Calibration of a Thomson scattering diagnostic for fluctuation measurements[a]

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Detailed calibrations of the Madison Symmetric Torus polychromator Thomson scattering system have been made suitable for electron temperature fluctuation measurements. All calibrations have taken place focusing on accuracy, ease of use and repeatability, and *in situ* measurements wherever possible. Novel calibration processes have been made possible with an insertable integrating sphere (ISIS), using an avalanche photodiode (APD) as a reference detector and optical parametric oscillator (OPO). Discussed are a novel *in situ* spatial calibration with the use of the ISIS, the use of an APD as a reference detector to streamline the APD calibration process, a standard dc spectral calibration, and *in situ* pulsed spectral calibration made possible with a combination of an OPO as a light source, the ISIS, and an APD used as a reference detector. In addition a relative quantum efficiency curve for the APDs is obtained to aid in uncertainty analysis. *© 2008 American Institute of Physics.* [DOI: 10.1063/1.2964229]

I. CALIBRATION

A unique application of the Thomson scattering diagnostic[1] on the Madison Symmetric Torus (MST) reversed-field pinch[2] is measurement of electron temperature fluctuations. In order to quantify fluctuations, accurate calibrations must be done and frequently checked to enable correct temperature and uncertainty derivation. With the calibration procedures now in place it is possible to quickly and easily check system stability and functionality over time. Calibrations performed include *in situ* spatial calibration, avalanche photodiode (APD) gain and noise determination, and spectral instrument function measurement. To improve the ease and accuracy of these calibrations an absolutely calibrated APD [for which the gain and relative quantum efficiency (QE) have been measured] is used as a reference detector. Procedures are in place that make it possible to easily and quickly check system stability and functionality over time. This includes an *in situ* pulsed spectral calibration (implemented with an insertable integrating sphere (ISIS) and a wavelength tunable laser), which checks all optical system components that can be done without disturbing the system. The following describes the calibration procedures used in detail. Section II describes the *in situ* spatial calibration done using an ISIS Section III describes the gain and uncertainty calibration of the APD detectors. This includes the implementation of using one absolutely calibrated APD to calibrate the remaining APDs, as it is easier to compare two similar detectors. Section IV includes a description of necessary spectral calibration of the polychromators in order to fit temperature to Thomson scattering data. This also includes a measurement of a relative QE curve for the APDs and a pulsed *in situ* spectral calibration that can be compared to laboratory calibrations to check the entire system.

II. RADIAL CALIBRATION

Each of the 21 Thomson scattering polychromators[3] views a different radial location between the core and edge of the MST. In order to determine the exact viewing location and resolution of each polychromator an *in situ* radial calibration is performed. A Nd:YVO_4 laser diode (Lasermate GMF-1064-100FBC2) operating at 1064 nm is coupled via fiber optic to an *in situ* ISIS.[4] The traverse of the ISIS is scanned inwards at a constant rate and the signal for each laser line polychromator channel is digitized using 10 ms sampling time and 42 000 samples. The ISIS scans from the edge to the core over 420 s. When the ISIS is in the viewing location of a given polychromator the laser line channel picks up the emitted laser light. As the ISIS moves inward each polychromator lights up in turn. The light gate, which is normally used to "home" the ISIS, is also digitized, giving the precise location during the scan. Figure 1 shows the radial calibration. The radial resolution of the diagnostic is 2.0 cm in the edge and 1.3 cm in the core, with a precision of approximately 1 mm.

III. APD ABSOLUTE CALIBRATION

The APD calibration process is two-step. First the gain (a combination of detector response and amplification) near the laser wavelength of one APD is obtained by comparison to an InGaAs detector absolutely calibrated by Optronic Laboratories. Then this APD that has been absolutely calibrated is used as a reference to obtain the gain near the laser

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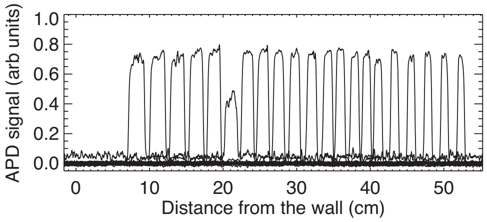

FIG. 1. The radial scan measures both the location and radial resolution of each polychromator view. The sixth channel shows the lower signal, which is due to a problematic detector at that location.

