Title
THE POWER SUPPLY FOR THE LBL 40 keV NEUTRAL BEAM SOURCE

Author
Baker, W.R.

Publication Date
1975-11-01

Presented at 6th Symposium on
Engineering Problems of Fusion Research,
San Diego, CA, November 18-21, 1975

LBL-4418
c.1

THE POWER SUPPLY FOR THE LBL 40 keV NEUTRAL BEAM SOURCE

W. R. Baker, M. L. Fitzgerald, and V. J. Honey

November 1975

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

LBL-4418

THE POWER SUPPLY FOR THE LBL 40 keV NEUTRAL BEAM SOURCE *

W. R. Baker, M. L. Fitzgerald, V. J. Honey
Lawrence Berkeley Laboratory
Berkeley, California 94720

Summary

A 20 keV, 50 Amp, 10 millisec pulse D^0 Neutral Beam Source[1] at the Lawrence Berkeley Laboratory that serves as the prototype for 12 similar sources now in operation on the 2XIIB Mirror Machine at the Lawrence Livermore Laboratory, has been recently upgraded to operate at 40 keV. The system of electronically regulated and controlled power supplies that drive the Source is described. Major features of the system include:

1. A closed loop feedback-type electronic accel voltage regulator and switch system that uses an Eimac 4CX35000C tetrode to provide the Source with up to 80 A, 0-40 kV $\pm 1\%$ with < 10 µsecs response time.

2. A 55 kV, 85 µf electrolytic capacitor energy source to supply the pulse power required by the accel voltage regulator.

3. A similar but smaller version of the above accel system to supply up to 20 A, 0-3 kV for the Source suppressor grid.

4. An electrolytic capacitor powered .035Ω Z_0, 4000 A, 0-150 V pulse line arc supply and a 12-pulse rectifier, 2200 A, 7-15 V low-capacitance to ground Source filament supply.

5. A logic system that provides timing and operating levels for these power supplies.

6. A monitoring system.

Accel Voltage Regulator

The present regulator system is a higher current version of the one designed for the LBL 10 Amp 40 keV conversion.[2] Both are currently operating systems and use the same 4CX35000C Eimac tetrode. An earlier model 20 kV, 20 Amp, 20 millisec regulator,[3] used two parallel 5771 triode tubes but otherwise was essentially the same system. A U.S. patent[4] describes such a system for regulating ion source accel potential in the Calutron development program for the Manhattan Project. In all cases the basic closed-loop feedback amplifier design[5] has been retained.

The regulator and most of its associated circuitry and equipment is housed in a 31" x 102" x 66" screened enclosure referred to as the "boxcar". See Figure 1.

Pulse power is obtained from an electrolytic capacitor bank that will be described in detail in a later section.

Figure 2 is a block diagram of the overall Neutral Beam power supply system and an associated chart of the logic functions.

The two most important roles of the regulator system are to maintain the Source accel voltage within $\pm 1\%$ of a set value, and to minimize damage to the Source by limiting the current when sparkdown occurs. To accomplish this the system must have fast voltage rise and current interrupt which means that the capacitance to ground of the Source and its associated power supplies and equipment must be held to a minimum. Because of this and other considerations such as complexity and cost, the feedback loop is stabilized against oscillation by frequency response limiting at the grid of the regulator tube. This has the advantage of allowing a simple high impedance 4PR250C tetrode driver that has its cathode and input amplifier at ground potential and its anode and series load resistor near regulator grid potential. The regulator tube grid is restricted to operation in the negative regime by a clamping diode. The negative excursion is also limited to the -2200 V of the bias supply by another diode between the driver tube anode and the regulator tube cathode. This allows the driver to act as a "tail biter" on accel voltage interrupt if the normal source load is not present to discharge the system capacitance of 2100 pf.

In order to operate the 4CX35000C in the negative grid regime and pass 80 Amps anode current requires somewhat higher than normal screen potential. Eimac has furnished curves to 3500 V. A value of 3000 V screen was indicated and three years of successful operation with these conditions has been the result.

