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MASTER

DEVELOPMENT OF NEUTRAL BEAMS FOR FUSION PLASMA HEATING*

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Abstract

A state-of-the-art account of neutral beam technology at the LBL/LLNL and ORNL facilities is given with emphasis on positive-ion-based systems. The advances made in the last few years are elaborated and problem areas are identified. The ORNL program has successfully completed the neutral injection systems for PLT, ISX-B, and, most recently, PDX and the ISX-B upgrade. All of these are high current (60-100 A), medium energy (40-50 keV) systems. This program is also engaged in the development of a reactor-grade advanced positive ion system (150-200 kV/100 A/5-10 s) and a multimegawatt, long pulse (30 s) heating system for ISX-C. In a joint program, LBL and LLNL are developing and testing neutral beam injection systems based on the acceleration of positive ions for application in the 80- to 160-keV range on MFTF-B, D-III, TFTR/TFM, ETF, MNS, etc. A conceptual design of a 160-keV injection system for the German ZEPHYR project is in progress at LBL/LLNL and independently at ORNL. The laboratories are also engaged in the development of negative-ion-based systems for future applications at higher energies.

I. Introduction

The best understood and most effective technique of elevating the temperature of a magnetically confined plasma is the injection of intense beams of hydrogen or deuterium atoms. Upon entering the plasma, these energetic neutrals are ionized, and the trapped ions transfer their energy to the plasma particles.

The successful heating experiments on CLEO,[1] ATC,[2] ORMAK,[3] TFR,[4] and DITE[5] have paved the way for neutral beam injection to be recognized as a viable means of plasma heating. Because of the record temperature of about 6.5 keV achieved in PLT,[6] the technique has been hailed as a breakthrough towards achieving commercial fusion. Neutral injectors have become an integral part of most of the present-day machines, and larger injection powers are planned for the upcoming machines.

While the principle of neutral injection appears simple and straightforward, the technology is quite complex, particularly in the context of larger machines. For effective heating the beam has to penetrate well into the plasma. In other words, the mean free path of the injected neutral has to be about one-half or two-thirds of the minor radius of the device. The mean free path λ is given by[7]

$$\lambda = \frac{1}{n_e \sigma_{eff}} , \tag{1}$$

where n_e is the plasma density and σ_{eff} is the effective trapping cross section which, in turn, decreases with beam energy and depends upon plasma purity. It would suffice to say that for reactor-grade plasma injection, energies of several hundred kiloelectron volts are required for proper penetration. Heating scenarios have been suggested to relieve the energy needs. In one scenario, the injection is applied at reduced density and the final density is attained only at the end of the heating pulse where the alpha particle heating begins to play a role at the center of the plasma.[8] Another technique for improving the penetration is the ripple injection method.[9] The amount of energy injected into the plasma is governed by energy confinement considerations. It must overcome the energy lost by radiation and by conduction and heat the plasma to the desired level. Injection powers of 50-75 MW at about 150-200 keV for pulse lengths lasting several seconds are presently being envisioned for the INTOR and ETF devices.[7] Injection parameters for some of the experiments are listed in Table 1.

The difficulties of achieving these enormous power levels are apparent only when we probe deep into the multifaceted technology of neutral beams. This technology has advanced considerably during the last few years, and this paper reviews the progress. Although neutral beams are being

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Table 1. Parameters of some neutral injectors

Device	Beam energy (keV)	Extracted current (A)	Pulse length (S)	Monatomic fraction	Sources per injector	Neutral power per injector (MW)
PLT/ISX-B	40	60	0.3/0.1	0.8-0.85	1	0.7-0.9
PDX/ISX-B(U)	50/40	100	0.5/0.2	0.8-0.85	1	1.5-1.8
D-III	80	85	0.5	0.8	2	3.6
TFTR	120	65	1.5	0.8	3	7
JET-I[illegible]	160	100	10	0.8		11
T-15	80	35	1.5	0.7	2	2.5
JT-60	75	35	10	0.75	2	1.5
INTOR	175	100	10	0.85-0.9		15

developed elsewhere in the world,[10-13] the subject matter will be centered around the U.S. efforts.

Neutral beams are formed by neutralizing energetic ion beams by charge exchange. For positive ion beams the cross section for electron attachment falls rapidly when the relative speed of encounter is greater than about 2×10^8 cm/s. In this regard, injection systems based on negative ions have the inherent advantage of providing high neutralization efficiencies even at high energies. Nevertheless, the emphasis of this paper will be on positive-ion-based systems in view of the fact that they represent a far more evolved and mature technology capable of meeting the injection demands of a reactor-grade plasma.

After a brief description of a neutral beam system, we shall examine the details of some of the components by following the research and development work that is in progress at the LBL/LLNL and the ORNL neutral beam facilities.

