Title
PRESENT AND FUTURE TECHNOLOGY OF HIGH VOLTAGE SYSTEMS FOR NEUTRAL BEAM INJECTORS

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INTRODUCTION

The intent of this paper is to present:

1. A brief review of existing neutral beam (NB) power supply technology for operating up to \( \sim 200 \text{ kV}, 65 \text{ A} \);

2. Possibilities for using existing systems for next-generation NB sources, and associated problems;

3. A summary of the features of present systems which contribute to a high degree of complexity and/or cost;

4. A plea and proposal for minimizing cost and complexity of future systems operating up to \( \sim 300 \text{ kV} \);

5. A few comments pertaining to special problems associated with operating in the 300 to 1000-kV range; and

6. A listing of some specific task areas which we believe should receive early R and D effort.

*Work done under the auspices of the Magnetic Fusion Energy Division of the United States Department of Energy.
EXISTING NB POWER SUPPLY TECHNOLOGY

General System Description

Figure 1 shows a simplified diagram of an NB source and the power supply system it requires. It happens to pertain specifically to the LBL 10 x 10-cm (extraction aperture) NB source and the 120-kV, 20-A, 0.5-sec Test Stand IIIA facility.\(^1\),\(^2\) Our intent here is not necessarily to emphasize or advocate one NB source and power system approach over another, but rather to discuss general principles.

The arrangement shown in Fig. 1 is typical for many positive ion extraction systems presently in use. As can be seen, the plasma chamber is operated at high positive accel potential and requires arc and filament power supplies insulated for the full accel voltage. Note also that the suppressor power supply (for reflecting back-streaming electrons) is ground-referenced and that the neutralizer is grounded.

Various approaches being pursued at several locations differ in NB source design, in the magnitude of filament and arc currents required, and in the details of switching and regulating the accel power supply. (The latter is discussed more fully in a later paragraph.) For LBL/LLL-type NB sources, the tape wound magnetic cores indicated in Fig. 1 have been found to be decidedly beneficial to successful operation for accel voltages as low as 20 kV and absolutely essential at voltages above 40 kV. Since this issue is increasingly important as accel voltage is raised, it is discussed in some detail in the next paragraph.
FIGURE 1

FILAMENT POWER SUPPLY
15 VDC
2.2 KA MAX
3 SEC.

ARC POWER SUPPLY
125 VDC
40-50VDC OPER
3 KA MAX
0.5 SEC.

ACCEL SWITCHING & SHUNT REG. SYSTEM
+150KV TYP.
+120-130KV TYP.

ACCEL POWER SUPPLY
10-150 KVDC
22A MAX
0.5 SEC.

SUPPRESSOR POWER SUPPLY
0-5 KVDC
5A MAX
0.5 SEC.

XBL 766-1996
The Stored Energy Problem

Figure 2 shows a simplified diagram of a system indicating the stray capacitance to ground from points at full accel potential. Without the core snubber, a spark in the NB source would rapidly (< 0.1 μsec) discharge these capacitances. A high peak current would flow (> 1 kA) and most of the energy stored in the stray capacitance would be dissipated in the NB source spark and at electrode surfaces, causing pitting. Structures operating in high vacuum have been found capable of tolerating sparking where the stored energy dissipated is of the order of 50 Joules. The initial discharge in a vacuum device such as a tube is space-charge limited for the first 1 to 2 μsec. The energy deposited on the anode during this phase is less concentrated so that electrode damage is very slight. On the other hand, when sparking occurs in structures operating in a low-pressure gas environment, e.g., NB sources, a low impedance arc can be established in a very short time, perhaps < 50 nsec, resulting in equally rapid voltage collapse and high peak currents. The process is totally different from that of a vacuum spark and has been observed in two different modes in LBL-type NB sources. The first is a "soft" high-impedance spark which may exhibit a voltage drop of > 1 kV and take > 1 μsec to develop. The second is the "hard" spark mentioned above which can develop in < 50 nsec when current is allowed to exceed ~ 200 to 300 A. The "hard" sparks cause rapid deconditioning of LBL sources, apparently by excessively pitting electrode
CORE TECHNIQUE TO ABSORB STRAY-FIELD ENERGY

FIGURE 2
surfaces. A preliminary study by one of us (W.R.B.) indicates that, for currents $\geq 200$ A, conditions might be approximately correct for establishing a high current-density "pinch"-type discharge which could cause such pitting.

