TFTR Neutral Beam Injected Power Measurement

J. H. Kamperschroer, L. R. Grisham, L. E. Dudek, G. M. Gammel,
G. A. Johnson,^{a)} H. W. Kugel, L. Lakin, T. E. O'Connor, P. A. Shah,^{b)} P. Sichta,
T. N. Stevenson, A. von Halle, and M. D. Williams
*Princeton Plasma Physics Laboratory, Princeton University, PO Box 451,
Princeton, NJ 08543*

R. Bastasz
*Physical Research Division, Sandia National Laboratories
Livermore, CA 94550*

ABSTRACT

Energy flow within TFTR neutral beamlines is measured with a waterflow calorimetry system capable of simultaneously measuring the energy deposited within four heating beamlines (three ion sources each), or of measuring the energy deposited in a separate neutral beam test stand. Of the energy extracted from the ion source on the well instrumented test stand, $99.5 \pm 3.5\%$ can be accounted for. When the ion deflection magnet is energized, however, 6.5% of the extracted energy is lost. This loss is attributed to a spray of devious particles onto unmonitored surfaces. A 30% discrepancy is also observed between energy measurements on the internal beamline calorimeter and energy measurements on a calorimeter located in the test stand target chamber. Particle reflection from the flat plate calorimeter in the target chamber, which the incident beam strikes at a near-grazing angle of 12° , is the primary loss of this energy. A slight improvement in energy accountability is observed as the beam pulse length is increased. This improvement is attributed to systematic error in the sensitivity of the energy measurement to small fluctuations in the supply water temperature. An overall accuracy of 15% is estimated for the total power injected into TFTR. Contributions to this error are uncertainties in the beam neutralization efficiency, reionization and beam scrape-off in the drift duct, and fluctuations in the temperature of the supply water.

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INTRODUCTION

Neutral beam injection is the primary mode of auxiliary heating in the Tokamak Fusion Test Reactor (TFTR), providing up to 30 MW of power, thereby enabling the study of high temperature, high density, reactor-like plasmas.¹ The ability to estimate accurately the power injected into the plasma is important for the determination of several plasma physics parameters. One such quantity is the energy confinement time, τ_E : defined as the energy content of the plasma divided by the input power. A second parameter is the power multiplication factor, Q : the fusion power divided by the input power. The principal goal of the TFTR device is to demonstrate scientific breakeven, $Q = 1$. Both of these quantities require that the neutral beam power be measured as accurately as possible. In addition, due to the high power and long pulse lengths of the TFTR neutral beams, it is important from a neutral beam operations perspective to ascertain where power is deposited with the beamlines. Unaccounted for, or devious particles² can cause considerable damage if not protected against. Devious particles are those particles not included as full-, half-, or third-energy atomic ions or neutrals. They are molecular ions and neutrals, partially accelerated ions and their neutralization products, negative ions, and charge-exchange products created within the deflection magnet. A fraction of these particles have trajectories within the magnet/ion dump system that miss power absorbing surfaces.

In section I, a description is given of the TFTR neutral beam waterflow calorimetry system. This system is the diagnostic tool developed to measure the beam energy deposited on beamline components. Energy is computed as the time integral of the product of waterflow rate and temperature rise of the cooling water as it passes through a beamline component. Based on the sum of the energies from all monitored flow paths, the energy accounted for can be compared to the energy extracted from the ion sources. The ratio of measured energy to extracted energy (power can also be used) is defined as the energy (power) accountability. Typical accountability values quoted at various neutral beam laboratories are 90+%.³⁻⁷ Measurements at the TFTR neutral beam test stand indicate comparable values.

