designed and built as a substitute. Earlier experience also had indicated a poor survival rate for a set of 6-in.-long, 15-ohm, carborundum resistors that were mounted in series with each trigger cable to damp out cable-to-cable

ringing. These resistors were replaced with short segments of Schedule 80 plastic pipe, filled with NH_4Cl solution, sealed, and capped with specially designed, high-voltage connectors.

More recently, we have ordered a complete set of newly developed, ceramic, Marx charging resistors from a different supplier. According to extended life tests performed on the Advanced Test Accelerator (ATA), these resistors have excellent survival characteristics. (The ATA, another LLNL project, will be used to study the propagation of intense, high-energy beams through the atmosphere.) We are also planning to replace the liquid, copper sulfate ballast load columns (two per cavity) with the same type of resistor. The original design for ballast loads had included recirculated liquid resistors primarily to allow external cooling during repeated-pulse operation of the FXR machine; as discussed below, our diagnostic capabilities are such that "rep-rated" operation is not required, and hence we do not need to cool the ballast resistors.

Fine-tuning the spark gaps for improved synchronization

A simplified block diagram of the FXR switching system is shown in Fig. 5. The system is roughly symmetrical, with the top half triggering the Marx banks to charge the Blumleins, and the bottom half firing the Blumlein switches. The

2-kV command pulse from the master trigger generator is amplified by eight, parallel, 18-kV thyatron trigger stages. Four of these serve as trigger sources for 100-kV Marx banks, which in turn charge the trigger cable banks mentioned earlier.

Fig. 5. The FXR switching and synchronization system.

The other four trigger, with some delay, auxiliary smaller Marx (Minimarx) units that fire the main synchronizing (Stage I) spark gap switches. The Stage I gaps place a short circuit across the charged cable banks, thereby creating a transient that propagates down each cable length and triggers either a Marx bank or an intermediate (Stage II) switch gap. The latter in turn each triggers four Blumlein switches by shorting out four short, charged cable segments.

Although the basic Marx-Blumlein pulse compression scheme had been pioneered by J. C. Martin at the Atomic Weapons Research Establishment (AWRE), United Kingdom, in the 1950s and had been used many times since then, an array of 54 water-filled Blumleins, charged in sets of 4 or 6 from single Marx banks, and discharged at the 300- to 400-kV level, had not heretofore been built. Not surprisingly, therefore, the successful, low-jitter operation of this system did require some development effort.

As the beam takes roughly 1.5 ns to travel from one accelerating gap to the next, the gaps must be energized in the same time sequence, and with a timing error (jitter) on the order of 1 ns. The switch gap performance is monitored automatically through a computerized data acquisition system. For any number of pulses, the firing delays with respect to the command pulse can be recalled from storage, displayed, and printed out in hard-copy form as a permanent record of machine performance. Through the use of this di-

agnostic, we initially discovered significant timing errors for entire groups of spark gaps.

Timing offsets of up to 10 ns in the 13 Stage II gaps were corrected by careful, mechanical recentering of the midplane electrodes, within 5% of the interelectrode spacing. Similarly, the jitter on the Stage III (Blumlein) gaps was reduced to a standard deviation of $\sigma \leq 1$ ns by readjusting the electrical bias of the coaxial midplane electrode. The overall timing accuracy can be gauged from a typical histogram (Fig. 6) for the delay times of one group of Blumlein gaps, with respect to the command pulse.

Fig. 6. Typical histogram of switch gap delay times. Data of this type can be recalled at will from the automated computer storage recorded for each shot.