LBL tests performed at 20, 40, and 120 kV indicate that the maximum tolerable energy stored in stray capacitance decreases with voltage and is only 3 to 5 J at 120 kV. At this voltage, the stored energy of the LBL source itself is approximately 1 J. Since capacitive energy increases as the square of the voltage, it is evident that new techniques will be required for successfully operating these large sources at voltages much in excess of $\sim 150$ kV. Because of the energy stored in the source itself, it is obviously difficult to scale the results from one type of source to another. A source geometry tested successfully in a fractional-size source may not perform identically or successfully in a full-size version.

Referring to Fig. 2 again, the function of the magnetic core snubber is to limit the peak current during an NB source spark to $\leq 200$ A, limit the energy delivered to an NB source spark to a few Joules, and to directly absorb the remainder of the stray capacitance energy in core losses governed by time-dependent eddy-current and hysteresis processes. There are still unknowns associated with stored energy. For example, a recent test at LBL showed that at 120 kV, a capacitively stored energy (on the power supply side of the core snubber) of $\sim 25$ J was barely tolerable while $\sim 40$ J was intolerable; i.e., it caused rapid source deconditioning so that it no
longer would hold voltage. In principle, it would seem possible to design a core snubber to "handle" any value of "upstream" capacitance. In practice, the above test indicates there is a limit, for unknown reasons, even when simulating a core snubber properly designed for the increased capacitance.* Certainly one limit is the fact that the snubber itself has stray capacitance to ground which increases with its size, obviously setting a practical limit on its size. These limits should be studied and defined, and thorough, systematic measurements of the effects of stored energy on NB sources should be made so that intelligent design of future NB systems can proceed.

Accel Power Supply Switching and Regulating

At the multimegawatt level of present NB systems, the extracted ion beam must be properly focussed so that only a negligibly small percent of the beam is permitted to intercept other NB source electrodes; otherwise, extreme heating, sputtering, sparking, and possibly damage to the source occur. Until recently, the risetime of the application of accel voltage to LBL NB sources has been made short (< 20 μsec). This minimizes the time period during which electrode voltages are improper and the incorrectly focussed extracted beam is "spraying" electrodes. Also, to date, it has been necessary to have the accel voltage well regulated (to < 1%, typically) to minimize neutral beam energy variations which would result in a variable beam divergence and possible beam interception.

*It is likely that stored energy of 40–50 J could be tolerated if, in addition to the core snubber, a fast-acting (~2 to 3 μsec) crowbar is provided and triggers on a source spark.
Figure 3 shows simplified diagrams of the two most-used types of accel regulating systems now in use at various locations. The series regulator approach is in use at LBL for systems operating up to 40 kV, 80 A, 10 msec, and being designed for operation up to 120 kV, 70 A for the Princeton TFTR systems, for 120 to 150-kV operation at ORNL, and for 80 to 200-kV operation in the LLL High Voltage Test Stand. The shunt regulator approach is fully operational in the LBL 120-kV, 20-A, 0.5-sec Test Stand IIIA facility, and will be used in the LBL 120-kV, 65-A, 0.5-sec NBSTF facility for TFTR NB source development and testing. The 200-kV high voltage switch tube, under development by both RCA and Eimac, is intended to serve as a combined series switch and regulator in the Princeton TFTR and LLL High Voltage Test Stand power supply systems. In the LBL 120-kV test facilities, shunt regulation is provided by paralleling existing Machlett DP-15 triodes with nonlinear plate resistors so that the tube anode voltage is always $V_{\text{shunt}} \leq \frac{1}{2} V_{\text{accel}}$. This system requires a separate series switch so that the full current and voltage can be first established in the shunt regulator before switching to the NB source with a fast rise-time. Series assemblies of silicon controlled rectifiers (SCR’s) have been developed for this purpose and are in routine use in LBL test facilities.

Two other configurations should also be mentioned. The first is an ORNL series switching and regulating system, nearing completion, which has three 60-kV floating decks in series to provide 150-kV, 50-A pulses. It is our understanding that this system is now under-
SERIES REGULATOR

FROM ACCEL DC P.S., LOW IMPEDANCE

REACTANCE COMPENSATING CAP, BANK

SHUNT SWITCH

TELEM

SCREEN SUPPLY

SERIES SWITCH

TO N.B. SOURCE

SHUNT REGULATOR

FROM ACCEL DC P.S., TYP 25% IMPEDANCE

NON-LINEAR RESISTOR

VARIABLE REFERENCE

SCREEN SUPPLY

BIAS P.S.