The 4CX35000C was originally selected for the LBL Source accel voltage regulator service for several reasons among which are the following: It has an active anode copper volume (without the cooling fin structure) of 170 cm^3 and a 25 mil tungsten screen active volume of 3.45 cm^3. Analysis shows that the anode temperature rise from an 80 Amp, 10 millisec pulse under the above conditions is approximately 14°C and for the screen 17°C. Heat penetration of the anode and screen is reasonably uniform in this time. Since the permissible rise is many times this value (anode ΔT ok to > 200°C and the screen can go to 1100°C) the tube should be good for much longer pulses than 10 millisecs. The tube is a tetrode (screen grid type) and for pulse service such as this it is practical to set the screen to a level where positive grid drive is not necessary, which allows a simple, high impedance driver. The anode current is not very sensitive to anode voltage. Therefore, a capacitor bank can be used for the pulse power supply with very little grid voltage variation needed to compensate for the changing anode voltage as charge is removed from the capacitor during the pulse. The LBL 85 µf bank, for example, drops approximately 10 kV after a 10 millisec, 80 Amp pulse. The tube has been in production for many years and represents a proven design with a good market volume. Its low cost reflects this.

The same tube, essentially, is available in a water cooled version as the 4CW100,000D but is more expensive and, for short pulse service, could not equal the air cooled version as it would be limited to an anode temperature rise set by the boiling point of water. The LBL and LLL tubes have 1/4"

---

*Work performed under the auspices of the US ERDA.

copper tubing soldered to the periphery of the cooling fin structure so that they can be "water cooled" without losing the superior heat absorbing capacity of the anode. At one pulse per minute the heat (mostly from the filament) is easily removed with two or three gallons of water per minute. The tube is also rated for pulse modulator service to 40 kV. With high voltage "processing" to 55 kV it becomes the Y-499, and with still further processing to 75 kV it becomes the Y-546. The regulator system described here is inherently an excellent processing facility for its own tube.

A GL37248 ignitron series switch allows the regulator tube to "idle" continuously at a dc output level corresponding to the desired Source pulse voltage but at only 7 mA which represents the current to the monitoring and feedback dividers and the 4PR250C control tube. Then, when Source power is desired, the ignitron switch is closed and the regulator anode current jumps from 7 mA to the Source level which, for the current 40 kV system is approximately 70 Amps. Since the regulator tube bias must swing from a near cutoff value of -1800 V to nearly zero in < 10 μsecs, 90 mA is required to remove the charge from the 450 pf grid capacitance. This is much more than the control tube can supply. Therefore, at this point a 6 μf capacitor charged to 3 kV is switched through a diode to a 20 kΩ tap on the plate resistor which raises the current to 150 mA so that it can. This large shift in control tube current would also produce an unacceptable step in the regulated output voltage, so a compensating voltage to offset this is simultaneously injected into the feedback voltage divider at the hot deck end to maintain the same dc level as at low current. This avoids having to use a higher feedback loop gain and the consequent loss of voltage rise and interrupt time. There are plans to replace the ignitron switch with an SCR system. The philosophy here is to reduce to a minimum the time that the regulator tube must hold off the full anode voltage which, with an SCR switch would be the commutation time of a few microsecs. The tube should then be good for even higher voltages.

Power for the regulator "hot deck" is only a few watts and is obtained from the regulator filament supply. The filament voltage is transformed to run a 60 VA Sola voltage regulator that feeds a power supply that charges an electrolytic capacitor bank screen supply. A 15 VA Sola and transformer-rectifier supplies -3 kV for the regulator tube bias. It also charges the 6 μf capacitor for the control tube current level shift circuit. The screen capacitor bank consists of seven series 1000 μf, 450 V capacitors, each with Zener diode voltage limiters. Screen voltage can be varied by the number of capacitors used. The Sola regulator provides a reasonably constant current charging system for the capacitors and permits regulator filament voltage changes without affecting hot deck potentials. 7Ω of series R and an overcurrent triggered crowbar system protect the screen in case of sparkdown.

The regulated voltage level is set by a reference voltage applied to one input of a differential amplifier. The other input comes from a 280:1 compensated divider on the regulated voltage output. The amplifier output drives the 4PR250C.

The amplifier was one of the most difficult design problems of the regulator system. It uses two 6550 tubes, has a 200 V common mode range and a 250 V output swing. It has 10^6 Hz frequency response with small phase shift to allow the fast response time of < 10 μsecs wanted from the regulator system.

The 40 kV operation made the problem even more difficult since it requires twice as much time for the same available current to charge essentially the same system capacitance as at 20 kV. To get the fast voltage rise a "trick" was used - a series R with a shunt diode was added to the loop stabilizer capacitor so that it only weakly affected the risetime but then became fully effective for damping the downswing. The control tube has plenty of current for the interrupt and the capacitor is no problem here.

