WFPS-TME-074
MAY 1978

MASTER

DESIGN OF A
NEGATIVE ION NEUTRAL BEAM SYSTEM FOR TNS

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COOPERATIVE GRADUATE EDUCATION PROGRAM IN FUSION TECHNOLOGY
ADMINISTERED FOR THE U.S. DEPARTMENT OF ENERGY
BY THE WESTINGHOUSE ELECTRIC CORPORATION
CONTRACT EG-77-C-02-4231-A000

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The author wishes to acknowledge Drs. D. A. Sink and G. Gibson for thier expert guidance and technical assistance during this project, as well as Dr. G. Miley for assistance in securing the opportunity to participate in the cooperative program. Interactions with Todd Pridgeon, Mike Culbert, John McCowan and Eric Frantz, as well as the entire Westinghouse Fusion Power Systems Department were greatly appreciated. Special thanks go to Yvonne Harlow for her professional competence in the organization and typing of this report and her unselfish personal assistance.

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ABSTRACT

A conceptual design of a neutral beam line based on the neutralization of negative deuterium ions is presented. This work is a detailed design of a complete neutral beam line based on using negative ions from a direct extraction source. Anticipating major technological advancements, beam line components have been scaled including the negative ion sources and components for the direct energy recovery of charged beams and high speed cryogenic pumping. With application to the next step in experimental fusion reactors (TNS), the neutral beam injector system that has been designed provides 10 MW of 200 keV neutral deuterium atoms. Several arms are required for plasma ignition.

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1.0 INTRODUCTION

Presently, it appears that intense neutral beams of deuterium atoms will be required to heat thermonuclear plasmas beyond the ohmic heating stage to temperatures necessary for high power operation. These neutral beams may also be required for fueling of the plasma. Neutral particle injection is necessary to penetrate the confining magnetic fields present in and about the plasma. Neutral beam injectors have already been proven capable of effectively heating plasmas on earlier devices such as ORMAK. Injection systems are being designed for all new magnetic fusion devices and have already been fabricated for the PLT machine at Princeton. Existing designs for neutral beams require energies of only 150 keV (TFTR) or less with powers of a few megawatts per arm. These designs are based on acceleration of positive ions with subsequent neutralization.

Because of the relatively developed state of positive ion production and transport, these systems are acceptable at the lower energies. However, as required injection energies increase with larger fusion devices, the efficiencies for neutralization of positive ions drop rapidly (see Figure 1-1). With decreasing neutralization efficiency, higher currents are necessary which in turn introduces a greater power input to maintain the system and higher gas loads to be pumped from the beam arm. These factors lower the performance efficiencies of the injectors. With future fusion devices attempting to achieve breakeven in power balance, an efficient injection system is a necessary requirement.

It is well known, (e.g., see Ref 1) that at energies above 150 keV, a more efficient approach to neutral beam production is through neutralization of energetic negative ions. Figure 1-1 shows the relatively constant neutralization efficiency of negative ions at higher energies. This is the major reason for the application of negative ion systems in the high energy regime. Schemes other than the gas neutralizer of Figure 1-1 are also available in the case of negative ions. By utilizing such schemes as photodetachment of the weakly

Figure 1-1. Neutralization Efficiency vs Energy for a Charged Beam Traversing an Optimum Thickness Gas Cell.

bound electron and detachment by electric or magnetic field gradients, the efficiency of neutralization can approach 100%. If these methods are proven successful, the dominance of negative ions would become even more dramatic. Unfortunately, these methods are currently untried with no immediate plans for a concentrated effort in the near future.

As mentioned previously, the main reason for the use of positive ions is their highly developed state of production and transport. This is due directly to physical laws which make it easier for electrons to be knocked off of an atom than attached in the environments connected with fusion devices. This means that the production and transport of negative ions are relatively difficult objectives. For this reason, high current and high power negative ion sources are not readily available for use in neutral beam arms. The development efforts in this area have only recently begun to show encouraging results⁽²⁾. Aside from the production and acceleration of negative ions, other aspects of the neutral beam line are almost identical to that used with positive ions. Therefore, if negative ion sources are developed to the required state, the impact on the fusion development program will be greatly beneficial.

Development of a conceptual neutral beam system is an important step in the realization of negative ion based neutral beams. Very few such designs now exist. Most, if not all, of these designs are based on the double charge exchange scheme which utilizes a positive ion source followed by a charge exchange medium in which a fraction of the positive ions capture two electrons to form negative ions. This is currently recognized as the approach requiring the least development time, basically due to the availability of high current positive ion sources. However, major problems exist in the operation of charge exchange cells and their interaction with the rest of the beam arm. The presence of molecular beam components introduce a large beam energy spread and produce adverse effects on power deposition in the reactor plasma.

The design presented in this report is based on a system where negative ions are directly extracted from an ion source, eliminating the aforementioned problems. The major drawback to a system of this type is the absence of negative

ion sources of necessary size and quality. Therefore, the design will have to be based on expected source development. Scaling of present experimental devices will be used at points in the design, most notably in the case of the ion sources.

In order to have a self-consistent set of design parameters and limits within which to work, a fusion device has been chosen to which the resultant neutral beam arms may be fitted. This device is the TNS tokamak, now in the study phase. A reference design (TNS-4)⁽³⁾ by the Westinghouse Fusion Power Systems Department will serve to determine such requirements as beam energy, beam power, vacuum system, beam arm size, and beam aiming. As a result of this approach, the conceptual design will essentially determine the applicability of a negative ion based neutral beam to TNS, keeping development time in mind. If the negative ion system can be fitted to TNS, applicability to later, larger machines might be assumed.

2.0 REQUIREMENTS AND OPTIONS

2.1 GENERAL NEGATIVE ION/NEUTRAL BEAM STRUCTURE

The general structure of the type of neutral beam being considered in this design is outlined in Figure 2-1. Each of the components must be evaluated separately while keeping in mind integration with the rest of the system.

The ion source must produce a current of ions which is compatible with the requirements set by plasma heating and transport losses. This ion current is extracted and accelerated by a system which must match various source parameters and the fusion plasma penetration requirements. The energetic ions are then neutralized. Only a fraction of the total beam is neutralized, so both ions and neutrals now remain in the beam. If the ions were to remain in the beam, they would produce excessive power loadings on downstream components and cause havoc with neutral transport when deflected by the confining magnetic field of the plasma. The ions are therefore removed and an attempt is made to recover this energy which may be recycled through the system. The neutrals are left to drift into the plasma for heating and fueling purposes. Beam diagnostic equipment is necessary at the end of the beam line for monitoring the performance of the neutral beam. Each of these systems may or may not require a power input, depending on the choice of technique.

To maintain a proper environment for a working system, a few auxiliary systems are necessary. The whole beam line must operate at very low pressures. The primary vacuum system accomplishes this. The secondary vacuum system is necessary to back up the primary, and in the case of cryogenic pumping, it is necessary for regeneration. Since surfaces will be subjected to high-power beam fluxes, cooling of various components will also be necessary.

In a detailed design, all of the components must be considered along with the many subdivisions of each one. In this conceptual design all of the basic components will be considered.

Figure 2-1. Negative Ion/Neutral Beam Flow Chart.

2.2 REQUIREMENTS SET BY TOKAMAK REFERENCE DESIGN

As mentioned previously, several requirements are set by the fusion device to which the beam arm is to be applied. The parameters used at the time of this writing are based primarily on the TNS-4 option; however, some parameters have been changed slightly for reasons indicated when the changes appear.

Neutral beam power and energy to the plasma are obviously parameters set by the tokamak. This device is a 5.0 m major radius, 1.2 m minor radius tokamak with 20 Nb₃Sn superconducting TF coils. For $Z_{\text{eff}} = 1$, an average plasma density of $1.3 \times 10^{20} \text{ m}^{-3}$, and for near radial injection an injector energy of 150 keV is necessary. For higher plasma densities, larger minor radii, off-radial injection, or plasma impurities the energy requirement could go as high as 300 keV. For this reason an injection energy of 200 keV has been chosen as the reference. The injection power is estimated to be 50 MW but values of 75 MW are required depending on various assumed values of beam trapping efficiencies by the plasma. A safe assumption would be to allow placement of neutral beam arms at every other spacing between TF coils, allowing a maximum of 10 neutral beam arms. For this reason, a per arm power of 10 MW has been chosen, allowing total neutral beam powers from 10 MW to 100 MW in multiples of 10. The total beam power can then be adjusted by varying the number of beam arms. The neutral beam must also be able to run for six sec pulses every 300 sec for the tokamak to reach ignition. Presumably, shorter pulse lengths may be required with higher powers, the pulse length being inversely proportional to the beam power. The six second pulse length was calculated assuming a beam power of 50 MW. Since the total beam power is left undetermined in this design, a pulse length of six seconds shall be assumed.

The tokamak design imposes restrictions on the overall size of the neutral beam line, but they turn out to be very lenient and, as will be seen later, are of no concern. Access space should be allowed between beam arms, but even taking this into consideration would allow beam arms on the order of 4 m wide, 8 m high, and 10 m long. Obviously it would be advantageous to make the beam arm as compact as possible.

A major restriction due to the neutral beam arm tokamak interface has to do with beam aiming. Taking into consideration the optimum point for beam convergence in multi-source systems, beam arm torus duct clearances, beam divergences and focusing, relationships can be developed between maximum lateral source displacement and the distance of the source from the torus. These relationships are developed later. At this point it will be noted that the neutral beam duct is 2 m long with an inside opening of 125 cm vertical and 47 cm horizontal. Also, the optimum multi-beam convergence point for best heating of the plasma is about midway between the plasma centerline and the outer plasma edge⁽⁴⁾. This point is about 103 cm inward from the torus end of the beam duct in the case of TNS-4, making the target 303 cm from the neutral beam end of the duct.

One final consideration is the gas load from the neutral beam arms flowing into the torus. No figures were available for the maximum acceptable cold gas flow into the torus for TNS. However, in the design of TFTR, a forerunner of TNS now under construction, a cold gas flow of 1 torr liter per pulse was allowed into the torus from all beam lines⁽⁵⁾. An attempt will be made to meet this criterion, although it may be considered a rather conservative value considering the relative sizes of the two machines. The vacuum at the torus end of the duct will be assumed to be approximately 10^{-8} torr at the start of the neutral beam pulse.

2.3 NEUTRALIZER

In the case of negative ion neutralization, several techniques are possible. Photodetachment and electromagnetic detachment are very attractive possibilities due to their theoretically high efficiencies of neutralization. But since they have barely been investigated on a theoretical level, much less experimental, these options shall be foregone in favor of more proven techniques. More proven techniques are alkali metal vapor jets and D_2 gas and plasma cells. The alkali metal vapor jet and the D_2 plasma cell are still under investigation. Both require power inputs, although minimal for the metal jet. The metal jet has neutralization efficiencies roughly equal to that of the D_2 gas cell and interesting vacuum properties, as it acts as a vacuum pump and gas barrier. But contamination of adjacent materials with stray metal vapors is a major

problem. The plasma cell has slightly higher (~10-20% higher) efficiencies, but plasma confinement and interaction with the beam give rise to serious problems.