SERIES SWITCH

TO N.B. SOURCE

XBL 7712-11293

FIGURE 3
going initial tests in a switching mode only. The second configuration of note is that developed by H.M. Owren at LBL for \( \sim 50\text{-msec} \) pulse testing of the TFTR NB sources at a 120-kV, 65-A level. Figure 4 shows a simplified diagram of this 1.2-MJ electrolytic capacitor bank stored energy system. It has three main capacitance modules, shown in Fig. 5, which are charged in parallel to 40 to 50 kV, then mechanically switched in series. A series SCR assembly provides fast-rise-time switching to the NB source. In order for this to operate, a one-Henry inductor and a free-wheeling diode in shunt with it provides essentially constant-current from the bank during the SCR commutation. A shunt SCR assembly and LC commutating network permit interrupting the accel current during source sparkdown. The SCR and LC assemblies are shown in Fig. 6. A unique feature of this system is its ability to regulate (i.e., flat-top) the output voltage, while the main capacitor bank voltage is sagging, by sequentially switching in series up to 68 low voltage charged capacitor increments in the "low" lead of the main bank. This results in efficient usage of the main bank energy; as much as 50% is delivered to the NB source during a pulse.

USE OF EXISTING POWER SUPPLIES FOR FUTURE REQUIREMENTS

E.B. Hooper of LLL has spoken of the desirability of using existing equipment as much as possible in future projects in the interest of minimizing costs and construction time. Time and space do not permit
a detailed study or survey of the possibilities for extended usage of existing power supply systems, but the following brief comments may be of benefit. We assume the trend will be toward higher voltages, possibly negative output, possibly bipolar output, longer pulse widths, and higher duty factor.

**Larger Pulse Widths; Duty Factors**

From 0.5 sec on to pulse widths of ~ 30 sec, nearly all transformers should be limited only by thermal considerations. Therefore, such longer pulses are likely to be possible. Because of the long thermal time constants of large transformers, however, the duty factor may need to be reduced. Alternatively, a short series of pulses may be permitted if this is followed by a relatively long cooling period. The addition of cooling coils, heat exchangers, oil agitators, and/or forced flow systems to existing tanks could alleviate this problem if it becomes a limiting factor. In any case, monitoring the temperature of such components is in order.

Solid state rectifiers and SCR’s designed for 0.5-sec operation are operating at nearly their dc ratings. Except for possible required cooling changes, no problems at longer pulse widths should exist. Tubes, and particularly SCR’s appear to be a better choice for series switches used in long pulse operation, e.g., 30 sec, than ignitrons or thyratrons. Ignitrons have limited coulomb ratings, typically < 300 A-sec/pulse. Thyratrons for such service are beyond the present state of the art. Additionally, they would have cathode life limitations.
Some auxiliary power supplies and components such as power resistor dividers for gradient grid supplies may require modification and additional cooling.

Finally, systems having tubes and other dissipative components such as linear and nonlinear resistors, water resistors, etc., which have been designed for a shorter pulse will usually require either a full rebuild with increased cooling, additional parallel elements, or a drastic change in the system configuration or operating procedure (see section below on Simplifying Future Systems).

**Higher Current**

Higher voltage systems are expected to require accel currents no larger than present rated currents. Required accel current may even be less than present rated currents where a limit on available power exists.

**Negative Output**

Usually it is relatively easy to reverse connections to rectifiers in order to obtain a negative power supply output for negative ion extraction. It also appears to be rather simple to reconnect either a series or shunt regulator and associated switching and crowbar systems for negative output. Minor changes in some areas may be required; e.g., inverting voltage dividers, relocating current monitors, modifying ignitron trigger circuitry, and insulating the shunt regulator tube filament transformer for high voltage. Some of the tube control electronics may also require modifications.
Bipolar Output

Some conceptual designs for future NB systems based on negative ion sources require bipolar power supplies. The negative-output supply described above can be combined with a standard positive-output supply to produce such a system. A preliminary study of this configuration reveals no major problems.

