Fusion Energy Division

CALIBRATION OF THE ORNL TWO-DIMENSIONAL THOMSON SCATTERING SYSTEM

C. E. Thomas, Jr.
E. A. Lazarus
R. R. Kindsfather
M. Murakami
K. A. Stewart

Date Published - October 1985

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400
## Contents

**Abstract** iii

**Introduction** 1

A. Purpose 1
B. System description 1
C. Thomson scattering calibrations 7

**I. Wavelength Calibration** 9

A. Wavelength calibration hardware 9
B. Software and procedures 12
C. Errors 13

**II. Stability Checking and Gain Calibration with Light-Emitting Diodes** 17

A. General description 17
B. Statistics for gain calibration 19
C. Technical problems 22
D. Experimental data 23

**III. Channel Efficiency Measurements** 29

A. Relation of channel efficiency constants to scattering theory 29
B. Measurement of relative channel efficiency constants 32
C. Some statistics for channel efficiency measurements 33
D. Calculation of spectral intensity 35
E. Gain calibration with the spectral source 36
F. Channel efficiency measurement hardware and procedures 36
G. Channel efficiency data 40
ABSTRACT. A unified presentation of the calibrations needed for accurate calculation of electron temperature and density from Thomson scattering data for the Oak Ridge National Laboratory two-dimensional Thomson scattering system (SCATPAK II) is made. Techniques are described for measuring the range of wavelengths to which each channel is responsive. A statistical method for calibrating the gain of each channel in the system is given, and methods of checking for internal consistency and accuracy are presented. The relationship between the constants describing the relative light collection efficiency of each channel and plasma light-scattering theory is developed, methods for measuring the channel efficiencies and evaluating their accuracy are described, and the effect on these constants of bending fiber optics is discussed. The use of Rayleigh or Raman scattering for absolute efficiency (density) calibration, stray light measurement, and system efficiency evaluation is discussed; the relative merits of Rayleigh vs Raman scattering are presented; and the relationship among the Rayleigh/Raman calibrations, relative channel efficiency constants, and absolute efficiencies is developed.
INTRODUCTION

A. Purpose

Most of the discussions of Thomson scattering systems available in the literature\textsuperscript{1-23} are concise and are not intended as guides to system calibration. This work has multiple purposes. First, it serves as a detailed record of the procedures used on a multipoint Thomson scattering system for reference by other workers. Second, genuinely new techniques are presented: a unique combination of a shutter synchronized with a chopper to give very short (100-\textmu s) exposures to the photomultipliers during calibration at arbitrary rates less than 1 Hz is described; statistical methods for evaluating the accuracy of various calibrations are presented; a light-emitting diode (LED) system for checking system stability is described; and the relationship among the channel efficiency constants, Rayleigh or Raman scattering, and plasma light-scattering theory is developed. Finally, a unified description of the calibrations necessary to successfully operate a Thomson scattering temperature/density measurement system is presented.

B. System description

The two-dimensional (2-D) Thomson scattering system, SCATPAK II, has operated on the Impurity Study Experiment (ISX) tokamak since March 1982. Considerable effort has gone into calibration so that the system's ability to make a 2-D map of the plasma density and temperature could be fully used. SCATPAK II is briefly described to make the calibration procedures comprehensible. Detailed descriptions are given elsewhere.\textsuperscript{24-26}
The system is shown in Fig. 1. Two lasers are located in a temperature- and humidity-controlled clean room on the floor below ISX. One is rated at 12 J and the other at 30 J; both have an intrinsic divergence of less than 300 μrad and a pulse width between 20 and 30 ns. The lasers are controlled by a VAX 11/780 computer (time-shared) through a fiber-optic link connected to a CAMAC crate in the laser room. A ratiometer measures the ratio of the energy that can be focused on target to the total laser energy, and a joule-meter measures the energy. The reflection from the uncoated window into the ISX vacuum vessel is directed into the joule-meter. Two optical (fiber-optic) signals from the laser room provide gates to the data.

FIG. 1. Schematic outline of the ORNL two-dimensional Thomson scattering system.
acquisition electronics. One signal, derived from the laser electronics 5 \( \mu s \) before the laser fires, gates on the photomultiplier tubes (PMTs). The other signal is obtained from an optical fiber placed where it views the oscillator/amplifier rods of the laser. Stray light from the laser pulse travels up this fiber and drives an amplifier system gating on the charge-integrating analog-to-digital converters (ADCs) that acquire the scattered light signal from the PMTs.

The laser beam enters the ISX vacuum vessel through a window on an extension approximately 4 m below the centerline of ISX. The vacuum extension is extensively baffled to provide stray light rejection. The beam exits the tokamak through another long extension and a Brewster window into a Brewster angle beam dump made of red-absorbing blue glass.

The final optics that reflect and focus the laser beam into the tokamak are mounted on a mill table translated under computer control. The beam can be scanned in major radius from 0.83 to 1.23 m. The centerline of ISX is at 0.93 m, and the plasma radius is 0.27 m.

The light collection optics and electronics are mounted on a large translating optical table; its movement is locked to the lower table. The electronics are enclosed in a temperature-controlled screen room mounted on the table. The two tables were aligned to move parallel to one another within \( 3 \times 10^{-5} \) m in 0.30 m when SCATPAK II was installed on ISX.

As illustrated in Fig. 2, two lenses mounted on the upper translating table view the scattering volume through two vacuum windows. The lenses focus the scattered laser light on two spherical image planes with a nominal magnification of 0.5. Fiber-optic bundles
FIG. 2. Electronics and data-flow block diagram for SCATPAK II.

1.6 mm thick and 12.5 mm high then conduct the scattered light to 15 spectrometers. One fiber-optic bundle connects each spectrometer to the image plane. A filter of 1.0% (by weight) Cr$_2$O$_3$-doped ruby is placed in front of each fiber to attenuate stray laser light. The ruby filters are anti-reflection coated and have a transmittance greater than 98% for wavelengths longer than 7000 Å and a transmittance of 11% at 6943 Å. There are 36 slots in the image plane into which the spectrometer input fibers can be inserted so that the scattered light from 15 positions along a vertical chord in the plasma can be analyzed after every laser pulse. The laser can be fired once during a discharge, since its repetition rate is 1 min and the tokamak shots are ≈0.3 s.
Three types of spectrometers (same physical design, different gratings) are used to analyze the scattered light into its spectral components. The spectrally analyzed light is transmitted from the exit plane of each spectrometer by fiber-optic bundles to PMTs with extended red GaAs photocathodes (Hamamatsu model R-943-03) and quantum efficiencies greater than 9% even beyond 8000 Å. The red-shifted part of the Thomson spectrum is used.

The designs for the three types of gratings are shown in Fig. 3. The channel center wavelength and channel width are chosen so that the spectrometers will measure temperature and density in overlapping temperature ranges. The "extra-low-temperature" spectrometers cover the range from 2 eV to 200 eV; the "low-temperature spectrometers," 10 eV to 1000 eV; and the "high-temperature spectrometers," 20 eV to 2000 eV.

The data acquisition system (Fig. 2) is conceptually simple but is replicated more than 100 times, once for each PMT. After the spectrally analyzed light is detected and highly amplified by the PMT, it is attenuated by a computer-controlled attenuator, to a level that will not saturate the charge-integrating ADCs. The PMT is gated on for only 3.6 μs so that it can be operated at high gain without charge depletion and without exceeding the duty cycle of the associated electronics. After passing through the attenuator, the signal is split. One half is fed directly into a charge-integrating ADC gated on for 100 ns with the gate centered around the scattered light signal. The other half is fed into a 200-ns delay line and then into a charge-integrating ADC. Both ADCs are gated simultaneously, so that one measures the scattered light plus any background light emitted by
FIG. 3. Spectrometer schematics. Three types of spectrometers are used on SCATPAK II: an extra-low-temperature design, a low-temperature design, and a high-temperature design. The input slit to the spectrometer is the 1.6-mm-wide by 15-mm-high fiber-optic cable from the image plane. The exit planes are also formed by fiber-optic cables, which lead to the individual PMTs, one tube for each wavelength channel.
the plasma, and the other measures the background light emitted by the plasma 200 ns before the laser was fired (this side has the delay line; the light from the laser firing would not arrive till 200 ns later). This allows the background light level to be subtracted from the scattered light signal.

C. Thomson scattering calibrations

Four calibrations are necessary before electron temperature and density are calculated from the scattering data.

1. Wavelength calibration characterizes the response of each channel to different wavelengths of light. The spectral width, central wavelength (response weighted), and the shape of the channel response vs wavelength are measured.

2. Channel efficiency calibration measures the light detection efficiency of the channels of a single spectrometer relative to one another.

3. Gain calibration measures the gain (in bits per photon) of each channel. These data are used to calculate the number of photons detected by a particular scattering channel, so that the data may be correctly weighted when fitting the electron temperature and density.

4. Rayleigh or Raman scattering is necessary to measure either the absolute efficiency of every channel, so that an absolute density can be calculated, or to calculate the efficiencies of the spectrometers relative to each other, so that the chordal
density can be integrated and normalized to an interferometer value to provide an absolute density calibration.