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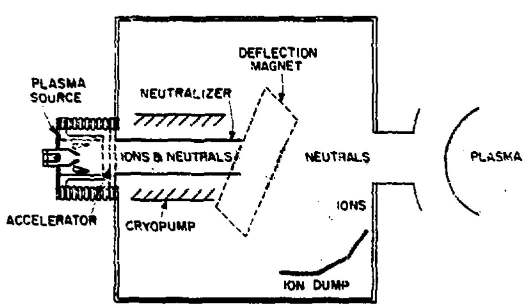

Fig. 1. Functional diagram of a neutral injection system.

II. Rudiments of a Neutral Injection System

Figure 1 is a schematic of a neutral injection system. The plasma generator provides a quiescent, uniform, and dense plasma from which the ions (hydrogen or deuterium) are extracted. The extracted ions, with a current density of about 0.3 A/cm^2, are accelerated to provide a beam of low angular divergence ($\leq 1°$ HWHM). The beam emanating from the source, several hundred square centimeters in cross section, is generally closely coupled to a conductance-limiting duct or neutralizer cell in which a fraction of the ions are converted into energetic neutrals by charge exchange with the background gas. The neutral fraction is given by

$$\frac{I_0}{I_1} = \frac{\sigma_{10}}{\sigma_{10} + \sigma_{01}} \left\{1 - \exp\left[- \int_0^L n\ell(\sigma_{10} + \sigma_{01})\, d\ell\right]\right\} , \quad (2)$$

where the subscripts 0 and 1 refer to neutral and charged states; σ_{01} and σ_{10} refer to reaction cross sections involving a change of state from 0 to 1 and 1 to 0, respectively; n is the neutral density; and L is the length of the gas cell. The dimensions of the neutralizer cell are selected to provide sufficient line density ($\int_0^L n\ell\, d\ell$) for near-equilibrium neutralization; the gas throughput is known from the ion source. The unneutralized component of the beam is magnetically deflected to a dump, and the neutrals stream straight into the plasma through a drift duct that serves as an interface between the injector and the plasma device. For a variety of reasons that will be explained later, the pressure beyond the gas cell exit should be in the 10^{-5}-torr range or less. The gas efficiency of the source (ratio of the number of ions emanating from the source to the number of gas particles introduced into the source) is typically around 50%, and the gas throughput is generally several tens of torr liters/s. Cryocondensation panels with enormous pumping speeds approaching ~100 kiloliters/s/m^2 are employed to ensure the "clean" vacuum requirement. The measurement of neutral beam power and the dumping of the unused ion beam are accomplished by the use of specially designed beam stops capable of dissipating megawatts of power, with peak power densities in the range of several kilowatts per square centimeter, for long pulse durations. A complex electrical system that repetitively switches several megawatts of electrical power for long pulse durations is employed to accelerate the beam. Last but not least is an elaborate diagnostic and data-handling system.

III. Neutral Beam Development at ORNL

Several neutral beam injectors, developed at ORNL, have been successfully utilized in various tokamaks. Four injectors,[14] operating simultaneously on PLT, delivered 2.4 MW of deuterium neutrals to the plasma and raised the ion temperature[6] to a record high of 6.5 keV. Two similar injectors[15] were used to heat the ISX-B plasma to $T_i(0) \cong 1$ keV and $<\beta> \cong 2.2\%$.[16] Each of these injectors, operating at 40 keV/60 A/100 ms, delivered about 750 kW of neutrals at the test stand to a target simulating the machine. Considerable improvement in performance has been realized in the recently developed 50-kV/100-A/500-ms PDX injectors.[17] Neutral powers of 2 MW (deuterium) and 1.8 MW (hydrogen) have been measured at a 30 x 34-cm target, simulating the machine opening, located 450 cm from the source. Reliability levels in excess of 90% have been measured at 1.5-1.7 MW(H^0) for 300-ms pulses. The atomic species emanating from all the above sources has been measured to be about 80-85%.[17,18] The ORNL program is now geared to the development of reactor-grade injectors (150-200 keV/100 A/5-10 s) as well as a long pulse (30 s), multimegawatt heating system for the ISX-C tokamak. A scaled-down source of a 10 x 25-cm grid pattern in a two-stage accelerator configuration has been operated at 107 keV/14 A/100 ms, and the pulse length of a 9-A beam at 90 keV has been extended to 5 s.[19] In a conventional injection system, the problem of disposing of several megajoules of unneutralized ion beam becomes formidable at higher energies and longer pulse lengths. Schemes of recovering the energy contained in the unneutralized fraction of the beam are being pursued[20] not only as a solution to the ion dump problem but also as a means of improving the system efficiency. In the area of negative ion sources, the ORNL group is pursuing two different approaches for producing negative ion plasma generators via the surface ionization concept. One is based on the modified Calutron,[21] and the other is based on using a cesium converter in conjunction with a modified duoPIGatron plasma generator.[22]

