Thomson scattering measurements on a hollow cathode discharge

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Thomson Scattering Measurements on a Hollow Cathode Discharge

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2. Abstract

This report describes the laser Thomson scattering technique and equipment used at a hollow cathode discharge in argon. The aim of the experiment was to measure the electron temperature and density in the core of the positive column of the hollow cathode discharge as a function of the radius and the axial coordinate of the positive column. The detecting device which was a combination of a \( f = 25 \text{ cm}/3.5 \) monochromator and a high quantum efficiency Ga As-photomultiplier tube proved to be sensitive enough to detect the low level Thomson scattering signal within 10% accuracy. However the detection system suffered of a high plasma background radiation signal caused by strong \( \text{Ar}^I \) and \( \text{Ar}^{II} \) lines that reached the output slit of the monochromator by multiple reflections at the inner walls. The measured signals were recorded on a magnetic tape and reduced with a process computer. Electron temperatures in the range of 5 eV and electron densities around \( 10^{20} \text{ m}^{-3} \) were measured. The radial dependency of these quantities could not be measured well, because of the behaviour of the discharge. Further it is concluded that the laser Thomson scattering technique can be applied to MHD power generating experiments after a series of technical improvements has been performed.
3. Nomenclature

Latin

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>constant coefficient (6.2)</td>
</tr>
<tr>
<td>b</td>
<td>constant coefficient (6.2)</td>
</tr>
<tr>
<td>B</td>
<td>magnetic induction</td>
</tr>
<tr>
<td>c</td>
<td>speed of light in vacuum: (2.9979 \times 10^8) m/s</td>
</tr>
<tr>
<td>d</td>
<td>diameter</td>
</tr>
<tr>
<td>dc</td>
<td>diameter of H.C.D.-cathode</td>
</tr>
<tr>
<td>e</td>
<td>electron charge: (1.60184 \times 10^{-19}) C</td>
</tr>
<tr>
<td>E</td>
<td>energy</td>
</tr>
<tr>
<td>E_i</td>
<td>ionization energy</td>
</tr>
<tr>
<td>E_L</td>
<td>laser energy in scattering volume (4.2)</td>
</tr>
<tr>
<td>E_T</td>
<td>Thomson scattered energy in detection system (4.8)</td>
</tr>
<tr>
<td>E_o</td>
<td>electric field of incident laser light (4.1), (4.2)</td>
</tr>
<tr>
<td>f</td>
<td>frequency; focal length of lens</td>
</tr>
<tr>
<td>h</td>
<td>Planck constant: (6.626176 \times 10^{-34}) J.s</td>
</tr>
<tr>
<td>i</td>
<td>H.C.D. current</td>
</tr>
<tr>
<td>I</td>
<td>scattered radiation energy intensity (4.9)</td>
</tr>
<tr>
<td>j</td>
<td>subscript for jth particle</td>
</tr>
<tr>
<td>k</td>
<td>Boltzmann constant: (1.380662 \times 10^{-23}) J/k</td>
</tr>
<tr>
<td>(k_0)</td>
<td>differential scattering vector (4.11)</td>
</tr>
<tr>
<td>(k_s)</td>
<td>incident light wave vector (Fig.4.1)</td>
</tr>
<tr>
<td>(k_s)</td>
<td>scattered light wave vector (Fig.4.1)</td>
</tr>
<tr>
<td>L</td>
<td>H.C.D. arc length</td>
</tr>
<tr>
<td>m</td>
<td>mass; mode number</td>
</tr>
<tr>
<td>m_e</td>
<td>electron mass: (9.109534 \times 10^{-31}) kg</td>
</tr>
<tr>
<td>m_A</td>
<td>argon atom mass</td>
</tr>
<tr>
<td>M</td>
<td>number of measuring points (Table 6.2)</td>
</tr>
<tr>
<td>n</td>
<td>number of particles</td>
</tr>
<tr>
<td>n_e</td>
<td>electron density</td>
</tr>
<tr>
<td>N</td>
<td>number of laser pulses per measuring point (Table 6.2)</td>
</tr>
<tr>
<td>N_s</td>
<td>number of scattering centres (4.10)</td>
</tr>
<tr>
<td>(O)</td>
<td>cross section area of scattering column (4.2)</td>
</tr>
<tr>
<td>P</td>
<td>pressure</td>
</tr>
<tr>
<td>P_R</td>
<td>time average of Poynting vector in direction R (4.4)</td>
</tr>
<tr>
<td>Q</td>
<td>gas flow debit</td>
</tr>
</tbody>
</table>
\( r \) = radius, radial distance
\( r_0 \) = classical electron radius (4.3)
\( R \) = resistor
\( \mathbf{R} \) = radius vector
\( S \) = dynamic form factor (4.11)
\( t \) = time
\( \Delta t \) = laser pulse time
\( T \) = wavelength temperature scale
\( T_e \) = electron temperature
\( T_{1-T} \) = diaphragm tubes
\( U_{ij} \) = signal voltage of \( j \)th data point
\( \bar{U}_B \) = mean value of background radiation signal voltage
\( U_{\text{Emax}} \) = maximum value of laser energy signal
\( v_j \) = velocity of \( j \)th electron
\( V \) = (scattering) volume
\( W \) = \( kT_e/e \) = electron temperature scaled in eV
\( x, y, z \) = Cartesian coordinates
\( Z \) = ion charge
\( Z_0 \) = vacuum wave impedance

Greek

\( \alpha \) = \( \frac{1}{|\mathbf{k}|\lambda_D} \) = ratio between differential scattering wavelength and Debye length (4.12)
\( \alpha_L \) = divergence of laser beam
\( \varepsilon_0 \) = permittivity of vacuum: \( 8.85419 \times 10^{-12} \) F/m
\( n \) = optical transmission coefficient
\( \theta \) = scattering angle (Fig.4.1)
\( \lambda \) = (optical) wavelength
\( \lambda_D \) = Debye length
\( \lambda_0 \) = wavelength of incident laser light: 694.3 nm
\( \lambda_a \) = apparatus half width of monochromator: 0.7 nm
\( \Delta \lambda \) = \( \lambda - \lambda_0 \) = wavelength Doppler shift
\( \nu \) = frequency
\( \nu_0 \) = frequency of incident laser light
\( \sigma(\xi) \) = standard deviation of quantity \( \xi \) (Table 6.1)
\( \sigma_T \) = total Thomson scattering cross section: \( 6.65 \times 10^{-29} \text{ m}^2 \)
\( \sigma_h \) = half width of Gaussian profile (Fig. 4.2)
\( \tau \) = correlation time coordinate
\( \psi \) = angle between incident light electrical field vector \( \vec{E}_o \) and observer radius vector \( \vec{R} \)
\( \omega \) = angular frequency
\( \omega_E \) = electron eigen-frequency
\( \omega_P \) = plasma angular frequency
\( \omega_0 \) = angular frequency of incident laser light
\( \Omega \) = solid angle
4. Introduction

4.1. General Theory

The Thomson scattering experiment, described in this report was meant to measure electron density and temperature in the hollow cathode discharge (H.C.D.) test rig "John Luce", designed and constructed by the Euratom "Rotating Plasma" group of Boeschoten et al. [1].