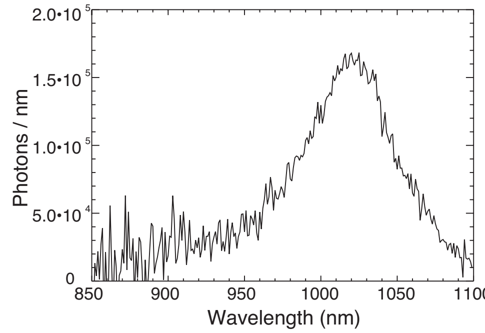

FIG. 2. Photons output by the pulsed LED and measured by the InGaAs absolutely calibrated detector at the monochromator exit. Measurements show a peak wavelength of 1020 nm with a full width at half maximum of 70 nm.

wavelength and noise enhancement factors of the rest of the APDs. The unbiased InGaAs detector setup is noisy, relative to the APD module, and prone to oscillations making it unstable. A substantial amount of work has been put into fixing this but it cannot be made reliable in all operating conditions. In addition to this the InGaAs detector, and corresponding current to voltage amplifier, has a much lower overall gain-bandwidth product than a typical APD and amplifier module. In a side by side calibration setup drastically different light levels are needed to get reasonable signal levels for the InGaAs detector and an APD. This difference in light levels results in a calibration setup that does not take advantage of the full scale bit resolution of the digitizers. The variance in light pulses detected by the APD becomes determined by digitizer bit resolution washing out the detector photon statistics. It is therefore advantageous to use an APD as an absolutely calibrated reference detector over the InGaAs in the second part of the calibration mainly to get accurate noise levels but also for ease of use. With the absolutely calibrated APD detector the calibration setup becomes simpler and more accurate. Similar light levels can be used for the absolute detector and APD to be calibrated, which allows for a physically simple setup and allows the full scale vertical resolution of the digitizers to be used. This is essential because it is important to have the bit transition voltage resolution much less than the statistical variation of the pulses.

A. Characterization of light source

The light source used in the calibration process is an infrared InGaAs light emitting diode (LED) (PerkinElmer, Model C30116/F). The light is pulsed to mimic a laser pulse with a width of 30 ns at 1 kHz. The normalized spectral output of the LED pulsed in this manner, P_{norm}, is characterized using the absolutely calibrated InGaAs detector. To do this the light from the LED is sent through a 0.5 m Czerny–Turner monochromator with a 1200 grooves/mm grating. The output of the monochromator is coupled to the InGaAs detector and the monochromator is scanned through the output wavelengths of the LED. It is assumed the throughput of the monochromator in the region of interest is relatively flat.

The InGaAs detector, which has been absolutely calibrated by Optronic Laboratories, outputs a current proportional to the power hitting the detector. The response as a function of wavelength is $C(\lambda)$. The current output is sent to a current to voltage amplifier with a gain, G_{amp}, of 3.3×10^7 V/A. Assuming the current to power ratio is the same as the charge to energy ratio[5] the integral under the digitized output pulse, S_{InGaAs}, gives the total Coulombs per pulse, $Q[C]=S_{\mathrm{InGaAs}}[\mathrm{V\,s}]/G_{\mathrm{amp}}[\mathrm{V/A}]$.

The number of photons detected for a pulse at a given wavelength, j, by the InGaAs detector can be calculated using the energy per photon$=hc/\gamma$ as $N_j=Q_j\lambda_j/C(\lambda_j)hc$.

Figure 2 shows the spectral output in photons for the pulsed LED. The measured peak output is 1020 nm even though it is nominally specified to be at 1060 nm by the manufacturer. The normalized output is then

$$P_{\mathrm{norm}}=\sum_j \frac{N_j}{S_{\mathrm{InGaAs}_j}}=\sum_j \frac{Q_j\lambda_j}{S_{\mathrm{InGaAs}_j}C(\lambda_j)hc}, \tag{1}$$

which is defined to be a convenient conversion so that the number of photons detected in a single LED pulse is simply $N_{\mathrm{InGaAs}}=S_{\mathrm{InGaAs}}P_{\mathrm{norm}}$.