All four calibrations are done under computer control. The calibration procedures and their theoretical basis are presented. Wavelength calibration is described in Sec. I. The use of an LED system for checking system stability is described in Sec. II, along with one procedure for gain calibration. The normally used procedure is described in Sec. III, which also contains a description of channel efficiency measurement. Rayleigh/Raman scattering is discussed in Sec. IV, which is followed by a summary.
I. WAVELENGTH CALIBRATION

Wavelength calibration characterizes the relative response of each spectrometer channel to different wavelengths of light. It is performed first since the other calibrations require a knowledge of the position and shape of the channel responses. This measurement is integral to data analysis on SCATPAK II, and the calibration data are stored in computer files for use in electron temperature and density calculations.

A. Wavelength calibration hardware

Figure 4 is a diagram of the wavelength calibration hardware. The light source is a 150-W, quartz-iodine, tungsten filament projection lamp, followed by 25 mm of BK-7 glass to prevent damage to the optics. Following the heat-absorbing glass is a lens to image the lamp on the monochromator input, and between the lens and the monochromator is an ultraviolet cutoff filter (Schott type GG yellow glass) to prevent multiple-order dispersion. An atomic line source lamp can be swung into place to calibrate the wavelength drive of the monochromator.

The monochromator is a 0.25-m Jarrell Ash, with a dispersion of ≈33 Å/mm. The input and output slits currently used are both 0.25 mm. A stepper motor drives the monochromator with a flexible toothed belt, and the gearing is set so that one step corresponds to a change in the output wavelength of 0.5 Å. The computer interface to the Joerger stepper motor controller is through CAMAC. The monochromator output goes directly into the input fiber of the spectrometer being calibrated (the spectrometer input fibers are readily unplugged from the image...
FIG. 4. Wavelength calibration system schematic. A 150-W tungsten filament projection lamp is wavelength analyzed with 11-Å resolution by a 0.25-m monochromator. The monochromator drive is driven by a stepper motor under computer control. The input fiber to the spectrometer being calibrated is mounted far enough behind the monochromator exit slit so that it is filled with light. Two pulse generators, one free-running (period set manually) and the other triggered by the first, trigger a shutter and the computer data acquisition system. The shutter reduces the average light on the PMT being calibrated. The Thomson scattering data acquisition system is used to acquire data for this calibration.
plane and plugged into the fiber holder on the output of the wavelength calibration system). The input fiber is set back from the monochromator exit slit so that the monochromator light output fills it. Even though the fiber output is "incoherent" (i.e., random; not imaged) with respect to the input, we feel that it is good practice to fill an area of the input fiber at least as large as that filled by the image of the scattered laser light.

A shutter between the focusing lens and the monochromator input reduces the light load on the PMT, thus protecting it from the fatigue that can be caused by overexposure.\textsuperscript{27} The shutter is open for \(\approx 5\) ms during each data acquisition. We estimate from the known photon flux and the data of Ref. \textsuperscript{27} that the PMT response changes no more than 1\% during calibration.

Wavelength calibration data acquisition uses the Thomson scattering data acquisition system,\textsuperscript{26} slightly modified. Instead of being triggered by the fire signal from the laser system, the PMTs are gated on by a delayed pulse generator triggered from the shutter-open pulse. The delayed pulse passes through a CAMAC pulse generator armed by the computer when it finishes acquiring data from the last shot. The gated integrators are also gated by the CAMAC pulse generator, 1\,\mu s after the PMT gate, and the integrator gate pulse is stretched to 1\,\mu s to give better photon statistics.

Figure 5 shows the instrument response function of the wavelength calibration system found by replacing the projection lamp with a mercury lamp and scanning the monochromator around the \(5461\text{-Å} \) line. The width of this line is \(\ll 1\text{ Å} \) (FWHM). The instrument width is \(\approx 11\text{ Å} \) FWHM. The output of the monochromator is coupled through a fiber to a
FIG. 5. Example of monochromator calibration data. The tungsten lamp is replaced with a mercury lamp, and the 5461-Å line is used to check the wavelength drive calibration and wavelength resolution.

B. Software and procedures

Wavelength calibration is performed interactively using a Tektronix 4006 graphics terminal (or equivalent) and menu-driven software. First the monochromator calibration is checked. Then channel 1 of the spectrometer being calibrated is iteratively scanned and the grating adjusted so that the center of the channel 1 response curve is correctly placed. The operator then scans each channel,
setting program parameters to give the desired accuracy. The available parameters are initial and final wavelength, the distance between wavelength points, and the number of data shots at each wavelength. A good calibration is one for which the uncertainty in the channel center response is less than 3% (due to photon statistics) and for which the response has gone to zero before the beginning and end of the scan. The spacing between wavelength points is typically 5 Å, and the operator chooses the number of shots at each point to give the desired 3% uncertainty in channel center response. Equation (3.19) is used to evaluate the number of shots necessary.

In addition to scanning the wavelength response for each channel, the operator fits a function consisting of six line segments to it. The coordinates of the data points corresponding to the ends of the line segments are stored in the "spectrometer file" on the computer, along with the wavelength of the channel center and the FWHM in wavelength of the channel response. Figure 6 is a sample calibration of a five-channel spectrometer. The solid lines with error bars [Fig. 6(a)] correspond to the data, and the dotted lines correspond to the line segments that the operator fitted to the data.

C. Errors

Estimating the error in electron temperature caused by statistical and systematic errors in measurement of the wavelength response functions is not trivial. The error in the calculated electron temperature will be a function of the error in the response measurement as a function of wavelength and electron temperature. Once the error is estimated for a given channel and electron temperature, it must be
FIG. 6. Wavelength calibration data for spectrometer 2. The channel response vs wavelength is shown for all five channels of this low-temperature spectrometer. Channel 1 is shown twice, (a) with typical error bars and (b) with dotted lines (as the other channels) showing the line-segment function fitted to the channel shape by the operator. The channel responses are normalized to have an integral of one when used.
correctly averaged over the channels with signal. This leads to a problem that is not tractable analytically. It is possible to make a simple estimate of the error in temperature caused by the calibration errors. Consider a single channel, and assume that the errors in measurement can be transformed into an equivalent error in the channel center wavelength. Let the equivalent error be \( \delta \lambda \). Then it can be shown [starting with Eq. (3.4)] that the error in the electron temperature is \( \frac{\delta T_e}{T_e} = 2\frac{\delta \lambda}{\Delta \lambda} \), where \( T_e \) is the electron temperature, \( \delta T_e \) is the error in temperature, and \( \Delta \lambda \) is the wavelength of the channel center minus the incident laser beam wavelength. For a 3\% uncertainty in the channel response function, and a 33-A channel width, we estimate the uncertainty in the channel center as \( \delta \lambda \sim 1 \) Å. Then if \( \Delta \lambda \) is 59 Å (consider a low-temperature spectrometer, Fig. 3) the uncertainty in \( T_e \) will be \( \frac{\delta T_e}{T_e} = 3.4\% \). The expected error goes down with the square root of the number of channels having significant signal; for channels with equivalent values of \( \delta \lambda \), channels farther from the laser line will have a smaller uncertainty. However, there is a characteristic temperature for each channel where the added channel width caused by the monochromator instrument function will dominate. Considering all these effects, 3\% should be a high estimate of the error in \( T_e \) due to wavelength calibration.
II. STABILITY CHECKING AND GAIN CALIBRATION WITH LIGHT-EMITTING DIODES

A. General description

Light-emitting diodes placed in each spectrometer can be used to calibrate the gain of the PMT, amplifier, and digital integrator electronics (refer to Fig. 2). The LEDs also verify the operational status of the electronic systems. The LED driver circuits were designed by G. R. Dyer of Oak Ridge National Laboratory (ORNL), and the LED output is demonstrated to be reproducible to better than 1%.

In this section we discuss gain calibration as performed with the LEDs. The method normally used is discussed in Sec. III, and the accuracy of the techniques is compared. The gain calibration procedure is based on a well-known property of systems that obey Poisson statistics. The statistical method used is presented in Sec. II.B.

