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.

INITIAL MEASUREMENT OF IMPURITY PRODUCTION AND HYDROGEN ENERGY DISTRIBUTION FROM NEUTRAL BEAM INJECTORS*

R. A. Langley

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830 U.S.A.

and

C. W. Magee

RCA Laboratories
Princeton, New Jersey 08540 U.S.A.

MASTER

ABSTRACT

Impurity production and hydrogen energy distributions for neutral beam injectors (NBI) developed by the Plasma Technology Section of Oak Ridge National Laboratory's (ORNL's) Fusion Energy Division have been measured by exposing silicon samples to beam pulses and analyzing them by nuclear microanalysis and secondary ion mass spectrometry (SIMS) techniques. The NBI's have been developed for use on the Princeton Large Torus (PLT), the Poloidal Divertor Experiment (PDX), and the Impurity Study Experiment (ISX). Extraction voltages of up to 50 kV are used, and maximum power injected for a 0.5-s pulse is ~1.2 MW with a design goal of 1.5 MW. The Medium Energy Test Facility (METF) was used for exposure of the single-crystal [100] silicon samples.

Neutral hydrogen from the injector is expected to have three major energy components (E , $E/2$, and $E/3$) arising from the formation of H^+ , H_2^+ , and H_3^+ in the ion source and the subsequent neutralization and

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

DISCLAIMER

This book 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.

dissociation in the neutralizer gas cell. The full-energy component (40 keV) is easily separated in the depth analysis, but the E/2 and E/3 components overlap, mainly because of range straggling. Analysis by SIMS is used to determine the depth profiles of the implanted hydrogen, and the three energy components are determined from this depth profile. Nuclear microanalysis is used to analyze for heavy impurities.

Initial results have shown that oxygen is the major atomic impurity and is present at levels of 1.5×10^{-3} O/H. Carbon is the next most abundant impurity, and copper is at or below the sensitivity of the analysis technique. The hydrogen species power distribution deduced from the implant profiles results in relative abundances at the ion source of 74:14:12 for the energy components E:E/2:E/3, respectively. These data do not agree with three other independent measurements at ORNL and Princeton Plasma Physics Laboratory that are in agreement and yield a hydrogen species power distribution of 85:10:5. At present the discrepancy is unaccounted for.

INITIAL MEASUREMENT OF IMPURITY PRODUCTION AND HYDROGEN
ENERGY DISTRIBUTION FROM NEUTRAL BEAM INJECTORS*

R. A. Langley

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830 U.S.A.

and

C. W. Magee

RCA Laboratories
Princeton, New Jersey 08540 U.S.A.

Introduction

This study was initiated to measure impurities and hydrogen energy distribution because direct measurements of both quantities have not been made and it was hoped that the present technique would be more direct than previously used methods [1,2]. These quantities are important because the energy distribution in a neutral beam has a strong influence on the beam penetration length and the resulting heating profile in the plasma, and the impurities injected into the plasma can add significantly to the energy loss through line and recombination radiation.

The neutral beam injector (NBI) used for these studies is an Oak Ridge National Laboratory (ORNL) design that is used on both the Poloidal Divertor Experiment (PDX) and the Impurity Study Experiment (ISX). It has a nominal accelerating voltage of 40 keV, an ion current of 75 A,

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

and a source diameter of 0.30 m. For these studies the neutralizer gas cell was used in the equilibrium mode, i.e., ($n\alpha L \gg 1$), and the neutralizer gas was hydrogen.

Saturation and Impurity Study

The initial experiment was to irradiate single-crystal [100] silicon samples ($1 \times 1 \times 0.1$ cm), inclined at about 10° to the beam direction to suppress channeling, for one, three, and six neutral beam shots to determine whether saturation effects occur, to determine what the major impurities and their concentrations are, to measure the absolute amount of neutral hydrogen implanted in the sample, and to determine the relative energy components of the hydrogen beam. Analysis of the irradiated samples was made by helium ion backscattering (IBS) and by secondary ion mass spectrometry (SIMS). Both of these techniques have been adequately described in the literature and will only be referenced here [3,4].

Initial concern that beam heating of the sample might induce migration of the hydrogen from its end of range necessitated the use of short-duration shots of 40 ms; however, the temperature rise during irradiation might still be excessive. Calibration of the SIMS instrumentation was made with samples prepared at much lower fluence rates than those used in these irradiations.

