THE TECHNOLOGY OF NEUTRAL-BEAM INJECTION BASED ON POSITIVE-ION SOURCES*

Madhavan M. Menon
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830
(615) 574-1115

I. INTRODUCTION

Injection of energetic neutrals of hydrogen and deuterium has been used quite effectively to heat the plasma in several fusion experiments.¹ In the United States, following the initial success with neutral beam injection into the ATC and ORMAK tokamaks, significant injection experiments have been conducted in the PLT, ISX, PDX, and D-III tokamaks. Examples from elsewhere in the world include the TFR in France, ASDEX in Germany, JFT-II in Japan, DITE in the United Kingdom, and T-II in the U.S.S.R. In tokamaks, apart from bulk heating of the plasma, neutral beam injection has been proposed for current drive, impurity control, and profile control. Neutral injection has also been applied in stellarators, examples of which are CLEO in the United Kingdom, Heliotron-E and JIPP T-II in Japan, and Wendelstein VII-A in Germany. Mirror machines have also used neutral beam injection. Examples in the United States are the 2XIIB and TMX devices. Proposed applications in mirror devices are sustaining and heating the end plugs, pumping thermal barriers, and heating the center cell.

All applications to date have used neutral beams with pulse lengths in the subsecond range. The injected power extends into the multimewatt level, approaching 10 MW in the case of PDX and D-III, and the beam energy is in the range from 20 to 80 keV. In the near future, key tokamak experiments in which neutral beam injection will be applied at power levels extending into the 10- to 25-MW range include TFTR in the United States, JET in Europe, and JT-60 in Japan (see Table I for the beam pulse lengths). In the area of mirror fusion, the MFTF-B experiment at the Lawrence Livermore National Laboratory (LLNL) plans to use a variety of quasi-dc neutral beam injectors. From a technological viewpoint, apart from the increased power

TABLE I. Neutral injection parameters for some fusion devices including those for INTOR, a conceptual reactor

Device	Beam energy (keV)	Neutral injection power (MW)	Beam pulse length (s)
PDX	50	6-8	0.3-0.5
D-III	80	7-10	0.5
TEXTOR	50	6	3-10
TFTR	120	20-25	0.5-1.5
T-15	80	6-9	1.5
JT-60	75	15	10
JET	80	10	5
MFTF	80		30
INTOR	150-200	75	5-10

levels, a major difference for the neutral injectors that are planned for the future from those that are operating today is in their need for longer pulse lengths. Extending the pulse length of the injectors at high power levels and at high beam brightness is the major goal of the neutral beam development laboratories. Other development areas include improving the atomic fraction in the beam to nearly 100%, increasing the beam brightness, and reducing the impurity content in the beam. Lifetime and reliability are, of course, important considerations. Advances made in each of these development areas are summarized in the following, elaborating on the work at Oak Ridge National Laboratory (ORNL).

II. LONG PULSE PLASMA SOURCES

In order to extract a beam for neutral injection it is necessary to create a high density plasma ($\sim 10^{12} \text{ cm}^{-3}$) that is spatially and temporally uniform (within 5%) over the several hundred square centimeters of the extraction surface. The richness in the atomic species content of this plasma is another important consideration. Several kinds of plasma sources are being used in neutral beam applications. This discussion, however, is mainly devoted to the duoPIGatron source² of ORNL and the magnetic multipole or "bucket" source³ of the Lawrence Berkeley National Laboratory (LBL).

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A. The Arc Discharge

Figure 1 shows the duoPIGatron ion source developed at ORNL for long pulse applications. Apart from providing active water cooling on all the components of the plasma source, a major change that has been introduced in the plasma source is in the electron emitter. The earlier versions (used successfully in the PLT, ISX, and PDX injectors) used oxide filaments for supplying electrons. The arc discharge current in these applications was several hundred amperes, while the filament heating current was only about 30% of the discharge current. Although the discharge current flowed through the filament, the operation was not affected because the discharge duration was less than the thermal time constant of the filament. For multisecond arc discharges this will no longer be the case; therefore, an indirectly heated cathode has been developed as a substitute for the oxide filaments. In this cathode the arc current is completed through the outer shell of the cathode, which has a low electrical resistance.

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Fig. 1. The ORNL long pulse ion source.

Figure 2 shows the indirectly heated cathode, which has an emission area of 100 cm^2 on the inside of a paraboloid. The emitter is made of La_2O_3 -doped molybdenum. Graphite heaters are employed to raise the temperature of the emitter to about 1900 K. Details of these cathodes are reported by Schechter and Tsai.⁴ Two of these cathodes in parallel were operated quite

Fig. 2. Indirectly heated cathode structure.

reliably, at a current density of $6 \text{ A}\cdot\text{cm}^{-2}$, to produce high power arc discharges ($120 \text{ V}/1200 \text{ A}$) with a 35-s pulse duration (Fig. 3). Thousands of discharge pulses of 30-s duration were produced recently at this arc level.

