MEASUREMENTS OF NEUTRAL BEAM SPECIES, IMPURITIES, SPATIAL DIVERGENCE, ENERGY DISPERSION, PRESSURE, AND REIONIZATION FOR THE TFTR U. S. COMMON LONG PULSE ION SOURCE

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ABSTRACT

Physical characteristics of TFTR neutral beams were measured during the first tests and initial operating experience with production TFTR U. S. Common Long Pulse Ion Sources on beamlines in the TFTR experimental environment under actual user conditions. These measurements were performed with different power supply systems, controls, diagnostics, and operating methods compared to those used at LBL during the development phase. The set of diagnostics included water calorimetry, thermocouples, vacuum ionization gauges, photodiodes, neutron, gamma-ray and charged particle spectroscopy, optical multichannel analysis, charge exchange spectroscopy, Rutherford backscatter spectroscopy, and implantation/ secondary ion mass spectroscopy. These systems were used to perform complementary measurements of neutral beam species, impurities, spatial divergence, energy dispersion, pressure, and reionization. The measurements were performed either in the neutralizer region, where the beam contained both ions and neutrals, or in the region of the output neutral beam. In general, the results from each system were found to be in agreement with each other, and consistent with estimates made during the LBL development phase. They can provide guidance for the optimization of TFTR neutral beam heating operations and the understanding of auxiliary heated TFTR plasmas.

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1.0 INTRODUCTION.

Long pulse, high power, neutral beam heating is required to obtain dense high temperature plasmas in the Tokamak Fusion Test Reactor (TFTR), for durations sufficient to achieve approximate breakeven between the plasma input heating power and the plasma output fusion power ($Q \sim 1$). As a result of this and similar requirements, the U. S. Common Long Pulse Ion Source was developed at the Lawrence Berkeley Laboratory (LBL) originally to support the TFTR, Doublet-IIID (D-IIID), and Mirror Fusion Test Facility (MFTF-B) programs.¹ The ion source accelerator grid structure for D-IIID and MFTF-B was designed for focused, 80 kV, 30 sec operation with a 12 cm x 48 cm aperture. The accelerator grid structure for TFTR was designed for unfocused, 120 kV, 2 sec operation with the accelerator aperture masked to 12 cm x 43 cm in order to accommodate existing beamlines. The prototype production ion sources and the final production ion sources were fabricated by a commercial vendor using the basic LBL design with extensive modifications for production requirements. The development procedure and testing of a smaller LBL ion source prototype^{2,3} and two larger production units⁴ were discussed previously. This work reports measurements performed during the first tests and initial operating experience with production TFTR U. S. Common Long Pulse Ion Sources on neutral beamlines in the TFTR experimental environment under actual user conditions. These measurements were performed with different power supply systems, controls, diagnostics, and operating methods compared to those used at LBL during the development phase. The results of beamline gas efficiency, and electrical performance measurements were discussed in companion papers.⁵⁻⁶ The results of the first measurements of neutral beam species, impurities, spatial divergence, energy dispersion, pressure, and reionization made using an initial production ion source mounted on the TFTR test beamline, and six final production ion sources mounted on two beamlines of the TFTR injection system in the tokamak test cell are presented.

2.0 EXPERIMENTAL DESCRIPTION.

The production ion sources used in this work were rated for 120 kV, 70 A, 2 sec deuterium operation. These ion sources were mechanically similar to each other except for minor design variations described elsewhere.⁴ In general, the TFTR test beamline measurements were able to be performed with more flexibility and direct

access than the measurements on the operating TFTR heating beamlines in the tokamak test cell.

Fig. 1 shows a schematic plan view of the TFTR test beamline, consisting of a fully equipped TFTR beamline and a target chamber with a target calorimeter mounted at a location corresponding to the plasma midplane. Fig. 2 is a schematic elevation view of the same facility. Shown are the neutralizers, calorimeters, ion dumps, ion deflection magnets, other major system components, and the location of various diagnostic systems. An optical multichannel analyzer (OMA) and a $n\text{-}^3\text{He}$ reaction product coincidence system were mounted in the neutralizer duct near the ion source. An OMA and an H-alpha detector were mounted in the transition duct. A charge exchange analyzer (CEX), a Rutherford backscatter spectrometer (RBS), and an Implantation chamber for secondary-ion-mass spectroscopy (SIMS) were mounted on the target chamber. Vacuum ionization gauges were mounted on the main chamber near the ion source, the middle of the transition duct, and on the target chamber.

The four identical heating beamlines mounted on TFTR in the tokamak test cell had diagnostic systems similar to those indicated in Fig. 2 with the exception of the transition duct OMA. The specific heating beamline diagnostics discussed in this work are the neutralizer duct OMA systems (one per ion source, three per beamline), and the transition duct H-alpha detector. Vacuum ionization gauges were mounted on the main chambers near the ion sources, at the entrance to the transition ducts, and at the middle of the transition ducts.

3.0 NEUTRAL BEAM SPECIES.

The TFTR U. S. Common Long Pulse Ion Source yields a positive ion beam with three major ionic species components [$D_1^+(E)$, $D_2^+(E)$, $D_3^+(E)$]. Subsequent charge exchange collisions in the beamline neutralization duct followed by magnetic deflection of the remaining ions result in an output neutral beam with three major atomic neutral components of full, one-half, and one-third energy [$D^0(E)$, $D^0(E/2)$, $D^0(E/3)$], respectively. In addition, much smaller amounts of other energy species and impurities are present. Accurate measurements of neutral beam species are essential for understanding power deposition in TFTR plasmas, and are useful for diagnostic purposes and optimizing injection system performance. Hence, four complementary methods were used to perform species measurements on beams from the TFTR neutral beam test beamline. OMA measurements were made near the output of the ion source, where the

beam contained both ions and neutrals, and OMA, CEX, RBS, and SIMS measurements were made in the region of the output neutral beam. In addition, interesting preliminary results are given for attempted species measurements using the coincident $n\text{-}^3\text{He}$ particles from D-D reactions.

4.0 OMA SPECIES MEASUREMENTS.

A window port viewing between the ion source and the ion source isolation valve of the test beamline (Fig. 1) allowed a direct line-of-sight view of the beam, at an angle of 60° relative to the beam-axis (Fig. 2), for OMA species measurements in the neutralizer region containing ions and neutrals. In addition, in the case of the test beamline, OMA measurements were performed using a port located at the middle of the transition drift duct. This port gave a view of an essentially fully neutralized beam in a region of low vacuum pressure and close to the beamline output. OMA species measurements for each of the six ion sources mounted on two injection system beamlines were performed using the ports nearest the ion sources as described above. These ports allowed approximately 65% of the extracted beam coming toward the observation point to be viewed in the plane perpendicular to the ion source grid rails. In the case of the test beamline transition drift duct port, the fraction of observed beam decreased to approximately 50%. Blue-shifted D_α light, observed at each of these ports within a half-angle of 0.13° , was collected by a 135 mm, $f/2$ photographic lens focused on a 600 μm anhydrous quartz fiber guide. This fiber transmitted the optical signal about 130 m to either a 1 m grating spectrometer with $f/9$ optics or a 0.64 m spectrometer with $f/5.6$ optics. Variable entrance slits were used in each spectrometer. They were typically set to 10 μm when viewing the neutralizer and 100 μm or greater when viewing the transition duct. The spectrometer dispersions were 5 $\text{\AA}/\text{mm}$ and the spectral ranges were 60 $\text{\AA}$. The Doppler shift associated with the full energy 120 keV deuterons was about 40 $\text{\AA}$ from the unshifted D_α line. The spectrally resolved light was collected with a vidicon detector. A novel feature of the OMA system used for the injection system ion sources was that a single, two-dimensional, intensified vidicon detector was used to gather simultaneous spectra from two ports on the test beamline or up to six different ion sources on the injection beamlines. A detailed discussion of this multi-fiber, multi-spectra OMA system is given elsewhere.⁷

