Title

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A SHUNT REGULATOR FOR 150-kV, 20-A, 0.5-Sec NEUTRAL-BEAM-SOURCE POWER SUPPLIES*

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Abstract

The Lawrence Berkeley Laboratory (LBL) is now constructing a test facility for the development of neutral beam (NB) sources which will operate up to a level of 150 kV, 20 A, 0.5 sec with a 1% duty cycle [1]. Such sources will provide neutral deuterium beams for injection into large-scale experimental fusion devices. These sources require an accel power supply capable of wide-range variation, voltage regulation of ± 1%, risetime ≤ 20 μsec, turnoff (crowbar) time of ≤ 10 μsec, repetitive crowbarring and restarting during a 0.5 sec pulse, and low rate of current increase during a short circuit. We describe a shunt regulator system which uses existing components and satisfies these requirements with simplicity and relatively low cost.

Introduction

The LBL 150-kV, 20-A, 0.5-sec neutral-beam (NB) source test facility and its specifications have been discussed in detail in another paper [2]. At the time of its writing, a saturable-reactor-controlled accel power supply was envisioned. This was to be shunt-regulated by a series combination of three vacuum tubes. Since that time, a simpler, improved accel power supply and shunt regulator design has evolved. This design employs simple series inductors in the ac primary feed lines to limit the output current and its rate of rise during a spark at the NB source. The total power source impedance is about 40%, limiting the steady-state short-circuit output current to a value 2.5 times the maximum normal operating current.

In systems operating at ≤ 40 kV, series vacuum tubes have been used to switch and regulate the NB source accel voltage [3]. At 150 kV, the series-controlled approach presents numerous problems which are avoided by a shunt regulator approach [4]. Figure 1 shows a block diagram of a 120 kV NB source and the power supply system it requires. The heart of the accel power supply system is the improved switching and shunt-regulating system described below.

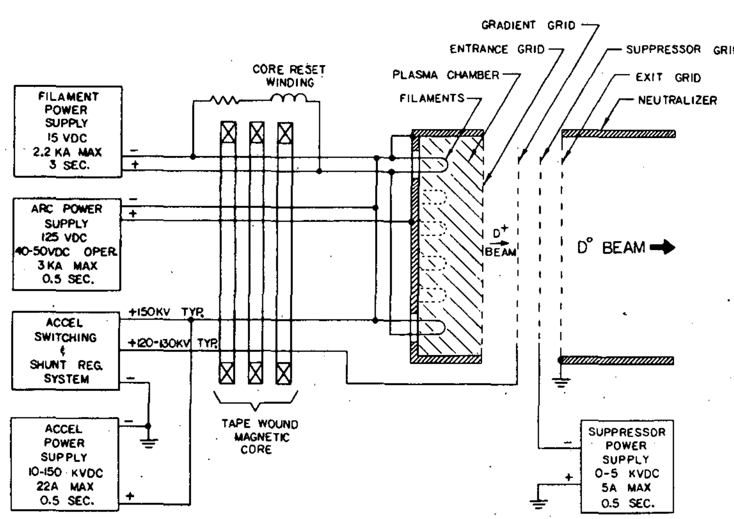

Figure 1. Block Diagram of Neutral Beam Source and Power Supply System

Accel Switching and Shunt Regulator System

The NB source accel power must be applied and removed with a rise- and fall-time of ≤ 20 μsec to minimize the "poor beam optics" period when grids are partially intercepting the extracted beam. When a source spark occurs, the accel voltage must be removed within ≤ 10 μsec to prevent damage to the source. After the source spark is extinguished, it is desirable to reapply accel voltage and continue with the output pulse. This "interrupt" sequence may occur many times during a 0.5 sec pulse. The desired "interrupt cycle time" is about 1 msec.

A simplified diagram of the switching and regulator system is shown in Figure 2. The two Machlett DP-15 tubes, V3 and V4, are the shunt regulator tubes. These have a rated peak anode voltage of 150 kV but their current and anode dissipation is somewhat limited. Their anode resistance, R5, is a switch-variable series-parallel assembly of non-linear resistors, or varistors (Thyrite). This material can absorb about 2 kJ/in.[3] The assembly is sized so as to be able to absorb the full power supply output for 0.5 sec (∿ 1.6 MJ) so it can serve as a dummy load. Being non-linear it also limits the DP-15 maximum plate voltage, under all operating conditions, to a value of ≤ 1/2 the maximum power supply output voltage, as will be explained below. The spark gap-resistor combination of G2 and R6 protects these tubes from excessive plate voltage during unpredictable transient conditions.