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Fig. 3. Oscilloscope of a 35-s arc discharge.

Other modifications introduced in the plasma source specifically for long pulse operation included providing active water cooling on all the components that are subjected to heat dissipation. Cooling channels are formed by an electrodeposition procedure on the intermediate electrode parts, anode 1, the anode 2 wall, and the backstreaming electron dump. The cusp field magnets are located inside the vacuum wall to effectively increase the field strength at the inner wall of the anode 2 chamber, thereby improving the confinement.

The "bucket" source developed at LBL consists essentially of a rectangular chamber with rows of permanent magnets to provide the cusped field confinement.⁵ Tungsten cathodes are located close to the side walls. The construction is thus quite simple. For long pulse discharges, the filament heater current is reduced as the discharge is established, allowing the arc current itself to heat the filament. Electronic protection is used to reduce the arc spotting problems. Similar sources, with some

modifications in the cusp field configuration, are also being used at the Japan Atomic Energy Research Institute (JAERI) for their JT-60 prototype neutral injector⁶ and at the Culham Laboratory for the JET neutral beam injection.⁷

A recent development from TRW that is relevant to long pulse arc formation is the use of radio-frequency rf power to create the plasma.⁸ The rf antenna is located inside the plasma chamber with magnetic cusp confinement, and the discharge is essentially suitable for dc operation. Recent tests show that the plasma density increases linearly with rf power, and in the operating pressure range of 1-10 mTorr, a plasma density in the region of 10^{10} - 10^{12} cm⁻³ can be obtained. The arc efficiency is found to be comparable to those of conventional arc discharge sources. The plasma density was uniform, and there were no deleterious noise effects due to the rf excitation. Damage to the ceramic antenna insulation due to backstreaming electron bombardment was reported during beam extraction.

B. The Atomic Species

The atomic species mix emanating from the extraction region of the source is becoming increasingly important as this fraction of the beam is primarily responsible for heating the plasma. In tokamaks the one-half and one-third energy components produced by the dissociation of the diatomic and triatomic components from the source could cause deleterious effects by way of edge heating. In the case of MFTF-B neutral beam injection, atomic species fractions in excess of 90% are required from the long pulse beams.⁹

The atomic fraction of the beam emerging from the ORNL-type ion sources has been measured to be about 80% at current densities of $0.2 \text{ A}\cdot\text{cm}^{-2}$ and higher.¹⁰ In this type of source, since the main ionization region is at the mouth of the intermediate electrode and since this region is followed by a long drift section (≈ 25 cm) that permits dissociation of the molecular ions, the atomic fraction is inherently high. The source magnetic field configuration, which diverges from the axis of the source, also helps to divert the hot electrons away from the extraction region. A low electron temperature is necessary not only to minimize ionization of molecules but also to aid dissociation of molecular ions. Studies are under way to optimize the electron feed region for maximum proton yield.

Bucket sources at LBL have also produced an atomic species fraction of about 80%.¹¹ The JAERI group has reported a 90% atomic yield from a bucket source, where the cusp field magnets are mounted azimuthally rather than longitudinally and the magnetic field at the inner wall of the plasma chamber is increased to about

2.7 kG by employing SmCo magnets with soft iron inserts between the thin wall and the magnet.¹² They claim that the atomic species mix scales with the ratio of the plasma volume to the loss area and the high field, azimuthal cusp field configuration essentially increases this ratio.

A different approach is being studied at LBL, where magnetic filters are used in the plasma chamber¹³ to separate a region near the extraction surface with a very low hot electron population. This, in turn, minimizes ionization occurring near the extraction grid and aids in the dissociation of molecular ions produced behind the filter. The price for increasing the species mix using such a filter is the increased arc power required to produce a dense plasma in the extraction region. Moreover, for long pulse operation, the magnets need to be shielded from backstreaming electrons that are generated in the accelerating column due to the finite pressure in this region. A full-scale, long pulse plasma source with a magnetic filter is currently being designed.

