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Publication Date
1979-11-01

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Engineering & Technical Services Division

Presented at IEEE 8th Symposium on Engineering Problems of Fusion Research, San Francisco, CA, November 13-16, 1979; also to be published by IEEE Nuclear and Plasma Sciences Society

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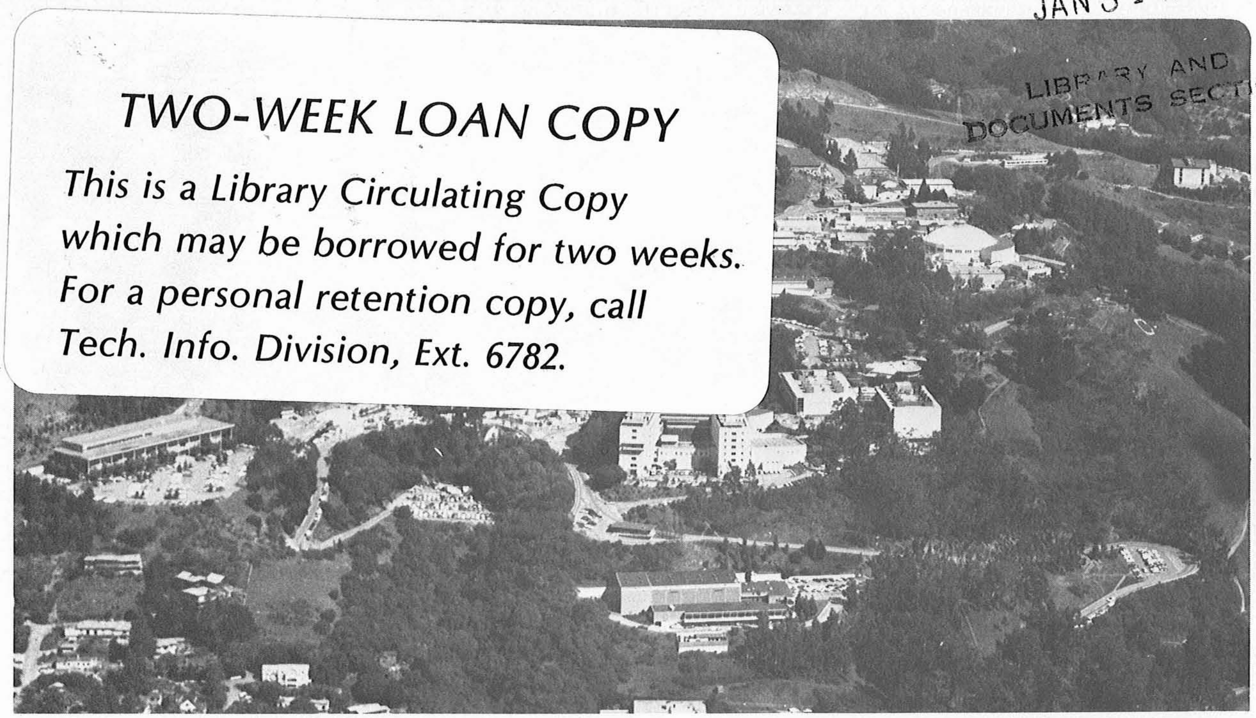

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Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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PROTECTION AND FAULT DETECTION FOR LAWRENCE BERKELEY LABORATORY NEUTRAL BEAM SOURCES*

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Summary

Testing of TFTR neutral beam (NB) sources has begun at the LBL Neutral Beam System Test Facility (NBSTF). Operation at 120 kV, 65 A, 0.5 sec should be achieved soon. Because NB sources spark down frequently during conditioning, the main accelerating (accel) power supply must be interrupted within a few microseconds to avoid degrading the voltage holding capability, or even the damaging, of the NB source. A variety of improper magnitudes and/or ratios of voltages, currents, and times can occur and must be recognized as fault conditions in order to initiate a prompt interruption of the accel power supply. This paper discusses in detail the key signals which must be monitored and the manner in which they are processed in fault detector circuitry for safe operation of LBL NB sources. The paper also reviews the more standard interlocks and protective features recommended for these sources.

