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The Lawrence Berkeley Laboratory Power Supply System For TFTR Neutral Beam Source Development

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I.C. Lutz, H.M. Owren and F. Voelker

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Lawrence Berkeley Laboratory University of California/Berkeley

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DISCLAIMER

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THE LAWRENCE BERKELEY LABORATORY POWER SUPPLY SYSTEM FOR TFTR NEUTRAL BEAM SOURCE DEVELOPMENT*

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The Lawrence Berkeley Laboratory is presently constructing a facility for the development and testing of multi-megawatt neutral atomic beam sources which will be used in the Princeton Plasma Physics Laboratory's TFTR magnetic fusion experiment. This paper describes the power supply system to be used in this effort.

The "accel" power required by the neutral beam (NB) source is 120 kV, 65 A for 0.5-sec pulses every 30 sec This is easily met by a supply constructed with two large existing transformers whose combined 12-pulse rectified output is rated for 170 kV, 34 A cw. For future developments, this supply can deliver 30-sec pulses at the 75-A level. System per-unit impedance is 25% for the 120-kV, 75-A condition. A shunt regulator will be provided which uses six Machlett DP-15 triodes in parallel. Series-switching to the load will be accomplished by a series arrangement of 528 silicon controlled rectifiers (SCR's). The power supply system can tolerate frequent load sparks during a 0.5-sec pulse. When this occurs, repetitive interrupts and restarts will be made to occur with the aid of an "impulse crowbar" and a shunt LC commutating network.

This overall power supply arrangement differs from that being planned by PPPL. We consider it a low-risk option and chose it because (1) it uses existing tubes in the regulator; (2) it is a straightforward extension of similar successful techniques now in service in the LBL 120-kV, 20-A, 0.5-sec test facility; and (3) the project schedule requires a fully operating power supply long before a newly configured supply could be developed.

The auxiliary power supplies, i.e., filament, arc, suppressor, and gradient grid supplies are also briefly described.

Introduction

Several earlier papers have discussed the general philosophy and design details of LBL's approach to neutral-beam (NB) source power supply systems for multi-megawatt 120 to 150-kV operation.[1,2,3,4] This paper specifically describes the power supply system being designed and constructed to develop and test the LBL-designed NB source which will be replicated and installed on the Princeton Plasma Physics Laboratory's (PPPL) TFTR experimental fusion device.

LBL's basic mission, funded by DOE through PPPL, is to develop the NB source, then to test it and certain other prototypical vacuum beamline mechanical equipment designs. There has been no imposed requirement that the power supply system be a prototype of that to be installed on TFTR,[5] only that it be capable of adequately testing the NB source within a relatively tight time schedule. In order to minimize risk, we have chosen a power supply configuration which is a straightforward extension of one of our operating systems[2] which has a demonstrated capability for long-pulse, multi-megawatt operation at 120 kV.

A block diagram of the NB source and the planned power supply system is shown in Fig. 1. The major subsystems are described in detail in the following sections.

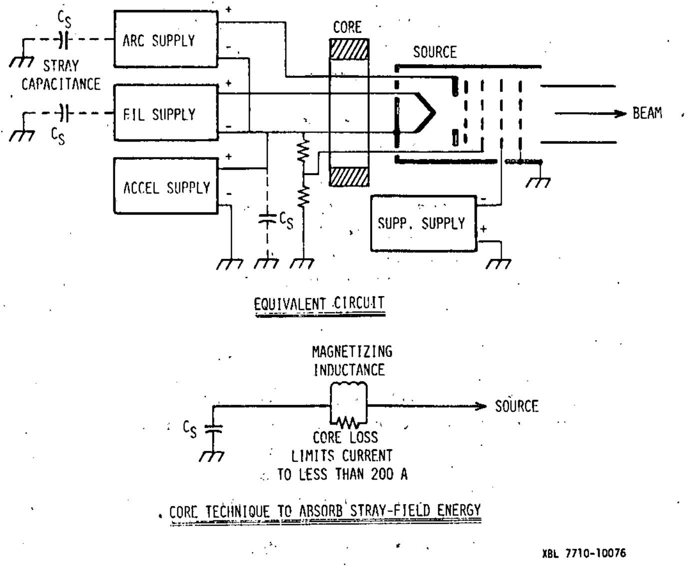

Figure 1. System Block Diagram and Core Snubber.