The simplest and most reliable neutralization method is the D_2 gas cell. No power is required and the D_2 gas is readily available in the form of unionized source gas. This is the neutralization technique to be used in the present design. Two choices exist for applying the technique. As shown in Figure 2-2, when a D^- beam traverses a D_2 gas cell the equilibrium fractions at the optimum thickness for D^0 production show an appreciable beam fraction in both the D^- and D^+ states. When trying to recover the energy of the charged beam portion, problems may be encountered with the presence of two oppositely charged beams moving in the same direction. If the cell is made denser, the D^- component gradually disappears leaving only the D^+ component for eventual collection, but with a loss of efficiency in the production of D^0 . The relative merits of each of these schemes will be treated later. For now, the schemes shall be designated as optimum and overdense with the following properties:

1. Optimum Cell - cell thickness; $4.1 \times 10^{15} D_2 \text{ molecule/cm}^2$
beam composition; 59.7% D^0
27.2% D^+
13.1% D^-
2. Overdense Cell - cell thickness; $9.3 \times 10^{15} D_2 \text{ molecule/cm}^2$
beam composition; 45.3% D^0
53.7% D^+
1.0% D^-

The overdense condition has been chosen to occur when D^- is 1% of the total beam. Since this fraction would eventually occur as a power loading somewhere in the system, its impact will be investigated later.

The required gas throughput will be determined by the neutralizer size and structure. The neutralizer design is determined from beam aiming and clearance considerations.

Figure 2-2. Neutralization of a 200 keV D^- Beam in a D_2 Gas Neutralizer.

2.4. CHARGED PARTICLE REMOVAL AND COLLECTION

As pointed out earlier, the charged beam component emerging from the neutralizer must be removed before allowing the beam to approach the magnetic fields of the torus. In present injectors, the charged component is merely deflected by an in-line magnet to a beam collector where the thermal energy is dumped. This energy could be recovered thermally at a thermal cycle efficiency (about 30%). Work is presently under way to develop means of recovering the charged beam energy electrically at efficiencies greater than 70%. Successful operation of such systems have occurred on small scales. Adaption to high power systems would greatly enhance the efficiency of neutral beam production.

The basic method of direct conversion is slowing down the energetic beam in an electric field, collecting the charged particles on a biased plate or electrode, and removing the charges as current through a power conversion system. Using this method, it would be possible to bend the charged beam out of the primary beam path, to a system of electrodes which would comprise the direct converter.

Another approach for charged particle removal involves use of the beam's inherent space charge. No bending magnet is used here. The charged beam is allowed to blow up due to space charge forces, decelerate and collect on biased electrodes. This type of system is inherently more compact, as the whole operation can be performed within a relatively small distance from the beam axis. Also, the problems of powering and cooling a bending magnet would be eliminated, as well as consideration for the effects of the bending magnetic field on upstream ion beam trajectories. For these reasons, the space charge controlled converter system will be used. Due to the common reliance on deceleration and collection techniques, the stage of development of both systems are nearly identical, therefore there is no need for comparison in this area.

An in-line space charge controlled converter must first eliminate particles oppositely charged to the particles to be collected from the space traversed by the beam. The beam space then has a net charge. Like charges are repelled out of the beam path and collected on a decelerating electrode. This has been tried experimentally with one energetic charge species (viz, positive ions).

A neutral beam system utilizing the overdense neutralization scheme, where, for the most part, only positive ions and neutrals are present, could then use a direct converter similar to and scaled from one of these experimental devices. In the optimum neutralization case, two energetic charged species are present and the problem becomes more difficult. Separation and collection of both species implies a multi-step process considerably more complex than the single charge system.

An energetic particle beam traversing a background gas is constantly ionizing the gas and producing slow ions and electrons which tend to move in or out of the beam to maintain space charge neutrality. Collection of positive ions requires three electrodes in the following order along the beam path (see Figure 2-3):

1. Electron Suppressor - negatively biased with respect to upstream potential to remove electrons from the beam, to allow space charge blow up of the positive ions.
2. Positive Ion Collector - positively biased (at voltage nearly corresponding to positive beam energy) for deceleration and collection of blown up ions.
3. Electron Suppressor - negatively biased with respect to downstream potential to prevent downstream electrons from being accelerated and collected on positive ion collector, cancelling collected positive charge.

In addition, the direct collection unit will require cooling of surfaces interacting with energetic particles, and power supplies which interface with the overall electrical system for the neutral beam arm.

Due to foreseen problems with particle control, electrode biasing and the general inexperience in collection of doubly charged beams, the overdense scheme will be used in this design. Therefore, the positive ion collection scheme will be used.

Figure 2-3. Positive Ion Direct Recovery Unit Scheme.

In the development of this design, an in-line space charge direct conversion scheme was contrived for doubly charged beams. Although only the basic scheme was outlined, and no parametric study was undertaken, it shall be mentioned below for possible further investigation.

Assuming a beam consistent with the optimum neutralization scheme (i.e., 27% D^+ , 13% D^-), the collection unit is basically a tandem version of the collection unit described above. Six electrodes are necessary as follows (see Figure 2-4):

1. Electron Suppressor - Biased slightly negative with respect to upstream potential, this electrode suppresses slow electrons to leave approximately half of the D^+ charge uncompensated.
2. Positive Ion Collector - Biased positively at a voltage corresponding nearly to the beam energy, this electrode slows down all and collects the uncompensated half of the positive ions. Negative ions are accelerated to almost twice the original beam energy.
3. Electron Suppressor - Biased slightly negative with respect to positive ion collector. Keeps downstream electrons from collecting on positive collector.
4. Slow Ion Suppressor - Biased near positive ion collector potential. Repels remainder of slow positive ions from beam space, allowing negative ions to expand.
5. Negative Ion Collector - Biased negatively with respect to downstream potential, at potential corresponding nearly to original beam energy. Slows down and collects double energy negative ions.
6. Positive Ion Suppressor - Biased slightly positive with respect to downstream potential. Keeps downstream positive ions from collecting on negative ion collector.

POSITIVE ION
SUPPRESSOR

NEGATIVE ION
COLLECTOR

SLOW POSITIVE
ION SUPPRESSOR

ELECTRON
SUPPRESSOR

POSITIVE ION
COLLECTOR

ELECTRON
SUPPRESSOR

NEUTRALIZER CELL

Figure 2-4. Tandem (Pos-Neg) Direct Recovery Unit Scheme.

2.5. ION SOURCE AND ACCELERATOR

The ion source requirements are set by the required neutral beam energy and power, and transport efficiencies along the beam line. The neutral beam power, P_{NB} , is defined as the product of I_- , the original negative ion current, η_T , the total transport efficiency with regards to particle loss, η_N , the neutralization efficiency for negative ions at the desired energy, and V_{NB} , the desired neutral beam energy.

$$P_{NB} = \eta_T \eta_N I_- V_{NB} \quad (1)$$

For this design P_{NB} is 10 MW and V_{NB} is 200 keV. Since the overdense neutralization scheme has been chosen, η_N is .453 from subsection 2.3. The final parameter, η_T , will be assigned a value of .9 assuming that 90% of the original beam can be guided through the neutral beam arm to the torus. Given these values, the required negative ion current is determined as 123 A.

Other source considerations are size, power need, beam divergence, gas efficiency, current density, beam size, and pulse length. These parameters will be determined by the actual characteristics of available sources or predicted characteristics in some cases. Although the choice of these parameters are limited by source availability, several experimental sources such as magnetrons, pennings, and duoplasmatrons⁽²⁾ exist and the source can be chosen by weighing the relative merits of each with respect to the above considerations and the ease of scaling. Scaling will be a necessity since the highest currents available are about 1 A per source, which would mean an unrealistic 123 sources per beam line.

Size and power need should be minimized, assuming all other parameters fit the system first. Beam size and divergence must be adequate for the beam to fit through the beam duct at the torus after proper aiming and focusing. Half angle divergences of less than two degrees are usually required. Current density and beam size are important factors which will have major effects on the accelerator structure and direct recovery units. Typical current densities for neutral beam injector use are between 0.1 and 1 A/cm². The pulse length

should be six sec as already noted for this design. Compared to the pulse lengths on the order of 100 ms for experimental sources, the six sec length can be considered as essentially dc operation.

The required gas efficiency can be estimated by comparison with positive ion systems. If it is assumed that operation with present positive ion sources presents no unsolvable pumping problems, negative ion systems should be able to operate under equivalent conditions of gas loading. Even though negative ion systems may require slightly lower pressures in the pre-neutralizer regions, additional space for pumping is usually available in positive ion systems which should compensate for this effect. Besides equivalent gas loads, other assumptions are: 30 to 50% gas efficiency for positive sources, 2 to 3 molecules of gas released per energetic ion hitting a surface; 18% neutralization efficiency for positive ions; 45% for negative ions; and equivalent neutral beam currents (i.e., $0.18 I_+ = 0.45 I_-$). If the total gas load is assumed to be from the total nonneutralized portion of the beam hitting walls plus unionized source gas, a value of approximately 10% for a reasonable negative ion source gas efficiency is arrived at. For reference, the above considerations produced the following equation.

$$G_- = \left[(Q-1) \frac{\eta_-}{\eta_+} + \frac{\eta_-}{\eta_+ G_+} - (Q-1) \right]^{-1} \quad (2)$$

where G_- = negative source gas efficiency
 G_+ = positive source gas efficiency
 η_- = negative ion neutralization efficiency
 η_+ = positive ion neutralization efficiency
 Q = number of gas molecules (D_2) released per energetic ion ($D^{+,-}$) hitting surface

The accelerator structure must be capable of extracting the D^- ion current from the source plasma and accelerating it to 200 keV within a reasonable distance. Focusing of the ions at prescribed points along the beam line is also performed by the accelerating grids.

For focusing of the ion beamlets a multiple grid arrangement is necessary. Successive grids are curved at prescribed radii and the grid openings laterally displaced from its counterpart of the previous grid. The displacement and radii are determined after detailed analysis of ion trajectories with consideration for grid shape, size, bias, and axial separation.

Grid size and shape will be determined mostly by beam size and shape. Axial separations and biases are determined by beam current densities and desired voltages. Child's law, which determines the maximum current densities one can accelerate over a given voltage difference and distance, and voltage breakdown considerations, which determine maximum voltages to be held across given gap sizes under given pressures, are the most restrictive considerations for grid bias and spacing.

In addition to acceleration of the primary beam, care must be taken to prevent acceleration of oppositely charged D^+ ions to the source. This is done by accelerating the D^- to an energy slightly above that desired, and then decelerating to the desired energy. This forms an electric field barrier at the far end of the accelerating line to slow D^+ ions which would otherwise be attracted and accelerated by the high negative field gradient.