Introduction

The LBL-type of neutral beam (NB) sources have, in the past seven years, evolved from 20 kV, 10 A, 10 msec injectors for the 2XIIB mirror experiment to the 120 kV, 65 A, 0.5 sec[1] injectors for TFTR and the 80 kV, 80 A, 0.5 sec[2] injectors for Doublet III, which are currently being tested.

Neutral beam sources resemble high power transmitting type vacuum tubes and incorporate such common elements as grid structures and thermionically emitting filaments. For successful operation of these sources at the multi-megawatt power levels mentioned above, it is imperative that reliable detection of abnormal operating conditions occur within microseconds so that prompt corrective measures can be taken. For example, such sources frequently spark down, especially during initial operation. In the normal operating mode, such sparks are detected within microseconds and cause the main accelerating power supply to be briefly interrupted, permitting the NB source spark to clear, then reapplied in order to continue the NB injection pulse. This spark-interruption-restart cycle takes place in a few milliseconds and may occur many times during a 0.5 sec pulse. In addition to the sparking fault just described, a variety of improper NB source voltages and currents can occur which must similarly be detected and stopped lest they result in damage to the source.

This paper will first review the more standard interlocks and protective features recommended by the LBL staff. Then we will discuss in detail the voltages and currents whose proper monitoring and processing in "fault detector" circuitry is critical to the safe operation of these NB sources. It is worth mentioning that NB source operating procedures, including fault detection circuit design and philosophy, are still evolving at LBL. This paper summarizes our present recommendations for source protection.

The design details for the LBL NB sources and power supply systems are described elsewhere.[3-6] For the purpose of clarifying our comments, we show in Fig. 1 a 120 kV, 15 A fractional-area source (i.e., with a 10 x 10 cm accelerator grid array rather than 10 x 40 cm). Figure 2 shows a general block diagram of LBL NB power supply systems. Except for some mechanical configuration changes and differences in some voltages and currents, the basic elements shown in these diagrams are common to most recent LBL NB sources and power supply systems.

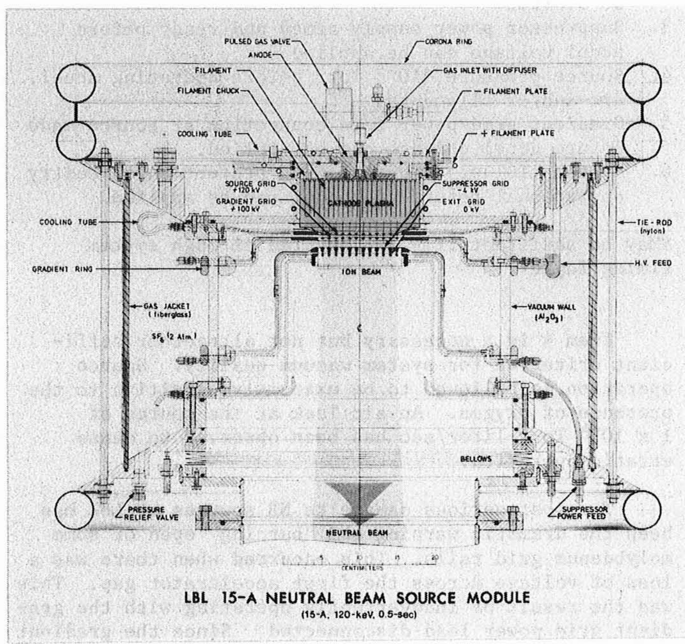

Figure 1 120 kV, 15 A, 0.5 sec Fractional-Area Source

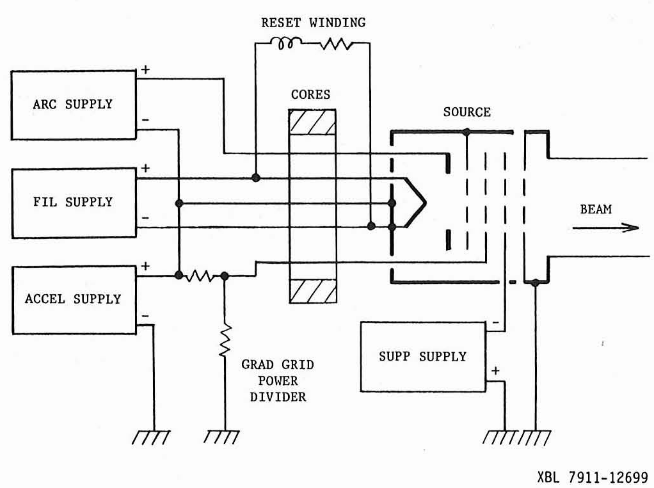

Figure 2 NB Power Supply System Block Diagram

*This work was supported by the Fusion Energy Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

