THE 2XII THOMSON SCATTERING SYSTEM

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THE 2XII THOMSON SCATTERING SYSTEM

Abstract

A Thomson scattering system using a 6 joule Q-switched ruby laser and an eight-channel polychromator has been constructed and employed to measure electron temperatures and densities at

the center of the 2XII mirror confinement experiment. This report discusses experimental considerations used to guide design, construction, alignment and operation of the Thomson scattering system.

I. Introduction

Thomson scattering techniques have been employed on theta pinch plasmas for a number of years and more recently on Tokamak plasmas. Several reviews of these measurements have been published¹⁻³ with reference to earlier work listed therein. The 2XII plasma parameters,⁴ $T_e \sim 30$ to 200 eV and $n_e \leq 1 \times 10^{14} \text{ cm}^{-3}$, are similar to Tokamak parameters⁵ and consequently the techniques employed here are similar. In 2XII the lower electron temperature and lower intensity of plasma light radiation together with the larger device size simplify our plasma light and stray light problems relative to those in Tokamaks. On the other hand 2XII's larger size and heavy titanium gettering, with its associated radiative heat-load, present stringent alignment problems. A schematic view of the 2XII scattering system is shown in Fig. 1.

Thomson scattering¹⁻³ involves directing laser light in direction k_0 and measuring the spectrum of light scattered by plasma electrons in the direction k_s

(Fig. 2). For a ruby laser $\lambda_0 = 2\pi/k_0 = 6943 \text{ \AA}$. The difference vector $\Delta k = 2k_0 \sin \theta/2$, when compared to the plasma Debye length, determines the character of the scattered light spectrum. If Δk is greater than $1/\lambda_D$ then the photons are scattered by uncorrelated electron motions and a Doppler shifted profile is produced which represents the electron velocity distribution in the direction $\Delta \vec{k}$. The 2XII plasma is in this so-called small α range.

$$\alpha = \frac{1}{|\Delta \vec{k}| \lambda_D} = \frac{7.43 \times 10^{-9}}{\sin \theta/2} \left(\frac{n_e}{T_e} \right)^{1/2} \quad (1)$$

where n_e is electron density in units of cm^{-3} and T_e is electron temperature in eV. For a Maxwellian electron velocity distribution the scattered spectrum is

$$I \propto n_e \cdot \frac{\lambda_0}{\Delta \lambda_\theta} \exp \left[- \left(\frac{\Delta \lambda}{\Delta \lambda_\theta} \right)^2 \right] \quad (2)$$

Fig. 1. Schematic view of 2XII Thomson scattering system.

where

$$\Delta\lambda_\theta = 19.4 \sqrt{2T_e} \sin \theta/2 \text{ \AA}$$

$$\Delta\lambda = \lambda - \lambda_0 = \text{wavelength shift \AA.}$$

Fig. 2. Scattering vector diagram.

The experimental requirements thus are: measuring the spectral width of the scattered light to determine T_e and the integrated intensity to determine n_e .

Plasma radiation competes with the Thomson scattering signals. Bremsstrahlung is unimportant for 2XII plasma parameters. Line radiation poses a problem without titanium gettering at low magnetic fields. With gettering, however, line radiation interferes only with the two furthest channels indicating radiation lines in the range 6650 $\text{\AA}$ to

6470 Å. This range includes the hydrogen H_{α} line at 6563 Å.

In the following section we present signal level and stray light estimates. The laser and polychromator detection system are described in Section III

followed by a description of the viewing and laser optical trains and baffles in Section IV. The alignment and calibration methods are discussed in Sections V and VI. Finally we report experimental results and indicate future system improvements.

II. Preliminary Considerations: Photon Budget and Stray Light Estimates

We calculate here the photon signal levels for the present scattering system. The number of collected photons is

$$N_{\text{collected}} = N_0 n_e \ell r_o^2 \delta\Omega \quad (3)$$

where

N_0 = number of incident photons

n_e = electron density

ℓ = viewing length ≈ 1 cm

$r_o^2 = 7.9 \times 10^{-26} \text{ cm}^2$ = electron radius squared

$\delta\Omega$ = viewing solid angle ≈ 0.02 steradians

For ruby light at 6943 Å, 1 joule = 3.5×10^{18} photons. For each joule of laser output, with $n_e = 10^{13} \text{ cm}^{-3}$, $N_{\text{collected}} \approx 2 \times 10^4$ photons per joule.