If the NB sources have a well-defined ground point, say a grounded intermediate grid as described by E.D. Hooper, it should be possible to prevent long-duration coupling of the two power supplies during a source spark which would otherwise develop troublesome twice-voltage levels. Short-duration overvoltage transients may be produced, but these are easily clamped and damped by surge suppressors. LBL has successfully and routinely used many series-assemblies of the relatively new metal-oxide varistors (nonlinear resistors) for this purpose. Larger units with energy ratings in the kJ range are just now appearing in the commercial market for use in power distribution surge arrestors.12

Coordinated control of the two power supplies is obviously necessary. The regulating, switching, and crowbarring functions all appear to be rather easily implemented by control through the reliable optical coupling links now available. These can be operated in such a manner as to permit the checking of their proper operation before a pulse, and inhibiting firing if any are malfunctioning. If regulators are used, an additional feedback link will probably have to be added if close tracking of the outputs is required.
With bipolar output power supplies, overall voltages up to 340 kV are obtainable from supplies now built or being constructed. The LBL NBSTF (Neutral Beam System Test Facility) transformer-rectifiers would be capable of supplying $\pm 170$ kV, 16 A dc, or $\pm 150$ kV, 32 A for 30-sec pulses. E. B. Hooper has stated that, at LLL, the High Voltage Test Stand power supply could be combined with an 80-kV, 80-A, 30-sec power supply now under construction to provide a range of bipolar outputs from $\pm 80$ kV, 80 A, 30 sec to $-200$ kV, $+80$ kV, $+80$ kV, 20 A, 30 sec. These capabilities are summarized in Table I. The capacitor bank is discussed in a later section.

COSTLY, COMPLEX FEATURES OF PRESENT POWER SUPPLIES

Table II lists the features of existing power supplies which contribute significantly to high cost and complexity (over and above the required transformer-rectifier systems). Several of these features are probably with us for some time; e.g., magnetic core arc snubbers, computers, and the need for repetitive interrupts and low available stored energy in the accel system stray capacitance. All of the others, however, appear to show promise for eventually being reduced, relaxed, or eliminated altogether. The potential for greater simplicity and reliability is high, while the possible cost savings in the many systems being planned for construction in the next several years is enormous.
TABLE I

SOME LBL/LLL P.S. CAPABILITIES FOR FUTURE USE

<table>
<thead>
<tr>
<th>LBL</th>
<th>TEST STAND IIIA</th>
<th>+ 170 kV, 20 A, 0.5 SEC</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>+ 80 kV, 20 A, 0.5 SEC</td>
</tr>
<tr>
<td>LBL</td>
<td>NBSTF</td>
<td>+ 170 kV, 16 A, DC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ 150 kV, 32 A, 30 SEC</td>
</tr>
<tr>
<td>LBL</td>
<td>1.3 MJ CAP. BANK (+ or -) 1 MV, 20 A, 20 mSEC</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(+ or -) 500 kV, 40 A, 60 mSEC</td>
</tr>
<tr>
<td>LLL</td>
<td>HVTS +80 kV P.S.</td>
<td>+ 80 kV, 80 A, 30 SEC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 200 kV, +80 kV, 20 A, 30 SEC</td>
</tr>
</tbody>
</table>
TABLE II

FEATURES CONTRIBUTING TO HIGH COST AND COMPLEXITY

<table>
<thead>
<tr>
<th>HARDWARE</th>
<th>PRIME CANDIDATE FOR SIMPLIFICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>REGULATORS</td>
<td>*</td>
</tr>
<tr>
<td>TUBES</td>
<td></td>
</tr>
<tr>
<td>POWER VARISTOR ASSEMBLIES</td>
<td></td>
</tr>
<tr>
<td>FAST HIGH VOLTAGE SWITCHES</td>
<td>*</td>
</tr>
<tr>
<td>TUBES</td>
<td></td>
</tr>
<tr>
<td>SCR ASSEMBLIES</td>
<td></td>
</tr>
<tr>
<td>CROSSED-FIELD INTERRUPTERS</td>
<td></td>
</tr>
<tr>
<td>MAGNETIC CORE ARC SNUBBERS</td>
<td></td>
</tr>
<tr>
<td>COMPUTERS FOR CONTROL AND DIAGNOSTICS</td>
<td></td>
</tr>
</tbody>
</table>