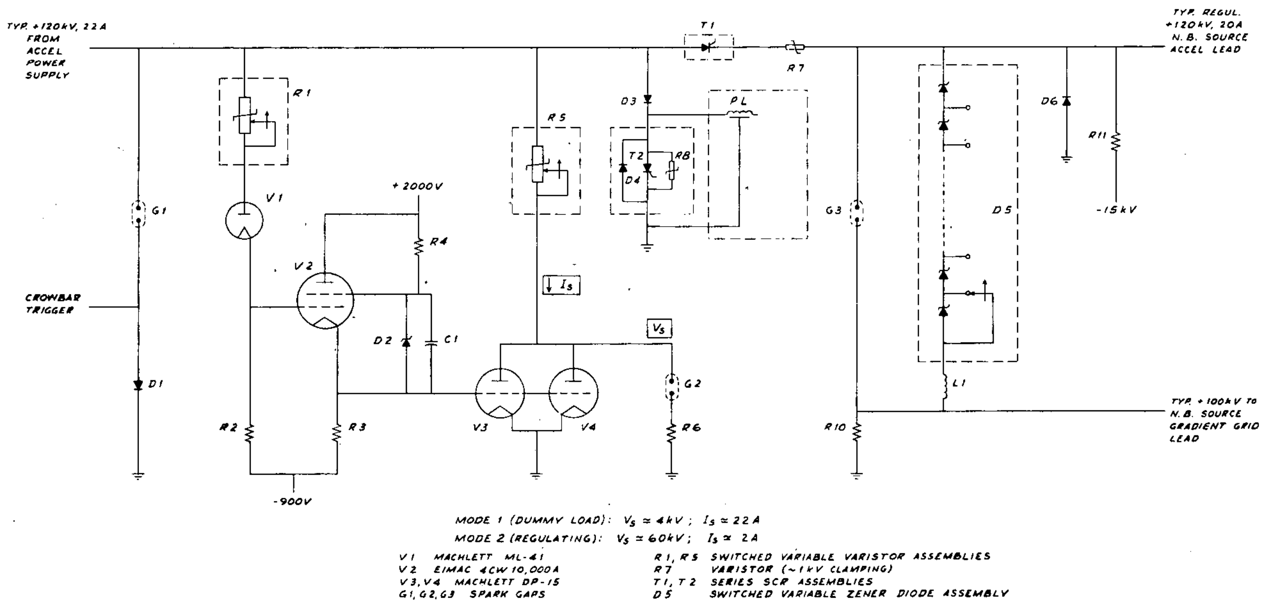

Figure 2. Switching and Shunt Regulator System Simplified Schematic Diagram

A 4CW10,000A cathode-follower drive for the DP-15's provides about +200 V/3-4 A grid drive when the DP-15's are asked to conduct the full 22 A power supply output. This causes the DP-15 anode voltage to be only a few kV, minimizing the anode dissipation. Regulation is achieved by feedback from the accel power supply bus, via a smaller variable varistor assembly and emission-limited diode (ML-41) to the 4CW10,000A grid. The ML-41 prevents the full power supply current from flowing in this circuit in case the DP-15's fail or their anode varistor assembly becomes open circuited. Regulation at various voltages is enabled by varying the two varistor assemblies in a prescribed manner by raise/lower motor-driven controls. The anode varistor, R5, can remain unchanged over a certain range of output voltage, perhaps ± 10% centered on a pre-selected value. The reference varistor, R1, is the primary voltage control for the system and has a minimum voltage increment of about 270 V.

The basic accel power supply consists of three 50-kV, 20-A, 0.5-sec transformer-rectifier modules connected in series. Either one, two, or all three of the 50 kV/20 A power supply modules may be turned on, depending on the desired output range. Because there is a voltage-varying element (induction voltage regulator) for only one of the modules, typical variable output ranges will be 0-50 kV, 50-100 kV, and 100-150 kV. Two high-voltage silicon-controlled, rectifier (SCR) assemblies T1 and T2, are being developed for our use by another group at LBL under the direction of J. V. Franck. One will act as a series switch between the accel power supply and the NB source. The other will be a momentary crowbar, whose action will be described in a later paragraph.