Preventing high-voltage breakdown in complex, 3-D geometries

A cross-sectional view of the typical Blumlein/feedline/cavity layout is shown in Fig. 3. In this part of the FXR machine, we must hold off 300- to 400-kV for time periods lasting from 90 ns to more than 1 μ s, while the Blumlein pulse-forming line is being charged from the Marx bank. The original design was based on a minimum safety factor of 1.6; that is, at the 400-kV level, the most strongly stressed component would still be below its calculated breakdown voltage by a factor of 1.6. Some difficulty arises when one attempts to calculate field stresses in areas such as, for example, near the upper Blumlein insulator, because existing, two-dimensional field codes cannot model the evidently three-dimensional geometry. In such cases, we had to resort to guesses and approximations. These proved to be accurate enough, with one exception. A vacuum port in the outer wall of each accelerating cavity turned out to be insufficiently shielded, so that many cavities began to arc over from the inner ferrite housing, across the epoxy insulator, to the edge of the vacuum port. We cured this problem by installing vacuum grilles, not unlike miniature hibachi grilles, in all vacuum ports.

Early on, we had discovered that in order to prevent air pockets and subsequent voltage breakdown at the upper feed-line insulators (water-oil interface), it helped to throttle down the flow of high-purity water through the lower part of each Blumlein. However, the resultant stagnation of water allowed debris to collect over the lower Blumlein insulators, causing eventual breakdown

there. All these insulators were removed and resurfaced as necessary to remove breakdown tracks. In addition, the water flow pattern was improved by installing a different, more efficient manifolding system.

Figure 7 shows a 10-shot overlay of a typical accelerating voltage pulse trace. Each cavity is equipped with a capacitive voltage divider for sensing this signal, and the resulting signal levels are recorded automatically for each shot, in terms of the area under the pulse trace. The constancy and repeatability of the time-integrated cavity voltage provide a powerful diagnostic tool for verifying trouble-free performance of the 54 Blumleins and cavities.

Fig. 7. Ten-shot overlay of typical accelerator cavity voltage pulse.

Accelerating and transporting the beam to the target

The FXR injector uses six standard accelerator cavities, acting in tandem as a 1.5-MV source, and driving a planar, cold-cathode diode. The 10- to 20-kA emitted beam is collimated to a 38-mm diameter through a carbon-faced, "beam scraper" aperture immediately following the anode mesh, leaving a 2- to 4-kA pulse to travel down the hollow anode stem and on through the accelerating cavities toward the target. Without external focusing, the beam would expand under its own space-charge forces and would soon be dissipated in the walls of the beam tunnel. Beam confinement is achieved through solenoid focusing magnets that are built into each cavity, and through additional magnets mounted between the blocks of four cavities and preceding in the drift section preceding the bremsstrahlung target. When a new accelerator is brought on line, it must be "tuned," that is, one must develop a table of exciting currents for all the focusing magnets that produces an axial magnetic field profile adequate to transport the beam. Codes are available that can serve as a guide in choosing an initial set of focusing currents, although invariably the calculated tune is modified by empirical corrections.

In tuning the machine, we followed the progress of the beam from readings on the resistive beam monitors (RBMs) that measure the total beam current and transverse position of the beam centroid after each block of four cavities. An RBM is essentially a band of carbon resistors (total $R \approx 0.03$ ohm) that interrupts the metallic beam tunnel wall while maintaining circular symmetry and that produces voltage signals proportional to the beam current. Beginning with a complete set of focus coil settings derived from TRANSPORT code runs, we observed the effect of small changes in field strength of the group of solenoids immediately preceding each RBM. In maximizing the beam transmission, we generally gave preference to good pulse shape rather than to perfect centering of the beam, as indicated by the RBM. The transverse beam position can be adjusted through steering coils that are positioned after every four cavities. In general, we try to minimize the external steering, and, in fact, beam steering was almost totally eliminated in recent tunes (profiles).

The early tuning operations were complicated by the fact that we had voltage breakdowns in many of the cavities, but did not at first realize it immediately. Repeatability was poor, and tuning became a tedious statistical exercise where one

simply looked for a majority of good beam pulses that would get to a given point along the beam line. Fortunately, things improved dramatically once the breakdown problem had been solved. Beam transmission to the target now is typically 95% at the 2.4-kA level. Interestingly, we are also obtaining a well-centered beam on target with a minimum of transverse beam steering, whereas before, the cavity breakdowns were producing beam deflections that had to be compensated periodically along the beam line, using the steering magnets.

