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Lawrence Livermore Laboratory

BASEBALL II-T MULTIPLE BEAM PROJECT 50 kV, 80 AMP, POWER SUPPLY
SYSTEM FOR SUSTAINING NEUTRAL BEAM SOURCES

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INTRODUCTION

This document describes a high power, high voltage power supply system required to operate sustaining neutral beam (NB) sources as would be used in the Baseball II-T Multiple Beam Project. Two such systems would be needed.

The rated outputs, as delivered to the (NB) source, by the several sub-systems power supplies making up the complete system are as follows:

	<u>VOLT</u>	<u>CURRENT</u>	<u>POWER</u>
Accel Supply	50 kV	80 A	4 MW
Gradient Grid P.S.	30 kV	5 A	150 kW
Suppressor P.S.	5 kV	16 A	80 kW
Arc Cur. P.S.	60 V	4000 A	240 kW
Filament P.S.	12 V	9000 A	108 kW

This system would operate from 13.8 kV and 480 V, 3 phase, utility power line service. Operation would be at a maximum duty factor of 10% with adjustable "On-Time" from 0.5 seconds to 5 minutes. (i.e. 30 seconds on - 300 seconds off; 3 minutes on - 30 minutes off.)

Appended are site plan installation drawings. These drawings show the locations of all utilities, equipment, and facilities required for this system installation.

The site plan location areas selected are actual, available spaces in and near the RRII-T experimental laboratory building at ILL in Livermore.

1.0 POWER CONVERSION SYSTEM FOR THE BBII-T MULTI BEAM NEUTRAL BEAM

SUSTAINING SOURCES

1.1 Introduction

1.1.1 Neutral Beam Source Description

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This describes the requirements of the plasma sustaining LBL/LLL neutral beam source. The following nomenclature for neutral beam source elements is used:

filament

arc anode

entrance grid (formerly grid #1 or extractor grid)

gradient grid (formerly grid #2)

suppressor grid (formerly grid #4 or decel grid)

exit grid (formerly ground grid at neutralizer)

Associated with these elements are five power supplies, termed the filament, arc, gradient grid, suppressor, and accel supplies. The relationship between the source elements and the supplies is diagrammed in Figure 1.1.

High energy neutral deuterium atoms are produced by extracting positively charged deuterium ions from a plasma, accelerating them to high energy, and then neutralizing them by adding an electron. Gas is admitted through a pulsed valve into the plasma region, called the arc chamber, as shown in Figure 1.1.

A pulsed hot filament supplies electrons for a diffuse arc discharge which produces the plasma. The entrance grid, which floats electrically at the plasma potential, forms the plasma boundary and provides defined openings for ion extraction and beam forming. The gradient grid is at an intermediate potential,

FIGURE 1.1 NEUTRAL BEAM SYSTEM

20 kV below the accel voltage, and provides the fields for ion extraction and focussing. Field shaping and voltage holding can be achieved more easily with a short, lower voltage gap, rather than one large gap with full voltage across it. The suppressor grid operates at a low negative voltage with respect to the grounded exit grid, to repel electrons from the downstream neutralizer and keep them from getting into the high voltage region and being accelerated to the gradient grid and arc chamber. The neutralizer is a long duct filled with the gas escaping from the arc chamber. Here charge exchange between the neutral gas and the positive ions, produces the neutral deuterium beam.

1.1.2 Design Approach

Separate power supply sub-systems are being proposed for each of the two neutral beam (NB) sources in order to ensure operational flexibility and ease of construction and maintenance. Each of these power supply subsystems will independently provide appropriate filament, arc, accel, gradient grid, and suppressor grid power to its associated NB source. Each will perform the electrical functions of primary line power conditioning, transformation and rectification, regulation, overload protection, monitoring, and control necessary for conditioning and operating a NB sustaining source.

The design will emphasize ease of maintenance while holding required floor space to a minimum. The following sections summarize the requirements of each of the 2 NB sustaining source power supply sub-systems. Figure 1.2 is a simplified schematic circuit diagram of the power supply system.

1.2 Accel Power Supply

1.2.1 Accel Power Supply Requirements (Figure 1.2.1)

The accel power supply is connected to the plasma arc anode; its specifications are given in Table 1.2.

