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Author

Smith, R.R.

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A CONVENIENT METHOD FOR THE MEASUREMENT OF SPECIES
COMPOSITION FROM AN INTENSE NEUTRAL BEAM

by

R.R. Smith and J.W. Stearns

University of California
Lawrence Berkeley Laboratory
Berkeley, California 94720

ABSTRACT

We present a method to infer the approximate species mixture of neutral beam sources which accelerate positive hydrogen ions. An idealized neutral beam is specified by the accelerating voltage, the neutralizer thickness [molecules of hydrogen cm^{-2}], and the currents of extracted H^+ , H_2^+ , and H_3^+ . These currents define two independent ratios which lie within a narrow parameter region and which can be determined by two independent measurements downstream from the source. The two suitable parameters are: 1) the ratio of neutral to total beam power; and 2) the ratio of hydrogen produced by the neutral beam in the target volume to the hydrogen produced by the total beam. We give experimental results from the $10 \times 10 \text{ cm}^2$ 120 KeV test stand at the Lawrence Berkeley Laboratory.

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Permanent address: Princeton Plasma Physics Laboratory.

Introduction

Neutral beams are directed streams of energetic atoms, usually hydrogen or deuterium. With fluxes equivalent to many amperes and average energies per particle from ten-to one-hundred twenty-kilo-electron volts per atom, these beams have been developed to heat and to sustain plasmas in several magnetic fusion experiments^[1-4]. The energetic atoms penetrate the confining magnetic field and become ionized and trapped within the plasma volume. Several projects currently under construction will use many neutral beam sources at once. With the number of beams as large as twelve, as was planned for the Tokamak Fusion Test Reactor, a method giving an approximate but easily obtainable characterization of neutral beam performance would be useful.

The proportions of H^+ , H_2 , and H_3 ions which are accelerated in the source, termed the species mixture, affects the deposition of beam energy in the target plasma. Under a set of assumptions which are further discussed below, the species mixture can be calculated from two simple ratio measurements by using equipment present on most neutral beam systems. Most systems have a deflecting magnet which is used to contain the unneutralized accelerated ions in a region with high pumping speed which thereby prevents these ions from striking surfaces in critical places under the influence of the confining field near the target plasma. The first ratio we use is that between the power in the neutral beam alone to the power in the total beam with ionic and neutral species together. The second ratio is the flux of hydrogen nuclei released from the target bombarded by the neutral beam divided by the flux due to the total beam. This is measured in a target volume by a residual gas analyzer (RGA) tuned to mass 2. These two ratios plus a known neutralizer thickness (molecules of hydrogen cm^{-2}) are sufficient in principle to determine the species mixture. Because these are ratio measurements, one does not need absolute calibration of the instruments.

Method

The source is assumed to produce H^+ , H_2^+ , H_3^+ ions only. These ions are accelerated from a high positive potential and enter a hydrogen neutralizer with a known thickness π (molecules cm^{-2}). These ions may charge exchange or dissociate and emerge as one of fourteen ionic and neutral species:

$$H^+, H_2^+, H_3^+, \frac{1}{2}H^+, \frac{2}{3}H_2^+, H^0, H_2^0, \frac{1}{2}H^0, \frac{2}{3}H_2^0, \frac{1}{3}H^0, H^-, \frac{1}{2}H^-, \text{ and } \frac{1}{3}H^-.$$

The number preceding each beam component indicates the fraction of the full accelerating potential energy carried by each particle. The flux of each component which reaches a downstream target volume is calculated with the assumption that the divergences of all species are equal. Then when we consider fractions f_1 , f_2 , and f_3 of the extracted current, there are two independent ratios which can be formed from the H^+ , H_2^+ , and H_3^+ currents. The power ratio RP and the hydrogen ratio RH are different because the fourteen species do not have the the same weighting to produce calorimeter heat as to produce cold gas in the the target volume. For example, one ampere of H^+ ions causes the same calorimeter heat as one ampere of H_2^+ ions, but one ampere of H^+ extracted current produces only half as much cold gas as one ampere of H_2^+ extracted current.

We compute the fourteen species with a program described previously.[5,6]. This program starts with 100 amperes of each of the three positive ion species and integrates step by step through charge exchange, ionization, and dissociation processes until the given neutralizer thickness has been reached. As an example, the fourteen computed output currents for an input beam at 80 KeV and a neutralizer thickness of $6 \times 10^{15} cm^{-2}$ are:

H^0	18.85	H^+	81.09	H^-	2.50								
H_2^0	6.09	H_2^+	11.55	$\frac{1}{2}H^0$	104.13	$\frac{1}{2}H^+$	59.22	$\frac{1}{2}H^-$	1.38				
H_3^+	2.50	$\frac{2}{3}H_2^0$	18.43	$\frac{2}{3}H_2^+$	9.22	$\frac{1}{3}H^0$	175.47	$\frac{1}{3}H^+$	2.50	$\frac{1}{3}H^-$	3.17		