OPERATIONAL REQUIREMENTS

- FAST-RISE SWITCHING (TYP. < 25 μsec) *
- TIGHT REGULATION (TYP. < 1 %) *
- WIDE RANGING (TYP. 5 TO 100%) *
- LOW AVAILABLE STORED ENERGY (TYP. < 5 J) *
- REPETITIVE Interrupts
- LARGE NUMBER OF SHORT CIRCUITS ?
- SMALL VOLTAGE-SELECTION RESOLUTION *
- "LOAD" RATHER THAN "NO LOAD" TAP-CHANGING OF TRANSFORMERS
Although it would be informative to have specific cost impact figures for the above features, it has been our experience that it is nearly impossible to obtain and present these in any kind of self-consistent manner which is not fraught with possibilities for misinterpretation. Accounting procedures vary from location to location. Private industry costs differ greatly from those in laboratories. Cost division between "Operating" and "Capital" accounts vary from project to project. Overhead, escalation, assignment of contingency, and the effects of various managerial decisions further confound the issue. It would certainly be beneficial if there were standard procedures, used by fusion research laboratories at least, for cost estimating and accounting.

The present dual, and different, funding procedures for "Capital" and "Operating" accounts lead to arbitrarily different divisions of funding at different laboratories and between various projects within a given laboratory. Although "Capital" funds committed in one fiscal year can be spent in the following year(s), the expenditure of "Operating" funds must cease on the last day of the fiscal year. This has always promoted inefficiency and, when projects have under-spent, wasteful near-panic spending at the end of the fiscal year. On the nationwide fusion research spending scale, this effect could easily account for tens of millions of dollars' worth of ill-conceived spending. Since it is possible to carry Capital expenditures over into the next fiscal year, it should be possible to conceive a system which has only one category of funding with the ability to carry expenditures over into the next fiscal year for some reasonable period.
Simplifying Future Systems for Operation to ~300 kV

In future systems, a close look should be taken at the need for small voltage selection resolution and wide range control of accel systems. Instead of each system being fully variable, it may be acceptable to have one or more fully variable "conditioning" power supplies for initial testing and conditioning of NB sources. If the remaining on-line "production" systems require only a small operating voltage range, or a few selected fixed operating points, a very large cost savings in the power conditioning transformers would result. Moreover, since most of the repetitive short circuits would occur while conditioning, the rated number of short circuits specified for the "production" system transformers could probably be in the industry-standard range, rather than being abnormally high and non-standard as is the case with some systems under construction. This would also result in large cost savings.

Simply settling for changing variable voltage transformer taps between pulses, under "no load", rather than specifying "load" tap changing can result in large savings for these costly components. Settling for coarser voltage selection resolution, say 7 to 10% steps rather than continuous variation, can also result in large savings.

We now come to a discussion of the area having the greatest potential for simplifying future systems and saving a great deal of money, perhaps tens of millions of dollars over the next 5 to 10 years. This subject centers on the need for accel voltage regulation and fast-rise switching.
If the NB source arc current were properly controlled so as to always maintain beam divergence at a minimum (e.g., by a feedback signal derived from the accel beam current), the accel voltage regulation requirement could be relaxed to the point where the neutral beam energy variations become unacceptable. Preliminary inquiries indicate that variations of at least \( \leq 10\% \) are tolerable from the standpoint of fusion device physics. This implies that accel power supplies could be operated unregulated on nearly every conceivable ac power source as long as an appropriate arc modulator system is provided. Furthermore, since such a system can be made to maintain proper beam divergence over the full range of accel voltage, it should become possible to operate with reasonably long risetimes for the accel voltage, perhaps in the millisecond range. This, then, may make it possible to turn the accel power supply on and off with conventional contactors in the primary ac lines. These can also momentarily interrupt the ac primary when an NB source spark and subsequent crowbar occur, then re-energize the system to continue the pulse.

To date, some physicists have stated that only a few-msec period of "wrong-energy" injected beam is tolerable, e.g., that injected during a long accel voltage risetime. If this remains as a fixed limitation, it probably will not be possible to eliminate the need for fast high-voltage accel switching; i.e., tubes or SCR's would still be required. If it were found permissible to have a 10 to \( \sim 40\)-msec risetime, the series switches could probably be eliminated, saving a great deal of money. (An installed developmental High Voltage Switch Tube with
its associated pure water system costs $150 to 200 k. An SCR system would probably cost about half of this when manufactured by private industry.) The resulting accel power supply would be extremely simple, involving as major components only primary contactors, voltage-variable transformer, transformer-rectifier, and dc crowbar. Preliminary studies indicate such a configuration is relatively easily adapted to pairing for bipolar outputs and/or running several smaller NB sources from one large power supply. This statement is also true if fast high voltage switching is still required.