The theory of electro-magnetic wave scattering in plasmas is extensively treated in general literature. Kunze [2] and Evans and Katzenstein [3] both give a brief review of the existing theories, the former gives a straightforward review, satisfactory to the engineer user, whereas Evans c.s. give more details about the mathematical support of the theory. In both survey articles much attention is paid to experimental results and extensive surveys of the existing literature are given.

As there was no intention to extend or improve existing theories on plasma-scattering of light, the necessary fundamental background of this report is fully based upon the references [2] and [3]. In these theories a free electron is regarded in the field of a linearly polarized E.M.-wave. This electron is accelerated in the electric field of the E.M.-wave and is emitting EM-radiation like a vibrating electric dipole. With the incident-beam wave vector \( \mathbf{k}_o \) and the scattered light wave vector \( \mathbf{k}_s = \frac{\omega_o}{c} \mathbf{R} \), in the direction of the observer, the scattering geometry is found from Fig.4.1.

The acceleration of the electron in the radiation field is given by

\[
\mathbf{F} = - \frac{e}{m} \mathbf{E}_o \cos \{ \mathbf{k}_o \cdot \mathbf{r}_j (t) - \omega_o t \} 
\]

(4.1)

where \( \mathbf{r}_j (t) \) is the position vector of the observed electron, other, not specified quantities can be found from the nomenclature. From (4.1) we see that the dipole field of the vibrating electron will be dependent upon time not only explicitly through the factor \( \omega_o t \) but also implicitly through the position vector \( \mathbf{r}_j (t) \), i.e. upon the motion of the electron. This means that next to the incident frequency the scattered light will contain additional frequencies characteristic to the electron motion. These additional frequencies yield the plasma information.
The electric field of the incident light beam is given by

\[ |E_0| = (2 \frac{E_L Z_0}{\phi \Delta t})^2 \]  

(4.2)

where \( E_L \), \( \phi \) and \( \Delta t \) are respectively laser energy, cross-section of focal spot in plasma and laser pulse time. With

\[ r_o = \frac{e^2}{4\pi \epsilon_0 m_e c^2} \]  

(4.3)

being the classical electron radius, the time averaged value of the Poynting vector in the direction \( \vec{R} \) of the observer yields:

\[ P_R = r_o^2 \frac{|E_0|^2}{2 Z_0} \sin^2 \phi \, d\Omega \]  

(4.4)

where \( \phi \) is the angle between \( \vec{R} \) and \( \vec{E}_0 \).

The total Thomson scattering cross section can be found by integrating (4.4) over a sphere, yielding

\[ \sigma_T = \frac{8\pi}{3} r_o^2 = 6.65 \times 10^{-29} \text{ m}^2 \]  

(4.5)

The Thomson scattering cross section, per unit solid angle, at angle \( \phi \) referred to \( \vec{E}_0 \) is defined by

\[ \frac{d\sigma}{d\Omega} = r_o^2 \sin^2 \phi \]  

(4.6)

The Thomson scattered energy from one electron in direction \( \phi \) in a small solid angle \( d\Omega \) is found from (4.2), (4.4) and (4.6):

\[ \Delta E_T = E_L \frac{d\sigma}{d\Omega} \, d\Omega \]  

(4.7)

For a Thomson scattering experiment, where the observed plasma volume equals \( \phi dz \), the solid angle of observation is \( d\Omega \) and the electron density is \( n_e \), the energy scattered into the detection system yield

\[ E_T = n_e E_L \frac{d\sigma}{d\Omega} \, d\Omega \, dz \]  

(4.8)
Here the assumption is made that all electrons scatter independently and that their signals can just be added. The conditions for (4.8) are treated in section 4.2.

The frequency dependency of the scattered signal can be found from a consideration of the Fourier transform of the auto-correlation function of the electric field $\mathbf{E}$ appearing in the Poynting vector [3]. The power spectrum of the scattered radiation is written

$$\tilde{I}(k, \omega) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{E_0(\bar{r}, t) E_0(\bar{r}, t+\tau)}{Z_o} e^{i \omega \tau} d\tau$$

yielding

$$I(k, \omega) d\omega d\Omega = \frac{n_s}{Z_o} \frac{|E_0|}{2} \frac{d\sigma}{d\Omega} S(k, \omega) d\omega d\Omega \quad (4.9)$$

where $n_s = n_e \int_0^\infty dz$ is the total number of scattering centres and,

$$S(k, \omega) = \frac{1}{\pi N} \int_{-\infty}^{+\infty} \sum_{j=1}^N \cos \{ k \cdot \mathbf{r}_j(t) - \omega \cdot t \} \cos \{ k \cdot \mathbf{r}_j(t+\tau) - \omega (t+\tau) \} e^{i \omega t} dt. \quad (4.10)$$

We see that the dynamic form factor $S(k, \omega)$ contains terms $\cos k \cdot \mathbf{r}_j(t) - \omega \cdot t$, which give account to Doppler shift frequencies $\omega_d = k \cdot \mathbf{v}_j$, where $k$ is the differential scattering vector defined in Fig.1. Thus it is the velocity component in the $k$-direction that gives the Doppler shift in the detected frequencies. Reversed, the frequency resolved detection of the Thomson-scattered light signal gives information upon the velocity distribution of the scattering centers (electrons). In the next section the conditions upon plasma and measuring equipment will be considered and some assumptions will be made, in order to simplify signal processing.

4.2. Limits of the Thomson Scattering Theory

The roughly sketched general Thomson scattering theory of the previous section can only be applied under certain limiting conditions, which may be superimposed by the plasma itself, the light source or the optical arrangement of the experiment.
1. Compton scattering. The photon energy $h\nu$ must be much smaller than the rest energy of the electron, $m_e c^2 = 0.5 \times 10^6 \text{eV}$ otherwise Compton scattering will occur, which deviates much from the classical Thomson scattering. For the ruby laser with $\lambda_o = 694.3 \text{ nm}$, $h\nu_o = 1.8 \text{ eV} < 0.5 \times 10^6 \text{ eV}$. This means that the classical Thomson scattering cross section (5) applies.

The observed scattered light must be due to free electrons. This means the plasma must be transparent to the incident light, so the frequency of the incident light must be much higher than the plasma frequency, $\omega_p = (n_e e^2 / \varepsilon_o m_e)^{1/2}$. For the electron densities $n_e = 10^{20} - 10^{22}$, $\omega \approx 10^{11} - 10^{12}$ rad/s, whereas $\omega_o = 2\pi v_o = 2\pi 4.32 \times 10^{14} \text{ rad/s}$, so $\omega >> \omega_p$.

2. Plasma frequency. The observed scattered light must be due to free electrons. This means the plasma must be transparant to the incident light, so the frequency of the incident light must be much higher than the plasma frequency,

$$\omega = (n_e e^2 / \varepsilon_o m_e)^{1/2}.$$ For the electron densities $n_e = 10^{20} - 10^{22}$, $\omega \approx 10^{11} - 10^{12}$ rad/s, whereas $\omega_o = 2\pi v_o = 2\pi 4.32 \times 10^{14}$ rad s$^{-1}$, so $\omega >> \omega_p$.

3. Electron oscillation. The simplified dipole theory for the scattering electron can only be applied for the case of non-relativistic electron velocity, $v_e << c$, and amplitudes of the electron oscillation $<< \lambda_o$. Here the condition $e |\mathbf{E}_o| / m_e \omega_o c \ll 1$ should hold. For the ruby laser used, with normal pulse operation of 1 ms duration and 30 J energy, focused to 1 mm$^2$ focal spot, the left hand side of the inequation is $7.10^{-6}$.