Finally, electrical and thermal power loading of the grids must be considered. Slow ions and electrons produced in the beam path by background gas ionization and charge exchange, are attracted by the biased grids and produce electrical as well as thermal loads on the system. Secondary electrons produced by these collisions on the grids complicate the matter even further. Also, any electrons present in the D^- beam are accelerated with the beam causing a power loading which is nonusable energy in the form of fast electrons. Therefore, care must be taken to provide adequate power supplies for holding of biases against the extra current, to construct the grids so they are capable of withstanding the thermal loads, and constructing and arranging the grids to minimize primary beam interception and maximize conductance, allowing lower pressures and lower ionization rates in the grid region.

2.6 BEAM DIAGNOSTICS

Assessment of the actual power delivered by the neutral beam arm is necessary for control and inspection of the injector. As in previous designs, this diagnostic step will be performed by inserting a calorimeter-beam stop in the beam line during testing or conditioning pulses. The beam arm would be sealed off from the torus during these tests. The calorimeter must be capable of receiving the full power generated by the sources, i.e., ~ 25 MW (123 A @ 200 keV). Water flowing through the calorimeter will be heated by the incident beam and the temperature rise calibrated to assess the incident beam power.

2.7 VACUUM SYSTEM

The vacuum system is a very critical part of the overall neutral beam arm. High vacuum must be maintained throughout the beam line to minimize beam-gas reactions thus maintaining the desired beam structure over the total path length.

The vacuum system consists of primary and secondary subsystems. The secondary subsystem serves to pump down the beam line from atmospheric pressure to about 10^{-6} torr where the primary subsystem takes over, to continue to back up the primary system, and, in the case of a regenerative primary system, for removal of the desorbed gases during regeneration. The primary vacuum system is responsible for evacuating the beam line to the pressures required for operation.

From experience with positive ion beam lines and expected lower pressures with negative ions, cryogenic pumping will be necessary to facilitate the high pumping speeds. Cryogenic pumping requires regeneration so the secondary subsystem will be required for this purpose also. Liquid helium and nitrogen supplies will be necessary, however, since the tokamak used for reference here has superconducting magnetic field coils, the refrigeration system would be necessary nevertheless. Due to the large amount of liquid helium and nitrogen expected to be required for these coils, the concern over providing the refrigeration for the cryopump system should be minimal as it is expected to be only about 10% of the total capacity of the refrigeration system.

Regeneration of the cryopumps should occur often enough so that an explosive mixture of hydrogen isotopes is not present in case of pump failure. This means that a pressure of no more than 13 torr (2% atmospheric) should be allowed in the vacuum vessel in the case of a release of all adsorbed gas from the cryopumps. A reasonable period between regeneration should be allowed to permit adequate on-time for the machine. Also, regeneration, meaning warming cryopumps, pumping of gases, recooling of pumps, and subsequent pump-down should be taken into account when making allowances for adequate on-time. The regeneration process should take less than one day. Adequate secondary pumping must be supplied to keep the regeneration time down. This can be done successfully with simple diffusion or turbomolecular pumps, backed by an adequate assembly of cold traps and mechanical pumps. Since radioactive tritium can advance into the system from the torus, the secondary subsystem must be closed to the atmosphere and a means of filtering out the tritium must be incorporated.

Actual pressure requirements will vary depending on the processes occurring in each portion of the beam line. Most of the pressure requirements evolve from considerations of change of charge state of the beam particles. For example, during acceleration the particle should remain as D^- and not change to D^+ or D^0 , where in the drift region to the torus, the neutral beam should remain neutral and not ionize to D^+ or D^- . Since the change in beam composition over a given distance is proportional to the product of pressure and distance, pressure requirements will be defined in this way. When the length of a given region is determined, the pressure is automatically determined.

Balance equations can be written for changes in beam particle charge states traversing a background gas. Given that σ_{xy} is the cross section for change from charge state x to charge state y of the beam particle in a background gas, N_x is the population of charge state x , and $d\pi$ is the differential thickness of reaction medium (i.e., $d\pi = \text{background gas density} \times \text{incremental path length}$), the balance equation for three possible charge states $+1$, -1 , and 0 are:

$$\frac{dN_1}{d\pi} = N_0 \sigma_{01} + N_{-1} \sigma_{-11} - N_1 (\sigma_{10} + \sigma_{1-1}) \quad (3)$$

$$\frac{dN_0}{d\pi} = N_1 \sigma_{10} + N_{-1} \sigma_{-10} - N_0 (\sigma_{01} + \sigma_{0-1}) \quad (4)$$

$$\frac{dN_{-1}}{d\pi} = N_1 \sigma_{1-1} + N_0 \sigma_{0-1} - N_{-1} (\sigma_{-10} + \sigma_{-11}) \quad (5)$$

Solving these three equations simultaneously with proper boundary conditions will determine beam compositions at given background gas thicknesses. From this, one may determine the fraction of initial beam lost to charge state changes at given pressure-distance products. This has been done both analytically and numerically⁽¹⁾ and can be applied to find gas pressure requirements in various beam line regions.

From the ion source through the acceleration grids up to the neutralizer, maintenance of as much of the original D^- beam is necessary. Negative ions have their extra electron stripped off readily in a background gas, thereby producing neutrals which would not be accelerated, being left behind to recombine and be pumped away as D_2 . Since the cross sections change with energy and the energy in this region is undergoing changes, the required line density will be estimated at an average energy. This will require a more detailed account of the structure of this region, which will be available later in the design description. For now, it shall be noted that a line density should be required which allows at least 98% of the original beam to remain in the D^- state throughout this region.

The line density in the neutralizer duct has already been established in subsection 2.3. A cell thickness of 9.3×10^{15} D_2 molecules/cm² translates to a line density of 2.82×10^{-3} torr m since one torr of D_2 corresponds to approximately 3.3×10^{19} D_2 molecules/liter at 300° K.

The line density in the ion collection region will be assessed later, as more information on the collection unit is presented.

Finally, reionization of the neutral beam from the collector region to the torus should be kept below 1% to eliminate excess power loading to the beam duct and avalanche pressure conditions, such as the Culham effect. This condition corresponds to a gas thickness of less than $4.6 \times 10^{11} \text{ cm}^{-2}$ corresponding to a line density of about $1.4 \times 10^{-5} \text{ torr m}$.

The beam calorimeter is included in the last $1.4 \times 10^{-5} \text{ torr m}$ region. When the beam is running into the torus no interference by the calorimeter is assumed, and pumping requirements will be calculated in this mode. When the calorimeter is intercepting the beam, an extra gas load will be introduced, thus increasing the pressure in that immediate region. It will be assumed that beam power measurements will not be affected by this increased pressure, due to the fact that the calorimeter will not differentiate between ions and neutrals, and scattering is minimal except at very high pressures which will not have sufficient time to develop. Therefore, pressure requirements will be ignored for the mode of operation with the beam on the calorimeter.

2.8 COMPONENT COOLING

All beam line components subject to energetic particle fluxes will develop heat loads. Virtually all components fall in this category, some to a much greater extent than others. Detailed thermal analysis must assess the cooling needs of each component. Due to the scope of this work and the uncertainties involved, the thermal analysis, although important, will not be attacked in detail. In most cases, mention will be made of the relative cooling needs for each component, trying to design without overstressing the components thermally.

3.0 DESIGN DESCRIPTION

3.1 GENERAL DESIGN

The neutral beam injector arm described in this design provides a 200 keV, 10 MW beam of neutral deuterium atoms to be injected to the plasma of the previously described TNS tokamak. Included in this system are means for production of negative deuterium ions, their subsequent acceleration and neutralization, recovery of the energy of the unneutralized beam, measurement of beam power, and adequate vacuum pumping to insure minimal beam loss and gas flow to the torus.

A total of 8-15 A, D^- magnetron ion sources, properly aimed, provide the initial beam current. Each of the 8 beams are accelerated to 200 keV and focused by their own five grid, 50% transparent, accel-decel system, which is closely coupled to the ion source. The ion beams are neutralized in 8 neutralizing ducts which are loosely coupled to the ion source accelerators. The proper line density of gas for approximately 45% neutralization is maintained by excess gas from the ion sources, leaving approximately 1% of the beam in the D^- state and the other 54% in the D^+ state. The energy of the D^+ current is then recovered electrically by four in-line space-charge controlled direct conversion units at about 70% efficiency, leaving the remaining D^0 beam to drift into the torus. Beam power is measured at the end of the beam line by one retractable thermal calorimeter consisting of 8 power dissipating units. This whole process is carried on in a high vacuum environment provided by four differential pumping regions fitted with LHe cryocondensation panels and backed by a secondary vacuum system utilizing turbomolecular, mechanical, and getter pumps and including means for tritium containment and D_2 gas recycling.

3.2 DETAILED DESIGN

3.2.1 ION SOURCES

Source Description - The ion source used in this design is a scaled version of the latest in a series of magnetron negative ion sources being developed at

Brookhaven National Laboratory⁽⁶⁻⁹⁾. After a review of existing negative ion sources⁽²⁾, it appears that this type of source is the one most applicable to neutral beam design and most readily scalable to higher currents. A currently available source provides almost 2 A of H^- for 50 ms with a current density before extraction of 0.5 A/cm^2 . Operating parameters are outlined in Table 3-1. The source requires maintenance of a magnetic field through the discharge for increased ionization, and perpendicular to the slits in the extraction region for bending electrons out of the primary ion beam during extraction. Other features are a water-cooled cathode to allow longer pulse and controlled discharge conditions, and Cs addition to the discharge to facilitate a surface-plasma H^- production mechanism⁽¹⁰⁾ by which the H^- ions are produced primarily by bombardment of the Cs coated cathode with H^+ ions from the primary discharge.

This experimental source is scaled to produce 15 A D^- , requiring a total of 8 sources to produce 120 of the originally required 123 A. This will reduce the anticipated 10 MW of neutral beam power by only 2%, a portion of which may return with better transmission efficiency through the beam arm.