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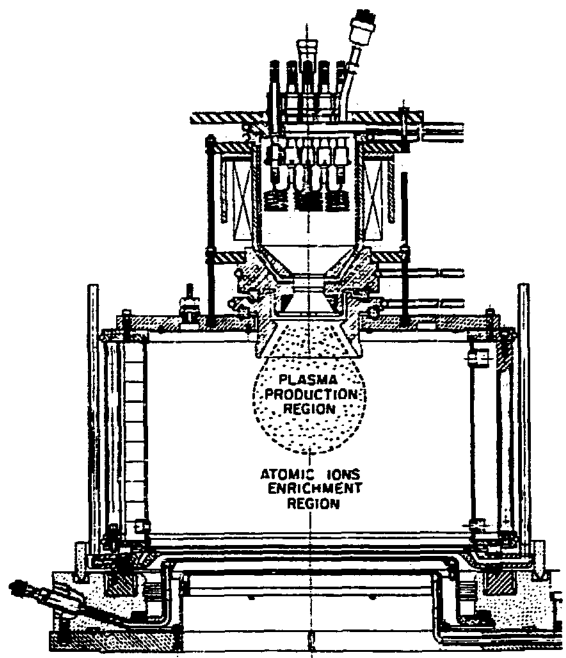

Fig. 2. The ion source used for PDX injection.

A. System Components

1. Plasma generator. The plasma generator should provide a hydrogen or deuterium plasma of high density (~10^{12} cm^{-3}) with combined spatial and temporal variations of less than ±5% over the several hundred square centimeters of extraction surface. Other highly desirable properties are the ability to provide a beam with high atomic species (>80%)[7] and operation with high gas efficiency ($\gtrsim$50%). The typical source configuration as demonstrated by the PDX injectors is shown in Fig. 2. It consists of 12 oxide-coated filaments carrying 40 A each, an intermediate electrode, two anodes, and the target cathode or extraction electrode. The second anode surface is lined with 30 permanent magnet columns to form a multipole magnetic line cusp field of ~2 kG (peak value). The source plasma is composed of a cathode plasma in the intermediate electrode and an anode plasma in the second anode chamber. The cathode plasma supplies the ionizing electrons to the anode region. The bulk of the ionization occurs at the mouth of the first anode. As they move towards the extraction surface, the molecular ions are converted into atomic ions, predominantly by dissociation, thereby enhancing the atomic species available for extraction. The atomic species in the range of

80-85% has been consistently measured in this type of source.

2. Accelerating structure. The several kilojoules of energy and the many meters of beam transport distance involved impose severe constraints on the accelerator design. In general, the beam is composed of thousands of beamlets, and the optical properties of the beam are primarily dictated by the beamlet optics. Current densities of about 0.3 A/cm^2 and HWHM divergence angles of less than a degree are expected of the beamlet. A high degree of grid transparency is obviously an advantage but is compromised to achieve beam brightness and grid stability. The grids are water-cooled and can tolerate about 100 W/cm^2 of dissipation for pulse lengths less than 500 ms. The beamlets are brought to a common focus by curving the grids. Thermal expansion, heat transfer, and voltage hold-off properties decide the selection of the material, molybdenum and OFHC copper being the prime candidates. So far the grids used in ORNL sources are made of copper, chosen as a compromise between cost and performance. Three grid-accelerating structures are used in PLT, ISX, and PDX injectors. The second gap provides a small potential barrier that prevents the electrons in the neutralizer plasma from streaming back to the plasma generator. At higher energies a two-stage acceleration scheme is favored because it offers higher current density and superior beam optics.[23] The size and shape of the individual apertures are crucial in deciding the beam optics. The accelerators employed in PLT injectors made use of 3.8-mm-diam straight cylindrical apertures. The power transmission efficiency (the ratio of the power reaching the target to the power drained from the accelerator supply) was only 40% for the 3.7×10^{-13}-sr PLT target.[14]

This efficiency was improved to 55% in ISX-B injectors[15] by shaping the beam-forming aperture. Calculations using sophisticated computer codes[24] have revealed that, by notching the plasma grid aperture as shown in Fig. 3, the ions that are extracted are those excluded from the aberrated region;[25] this results in vastly improved beam optics. This shape was adopted after a careful experimental study for the PDX sources,[26] and transmission efficiencies of about 70% in a 5.0×10^{-3}-sr target have been measured.[17,26] So far only the apertures on the beam-forming electrode are shaped to improve the optics. Optimization of the remaining electrodes is presently under way to minimize grid loadings.