Basic Source Protection Requirements

Table 1 lists the minimum "hard-wired" interlocks recommended for source protection. Items 1, 2 and 6 are self explanatory. We recommend that the suppressor voltage be gated on and off by the accel voltage. Improper, possibly dangerous, operation results if the accel voltage is maintained without proper bias on the suppressor grid; hence, item 3.

Table 1

Minimum Recommended Interlocks

1. NB source cooling water on before filament, arc and accel operation.
2. Filaments at operating temperature before arc can be started.*
3. Suppressor power supply armed and ready before accel voltage can be applied.
4. Source pressure $<10^{-5}$ Torr before operating accel, arc and/or filaments.
5. Gradient grid power feed connection at source made before accel voltage can be applied.
6. System timing, telemetry, and protection circuitry operational before any power can be applied.

*May be satisfactorily implemented through system timing logic

Item 4 is a necessary but not altogether sufficient criterion for system vacuum quality. Source operation is believed to be extremely sensitive to the presence of oxygen. An air leak at the source of 1×10^{-4} Torr-liter/sec has been observed to cause erratic operation.

The most serious damage to NB sources at LBL has been the dramatic warping and "burning" open of some molybdenum grid rails. This occurred when there was a loss of voltage across the first accelerator gap. This was the result of inadvertently operating with the gradient grid power lead disconnected. Since the gradient grid voltage was being measured back at the resistor divider supply fed by V_{accel}, there was no indication of trouble. We recommend that the gradient grid voltage be monitored right at the NB source. Further, this monitor should be connected to the NB source at a location that is different from that where the power lead is connected. This minimizes the chances for obtaining false information that the gradient grid voltage is present. Finally, the gradient grid voltage monitoring should be extremely reliable since it is one of a few key parameters which must be monitored by fault-detection circuitry. (More on this in the next section.)

Some other requirements for proper source operation are listed in Table 2. Item 1 refers to the cooling water required by the source at accel, gradient grid, and suppressor grid potentials. At LBL, one low-conductivity water circuit is connected to a manifold at accel potential. This feeds coolant to the plasma chamber and grid #1, and the gradient grid cooling circuit which operate up to -25 kV relative to accel potential. Two other cooling circuits are supplied by separate low-conductivity water lines near ground potential; these are the grounded grid (grid #4) and the suppressor grid (grid #3). The latter normally operates at <4 kV (negative) with respect to ground, but may "spike up" to 30 kV or more for ∿1 μsec during source sparks. All water circuits just described are implemented at LBL with plastic hoses of appropriate length which are properly dressed for high voltage-holding.

Table 2

Other Source Requirements

1. NB source cooling water resistivity $>10^6$ Ω-cm.
2. Pure H_2 (or D_2), 45% Torr-liter/sec, pulsed and isolated for accel voltage.
3. SF_6 "blanket" over source insulators required for $V_{accel} \gtrsim 70$ kV.
4. Low-inductance $\lesssim 200$ V varistor clamping of all plasma-chamber electrodes and hardware* to Filament (-) plate.

*Includes Filament (+) plate, 3 each Arc (+) electrodes, probe plate, gas valve wiring, and overtemperature thermostat wiring.

As item 2 implies, the supply of gas required at HV potential must be pure. It is important to ensure that all lines are clean.

The source insulators spark-over their outside surfaces at 70-80 kV when operated in air. We provide plastic bagging, fiberglas housings, or full metal enclosures to maintain a sulfur-hexafluoride (SF_6) atmosphere which surrounds the source when operating at or above this voltage level. Pure SF_6 is recommended since long-term stratification of air-SF_6 mixtures might leave some insulating surfaces exposed to an air environment.

Some NB source sparks develop very rapidly, perhaps in 10 nsec or so. Transient voltages of many kilovolts may be produced between the various electrodes associated with the plasma source at such a time. Since the insulating material (Kapton®) is only intended for few-hundred-volt service, it is necessary to protect this from high voltage punctures. With metal oxide-type varistors and short, low inductance lead dressing, we tie all plasma source elements to the Filament (-) plate, as mentioned in item 4 of Table 2.

