SATURABLE REACTOR-CONTROLLED POWER SUPPLY SYSTEM FOR TCT/TFTR NEUTRAL BEAM SOURCES*

W. R. Baker, D. B. Hopkins, W. L. Dexter,
R. W. Kuenning, and B. H. Smith
Lawrence Berkeley Laboratory and Lawrence Livermore Laboratory
Berkeley, California 94720 Livermore, California 94550

Introduction

The Tokamak Fusion Test Reactor (hereinafter designated TFTR) will have four "beam line" modules, each of which will include three neutral beam (NB) sources for injection of neutral atomic deuterium beams into the TFTR toroidal plasma.[1,2] Each NB source will require beam acceleration (accel) power at ≈ 120 kV, 65 A level for 0.5 sec pulses every 5 minutes.

The functions of the various elements of a NB source are almost exactly analogous to those of a pentode vacuum tube (except, of course, that the accelerated particles are positive ions instead of electrons). With this in mind, we have chosen to adopt the following NB source nomenclature in order to clarify our terminology:

entrance grid (formerly grid #1 or extractor grid)

gradient grid #1 (formerly grid #2)

gradient grid #2, if used (formerly grid #3)

suppressor grid (formerly grid #4 or decel grid)

exit grid (formerly ground grid at neutralizer).

Separate power supply sub-systems are being proposed for each NB source in order to ensure operational flexibility and ease of construction and maintenance, to conduct a cost-effective initial development and test program, and to permit easy future expansion. Each of these power supply sub-systems 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 source. Collectively, the twelve power supply sub-systems and their common controls, monitors, and housings comprise the complete NB source power supply system.

This design description specifically addresses the requirements of the LBL/LLL neutral beam source design although the power supply design can also accommodate other sources.

Specifications and Requirements

Each NB source requires one major power supply, the accel supply, and four auxiliary power supplies. The specifications for these are summarized in Tables 1-5.

The power supplies will be designed to permit independent interruption of current to any source and crowbarring within 20 µsec, in the event of a source spark, while not disturbing the normal pulsing of all other adjacent sources. This is called an "interrupt" and permits the source spark to extinguish. After an interrupt cycle time of about 2 msec, accel voltage will be automatically reapplied to the source, resuming beam output. Many such interrupts can occur during the 0.5 sec pulse, particularly while conditioning a new source. The power supply will be shut down if an excessive number or rate of interrupts is detected.

The power supply will be designed to minimize stray capacitance and the energy delivered to a source spark from this and other sources.

*Work done under the auspices of the US ERDA.

In case two gradient grids are required, grid #3 would be a second gradient grid with the same regulation, selection, and current specifications as for gradient grid #1.

Those power supply components that are to be located at the sources, in a radiation environment, will be designed to permit full remote handling when maintenance access is required.

The controls, monitors, and instrumentation will provide the necessary capability for properly operating all sources.[2,3] The design will emphasize flexibility and ease of control and status monitoring.

Table 1 - Accel Power Supply Specifications

Parameter	Unit	Source Reqmt	Recomm. P.S. Spec.
Voltage, nominal	kV	+120	variable, +10 to +150
Voltage regulation	%	±1	±1
Current, max	A	61	65[1]
Power, max	MW	7.3	9.8
Pulse width, operating	msec	500	variable, 10 to 500
Repetition Period, minimum	min	5	5
Current Risetime,[2] max (10-90%)	µsec	20	20
Current Falltime,[3] max	µsec	20	20

[1]Includes 55 A max accel, 5.5 A max gradient grids, and 4.5 A max shunt regulator idling or ripple current.
[2]At max output current.
[3]At max output current, or when source sparks.

Table 2 - Gradient Grid Power Supply Specifications

Parameter	Unit	Source Reqmt	Recomm. P.S. Spec.
Voltage, nominal	kV	+98	+98
Voltage selection[1]	kV	+7 to +120	+7 to +130[2]
Voltage regulation[3]	%	±1	±1
Current, max	A	±5.5	±5.5

[1]When conditioning sources over full accel voltage range from +10 to +150 kV, the gradient grid voltage must be varied so as to maintain a constant ratio of accel to gradient grid voltage.
[2]Selectable by coarse and 50 V fine steps, and changing tap point on shunt regulator tube string.
[3]Regulated with respect to accel voltage.

