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THE HIGH-VOLTAGE TEST STAND AT LIVERMORE*

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Summary

This paper describes the present design and future capability of the high-voltage test stand for neutral-beam sources at Lawrence Livermore Laboratory. The stand's immediate use will be for testing the full-scale sources (120 kV, 65 A) for the Tokamak Fusion Test Reactor. It will then be used to test parts of the sustaining source system (80 kV, 85 A) being designed for the Magnetic Fusion Test Facility. Following that will be an intensive effort to develop beams of up to 200 kV at 20 A by accelerating negative ions. The design of the test stand features a 5-MVA power supply feeding a vacuum tetrode that is used as a switch and regulator. The 500-kW arc supply and the 100-kW filament supply for the neutral-beam source are battery powered, thus eliminating one or two costly isolation transformers.

System Design

Positive-Ion Mode

Fig. 1 shows the present system design of the high-voltage test stand (HVTS). This configuration is called the positive-ion mode and it is for testing neutral-beam sources that operate by accelerating positive ions. It was designed to test neutral-beam sources for the Tokamak Fusion Test Reactor (TFTR) and the Magnetic Fusion Test Facility (MFTF). While no actual operation of a source has yet taken place, the equipment presently installed provides the following maximum power for the source:

Filament —1[illegible] V at 7500 A,
Arc anode —[illegible] A at 75 V
Suppressor grid —10 kV at 16 A,
Acceleration grid —120 kV at 90 A

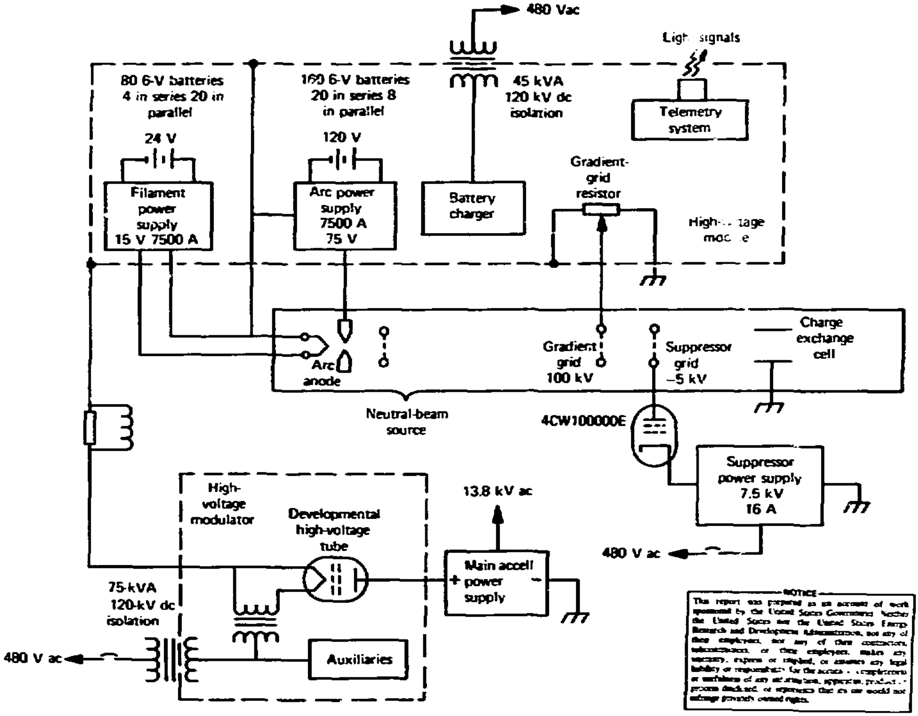

Fig. 1. HVTS system design, positive-ion mode.

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The equipment presently installed for the source's gradient grid is a resistive voltage divider designed specifically for the TFTR source.