Another basic element required for proper NB source operation is a transiently-dissipative snubber which absorbs most of the energy stored in stray capacitance at accel potential during a source spark. For LBL NB sources, it is necessary to limit the "unsnubbed" $1/2\,CV^2$ stored energy immediately available to a source spark to $\lesssim 3$ joules.[1,2] We employ a stack of high quality tape-wound cores, as implied by Figure 1. Design details are in an earlier report.[6]

Fault Signals And Philosophy

Neutral beam sources and power supply systems are intimately linked. A full discussion of fault detection would include mention of such power supply-related conditions as overvoltage, over/under current, tube sparking, excessive pulse length, improper settings, and open interlocks. However, we shall confine our comments to a discussion of those signals directly related to NB source operating parameters, and whose improper magnitude or treatment in fault detection circuitry could cause source damage.

Table 3 lists the five critical fault conditions for LBL sources. The "Typical Limit Setting" is the adjustable threshold limit value set into the fault detector controls by the operator. With the possible exception of condition #5, if any or all of these signals exceed this "Typical Limit Setting", an interrupt-restart cycle is initiated as previously described. The "Maximum Fault Detector Limit" is simply the maximum value of limit setting permitted by the range of the adjustable fault detector controls.

Table 3

Fault Conditions, Signal Magnitudes And

Response Delays For 80 And 120 kV 10 x 40 cm NB Sources

NO.	FAULT CONDITION	TYPICAL LIMIT SETTING	MAXIMUM FAULT DETECTOR LIMIT	MAXIMUM INITIAL INHIBIT DURATION τ_1	MAXIMUM FAULT PERSISTENCE DURATION τ_2
1	SPARK $\left[\frac{-\Delta V_{ACCFL}}{V_{ACCEL}}\right]$	20% OF V_{ACCEL}	50% OF V_{ACCEL}	0	$\sim$1 μs
2	LOW $\frac{V_{1-2}}{V_{ACCEL}}$ RATIO OR HIGH $\frac{V_{GRAD\ GRID}}{V_{ACCEL}}$ RATIO	20% OF NOM. $\sim$3% OF NOM.	50% OF NOM. 7.5% OF NOM.	1 ms	100 μs
3	$I_{GRAD\ GRID\ DC}$ OVERCURRENT (BIPOLAR SENSING)	$\leq$0.5 A	1 A	1 ms	100 μs
4	$I_{SUPP\ GRID}$ OVERCURRENT	10-15 A	20 A	1 ms	100 μs
5	ARC CATHODE SPOT	N.A.	N.A.	N.A.	10 ms*

* TENTATIVE

It is desirable to ignore out-of-range but briefly acceptable signal values which may transiently occur at the time of initial turn-on (e.g., during the V_{accel} risetime). We accomplish this by incorporating independently adjustable Initial Inhibit Duration delays into each channel of the Fault Detector. These are strobed by an appropriate timing gate and simply inhibit an output fault signal for the delay time, τ_1. A second independently adjustable delay, the Fault Persistence Duration, τ_2, is also provided in each channel. This makes it possible to temporarily ignore a fault condition unless it persists for a time, τ_2. A fault at turn-on is then allowed to persist for a time no longer than $\tau_1 + \tau_2$.

The five fault conditions listed in Table 3 will now be discussed in detail.

Spark

The first and most fundamental of all faults is a source sparkdown. Ironically, we are not yet in full agreement as to which signal yields the most desirable indication of this condition. To date, we have used a $-\Delta V_{accel}/V_{accel}$ signal to indicate a dip in or the collapse of V_{accel}. This is certainly a necessary and sufficient criterion and is therefore a conservative approach. We recommend that the "Spark" detector respond promptly to $\gtrsim$30 kV dips in V_{accel}.