Operating parameters of the scaled source are also listed in Table 3-1 for comparison. Current and gas efficiency were initially set at 15 A and 10% as required for the proposed beam line. D_2 gas flow to the source during operation is therefore 14.6 torr liter per second. A 10 A H^- scaling by the developers of the experimental source⁽⁹⁾, led to predicted values of ion current density, pulse length, cathode power density, discharge voltage, and power efficiency (mA of ion current produced per kW of power consumed). Due to the change in ion type from H^- to D^- , ion current density and power efficiency were reduced by 50% while the discharge voltage doubled. These are assumptions drawn from observations in the performance of similar BNL penning source when ion type was changed⁽⁹⁾. Values of discharge power and current were a direct result of the already determined ion current, power efficiency, and discharge voltage. Keeping the cathode current density at a reasonable 20 A/cm^2 determines the necessary cathode surface area, given the discharge current. The cathode area subsequently increases by a factor of six. Therefore, the linear dimensions should scale as $\sqrt{6}$. If the whole source is maintained in the same proportions, all linear dimensions scale as $\sqrt{6}$, with one exception. The active area for

TABLE 3-1
NEGATIVE ION SOURCE SCALING

PRODUCTION	EXPERIMENTAL H ⁻ MAGNETRON	SCALED D ⁻ MAGNETRON
ION CURRENT (I ₋)	1.8 A	15 A
ION CURRENT DENSITY (j ₋)	0.5 A/cm ²	0.25 A/cm ²
PULSE LENGTH (τ)	50 ms	dc
DISCHARGE CURRENT (I _D)	500 A	3000 A
CATHODE CURRENT DENSITY (j _c)	20 A/cm ²	20 A/cm ²
DISCHARGE VOLTAGE (V _D)	120 V	200 V
DISCHARGE POWER (P _D)	60 kW	600 kW
CATHODE POWER DENSITY (p _c)	1.6 kW/cm ²	1.3 kW/cm ²
POWER EFFICIENCY (ε)	30 mA/k	25 mA/kW
GAS EFFICIENCY (G _E)	5%	10%
CATHODE AREA (A _c)	25 cm ²	150 cm ²
ACTIVE AREA (A _{B0})	5 slits (1 mm x 7 cm, 3 mm pitch) ARRAY (1.3 cm x 7 cm)	17 slits (2 mm x 17.6 cm, 4 mm pitch) ARRAY (6.6 cm x 17.1 cm)
OUTSIDE DIMENSIONS (EXCLUDING MAGNET)	9.0 cm x 7.0 cm x 4.0 cm deep	22.0 cm x 17.1 cm x 9.8 cm deep
<u>EXTRACTION</u> (of 1 A H ⁻)		
EXTRACTION POTENTIAL (V _e)	13.1 kV	25 kV
MAGNETIC FIELD (B)	1.0 kG	1.2 kG
FIRST GRID TRANSPARENCY (T)	40%	50%
1/e HALF-ANGLE DIVERGENCE		
PERPENDICULAR TO SLITS, α _⊥	< 10° @ 120 keV	2°
PARALLEL TO SLITS, α	< 1° @ 120 keV	1°
ELECTRON CURRENT	0.3 A @ 120 keV	3A

beam extraction must correspond to 15 A extracted at 0.25 A/cm^2 . Long narrow slits are desirable and all slits must occur adjacent to the discharge volume. Therefore, a tighter array of 17 slits, 2 mm x 17 cm each, was formed which in turn improved the first grid (anode) transparency from slightly less than 40% to slightly over 50%. The 15 A source is illustrated in Figure 3-1.

To introduce Cs vapors into the source discharge, a cesium boiler chamber is included in the source which vaporizes the Cs and mixes it with the incoming D_2 gas. The amount of Cs allowed into the system is controlled by the temperature of the cesium heaters. This feature is present in the 2 A H^- source also. The rate of Cs required is estimated at about 10^{17} Cs atom/sec per square centimeter of cathode surface area⁽¹⁰⁾. Assuming six sec pulses, a 150 cm^2 cathode surface, and a boiler chamber capacity of about 100 cc, the source should be able to operate for about 10^4 pulses on one load of Cs. This is well within the regeneration time of the beam arm cryopanel. Therefore, the cesium boiler may be reloaded during cryopanel regenerations by feeding liquid Cs (melting point $\sim 29^\circ\text{C}$) into the boiler through a feed line without having to let the source region up to atmospheric pressure.

The magnitude of the magnetic field is determined by a scaling law presented by T. S. Green of Culham Laboratory⁽¹¹⁾. This requires that electrons must be turned out of the primary beam path before traversing the distance to the extraction electrode. Assuming an extraction potential of 25 kV, the required magnetic field intensity is approximately 0.12 tesla. To produce this magnetic field each source is surrounded by a magnetic field path made of some high permeability metal such as silicon steel. The required B field is provided in a gap between the poles of this magnet by adjusting the current through a coil wrapped about the magnet yoke. This arrangement is illustrated in Figure 3-2. The required amp-turns for the coil may be estimated by using Ampere's law (steady state).

$$\oint \vec{H} \cdot d\vec{\ell} = I_T = NI \quad (6)$$

Assuming a gap length of 17 cm, cross-sectional area of 17 cm x 3 cm, B field in gap of 0.12 tesla, various field path lengths according to Figure 3-2, and

Figure 3-1. 15 A D⁻ Magnetron Ion Source.

Figure 3-2. Source-Magnet Arrangement With Support Structure Attachments.

a flux leakage factor of 1.3, the coil should provide approximately 2×10^4 A-turns. Assuming 0.5 cm diameter copper wire, carrying a current density of 1300 A/cm^2 , the coil should consist of about 80 turns (about four layers) and would require a 2 kW power supply (250 A @ 8 V). The coil wire should be insulated compatible with the high vacuum environment, or be contained in a vacuum tight enclosure. Low level water-cooling of the magnet and coils will be probably be necessary due to poor convective cooling in the vacuum environment.

Source Aiming And Mounting - The 8 ion sources are set in a 4×2 array, 4 high with 2 wide to facilitate aiming of the beams through the torus duct. Each source is mounted with the slits running horizontal. This scheme is illustrated in Figure 3-3.

As mentioned previously, in a multi-beam arrangement, all sources will be aimed at a point midway between the plasma edge and centerline inside the torus. This aiming determines the placement of the sources with respect to each other. Using only geometrical considerations and assuming no focusing, it was found that for a reasonable source to target distance of 8 m or greater, 1/e half-angle beam divergences of 2° perpendicular to the slits and 1° parallel to the slits would be required. These geometrical considerations gave rise to the following approximation relating axial beam path, beam divergence, and source displacement for complete transmission of the 1/e beam portion to the torus.

$$L < \frac{\left(\frac{\phi_i}{2} - 3.03 \text{ m} \tan \theta_i - \frac{B_i}{2 \cos \theta_i} \right)}{\tan \theta_i - \tan (\theta_i - \alpha_i)} \quad (7)$$

where L is the distance from the last accelerator grid to the start of the neutral beam duct (neutral beam end)

B_i is the beam dimension in the i direction at the last accelerator grid.

θ_i is the angle subtended by the displacement of the source from the center of the array with the target position of the plasma at the vertex

α_i is the 1/e half-angle beam divergence in the i direction

ϕ_i is the inside dimension of the beam duct in the i direction.

Figure 3-3. Ion Source Array And Support Structure.

The distance from the start of the neutral beam duct to the target is assumed to be 3.03 m. With the horizontal direction denoted by the subscript y and the vertical by x, the final design parameters are:

$$\alpha_x = 2^\circ, B_x = 17.1 \text{ cm}, \phi_x = 125 \text{ cm}, \theta_x = 7.8^\circ,$$

$$\alpha_y = 1^\circ, B_y = 6.6 \text{ cm}, \phi_y = 47 \text{ cm}, \theta_y = 2.0^\circ, \text{ and } L = 806 \text{ cm}.$$

Given these parameters and the array description, the source separations of Figure 3-3 are estimated. Better beam transmission should be possible with focusing by the acceleration electrodes.

Each source-magnet combination is estimated to weigh less than 30 kg. Therefore, the support structure shown in Figure 3-3 should be capable of supporting the array with small I-beams with cross section approximately 1 cm square keeping movement of the sources within tolerable limits. A more detailed structural analysis should show that this type of structure is adequate. The support system is attached to the magnetic yoke and the vacuum vessel walls, the source being supported by the magnetic yoke. To prevent unwanted magnetic flux leakage through the support structure, it should be constructed of low magnetic permeability material, possibly stainless steel. A remote steering system may be incorporated into the structure utilizing small servo motors for fine aiming of the sources. Gross aiming of approximately 2° from normal in the vertical plane and 7.8° (outer sources) and 2.6° (inner sources) from normal in the horizontal plane should be performed during construction of the source-support interface. The source should be quickly and easily removable from the magnetic yoke in case of source failure.

Feed lines and connectors compatible with the high vacuum environment are necessary for source operation. Water-cooling, power, D_2 gas feed, and Cs refill lines must be provided, all of which may be hooked up in parallel (except the power lines - 3000 A - 200 V per source) and possibly located within or upon the support structure. Also, remotely pulsed valves at each source will be necessary for the D_2 gas regulation during operation.

3.2.2 ACCELERATOR

Acceleration of intense beams of negative ions from plasma sources is only in the beginning stages of investigation. Presently, only the ion source group at BNL has investigated this area. Fortunately, promising results have been found and with the very sources used for scaling in this design.

Accelerator Description - The accelerator consists of five multi-slit grids closely coupled to the ion source. The anode cover plate of the source constitutes the first grid. The second grid extracts the D^- ions at 25 keV while the third and fourth grids accelerate the beam to 205 keV in two steps. The fifth grid decelerates the beam to 200 keV and suppresses downstream positive ions from the accelerator structure. The fifth grid is at the same potential as the neutralizer duct, which is grounded.

The typical grid structure is illustrated in Figure 3-4. Each grid is rectangular, following the beam dimensions. Water-cooled lateral rods about 0.3 cm in diameter run parallel to the source slits. Spacings of approximately 0.6 cm between the laterals allow the beam to pass through the grids. The lateral rods are fixed to the grid plate at one end. At the other end they are supported and guided by the grid plate but are free to move, thus allowing for thermal expansion. The dimensions of the spacings and laterals are rather arbitrary and must be established after a detailed study of ion trajectories. The material used should have good thermal properties and low secondary particle emission coefficient for bombardment by energetic particles.

The transparency of the grid system is almost totally defined by the transparency of the first grid. When the positions, shapes, and biases of the grids are optimized, interception of the primary beam by grid laterals is almost nonexistent. Since the total area of the slit array in the anode cover plate is 112.9 cm^2 and the actual slit area is 58.1 cm^2 , the transparency is 51.5%.

If the current density is 0.25 A/cm^2 at the slits before extraction, after extraction the current density is approximately 0.13 A/cm^2 .

The axial displacements of the five grids may be estimated from Child's law (Eq. 8) which relates grid spacing, voltage difference between grids, and the

Figure 3-4. Typical Extractor/Accelerator Grid as Seen by the Beam.

allowable accelerated current density.

$$j = \frac{C (\Delta V)^{3/2}}{m^{1/2} d^2} \quad (8)$$

where j is the accelerated current density (A/cm^2)
 ΔV is the acceleration voltage step (V)
 m is the mass of the accelerated ion (amu)
 d is the grid separation (cm)

C is a constant depending on beam structure and background conditions, taken to be $5 \times 10^{-8} A/V^{3/2}$. Voltage steps and related gap sizes must also be sufficient to preclude voltage breakdown and arcing across vacuum gaps and insulators. Absolute relations for voltage breakdown do not exist and laboratory experience must be relied upon. However, an estimate can be made from Eqs. (9) and (10) which give typical breakdown characteristics.

$$\Delta V \leq k d^{1/2} \quad \text{for } d > 1 \text{ cm} \quad (9)$$

$$\Delta V \leq k d \quad \text{for } d < 1 \text{ cm} \quad (10)$$

where $k \approx 8 \times 10^4$ in both cases
 d is in cm, and
 ΔV is in volts.

Table 3-2 lists design parameters for the five grid system, assuming extraction of $0.25 A/cm^2 D^-$ at 25 kV, acceleration of $0.13 A/cm^2 D^-$ in two steps of 90 kV, and deceleration of $0.13 A/cm^2 D^-$ in one 5 kV step. Note that the voltage steps are well within the estimated breakdown limit.