We now develop criteria for using the LEDs without saturating the electronics. The LEDs emit a ~20-ns pulse of photons. Some percentage of these photons are incident on the fibers in the exit plane of the spectrometer, and an even smaller percentage are detected by the PMT (4% loss at each fiber surface, 70% fiber packing, 8% loss at PMT glass, and ~9% quantum efficiency of PMT, for about 4.6% detection efficiency). The PMT signal is amplified a factor of 10 and then attenuated enough to prevent saturation of the gated integrator. The integrator is gated on for a period of ~100 ns, with the LED pulse centered in the gate. The integrator also converts the signal to bits for the computer. The 10x amplifier saturates for signals greater than
-0.5 V, and the integrator saturates for charges greater than 500 pC. We define the following quantities:

\[ \tau_p = \text{FWHM of incident light pulse}, \]

\[ V_i^M = \text{maximum allowable input voltage to 10x amplifier}, \]

\[ A = \text{attenuation of attenuator} = \frac{\text{voltage in}}{\text{voltage out}}, \]

\[ R_I = \text{input resistance of attenuator}, \]

\[ B^M = \text{maximum allowable signal, in bits, out of integrator}, \]

\[ \alpha = \text{conversion constant (bits/picocoulomb) of gated integrator} = 1940 \text{ bits/500 pC.} \]

Since the attenuator follows the preamplifier (see Fig. 2), it is possible to saturate the preamplifier without saturating the integrator. The maximum allowable attenuation without saturation of the preamplifier (assuming the integrator is not saturated) is

\[ A^M = \frac{10V_i^M\tau_p\alpha}{R_I(2)B^M}. \quad (2.1) \]

Equation (2.1) models the light pulse as triangular in time; the factor of 2 in the denominator results from splitting the signal for the background reading. For the values \( V_i^M = 0.5 \text{ V}, \tau_p = 20 \text{ ns}, \alpha = 3.88 \text{ bits/pC}, R_I = 50 \Omega, \) and \( B^M = 1900 \text{ bits}, \)
If the pulses are not attenuated more than 3 dB and the integrators are not saturated, then none of the electronic components will be saturated. During gain calibration, care must be taken to allow at least 3σ of variation in the integrator signal (see Sec. II.C).

B. Statistics for gain calibration

The statistics that justify the gain calibration procedure are presented here. We define the following:

\[ B^K = \text{The absolute signal, in bits, from the integrator of the} \]
\[ \quad \text{jth channel of the ith spectrometer on the kth shot} \]
\[ \quad \text{of any procedure.} \]
\[ P = \text{The average reading from integrator } i,j \text{ when it is gated on} \]
\[ \quad \text{but no signal is applied to its input (pedestal).} \]
\[ \sigma_P = \text{The standard deviation of } P. \]
\[ G = \text{The total system gain (bits/photoelectron) for} \]
\[ \quad \text{spectrometer } i, \text{ channel } j. \]
\[ N^K = \text{The number of photons collected by channel } j \text{ of spectrometer} \]
\[ \quad i \text{ for event } k. \]
\[ N_{\text{tot}}^k = \text{The total number of photons emitted during event } k. \]
Then the signal in bits $S^k$ for spectrometer $i$, channel $j$, and event $k$ is

$$S^k = B^k - P,$$  \hspace{1cm} (2.3)

and the average experimental signal for $M$ events (the source is pulsed $M$ times) is

$$\bar{S} = \frac{1}{M} \sum_{k=1}^{M} S^k.$$ \hspace{1cm} (2.4)

The experimental standard deviation of $S^k$ is

$$\langle \sigma_S \rangle^2 = \frac{1}{M - 1} \sum_{k=1}^{M} [(S^k)^2 - (\bar{S})^2].$$ \hspace{1cm} (2.5)

The expression for the gain of the given channel is

$$G = \frac{\langle \sigma_S \rangle^2}{\bar{S}}.$$ \hspace{1cm} (2.6)

This follows for Poisson statistics because the average signal equals the gain times the average number of photons, whereas the standard deviation equals the gain times the square root of the average number of photons. This is a well-known property of systems that obey Poisson statistics and is true if $N_T^k \gg N^k$ and if all quantities are constant except the statistical variation of photon flux.
Once $G$ is known, we wish to know its error. The expected standard deviation of $G$ (assuming photon statistics is the only source of variation) is

$$
(\sigma_G)^2 = (\sigma_\sigma)^2 \left( \frac{\partial G}{\partial \sigma_S} \right)^2 + (\sigma_S)^2 \left( \frac{\partial G}{\partial S} \right)^2,
$$

(2.7)

where $\sigma_S$ is the standard deviation of $S$ and $\sigma_\sigma$ is the standard deviation of $\sigma_S$. For Poisson statistics,

$$
(\sigma_G)^2 = \frac{4\sigma_\sigma^2}{M^2} + \frac{G^2}{NM},
$$

(2.8)

where $N$ is the average number of photons per measurement and $M$ is the total number of measurements.

Equation (2.8) allows the nonreproducibility of the system (due to sources other than photon statistics) to be measured. It is easy to show that for small photon fluxes [see Eq. (2.11)] $\sigma_S$ is dominated by photon statistics. As the number of photons per event $N$ becomes very large, the variance in other variables (here assumed constant) dominates. By making several sequences of $M$ measurements at varying photon fluxes, and noting where the experimental standard deviation of $G$ starts to differ substantially from that predicted by Eq. (2.8), we can measure the level of nonreproducibility of the system. For SCATPAK II, the system nonreproducibility is approximately 1%.

It is appropriate to mention significant digits. If these formulas are taken literally, they imply that the uncertainty in the
average measurements can be made infinitely small. However, the
calibrations on our measuring instruments are generally not better than
1%. Calibration to 1% is adequate for all of the measurements
performed with SCATPAK II to date and seems a reasonable goal.

C. Technical problems

Possible technical problems with gain calibration relate to
Eq. (2.6). If there is some source of \( (\sigma_s)^2 \) other than statistical
fluctuations in the number of photons collected, then Eq. (2.6) is
wrong. Possible sources of fluctuation are:

1. variations in the source intensity,
2. variations in photocathode collection efficiency with light
   intensity or time (photocathode fatigue),
3. variations in the PMT gain with temperature, and
4. a wide Gaussian spread in electrons/photoelectron from the
   PMT.

If, for instance, there is a fractional variation \( \gamma \) in the source
intensity, \( \sigma_N^2 = (\gamma N_T^k)^2 \), then

\[
(\sigma_s)^2 = \gamma^2 (\bar{S})^2 + G \bar{S} .
\]  

(2.9)

Solving Eq. (2.9) for \( G \) gives

\[
G = \frac{(\sigma_s)^2}{\bar{S}} - \gamma^2 \bar{S} .
\]  

(2.10)
Thus, if \( Y^2 S > G \), the error in estimating \( G \) using Eq. (2.6) is more than 100%. If Eq. (2.6) is to be correct within some fraction \( f \), then

\[
Y \leq \left( \frac{fG}{S} \right)^{1/2}.
\]

(2.11)

Since \( G/S \) is just \( 1/N \), Eq. (2.11) demonstrates that the allowable variation in quantities other than photon flux becomes large as the number of photons per event becomes small.

D. Experimental data

The data presented here relate to system stability as measured with the LEDs. Gain data are presented in Sec. III.

The LED system was first used to test for change in the response of the system with temperature. All of the data acquisition electronics are in a temperature-controlled screen room; nevertheless, it was suspected that the system response might change as the electronics warmed up. In particular, the response of the PMTs, which have limited air flow due to the magnetic/electrostatic shielding and significant heat dissipation in the high-voltage divider string, preamplifier, and gating circuits in their bases, might change. From a cold start, the response of the data acquisition electronics system changed 5 to 10% over 8 h (see Fig. 7), after which it stabilized. This change probably resulted from the temperature coefficient of the PMT gain, which is about \(-0.004\) per degree centigrade, and from any temperature coefficient of the resistor string and preamplifier.
FIG. 7. Typical response vs time of the data acquisition electronics when subjected to a low photon flux from a cold start. Response decreases slightly as the system reaches thermal equilibrium. PMT temperature coefficient is believed to be the chief cause.

The LED system was next used to test for change in response at high photon fluxes. Figure 8 shows the change in a typical tube vs time at a high photon flux. These data were taken after the system had warmed up in the dark for 12 h. The LEDs were then operated at a rate of 500 shots per minute for 6 h, with approximately 370 photons detected per shot in the channel displayed. Thus, this channel was detecting $\approx 3 \times 10^3$ photons/s, and the response decreased approximately 6% during the test. This result was repeated using the channel efficiency calibration system. Figure 8 is not inconsistent with the data of Ref. 27, and we believe that the response change is caused by fatigue of the GaAs photocathodes.
Figure 8 shows the system response at a low photon flux (approximately the same flux as Fig. 7) as measured with the LEDs. The system was warmed up in the dark for 8 h, and then the LEDs were run at 1 Hz, \( \approx 100 \) photons detected per shot, for 12 h. The average response of the two channels displayed changed less than 1% during the run. Each point is the signal in bits, averaged over 1 h. The expected standard deviation is approximately 0.5%, which equals the 0.5% observed. A longer run of \( 2.6 \times 10^5 \) shots, taken at 10 shots per
FIG. 9. Typical response vs time of PMTs subjected to low photon flux after an 8-h warmup in the dark. Any change in response is less than the uncertainty due to photon collection statistics (<1%).

second and 10 to 20 photons per shot, showed a standard deviation in the average gain of ≈1%, as opposed to the ≈0.3% predicted by Eq. (2.8). This result is the basis for the statement that the system nonreproducibility is on the order of 1%.

The final use of the LED system is shown by Fig. 10, which displays the daily change in absolute response of all five channels of spectrometer 1. Each point represents an average of 1000 shots with about 10 photons detected per shot. The expected change was σ = 1%, and this is approximately what was achieved. This system has proved useful for detecting bad electronic components and PMTs.
FIG. 10. Typical daily changes in system gain for the five channels of spectrometer 5. The expected standard deviation was 1%. Each unit of average change (the y-axis of the graph) represents a 100% change in gain.
III. CHANNEL EFFICIENCY MEASUREMENTS

A. Relation of channel efficiency constants to Thomson scattering theory

We establish the relationship between the channel efficiency constants and the theoretical expression for the radiation scattered into each channel.