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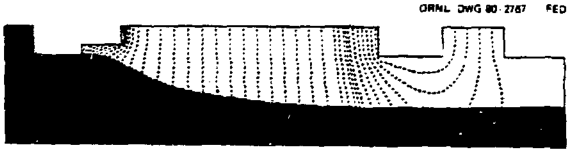

Fig. 3. Beamlet envelope in a three-grid accelerator using notched apertures.

3. Beam transport system. The beam transport system should satisfy the following requirements: (1) convert the energetic ion beam to energetic neutrals; (2) prevent the unneutralized ions from flowing towards the tokamak; and (3) act as an interface between the injector and the tokamak, ensuring as little perturbation as possible to the tokamak operation. In addition, the design should be such as to maximize the power that can be transmitted to the machine. In general, the design involves many compromises, and the PDX beam line is illustrated as an example. Figure 4 shows an exploded view of the beam line designed to deliver about 1.5 MW of neutrals through a 30 x 34-cm torus aperture located 4.5 m downstream from a 50-kV/100-A/0.5-s ion source with a 30-cm-diam grid pattern. The grids are curved to focus the beamlets to the torus aperture. The source is equipped with a gimbal mechanism for precise alignment of the beam and is shielded from the tokamak magnetic field by a soft iron skirt. The neutralizer is closely coupled to the source to minimize gas throughput and space charge blowup, and the dimensions of the neutralizer are selected to provide about 95% equilibrium neutralization.

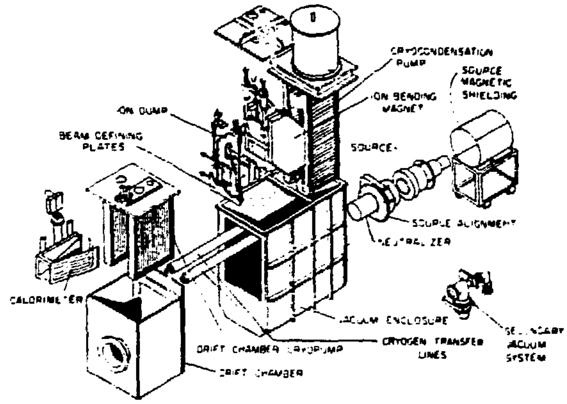

Fig. 4. The PDX beam line.

While a reduced density and increased length are favored for minimizing grid loading,[27] the reverse is true from the point of view of increasing the transmission efficiency. The selection of a 1.4-m-long neutralizer cell with provision to introduce additional gas into the cell is thus a compromise. The pressure beyond the gas cell should be in the 10^{-5}-torr range or less to minimize reionization losses[28] and to satisfy the tokamak operational requirements. The vacuum should also be "clean" to satisfy the stringent requirements on plasma purity in the tokamak. The gas throughput and the vacuum requirement necessitate pumping speeds of several hundred thousand liters/s in the region beyond the gas cell exit. Liquid-helium-cooled cryocondensation panels with approximately 4 m^2 of pumping surface are used to provide a pumping speed of about 300,000 liters/s. The cryopumps also satisfy the "clean vacuum" requirement. Immediately following the neutralizer is an electromagnet that deflects the unneutralized beam onto a water-cooled ion dump. The water-cooled dump surfaces are kept at a grazing angle to the beam to reduce the power density. The beam now enters a drift chamber through a defining aperture that scrapes off the wings of the beam. The drift aperture size could be varied in the range of 15 × 15 cm to 30 × 30 cm. The drift chamber is designed to avoid beam impingement problems[29] and to maintain a pressure of less than 3×10^{-5} torr to minimize reionization losses. A small cryopump (≅100,000 liters/s) is located inside the drift chamber to reduce the background pressure. The chamber also contains a retractable calorimeter, V-shaped to reduce the power density, for measuring power as well as allowing high duty cycle conditioning. When the calorimeter is retracted the beam passes through a second defining aperture, the size of which corresponds to the PDX machine opening (30 × 34 cm).

An inertial target is provided at the test stand to monitor the power that flows past the 30 × 34-cm aperture. A typical power flow diagram for one of the PDX sources is shown in Fig. 5.

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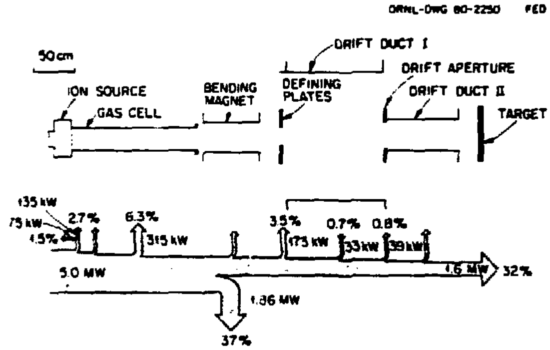

Fig. 5. Power flow diagram for a PDX injector.