Accel Transformer-Rectifier System

The accel power supply is required to supply about 75 A at 120 kV for 0.5 sec every 30 sec; i.e., 9.0 MW on a 0.017 duty cycle. Figure 2 shows a simplified one-line diagram of the major components of this supply. Its three-phase input is obtained from a 12.4-kV ac, 1%-regulated line. Its dc output has 12-pulse (720-Hz) ripple, approximately 4% peak-to-peak, to allow operation without a filter capacitor and ease the load on the downstream shunt regulator.

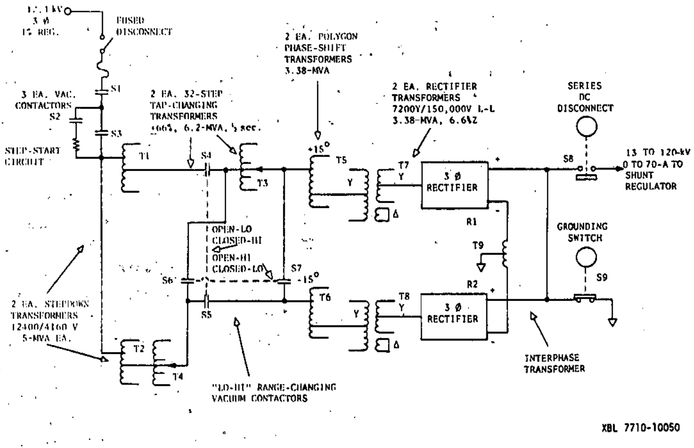

Figure 2. Accel Transformer-Rectifier Power Supply.

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*Work done under the auspices of the United States Department of Energy.

The two large rectifier transformers, T7 and T8, were recently obtained as surplus items through the Government Services Administration program. The step-down transformers, T1 and T2, required for matching the rectifier transformers' required input voltage were also obtained essentially free from local University of California facilities. The polygon transformers, T5 and T6, now on order, provide the 30° phase shift necessary for obtaining 12-pulse rectified output. The interphase transformer, T9, also is required. It provides the impedance necessary to permit independent operation of the two rectifier commutating groups, R1 and R2. The tap-changing transformers, T3 and T4, are of the "no-load switching" type and enable the output voltage to be varied between pulses.

The minimum obtainable output voltage with the system just described would be about 38 kV dc, depending on load current, a value felt to be too high for initial NB source testing. A vacuum contactor "no-load switching" arrangement, S4 through S7, will be installed to provide "low" and "high" range switching for approximate output variability of 12 to 60 kV dc and 38 to 170 kV dc, respectively.

All reasonable steps will be taken, and appropriate equipment included, to minimize possible equipment damage during malfunctions. Even more important, the safety of operating and maintenance personnel is a primary concern. This will be maximized by a well thought-out combination of hardware interlocks, procedures controlled by Kirk-key locks, mechanical devices backing up electrical switches, and redundant hardware where appropriate. As an example, electrical linear actuators will control dc output series-disconnect and grounding switch mechanisms at the power supply. The same two switch mechanisms will be duplicated at the load end, near the shunt regulator, in the main experimental area.

Per-unit impedance of the transformer-rectifier system will be about 25% at the 120-kV, 75-A level, limiting steady-state short circuit currents to a value of ≤ 300 A. The number of full-load short circuits which can be tolerated by the rectifier diodes within their average lifetime, as dominated by thermal cycling, may only be of the order of a few hundred. Consequently, all efforts will be made to minimize the need for "hard" crowbars. Additionally, a circuit breaker and vacuum contactor (S1 in Fig. 2) with the fastest practical interrupting time will be provided.

The input vacuum contactor, S1, is mainly included as a backup fast interrupter in case S3 fails. Normally, S1 will remain closed while S2 and S3 perform the step-start and step-stop function.

