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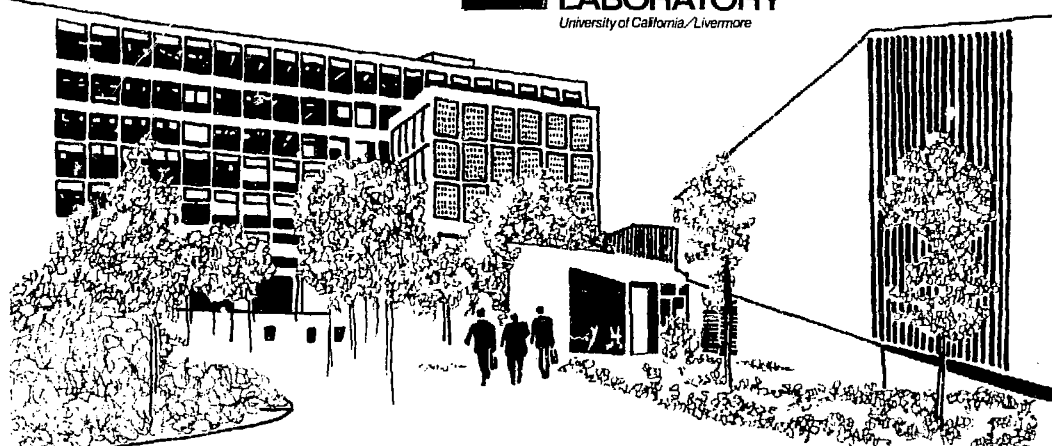
ELECTRONICS ENGINEERING DEPARTMENT QUARTERLY REPORT NO. 1—1978

Inside: Neutral-beam power supplies for magnetic fusion.
Ion-beam current-density profile monitor.
Isolation and control system for Shiva's pulse-power system.
Television intrusion protection system.

July 10, 1978

Work performed under the auspices of the U.S. Department of Energy by the UCLLL under contract number W-7405-ENG-48.

LAWRENCE LIVERMORE LABORATORY
University of California/Livermore



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FOREWORD

The EE Department Quarterly Report is published with two purposes in mind: (1) to inform readers of various activities within the Department, and (2) 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 the individual listed at the beginning of the article in question; that person is primarily responsible for the content of the article. Inasmuch as most projects are the result of the cooperative efforts of many individuals, the article contact may either provide the requested information directly or refer you to the appropriate person to answer your question.

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AES

NEW GENERATION OF NEUTRAL-BEAM POWER SUPPLIES DEVELOPED FOR MAGNETIC MIRROR FUSION

The Department of Energy has designated LLL as the lead laboratory for magnetic mirror fusion. Our role includes responsibilities for overseeing and guiding the United States mirror program. Here at Livermore, the country's largest mirror physics machine, 2XIIB, is operational, and two new major facilities are under construction: the tandem mirror experiment (TMX) and the mirror fusion test facility (MFTF). Among the equipment that Electronics Engineering is providing for this program are the power supply systems for the neutral beams that raise the plasma's temperature and maintain its density.

Why Mirrors? A Brief History

To create fusion reactions, a tiny amount of deuterium gas (or a deuterium tritium mixture) is heated to temperatures between 10 and 100 million K and sustained long enough for fusion reactions to occur. At these elevated temperatures, the gas cannot contact a material vessel, because the enormously greater heat content of the vessel will cool the gas to temperatures below which fusion can occur. Magnetic fields have been used for many years to attempt plasma confinement. In early solenoidal mirror machines, the magnetic field was used to provide both the axial and radial confinement. 2X, an early solenodial machine, was found susceptible to gross magnetohydrodynamic (MHD) instabilities and to a high axial loss rate. 2XII attempted to stabilize the plasma against the macro-instabilities by providing what is known today as a single-cell mirror. Stabilization against the gross MHD instabilities was demonstrated, but the plasma was still susceptible to a very high loss rate through the ends of the machine. 2XIIB, an extension of 2XII, showed that plasma could be sustained by neutral particle injection. However, the plasma experienced micro-instabilities. 2XIIB overcame these micro-instabilities in 1975 and early 1976 by streaming cold gas into the reaction volume. With 2XIIB sustained by neutral beams and stabilized by cold gas injection, a new machine to test scaling laws to large radius plasmas was proposed. This was the MFTF, a single-cell mirror machine nominally five times larger than 2XIIB, and Congress appropriated $94.2 million.

At about the same time, Grant Logan of LLL (and simultaneously G. Dimov of the Soviet Union) realized it was possible to use a single-cell mirror to electrostatically plug a long solenoid in the axial direction. This tandem mirror concept led to LLL building TMX—an $11-million major device fabrication, with a scheduled completion date of October 1, 1978.

All of the above machines—2XIIB, TMX, and MFTF—have very powerful sets of neutral beam injectors. As the machines have grown in size and the mirror program pushes toward steady-state operation, the demands on the neutral beam power supplies have increased in both energy and pulse duration. Table 1 lists the fundamental operating parameters of the neutral beams on the three machines. Of particular interest is the increase in the voltage from 20 to 40 to 80 kV and the increase in pulse duration from 10 to 25 to 500 ms.

Table 1. Neutral beam power supplies for the magnetic mirror fusion machines at LLL.

Machine	No. of beams	Voltage (kV)	Pulse duration (ms)
2XIIB	12	20	10
TMX	8	40	25
	17	20	25
MFTF	24	20	10
	24	80	500

For further information about this article, contact Leonard J. Mooney (Ext. 29879).

Neutral Beams

The single-cell mirror effectively confines plasma in the radial direction; it therefore is effective at excluding radially directed charged particles. Injection of energetic particles into the reaction region is accomplished by electrostatically accelerating, focusing, and then collisionally neutralizing them before injection. Figure 1 shows the schematic representation of a single neutral beam source. The operational sequence is as follows:

- An array of nearly 100 tungsten filaments is heated to 3000 K by the filament power supply, thus creating a sea of thermal electrons.
- A burst of hydrogen or deuterium gas is injected into the arc chamber.
- The arc power supply sweeps the thermal electrons through the deuterium (or hydrogen) gas and ionizes it.
- The accel power supply raises the arc chamber to the required accelerating voltage (20, 40, or 80 kV); positive ions are then accelerated and focused.
- The energetic ion beam then passes through a charge-exchange neutral gas cell.

(The suppressor, or decel, power supply is used to retard the flow of negative particles to the arc chamber where they could damage the filaments.)

2XIIB represents our first attempt to operate multiple neutral beams on a single experiment. Extensive experience gained with 2XIIB has led to significant improvements in the TMX beam system.

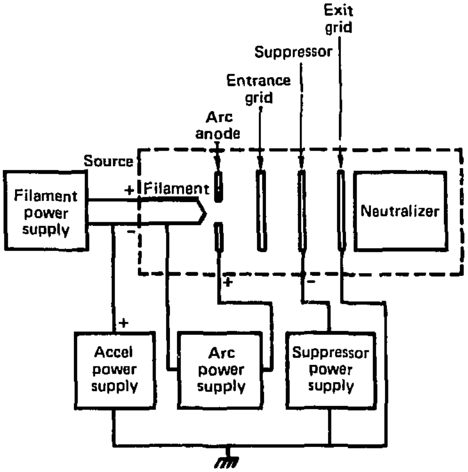
The Electronic Engineering department's contributions to the neutral beam power supplies on TMX include:

- The upgrade of the accel power supply from 20 kV, 10 ms to 40 kV, 25 ms while achieving greater reliability, noise immunity, and maintainability.
- The upgrade of the decel power supply from 10 to 25 ms.
- The development of new accel voltage regulator for improved control and reliability.
- The development of a new generation of arc and filament supplies based on batteries.

The Accel/Decel Power Supply (ADS)

Many features of the accel/decel power supply (ADS) for TMX were redesigned to enhance system compatibility, reliability, and maintainability (Figs. 2 and 3). This involved some change in the conceptual design of the accel supply. The TMX ADS retains the 4CW100000E tetrode modulator to control the discharge of a capacitor bank and to present regulated voltage to the neutral beam source. We developed a new, closed-loop feedback accel voltage regulator that has eliminated the need for the series ignitrons used on 2XIIB. In the TMX beam system, the tetrode not only performs the regulation function, but also the switching function. By improving the reliability of the accel voltage regulator series-tetrode combination, we have also eliminated the need for shunt ignitron crowbars that are used in the 2XIIB 20-kV beam systems. The limitation on this may be the need to protect a neutral beam source against spark-down (tube shorts internally) of the series tetrode at higher operating voltages (e.g., 40 kV).

We increased the pulse length in TMX by increasing the capacitive energy storage 2-1/2 times. The capacitor banks for the 2XIIB 20 kV and TMS 40-kV beams are constructed of series/parallel combinations of 450-V aluminum electrolytics. These banks are typically charged early in the morning and left charged continuously for 8 to 16 hr. Neutral beams are relatively slow, with rise times to



Supply	Voltage	Current (A)	Pulse
Accel	40 kV	80	25 ms
Arc	150 kV	4000	25 ms
Suppressor	-5 kV	20	25 ms
Filament	15 V	2500	1.6 s

Fig. 1. Power supply (40 kV, 80 A, 25 ms) for pulsed neutral-beam injector consists of four separate power supplies.

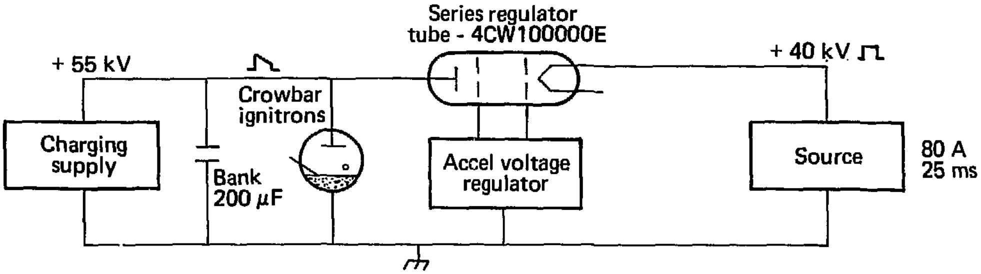


Fig. 2. Accel/suppression power-supply circuit: 40-kV, 80-A, 25-ms neutral-beam power supply for TMX. A series-regulator tetrode controls the output voltage supplied to the injection source.