An optical transmission efficiency of 0.15 (i.e. viewing lens, filter box, polychromator, light pipes), and a photomultiplier (PM) quantum efficiency of 8%, convert 2×10^4 photons per joule into 180 photoelectrons per joule. For a 6 joule laser pulse, with 10% of the signal in each channel, 100 photoelectrons are collected in each channel at a density n_e of 10^{13} cm^{-3} . This signal produces a PM output voltage

$$V_{\text{out}} = \frac{NeGZ_o}{\pi \Delta t/2} \approx 3 \text{ V} \quad (4)$$

where

N = number of photoelectrons = 100

e = electron charge = $1.6 \times 10^{-19} \text{ C}$

Δt = laser pulse width = 40 nsec

G = PM gain = 10^8

Z_o = PM output impedance = 130 Ω.

Stray light scattering at the ruby wave length is a potential difficulty that can be overcome with proper baffling and light dump design. Since the incident ruby laser pulse contains 3.5×10^{18} photons/joule, it takes a rejection factor exceeding 10^{15} to reduce stray light on the central channel below ~ 2000 photons/joule. Eliminating the center channel would relax this requirement by the amount of the polychromator rejection ratio. The present system was designed to utilize the center channel signal, however, and has a rejection factor exceeding 10^{17} .

Stray light calculations^{1-3,6} are at best estimates intended to guide the optical design of baffle systems. Careless alignment can make these estimates meaningless.

Figure 3 shows a cross section of the vacuum chamber together with baffles used to reduce the stray light level. Conservative estimates, as outlined in

Fig. 3. Schematic diagram of laser and viewing baffles and dumps.

Table I, indicate stray light levels of at most 5×10^3 photons/joule. This is $1/4$ of the Thomson scattering signal from a density of 10^{13} cm^{-3} [see discussion of Eq. (3)]. Thus we conclude that stray light poses no serious problem in the

2XII system even for the pessimistic conditions assumed in Table I. In fact, as described subsequently, proper alignment of the laser input baffles can make the stray laser light undetectable even on the channel centered on the ruby wavelength.

Table 1. Conservative estimates of the stray light levels at different points in the 2XII experiment.

	Attenuation factors	Stray light components	Stray light level photons/J
Laser input			3.5×10^{18}
Stray light input to vacuum vessel			
<u>Input lens</u>			
Diffuse scatter	$10^{-4}/\text{str}$	3.5×10^{14} photons/J $\cdot$ str	
Collimation	$2 \times 10^{-4} \text{ str}$	0.7×10^{11} photons/J	
<u>Beam dump</u>			
Diffuse scatter	$10^{-4}/\text{str}$	3.5×10^{14} photons/J $\cdot$ str	
Collimation	$4 \times 10^{-4} \text{ str}$	1.4×10^{11} photons/J	
Total (lens + dump)		2.1×10^{11} photons/J	2.1×10^{11}
Stray light intercepted by lens	2.5×10^{-1}		5×10^{10}
Diffuse scatter into polychromator	10^{-3}		5×10^7
Ruby laser line rejection filter	10^{-1}		5×10^6
Polychromator rejection	10^{-3}		5×10^3

III. Laser and Detection System

The laser was built from standard components as illustrated in Fig. 4. The oscillator, 1/2 in. diam $\times$ 6 in. long, generates single 40 nsec pulses up to 2 joules output or, by double pulsing the Pockels cell, double pulses separated by ~ 200 μ sec each with 1 joule output. The amplifier, 3/4 in. diam $\times$ 8 in. long, delivers 6 to 10 joules. The full angle beam divergence of the laser is approximately 1 mrad. A 10 mW HeNe laser shines through the Pockels cell dielectric mirror and traces out the ruby laser path to assist in alignment.

The detection system employs an f/6.5 Czerny-Turner 3/4 m polychromator using a 10 $\times$ 10 cm 590 line/mm grating to produce a linear dispersion of 22 $\text{\AA}/\text{mm}$. The grating is blazed for 5000 $\text{\AA}$ with a 70% efficiency. The three aluminized mirrors used in the polychromator reduce the overall efficiency to $\leq 50\%$. The 3 mm entrance and exit slit widths employed result in a 70 $\text{\AA}$ FWHM bandwidth. The overlapping channels are spaced at 80 $\text{\AA}$ intervals.