Of primary concern is the estimation of power injected into the torus during neutral beam heating pulses. During heating experiments, the measurement of injected power is not straightforward since the energy to be measured is injected into the tokamak and is not available to the waterflow calorimetry system. Injected power is an estimate based on calibrations of the power delivered to the beamline calorimeter under a wide variety of operating conditions. Complications in arriving at the estimate include: during plasma heating experiments the beamline calorimeter is withdrawn for long

periods of time and the power on the calorimeter cannot be determined during these experiments; much power is dissipated in the cooling system during multiple beam operation causing small, but significant, water temperature fluctuations; beam particles scraped off and reionized in the duct between the beamline and torus are not monitored. These effects together with the instrumentation accuracy determine the system accuracy. Data from the neutral beam test stand are used to quantify the instrumentation accuracy. Data from the heating beams are used to quantify performance of each individual ion source and estimate the reionization loss. Results from these calibrations and their role in determining the injected power measurement are described in sections II, III, and IV.

I. EXPERIMENTAL APPARATUS

A. Hardware

Figures 1 and 2 are schematic plan and elevation views, respectively, of the TFTR neutral beam test stand. The test stand was a TFTR neutral beamline connected to a target chamber. It was more fully instrumented than a heating beamline and its function was to qualify the integration of beamline to power system at PPPL. Upon conclusion of the experiments described here the test stand was disassembled. During operation of the test stand only the central of the three ion source positions was used.

Four beamlines are installed on TFTR, each with three long pulse ion sources⁸⁻¹⁰ from which up to 70 A of deuterium ions can be extracted at potentials up to 120 kV. Three types of deuterium ion are extracted from the plasmas of such ion sources: D^+ , D_2^+ , and D_3^+ . These ions, together with residual D_2 ion source gas, flow through a neutralizer close-coupled to the ion source. In the neutralizer, charge-changing collisions between the ions and gas molecules convert a fraction of the ions to D atoms. At 120 kV, the fractions of the D^+ , D_2^+ , and D_3^+ power converted to neutral deuterium atoms are 0.44, 0.73, and 0.82, respectively. Equipartition of energy upon dissociation of the molecular ions results in atomic particles with all (full-energy), one-half (half-energy), and one-third (third-energy) the extraction energy. The ion deflection magnet separates the ions from the neutral particles, deflecting the ions to the three ion dumps labelled full, half, and third in figure 2. Neutral particles pass unimpeded through the magnet and are either deposited on the internal beamline "V"-shaped calorimeters or pass into the tokamak (or are deposited on the target chamber calorimeter). Beam-defining collimators located at various locations prevent beam particles from impinging on unprotected surfaces. Collimators are located before the magnet and both before and after the beamline calorimeter. In figure 1 there is a calorimeter in the target chamber at a location approximating that of the

tokamak plasma. The angle of incidence of the beam on this calorimeter is 12° . A near-grazing angle was chosen to reduce the surface power density to levels consistent with inertial (i.e., heat removal between pulses) calorimetry.

Components having waterflow calorimetry on the neutral beam test stand included: the full-, half-, and third-energy ion dumps, the three beamline calorimeters, the target chamber calorimeter, and the neutralizer/collimators. In the neutralizer/collimator water circuit the water flows in series through the neutralizer and three collimators. For the heating beams in the tokamak test cell, only the ion dump and beamline calorimeter water circuits are instrumented. A typical water circuit is indicated schematically in figure 3. Water flow rate is measured with a turbine flowmeter¹¹ and the water temperature rise is measured with a differential temperature transducer (δT).¹² This instrumentation is located on the side of the beamline with a typical flow path from the δT transducer to the component consisting of 4.5 m of 1.5" pipe. Manifolding and pipe size reduction at the monitored component are component dependent. All water circuits on a beamline are in parallel with that beamline's supply and return manifold. All four beamlines are manifolded together near the heat exchanger. Water from a cooling tower feeds the primary side of the heat exchanger.