80 A over a period of 100 μs and require very low current density from the bank. This, coupled with the very long dc life requirement, makes aluminum electrolytics attractive. A single 40-kV, 25-ms neutral beam requires about 168 μF charged to 55 kV or 0.25 MJ.

The most stringent requirement on the accel voltage regulator and tetrode combination is to protect a neutral beam source from internal damage due to spark-down. Like all high voltage tubes, neutral beam sources must be conditioned to voltage; during the conditioning process, internal spark-down is frequent. When the source sparks-down, the accel power supply must be turned off quickly to minimize energy deposited in the spark. This quick interrupt clamps the regulated output voltage from 40 kV to zero in a few microseconds, and produces a propagating transient from the source to the ADS (which is 100 ft away) to the capacitor bank located in the next building. The quick interrupt is thus a potentially severe source of transient interference.

TMS is protected against severe transient difficulties by carefully ensuring that each neutral beam power supply is single-point grounded at the source only, and is satisfactorily shielded from all other neutral beam power supplies in the system so that ground loops are eliminated and pick-up is minimized.

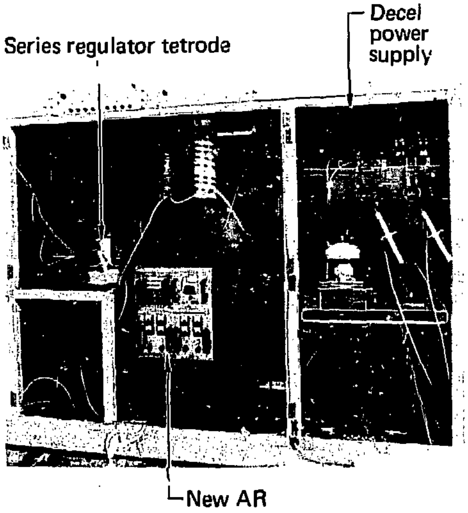


Fig. 3. The new accel/decel power supply (ADS) is 6.5 by 9 by 3 ft.

The Accel Voltage Regulator (AVR)

The series tetrode that supplies the accel voltage to the neutral beam source is controlled by a fast, closed-loop feedback system known as the accel voltage regulator (AVR). The new AVR provides optimal transient switching control and permits tailoring the rise of the accel voltage to optimize beam focusing during turn-on. The redesign also places the bulk of the electronics at high voltage along with the tube it must control. Communication with the ground world is by fiber optics. This feature allows the AVR to be adapted to higher voltages in the future, and makes it possible to do bench testing using ground referenced test methods.

An understanding of the operation of the AVR can be gained from the signal flow diagram in Fig. 4. The essential elements are the optical interface, the preamplifier, and the rf driver amplifier. The interface communicates to the AVR on four optical channels; two uplinks and two downlinks. The first uplink is a fast channel containing binary on-off information and is fail-safe because the absence of light turns the AVR full off. The second uplink contains a fm pulse train which sets the required output voltage. The response of this channel is deliberately made slow for noise immunity with a low-pass ripple filter because changes in the reference voltage only occur between pulses. The dc accuracy of the reference signal is adjustable to better then 3/10% of full range. The two downlinks provide interlock information to the control room and permit binary and analog monitoring of the AVR.

The preamplifier and compensation section consists of three commercially available, high performance, solid-state, differential operational amplifiers. The operational amplifiers specified have a gain-bandwidth product of 50-MHz, 100-mA output rating to 10-Mz and 1000-V/μs slew rates. Although the performance is better than required, the absence of undesired poles in the closed loop response assures stable operation.

Good driver amplifier performance is essential to fast response (both interrupt and regulation) of the overall system. A major feature is the separation of the regulation and switching functions so they do not interact. This separation is done by the control grid circuit of tetrode V1 (Fig. 4). Under regulation, the binary interrupt channel holds transitor Q2 in saturation, which grounds the V1 grid. The feed-forward path then controls V1. Tetrode V2, driven as a cathode follower, controls the grid of the series tetrode, V3. In this mode, the small signal response is flat to 500-kHz where it rolls off at a single pole rate to at least 5 MHz. This well-behaved frequency response is a major feature of system operation.

When an interrupt is required, the binary interrupt signal to Q2 is removed; even though the feed-forward path may still be asking for regulated voltage; V1 is turned full on and reduces the grid of V2 to −1300 V. (All voltages quoted for the AVR are with reference to AVR common.) The output of V2 reduces the series tetrode control grid to a −1250-V cutoff condition. The cutoff response time from the V1 grid to V3 is limited by the V2 cathode circuit rc time constant to approximately 1 μs.

The AVR is housed in a single 19-by-19-by-14-in. chassis subdivided into four modules with rear plug-in connectors for ease of servicing. A printed circuit card module contains the preamplifier, compensation, and optical interface cards. The driver amplifier is in a second module. The remaining two modules are the dc power supplies for the driver amplifier and the series regulator screen supply.

The greater dependability of the AVR has eliminated the series switch ignitrons and the associated triggering electronics with a concomitant savings in cost and valuable space in the accel supply. Also, the ability to tailor the rise of the accel

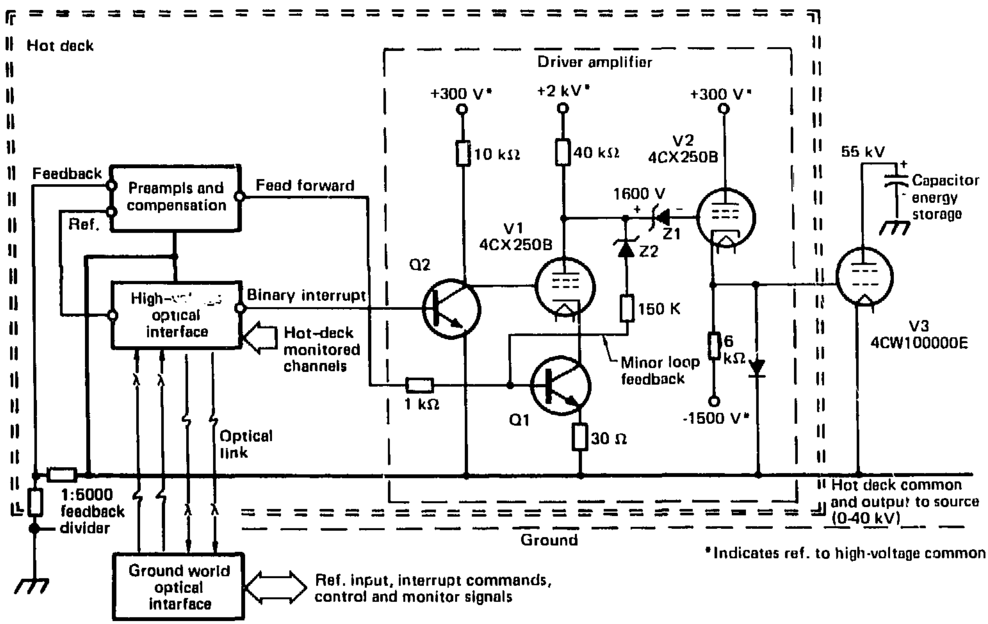


Fig. 4. Signal flow diagram of the accel voltage regulator (AVR) showing the optical links, preamplifier, and the driver amplifier.

pulse allows more reliable turn-on of the neutral beam source for reasons related to beam focusing.

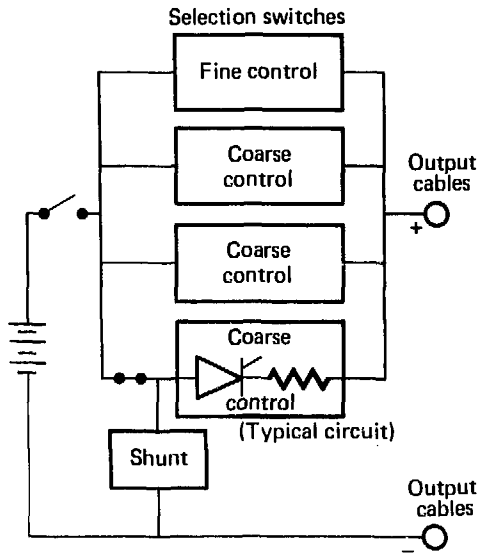
The Battery Arc Power Supply (BAPS)

The arc supply is a low voltage, high current (50-V, 4000-A) supply that must float to 40 kV. In addition, it is desirable to interrupt the arc along with the accel during a source fault. This hastens the extinction of the fault and eases the problem of restarting the neutral beam source. Thus a particularly challenging feature of the arc power supply control system is to commutate the arc off in a few microseconds. We conducted cost-performance trade-off study of several different possible arc power supplies. Of the alternatives examined—pulse-forming networks; phase-controlled, 60-Hz ac, inverter-driven, high-frequency isloation transformers; motor alternator sets; and battery banks—the battery banks appear to be the most cost effective for the TMS application.

A battery arc power supply manufactured for TMX costs about the same as a 25-ms arc pulse line of the variety used on 2XIIB. However, the battery supply has the advantage of longer pulse lengths with little additional cost. (TMX is initially a 25-ms pulse width machine. However, future upgrades to 50 ms and possibly 100 ms are envisioned.) Figure 5 shows a block diagram of the battery arc power supply. The supply is conceptually a battery with switches that parallel resistors to control the arc current. Additional shunt switches commutate the arc off. It is these switches that permit rapid fall times of the arc current without the characteristics turn-off spikes of series switches.

Control of the arc current is divided between four power circuit modules. Three modules provide coarse current steps of about 750 A each. The remaining one has a group of five resistors for fine control. In all, 128 steps are available. A control module determines the appropriate combination of resistors for a selected arc current and generates the pulses to select them. These pulses are transmitted over fiber optics to the power supply. The power supply uses another optic link to return status information to the controller.