B. Measure the gain for one APD

For the first step in the calibration process light from the LED is split into two fiber optic cables. One is sent to underfill the InGaAs detector and the other underfills the APD to be absolutely calibrated. Both detectors sit on a water cooled block to ensure that their temperatures remain constant. The system is on and warmed up for 10 min before the calibration to allow everything to reach an equilibrium temperature and the temperature is monitored continuously during the calibration. If the temperature changes by more than 0.2 °C the calibration is redone. The pulse to pulse variation of the LED is assumed to be small and N_{InGaAs} is averaged over several thousand pulses to give $N_{\mathrm{InGaAs}_{\mathrm{av}}}$. In addition to the data taken while the LED is pulsing data are taken when the LED is off to get a dark signal necessary to measure the background electronic noise and APD noise enhancement factor (see Fig. 3). The signal level of the APD is simply the dark signal subtracted from the light signal. The APD signal level is averaged over the several thousand pulses to give $S_{\mathrm{APD}_{\mathrm{av}}}$. The fiber optic cables are then switched to find the light ratio, L, between the two detectors. Finally the gain of the absolutely calibrated APD is calculated $G_{\mathrm{absAPD}}=S_{\mathrm{APD}_{\mathrm{av}}}L/N_{\mathrm{InGaAs}_{\mathrm{av}}}$.

In actuality, G_{absAPD} is a function of wavelength, but the variation is assumed to be small and it is taken to be a constant of wavelength and used in the second calibration step.

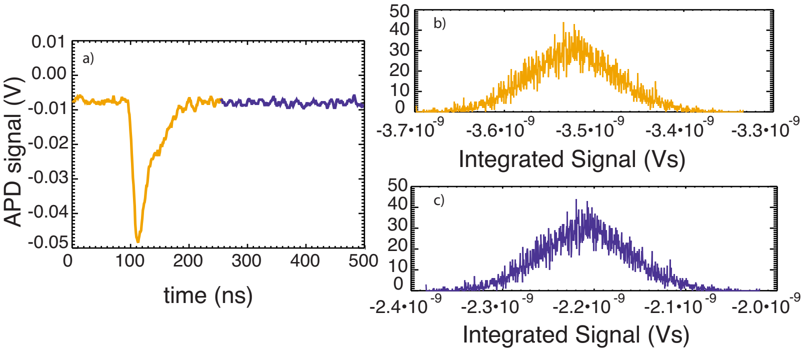

FIG. 3. (Color online) (a) A pulse of the LED as seen by an APD. The first half of the raw signal is integrated to get the light signal (orange). The second half of the light signal is integrated to get a baseline dark signal level (blue). Histograms of the 100 000 pulses for the (b) light and (c) dark signals are shown.

C. Finding the gain and noise enhancement of all APDs

For the second step of calibration the light from the LED is input into an integrating sphere with four outputs. The outputs are sent to three APDs to be simultaneously calibrated and the one absolutely calibrated APD. All four APDs in this setup are mounted on a water cooled block for temperature control. The light ratios L_i for each position, i, on the cooling block are calculated relative to the absolutely calibrated APD. 100 000 pulses of the LED are recorded (see Fig. 3) for typical LED pulse and histogram of light and dark signals and the gain is $G_{\mathrm{APD}_i}=S_{\mathrm{APD}_{\mathrm{av}_i}}G_{\mathrm{absAPD}}L_i/S_{\mathrm{absAPD}_{\mathrm{av}}}$.