The main acceleration power supply has a continuous input rating of 5 MVA. However, it will be able to supply up to 12 MW (required for TFTR) in pulses several minutes long at a duty cycle of about 60%. The filament, arc, and gradient-grid supplies are in a metal-shielded box about 10 by 22 by 7 ft high. This box is called the high-voltage module and is mounted on insulators tall enough for 200-kV operation. The filament and arc supplies are presently limited to pulse lengths of about 30 sec at full power because they use storage batteries for primary power. Their allowable duty cycle, at the TFTR level, is presently about 2%, limited by the rating of the small isolation transformer used to charge the batteries.

Negative-Ion Mode

One of the reasons for building the HVTS was to use it in developing a neutral-beam source capable of continuously supplying 20 A at 200 kV. Theoretically, the conversion of negative ions to neutral atoms is more efficient than the conversion of positive ions to neutral atoms. Consequently, high energy sources are expected to operate by accelerating negative ions. No modification of the main acceleration supply will be required to accelerate negative ions. Depending on the success of new high-voltage vacuum tubes currently being developed, the system may need an ignition or SCR switch to provide long-term hold-off of the 250-kV dc output of the main acceleration power supply. The duty cycle of the arc and filament supplies can be increased to about 10%, at very low cost, by the addition of a mechanically operated disconnect switch for the battery charging power. Continuous duty for these supplies will require the addition of one or two large isolation transformers (about 700-kVA).

Research on negative-ion generation and acceleration is continuing at LLL. Questions still exist concerning appropriate voltage and current levels for various gradient grids. As these levels are set, equipment will be designed to supply them. Hopefully, most can be supplied by resistive dividers operating off the main acceleration power supply. If separate modulators are required, they will be built with existing vacuum tetrodes.

Main Acceleration Power Supply

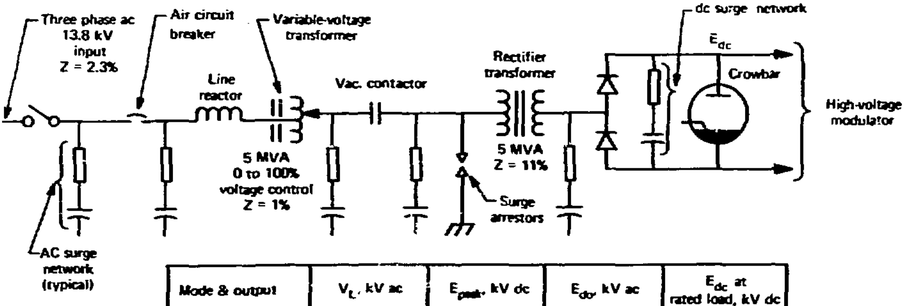
Fig. 2 shows a one-line diagram of the main acceleration power supply and a listing of its capabilities. Fig. 3 is a photograph of the supply. The major components of the supply are described in the following paragraphs.

Circuit Breakers

Two circuit breakers are included in the system: a vacuum contactor and an air circuit breaker. The vacuum contactor is considered the primary protection for normal load faults. It can be tripped by its built-in current relays and by a trigger applied to an SCR that dumps a capacitor bank into the trip coil. The vacuum contactor is expected to open in three cycles, or less. The air circuit breaker is tripped only by its own current relays. These relays are set to trip the breaker for all faults other than a normal load fault. However, long-term load faults will trip the air breaker if the vacuum contactor does not operate. Thus the primary protection is provided by the easily maintained vacuum contactor. The more rugged air breaker is operated only infrequently, so we avoid the expensive and time consuming overhaul these units require periodically.

Variable-Voltage Transformer

This 5-MVA unit controls the output voltage of the power supply. In all operation to date, we have brought the power supply on at zero output. With some minor changes in relay logic, we could come on at almost any preset voltage. The transformer is built



Mode & output	V_L, kV ac	E_{peak}, kV dc	E_{do}, kV ac	E_{dc} at rated load, kV dc
Negative ion 200 kV 20 A cw	177.2	250.6	239.2 kV dc	217.7
TFTR 120 kV 65 A 2 sec	139.2	196.9	188.0	141.0
MFTF 80 kV 85 A 30 sec	88.6	125.3	119.6	98.5

Fig. 2. Main acceleration power supply, one-line diagram.