Four strings of eight batteries of the type used to start large internal combustion engines are placed in series. When serviced, three fusible switches isolate the bank into sections of 50 V maximum. Battery charge is maintained with a 5-A charger fed from a 40-kV isolation transformer. A picture of the prototype bank appears in Fig. 6.



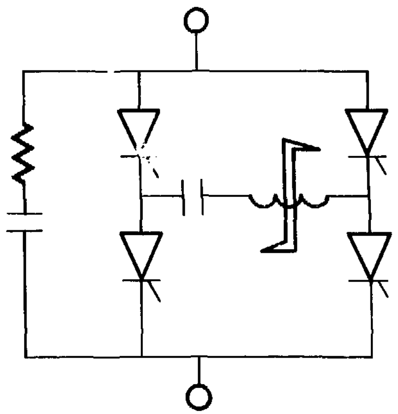


Fig. 5. The battery arc power supply (BAPS) selects arc current by firing appropriate SCR's.

The Battery Filament Power Supply (BFPS)

The filament power supply heats numerous tungsten hairpin filaments to incandescence to provide electrons in the source arc chamber. Like the arc supply, it too is a low voltage, high current (11.4-V, 5000-A) supply that must float to 40 kV. However, the control problems are relatively simple, since it need only be turned on for 1.6 s then turned off with no particular rise-time requirement. The principal virtues of a battery supply are its simplicity and moderate cost.

The conceptual circuit is a battery, a series resistor to adjust for filament aging, and four fiber-optic-controlled relays for an on-off switch (Fig. 6). Internal resistance regulates the output and limits surge currents to 10,000 A. Filament voltage is monitored by a voltage-to-frequency-to-light converter and transmitted to the control room via fiber optics to a digital panel meter.

Twenty batteries of the type selected for the arc power supply are combined to provide ten 500-A circuits (Fig. 7). Fault protection fuses are monitored through a fiber optic cable; a blown fuse will lock out the supply. The batteries are constantly charged with a regulated power supply. Figure 8 shows the installation of the batteries in a typical rack.

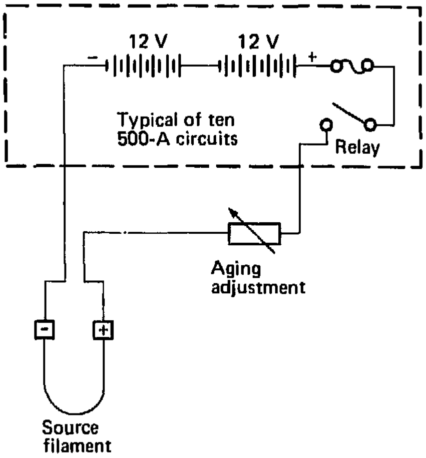


Fig. 7. Circuit block diagram of the battery filament power supply (BRPS). Ten of these circuits feed one source filament.

Fig 6. Prototype of battery arc power supply.

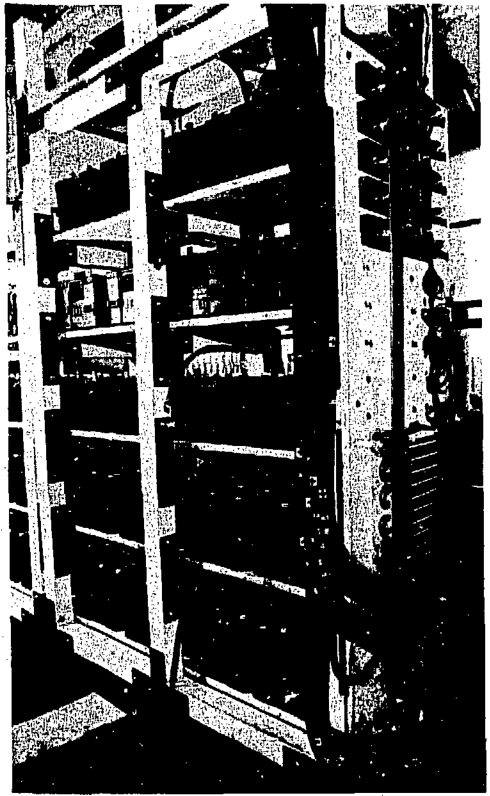


Fig. 8. BFPS and its associated hardware. The rack is 8.5 by 6 by 2.5 ft.

Summary

The TMX beams represent a significant step forward in neutral beam system technology. When TMX turns on in Fall of 1978, it will be capable of approximately 32 MW of neutral injection, and an early planned upgrade will increase that to near 48 MW. Contrast this with 2XIIB, currently the most powerful neutral beam system in the country, which routinely injects about 8 MW of neutral power into the plasma. Along with the factor of four increase in available neutral power, the TMX beam system has higher average energies and longer pulse widths. Careful attention to detail in the TMX beam system will ensure compatible, reliable, maintainable operation.

Another major step in neutral beam technology is required for MFTF to come on-line in early 1982 with 160 MW of neutral injection at 80 kV for 0.5 s.

FAST-SCAN MONITOR EXAMINES NEUTRAL-BEAM ION-DENSITY PROFILE

All of the magnetic mirror confinement fusion experiments at LLL and at other laboratories depend on pulsed, energetic neutral-beam injection for fueling and imparting energy to the trapped plasma for density build-up and stability studies. It is vital to be able to monitor how well the injected ion beam is aimed and focused. To do this, we have designed an ion-beam current-density profile monitor that uses a commercial minimodular data acquisition system. Our prototype model monitors a single 20-kV, 50-A, 10-ms beam. However, the method is applicable to any number of beams with similar sampling target arrays. Also, the electronics can be switched to monitor any one of several target collectors.

Three mirror confinement fusion experiments at LLL depend on neutral-beam ion sources for injecting beam pulses into their confinement fields for heating plasmas to thermonuclear temperatures: the 2XIIB experiment, the tandem mirror experiment (TMX), and the mirror fusion test facility (MFTF).

- The 2XIIB experiment has twelve 20-kV, 50-A sources injecting 10-ms pulses.
- The TMX machine will have 24 sources (16 of which are 20 kV and 8 are 40 kV) injecting pulses of 25-ms duration.
- The large MFTF experiment will have 24 sustaining-beam injectors of 0.5 s duration time to eventually 30 s, in addition to some 48 pulsed, short-duration start-up injectors.

It is necessary and important to develop diagnostic techniques to monitor the performance quality of these neutral-beam injector systems.

How to Monitor the Neutral Beams

One of the most vital performance features to be able to monitor is how well the injected beam is aimed and focused. This could be done if one can determine the relative beam-current density over the beam cross section at the aiming point of interest. This requires the capability to interrogate very rapidly a matrix array of minitargets over the beam cross section during the few milliseconds of beam duration. For maximum usefulness, the information should be provided immediately to the operator in an easily recognizable and interpretable form that indicates the beam position and quality of focus on the target.

The present neutral-beam ion sources that we use were developed by Lawrence Berkeley Laboratory and have a rectangular beam cross section of approximately 3-by-12 in. Our beam-profile monitor scans a 45-point-minitarget array over this cross section. The diagnostics system operates at a throughput rate of 12-μs per channel and, therefore, makes several complete scans during the 10-ms beam pulse. The data obtained are available in both analog and digital form. The analog signal is used to create an immediately interpretable bar-graph-type cathode-ray-tube (CRT) display of the beam-current density profile that shows how well the source is aimed and focused. The digital data are held in buffer memory until transferred to a minicomputer for software processing and plotting.

The Beam-Current Sampling Target Array

Another important beam performance characteristic is the total energy per pulse deposited on a beam-stopper plate. This is a calorimetric measurement made by observing the temperature rise of the known thermal mass of the beam-stopping plate (Fig. 1). We used the beam-stopper plate as a shield and mask for the array of beam-sampling minitargets. The beam-stopper calorimeter plate is 1/4 in. thick, made of copper, and cooled on the edges by water. It has 45 beam-sampling holes

For further information about this article, contact Alfred F. Waugh (Ext. 29899).

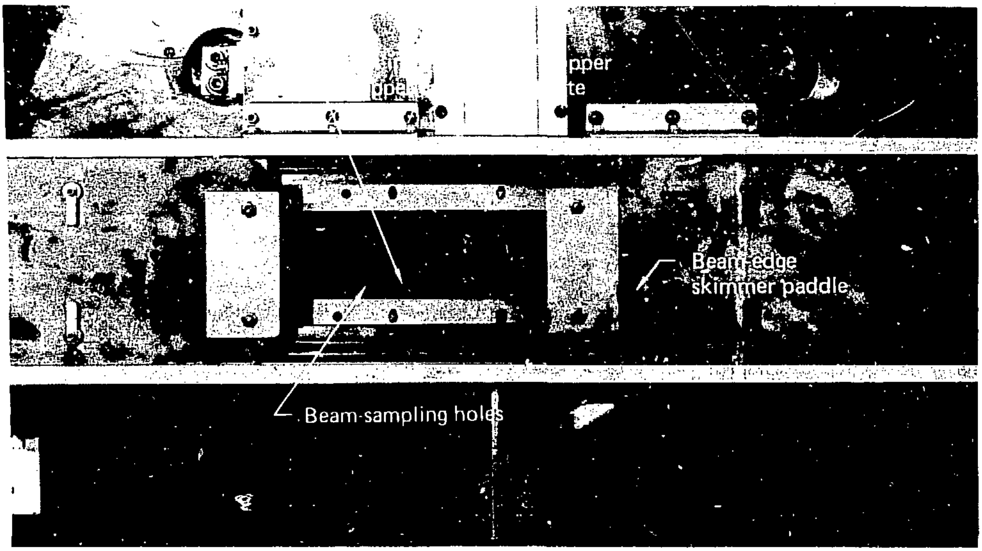


Fig. 1. Front (beam side) of beam-stopper calorimeter plate mounted in beam-target assembly. We calculate the total energy per pulse deposited on the beam-stopper plate by observing the temperature rise of its known thermal mass.

through it to allow sampled beam currents to be monitored by an array of minitargets. These forty-five 1/16-in. diameter, beam-sampling holes are arranged in five horizontal rows of nine holes each. The rows are 1/2 in. apart, and the distance between adjacent horizontal holes is 1-3/8 in. One horizontal and one vertical row pass through the geometric center of the calorimeter plate with one hole at the center point.