A vexing problem in connection with beam transport, which took some time to diagnose, was the intermittent, short-term dropout of some focusing power supply. Depending on the location of the supply along the beam line, this would cause severe clipping of the transmitted pulse, or else pulse shortening. We finally identified two separate culprits. First, the thermal sensors on some focus coils, which are interlocked with the power supply for protection against overheating, had developed loose solder tabs that would intermittently open, thereby dropping the supply. The second problem had to do with the regulating transient of the high-voltage power supplies charging the Marx banks. It turned out that these transients feed back via the ac primary lines, to the focusing supplies, and interfere there with the current-regulating cycle. We have installed transient absorbers across the offending power supplies to remedy the problem.

Interestingly, the intermittent, short-term dropout in both cases did not show up in the normal CAMAC data readout, as the complete scan takes roughly 10 s to complete; this made the problem especially difficult to find.

Figure 8 shows a typical beam pulse as measured on the beam-current monitor immediately preceding the bremsstrahlung target. The 2.2-kA current level, at an energy level of 18 MeV, represents the tune as frozen in September 1983, in preparation for shot 693B; we expect to get somewhat higher currents from the injector and on target once tuning is resumed after this experiment. The dose rate is measured by means of thermoluminescent detectors (TLDs); these are crystals of calcium fluoride that are placed in the photon beam, typically at a distance 1 m from the bremsstrahlung target. Irradiation produces a fixed population inversion of energy levels in the crystal, proportional to the absorbed dose; the readout is achieved by placing the crystal in a calibrated

Fig. 8. Typical current pulse impacting on the bremsstrahlung target. This pulse produced the successful, dynamic radiograph of shot 693B, on September 16, 1983. The scales are 392 A/div, 20 ns/div, corresponding to a total charge on the target of 143 μC at 19 MeV.

heating element and observing the emitted light as annealing returns the energy states to their ground level. Current pulses such as the one shown in Fig. 8 typically produced dose rates of 550 R at 1 m, repeatable within $\pm 10\%$. However,

because of the narrow collimation of the photon beam for shot 693B, combined with a certain amount of spot movement across the target, the actual dose on axis here was probably closer to 300 R, still adequate to produce an excellent radiograph.

For the radiographer, an important machine parameter is the radiographic spot size, as this determines how well one can resolve detail in the object to be radiographed. The spot size can be measured directly by observing the fuzziness of the x-ray image of an opaque edge, such as a uranium cylinder; this type of measurement gave a 3- to 5-mm spot size for the FXR machine at the 500-R level.

A very rough idea of the final beam diameter, and hence also of the radiographic spot size, can be gained from looking at the holes made by the beam in the tungsten target. Figure 9 shows a display of punctured 0.75-mm-thick tungsten target platelets that were taken from our 18-target, rotatable array. The holes here are 5- to 10-mm in diameter; evidently the thermal effects damaged an area that is larger than the radiographic spot size. Larger-than-minimum spots also result from detuning the final focusing solenoid by a small amount from the optimum value.

Fig. 9. Tungsten target platelets, each damaged by a single pulse, arranged approximately as in the FXR rotatable target array.

Computer-driven, single-operator control of a multielement machine

As seen earlier from the diagram of the FXR switching system (Fig. 5), the operation of the FXR accelerator depends on the synchronized functioning of a large number of pulsed-power subsystems and components. From the outset, it was clear that automated monitoring of this multitude of different components would be essential to ascertain reliable machine performance before an important radiographic experiment, as well as for assessing that performance after such an event. At the same time, computer-assisted recall of previously developed and optimized control settings, i.e., machine tunes, would be important in order to minimize both operator fatigue and the chance for human error. These three functions—automated monitoring, fault flagging, and centralized, automated recall of control settings—have been realized in the FXR monitoring and control system, shown in Fig. 10.

