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RECENT DIII-D NEUTRAL BEAM CALIBRATION RESULTS

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Abstract: Injected DIII-D neutral beam power is estimated based on three principle quantities: the fraction of ion beam that is neutralized in the neutralizer gas cell, the beamline transmission efficiency, and the fraction of beam reionized in the drift duct. System changes in the past few years have included a new gradient grid voltage operating point, ion source arc regulation, routine deuterium operations and new neutralizer gas flow controllers. Additionally, beam diagnostics have been improved and better calibrated. To properly characterize the beams the principle quantities have been re-measured.

Two diagnostics are primarily used to measure the quantities. The beamline waterflow calorimetry system measures the neutralization efficiency and the beamline transmission efficiency, and the target tile thermocouples measure the reionization loss. An additional diagnostic, the target tile pyrometer, confirmed the reionization loss measurement. Descriptions and results of these measurements will be presented.

Introduction

The DIII-D tokamak has four neutral beamlines, each containing two independent neutral beams (left and right). The major components for one beam are shown schematically in Fig. 1. An ion beam is extracted from the source, and travels through a one meter gas cell neutralizer. The beam passes

through a separation magnet where the non-neutralized fraction of the beam is deflected into an ion dump. A movable calorimeter can be positioned to intercept the neutral beam or allow it to pass through the drift duct and into the tokamak. If a plasma is not present in the tokamak a beam of short duration can be absorbed by graphite target tiles lining the tokamak walls. Temperature interlocks prevent long duration tile shots. Both left and right beams pass through the same drift duct collimator, the only shared component in the beamline.

The power injected into the DIII-D tokamak is estimated according to equation

$$P_{\text{injected}} = P_{\text{extraction}} f_{\text{neutralisation}} \eta_{\text{transmission}} \eta_{\text{reionisation}} \quad (1)$$

where $P_{\text{extraction}}$ is the product of acceleration voltage and current power supply, $f_{\text{neutralisation}}$ is the fraction of the beam that is neutralized in the gas-cell neutralizer, $\eta_{\text{transmission}}$ is the beamline transmission efficiency, and $\eta_{\text{reionisation}}$ is the fraction of the beam not reionized in the drift duct. The measurement of $P_{\text{extraction}}$ is a simple process of determining the acceleration voltage and current by sampling voltages across a divider network. This paper focuses on the measurement of the last three quantities, measured primarily by two specialized diagnostics: beamline waterflow calorimetry and target tile thermocouples.

FIG. 1. DIII-D neutral beamline components. Illustrates beam path, components monitored by the waterflow calorimetry system, and the target tile thermocouples.

Waterflow calorimetry data are used to calculate both neutralization efficiency and transmission efficiency, while target tile thermocouples data are used to calculate the duct reionization.

Transmission Efficiency

Beamline transmission efficiency $\eta_{\text{transmission}}$ is calculated as the product of two factors: the fraction of the beam reaching the calorimeter ($\eta_{\text{calorimeter}}$), and the remaining fraction that passes through the drift duct collimator ($\eta_{\text{duct collimator}}$), downstream from the calorimeter. Both quantities are measured using waterflow calorimetry.

Waterflow calorimetry provides an accurate measurement of the energy impinging on ten of the main beamline components [1]. Each component is water-cooled at a carefully measured rate. During the five minute cooldown period following a beam pulse, the difference in temperature of the cooling water before and after passing through each element is measured at a 1 Hz rate. The integral of this temperature difference times the flowrate over time represents the energy striking the component.

To measure $\eta_{\text{calorimeter}}$, the beamline ion separation magnet is switched off and beam pulses are fired into the calorimeter. Pulses containing 1 MJ of beam energy or more provide the best thermocouple response. The beamline transmission efficiency depends on the beam optics, which in turn depend upon beam perveance. The perveance is methodically varied from shot to shot, providing a perveance scan. An example scan is shown in Fig. 2. Typically, the ion sources operate in deuterium at a perveance of about $3.0 \mu\text{P}$. Although $\eta_{\text{calorimeter}}$ is not truly linear with perveance, the slope and efficiency at perveance $3.0 \mu\text{P}$ are useful numbers to quantify a scan. Each ion source has slightly different characteristics, and $\eta_{\text{calorimeter}}$ varies somewhat among the beams, although 80% at deuterium perveance $3.0 \mu\text{P}$ is typical. A summary table of many such scans for all beams is given in Table I (all 75 kV deuterium).

FIG. 2. Calorimeter transmission efficiency versus perveance. Waterflow calorimetry measurement of $\eta_{\text{calorimeter}}$ for a 75 kV deuterium beam as perveance is varied. A perv is an ampere per volt to the $3/2$ power.