4.1 Comparison of Test Beamline Neutralizer and Transition Duct OMA Measurements.

During the test beamline measurements, OMA species measurements were performed using windows in the neutralizer and transition duct regions. Fig. 3a exhibits a typical OMA spectrum detected in the neutralizer duct for a 100 keV D⁰ beam. Fig. 3b shows a similar spectrum detected in the transition duct. OMA measurements performed in the transition duct had the advantage that the predominant Doppler-shifted signal was due to atomic neutrals excited by collisions with background gas. This eliminated signal contributions from the decay of states populated via cascades from neutral molecular and positive ion captures into high n- states, simplified data analysis, and yielded species measurements that were independent of neutralizer line density. Conversely, the detected OMA signal was much less intense, since the transition duct measurement sampled a smaller fraction of beam volume (50%) than the neutralizer measurement (65%), and the transition duct background gas pressure was more than two orders of magnitude smaller than in the neutralizer, thus reducing the population of excited states. Hence, the D_α signal was correspondingly decreased requiring much wider spectrometer entrance slits (300 μm) with the consequent decrease in spectral resolution, decrease in signal-to-noise ratio, and increased deconvolution uncertainties. In practice, the transition duct OMA measurements were used to interpret and confirm the neutralizer OMA measurements so as to facilitate species measurements for the injection beamlines, which are only equipped for OMA measurements in the neutralizers. In general, the results are in good agreement to within the present experimental uncertainties. Results of the neutralizer [N] and transition duct [D] species measurements are included in the species summary table, Table 1, together with results from other measurements, and will be discussed below.

4.2 Isotopic Species Identification via OMA Measurements.

Although initially some TFTR plasmas were heated with H⁰ beams using the previous short pulse ion sources, most TFTR injection experiments to date have required D⁰ beams. Future TFTR experimental program needs, however, may require heating with either H⁰, D⁰, or T⁰ beams, in a manner that would enable expeditious conversion between these isotopes, operating with optimum gas efficiency, and the capability to identify trace amounts of impurity isotopes from beamline or tokamak sources. In anticipation of such experiments, the TFTR test beamline was used to study fast isotopic

changes from D^0 to H^0 and from H^0 to D^0 . During these experiments, OMA measurements were made in the neutralizer to study the neutral beam and residual gas isotopic species. In general, the species ratios exhibited their normal well-conditioned values with the first high voltage beam extraction pulse following relatively little arc conditioning. Trace amounts of the previous isotopic species in the system gas were easily resolvable with the available spectral resolution. Fig. 4 shows an OMA spectrum for the first D^0 beam pulse (105 keV) obtained after changing the working gas from hydrogen to deuterium, and Fig. 5 shows the same data on an expanded scale in the region of the Doppler-shifted signals. There was no evidence of any significant amount of accelerated hydrogen, but a small amount of unshifted H_α light was observed (Fig. 4) due to beam collisions with thermal hydrogen. This hydrogen gas was tentatively attributed to desorption in the accelerator column or neutralizer, since it was present during beam extraction but not during the pre-extraction arc. The species fractions measured under these conditions were in agreement with other results shown in Table 1 and discussed below.

4.3 OMA Species Measurements *versus* Ion Source Gas Flow and Acceleration Voltage.

The dependence of species yield on ion source gas flow rates was studied with the test beamline using a 100 keV D^0 beam. Fig. 6 shows ionic species fractions at the ion source as determined from OMA spectra measured in the neutralizer *versus* ion source gas flow rate. Relatively little dependence on gas flow rate was observed, in agreement with previous measurements.³

Fig. 7 shows ionic species fractions at the ion source *versus* acceleration voltage as determined from OMA spectra measured in the test beamline neutralizer for D^0 beams. A similar behavior occurs for species yield *versus* arc power, since the TFTR beam systems are operated along the line of best focus (*i.e.*, optimum perveance) which exhibits a slowly varying relationship between acceleration voltage and arc power over the 80-120 keV beam energy range.⁵ The results shown are in agreement with previous measurements³ within experimental uncertainty, and are relatively constant above 80 keV.

5.0 CEX Species Measurements.

A TFTR charge exchange analyzer (CEX), configured with an E//B analyzer

module and a gas stripper cell,⁸ was used to measure the differential species fractions of the output neutral beam on the axis of the test beamline. A 2.5 cm diameter aperture in the center of the target calorimeter allowed a central sample of the incident neutral beam to enter the 1 mm diameter input aperture of the CEX gas stripper cell. This input aperture was located about 150 cm beyond the target calorimeter and 1245 cm from the ion source exit plane. Ion deflection plates at the input to the CEX stripper cell were used to remove reionized beam particles from the incident neutral beam. Fig. 8 shows a schematic cross-sectional view of the CEX experimental apparatus. The intensities of the E, E/2, and E/3 beam components of the neutral beam were measured simultaneously using aligned Faraday cups. Smaller Faraday cups were used to perform beam energy dispersion measurements. Fig. 9 shows a photograph of the Faraday cup arrays as configured inside the CEX analyzer. Fig. 10 shows a typical signal spectrum *versus* time for the three major beam species for a 95 keV D⁰ beam. These signals gave a direct measurement of the output neutral beam particle current *versus* time and provided useful and sensitive indicators of subtle changes in ion source operating conditions.

5.1 CEX Measurements of Neutral Beam Species Radial Distributions.

The neutral beam incident on the target calorimeter exhibited a power density distribution that was the sum of the power density distributions of the individual species components. Since the CEX input aperture accepted only a 1 mm diameter sample of the beam, the direct CEX species measurements represent differential species fraction measurements on the beam axis. In order to compare these differential species fractions with the OMA results, and to obtain the total integrated species fractions in the output neutral beam, it was necessary to measure the radial distributions of each species component. This was accomplished by steering the ion source so as to raster the beam in the horizontal plane across the input aperture of the CEX. Fig. 11 shows the results of rastering the neutral beam in the horizontal plane across the CEX aperture. Shown are the differential neutral particle species fractions in the output neutral beam measured on-axis with the CEX system *versus* perpendicular horizontal distance from the beam axis. The total integral species fractions in the output neutral beam were obtained by using these measured horizontal radial distributions and by assuming that all points of equi-intensity on the beam power density distribution as determined from calorimeter thermocouple measurements had the same species fractions. The results for a 100 keV D⁰ are included in the species summary table, Table 1, and are in agreement with the

OMA results which represent a volume-averaged (integral) measurement close to the ion source.

