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# Status Of The LBL/LLL Development Program

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The status and near-term goals of the LBL/LLL neutral-beam-development program are described. The emphasis in this paper is on the technology of systems based on the acceleration and neutralization of positive ions; this approach will be used in the near term, probably through 1985 at least. For more efficient injection, part of our plan is to develop a negative-ion approach suitable for 200- to 400-kV injectors on confinement experiments in the 1985-90 period. However, the negative-ion based program is still very much in the research phase, and it is difficult to project how it will phase into fusion reactor fueling experiments.

## I. Introduction

The LBL/LLL Neutral-Beam Development Group has the responsibility for developing injection systems for mirror experiments and, is one of the two major efforts within DMFE developing systems suitable for tokamak confinement devices. Part of the application will be fusion reactor fueling.

The work proceeds along two lines: The first, based on positive-ion technology, is required for the near-term (perhaps to 1985) applications. The presently identified experiments, 2XIIB, TMX, MFTF, TFTR, and DIII, require injection at energies up to 120 keV, ion currents per module up to 80 A, and pulse lengths to 0.5 sec. Although much work remains to be done, we have achieved 120-kV, 0.5-sec operation of a fractional area (12 A) TFTR prototype source, and are fairly confident about developing useful injectors for the near-term applications, including up-grades for longer pulses. We will go into the present status in some detail to permit the reader to evaluate the work yet to be done.

The second development effort is oriented toward longer term applications requiring efficient neutral-beam systems at energies above 120 keV. These systems will require the production and acceleration of large currents of negative ions. Two of our goals are the demonstration of a 200-kV, 20-A ($D^o$), ∿ dc system by 1981, and a 400-kV. 20-A ($D^o$), ∿ dc system by 1983. These achievements will make it possible to have 200- to 400-kV injectors on confinement experiments in the 1985-90 period.

## II. The Positive-Ion System Status

The injection of intense, 80-keV $H^o$- or $D^o$-beams is planned for the Doublet III-tokamak and the MFTF-mirror experiments for plasma heating; for the Tokamak Fusion Test Reactor (TFTR), 120-keV D atoms (20 MW in 0.5-sec pulses at 5-minute intervals) will be injected into a tritium plasma to produce two-component d-t reactions. The principal components of these neutral-beam injection systems are shown schematically in Fig. 1.

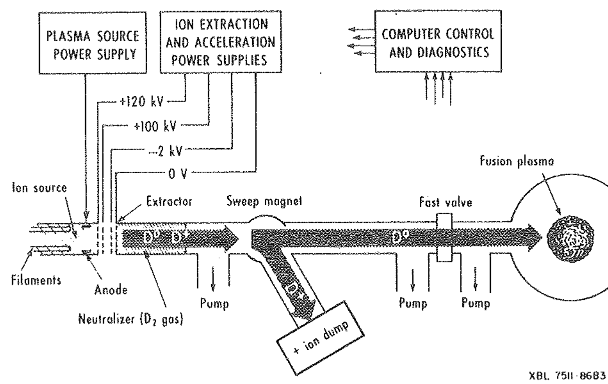


Figure 1. Schematic of a typical neutral-beam injection system.

The system operation is as follows: A deuterium plasma is created in the plasma generator by means of a high-current discharge. Ions from this plasma are accelerated in a carefully designed multi-electrode structure. The ions then pass through a neutralizer containing deuterium gas, and a fraction becomes neutralized by charge-exchange collisions. Remaining ions are removed from the beam by the sweep magnet; otherwise, the various reactor magnetic fields would bend the ions into surfaces near the entrance port, possibly releasing gas bursts or melting the surfaces. The considerable power in this ion beam must be handled by the ion-beam dump. The vacuum pumps distributed along the beam line remove most of the gas emerging from the neutralizer and the ion-beam dump and must maintain the pressure between the sweep magnet and the entrance port at a sufficiently low value that very little of the neutral beam is reionized. Well-regulated power supplies are required to assure good beam optics; to minimize accelerator damage when a spark occurs, the power supplies must also be capable of rapid turn-off with a minimum of stored energy (e.g. in cable capacitance). Optical, mechanical, and electrical sensors determine the condition and performance of the neutral-beam system and permit the control system to adjust the power-supply voltages and to shut down the system if a malfunction occurs.