The beam-sampling minitargets are forty-five 4-40 stainless steel machine screws (Fig. 2). They are mounted on a custom-designed printed circuit (PC) board that is insulated from and about 1/4 in. behind the beam stopper calorimeter plate. The PC

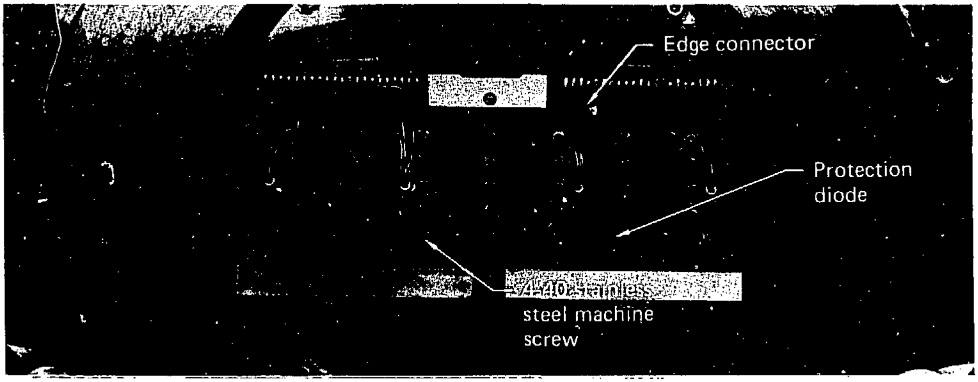


Fig. 2. Back view of beam-profile monitor PC board in the beam-target assembly. The PC board positions the minitargets directly behind the 1/16-in.-diam beam-sampling holes in the beam-stopper plate.

board positions the targets directly behind the 1/16-in.-diam, beam-sampling holes in the plate. Leads on the back (away from the beam) of the PC board connect the conductive pad around each screw hole to a tab of either of two 22-pin edge connectors mounted on the upper edge of the PC board.

Beam-Target Assembly

The beam-target assembly is located about 1 m from the exit grid of the ion sources and near the exit port of the experiment's beam-neutralizer chamber. The assembly can be moved vertically out of the beam line for beam injection into the experiment or lowered into place for monitoring the source performance. The 1/16-in.-diam beam-sampling holes in the copper calorimeter plate are clearly discernable in Fig. 1. When this photograph was taken, the right beam-edge-skimmer paddle was pushed in about 1 in. from the beam center line. The paddles are used to skim out some beams, if desired, during testing.

The beam at the target location should be composed entirely of energetic neutral particles. The actual current monitored at the beam-sampling minitargets is electron current from ground to replace secondary electrons produced at the surface of the screw heads by the energetic incident atoms. A small (5- to 10-V) negative bias ensures that all emitted secondary electrons are driven away and do not fall back on the screw heads. Should the beam no longer be neutralized and positive beam currents terminate on the minitargets, the monitoring system would be damaged because the minitargets would then be electrically connected to the 20- to 40-kV acceleration potential of the ion source. To prevent this, each minitarget is connected by a small, solid-state protection diode to a ground bus on the PC board. This diode would be forward biased if the target tended to go positive, and would clamp the target to a 0.8-V, forward-diode voltage drop above ground. The negative bias, needed on the minitargets to drive away secondary electrons, also reverse biases the protection diodes so they appear as open circuits to the monitoring system.

Wire leads from the PC board edge connectors carry beam-current signals from the beam-line vacuum tank to the outside via a multipin, hermetically sealed connector. The beam currents pass through current-monitoring resistors and the common negative bias to ground. Voltages produced across the 45 resistors must be rapidly scanned in a time short compared to the 10- to 25-ms duration beam pulse. The diagnostic system does this, and the output produced is useful to and interpretable by a knowledgeable operator.

The Minimodular Data Acquisition System

We acquired a commercially available, minimodular, data acquisition system that is ideally suited to this and similar fast-scanning applications. Although the unit selected was one of the first on the market, similar models are now available from four or five data processing component manufacturers.

Our minimodular data-acquisition system contains the following interconnected elements (Fig. 3): a 16-channel, single-ended multiplexer (also available as 8-channel differential inputs); a signal-conditioning differential amplifier; a high-speed sample and hold amplifier, a fast, 12-bit analog-to-digital converter; and control and programming logic. These elements are contained in a 3-by-5-by-3/8-in. package with a multipin edge connector. We also purchased an auxiliary module of the same size that contains 48 single-ended channels of multiplexer input. The two units together provide 64 channels of multiplexer input. Fortunately, the differential amplifier treats the common negative target bias as a common-mode signal and only amplifies the voltage drops across the current-monitoring resistors of interest.

The data acquisition system has a nominal throughput rate of 50 kHz (20 μs) per input channel. Newer units have throughput rates of up to 100 kHz (10 μs) per input channel. Control points brought out and made available to the user increase clock rate and shorten digital output work length to 8 bits. This allows the modules to operate at a throughput rate of about 80 kHz (12 μs) per input channel. We normally use this 12-μs rate to scan all 64 input channels in about 770 μs.

The analog signal is conveniently available from a point at the output of the differential amplifier and the input of the sample and hold amplifier. This signal is used to create a useful and immediately interpretable CRT display (Fig. 4). A vertical bar-graph type display is created by committing the 64 input channels as follows: first channel has no signal; the module is set to dwell on it until triggered to start scan. The second channel is connected to a 10-V level for use as an oscilloscope sweep trigger, and the third channel has no signal. Channels 4 through 12 are connected (in order) to current-monitoring resistors in the first row of the beam-profile PC board. Three "no-signal" channels are

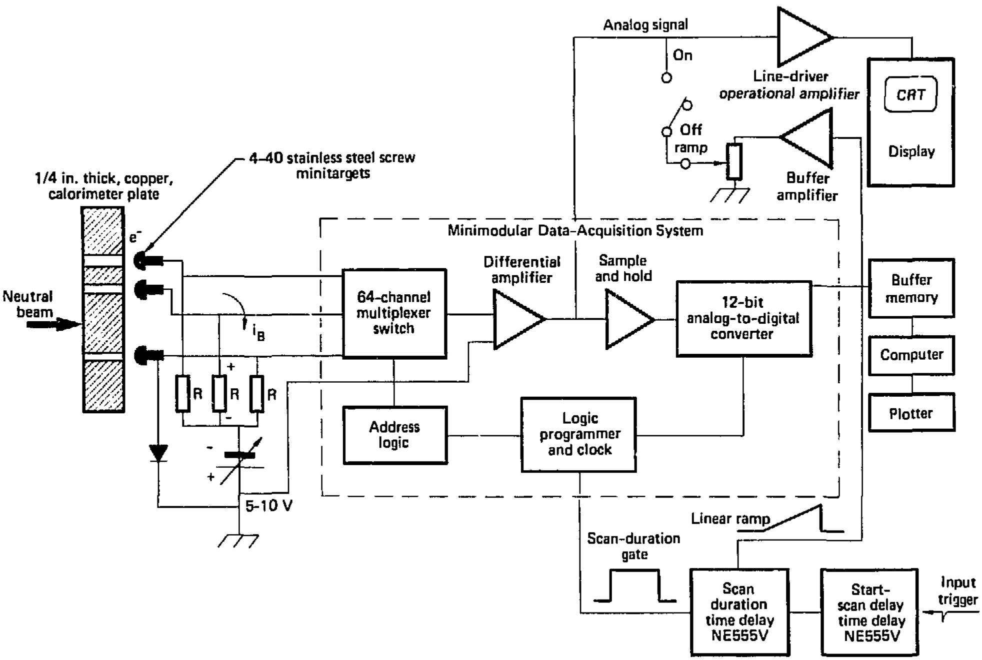


Fig. 3. Block diagram of the beam-profile monitor diagnostic system.

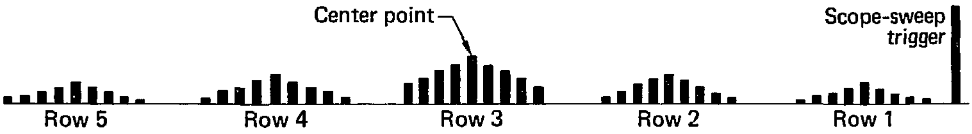


Fig. 4. Test pattern CRT bar graph display from the differential amplifier.

left between every nine inputs from the remaining four rows. The "no-signal" inputs are terminated in the same resistors as the current-monitoring channels to prevent noise pickup, but no signal is connected to them. Thus, 5 channels are left after all 45 minitargets have been interrogated. This fortunately provides about a 60-μs time interval for the oscilloscope sweep circuit to recover enough to respond to the next sweep trigger when in multiple-sweep mode. If we look at the beam-input side of the target assembly, we see that each horizontal line is scanned, in turn, from the upper left to the lower right corner.

The monitored voltage levels rise and fall very fast when the scanner is used at a 12-μs-per-channel throughput rate. The pulse train produced by the voltage fluctuation is amplified by a line-driver operational amplifier before it is transmitted to the oscilloscope. Whenever a "start-scan" trigger from the ion-source control system enters the scanner chassis, the multiplexer switch steps off from channel 1 and sequentially scans the 64-input channels. The unit continues to scan the input channels sequentially for a time interval set by an adjustable "scan-duration" timer that has a 1- to 20-ms-duration range. (Actually, the trigger first goes to a "start-scan-delay" timer with a 1- to 20-ms-duration range so the operator can preselect the portion of the beam pulse he wished to investigate.)

A 10-V oscilloscope-sweep trigger appears at the output each time the multiplexer switch steps to the second channel. The operator can select a built-in, dummy test-voltage pattern to appear across the input resistors. The dummy pattern resembles an actual target pattern, and this built-in feature enables the operator to adjust oscilloscope sweep speed so that the 45-line, vertical bar-graph pattern is spread across the full face of the CRT.