The polychromator output is coupled to PM tubes with 3 mm $\times$ 20 mm plexiglass

Fig. 4. Schematic diagram of laser beam path.

Fig. 5. Detail of light pipe termination on photocathode showing multiple bounces of light.

light pipes as shown in Fig. 5. Light impinges at an angle on the PM tube face in order to improve the quantum efficiency by multiple internal reflections within the PM tube face.⁷

The PM tubes employed were selected RCA 8852^{*} having a quantum efficiency exceeding 6% at 6943 Å. These tubes were arranged as shown in Fig. 6 and enclosed in individual mu-metal magnetic shields. A double wall box of 1/4 in. soft iron enclosed the entire set of eight tubes. These shields proved adequate to exclude

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

Fig. 6. Photomultiplier arrangement in magnetic shielding.

the 100 Gauss stray magnetic field. In order to protect the PM tubes from plasma light during the plasma injection period

they were gated on with a 5 V, 1.5 μ sec pulse. See Fig. 7. The extinction ratio is 5,000:1.

Fig. 7. Gated photomultiplier tube base circuit.

IV. Viewing and Laser Baffling System

The viewing system is schematically illustrated in Fig. 8. It employs a 3-1/2 in. diam X 12 in. focal length, antireflection-coated lens located 18 in.

from the plasma. After the light beam emerges from the vacuum system it is collimated into parallel bundles of rays and passed through the 6943 Å notch

Fig. 8. Schematic diagram of viewing system.

rejection filter. The rejection filter consists of two 30-Å wide filters with 70% transmission at 6943 Å that act as mirrors outside the 30 Å passband. The filter reduces the stray laser light at 6943 Å by 91% while introducing negligible loss in the Thomson scattered light at wavelengths shifted beyond 20 Å. After the rejection filters the light passes through a polarizer that removes all light lacking the laser polarization and a filter that rejects any plasma light below - 6000 Å, eliminating a possible contribution in higher orders to the background light level. Finally the light beam focusses onto the 3 mm X 20 mm polychromator entrance slit.

Three requirements have increased the complexity of the viewing system. First, it must be nonconducting since it functions in a pulsed magnetic field. Second, it must maintain alignment under the titanium gettering heat loads. Third, its lens must not be coated with titanium during gettering.

The viewing lens was held in a ceramic holder to a Vycor tube in compression by 0.060 in. molybdenum wires in tension. Thin wall stainless steel tubes 3/16 in. in diam provided heat shielding of the molybdenum wires. A 4 in. diam mica-lex sheet activated from outside acts as the shutter. This shutter, and the laser input and dump shutters, operate automatically with the normal machine cycle and are interlocked to stay closed during gettering.

The 10 in. diam X 48 in. long bottom diagnostics side arm proved to be a very effective light trap, making an additional viewing dump unnecessary.

The 3/4 in. diam input laser beam is baffled as shown in Figs. 1 and 3. The

Fig. 9. Dye glass baffles employing internal reflection to minimize transmission through knife edge section.

3/4 in. dye glass baffles trim stray light from the beam. The 60 in. focal length lens focuses the laser to a 1/8 in. diam spot at the center of the plasma. All baffles employed in the laser input are dye glass cut at 45° as shown in Fig. 9. Internal reflection on the 45° knife edge section of the baffle greatly reduces transmission through the thin section. The shutter to protect the input mirror from titanium gettering was also fabricated with dye glass. Material sputtered from metal baffles could dirty mirrors or lenses. These difficulties were avoided with the glass baffles. Most of the uncollimated light scattered by the lens, the mirror, and the first baffle, is stopped by the input baffles. Of the balance, 50% dumps into the opposite side arm as seen in Fig. 3.

The laser dump consists of a wedge of Corning 1-72 blue dye glass with the first plate set at Brewster angle to minimize reflection and thereby maximize attenuation on first contact. The second dye glass plate was set to be hidden from the

plasma. Additional baffles reduce diffuse scattered light from the first surface. Again a shutter was employed to protect this dump from titanium gettering. A

solid state diode detector behind a diffuser was located behind the Brewster plate to monitor the transmitted laser intensity.

V. Alignment

The primary features that have facilitated alignment include the HeNe alignment laser, cross hairs with film-holders to indicate ruby laser alignments by burn patterns, and differential screws to provide smooth and continuous laser input and viewing system fine adjustments. Until a systematic procedure was developed, aligning the complete Thomson scattering system took several days. Following this procedure alignment is completed within a day.