Parasitic oscillations in the regulator tube and circuit had to be damped by a number of measures. A 30Ω resistor was put in series with the grid. The resonant circuit formed by the screen bypass capacitor system and the screen capacitance was damped by series R. A 125 pf capacitor and a series R made of non-inductive permalloy tape was connected between the anode and cathode as close to the tube as voltage holding considerations would allow. A 50Ω, series 1200 pf snubber is between the anode and ground. Finally, the placement of the wiring was arranged to minimize coupling between the high current regulator output leads and the hot deck and amplifier.

If the source ion density is set for best beam at full voltage, the accel current goes through a double current phase during the voltage rise - presumably because of secondary electron backstreaming from ions striking downstream grids. Rather than make the accel system supply this, the ion density is reduced to half value for the few μsecs that it takes the voltage to rise. This is done by a special 60:1 current transformer with its primary in series with the accel supply and the Source and its secondary coupled to the arc voltage through varistors. Initial accel current then diverts the arc current and lowers the ion density until the transformer core saturates, at which time the accel voltage is up and the ion density rises to full level. For the LBL Source this time is approximately 20 μsecs. The varistors serve to decouple the arc from the transformer for normal arc voltage. They are resistive enough, however, to reset the core from arc voltage for the next operation.

Source sparkdown occurs in a few nanoseconds. It is much faster than in a vacuum device such as a tube because the Source has several microns of gas present that can ionize and neutralize the space charge faster. This leads to very steep transients that can cause lots of trouble, particularly at higher voltages. Understanding and solving this problem was essential above 30 kV. A copper sulfate solution in a small 6" long plastic tube with metal ends placed in series with the accel lead at the Source effectively blocks the transient. A bridging inductance of approximately 10^{-4} H wound on it as a coil form then removes the resistance in approximately a μsec. When a Source sparkdown occurs the energy in $1/2\ LI^2$ decays rapidly through a diode and a series 5Ω resistor between the regulator tube cathode and ground.

An unexpected difficulty was that Source sparks above approximately 30 kV induced breakdown in the regulator tube. Previous analysis of the anode surface temperature rise under the maximum transient 55 kV and 120 Amp conditions had given a value of only 18.5°C for 10 μsecs. At this time, because of the way the logic was arranged, it required 30 μsecs to fully interrupt the tube. Sparkdown started at about the same time as the interrupt did. Sometimes the spark beat the interrupt and other times it didn't. By speeding up the interrupt to 20 μsecs the problem disappeared. Now, instead of going through the logic, Source sparkdown information is made to interrupt the series tube directly in approximately 2 μsecs.

The reason for this unexpected breakdown problem is not clear but may be because of the microscopic structure of the anode metal. This is granular and the individual copper grains (of a few microns size) are not necessarily all thermally bonded to the main anode mass as the homogenous model used in the calculations assumed.

An ignitron crowbar system gives backup protection in case the electronic interrupt fails, as with a flasharc in the regulator tube. This consists of two series GL37248 tubes across the electrolytic capacitor bank that powers the regulator. It is "self-triggered" from a shunt resistor and spark gap set to fire at approximately double normal Source current.

Another protective feature is the overload crowbar firing circuit commonly referred to as the "Jackass Crowbar." This is a simple circuit near the crowbar tube that automatically triggers it if the accel current (over a threshold value) persists without accel voltage for more than 30 μsecs. It also operates if accel voltage is present on the output side of the series switch for more than 15 millisecs at full voltage.

Reducing the filament voltage from 10 V to 9 V lowers the 4CX35000C emission current from approximately 200 Amps to 100 Amps. This appears to be better for the regulator and should greatly extend filament life. The "emission limited tetrode" appears to combine the best features of the screen grid tube and the emission limited diode, at least for this case where the emission limit is set 20% above the normal operating current and is only used for the few μsecs during Source sparkdown and current interrupt. In a recent discussion of this, Mr. C. Kirka (Product Manager, Power Tubes) of Machlett Company was of the opinion that emission limiting of a thoriated tungsten filament was ok provided it was not carried too far.

High Voltage Electrolytic Capacitor Bank

Power for the accel voltage regulator is supplied by a 55 kV electrolytic capacitor system of three parallel basic modules. Each module contains 272 Mallory type CG5, 1500 μf rated, 450 V capacitors arranged in two parallel strings of 136 units in series. Figure 3 shows one of these modules. Overall dimensions are 2.5' wide, 20" deep and 5' high. Actual measured capacitance per module is approximately 29.5 μf, which is 1/3 more than the rated value. The actual energy stored is 44,000 Joules. The cost was $5000.00, which amounts to 11.3¢/Joule.

