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Improvements to the calibration of the MST Thomson scattering diagnostic[a)]

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Calibration of the Madison Symmetric Torus Thomson scattering system has been refined to improve temperature fluctuation measurements. Multiple avalanche photodiodes have been directly calibrated for use as reference detectors during calibration, improving accuracy and ease of use. From the absolute calibration we calculate corrections to the gain for variation in detector operating temperature. We also measure the spatial uniformity of detector responsivity for several photodiodes, and present a method of accounting for non-uniformity in the calibration process. Finally, the gain and noise enhancement are measured at multiple wavelengths to improve temperature and uncertainty measurements. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4733566]

I. INTRODUCTION

Measurement of electron temperature fluctuations in high temperature plasmas requires an accurate derivation of both temperature and uncertainty. The Thomson scattering diagnostic on the Madison Symmetric Torus (MST) uses a Nd:YAG laser as a light source and filter polychromators with EG&G C30956E avalanche photodiodes (APDs) as a spectral detection system.[1] Previous work[2] has established a calibration procedure for measuring the gain and noise enhancement of the APDs and characterizing the filter polychromators. To improve the accuracy of this procedure, we have characterized the behavior of the APDs at multiple wavelengths. These measurements allow us to calculate the gain and noise enhancement across the entire range of scattered wavelengths observed during operation.

We have also investigated the uniformity of the APD responsivity across the surface of the active area. Significant non-uniformity has been measured in some cases, and since the calibration procedure requires illuminating the APDs with a spot size smaller than the active area, these effects must be taken into account. Additionally, we have improved the robustness of the calibration procedure through the use of multiple reference detectors as well as inclusion of a correction factor for operating temperature variations.

II. ABSOLUTE CALIBRATION OF REFERENCE DETECTORS

In the calibration procedure described in Sec. IV, we measure the gain and noise enhancement of each APD relative to a reference APD with known gain. The gain is the product of photodiode spectral responsivity and amplification, while the noise enhancement is the ratio F/qe where qe is the quantum efficiency and F describes the noise enhancement beyond Poisson statistics. In the past, the reference APD had been calibrated by comparison to an absolutely calibrated InGaAs detector at a single wavelength (1020 nm) near the laser line.[2] In order to obtain a more accurate comparison to the individual APDs, as well as to avoid the difficulties associated with using the InGaAs detector discussed in Ref. 2, three reference APDs have been absolutely calibrated by the Canadian National Research Council's Institute for National Measurement Standards at a range of wavelengths (700–1100 nm). One of the reference APDs was further calibrated at multiple operating temperatures (67, 68, and 69 °F). The calibrations were performed with a continuous light source and the output voltage was measured using a digital volt meter with input impedance greater than 10^{10} Ω.

The gain of one of the reference APDs is shown in Figure 1. In prior calibrations, we could only measure the gain at a single wavelength and so were forced to make the poor assumption that the wavelength dependence of the gain was small. However, the gain varies by nearly a factor of two across the range of wavelengths typically used during operation. This variation affects the number of photons measured, and should be included for accurate temperature and uncertainty measurements.

The polychromators are water-cooled to provide stable operating temperatures, but drifts of 1–2 °F can occur in extreme cases. APD gain is sensitive to operating temperature, so we use the reference APD calibrated at multiple temperatures as a "typical" case to create a temperature correction profile. At each wavelength, the gain is fit by a

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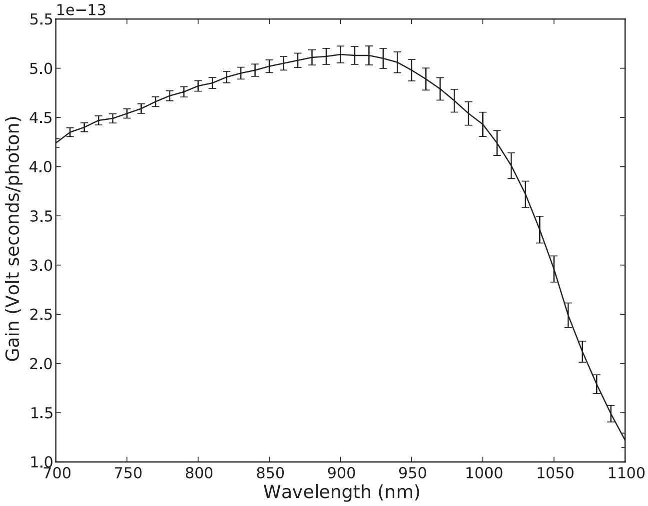

FIG. 1. Measured gain for one of the reference APDs. This is the dc gain value for a continuous light source.