4. Electrical system. The electrical system as depicted in Fig. 6 is designed to provide a wide range of voltages, currents, and pulse widths so that it can be matched to ever-evolving ion source requirements. The low voltage power supplies that power the plasma source are located on an isolation deck floating at the accel potential, with prime power brought across this potential via isolation transformers. The arc supply[30] is capable of delivering up to 2500 A at 240 V. Signals for monitoring and control of the plasma generator are transmitted across the accelerator potential through light pipes.[31] At one end a voltage-to-frequency converter and a LED convert the desired signal to a frequency-modulated light signal; at the other end a phototransistor and a frequency-to-voltage converter reconstruct the original signal. The high voltage power supplies are of modular construction capable of providing 168 kV/50 A/20 s in series mode and 84 kV/100 A/20 s in parallel mode. A high speed, high voltage switch or modulator[32] is installed between the accel supply and the beam-forming grid for pulse formation and protection of the source during high voltage breakdown. The capacity of the modulator is being upgraded to switch up to 100 A at 200 kV for pulse lengths extending to dc.

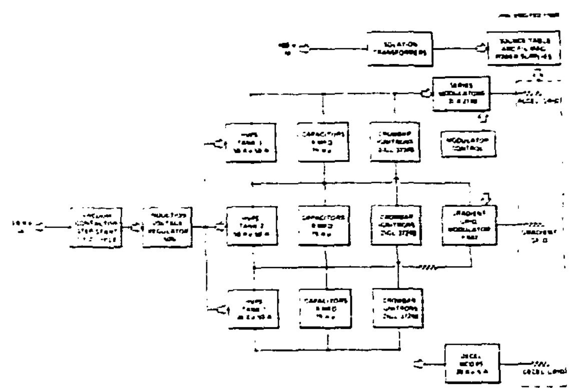

Fig. 6. Block diagram of the electrical system.

B. Advanced Positive Ion System (APIS)

The development of an advanced positive ion system is geared to the heating requirements of a fusion reactor. Several ion sources, each capable of delivering about 100 A at 150-200 keV for 5-10-s-long pulses, are presently being envisioned for heating the ETF or INTOR[33] devices. High reliability, long life, remote handling capability, and the ability to survive in an intense neutron radiation environment are some of the features that need to be incorporated in a reactor-grade injector. The problems that are presently being addressed in the APIS program are (1) ion source development, (2) energy recovery, and (3) beam line design.

1. Ion source development. The weakest link in the plasma generator for long pulses is the cathode. Several new cathode designs are being investigated in this connection. The LaB_6 hollow cathodes[34] and the indirectly heated cathodes are being extensively studied, and some of these cathodes[19] have been operated to provide about 1000 A of arc current for 10-s pulse lengths.[35] In the area of accelerator design, investigations are in progress to optimize the aperture geometry[36] for maximum power transmission with minimal grid loadings.

A rectangular accelerator geometry has been selected to improve the cooling efficiency. A two-stage source with a 10 × 25-cm grid pattern has been operated at 107 keV/14 A, and the pulse length of a 90-kV/9-A beam was extended to 5 s, while maintaining the optical quality of the beam.[19] The power transmission and grid loading characteristics of the source are shown in Fig. 7. For this particular source, care was taken to optimize only the primary beam optics. Investigations are under way to further minimize the grid loadings by shaping the apertures on all four grids. Detailed studies[37] involving the stability of the grids during high power beam extraction have been carried out, and design modifications to minimize grid deflections are being incorporated. Improved cooling schemes that will enhance the overall grid transparency are being evaluated. The grids will eventually be made of molybdenum to take advantage of its superior voltage hold-off and thermal deformation characteristics, low sputtering yield, and low secondary electron coefficient.