The LBL 120-keV Neutral-Beam Test Facility[1,2] is used for the development and testing of neutral-beam-system components. It has two beam lines and associated power supplies: (A) a 150-kV, 20-A, 0.5-sec power-supply system[3,4] to test small-area injector modules (plasma source and accelerator), and (B) a 120-kV, 70-A, 30-msec power-supply system to test full-scale modules for short pulses. The beam-diagnostic system for these beam lines is described in Ref. 5.

Long-pulse testing of high-current ion sources will be completed on the High Voltage Test Stand (HVTS) at LLL. This facility is nearing completion in a configuration suitable for testing positive ion sources in

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various voltage-current combinations. The initial application will be for TFTR 120-kV, 65-A, 0.5-sec modules. In a year or so, the HVTS will be modified to permit testing of a negative-ion system at 200 kV, 20 A, dc.

Next we describe the operation of a 120-kV, 0.5-sec injector module which, from an 8- x 10-cm accelerator-grid array, produces 14 A of hydrogen ions or 10 A of deuterium ions. This module was used to test the design concepts of the 10- x 40-cm, 120-kV, 65-A, 0.5-sec TFTR module[6-8] which is currently under test.

## Injector Module

A cross-section of the 120-kV, 8- x 10-cm injector module is shown in Fig. 2. The ions are produced in a high-current low-voltage discharge with no externally applied magnetic fields. The cathode consists of eighty-four 0.5-mm-diam, 11-cm-long tungsten filaments; the anode is a 10- x 10-cm molybdenum plate shown in the top of the figure. A photograph of the plasma source is shown in Fig. 3; details on this type of plasma generator can be found in Ref. 2.

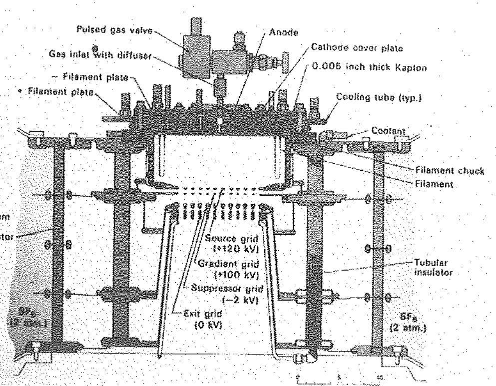


Figure 2. Cross-section of the 120-kV, 0.5-sec source module with an 8- x 10-cm grid array.

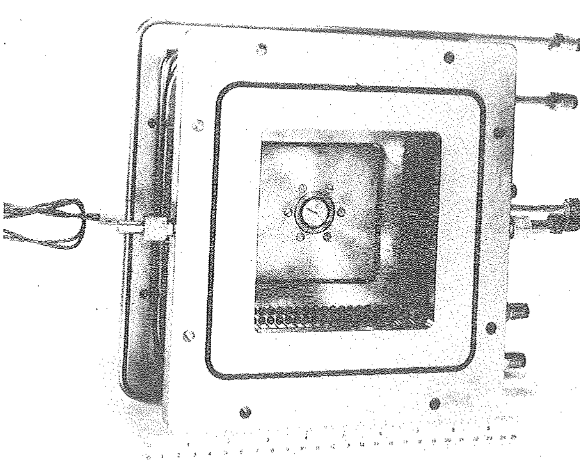

Figure 3. Photograph of the plasma source, illustrating the filament geometry. The flange with the O-ring was used for plasma-uniformity tests; it is not part of the structure shown in Fig. 2.

A four-grid (three-gap) multiple-slot accelerator array (a cross section of a single slot of the array is shown in Fig. 4) is used. Ions are accelerated and electrostatically focused in the first two gaps; the third gap has a weak decelerating field to suppress down-stream electrons. The transparency of the array is 60%; the scale size was set by the desire to limit the maximum potential gradient to about 100 kV/cm (our estimate of the breakdown limit) and resulted in a design ion-current density of 0.31 A/cm$^2$ for a pure $D^+$ beam, or about 0.25 A/cm$^2$ for a beam with a realistic mixture of $D^+$, $D_2^+$, and $D_3^+$. The design shown in Fig. 4 was optimized, using the WOLF code,[9] by varying the shape of the first, beam-forming, electrode and the potential of the second, gradient-grid, electrode. The shapes of all electrodes except the first were chosen to minimize energy deposition in the structure by secondary particles created by ionization of the background gas or by secondary emission from grid surfaces.