The height of each voltage pedestal is directly proportional to the beam current going to its corresponding minitarget. Since the display always starts with the left end of the first row of current-monitoring resistors, and there are three dead channels between each row, it is easy to identify the pattern associated with a particular tow. Figures 5 and 6 are typical oscilloscope traces of single- and multiple-sweep, beam-density profile patterns.

To prevent overlapping and illegible repetitive display sweeps, we make use of a switch-selected, linear-ramp signal. This signal, which can be made to appear at the input summing point of the line-driver operational amplifier, superimposes the data pulse train on the linear ramp. Vertically displaced repetitive sweeps will then appear on the face of the CRT. This linear-ramp signal is obtained from one terminal of the NE555V "scan-duration" timer chip, so that the ramp always starts from zero and exactly coincides with the duration of the scan. The ramp signal is taken through a buffer amplifier with an output amplitude adjust so that the operator can preferentially adjust the vertical displacement of the CRT display.

The beam-current monitoring resistors are located on PC cards in the scanner chassis. They are socket-mounted, 16-pin dual-in-line-package (DIP) film-resistor chips with 15 resistors per chip. Although we find 1-k resistors (which develop 1 V per milliampere) about right for our application, input sensitivity can be easily changed by plugging in different ohmic-value resistor chips. A companion buffer-memory chassis stores the output of the analog-to-digital converter in the data-acquisition module. The digital data can then be transferred to a minicomputer where they can be software-processed to produce equidensity contour plots, or whatever the investigator deems most useful.

Fig. 5. Oscilloscope trace of an actual single-sweep, beam-density profile pattern from the 45 minitargets. The height of each voltage pedestal is directly proportional to the beam current going to its corresponding minitarget. The beam is strongest at the center of the target and weakens with increasing distance from the center, both vertically and horizontally.

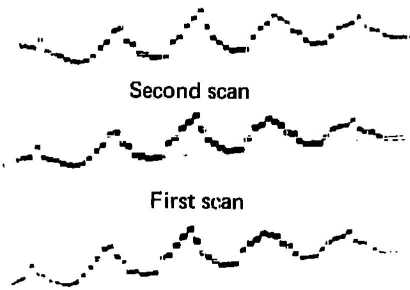


Fig. 6. Oscilloscope trace of multiple-sweep, beam-density profile pattern.

Conclusions

Our minimodular data acquisition system proved excellent for this fast-scan, beam-profile monitoring application. Although this article describes only the simplest mode of operation, that of continuous sequential scanning, these diagnostics systems are able to select input channels randomly or to single step on command, or both. The systems collect data in both analog and digital form and are ideal for any application requiring rapid interrogation of multipoint signal sources.

NEW ISOLATION AND CONTROL SYSTEM CONTROLS SHIVA'S LARGE, PULSE-POWER SYSTEM

One of the major problems in controlling large, pulse-power systems is the displacement current and attendant voltage swing in nominal "grounds" during the pulse. We developed a unique solution to this problem that is far more flexible than the relay coil-to-contact isolation used in most traditional pulse-power control systems. We successfully demonstrated the method on a 600-kJ, 20-kV prototype capacitor bank and, most recently, on the 25-MJ Shiva laser capacitor bank. In these systems, a potential difference of 700 V exists between "grounds" of monitor and control points during a normal pulse, and a few kilovolts can appear during a fault.

The Shiva laser is a 20-arm, solid-state laser developed by the Laboratory for laser fusion experiments. Shiva has delivered 10.2 kJ of energy in a 0.9-ns pulse. To achieve this optical pulse, a 25-MJ capacitor bank is discharged into 2300 xenon flashlamps and 40 Faraday rotators. (See UCRL-50025-77-3 for details of this 25-MJ energy-storage system.) The bank is discharged in less than a millisecond with precision timing achieved between components. Such a discharge provides ample opportunity for control system development in a noisy, high-level common mode environment.

The Shiva control system includes more than 1200 individual circuit waveform pickups, 72 triggers, 33 100-kVA power supply controls, and miscellaneous control and monitoring points required for laser operation. Data and control throughput rates of 1.6 Mbits and event time resolutions of 10 μs have been achieved during time-critical sequences.

18 Months to On-line Status

The total Shiva control system (Fig. 1) was developed from conception and brought to an on-line status in 18 months. We did this by subdividing the Shiva control tasks and diagnostic tasks into four areas, each with its own peculiar constraints, and assigning a project team to each area. The four areas are: 1) power conditioning, 2) alignment, 3) laser beam diagnostics, and 4) target diagnostics. After the hardware and software of each area was fully developed, they were joined together by a supervisory system to form the effective Shiva control network.

This article discusses the development of the power-conditioning control element of the total Shiva control system. This control element, or control system, monitors, controls, and times the capacitor bank discharge. It possesses a unique set of problems, primarily because timing signals for discharge initiation must be thoroughly isolated and sequentially delivered to 75 uniformly distributed locations throughout the 200-by-80-by-14-ft capacitor bank.

Requirements for the Power-Conditioning Control System

The power-conditioning control system is located in the control room. It communicates with a master control system and is also capable of stand-alone operation. The system controls the power-conditioning system and diagnoses its failures. It also allows for either direct manual intervention and control or semi-automatic operation with manual supervision. A brief description of its basic control requirement follow.

Preionization Lamp Check (PILC)

Before and after a laser firing sequence, all xenon flashlamps are checked by PILC to ensure integrity. Each set of flashlamps common to one ignitron switch assembly is ionized with about 1% of the normal pulse energy. If any lamp circuit indicated that it has not ionized, the control system commands the PILC electronics to perform a self test. If this self-test function indicates that the PILC monitoring system itself is functioning properly, the firing is aborted, and the defective laser amplifier and flashlamp circuit combination is replaced.

For further information about this article, contact Paul R. Rupert (Ext. 25462).

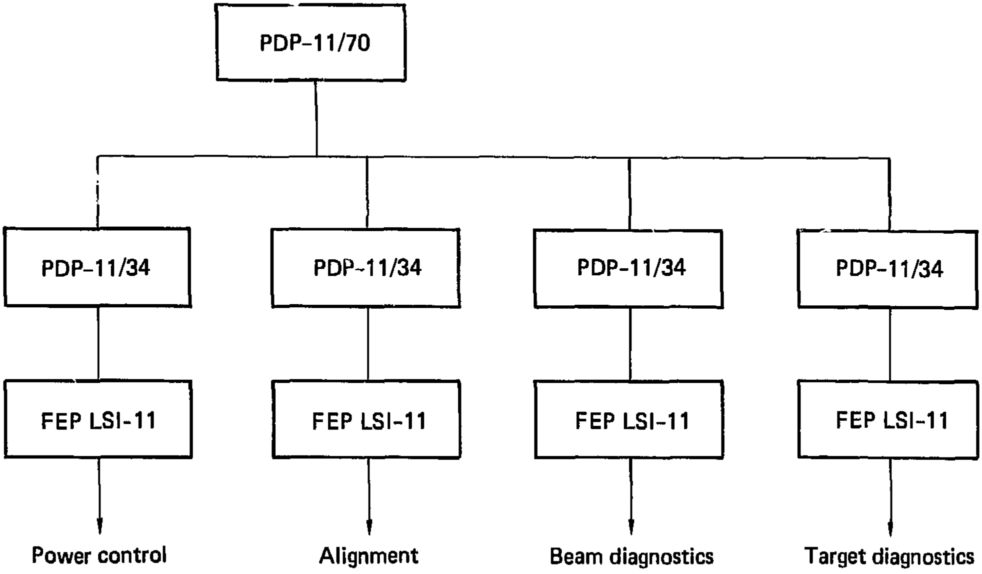


Fig. 1. A network of computers control the Shiva laser system. Each of the four major laser sections (power conditioning, alignment, laser beam diagnostics, and target diagnostics) are interfaced to sets of first-level LSI-11 microprocessors, which are connected to four second-level PDP-11/34 minicomputers associated with each laser section. The front end processors (FEP's) LSI-11's handle the bulk of the hardware input/output functions: the PDP-11/34's perform system logic functions and provide man-machine interfaces. A top level PDP-11/70 connected to the four minicomputers provides overall integrated control of common peripheral devices.

Control of Power Supplies

The power supplies are arranged to allow individual gain control of the various amplifier stages and of each arm. The supplies can be adjusted to the nearest 10 V to control the energy delivered to each amplifier stage of the Shiva. We evaluate the energy data from the previous laser firing to ensure that the proper buildup of the laser intensity occurred as the beam propagated through the laser amplifiers. These data are then used to modify the stored energy for each section of the laser through an adjustment of the power supply voltage for that stage.

The variation in loads on the various power supplies places an additional requirement on the control system. To maximize capacitor life, all should reach the charge voltage at the same time. This requires sequential initiation of the charging sequence.

Shot Initiation

The control system triggers the rotators and flashlamps, and it enables the Pockels cells. These Pockels cells are electro-optic devices that provide fast shutters or gates for a fast laser-output pulse (see also UCRL-50025-76-3). Each of the major amplifier and rotator types require a trigger at a different time to arrive at peak gain and correct rotation in coincidence. The control system provides eight initiation times with delays of tens to hundreds of microseconds between each triggering signal.

Waveform Monitoring

To detect problems before they become hard failures detectable by the PILC or power supply current monitors, the total current waveforms in the Shiva system are monitored and compared against a reference waveform during each shot. This detection identifies lamps that have been contaminated by a small leak, defective charging resistors, open connections that are still making connection during the shots by arcing, and section opens and shorts within the capacitors.

Redundancy

Because the total number of components in Shiva greatly increased over existing laser systems, we implemented redundancy in all places where a substantial increase in reliability can be obtained at minimum cost. As a result, the control system provides for redundancy management so that failures in the Shiva system will be transparent to the operators during the actual shot and then are indicated at the conclusion of the experiment.

Safety and Facilities

In addition to the foregoing power-conditioning controls, we established a separate safety and facilities controls system. All safety interlocks are hardwired to prevent the initiation of a charge or fire sequence when they are not satisfied. These interlocks are monitored in the control room.