The differential temperature transducer provides a signal proportional to the temperature difference between the supply and return paths to the component. Part of the transducer is immersed in the supply line and another part in the return line. A vendor-supplied calibration, with an accuracy of 0.04°C , is used in the energy algorithm. For a typical water circuit this accuracy represents an error of order 1%. While the time response of the instrument is relatively slow (0.5 s), it is fast compared to the approximately one minute thermal time constants of the water circuits, and comparable to the data sample rate of 6 Hz. The turbine flowmeter signals are linearized to provide linear signals over a wide range of flow rates. Modifications were made to the signal conditioning electronics to accommodate the long (100 m) cable runs from the heating beamlines to the signal conditioners. (Cable capacitance affected the circuit Q for the modulated carrier pickup transducers.) Modification consisted of installing an external, user-controlled, oscillator capable of driving the cable capacitance. Post-modification calibration of the transducer-signal conditioner pairs yielded a flow rate accuracy of 2.5%. Time response of the flowmeter electronics is ~ 0.2 s.

B. Software

Data acquisition and analysis is performed by the TFTR computer system.¹³ Waveforms of the flow rate and temperature difference for each water circuit are digitized and stored in a 32 channel CAMAC-based 12-bit digitizer. 1024

samples are taken for each waveform at an externally clocked, user-set rate (6.21 Hz for the test stand data). Signals from the flowmeter signal conditioner are 0-5 V and plug directly into the digitizer. Signals from the δT 's are amplified by a factor of 512 in a CAMAC-based 16-channel amplifier prior to digitization.

Following each neutral beam pulse, the data from the digitizers, together with other neutral beam waveforms, are automatically read and stored in a shot file on disk. Waterflow calorimetry data analysis is performed by an off-line interactive code. Energy is computed from the time integral of the differential temperature signal corrected for any offset existing prior to the pulse. Since the data acquisition time is on the order of the thermal time constant for most of the components, energy still remains in the component at the end of the last data point (i.e., the δT signal has not returned to its prepulse level). The amount of energy remaining in this "tail" can be simply approximated for a signal with an exponential time decay (which is what is observed after the temperature has decayed to about one-half of its peak value). From

$$\int_0^{\infty} A \exp(-t/\tau) dt = A \tau$$

the estimate of the "tail" energy is the product of the temperature at the last data point and the e-folding time. Exponential time constants have been determined from fits to the data for each component. The values found were: 27 s for the beamline calorimeter, 70 s for the target chamber calorimeter, 110 s for the neutralizer/collimator (this water circuit actually has several time constants for which, this is the longest), 85 s for both the full- and half-energy ion dumps. No mention is made of the third-energy ion dump since it does not absorb enough energy to measure. For the beamline calorimeter, the temperature signal decays to nearly zero by the end of the 165 s test stand data acquisition time and no "tail" correction is necessary. Corrections for the other water circuits range from 15 to 24%. The sum of the numerical integration and the "tail" is multiplied by the average flow rate and a conversion factor to produce energy. Average flow is used since the flow rate is constant over the time of the measurement. The algorithm just described is based on one developed by the Lawrence Berkeley Laboratory for a real time waterflow calorimetry CAMAC module.¹⁴

A problem related to calculation of the "tail" is the "energy remaining" in the component due to a preceding pulse. Normal TFTR neutral beam operation consists of a beam pulse every 2.5 min to keep the emission-limited filament temperature the same at the beginning of each pulse.¹⁵ Under conditions

where the beam is pulsed every 2.5 min, the data acquisition time must be shortened to approximately one minute. This increases the value of the "tail," and the "energy remaining" can be a considerable fraction of the energy deposited. These problems are discussed further in section IV. During neutral beam test stand operation this problem was all but eliminated by pulsing only the arc (no beam) on shots preceding and following a waterflow pulse. By carefully controlling the energy input into the system the data acquisition time could be increased, minimizing the "tail" and the "energy remaining."

Typical waveforms from the four components of interest on the neutral beam test stand are shown in figure 4. Part *a* is the beamline calorimeter, *b* is the full-energy ion dump, *c* is the half-energy ion dump, and *d* is the series neutralizer/collimators. As mentioned above, the beamline calorimeter signal has decayed to zero by the end of the data and no "tail" correction is necessary. Several time constants are apparent in *d* and are due to the fact that four components (neutralizer and three collimators) are in series in this particular water circuit. For comparison, figure 5 shows the signal from the full-energy ion dump for a case where there was a beam pulse immediately preceding the one in question. The entire signal is seen to be superimposed on the exponential decay of the preceding pulse.