Table 3 - Suppressor Grid Power Supply Specifications

Parameter	Unit	Source Reqmt	Recomm. P.S. Spec.
Voltage, nominal	kV	-2.3	-1 to -5
Voltage selection	steps	100V	100V
Voltage regulation	%	±2	±2
Current, max cw	A	11	11
Current, max, 50 µsec pulse	A	20	20

Table 4 - Filament Power Supply Specifications

Parameter	Unit	Source Reqmt	Recomm. P.S. Spec.
Voltage, adj. range[1]	V	9 to 12.5	11.3 to 15.8
Voltage selection	-	continuous	continuous
Voltage ripple, max[1]	%pk-pk	±1	±1
Voltage ripple filter	-	capacitive	capacitive
Voltage regulation[1]	%	±3	±3
Current, max	A	5000	5000
Risetime to full emission, max[1]	sec	1.5	1.5
Inrush/Operate Current Ratio	-	2.8	2.5 to 3.0
Output bus length, one way, max	ft	-	50
Pulse width, max	sec	2.2	2.2
Repetition Period, minimum	min	5	5

[1]At *maximum current output.*

Table 5 - Arc Power Supply Specifications

Parameter	Unit	Source Reqmt	Recomm. P.S. Spec.
Voltage, Open Circuit, minimum	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	sec	0.5	0.5
Repetition Period, minimum	min	5	5

Full manual control of any or all sources will be possible. Local computers at each source power supply control panel will permit both manual and TFTR central computer control. As manual experience is gained, it is expected that an increasing number of functions will be automatically controlled. A simple display of the status of all NB sources will be made available at the central TFTR control console.

Design Description

Figure 1 shows a block diagram of the power supply sub-system required for each neutral beam source. The elements shown in dotted boxes are common to all twelve NB source power supply sub-systems.

The twelve NB source accel power supplies operating at full 150 kV output comprise a 117 MW pulsed load. The primary ac power will be supplied by a motor-generator set at a 3 ϕ, 13.8 kV level. All other auxiliary power supplies and other equipment will obtain power from the public electric utility system.

From the 13.8 kV bus, each source power supply sub-system will require a maximum of 9.75 MW. Each will be fed through a motor-driven 600 A, 14.3 MVA circuit breaker with a 44,000 A interrupting capacity. Quarter-ohm line reactors will be employed between the bus and each breaker to limit fault currents to a value within the breaker rating.

Figure 2 shows the arrangement of the voltage controlling element, a saturable reactor (SR), along with the transformer and rectifier system for the accel power supply. Saturable reactor 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 so as to get a net cancellation of fundamental ac voltages. The SR dc windings are 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 rectifier transformer secondary windings. This forces current limited flat-top current in the rectifier transformer secondary windings, giving current-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. With zero saturating current, there will be a small magnetizing current through the saturable reactor ac windings. This will produce a small secondary current and rectified output which will be carried by the shunt tubes with low drop. Analysis and experiments indicate that a practical value for the real power gain of this circuit (accel power ÷ dc bias power) is in the 20 to 50 range.

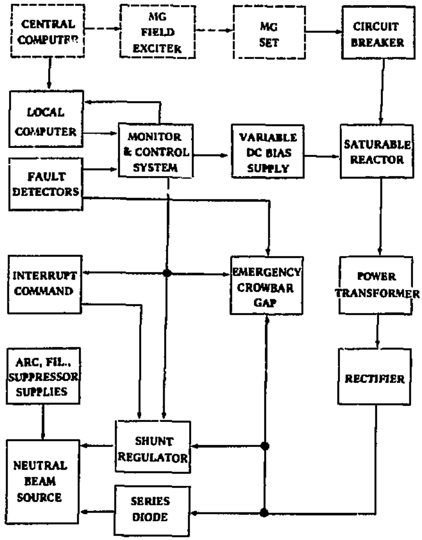

Figure 1. Block Diagram of Power Supply System for TFTR Neutral Beam Source

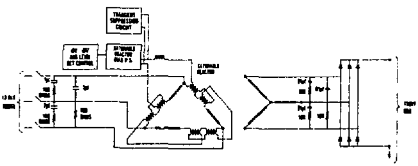
Figure 2. H. V. Accel Supply

The HV transformer will be rated at 10.6 MVA, pulsed. The SR dc bias inductor will be of the "swinging choke" type, to obtain increased inductance at low output levels; it will permit about 8% P-P power supply output current ripple. This requires the shunt regulator system to carry a maximum of about 5 A P-P ripple current.