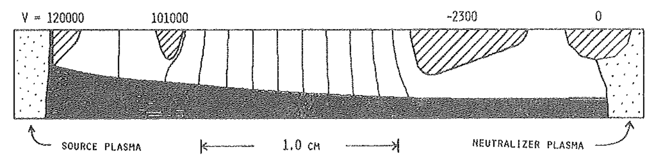


Figure 4. Calculated beam trajectories and equipotentials for a 120-kV accelerator.

The module (Fig. 2) consists of an outer, vacuum-wall insulator that is sectioned to distribute the potential gradients; to keep these insulators reasonably short, the outside of this insulator is pressurized with two atmospheres (absolute) of $SF_6$ gas. The plasma source and grid assembly are mounted on an inner plug-in structure (Fig. 5). The tubular insulators to which the grid assemblies are mounted also carry de-ionized cooling water to the plates that support the final three grid arrays; cooling for the first (beam-forming) grid is obtained from the plasma-source chamber. The 8-cm long grid rails, arranged in a 10-cm-wide array, are end cooled. The solid molybdenum rails are brazed to a fixed support on one end, forming a comb-shaped structure, and allowed to expand in the long direction to prevent buckling when heated.[7,8] The heat is conducted away in the 1-min interval between pulses.

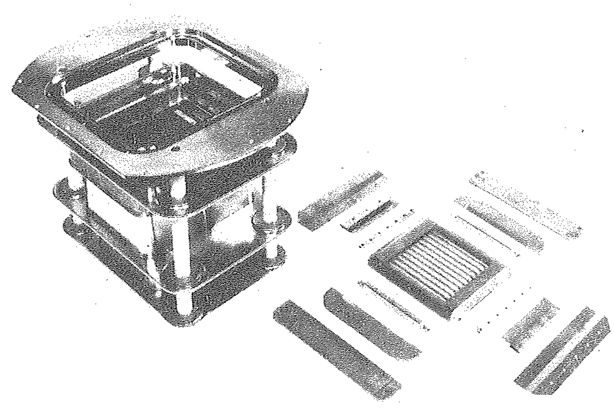

Figure 5. Photograph of the accelerator plug-in structure and one of four multi-slot grids.

The neutralizer to which this structure is attached is constructed of iron to shield the beam from stray magnetic fields. It has an internal cross section of 20 cm x 30 cm and is two meters long. $D_2$ gas emerging from the plasma generator through the grids produces a line density of $\sim 10^{16}$ molecules/cm$^2$ ($\sim$0.5 Pa-m) in this section.

The beam is stopped by a copper-plate calorimeter, instrumented with an array of thermistors, located 8.5 m from the grids. The beam divergence is determined from the shape of the heat pattern on the calorimeter[5]; the plate is water cooled in the 1-minute interval between shots.

A deflection magnet, located between the neutralizer and the calorimeter, can be used to sweep the ions out of the beam. An instrumented ion dump, similar to the calorimeter, is used to determine the focusing effects of the magnet (and possibly space charge) on the ions.

Two structures of type shown in Fig. 2 have been operated up to 120 kV with 0.5-sec pulses. In the first (Mark I) the rails of the first two grids, beam-forming and gradient-grid, were curved to an 8.5-m radius to focus the beam in the direction parallel to the slots. The second structure (Mark II) had planar grid arrays.