II. RESULTS

Neutral beam test stand operation included scans of beam pulse length for four different conditions. Beam power was deposited onto either the beamline calorimeter or the target chamber calorimeter. The case with the beamline calorimeter was studied both with and without the deflection magnet energized, while the case with the target chamber calorimeter was examined primarily with the magnet on. Beam parameters during this study were 105 kV extraction potential with 53 ± 1 A of ions extracted. Pulse lengths of 0.5 s, 1 s, 1.5 s, and 2 s were used. By varying the pulse length, changes in power as a function of time due to turn-on transients or thermal dependence can be determined.⁸ Possible errors due to the shot-to-shot variation of beam current, beam voltage, and beam blocks (high voltage interruption following grid sparks) were eliminated by displaying the measured energy as a fraction of extracted beam energy, IVt , where I is the beam current, V is the extraction potential, and t is the length of time the beam is on. It has been determined that the beam current and voltage signals are accurate to better than 1%. During beam extraction there is a fluctuation of order 1% on the beam current due to imperfect regulation of the arc. As will be seen shortly,

power delivery scales nearly linearly with beam current and, hence, on the average the fluctuations cancel out. Uncertainties in the energy measurement due to beam current and voltage signals are henceforth neglected.

Figure 6 shows the energy removed from the four primary water circuits, displayed as a fraction of energy extracted from the ion source, versus pulse length. Data for this figure are for the beamline calorimeter with the deflection magnet energized (ion dump data at 1.5 s were unavailable). The fraction of extracted energy deposited on the various components are: 40% to the beamline calorimeter, 19% to the full-energy ion dump, 14% to the neutralizer/collimators, and 9% to the half-energy ion dump. Total energy accountability is 82%. There appears to be a trend, with notable exceptions (due to slight variations in operating parameters), of increasing energy accountability with increasing pulse length.

In figure 7, the sum of the energy accounted for on all monitored water circuits is plotted versus time for each of the three cases of beam onto the beamline calorimeter, with and without the magnet energized, and for beam onto the target calorimeter with the magnet energized. Several interesting facts are evident. First, there is a definite trend of increasing accountability with increasing pulse length. While within the error bars, most of the errors present in the error bars will be shown to be due to systematic errors. The precision of the measurement (i.e., the reproducibility, which is a function of the magnitude of the random error) is much greater than the accuracy (this being the total error, the sum of the random and systematic errors). Second, the accountability for the cases with the beam deposited on the beamline calorimeter is greater with the magnet off than with the magnet on. (At a pulse length of one second, the energy fraction accounted for with the magnet off is 88% versus 81% with the magnet on.) Third, the accountability is much poorer when the beam is incident on the target chamber calorimeter than it is when the beam is incident on the beamline calorimeter. A comparison at a pulse length of 2 s indicates an accountability of 83% with the beam incident on the beamline calorimeter versus 69% using the target chamber calorimeter (magnet on in both cases).

A limited amount of data was taken with the beam incident on the target chamber calorimeter with the deflection magnet off. Data taken with a one second pulse length indicate an energy accountability of 61% versus 68% with the magnet on. Accountability improves when the magnet is on. The neutral fraction, ratio of calorimeter energy with the magnet on (neutrals only) to with the magnet off (ions + neutrals), measured on the target chamber calorimeter is 61%.

A tune, consisting of a scan in beam current from 43 A to 55.5 A at a fixed beam voltage of 95 kV, is shown in figure 8. As the beam current is increased the optical qualities of the beam improve, optimize, and then deteriorate. The optical quality of the beam used here is the divergence angle: the $1/e$ half-width of the angular distribution of ions as measured from the beam axis. It is determined using an array of thermocouples embedded into the calorimeter.¹⁶ As a result of the changing beam optics, the power on target is not a linear function of beam current. Power delivered to the target should decrease linearly with beam current, but in fact drops faster than linear as the beam optics deteriorate.