Each capacitor is voltage limited by two complimentary 200 V, 10 W Zener diodes that also hold the capacitors on a fiberglass board along with large area aluminum plates that serve both as heat sinks for the diodes and as series connections between capacitors. The diodes have 10/32 screw type bases that fit the 10/32 female posts on the capacitors. The diodes are connected by 1kΩ,2W resistors that serve to limit current for any operating condition that could produce reverse voltage on a capacitor.

There are 17 rows of 8 capacitors each. All negative potentials are on one side and positives on the other. There is a 3.5Ω polyethylene tube covered resistor coupling these in series so that they serve as a distributed resistance to limit the short circuit current of each string to <1000 A. The poly tubes also serve as corona shields over the Zener diodes. An earlier high voltage megajoule electrolytic bank without Zener diode voltage limiting is described in reference 6.

Suppressor Grid Power Supply

This is a small scale version of the accel supply arranged to give a negative output. An electrolytic capacitor bank of 80 μf at 6400 V is in series with the anode of a 4CX15000A tetrode and the line to the suppressor grid. The tube cathode is at ground potential and its grid is normally held at a tube current cutoff negative potential by a high impedance resistive connection to a bias supply. When accel voltage is applied to the Source the tube bias is also removed. This makes the tube conduct and apply negative voltage to the suppressor grid that is just enough to overcome the reference Zener diode potential selected. This then feeds a negative voltage back to the grid to regulate the supply output. Most of the parasitic suppressor features of the accel supply were also necessary here.

Arc and Filament Power Supplies

Arc power at essentially constant current is supplied by a .035Ω Z_0 pulse line (Figure 4) that is charged to an initial potential of 300 V which is about 5 times the required arc voltage. A series resistor absorbs the extra voltage and energy so that the line is effectively terminated for all arc conditions. Current is set by the voltage on the line capacitors which is regulated by a feedback type voltage regulator.

There are 200 electrolytic 450 V, 1000 μf capacitors mounted on an aluminum frame which also serves as the negative return for the system. Because of the Coulomb limit of the 7703 ignitron switch tubes, the line is actually made of two identical parallel lines, each with a separate ignitron series switch and crowbar. Each line has eight LC sections with a double C at the back end and a Gibbs network at the front. Each L is 43.6 μf and is made of 8 Arnold Engr. AA-111 cores with 1/4" air gaps and 6 turn bifilar #2 welding cable windings. The L/2 Gibbs network inductors have 4 cores each. The bifilar windings distribute current more evenly to the capacitors and make best use of the flexible cables and the choke core window area.

Twelve 30' pairs of #10 motor lead cables form a low inductance output line to the Source arc electrodes.

Each positive terminal is secured to an insulating washer in the frame by a 10/32 screw base 400 Amp surge rated diode that is shunted with a 1 kΩ, 10 W resistor. These diodes isolate the capacitors from each other so that if one shorts the others don't discharge into it (with explosive violence!). The diodes connect the capacitors on discharge and the shunt resistors allow them to charge from a common supply.

The Source filament supply uses a 3φ transformer with air insulated, low capacitance to ground separate

Δ and Y secondarys (QT & E Co. #1882), each with a full wave bridge rectifier (Figure 5). The outputs are paralleled through a center-tapped interphase reactor to give a 720 Hz, low ripple supply. Further ripple reduction is effected by a 1.8 F electrolytic capacitor system across the output.

The supply is variable from 7-15 V at 2200 A by an inductrol in the primary.

The reactance of the system sets the Source filament inrush current at 2.8X the operating level which brings it up to this value in 1.2 secs. A fast filament rise time reduces the heat load on the Source Grids. There has been no problem with magnetic forces affecting the filament system at this level.

The filament supply was originally (and very well) filtered by an inductive rather than a capacitive system. This led to arc spotting problems and had to be abandoned.

Logic System

The logic unit provides two important functions, namely the timing of gates and triggers, at the proper level necessary for the operation of the filament, arc and accel power supplies, and an overcurrent protection system to shut down the accel and suppressor power supplies due to a source sparkdown.

The timing section consists of several timing circuits in tandem producing the proper delays and gates. These are adjustable from the front panel of the logic unit. Outputs of appropriate timers drive either SCR pulse or emitter follower drivers, depending on the function. See the block diagram for details.

