Title
ADVANCED NEUTRAL-BEAM TECHNOLOGY

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Abstract

The successful heating of plasmas in confinement experiments such as 2XII, ORMAK, TFR, and PLT by the injection of energetic hydrogen or deuterium atoms (neutral beams) has led to requirements for neutral beams with more power, higher energies, and longer pulse lengths for the next generation of confinement devices (TFTR, DIII, MFTF-B, JET, JT-60, T-20). The 20-keV, 10-A, tens-of-millisecond injector modules of the early 70's have evolved to 80-kV, 80-A, 0.5-sec and 120-kV, 65-A, 0.5 sec modules which are currently in the final testing stages. Considerably more development will be required to achieve the 50- to 75-MW, 175- to 200-keV, 5- to 10-sec pulses of deuterium atoms envisioned for ETF and INTOR. Multi-megawatt injector systems are large (and expensive); they consist of large vacuum tanks with many square meters of cryogenic pumping panels, beam dumps capable of dissipating several megawatts of un-neutralized beam, bending magnets, electrical power systems capable of fast turnoff with low (capacity) stored energy, and, of course, the injector modules (ion sources and accelerators). The technology requirements associated with these components are described. At present the beams are produced by charge-exchange neutralization of high-current beams of protons or deuterons. The efficiency of neutral injection systems could be improved significantly if a) the energy of the un-neutralized ions could be recovered electrostatically or b) the neutral beams are formed by electron detachment from energetic D^- ions. The technology for either of these schemes has not been developed sufficiently to incorporate them into present injector systems; development efforts in these areas will be mentioned.

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I. Introduction

Most of the large magnetic confinement experiments now in operation or planned for the near future use high-power beams of hydrogen or deuterium atoms to heat the plasma. The concept of using energetic atoms, which penetrate the magnetic confinement field and are trapped when ionized by collisions with the confined plasma, was proposed in the 1950's[1] and used on the PHOENIX, OGRA, and ALICE mirror machines in the 1960's; but the technology for producing neutral beams with enough power to significantly heat a confined plasma did not evolve until the 1970's. World Wide progress since the first 20-kV, 10-A, tens-of-millisecond injector modules[2] has been so rapid that it is difficult to characterize the current status[3]. I believe it is fair to say that the state-of-the-art for neutral beams on operating confinement devices is the injection of 3 to 7 MW of neutral power, using multiple arrays of ion sources that operate in the range 15-50 kV, 30-100 A, for pulses ranging from tens to hundreds of milliseconds. As machines get larger, and confinement times improve, higher beam energies, more power, and longer pulse lengths are required. Ion sources that produce 80-kV, 80-A, 0.5-sec (for DIII and MFTF) and 120-kV, 65-A, 0.5-sec (for TFTR) beam pulses are in the final testing stages, and longer-pulse modules are under development in several laboratories. Considerably more development will be required to achieve the 50- to 75- MW, 175- to 200-keV, 5- to 10-sec pulses of deuterium atoms envisioned for ETF and INTOR.

The ion sources are the sine qua non of a neutral-beam injection system, but the entire system is required to deliver a neutral beam to the plasma. Whether a separate beamline (as used on tokamaks) or an integral part of the confinement vessel (as used on mirrors), a neutral beam system has the principal components illustrated in Fig. 1. 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 of the entrance duct, possibly releasing gas bursts or melting the surface. 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 re-ionized and lost in the magnetic field.

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.

An optimum design for a beamline involves a series of compromises in the selection and location of the components: the opening through the field coils, the position of the plasma, and the divergence of the neutral beam establish a solid angle for the location of the ion sources. On tokamaks it is desirable to have a valve at the end of the beamline; this can restrict the opening. The maximum length of the beamline is constrained by the building and by the size of the neutralizer, magnet, and ion dump and the requirement that there be adequate gas conductance to the pumps. The ion dump size and location must be chosen to be compatible with power densities that can be dissipated within the limits of heat-dump technology; the power density in the ion beam is, of course, determined by the beam optics of the accelerator and magnet and by the neutralization efficiency in the neutralizer. The ions striking the dump are a source of gas that must be pumped. For differential pumping, gas baffles should have small openings, yet they have to be large enough so that the beam can pass through; if gas baffles are located too near the neutralizer they do not block the streaming component from the duct-like neutralizer. The region between the accelerator and the sweep magnet is the effective neutralizer; this region must be shielded against magnetic fields from the confinement device (to prevent an enhanced divergence of the neutral beam) without significantly impeding the gas flow to the pumps. Computer codes have been developed to aid in optimizing beamline designs, but comparisons of predicted and actual beamline performance are scarce.