Figure 3-5 shows the basic acceleration region set up. Insulating posts are placed at the corners of each grid, separating the grids, and providing as much gas conductance between the grids as possible, for maximum pumping speed in the grid region. Also, a drift region is included before the neutralizer entrance in an attempt to eliminate formation of a direct gas flow path from the source to the neutralizer. This concept is employed with the hope of improving local vacuum conditions in the beam path.

TABLE 3-2
ACCELERATOR DESCRIPTION

GRID	BIAS	VOLTAGE STEP	GRID SEPARATION	BREAKDOWN VOLTAGE	AVERAGE AXIAL* DISPLACEMENT	ESTIMATED THERMAL LOAD	ESTIMATED ELECTRICAL LOAD
ANODE	-200 kV				-7.55 cm	- -	3.60 MW
		25 kV	0.73 cm	58 kV			
EXTRACTOR	-175 kV				-6.52 cm	1 kW	14 kW
		90 kV	2.66 cm	130 kV			
ACCEL #1	- 85 kV				-3.56 cm	9 kW	17 kW
		90 kV	2.66 cm	130 kV			
ACCEL #2	+ 5 kV				-0.60 cm	8 kW	3 kW
		5 kV	0.30 cm	24 kV			
DECEL	0 kV				0 cm	NEGLIGIBLE	NEGLIGIBLE
		0 kV	7.45 cm	- -			
NEUTRALIZER	0 kV				+7.45 cm		
TOTAL		200 kV			15 cm	18 kW	3.63 MW

* Displacement at center of given electrode with $Z = 0$ at center of last grid for reference to entire beam arm.

Figure 3-5. Ion Extraction/Acceleration Region.

Focusing of the beam in the acceleration process is performed in an attempt to increase beam transmission. Focusing in the vertical plane at $Z = f_x = 450$ cm and $Z = f_y = 750$ cm in the horizontal plane is assumed. These positions are rather arbitrary but give preferred beam conditions at critical points through the direct conversion unit, at the calorimeter, and at the end of the neutral beam duct. Focusing at Z values too low or high would give rise to larger beam spreads downstream, which have adverse effects on beam transmission and beam arm compactness. Equation (11) gives an approximate relation for a single beam width (full $1/e$) for given downstream distance Z , initial beam width B , half-angle divergence α , and focal point f .

$$x_b \simeq 2 Z \tan \alpha_x + B_x \left| 1 - \frac{Z}{f_x} \right| \quad (11)$$

included assumptions are $B \ll f$ and $\alpha \ll 90^\circ$. For the beam width in the y -direction a similar relation holds.

$$y_b \simeq 2 Z \tan \alpha_y + B_y \left| 1 - \frac{Z}{f_y} \right| \quad (12)$$

Table 3-3 gives beam dimensions at critical values of Z for the neutral beam arm. The parameters of this table are described graphically in Figures 3-6 and 3-7. Beam aiming and focusing, as well as the initial array size, is taken into consideration. These dimensions are all based on a beam composed of individual beamlets each propagating downstream with an expanding gaussian profile and aimed at the focal point. The total beam intensity distribution is a superposition of all beamlets and in the case of this rectangular beam will appear as a flat-topped distribution with gaussian tails. Therefore, a generous portion of the beam, probably greater than 95% is included in the defined beam width at most points along the beam line.

Focusing is performed, as mentioned previously, by lateral displacement of successive grid apertures and curving of the electrodes. Figure 3-5 does not account for this arrangement. The exact alignment of the grids is accomplished after computer simulation of the beam trajectories in the electrostatic fields of the grid structure. This procedure is not possible at this stage of the design.

TABLE 3-3

BEAM DIMENSIONS AT CRITICAL AXIAL BEAM DISTANCES, Z

BEAM LINE COMPONENT	Z (cm)	x_b (cm)	y_b (cm)	x_{CC} (cm)	y_{CC} (cm)	x_T (cm)	y_T (cm)	x_S (cm)	y_S (cm)
DECEL GRID	0	6.6	17.1	73.8	56.4	228.0	73.5	67.2	39.3
NEUTRALIZER ENTRANCE	8	7.0	17.3	73.1	55.8	226.3	73.1	66.1	38.5
NEUTRALIZER EXIT	83	11.2	18.1	66.2	50.6	209.8	68.7	55.0	32.5
REGION 2-3 WALL	103	12.3	18.3	64.4	40.2	205.5	67.5	52.1	30.9
1ST ELECTRON REPELLER	125	13.5	18.5	62.4	47.6	200.7	66.1	48.9	29.1
COLLECTOR ENTRANCE	177	16.4	19.0	57.6	44.0	189.2	63.0	41.2	25.0
COLLECTOR EXIT	330	24.9	20.6	43.3	33.3	154.8	53.0	18.4	12.7
2ND ELECTRON REPELLER CENTER	416	29.6	21.5	36.0	27.3	137.6	48.8	6.4	5.8
REGION 3-4 WALL	438	30.7	21.7	33.7	25.7	131.8	47.4	3.0	4.0
CALORIMETER	445	31.2	21.8	33.1	25.2	130.5	47.0	1.9	3.4
NEUTRAL BEAM DUCT ENTRANCE	503	35.9	22.4	27.8	21.2	119.3	43.6	0	0
NEUTRAL BEAM DUCT EXIT	703	52.8	24.6	9.4	7.2	81.0	31.8	0	0

Figure 3-6. Vertical Beam Dimension Definitions for Table 3-3.

Figure 3-7. Horizontal Beam Dimension Definitions for Table 3-3.

Vacuum Requirements - In Section 2.7 it was mentioned that a requirement of the region from source to neutralizer was that 98% of the original D^- beam should be maintained in the negative charge state. Since the energy is changing in this region the required gas thickness will change. The sum of the particle losses between each of the grids and from the last grid to the neutralizer should be less than 2% of the initial beam. An approximate gas thickness may be found by noting that the beam is accelerated to 200 keV over about 7.5 cm and left to drift at 200 keV for another 7.5 cm. An average energy of 150 keV over the full 15 cm may then be assumed. For 2% D^- beam loss at 150 keV, the required thickness is approximately $4.6 \times 10^3 \text{ cm}^{-2}$ corresponding to a line density of about $1.4 \times 10^{-3} \text{ torr cm}$. Over 15 cm an average pressure of $9.3 \times 10^{-5} \text{ torr}$ would be required.

Power Loading - Power is dissipated on the accelerator structure in two forms, thermal and electrical. Both are a result of stray particle collection by the biased electrodes. Determination of these power loadings is difficult and actual operation is the only true determinant. Computer simulation of particle trajectories, as used in determination of electrode size, shape, and placement, is probably the best method for estimating the power loading⁽¹³⁾. However, rough estimates will be made here using various simplified assumptions.

The major source of electrode bombardment will be assumed to be electrons produced from stripping of D^- atoms. The cross sections for stripping of one σ_{10} , and two, σ_{11} , electrons dominate most of the other cross sections for electron production in this situation. Any positive ions produced will be assumed to remain in the beam path due to the high negative space charge of the ion beam. Background gas ionization by D^- is small compared with electron stripping of D^- and will be assumed negligible. High energy electrons which have been accelerated along with the D^- ions will have a negligible effect since the cross sections for electron ionization are small at the energies involved. These electrons will, however, require power for their acceleration. Experiments with the magnetron source have shown accelerated electron currents of about 30% of the D^- current at 120 keV⁽¹²⁾. Improvement on this figure to 20% will be assumed here, giving an electron current of 3 A associated with the 15 A D^- .

The loading to the grids may now be estimated. Electrons produced via σ_{-10} and σ_{-11} reactions in a given electrode-electrode gap will be accelerated to and collected at the electrode of the higher potential. This current may be approximated by Eq. (13).

$$I_e = (\sigma_{-10} + 2 \sigma_{-11}) n_b d I_- \quad (13)$$

where σ_{-10} and σ_{-11} are the respective cross sections for one electron and two electron loss of D^- at an average energy in the associated gap

n_b is the gas density in the gap

d is the gap length

I_- is the D^- ion current

Being conservative and allowing for secondary particle emission, these currents will be doubled.

The electrical load at each grid will be given by the collected current as defined above at the electrode voltage. The first grid will be loaded by the accelerated 15 A D^- plus the 3 A of electrons. Estimated electrical loads are listed in Table 3-2. It must be kept in mind that these loadings are extremely crude estimates, although a total electrical loading of about 1.3 times the power of the accelerated D^- beam could be expected.

The thermal load at each grid will be given by the collected current at average gap energies (i.e., if the gap voltage step is ΔV , the average gap energy is $0.5 e\Delta V$). The estimated thermal loads, once again a very crude estimate, are also given in Table 3-2.

If the thermal power loadings are assumed to be distributed uniformly over the grid lateral surfaces, the heat fluxes to the second, third, and fourth grids are approximately 0.02 kW/cm^2 , 0.14 kW/cm^2 , and 0.12 kW/cm^2 (assuming eight 0.3 cm diameter rods per grid). These heat fluxes should not present too much of a cooling problem. However, because of the 6 sec pulse length, water-cooling should be provided to reduce heat build up.

3.2.3 NEUTRALIZER

Description - Each source accelerator combination has an associated D_2 gas neutralizer. The neutralizer has an effective length of 75 cm through which the beam travels. To minimize beam interception, the neutralizer inside dimensions were chosen as 14 cm vertical by 20 cm horizontal to admit a maximum 1/e beam cross section of 11.2 cm by 18.1 cm. The neutralizers are set at angles prescribed by their associated sources so as to provide maximum neutralizer wall clearance by the ion beam. The duct walls should be about 0.5 cm thick copper with water-cooling lines brazed to the outside surface. A heat load of about 30 kW per duct (240 kW) will be a result of interception of the beam gaussian "wings" by the neutralizer walls. This heat load will be described in the next subsection. Due to the electron mobility, beam space charge before neutralization, and fringing magnetic field effects, the 200 keV electrons are assumed to expand rapidly and collect on the neutralizer walls and beam defining plate before the direct collection unit. A total heat load of approximately 500 kW per beam will be apparent as a result of the electrons, although they will be extremely defocused and spread over wide areas for tolerable power densities on the order of 0.3 kW/cm^2 . The temperature of the duct should be maintained at about 300 K to be consistent with gas flow calculations.

The neutralizers are loosely coupled to the ion sources. They are mounted on a vacuum tight wall at ground potential about 15 cm from the emitting surfaces of the sources (about 7.5 cm from the last accelerator grid). The only gas flow path connecting the sources to the rest of the beam arm is through the neutralizer ducts. The required line density of gas ($9.3 \times 10^{15} \text{ cm}^{-2}$) is maintained by unionized gas from the sources. Assuming viscous and molecular conductance through rectangular ducts at 300 K⁽¹⁴⁾, a gas flow of $4.6 \frac{\text{t-l}}{\text{sec}}$ per duct is required to maintain the proper neutralizing medium. With a 10% gas efficiency, each source emits $13.1 \frac{\text{t-l}}{\text{sec}}$ of D_2 gas which is more than adequate to supply the neutralizers.