5.2 CEX Measurements *versus* Ion Source Gas Flow and Acceleration Voltage.

The dependence of the total integral species yields on ion source gas flow rates was studied using a 100 keV D^o beam. Fig. 12 shows the differential species fractions in the output neutral beam, measured on-axis with the CEX analyzer, *versus* ion source gas flow rate. Relatively little dependence on gas flow rate was observed and the results are in agreement with the OMA measurements described above (Section 4.3)

The CEX differential neutral species fractions in the output beam were measured on-axis *versus* ion source acceleration voltage for D^o beams. The results were relatively constant above 80 keV in agreement with the behavior observed with the OMA measurements described above (Section 4.3).

6.0 RBS Species Measurements.

Beam particles elastically backscattered at 95° from the beam axis at the surface of the copper target calorimeter were detected with an electrostatic analyzer⁹ to measure beam species fractions via Rutherford Backscatter Spectroscopy (RBS).¹⁰ The target calorimeter was inclined so that the angle between a line tangent to its surface and the beam axis was 12° to reduce the effective incident beam power density. All backscattered particles entering the spectrometer passed through a 100 Å carbon stripper foil. The electrostatic plate separation was 1 cm and the potential applied between the plates for the analysis of 100 keV particles was 20 kV. A Channeltron electron multiplier was used to detect the analyzed particles. The detector viewed a rectangular area of approximately 7.6 cm x 12.7 cm at the surface of the target calorimeter. A bellows mechanism allowed the detection angle to be variable in the horizontal plane, thus permitting scans of the species horizontal radial distribution at the target calorimeter surface. The experimental alignment geometry is shown in Fig. 1. The detector geometry is shown schematically in Fig. 13. Typical signals *versus* backscatter particle energy are shown in Fig. 14(a) for an 84 keV D^o beam using the TFTR U. S. Common Long Pulse Ion Source and in Figure 14(b) for an 80 keV D^o beam from the TFTR Short Pulse Ion Source previously used for TFTR heating experiments. The vertical arrows in Fig. 14 are drawn to indicate approximately the energy region where the signal increases due to

each detected backscattered species.¹⁰ Note the relatively large increase in the full energy species yield exhibited in Fig. 14(a).

6.1 RBS Measurements of Neutral Beam Species Radial Distributions.

As discussed above, at increasing distances from the ion source, the output neutral beam exhibited measurably different radial species distributions. Hence, the radial species distributions of the neutral beam incident on the target calorimeter were measured by horizontally scanning the field-of-view of the RBS spectrometer across the target calorimeter. In general, the detected RBS radial distributions differed from those measured using the CEX because of differences in detector solid angle. Fig. 15(a) shows typical signal amplitudes for horizontal radial species profile measurements obtained by scanning the field-of-view of the analyzer across the footprint of a 100 keV D^o beam incident on the copper target calorimeter surface. Fig. 15(b) shows the resulting differential neutral species fractions obtained from the above signals. Similar scans made at beam energies from 80 to 110 keV at optimum perveance were relatively independent of energy to within the present experimental uncertainties. The total integral species fractions in the output neutral beam were obtained by using these measured horizontal radial distributions and by assuming that all points of the same intensity on the beam power density distribution had the same species fractions, as discussed above. The results are included in the species summary table, Table 1, and are in agreement with the OMA and CEX results given above.

6.2 RBS Species Measurements *versus* Ion source Gas Flow and Acceleration Voltage.

The dependence of species yield on ion source gas flow was studied using RBS to measure the differential neutral particle species fractions in the output neutral beam *versus* arc chamber gas flow rate. Fig. 16(a) shows the on-axis signal amplitude for each species component *versus* ion source gas flow rate. Fig. 16(b) shows the total integral neutral species fractions obtained using the measured horizontal radial distributions discussed above. Relatively little dependence on gas flow rate was observed and the results are in agreement with the OMA and CEX measurements described above.

Total integral neutral species fractions *versus* ion source acceleration voltage were obtained using on-axis RBS measurements and the measured horizontal radial species distributions. The results indicate that the neutral species fractions in the output

neutral beam were relatively constant above 80 keV as was also exhibited in the OMA and CEX results.

7.0 Beam Implantation SIMS Species Measurements.

Differential, on-axis, species measurements were performed on the output neutral beam by implanting beam particles into electronics grade silicon crystals, and profiling the implanted concentration *versus* depth using Secondary Ion Mass Spectroscopy (SIMS).¹¹ The experimental geometry was similar to that used for the CEX measurements (Fig.1). The apparatus for the implantation measurements consisted of a special adapter flange which was mounted on the CEX gas stripper cell chamber (Fig. 8) and allowed silicon samples to be inserted into the neutral beam at the input aperture to the CEX system. Fig. 17(a) shows a photograph of the CEX gas stripper cell chamber with the side port flange removed to show the gas stripper cell input region. Figure 17(b) shows the implantation sample holder apparatus positioned at the side of the CEX gas stripper cell chamber. Figure 17(c) shows the implantation sample holder with ten mounted silicon samples and a retractable copper beam stop. When a sample was not in the exposure position, spaces in the sample holder wheel allowed the passage of beam through the sample holder and into the CEX system. This permitted CEX measurements on the same or different beam pulses. A stepper motor, synchronized to the neutral beam pulse timing system, allowed insertion of samples into the beam at preselected times for preselected exposure intervals. Tantalum masks on the silicon samples defined the incident beam area to approximately 5 mm x 6.5 mm. The typical incident beam power density for a 100 keV beam was about 2 kW/cm². The exposed samples were removed and analyzed using a SIMS system method that has been described previously.¹¹ The total integral species fractions were obtained from the measured differential, on-axis species fractions using the radial distributions measured with the CEX system as described in Section 5.1.

Fig. 18(a) shows the implanted concentration *versus* implantation depth for a 100 msec exposure at 380 msec for an 81 keV, 36 A, 2 sec, D⁰ pulse. The full, half, and third energy species components correlate well with the expected depth range *versus* incident energy. Fig. 18(b) shows the implanted concentration *versus* implantation depth for a 100 msec exposure at 380 msec for a 100 keV, 62 A, 2 sec, D⁰ pulse. The full energy peak is seen to shift from a depth of about 0.85 microns to a depth of about 0.95 microns as the beam energy was raised from 81 to 100 keV. Table 1 includes the

averaged results from 2 samples for the total integral species ratios at 100 keV obtained using the radial distributions measured with the CEX system as described above. The results for the differential species measurements are in agreement with the CEX measurements made at the same location (Fig.12), and the total integral species ratios are in agreement with the OMA, CEX, and RBS measurements discussed below.