Control System Architecture

Figure 2 shows how we designed the power-conditioning control system to satisfy the above requirements. The control system is isolated into three sections: 1) control room and front end processors (FEP's), 2) 50-V "Q"-bus and, 3) local functional logic. LSI-II microcomputers address each control or diagnostic element in the system with a digital data bus. Bus interface units (BIU's) provide common-mode isolation. BIU's also transfer the digital information between the data bus and each element of control or diagnostics.

This system allows for rudimentary stand-alone operations through the use of manual controls and readouts. In this mode, all decisions are made by the operator who is allowed to issue all system commands. Only personnel safety interlocks are outside of his direct control. These interlocks are a triply redundant fail-operational system with front end processors (FEP's) readout to ensure prompt maintenance in the event of a failure. The FEP's also provide summary readouts of all proper configuration data. Commands are also available that provide for in-depth display of most system faults.

In the normal operational mode, operator-system interaction takes place through a page-selectable, color video display. Input data is provided through programmable switches, which give full system access through a menu-selection scheme.

The integration of a low-level, digital control system into a pulse-power environment is a difficult task. We paid much attention to understanding the many possible transient coupling modes that can exist between the pulse power and control circuitry.

To minimize destructive coupling, we designed two levels of optical isolation into the system. A 60-kV optical isolator separates the FEP from the data bus, and 3-kV optical isolators separate each element in the system from the data bus.

Control in a Severe Environment

We spent a great deal of effort to define the environment in which the power-conditioning controls would function. During a shot, the "ground" reference at each power supply, ignitron switch, capacitor assembly, and laser amplifier goes to a different voltage level with respect to each of the other system "grounds." This is because of the extremely high currents in the circuit. The voltage between the "grounds" is about 400 V from the capacitors to the laser amplifier and 300 V from the capacitors to the ignitron switch. Each circuit exhibits slightly different drops (±50 V) because of different cable lengths. Of course, these drops are also twice as severe during a lamp fault at the laser amplifier, which is the most common fault. Other faults can lead to still higher localized displacements between "grounds." Considering that 3.5 MA are flowing during the peak of normal shot, the observed ground displacements are not severe.

As a consequence of these "displaced grounds" during a shot, current also flows in the building ground because of the capacitance between this system and the isolated power-conditioning ground system. With much effort, we minimized this capacitance so that other instrumentation systems in Shiva will not be affected by the pulse. The result has been that the measured capacitance between 70 circuits (one continuous capacitor rack of circuits) and the building is about 5 nF. Thus, during a normal shot, the charge transferred in this circuit is negligible, and the voltage between different areas of the building ground mesh are less than a few millivolts, depending primarily on the impedance of building ground mesh.

The price paid to achieve this low coupling capacitance between the pulse-power system and the building has been to float the capacitor racks. This single item has reduced the effective coupling capacitance by a factor 10. However, the rack, which then forms a capacitor plate between the pulse-power system and the building ground, goes to about 4.5 kV during a shot; thus, any measurements gathered from the capacitor assemblies must be isolated from the racks to at least 5 kV.

Another factor we considered is the high rf noise generated nominally during an ignitron startup and during air arc faults. Thus, we needed a low-impedance control circuitry with large voltage swings to increase noise immunity.

System Design

With these environmental considerations in mind, we designed a control system (Fig. 2) that has

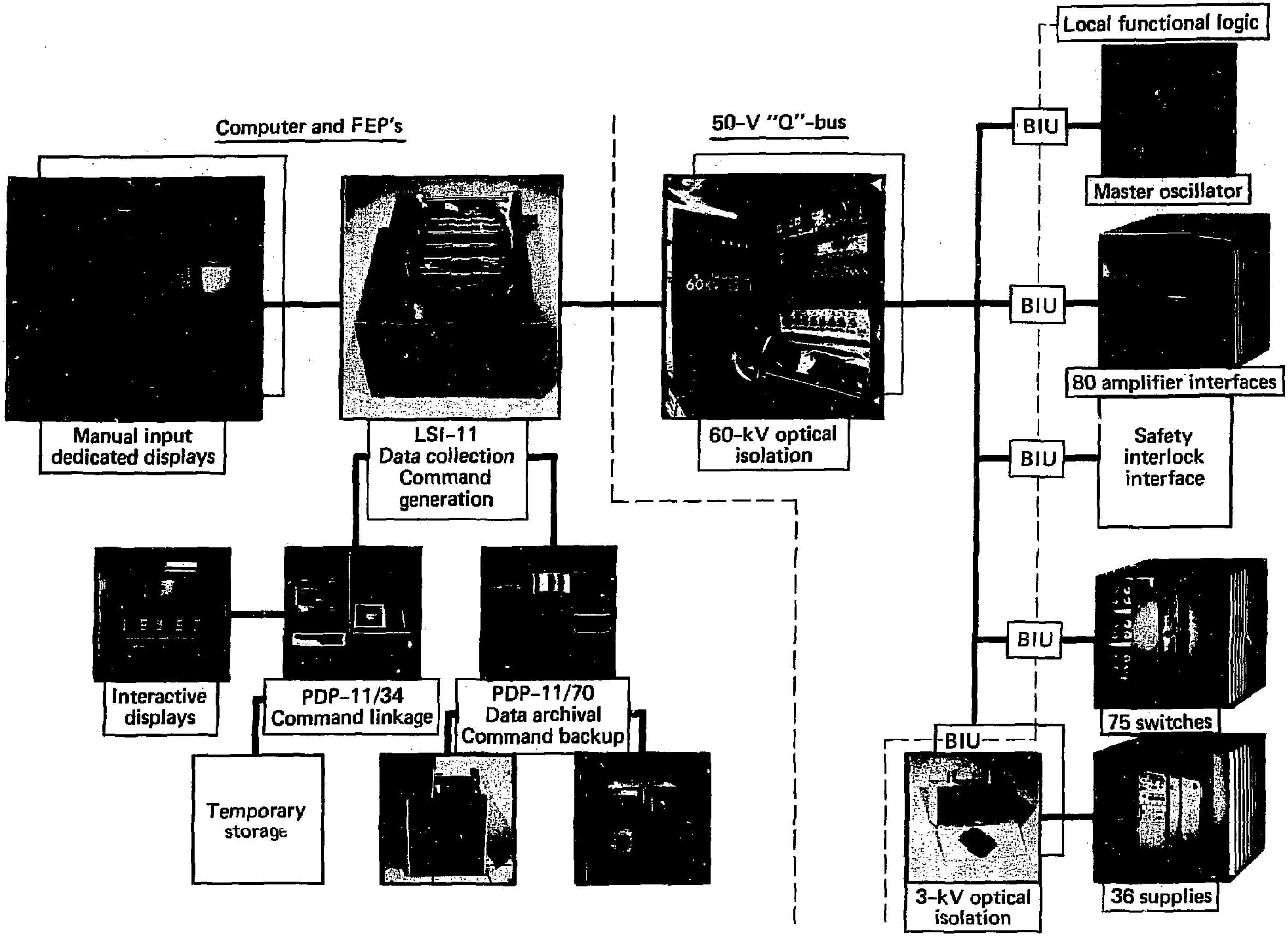


Fig. 2. The power-conditioning control system is isolated into three sections: 1) control room and FEP's, 2) 50-V "Q"-bus, and 3) local functional logic. The equipment is connected to the laser bay through two redundant 60-kV isolators to a 50-V "Q"-bus. The 50-V bus is coupled to local control points through BIU's that provide bidirectional coupling to the 15-V CMOS logic circuits. There are 203 BIU's and local control points in the control system.

flexibility, room for expansion, and data rates commensurate with shot-initiation-timing requirements. The environmental considerations (i.e., ground reference displacements) dictate that each control point in the system must float freely from the other control point in the system. If this were not done, severe cross coupling in the form of ground loops would occur.

The isolation thus required manifests itself in the BIU's. There is an independent BIU for every power supply and each group of four ignitron switches as well as for every five laser disk amplifiers. The secondary, 20-kV isolation of the triggers and the physical proximity of the switches make it possible to address four ignitron switches from a common BIU. The disk amplifier grouping is practical because the amplifiers form the common single-point ground; in this configuration, the ground inductance between amplifiers spaced nearby is negligible.

The noise immunity was met by providing a 50-V signal level, operating into a 100-Ω transmission line. These twisted pairs are inexpensively terminated with mass termination techniques.

System Hardware

Front End Processor (FEP)

We chose a Digital Equipment Corporation (DEC) LSI-11 microcomputer as a FEP (Fig. 3) and developed a chassis for common use throughout the Shiva control system. This chassis was designed to meet the maximum requirement within this system. In this configuration, the LSI-11 is composed of a central processing unit (CPU), 28K of core memory, a disk interface, a paper tape interface, a teletypewriter interface, and a read-only memory (ROM) boot terminator card. Sixteen slots are provided for external interface cards, programmable clocks, and user-design interfaces.

The Power Supply ensures 4 ms of operation under full load after a power supply fault or an ac line failure. Power-up and power-fail routines provide continued operation after a power failure. Plugs for a teletypewriter and disk provided stand-alone capability as the system was brought up.

Control Panels

The control panels provide for either manual switching or automatic operation. In the manual mode, the operator has direct control over all system functions except safety interlocks; he may exercise these functions in any manner he chooses. Sufficient summary data and detailed quick-look panels are provided to identify any system element not in compliance with issued commands.

Figure 4 shows the layout of the entire power-conditioning control console. To support the indicated number of interfaces on an LSI-11, required the design of a transistor-transistor-logic (TTL) interface capable of driving a larger number of inputs and outputs per bus load than standard TTL interfaces. We designed and tested such a pair of cards with 64 inputs or outputs per bus load.

A bus repeater card for the LSI-11 Q-bus has also been developed. This card is designed for the DEC backplane and drives an entire second set of bus loads. This bus extender has successfully driven a system with floppy disk and dynamic random access memory (RAM), which used direct memory access (DMA) refresh, over a 100 ft. of ribbon cable. Artwork for any of the cards we developed is available through the Laboratory's Technology Transfer Program.