Beam Scrape-Off - All openings through which the beam must pass have been sized to admit a beam of 1/e width. Since the beams have a gaussian profile near the edges, the "wings" of the beam will not clear the openings. Calculations of the transmitted beam fraction through given openings have been made

as per Reference (15). Portions of the beam which are scraped off appear as power loadings on the interfering components. Table 3-4 gives the transmitted beam power and power loadings at critical points along the beam line. Only beam scrape-off loadings are listed; other loadings due to electrostatic collection of charged particles and heat loads due to heating of the background gas by the beam are not included here, although these sources can be significant, most notably in the case of the electrodes of the direct collection unit. In some cases a component clears all of the beam because a previous component has scraped off the "wing" portions which would have been stopped by the downstream component if there was no interference upstream. From Table 3-4, a transmission efficiency of 90% can be deduced due to beam scrape-off and charge changing reactions with the background gas as predicted originally. Note that beam scattering and space charge blow up (except in the D^+ collection process) have been ignored.

3.2.4 DIRECT RECOVERY UNIT

The direct collection of positive ions is performed by four in-line space charge controlled direct convertors. The conversion units are scaled from an experimental set up at Lawrence Livermore Laboratory⁽¹⁶⁻¹⁸⁾, based on the same principles outlined previously in Section 2.3. Each convertor handles two horizontally adjacent beams, thus attempting to recover the power of approximately 15.6 A of 200 keV D^+ ions.

The suppression of electrons for creation of space charge forces on the positive ion beam along with maintaining a very high vacuum in the convertor region are probably the two most crucial aspects of the design. Without electron suppression at both ends of the convertor, space charge neutrality would eliminate the positive ion blow up and collection of electrons on the positive collector electrode would cancel the positive current and reverse bias the electrode. A high vacuum is necessary to maintain beam charge composition and reduce ionization of the background gas which produces electrons for space charge neutrality, reverse biasing, and along with the cold ions, electrode power loadings.

From Gauss' law and proper boundary conditions for a slab shaped beam, Eq. (14)⁽¹⁶⁾ gives the required electron suppression voltage, V_- , for a given

TABLE 3-4
BEAM TRANSMISSION PARAMETERS

LOCATION	BEAM TRANSMISSION COEFFICIENT	TOTAL* BEAM POWER TRANSMITTED	NEUTRAL BEAM POWER TRANSMITTED	BEAM SCRAPE-OFF POWER DEPOSITION	CAUSE OF BEAM LOSS
ACCELERATOR REGION	.980	23.52 MW	0	- - -	PREMATURE NEUTRAL- IZATION OF SLOW D ⁻
NEUTRALIZER DUCTS	.990	23.28 MW	10.55 MW	240 kW	BEAM SCRAPE-OFF
REGION 2-3 PLATE	.988	23.24 MW	10.53 MW	50 kW	BEAM SCRAPE-OFF
1st e-REPELLER	.993	23.24 MW	10.53 MW	0 kW**	- - - - -
D ⁺ COLLECTOR	.966	10.29 MW	10.29 MW	235 kW**	BEAM SCRAPE-OFF
CONVERTOR REGION	.990	10.19 MW	10.19 MW	- - -	D ^o REIONIZATION
2nd e-REPELLER	.970	10.19 MW	10.19 MW	0 kW**	- - - - -
REGION 3-4 PLATE	.936	9.87 MW	9.87 MW	320 kW	BEAM SCRAPE-OFF
CALORIMETER (RETRACTED)	.978	9.87 MW	9.87 MW	0 kW	- - - - -
DUCT ENTRANCE	.945	9.87 MW	9.87 MW	0 kW	- - - - -
CALORIMETER - DUCT REGION	.990	9.77 MW	9.77 MW	- - -	D ^o REIONIZATION
* Neglecting fast electron power and D ⁻ power after D ⁺ collection					
** Electrostatic collection of charged particles not included					

effective positive current density j_+ , beam thickness h , particle velocity v and vertical electrode spacing b .

$$V_- > j_+ h^2 / 8 \epsilon_0 v (2 b/a - 1) \quad (14)$$

The effective positive current density, j_+ , is the positive ion current (7.80 A) less the negative ion current (0.15 A) divided by the 1/e beam cross-sectional area at the center of the electron suppressor. Therefore, $j_+ \approx 306 \frac{\text{A}}{\text{cm}^2}$ when $h = 13.5 \text{ cm}$. The particle velocity is that of a 200 keV deuterium atom and the electrode separation is assumed to be 1.5 times the beam thickness, i.e., $b/a = 1.5$. Thus, a negative bias of approximately 9.0 kV is required on both of the electron suppressors. The positive ion collector should be biased at about 180 keV positive with respect to ground in an attempt to eliminate the appearance of retrograde ions in the decelerating 200 keV beam.

Reference 17 gives an approximate scaling law for the converter from which an effective retarding electric field length (L) can be calculated given the beam thickness (h), positive current density (j_+), and energy (W_0).

$$j_+ = \frac{2 \epsilon_0}{ehL} \sqrt{\frac{2}{M}} W_0^{3/2} \frac{[\phi_d/2 \phi_0]^{1/2}}{\ln[2 \phi_0 / \phi_d]^{1/2}} \quad (15)$$

In this case $\phi_d = \phi_0 = \frac{W_0}{e} = 200 \text{ keV}$

M = deuteron mass = 2 amu

h = average beam height over length L

An average current density j_+ over the retarding field length is about 260 A/m^2 , decreasing from the prior j_+ due to beam expansion. Thus, the effective field length should be about 80 cm. Assuming that L runs from the center of the first electron suppressor to the bend in the positive ion collector, all axial dimensions of the recovery unit are determined from drawings in the references keeping the same proportions with $L = 80 \text{ cm}$. The overall length of the recovery unit, from entrance vacuum wall at ground potential to exit vacuum wall at ground potential is approximately 335 cm. The total collector length is approx-

imately 152 cm, as shown in Figures 3-8 and 3-9. The vertical dimensions are scaled according to the beam thicknesses at corresponding points. An inside wall to wall vertical separation of approximately $1.5 x_b$ is maintained throughout. The widening of the ion collector with the expanding beam is illustrated in Figure 3-8. Horizontal dimensions were chosen to clear two beams with almost no interference of the neutral portion. Space charge blow up of the beam in vertical directions is assumed to be the major means of positive ion collection, far outweighing the contributions from collection at the side walls. The first electron repeller is 70 cm wide inside, the collector opens at 90 cm and quickly slims down to 70 cm. The second electron repeller is 60 cm wide. The shaping of the electrodes should be consistent with the beam shape. In this case a rectangular beam will probably be apparent, due to beam defining properties of the rectangular neutralizer ducts and rectangular openings in the grounded vacuum wall before entering the direct recovery region.

The electrodes for the experimental recovery unit at low power were fabricated from nickel-plated copper. But for the higher power loadings anticipated in this scaling, refractory metal coatings or fabrications have been suggested as possible requirements. In any case, water-cooling lines will be necessary for heat removal on all electrodes.

The direct recovery units involve a completely separate pumping region, defined by conductance limiting plates at ground potential at either end of the unit. The entrance plate is located 20 cm from the end of the neutralizer ducts to minimize gas streaming into the convertor and defining a differential pumping region around the neutralizers. Each of the four convertor units are aligned vertically to coincide with the projected beam paths allowing for maximum beam transmission. Beam scrape-off calculations from Table 3-4 show neutral beam interception by only the lengthy collector electrode. The electron suppressors allow virtually all of the incident neutral beam to pass. The power deposition on the collector from neutral beam scrape-off is estimated to be only 60 kW per collector, well within tolerable heat loads when considering the large surface area of the collectors. As shown in Figure 3-8, each of the electrodes are supported at the corners by stainless steel vertical tubes. The tubes support identical electrodes for each of the four convertor units. Thus, the

Figure 3-8. Side View of one Direct Recovery Unit (Handles 2 of 8 Beams).

Figure 3-9. Top View of Direct Recovery Units.

collectors for all four units are installed as one assembly, as are the first and second electron suppressors. This scheme is illustrated in the total beam line view of Figures 3-10 and 3-11. The vertical tubes are attached to the bottom of the vacuum chamber by high voltage insulators and to the top by high vacuum feedthroughs which are also insulated for high voltage hold-off. The power lines and cooling-water feed lines are located inside the supporting tubes, with proper connections made at the electrode-support interfaces.

An estimate of the total electrical direct convertor efficiency can be made by utilizing another scaling equation from Reference 17.

$$\eta_{DC} = 0.92 - (0.107) \frac{j_+ h L}{2 \epsilon_0 \left(\frac{W_0}{e} \right)^{3/2}} \sqrt{\frac{M}{2e}} \quad (16)$$

All quantities are identical to those used in Equation (15), therefore, the estimated direct conversion efficiency is 70%. Optimization of voltages, electrode shape, electrode placement, and vacuum conditions have already produced experimental efficiencies as high as 70% at low power levels.

Vacuum Requirements and Power Loading - The gas pressure requirements for efficient direct conversion are assumed to be set indirectly by the power loads resulting from ionization of background gas, charge exchange of fast ions, and secondary electron emission from electrodes. This power loading must be negligible compared to the total power of the collected D^+ beam. This relation produces the following inequality⁽¹⁶⁾,

$$[I_+ n d (\sigma_{10} + \sigma_{ion,+}) + I_0 n d \sigma_{ion,0}] (V_+ + V_-) (1 + \epsilon) \ll I_+ V_+ \quad (17)$$

where I_+ is the positive ion current collected (15.60 A/collector)

I_0 is the neutral deuterium beam current (13.16 A/collector)

$n d$ is the line density of the background gas

V_+ is the collector voltage (180 kV)

V_- is the electron suppression voltage (9 kV)

ϵ is the secondary electron emission coefficient (~ 1)

Figure 3-10. Side View of Complete Neutral Beam Arm.

Figure 3-11. Top View of Complete Neutral Beam Arm.

σ_{10} is the cross section for slow ion production by charge exchange at 200 keV ($\sim 1.4 \times 10^{-17} \text{ cm}^2$)

$\sigma_{\text{ion},+}$ is the cross section for ionization of the background gas by fast positive ions at 200 keV ($\sim 2.0 \times 10^{-16} \text{ cm}^2$)

$\sigma_{\text{ion},0}$ is the cross section for ionization of the background gas by fast neutrals at 200 keV ($\sim 1.0 \times 10^{-16} \text{ cm}^2$)

Using the above parameters, a line density negligible with respect to $1.6 \times 10^{15} \text{ cm}^{-2}$ is required. For a neutral beam loss due to reionization of approximately 1%, a line density of $4.5 \times 10^{13} \text{ cm}^{-2}$ is required. Using this value for the line density implies a power loading of only 80 kW (left-hand side of Eq. (17)) which is less than 3% of the total collected D^+ power. Therefore, for a 1% loss at 300 K with a total convertor region length of 335 cm, the required pressure in this region is approximately 4.1×10^{-6} torr.