8.0 Discussion of the Species Results.

Table 1 summarizes the integral neutral and ionic species particle fraction results of the above OMA, CEX, RBS, and SIMS species measurements. The OMA species measurements designated OMA^[N] in Table 1 were made in the neutralizer region about 100 cm from the output of the ion source. Since the original ion beam was partially neutralized by the time it reached the OMA^[N] viewing location, the species fractions determined from this technique were not measured directly, but rather calculated from the volume-averaged D_α light emissions from within the viewed volume.⁷ Extracted ion beam composition and final neutral composition were computed from this intermediate viewing point using measured cross sections,¹² measured gas flow rates, and neutralizer conductances corrected for heating effects.⁶ The estimated experimental uncertainties (shown in parentheses) include the uncertainties in the neutralizer line density, the measured cross sections, uncertainties in background subtraction and data analysis, and uncertainties due to variations in operating conditions.

The OMA measurements designated OMA^[D] in Table 1 were made on the output neutral beam, and yielded the neutral particle fractions independent of the neutralizer line density. At this location, the neutral particle fractions were computed directly from the observed D_α light amplitudes and known cross sections.¹² These results appear to be systematically higher than the OMA^[N] measurements, although within experimental uncertainty. In this case, the adoption of these fractions as representing the total integrated neutral species fractions may be less certain than for the OMA measurements made near the ion source, because the duct OMA fiber optic observed only 50% of the beam in the horizontal plane. As discussed above, breakup in the neutralizer tends to broaden the half and third energy species components, and hence tends to enrich apparently the full energy fraction when observed in central-axis species measurements. However, all uncertainty due to integrated line density up to the viewing point (which is included in the OMA^[N] measurements) is eliminated.

The CEX total integral neutral species fractions listed in Table 1 were

obtained from the on-axis differential species fractions and the radial species distribution obtained by rastering the neutral beam across the input aperture of the analyzer. The differential species fractions were obtained from the measured Faraday cup signal as discussed above and corrected for the efficiency of the gas stripper cell at the input to the analyzer. The experimental uncertainties in the differential species fraction measurements include uncertainties in the stripper gas line density, and the measured charge exchange cross sections. The principal experimental uncertainty in the CEX total integrated neutral species fractions is in the shape of the radial species distribution due to limited statistics.

The RBS total integrated neutral species fractions listed in Table 1 were obtained from the on-axis differential species fractions and the radial species distribution obtained by rastering the neutral beam across the surface of the target calorimeter. The dominant experimental uncertainties in the differential neutral species fractions include uncertainties in the shape of the subtracted background under the half and third energy signals, and the signal-to-noise ratio. Smaller uncertainties were due to uncertainties in the stripper foil efficiency, the detector energy resolution, and the estimated stopping rates (dE/dx) taken from the literature. The principal uncertainty in the integral species fractions derived from the differential measurements was the statistical uncertainty in the shape of the radial species distribution due to the limited number of position measurements.

It is seen from Table 1, that there is little variation in the measured neutral species fractions in the range of beam energies from 80 to 114 keV, within the available experimental resolution. An unweighted average of these results gives a neutral particle species ratio of $D^0[E]:D^0[E/2]:D^0[E/3] = 53(5):27(4):20(4)$, where the quantities in parentheses are the average experimental uncertainties. The corresponding neutral power ratio is $P^0[E]:P^0[E/2]:P^0[E/3] = 72(9):19(3):9(2)$.

The Injection Beamline OMA systems (Section 4.0) include a view of each beam in the neutralizer region in the plane perpendicular to the respective ion source grid rails. Typical values and variations in ionic species fractions measured at different injection system locations at different dates during the TFTR 1987 experimental period for different ion sources, beamlines, and operating conditions were typically within a range of about 5% of each other and the average values given above.

9.0 Other Species Related Experiments.

Previous work¹³ using a scanning OMA to obtain species profiles at the exit of a small ion source under special conditions measured increased divergence and reduced atomic species fractions near the edge of the beam. These effects were attributed to the breakdown in two-dimensional symmetry near the edge of the accelerator grids relative to the central region and to possible ion source wall phenomena. Similar measurements are of interest for the TFTR neutral beams, since variations in the radial species profiles are clearly evident in the output neutral particle beams, as discussed above. However, OMA measurements made on operating TFTR Injection Systems, in the neutralizer region near the exit of an ion source, do not presently include corrections for possible small variations in radial species fractions near the beam edge. Measurements of species spatial profiles at the exit of the ion source would allow for more accurate total integral OMA species fractions, and eliminate a possible systematic experimental uncertainty in comparing species measurements made at different beamline locations and on different beamlines. Hence, the feasibility of measuring individual beam species profiles in the ion source region was explored using the test beamline by attempting to measure the time-of-flight between the $n\text{-}^3\text{He}$ reaction fusion products from deuteron beam particles incident on deuterium neutralizer gas.¹⁴ In addition to providing neutral beam species information, the methodology of this measurement could also be applicable to tokamak fusion product studies.

The experimental geometry is shown in Fig. 19. The apparatus consisted of two detectors and the typical timing-energy coincidence circuit modules^{15,16} shown in Fig. 20 for detecting the energies, and flight-time differences at the arrival of coincident 0.82 MeV ^3He charged particles and 2.45 MeV neutrons at their respective detectors. The ^3He charged particle detector consisted of a ruggedized 150 mm² silicon surface barrier detector, with a 240 $\mu\text{g}/\text{cm}^2$ layer of aluminum evaporated on the surface to attenuate light and x-rays.¹⁵ The detector viewed the beam from inside a retractable aluminum probe housing, through an aluminum collimator with thirty circular apertures, each 1.6 mm in diameter. The neutron detector consisted of a 5 cm long, 6 cm diameter, NE-213, recoil-proton, liquid scintillator mounted on an RCA 8850 fast photomultiplier tube. The detector was enclosed in an aluminum case with a shield of paraffin and Li_2CO_3 mixture,¹⁷ and viewed the neutralizer region of the beamline through a 53 cm long, 25 cm diameter polyethylene cylindrical collimator with a 6 cm diameter bore. The detector solid angle was reduced by inserting a PVC-paraffin cylinder with a 2.1 cm bore

into the polyethylene collimator.

Detected ^3He (0.82 MeV) signals were discriminated from other signals of the high energy charged particle spectrum [i.e., T (1 MeV), H (3 MeV)] by selecting pulse heights corresponding to the appropriate energy interval using a single channel analyzer (Fig. 20). The neutron signals were separated from background γ -rays using a pulse shape discriminator. The time differences between the resulting energy and shape-discriminated signals were measured using a time-to-amplitude converter and a multichannel analyzer system with a 50 nanosec time resolution.