For low $T_e$ ($T_e$ in eV) and scattering perpendicular to the incident polarization, the energy scattered per unit wavelength per unit solid angle is given by

$$E_s(\Delta \lambda) = \frac{E_I r_0^2 n_e L c}{2\pi^{1/2}\sin(\theta/2)a_{\lambda I}} \exp \left[ \frac{-c^2(\Delta \lambda)^2}{4a^2\lambda_I^2\sin^2(\theta/2)} \right],$$

where

- $E_s(\Delta \lambda)$ = energy scattered at $\Delta \lambda$ (J·m·sr⁻¹)
- $E_I$ = incident energy (J)
- $r_0$ = classical radius of electron (m)
- $n_e$ = electron density (m⁻³)
- $L$ = length of scattering volume (m)
- $\theta$ = angle between incident and scattered radiation (rad)
- $c$ = velocity of light (m/s)
- $a$ = electron thermal velocity = $[(2qT_e)/m_e]^{1/2}$ (m/s), with $q$ the electron charge (C) and $m_e$ the electron mass (kg)
- $\lambda_I$ = incident radiation wavelength (m)
- $\Delta \lambda$ = difference of scattered and incident wavelength = $(\lambda_s - \lambda_I)$.
For an interval of wavelength $\delta \lambda$, centered about $\Delta \lambda_0$ and solid angle $\Delta \Omega$, the total scattered energy is:

\[ \phi = \frac{E_{\text{sc}}^2 n_e L c}{2 \pi^{1/2} \sin(\theta/2) a \lambda_I} \exp \left[ \frac{-c^2 \Delta \lambda_0^2}{4 a^2 \lambda_I^2 \sin^2(\theta/2)} \right] \]  

(3.2)

where $\phi$ is the energy scattered in $\delta \lambda$, $\Delta \Omega$ and the integrals have been approximated by a central value times the integration interval. The errors introduced by using the low-temperature expression and approximating the integrals are corrected in the calculation of temperature and density from Thomson scattering data. If we had "perfect" systems for collecting and detecting photons (consisting of lossless lenses, spectrometers, intermediate optics, and PMTs) the signal detected in a channel $j$ centered a distance $\Delta \lambda_j$ from the incident wavelength, having channel width $\delta \lambda_j$ with solid angle $\Delta \Omega_i$, would be (for spectrometer $i$)

\[ S_{ij} = \frac{\phi_{ij} G_{ij}}{h \nu_{ij} A_{ij}} \]  

(3.3)

where $G$ and $A$ are as defined in Sec. II, $h$ is Planck's constant, and

\[ \nu_{ij} = \text{frequency of channel center} = \frac{c}{(\lambda_I + \Delta \lambda_j)} \]  

In Eq. (3.3) the approximation has been made that all photons in channel $j$ have the energy of the channel center. The error due to this is $\approx 1\%$ for SCATPAK II. Using channel $j$ and spectrometer $i$ in Eq. (3.2) gives:
\[ \frac{\phi_{ij}}{\delta \lambda_{ij} \Delta \Omega_i} = \frac{E_{\text{fr}}^2 n_e L_i c}{2 \pi^{1/2} \sin(\theta/2) a \lambda_i} \exp \left[ \frac{-c^2 \Delta \lambda_{ij}^2}{4 a^2 \lambda_i^2 \sin^2(\theta/2)} \right]. \quad (3.4) \]

For a real system we introduce a collection efficiency \( R_{ij} \), which accounts for all losses. Then Eq. (3.3) becomes

\[ S_{ij} = \frac{\phi_{ij} R_{ij} G_{ij}}{h \nu_{ij} A_{ij}} . \quad (3.5) \]

Channel efficiency calibration must relate Eq. (3.5) to Eq. (3.4); that is, we seek a constant \( C_{ij} \) such that

\[ C_{ij} A_{ij} S_{ij} = \frac{\phi_{ij}}{\delta \lambda_{ij} \Delta \Omega_i L_i}. \quad (3.6) \]

Using Eq. (3.5) in Eq. (3.6) gives

\[ C_{ij} = \frac{h \nu_{ij}}{\delta \lambda_{ij} \Delta \Omega_i R_{ij} G_{ij} L_i}. \quad (3.7) \]

The electron temperature is independent of \( \Delta \Omega_i \), so if only a relative density from one shot to the next is wanted, relative efficiency constants (for spectrometer \( i \)) can be defined:

\[ C_{ij}' = \frac{C_{ij}}{C_{iM}^{'}} , \quad (3.8) \]
where $M$ is some arbitrary but specified channel of spectrometer $i$. Then, using Eq. (3.7) in Eq. (3.8),

$$
C_{ij} = \frac{\nu_{ij} \delta \lambda_{iM} R_{iM} G_{iM}}{\nu_{iM} \delta \lambda_{ij} R_{ij} G_{ij}}.
$$

(3.9)

If $C_{iM}$ is measured (using Rayleigh or Raman scattering), then an absolute calibration constant can again be defined:

$$
C_{ij} = C_{ij} C_{iM} = C_{ij} \frac{\hbar \nu_{iM}}{\delta \lambda_{iM} G_{iM} \Delta \Omega_i R_{iM}}.
$$

(3.10)

The purpose of channel efficiency calibration is to measure $C_{ij}'$ for each channel.

B. Measurement of relative channel efficiency constants

Suppose that a source of known intensity $I(\lambda)$ watts per square meter per unit wavelength at wavelength $\lambda$ and distance $x$ is available. If the source is imaged on the input fiber to spectrometer $i$ using a lens with solid angle $\Delta \Omega_i$ at distance $x$ from the source, then the signal detected by channel $j$ of spectrometer $i$ will be

$$
S_{ij} = \frac{I(\Delta \lambda_{ij})}{\hbar \nu_{ij}} R_{ij} G_{ij} \tau \delta \lambda_{ij} \Delta \Omega_i 4\pi x^2,
$$

(3.11)

where all quantities have been defined, except that $\tau$ is the gate width in seconds of the integrator gate and $I(\Delta \lambda)$ is assumed constant over
δλ_{ij}. Then an experimental measurement of the relative channel efficiencies is given by

\[ C'_{ij} = \frac{A_{iM} S_{iM}}{I(\Delta \lambda_{ij}) A_{ij} S_{ij}}, \quad (3.12) \]

with \( M \) a specific channel of spectrometer \( i \). All of the quantities on the right-hand side (RHS) of Eq. (3.12) are measured quantities (lamp intensities, experimentally measured PMT signals, and signal attenuation settings). The reader may verify Eq. (3.12) by substituting Eq. (3.11) in Eq. (3.12) and comparing to Eq. (3.9). If \( S_{ij} \) is measured for each spectrometer with a known lamp, then the relative channel efficiencies \( C'_{ij} \) can be calculated for all channels \( j \) and spectrometers \( i \) from Eq. (3.12).

This analysis assumes that the spectrometer input and output fiber ends are incoherent with respect to one another. Otherwise, the effective channel widths \( \delta \lambda_{ij} \) vary as the source width varies if a fiber is underfilled. It is also assumed that the response is independent of whether the source pulse is "long" (=100 μs) or "short" (=100 ns) since the calibration source has a =100-μs pulse, whereas the laser signal is ≈30 ns.

C. Some statistics for channel efficiency measurements

The relative channel efficiencies can be measured from a single gating of the system as

\[ C'_{ij} = \frac{I(\Delta \lambda_{ij})}{A_{ij} S_{ij} C'_{iM}}, \quad (3.13) \]
where

\[ C'_{iM} = \frac{I(\Delta \lambda_{iM})}{A_{iM} S_{iM}} \]  

(3.14)

(all other quantities have been defined). If \( C'_{iM} \) is perfectly known and photon statistics dominate, then after one measurement the expected error in \( C'_{ij} \) will be

\[
\frac{(\sigma_{C'_{ij}})^2}{(C'_{ij})^2} = \frac{G_{ij}}{A_{ij} S_{ij}}.
\]  

(3.15)

This is just \((N)^{-1}\), where \( N \) is the number of photons detected in channel \( i,j \). If an average is made over \( Q \) shots, then

\[
\bar{C}'_{ij} = \frac{1}{Q} \sum_{k=1}^{Q} C'_{ij},
\]  

(3.16)

where \( k \) identifies the \( k \)th measurement. The expected variance of \( \bar{C}'_{ij} \) is given by

\[
\frac{(\sigma_{C'_{ij}})^2}{(\bar{C}'_{ij})^2} = \frac{1}{NQ}.
\]  

(3.17)

If \( \Delta \) is defined as

\[
\Delta = \frac{\sigma_{C'_{ij}}}{\bar{C}'_{ij}},
\]  

(3.18)
then the predicted number of shots to achieve an uncertainty $\Delta$ in the efficiency constant is [using Eq. (3.17) in Eq. (3.18)]

$$Q = \frac{1}{N\Delta^2}.$$ \hspace{1cm} (3.19)

When calculating $(\sigma_{C_{ij}'})^2$ for a particular set of $Q$ shots, if Poisson statistics dominate, then the value of $(\sigma_{C_{ij}'})/(\bar{C}_{ij}')$ will converge to $(N)^{-1/2}$ as $Q$ and $N$ become large. The shot-to-shot variation in $C_{ij}'$ reflects the Poisson statistics of the photon collection process, and not the uncertainty in the value of $\bar{C}_{ij}'$ after $Q$ shots. If an experimental measurement of the uncertainty in $\bar{C}_{ij}'$, $\sigma_{C_{ij}'}$ is wanted, then $P$ sequences of $Q$ shots must be taken and the standard deviation calculated from the different measurements of $\bar{C}_{ij}'$. It is easy to miss this point when calculating the experimental uncertainties of the efficiency constants.