4. Electron density fluctuations. It is the fluctuation of the electron density that yields the scattering effect of the incident light. Evans [3] shows from the expression of the dynamic form factor $S(\mathbf{k}, \omega)$ that for two particle correlation there exists a correlation length, viz. the Debye shielding length $\lambda_D$ and that the scattered intensity contains a part due to the fluctuations of free electrons and a part due to the fluctuations of electrons which are correlated with the motion of ions. There is no correlation of the electron scattered signals if $|\mathbf{k}| >> \lambda_D^{-1}$, or otherwise defined if

$$a = \frac{1}{|\mathbf{k}| \lambda_D} = \frac{\lambda_o}{4\pi \lambda_D \sin \theta} \ll 1 \quad(4.12)$$

For the plasmas under consideration with $T_e = 5 \text{ eV}$ and $n_e = 5.10^{19}$, we find $\lambda_D \approx 2.10^{-6} \text{ m}$, so for scattering angle $\theta = 90^\circ$ $a \approx 0.04 \ll 1$. This means the scattered intensity is due only to free electron scattering, and $S(\mathbf{k}) = 1$; the case of normal Thomson scattering.
5. **L.T.E. and Maxwell-distribution.** For the plasma conditions, mentioned in section 4, it has been shown by van der Sijde [5] that the population of the important energy levels is mainly caused by electron-collision, whereas the de-population of these energy levels is caused by spontaneous emission for over 50%. So no L.T.E. can be assumed. On the other hand, measurements of the authors and others on the same kind of H.C.D. give no indication to deviation of the Maxwell-distribution of the free electrons, so the Maxwell-distribution of the free electrons, so the Maxwell-distribution is assumed to hold.

6. **Plasma disturbance by incident light.** The diagnostics tool used should not influence the measured object: so the incident laser light should neither enhance the electron energy, nor increase the electron density. The electron energy can be influenced in two ways:

   a. The electron picks up energy from the electric field of the incident wave. The maximum energy of an electron in the wave field is

   \[
   E_{\text{max}} = \frac{1}{4} m_e v_{\text{max}}^2 = \frac{1}{m_e} \left( \frac{e \lambda_o}{2\pi c} \right)^2 z \frac{E_L}{\Delta t}
   \]  

   (4.13)

   For the experiment with laser energy \( E_L = 30 \text{ J} \), focussed into a focal spot \( 0 = 1 \text{ mm}^2 \) in normal pulse operation, \( \Delta t = 10^{-3} \text{ s} \),

   b. The electron absorbs bremsstrahlung from the incident light, according to Evans [3];

   \[
   \frac{\Delta W}{W} = 5.32 \times 10^{-11} \frac{n_e Z}{W^{3/2}} \frac{\lambda^3}{\lambda_o} \sigma_o \frac{\nu}{W} \frac{E_L}{W}
   \]  

   (4.14)

   with \( W = \frac{e}{kT} \) in eV. For the above mentioned situation this yields

   \[
   \frac{\Delta W}{W} = 1.7 \times 10^{-4}, \text{ also being negligible.}
   \]

   At last laser energy could be absorbed by excitation and ionization of the heavy particles (\( A^+ \)-ions). As no plasma lines are present at \( \lambda_o \) and the upper energy levels are rarely populated because there is no Saha-Equilibrium [5], whereas the ionization energy \( E_i(A^+) \) is much higher.
than the photon energy $h \nu_0$, no laser induced ionization will take place. The plasma will not be disturbed by the incident laser light.

7. Spatial Dimensions. The dimensions of the system should be such that the wavelength ($\lambda_0$) be small with regard to the electron position vector ($|\vec{r}_j|$), which on its turn should be smaller than the detector position vector ($|\vec{R}|$): $\lambda_0 \ll |\vec{r}_j| \ll |\vec{R}|$. With $|\vec{r}_j| = 10^{-3} \text{m}$ and $|\vec{R}| = 0.5 \text{m}$, these conditions are fulfilled.

4.3. Thomson Scattering Spectrum

Within the limits mentioned in section 4.2 and with the assumption of a Maxwellian distribution of the free electrons, the form factor $S(\vec{k}, \omega)$ (4.11) has a Gaussian profile, given by

$$S(\vec{k}, \omega) \, d\omega = \left(\frac{m_e}{2\pi |\vec{k}|^2 kT_e}\right)^{\frac{1}{2}} \exp\left(-\frac{m_0^2}{2|\vec{k}|^2 kT_e}\right) \, d\omega$$

With (4.2) and (4.10) we obtain for the detected energy spectrum the following expression

$$I(\vec{k}, \omega) \, d\omega \, d\Omega \, dV = n_e \, \frac{E_L}{c} \, d\sigma \left(\frac{m_e}{2\pi |\vec{k}|^2 kT_e}\right)^{\frac{1}{2}} \exp\left(-\frac{m_0^2}{2|\vec{k}|^2 kT_e}\right) \, d\omega \, d\Omega \, dV$$

where $|\vec{k}| = \frac{\omega_0}{c} \sin \theta$ and $dV$ the observed volume. Integrating (4.16) over the frequency range $- \infty < \omega < + \infty$ yields eq. (4.8). Equation (4.16) offers the possibility of measuring the electron temperature from the measured energy profile. For the experiment under consideration $\theta = 90^\circ$ and the dispersing element, a monochromator, is calibrated in wavelength units, so (4.16) can be transformed to the wavelength region and expressed in terms of detected energy, giving

$$E(\Delta \lambda) \, d(\Delta \lambda) = n_e \, \frac{E_L}{c} \, d\sigma \, \frac{1}{\lambda_0} \left(\frac{m_e}{4\pi kT_e}\right)^{\frac{1}{2}} \exp\left(-\frac{m_0^2}{4kT_e\lambda_0^2}\right) \, dV(\Delta \lambda)$$

where $\lambda = \lambda_s - \lambda_0$. For the Maxwellian velocity distribution of the electrons we obtain the well known Gaussian curve of Fig. 4.2.
This curve being measured, the electron temperature can be found from the halfwidth $\sigma_4$
\[
\sigma_4 = \frac{\lambda}{c} \left( \frac{16 kT \ln 2}{m_e} \right)^\frac{1}{2}
\]
whereas the electron density can be found from the area enclosed by the curve and the abcis. These points will be discussed further in section 6.4.

4.4. Rayleigh Scattering

Besides the scattering by free electrons also the scattering by bound electrons should be considered. For particles where the eigenfrequency of the electrons ($\omega_{E}$) is much higher than the incident light frequency $\omega_0$. Kunze [2] gives the following expression for the scattering cross-section per unit solid angle ($\omega_0 \ll \omega_{E}$):
\[
\frac{d\sigma}{d\Omega} = r_o^2 \sin^2 \theta \cdot \left( \frac{\omega_0}{\omega_{E}} \right)^4
\]
For neutral particles this means the scattering cross-section per atom is determined by the total polarizability of the atom. This is known as the Rayleigh scattering. Comparing (4.6) and (4.19) we see that for fully ionized plasmas, like the H.C.D., the Rayleigh scattering will not play any role. On the other hand, for plasma's with an abundance of neutral particles, like MHD-generating plasma's, the Rayleigh scattering can outrange the Thomson scattering by far. However, the ratio of halfwidths of the Rayleigh and Thomson scattering spectra is proportional to $(\frac{m_e}{m_h})^\frac{1}{2}$, which means that the Rayleigh scattering spectrum will be found very close to the central wavelength $\lambda_0$, whereas the Thomson scattering spectrum can be measured easily in the region outside the central line. The Rayleigh scattering can be made very useful as a tool to calibrate the detection system of the Thomson scattering experiment, as described in section 6.4.
Fig. 4.1 Scattering geometry: $\vec{k}_o$ = incident wave vector, $\vec{k}_s$ = scattered wave vector and $\vec{k}$ = differential scattering wave vector.