Since both left and right beams pass through the same drift duct collimator, $\eta_{\text{duct collimator}}$ is most easily measured on injection shots where only one of the two beams has fired. The scraped-off fraction is small, so long pulse lengths are necessary

Table I: Calorimeter Transmission Efficiency Among DIII-D Beams

Beam	$\eta_{\text{calorimeter}}$ at Pervance $3.0 \mu\text{P}$ (%)	Scan Slope % per μP
30 Left	82.5	16.2
30 Right	83.9	19.0
150 Left	80.6	15.4
150 Right	77.6	9.2
210 Left	82.3	17.9
210 Right	75.4	17.6
330 Left	78.0	21.4
330 Right	78.3	16.4

to achieve good results. Table II shows how beam power is distributed in the beamline during deuterium injection (4 sec at 75 kV). The fraction of power supplied by the accelerator power supply striking each component is shown. The power fraction scraped by the drift duct collimator (f_{duct}) is 1.6%. From this, $\eta_{\text{duct collimator}}$ is computed as follows (Fig. 3):

$$\eta_{\text{duct collimator}} = 1 - \frac{f_{\text{duct}}}{f_{\text{neutralization}} \eta_{\text{calorimeter}}} = 97\% \quad (2)$$

The value of $f_{\text{neutralization}}$ used was 70%, and will be discussed in the next section.

FIG. 3. Power losses prior to the drift duct. Shows the relationship between the fraction of accelerator power striking the duct collimator (f_{duct}) and the fraction of incident power transmitted through the collimator ($\eta_{\text{duct collimator}}$).

The combined parameter $\eta_{\text{transmission}}$ varies from beam to beam, but using the 80% average number for $\eta_{\text{calorimeter}}$ and 97% for $\eta_{\text{duct collimator}}$, $\eta_{\text{transmission}}$ becomes about 78%.

Neutralization Efficiency

The neutralization efficiency is a function of beam energy, beam species mix and neutralizer line density, and has been modeled successfully by J. Kim and H.H. Haselton [2]. Their model, named GASEL (for *gas cell*) shows that the neutralization efficiency is a strong function of beam particle energy and a

Table II: Power Distribution
Within DIII-D Neutral Beamline

Beamline Component	Fraction of Accelerator Energy
Source Collimator	3.6%
Neutralizer	5.2%
Ion Dump	18.6%
Baffle Collimator	1.3%
Ion Return Collimator	1.8%
Magnet Entrance Collimator	1.4%
Magnet Exit Collimator	3.6%
Magnet Pole Shield	5.7%
Calorimeter	0.7%
Drift Duct Collimator	1.6%
Injected or Unaccounted for	56.4%
Total	100.0%

weak function of the beam species mix. For a 75 kV deuterium beam with species mix of 70:20:10 (full:half:third) beam energy components, the neutralization efficiency is predicted to be 70%, given sufficient gas in the neutralizer to achieve equilibrium. Gas is introduced into the neutralizer directly through a neutralizer gas-puffing system (10 Torr-ℓ/s), and indirectly from the ion source gas puffing system (20 Torr-ℓ/s).

To measure the neutralization efficiency, a set of beam shots are taken into the calorimeter. The beamline ion separation magnet is turned on for some shots and off for the others. Assuming that the beamline transmission efficiency is the same whether or not the magnet is on, the neutralization efficiency is determined by the ratio of beam power deposited on the calorimeter with the magnet on to that with the magnet off. To see the effect of the gas puffed directly into the neutralizer, this experiment is performed for a variety of gas flow rates. The results for such a scan are shown in Fig. 4. The deuterium beam had an energy of 75 kV, and the GASEL neutralization prediction was 70%. As the neutralizer gas flow increases to 10 Torr-ℓ/s, the neutralization efficiency comes to within 4% of this value. Beyond the 10 Torr-ℓ/s rate, operations are adversely affected due to excessive gas flowing back from the neutralizer into the ion source, which causes additional beam collisional loss in the accelerator.

Previously, calorimetry data with the ion separation magnet on was not fully trusted due to an "uncertainty effect" [1,3]. Beam gas trapped within the calorimeter migrates back into the ion separation magnet, causing the reionization within the magnet of some of the neutrals. Although this effect appears smaller than previously believed, it may account for the 4% difference between measured neutralization efficiency and the GASEL model. A species mix other than 70:20:10 could also produce the difference.

Duct Reionization

Due to poor conductance and distance from vacuum pumps, the long, narrow drift duct ($\sim 100 \times 49 \times 43$ cm) is a region of higher pressure than either the beamline or the tokamak. Collision with this background gas reionizes a fraction of the neutral beam. The fraction of beam lost to this phenomena can be measured by means of the target tile thermocouples.

FIG. 4. Neutralization efficiency versus neutralizer gas puffing. Waterflow calorimetry measurement compared to GASEL model at equilibrium for a 75 kV 70:20:10 full:half:third energy beam. Each calorimetry point represents several shots into the calorimeter with and without the ion separation magnet on. The neutralization efficiency is the ratio of calorimeter power with and without the magnet.

