

By acceptance of this article, the publisher or recipient acknowledges the U.S. Government's right to retain a nonexclusive, royalty-free license in and to any copyright covering the article.

CONF - 820545 -- 25 - DRAFT  
Draft

Determination of Species Yield of Ion Sources  
Used for Intense Neutral-Beam Injection

C. C. Tsai, C. F. Barnett, H. H. Haselton  
R. A. Langley, and W. L. Stirling

CONF-820545--25-Draft

DE83 017187

Abstract

For efficient plasma heating, ion sources of neutral-beam injectors should be capable of producing ion beams with an atomic fraction of 90% or higher. Diagnostic techniques for quantitatively determining source species yield have been developed and evaluated. These include magnetic momentum analysis of the unneutralized ions passing through the neutralizer, energy analysis of the neutral beam by electrostatic separation of ions emanating from a stripping cell, and quantity vs implantation-depth analysis of hydrogen implanted into a crystal by SIMS technique. The operational features and advantages and disadvantages of each technique will be discussed. If the effects of beamlet optics, energy straggling in the accelerator, and neutralizer gas scattering are taken into account, the results of the measurements using the three techniques are shown to be mutually consistent within experimental error.

**DISCLAIMER**

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

\*  
Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

**MASLEN**

*mp*  
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

## 1. Introduction

The injection of energetic neutral beams of  $D^0$  (or  $H^0$ ) is an effective heating technique for plasmas in magnetically confined fusion devices [1-6]. The development of the neutral beam technology has been aggressively pursued during the past decade [4,5]. In the United States, short-pulse neutral beam injectors have been developed for ATC, ORMAK, PLT, ISX-B, PDX, DIII, TFTR, 2XIIB, and TMX. The ongoing experiments on PLT, ISX-B, and PDX utilize low energy (<50 keV) neutral beam injectors, which have been developed at Oak Ridge National Laboratory (ORNL). Other high energy (80 to 120 keV) injectors developed at Lawrence Berkeley National Laboratory (LBNL) will be used for experiments on DIII and TFTR. For the applications to MFTF-B, ATF, and TFET, long pulse (20 to 30 sec) neutral beam injectors are being developed at both laboratories. Subsequently, long pulse injectors may be developed to fulfill the application requirements for FED, INTOR, and FDP. Injection power of 30 to 100 MW at particle energies of 100 to 200 keV, and pulse lengths of 10 to 100 sec are the essential neutral beam parameters envisioned [7-12]. Moreover, a source atomic ion yield >90% is highly desirable. Procedures to measure the source atomic ion yield are necessary in order to optimize the injectors.

Multi-megawatt neutral beams are produced by efficient and powerful neutral beam injectors which are positive-ion-based injection systems. The main components of the neutral beam injectors are an ion source, a neutralizer, a bending magnet, ion dumps, and a neutral beam calorimeter, as shown in Figure 1. The ion source consists of a plasma generator and an ion accelerator. The plasma generator supplies positive ions which are extracted and accelerated to form an ion beam by a set of multi-aperture (or multi-slot) grids of the ion accelerator. The ion beams contain atomic and molecular ions of  $D^+$  ( $H^+$ ),  $D_2^+$  ( $H_2^+$ ), and  $D_3^+$  ( $H_3^+$ ). Passing through the  $D_2$  ( $H_2$ ) neutralizer, the ion beams are partially converted into neutral beams by dissociative and electron capture collisions. The energetic  $D^0$  particles possess a kinetic energy of full, one-half, or one-third of the ion acceleration energy. After removing the unneutralized ions at the neutralizer exit, the powerful neutral beams are injected into the target plasma of a fusion device.

The neutralization efficiency of positive ions decreases as the beam particle energy increases. For instance, the neutral fraction will decrease from 52% to 13% as  $D^+$  energy is increased from 100 keV to 200 keV. In addition, the ion removal problem becomes more difficult as the beam particle energy is raised. However, if the kinetic energy of unneutralized ions can be effectively recovered, the ion removal problem can be eliminated and the production efficiency of neutral beams can be improved. To do so, the development of various energy recovery techniques [13-15] are being pursued. To date, only the kinetic energy of full energy ions can be effectively recovered. Thus,

ion sources with high atomic ion yield are needed for future efficient and reliable neutral beam injectors.