Analog sensor signals from the machine are processed through the analog-to-digital converters (A/D) and transmitted along a CAMAC serial highway, via fiber optics links, to the control room for real-time display, as well as for storage in a permanent database. Keyboard or touchpanel commands, originating from the control console, take the same path in the opposite direction. For every machine pulse, the following diagnostic signals are monitored and entered into the database: beam current and beam centroid position at 14 different positions along the beam line; time-integrated accelerating potential in 54 accelerator cavities; trigger delay times at some 45 different points in the switching system, referenced to a common start pulse; leading-edge arrival times of the accelerating potential pulse in all 54 accelerator cavities; and current and/or voltage settings (i.e., the machine tune) for 5 high-voltage supplies, 31 focus coil supplies, and 30 steering coil supplies. Up to 10 different tunes may be stored in the database for recall on demand. In the following sections we describe in more detail some of these functions and the requisite hardware and software.

The 214 fast-pulse signals from transducers located along the FXR beam line are transmitted through triaxial cables to four instrumentation racks located along the electronics corridor. These racks contain instrumentation, conforming to CAMAC and nuclear instrument modules (NIM) standards, which capture and process these fast analog signals into digital levels.

Also entering these racks are control cables from 68 power supplies used to excite magnets and provide high voltage to power the accelerator. These power supplies are located adjacent to the racks in the electronics corridor. CAMAC instrumentation in the racks provides for supervisory control of these power supplies.

Digital signal data is transferred through a fiber optics cable between the instrumentation racks in the electronics corridor to the active one of the two Hewlett-Packard 1000 computer systems in the control room. Note that two minicomputers have been provided for redundancy. A standard 5-Mbps CAMAC serial highway, routed in an unidirectional loop, couples the four instrumentation racks in the electronics corridor and a fifth instrumentation rack in the control room to the computer system. A fast instrumentation trigger for triggering diagnostics equipment is also routed from the control room to each instrumentation rack by an independent set of fiber optics cables.

The FXR operator's console (Fig. 11) in the control room contains two identical operator stations, each of which includes a color graphics terminal equipped with a Carroll touch-panel terminal for logging status and alarm messages, and a "knob and readout" panel for adjusting power supply levels.

The following are examples of the type of functions that an operator is able to perform or initiate from the operator's console:

- Define and update the monitoring and control model of the FXR system by simply editing a database.
- Configure the control program from a database.
- Set acceptance windows for monitored data channels.
- Initiate autonomous monitoring processes. "Autonomous" means that the process then proceeds without further human intervention. For example, when the system is first initialized, it loads and arms a set of programs required for a given process; or a time schedule then triggers execution of the process. The process will continue to be scheduled until terminated by some internal condition or from the keyboard.
- Selectively energize a subgroup of power supplies.

Fig. 10. Major units of the FXR monitor and control system.

Fig. 11. FXR control console.

- Select the appropriate accelerator tune from among many stored in a database.
- Turn individual or groups of the power supplies on or off.
- Display real-time status and performance data for each pulse.
- Autonomously store the monitored data and the status of the FXR facility in a database following each accelerator shot.
- Use the monitored data as stored in a database to generate tables and graphs for off-line analysis.
- The CAMAC serial highway is switchable between two redundant computer systems.
- Each computer system is totally redundant from the CAMAC serial highway driver through the operator interface.
- Dual access disks are used so that either computer system can access the database.
- The software is identical on both computers. If one computer system fails, all that needs to be done to restart, using the other computer system, is to switch the CAMAC serial highway and restart the control program on the other operator's console.