C. Impurities

Impurities injected along with the neutral beam have always been a concern in beam-heated plasmas because of their effect in increasing radiative losses. However, significant effects resulting from impurity injection have not been reported from the PLT, ISX, or PDX experiments. On the other hand, recent experiments in the D-III tokamak show increased levels of oxygen and hydroxide impurities with neutral beam injection.¹⁴ The impurity level decreases with the number of injection shots and approaches a plateau in the region of 1% for oxygen. Results from DITE also show impurities with beam injection; 4.5% oxygen and 1.6% carbon impurities have been analyzed.¹⁵ Significant levels of low Z impurities are reported in the case of the 2XIIB experiments¹⁶ and the more recent TMX experiments.¹⁷

Systematic studies of impurity content in the neutral beam have not been carried out in the United States. However, the JAERI team has conducted extensive measurements¹⁸ and has found appreciable impurities. These measurements show that the ion beams extracted from bucket sources contain more impurities, particularly the heavy impurities like copper, molybdenum, and tungsten, than do beams from duoPIGatron sources. Typical values measured are 3-8% light impurities (C^+ , O^+ , H_2O^+) and 0.05-0.4% heavy impurities. The light impurities are believed to come from the walls of the arc chamber and are reduced by source conditioning. Heavy impurities are presumed to originate from the filaments and accelerator by sputtering and are found to be lower when the plasma grid is kept floating. Extending the pulse length was found to increase the carbon, copper, and tungsten levels slightly, but the oxygen-related impurities were found to be lower. High duty cycle

conditioning and discharge cleaning were found to reduce the oxygen impurities from their initial level of 5-10% to about 1% or less. Recently Ott et al. have reported reducing the low Z impurities from 5% to 0.6% by titanium gettering of the inner walls of the arc chamber.¹⁹ Using SIMS and RBS techniques, Langley and Magee measured the impurity levels from the ORNL duoPIGatron sources used for PDK neutral beam injection.²⁰ The results are 1×10^{-3} C, 1.5×10^{-3} O, $<10^{-5}$ Cu, and $<10^{-5}$ all Z greater than 14.

Preliminary calculations²¹ suggest that, for the MFTF-B experiment, the oxygen impurity level from the sloshing neutral beam injectors should be less than 0.001% assuming no enhanced radial transport. The tolerable levels for higher Z impurities are even less because of the inverse Z^2 dependence. Since these levels of impurities are orders of magnitude less than those measured so far, it may be necessary to magnetically separate the full energy fraction of the beam prior to neutralization. The location of the magnet, the degree of decoupling to minimize the neutralization in the region between the accelerator and the analyzer magnet while preventing space charge blowup of the beam, and the effect of the magnetic field on beam optics are some of the critical issues in this scheme that must be addressed.

III. ACCELERATOR DEVELOPMENT

Considerable progress has been made in recent years in the development of accelerators suitable for extracting quasi-dc ion beams at multimewatt power levels.

The accelerator at ORNL is designed for 80-kV/50-A/30-s beam operation.²² It is a two-stage version with apertures shaped to improve the beam brightness (ratio of current density to the square of beamlet divergence) while minimizing the heat loading on the grids. The aperture geometry is shown in Fig. 4, and the design is based on numerical calculations²³ that predict a beamlet divergence of 0.26° (θ_{rms}) at a current density (H^+) of $0.21 \text{ A}\cdot\text{cm}^{-2}$. The accelerator, with a 13- by 43-cm active grid pattern, is made of OFHC copper. In order to maximize the cooling efficiency without sacrificing the overall grid transparency, the cooling passages are formed in a serpentine manner, running between each row of apertures. An electrodeposition technique is employed to form these cooling passages. The wavy cooling channels, coupled with the use of large ($\approx 8\text{-mm}$ -diam) apertures, enable high transparency (43.2%) even with the complex aperture geometry shown in Fig. 4. Figure 5 shows a grid before it is brazed to the water manifold. ORNL is also fabricating a set of water-cooled molybdenum grids using industrial capabilities (United Technologies Research Center). Like the copper grids, they also employ serpentine

Fig. 4. Aperture geometry for the 80-keV accelerator.

Fig. 5. An electroformed copper grid.

cooling passages, but unlike the copper grids, the fabrication procedure involves the brazing of two thin sections of plates with water cooling passages formed by chemical milling. Two grids have been successfully completed. One of these grids, with apertures optimized for 120-keV beam extraction,²⁴ is shown in Fig. 6.

Fig. 6. Water-cooled molybdenum grid made by United Technologies Research Center.

Testing of the 30-s ion source with copper grids is under way at ORNL. The ion source was operated at subsecond pulse lengths at full power, and the pulse lengths at 75 kV/35 A was extended to 2 s satisfactorily. The present limitation on pulse length is the lack of a long pulse beam stop at the test facility. A beam stop for long pulse operation (see next section) is being fabricated, and the pulse length will be extended to 30 s after its installation.

The electroforming technique is also being used for the fabrication of accelerators for JET²⁵ and TEXOR²⁶ long pulse neutral injection. The JAERI group, which has already operated 100-kV/35-A/10-s ion beams,²⁷ employs molybdenum grids with straight-water cooling tubes embedded between each row of apertures. Embedding the cooling tubes had been the practice at ORNL for the past several years, but the use of straight tubes adversely affected the overall grid transparency.