The high voltage dc output will be conducted approximately 90 feet from the transformer-rectifier pad to the shunt-regulator in the main experiment building. In order to reduce capacitively stored energy in this transmission system and avoid the high cost and extreme stiffness of commercial cables, a novel high-impedance coaxial line will be constructed. It will have a gas-tight 6-inch steel conduit outer conductor and an RG-218/U as a center conductor which was procured without its vinyl jacket and outer braid. The cable will be centered by inexpensive polyethylene ellipsoidal swimming pool floats approximately 5 inches in diameter and 8-1/2 inches long. These will be placed end-to-end along the cable length. The polyethylene dielectric of the cable will provide the required high voltage strength. (A similar system having back-to-back polypropylene funnels as spacers has been operating in another NB test facility at voltages up to 120 kV for two years.) If necessary, the line can be filled with SF_6 to increase its insulation and suppress low-level corona and the consequent production of small amounts of ozone.

All leads at accel potential which connect to the source, including monitors, actuators, and filament, arc, and gradient grid supply leads, will pass through a stack of tape-wound magnetic cores. This "snubber", referred to in Fig. 1, is critical to successful operation of the NB source; it has been mentioned in earlier reports and analyzed in detail.[10] During a NB source spark, the energy stored in "upstream" stray capacitance is directly absorbed by the cores in dissipative hysteresis and eddy-current losses. The snubber was designed to provide a 1/e RC discharge time of about 1.0 μsec, limit the energy delivered to a NB source spark to a few Joules, and have sufficient core cross-sectional area to exhibit about 0.9 μsec time to saturation at full voltage. At all other times, the core is biased (i.e. flux-reset) by current obtained from the NB source filament power supply. Originally, we had planned to use 72 cores, each of which was 6 inches i.d., 10 inches o.d., 0.5 inches thick, and wound with 0.002 inch 50-50 nickel-iron (Deltamax) material. Because of the availability of surplus equipment from the recently discontinued Astron experiment at Lawrence Livermore Laboratory, we now plan to use 30 of their injector cores in this snubber. These are each 8.75 inches i.d., 24 inches o.d., 0.5 inches wide, and are wound with 0.0005 inch Deltamax material. Including the impact of a simplified mounting structure, this substitution will save approximately $10,000. It will also provide 30% more volt sec.

Shunt Regulator and SCR Switch System

Figure 3 shows a simplified diagram of the shunt regulator and SCR switching system. The engineering design of this system is described in detail elsewhere;[6] space limitations permit only a brief summary here.

The shunt regulator is similar to an earlier version[2] and employs six Machlett DP-15 tubes in parallel. Variable non-linear resistor assemblies are employed for the feedback link, V 1, and plate load impedance V 2. A 4CW50,000E tube is used as a cathode follower for driving the DP-15 grids. System gain results in accel voltage regulation of better than 1%. The setting of V1 determines the voltage at which the system regulates. The setting of V2 determines the voltage division between V2 and the DP-15 tubes and, of course, their power dissipation. Once V1 and V2 are set, the amount of current to be carried by the shunt regulator is determined by the setting of the accel power supply tap-changing transformers, T3 and T4 of Fig. 2.

The experiment operator will "dial in" the desired accel voltage with "digiswitches". This will transmit a set-point voltage to a dedicated microprocessor in the

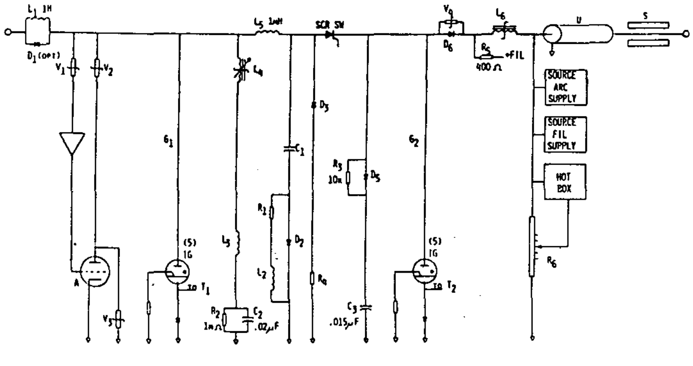

Figure 3. Accel Shunt Regulator and Switching System.

control system. By use of programmed "look-up tables", it will properly position the three variable systems for correct shunt regulator operation at the anticipated NB source accel current level. What is required is to turn on the accel power supply, establish full-voltage regulation while carrying an appropriate current through the shunt regulator, then switch to the NB source load delivering proper voltage and current while leaving a few % of the original current being conducted through the shunt system. This enables voltage regulation to continue in the presence of accel power supply ripple and small load changes. Note that the power supply current drain is essentially constant; current is simply transferred from the shunt system to the load.