After being injected into a target plasma, the energetic neutrals are converted into fast ions and trapped in the confinement region by charge exchange and ionization collisions. Gradually the energy of the injected particles transfers to the plasma particles via Coulomb collisions. This process results in the bulk heating of the target plasma. Obviously, the higher the fraction of the injected neutrals which are trapped in the confinement region (plasma core), the smaller the amount of beam energy deposited in the plasma edge and the resulting heating efficiency is higher. It is clear that the highest heating efficiency may be achieved only by utilizing monoenergetic neutral beams [11]. Again, ion sources with high atomic ion yield are favorable candidates for efficient and reliable neutral beam injectors.

The source atomic ion yield is strongly dependent on ion source conditions, accelerator and neutralizer gas density distribution. Thus reliable and accurate diagnostics are needed in order to optimize this yield. During recent years various diagnostics have been used to estimate the source ion species mix in various fusion research centers [16-21]. These diagnostics are:

- (1) Magnetic spectrometry of reionized neutral beams.
- (2) Doppler optical spectrometry of neutral beams.
- (3) Ion and/or neutral implantation into target crystal and subsequent SIMS (Secondary Ion Mass Spectrometer) analysis.
- (4) Neutral particle analyzer with a calibrated stripping cell and energy analyzer.

(5) Magnetic momentum analysis of unneutralized beam.

Depending upon the beam conditions and properties, and the location and the acceptance angle of the analyzer, the source atomic ion yield so determined varies from below 70% to above 90%. Thus, a reliable and dependable diagnostics is urgently needed. At ORNL, the principal diagnostic used in the past is the magnetic momentum analyzer. To improve the accuracy of the species mix estimation, the last three diagnostics are currently being studied. The operating feature and characteristics of each of these three diagnostics will be described and discussed.

2. Magnetic Momentum Analyzer

The magnetic momentum analyzer consists of a bending magnet at the neutralizer exit and a water-cooled calorimetric tube across the image center of the one-half energy ion dump. Normally, the unneutralized ions, which emanate from an equilibrium neutralizer and pass through the bending magnet, will be separated into full, one-half, and one-third energy components and impinge upon their corresponding ion dumps. The power loadings of the ion dumps provide a rough indication of ion species mix in the source. Some of the ions will impinge on the calorimetric tube, dissipate their energy, and raise the cooling water temperature. The temperature peak of the cooling water is used to represent the relative amount of ions intercepted by the tube. Thus, the ion composition of the entire beam can be measured by changing the exciting current of the bending magnet. A typical curve so obtained for an 80 keV beam is shown in Figure 2. The three peaks denoted by  $E$ ,  $E/2$ , and  $E/3$  are, respectively, for the unneutralized ions originated

from  $H_1^+$ ,  $H_2^+$ , and  $H_3^+$  components of the ion beams emanating from the source. The distance between the calorimetric tube and the source is almost equal to the focal length of the source. Under this condition, the three peak heights in the curve of Figure 2 may be used to estimate the source species mix, since most of a species hits the tube at peak response. From this curve, the species current ratio at the ion dump is:

$$J_1 : J_2 : J_3 = 90.0 : 5.3 : 4.7$$

Assuming measured, unneutralized ions emerging from an equilibrium neutralizer, the estimated current ratio at the source is:

$$J_1 : J_2 : J_3 = 79 : 9 : 12$$

Using the peak height analysis, the variations of the source atomic ion yield with respect to the beam current density were studied for PLT/ISX-B sources, and the results are shown in Figure 3. From the curve denoted by ORNL, we notice that the source atomic ion yield increases from ~70% to ~80%, as the beam current density is increased from ~0.2 A/cm<sup>2</sup> to 0.43 A/cm<sup>2</sup>. The other curve in the figure is the experimental results which were obtained independently at Princeton Plasma Physics Laboratory (PPPL) by utilizing a neutral particle analyzer[22]. The agreement between these two measurements is excellent. In fact, at PPPL, the maximum source atomic ion yield of ~87% was measured by a Doppler broadening scanning spectrometer.