Fig. 3. HVTS main acceleration power supply.

somewhat like a load-tap changer, with voltage variation between taps provided by small variable transformers built on linear cores. Cost and delivery time for this unit were much better than for the more traditional induction voltage regulator.

Line Reactors

Line reactors were included in the system to keep the reactance as high as possible. A private communication[1] indicates that transformer life varies inversely as the fifth power of the ratio of fault current to rated current. This data showed that for a life of 100,000 faults, the overcurrent ratio must not exceed 6.1. This corresponds to a minimum system reactance of 16.4%. The line reactors were specified accordingly.

Rectifier Transformer

The rectifier transformer is a 5-MVA unit with taps on the secondary to provide the required voltages. The secondary is always operated in wye and the primary in delta. The basic impulse level is 650 kV for the secondary and 110 kV for the primary. In addition to impulse testing, the manufacturer was required to do an induced-voltage test at twice rated voltage. The transformer was also tested with a low-power rectifier at 350 kV dc with one side of the rectifier grounded.

During the design of the transformer, the manufacturer was having difficulty predicting the reactance of the unit. He was sure of meeting our specification for the maximum allowable reactance but was not able to give numbers he considered accurate enough for us to specify our line reactors. Because line reactors must be ordered well before they're needed, we could not wait for construction of the transformer to specify the reactors. A computer program was written at LLL to calculate leakage reactance in a transformer with cylindrical core and coils. From the results, we were able to get our line reactors delivered almost the same day the transformer came. On the basis of the planned transformer geometry, the computer program predicted a reactance of 11.1%; the measured reactance was 11.5%. The numbers agree to within the accuracy of the instruments used.

Rectifier

The rectifier is a standard three-phase bridge. Each of the six legs of the bridge is made of 768 diodes each rated at 800 V and 125 A. Each diode is shunted by a 25-kΩ resistor and a 0.22-μf capacitor. The original intent was to build the rectifier in three separate insulating tanks with suitable corona rings. The ac current would have been fed into the middle of the vertical tank sides, and the dc connections would have been at the top and bottom. The insulating oil would have been pumped through a heat exchanger for cooling. This plan was abandoned when three large steel tanks became available at no cost. Each of the three phases of the bridge is housed in a separate tank with conventional bushings.

Crowbar

Load protection is provided by two identical crowbars, connected in parallel, close to the modulator. Each crowbar consists of seven 3724B ignitrons connected in series. Each unit is housed in a 16-in. PVC pipe with aluminum corona rings at the top and bottom. Each ignitron has a separate firing circuit that operates from a 12-V storage battery. A dc-dc converter provides 3-kV to charge the trigger capacitor. The voltage across the trigger capacitor is monitored, and if it falls below a preset value a light signal is interrupted, breaking the interlock chain for the main acceleration power supply. Triggers for the ignitrons are also coupled by light signals: the absence of light causes the crowbar to fire. To minimize the number of spurious ignitron firings, the anodes are heated to a temperature about 30°C above the cathodes. Thus, there are two water columns in each crowbar. The resistance of these water columns provides voltage division between the seven series ignitrons. Fig. 4 is a photograph of the crowbars, one with the side cover removed.

AC Surge Networks

Several resistor-capacitor surge networks are included in the ac system. Except for the network on the secondary of the rectifier transformer, the primary function of the networks is to reduce voltage transients that are caused by circuit-breaker operations. Vacuum breakers are particularly notorious for producing large voltage transients and many large transformers have been damaged or destroyed by these transients.[3] In the past, the standard surge network has consisted of three 0.25-μF capacitors connected directly across the output terminals of the breaker. These were not effective, and actually aggravated the situation in many cases.[4] The problem arises from the vacuum breaker's ability to chop a small current abruptly to zero. The energy stored in the inductance of the system causes a system overvoltage at a level determined by the amount of stray capacitance. Oscillatory transients often develop that cause the vacuum breaker to restrike many times. Because the breaker contacts are moving apart, the restrikes occur at ever higher and higher voltages. Inclusion of the resistor to damp the inductance/capacitance circuit prevents the restrike problem. Because these resistance/capacitance networks are relatively inexpensive, we made no great effort to optimize them. Problems in obtaining power resistors indicated that we should treat each network almost as if it stood alone and order the components quickly. Later, analysis by digital computer[5] showed the networks were adequate to protect the system.