If V2 were a linear resistor, a 10:1 current change in the shunt system would permit the DP-15 plate voltage to rise from, say, 5 kV to 109 kV for 120-kV, 70-A operation which leaves 7 A in the shunt regulator. With a non-linear resistance material such as silicon-carbide (Thyrite) for V2, the DP-15 plate voltage rise is from 5 kV to only 58 kV. This permits a much more reliable and conservative use of these tubes. V3 is a Thyrite clamp to prevent the DP-15 plate voltage from transiently exceeding ~75 kV. Figure 4 shows details of one of the six required Thyrite assemblies. These will immerse the Thyrite discs in liquid Freon-11, selected for efficient cooling, and employ vapor-phase heat exchanging in a low-conductivity water-cooled condenser.

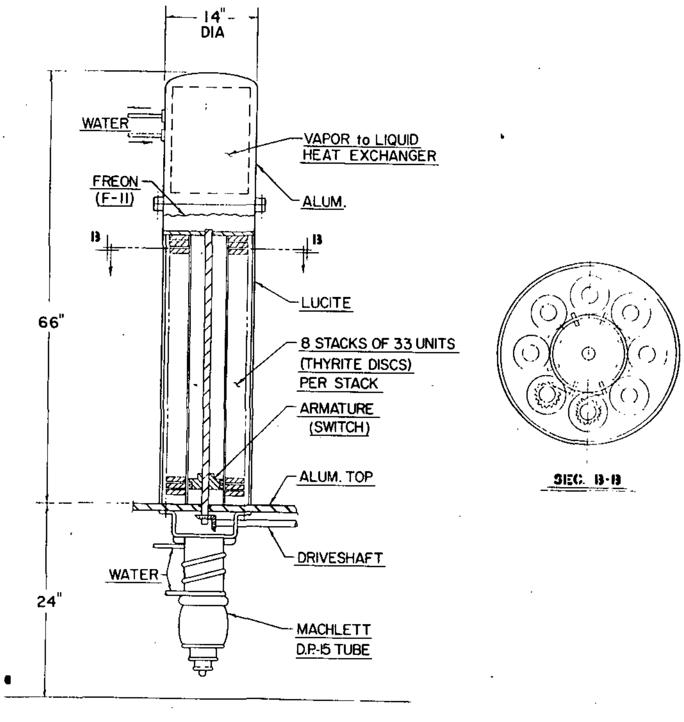

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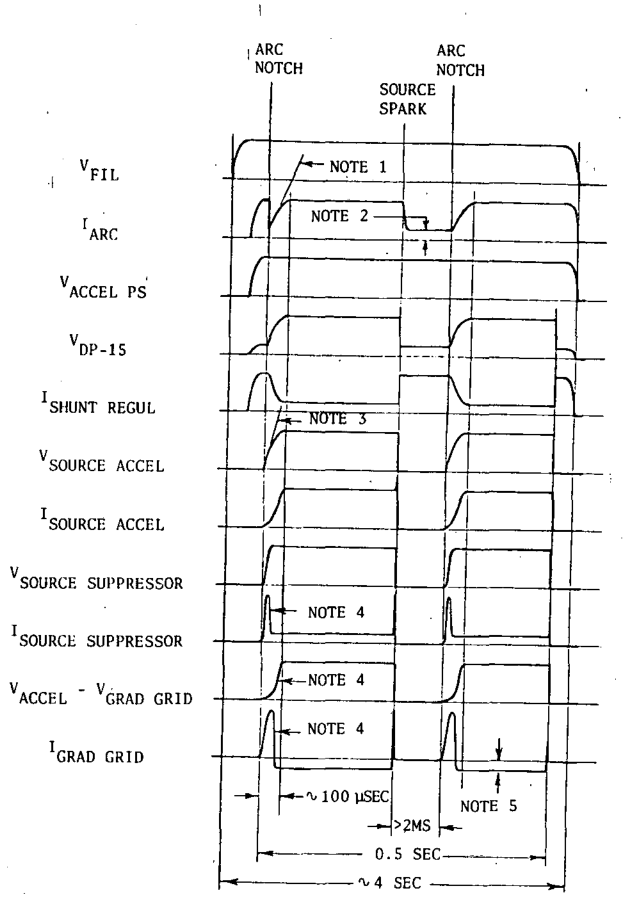
Figure 4. Variable Thyrite Plate Varistor Assembly