TABLE 1.2 - ACCEL POWER SUPPLY SPECIFICATIONS

<u>Parameter</u>	<u>Unit</u>	<u>Source Reqmt</u>	<u>Recomm. P.S. Spec.</u>
Voltage, nominal	kV	10-50	variable, 50
Voltage regulation	%	+/- 1	+/- 1 1
Current, max.	A	80	80
Power, max.	MW	4.0	4.0
Pulse Width, operating	min	5	variable, 0.5 sec to 5 min
Repetition Period, minimum	min	5	5
Current Risettime ² , max (10-90%)	microsec	20	20
Current Falltime ³ , max	microsec	20	20
Duty Factor	%	10	10

1
Includes 75 A max accel, 5 A max gradient grid.

2
At max output current.

3
At max output current, or when source sparks.

The minimum interrupt cycle time, before reapplication of accel voltage, will be about 2 msec. If continuous interrupts occur, only about 20 will be allowed before the power supply for that source is shut down.

These power supplies will be designed to permit independent interruption of current to the source within 2 microsec, in the event of a source spark, while not disturbing the normal pulsing of any adjacent source.

A one-line diagram of this supply is shown in Figure 1.2.1 and is described in the remainder of this section.

FIGURE 1.2.1 BBII-MULT. BEAM ACCEL POWER SUPPLY

1.2.2 Primary Voltage Control

A 40% buck-boost variable voltage transformer will accomplish two functions. First, it will allow reduction of the output voltage of the supply for conditioning of the NB sources. Secondly, it will accomodate variations in incoming line voltage over times consistent with its mechanical operation.

1.2.3 Rectifier Transformer and Rectification

Step up from 13.8 kV to 70 kV dc will be accomplished by a delta primary/dual delta-ye secondary transformer. Each secondary will connect to a conventional three phase bridge rectifier made up of six stacks of discrete silicon diodes. The two bridge rectifiers will be connected in series aiding to deliver the needed dc output voltage with a low 2% rms, 12 phase ripple.

Each stack will include overvoltage protection and voltage dividing networks and will be in an oil bath for cooling and for adequate voltage holding capability.

1.2.5 Crowbar

A crowbar is necessary to protect the switch tube and source during a switch tube breakdown. A string of three size A ignitrons, each having molybdenum anodes to increase their voltage capability, will be utilized for this purpose.

A high speed vacuum contactor will be used for input power interruptions.

1.2.6 Risetime Compensation

The NB sources require a rapid current and voltage rise in order to prevent voltage breakdown at turn-on. Because

the supply impedance is too large to provide the needed risetime, an additional energy source is required. This is in the form of a compensating R-C network with a time constant matching that of the main supply. In this specific case 40 kJ (20 microfarads at 75 kV rating, 70 kV operating) of storage with a time constant of 6-8 ms is necessary.

This network will also absorb the stored energy in the supply inductance upon opening of the series switch (section 1.2.9) in the event of a NB source breakdown.

1.2.7 Series Regulator

A series regulator is required both to accommodate line voltage changes during time intervals shorter than can be smoothed by the Primary Voltage Control variable transformer and to act as an active filter to remove the ripple output of the 12 phase rectifier. An Eimac X-2170 tetrode rated at 60 kV, 650 kW, and nominally operating at 80 A, 5 kV, 400 kW, will be used for this purpose.

1.2.8 Lag Compensation

To reduce the high frequency demands placed upon the series regulator, a shunt capacitance of 1 to 2 microfarad will be used. This will yield a load crossover time constant of about 1 ms, but will not increase the energy dissipated in the NB source in the event of an arc because of the isolating capabilities of the series switch.

1.2.9 Series Switch

Isolation of the NB source from energy stored in the power

supply will be accomplished by a series switch consisting of the EIMAC X-2170 regulator tube, also functioning as a switch tube, in series with a second EIMAC X-2170 tetrode functioning only as a switch tube. This second X-2170 will operate at a nominal on-voltage drop of 3 kV, resulting in a dissipation of 240 kW at 80 amps.

1.2.10 Other Accel Power Supply Features

The power supply design will minimize the total capacitance measured from the accel power supply terminal at the source, and from the gradient grid terminal, to ground.