Fig. 4.2 Energy spectrum of Thomson scattering at electrons with Maxwellian distribution.
5. Thomson Scattering Equipment (T.S.E.)

The Thomson scattering measurements were performed at the hollow cathode discharge "John Luce" [1]. The measurements were especially focussed to the determination of the electron density and temperature in the core of the positive column where probe measurements were impossible and other spectroscopic techniques did not produce the wanted results. Besides these measurements were performed to obtain experience in this difficult diagnostic and to investigate if Thomson scattering can be applied to MHD-generating experiments, working with an Argon-Cesium plasma.

The aim of the experimental lay-out was to determine how $n_e$ and $T_e$ depend upon the radius and axial coordinate. The behaviour of $n_e$ and $T_e$ as a function of $r$ and $z$ is very important for the performance of the H.C.D. and the determination of these quantities will be a great support to the theoretical modelling of the H.C.D. These goals have been of influence of course upon the lay-out of the T.S.E.

The H.C.D. experiment is extensively described by Boeschoten, [1]. The parameters of the discharge can be varied in a wide range:

- **gas**: Ar, Ne, He, H₂
- **pressure**: $10^{-2} - 10^{-3}$ torr
- **gasflow**: $Q = 0.5 - 8$ cm$^3$ NTP s$^{-1}$
- **arc length**: $L = 0.5 - 2$ m
- **current**: $i = 25 - 200$ A
- **magn. induction**: $B = 0 - 0.51$ T
- **cathode diameter**: $d_c = 6 - 20$ mm

The T.S. measurements were mainly performed at Ar, at standard conditions: $Q = 2.5$ cm$^3$ NTP s$^{-1}$, $L = 1.5$ m; $i = 50$ A, $\mu_0T_d = 9$ mm.

5.1. Optical Arrangement

Fig.5.1. gives an overall view of the H.C.D.-vessel and the optical bench. It shows a cross section of the H.C.D. vessel with two optical axes perpendicular to each other and to the axis of the H.C.D. The optical bench can be moved in vertical direction over 8 cm.
in order to scan along the radius of the discharge (ARC).

The ruby laser light is focussed into the discharge through a coated quartz window $W_1$, along the horizontal optical axis, the optical devices like ruby laser cavity, energy monitor, diaphragms and lenses being mounted on the upper bar. In the H.C.D.-vessel two adjustable tubes are mounted horizontally, $T_1$ equipped with three diaphragms to intercept incident stray light and $T_2$ with a diaphragm and Brewster-plate beam dump. $T_1$ and $T_2$ can be aligned along the optical axis.

The 15 cm long ruby-cristal produces a laser light beam of 16 mm diameter ($d_L$) and 8 mrad divergence ($a_L$). In normal mode operation, as it was used, the energy production is 30 J at the focal point in the plasma. The laser beam is focussed with the first lens ($f_1 = 150$ mm) into a focal plane stop (not shown) and with a second lens ($f_2 = 250$ mm, $d_2 = 50$ mm), projected into the plasma column. The diameter of this focal point is found from

$$\Delta y = \frac{d_L \alpha}{d_2/f_2}, \text{ yielding } \Delta y = 1.28 \text{ mm}.$$ (5.1)

This measure defines the energy density of the laser beam in the observed plasma volume. Spheric aberration can be neglected here. The axis of observation is arranged vertically in the H.C.D.-vessel. Again two tubes protect the detector system from stray light, $T_4$ contains two diaphragms and a Brewster-plate to provide a black background, $T_3$ contains three diaphragms, the middle one defining the maximum solid angle of observation, a coe of 222 mm height and 19 mm basic diameter, yielding $d\Omega = 5.75 \times 10^{-3}$ ster. The detector itself is mounted upon the lower optical bar, together with prism $P$, lens $L_3$, and a series of filters $F_1 - F_2$. The lens $L_3$ ($f_3 = 200$ mm, $d_3 = 70$ mm) provides a 2.5 times enlarged image of the entrance slit of the monochromator $M$ upon the observed plasma volume. The height of the entrance slit is projected along the axis of the discharge, thus obtaining an optimal spatial resolution in the radial direction, however the observed volume is not maximal.

The set of filters $F_1 - F_2$ include a polarization filter, to reduce the plasma background light by a factor 2 and a yellow filter to reject the UV-lines of the plasma around 350 nm that might reach the exit slit in second order, and to reduce some intense blue lines.
The monochromator is equipped with a 1200 lines/mm grid, blazed for 700 nm, yielding at 250 mm focal length a dispersion of 3.3 nm/mm. Using a slit width of 200 μm we obtain an instrumental profile halfwidth $\lambda_i$ of 0.66 nm, which was actually measured at narrow shaped argon lines.

A high quantum efficiency photomultiplier P.M. with Ga-As-cathode was used as the photo-electric detector. To transmit all detected photons from the exit slit of the monochromator upon the $4 \times 10 \text{ mm}^2$ photo-cathode, a lens $L_4$ ($f_4 = 20 \text{ mm}$) was used to project a soft image of the exit slit upon the photo-cathode, see Fig.5.2. The heated window $W_3$ protects the cooled photomultiplier tube from deposit of condens.

All these optical devices together severely reduce the number of photons falling upon the PM-cathode. Further technical data of these devices can be found from Appendices A.1. through A.6.

5.2. Electrical Arrangement

Fig.5.3 shows the general lay-out of the electrical system. The laser power supply unit (App.A.1), with 2400 μF capacitor bank and 2.4 kV maximum voltage, feeds the Xe-flash tube in the laser cavity. The laser output is maximal 55 J in the normal mode and is measured by the energy monitor, which is calibrated with a calorimeter for the energy reaching the focal spot in the plasma, being 30 J. A photo-diode behind the beam dump Brewster plate gives the real time laser light signal. The scattered light from the plasma is detected by a photomultiplier, cooled to -40 C, Ga-As-cathode yielding 12 - 20% quantum-efficiency in the 690 nm range (App.A.5). The scattering and laser energy signals are displayed on a double beam persistence oscilloscope, whereas these signals together with trigger pulse and laser light real time signal are recorded on a magnetic tape recorder for data-processing in a later stage. For recording of the back-ground H.C.D.-spectrum the photomultiplier can be connected to the x-y-recorder. The grid of the monochromator is driven by a stepping motor and its position is electrically transmitted by means of a 20 turns potentiometer. Further technical specifications of the electrical equipment can be found from Appendices A.7 through A.9.
FIG. 5.1 General layout of the Thomson scattering equipment.