Define the conversion factors between the power of an accelerated H^+ , H_2^+ , and H_3^+ beam and the power in the resulting neutral components to be Q_1 , Q_2 , and Q_3 respectively. Then under the above simplifying assumptions we can express RP and RH as:

$$RP = f_1 \times Q_1 + f_2 \times Q_2 + f_3 \times Q_3$$

$$RH = (f_1 \times Q_1 + 2 \times f_2 \times Q_2 + 3 \times f_3 \times Q_3) / (f_1 + 2 \times f_2 + 3 \times f_3).$$

Figure 1 shows a sample graph of the predicted power and hydrogen ratios for an accelerating potential of 80 KV and a neutralizer thickness of 6×10^{15} . From this figure we can see that the precision in the measurement of the hydrogen ratio must be very great in order to determine the percentages of H_2^+ and H_3^+ . However, a rough estimate of the H^+ fraction can be made with only a measurement of RP, especially when f_1 exceeds 0.5.

Because the charge exchange cross section for H^+ decreases so rapidly with increasing energy, the power and pressure ratios become much more sensitive functions of the species composition at higher accelerating voltages. This is shown in Figure 2, where the neutralizer thickness has been kept constant and the results for three accelerating voltages are shown.

At this point we will estimate the errors caused by two of the assumptions made above. The first error we will consider is that due to differing divergences or differences in the location of the centroids for the ions and for the neutral species. Such a difference in the divergences is in fact observed and may be due to space charge effects in the neutralizer or to residual magnetic fields in the beamline. By examining the temperature distribution on the calorimeter one can infer the separate divergences of the neutral beam and of the total beam including ions and neutrals. One can then further assume that the divergence of the total beam is representative of the divergence of the ionic species. Then one can calculate the fractions of the five neutral species and of the nine charged species which strike the calorimeter or which produce cold hydrogen in the target volume. The different collection fractions of the ions and of the neutrals causes a slight error in the measured RP and RH. Of course, the power ratio can be correctly measured if the calorimeter temperature profiles are fitted to profiles which can be integrated over all space. This error will clearly become smaller for larger target areas. An example is discussed below.

A second error arises from the assumption of a purely hydrogenic beam. It is known that neutral beams contain various impurities, of which the most serious is believed to be water vapor. As an estimate of the error introduced by a contamination with a small fraction of water ions in the accelerated beam, assume that the slow-moving fragments of the water ions all become neutralized. Then one can simply re-calculate the power and hydrogen ratios by giving each ampere of water a weight of one for power and a weight of two for hydrogen production.

A third assumption implicit in the analysis above is that the hydrogen in the target volume is solely due to the hydrogen nuclei in the beam. We experimentally observe that the hydrogen released into the beamline is independent of pulse length when the ion and neutral components of an accelerated hydrogen beam repetitively land in the target volume. Thus we conclude that our copper calorimeter reaches an equilibrium condition where it no longer buries or absorbs much hydrogen.

Experimental Results

As an example of the method described above, we discuss data taken under conditions appropriate to Figure 1. Figure 3 shows a schematic drawing of the diagnostics in use on the $10 \times 10 \text{ cm}^2$ 120 KeV test stand at the Lawrence Berkeley Laboratory. The quadrupole residual gas analyzer was tuned to mass two and was attached to the side arm of the vacuum system containing the copper target calorimeter.

The histories of the hydrogen level in the target volume are shown in Figure 4 for the cases with and without deflecting the charged species away from the target volume. Although we noted above that the total amount of hydrogen which was released into the vacuum system was independent of the time of extraction when the ions were undeflected, we note that deflecting the charged species increases the total hydrogen released into the vacuum system. Whatever the source of the additional hydrogen, the interpretation of Fig. 4 is more complicated than one would expect from a vacuum system more suitable for the present measurements.

We interpret Fig. 4 as follows: after an initial transient phase, the pressure of the entire vacuum system rises due to the $5 \text{ torr liters sec}^{-1}$ of gas fed into the plasma source. At $t = 0.3$ seconds, the high voltage is

turned on and the hydrogen pressure in the target volume rises rapidly over the value it would have with no accelerating voltage. After 0.1 seconds, the accelerating voltage is turned off and the hydrogen pressure in the target volume relaxes toward its value with no HV. Note that the zero level which is appropriate to measuring the hydrogen level with HV on is not necessarily the extrapolation of the curve without HV, because approximately 15% of the gas is accelerated. The excess hydrogen in the case of deflected ions is assumed to be a lightly bound surface layer which is released immediately and which we subtract from the hydrogen associated with the neutral beam entering the target volume. The value of RH was measured to be 0.44 ± 0.1 .