60-kV Optical Isolator and 50-V "Q"-Bus

Figure 5 shows a 60-kV optical isolator. The isolator has 21 bidirectional channels and also provides three dedicated signals for interlock purposes. These 21 channels form a subset of the DEC LSI-11 Q-bus. The air gap between the light-emitting diodes (LED's) and photodiodes (transmitters and receivers) provide isolation up to 72 kV.

The 50-V "Q"-bus uses twenty-one 24-gage twisted pair terminated in 100 Ω. Each leg of this

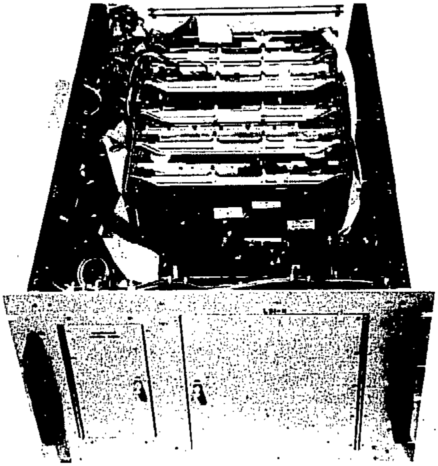


Fig. 3. This LSI-11 chassis is used as a front end processor (FEP). It contains a CPU, 24K of core memory, a Unibus to Q-bus adapter, a disk interface, a teletypewriter interface, a ROM boot terminator, and a power fail board. There are about 65 such chassis in the total Shiva control system.

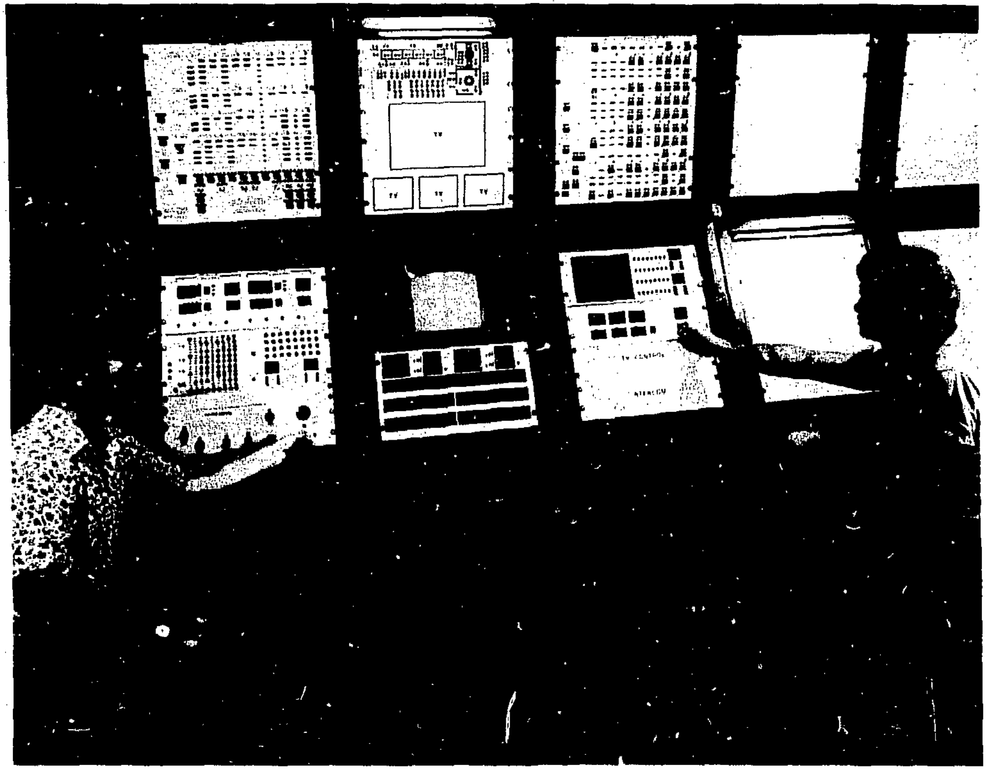


Fig. 4. Power-conditioning control room console. The console is a mix of dedicated readouts and sophisticated computer-driven color CRT display. Rudimentary system control and readout may be accomplished using the LSI-11 and the dedicated displays. With the integration of the power conditioning PDP-11/34, the applications programs will disabled in the LSI-11's, and they will perform data gathering, compaction, and command functions. At this point, the color CRT and the programmable switches will be the primary means of communicating with the system, while the PDP-11/34 performs the applications software and control linkages.

bus is designed to be up to 600 ft. long and to provide for 200 BIU's. The bus can issue sequential commands at a 500-kHz rate. The bus structure provides for input and output at each capacitor rack power supply and laser amplifier. Because the bus effectively blankets the laser bay, it is also used to monitor miscellaneous items such as laser beam blocks, air flow, and nitrogen temperatures.

Bus Interface Units (BIU's)

The key to providing a distributed bus system that allows each interface to float independently is

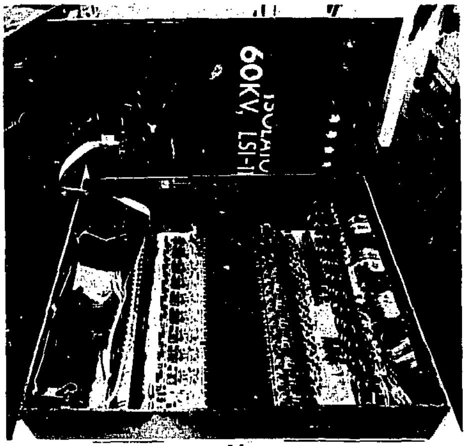


Fig. 5. This 60-kV isolator, dielectric tested to 72 kV, provides isolation of control room personnel and equipment from potential faults in the 25-MJ capacitor bank. It couples an abbreviated LSI-11 Q-bus to a 50-V "Q"-bus in the laser bay and capacitor bank. Three dedicated lines provide a fail operational interlock system.

the cost-effective isolated BIU. Figure 6 shows the BIU and the actual isolation cards used internally. As shown in Fig. 2, this unit provides a bridge between a 50-V "Q" bus and local CMOS decode logic. The BIU isolates to 3.5 kV without failure and to 4.2 kV without breakdown. The BIU costs about $400 each.

As any faulty external device can stop bus transfers in an open collector bus, the BIU is designed to minimize these hard failures. A reply to the system is only enabled by the BIU when a reply is expected. If, because of a fault, a decode logic board attempts to maintain a reply (thus hanging up the bus), a time delay on the 50-V side of the BIU expires and disables that BIU. A LED on the BIU is also lighted to notify the operator. Failure of a BIU bus driver will also hang-up the bus. This failure is detected by a current monitor on the BIU, which turns on another LED; the failed branch is identified at the 60-kV isolator. That branch is then physically checked to determine the specific BIU at fault.

CMOS Decode Logic

The decode logic for the system must exist in a relatively noisy environment. For this reason, we chose CMOS (operating at 14 V) as the logic family. Each input or output card is able to handle 64 interface bits. Switches on the board allow address selection. These boards provide the bulk of the system logic and cost about $75 each.

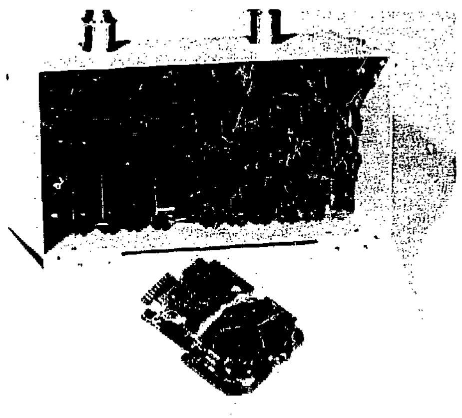


Fig. 6. Bus interface unit (BIU) and data card. The BIU provides local isolation of 3 kV at each point the 50-V, 100-Ω power-conditioning control bus is required to service (power supplies, PILC, disk and rod amplifiers). The unit successfully isolated to 4.5 kV before breakdown occurred through the optical isolator; hence, it will isolate faults on a smaller excursion than this from the main bus. Also, each control point in the system is free to float to its own level during shot time. This is an important consideration in systems with large displacement currents.

Summary

The Shiva control system has been successfully demonstrated. In addition, more than 50 hard arc faults have occurred during the debugging of the energy storage bank, and none of these faults has penetrated past the BIU's into the control system. For more than 95% of these faults, the control system continued to function during the occurrence and promptly pinpointed the failed area.

FE

FM CATV PROVIDES INTRUSION PROTECTION

We designed and fielded a FM cable television (CATV) intrusion protection system for remote sites that house sensitive nuclear material. These sites are spread over a wide area; the farthest one is more than 25,000 ft from the observation post.

The design requirements for an intrusion protection system at the Laboratory's Site 300 test site posed some unique problems for a transmission system.

- Real-time television transmission. We need a rapid response to a potential intrusion incident because of the remote location of the sites from personnel.
- Motion detection in selected areas of each camera site's picture. This requires a stable, noise-free picture at the observation post.
- Fifteen different camera sites with the possibility of 14 simultaneous video channels.
- Sites relocatable, without major system redesign. The location of the materials changes from time to time, and the possible sites are too numerous to provide fixed system capability at all of them.
- Both installation and operation costs be minimized.
- Reliable operation in weather extremes.

Design Considerations

The security requirements for instant viewing of any monitored scene results in the need for real-time video transmission. This "live" video need means that standard telephone circuits which are readily available can't be used because of their inadequate bandwidth. A microwave system approach is a possibility, but the widespread locations of the sites results in an expensive system, as would the multiplexing of video channels on a single microwave link. The use of direct video transmission in straightforward, but the long distances and the need for multiple channels mean lots of (expensive) cable. A video system is also unattractive because noise immunity and ground loops in a far-flung system like this promised to be troublesome at video frequencies.

After analyzing all these factors, we decided that a CATV system approach could best meet the design requirements, both on a cost and a technical basis. In this approach, every site is like a cable TV customer who sends a picture *to* the "head end" instead of getting a picture *from* it. (Each site must use a different channel to prevent interference.)