If the calorimetric tube is not located near the focal plane of the source, or the source is not a focused one, the peak height analysis is not valid and the following area analysis would be used. The required magnetic field strength to deflect the ions to the calorimetric tube is proportional to the square root of the ion energy. Changing the horizontal coordinate accordingly, the peaks  $E/2$  and  $E/3$  in Figure 2 are redrawn and shown in Figure 4 by the solid curves. The species ratio at the ion dump is estimated to be:

$$J_1 : J_2 : J_3 = 84.5 : 7.0 : 8.5$$

The estimated species ratio at the source is:

$$J_1 : J_2 : J_3 = 72 : 11 : 17$$

It should be pointed out that the beam properties of  $H^+$ ,  $H_2^+$ , and  $H_3^+$  emanating from the source should be the same. However, the shapes of the solid curves in Figure 4 are different for different energy components. The energy straggling effect [23] in the accelerator and the energy dispersion effect [24] in the neutralizer could account for the shape difference of these curves. If we normalize the solid curves for the  $E/2$  and  $E/3$  ions to that of the  $E$  ions, the new curves are shown by the dashed curves. These new curves can be used to represent the actual ion species mix at the extraction surface region in the plasma generator. The secondary particles created in the accelerator [23] can be estimated by the area difference between the solid and dashed curves. Obviously, the area analysis will give a reasonable estimation of the species mix in the beam at the source, but will underestimate the atomic ion yield in the source plasma. Hence, the peak height analysis is a reasonable way to determine the source atomic ion yield for a focused source.

The accuracy of this analyzer is degraded by the uncertainty of the equilibrium gas-line density in the neutralizer, the reionization and neutralization effect in the bending magnet, turbulence of cooling water, and the reflection of energetic ions from the calorimetric tubes. The percentage of error is on the order of  $\pm 3\%$  of 79%. The measured results seem to be independent of beam optics and neutralizer dispersion effect. Moreover, at the moment, only this analyzer is capable of doing species composition study for the entire beam.

### 3. Neutral Particle Analyzer

At the downstream of the neutral target (Figure 1), a neutral particle analyzer is located to study ion or neutral beamlets passing through a hole of 6.4 mm diam. in the target. This analyzer consists of a calibrated stripping cell and a parallel plate electrostatic energy analyzer[20]. The designed acceptance angles of the Faraday cups are sufficiently large for minimizing the effect of energy dispersion in the stripping cell and in the energy analyzer. The study of the composition of ion beams produced by a PDX/ISX source is elaborated below.

At a beam current density of  $\sim 0.1 \text{ A/cm}^2$  the source atomic ion yield- estimated is about 79% from the total beam including ions and neutrals. Under the same beam condition, the estimated source atomic ion yield which is based on the peak height analysis of the magnetic momentum analyzer is about 73%. The 6% discrepancy could be due to the fact that the former measures the center beam and the latter measures the total beam. From the following discussion, such a percentage error is acceptable.

The neutral particle analyzer was installed on a movable frame. It can be moved in three directions: along the beam axis, up-down and left-right across the beam. After aligning the analyzer to the beam, the data for the above results were collected. This method only samples a small fraction of the beam. During this experiment, we observed the following interesting features:

(1) The source atomic ion yield increases with the beam density, for instance, from 79% at  $0.1 \text{ A/cm}^2$  to 82% at  $0.13 \text{ A/cm}^2$ .

This fact is consistent with that shown in Figure 3.

(2) The source atomic ion yield estimated is a sensitive function of beam optics. For instance, the species ratio for 22 keV beams with various beam current densities is given as:

$J_1 : J_2 : J_3 = 70 : 8 : 22$  at  $0.075 \text{ A/cm}^2$  under-dense

$J_1 : J_2 : J_3 = 73 : 8 : 19$  at  $0.092 \text{ A/cm}^2$  minimum divergence

$J_1 : J_2 : J_3 = 67 : 10 : 22$  at  $0.103 \text{ A/cm}^2$  over-dense

Obviously, the beams with minimum divergence will have highest measured source atomic yield.

(3) The measured source atomic ion yield is ~80% at the beam center, but drops below 70% at the beam edge. Considering the fact that the energy dispersion in the neutralizer is worse for molecular ions than that for atomic ions, this observed phenomenon is understandable. The other fact that the backstreaming electrons may create molecular ions around the circumference of the emitting apertures of the plasma grid, may be another reason.

(4) The measured source atomic ion yield is higher for the center beamlets, for example, >80% for the center beamlets and <70% for the edge beamlets.