The thermocouples are embedded into four or five of the target tiles for each beam, about 2 cm from the front surface. The temperature of the tiles is measured twice: about 20 sec before and 40 sec after a beam shot. The first reading is termed the base reading and the difference between the two the delta reading. The 40 sec delay ensures that the heat has flowed throughout the tile, and yet is not so long as to be significantly lost to the vessel wall.

To measure $\eta_{\text{reionization}}$, a series of beam shots are injected into the tokamak without any plasma. The toroidal magnetic field of the tokamak is switched on for some of shots, and off for the others. The magnetic field deflects reionized particles away from the target tiles. The delta temperature reading is essentially proportional to the beam energy impacting the tiles. The non-reionized fraction ($\eta_{\text{reionization}}$) is the ratio of normalized delta tile temperatures with and without toroidal field present. To account for variations among the shots, the delta temperature is normalized to the energy supplied to the ion source accelerator.

The computation is made somewhat more complicated due to the fact that the temperature of the tile is taken 40 sec after the beam rather than immediately after, and that the tiles take sufficiently long to cool off that they may contain residual heat from a previous shot. This has the effect of making the normalized temperature a decreasing function of the base temperature. As an extreme example, imagine that a shot of relatively little energy is taken while the tiles still contain heat from a previous shot of larger energy. After 40 sec, the second temperature reading is made. The second temperature reading may actually be lower than the first, since the tiles were still cooling from the earlier shot and very little energy was added from the second beam.

To account for the tile cooling effect, a plot is made of normalized delta temperature versus base temperature (see Fig. 5). Assume the following: (1) duct reionization is independent of

FIG. 5. Normalized tile temperature change versus pre-shot tile temperature. Target tile thermocouple measurement of beam injected into empty tokamak with and without toroidal field. Drift duct reionization survival ($\eta_{\text{reionization}}$) is the ratio of normalized change with and without toroidal field at any fixed pre-shot temperature.

the base temperature of the tiles, (2) the ratio of normalized delta temperature with toroidal magnet on to magnet off represents the non-reionized fraction for all base temperatures, and (3) within the small range of base temperatures our measurements were made, the dependence of normalized delta temperatures to base temperature is linear. This last assumption is based on observation of Fig. 5. With these assumptions, the lines fitting the magnet-on and magnet-off series must intersect on the horizontal axis, even if this point should lie outside the validity range of assumption 3. This fact greatly increases the precision to which the data can be fitted. The parameter $\eta_{\text{reionization}}$ is about 95%.

The specific heat of graphite varies with temperature [4], but it is now believed that the effect of this variation is small compared to cooling from the previous shot. If both left and right beams are present simultaneously it is believed reionization rates are higher. The two-beam enhanced reionization was not noticed in our target tile data, however. The neutralization efficiency could in principle be measured by turning on and off the ion separation magnet instead of the toroidal field. In practice, this has not yet yielded consistent results; one thermocouple consistently overestimates the neutralized fraction, another underestimates it. This is likely due to spatial deflection of the ion

beam with respect to the neutral beam due to stray magnetic fields in the tokamak when the ion separation magnet is turned off [4].

The measurement of $\eta_{\text{reionization}}$ was confirmed using an optical pyrometer. The pyrometer views a spot on one of the target tiles and provides a time-resolved surface temperature whenever the temperature exceeds 200°C. The analysis is carried out identically to the target tile thermocouple analysis, except that the normalization contains an additional factor of the square root of the pulselength since the surface temperature rather than the bulk temperature is measured.

Conclusion

The fundamental parameters by which injected power is calculated have all been recently measured using waterflow calorimetry and target tile thermocouples. The measured neutralization efficiency is 66%, close to the modeled equilibrium value of 70% for a 75 kV deuterium beam. Waterflow calorimetry has proven to be a useful tool to measure the neutralization efficiency, contrary to earlier results. The beamline transmission efficiency has been measured for each beam independently, and averages about 78% among the beams. Finally, the drift duct reionization survival rate is 95%. By making use of the independence of pre-shot target tile temperature and duct reionization, interpretation of thermocouple data has yielded more accurate results.

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References

- [1] J. Wight et al., *Beam Transmission Properties in the DIII-D Neutral Beamlines*, in Proceedings of the 12th Symposium on Fusion Engineering (IEEE), 1987.
- [2] J. Kim and H.H. Haselton, *Analysis of Particle Species Evolution in Neutral-Beam Injection Lines*, J. Appl. Phys. 50 (1979) 3802.
- [3] R.M. Hong et al., *Performance Analysis of 180° Reflection Magnet in Doublet III Neutral Beamline*, in Proceedings of the 10th Symposium on Fusion Engineering (IEEE), 1983.
- [4] J. Wight et al., *Maximization and Measurement of Ion-to-Neutral Conversion Efficiency in the DIII-D Beamlines*, Bull. Am. Phys. Soc. 33 (1988) 2055.

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