Minimum downtime through a redundant control system

To minimize downtime, redundancy has been incorporated into the computer system as follows:

The redundant approach to machine control has been quite successful; for although there have been several component failures in the computer

system since it was installed in August 1981, with time-to-repair of up to 3 days, the machine downtime chargeable to the monitoring and control system has been almost negligible.

Effective EMI protection

Both the accelerator and the switching system are well shielded against electromagnetic interference (EMI) from within. We took great care to install signal cabling, grounding, and shielding so as to safeguard the monitoring and control system from the noise-generating potential of the accelerator (e.g., 54 Blumleins generate 250-kV, 25-kA, 90-ns pulses). Accordingly the instrumentation racks in the electronics corridor were built to screen-room specifications (e.g., steel construction, EMI gasketed doors front and back, honeycomb filters). Furthermore, the equipment mounted within is isolated from the outer, sheet metal shield and the outer shields of the triaxial signal cables are connected to the shell, which effectively extends the shield completely around the equipment. All other cables entering the instrumentation racks are either fiber optics or have been electrically isolated. An indication of the success of this effort is that fast-pulse, analog signals of 400 kV are attenuated to a level of 128 mV, and are measured at an instrumentation module without apparent detrimental EMI problems.

Beam line data acquisition

The signal conditioning used for beam line data acquisition is shown in detail in Fig. 12. The 90-ns-wide cavity voltages sensed by E-field probes in each cavity are sampled for 40 ns at the flat peak of the waveform by the integrating analog-to-digital converter (ADC). The 60-ns-wide, beam-current pulses sensed by four quadrant beam-position monitors at 15 locations along the beam pipe are sampled for 20 ns at near the peak of the waveforms.

Time intervals are monitored as follows. Signals from cavity voltage transducers, for example, first are level-discriminated. The discriminator signals then are sent to an array of 8-channel, time-interval-monitor (TIM) modules. These modules are capable of resolving 0.25 ns out of a 500-ns range. Channel assignments are such that each module monitors a reference channel common to all other TIM modules. Thus, we can determine relative time intervals between any given channel

and the selected reference channel. Cable lengths are taken into account such that the time interval measurement data refer to signals at the transducers. End-to-end tests indicated that the accuracy of the time interval measurement is about 1 ns.

Self-test of the above channels is done by injecting a self-test pulse into the signal path as shown in Fig. 12. This tests all cables, connections, and components in the signal path, as well as the instrumentation module and application software.

A compact power supply controller

All magnet and high-voltage power supplies are controlled through a simple, compact eight-channel module (Fig. 13). The power supply control reference level and output level monitoring are done with 12-bit accuracy. Safeguards for the entire system include a digital combination lock for "power on" and "reset level" operations; an absolute limit on the control reference voltage level; and "watchdog" monitors on both the power supply and the controlling computer. A loopback self-test is one that compares 10 points, within the control level range for each channel, against an operator-defined acceptance window.

CAMAC-minicomputer interface design

Because an adequate CAMAC serial highway driver compatible with the HP-1000 computers was unavailable, we developed our own CAMAC channel controller. We used an LSI-11 microcomputer interfaced to the HP-1000 through a 16-bit parallel interface and a special CAMAC serial highway driver board developed at LLNL to implement the CAMAC channel controller. Some of its channel control functions include command-list execution of a block of up to 128 commands, demand handling (where outside events cause computer interrupts), hung-demand handling (where computer did not recognize the demand message, which must be reissued periodically until recognized), and self-test. The LSI-11 control procedure was put in nonvolatile memory to implement stand-alone operation.

Recommended CAMAC operating procedures and standards were followed, where applicable, including the implementation of an access library of FORTRAN standard subroutines. However, an additional safeguard was necessary under accelerator fault conditions when it was evident

Fig. 12. Beam line data acquisition.

that CAMAC demand messages were being corrupted (messages were altered in transit due to noise); all demands are now confirmed by checking the demand flag at the source before further action is taken.