The power supply design will incorporate features to minimize the transient energy delivered to a source spark.

Transient suppressors, snubbers, protective spark gaps, and other techniques will be employed to limit transient and steady state voltages to a level less than that capable of causing damage to any component or sub-system.

1.2.11 Modulator Assembly

Figure 1.2.2 shows the hard tube modulator assembly. Currently available tube types are used in this design. Sulfur hexafluoride or dry solid dielectric insulated filament isolation transformers are used to avoid the problem of having oil filled tanks indoors.

1.3 Gradient Grid Power Supply

1.3.1 Gradient Grid Power Supply Requirements (Figure 1.3)

The gradient grid power supply specifications are given in Table 1.3.

FIGURE 1.2.2 BBII-T MULTIBEAM HARD TUBE MODULATOR ASSEMBLY

TABLE 1.3 - GRADIENT GRID POWER SUPPLY SPECIFICATIONS

<u>Parameter</u>	<u>Unit</u>	<u>Source Reqmt</u>	<u>Recomm. P.S. Spec.</u>
Voltage, nominal	kV	5 to 30	5 to 30
Voltage selection		continuously variable ¹	
Voltage regulation	%	+/-1	+/-1
Current, max	A	+/-5	+/-5
Duty Factor	%	10	10

¹

Regulated with respect to accel voltage

When conditioning sources over full accel voltage range from 10 to 50 kV, the gradient grid voltage must be varied so as to maintain a constant ratio of accel to gradient grid voltage. Because of the need for coordination between the accel and gradient grid power supply outputs and because of the low gradient grid power level, the power for the gradient grid will be taken from the accel power supply output.

1.3.2 Gradient Grid Regulator

The gradient grid will be supplied from the 50 kV source anode line through a water cooled, IT&T F-1074, high vacuum, thermionic diode, dropping the voltage difference between the anode and the gradient grid. This diode, rated at 225 kW anode dissipation, and operating emission-limited, acts as the plate load resistor of an EIMAC 4CW 250,000 A tetrode gradient grid voltage regulator.

Under typical conditions, with the anode at 50 kV, the gradient grid at 30 kV and drawing very little current, approximately 4 A will be passing through the diode and tetrode to ground. The plate dissipations under these conditions would be 80 kW in the

**FIGURE 1.3 ARC & FILAMENT SUPPLIES AND GRADIENT GRID REGULATOR
FOR SUSTAINING NEUTRAL BEAM SOURCE**

F-1074 and 120 kW in the 4CW 250,000 A.

When the gradient grid draws up to 3 A, the dissipation in the F-1074 will be unchanged but the current through the tetrode will drop to 1 A and its dissipation will drop to 30 kW. Under the worst case when the gradient grid is sinking up to 3 A from the source, the dissipation in the F-1074 still remains unchanged but the current through the tetrode goes up to 7 A resulting in a plate dissipation of 210 kW. High current loading by the gradient grid is abnormal and such conditions should last only for very short time intervals.

1.4 Suppressor Grid Power Supply

1.4.1 Suppressor Grid Power Supply Requirements (Figure 1.3)

The suppressor grid power supply specifications are given in Table 1.4.

TABLE 1.4 - SUPPRESSOR GRID POWER SUPPLY SPECIFICATIONS

<u>Parameter</u>	<u>Unit</u>	<u>Source Reqmt</u>	<u>Recomm. P.S. Spec.</u>
Voltage, nominal	kV	-2.3	-1 to -5
Voltage selection	steps	100 v	100 v
Voltage regulation	%	+/-2	+/-2
Current, max. cw	A	16	16
Current max. 50 microsec pulse	A	29	29
Duty Factor	%	10	10

1.4.2 Suppressor Grid Power Supply Description

The suppressor grid power supply supplies -1 to -5 kV to the NB source suppressor grid at a maximum current level of 16 A. This grid reflects electrons produced in the exit grid, neutralizer, and other downstream regions, preventing them from returning to the source.