The lengths and placement of the cable runs are fixed by the locations and topology of the areas and site locations, thus basically defining the system configuration. Installation is straightforward and follows usual CATV construction practices. The work can be done by a standard CATV construction crew using conventional hardware.

System Description

A conventional AM CATV system of the type used in providing commercial TV to homes was considered and compared to an FM system that has recently become available.

We selected the FM system because it has many beneficial features making it easier to use. For example, fewer amplifiers are needed because higher gain can be used in each one and because FM is less sensitive to amplifier distortion and temperature drift. FM transmission has better immunity to man-made noise that would cause false alarms in the motion detectors. Carrier frequency drift is no problem, when compared to the standard AM system with its "fine tuning."

The FM system we used, the CATEL VFMS 2000, requires more bandwidth than an AM system would (14-MHz spacing vs 6 MHz for AM), but our requirement for 14 channels is still met by a standard CATV trunk with 50- to 250-MHz response. A seven-amplifier cascade is needed to make up the losses from site A (Fig. 1) to the observation post. Both thermal and cable equalization are used in the amplifiers, C-COR D444 distribution type, which were selected because they have a high gain and thus can be spaced at longer intervals. (Figure 2 is a simplified block diagram of the entire system.)

For further information about this article, contact Richard P. Rufer (Ex. 29186).

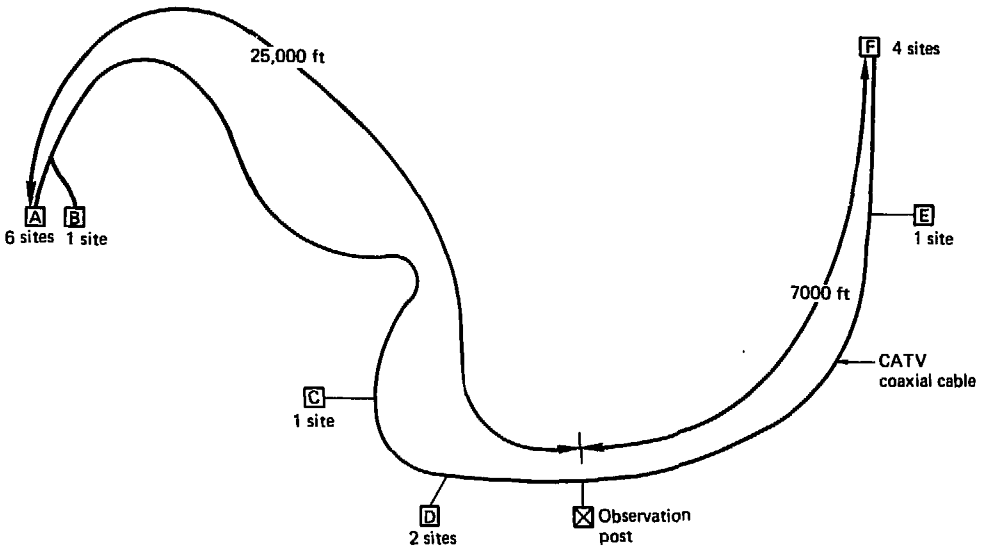


Fig. 1. Layout of area showing surveillance sites.

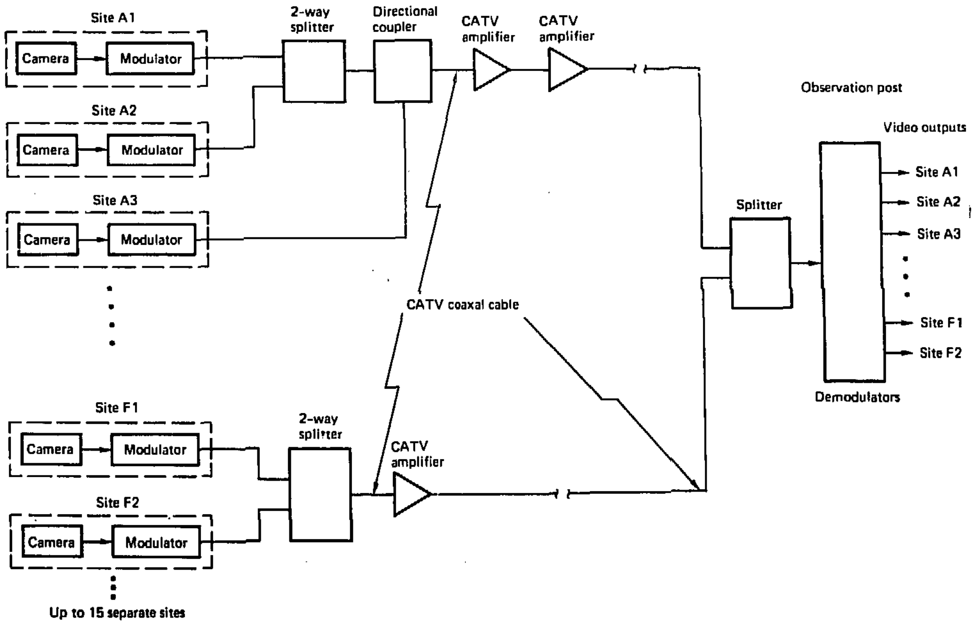


Fig. 2. Simplified block diagram of surveillance system.

Each surveillance site (Fig. 3) includes the camera and a weatherproof housing containing the modulator, which converts the camera's video signal to the FM carrier frequency. Signals from all the sites are combined on the cable network for transmission to the remote observation post.

When the combined signals reach the observation post, they are split off through standard CATV hardware to the FM demodulators. Demodulator video output is delivered to a standard video monitoring console with motion-detection capabilities (Fig. 4).

System construction uses standard hardware and cable. A notable departure from standard practice is the mounting of the amplifiers near the bottom of the poles for easy access (Figs. 5 and 6). This can be done because in our system there is no problem with unauthorized access to the amplifiers, and the ability to check system and unit performance without pole-climbing is valuable.

The system design allows for the use of any frequency at any site so that as the locations change, the modulator can be moved without disturbing the remaining sites. The flexibility of this CATV approach has already been valuable; we've added another site to the system after initial construction was completed. The insertion of a directional coupler into the main trunk and a cable drop to the new site was all that was required. The rest of the system remained the same.

The system is successfully operating with noise-free, hum-free pictures of each site; it promises to be a flexible and versatile method of remote large-area surveillance.

Fig. 3. A typical site for TV surveillance. The observation post that monitors all the sites is located beyond the hills in the background.

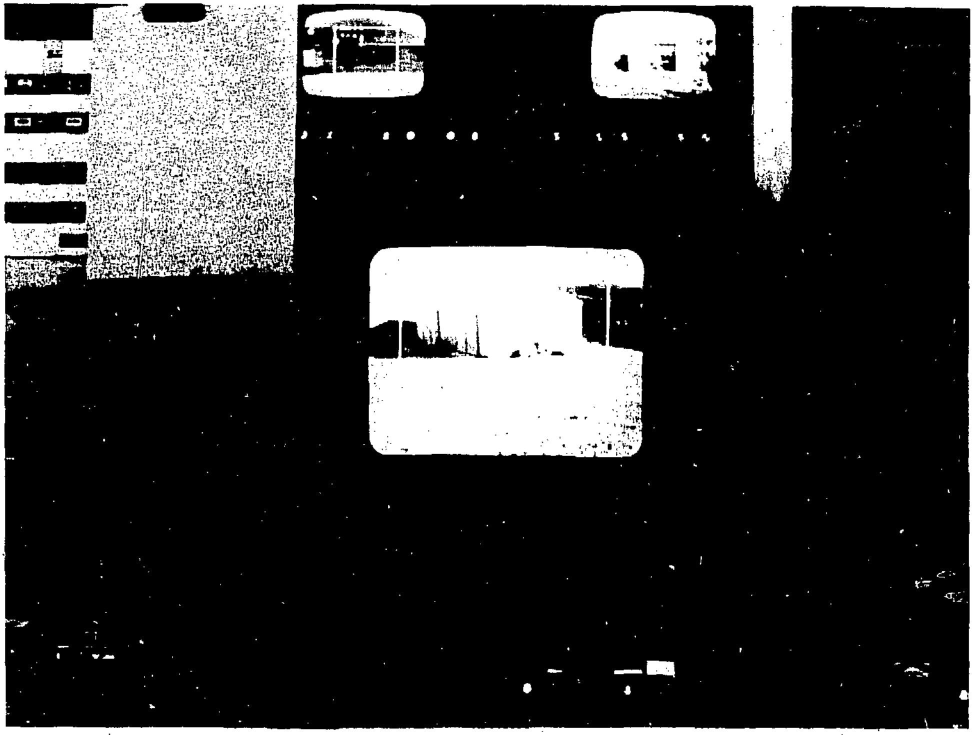


Fig. 4. Video picture received at the observation post. One of the 14 channels is shown switched up on the large-screen monitor for close inspection. (The white-bordered area is being monitored by a motion detector connected to an audio alarm.)

Fig. 5. Typical amplifier mounting location showing convenience of adjusting system. In this system, there is no problem with unauthorized access to the amplifiers, and the ability to check system and unit performance without pole-climbing is valuable.

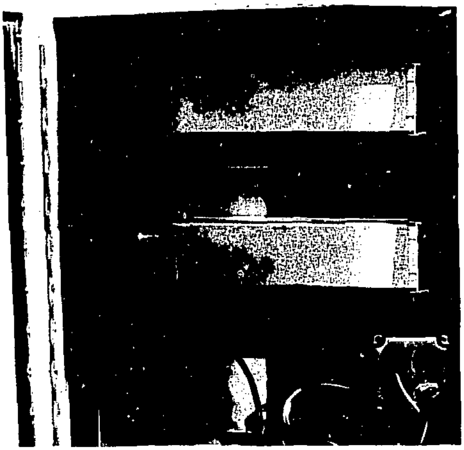


Fig. 6. Interior view of a camera site weatherproof housing showing the easy access to the FM modulator and its power supply. The system design allows for the use of any frequency at any site so that, as the locations change, the modulator can be mounted without disturbing the remaining sites.

RAC