D. Calculation of spectral intensity

The spectral intensity incident on the system collection lens (power per unit area per unit wavelength) at wavelength $(\lambda_I + \Delta\lambda_{ij})$ is denoted by $I(\Delta\lambda_{ij})$. If a neutral density filter is inserted between the calibration source and the lens, then

$$I(\Delta\lambda_{ij}) = I_s(\Delta\lambda_{ij})T(\Delta\lambda_{ij}),$$ \hspace{1cm} (3.20)

where $I_s(\Delta\lambda_{ij})$ is the source spectral intensity and $T(\Delta\lambda_{ij})$ is the transmittance of the neutral density at $(\lambda_I + \Delta\lambda_{ij})$. 
E. Gain calibration with the spectral source

Gain calibration can be performed simultaneously with efficiency calibration (now using the spectral source), with the calculation done just as in Sec. II. The statistical test for validity also remains correct. However, with the spectral source the calibration will be with a ≈100-μs signal, as opposed to a ≈20-ns signal with the LED source. If a good calibration is achieved with the LED sources and with the spectral source, then any differences may be attributable to the long-pulse nature of the spectral source.

F. Channel efficiency measurement hardware and procedures

Figure 11 is a schematic of the efficiency calibration hardware and timing electronics. The spectral source consists of a General Electric 45-W, 6.6-A, quartz-halogen lamp with a fan and a 6000-rpm chopper wheel enclosed in an aluminum box painted flat black. The chopper has a ≈3-mm slit cut radially in it, so that the source is visible for 100 μs every 10 ms. A shutter is mounted after the chopper wheel. The shutter has a minimum effective open time of 5 ms, so that synchronizing the shutter with the chopper allows a single 100-μs pulse of light from the calibration source at arbitrary frequencies less than or equal to 1 Hz, which is the maximum shutter rate. The timing electronics consists of a series of pulse/delay generators with enable gates connected to synchronize the shutter with the chopper wheel. A phototransistor next to the shutter produces a pulse several microseconds before the slit in the chopper is aligned with the shutter; the phototransistor signal and the first pulse generator control the system timing. The first pulse generator is free-running
FIG. 11. Schematic diagram of spectral source and pulse generators used to synchronize the chopper wheel and shutter. The first pulse generator is free running (period set manually), usually at 0.5 Hz. The first pulse generator drives the enable gate on the second pulse generator. The second pulse generator is triggered by a phototransistor signal just before the chopper wheel is lined up with the lamp. The output of the second pulse generator triggers the shutter, so that it will be fully open the next time the chopper wheel comes by, and also triggers the third pulse generator, which produces an enable gate enabling the fourth pulse generator. When the shutter is fully open, the fourth pulse generator is enabled so that the phototransistor signal can trigger it. The output of the fourth pulse generator triggers the CAMAC data acquisition system. The delay of the fourth pulse generator is set so that the PMTs will be gated on for 2 μs during the peak of the 100-μs light pulse passed by the chopper wheel.
with frequency adjusted manually to a value typically between 0.1 and 1 Hz.

The lamps used for channel efficiency measurements are calibrated by Eppley Laboratories and have a National Bureau of Standards traceable calibration. The current source driving the lamp is adjusted and regulated to one part in $10^5$, so that the lamp output is flicker free. The lamp output has been measured using a radiometer to be constant for at least 50 h, which is also the minimum calibrated time quoted by Eppley Laboratories. Figure 12 is a typical lamp calibration.

![Figure 12](ORNL-DWG 83-3410)

**FIG. 12.** Typical relative spectral intensity vs wavelenth for one of the 45-W quartz-halogen lamps used for channel efficiency calibration. The points represent data from Eppley Laboratories. The curve through the points is a third-order polynomial fit used by the computer to interpolate between points. The spectral intensity has been normalized to be one at 7000 Å.
curve taken at a distance of 0.50 m and a current of 6.50 A dc. The points represent the Eppley lab data, and the curve through them is a computer-generated, third-order polynomial fit. The lamp intensity is normalized to be unity at 7000 Å.

The only optical element between the spectral source and the SCATPAK II collection optics is a neutral density (ND) filter. The filter is necessary to adjust the lamp intensity to a level that does not saturate the charge-integrating ADCs. The filter transmittance is either measured by the vendor or calibrated at ORNL. Both absorptive Schott glass and reflective metallic-coated filters have been used. A curve is fitted to the transmittance of the filter and used by the computer in calculating $I(\lambda)$.

The spectral source itself is mounted in a large aluminum box on an optical breadboard. The large aluminum box, called the "calibration box," has holes that just allow the collection lenses for SCATPAK II to penetrate. During calibration the system sees light only from the spectral source. This is checked by gating the data acquisition system with the spectral source off to verify that there is no signal. Once the calibration box and spectral source are in place, the source is aligned through the collection lens on the image plane fiber to be calibrated, and the timing of the pulse/delay generators is set with a photodiode and oscilloscope to produce 100-μs pulses at the desired frequency. The operator inserts ND filters to adjust the number of detected photons to be between 20 and 100 per shot in each channel. At a repetition rate of 0.5 Hz, this corresponds to an equivalent detected photon rate between $1 \times 10^4$ and $5 \times 10^4$ photons per second (20 photons in the 100-ns integrator gate implies $\approx 2 \times 10^4$ photons "detected" in the 100-μs pulse). It is shown in Sec. II that this photon rate might
lead to response changes if continued for long per[...]. However, measurement at these rates for the 10 to 20 min necessary to calibrate a single spectrometer does not lead to a detectable change in the system response.

A calibration normally consists of 250 to 300 shots taken in sets of 50 to 60 shots each. Depending on the exact number of photons detected (20-100) in each channel, the expected uncertainty in the efficiency constants is 1-3% [see Eq. (3.19)]. The data acquisition and analysis for channel efficiency measurement are done with the computer. Average signal, gain, and channel efficiency constants are calculated for each set of shots, and the standard deviations of these quantities are calculated from the average data for each set to check statistical consistency.

G. Channel efficiency data

The channel efficiency constants are calculated and stored according to the formulas

$$c_{ij}^{k'} = \frac{I(\Delta \lambda_{ij})}{A_{ij} s_{ij}^k},$$

(3.21)

$$\overline{c}_{ij}' = \frac{1}{Q} \sum_{k=1}^{K} c_{ij}^{k'},$$

(3.22)

where k again signifies the kth measurement. The quantity stored in the computer file is \(\overline{c}_{ij}'\). When the efficiency constants are used, they are normalized to the given channel of each spectrometer, as in
Eq. (3.8), and multiplied by the appropriate constant from Rayleigh or Raman scattering (see Sec. IV) to give the correct efficiency constants. It is convenient to store the efficiency constants in the form of Eq. (3.22) since it is occasionally useful to compare the absolute values from one calibration to the next, even though absolute values are not expected to reproduce well due to variations in setup distances and alignment.

We now return to the question raised in Sec. III.C concerning possible differences in gain as measured during efficiency calibration and as measured with the LEDs. Table I compares gain calibration data for spectrometer 3 from an efficiency calibration of 500 shots with ≈25 photons per shot and from the gain calibration run of 2.6 x 10^5 shots discussed in Sec. II.D. Three of the PMTs showed gain variations of 10 to 20%, and two showed differences of less than 1%. These numbers are typical and appear to be due to variation within the efficiency measurement procedure rather than to any difference between LED gain calibration and gain calibration with the spectral source.

Table II demonstrates the reproducibility of the channel efficiency constants. The efficiency constants and gains are shown from three calibrations of spectrometer 3. The gain is in parentheses under the efficiency. Each calibration had 120 shots with ≈40 photons per shot in each channel. Line 4 lists the ratio of the standard deviation to the average efficiency constant, and line 5 lists the ratio of the actual standard deviation to that predicted from photon statistics using Eq. (3.17). The average standard deviation was 2%, and only one was more than twice the theoretical standard deviation. These measurements were done on consecutive days without moving the
### TABLE I. Gain (bits/photon) for spectrometer 3.