An understanding of the operational timing sequence is necessary for the remainder of the switching system description. This is shown in Fig. 5. Switching to the load is accomplished by triggering a series arrangement of 528 series silicon controlled rectifiers (SCR's). This and similar SCR assemblies are discussed in detail in another paper.[7] In Fig. 3, L5 limits the dI/dt to 120-A/µsec for the SCR's, which have a maximum rating of 400-A/µsec. C3 controls the risetime of Vsource accel. D5 prevents the stored energy of C3 from being delivered to a NB source spark. R3 discharges C3 during an "interrupt", described below.



NOTES

1. ARC PLASMA DENSITY SHOULD IDEALLY BE $\alpha\ (V_{ACCEL})^{3/2}$
2. A FIXED, OPTIMIZED VALUE REGARDLESS OF V_{ACCEL} LEVEL
3. INITIAL SLOPE ≈ 5 kV/µSEC FOR 120 kV OUTPUT
4. AMPLITUDE AND DURATION DEPEND ON OPERATING PARAMETERS
5. POLARITY AND AMPLITUDE DEPEND ON OPERATING PARAMETERS

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Figure 5. Typical System Waveforms and Timing

When an NB source spark occurs, the impulse crowbar, G2, (discussed in the next paragraph) is triggered, causing its anode to momentarily be at approximately -3 kV. This diverts current from the NB source, which is decoupled by diode D6 and L6, which is now brought out of saturation. R5 fully damps the circuit of L6 and all stray capacitance on the NB source side of L6. C2 and L5 are the major components of a 75-µsec period, 600-Ω ringing circuit which can supply about 200 A to divert current from the SCR for a sufficiently long time (~ 30µsec) to commutate it. R2, L4, D3, and R4 are also necessary for proper commutation and transient damping. When commutation is complete, voltage again rises to the regulated value and full current is again carried by the shunt regulator. C1 controls the dV/dt at the SCR anode to $\lesssim$100 V/µsec; the SCR's are rated for 400 V/µsec. The process just described is called an "interrupt". After a period of $\gtrsim$ 2 msec (typically 20 ms), the SCR can again be triggered, to resume source operation. Up to 100 such interrupts (typically<6), may be permitted during a 0.5-sec pulse.

The ignitron crowbars each employ five GL37248 tubes in series with a novel connection which eliminates the need for the usual ignitor pulse transformers having high voltage insulation. The circuit diagram is shown in Fig. 6. The engineering design is described in detail elsewhere.[8] As can be seen, only a ground-referenced -3-kV trigger pulse is required. The tubes break down sequentially with parallel varistors acting as clamps to prevent overvoltaging any tube and also to conduct trigger current to the ignitors. A five-tube circuit has been tested and shown to complete overall breakdown in approximately 2 μsec. To maintain maximum voltage holdoff capability, anode heating will be provided for each tube that prevents mercury condensation on the insulator. This will be implemented by a heat pipe system having one central Freon-11 boiler. Teflon tubes will feed warm vapor to simple heat exchangers built into the anode connectors. Condensed vapor will return by gravity to the boiler by the same tubes. (Single ignitron anode heaters of this type have been in use at LBL for several years.) A five-tube ignitron crowbar assembly will be approximately 24 inches in diameter by 44 inches high.

In Fig. 3, L1 is a high-quality multiple-pie, tape-wound, air-core inductor. It and the power supply leakage reactance limit the accel current increase, during SCR switching and commutating, to a small fraction of the nominal 75-A, 120-kV load. It is also an instantaneous current limiter for transients generated by NB source sparks and the "hard" crowbar. D1 may be required to prevent possible resonant overvoltage surges caused by the inductive energy stored in L1.