Data were obtained for an 85 keV, D^0 beam with the neutron collimator aimed vertically. The resulting coincidence spectra are shown in Fig. 21 for three separate groups of beam pulses; (a) 12 beam pulses, (b) 42 beam pulses, and (c) 14 beam pulses. The presence of true coincident events is not evident in these spectra to within the indicated statistical uncertainty. The neutron detector pulse rate without pulse shape discrimination was approximately 7×10^4 events/sec, and the ^3He pulse rate was approximately 7×10^3 events/sec. These rates and the 50 nsec coincidence resolution time yielded a random coincidence rate of approximately 25 events/sec per 50 nsec channel. The application of the available pulse shape discrimination reduced the random coincidence rate to 2.7 events/sec per 50 nsec channel. Using these signal rates, the estimated maximum true coincidence rate was 0.4 events/sec assuming 100% detector efficiency and neglecting neutron attenuation due to beamline material between the detector and the neutralizer region. Inclusion of a realistic neutron detector efficiency and shielding effects reduced the neutron detection rate to 10% of ideal and yielded an estimated true-to-chance ratio of 1/70. This is consistent with the three spectra obtained within the limited available experimental time, which indicate that a relatively small number of coincident events were obscured by a high background of random non-coincident events.

This work suggests that the successful application of this technique requires a significantly improved true-to-chance ratio. This might be accomplished with improved neutron/ γ -ray pulse shape discrimination, improved collimation for the charged particle and neutron detectors to reduce the detection of non-coincident events, and reducing the sensitivity of the charged particle detector to beam-induced electrical noise and x-rays.

10.0 Impurities.

Neutral beam impurities can originate from ion source arc gas impurities, and the desorption, decomposition, and sputtering of beamline materials. Impurities observable in the ion source region may or may not be observable in the output neutral beam depending on the energy, divergence, and neutralization involved. In this work, the OMA, CEX, RBS, and SIMS diagnostics were used to survey beams from the test beamline and the OMA diagnostics were used to survey the injection system beams for possible impurity components.

The existence of water impurities can be evidenced in OMA spectra by the appearance of low intensity H_{α} or D_{α} light of 1/18 or 1/10 full energy resulting from the decomposition of H_2O or D_2O . The measurements reported in this work were performed after the ion sources were under vacuum for long periods and were well-conditioned. In general, the OMA spectra indicated that the water content of the beam in the neutralizer region near the output of the ion source was typically less than 0.5% of the total beam intensity.

The CEX system was used to scan the output neutral beam for possible minor fractional energy species. No minor fractional energy species having an intensity greater than 0.1% of that of the full energy component were observed in the output neutral beam.

The RBS system was used to scan for possible higher Z impurities implanted in the copper target calorimeter by the output neutral beam. No evidence was found for the existence of elastically backscattered beam particles (D) from target nuclei (Z) with a Z greater than that of copper.

The beam implantation SIMS diagnostic was used to measure impurities at the output of an 80 keV D^0 beam during well-conditioned ion source operation. The principal low-Z, central-beam, impurities observed on-axis were very low concentrations of carbon and oxygen. The samples exhibited a carbon content not greater than 2×10^{-4} per implanted D^0 and an oxygen content not greater than 5×10^{-4} per implanted D^0 , and the implantation depths implied acceleration in the form of C^+ and O^+ .

11.0 Spatial Divergence.

The net spatial divergence of the output neutral beam is primarily attributable to ion source focusing properties, ion source operating procedure, and decomposition of the molecular species components during neutralization. Ionic species steering due to stray magnetic fields and scattering effects may also cause additional apparent beam

broadening. During most test beamline experiments and typically during TFTR injection heating experiments, the ion sources were operated at perveance values empirically determined to yield optimum transmission and minimum divergence. Typically, measurements of beam divergence *versus* perveance using the target calorimeter thermocouple arrays exhibited minimum source beamlet divergence values of about $\theta(v) = 1^\circ$, and $\theta(h) = 0.35^\circ$ for the $1/e$ half-width in the vertical and horizontal planes, respectively, in agreement with values measured previously³. Fig. 22 (a) shows OMA^[N] results for the perpendicular divergence (*i.e.*, perpendicular to the grid rails) *versus* perveance for two ion sources. Although there are fewer data points in the high perveance range due to unstable ion source operating conditions (*i.e.*, over-dense arc plasma), the perveance values can be seen to be at or near minima. Fig. 22 (b) shows similar divergence data *versus* ion source gas flow. The results exhibit a very weak dependence on gas flow, thus allowing minimal gas utilization without greatly affecting either species fractions or divergence. No OMA results were obtained for the divergence in the plane parallel to the grid rails; however, previous results for the parallel divergence have shown a much weaker dependence on perveance than the perpendicular divergence.

Table 2 gives a summary of species divergence measurements at the output neutral beam. There is little dependence on beam energy over the indicated range within the experimental uncertainties. A derivation of the divergence of the power density profile using the average of values for the species results given in Table 2 yields a value of $\theta(h) = 0.35^\circ$ in the horizontal plane, which is consistent with the thermocouple results.

12.0 Energy Dispersion.

The small energy dispersions in the energies of the principal species components of the output neutral beam were measured using the array of 15, 2 mm wide, Faraday cups in the CEX analyzer. The effective energy resolution of each small Faraday Cup was measured using a thin collimated ion beam⁸ to be $\Delta E/E = 0.03$. The procedure for a beam energy measurement consisted in adjusting the CEX deflection magnetic field so as to center the beam on the Faraday cup array during a series of constant condition beam pulses.

The small Faraday Cup array was also used to measure the energy dispersion of each of the three major beam species. Fig. 23 shows the relative signal intensity for each major species component *versus* energy (keV) for a nominal 80 keV,

D^o beam. The measured energy spread of the full energy component measured over the range of observable signal was 1.20 keV. The full energy component also exhibited an asymmetry toward lower energies (Fig. 23(a)). This asymmetry is less evident in the half and third energy spectra. The energy widths for the half and third energy components were 2.35 keV and 2.26 keV, respectively. The additional energy broadening of the half and third energy components relative to that of the full energy component is attributable to the Franck-Condon molecular excess energy, although a few eV (4 eV and 3 eV for the half and third energy components, respectively) can induce energy spreads of about a keV in this molecular breakup.¹⁸ Assuming Franck-Condon dissociation, the estimated additional energy spread for the half and third energy components of an 80 keV, D^o beam was 1.13 keV and 0.92 keV, is close to the measured additional broadenings of 1.15 keV and 1.06 keV, respectively. Similar results were obtained for a 100 keV D^o beam. The low energy asymmetry in the energy distribution that is evident in the full energy component is also evident to a lesser extent in the half and third energy components. These asymmetries may be due in part to variations in the ion source power supply voltages. The incomplete acceleration of ions in the grid structure due to premature neutralization may also contribute. Unfortunately, the test beamline experimental schedule did not permit a more extensive systematic investigation of the origins of the observed widths and asymmetries. In particular, it would be of interest to study these effects *versus* ion source gas pressure and other operating parameters.