Figure 1 shows the SIMS raw data for the sample that was exposed for six shots. The masses scanned were 1, 12, 18, 30, and 63; these particular isotopes were chosen to facilitate as much as possible positive identification of the following masses: hydrogen, carbon,

40 keV HYDROGEN NEUTRAL BEAM $\rightarrow$ SILICON

ORNL-DWG 80-2569

FED

oxygen, silicon, and copper, respectively. Mass 1 has two distinct peaks; the one nearer the surface is much broader than the deeper peak that has a hump on the deeper side. The three energy components expected are 40 keV (E), 20 keV ($E/2$), and 13.3 keV ($E/3$). Although the full-energy component is easily resolved, the half- and third-energy components are not; however, overlapping of these two components is expected because of range straggling [5]. On both the mass 12 and 18 spectra a background level from an unimplanted sample is shown by a dotted line. The level of the mass 63 spectra is at the sensitivity limit of the SIMS instrument. In Fig. 2 is shown the shape of the mass 18 peak with background subtracted. The mean depth and FWHM agree remarkably with theoretical calculations of the mean range and range straggling for 40-keV oxygen implanted into silicon. The total amount of implanted hydrogen and oxygen scales linearly with the number of pulses up to six pulses, as shown in Fig. 3. No saturation effects were observed. From these data the impurity levels in the beam can be obtained. These are given in Table 1.

Beam Heating Effects and Hydrogen Species Distribution

In order to determine whether beam heating could prove to be a major source of error, irradiations were made with increasing shot lengths, i.e., 40, 100, 150, and 200 ms. For these irradiations each silicon sample was soldered to a copper block ($20 \times 20 \times 3$ mm) using pure indium. Because the silicon had a thin SiO_2 layer, good bonding to the copper was difficult and did not make for reproducible bondings. A spectrum of the implanted hydrogen profile for a pulse duration of 150 ms

is shown in Fig. 4. There is excellent correspondence both in shape and fluence rate for the 150- and 40-ms pulses, but there is almost no correspondence with the 100-ms pulse. Shown in Fig. 5 is the depth profile for the 100-ms irradiation; both the predicted and measured profiles are shown. It is obvious that substantial loss of hydrogen from the sample has occurred and that the profile shape has changed drastically, indicating severe heating of the sample probably caused by bad bonding between the sample and the heat sink. The deeper peak has gotten substantially lower and narrower. This narrowing effect has previously been observed on isochronal (1 h) annealing of samples implanted with 100-keV hydrogen to a fluence of $10^{16}/\text{cm}^2$. These studies [6], although not yet published, showed significant loss and narrowing of the profile by 400°C and almost total loss of hydrogen by 700°C. Calculations using the silicon thermal conductivity and capacity would indicate that the instantaneous surface temperature may reach 300°C for a 40-ms shot and 1000°C for a 200-ms shot. The sample irradiated for 200 ms was severely damaged by the beam. The apparent failure mechanism was thermal shock.

Analysis of data for the 150-ms shot is shown in Fig. 6. The data are reduced by assuming a Gaussian distribution for the implant profile and a mean range and spread derived from both theory and monoenergetic implants. The fit for the three energy components is accomplished by only adjusting the peak heights of the three individual peaks. Shown are the individual Gaussian profiles (E , $E/2$, $E/3$), a composite curve

40 keV HYDROGEN
NEUTRAL BEAM → SILICON

ORNL-DWG 80-2568 FED

40 keV HYDROGEN
NEUTRAL BEAM → SILICON

ORNL-DWG 80-2567 FED

40 keV HYDROGEN NEUTRAL BEAM → SILICON

ORNL-DWG 80-2566 FED

for the Gaussians, and the profile determined by SIMS. The curves fit well on the high-energy side but disagree on the low-energy side. The results are given in Table 2.

It is well known that the implant profiles are not Gaussian but are skewed toward the surface. These profile shapes have been calculated by Gibbons et al. [7] and Winterbon [8]. Using these results Brice [9] has compiled the projected range, relative variance, skewness, and kurtosis for $H \rightarrow Si$ for energies from 1 keV to 60 keV. Using the data from Brice an estimate is made that, at most, a 10% change can result in the individual peak areas because of this effect. The results are summarized in Table 3.

Immediately after irradiation of the samples a power profile of the ion fraction that had passed through the neutralizer gas cell was measured by changing the magnetic field in the deflection magnet so as to direct the ion beam onto a calorimeter. The results are shown in Fig. 7. Using known charge transfer cross sections, one can estimate the species distribution at the ion source and then in turn estimate the neutral species components. The results of these calculations are given in Table 3 along with estimates of the presently measured species distributions. There is about a 13% difference in the results in the full-energy component between the two measurements. There have been two previous independent measurements [2] that substantiate the magnetic scan results. The first is a measurement of the relative intensities of the Doppler-shifted and unshifted peaks of H_α light from the beam, and the second is a charge exchange analyzer measurement on the tokamak with

only toroidal and vertical fields energized. The discrepancy between the present results and the other measurements has not yet been resolved.