Calculations to estimate thermal power loads at each of the electrodes were carried out using the same basic methods and assumptions as were used in Section 3.2.2 for the accelerator grids. It is found that these thermal loads are negligible compared to the 50 kW and 320 kW from beam scrape-off at the front and rear plates. Each of the electron suppressors are expected to receive about 10 kW thermal. Each collector receives about 50 kW from collection of electrons plus the 450 kW from collection of the 29 keV D^+ current (200 keV accelerated by 9 keV and decelerated by 180 keV). As mentioned previously, the collector also scrapes off about 60 kW of the primary beam for a total load of 560 kW. Taking only the top and bottom sections of the collector into consideration, a heat load of about 0.03 kW/cm^2 is apparent, which is only a moderate power density to be handled by the water-cooled collector electrode.

The 1% D^- entering the direct recovery region is assumed to focus and accelerate to 380 keV in the collector region and then decelerate back to 200 keV from the collector to the grounded beam defining plate. This represents a power of about 250 kW for all eight beams combined, which will deposit at several points downstream. Probably a major portion will end up on the walls of the neutral beam duct. Spread over a large area, this beam component should not prove to be a major problem.

Since the electrical efficiency of direct conversion is assumed to be 70%, and the total D^+ beam is 3.12 MW per collector, approximately 2.18 MW of electrical energy per collector is available for recycle. Proper power supply configurations should be arranged to allow this recovered power to supplement the accelerator supplies.

3.2.5 CALORIMETER

The thermal calorimeter used in this design is a derivative of a proposed calorimeter for the TFTR beam lines by Oak Ridge National Lab⁽⁵⁾. The basic target is a set of two beam intercepting panels meeting at the beam center but angled to form a "V" type arrangement to reduce the effective beam power density by off-normal interception. Each panel is composed of a series of copper swirl tubes connected to water supply manifolds at each end. The water temperature rise is measured during a beam pulse on the target and is calibrated to deduce the incident beam power.

For the system under consideration, eight targets, as described above, are incorporated into one calorimeter. Each target must be capable of accepting the full power of one ion source, i.e., 3 MW. The calorimeter opening occurs at about $Z = 445$ cm where the $1/e$ beam dimensions are 21.8 cm x 31.2 cm. The opening of each calorimeter target opens at these dimensions and shrinks to 0 cm in the x direction while maintaining the 21.8 cm in the y direction.

A conservative estimate of the acceptable effective power load can be made from Eq. (18) which relates the maximum heat flux, q'' , pulse length, τ , temperature rise, ΔT , and various material properties for a metal slab. The copper swirl tubes can be expected to surpass this calculated q'' .

$$q'' = \frac{\Delta T}{2} \left(\frac{\pi k \rho c}{\tau} \right)^{1/2} \quad (18)$$

For copper:

ΔT = melting point - 300 K $\simeq$ 1056 K

k = thermal conductivity = 389 W/K·m

ρ = mass density = 9×10^3 kg/m³

c = specific heat = 389 J/K·kg

If the pulse length is assumed to be six seconds, the acceptable heat flux is 1.45 kW/cm^2 . An average heat flux can be found by dividing the beam power (3 MW) by the cross-sectional area of the beam ($21.8 \text{ cm} \times 31.2 \text{ cm}$), to give approximately 4.4 kW/cm^2 . Variation in beam intensity, as calculated per Reference 15, produces a maximum heat flux of 6.1 kW/cm^2 at the beam center and 28 W/cm^2 at the edges. The ratio of the desired effective heat flux to the actual beam heat flux gives the sine of the necessary angle formed by the beam and the target. At the beam center this angle is 19° , reduces to 14° for an average beam intensity of 4.4 kW/cm^2 , and allows normal beam interception at the edges. Ideally, a shape following the beam intensity profile would give the shortest axial depth for the calorimeter. For simplicity, the calorimeter swirl tubes are formed in circular arcs of radius 71 cm. The two arcs are mounted back to back to form a distorted V-shape. The required axial depth of the beam collecting portion of the target is then approximately 44 cm. Figure 3-12 shows a side view of the calorimeter with each of the targets aligned for the described beam interception. The copper swirl tubes are connected to three inch diameter pipes at each end, which in turn are connected to 5 inch manifolds which run the length of the calorimeter. Water flows are indicated in Figures 3-12 and 3-13. Figure 3-13 shows all eight targets in position for beam power measurement.

For neutral beam operation, the calorimeter retracts out of the beam path, clearing all of the beam for complete transmission as shown in Table 3-4. The calorimeter is comprised of two halves which separate at the center and rotate about the main 8" diameter stainless steel inlet and outlet manifolds by means of vacuum tight rotatable joints. The two main manifolds exit the top of the vacuum vessel through a static high vacuum connection. Figures 3-14 and 3-15 show two views of the calorimeter in the retracted position. An enclosed mechanical drive connected to the bottom of the calorimeter at the axes of rotation allows for remote retraction of the calorimeter via a rotatable high vacuum connection. External motorized drive and calibration can be used for control of the calorimeter position.

The whole calorimeter assembly is operated in a region from the beam defining plate at $Z = 438 \text{ cm}$ to the entrance of the neutral beam duct (end of the neutral

Figure 3-12. Calorimeter/Beam Stop Side View.

Figure 3-13. Calorimeter/Beam Stop (Operating Position) Front View.

Figure 3-14. Calorimeter Assembly (Retracted Position) Front View.

Figure 3-15. Calorimeter Assembly (Retracted Position) Side View.

beam arm) at $Z = 503$ cm, for a total depth of 65 cm. As mentioned previously, the background gas line density requirement through this region insures a neutral beam loss of less than 1%, for a total neutral beam transport efficiency of approximately 90% from source to torus.

3.2.6 PRIMARY VACUUM SYSTEM

The primary vacuum system utilizes several arrays of high speed cryocondensation pumps within the main vacuum chamber for maintenance of the required low pressures during neutral beam operation. These cryopumps are backed and regenerated by the secondary vacuum system described in the next section.

The main vacuum chamber houses the entire neutral beam arm and is connected at one end to the neutral beam duct by a high vacuum isolation valve large enough to span the 125 cm x 47 cm opening. The vacuum chamber is a rectangular box approximately 580 cm x 240 cm x 440 cm made of 2 cm thick stainless steel plates with reinforcing ribs to withstand atmospheric pressure. Several access ports for beam line maintenance are included in the walls with vacuum tight "hard" seals. All beam line components are mounted to these walls. All remote connections (i.e., power lines, water lines, cryogen supply lines, mechanical connections, etc.) are made via high voltage vacuum connections appropriate to the intended purpose of the connection. The whole chamber is mounted on rails for ease of disconnection and removal from the torus duct. Adequate radiation shielding must also be provided around the outside of the chamber according to health physics and materials damage requirements.

The vacuum chamber is divided into four distinct vacuum regions which are illustrated schematically in Figure 3-16. Each of the regions are connected by a well defined conductance. Region 1 contains the source and accelerator assemblies, requires a pressure of 9.3×10^{-5} torr, and is connected to Region 2 by the conductance of the eight neutralizing cells. The cells are mounted on a bulkhead of about 0.5 cm thick stainless steel which is welded to the vacuum chamber walls. The gas load in Region 1, Q_s , arises from the unionized source gas, some of which flows through the neutralizer ducts to maintain the required line density for neutralization. The gas balance equation is given on Figure 3-16.

$$\begin{aligned}
 \text{REGION (1)} \quad Q_S &= Q_N + S_1 P_1 = C_{12} (P_1 - P_2) + S_1 P_1 \\
 \text{REGION (2)} \quad Q_N + Q_{S02} &= C_{23} (P_2 - P_3) + S_2 P_2 \\
 \text{REGION (3)} \quad Q_C + Q_{S03} + C_{23} (P_2 - P_3) &= S_3 P_3 + C_{34} (P_3 - P_4) \\
 \text{REGION (4)} \quad Q_{S04} + C_{34} (P_3 - P_4) &= S_4 P_4 + C_D (P_4 - P_T)
 \end{aligned}$$

Figure 3-16. Beam Arm Pumping Regions and Gas Flow Balances for Primary Vacuum System.

Region 2 is a differential pumping region. It surrounds the neutralizer cells in an attempt to pump most of the neutralizer gas throughput. This alleviates pumping requirements in Region 3 which requires a very high vacuum. Regions 2 and 3 are connected by a 0.5 cm plate located 20 cm from the neutralizer exits. The plate contains eight rectangular holes, 15 cm x 20 cm, which limit gas flow between regions and help to define eight rectangular beams for direct conversion. The plate scrapes off about 50 kW of beam particles which appear as a heat load, requiring low level water-cooling between pulses. The gas loads in Region 2 are the neutralizer throughput, Q_N , and D_2 released from beam scrape-off on the neutralizer walls and the Region 2-3 plate, Q_{S02} . Throughout the beam arm, it is assumed that for every energetic deuterium atom which is intercepted by some beam line structure, one molecule of D_2 is released. Therefore, for each ampere of deuterium collected on beam line components, 0.19 torr ℓ /sec of D_2 gas is released. This assumes an ambient gas temperature of 300 K.

Region 3 contains the four direct conversion units. The pressure requirement from Section 3.2.4 is a very low 4.1×10^{-6} torr. Another 0.5 cm water-cooled conductance limiting plate is located at the end of this region. One large opening of 140 cm x 50 cm allows transmission of all eight beams to the calorimeter. The power deposition on the plate due to beam scrape-off is approximately 320 kW. The gas loading to Region 3 arises from collection of positive ions on the collector electrode, Q_C , and beam scrape-off on the collector and Region 3-4 plate, Q_{S03} . Quantities of D_2 gas from Region 2 also must be taken into consideration.

The last region contains the calorimeter. During beam power measurements and source conditioning, Region 4 is sealed off from the torus by a high vacuum isolation valve. During operation, the valve is opened and the beam arm and torus are vacuum connected through the conductance of the 2 m long, 47 cm x 125 cm neutral beam duct. The pressure at the torus end of the duct is assumed to be about 10^{-8} torr. A maximum line density of 1.4×10^{-5} torr m is required in the combined Region 4 beam duct path. If one assumes a linear pressure profile through the beam duct with the duct pressure being the average of the torus and Region 4 pressures, a maximum pressure of 8.5×10^{-6} torr is allowed

in the 65 cm calorimeter region. To reduce backflow of gas into the critical Region 3, the Region 4 pressure should be maintained less than 4.1×10^{-6} torr.

The cryopumping requirements for this design are satisfied by modular units of cryocondensation pumps. The modules are designed to fit the specific regions defined above. Each module is in the form of a rectangular panel which is attached by a supporting stainless steel structure to the vacuum chamber inside walls. Cryogenic transfer lines which maintain the required pump temperatures are connected to the total reactor refrigeration system by means of high vacuum connections through the vacuum chamber top and bottom walls.