A typical beam-pulse sequence is as follows: The water to the calorimeter is turned off and the diagnostic computer receives a signal to record the pre-shot thermistor temperatures on the calorimeter. Approximately 5 sec later the filament-power supply is turned on; approximately 2 sec later the filaments have reached their emission temperature and gas is pulsed into the plasma chamber. Within 20 msec the arc-power supply is turned on. When the discharge has stabilized ($\sim$50 msec after the supply has been turned on) the accelerator voltage is applied to the grids by firing the series switch.[3,4] The potential for the gradient grid is obtained from the accelerator power supply by means of a resistive voltage divider; the suppressor supply is slaved to the accelerator supply in that it is gated on by a signal from the high-voltage divider. The rise time of the potentials applied to the three grids is approximately 30 μsec. When any of a number of fault sensors is activated (drop in high voltage below a preset threshold, loss of voltage across the first gap, excessive suppressor current, excessive gradient-grid current, etc.) the series switch is "opened" by firing the shunt switch.[3,4] This removes all high voltage from the grids; the discharge, however, is not turned off. After a preset "interrupt" time, typically 21 msec, the series switch is again fired and the sequence is repeated. At the end of the 0.5-sec pulse all power supplies are turned off. Approximately 5 sec later the final temperatures of the calorimeter thermistor array are recorded by the computer, and the calorimeter water is turned on to cool the plates.

A saturable-core reactor[3,4] dissipates much of the energy stored in the stray capacitance of the power supplies and cables; the stored energy delivered to the grids by a spark is approximately 2 J (the energy stored in the capacitance of the module). We have tried to determine the maximum stored energy allowed without adversely affecting operation of the module by adding capacitance to the source. Very preliminary results indicate that source performance is degraded when more than 7 J are dissipated in a spark.

Operation of the module by interrupting only the grid voltages and leaving the discharge on permits rapid re-starts. It does, however, cause a problem when the potentials are applied to the grids: Without any potential difference between the grids, ions and electrons from the discharge fill the grid region; when the potentials are applied, these ions and electrons must be swept out of the gaps (possibly emitting secondary electrons as they strike the grids) resulting in large currents from the power supply. If the power supply is not capable of providing the extra current this can load down the supply and prevent the required potentials from being applied to the grids — which in turn gives rise to large currents, and so on. We have found that we can minimize this effect by "step-starting" the discharge: An RC circuit, with a time-constant of about 20 μsec, in series with a thyristor, is connected in parallel with the discharge; when the high-voltage series switch is fired, this thyristor is also fired to shunt the discharge current until the capacitor is charged. Because of the rapid deionization time (sub μsec) of the discharge, this puts a corresponding dip in the plasma density and thus decreases the ion and electron density in the grid region, minimizing the current surge when the voltages are applied to the grids. The recovery time of the plasma density in the discharge is comparable to the RC time of the circuit.

Typical operating parameters for both the Mark I and Mark II structures are given in Table I. The quoted beam widths, || and ⊥ to the slots of the accelerator grid, were obtained from the temperature profile of the calorimeter located 8.5 m from the grids. The temperature profile was found to be bi-gaussian, i.e. of the form $A\exp-(x/x_o)^2\exp-(y/y_o)^2$, so that it is possible to characterize the beam width by two parameters, $x_o$ and $y_o$; we express these parameters as angles with respect to a point source located at the center of the grid array (no correction is made for the finite size of the source). Since the 8.5-m-radius grids of the Mark I structures focus the beam (in the direction parallel to the slots) at 8.5m, the parallel beam width of the Mark I structure is narrower than that of the Mark II (flat-grid) source.

The parameters given in Table I are for beams tuned for minimum divergence by adjusting the plasma density for a fixed set of grid potentials. The perpendicular beam width, as well as the gradient-grid and suppressor currents, increase drastically if the plasma density deviates from the optimum value by more than ±10%.

TABLE I. 120-kV 0.5-sec PERFORMANCE CHARACTERISTICS OF TWO TEST MODULES WITH 8-cm x 10-cm ACCELERATOR-GRID ARRAYS. THE PARAMETERS LISTED ARE FOR BEAMS TUNED FOR MINIMUM DIVERGENCE (SEE TEXT).

| | Mark I | Mark I | Mark II |
|---|---|---|---|
| Gas | $H_2$ | $D_2$ | $H_2$ |
| Gas flow (T-ℓ/sec) | 4 | 7 | 7 |
| Accelerator Current (A) | 13 | 10 | 14 |
| Gap 1 voltage (kV) | 23 | 23 | 19 |
| Gradient-grid current, electrons to grid (mA) | 10 | 10 | 40 |
| Suppressor Voltage (kV) | 2.8 | 2.8 | 2.3 |
| Suppressor Current (A) | 1.0 | 0.9 | 1.2 |
| 1/e beam width[a] measured at 8.5 m: | | | |
| ⊥ to slots | ±1.34° | ±1.28° | ±1.24° |
| \|\| to slots | ±0.42° | ±0.42° | ±0.76° |
| Arc power (kW) | 25 | 19 | 23 |
| Filament power (kW) | 18 | 18 | 18 |