The technology base for advanced neutral beam injectors was recently reviewed, worldwide, by the various INTOR teams.[4] In this paper I briefly describe the design considerations for the beamline components.

The translation of Fig. 1 into a hardware design, after considering all the factors just discussed, is illustrated by the TFTR beamline (Fig. 2).

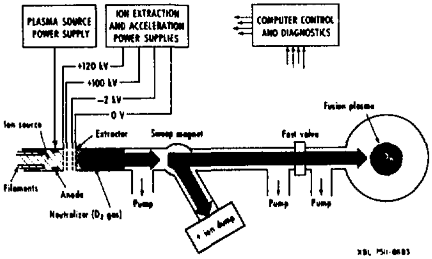

Fig. 1. Schematic of a typical neutral-beam injection system.

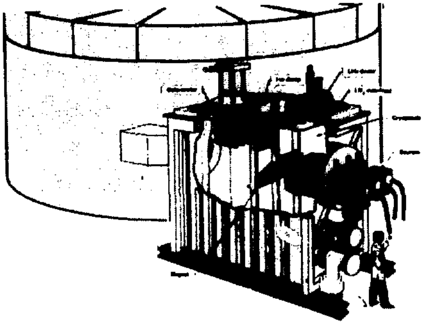

Fig. 2. TFTR Beamline

II. Injectors

A. Accelerators

The accelerators designed for neutral injectors must produce tens of amperes of well-collimated ions. The beam optics are established by a balance between the electrostatic fields in the accelerating region and the space charge of the ions. The maximum electric fields that can be maintained in the accelerator are limited by breakdown to about 100 kV/cm, and the space-charge balanced current densities are 500 to 150 mA/cm^2 in the 20- to 150-kV range. Thus many hundreds of square centimeters of accelerator area are required to produce the tens of amperes of interest for neutral injection sources. To maintain electrostatic control over such large areas, carefully aligned multiple-aperture grid arrays of either holes or slots are used; such arrays, for heavier ions accelerated to lower energies at lower current densities, were first developed as ion thrustors in the space program.[5] If the accelerator area gets very large, it is advantageous to concentrate the beam at a distant focus by curving the multiple-aperture arrays to aim the beamlets toward the focal point.

The apertures are often shaped to minimize beam aberrations (analagous to the Pierce angle in electron guns) and to minimize energy deposition in the structure by secondary particles created by ionization of the background gas or by secondary emission from the grids. Slots, formed by parallel arrays of shaped rails, have the advantages of high transparency of the accelerator array (60% is typical) and ready accommodation for thermal expansion of the rails without affecting the relative alignment of the slots; however, beam aberrations occur at the ends of the slots. Such aberrations are not a problem with arrays of holes, but the transparency of such arrays is lower (typically 40%) and misalignment due to thermal expansion of the grids may be a problem.

To block electrons produced by beam collisions with the gas in the neutralizer, the grid arrays are arranged such that the acceleration gap (above about 50 kV two acceleration gaps are frequently used) is followed by a gap with a small deceleration potential.[3] Although electrons are blocked by this gap, ions created in the neutralizer are accelerated into the accelerator. These ions produce secondary electrons which can cause appreciable heat loads if their trajectories are not considered in the design of the grids.

Since the limit on the useful current density is set by electrical breakdown between the grids, it would be highly desirable to find ways to raise the breakdown limit in the beam environment of the accelerator. Very little systematic work has been done on this complex problem. By comparing operating experiences at various laboratories, we find that 100 kV/cm seems to be an upper limit for copper, tungsten and molybdenum, the materials commonly used for grids. Hydrogen-fired molybdenum may have a slight advantage over copper, in voltage holding and it is more rugged; however, fabrication of grids out of molybdenum is generally more difficult and expensive. At LBL we have found that the ability to condition grids to their maximum voltage is impaired if too much energy (stored in the capacitance of the grids and power supplies) is available in a spark, unless the peak current in the spark is limited to several hundred amperes. The peak current from the power supplies can be limited by lossy elements in the cables connecting the accelerator,[6] but there is no straightforward way to limit the current from the capacitive energy stored in the accelerator structure. This may ultimately limit the size of high-voltage accelerator structures.