From the combination of light and dark pulses F/QE values for each APD are calculated where QE is the quantum efficiency and F is a factor describing the noise enhancement beyond Poisson statistics[6] for each APD so that

$$\mathrm{SNR}=\frac{N\mathrm{QE}}{\sqrt{N\mathrm{QE}F}}=\sqrt{\frac{N\mathrm{QE}}{F}}. \tag{2}$$

Calculating both the variance of the pulsed LED signal, $\sigma^2_{\mathrm{pulsed}}$, and dark signal, σ^2_{dark}, the value of F/QE for each APD is then calculated to be

$$\frac{F}{\mathrm{QE}}=N_{\mathrm{APD}}\frac{\sigma^2_{\mathrm{pulsed}}-\sigma^2_{\mathrm{dark}}}{S^2_{\mathrm{APD}}}. \tag{3}$$

QE is a function of wavelength but for uncertainty analysis we assume that this value of F/QE is constant. However, Sec. IV A describes how a relative QE curve is obtained, which can transform this constant F/QE measurement into one that is a function of wavelength. Future refinements will also include repeating this calibration with pulsed LEDs at other wavelengths.

Since this calibration step can take up to 30 min the temperature of the APDs during this process must be monitored closely. Both gain and dark currents are highly dependent on APD temperature. Temperature differences of just 0.5 °C can make this measurement unreliable if the temperature difference is not taken into account. With the environmental control and monitoring system currently in use[4] the temperature can be kept constant to within 0.2 °C and this is not a concern.

IV. SPECTRAL CALIBRATION

In general the spectrum of Thomson scattered light is a relativistic Maxwellian and depends on two parameters: the temperature and the density.[7] The width of the Maxwellian is determined by the temperature and the integral underneath the spectrum determined by the density. In order to correctly fit Thomson scattering data to a Maxwellian the instrument function, a combination of transmission and gain of the spectral channels of each polychromator, must be known.

Two different methods of measuring the polychromator instrument function are described below. The first, a more traditional method,[8] uses a dc light source and is done in the laboratory whereas the second uses a pulsed light source and is done *in situ*. The dc calibration can be done quickly and does not require access to the MST machine area. The ease of this calibration allows it to be performed more frequently to check changes in the polychromators and its components over time. It is an advantage to use a pulsed light source in the second calibration to reveal any slight dependencies on pulsed light of the system performance. It is also beneficial because this is done *in situ* so that it includes the entire path of Thomson scattered light. It is used to check for any systematic changes in the spectral response of the nonpolychromator optical components. This includes plasma facing components that are difficult to access and which may be damaged during operation.[9,10] However, the pulsed light source used for this calibration has an inconsistent pulse to pulse power output and an inconsistent maximum power output in the spectral region of interest. This makes the needed measurements very difficult. In addition to this to get the same resolution as the dc measurement the procedure is tedious and time consuming. A different light source such as a supercontinuum light source used for spectral calibrations on reversed field experiment (RFX) (Ref. 11) could solve these problems but is currently not an option for this system. Because of this the pulsed *in situ* calibration is only done before and after long periods of Thomson scattering operation when the first element of the collection lens has been exposed to plasma and at much lower spectral resolution.

As with the gain and noise enhancement calibrations discussed above the absolutely calibrated APD used as a reference detector is also used in these calibrations. This allows for a simpler setup and an easy comparison between the dc and pulsed *in situ* measurements. The dc calibration is also used to find a relative QE curve for the APD, which allows for the separation of the QE and transmission of the instrument function.

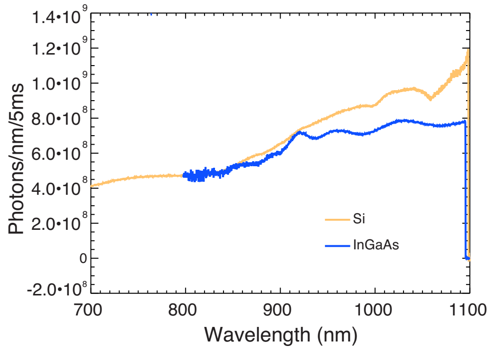

FIG. 4. (Color online) Number of photons collected as a function of wavelength in 5 ms period for Si and InGaAs detectors.