The overcurrent protection system called the interrupt generator consists of current and voltage comparators, timers and gate circuits arranged to respond when the accel power supply current exceeds 50A if the accel power supply output voltage is less than 2 kV. If this condition exists, the system produces a gate called "interrupt" which cuts off the regulator current for a predetermined time, allowing the sparking condition in the source to clear. Another timing command the interrupt generator produces is "keep-alive extinguish," which occurs at the end of the accel duration. This allows the accel power supply series switch ignitron to extinguish, thus ending the extraction cycle. One operational mode of the interrupt generator is to crowbar the arc power supply earlier than normal if an "interrupt" is generated. This mode is used when the accel power supply is 15 kV or higher. Operation is controlled by a switch on the front panel of the logic unit.

Monitoring System

Monitoring of the accel power supply capacitor bank and regulated output voltages is accomplished by two precision 100 meg-Ω silicone-oil filled voltage dividers, each feeding voltage-follower circuits. The output of the capacitor bank voltage monitor drives a 1 mA, 0-60 kV F. S. Weston type 1301 meter. An Analogic 3-1/2 digit digital panel meter is driven by the output of the regulated output voltage monitor.

The arc power supply d.c. voltage is monitored by a 30 meg-Ω voltage divider capable of withstanding the full accel voltage pulse. The output of this voltage divider drives a voltage-follower and digital panel meter circuit similar to the accel system.

The arc power supply output pulse voltage, current and plasma probe signals are monitored by a three channel linear photo-isolated telemetry unit capable of withstanding 40 kV DC from input to output.

The accel and suppressor power supply output voltages are monitored by 2000:1 and 100:1 voltage dividers, respectively.

Output currents of both the accel and suppressor power supplies are monitored by separate 0.1 V/A current transformers. The logic unit provides reset gates to the transformer cores after each source cycle.

References

1. W. R. Baker et al., Plasma Physics and Controlled Nuclear Fusion Research 1974, IAEA, Vol I, p 329 (1975).

2. K. H. Berkner et al., "Beam Optics of a Staged 40-kV, '10-Ampere' Size Neutral Beam Source." Abstract submitted to APS Meeting, St. Petersburg, Florida, November 10-14, 1975.