[a] See text

Operation with deuterium was limited because of the large neutron fluxes produced by d-d reactions between the energetic deuterium ions of the beam and deuterium atoms buried in the copper calorimeter. The reaction rate built up gradually as the copper was loaded with deuterium from successive beam pulses. After approximately one-hundred 120-keV beam pulses the neutron-production rate reached an asymptotic value -- approximately $10^{11}$ neutrons/sec during a beam pulse.

Topics such as reliability, grid heating, molecular-ion composition of the beam, and improvements in beam optics are being investigated.

Based on the R and D effort described above, LBL/LLL engineering groups have designed and started construction of complete prototype injection lines for the PPPL TFTR tokamak[10] and the GA DIII tokamak.[11] Testing of these prototypes is scheduled to start in a little over a year.

Summarizing the positive-ion based program, we note that enormous progress has been made in the last five years, and experimental modules are operating in an energy range that may be suitable for fueling some fusion devices. However, there is a great deal of work to be done before the present systems can be described as reliable components on which reactor engineers can base designs and cost estimates. In addition to emphasizing reliability and gas/electrical efficiency, we will work toward dc operation, and perhaps higher voltages, during the next few years.

## III. The Negative-Ion System Status

As mentioned earlier, negative-ion based systems, whether predicated on direct extraction of negative ions from sources, or conversion of positive ions to negative, is still in the R and D stage and will not be discussed here. Our efforts are mainly directed toward experimental and theoretical studies of methods of producing, transporting and accelerating negative-ion beams. The main investigation at present is based on implementation of a conceptual design for a 200-kW, $\geq$ 5-A $D^o$, dc (1-MW) system. Negative ions are being produced by double charge exchange of $\sim$ 1 keV. The demonstration of the 200-kV, 1-MW dc $D^o$ beam is presently scheduled for about 1980.

## References


1. J. M. Haughian et al., Proc. Sixth Symp. on Engineering Problems of Fusion Research, San Diego, Ca., 1975, (IEEE Nuclear and Plasma Science Society, 1975), p. 53.

2. K. W. Ehlers et al., Proc. 9th Symp. on Fusion Technology, Garmisch, Germany, 1976, (Pergamon Press Oxford, 1976), p. 795.

3. D. B. Hopkins et al., Proc. 9th Symp. on Fusion Technology, Garmisch, Germany, 1976, (Pergamon Press, Oxford and New York, 1976), p. 897.

4. H. M. Owren, W. R. Baker, D. B. Hopkins, and R. C. Acker, "The Lawrence Berkeley Laboratory Power Supply System for Neutral Beam Source Development," Proc. Seventh Symp. on Engineering Problems of Fusion Research, Knoxville, Tenn., 1977.

5. C. F. Burrell et al., "Calorimetric and Optical Beam Diagnostics on the LBL 120-keV Neutral Beam Test Facility," ibid.

6. K. W. Ehlers, "Rectangularly Shaped Large Area Plasma Source," ibid.

7. J. A. Paterson et al., "The Design and Fabrication of an Ion Accelerator for TFTR-Type Neutral Beam Systems," ibid.

8. L. A. Biagi and J. A. Paterson, "On Fabrication and Brazing of 120-kV, 65-A, 0.5-Sec Accelerator Grid Assemblies," ibid.

9. W. S. Cooper, K. Halbach, and S. B. Magyary, Proc. of the Second Symposium on Ion Sources and the Formation of Ion Beams, Berkeley, Ca, 1974, p. II-1.

10. "TFTR Neutral Beam Injection System Conceptual Design," Lawrence Berkeley Laboratory Report LBL-3296.

11. A. P. Colleraine et al., "The Doublet III Neutral Beam Injection System," Seventh Symp. on Engineering Problems of Fusion Research, Knoxville, Tenn., 1977.