<table>
<thead>
<tr>
<th>Channel</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.08</td>
<td>7.02</td>
<td>5.60</td>
<td>5.40</td>
<td>5.84</td>
</tr>
<tr>
<td>2</td>
<td>5.87</td>
<td>7.06</td>
<td>6.60</td>
<td>6.08</td>
<td>5.85</td>
</tr>
<tr>
<td>3</td>
<td>19%</td>
<td>0.06%</td>
<td>16%</td>
<td>12%</td>
<td>0.17%</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **LED calibration** (4/13/82)
- **Efficiency calibration** (5/24/82)

\[\Delta (\%)^a\]

- 19%
- 0.06%
- 16%
- 12%
- 0.17%

\[\Delta \text{ expected } -1\%\]
### TABLE II. Channel efficiency constants for spectrometer 4.

<table>
<thead>
<tr>
<th>Date</th>
<th>Channel 1</th>
<th>Channel 2</th>
<th>Channel 3</th>
<th>Channel 4</th>
<th>Channel 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/20/82</td>
<td>1.28</td>
<td>0.896</td>
<td>1.09</td>
<td>1.63</td>
<td>$1.66 \times 10^{-4}$</td>
</tr>
<tr>
<td>09:36</td>
<td>(6.6)</td>
<td>(5.3)</td>
<td>(4.3)</td>
<td>(4.7)</td>
<td>(4.7)</td>
</tr>
<tr>
<td>12/21/82</td>
<td>1.24</td>
<td>0.888</td>
<td>1.11</td>
<td>1.67</td>
<td>1.55</td>
</tr>
<tr>
<td>09:36</td>
<td>(6.5)</td>
<td>(4.8)</td>
<td>(4.1)</td>
<td>(6.0)</td>
<td>(5.2)</td>
</tr>
<tr>
<td>12/21/82</td>
<td>1.27</td>
<td>0.909</td>
<td>1.12</td>
<td>1.59</td>
<td>1.58</td>
</tr>
<tr>
<td>09:58</td>
<td>(6.9)</td>
<td>(5.7)</td>
<td>(5.0)</td>
<td>(5.2)</td>
<td>(4.5)</td>
</tr>
<tr>
<td>$\sigma/\bar{x}$</td>
<td>0.016</td>
<td>0.012</td>
<td>0.013</td>
<td>0.025</td>
<td>0.036</td>
</tr>
<tr>
<td></td>
<td>(0.031)</td>
<td>(0.085)</td>
<td>(0.105)</td>
<td>(0.124)</td>
<td>(0.075)</td>
</tr>
<tr>
<td>$\sigma/\sigma$</td>
<td>1.03</td>
<td>1.02</td>
<td>1.09</td>
<td>1.63</td>
<td>2.27</td>
</tr>
<tr>
<td></td>
<td>(1.41)</td>
<td>(4.2)</td>
<td>(5.3)</td>
<td>(5.5)</td>
<td>(2.64)</td>
</tr>
</tbody>
</table>
input fiber to the spectrometer. The gain measurement had a standard deviation of ≈10%, about four times that predicted by Eq. (2.8), assuming photon statistics as the source of variation. The efficiency calibration error is within that predicted by photon statistics, but the gain calibration has a standard deviation much larger than that predicted by photon statistics. The resolution lies in Eqs. (2.6) and (3.16). Since the efficiency constants depend only on the average signal but the gain measurements depend on the standard deviation of the signal, the gain measurements are more sensitive to fluctuations than the efficiency constants. Our conclusion is that the efficiency constants can be measured to within at least 2% using the spectral source, but the gain measurements will only be good to ≈10% unless the source is further improved or the number of photons per shot is further decreased.

The final point of Table II is that any PMT fatigue is within the statistics of the calibration (i.e., ≤ 2%). The third calibration immediately followed the second so that any significant fatigue would be observable.

The effects of excessive photon flux from the spectral source are displayed in Fig. 13. The signal averaged over 2-min intervals from two channels is plotted vs time for a flux of ≈4 x 10^6 photons per second detected. In one channel the signal decreased 5% in 40 min; in the other it decreased 15%. The high flux was produced by holding the shutter open so that the PMTs were exposed to the source every 10 ms. This demonstrates that the apparent PMT fatigue is not specific to the LED calibration and increases with increasing photon flux (again consistent with the data of Ref. 27).
FIG. 13. Typical response vs time of PMTs subjected to an excessively high flux of $\approx 4 \times 10^6$ photons/s (detected). The drop in response is attributed to PMT fatigue. The high photon flux was produced with the spectral source and shows that the drop in system response is independent of light source (LED or spectral source).
Table III displays the relative channel efficiency constants (with channel 1 normalized to unity) of spectrometer 3 for two calibrations performed six months apart. Three of the four observable channels reproduced to 3% or better, but the fourth showed a ~20% change in response. This is typical. For calibration runs separated by long periods, 80 to 90% of the channels will reproduce within 2%, but the remaining channels show greater changes. Our evaluation is that the system should be recalibrated every three months, or whenever a significant number of tubes show response changes when checked with the LED system.

The last item of efficiency data concerns an unexpected system feature revealed by calibration. During a long measurement period, random changes of the absolute channel efficiency constants, of up to 50%, were observed. The source of this problem was identified as bending of the spectrometer input fibers. The system design allows free movement of the 15 spectrometer input fibers among the 36 available slots in the image plane. However, removing and replacing a fiber bundle occasionally causes large changes in transmission, since bending can cause lossy surface modes. This is a major inconvenience. It requires that the system be recalibrated if the fiber positions are changed and makes relative density calibration of the spectrometers using the spectral source difficult or impossible.
TABLE III. Relative calibration constants for spectrometer 3.

<table>
<thead>
<tr>
<th>Channel</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/24/82</td>
<td>1.0</td>
<td>0.639</td>
<td>0.768</td>
<td>2.44</td>
<td>1.37</td>
</tr>
<tr>
<td>12/3/83</td>
<td>1.0</td>
<td>0.620</td>
<td>0.772</td>
<td>2.96</td>
<td>1.35</td>
</tr>
<tr>
<td>Δ (%)</td>
<td>-</td>
<td>3.02</td>
<td>0.52</td>
<td>19.3</td>
<td>1.47</td>
</tr>
</tbody>
</table>
IV. RAYLEIGH/RAMAN CALIBRATION

Rayleigh or Raman calibration consists of looking with the Thomson scattering system at laser light scattered by a gas\(^6,19-21,30-32\) rather than by a plasma. Raman scattering is a subset of Rayleigh scattering\(^6,32\) but for our purposes Rayleigh scattering is defined as scattering from molecules or atoms with no change in wavelength, and Raman scattering is defined as scattering with a change in wavelength due to interaction with the rotational/vibrational states of the target gas. Rayleigh/Raman scattering can be used to

1. check system timing, data acquisition, and alignment with real scattered signals, but with a steady-state scattering target;
2. measure the stray light generated per joule of incident laser energy;
3. perform an absolute density calibration of the system; and
4. check the gain calibrations.

Items 2 and 3 are discussed below. For SCATPAK II, \(\text{H}_2\) is normally used for gas scattering to prevent contamination of the tokamak.

A. Measuring absolute channel efficiency constants

The expected Rayleigh/Raman signal (for spectrometer \(i\), channel \(M\)) is given by

\[
S_{iM}^R = \frac{E_i}{h\nu_{iM}} r_0^2 n_i L_i \Delta \Omega_i \frac{G_{iM}}{A_{iM}} \frac{\sigma}{\sigma_T} \eta_{iM}(\lambda_s) , \tag{4.1}
\]
where all symbols are defined in Sec. III, except that $\sigma/\sigma_T$ is the ratio of the Rayleigh/Raman cross section to the Thomson cross section, $\eta_{iM}(\lambda_s)$ is the system efficiency for spectrometer $i$ and channel $M$ at wavelength $\lambda_s$, and $n_H$ is the density of molecular hydrogen for the gas scattering. In words, Eq. (4.1) says that the expected signal from gas scattering is given by the expected total Thomson signal times the ratio of the gas scattering to total Thomson scattering cross sections, times the system efficiency at the scattered wavelength.

The difference between gas scattering and Thomson scattering is that the signal from gas scattering appears at discrete wavelengths (line width $< 1^\circ$).