Figure 3 shows the shunt regulator/modulator configuration and NB source, and also the arc, filament, and suppressor grid power supplies. The current-limited source permits the use of a shunt regulator tube system which can employ existing tubes (e.g. Eimac X2170) in series. This configuration can regulate the source accel and gradient grid voltages during normal pulsing or be made fully conducting, when a source spark occurs, to remove the accel voltage and extinguish the spark. About 2 msec later, the shunt tubes are again switched to regulate accel voltage. During this "interrupt" sequence, while the SR maintains the power supply current constant, the action of the shunt regulator is simply to transfer this current from the source to the shunt tubes and back to the source. At the end of the 0.5 sec pulse and during the interpulse period, the SR dc bias current is turned off within a few cycles of the line frequency. Variable voltage regulation will be controlled by a switched zener diode reference string.

A preliminary study of the dynamics of the current transfer process has been made. This indicates that there are no formidable voltage transients or other problems. To speed up the current transfer to the source following an interrupt, it may be necessary to briefly (few msec) couple a capacitive discharge current into the SR dc bias system, a simple matter.

Eimac X2170 tubes are planned for the shunt regulator tubes. During a normal pulse, each will carry a maximum of 10 A at a plate voltage of < 35 kV. (For 120 kV maximum output, five tubes will possibly be required.) During a source accel current interrupt, each will carry a maximum of 65 A with a plate voltage of $\leq$ 1500 V.

To extinguish a source spark, during an interrupt, the anode of the top tube must be taken to ground potential, or below. Allowing for the additive tube drops, this requires that the cathode of the bottom tube be briefly pulsed to a voltage of ≈ -7 to -10 kV. This is accomplished by the pulse-line discharge circuit shown in Figure 3.

Because of the current-limiting feature of the accel power supply, the shunt regulator system can function as a crowbar. As a redundant fail-safe feature, a crowbar spark gap is placed across the accel power supply output terminals, near the source. Improper operation of the shunt regulator (e.g., when a flash-arc or tube failure occurs) will be sensed and cause a spark gap to be triggered and the dc bias to be removed from the shunt regulator.

The filament power supply may be controlled by an induction voltage regulator (IVR) or a top changing transformer. For proper operation, for reasons involving the magnetic fields of the filament wires, it has been found necessary to maintain the output voltage ripple to $\pm$ 1% P-P. Moreover, a capacitive ripple filter is required at 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

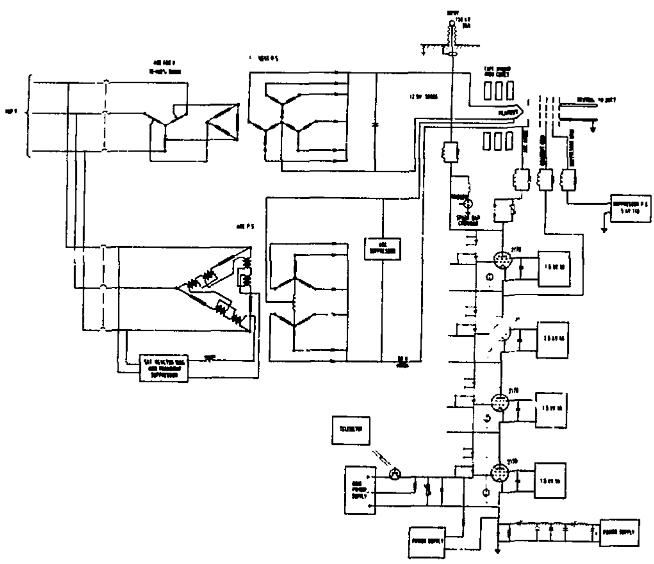

Figure 3. Auxiliary Supplies and Shunt Regulator for Neutral Beam Source

filament and destroys it. 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 ± 3%.

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 10-inch O.D., ½ inch thick, 2-mil tape-wound cores will be used.