III. DISCUSSION

A. Energy Accountability

A trend of increasing energy accountability is evident in figure 7. The trend is evident down to pulse lengths of 100 ms where only 60% of the expected power was measured on the calorimeter. Data from pulse lengths of 100 ms to 2 s all scale as if 40 ms of beam pulse were missing.

Initiation of the beam pulse in the accelerator column takes some time as plasma is cleared from the grid structure. During this time beam optics, and hence power delivery, are poor. Estimates of the time for this to occur are < 1 ms. This is considerably less than the 40 ms that appears to be missing. Most of the discrepancy is attributed to systematic error in the supply water temperature. As the pulse length is shortened, the shape of the differential temperature signals is seen to change slightly. This is caused by the supply water temperature changing. See figure 5 for an extreme example. Even under the conditions where the previous pulse was arc only, there is a small but measurable change in the supply temperature. On a beam pulse, a decrease in the differential temperature signal on a water circuit receiving no power is observed to decrease by 0.05°C from the beginning of the pulse to the end of data acquisition. Since the energy removed by the water is 264 Joules per $^\circ\text{C}$ -GPM-sec, the apparent energy associated with this drift is 40 kJ; enough to explain the discrepancy. It is thought that the drift is due to a combination of energy remaining in the component from an earlier beam pulse and heat (input into the system on the pulse being measured) returning to the supply side of the temperature transducer as the result of the inefficiency of the heat exchanger. Corrections for this effect are 6% at 0.5 s, 3% at 1 s, 2% at 1.5 s, and 1% at 2 s.

How much of the beam energy is accounted for is also a function of whether or not the deflection magnet is energized (see figure 7). For the case with the beam incident on the beamline calorimeter, 6.5% less energy is accounted for when the magnet is energized than when the magnet is off. One shortfall of energy is due to the fact that the energy deposited on the third-energy ion

dump is not measured. Signal levels for this water circuit were too small to produce meaningful information. An estimate of the power associated with the third-energy ions can be obtained from the extracted D_3^+ fraction, 7%, and the fraction of this remaining charged, 17%; 1.2% of the missing 6.5% is thereby accounted for. It is speculated that the remainder of the loss is due to devious particles. At the beam energy and neutralization cell conditions of this experiment, approximately 1% of the beam power is in the form of D^- . These ions are deflected to the bottom of the beamline and are not counted. A fraction of the particles are only partially accelerated due to the high pressure, and subsequent charge exchange, existing in the accelerator column. If it is assumed that the 2% of extracted power in the form of backstreaming electrons⁸ arises primarily from charge exchange in the grid structure, then 2% serves as an estimate for the partially accelerated ion power. A final devious particle category is that of charge exchange product created within the magnetic field of the deflection magnet. Assuming a pressure of 10^{-4} torr in the magnet (following pressure distributions inside the Neutral Beam System Test Facility at Berkeley¹⁷ and in Joint European Torus beamlines at Culham²), approximately 2% of both incident ions and neutrals charge exchange within the magnet.

Based on calculated ion trajectories within the magnet and assuming a uniform pressure distribution, we estimate that 50% of the devious particles created from incident ions via electron capture in the vicinity of the entrance to the magnet and 50% of those created from incident neutrals via electron loss near the exit of the magnet will escape power absorbing surfaces. Approximately 2% of IVt can thereby be ascribed to charge exchange in the magnet. Partial energy ions with energy less than 35 keV will be deflected so strongly as to miss the third-energy ion dump. This contributes an additional 1% loss. A total of 4% of IVt can, therefore, be expected to be lost as devious particles. These values are similar to the 3% estimated for the JET beamlines² (which have similar transmission magnet geometry and neutralizer proximity to TFTR beamlines) and the 3-5% as measured on ISX beamlines.¹⁸

The combined effects described above account, to within the estimated measurement uncertainty of 3.5%, for the missing 6.5% of the extracted energy.

How much energy is accounted for is a function of whether the final beam stop is the beamline calorimeter or the target chamber calorimeter. Expressed as a ratio of the energy on the target chamber calorimeter to that on the beamline calorimeter, the difference is in the range of 0.66 to 0.71. Implications are that 29% to 34% of the neutral power delivered to the beamline calorimeter does not appear on target.