$V_{grad\ grid}$

As mentioned before, the signal most closely associated with possible source damage is the gradient grid voltage. Measured with respect to ground, this is referred to as $V_{grad\ grid}$; measured with respect to the plasma source, this is V_{1-2} (voltage between grids 1 and 2). If at all possible, we recommend monitoring $V_{grad\ grid}$ (at the source!) in order to be independent of telemetry, even though tolerances are more restrictive. Usually, the desired $V_{grad\ grid}/V_{accel}$ ratio is known and fixed. With the V_{accel} monitor signal supplied to the fault detector circuitry, the measured $V_{grad\ grid}/V_{accel}$ ratio can be electronically calculated and compared to the desired value which serves as a reference. If these two values differ by more than $\sim$3% for the times shown in Table 3, an interrupt is triggered. For grid damage, the most dangerous mode is when $V_{grad\ grid}$ approaches V_{accel}, i.e., V_{1-2} collapses.

It may be inconvenient to monitor $V_{grad\ grid}$, as in the NBSTF facility for TFTR source testing at LBL. Then V_{1-2} is monitored, telemetered to ground potential, and processed in the fault detector for determining a low V_{1-2}/V_{accel} ratio. This is not as reliable a method as that described above since telemetry is involved. However, should the telemetry fail in a no-signal fashion, a fault indication will be given. This is thus a partially fail-safe method and is believed to be adequate as long as telemetry output dc drifts are negligible.

$I_{grad\ grid}$

The gradient grid current signal, $I_{grad\ grid}$, is an important indication of proper source behavior and must be maintained at a low value to prevent source damage. (Actually, it only indicates the net current to the grid, consisting of ions and electrons impinging on the gradient grid, and as such gives no indication as to the actual energy deposited in the grid structure.) The polarity of $I_{grad\ grid}$ is a sensitive indicator of whether the plasma is "overdense" or "underdense"; that is whether the arc current is higher or lower, respectively, than it should be for optimum beam optics. We define the direction of positive $I_{grad\ grid}$ as pertaining to conventional current flowing from grid to power supply (i.e., when electrons enter the terminal from the power supply). Normally for 10 x 40 cm sources at initial turn-on, one sees a relatively large spike (typical 0.5 to 2.5 amps) of positive $I_{grad\ grid}$ which then swings slightly negative (typically 100 to 300 mA) and remains there. (The positive spike can be minimized or eliminated by proper matching of accel voltage and arc power risetimes.)[6,7] Because wide variations in this behavior are possible, the $I_{grad\ grid}$ fault detector channel must have a bipolar threshold detector, i.e., currents of either polarity which exceed the limit setting must cause interrupts to be triggered. Gradient grid current does not scale with V_{accel}; it depends on gas pressure, grid condition, and match for optimum perveance. It may be as high in a new source at 30 kV as it will be in the same source fully conditioned to 120 kV. After beam turn-on, $I_{grad\ grid}$ should never exceed 500 mA. This signal does not lend itself to a ratio approach in the fault detector, as with $V_{grad\ grid}$ above, and can be monitored by a simple threshold comparator in the fault detector.

$I_{supp\ grid}$

The suppressor grid current, $I_{supp\ grid}$, is also a sensitive indicator of source performance and state of conditioning. In a fully-conditioned source, it should theoretically scale with V_{accel}, thereby lending itself to a ratio-type fault-detector threshold circuit. However, we find that during source conditioning the scaling is frequently improper and that it is desirable to be able to adjust the threshold according to prevailing conditions. We therefore use a simple comparator circuit with an adjustable threshold. Like $I_{grad\ grid}$, $I_{supp\ grid}$ may display a spike of current at initial turn-on which may be 30 to 300% of the normal value. This quickly settles down to a lower value (typically 10 to 15% of I_{accel}) for the remainder of the pulse. Again, this spike can be minimized or eliminated by proper matching of arc power and accel voltage during turn-on. During abnormal operation, in addition to larger currents, at least one different mode of operation is frequently seen. During this mode, following the initial spike and the falling to a lower value,

$I_{supp\ grid}$ begins a relatively long ramping upwards until a spark occurs or the $I_{supp\ grid}$ overcurrent channel responds. During a source sparkdown, the current to the suppressor grid usually (but perhaps not always) spikes to the 100 A to several hundred ampere range. In the 120 kV, 15 A, 0.5 sec test stand at LBL, the output from a current transformer which monitors this current is being used successfully to directly trigger the interrupting switch, avoiding the inherent delays in electronic circuitry. This is thus a prompt, redundant "Spark" detector operating in parallel with the $-\Delta V_{accel}/V_{accel}$ signal already discussed.