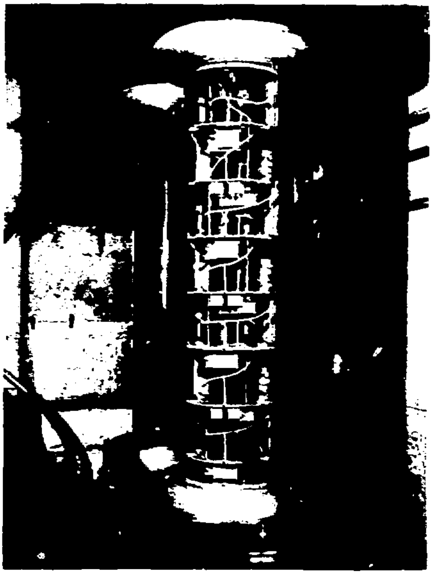


Fig. 4. The two 250-kV crowbars; each is composed of seven ignitrons in series.

The resistance/capacitance surge network on the secondary of the rectifier transformer is provided primarily to remove the transients caused by commutation of the rectifiers. An optimum design requires information that can usually be had only after the transformer is built. A conservative network was designed and built prior to delivery of the transformer and this network serves its purpose. It is important, of course, to use noninductive resistors for all these networks.

Surge (lightning) arrestors are included on the rectifier-transformer primary. Three 12-kV arrestors are connected line-to-ground. Three 15-kV arrestors are connected line-to-line. No lightning arrestors are included on the high voltage side of the rectifier transformer. Lightning is a rare occurence at Livermore. Furthermore, our power supply is located between two metal roofed buildings much taller than the supply itself. If one assumes that switching and lightning surges are passed through a transformer at a level determined directly by the turns ratio, the arrestors on the primary adequately protect our transformer. In addition, standard surge arrestors are not designed for the dc offset involved in rectifier operation, so an adequate set of arrestors for the secondary would have cost more than half as much as the transformer.

DC Surge Networks

The main surge network on the dc side of the power supply is something of a compromise. A large number of 1500-μF, 450-V electrolytic capacitors were available to be used in this network, but they could not quite provide the desired capacitance. However, a small analog model of the supply verified that this capacitance would provide adequate performance. The difficulty only exists on the lowest voltage tap, so a slight voltage overshoot is not terribly important. The housed surge network is shown in Fig. 5. The noninductive resistors are mounted between the top and middle corona rings. The capacitors are mounted between the middle and lower corona rings. Zener diodes and resistors are connected in parallel with each capacitor. When the transformer is operated from the highest-voltage tap, all the surge capacitors are connected in series. When operation is from the middle transformer top, the capacitor bank is tapped. When operation is from the low voltage transformer tap, the capacitor bank is split in half and the two halves paralleled.

Two smaller surge networks are used, one at each end of the coaxial cable that connects the modulator to the power supply. These networks consist of 40- resistors and 0.027-μF capacitors and provide an approximate impedance match for the coaxial cable.

Other System Components

High-Voltage Modulator

The modulator for the main acceleration supply is described in another paper accepted for publication in these proceedings.[6] The unit is designed to use either of the new high voltage tubes being developed for ERDA by RCA and EIMAC*. The RCA tube (A3012) is presently being installed in the modulator. The modulator both regulates and switches the voltage applied to the neutral beam source. We anticipate no great difficulty in voltage holding with this modulator when the power supply is operated on the two lower taps. On the highest tap, the open-circuit voltage is over 250-kV. If we have trouble at that level, we plan to add either an SCR or ignition switch. The modulator tube will then have to hold the full voltage for only a very short time on each load pulse. The modulator's major functions will remain the same—voltage regulation and current interruption.