A large part of the difference is due to reflection of energy off the target chamber calorimeter surface. Significant energy reflection is realized due to the near-grazing (12°) angle of incidence of the beam with the simple flat plate calorimeter. Reflected particles are not captured as they would be on a "V" shaped calorimeter. (Measurement of the backscattered particles has been used as a beam diagnostic.¹⁹) Estimates of the energy reflection have been made with the TRIM code^{20,21} using stopping powers compiled by Andersen and Ziegler.²² Results of the computation are summarized in Table I. The three energies correspond to the full-, half-, and third-energy constituents of the 105 keV beam. A spread in angle about the nominal 12° is given since the finite size of the ion source (12 cm x 43 cm) and the beam's divergence create a 1° angular beam width at the target. A population of 1000 particles was considered in each case, resulting in a statistical uncertainty of 3%.

Based on the extracted species fractions²³ of 0.78, 0.15, and 0.07, together with the equilibrium neutralization fractions²⁴ of 0.51, 0.78, and 0.83 for the extracted D^+ , D_2^+ , and D_3^+ , respectively, of a 105 keV deuterium beam, the neutral power fractions exiting the magnet are 0.7, 0.2, and 0.1 for 105 keV, 52.5 keV, and 35 keV D^0 , respectively. With these weighting factors, the fraction of incident power reflected from the target chamber calorimeter is estimated to be no more than 15% (3% statistical uncertainty included).

Further beam loss is incurred in transporting the beam through the duct connecting the beamline to the target chamber. The most restrictive aperture in the beamline occurs here and is represented by a rectangular cross section 53 cm wide by 79 cm high located 9 m from the ion source. For the beam conditions of this experiment the beam divergence was $\sim 0.4^\circ \times 1.4^\circ$ (1/e half-widths in the horizontal and vertical directions, respectively). Assuming pure gaussian beamlets, the transmission through the duct can be calculated in a straightforward manner²⁵ and is 95%.

It has been shown²⁶ that, for ion sources such as those in use on TFTR, there are aberrations in the beam producing bumps on the wings of the beamlets' velocity distribution. Such wings are evident in the 6% of extracted power measured on the neutralizer and in an equivalent value in the OMA box. Losses such as these are not predicted by a gaussian distribution with the measured half-widths of $0.4^\circ \times 1.4^\circ$. Insufficient data do not allow an estimate of the non-gaussian wings of the beam in TFTR beamlines as presently instrumented, and scrape-off in the duct due to such an effect can only be estimated.

Most of the 29-34% loss of neutral power is accounted for by those processes just described: 15% reflected, 5% transmission loss for the central gaussian distribution, and 3% uncertainty in determining the ratio of power to the two calorimeters. The remaining 5-10% provides an estimate of the contribution to duct transmission loss attributed to non-gaussian beam profile effects.

Comparison of the power delivered to the beamline calorimeter when the deflection magnet is energized to when it is off provides a measure of the neutralization efficiency. The gross neutralization efficiency measured on the beamline calorimeter in this manner is 53%. Based on published data for the equilibrium neutralization efficiency at 105 kV and the measured species composition, the anticipated neutralization efficiency is 57%. These values agree within the experimental uncertainty, indicating that there is sufficient gas left over, after those molecules comprising the beam are removed, to provide close to equilibrium charge exchange conditions. At the gas throughput used for these experiments the gas efficiency inferred from the ion gauge signals is 33%, implying that 67% of the injected gas is available as charge exchange medium in the neutralizer. (With reduced gas flow, the neutralization efficiency decreases more rapidly than predicted from room temperature gas dynamics, and agreement with measured values is poor.²⁷⁾