We define $C_{iM}$ as

$$C_{iM} = \left\{ \frac{E_i}{S_{iM}} \right\} \frac{r_0^2 n_H}{\sigma_T} \int \frac{\eta_{iM}(\lambda_s)}{\eta_{iM}(\lambda)} \, d\lambda,$$

(4.2)

where the braces indicate the average over several shots and $\eta_{iM}(\lambda)$ is the measured system response vs wavelength of channel $i,M$, so that (by definition):

$$R_{iM} \delta\lambda_{iM} = \int \eta_{iM}(\lambda) \, d\lambda.$$

(4.3)

Then using Eqs. (4.3) and (4.1) in Eq. (4.2) gives

$$C_{iM} = \frac{\hbar \nu_{iM}}{\delta\lambda_{iM}} \frac{1}{G_{iM} \Delta \Omega_i R_{iM} L_i}.$$

(4.4)
Comparing Eq. (4.4) to Eq. (3.10), we see that

$$C_{ij} = C_{ij}' C_{iM}. \quad (4.5)$$

If all the quantities on the RHS of Eq. (4.2) are known, then the absolute channel efficiency constants can be calculated using the measured relative constants (Sec. III.B) and the Rayleigh/Raman constants defined by Eq. (4.2). Examining the RHS of Eq. (4.2) shows that all of the quantities are known or measured:

$$\left\{ S_{iM}^R / E_I \right\} = \text{the average of the measured signal from the Rayleigh/Raman scattering divided by the measured laser energy for channel M of the ith spectrometer.}$$

$$r_0 = \text{the classical electron radius} = 2.82 \times 10^{-15} \text{ m.}$$

$$n_H = \text{the molecular hydrogen gas density calculated from the measured pressure.}$$

$$\left( \sigma / \sigma_T \right) = \text{the ratio of the Rayleigh/Raman cross section to the Thomson cross section.}$$

$$[\eta_{iM}(\lambda_s)] / [\int \eta_{iM}(\lambda) \, d\lambda] = \text{the response of channel M of spectrometer i at the scattering wavelength divided by the integral of the response over all wavelengths. This ratio is calculated from the data of Sec. I.}$$
Absolute calibration of the density measured by each spectrometer is more difficult than calibration relative to the other spectrometers. Also, the line-integrated plasma density along a vertical or horizontal chord is generally known for every plasma shot from either microwave or far-infrared interferometry. Given the relative density profile from Thomson scattering and the line-integrated density from interferometry, an absolute electron density can be calculated for each Thomson scattering volume:

\[ n_{ei} = \frac{n'_{ei}}{\int n_{ei}' \, dr} n_{el}, \quad (4.6) \]

where \( n_{ei} \) is the absolute electron density for the \( i \)th Thomson scattering position, \( n'_{ei} \) is the relative electron density measured with Thomson scattering (arbitrary units), and \( n_{el} \) is the line-averaged electron density times path length measured with interferometry.

If only relative channel efficiency constants are desired, it is possible to calculate from the channel efficiency measurements and gas scattering data a relative constant that does not require measurement of the laser energy, the molecular hydrogen density, or the ratio of the gas-scattering cross section to the Thomson cross section. Let the relative channel efficiency measured from gas scattering be defined as

\[ C'_{iM} = \frac{C_{iM}}{C_{LM}} = \frac{s_{LM} \cdot n_{iM}(\lambda_s)}{s_{iM} \cdot n_{LM}(\lambda_s)} \frac{\int n_{LM}(\lambda) \, d\lambda}{\int n_{iM}(\lambda) \, d\lambda}, \quad (4.7) \]
where $L$ stands for an arbitrary but specific spectrometer (spectrometer 1, for instance). Then the relative calibration constant for each channel $j$ of each spectrometer $i$ becomes:

$$C_{ij}' = C_{ij}C_{iM}'$$

(4.8)

Within an arbitrary constant that is the same for all spectrometers $i$ and channels $j$, $C_{ij}'$ is equal to the absolute calibration constant defined by Eq. (3.10). Thus, measurement of the channel response (wavelength calibration), gain calibration (for weighting the data), relative channel efficiency constants, relative Rayleigh/Raman constants, and line-integrated density (from interferometry) allows calculation of the absolute temperature and density from Thomson scattering data.

B. Rayleigh vs Raman scattering

The relative merits of Rayleigh and Raman scattering can be summarized from Table IV, which displays $\sigma/\sigma_T$ and $\lambda$ for both processes in $H_2$. The advantage of Rayleigh scattering is that the cross section is more than two orders of magnitude larger than the cross section for Raman scattering. The disadvantage of Rayleigh scattering is that it occurs with no shift in wavelength. This means that with the system set up for Thomson scattering, no signal appears in any of the spectrometer channels. To use the Rayleigh line, the grating drive of the spectrometer must be changed to center the Rayleigh line in a convenient channel. This causes two problems:
TABLE IV. Ratio of Rayleigh/Raman cross section to Thomson cross section for \( \lambda = 6943\text{Å} \) on \( \text{H}_2 \),\(^{6,21}\)

<table>
<thead>
<tr>
<th>Wavelength (Å)</th>
<th>(\frac{\sigma}{\sigma_T} )</th>
<th>Type of scattering</th>
</tr>
</thead>
<tbody>
<tr>
<td>6943</td>
<td>(\frac{1}{1769})</td>
<td>Rayleigh</td>
</tr>
<tr>
<td>7118</td>
<td>(\frac{1}{675} \cdot \frac{1}{1769})</td>
<td>Raman</td>
</tr>
<tr>
<td>7238</td>
<td>(\frac{1}{240} \cdot \frac{1}{1769})</td>
<td>Raman</td>
</tr>
<tr>
<td>7359</td>
<td>(\frac{1}{1733} \cdot \frac{1}{1769})</td>
<td>Raman</td>
</tr>
<tr>
<td>7480</td>
<td>(\frac{1}{2750} \cdot \frac{1}{1769})</td>
<td>Raman</td>
</tr>
</tbody>
</table>
1. It would be preferable not to move the spectrometer grating drive after completing wavelength calibration.

2. The system efficiency at the channel center may change as the grating drive is moved.

Beyond these problems, it is inconvenient to twice reset the grating drives on 15 spectrometers.

If this problem is taken into account when the system is designed, then the strongest Raman line will be centered on a spectrometer channel (this should be the only line appearing in that channel). In this case, the gas-scattering calibration can be done without moving the spectrometer grating drives, giving Raman scattering an advantage over Rayleigh scattering. In systems where stray light is a problem, Raman scattering may also have the advantage of reducing the stray light by the spectrometer rejection ratio (typically $10^3$ to $10^6$). The disadvantage of Raman scattering is that the cross section of the strongest line is less than 1% of the Rayleigh cross section. For SCATPAK II when scattering from 10 Torr of H_2, five to ten photons per joule of laser energy are detected with the strongest Raman line centered on a spectrometer channel. Since the ruby laser is typically run at 20 J on target, this implies 100 to 200 photons detected per shot. Firing the laser 100 times leads to a relative Raman calibration with an expected error $\sigma = 1\%$ due to photon statistics. Error in the absolute calibration would, of course, increase with errors in measuring the laser energy on each shot or the gas pressure, and both constants include any error made in measuring the ratio of the response at the scattering wavelength to the integral of the channel response.
C. Gas scattering for stray light and system efficiency measurements

The normal procedure for measurement of stray light is to do Rayleigh or Raman scattering and scan the gas pressure in the scattering volume. Then the stray light intensity can be calculated from the slope and intercept of the straight-line plot of scattered intensity vs pressure generated. Any deviation from a straight line is due to unplanned changes in the filling pressure, dust in the scattering volume, or other measurement error. Figure 14 is a typical scan of Rayleigh signal vs pressure made using $N_2$ for a scattering gas.

FIG. 14. Rayleigh scattering pressure scan. The number of photoelectrons detected per joule of laser energy is plotted vs nitrogen gas pressure in the ISX vacuum vessel. The intercept of the data with the zero-pressure line represents the stray light in the system. The stray light level is equivalent to a filling pressure of 2.7 Torr of $N_2$. 
The zero-pressure intercept of Fig. 14 corresponds to a stray light level of 2.7 Torr of N₂ (dividing the intercept by the slope) or, taking into account the ratio of the Rayleigh to the Thomson cross section and a conservative spectrometer and ruby filter rejection of 10⁴ (the manufacturer's specification is 10⁵ for the spectrometer), corresponds to an equivalent plasma density of \( n_e \approx 2 \times 10^{17} \text{ m}^{-3} \). This is a factor of 10 less than the lowest plasma density expected to be measured with Thomson scattering in ISX which is \( \approx 2 \times 10^{18} \text{ m}^{-3} \) in the scrape-off layer outside the limiter radius. The system efficiency implied by Fig. 14, where efficiency is defined as photons detected divided by photons incident on the collection lens, is approximately 0.06%, where Eq. (4.1) has been used to calculate the expected signal with the factors G/A and \( \eta \) dropped. Given the SCATPAK II solid angle (\( \Delta \Omega = 2 \times 10^{-2} \text{ sr} \)), this corresponds to an expected Thomson scattering signal, integrated over wavelength, of \( \approx 20 \) photons per joule per \( 10^{19} \text{ m}^{-3} \) of plasma density. The efficiency used for this calculation is half that of the Rayleigh scattering measured efficiency to allow for the peak-to-average ratios of the channel efficiencies. This implies that SCATPAK II should be able to make statistically significant measurements of electron temperature and density down to \( n_e \approx 2 \times 10^{18} \text{ m}^{-3} \), limited only by the intensity of the background plasma light, not by the stray light seen by the system.
SUMMARY

In order to calculate electron temperature and density for Thomson scattering data from SCATPAK II, four calibrations are performed.

1. Wavelength calibration measures the wavelength of the center of each channel and the shape of the channel response vs wavelength. The channel center data are used in making the temperature and density calculations [see Eq. (3.4), $\Delta \lambda_{ij}$], and the shape of the channel response is used in making the finite channel width correction to the calculations. These data are also used in the Rayleigh/Raman scattering measurement of absolute efficiency.