This fact could be caused by the variation of:

- (i) the source atomic ion yield across the grid,
- (ii) the beamlet optics due to the nonuniform source plasma,
- (iii) the energy straggling due to the nonuniform distribution of the gas density in the accelerator and/or in the neutralizer.

The exact cause of this feature needs further study.

(5) The measured source atomic ion yield is higher for overdense gas density in the neutralizer, the stripping cell, and/or in the region between them. This can be understood because the partial energy particles suffer serious energy dispersion under such low beam energy (~20 keV).

In addition to the valuable information just mentioned, this analyzer is capable of studying beam composition during the pulse. It is an on-line in situ instrument. Thus, it can be used for studying the effect of the source operating parameters on the species variations. Obviously, it can be used for optimizing the atomic fraction in neutral beams. Regarding the accuracy of measuring the source atomic ion yield, the results from ion beams will be better than that from neutral beams. This is because the species composition of neutral beams changes with the gas line density of the neutralizer. However, the difference between these measured results may be used to indicate the percentage of equilibrium of the neutralizer. Moreover, the capability of measuring neutral beam composition can be used for optimizing the fraction of full energy neutrals for some applications.

Since the measured species mix changes with the beam divergence, beam position, and gas scattering, the highest source atomic ion yield measured could be higher than the actual source atomic ion yield that is an average over the whole beam.

#### 4. Implanted Particle Analyzer

Silicon crystals were located near the center of the neutral beam either in front of or behind the neutral target and were irradiated by the neutral beam. The depth profiles of implanted hydrogen were then determined by the analysis of SIMS (Secondary Ion Mass Spectrometry). As reported elsewhere[19], the measured source atomic ion yield for 40 keV, 75 A beams is:

$$J_1 : J_2 : J_3 = 68 : 16 : 16 \quad \text{Gaussian Profiles}$$

$$J_1 : J_2 : J_3 = 74 : 14 : 12 \quad \text{Skewed Profiles}$$

The corresponding ion current density is about  $0.25 \text{ A/cm}^2$ . Under the same beam conditions, the magnetic momentum analyzer was used to measure the unneutralized ions. The estimated source atomic ion yield from the three peak heights similar to that in Figure 2 is:

$$J_1 : J_2 : J_3 = 78 : 14 : 8$$

As mentioned in Section 2, the estimated atomic fraction in the beam (based on the area analysis) will be about 70%, instead of 78%. Detecting both the primary and the secondary particles of the beam, the SIMS analyzer will properly estimate the atomic fraction of the beam, similar to the area analysis. Thus, the difference of the estimated source atomic ion yield between the SIMS analyzer and magnetic momentum analyzer seems within the experimental error.

This analyzer only measures a small sample of the beam. With many samples of irradiated crystals, it is capable of studying species composition across the beam, of center beamlets and of edge beamlets. It can study source species mix from both ion and neutral beams. One of the outstanding features is that the accuracy of this measurement is independent of the beam optics and the energy dispersion in the neutralizer, because the deposition profile depends upon the particle energy. However, the measurement accuracy does depend upon crystal temperature, particle flux saturation, and profile distribution assumption. The resolution between the E/2 and E/3 components can be substantially improved for higher particle energy ( $>80$  keV). As given above, it tends to give a lower source atomic ion yield. This technique does not lend itself to in situ measurements.

## 5. Discussions

From the above three analyzers, the estimated source atomic ion yield for duoPIGatron ion sources is from 70% to 80% at  $\sim 0.15$  A/cm<sup>2</sup>. The variation can be the result of measurement errors and different beam conditions. In general, these analyzers can be used to estimate the source species mix and the neutral beam composition. Their merits are summarized below:

(1) The magnetic momentum analyzer can estimate the average source species mix. The area analysis technique can reveal the energy straggling effect in the ion accelerator.

(2) The neutral particle analyzer can study the distribution of source species mix as a function of beam divergence, beam current density, gas feed in the source and in the neutralizer, beam radius, and grid radius. It is portable and can be used in various test facilities. It can be used for optimizing full energy neutrals for neutral beam applications.

(3) The Si crystal SIMS analyzer can study the species of neutral and ion beams. Its capabilities are similar to that of the neutral particle analyzer; particularly, it is immune from the effect of beam optics and energy dispersion. It is not an in situ instrument. The implanted particle profile in crystals is analyzed at another facility; however, it is very convenient for comparison purposes of various ion sources. It can be used to study both low, medium and high Z impurities and their energy distributions.