Conclusions and Future Plans

The present measurements have shown that oxygen and carbon are the major impurities and that high- Z ($Z > 14$) impurities are much smaller (by 10^2). Hydrogen energy distributions have been measured but were found to disagree with previous independent measurements using other techniques. Future plans are to do both temporal and spatial studies of the hydrogen species distributions and impurity content and to investigate further the beam heating and implant flux rate effects in order to resolve the differences observed in the results of the different measurements. In addition, measurements are planned for other types of NBI's in order to directly compare neutral beam power and impurity content using the same technique and analysis equipment.

Acknowledgments

Appreciation goes to the ORNL Neutral Beam Group for doing the sample irradiations and the magnetic scan and for many fruitful discussions. Also thanks are due to Ray Zuhr for performing the ion back-scattering analysis.

References

- [1] C. C. Tsai et al., Oak Ridge National Laboratory Report ORNL/TM-6360, September 1979.
- [2] L. R. Grisham, H. P. Eubank, H. F. Dylla, R. J. Goldston, G. Schilling, L. D. Stewart, R. W. Stookesberry, and M. Ulrickson, Princeton Plasma Physics Laboratory Report PPPL-1484, October 1978.
- [3] W-K. Chu, J. W. Mayer, and M-A. Nicolet, Backscattering Spectrometry (Academic Press, New York, 1978).
- [4] C. W. Magee and C. P. Wu, Nucl. Instrum. Meth. 149 (1978) 529.
- [5] H. H. Anderson and J. F. Ziegler, Hydrogen Stopping Powers and Ranges in All Elements (Pergamon Press, New York, 1977).
- [6] C. P. Wu and C. W. Magee (RCA Laboratories, Princeton), private communication, 1980.
- [7] J. F. Gibbons, W. S. Johnson, and S. W. Mylroie, Projected Range Statistics (Halsted Press, Stroudsburg, Pennsylvania, 1976).
- [8] K. B. Winterbon, P. Sigmund, and J. B. Sanders, Mat. Fys. Medd. Vid. Selsk. 37 (1970) No. 14.
- [9] D. K. Brice (Sandia Laboratories, Albuquerque), private communication, 1980.

Figure Captions

- Fig. 1. SIMS analysis of silicon sample irradiated with six 40-ms pulses. Accelerating voltage is 40 kV. Dashed lines for ^{18}O and ^{12}C represent those levels for nonirradiated samples.
- Fig. 2. Depth profile of ^{18}O as determined from data of Fig. 1. Mean range and range straggle agree with theoretical predictions.
- Fig. 3. ^1H and ^{18}O relative signal versus number of 40-ms pulses.
- Fig. 4. SIMS spectra for ^1H for pulse duration of 150 ms.
- Fig. 5. SIMS spectra for ^1H for pulse duration of 100 ms. Note difference in predicted and actual profiles.
- Fig. 6. Analysis of SIMS spectra for ^1H for pulse duration of 150 ms.
- Fig. 7. Ion beam power measurement using magnetic scan.

Table 1.
 Impurity levels in 30-cm-diam ORNL neutral beam injector (40 keV)

Impurity species	Relative amount per (incident H^0)	Analysis technique
C	1×10^{-3}	SIMS
O	1.5×10^{-3}	SIMS
Cu	$\leq 10^{-5}$	SIMS
All $Z > 14$	$\leq 10^{-5}$	IBS

Table 2. Species distribution of 40-keV hydrogen NBI*

Hydrogen energy (keV)	% of injected atoms	% of injected power	Flux rate of injected atoms ($10^{17}/\text{cm}^2 \cdot \text{s}$)	Injected power ($\text{W} \cdot \text{cm}^{-2}$)
40	38	61	0.76	508
20	24	19	0.48	165
13.3	<u>38</u>	<u>20</u>	<u>0.76</u>	<u>160</u>
Total	100	100	2.00	833

*Data reduced assuming Gaussian distributions for implant profiles.

Table 3.

Comparison of power distributions in NBI determined by implant profiles of H^0 and determined by magnetic scan of H^+ in beam dump

Energy component	Implant profiles of H^0				Magnetic scan of H^+		
	Neutrals [*]	At ion source	Neutrals [†]	At ion source	Charged particles at beam dump	At ion source	Neutrals
E	61	68	67	74	92.8	85	80
E/2	19	16	17	14	5.4	10	13
E/3	<u>20</u>	<u>16</u>	<u>16</u>	<u>12</u>	<u>1.8</u>	<u>5</u>	<u>7</u>
Total	100	100	100	100	100.0	100	100

^{*} Estimates of species distributions using Gaussian distributions.

[†] Estimates of species distributions using skewed distributions (see text for explanation).