The current generation of accelerators installed on confinement devices have insufficient cooling of the grids to allow long-pulse operation; most rely in the heat capacity of the grids to limit the temperature rise for the relatively short beam pulses. Grids with active cooling for multi-second pulses have been developed at several laboratories and are currently under test.[3]

B. Plasma Sources

Since the beam optics are determined by the space charge in the beamlets, it is essential that the accelerator array be illuminated by a uniform flux of ions from the plasma source. Several sources that produce quiescent plasmas over an area of several hundred square centimeters have been developed:[3] The ORNL duo PIGatron, the FAR periplasmatron, the LBL field-free source, and the magnetic bucket[7] first adapted for injectors by Culham.

Besides plasma uniformity, an important criterion for a plasma source is that it produce a high fraction of atomic ions (D^+ vs D_2^+ and D_3^+) and a low level of higher Z impurity ions. The molecular ions are undesirable since they result in half-energy and third-energy atoms when dissociated in the neutralizer. These low-energy atoms do not penetrate as far into the confined fusion plasma, decrease the average energy of the injected particles, and may contribute to impurity release from the walls by sputtering. D^+ fractions of 80 to 85% have been obtained with several of the plasma sources.[3] Few detailed measurements of higher Z impurities in the beams have been reported. There have been indications that up to 2% contamination of oxygen may have been present in some of the beams,[8-10] but the injected impurity levels were too small to degrade plasma performance. A detailed impurity analysis by Okumura et al[11] has revealed several percent of water and hydrocarbon impurities plus some smaller contamination of higher Z impurities; a magnetic bucket, operated at higher arc potentials, produced slightly more copper impurity than a duoPIGatron source. A systematic comparison of relative impurity levels of the various plasma sources is not yet available.

For multi-second pulses the heat from electrons produced in the accelerator gap and accelerated into the plasma generator must be dissipated. Estimates of power densities of several kilowatts/cm^2 have been made - a not unreasonable number, since of the order of 10% (depending on the pressure in the accelerator) of the accelerator power could be in back-streaming electrons. The JAERI group is proposing a lambdatron source with an inclined heat dump to handle this power.[3]

III. Beamline Components

A. Neutralizer

The neutralizer must provide a D_2 line-density of gas sufficient to achieve the maximum neutralization of the beam. The neutralization efficiency for positive ions decreases with increasing energy (Fig. 3) and the line-density to achieve that neutralization fraction increases with energy.[12] At 20 keV only 100 mTorr-cm are required for deuterium, whereas 500 mTorr-cm are required at 160 keV. Other gases yield about the same neutralization efficiency but require smaller line densities; but the use of other gases introduces possible impurity contamination in the beam (due to gas diffusion into the plasma source) or the confined plasma.

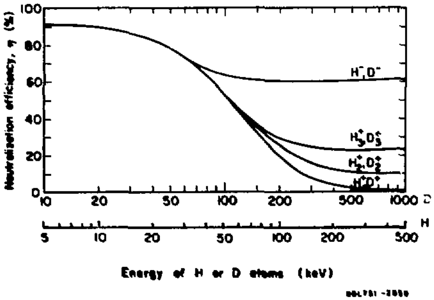

Fig. 3. *Neutralization efficiency* for deuterium ions.

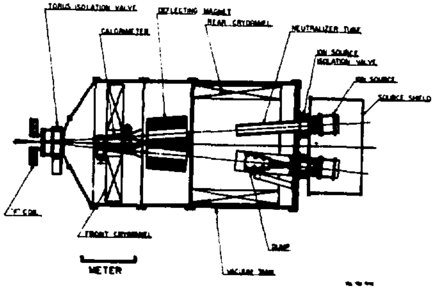

Fig. 4. *Schematic of the* DIII beamline.