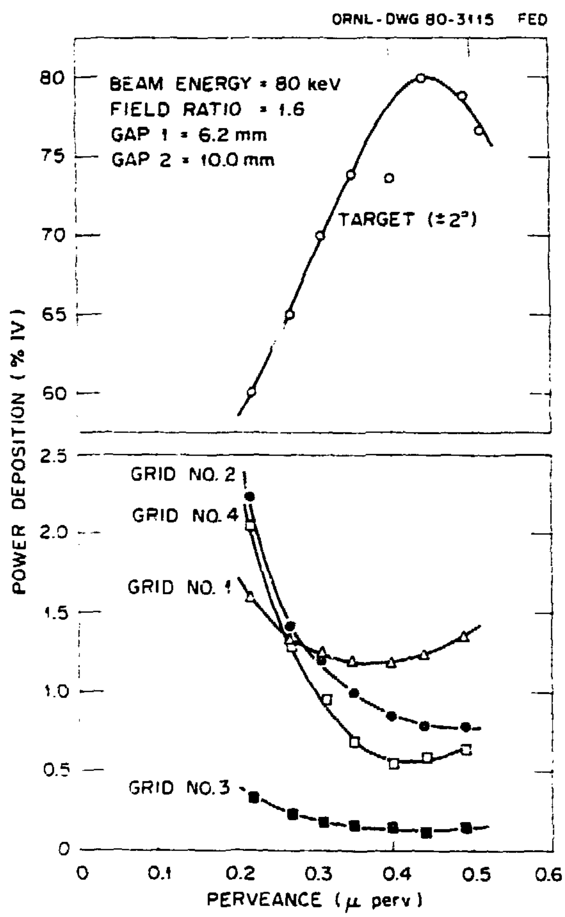

Fig. 7. Power transmission and grid loading characteristics for a two-stage accelerator.

2. Energy recovery. For relieving the problem of energy dissipation on the ion dump and improving the system efficiency, recovering the energy contained in the atomic ion fraction is quite important. The ORNL scheme consists of blocking the electrons from escaping the gas cell plasma with a transverse magnetic field and decelerating the ions to recover their energy (Fig. 8). Preliminary results are quite encouraging,[20] and additional experiments are planned with the ultimate idea of incorporating the energy recovery scheme into a full-scale system.

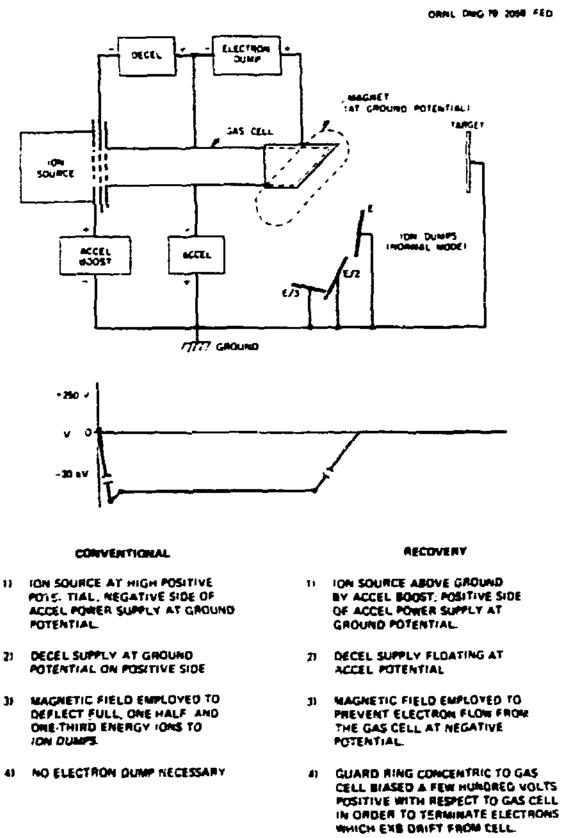

Fig. 8. Schematic of the energy recovery experiment.

3. Beam line design. Efforts are under way to make the beam line more compact, provide improvements in pumping, and incorporate the energy recovery concept in the beam line design. Extensive Monte Carlo simulation of neutral particle transport has been carried out[38] in complex beam line geometries to optimize beam line and cryopanel design.[39] As a possible alternative to cryocondensation pumps, cryosorption pumps are being evaluated.[39] Conceptual beam lines incorporating energy recovery techniques are being designed for the ZEPHYR project as well as for ISX-C injection.

C. Negative Ion Source Development

Two separate types of negative ion sources are being developed at ORNL, utilizing the surface ionization of positive ions on cesiated surfaces. One of them employs a Penning discharge that exists in a modified Calutron source for producing the positive ions. The positive ions are accelerated to a cesiated surface to generate negative ions. The other concept utilizes a modified duoPIGatron in conjunction with a cesium converter. Negative ion beams have been extracted from both these sources, and the latest results have been reported[21,22] in a recent international symposium.

IV. Neutral Beam Development at LBL/LLNL

LBL and LLNL have a joint program to develop and test neutral beam injection systems for mirror and tokamak experiments. There are several program elements, which we could categorize as research, development of hardware components and systems, prototyping, transfer of technology, and manufacturing. We also can divide the program in a different way, namely, into activities based on the production, acceleration, and neutralization of either positive or negative ions. Most of our activities, and all of the near-term applications, are based on positive ion technology, including development in the 80- to 160-keV range for MFTF-B, D-III, TFTR/TFM, ETF, MNS, and ZEPHYR. At energies above about 200 keV, positive-ion-based system efficiencies are unacceptably low for most applications, and negative-ion-based systems are being developed. Applications of negative ion technology are 5 to 10 years away.