The switch-variable zener diode assembly, D5, regulates the voltage at the NB source gradient grid at typically 20 to 30 kV below the accel voltage. Gradient grid current may be either positive or negative and should approach zero in a fully optimized NB source. The return resistor, R8, will provide regulator current of about 1 A. To minimize power loss in R8 at higher accel voltages, it can be returned to the 1/3 or 2/3 tap point on the accel power supply rather than to ground. The spark gap, G3, protects the zener regulator assembly in the event of a spark from the gradient grid to ground.

The diode and spark gap combination, D1 and G1, constitute a crowbar system capable of being triggered over the broad output voltage range of 10 to 150 kV. This is only infrequently triggered when a malfunction of the shunt regulator system is detected. It then carries the full power supply output current until the ac primary power is interrupted.

The actions occurring during a normal pulse with interrupts are as follows. At the start, both SCR's are OFF. The variable varistor stacks are preset to the position appropriate for the desired output voltage. The primary ac power is applied by turning on electronic contactors. The power supply voltage builds up to, say, +150 kV, at which time R1 and V1 conduct. This causes V2 to conduct, finally producing positive grid drive to the DP-15's causing them to conduct about 22 A with $\sim$4 kV anode voltage. This is the "dummy load" operating mode, Mode 1, where the power supply output voltage is regulated and the anode varistor dissipates nearly the full output power.

The series SCR is then turned on, applying voltage to the source with a risetime determined by the stray capacity and current available to charge it to the full output voltage ($\leq$ 20 μsec). The NB source arc is turned on at an experimentally-determined optimum time during the accel voltage rise, presenting a resistive load to the accel supply. Proper varistor settings permit $\sim$20 A to transfer to the NB source while $\sim$2 A remains flowing in the shunt regulator circuit. This permits accel voltage regulation in the presence of power supply ripple ($\sim$4% P-P for our 12-pulse rectifier connection) and small ac line voltage variations. The DP-15 anode voltage has now increased to $\sim$60 kV while the grid voltage is $\sim$-400 V. This is the "regulating mode", Mode 2.

When a source spark occurs, the shunt SCR is turned on long enough (50-100 μsec) to commutate (turn off) the series SCR and permit it to recover its voltage-holding ability. The shunt SCR string is then turned off by a pulse-line type of commutator, described below. The power supply current, which will have increased some 10% is again conducted through the shunt regulator in Mode 1 operation. Regulator action causes the current to quickly fall to the desired 22 A value. The NB source spark is expected to clear in a few hundred μsec so that at about 1 msec after the spark occurs, the series SCR will again be triggered, restoring Mode 2 operation. The system is designed to permit 20 or more such "interrupts" during a 0.5 sec pulse.

The varistor, R7, and resistor, R9, could be installed to aid in extinguishing the NB source spark although it is likely that they will not be required. R7 would be rated at ∿1 kV, somewhat higher than the expected series voltage drop of T2 in the conducting state. R8 would conduct ∿1 mA when T2 is conducting.

The action of T2, the "momentary crowbar" is crucial for obtaining several significant benefits of this regulator configuration. Namely, except for a submicrosecond high current transient discharging stray capacitance, the power supply current increases only ≤ 10% during a NB source spark. Furthermore, since the time for transition to Mode 1 operation following a NB source spark is only ∿100 μsec, a period much shorter than that of the primary ac line frequency, the primary ac power components are essentially "unaware" that anything unusual is taking place in the load circuit.

T2 is composed of six 25 kV modules in series, each having 59 series 800 V, 30 A SCR's with a rated commutation time of about 25 μsec. Each module has a single trigger transformer with multiple secondary windings, one for each SCR. Two methods for delivering simultaneous trigger pulses to each module are now being examined: optical trigger links and cascaded pulse transformers. The series SCR switch, T1, has a construction similar to T2 but without the commutating pulse line, PL. PL is charged to the Mode 1 accel voltage through the diode, D3, which prevents PL from discharging through a source spark in the event that T2 is not promptly triggered. The pulse line is of sufficient size to successfully commutate T2 during 20 or more rapid, repetitive interrupts. If more than this number occur, an interrupt counter will trigger the crowbar, G1 and D1.