A HeNe laser was aligned co-linear with the ruby laser by first firing the ruby laser at an exposed piece of polaroid film, then adjusting the position and direction of the HeNe laser to coincide with the center of the burn. Then the aligned HeNe laser beam was steered through the center of the input baffles and into the center of the laser dump. This alignment was double checked by making burns at the first input baffle, vacuum window, input baffle output and laser dump input. Since the HeNe laser shines through the Pockels cell mirror and ruby rods its intensity is reduced considerably. It can, however, stay in position during operation of the ruby laser.

After the position of the laser beam was set, we suspended a Mylar diffusing screen at the center of the machine at a 45° angle to intercept the HeNe beam.

The viewing lens was adjusted to focus on this red HeNe spot. The beam spot, though easily visible, was too weak to project an image beyond the viewing lens. To produce a sufficiently intense image, we focussed a white light on the beam spot from below. This image could be traced out through the filter box while adjusting the mirror and filters to direct the light into the polychromator slit.

Following the HeNe alignment final adjustments were made by Rayleigh scattering in air using the ruby laser and the PM channel centered at 6943 Å. To prevent the vacuum load from disturbing the alignment, the Rayleigh scattering was done at ≤ 20 mm pressure. Generally the HeNe alignment was within a factor 2 of optimum. Differential screws in the lens adjustment mechanism provide two full turns to scan through alignment.

To check baffle alignment we pumped the machine down to high vacuum and measured the residual stray light level. Laser beam position was adjusted until the center channel signals were less than 20% typical Thomson scattering signals. On numerous occasions the alignment completely eliminated the residual stray light.

The system required realignment only when the 2XII machine was let up to air for modifications.

VI. Calibration

Calibration of the Thomson scattering system consists of a relative calibration of individual polychromator channels and their respective PM tubes to determine electron temperature, an absolute calibration to determine electron density, and a polychromator wavelength calibration.

The PM tube channel relative calibration used a standard lamp with known output vs wavelength in the filterbox as shown in Fig. 8. This light passes through the filter, polychromator, and light pipes and thereby calibrates the entire system rather than only the PM tubes. Calibrations are made at two or three polychromator settings with the laser centered on different channels. A pulsed light diode illuminating the light pipes provided an additional regular check on the relative sensitivity of the PM tubes.

Absolute calibration is obtained from Rayleigh scattering in either air or dry nitrogen. Figure 10 shows a calibration determined in this manner. This calibration was repeated at each realignment. Variations from time to time were on the

Fig. 10. Absolute calibration using Rayleigh scattering.

order of 10%. The filter rejection is taken into account in determining the absolute calibration factors.

The polychromator is calibrated to read in angstroms. A plot of detected Rayleigh scattering signal vs grating angle determines the location and shape of individual channels. This in turn determines the grating position that centers the ruby wavelength at a given channel.

VII. Results

After three iterations on the original design the system was capable of maintaining alignment under the gettering heat loads. Figure 11 shows signals recorded on oscilloscopes. Without plasma no signal was recorded on the center channel. No scattered signals were detected above plasma light levels on channels 7 and 8.

From such scattered signals and the system calibration, electron temperatures are obtained as in Fig. 12. A small computer is used to obtain a linear least squares fit of the data. Data with a correlation coefficient less than 0.9 was regarded as unacceptable and that above 0.95 as good. Electron temperature

Fig. 11. Examples of Thomson scattering data for $n_e = 3.3 \times 10^{13}$ and $T_e = 97$ eV.

Fig. 12. Examples of reduced scattering data to determine electron temperature.

measurements were obtained on over 600 shots.

Electron density as a function of time is shown in Fig. 13. The laser density measurements are in general agreement with microwave line density and neutral beam attenuation measurements. The

laser density measurements were restricted to densities above $1 \times 10^{13} \text{ cm}^{-3}$ and were typically made at densities between 2 and $4 \times 10^{13} \text{ cm}^{-3}$.

Future improvements anticipated in the scattering system include increasing the laser output to 20 joules, interfacing to an on-line computer, increasing the viewing system sensitivity, and adding the capability of measuring radial density and temperature profiles.

Fig. 13. Measurements of plasma density as a function of time.

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