Arc Cathode Spot

Normally, the arc current creates the diffuse discharge in the plasma chamber from which some ions are accelerated. During certain improper operating conditions, a cathode spot may form on one or more filaments or at the walls of the plasma chamber. This "spotting" results in a noisy metal-arc discharge between the arc anode and the cathode spot.

Four causes of spotting have been identified: a dirty source, air leaks, operation at high arc voltages such as $\gtrsim$60 VDC (e.g., resulting from insufficient gas flow), or operation at an excessive filament temperature (probably caused by a high tungsten vapor pressure at the negative leg of the filaments; these receive additional heating because of the superimposed arc current). During spotting, the uniformity of plasma density in the plasma chamber is disturbed and the filaments can be severely damaged. Furthermore, a degradation in accel voltage-holding is often observed.

Since spots are potentially damaging, we recommend sensing their presence and stopping them as soon as possible, at least within milliseconds. Our development of spot-detecting circuitry is in an early stage; we have not yet succeeded in unambiguously detecting them. One promising circuit is about to be installed at our 120 kV, 65 A, 0.5 sec test stand; a summary of its performance must come later.

Four telemetered signals are available which show changes during a spot: V_{arc}, I_{arc}, I_{fil}, and I_{probe}. The latter refers to positive ion current drawn by negatively biased Langmuir plasma probes usually provided with each NB source. During a spot, all of these signals become decidedly noisy. The frequency spectrum of the noise is typically broad, covering the ~1 to 40 kHz range. The character and magnitude of the changes are not always the same. Usually, however, we see a slight decrease in the average value of V_{arc}, a slight increase in the average value of I_{arc}, and an I_{probe} signal that shows a pronounced drop and a peak-to-peak noise that is several times the amplitude of the signal.

In terms of percent, the change in I_{probe} is the largest of the three signals. The absolute noise amplitude is usually greatest on V_{arc}, being a ~5 to 15 V peak-to-peak disturbance which rides on the V_{arc} signal. We intend to exploit this large amplitude in the circuit to be tested soon. Two earlier attempts to detect the decrease in V_{arc} succeeded, but resulted in nuisance trips caused by the normal fall in V_{arc} during the arc notching process.[6-7]

To date, spot detectors have triggered SCR-type crowbars and terminated the NB pulse. Recent preliminary results with the arc modulator[7] on the 120 kV, 65 A, 0.5 sec test stand indicate that it may be possible and acceptable to extinguish the arc with the arc notcher, when spotting occurs, then restrike the arc within milliseconds and continue the NB pulse. We will be obtaining further data on this possibility in the near future.

Fault Detector Hardware

The fault detector hardware should be considered the primary protection against very expensive NB source damage and associated downtime for repairs or replacement. It should be the most foolproof and reliable electronics gear in a NB system. Unfortunately, we have not always heeded our own advice and have therefore accumulated a wealth of experience as regards what not to do. For the benefit of those designing such equipment, we offer in Table 4 a number of suggestions of what to do. Most are self explanatory but some deserve additional comment.

Table 4

Fault Detector Design Recommendations

1. Use rfi-proof packaging and cabling techniques.
2. Rolloff filter all inputs for the longest tolerable risetime.
3. Obtain signals from calibrated, h-f compensated monitors.
4. Obtain inputs from dedicated, buffered signal amplifiers.
5. Place little or no reliance in telemetered signals.
6. Use MIL-Spec high noise-immunity logic (e.g., CMOS).
7. Provide "First Fault" and "Later Fault" indicators, or individual "Time-of-Fault" Indicators.
8. Use LED indicators with wide-angle visibility.
9. Incorporate backup "Persistent Fault" sensing.
10. Make individual channel and summary channel output monitors available for easy debugging and trouble diagnosing.
11. Provide reliable Push-to-Test self-checking and lamp-test features.
12. Maximize accessibility for easy maintenance; consider modular design.
13. Provide "Ready" interlock to source firing controls.
14. Separate NB source protection circuits from power supply protection circuits.

Referring to item 6, we have used industrial-grade integrated circuits and have paid the price of significant downtime traceable to infant mortality of CMOS chips. Since MIL-Spec chips are burned-in, we strongly believe they are worth their premium price.