The supply is vacuum tube regulated to $\pm 2\%$. A switched zener-diode reference string provides 100 V incremental adjustment of the output voltage. Experience has shown that it may be desirable to slave the operation of this supply to the accel voltage. A variable threshold circuit can monitor the accel voltage and cause the suppressor supply to be turned on at the optimum time (to be determined experimentally). Risetime of voltage at the suppressor grid will be a few microsec. At the end of a normal pulse or during an accel current interrupt cycle, the suppressor supply is interrupted simultaneously with the accel supply.

1.5 Filament Power Supply

1.5.1 Filament Power Supply Requirements (Figure 1.3)

The source filament power supply specifications are given in Table 1.5.

TABLE 1.5 - FILAMENT POWER SUPPLY SPECIFICATIONS

<u>Parameter</u>	<u>Unit</u>	<u>Source Reqmt</u>	<u>Recomm. P.S. Spec.</u>
Voltage, adj. range	V	7.7 to 11 ¹	10 to 14
Voltage selection	-	continuous	continuous
Voltage ripple, max	%pk-pk	1	1
Voltage ripple filter	-	capacitive	capacitive
Voltage regulation	%	+/-3	+/-3
Current, max	A	9000	9000
Risetime to full emission, max ²	sec	1.5	1.5
Inrush/Operate Current Ratio	-	2.8	2.5 to 3.0
Pulse Width, max	min	5	10
Repetition Period, minimum	min	5	5
Duty Factor	%	10	10

¹
Plus Lead Drop

²
At maximum current output.

The filament power supply (see Figure 1.3) heats the filaments in the NB source to provide thermionic emission for the arc plasma system. The power supply voltage contains an allowance for IR drops in the filament leads.

For proper source operation, for reasons involving the magnetic fields of the filament wires, it has been found necessary to maintain the output voltage ripple to 1% p-p. Moreover, a capacitive ripple filter is required at the the output terminals, rather than an inductive filter. This is because the latter greatly increases the likelihood of "spotting," the condition where arc current channels into

a single filament and destroys it. An output filter capacitance of a few farads is required.

The power supply impedance is designed to permit an inrush current that is about 2.8 times the cw operating level. Higher values would result in higher magnetic forces on the filaments which might cause damage.

Proper source operation is only moderately dependent on the absolute filament voltage. Therefore, normal short-term ac line fluctuations are tolerable. Long-term variations must be less than $\pm 3\%$.

1.5.2 Filament Power Supply Description

The power supply configuration is that of a delta primary, midpoint connected fork secondary, with half-wave rectification. For low voltage circuits, this configuration has the advantages of providing 6-pulse operation, i.e., 360 Hz ripple frequency, while requiring only one diode to conduct at any time, thereby minimizing diode losses. It has good regulation and relatively low ripple, and has complete balance of dc ampere-turns in the core.

1.5.3 Filament Power Supply Assembly

Figure 1.4 shows the tank containing the arc and filament isolation-rectifier transformers and rectifiers. A fiberglass tank is used so that high current, high voltage, bushings are not required. Sulfur hexafluoride is used for insulation to avoid the problem of having oil filled tanks indoors. Water cooled windings are used to reduce the size and weight of the transformers.

FIGURE 1.4 ARC AND FILAMENT POWER SUPPLIES HOUSING

1.5.4 Filament Connections

Near the NB source, the filament power supply leads are "fanned out" or subdivided into about a dozen short twisted cable pairs. This permits a distributed, symmetrical connection of this high current feed system to the source in such a manner as to minimize inductive loops which would generate undesirable stray magnetic fields. It also prevents gross transverse current flow in the source structure and arc plasma which could degrade performance.

In past systems, maximum performance has been obtained when the common impedance coupling between the arc and filament power supplies was minimized. For this reason, the negative leads of these supplies, although schematically connected, are separately run the relatively long distance from the power supplies to the source and are connected to the source in a distributed array. Additionally, separate and independent isolation/rectifier transformers are used for the two power supplies. For cost and space economy, these can share a common tank housing.

1.5.5 Magnetic Cores for Capacitance Isolation

The filament power supply leads thread a magnetic core assembly near the NB source, as do the arc power supply leads. The purpose of the cores is to absorb the energy stored in the stray capacitance of the two power supplies and their leads when a source spark occurs.