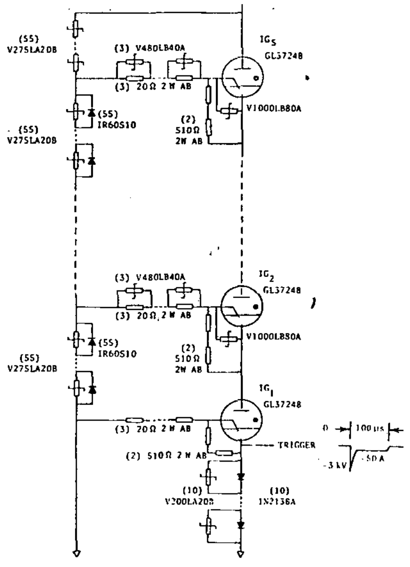

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Figure 6. Series Ignitron Crowbar Schematic Diagram.

Auxiliary Power Supplies

The NB source filament power supply is rated at 9 to 18-V dc, 6000-A maximum, and can be pulsed for 4 sec every 30 sec. It typically supplies 12 V, 4000 A to the NB source. Figure 7 shows a simplified diagram for this supply which is mainly self explanatory. The impedance of the supply and the voltage drop in the leads to the NB source are designed to below: ≲ 30% and ≲ 6 V, respectively. This prevents a progressive filament burnout problem observed with an early high impedance supply. In that case, when some filaments burned out, the voltage rose on the remaining ones, finally burning them all out.

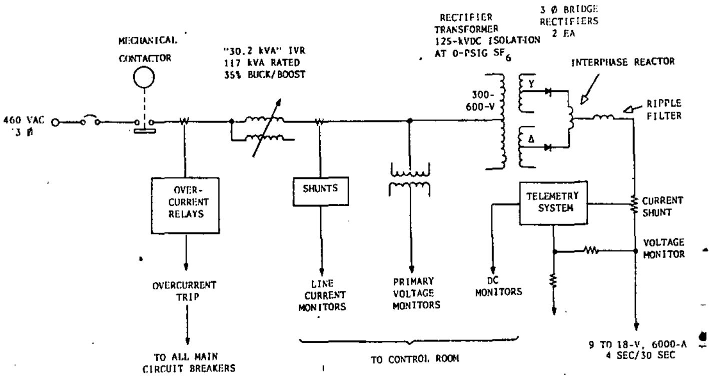

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Figure 7. Filament Power Supply Diagram

A simplified arc power supply diagram is shown in Fig. 8. This supply must have a high degree of reactive impedance in order to provide nearly constant current to the arc load. This also provides instantaneous current limiting during source sparks. The supply will have a 140-V dc open circuit output, with a 70-V dc output at 4000 A (50% regulation). It can be pulsed for 0.6 sec every 30 sec. An output current range of 150 to 4000 A must be provided for all possible operating modes. Coarse range-changing is provided by switch-selectable line reactors in the ac primary feed system. Fine control is effected by varying an induction voltage regulator (IVR). A vacuum contactor in the ac primary feed system will enable 1 to 2 cycle interruption during faults. As with the accel power supply, the variable elements of the arc power supply will be controlled in a properly coordinated manner by the dedicated microprocessor. The operator will only need to select a desired arc current value with digiswitches.

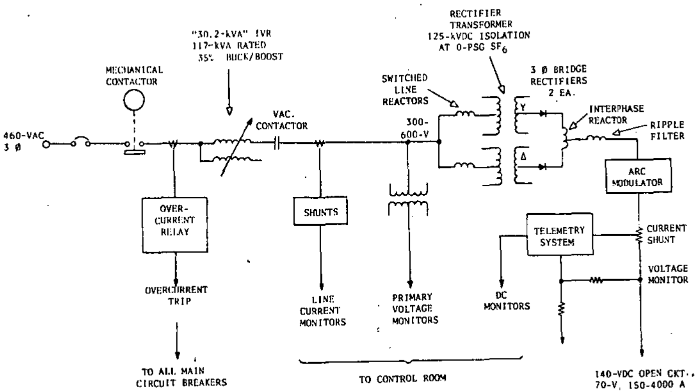

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Figure 8. Arc Power Supply Diagram.