FIG. 5.1 LASER EQUIPMENT

RL  RUBY LASER
EM  ENERGY MONITOR
BP  BREWSTER PLATE
P   PRISM
M   MONOCHROMATOR
PM  PHOTOMULTIPLIER
DI-D3  DIAPHRAGM
F1-F2  FILTER
L1-L4  LENS
T1-T4  TUBE
W1-W3  WINDOW
Fig. 5.2 Mounting of photomultiplier tube to exit slit of monochromator.
Fig. 5.3 General electric diagram of the Thomson scattering equipment.
6. Experimental Results

The preceding chapter and the associated Appendices A.1 through A.10 give the details of the lay-out of the Thomson scattering equipment. The detection system collects and transforms the scattered light signals. The recording and further processing of this data is described in the following sections.

6.1. Data Collecting and Recording

The wavelength dependent scattered light intensity, collected by the detection system as a function of time, is transformed by the photomultiplier into an electrical signal, see App.A.5. The voltage over anode resistor \( R_2 \) is AC-coupled to the display instrument, a Tektronix persistence oscilloscope, App.A.7. The C.R.O. display allows for direct reading, to have a first impression upon the experimental results, and may be fixed by polaroid pictures. On the other hand, the measured voltage is amplified and supplied to a high speed tape recorder with 60 inch/s recording speed, which can be replayed at a speed of 1 7/8 inch/s. This offers the possibility of further data processing by means of a VARIAN process computer, App.A.10, in order to obtain the most extended information upon Thomson scattering and background radiation, statistical behaviour, reproducibility and error sources.

The recorded signals are: (Thomson) scattered light intensity, incident laser light intensity, laser energy and trigger pulse.

6.2. Data processing

The first stage of the data processing is performed by the VARIAN computer (App.A.10). The following signals have been used: scattered light intensity \( I(\lambda,t) \), laser energy \( E_L \) and the trigger pulse of the laser supply unit, Fig.6.1 and Fig.6.2.

The trigger pulse, which triggers the scope and the computer reading, defines the point \( t = 0 \) on the time axis. The laser always starts emitting at \( t = 1 \text{ ms} \), visualized by the energy signal \( E_L \) which rapidly increases at \( t = 1 \text{ ms} \) until the laser stops emission where \( E_L \) reaches its maximum value.
$U_{\text{Emax}}$. This value is reached around $t = 3 \text{ ms}$. All scattering measurements are referred to one standard value of the laser energy $E_{L_0}$. The scattered light signal lasts 2.5 to 3 ms which is clearly shown by the Rayleigh scattering signal in Fig. 6.3.

To be sure that the entire scattered signal will be measured, $I(\lambda, t)$ is integrated from $t = 1$ through $t = 4 \text{ ms}$. This integration is neither referred to the abcis $u = 0$, nor to the mean value of the background signal $\bar{u}$, but to the straight line piece $\bar{u}_{75} - \bar{u}_{300}$, yielding the hatched area in Fig. 6.1.

To overcome problems caused by spike signals on $I(\lambda, t)$, the $I(\lambda, t)$ curve is smoothed by introducing local mean values $\bar{u}_j$ first, by averaging over 25 momentary values around point $t_j$, yielding the dotted line.

In order to obtain information upon the signal-to-background noise-ratio also the background radiation alone was observed. In our experiment we have the case of the plasma lifetime being much longer than the laser pulse, as treated by Kunze [2] and Evans [3], where the ratio of the scattered light to the level of fluctuations on the plasma light is significant. Rather, in the H.C.D.-plasma it is not just the electron-ion bremsstrahlung and its statistical behaviour that play a role in the background light but moreover the stray light of some strong argon-ion lines from within the monochromator. This stray light fluctuates because of stochastic processes and some specific kinds of instabilities in the positive column of the H.C.D. and 12th harmonics of the network frequency, due to the S.C.R. power supply. These fluctuations at 30 kc/s and 600 c/s determine the data sampling. The sampling duration is chosen to be ten times the low frequency period, yielding 16 ms, whereas during each high frequency period at least two samples should be taken, giving a sample time of less than $16 \times 10^{-6} \text{ sec}$. The amount of samples than yields 1000. Actually a sample time of 13.3 $\mu$s was chosen.

The scattered light signal (3 ms) thus contains 225 samples, ranging from $j = 76$ through $j = 300$. During each sampling sequence 1500 samples were taken.

The background signal ranges from $j = 501$ through $j = 1500$ or on real time scale from $t = 6.66$ to $t = 20 \text{ ms}$. From these data of the background signal the mean value ($\bar{u}$), the variance ($\text{var}(u)$) and the standard deviation ($\sigma(u)$) were calculated. The influence of these quantities upon the accuracy of the final results will be treated in section 6.3.
6.3. Errors and Error Sources

Regarding the complexity of the Thomson scattering diagnostic, the behaviour of the H.C.D. and the way the curve $E(\lambda)$ in Fig.4.2. is measured by changing $\lambda$ step by step, it is clear that many error sources exist and errors are introduced in the experimental results. Systematic errors, due to parameter settings of the H.C.D., calibration and reading of general instrumentation are mostly known and can be taken into account but will prove to play a minor role in the overall accuracy of the measurements. So attention will only be given to the main error sources that are inherent to the specific experiment.

6.3.1. Laser Stray Light

In section 5.1. it has been emphasized that much effort is made to reduce the amount of laser stray light that enters the detecting system. This is necessary because the incident laser energy is rated to the Thomson scattered energy by a factor $10^{12} - 10^{14}$. Fortunately the laser stray light is only present at the central laser line 694.3 nm, but when its energy level in the detection system is high, it can be detected at the exit slit of the monochromator by multiple reflections inside the monochromator, which has a rejection ratio of $10^{-3}$ for blocked to transmitted wavelengths. For the reported experiments the laser stray light level at 694.3 nm was of the same order as the Rayleigh scattering at 5 torr $N_e$, or about four times the total Thomson scattering signal at $n_e = 10^{20} \text{ m}^{-3}$. This proved to be acceptable because the stray light level rapidly decreases at 697 nm from the central line.

6.3.2. Plasma Background Radiation

The Argon-plasma used in the experiments, although being nearly fully ionized still produces some strong neutral Argon lines in the region of interest. Especially the $\text{A}^\text{I}$ lines 696.543 nm and 706.7 nm may contribute to the background level which is caused by multiple reflections in the monochromator, whereas the $\text{A}^\text{I}$ lines at 687.129, 688.817, 693.767, 696.543 and 703.026 lay within the region of interest just leaving small intervals for measuring the Thomson scattered signals. Most data is sampled between 693.767 and 688.817 nm whereas two points were measured around 700 nm.
In so far as the background radiation is constant, it can be offset by A.C.-coupling of the P.M.-output, however there are fluctuations of the background radiation, caused by stochastic emission and detection processes, but also at the aforementioned specific frequencies 600 c/s and 30 kc/s. The latter is caused by a m = 1 mode rotation of the positive column of the H.C.D. as was measured with a streak camera [1], Fig.6.4, actually yielding f = 19 kc/s. The contribution of these fluctuations to the 3 ms scattering signal may cancel rather well (see Table 6.1.). The 600 c/s fluctuation is caused by the 12th harmonic current ripple and works in two ways, first through the fluctuation of background radiation, second through fluctuation of the actual value of T_e (and n_e). It is of the same frequency order as the signal pulse and will therefore severely interact with the measuring results. This is the more true as the E(A) is not measured simultaneously at a series of λ-values, but is measured step by step, so weak correlation will exist between any single set of measurements. So at each λ-setting 10 (or 20) measurements were made and mean values and standard deviations of the measured signals were calculated, thus increasing the final accuracy at cost of time consuming measurements.