Neutral beam sources at LBL use slot apertures for their accelerator.²⁸ A 10- by 40-cm molybdenum accelerator has been fabricated using water-cooled tubes shaped to optimize the beam optics. The individual tubes are supplied with water through bellows mounted to permit free lateral expansion.²⁹ This accelerator was operated at 80 kV and 38 A, using deuterium gas at subsecond pulses. The maximum pulse length was limited to 2 s due to test stand limitations. The e-folding divergence angle in the direction parallel to the slots was only 0.24° at optimum perveance.

Both ORNL and LBL plan to test their 80-kV/40-A(D⁺)/30-s ion sources before the end of 1983 at the Neutral Beam Engineering Test Facility (NBETF) that is being completed at LBL.

IV. BEAM LINE COMPONENTS

In operating with long pulse lengths at high power, the only difficult component is the beam stop. The ion beam stop or ion dump is more problematic at higher beam energies. The beam power from the ion source is several megawatts and, for the ion source in which the grids are made to focus the beam downstream, the power density at the focal point can be several tens of megawatts. Inclining the targets at shallow angles with respect to the beam to relieve the power density on the beam stop is a common solution adopted at several laboratories.

The long pulse target made for the NBETF consists of 40 actively cooled plates, each of which can be remotely manipulated to select any angle or position with respect to the beam.³⁰ Each 20- by 20-cm Amzirc panel, designed for LBL by McDonnell Douglas Astronautics Company, is capable of dissipating 2 kW/cm² over its entire front surface.

ORNL is building a long pulse target using swirl tubes. The swirl tubes are formed by drawing a tube over a pretwisted tape. Past experience with such targets at ORNL shows that the tapes break loose from the tube due to the combined action of high pressure water flow and the beam-induced thermal cycling. The vibrations that result when high pressure water flows through the tube could cause water leaks in the target. In their latest design, thicker-walled (1.5-mm) tubes are used to minimize this problem, and the 9.5-mm-OD tubes are bent to match the beam profile in order to help locate the tapes inside the tubes. The ORNL design also permits replacement of the swirl tubes with internally finned tubes, which were shown to possess high heat flux handling characteristic during tests at LLNL and at Sandia National Laboratories. LLNL is designing beam stops with such tubes. A thin coating of vanadium is being considered in the LLNL design for increasing the sputter life.

The beam stops for the JET neutral injection system³¹ have adopted the so-called "hypervapatron cooling." The JT-60 injection system design employs tubes with fins on the outside.³² Both JET and JT-60 target designs are conservative, as they allow only <1 kW/cm² normal to the target. A different idea is being incorporated in the TEXTOR neutral beam injectors, where two rotating drums are used as the target.³³ The drums are 35 cm in diameter and 70 cm in length, with 250 axial cooling ducts 2.5 by 2.5 mm in cross section. They rotate at 3000 rpm and are designed for 30-40 kW/cm² normal to the target. Another rotating target,³⁴ with hypervapatron cooling channels 70 cm in diameter and rotating at 300 rpm, is being designed for the 160-keV neutral beam test facility³⁵ at Fontenay-aux-Roses. Instead of rotating the target, ORNL has proposed magnetically sweeping the beam to relieve the power density at the target.³⁶

V. THE ROLE OF POSITIVE-ION-BASED INJECTION SYSTEMS FOR REACTOR-SIZE DEVICES

It is clear from the preceding discussion that the technology of positive-ion-based injection systems has advanced considerably in recent years. Quasi-dc injection systems at energies up to 120 keV should be available within the next couple of years. The Fontenay group is extending the beam energy to 160 keV for the second phase of JET injection. Efforts in the direction of improving the atomic species fraction in the beam are also paying off, with several laboratories in the world quoting 90% atomic species yield from the ion source.

Certain calculations³⁷ show that a beam energy in the range from 100 to 150 keV might be adequate for optimal heating of reactor-size tokamaks. If this is indeed the case, the positive-ion-based systems appear to be the

closest in terms of technological readiness. However, if neutral beam injection is required for driving the current in large tokamaks, a beam energy of 150 keV may not be adequate. Since the efficiency of positive ion systems is dismally poor at higher energies, alternate techniques should be adopted. For reactor-size mirror applications, apart from the beam energy consideration, beam purity (monoenergetic beams with low impurity) is becoming increasingly important. Negative-ion-based injection systems³⁸ and/or rf techniques³⁹ might be the alternative. However, these alternative techniques, particularly the negative-ion-based systems, have not been developed to the same level as positive-ion-based systems. Therefore, it is too early to make a decision either in favor of or against any particular technique at this time.

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