13.0 Beamline Pressure Waveforms.

During TFTR heating beam injection pulses into the torus, three dynamic waveforms were measured in each beamline to monitor ion source performance, vacuum system behavior, duct outgassing, duct reionization losses, and gas flow into the torus. The pressure waveforms were measured in the main beamline chamber, at the input to the transition duct, and at the middle of the transition duct using standard nude Bayard-Alpert ionization gauges mounted so as not to view the beam directly, and shielded from the magnetic fringe fields of the torus. Prior to installation, the gauges were calibrated over the pressure range from 5×10^{-5} torr to 8×10^{-4} torr with hydrogen and nitrogen gas using a capacitance manometer that was calibrated at the National Bureau of Standards to within an absolute accuracy of $\pm 10\%$. The mean of the hydrogen gauge factors for 32 calibrated gauges was 3.18 ± 0.86 and the mean of the nitrogen gauge factors was 1.52 ± 0.39 . The mean of the ratios of the individual hydrogen to nitrogen

gauge factors was 2.09 ± 0.25 , in agreement with accepted ratios of the hydrogen and nitrogen electron ionization cross sections.

Typically, at injection time, each of the three individual ion sources of a given injection system beamline were in one of the following states: a complete shutdown, a gas-only pulse, a gas and filament pulse, a full arc pulse, a full acceleration pulse, or a full acceleration pulse followed by an ion source electrical fault. Hence, in general, beamline pressure conditions varied considerably depending on the particular operating conditions. Typically, ion source gas flow rates were about 15-20 torr-l/sec, and the ion source gas efficiencies were in the range from 35% at flows of 21 torr-l/sec to 60% at flows of 13 torr-l/sec. Prior to the introduction of these pulsed gas flows, the beamline base pressures were about 2×10^{-8} torr. Pressures in the main beamline chamber near the neutralizers (Fig. 2) at the start of the arc pulse were about 5×10^{-5} torr and dropped to about 3×10^{-5} torr during the arc pulse when measured with an ionization gauge at room temperature, or actually lower by a factor of $(120/300)^{1/2}$ assuming an effective gas temperature of 120 K inside the main beamline chamber due to the liquid-nitrogen cooled cryopump baffles.¹⁹ Gas in the transition duct was tentatively taken to be at or near room temperature. Pressures inside the transition duct, at the entrance, at the start of the acceleration pulse, were typically about $(3-6) \times 10^{-6}$ torr and rose to about $(0.7-3) \times 10^{-5}$ torr by the end of an acceleration pulse. Pressures in the middle of the transition duct at the start of an acceleration pulse were about $(0.3-0.7) \times 10^{-5}$ torr and rose to about $(0.6-2) \times 10^{-5}$ torr by the end of the acceleration pulse for plasma conditions which yielded a drop in transition duct pressure near the torus. Plasma current disruptions and pellet injection experiments can yield conditions which cause an increase in transition duct pressure near the torus. Often there was not a direct proportionality between the peak pressure rise and the length of the pulse (0.5 to 2 sec), since longer pulse lengths were able to achieve a greater degree of transition duct conditioning more rapidly than shorter pulse lengths. In addition, it was found that ion source electrical interruptions (*i.e.*, faulting) could decondition the transition duct. Typically, the beam operation gas flow to the torus varied from about 0.2 torr-l/sec to about 1.4 torr-l/sec depending on the conditions described above.

Fig. 24 shows pressure waveforms from one beamline for a three ion source (93-keV/50-A, 92-keV/44-A, 108-keV/60-A), 1-sec, 6.3 MW, D⁰ injection pulse. In Fig. 24(a), pressure drops are seen in the main beamline chamber at the arc initiation (1.1 sec) and at the acceleration initiation (3 sec), followed by slow rises due to outgassing.

The pressure returned to the prepulse level when the acceleration pulse was completed (4 sec). The average gas efficiency during the beam extraction is defined in terms of the net drop in pressure during acceleration voltage relative to the immediately prior pressure.⁶ In Fig. 24(b), the pressure waveform, measured at the input to the transition duct exhibits the exponential-like outgassing behavior associated with a relatively unconditioned duct.²⁰ The qualitative behavior of the mid-duct pressure was similar to that at the duct input, but of reduced intensity due to the duct conductance to the torus. Fig. 24(c) shows the pressure waveform measured at the mid-transition duct. The shape and intensity of the mid-duct pressure waveform was found to vary with the detailed duct and operating conditions. For example, Fig. 25 shows a one ion source injection pulse with a minor mid-pulse interruption, which yielded a faster duct outgassing rate after the resumption of beam but with a more linear behavior than is exhibited in Fig. 24(c).

The visible and near-visible infrared light in the transition duct is a sensitive monitor of duct conditions and beam performance. Fig. 26 shows a schematic diagram of the tritium-compatible duct light telescope and fiber optic system. A 1-cm diameter f/2 silica lens was used to focus beam-related light at a focal point containing three 600 μm silica fiber optics, which transmitted the signal 100 m to three silicon photodiodes with a spectral range of 400 nm to 1100 nm. These detectors had a much faster time response (1 msec) than the ionization gauges, and thus could be used to observe transient phenomena. Since the three fiber optic channels contained the same signal information, interference filters, long pass filters, and different gain settings could be used to analyze simultaneously the observed duct light in different ways. This system was used to examine the duct light yielded by the previous TFTR Short Pulse Ion Sources²¹ for which it was found that the observed duct light consisted primarily of hydrogen light from beam-gas collisions, reflected light from beam-surface collisions, reflected infrared signal from the ion source filaments, and smaller signals from possible impurities, unidentified beamline sources, and the torus. This system was also used to study TFTR U. S. Common Long Pulse Ion Source neutral beams which were found to exhibit several similarities. In this work, we report initial results obtained by detecting the total accessible spectral range of duct light. Fig. 27 shows a total duct light signal waveform for an 89 keV, 42 A, 0.5 sec, D⁰ pulse. Shown is the fast exponential-like signal induced by beam incident on duct gas which rises above a background associated with the pulsed ion source filaments. An interruption of the beam can be seen shortly after the initiation of the acceleration pulse. Fig. 28 shows a complex behavior in total detected

duct light signal for an attempted three ion source pulse (~ 100 keV) during which two ion sources were interrupted. Fig. 28 illustrates how ion source disruptions can decondition a transition duct and significantly alter its outgassing behavior during a pulse. Figs. 28 (a), (b), (c) show the three neutral power waveforms of one beamline during an attempted three pulse injection during which ion source (a) was interrupted prior to completing the pulse and ion source (c) was interrupted at turn-on. Figs. 28 (d), (e), (f) show the main chamber, transition duct input, and mid-duct vacuum pressures, and Fig. 28 (g) shows the associated duct light signal which exhibits much greater detail than the ionization gauge pressure signals.

14.0 Reionization.

Residual system gas between the deflection magnet and the torus causes a loss of neutral power due to reionization of neutral particles and their subsequent deflection to the walls of the beamline by the fringing fields of the tokamak. Measurements of reionized power losses are made to facilitate accurate injected power estimates, power accountability, and optimization of beamline operations. At present, the reionized power loss between the magnet and the torus can be determined for injection pulses only from the measured gas pressures in this region.