<table>
<thead>
<tr>
<th>(Δλ)^2</th>
<th>E(Δλ)</th>
<th>σ(E)</th>
<th>ΔO</th>
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Table 6.1
Measuring results at z = 70 cm; d_c = 9 mm; standard conditions of H.C.D.
E(Δλ) = mean Thomson scattering signal (4.17); 10 pulses per measuring point.
σ(E) = standard deviation of mean Thomson scattering signal.
ΔO = contribution of standard deviation of mean background radiation during measuring time (3 ms).
6.3.3. Photon Absorption

From the optical arrangement, described in section 5.1 it is clear that the scattered light has to pass a lot of air-glass or mirror surfaces in the detection system before it falls upon the photo-cathode of the P.M. Along this path a lot of signal will be lost by reflection or absorption. To calculate the transmission of the detecting system, the transmission of every optical element should be known. Now, for glass bodies the transmission is mostly given for perpendicular incident light, whereas in the experimental set up incident rays are not always perpendicular to the air-glass surfaces, so a lower transmission will be found. Straight through calculation of the total transmission coefficient yields $\eta = 13.5\%$.

As the calculation of $n_e$ with (4.17) from the Gaussian curve, Fig.4.2, is based upon an absolute measurement, with exactly known transmission coefficient, it proves to be necessary to calibrate the detection system. This is performed by measuring Rayleigh scattering at $N_2$, with a well known scattering cross section and a well defined solid angle of observation $d\Omega = 5.75 \times 10^{-3}$ ster$^r$. This method has the advantage that the calibration is made at exactly the same optical conditions as the actual experiments. The total transmission coefficient was found to be $\eta = 10.2\%$. To obtain this value also the quantum efficiency and amplification factor of the P.M. should be known. These were measured by standard methods. The accuracy of $n_e$ measurements is related directly to the accuracy to which the cross section ($\frac{d\sigma}{d\Omega}$) is known ($1.84 \times 10^{-32}$ m$^2$).

6.3.4. Quantum Statistical Behaviour

For the experimental region of interest, $n_e = 10^{20}$ m$^{-3}$ and $T_e = 5$ eV, the number of photons that reach the photo cathode of the P.M. by Thomson scattering can easily be estimated.

From (4.6) with $\vartheta = 90^\circ$ the T.S. cross section per unit solid angle is found

$$\left(\frac{d\sigma}{d\Omega}\right)_{90} = 7.95 \times 10^{-30} \text{ m}^2/\text{ster}$$

With $dz = 5.14 \times 10^{-4}$ m, $d\Omega = 5.75 \times 10^{-3}$ and $E_L = 30$ J the total energy scattered into the detection system yields (4.8)

$$E_T = 7.05 \times 10^{-14} \text{ J}$$
The total number of T.S. photons entering the detection system is

\[ n_{fd} = \frac{E_{Th}}{h\nu_0} = 2.47 \times 10^5. \]

The instrumental half width \( \lambda_h \) of the monochromator being 0.7 nm and the half width \( \sigma_h \) of the T.S. curve being 7.23 nm, the number of photons on the centerline \( (\lambda) \) collected at the photo cathode will be:

\[ n_{fc} = n_{fd} \cdot \frac{\lambda_h}{\sigma_h}, \eta = n_{fc} = 2.44 \times 10^3 \]

The quantum efficiency of the P.M. was measured to be \( \text{QE} = 0.107 \), so the mean number of photo electrons emitted by the cathode during a laser pulse will be \( n_{ec} = 503 \).

As the electron emission is a stochastic process the standard deviation of the emitted electrons is:

\[ \sigma(n_{ec}) = 22, \quad \frac{\sigma(n_{ec})}{n_{ec}} = 4.5\% \]

At any other \( \lambda \)-setting the number of photo-electrons will be smaller and the relative standard deviation will be higher, at \( \sigma_{\eta} \) yielding 6.3\%. To obtain an accurate mean value of \( n_{ec} \) several measurements at each \( \lambda \)-setting are necessary. From table 6.1 we see that the standard deviation due to the plasma behaviour is still much higher.

### 6.4. Electron Temperature and Density

In Fig.6.5 the Gaussian energy profiles of the Thomson and Rayleigh scattering signals are represented (at different arbitrary scales). Taking the logarithm of (4.17) we see that \( \ln E(\Delta\lambda) \) is a linear function of \( (\Delta\lambda)^2 \):

\[ \ln E(\Delta\lambda) = C_1 - \frac{m_c^2}{4kT_e} \frac{(\Delta\lambda)^2}{\lambda_0^2} \]

so representing \( \ln E(\Delta\lambda) = F(\Delta\lambda)^2 \) yields a straight line a shown in Fig.6.6. The electron temperature is inversely proportional to the coefficient of \( (\Delta\lambda)^2 \). Scaling the abscissa with \( T = \frac{mc^2}{4e} \frac{(\Delta\lambda)^2}{\lambda_0^2} \) yields as a unit "eV".
With the straight line $\ln E(\Delta \lambda) = b + a \left[ \frac{BE^2}{4e} \frac{(\Delta \lambda)^2}{\lambda_0^2} \right] \quad (6.2)$

known from measurements, the electron temperature can be found from

$$\frac{T_e}{T} = \frac{1}{a} \quad (6.3)$$

whereas

$$b = \ln E_o \quad (6.4)$$

contains the information to calculate $n_e$.

The straight line (6.2) is found as a least squares approximation to the measuring points, each weighted with the inverse of its standard deviation (see Table 6.1). This was performed with the standard procedure WEIGHTED MULTIPLE REGRESSION. As a result of these calculations we obtain the coefficients $a$ and $b$, each with its variance and standard deviations.

So $T_e$ and $\sigma(T_e)$ are found with (6.3).

$E_o = \exp (b)$ is a measure for the electron density. As the absolute sensitivity of the detection system is not known the calibration with the Rayleigh scattering is used [6]. The R.S. profile is much more narrow than the instrumental half-width $\lambda_i = 0.7$ nm of the monochromator, so at setting $\lambda = \lambda_o$ the total R.S. energy is measured in one pulse, $E(\Delta \lambda)d(\Delta \lambda) = E_{RS}\lambda_i$ (Fig.6.5).

The total T.S. energy equals $E(\Delta \lambda)d(\Delta \lambda) = E_o\sigma_{\lambda_i}$ with $\sigma_{\lambda_i}$ given by (4.18).

From the scattering cross section $\frac{dC_0}{d\Omega}$ for $N_2$ and electrons (sections 6.3.3. and 6.3.4.) it is found that the total R.S. energy at $p = 1.30$ torr $N_2$ equals the total T.S. energy at $n_e = 10^{20}$ m$^{-3}$.

$$E_{RS1.3} \times \lambda_i = (E_o)n_e = 10^{20} \times \sigma_{\lambda_i}$$

Thus the electron density can be calculated from

$$n_e = E_o \frac{\sigma_{\lambda_i}}{E_{RS}\lambda_i} \frac{P}{1.3} \times 10^{20} \text{ m}^{-3} \quad (6.5)$$

where $E_{RS}$ is measured at pressure $p$ torr.