3. K. W. Ehlers et al., J. Vac. Sci. Technol., Vol. 10, No. 6 (1973).

4. W. R. Baker et al., U.S. Patent No. 2,745,018, filed September 26, 1947.

5. H. W. Bode, Bel Tel. Labs., Monograph 1239.

6. D. B. Hopkins et al., IRE Transactions on Nuclear Science, N5-9, April 1962.

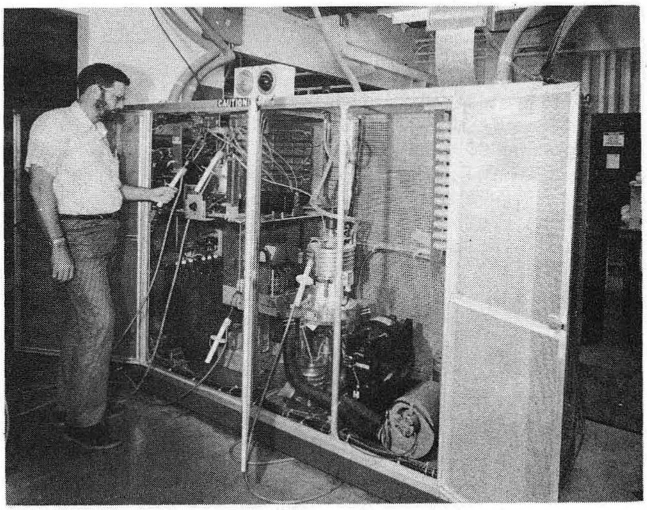

Figure 1. Accel Voltage Regulator

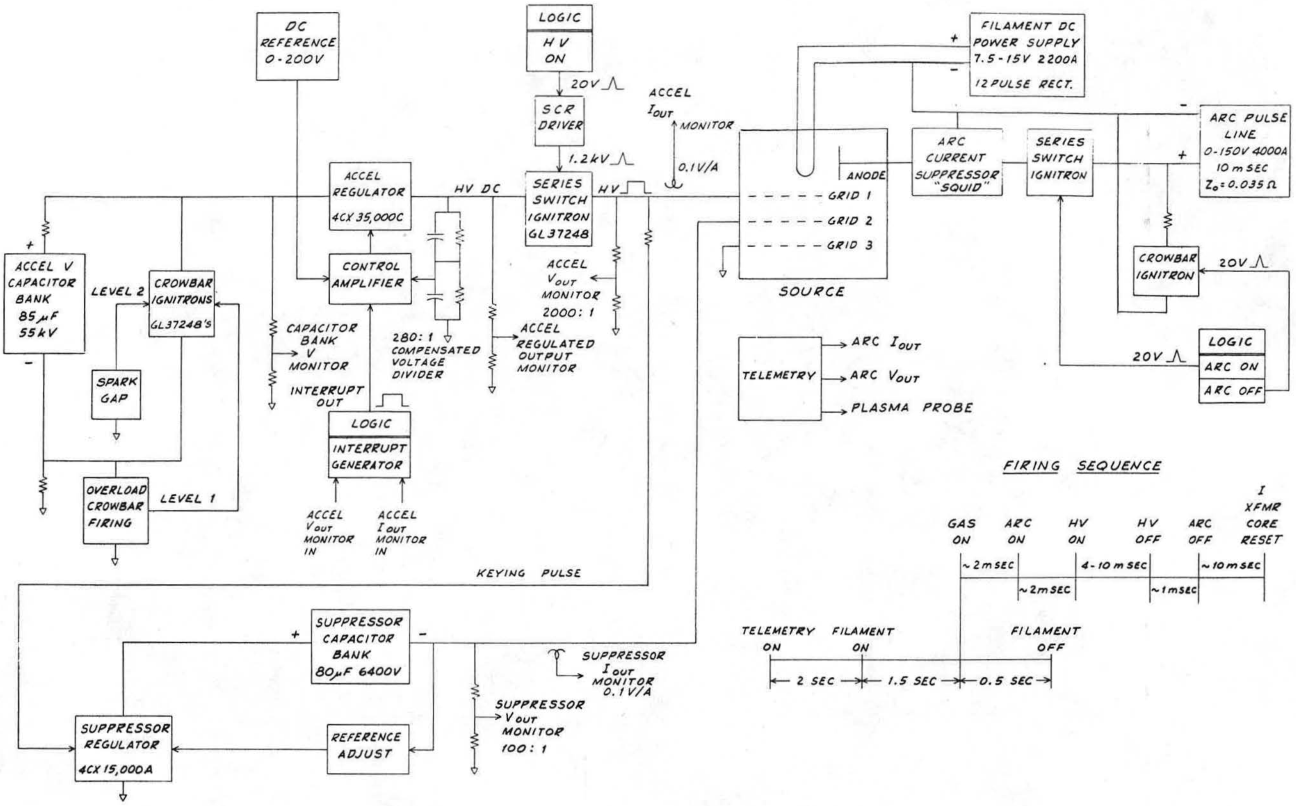

Figure 2. 40 kV, 50 A Neutral Beam Power Supply System

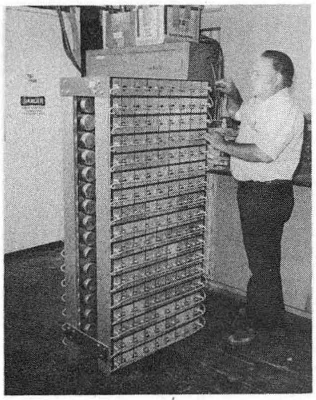

Figure 3. High Voltage Electrolytic Capacitor Module

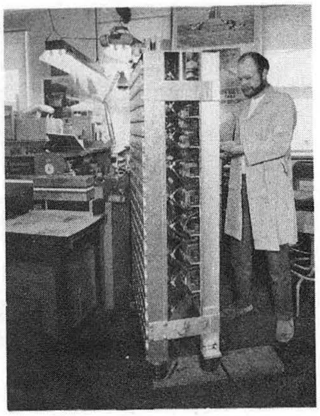

Figure 4. ARC Pulse Line

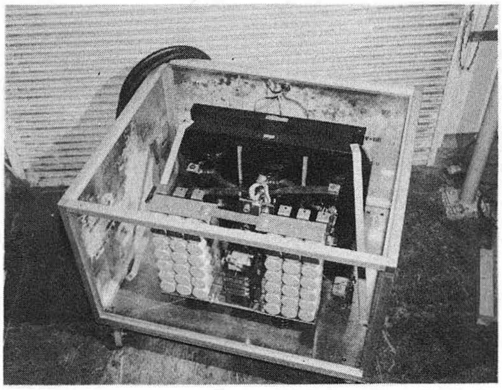

Figure 5. Source Filament Supply