Fifteen to twenty .25 m (10 inch) O.D., 12.7 mm (1/2 inch) thick, 0.05 mm (2-mil) Silectron tapewound cores will be

used. A spark inside the source can develop in nanosecond time scales, causing a collapse of accel voltage at the source. Under this condition the cores transiently couple an effective time-varying resistance of a few hundred ohms into the accel power supply feed line. Since a typical spark impedance is very low by comparison, this resistance dissipates the energy in a stray capacitance of, say, 2 nF in about 200 nsec, preventing this energy from dissipating in the source. The cores are selected to provide this amount of one-turn volt-seconds. They are only stressed to about 4 V per lamination, i.e., 2 V per inter-lamination edge gap, an acceptable value recommended by the manufacturer.

1.6 Arc Power Supply

1.6.1 Arc Power Supply Requirements (Figure 1.3)

The arc power supply specifications are given in Table 1.6

TABLE 1.6 - ARC POWER SUPPLY SPECIFICATIONS

<u>Parameter</u>	<u>Unit</u>	<u>Source Reqmt</u>	<u>Recomm. P.S. Spec.</u>
Voltage, Open Circuit, min	V	-	100
Voltage Operating, typ.	V	40 to 60	80 max
Current, max	A	4000	4000
Current Regulation	%	+/-1	+/-1
Current Selection, continuous	A	500 to 4000	500 to 4000
Pulse Width, max	min	5	10
Repetition Period, minimum	min.	5	5
Duty Factor	%	10	10

Allowance is made in the power supply voltage for IR drop in the arc leads.

1.6.2 Arc Power Supply Description

The arc power supply configuration is that of a delta primary, double-wye secondary with an interphase transformer, and half-wave rectifiers. Like the filament power supply described in the last section, it has the advantages of low ripple, low diode losses, and good regulation. With a saturable reactor as the power controlling element, it has the additional advantage of always providing instantaneous current limiting, even when transiently loaded.

Saturable reactor (SR) control of the output is achieved by placing the three SR ac winding pairs in series with the rectifier transformer's delta primary windings, as shown. Each pair of SR dc windings are connected in series and phased to get a net cancellation of fundamental ac voltages.

All the SR dc windings are connected in series and fed from a variable dc bias power supply through an inductor. Analysis and experiment have shown that with an inductor large enough to force a nearly constant current flow (low ripple) in the dc bias circuit through the SR secondary windings, current-limited flat top current flows in the SR ac windings. This forces current-limited flat top current in the rectifier transformer secondary windings, giving limited constant amplitude dc current. Moreover, the amplitude of this dc current is directly proportional to the dc bias current; i.e., a constant current characteristic is achieved that is easily varied by controlling the dc bias current.

The practical power gain of the SR circuit is expected to be 20 to 50. This requires a dc bias power supply with a pulsed rating of 6.4 to 16 kW.

1.6.3 Arc Suppression

When the accel voltage is transiently increasing from zero, when first coming on or after an interrupt, divergent defocussed beam operation should be minimized. A divergent beam, caused by an overdense plasma, strikes the grids and tends to cause sparking if it persists too long. If the plasma density is transiently reduced to approximately match the reduced accel voltage, non-sparking operation can be achieved. This is conveniently accomplished by triggering an SCR, capacitively coupled to the arc anode, which briefly reduces the arc current.

It may be found that it is desirable to reduce the arc current to nearly zero during each accel current interrupt. To accomplish this, a silicon-controlled rectifier (SCR), rated for the full arc current, is connected as a crowbar shunting the arc supply output. When an accel current interrupt occurs, the crowbar SCR is triggered. A small saturable inductor in series with its anode allows an acceptable rate of rise of current in the SCR for a few microsec, then saturates and permits a much higher current to flow.

At the end of the interrupt period, the crowbar SCR is commutated (turned off) by temporarily diverting current from it with a separate capacitively coupled SCR pulser. As the crowbar SCR recovers its voltage holding ability and the commu-

tating current decays, current is again transferred to the source.

During the entire interrupt sequence just described, the saturable reactor (SR) bias current and the power supply output current remain essentially constant. The same is true of a full on time pulse which may include many interrupts. Only at the end of the pulse or as a result of some abnormal condition (e.g., filament hot-spots, improper source filament current, or gas density) is it necessary to reduce the SR dc bias current to zero.