The standard deviation of $n_e$ is found from $\sigma(b)$ through

$$\frac{\sigma(n_e)}{n_e} = \left( \exp\{\sigma(b)\} - 1 \right) \frac{1 - \exp \{ -\sigma(b) \}}{\sigma(b)^2} \quad (6.6)$$
Although many measurements were made with the T.S. diagnostic, only three series of measurements were elaborated with the time consuming method presented in this report. The results are summed up in Table 6.2. The measurements were made at two positions of the H.C.D., with distance $Z$ from the cathode being 70 and 90 cm respectively. 6 measuring points ($M$) of measurements II have been repeated after several hours of operation of the H.C.D. to check the repeatability, laid down in resp. in III and IV. Comparing the results of the repeatability check (IV) with the data derived from the corresponding preceding measuring points (III) yields a good agreement within the accuracy range for $T_e$ whereas the value of $n_e$ is beyond the limits defined by $\sigma(n_e)$. This might partly be due to an inaccuracy of the R.S. calibration, which was observed to be 10%, probably caused by incorrect settings of instruments. The measuring results shown in Table 6.1 are concentrated in measurements II in Table 6.2. The semi logarithmic plots of the T.S. lines of the measurements are represented in Figure 6.7 through 6.9.

<table>
<thead>
<tr>
<th>$Z$</th>
<th>$M$</th>
<th>$N$</th>
<th>$T_e$ (eV)</th>
<th>$\sigma(T_e)$ (eV)</th>
<th>$n_e$ ($10^{20}$ m$^{-3}$)</th>
<th>$\sigma(n_e)$ %</th>
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<td>I</td>
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<tr>
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<td>10</td>
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<td>90</td>
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<tr>
<td>IV</td>
<td>90</td>
<td>6</td>
<td>4.6</td>
<td>0.5</td>
<td>2.71</td>
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</tr>
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Table 6.2. Measuring results of $T_e$ and $n_e$ at two positions ($Z$) of the H.C.D. $M =$ number of measuring points; $N =$ number of laser pulses per measuring point. Measurements IV compared with III denotes the repeatability of the experiments.
Fig. 6.1 Schematic view of the processed signals. The hatched area enclosed by the $I(\lambda,t)$-curve and $\bar{u}_{75}-\bar{u}_{300}$ is the wanted scattered light signal. $U_{E_{\text{max}}}$ determines the laser energy.
Fig. 6.2 Example of the Thomson scattering signal, directly measured with the storage C.R.O.

Fig. 6.3 Rayleigh scattering signal, directly measured with the storage C.R.O.
Fig. 6.4a Streak photograph of the core of the H.C.D.:
streak length 200 μs, slit width 0.5 mm, z = 60 cm,
d_c = 9 mm, standard arc conditions.

Fig. 6.4b Streak photographs for various values of arc current i

i = 25 A

i = 50 A

i = 75 A
Fig. 6.5 Schematic view of Thomson scattering and Rayleigh scattering energy profiles.

Fig. 6.6 Thomson scattering energy profile in semi logarithmic representation: $\ln E(\Delta \lambda) = b + a.(\Delta \lambda)^2$. 
Fig. 6.7 Measurements series I, with 8 measuring points. The ramp of the straight line gives an electron temperature $T_e = 5.7$ eV, $\ln(E_0) = 6.80$ yields for the electron density $n_e = 1.87 \times 10^{20}$ m$^{-3}$. 
Fig. 6.8. Measurements series II, with 10 measuring points. The ramp of the straight line gives an electron temperature $T_e = 5.9$ eV, $\ln(E_o) = 6.79$ yields for the electron density

$$n_e = 2.03 \times 10^{20} \text{ m}^{-3}.$$
Fig. 6.9 Measurements series III(0) and IV(+), with each 6 measuring points. Comparing IV with III gives a check for the repeatability of the measurements.

$T_e(III) = 5.5 \text{ eV}; \ln(E_0) = 6.83$ yields $n_e(III) = 2.03 \times 10^{20} \text{ m}^{-3}$.

$T_e(IV) = 4.6 \text{ eV}; \ln(E_0) = 7.20$ yields $n_e(IV) = 2.71 \times 10^{20} \text{ m}^{-3}$. 
7. Conclusions

The Thomson scattering measurements, performed at the "John Luce" H.C.D have proved that the T.S. diagnostic is a valuable method to measure electron temperature and density in the density range of $10^{20}$ m$^{-3}$ with high spatial resolution. This means that in principle the T.S.D. is applicable to MHD generating experiments where the same order of electron density is present.

On the other hand the experiments have shown that still a greater effort has to be put into the optical arrangement of the equipment, especially into the detection path. More sophisticated optical arrangements should be used to reduce the severe effect of laser stray light and plasma background radiation. Moreover this is necessary because in MHD generation plasmas the Argon density is much higher than in the H.C.D. and Cs or K seed will increase the background radiation.

The accuracy depending upon fluctuations, represented in Table 6.2, is acceptable in regard with the relatively simple experimental lay-out. This can be improved by using a more sophisticated detection path as will be described in chapter 8. Absolute accuracy depending upon systematic errors of standard equipment and introduced by the theoretical assumptions can be taken into account.
8. Recommendations

The recommendations to be made are mainly involved with improvement of the system performance. In the previous chapters improvements have been suggested already for several specific elements of the equipment. These will be specified now in sections 8.1 through 8.5. In section 8.6, some remarks will be made in case analog data recording will be continued.

8.1. Simultaneous Spectrum Measuring

The step by step scanning of the T.S. curve by one P.M. is not only time consuming but introduces extra inaccuracy by relatively bad correlation between the measuring points, due to the plasma fluctuations. This problem can be overcome by simultaneously measuring the T.S. spectrum with a set of 5 or more P.M.'s, attached to a multy lead optical fibre. Then at each laser pulse 5 or more points of the T.S. spectrum are measured in strong correlation. Averaging over a number of laser pulses will produce much higher accuracy.

8.2. Three Monochromators Filtering

The most important limitation to the T.S.D. is the background radiation of the plasma reaching the exit slit of the monochromator by multiple reflections at the inner walls. This effect can be suppressed by a factor $10^{-3}$ using a second monochromator in series, whereas the T.S. signal is only decreased by a factor $43$. A more refined method was recommended by Evans [ref.7], based upon a paper of van Cittert [ref.8]. Here three monochromators are used; the first in normal operation, the second in the reversed mode and the third again in normal operation. The exit slit of nr. 1 is the inlet slit of nr. 2, and so on. With good optical alignment a reduction of the stray light level by a factor $10^{-12}$ should be possible. The exit slit of nr. 1 should be so wide to give way to the full T.S. spectrum. The central line, containing R.S. and laser stray light can be intercepted by a thin, wire like blocking area. This lay-out has the advantage that no extended measures ought to be taken to suppress the laser stray light in the plasma container. A disadvantage is that calibration with R.S. will not be possible in this case.
8.3. Photon Counting

Having in mind the number of photo-electrons leaving the photo-cathode at $\lambda = \lambda_0$, $n_0 = 500$, within an interval of 1.5 to 2 ms, we know it is possible with nowadays electronic counters, with counting speed of 100 Mc/s, to count the resulting anode current pulses at the P.M. directly, at a reasonable price. This means that at any measurement the T.S. pulse together with the background radiation are integrated over the measuring time. Repeating the measurement without laser pulse gives the background signal which can be substracted from the combined signal, thus giving the integrated T.S. pulse directly, within the limits superimposed by the kind of background radiation fluctuations. From this technical point of view photon counting is preferable because it can be substantially increase the accuracy and the speed of data processing because the signals are already available in digital mode.