There is evidence that the neutral power available for injection exceeds that measured on the beamline calorimeter. Beam-turned-to-gas on the beamline calorimeter can enhance the devious particle production in the magnet.²⁸ Evidence is found for this phenomenon in the fact that the neutralizer efficiency as measured on the target chamber calorimeter (0.61 ± 0.03) exceeds that measured on the beamline calorimeter (0.53 ± 0.03). Gas from the calorimeter, flowing into the magnet, inducing devious particle loss in the magnet, would artificially reduce the neutral power measured on the beamline calorimeter. Evidence for this phenomenon is weak, just within the error bars (but some systematic errors would be expected to cancel in computing the power ratios). Also, excess power is not evident on the target chamber calorimeter. (However, absolute power data measured on the target chamber calorimeter have a large uncertainty due to the not-well-understood energy reflection from its surface.) How much, if any, power in excess of that measured on the beamline calorimeter is available for injection requires detailed gas dynamics calculations. Only the power measured on the beamline calorimeter is assumed available for injection.

B. Instrumental Accuracy

An estimate of the instrumental accuracy of the neutral beam test stand waterflow calorimetry system can be made from the data for the case of 1.5 s beam impinging upon the beamline calorimeter with the deflection magnet off. This case is chosen since the magnet is off and devious particles are

measured on the beamline calorimeter. In this case (see figure 7) 89% of the energy extracted from the ion source is accounted for. Corrections in the amount of 2% need to be made due to the time dependent factor, 6.5% for power dissipated on the OMA box, 0.5% on the accelerator grids, and 1.5% to the arc chamber. The last three items were not included in the water system at TFTR, but were instrumented on an identical system at the Lawrence Berkeley Laboratory.⁸ With the addition of these corrections, the energy inventory is 99.5% of that extracted from the source.

Sources of error in the measurement technique have been discussed above as the system was described. These are: 2.5% for the turbine flowmeters, 1% for the δT transducer, 1% for the determination of the energy in the "tail" of the δT waveform, and 1% for the subtraction of energy remaining in the δT waveform when the shot in question comes along. Rms addition of these errors yields a net uncertainty of 3.5%, the value used in the error bars in figures 6 and 7. Most of the experimental uncertainties in this system are systematic in origin and could be reduced with additional calibration. However, the magnitude of the errors are small compared to those to be described in the next section and, hence, are deemed inconsequential at this time.

IV. PREDICTION OF INJECTED POWER

The measurement accuracies quoted above pertain only for data acquired in a controlled manner similar to that used on the neutral beam test stand; i.e., where only one ion source is involved and both preceding and following pulses have no beam extraction. Errors due to supply water temperature fluctuations as a result of heat exchanger inefficiencies and errors in the estimation of both the "tail" and "energy remaining" are all exacerbated for the case of multiple beam operation on TFTR heating beamlines. More energy is put into the water system, and the data acquisition cycle must be shortened to accommodate computer system inefficiencies. These effects are evident in figure 9. With the short cycle it is seen that even the beamline calorimeter, which has the shortest cooling time of all the monitored components, does not return to its prepulse value. In part *b* the signal from a differential temperature transducer in a beamline calorimeter water circuit that did not receive any beam power during the same pulse is shown. The variation in supply water temperature during the pulse has pronounced effects on the computed energy associated with the signal in part *a*.

An algorithm was developed to reduce the errors introduced due to these supply water temperature fluctuations. Data were taken for most calorimeters in a manner consistent with the techniques used during

operation of the test stand. A calibration factor was then created by dividing the measured energy by the peak temperature rise. Energy deposited on calorimeters during pulses with multiple beams is determined as the product of the peak temperature rise and this calibration factor (signal integration is not used). The error introduced by the supply water temperature change from the beginning of the beam pulse to the time of peak signal is of order 5%. Measurements carried out with this technique are only affected by supply water temperature variations over a small portion, 8s, of the total data acquisition time. Reasonable waterflow calorimetry accuracy can thereby be obtained during multiple beam operation.

Estimates of the power injected into the tokamak are based on an energy transmission factor determined as a function of beam voltage. The transmission factor is the energy delivered to the beamline calorimeter divided by the energy extracted from the ion source. Many ion sources operating over a wide range of voltages were used to determine this factor. Injected power is computed as the time point by time point product of this factor and the beam voltage and current.