In the output dc circuit of the arc power supply, a current modulator is required. This will accomplish the current changes indicated in the timing diagram, Fig. 5. This action has been found to be an absolute necessity for reliable source operation. It functions to ensure proper start-up of the source by establishing "good" beam optics during the risetime and to further protect the source following a spark. This circuit is not yet designed but should not be too complex. An SCR could provide the longer-duration current shunting. This can be commutated by another SCR, after which the current-rise characteristic would be controlled by a programmed power transistor bank with resistors in the collector circuits or perhaps by a simple diode-capacitor network.

A simplified diagram of the suppressor power supply is shown in Fig. 9. It can provide a regulated continuous output of 5 kV, 10 A, or 5 kV, 20 A at a reduced duty factor. During a normal pulse, the NB source is expected to require 8 to 10 A of suppressor current. The combined turn-on risetime and delay with respect to the accel gating signal will be short, $\lesssim 15\ \mu$sec, to help minimize the amplitude and duration of the initial turn-on current spike (see Fig. 5).

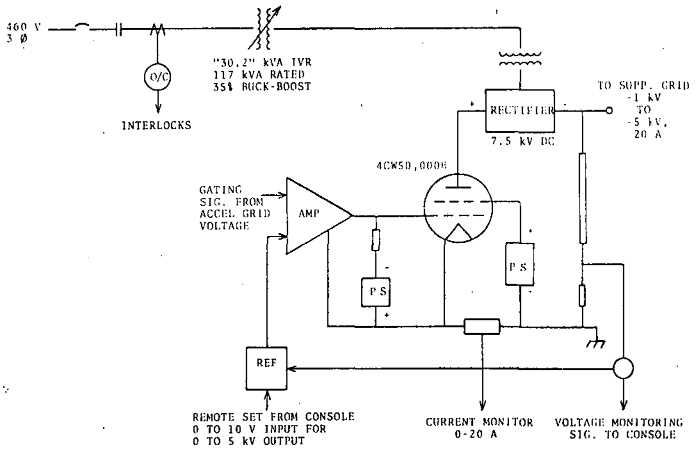

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Figure 9. Suppressor Power Supply Diagram.

The output level of the suppressor supply is determined by a set-point voltage received from the control system. It is automatically gated on and off with the accel voltage, a system proven simple and reliable in other NB test facilities. The IVR will be positioned either at its lower or upper limit, depending on the operating level, to maintain the tube plate dissipation within rated limits. (The choice of IVR's here and for the arc and filament power supplies was governed by their ready availability from the LBL equipment pool.) A diode string, not shown on the diagram, will be installed from the output terminal to ground. This will clamp the output from going positive and can momentarily carry the accel current when a NB source spark occurs.

Proper arc and gradient grid behavior are probably the two most critical items for reliable NB source operation. At any level of accel voltage, the ratio of gradient grid to accel voltage should ideally be maintained at a fixed value in order to achieve optimally focussed extracted beams which do not appreciably intercept the grid structure. In an earlier NB source test facility,[2] the gradient grid was supplied from a zener diode-string regulator connected between the accel and gradient-grid leads, which had a return resistor to ground. Recent experience has shown that a simple resistive divider from the accel lead to ground, with a properly placed tap for the gradient grid supply, can meet the ratio requirement described above.

Figure 10 shows a diagram of the gradient grid supply. It is described in detail elsewhere[9]. The nominal design value of gradient grid voltage, Vg, with respect to ground, is 83% of the accel voltage, Va. This circuit will provide an adjustable ratio of (Va - Vg)/Va = 0.13 to 0.21 with a selection resolution of (Va - Vg) of 1.5%. For Va = 120 kV, (Va - Vg) can be adjusted from 15.6 kV to 25.2 kV, in steps of 300 V, by a motor-driven, spiral-wound tap-switch assembly. A manually adjusted shorting link at the ground end of the divider can be moved to provide some coarse adjustment of the divider string current. This may be required at low operating voltages.