Use of in-house and commercial software

During the past 2 years, we have developed about 22,000 lines of documented code. The development effort loosely followed the phases of requirements definition, architecture design, detailed design, implementation, installation, and incremental test. We used Yourdon analysis and design techniques⁵ in the initial stages to better

define the problem. Documentation was developed in parallel and resides at the head of the source code. The software can roughly be divided into utility, diagnostics/calibration, database, CAMAC support, real-time applications, operator interface, and analysis routines.

Real-time application software is organized around the Hewlett-Packard RTE-IVB operating system in the HP-1000s. It is structured in a hierarchy with central processes common to all subsystems at the top of the module tree. Software subsystems are oriented toward physical subsystems, such as power supplies, beam line, switching system, FXR facilities, and auxiliary systems (all mechanical systems that support the FXR facility). Each subsystem operates out of control tables located in memory common to modules of a

Fig. 13. Power supply controller.

given subsystem, but protected from all others. Each subsystem can be run independently of all other subsystems.

The application database is organized around the Hewlett-Packard IMAGE/1000 database product. It is partitioned into a configuration database and an output database. The configuration database contains datasets for each class of object that is included in the FXR control model (channels, transducers, cables, CAMAC instrumentation, etc.). It also contains datasets used to set operating parameters (defaults and tuning tables). The detailed configuration of the monitoring and control system is defined and altered by simply editing this database.

The output database contains control/status and raw-data datasets. Status information from up

to 5000 FXR shots can be stored in this database and later retrieved for analysis. We wrote a database editor and report generators to implement needed utilities that were not provided with the IMAGE/1000 package.

The operator interface software is distributed among the central system and the subsystems. It was originally implemented to run on an alphanumeric terminal and operate strictly in text mode. This was done to save time in order to enable bringing up the machine on schedule.

The operator interface has since been implemented to use a Chromatics CG1599 color graphics terminal equipped with a Carroll touch panel that permits operator interaction and status display in a more natural and flexible format.

Conclusion

Improvements to the pulsed power system of FXR made during the past year have resulted in much better reliability and repeatability. At a current level of 2.2 kA on target, the machine produces a radiation dose of 480 R at 1 m, with a spot size of 3 to 5 mm and with the dose repeatable

within $\pm 10\%$. With this new capability, researchers have already begun to improve their understanding of material behavior at high pressure and densities, working in a heretofore inaccessible regime of radiographic penetration and resolution.

References

1. *Energy and Technology Review*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52000-81-5 (1981).
2. R. D. Scarpetti and C. D. Parkinsin, "Switching System for the FXR Accelerator," *14th Pulse Power Symposium*, Orlando, FL (June 1980).
3. B. Kulke et al., *Design of a 20 MeV, 4 kA Linear Induction Accelerator for Flash Radiography*, Lawrence Livermore National Laboratory, Livermore, CA, UCID-18939 (1981).
4. B. Kulke, R. Kihara, D. Ravenscroft, R. Scarpetti, and G. Vogtlin, "Beam Tests on the 4 kA, 1.5 MeV Injector for FXR," *Proc. 4th Int. Topical Conf. Electron and Ion Beam Research and Technology*, Palaiseau, France (1981), pp. 821-828.
5. B. Kulke, D. S. Ravenscroft, and G. E. Vogtlin, "Design and Performance of the 1.5 MeV Injector for FXR," *Trans. IEEE NS-28*, 2882-2884 (1981).
6. B. Kulke, T. G. Innes, R. Kihara, and R. Scarpetti, "Initial Performance Parameters on FXR," *IEEE Fifteenth Power Modulator Symposium*, Baltimore, MD (June 1982).
7. B. Kulke, R. Kihara, "Recent Performance Improvements on FXR," *Particle Accelerator Conf.*, Santa Fe, NM (March 1983).
8. E. Yourdon and L. L. Constantine, *Structured Design*, Yourdon Press, New York (1978).

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