The primary uncertainty in determining the power in this manner is that ion source operation generally deviates from the conditions under which the energy transmission factor was measured. These shifts affect the beam optics (figure 8) and the beam neutralization efficiency. Errors introduced due to the nonlinearity of the beam optics are 1.5%. Errors introduced due to insufficient

gas flow to maintain beam neutralization can be estimated from the logarithmic derivative of the neutral fraction as a function of neutralizer line density:

$$\frac{d \ln f(E, \pi)}{d \ln \pi} = \frac{\pi(\sigma_{10} + \sigma_{01})}{\exp(\pi(\sigma_{10} + \sigma_{01})) - 1}$$

where f is the neutral fraction at energy E and π is the neutralizer line density. The latter quantity is the integral of the gas density along the neutralizer length; σ_{10} is the cross section for electron capture by D^+ , and σ_{01} is the cross section for electron loss by D^0 . Evaluated at a line density of $7 \times 10^{15} \text{ cm}^2$ and at a beam energy of 105 keV, values for this derivative for the three energy components are 0.35 for full-energy, 0.08 for half-energy, and 0.03 for third-energy. The derivative for the composite beam is 0.24. Errors in beam neutralization due to a possible 20% gas deficiency are, therefore, 5%.

Additional losses, not accounted for in the energy transmission factor, are those occurring in the duct connecting the beamline to the tokamak. These losses include reionization of neutrals, with the ions swept to the duct wall by the fringing field of the tokamak, and direct beam interception on the duct collimators as the result of the beam divergence. An estimate of 2-6% has been made for the reionization loss on TFTR beamlines from ion gauges located in the duct and in the beamline.^{17,26} As discussed in the previous section, scrape-off due to beam divergence is 10-15%.

Based on these errors and the 3.5% accuracy of the overall power accountability, the total error of the measurement of power injected into TFTR is of order 15%.

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^aPresent address: Yale Material Handling Corporation, Piscataway, NJ.

^bPresent address: Turnkey Solutions, New York, NY.

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Table I. Energy reflection coefficients for the three beam constituents of a 105 keV deuterium beam over the range of angles of incidence on the target chamber calorimeter.

<u>energy</u>	<u>angle of incidence</u>		
	11°	12°	13°
105 keV	0.10	0.08	0.07
52.5 keV	0.16	0.14	0.14
35 keV	0.21	0.18	0.17

FIGURE CAPTIONS

- Figure 1. Schematic plan view of a TFTR neutral beamline connected to the neutral beam target chamber forming the TFTR neutral beam test stand.
- Figure 2. Schematic elevation view of a TFTR neutral beamline.
- Figure 3. Schematic of a typical instrumented water circuit.
- Figure 4. δT waveforms for 105 kV, 53 A, 2 s operation: a) beamline calorimeter, b) full-energy ion dump, c) half-energy ion dump, and d) neutralizer/collimators.
- Figure 5. δT waveform for the full-energy ion dump with a beam pulse preceding this one by 150 s.
- Figure 6. Energy inventory, displayed as a fraction of energy extracted from the ion source, for the four instrumented water circuits. The beamline calorimeter is inserted into the beam path and the deflection magnet energized.
- Figure 7. Energy accountability (sum of all instrumented loops) as a fraction of energy extracted from the ion source for: beamline calorimeter as target and deflection magnet energized, beamline calorimeter with deflection magnet off, and target chamber calorimeter as target with deflection magnet on.
- Figure 8. Ion source tune at 95 kV showing power delivered to the beamline calorimeter and the beam divergence.
- Figure 9. Water temperature rise waveforms obtained during multiple beam operation on a TFTR heating beamline. Both parts, *a* and *b*, are for beamline calorimeters; part *a* had an incident beam, part *b* did not.

Fig. 1

Fig. 2

#89X0197

Fig. 3

#89X0200

Fig. 7

#89X0195

Fig. 8

EXTERNAL DISTRIBUTION IN ADDITION TO UC-420

7

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