2. Gain calibration measures the gain of each channel of the system in bits per photon, so that the number of photons detected by each channel can be calculated and used to weight the data when fitting the temperature and density.

3. Channel efficiency calibration characterizes the relative light collection efficiency of each channel within a particular spectrometer.

4. Rayleigh/Raman calibration measures the absolute efficiency for a single channel in a spectrometer. This constant can be used either absolutely or in a relative sense to calculate electron densities for the data from each spectrometer. If used in a relative sense, the chord integral of the density is equated to interferometer data to calculate an absolute density.
The goal of the calibration procedure is to measure these constants to within 1%. The gain, channel efficiency, and Rayleigh/Raman calibrations can actually be done to better than 2%. The wavelength calibration procedure has only achieved an accuracy of ≈3%, but the effect on electron temperature calculations is smaller than this.

It is believed that the effects of all known calibration errors on electron temperature calculations for SCATPAK II are less than 3%, and that calibration errors cause less than a 5% error in the density calculations for SCATPAK II.

As a final thought, we point out that a pulsed dye laser could simultaneously perform all of the calibrations necessary for a Thomson scattering system. Since the dye laser can be scanned in wavelength, an appropriately installed dye laser with an energy per pulse of 50 mJ, along with a wave-meter and energy-meter, could be used with Rayleigh scattering, under computer control to perform all four calibrations at once with very high accuracy and with the system (except for the laser) configured as it is normally used. This would admittedly be expensive, and data acquisition and control would of necessity be computer driven. However, the accuracy and simplicity of calibration might well justify the cost for some of the larger fusion devices now beginning operation or coming on line. The only caveat is that recent work suggests a dependence of the Rayleigh cross section on pulse length and wavelength for short-pulse lasers.33
ACKNOWLEDGMENTS

The authors wish to acknowledge the members of the ISX operations and support staffs and the ISX crafts workers for their help: E. T. Blair, J. Campbell, W. A. GABBARD, M. Holland, G. King, W. Lethgo, C. McCollough, P. Morgan, T. Muhammed, G. Purdy, T. F. Rayburn, W. J. Redmond, and T. West. Particular thanks go to R. Foskett, who played a large part in bringing SCATPAK II on line and in developing the calibration electronic hardware. Finally, we express our gratitude for the help and support of M. J. Saltmarsh, J. L. Dunlap, O. B. Morgan, and J. Sheffield.

This research was sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-840R21400 with Martin Marietta Energy Systems, Inc.
REFERENCES


29 C. E. Thomas, to be published.


1. B. A. Carreras
2. R. J. Colchin
3. T. B. Cook
4. R. A. Dory
5. R. D. Foskett
6. J. C. Glowienka
7. D. L. Hillis
8. S. Hiroe
9. R. R. Kindsfather
10. P. W. King
11. E. A. Lazarus
12. J. F. Lyon
13. M. Murakami
14. D. A. Rasmussen
15. R. K. Richards
16. M. J. Saltmarsh
17. D. D. Schuresko
18. K. C. Shaing
19. J. Sheffield
20. K. A. Stewart
21-25. C. E. Thomas, Jr.
26. C. C. Tsai
27. T. Uckan
28. J. B. Wilgen
29-30. Laboratory Records Department
31. Laboratory Records, ORNL-RC
32. Document Reference Section
33. Central Research Library
34. Fusion Energy Division
Library
35-36. Fusion Energy Division
   Publications Office
37. ORNL Patent Office

EXTERNAL DISTRIBUTION

38. Office of the Assistant Manager for Energy Research and Development, Department of Energy, Oak Ridge Operations Office, P. O. Box E, Oak Ridge, TN 37831
39. J. D. Callen, Department of Nuclear Engineering, University of Wisconsin, Madison, WI 53706
40. R. W. Conn, Department of Chemical, Nuclear, and Thermal Engineering, University of California, Los Angeles, CA 90024
41. S. O. Dean, Director, Fusion Energy Development, Science Applications International Corporation, Gaithersburg, MD 20760
42. H. K. Forsen, Bechtel Group, Inc., Research Engineering, P. O. Box 3965, San Francisco, CA 94105
43. J. R. Gilleland, GA Technologies, Inc., Fusion and Advanced Technology, P.O. Box 81608, San Diego, CA 92138
44. R. W. Gould, Department of Applied Physics, California Institute of Technology, Pasadena, CA 91125
45. R. A. Gros, Plasma Research Library, Columbia University, New York, NY 10027
46. D. M. Meade, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
48. W. M. Stacey, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332
49. D. Steiner, Nuclear Engineering Department, Rensselaer Polytechnic Institute, Troy, NY 12181
50. R. Varma, Physical Research Laboratory, Navrangpura, Ahmedabad 380009, India
51. Bibliothek, Max-Planck Institut fur Plasmaphysik, D-8046 Garching bei Munchen, Federal Republic of Germany
52. Bibliothek, Institut fur Plasmaphysik, KFA, Postfach 1913, D-5170 Julich, Federal Republic of Germany
53. Bibliotheque, Centre des Recherches en Physique des Plasmas, 21 Avenue des Bains, 1007 Lausanne, Switzerland
54. Bibliotheque, Service du Confinement des Plasmas, CEA, B.P. No. 6, 92 Fontenay-aux-Roses (Seine), France
55. Documentation S.I.G.N., Departement de la Physique du Plasma et de la Fusion Controlee, Centre d'Etudes Nucleaires, B.P. 85, Centre du Tri, 38081 Cedex, Grenoble, France
56. Library, Culham Laboratory, UKAEA, Abingdon, Oxfordshire, OX14 3Dk, England
57. Library, FOM-Instituut voor Plasma-Fysica, Edisonbaan 14, 3439 MN Nieuwegein, The Netherlands
58. Library, Institute of Plasma Physics, Nagoya University, Nagoya, Japan
59. Library, International Centre for Theoretical Physics, Trieste, Italy
60. Library, Laboratorio Gas Ionizatti, CP 56, I-00044 Frascati, Rome, Italy
61. Library, Plasma Physics Laboratory, Kyoto University, Gokasho, Uji, Kyoto, Japan
62. Plasma Research Laboratory, Australian National University, P.O. Box 4, Canberra, A.C.T. 2000, Australia
63. Thermonuclear Library, Japan Atomic Energy Research Institute, Tokai, Naka, Ibaraki, Japan
64. G. A. Eliseev, I. V. Kurchatov Institute of Atomic Energy, P. O. Box 3402, 123182 Moscow, U.S.S.R.
65. V. A. Glukhikh, Scientific-Research Institute of Electro-Physical Apparatus, 188631 Leningrad, U.S.S.R.


68. V. T. Tolok, Kharkov Physical-Technical Institute, Academical St. 1, 310108 Kharkov, U.S.S.R.

69. Library, Institute of Physics, Academia Sinica, Beijing, Peoples Republic of China


71. K. Bol, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544

72. R. A. E. Bolton, IREQ Hydro-Quebec Research Institute, 1800 Montee Ste.-Julie, Varennes, P.Q. J0L 2P0, Canada

73. R. L. Freeman, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138

74. K. W. Gentle, RLM 11.222, Institute for Fusion Studies, University of Texas, Austin, TX 78712

75. R. J. Goldston, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544

76. J. C. Hosea, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544


79. D. Overskei, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138

80. R. R. Parker, Plasma Fusion Center, 167 Albany Street, Cambridge, MA 02139
83. A. P. Navarro, Division de Fusion, Junta de Energia Nuclear, Avenida Complutense 22, Madrid (3), Spain
84. Laboratory for Plasma and Fusion Studies, Department of Nuclear Engineering, Seoul National University, Shinrim-dong, Gwanak-ku, Seoul 151, Korea
85. N. Bretz, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
86. D. Dimock, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
87. D. Johnson, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
88. R. Watterson, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139
89. S. McCool, University of Texas at Austin, Austin, TX 78712
90. P. Politzer, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
91. O. Motojima, Plasma Physics Laboratory, Kyoto University, Gokasho, Uji, Kyoto, Japan
92. S. Sudo, Plasma Physics Laboratory, Kyoto University, Gokasho, Uji, Kyoto, Japan
93. M. J. Forrest, Culham Laboratory, Abingdon, Oxfordshire OX14 3DB, England
94. N. J. Peacock, Culham Laboratory, Abingdon, Oxfordshire OX14 3DB, England
95. R. Prentice, Culham Laboratory, Abingdon, Oxfordshire OX14 3DB, England
96. K. B. Freece, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87544
97. R. E. Siemon, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87544
98. K. A. Gerber, Naval Research Laboratory, 4555 Overlook Avenue, S.W., Washington, DC 20375
99. T. C. Simonen, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
100. R. K. Goodman, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
101. A. M. Frank, Lawrence Livermore National Laboratory, Livermore, CA 94550
102. J. A. Brighton, Georgia Institute of Technology, Atlanta, GA 30332
103. A. W. DeSilva, Physics Program, University of Maryland, College Park, MD 20742
104-262. Given distribution as shown in TIC-4500, Magnetic Fusion Energy (Category Distribution UC-20f, Experimental Plasma Physics)