The neutralizers currently in use are ducts which provide a limiting conductance for the gas from the plasma source that flows through the accelerator grids; supplemental gas feeds to the neutralizer may be used to increase the line density. Larger-area accelerators require neutralizers with larger cross sections and higher conductance per unit length; thus, to maintain the required line-density of gas the neutralizers must be longer or the gas flow must be increased. For TFTR the neutralizer has a cross section of 15 x 50 cm and is 2-m long, requiring an average pressure of about 2 mTorr D_2 for optimum neutralization. In calculating the pressure profile in the beamline and selecting the location of differential-pumping baffles the forward-streaming gas from the neutralizer must be considered.

Neutralization efficiencies as shown in Fig. 3 are calculated on the assumption that the neutralizer gas is molecular deuterium at room temperature. The neutralizer gas is partially ionized by the beam and collisions with the ions and electrons will tend to decrease the neutralization efficiency slightly. It is also possible that beam-plasma interactions could increase the divergence of the beam and that the gas temperature is higher than room temperature. Up to now, little attention has been paid to these possible complications in the neutralizer.

For long-pulse, high-energy beams it may be necessary to abandon the close coupled neutralizer to minimize heat loads on the grids, backstreaming electrons, and gas throughout. An alternative may be the use of crossed jets of condensible gas.

B. Sweep Magnet

The standard approach for removing the ions from the beam has been deflection in a transmission magnet. Limited space and high power densities have dictated the use of reflection magnets for DIII and JT60. The DIII beamline is shown in Fig. 4. Reflection magnets require more gap length along the beam, with the possibility of a high-pressure region (due to desorption of gas by beam bombardment with limited pumping conductance) which may result in a fan of ions produced by ionization of the beam in the gap. The advantage of a 180° reflection magnet is that the gas load from the ions striking the dump is produced in the high-pressure neutralizer section of the beamline; the disadvantage is that the differential-pumping baffle separating the neutralizer section from the magnet section has to have two apertures -

one for the total beam and one for the reflected ion beam - thus increasing the conductance of the baffle. Fringe-field defocusing of the beam in the direction perpendicular to the pole faces can be quite dramatic in a reflection magnet and careful design is required to keep the beam off the pole faces.

The magnet can be designed to defocus the beam at the ion dump, thus reducing the peak power density at the dump. The beam trajectories through the magnet are calculated on the basis of single-particle trajectories, neglecting space-charge effects. Space charge could possibly move the focus and result in a power density at the dump higher than calculated. Preliminary tests on the TFTR beamline indicate that this is not a significant effect.

C. Ion Dump

The ion dump must dissipate the power in the un-neutralized fraction of the beam. Since the neutralization fraction decreases with energy (Fig. 3) the power to the ion dump increases with beam energy. Most of the power is in the full energy D^+ component; however, the power in the half- and third-energy ions from dissociation of molecular ions is not negligible and dumps must also be provided for these ions.

For pulses up to 0.5 sec inertial dumps - thick copper plates with cooling lines to remove the heat between pulses - have been adequate. Longer pulse beams will require active dumps - thin metal cooled by high-velocity water. Although active dumps for higher power dissipation have been developed, a prudent design parameter for long pulses seems to be 2-3 kW/cm^2. Since there may be several megawatts in the ion beam with peak power densities of tens of kW/cm^2, the dumps must be inclined to reduce the power density at the surface.

The life of the ion dumps will be determined by thermal fatigue, sputtering of the surface, and possible neutron damage from d-d reactions of the incoming beam with deuterium implanted in the dump by the beam.

D. Pumping

The re-ionization of D atoms by collisions with D_2 in the energy range of interest for neutral injection, is about 1% per 2 x 10^{-5} T-m of gas. The gas flow per injector module is about 20 T-l/sec, with an additional gas load produced when the ions are stopped at the dumps. To keep re-ionization of the beam to a few percent, a pump speed of 0.5 to 1 Ml/sec per source module is required; the exact number is determined by the selection of components, pumps, and baffles for a particular beamline. To achieve such high pumping speeds, cyrocondensation pumps - metal panels cooled to liquid helium temperatures on which the deuterium gas is condensed - are used. These panels must be shielded from room-temperature radiation by liquid nitrogn cooled surfaces which are arranged so that gas, but not radiation, can reach the liquid helium panels. The pumping speed for deuterium for cryo-condensation pumps is 80 to 100 kl/sec per square meter of panel. Thus 5 to 10 m^2 of pumping panel are required per injector module. Sufficient space must be allowed between beamline components to ensure that the system pumping speed is not limited by gas conductance to the pumps.