The arc power supply leads are run separately from the filament power supply leads, to minimize common impedance coupling. Their connection to the source *must be made in a distributed manner, as must those of* the filament power supply, to minimize inductive loops and their stray magnetic fields. Moreover, it is necessary to incorporate resistive decoupling of the distributed lead connections at the source in order to prevent gross transverse current flow within the source structure and the arc plasma. The arc power supply controlling element is a saturable reactor operating in the same manner as that controlling the accel power supply. It provides an adjustable constant current to the source arc, whose operating parameters determine the arc voltage which acts as a nearly constant voltage clamp on the power supply. Whether or not the arc power supply should be crowbarred during every accel current interrupt will be determined by experiment. Assuming the arc is to be crowbarred during an interrupt and subsequently re-energized with the accel voltage, the process of arc current transfer is exactly analogous to that described for the accel current interrupt. In place of the shunt regulator, the arc supply will have a shunt silicon-controlled rectifier (SCR) rated for the full arc current. This will be commutated (turned off) at the end of the interrupt to transfer arc current to the source with a risetime of ≤ 15 μsec.

The suppressor grid power supply reflects electrons produced in the exit grid, neutralizer, and other downstream regions, preventing them from returning to the source and initiating sparking. 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).

Table 6 shows the approximate recommended time sequence for a normal TFTR shot, assuming all sources are fully conditioned and no accel interrupts occur. As discussed above, the optimum sequence, on a μsec time scale, of the relative timing of the accel, arc, and suppressor supplies will be determined experimentally.

Present plans call for new or rebuilt NB sources to be conditioned on a test stand separate from the four TFTR beam lines. However, all power supplies, including those for the beam lines, will be fully capable of conditioning NB sources from a possible initial low voltage, current, and pulse width capability to their maximum rated capability. 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 would be detected and cause a full shutdown and alarm. The most prevalent failure mode is expected to be sparking within the source or from external high-voltage structures to ground. The constant current nature of the accel power supply permits most of these to be treated as simple interrupts, allowing accel voltage to be reapplied within 2 msec.

Table 6 - Approximate Sequence for a TFTR Shot

Time (Sec.)	Event
0.0	TFTR field magnets "ON"
1.0	Computer checks beam line monitors for proper settings and mechanical alignment
1.5	Turn filament power supplies on
2.75	Receive TFTR trigger signal
3.0	Check and adjust filament voltage and current open-fast valve
3.080	Open gas valve
3.100	Briefly apply accel and suppressor voltages to each Neutral Beam source sequentially to check alignment
3.120	Apply accel and suppressor voltage to all sources
3.620	Shut down; crowbar accel, arc, and suppressor supplies, turn off filament power supplies, turn off accel and arc supply saturable reactor bias supplies

System Arrangement

Figure 4 shows a side view of the high-voltage assembly of the shunt regulator system and the filament and arc power supplies for a single NB source. The top hot deck contains telemetry, arc suppression circuitry, and the filament filter. Separate isolation transformers supply filament and grid power supply voltages. Sections of the floating deck and corona ring assemblies are removable to allow lifting of the tubes with an overhead crane. The shunt regulator assembly is 30 in. wide. A removable, grounded sliding metal shield wall is placed between adjacent shunt regulator assemblies *in the center of the aisle, with 15 in. clearance.* This results in a 5-ft center-to-center spacing.

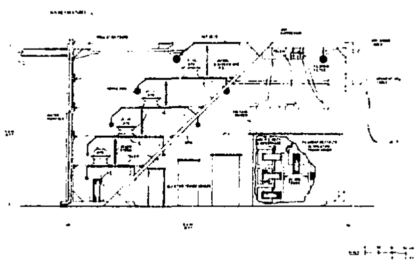

Figure 4. Shunt Regulator & Aux. Supplies for Neutral Beam Source (Side View)

Figure 5 shows the NB source enclosure arranged for remote handling. The small cables are sufficiently flexible to be unplugged vertically downward. They plug into a fixed socket, guiding with guide pins. The accel connection is made at the arc anode terminal. The parallel resistance-inductance transient snubber is attached to the end of the cable. Connection to the source electrode is made by a spring-loaded ball to allow for a small source alignment movement. The large cable carrying the filament and arc leads will be very rigid, as the core will be about 2-½ in. in diameter, with at least one in. of insulatio... Therefore, this cable is arranged to be pulled off horizontally, sliding through a horizontal trench in the floor, which leads to a horizontal hole in the floor, ending in the power conversion equipment room. The NB source enclosure will be pressurized with one to two atmospheres, gage, of sulphur hexafluoride, to provide adequate voltage insulation with the close spacings required, primarily between the three sources.