The commutating action of T2 occurs as follows. Firing T2 shorts PL sending a zero-voltage wave to the end of PL, which then returns as a negative voltage wave to T2. When it reaches T2 it tries to reverse the voltage and drive the T2 anode negative. The diodes D4 prevent this (except for a small negative voltage which aids in commutating T2) so that PL is still shorted. The zero-voltage wave again travels to the end of PL and returns as a positive voltage wave to T2. The electrical length of PL is sufficiently long to insure that T2 has commutated and recovered its voltage-holding ability by this time. The voltage again reverses, driving the T2 anode positive. The pulse line thus aids in charging stray capacitance and restoring the power supply output voltage to nearly full value. Since the energy loss from the pulse line during an interrupt cycle is small, the voltage promptly recovered can be ≳ 80% of the desired output. The 20% difference is

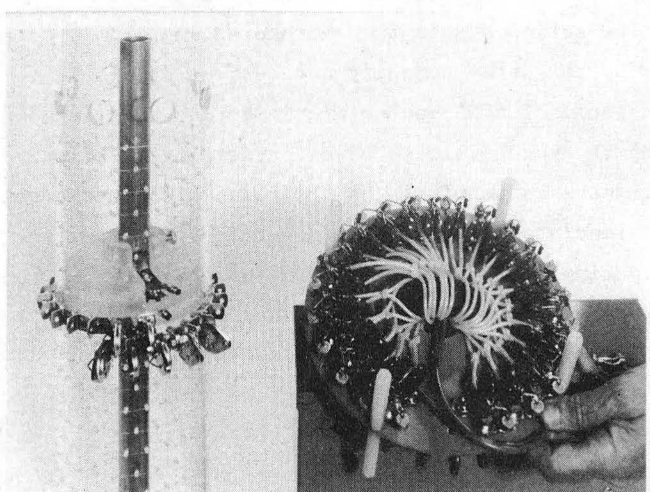

Figure 3. Gradient Grid Zener Regulator Assembly and Prototype Series SCR Module

quickly made up by the power supply, then T1 can again be triggered to restore the pulse output.

Figure 3 shows, on the right, a prototype SCR module which has successfully repetitively switched and commutated currents exceeding 100 A at a 21 kV level in air. The final assemblies will be housed in a silicone oil-filled container for improved cooling. The pulse line will be housed in separate SF_6-filled modules.

On the left, in Figure 3, is shown the variable 30 kV gradient grid regulator in an early stage of assembly. This will be housed in a silicone-oil container and will be varied by motor-driven raise/lower controls. The reference varistor assembly, R1 in Figure 2, is constructed in a similar fashion except that varistors are used and the assembly is shorter.

Figure 4 shows a drawing of the anode varistor assembly, R5 in Figure 2, now being fabricated. This will be cooled by flowing silicone oil.

The switching and shunt regulator system and its controls are being assembled on a cart for easy assembly and movement. This is shown in Figure 5 with some related components. The dual DP-15 tube mount is shown on the left. Two high voltage diode assemblies and a compensated resistive divider are also shown; these will be filled with silicone oil. The 4CW10000A amplifier, power supplies, and other controls will be located in the electronics racks on the right.

Initial testing of this system is scheduled to begin in late June of this year.

There is some preliminary evidence which indicates that it may not be necessary to provide regulation better than ± 3% or so to obtain acceptable beam divergence. If this is borne out in testing, G2 and R6 will be replaced by a varistor which clamps the DP-15 anode voltage to a