Arc and Filament Supplies

These two supplies are both powered by banks of 6-V, 244-A-h golf-cart batteries. The filament supply is described in a paper accepted for publication in these proceedings.[7] It is a voltage-regulated supply rated at 15 V and 7500 A. Control of the filament voltage is provided by switching stainless steel resistors in or out of the circuit with small contactors.

The arc supply is a current-regulated supply rated at 7500 A and 75 V. It is similar to the filament supply except SCR's are used to do the switching. An LSI-11 microcomputer is used to control the SCR's.

We expect the battery banks to be useful for both the arc and filament supplies for some time. When the required pulse length for sources goes beyond about 30 sec, we will have to add more batteries or install a large isolation transformer to provide the required power.

Suppressor Grid System

DC Supply. The dc power supply for the suppressor grid is a three-phase supply using a bridge rectifier. It is rated for 90 kVA continuous duty at either 8.5 or 14.7 kV dc. The supply operates from 480 V ac input and has vacuum contactors for fast overload protection. A resistive step-start system is included on the dc side of the rectifiers. The supply is installed outdoors on the same pad as the main acceleration power supply.

Suppressor Grid Modulator. This unit uses an EIMAC 4CW100000E tetrode to regulate and switch the source-suppressor grid. The control and drive circuitry are very similar to that used for the high-voltage modulator. The modulator is in the same room as the neutral-beam source. An ignition crowbar for the dc power supply is included in the modulator enclosure.

Gradient-Grid System

It was originally thought that the gradient grid of the neutral-beam source would also require some kind of vacuum-tube modulator. Recent results at Lawrence Berkeley Laboratory indicate that a resistive voltage divider can meet the gradient grid power requirements for the TFTR source. Consequently, we have built a potentiometer using copper-sulfate solution as the resistive element. The unit is built in a 12 in. PVC tube about 40 in. long. The upper electrode is connected to the source filament, the middle electrode is connected to the gradient grid, and the bottom electrode is grounded. All electrodes are copper, and the middle one can be driven up or down by a remotely controlled motor. A small multiturn potentiometer is geared to the motor shaft to give a remote readout of shaft position. The copper-sulfate solution is pumped through a heat exchanger to dissipate excess energy.

The Telemetry System

The telemetry system designed and built for HVTS is described in a paper accepted for publication in these proceedings.[8] The system is used for control signals as well as for diagnostics. All signals are transmitted by light pipes installed between the control room and the room housing the neutral-beam source. The light pipes are about 100 ft. long and the data is handled at a rate of 2 X 10[illegible] bits/second. Both analog and digital data are handled.

Arc Snubber

A set of magnetic cores is installed between the high-voltage module and the neutral-beam source. All power for the source passes through these cores. When the

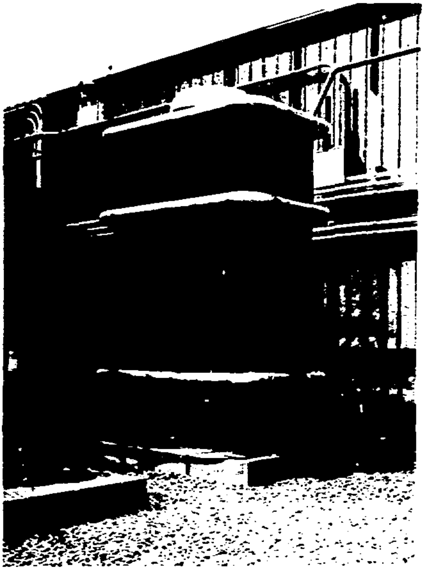


Fig. 5. DC surge network in housing.

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*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research and Development Administration to the exclusion of others that may be suitable.

source sparks, the cores present an effective resistance of a few hundred ohms between the source and the energy stored in the stray capacitance of all the power supplies. A recent paper[9] describes such devices in more detail and gives design information.

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