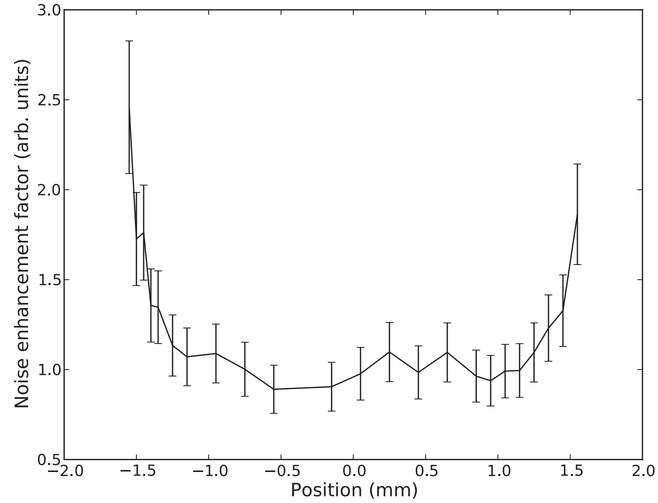

FIG. 3. Typical relative spatial profile of noise enhancement factor, measured by scanning a 0.1 mm diameter spot ($\lambda = 1064$ nm) across the active area.

linear dependence on temperature. The linear coefficients C_λ, relative to the gain at 68 °F, are shown in Figure 2. For the wavelengths below 1100 nm, the coefficients are all roughly uniform with a mean value of 2.04% per °F.

Having multiple absolutely calibrated APDs provide a useful baseline for tracking the calibration status of the system. Any changes in gain of a single reference APD can be monitored by comparison to the others. Should changes occur, the reference APDs can be recalibrated.

III. SPATIAL UNIFORMITY OF APD RESPONSIVITY

Comparison of individual APD gain and noise enhancement to the reference APD is complicated by the uniformity of the responsivity across the detector active area. During normal operation, each APD is slightly overfilled—the polychromator focusing optics image the scattered light to a spot size slightly larger than the detector active area (3.0 mm diameter). However, during calibration, the focusing optics image the light source to a spot size of roughly 2.0 mm diameter, underfilling the APD. Underfilling of the APDs during the calibration procedure ensures that all of the photons are counted and is necessary for an accurate comparison of the individual APDs to the reference APD. Additionally, the reference APDs were absolutely calibrated using a spot size of 1.0 mm diameter. Each of these measurements covers different, overlapping regions of the active area, and correctly calculating the gain and noise enhancement requires a quantitative understanding of the spatial uniformity of the APD responsivity.

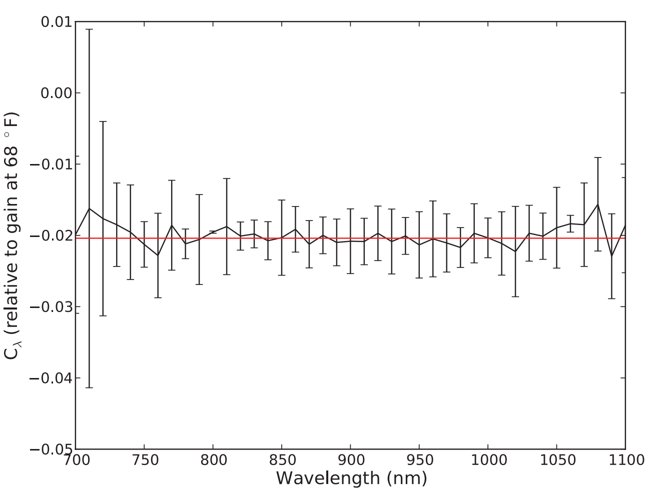

FIG. 2. Linear fit coefficients, C_λ, for the temperature dependence of APD gain. The mean value is indicated by the red line.

Quoted typical responsivities[3] for the APDs used in this diagnostic indicate that, although the responsivity is reasonably constant near the center of the active area, it can vary by a factor of two near the edges. Spatial non-uniformity of APDs at high bias voltage is a known problem,[4] and some of these APDs are over a decade old and may not reflect recent fabrication advances that have improved uniformity. To account for non-uniformity, two steps are required: comparing the gain and noise enhancement between the 1.0 mm and the 2.0 mm spot sizes for the reference APDs, and correcting the gain and noise enhancement for each of the individual APDs to account for overfilling during normal operation.

Responsivity profiles have been measured for several APDs using a spot size of ~0.1 mm diameter. These profiles have been measured at only a single wavelength (1064 nm). While the noise enhancement is typically uniform across the center of the diode, see Figure 3, the gain shows even greater variability than indicated by the data sheet. An extreme example is plotted in Figure 4, with a double-peaked structure visible. The measured profile for each reference APD is normalized to the gain measured during absolute calibration by integration over a centered, 1.0 mm diameter spot. The normalized curve is then integrated over the 2.0 mm diameter spot to obtain the value of the gain used to calibrate the individual APDs. Future measurements are planned for a two-dimensional scan across the active area to obtain a more accurate characterization of the reference APDs.