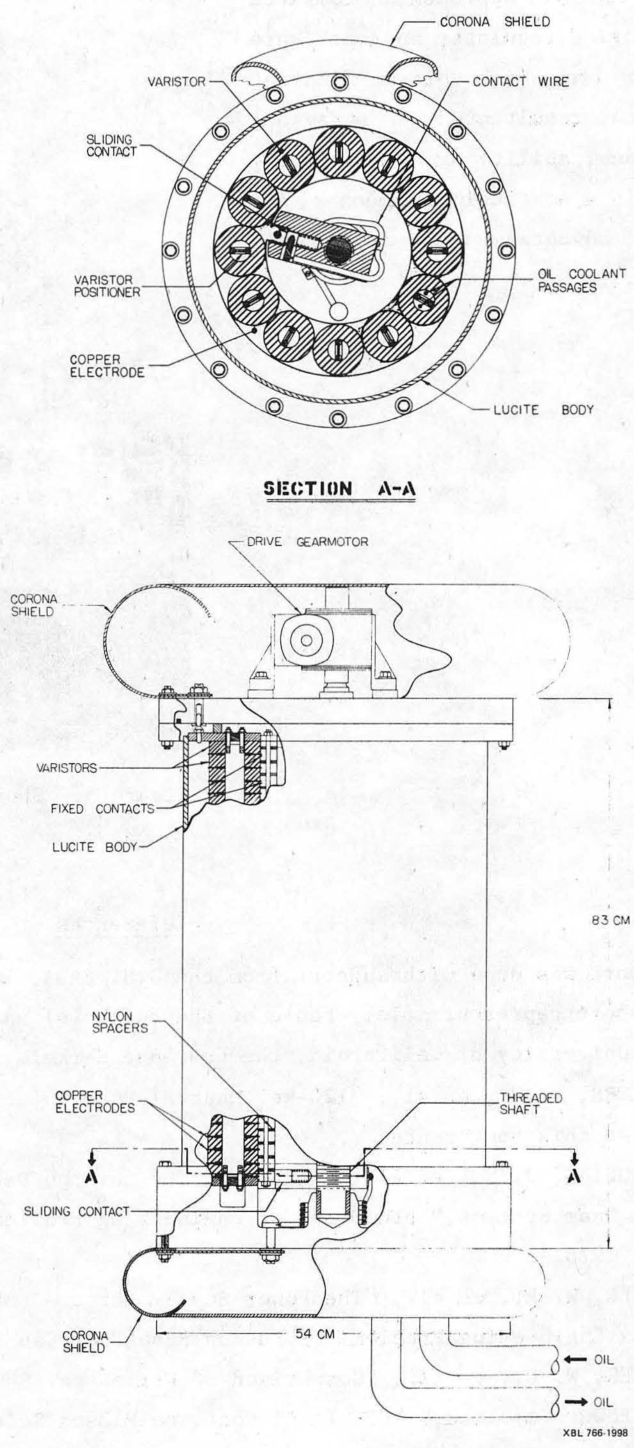

Figure 4. Anode Variable Varistor Assembly

safe value (e.g. 70-80 kV). These tubes are then necessary only for the "startup", Mode 1, and can be gated off during the output pulse.

Among the many advantages of a shunt regulator approach, as compared to a series regulator approach, are freedom from high voltage floating decks and resultant high stray capacitance, ability to use existing tubes in a non-stringent manner, and a cost advantage that can exceed 30% [4,5].

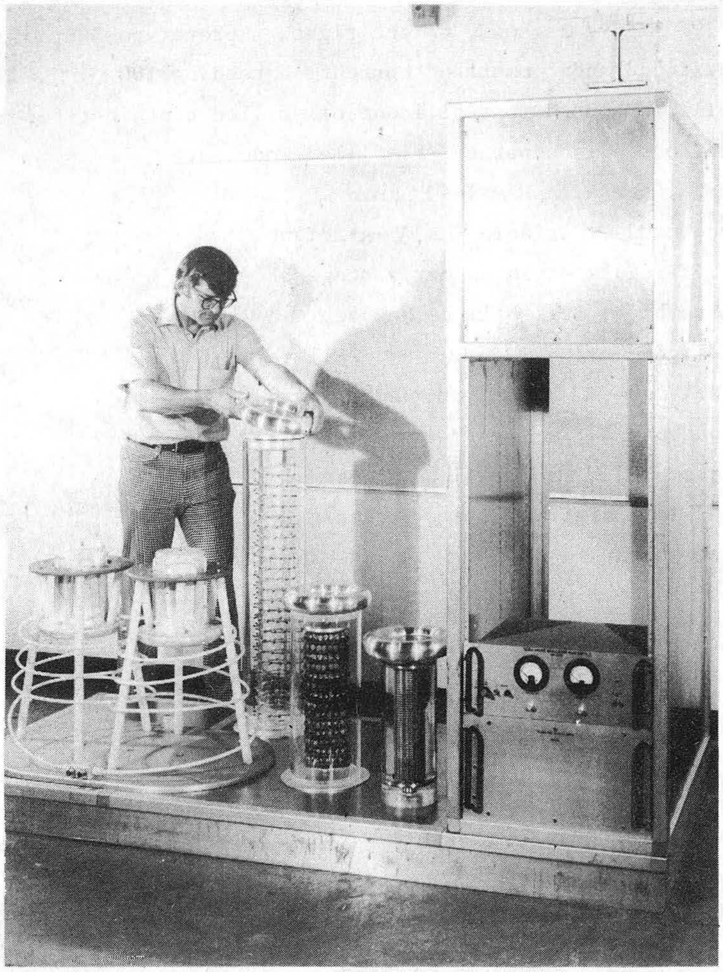

Figure 5. Shunt Regulator Cart and Related Components

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