Typically, for the TFTR neutral beam injection system, there was a relatively low line density of system gas between the beamline magnet and the torus port due to the high speed liquid helium cryopumping (2.5×10^6 liter/sec), the differential pumping due to three internal chambers, and the high transmission, high conductance, transition duct. This resulted in a relatively small percentage loss of transmitted neutral power due to reionizing collisions with background system gas. However, with three ion sources injecting at full power and pulse length, more than 7 MW of D^0 beam power traversed the transition duct for up to two seconds. Hence, even a relatively small percentage of reionized power loss, if concentrated, could yield a significant thermal load. The beamline absorption of reionized power will be discussed in a later work. In this section, we discuss the magnitude and behavior of the reionized power loss in the region between the calorimeter and the torus as it pertains to accurate determinations of injected power.

The time dependence and net reionized power loss for a particular TFTR beamline depended on the operating conditions. Since each beamline had three ion sources, the system gas load during injection pulses depended on the number of

injecting ion sources, the number of ion sources performing arc-only conditioning pulses during the injection pulses of other ion sources which might be staggered in time, the number of ion sources pulsing gas without electrical pulses during the injection pulses of other ion sources, their respective gas flow rates, the pumping efficiency of the beamline, ion source disruptions, beam-solid interactions, the condition of the transition duct walls, and unusual torus gas loads (e.g., certain plasma current disruptions and pellet injection modes).

Using the measured gas pressures discussed above, the calculated reionization power losses between the magnet and the transition duct were in the range of 0.75% to 1.5% of incident power at the beginning of the injection pulse, and 2% to 6% of incident power at the end of the injection pulse. Larger losses were observed for some injection pulses during unusual plasma conditions. The actual time dependence of the reionization power loss varied as the transition duct pressure, as discussed above.

15.0 Discussion and Conclusions.

Measurements of neutral beam species components were made near the ion source in the neutralizer region using an OMA diagnostic, and in the region of the output neutral beam using OMA, CEX, RBS, and SIMS diagnostics. The application of these techniques involved different measurement principles, approximations, and corrections. The results were found to be in agreement to within experimental uncertainties and with previous measurements during development at the LBL test facility¹⁻³. An unweighted average of the results yielded neutral particle ratios $D^0[E]:D^0[E/2]:D^0[E/3] = 53(5):27(4):20(4)$, and the corresponding neutral power ratios $P^0[E]:P^0[E/2]:P^0[E/3] = 72(9):19(3):9(2)$, where the quantities in parentheses are the average experimental uncertainties.

The different radial species profiles in the output neutral beam were measured using the CEX and RBS diagnostics. The average of the measured results yielded half-widths ($1/e$) in the horizontal plane for the full, half, and third energy components of 0.26° , 0.34° , and 0.42° , respectively. The appropriate summation of these species profiles yielded a half-width ($1/e$) in the horizontal plane for the power density distribution of 0.35° , in agreement with that measured with the thermocouple diagnostics.

The small energy dispersions in the energies of the principal species components of the output neutral beam were measured. The measured width of the full energy component over the range of observable signal was 1.20 keV. The corresponding

energy widths for the half and third energy components were 2.35 and 2.26 keV, respectively. The additional broadenings of the half and third energy components relative to that of the full energy component were in agreement with the Franck-Condon effect.

Impurity measurements were made in the neutralizer region and at the output neutral beam. The presence of an oxygen impurity associated with the decomposition of water was measured in the neutralizer region using the OMA diagnostic, and found to be typically less than 0.5% during well-conditioned ion source operations. Impurity measurements were made at the output neutral beam using the RBS, CEX, and SIMS diagnostics. A search for the presence of beam components with Z greater than that of copper was made using the RBS diagnostic, and showed no evidence of heavy metal in the output neutral beam. A search for low intensity on-axis fractional energy components in the output neutral beam using the CEX diagnostic found no evidence of low intensity (minor) beam energy components, above a 0.5% threshold level. The SIMS diagnostic yielded measurements of carbon and oxygen impurities on-axis in the output neutral beam. The carbon concentration in a 80 keV D^0 beam was not greater than 2×10^{-4} per implanted D^0 , and reached an implantation depth consistent with an apparent acceleration state of C^+ . The oxygen concentration was not greater than 5×10^{-4} per implanted D^0 , and reached an implantation depth consistent with an apparent acceleration state of O^+ .

The gas pressures during a three ion source D^0 injection pulse were typically about 3×10^{-5} torr in the main beamline chamber during an acceleration pulse, when measured with an ionization gauge at room temperature, or actually lower by a factor of $(120/300)^{1/2}$ assuming an effective gas temperature of 120 K inside the main beamline chamber due to the liquid-nitrogen-cooled cryopump baffles.¹⁹ Under the same operating conditions, the gas pressures at the input to the transition duct varied from $(3-6) \times 10^{-6}$ torr at the beginning of the injection pulse and rose to $(0.7-3) \times 10^{-5}$ torr at the end of an injection pulse; the pressures at the middle of the transition duct varied from $(0.3-0.7) \times 10^{-5}$ torr and rose to $(0.6-2) \times 10^{-5}$ torr at the end of an injection pulse. The total gas flow rate to the torus per beamline was $(0.2-1)$ torr-l/sec, depending on the operating conditions.

Transition duct outgassing rates and behavior were found to vary with beamline operating history and conditions. Reionized power losses varied with a time dependence related to that of the gas pressure, and varied from about 0.75% to 1.5% of incident power at the beginning of injection pulses, and 2% to 6% of incident power at the

end of injection pulses.

The present measurements were performed with production U. S. Common Long Pulse Ion Sources mounted on both the TFTR test beamline and injection system beamlines, under actual user conditions, with different power supply systems, controls, and operating methods. In general, the results from each system were found to be in agreement with each other, and were consistent with estimates made during the LBL development phase. They can provide guidance for the optimization of TFTR neutral beam heating operations and the understanding of auxiliary heated TFTR plasmas.

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Table 1. SUMMARY OF INTEGRAL BEAM SPECIES MEASUREMENTS.

keV	METHOD	$D^+_1[E]$	$D^+_2[E]$	$D^+_3[E]$	$D^0[E]$	$D^0[E/2]$	$D^0[E/3]$
60	OMA ^[N]	72(7)	11(2)	17(2)	50(5)	16(2)	34(3)
70	OMA ^[N]	77(8)	13(2)	10(2)	56(6)	21(3)	23(3)
80	OMA ^[N]	78(8)	13(2)	9(1)	56(6)	22(3)	22(3)
85	OMA ^[N]	79(8)	12(2)	9(1)	56(6)	22(3)	22(3)
90	OMA ^[N]	76(8)	15(2)	10(2)	50(5)	25(4)	25(4)
95	OMA ^[N]	78(8)	15(2)	8(1)	52(5)	26(4)	21(3)
100	OMA ^[D]				59(6)	25(4)	17(3)
100	RBS				60(6)	25(6)	15(7)
100	CEX				52(5)	26(4)	22(4)
100	SIMS				50(5)	29(4)	21(4)
105	OMA ^[N]	78(8)	15(2)	7(2)	50(5)	29(4)	21(3)
109	OMA ^[N]	79(8)	15(2)	6(2)	51(5)	31(5)	18(3)
114	RBS				51(5)	35(7)	14(7)

1. OMA ^[N] refers to measurements made in the neutralizer duct. OMA^[D] refers to measurements made in the transition duct.