Item 7 is extremely important for rapid diagnosis of source problems. We have used both types of indicator systems mentioned.

In keeping with item 9, we provide backup "Persistent-Fault" channels which monitor whether or not the output from a normal fault channel actually does initiate the desired corrective action and clears the fault in a reasonable time. If not, and the fault persists for a few hundred μsec, we trigger a "hard crowbar" and/or open the accel power supply primaries.

Item 11 mentions a Push-to-Test self-checking feature which we have not yet provided in our equipment. However, we recognize its usefulness in saving much time now spent in verifying that the fault detector is properly functional. With such circuitry provided, it would be a simple and desirable next step to interrogate and test the fault detector before every NB pulse and inhibit machine firing if it malfunctions.

Item 14 is mentioned in the interest of human engineering and minimizing confusion about control settings for two distinctly different major systems.

As an example of a fault detector system, Figure 3 shows the circuit module of the system in use at our 120 kV, 65 A, 0.5 sec test stand. Figure 4 shows the control panel at which the operator sets in the limit settings and monitors which faults came first or later. The indicators are automatically reset before every machine pulse. Shortcomings of this and other fault detector systems in use at LBL have prompted the comments in Table 4.

Acknowledgements

The authors gratefully acknowledge helpful discussions with D. Bereznai, K. Chesley and D. Massoletti. We also thank Carolyn Wong for typing and otherwise preparing the manuscript.

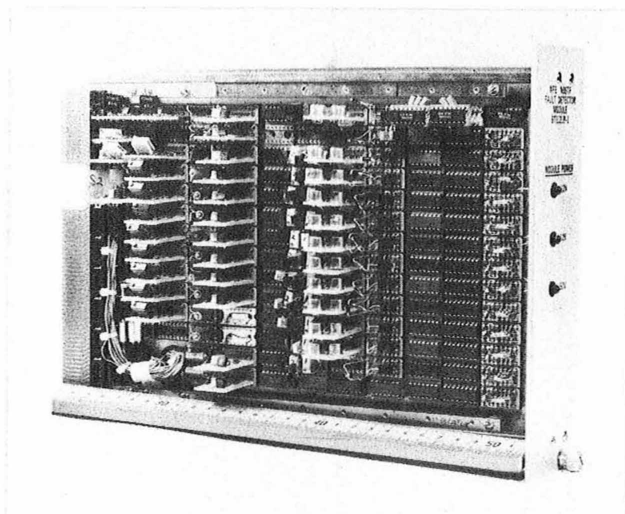

Figure 3 Fault Detector Circuit Module

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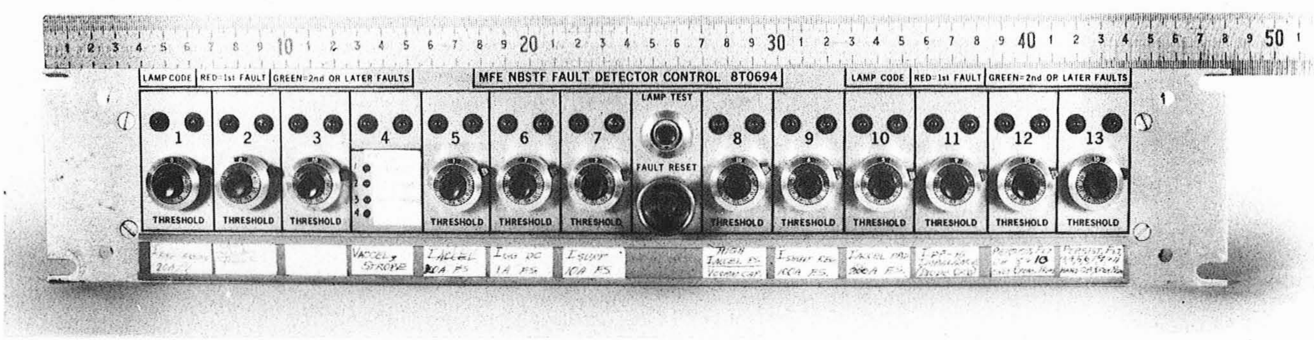

Figure 4 Fault Detector Control And Indicator Panel

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