Likewise, the ratio of integrals over 2.0 mm and 3.0 mm diameter spots is used to correct the gain and noise enhancement measured for the individual APDs. However,

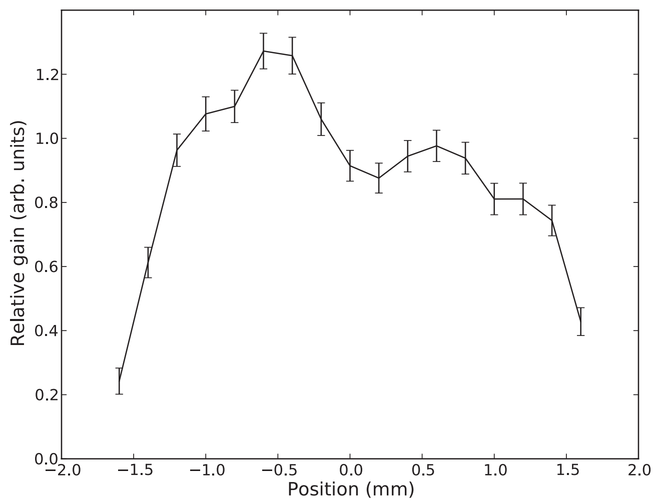

FIG. 4. Relative spatial profile of gain, measured by scanning a 0.1 mm diameter spot ($\lambda = 1064$ nm) across the active area.

with 138 APDs in use, performing a full measurement of the uniformity of each APD is prohibitively time and labor intensive. Instead, we use "typical" profiles from a smaller sample set. The area weighting effects at the edge of the profiles can significantly affect both the gain and noise enhancement—the gain, for example, can be overestimated by 15%–20% without spot size corrections.

IV. CALIBRATION OF ALL AVALANCHE PHOTODIODES

To calibrate the APDs, we mount five APD modules on a water cooled block along with one of the reference detectors. The APD modules are coupled into an integrating sphere via fiber optic, and multiple LEDs are pulsed into the integrating sphere. The LEDs used cover a range of wavelengths (Osram SFH 4860 at 660 nm, Optek OP230WPS at 852 ± 1.4 nm, Osram SFH 4545 at 959 ± 2.5 nm, and Roithner LED1050-35K42 at 1005 ± 37 nm) and are driven by an OmniPulse PLDD-50-SP compact current source to obtain pulses that are 15–30 ns wide with 1 kHz repetition rate in order to replicate the scattered light from the laser system. The center wavelength and width of the SFH 4860 have not been independently measured. The LED pulses are spaced 5 μs apart to allow the APD voltage output to return to its dark value. Although the pulse-to-pulse variation of the LED outputs is too small to measure directly, we estimate the maximum value to be below the error in the noise enhancement measurement. Measurements of pulse-to-pulse variation with a photomultiplier tube put the upper bound at 1.2%, while measurements with a biased Si photodiode are even lower at 0.8%. We record 100 000 pulses from each LED, and calculate the gain and noise enhancement as in Ref. 2.

We have chosen the LED wavelengths to cover both the typical operating range as well as the critical features of the APD responsivity. The spectral responsivity curves for the

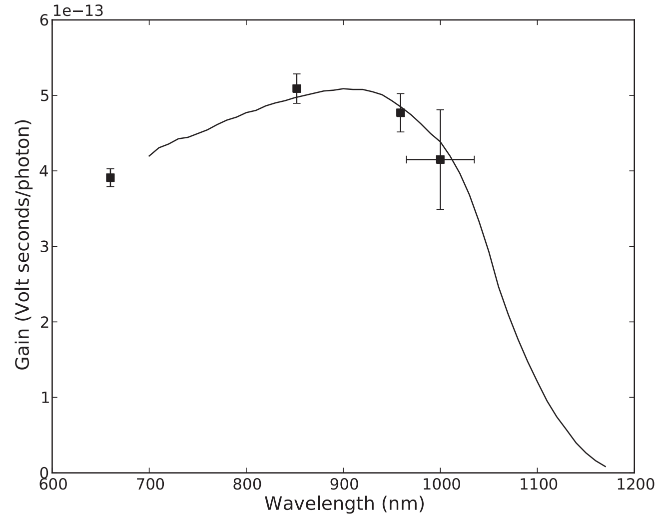

FIG. 5. Gain of an APD measured at the four LED wavelengths with characteristic curve fit.

reference APDs are treated as "typical" and averaged to establish a characteristic responsivity curve. We then fit this characteristic curve to the measured gains for each APD to create a function of wavelength for use in temperature measurements. An example is shown in Figure 5.

V. CONCLUSION

Measurements of gain and noise enhancement at multiple wavelengths, as well as APD uniformity, have yielded a more accurate characterization of APD spectral response. Corrections for the dependence of gain on operating temperature have also made this calibration more robust. These improvements to the diagnostic calibration will lead to a more accurate determination of electron temperature and uncertainty. Ongoing and future measurements of electron temperature fluctuations in a variety of MST plasma conditions will benefit from the increased accuracy provided by these calibrations.

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