The generic focus for the postive ion development is the 150-kV, 10- to 30-s APIS. The studies are first carried out on a fractional area (~15-A) source system and then extrapolated to full-sized (about 50- to 100-A) modules. Specifications for a negative ion system have not been fixed, but a general objective is the production of dc beams with particle energies of 200 keV and higher.

In the following sections a brief outline of the program is given, with recent references cited for details.

A. Positive Ion Technology

1. System elements. The main elements of a typical neutral beam injection system are shown schematically in Fig. 9.

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, multielectrode structure. The ions then pass through a neutralizer containing deuterium gas, and a fraction become 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 ensure good beam optics; to minimize accelerator damage when a spark occurs, the power supplies must also be capable of rapid turnoff 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.

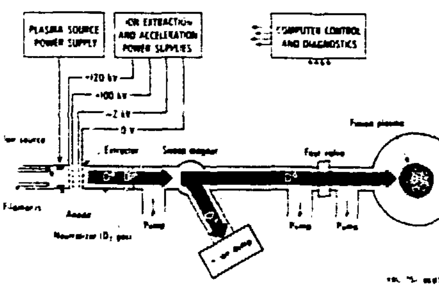

Fig. 9. Schematic of a typical neutral beam injection system.

In this discussion of the status of the program, the elements of the injection system will be described in turn. Background material is given in Ref. 40.

1.1 Plasma source. The plasma sources from which ions are extracted in all of our applications to date are of the "field-free" type,[41] in which the plasma is produced by a high current arc from many small filaments. These plasma sources have given fairly satisfactory operation for pulse lengths up to 1.5 s and give an atomic ion (D^+) fraction in the accelerated beam of about 65%. We are presently testing a larger volume "magnetic bucket" plasma source,[42,43] in which the walls are lined with permanent magnets in a cusp arrangement, and there are fewer but larger-diameter filaments. This source has been tested for several seconds without ion acceleration and appears suitable for 30-s operation. No facility is available for determining long pulse properties of an accelerated beam, but short pulse (20-ms) testing at 100 kV indicates that the atomic ion (D^+) fraction will be 75 to 80% at the arc power appropriate for 120 kV.

When operated under proper conditions, including electronic control of the heating current, plasma sources with filaments of the present bucket kind are expected to go 10^5 to 10^6 s before requiring replacement. Longer-lived and more rugged cathodes, perhaps hollow cathodes, are desirable and under investigation.

1.2 Accelerator. A four-grid, 10 x 40-cm accelerator electrode array is used. A cross section of one-half of a single slot is shown in Fig. 10.

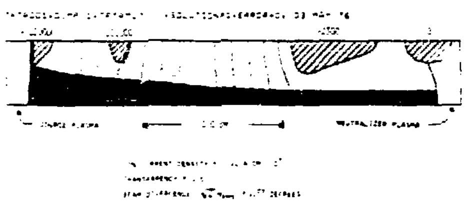

Fig. 10. Calculated beam trajectories and equipotentials for a 120-kV accelerator.

Ions are accelerated and electrostatically focused in the first two gaps; the third gap has a weak decelerating field to suppress downstream 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. The ion current density would be 0.31 A/cm^2 for a pure D^+ beam and is about 0.25 A/cm^2 for a beam with a realistic mixture of D^+, D_2^+, and D_3^+ ions.

During a pulse these electrodes are heated by the impingement of secondary particles produced by the beam. Uncooled electrodes of the kind shown in Fig. 10 have sufficient thermal capacity to permit operation for about 1.5 s — enough for present-generation experiments.

A prototype fractional area (~10 A) 120-keV accelerator designed for continuous operation is being tested.[44,45] The molybdenum grids are convectively cooled by flowing water through individual grid rails, and the thermal expansions are accommodated by the rail support modules. The design of these modules is such as to allow deflection and rotation at the grid rail ends, each rail being free to move independent of its neighbors. The accelerator module has been operated for 5-s pulses at 100 kV. The heat loads to the individual electrodes are monitored and found to be roughly 0.5% of the total beam power for each of the electrodes, under optimum tuning conditions. If the plasma density is not appropriate to the accelerating voltage, the heat loads are considerably larger. A larger unit, capable of 65-A operation at 120 kV, is under construction. As there is at present no facility capable of testing such a unit at full voltage and pulse length, the initial testing probably will be at 80 kV.