8.4. Improvements on Optical Transmission

We have seen in section 6.3.3. that the transmission factor of the actual detection is rather low, $\eta = 0.102$. This transmission factor would severely be decreased using the 3-monochromators filtering method, because the original monochromator has a transmission $\eta_M = 0.31$. Now the photons in the detection path have to pass through many air-glass surfaces and 4 aluminum mirrors in the monochromator. None of these surfaces is coated, so supplying coating to all surfaces might increase the transmission of a glass body from 0.92 until 0.97 and the transmission of a monochromator by a factor of 1.5. This is absolutely necessary in case the 3-monochromator filtering method is used.

8.5. Q-Switching

The ruby laser can be operated in the giant pulse mode, using a Q-switch in the laser cavity. With Q-Switching a laser pulse is produced with energy $E_L = 2$ J, released in 20 ns. If we assume a measuring time of 100 ns, then the T.S. signal is reduced by a factor 15, but the background radiation is reduced by a factor $2 \times 10^4$, so a substantial increase in signal to noise ratio is obtained.
A disadvantage of Q-switching is the problem of data processing. Photon counting can not be used anymore and analog integration of the fast signal also will be very difficult. So in this case much more effort should be put into the data processing. Further, due to the lower signal level the stochastic fluctuations will increase from 4.5% to 17%.

8.6. Improvement in Data Processing

As mentioned in section 8.3, a simple improvement in data processing can be obtained in using photon counting.

On the other hand, using analog recording techniques defined by available equipment, an increase of the accuracy may be obtained when the real time laser pulse signal is used in cooperation with correlation techniques. A strong correlation exists between the laser pulse and the T.S. signal. This effect might be used to separate the T.S. signal from the overwhelming background radiation.

Some of the recommendations mentioned in this chapter are incorporated within the newly designed Thomson Scattering Equipment to be used at MHD generating experiments.
9. Acknowledgements

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10. List of References


11. Appendices

A.1. Laser Equipment

Manufacturer: Laser Associates Limited,  
Type: 211.  
Stored Energy: 7500 J nominal at 2.5 kV  
Flash tube: EG&G, Type FX 47c-6.5"  
Ruby Laser Rod: length 6\textquoteleft, diameter 5/8"  
Output wavelength: 694.3 nm  
Output Energy: normal mode 55 J/pulse  
Energy Monitor: transmission factor $\eta_{\text{EM}} = 0.89$

A.2. Lenses

L1, L2 and L3, Manufacturer: Spindler & Hoyer.  
f_1 = 150 \text{ mm}, d_1 = 30 \text{ mm}  
f_2 = 250 \text{ mm}, d_2 = 50 \text{ mm}  
f_4 = 20 \text{ mm}, d_4 = 10 \text{ mm}  

L_3, Manufacturer: THE - glasswork shop  
f_3 = 200 \text{ mm}, d_3 = 70 \text{ mm}  

A.3. Monochromator

Manufacturer: Jarrell-Ash,  
Type 82-410; 0.25 m, Ebert Mount.  
Aperture: f/3.5 specified  
Grating: Bausch & Lomb, 1200 lines/mm, blazed for $\lambda = 750.0$ nm  
Linear dispersion: 3.3 nm/mm  
Slits: width 200 \text{\mu m}, height 1 mm  
Polarisation laser light parallel to grid grooves  
From Fig.A3.1, where the reflectance of the aluminium mirrors and the efficiency of the diffraction grating are shown, the transmission of the monochromator can be calculated at 694.3 nm:  
$\eta_{\text{M}} = (0.88)^4 \times 0.8 = .48$
In practice this figure is never obtained. At low apertures (< f/5) \( \eta_M = 0.37 \) was found and at the actually used aperture f/4 the transmission proved to be \( \eta_M = 0.31 \). The specified high aperture f/3.5 is obviously referred to the diagonal of the square refraction grating and can not be used in practical situations.
The solid angle at the inlet slit is \( d\Omega = 8 \times 10^{-3} \) ster.

A.4. Filters

2 filters are used:
Yellow filter, type GC 475, \( \eta = 0.99 \) for >520 nm
Polarization filter, Spindler & Hoyer, \( \eta = 0.75 \) for // polarized light.

A.5. Photomultiplier (P.M.)

Manufacturer: R.C.A.
Type C 31034 A
Cathode type: Ga-As- 4 x 10 mm²
Cathode sensitivity: 108 mA/W, specified.
Quantum efficiency \( QE = 0.207 \) at 694.3 nm (measured)
Amplification factor: \( A_v = 6.49 \times 10^5 \) at 1510 V (measured)
The P.M. is mounted in a standard \( \mu \)-metal screen and this combination is mounted in a 1 cm thick housing of iron, thus giving a satisfactory screening of the P.M. from the magnetic fringe field of the H.C.D. The P.M. was cooled to -40°C by means of CO₂-ice.
Dark current at -40°C: \( I_d < 10 \) counts/s
The electrical connections of the P.M. dynode chain is shown in Fig.A5.1

A.6. Miscellaneous

The quartz windows \( W_1 \) and \( W_2 \), are coated especially for the high intensity laser light; transmission \( \eta_w = 0.97 \)
Herewith also the reflection of the incident laser beam is decreased, which in turn reduces the amount of laser stray light.

The Brewster plate (B.P.) is grinded concavely such that the divergent incident laser beam meets the B.P. everywhere at the Brewster angle.
A.7. Storage Oscilloscope

Manufacturer: Tektronix
Type: 7633; persistence
Time base unit: 7 B 53 A
5 sec - 0.05 μs/div.
Amplifier unit: 7 A 22 - Differential Amplifier
10 V - 10 μV/div.
Bandwidth 1 MHz
Amplifier unit: 7 A 18 - Dual Trace Amplifier
5 V - 5 mV/div.
Bandwidth 60 MHz

A.8. Magnetic Tape Recorder

Manufacture: Consolidated Electrodynamics Corp.
Type: Data Tape VR - 3300
Speed: 1 7/8 - 60 inch per second
Tracks: 14 at 1" tape
Bandwidth: Direct recording - 100 cps to 200 kcps at 60 ips
FM-recording - d.c. to 20 kcps.

A.9. X-Y-Recorder

Manufacturer: Houston Instrument
Type: 2000 X-Y-Recorder-Omnigraph
Paper size: 11 x 17" or A3
Slewing speed: 50 cm/s
Acceleration: 4500 cm/s²
Frequency response: 1" peak to peak at 1 Hz.
X-Amplifier: Type 5; .5 mV/cm to 10 V/cm
Y-Amplifier: Type 3; 5 mV/cm to 5 V/cm.

Manufacturer: Varian Data Machines
Type: 620/f
Core memory: 12 k, 16 bits
Input Channels: 32
I/O transfer rate: 200.000, 12 bits words per second
Cycle time 750 ns
Fig. A3.1 Diffraction grating efficiency and aluminum mirror reflectivity. Diffraction grating with 1200 grooves/mm, blazed for 750 nm.
Fig. A5.1 Electrical diagram of dynode chain and anode circuitry of the photomultiplier tube.

\[ R = 220 \, \text{k}\Omega \]
\[ R_1 = 1 \, \text{M}\Omega \]
\[ C_1 = 0.005 \, \mu\text{F} \]
\[ C_2 = 0.001 \, \mu\text{F} \]