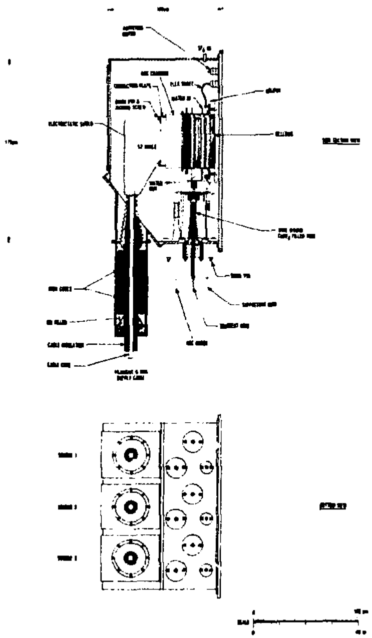

Figure 5. Neutral Beam Source Enclosure (arranged for remote handling)

Figure 6 shows the floor plan of the NB power conversion equipment with relation to the TFTR test cell and NB test cell. The shunt regulator high-voltage assembly has been located close to the TFTR shielding wall to minimize the stray capacitance to ground by minimizing the length of the high-voltage cable run.

Space for 21 complete NB source supplies has been shown, which includes six for future expansion and three to run the NB source test cell. The large equipment such as the rectifier, rectifier transformer, saturable reactor, and switchgear could go outdoors.

The overall philosophy and detailed planning of the control system for the neutral beam sources has been described in another paper[3] and will not be repeated here. The 250 kV switch tube shown and mentioned in that description refers to an earlier approach to accel power supply control. The saturable reactor/shunt regulator type of accel control eliminates the need for these tubes.

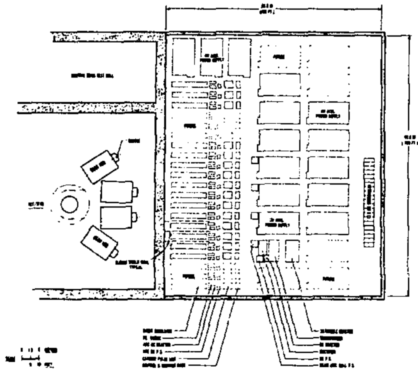

Figure 6. Neutral Beam Power Conversion Equipment (Plan View - Main Floor)

Conclusions

The principal benefits of the saturable reactor approach to accel control are to ensure inherent limiting of current (and energy) to any source spark while eliminating the need for series switch or regulator tubes which are presently beyond the state of the art. Furthermore, there is no need for expensive fast disconnects, i.e., electronic contactors, between the circuit breaker and the transformer. Finally, no large capacitor bank is required for the snubbing and impedance-matching function that is necessary with a series-switch approach to accel control.

Acknowledgments

This study was conducted under the direction of R. V. Pyle, LBL CTR Group Head, and with the scientific guidance of K. H. Berkner, W. S. Cooper, K. W. Ehlers, and E. B. Hooper. The authors also wish to thank W. J. Abraham, L. T. Jackson, P. S. Maslin, and D. I. Ryder for engineering support.

References

1. K. W. Ehlers, K. H. Berkner, W. S. Cooper, E. B. Hooper, R. V. Pyle, and J. W. Stearns, "Conceptual Design of a Neutral-Beam Injection System for the TFTR," Sixth Symposium on Engineering Problems of Fusion Research, San Diego, Calif., 1975, paper G3-2.

2. TFTR Neutral Beam Injection System, Conceptual Design, Lawrence Berkeley Laboratory Report LBL-3296 (unpublished) 1975.

3. V. Elischer, S. Fehr, V. Jacobson, and K. Wiley, "Designing the TFTR Neutral Beam Line Control System Software to Aid the Engineer," Sixth Symposium on Engineering Problems of Fusion Research, San Diego, Calif., 1975, paper C1-12.