For some applications bakeable, neutron-resistant ceramic insulators with metal seals have been specified for the modules. The design and manufacture of large ceramic insulator assemblies have proven to be quite difficult. In Ref. 46 the development of two candidate materials, machinable glass ceramic and alumina, is described along with the ceramic-to-metal brazing techniques developed for each material. The microstructures of the brazed joints are examined and the results of microprobe studies presented. It has been found that the surfaces produced by different machining methods have a significant effect on the strength of brazed joints to the machinable glass ceramic. Lapped surfaces have given bond strengths up to three times those produced with other surfaces. Successful full-sized brazes have been realized between alumina and titanium and between machinable glass and titanium. Vacuum-tight joints between machinable glass and titanium have not been reliably achieved.

1.3 Neutralizer. Our beam neutralizers are channels with restricted pumping speed fed by excess gas passing from the ion source through the accelerator structure, in which some of the positive ions capture electrons from the gas. For future applications it is possible that we must pump out the excess gas from the ion source before it reaches the accelerator structure, for example, by conducting the plasma through a magnetic multipole guide structure[47] with radial pumping. In this case gas, not necessarily hydrogen, will have to be supplied for neutralization.

There is a possibility that at high energies, >80 keV, for example, there can be an interaction between the charged component of the beam and the plasma produced in the neutralizer by the beam. This possibility is being studied theoretically and experimentally.

1.4 Bending magnet. A bending magnet is used to separate the charged component from the neutral component. To date the magnet design has been fairly straightforward, but very careful attention to the design is required in the future for high energy, high power, longer pulse operation, because the power density on calorimeters and beam stops is uncomfortably high, and poor optics of the deflected ion beam could be disastrous. The beam dump problem will be eased when direct energy recovery techniques are developed.

1.5 Direct recovery. Following the neutralizer, it is possible, in principle, to decelerate the remaining charged beam and collect it at low energy. We have performed some experiments[48] that showed promise, but we have no experimental program at this time and are following with interest the work at ORNL reported elsewhere in this paper.

1.6 Calorimeter and ion beam dump. At present, beams are stopped on thick copper plates instrumented with arrays of thermocouples. The beam divergence is determined by on-line computation from the heat profiles.[49] Actively cooled calorimeters and beam stops are required for the HVTS upgrade and the NBETF (see next section).

2. Test facilities. The availability of high voltage, high power, long pulse test facilities continues to pace the development program. At LBL three facilities are operational: Test Stand IIIA has 150-kV/15-A/5-s capability and will be upgraded for 30-s operation during the coming year. TS IIIB has a capacitor-bank high voltage supply configured for 120-kV/70-A/20-ms operation. The Neutral Beam System Test Facility (NBSTF) is devoted completely, through September 1981, to work for the PPPL TFTR/TFM Program. It presently has 120-kV/65-A/0.5-s capability and is being upgraded to operate for 1.5 s. Following the work for PPPL, the NBSTF will be converted to a facility that can test the next generation of positive ion sources. It will be called the Neutral Beam Engineering Test Facility (NBETF) and will be capable of operation at 170 kV/65 A/30 s with a 10% duty factor. The NBETF is scheduled to be operational in April 1983. At LLNL the High Voltage Test Stand (HVTS) is operational for 80-kV/80-A/0.5-s development work and will be upgraded for 30-s operation in about 18 months.

Most confinement experiments will use deuterium neutral beams, and most of our development tasks involve deuterium operation. The instantaneous neutron production rates from D-D interactions in the neutralizers and in the calorimeter and beam stops are high.[50] TS IIIA and TS IIIB are not shielded and must operate at very low duty factors when deuterons are used. The NBSTF and HVTS are adequately shielded for deuterium operation.

Electronic development is vitally important to the successful operation of these test facilities. We are aiming at components and techniques to make the operation of neutral beam systems more reliable and to reduce the construction costs.[51] For example, we have developed reliable high voltage, high current, solid-state switches and a feedback-controlled arc power modulator. The arc modulator has been successfully used to vary the beam current as $V^{3/2}$ when V was changing with time, permitting operation with good beam optics even with no regulation of the high voltage. This is a promising approach for reducing the costs of neutral injection systems.

B. Negative Ion Technology

Next we describe the status of the LBL/LLNL negative-ion-based neutral beam development program, which has as its objective the development of megawatt dc injection systems. Until last year we concentrated on a system in which the negative ions were produced by double charge exchange in sodium vapor. At present, the emphasis is on a "self-extraction" source in which the negative ions are produced on a biased surface imbedded in a plasma.

In a short pulse experiment using double charge exchange, a beam of approximately 10-keV D^+ ions was converted to 2 A of D^- ions in a supersonic sodium vapor jet, demonstrating one way to produce a useful negative ion source.[52] A dc, surface-production, self-extraction source[53] is operating with ~0.5 A of self-extracted, 200-eV negative ions. Negative ion research should develop into negative ion technology within a few years.

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