By using the temperature profiles on the target calorimeter and assuming a bi-Gaussian distribution for the power emitted by each source point, we inferred 130 KW of neutral power extracted from the source and 411 KW of neutral and charged species for a ratio RP of 0.32. Due to the somewhat larger divergence of the charged species, the fraction of the total beam which struck the calorimeter was 82% while the corresponding fraction of the neutral beam was 87%.

The neutralizer thickness was 6×10^{15} and was obtained in this case from a momentum analysis of the charged species. The thickness could also be computed for a known flow and duct geometry. The neutralizer was near equilibrium, where the resultant species mixture was insensitive to changes in the thickness. By the method used to produce Figure 1 we obtained a range $0.67 < f_1 < 0.75$ for $RP = 0.32$ and with $\pi = 6 \times 10^{15}$. The value $RH = 0.44$ implies a value of f_1 near the high end of its range. We estimated the effects of a 2% water contamination, a different collection of neutral and ion species, and of a 10% error in the value of π . We obtained corrected values of RP and RH of 0.30 and 0.42, respectively, and a range $0.65 < f_1 < 0.81$. This agreed well with the momentum analysis, which gave 0.79 for f_1 , the accelerated H^+ fraction.

Discussion

The vacuum system used for the present experiments complicates the measurement of the hydrogen ratio. The close coupling between the target and ballast volumes means that: 1) the arc and neutralizer gas is a large background in the measurement of the hydrogen nuclei in the accelerated beam; 2) the gas desorbed by the ions is present in the target volume; and 3) the equilibrium time between the target and ballast volumes is comparable to the pulse length, and therefore the time history of the hydrogen level in the target volume is complicated. These problems should be much less severe in a system intended to simulate neutral beam injection into a tokamak. In such a system there would be relatively little coupling between the target tank and the source tank, where most of the arc and neutralizer gas as well as gas liberated from the ion dump will be contained.

Conclusions

We have shown that the measurement of two easily determined ratios allows the ionic species mixture accelerated by a positive ion neutral beam source to be calculated when one has knowledge of the neutralizer thickness and when certain assumptions are valid. These measurements are the ratio of neutral to total beam power and the ratio of equivalent hydrogen flux in the neutral beam to that in the total beam. For a particular case discussed in detail, the present method gives a result comparable to that obtained by a more elaborate analysis. The present method is not intended as a replacement for more complete and accurate measurements of the species mixture but is instead intended as a quick indication of source performance which will be useful for systems with many beam lines.

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References

1. H.P. Eubank, "Neutral Beam Injection into the PLT Tokamak," Bull. Am. Phys. Soc. 23, 745 (1978).
2. Equipe TFR "High-power Neutral Injection and Ion Power Balance in TFR," Nuclear Fusion 18, 1271 (1978).
3. K.B. Axon, et al., "Electron and Ion Heating by Neutral Injection in the DITE Tokamak," Nuc. Fus. 18, 981 (1978).
4. M. Murakami, et al., "Electron Heating by Neutral Beam Injection in the Oak Ridge Tokamak," P.R.L. 39, 615 (1977).
5. K.H. Berkner, R.V. Pyle, and J.W. Stearns, "Nucl. Fus. 15, 249 (1975).
6. J.W. Stearns, K.H. Berkner, R.V. Pyle, "Neutral Beam Design Options," in Proc. Tech. of Controlled Nuclear Fusion, Richland, Wash. 1976, VIV, p. 1221, and LBL-4492.

Captions to figures:

- 1) The range of possible power and hydrogen production ratios which is computed for an 80 KeV hydrogen beam through a neutralizer with a line density of $6 \times 10^{15} \text{ cm}^{-2}$. The ratios are obtained from equivalent measurements on successive shots with and without deflecting the charged components away from the target volume. The point at the lower left is for a pure proton beam. The sloping lines within the region are for relative proton currents of 90%, 80%, etc. The remainder of the beam is composed of H_2^+ and H_3^+ .
- 2) The ranges of possible power and hydrogen production ratios for $\pi = 6 \times 10^{15} \text{ cm}^{-2}$, for accelerating voltages of 30, 60, and 120 KeV.
- 3) A schematic of the diagnostics available on the $10 \times 10 \text{ cm}^2$ 120 KeV neutral beam test stand at the Lawrence Berkeley Laboratory. The close coupling between the source, ballast, and target volumes was inconvenient for the present experiments.
- 4) The histories of the hydrogen levels in the target volume for the cases with and without deflecting the charged species away from the target volume. The hydrogen gas equivalent that was contained in the beam is taken to be proportional to the peak pressure difference between the measurement and the dashed line connecting points before and after the shot.

XBL 793-892

Fig. 1

XBL 793-893

Fig. 2

LBL BEAMLINE DIAGNOSTICS

Fig. 3

XBL 793-894

Fig. 4

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