DC arc modulators are already required in existing systems for depressing the arc current prior to switching on accel voltage. This causes beam focussing to be approximately correct during the ~25-μsec risetime of accel voltage. Therefore, it would seem that by increasing the control and modulating capabilities of the arc power supply system (involving only 150 to 250 kW of power) the following significant advantages could be obtained for multimegawatt systems:

1. Accel voltage regulators can be eliminated.
2. Fast accel switching tubes or SCR’s can be eliminated.
3. Standard ac primary switchgear can be used for controlling the accel supply.
4. Fast-transient problems associated with fast switching can be eliminated.
5. Neutral beam divergence can automatically be maintained at a minimum over a wide range of conditions.
6. Cost and complexity can be greatly reduced.
7. Reliability can be vastly improved.
Table III summarizes the desirable features of simplified power supply systems.

An attractive technique for reliable and flexible control of the arc power supply is the use of a "star-point controller" at the neutral point of the wye-connected ac primary. One version of this circuit is the Kerns Actuator, shown in Fig. 7a, connected in the primary side of the rectifier transformer. This circuit makes it possible to satisfy an ac control requirement by a dc control means. In this case, the tube can provide variable full-range ac primary excitation as well as a fast turn-off function (typically ~1-msec). If the arc supply transformer has a 12 or 13.8-kV rated primary winding, a standard 100 or 250-kW tube could be used and would be conservatively operating within its ratings. Such variable control permits the correct matching of ion density for achieving minimum beam divergence during the accel voltage risetime as well as during the pulse.

In principle, a Kerns Actuator could be used to control the accel power supply; however, this may be impractical because of the large magnitude of power involved. A different arrangement of the circuit, shown in Fig. 7b, appears to have many advantages and intriguing possibilities for overall power supply simplification. In this version, an inductor replaces the tube and SCR’s (or ignitrons) replace the diodes. A varistor limits possible inductively generated over-voltage transients to safe levels. It achieves several simultaneous functions:
TABLE III

SIMPLIFIED FUTURE PS SYSTEMS

1. ACCEL RISETIME > 8 mSEC.
2. FAST CONTROLLED ARC PS TO MATCH REQUIREMENT DENSITY.
3. CONTINUALLY OPTIMIZED BEAM DIVERGENCE.
4. NO ACCEL REGULATOR.
5. NO FAST HV DC SWITCHING.
6. OPERATES OFF STANDARD POWER LINES.
7. CONTROLLED BY STANDARD AC PRIMARY SWITCHGEAR.
8. ONLY MAJOR COMPONENTS.

AC PRIMARY CONTACTORS
VOLTAGE-VARIABLE TRANSFORMER
TRANSFORMER-RECTIFIER
DC CROWBAR
A. KERNS ACTUATOR

B. MONDINO'S CIRCUIT

FIGURE 7
1. Provides output dc ripple filtering equivalent to that provided by HV dc output choke, but at somewhat lower cost because of the reduced insulation requirement;

2. In the process of providing energy for ripple filtering, some of the inductor's energy is returned to the power mains reducing line current harmonics and required telephone interference filtering;

3. The SCR's can provide the pulse-to-pulse ON-OFF switching and probably a small amount of voltage control, with the primary contactor serving as a backup interruptor or disconnect switch;

4. Eliminates the need for a "step-start" by limiting inrush currents, even in the presence of "asymmetrical offset" effects, to acceptable levels (perhaps ~4 times normal);

5. During crowbars, the transient current rate-of-rise is limited to reasonable levels while the primary power is being interrupted.

6. While it has a high transient impedance, the system can have a relatively low steady-state impedance, permitting essentially full dc output; this is in contrast to the somewhat lower output available from systems where impedance is increased by ac line reactors or higher transformer reactance.

For the LBL 160-kV, 75-A NBSTF Accel power supply, it appears that an inductor storing only 20 to 30 kJ should be adequate. These circuits have only been studied in a preliminary way so far, but we
believe they can play an important role in simplifying future NB power systems.