1.6.4 Arc Connections

As mentioned above (section 1.5.4), the arc power supply leads are run separately from the filament power supply leads, to minimize common impedance coupling, and thread the magnetic core assembly near the source. The connections to the source must be made in a distributed manner, as described above, to minimize inductive loops and their stray magnetic fields. Moreover, it is necessary to incorporate resistive decoupling of the distributed lead connections at the arc chamber. With resistance distributed in, say, 12 pairs of #6 AWG leads to both arc anode and cathode terminals, a 4000 A current produces voltage drop in the leads of about 15 V, a reasonable value. It is imperative that the leads be run closely paired the entire length from the power supply to the source. This will result in a lead inductance low enough to permit current rise and fall times of 10 to 20 microsec.

1.7 System Operational Sequences

The time sequence of events of the power supply system during normal pulsing and accel current interrupts is described in detail in the above power supply discussions. It is summarized in this section and its relationship to BBII-T timing described.

1.7.1 Normal Operation

Table 1.7 shows the approximate time sequence for a normal BBII-T pulse, assuming all sources are fully conditioned and no accel interrupts occur. As discussed in previous sections, the optimum sequence, on a microsec time scale, of the relative timing of the accel, arc, and suppressor supplies will be determined experimentally.

TABLE 1.7 - APPROXIMATE SEQUENCE FOR A BBII-T PULSE

<u>Time (Sec.)</u>	<u>Event</u>
0	Receive BBII-T trigger signal Turn filament power supplies on
2.2	Check and adjust filament voltage and current
2.28	Open gas valve
2.3	Turn on arc power supplies
2.32	Apply accel and suppressor voltage
32.32	Shut down supplies

1.7.2 Conditioning Modes

Present plans call for new or rebuilt NB sources to be conditioned on-line.

While the accel voltage, current, and pulse width is being increased during conditioning, the proper ratio of accel voltage to gradient grid voltage will be maintained. This will optimize extracted beam optics, minimize ion bombardment of grids, maximize their life, and hasten the conditioning process.

The conditioning process lends itself to automatic computer control. The rate of accel interrupts may simply be monitored and the accel voltage adjusted accordingly, up or down, to maintain this rate at an experimentally determined optimum value. Unusual and improper source and/or power supply conditions will be detected and cause a full shutdown and alarm.

1.7.3 Failure Mode

The most prevalent failure mode is expected to be sparking within the source. Series switch tube turn off permits most of these to be treated as simple interrupts, allowing accel voltage to be re-applied within 2 msec. Normal overload circuitry will protect the power supplies themselves, shutting down the system when an improper condition of longer duration is detected. The same will occur if an excessive rate of interrupts exists, as previously discussed.

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3	MAIN BAY BLDG. 435			
UNIVERSITY OF CALIFORNIA				
LAWRENCE RADIATION LABORATORY				
ELECTRONICS ENGINEERING DEPARTMENT				
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ORIGINATOR	A. WAUGH	DATE	9-8-76	
CHECKED		DATE		
APPROVED		DATE		
SHEET				OF

EXISTING 13.8KV. SERVICE

EXISTING TRANSFORMER PAD

REMOTE INDOOR SPACE

BLDG #442

COOLING TOWER

ADG #448

EXISTING PLATFORM

MAGNET TANK

NEW ELECT. EQT. PLATFORM

NEW ELECT. EQT. PLATFORM

BLDG #435

NEW SOURCE TANKS

BBII EXP. AREA

BLDG #436

NEW 500' x 100' RUN OF 13KV. 12MVA. SERVICE
UNDERGROUND CONDUIT TO OBTAIN
INDEPENDENT 13.8KV. 12MVA. SERVICE
FROM A DEDICATED CIRCUIT BREAKER
AT PLANT SUBSTATION.

BLDG #431

BLDG #432

BLDG #434

BII-T, MULTIBEAM
SUSTAINING ION
SOURCE SYSTEM,
SITE PLAN.

2-25-76 A. WAUGH

LEGEND

- POWER POLE, LIGHT POLE
- SEWER MANHOLE
- ELECTRICAL MANHOLE
- TELEPHONE MANHOLE
- PIPE HYDRANT
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