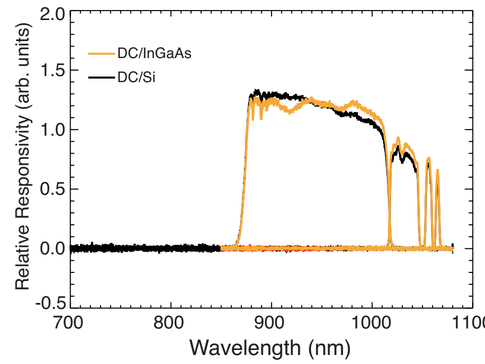

FIG. 5. (Color online) Instrument function, which is the product of transmission and QE, for a four channel polychromator.

A. DC measurement of polychromator instrument function

The first step in the dc measurement serves two purposes: to characterize the dc light source used in the calibration and to obtain a relative spectral calibration between the APD detector and the absolutely calibrated detectors.

The light source used is a quartz-halogen dc light source. The output of the light source is coupled to the monochromator. The monochromator is scanned at a constant rate from 700 to 1100 nm. The light source has a relatively constant output in this range. The output of the monochromator is coupled to a fiber optic that is coupled directly to each of the three detectors: The absolutely calibrated APD in Sec. III B biased and amplified in the normal way and InGaAs and Si absolutely calibrated detectors, not biased, amplified by a 3.3×10^7 transimpedance voltage amplifier. Each detector was illuminated in turn, then the process was repeated. This was done to check two things: that the output from the light source did not change over time and that reinsertion of the fiber into the SMA mount did not change the amount of collected light. At the end of the scan, >1080 nm, the light source was blocked allowing the offset to be measured for each detector. After this a new fiber was connected to each of the polychromators in turn and the signal from the four (or eight) channels was recorded.

The spectral response of the InGaAs and Si detectors is known. This is used to determine the number of photons as a function of wavelength shown in Fig. 4.

There are some important differences between the two detectors, even in the regions where the responses for both detectors overlap and should be trustworthy. Perhaps this is due to differences in the absolute calibration setup for the two detectors, differences in the absolute calibration process, and use (collimated versus diverging light sources) or changes that have occurred since the detectors were calibrated. This disagreement is currently unresolved. The answer given by the Si detector is the one used in the following calculations for two reasons: (1) It has a good wavelength response over the entire region of interest for the eight channel polychromators, and (2) its response closely resembles that of the APDs.

The instrument function for a given wavelength, i, spectral channel, j, and polychromator, k, is $R_{i,j,k} = N_{\mathrm{abs}_i}/N_{\mathrm{APD}i,j,k}$. N_{abs} is the number of photons collected by the absolute detector and $N_{\mathrm{APD}_{i,j,k}} = S_{\mathrm{APD}i,j,k}/G_{\mathrm{APD}_{j,k}}$. Figure 5 compares the instrument functions for a polychromator using the Si and InGaAs detectors. Again, for the reasons above, the instrument function using the Si detector is chosen.

The instrument function is a product of the optical transmission of the polychromator system, $T_{i,j,k}$, and the QE of the APDs, $R_{i,j,k} = T_{i,j,k}\mathrm{QE}_i$.

The gain of the APD detector, which is a combination of QE (a function of wavelength) and APD amplifier gain (a constant of wavelength), is only measured at 1020 nm (see Sec. III). As it has been applied thus far the dependence on wavelength has been ignored. However, using the absolutely calibrated APD these two components can be separated. This is an important measurement because the statistical photon noise analysis is tied to the ratio of F/QE (see above discussion). F, a wavelength independent number, and QE cannot be measured independently and currently their ratio is only measured at one wavelength. The measurement of a relative QE curve of the APD can be applied to get F/QE as a function of wavelength and therefore improve uncertainty analysis.

A relative spectral calibration between the absolute APD detector and the absolutelycalibrated detectors is made to get the relative quantum efficiency, $\mathrm{QE}_i^* = S_{\mathrm{absAPD}_i}/G_{\mathrm{absAPD}}N_{\mathrm{abs}_i}$.

This is not absolute because the QE at 1020 nm is coupled to G_{absAPD}. Figure 6 shows $S_{\mathrm{absAPD}_i}/G_{\mathrm{absAPD}}$ and the QE* curve.

A purely optical transmission function can now be found $T_{i,j,k} = R_{i,j,k}/QE_i^*$. The next section describes how this optical transmission is found *in situ*.