OPERATION TO $\sim$1-MV

To our knowledge, J.H. Fink of LLL has devoted the most time to conceptual thinking and design related to possible future 1-MV neutral beam source and power supply systems.¹⁴

A primary concern is the self-capacitance of NB sources and its stored energy which increases as the square of the voltage. Extending the use of present NB source designs to the $\sim$1-MV range appears to be impractical, not only from the electrical standpoint but because of a beam neutralization efficiency which is rapidly decreasing at these levels. Negative ion sources are being proposed for use at these higher voltage levels since they enjoy a much larger neutralization efficiency. These may be constructed in such a manner as to effectively separate the plasma source from the accelerator grid system permitting high vacuum pumping in between. This may mean that any high voltage sparking present could be of the vacuum-spark type (rather than the low pressure gas type) which is much more tolerant of the magnitude of stored energy delivered to the spark.

It may be possible to construct NB source and accelerator systems, with magnetic core stacks or other types of arc snubbers built into the structure, inside the vacuum chamber. J.H. Fink has mentioned that it may be possible to design an accelerator structure which
could suffer a local sparkdown in a single section, and recover from it, without initiating an overall breakdown. The potential impact of this on improving the reliability and "ON-time" of fusion power reactors is obvious. To date, the effort spent on conceptual designs aimed at solving these problems appears to be very small.

It may not be difficult or too costly to conduct initial experiments in the 300 to 1000-kV range. When the LBL 120-kV, 65-A, 0.5-sec power supply becomes operational (mid to late 1978), the 1.3-MJ capacitive energy-storage system shown in Fig. 5 should become available. It can be relatively easily reconfigured in a number of different ways for various voltage levels. Figure 8 shows an arrangement capable of supplying a pulse of approximately 20-A, 30-msec at 1-MV, voltage-regulated (flat-topped) to 1%. If good regulation is not a prime requirement, higher current and/or longer pulses could be supplied. The metal clad room now housing the capacitor bank is large enough to accommodate such equipment operating at voltage levels in excess of 500-kV, possibly up to 1 MV. The shunt SCR and LC commutating system now used for repetitively interrupting the current during source sparking could be expanded to provide the same function at higher voltage levels. Alternatively, an inexpensive crowbar could be provided for terminating the pulse if sparking occurs.

SUGGESTED TASK AREAS FOR EARLY R & D EFFORT

We believe the following tasks should receive early R and D effort in order to help guide the design and minimize the costs of not only the next generation but the long-term power system needs of neutral
20 SECTIONS
44 μF
50 kV EACH

MAIN BANKS

OUTPUT TO COMMUTATING CIRCUIT

REGULATOR BANKS

40 SECTIONS
250 μF
9 kV EACH

1 MV CAPACITOR BANK

FIGURE 8

XBL 7712-11294
beam injectors. Without this, there will very likely be a tendency to proliferate the construction of the unnecessarily complex and expensive earliest designs of these systems.

1. Feasibility testing of 1-msec accel voltage risetime, appropriately controlling the arc current, aimed at eliminating the need for accel regulators and fast switches.

2. Tests of star-point controllers in ac primary systems.

3. Low-level hardware circuit modeling and testing of power supply configurations.

4. Long-pulse (e.g., 30-sec) testing of NB sources.

5. Development of a dummy load for accel power supplies which simulates the ∼50-nsec sparking of NB sources. (It has been demonstrated that resistive dummy load testing leads to a false sense of security; it is no guarantee of proper power supply operation with NB source loads.)

6. Cost studies of various possible power system configurations.

7. Determination of the acceptability of 10 to 40-msec periods of "wrong-energy" beam injection during accel voltage risetime.

8. A thorough study and optimization of construction and assembly procedures aimed at reducing costs of SCR assemblies (as was done earlier for electrolytic capacitor bank modules).

9. Thorough tests to determine stored-energy limits of NB sources.

10. A literature search for voltage-holding and sparking data and experience for vacuum high voltage systems operating up to 1 MV.
11. Establishing a test facility for basic measurements on vacuum voltage holding and sparking up to 1 MV.

12. Conceptual design studies of higher voltage NB sources and power system geometries, possibly incorporating internal arc snubbers.

CONCLUSIONS

For the near-term, we see no great difficulty in adapting existing power supply systems to the 150 to 300-kV level. Fears of power supply system unreliability due to mysterious transient voltage problems have been calmed by the learning experience of the past few years.

Above all, we hope we have successfully argued that NB source and power supply systems are as yet in an early stage of development. It should be clear that there is much room for simplification and improvement. The consequences of implementing these changes may well be cost savings measured in tens of millions of dollars over the next several years, as well as significantly improved reliability.
REFERENCES


REFERENCES (cont'd)