Under neutral beam conditions, the gas density in the accelerator can be of the order of  $3 \times 10^{14} \text{ cm}^{-3}$ . With such high gas density, the energy straggling effect can seriously degrade the source atomic ion yields. The ion sources being developed for neutral beam application in various fusion research centers can be operated at different source gas efficiencies, grid temperatures, beam energy, and gas line densities in the neutralizer. The variation of the gas line density in the accelerator of these ion sources can be as large as  $\pm 50\%$ . Even with the same ion source and the same species analyzer, such a large fluctuation in the gas density will lead to at least  $\pm 10\%$  fluctuation of the source atomic ion yield. This may explain why some people claim  $>90\%$  source atomic ion yield. Moreover, different analyzers in different test facilities have different acceptance angles. For

instance, for an analyzer with  $\pm 0.2^\circ$  acceptance angle, the atomic ions will be the dominant particles to be measured because the partial energy particles with a larger energy dispersion will not be measured as efficiently as the full energy component. Consequently, the measured source atomic ion yield will be unusually high, say >95%. Thus, the source atomic ion yield should be determined under standardized conditions by a few reliable analyzers.

#### ACKNOWLEDGEMENTS

The authors would like to thank their colleagues for their assistance in this work: G. C. Barber, N. S. Ponte, D. O. Sparks, and R. E. Wright for electrical and electronics support; C. W. Blue, R. R. Feezeli, S. C. Forrester, and J. A. Mbeller for the test stand maintenance; D. E. Schechter and F. Sluss for the preparation of ion sources; and W. K. Dagenhart, W. L. Gardner, G. G. Kelley, M. M. Menon, P. M. Ryan, and J. H. Whealton for the fruitful discussions and the participation in experiments.

REFERENCES

1. J. F. Clarke, Proc. of the IEEE, 69, 867 (1981).
2. J. Sheffield, *ibid*, 69, 885 (1981).
3. T. C. Simonen, *ibid*, 69, 935 (1981).
4. M. M. Menon, *ibid*, 69, 1012 (1981).
5. W. B. Kunkel, LBL-10447 (1980).
6. H. Eubar et al., Phys. Rev. Lett. 43, 270 (1979).
7. Proc. of the 3rd IAEA Neutral Beam Workshop, to be published (1981).
8. INTOR Group, in Rep. Int. Tokamak Workshop (IAEA, Vienna), (1980).
9. D. H. Metzler and L. D. Stewart, in EPFR-9, 748 (1981).
10. W. A. Houlberg et al., *ibid*, 688 (1981).
11. L. M. Hively et al., *ibid*, 715 (1981).
12. D. H. Metzler, *ibid*, 1286 (1981).

13. W. L. Barr et al., in EPFR-8, 1030 (1979).
14. P. Raimbault et al., Proc. Joint Varenna-Grenoble Int. Sump. on Heating in Toroidal Plasma, 1, 71 (1978).
15. W. L. Stirling et al., Appl. Phys., Lett. 35, 104 (1979).
16. Y. Okumura et al., Rev. Sci. Instrum. 52, 1 (1981).
17. T. Obiki et al., Rev. Sci. Instrum. 52, 1445 (1981).
18. C. F. Burrell et al., Rev. Sci. Instrum. 51, 1451 (1980).
19. R. A. Langley and C. W. Magee, J. Nucl. Material 93 and 94, 390 (1981).
20. C. F. Barnett and J. A. Ray, ORNL/TM-7656 (1980).
21. C. C. Tsai et al., ORNL/TM-6360 (1978).
22. L. R. Grisham et al., PPPL-1484 (1978).
23. C. C. Tsai, Proc. of the 3rd IAEA Neutral Beam Workshop, to be published (1981).
24. H. H. Fleischmann, C. F. Barnett, and J. A. Ray, Phys. Rev. A 10, 569 (1974).

Figure Captions

- Figure 1. Schematic of a conventional neutral beam injector and beam species analyzer.
- Figure 2. Typical calorimetric scan of unneutralized ions over ion dumps.
- Figure 3. Variation of source atomic ion yield with respect to beam current density measured at PPPL and ORNL.
- Figure 4. Unnormalized (solid) and normalized (dashed) curves for  $E/2$  and  $E/3$  unneutralized  $H^+$  ions as shown in Figure 2.