Figures 3-17 and 3-18 illustrate the basic composition of the cryopanel. The actual pumping surface is a bare stainless steel panel maintained at 4.2 K by LHe cooling channels spot welded to the back of the panel. Copper chevrons between the pumping surface and the volume to be pumped serve to slow gas molecules and shield the pumping surface from direct radiation, thus reducing the heat load to the pump and increasing the molecular sticking coefficient. The chevrons are conductively cooled by LN_2 manifolds at 77 K and blackened to prevent reflected radiation. A 77 K panel on the other side of the pumping surface, identical in structure but utilizing LN_2 , shields the 4.2 K panel from the 300 K vacuum chamber wall. For situations where pumping from both sides is desired, such as on an interior bulkhead, the scheme of Figure 3-18 may be used. This eliminates the need for the 77 K panel since no shielding from an outer 300 K wall is necessary. The depth necessary for a single pump located on an outside wall is approximately 14 cm from the chamber wall to the outer tips of the chevrons. For a double pump on an interior wall, the clearance is only about 8 cm between outer tips of opposite chevrons.

Present experimental pumps of similar construction have been achieving specific pumping speeds approaching 10^5 $\ell/\text{sec m}^2$ (19-21). Development efforts are under way to increase this speed even further. Specific speeds as high as 1.5×10^5 $\ell/\text{sec m}^2$ could quite possibly be available by the time suitable ion sources for this design are developed. However, a specific speed of 10^5 $\ell/\text{sec m}^2$ will be used to evaluate the present system capabilities.

Figure 3-17. Cross Section of a Typical Single Surface Cryopump Mounted on an Outside Vacuum Vessel Wall.

Figure 3-18. Cross Section of Double Surface Internal Cryopump.

Vacuum System Operating Parameters - Table 3-5 summarizes the operating parameters of the primary vacuum system during a typical neutral beam pulse. Conductances and gas loads were calculated for deuterium gas at 300 K. The parameters of Table 3-5 are consistent with the gas flow balance equations of Figure 3-16 and the following assumptions:

1. For each energetic atom impinging on a beam line component, one molecule of D_2 gas is released.
2. The gas efficiency of the 8-15 A sources is 10%.
3. The assumed pressure in the neutralizer and torus ducts is an average of the pressures at each end.
4. The specific pumping speed of the cryopanel is 10^5 $\ell/\text{sec m}^2$

The pressures in each region meet the requirements as assessed previously. The pressure in the calorimeter region is far below the requirement for less than 1% ionization of the neutral beam. This fact will increase the total beam transmission efficiency slightly. The gas flow to the torus during a typical beam pulse is only 0.1 torr-liter for one arm. Up to ten beam arms could then be attached to the torus while keeping the cold gas input to less than one torr-liter as required previously. This would allow a maximum injection power of 100 MW.

The total required pumping speed for the arrangement of Table 3-5 is approximately 5.7×10^6 ℓ/sec . This means approximately 57 m^2 of cryopanel. The pumping speeds required for each region are less than the estimated available pumping speed. The available pumping speed is estimated from Figures 3-10 and 3-11, assuming placement of cryopanel on all vacuum walls but keeping away from areas where a possibility exists for direct interception of energetic particles.

Regeneration Period - The cryopanel must be regenerated before collecting a quantity of gas sufficient to produce a pressure of 13 torr in the vacuum

TABLE 3-5
PRIMARY VACUUM SYSTEM PARAMETERS

PRESSURES (torr)		GAS THROUGHPUTS AND LOADS ($\frac{\text{torr } \ell}{\text{sec}}$)	
P_1	$= 9.3 \times 10^{-5}$	Q_S	$= 104.8$
$\overline{P}_N$	$= 6.2 \times 10^{-5}$	Q_N	$= 36.5$
P_2	$= 3.1 \times 10^{-5}$	Q_{S02}	$= 0.4$
P_3	$= 4.1 \times 10^{-6}$	Q_{S03}	$= 0.5$
P_4	$= 2.1 \times 10^{-6}$	Q_C	$= 12.1$
$\overline{P}_d$	$= 1.1 \times 10^{-6}$	Q_{S04}	$= 0.2$
P_T	$= 1.0 \times 10^{-8}$	Q_T	$= 0.1 \frac{\text{torr } \ell}{\text{pulse}}$
CONDUCTANCE (ℓ/sec)		REQUIRED PUMPING SPEEDS (ℓ/sec)	
C_{12}	$= C_N = 5.9 \times 10^5$	S_1	$= 7.3 \times 10^5$
C_{23}	$= 7.6 \times 10^4$	S_2	$= 1.1 \times 10^6$
C_{34}	$= 2.2 \times 10^5$	S_3	$= 3.6 \times 10^6$
C_D	$= 6.6 \times 10^3$	S_4	$= 3.0 \times 10^5$
AVAILABLE PUMPING SPEEDS* (ℓ/sec)		REGION VOLUMES (liter)	
S_1	$= 1.3 \times 10^6$	V_1	$= 4.4 \times 10^3$
S_2	$= 1.5 \times 10^6$	V_2	$= 7.6 \times 10^3$
S_3	$= 4.4 \times 10^6$	V_3	$= 2.7 \times 10^4$
S_4	$= 5.0 \times 10^5$	V_4	$= 5.2 \times 10^3$
		TOTAL	$= 4.42 \times 10^4 \ell$

*Calculated from available cryopanel placement area at $10^5 \ell/\text{sec m}^2$

chamber upon total release from the pumping surfaces. This process involves warming of the cryopanel to about 50 K and pumping the evolved gases with the secondary vacuum system. This process will be described more completely in the next section.

The frequency of regeneration should be long enough to allow reasonable operating times for the neutral beam arm. The total volume of the beam arm is 4.42×10^4 l. Therefore, to stay below the 13 torr limit the panels must be regenerated after pumping a total of 5.75×10^5 torr-liter of D_2 . The total gas load due to the sources plus beam scrape-off and ion collection is 118 torr l/sec. For a 6 sec pulse, 708 torr liters are introduced, thus allowing a maximum of 812 shots between panel regenerations. At a rate of one shot every 5 minutes, the beam arm can operate 4060 minutes between regenerations. Since TNS is only envisioned as a test reactor and not a commercial power producing reactor, continuous operation is not necessary. If the reactor is run eight hours per day, panel regeneration would be required only every 8.5 days. Regeneration once a week would fit into a reasonable operating schedule.

3.2.7 SECONDARY VACUUM SYSTEM

The secondary vacuum system serves to pump out the vacuum chamber to acceptable pressures for operation of the primary vacuum system, and pumps gases evolved from the cryopanel during regeneration.

Initial pumpdown from atmospheric pressure where the cryopanel take over, around 10^{-6} torr, can be performed by a simple diffusion or turbomolecular pump backed by mechanical pumps and proper cold trapping. However, once the device has been operational, radioactive tritium contamination of the vacuum system is probable due to backflow of small amounts of tritium from the torus during the beam pulse. Care must be taken to contain this tritium.

Figure 3-19 shows a possible arrangement of the secondary vacuum system involving a turbomolecular pump, tritium getter canisters, LN_2 cold traps, suitable mechanical backing pumps and valves, and a tritium decontamination- D_2 recycle system. Turbomolecular pumps are available for operation with

tritium contaminated gas⁽²²⁾, and eliminate the possibility of backstreaming oil or mercury from conventional diffusion pumps. Baffling or cold trapping the inlet side of the turbopump is not necessary, thus maintaining a high effective pumping speed.

Typical pumpdown from atmospheric pressure involves roughing of the chamber and vacuum lines with the mechanical pump until the chamber pressure reaches 10^{-3} torr. The getter pumps are valved off during the whole process. At 10^{-3} torr the turbopump is started, which pumps down to about 10^{-6} torr before the cryopanel is brought down to pumping temperature. Pumpdown times may be estimated from Eq. (19) where V is the system volume, S is the effective pump speed at the volume interface, and P_i and P_f are the initial and final pressures.

$$t = 2.3 \frac{V}{S} \log \frac{P_i}{P_f} \quad (19)$$

Rough pumping should take about four hours assuming pumpdown from atmospheric pressure to 10^{-3} torr by a 30 ℓ /sec mechanical pump. Pumping from 10^{-3} torr to 10^{-6} torr by a 500 ℓ /sec turbopump should take less than 10 minutes. The turbopump is mounted vertically on the bottom of the vacuum vessel, connected to the source region by a high vacuum valve.

Regeneration of the cryopanel involves valving in the tritium getter canisters and recycling all pumped gas through a D_2 gas recycle and tritium cleanup system. The clean D_2 gas is stored and eventually fed back into the ion sources. Pumping of desorbed gas should take about four hours. Warming of the cryopanel to 50 K to release the gases should only require about two hours. But recooling of the cryopanel could increase the total regeneration time to almost a full day.

Figure 3-19. Secondary Vacuum System Schematic.

4.0 CONCLUSIONS

The result of this design study is a basic definition of the requirements and structure of a negative ion based neutral beam arm. This study may form a basis for more complete designs upon realization of the required component performances. The following design features summarize the production of a 200 keV, 10 MW D^0 beam as documented in this report.

- Eight D^- magnetron ion sources at 15 A and 10% gas efficiency.
- Eight close coupled, 5-electrode accel-decel systems with 50% transparency accelerating 0.13 A/cm^2 slab-shaped D^- ion beams.
- Eight 75 cm long, loose coupled D_2 gas neutralizers which, operating in an overdense mode, change an initially pure D^- beam to a mixed beam of $D^+/D^0/D^-$ with a composition ratio of 54/45/1.
- Four space charge controlled direct recovery units for electrical recovery of the D^+ beam which comprise approximately 335 cm of the 503 cm beam arm length (excluding duct to torus).
- Four differential vacuum pumping regions for a total of 57.3 m^2 of LHe cryocondensation panel surface area. A total pumping speed of $\sim 6 \times 10^6 \text{ l/sec}$.
- One retractable thermal calorimeter comprised of eight power dissipation units for beam power measurements.
- A secondary vacuum system for regeneration of cryopanel and initial pump down, incorporating a 500 l/sec turbopump backed by an appropriate set-up of cold traps, mechanical pumps, getter pumps, and tritium handling- D_2 recycle system.

- The whole beam arm is enclosed in a stainless steel vacuum chamber in form of a rectangular box approximately 440 cm high by 240 cm wide by 580 cm long.

The total electrical efficiency of this system, disregarding vacuum pumping power and the inefficiencies of power supplies and lines, is approximately 40%. A comparable efficiency for a positive ion based system producing the same neutral beam is about 25%⁽¹⁾. The vacuum pumping requirements, as estimated by total gas loading, are approximately the same. Fabrication costs of the negative ion based system can be assumed to be very close to that of positive ion systems, due to the similarity in total beam arm structure. However, development costs for the negative ion sources will be an added expense far more extreme to that incurred with a positive ion system.

The design presented here suggests that a negative ion based neutral beam system is applicable to TNS, assuming technological advancements in several areas. Improvements in negative ion sources, direct energy conversion of charged beams, and high speed cryogenic pumping are needed as documented. It would not be unrealistic to assume that given adequate funding a period of 10 years would be required to develop these areas to the extent deemed necessary in this design. The increase in total electrical efficiency over a positive ion based system and the encouraging results of this first attempt at a working design justify increased effort and capital in the development of the above mentioned areas.

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