The vapor pressure of the deuterium increases rapidly with temperature, and the condensed gas will be released if the temperature of the panels increases a few degrees above 4.2 K. The deuterium and tritium inventory condensed on the panels must be limited in case there is an up-to-air accident. The deuterium limit is set such that an explosive mixture of D_2 and O_2 will not be formed - the partial pressure of deuterium in an up-to-air accident should not exceed 13 T.[13] The tritium limit is set by the allowed inventory of potentially releasable tritium at the facility. To maintain the gas inventory below these limits, the cryopanels must be defrosted periodically and the gas removed by slower conventional pumps (e.g turbo-molecular pumps). During this defrost mode, which may require several hours, the beamline cannot be used for beam injection.

The radiation environment must also be considered in the cryopump design for a beamline. Neutrons and gamma rays can thermally heat the liquid helium panels, thus raising the vapor pressure of the condensed gas, or desorb gas by knock-on collisions.[13]

Alternate pumping schemes in which the gas is trapped more securely are desirable. Zirconium-aluminum getter pumps have been proposed as an alternative;[14] however, these require regeneration temperatures of 700°C.

E. Duct

When an external beamline is used, the beamline is connected to the confinement vessel by a duct that fits between the field coils. This is a region of high magnetic field with limited cross-sectional area. Gas released by wall bombardment in this region, either by direct interception of the neutral beam or by ions produced beyond the sweep magnet that are deflected into the wall by the magnetic field, will produce more ions in this region which will strike the walls to release more gas, etc.[15] This duct effect has been observed on PLT and is of particular concern for multi-second beam pulses, for which there is more time for gas buildup to occur. Experimental verification of the model used to describe this phenomenon is limited, but the duct should be designed to reduce direct beam interception and to maximize the conductance to remove gas from this region. The outgassing rate of the duct wall should be reduced by choice of material, baking, coating, or active cooling.[15]

The duct is a penetration through the neutron shielding surrounding a reactor-like confinement vessel. For operational modes in which beams are used only to reach ignition, and the injection pulse is followed by a long burn time, it may be desirable to block the duct with a shielding plug during the burn.

F. Power Systems

The several megawatts of electrical power required to produce the beams must be switched off rapidly if a spark occurs, to prevent damage to the accelerator structure. Regulation and rapid switching is usually accomplished by electronic tubes, which dissipate up to 10% of the required power. Thyristor switches, with negligible power dissipation, have been used on some test stands.[16] For reactor-like conditions, the sources will have to have evolved to a higher level of reliability, and certain simplifications which may be possible in the power system[16] should be investigated: elimination of the high-voltage regulation by feedback regulation of the arc power supply to maintain optimally focused beam at various accelerator voltages; no fast high-voltage switching, relying instead on star-point regulators and contactors in the primary lines; elimination of the fast-restartingafter-a-fault requirement; elimination of wide-selection-range for accelerator voltage; etc. None of these options have yet been tried. They will require interactive development of sources and power systems.

V. Direct Recovery and Negative Ions

At high energies, for which the neutralization efficiency is quite low, it would be highly desirable to electrostatically decelerate the ions and recover an appreciable fraction of their kinetic energy. This would not only improve the overall electrical efficiency of the system but also reduce the heat load to the ion dump. This is an extremely difficult problem in beam technology, primarily because electrons tend to load down the positive-potential electrodes. Only limited successes have been obtained on test stands.[4] A promising technique, being developed at ORNL,[17] is to have the injector slightly above ground potential and the neutralizer at the negative acceleration potential; electrons in the neutralizer are contained by a magnetic field across the exit of the neutralizer; ions remaining in the beam are decelerated on leaving the neutralizer.

Another way to improve the system efficiency at high energies is to form neutral beams by electron detachment of energetic D^- beams. The detachment of the weakly bound electron can be accomplished with relatively thin gas targets without appreciable ionization of the deuterium atoms, and neutralization efficiencies of 60% can be achieved even at very high energies (Fig. 4) Improved efficiencies may be possible with plasma targets or photo-detachment. There has been steady progress in the development of negative-ion sources, but the technology has not advanced sufficiently to incorporate negative-ion systems into planned beamlines.

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