2. The quantities $D^+_1[E]$, $D^+_2[E]$, $D^+_3[E]$ are the ionic particle species fractions at the ion source. The quantities $D^0[E]$, $D^0[E/2]$, $D^0[E/3]$ are the output neutral particle fractions.

3. The values are the measured species fractions multiplied by 100 and the numbers in parentheses refer to the respective experimental uncertainties.

Table 2. SUMMARY OF SPECIES DIVERGENCE MEASUREMENTS

keV	METHOD	h_1	h_2	h_3	θ_1	θ_2	θ_3
65	RBS	5.0 cm	6.3 cm	8.0 cm	0.26°	0.33°	0.42°
100	CEX	4.8 cm	7.3 cm	8.8 cm	0.25°	0.38°	0.46°
114	RBS	5.0 cm	6.0 cm	7.5 cm	0.26°	0.31°	0.39°

1. h_1 , h_2 , h_3 are the horizontal half-widths (1/e) of the three major species components.
2. θ_1 , θ_2 , θ_3 are the horizontal half-width divergences in degrees (1/e) of the three major species components.

Figure Captions

1. A schematic plan view of the TFTR neutral beam test facility.
2. A schematic elevation view of the TFTR neutral beam test facility.
3. (a) A typical OMA spectrum detected in the neutralizer duct from a 100 keV D⁰ beam. (b) A similar spectrum from a 100 keV D⁰ beam detected in the transition duct.
4. An OMA spectrum from the first D⁰ beam pulse (105 keV) obtained after changing the working gas from hydrogen to deuterium showing the absence of accelerated hydrogen components and relatively low intensity unshifted light from residual desorbed thermal hydrogen.
5. An expanded view of the Doppler-shifted signals shown in Fig. 4 which exhibits the absence of accelerated hydrogen components on the first D⁰ beam pulse after the working gas was changed from hydrogen to deuterium.
6. Ionic species fractions for a 100 keV D⁰ beam measured in the neutralizer with an OMA *versus* ion source gas flow rate.
7. Ionic species fractions for a D⁰ beam measured in the neutralizer with an OMA *versus* acceleration voltage.
8. A schematic cross-sectional view of the charge exchange spectrometer (CEX) experimental geometry.
9. A photograph of the Faraday cup arrays as configured inside the CEX analyzer showing the large upper cups used for species measurements and the small lower cups used for energy dispersion measurements.
10. Typical CEX signal spectra for a) full energy, b) half energy, and c) third energy species components *versus* time for a 95 keV, 1.5 sec D⁰ beam.
11. CEX differential species fractions for a 100 keV D⁰ beam as a function of position obtained by scanning the beam horizontally across the CEX input aperture.
12. CEX differential species fractions for a 100 keV D⁰ beam *versus* ion source gas flow rate. Shown also are measurements using the SIMS diagnostic.

13. A schematic of the RBS analyzer geometry.
14. (a) A typical RBS spectrum of detected backscattered particle energies for a 84 keV D⁰ beam using the TFTR Common Long Pulse Ion Source and (b) the same signal for a 80 keV D⁰ beam from the short pulse ion source previously used for TFTR injection experiments. The vertical arrows at E₁, E₂, E₃ indicate the energy region where the signal increases due to each detected backscattered species.
15. (a) The normalized signal amplitudes for RBS radial species profile measurements *versus* horizontal perpendicular distance from the beam axis for a 100 keV D⁰ beam. (b) The resulting differential neutral species fractions obtained from the above signals.
16. (a) The on-axis, RBS signal for each species component *versus* ion source gas flow rate. (b) The total integral neutral species fractions in the output neutral beam obtained using the measured radial distributions discussed above.
17. Photographs of (a) the CEX gas stripper cell chamber with side port flange removed to show the gas stripper cell input region, (b) the implantation sample holder apparatus positioned at the side of the CEX gas stripper cell chamber, (c) the implantation sample holder with ten mounted silicon samples and a retractable copper beam stop.
18. (a) The implanted beam concentration in a silicon target for a 100 msec exposure at 380 msec into a 81 keV, 36A, 2 sec, D⁰ pulse *versus* depth. (b) The implanted beam concentration in a silicon target for a 100 msec exposure at 380 msec into a 100 keV, 62 A, 2 sec, D⁰ pulse.
19. Schematic diagram of the experimental geometry used for n-³He coincidence measurements. Shown are the placement of the two detectors relative to the neutralizer region and the relationship between the position of the reaction and the arrival time difference (Δ).
20. Schematic diagram of the standard fast-slow coincidence circuit used for n-³He coincidence measurements. Signals detected by the surface barrier detector (SBD) and the neutron detector (NE-213) were processed by the indicated electronic modules which are identified by their commercial model numbers (refer to references 15,16).
21. The resulting coincidence spectra of counts per 8 channels *versus* the arrival time difference in microseconds are shown for three separate

groups of beam pulses; (a) 12 beam pulses, (b) 42 beam pulses, and (c) 14 beam pulses.

22. (a) The divergence of the full energy species component in the plane perpendicular to the grid rails (*i.e.*, vertical plane) *versus* perveance for two different ion sources, (b) the divergence of the three major beam species in the plane perpendicular to the grid rails *versus* ion source gas flow rate.
23. The signal intensity for full (a), half (b), and third (c) energy species components using the CEX small Faraday cup array *versus* energy for a nominal 80 keV D^o beam.
24. Vacuum pressure waveforms *versus* time for a three ion source (93 keV, 50 A; 92 keV, 44 A; 108 keV, 60 A), 6.3 MW, 1 sec D^o injection into TFTR; (a) main beamline chamber, (b) at the input to the transition duct, (c) at the middle of the transition duct.
25. Vacuum pressure waveform *versus* time for a one ion source (101 keV, 51 A, 2 sec) injection pulse into TFTR with a minor mid-pulse interruption.
26. Schematic diagram of the transition duct beam light detector telescope.
27. Total duct light signal waveform *versus* time for a 89 keV, 49 A, 0.5 sec, D^o injection into TFTR. Shown is the fast exponential-like signal induced by beam incident on duct gas which rises above a background associated with the pulsed filaments.
28. Total duct light signal *versus* time for an attempted three ion source (~100 keV) injection pulse from one beamline during which two of the ion sources were interrupted. Figs (a), (b), (c) show three power waveforms of the three ion sources. Figs (d), (e), (f) show the main chamber, transition duct input, and mid-duct vacuum pressures, and Fig. (g) shows the associated duct light signal.

Fig. 1

Fig. 2

#88X0189

Fig. 3

Fig. 4

Fig. 5

#88X0181

Fig. 6

Fig. 7

Fig. 8

#88E0015

Large Faraday Cups (TYP.)

Small Faraday Cups (TYP.)

Fig. 9

#88X0193

Fig. 10

#88X0192

Fig. 11

Fig. 12

#84X1149

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Fig. 20

Fig. 21

Fig. 22

Fig. 23

#88X0195

Fig. 24

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Fig. 25

Fig. 26

Fig. 27

Fig. 28

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