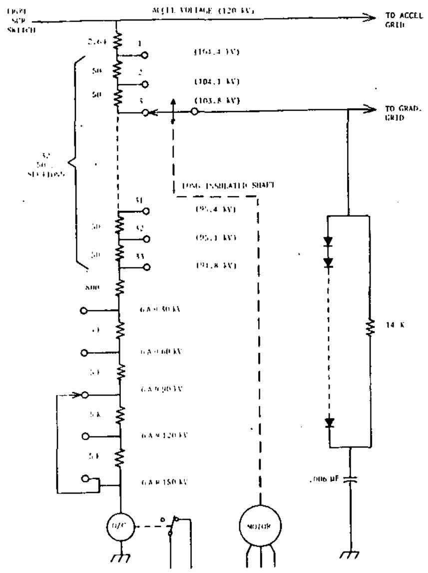

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Figure 10. Gradient Grid Power Supply Diagram.

Referring to Fig. 5, at the moment of turn-on, a high spike of conventional current momentarily flows from the NB source gradient-grid to the resistive divider tap. This may be as much as several amperes. It occurs because the initial effective impedance of the NB source between the accel and gradient-grid terminals is very low. Recent experience has shown that at higher operating voltages, the resistive divider impedance is too high to maintain even a rough approximation to the correct value of (Va - Vg)/VA during this initial heavy loading. As a result, the extracted beam excessively bombards the grids and the NB source sparks. In the LBL 120-kV, 20-A, 0.5-sec test facility, this problem was successfully eliminated by incorporating an RC network and diode "start circuit" similar to that shown in Fig. 10. During turn-on, the capacitor "stiffens" the low end of the divider and tends to force a more proper Vg even in the presence of the large current spike. The diode prevents the capacitor from delivering its energy to a NB source spark. The resistor discharges the capacitor between interrupts. The size of the capacitor is chosen to produce a Vg risetime approximately equal to that of Va.

Initial testing of the full-size TFTR NB source is just getting underway at a 30-kV level using a 120-kV, 75-A, 50-msec power supply system. So far, at a very early stage of testing with a similar resistive divider feeding the gradient grid, results are inconclusive as to reliable start-up. The RC and diode start-circuit was briefly installed but produced NB source oscillations and sparking. Further work is needed before a final design can be specified.

The resistive divider will be constructed with 15,538 ft. of No. 24 AWG nichrome wire, which will be prespiraled on a 3/8 inch diameter mandrel. This will then be wound on a fiberglass form 30 inches in diameter with a 3/4 inch pitch over a 4.5 ft length. The motor-driven switching mechanism will be placed in the center of the fiberglass form. An outer cylinder forms an air duct for forced-air cooling. The divider can absorb 450 kJ with a 100°C temperature rise, and can dissipate the worst-case average power level of 15 kW.

Schedule and Future Usage

Within manpower constraints, we intend to complete as early as possible the various sub-systems involved in the overall power supply task. By March 1978, major work should be completed and initial checkouts started on all four auxiliary power supplies, the telemetry system for transmitting information generated at accel potential to ground potential, the SCR switching system, and the ignitron crowbar systems. Installation and wiring of the accel transformer and switchgear pad and fabrication of the accel rectifier assemblies should also be completed by then. Major fabrications for the shunt regulator and one Thyrite plate varistor assembly should be completed by April or May 1978, ready for initial testing. We have allocated several months, following May, for completing the fabrication of full-system controls and final installation and interconnection, all the while overlapping final checkout testing of sub-systems. Our present goal is to be ready for starting initial NB source testing in December 1978. NB source testing is scheduled to continue at least until October 1, 1979.

Next-generation development of NB sources is expected to continue into the foreseeable future. There is much interest in higher voltage NB sources and pulse widths up to 30 sec. Because of the much more favorable neutralization efficiency, development of large negative-ion sources has begun. These will require negative or bipolar accel power supply systems. An output dc transmission line is also being installed to make the output of the large accel transformer-rectifier system just described available at the existing NB source R & D facility (Test Stand III area, Building 16). This effort may well be the first user of this supply. Controls and interlocks are being designed to permit safe usage of the supply in either area. It will be a relatively easy matter to reverse the output polarity for operation with negative output. Because the system uses two identical transformer-rectifier systems in parallel, it will also be possible to produce a bipolar output of ± 170 kV dc at 16 A cw, or at higher currents for pulse widths proportional to the square of the duty cycle.

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