B. *In situ* spectral calibrations

These calibrations are made possible by two key pieces of equipment: the ISIS and a tunable wavelength laser or optical parametric oscillator (OPO). Similar calibrations have been done before using an OPO,[12] but with this coupled to the ISIS this is a unique *in situ* calibration. The OPO, which is located in a separate laboratory from MST, is coupled to an ISIS with two fiber optic outputs: one to the calibrated reference APD on the cooling block and one to the ISIS inserted to a depth corresponding to the first polychromator to be calibrated. The OPO is pulsed at eight key wavelengths (740, 790, 830, 880, 950, 990, 1025, and 1056 nm). At each of these wavelengths 500 OPO pulses of varying

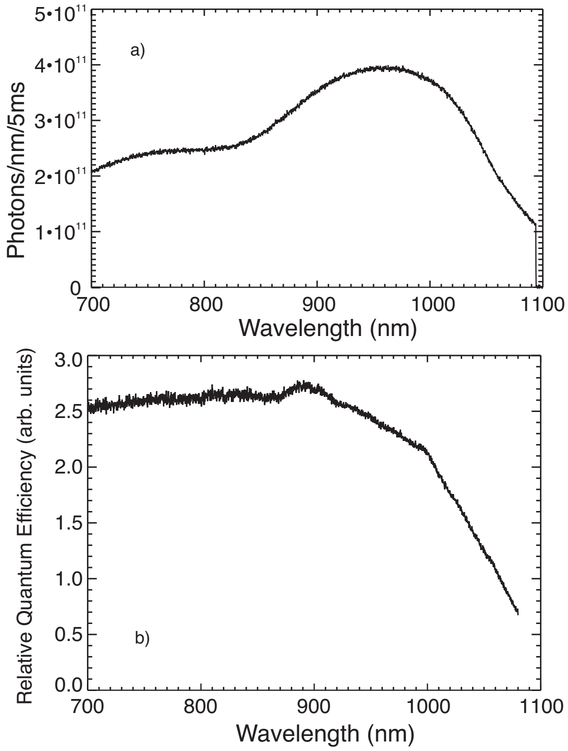

FIG. 6. (a) Number of photons collected as a function of wavelength in a 5 ms period for the absolute APD detector. (b) Relative QE of the APD.

height are recorded by the calibrated reference APD and the corresponding polychromator APDs. These pulses are filtered for good pulses (i.e., light level above noise, not saturated, etc.). If the number of good pulses exceeds a threshold value then a line is fitted through $N_{\mathrm{APD}_{\mathrm{abs}}}$ vs N_{APD} data taking the slope to be the transmission. This is then compared to the dc transmission measurement. This measurement is made initially as a baseline measurement and then again after the first element of the collection lens has been exposed to plasma for long periods of time. If a significant change in spectral transmission is seen the first element of the collection lens can be replaced. Figure 7 shows a comparison between these measurements. Even though a damaged lens has decreased in overall transmission this is not a function of wavelength and does not affect temperature measurements. However, the signal to noise ratio is increased and future density measurements must take this drop into account.

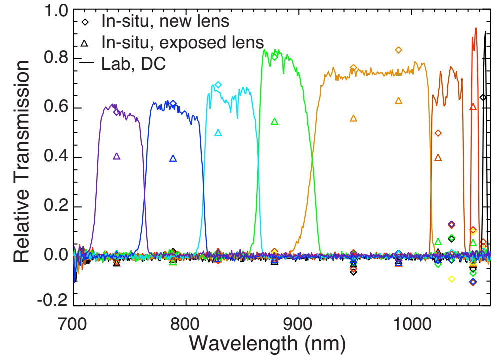

FIG. 7. (Color online) Transmission for an eight channel polychromator measured in the laboratory with a broad dc light source (solid line), measured *in situ* with a lens that has not been exposed to plasma using the OPO light source (diamonds), and measured *in situ* after the lens has been exposed to the plasma for several weeks of operation (triangle). Note that the drop in transmission does not have a strong wavelength dependence. The output of the OPO decreases above 980 nm and the measurements become unreliable.

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