1. Introduction
An updated version of *Plasma Scattering of Electromagnetic Radiation* [1] is being prepared for publication in 2010. This paper reviews advances that have been made since 1973, when the original manuscript was completed. It is recommended that readers, who can’t wait until 2010, look at the numerous excellent books and review articles that have been written in the meantime: for example, Hutchinson [2], Bretz [3], DeSilva [4], Luhmann et al. [5], Donné et al. [6].

Application of Thomson scattering in two extremes of electron temperature stand out: very high temperatures, up to 25 keV, achieved in fusion research in which relativistic effects are important; and low temperatures, 1 to 30+ eV, and minute plasmas in industrial applications. Measurements of microinstabilities have been important to validating theories of transport in toroidal devices. Measurements in warm dense matter have burgeoned; Glenzer and Redmer [7] discuss the use of X-ray lasers. In all cases, measurement capabilities have been enhanced by the growing range of radiation sources, detectors and innovative techniques.

Consequently, Thomson scattering will play an important role in the diagnosis of the major new fusion facilities that are built or under construction—the National Ignition Facility (NIF), Laser MégaJoule (LMJ), and International Thermonuclear Experimental Reactor (ITER).

2. Sources, Detectors, and Innovative Techniques
Key developments in Thomson scattering techniques are discussed in Luhmann et al. [5], Donné et al. [6], and Muraoka [8]. The earliest Thomson scattering measurements in the laboratory were made one
point at a time in the plasma. The television Thomson scattering system (TVTS), developed at PPPL, and applied on PLT and TFTR Johnson et al. [9], allowed the collection of scattered signals from many points along the input beam, for example, 74 points with 1 cm resolution. This approach made it easier to obtain 2-dimensional plots of $n_e$ and $T_e$. In general, compared to 1975, a far wider range of efficient detectors exist today. In the wavelength range of 115 to 1040 nm, the quantum efficiency of various photocathodes runs from 0.15 to 1.0 and is typically 0.5. The use of micromachining and thin-film lithography fabrication with new materials and antenna coupling schemes resulted in sensitive high speed microbolometers. These have found widespread application in the millimeter wave and THz region.

A second important advance was the use of a high-repetition rate YAG laser at Garching, Roehr et al. [10], which permitted data to be obtained at 100 Hz or more. This laser plays an important role in measurements on industrial plasmas. Today, a wide range of sources is available, see table 1.

Table 1. Some representative sources: used by 1973 in italics.

| Source        | $\lambda_i$ | Pulse duration | Peak power | Energy          |
|---------------|-------------|----------------|------------|-----------------|
| X-ray         | $3 \times 10^4$ eV | 100 ps         | $5 \times 10^{15}$ photons on target |
| Argon ion     | 488 nm      | CW             | ~100 W     |
| Nd-YAG 2xf    | 532 nm      | ~10 ns         | ~50 MW     | 0.5 J           |
| Ruby          | 694.3 nm    | 15 ns          | 1.7 GW     | ~25 J           |
| Alexandrite   | 750 nm      | 350 ps         | <1 MW      | 2 J             |
| Nd-YAG        | 1.064 µm    | ~20 ns         | >100 MW    | >2 J            |
| CO$_2$        | 10.6 µm     | CW             | 25-60 W    |
| CH$_3$OD      | 57.2 µm     | CW             | 1.6 W      |
| CH$_3$OH      | 118.8 µm    | CW             | 1.6 W      |
| HCN           | 337 µm      | ~20 ns         | 1 kW peak  | 20 mJ           |
| D$_2$O        | 385 µm      | 1 µs           | 2.5 MW     | ~2.5 J          |
| Gyrotron      | 0.87 mm     | CW             | 80 W       |
| $^{17}$CH$_3$F| 1.22 mm     | ~1 µs          | 4 kW       | 0.5 mJ          |
| Gyrotron      | 1.76 - 5.0 mm | CW-long pulse | 1 MW peak  |

A further advance was the light detection and ranging (LIDAR) system was jointly developed by the University of Stuttgart and JET, Salzmann et al. [11]. It uses a very short laser pulse 0.3 ns duration (length 90 mm) and collects backscattered light; permitting measurements to be made along a chord through the plasma.

A triple grating spectograph with a mask used to filter out the central wavelength radiation, was used by Kono and Nakatani [12], van der Mullen et al. [13] applied the technique in measurements on a magnetic multipole plasma with electron temperature in the range $1.5 - 5$ eV, and density $10^{18} - 5 \times 10^{18}$ m$^{-3}$.

3. Relativistic effects

High temperature and relativistic effects on the scattered spectra were analyzed from the early 1960s, but their true impact only came in as fusion plasmas reached successively higher temperatures, starting in the 1970s. The spectral profile of the scattered radiation is given for the case in which $E_i$ is perpendicular to the scattering plane and only the component in the direction of $E_i$ is measured, by

$$
S(\omega_s, \theta, 2\alpha) = \left(\frac{\omega_i}{\omega_s}\right)^2 \int \left[1 - \frac{(1 - \cos \theta) \beta_i^2}{(1 - \beta_i^2)(1 - \beta_s^2)}\right] \int (1 - \beta^2) f(\beta) \delta(k \cdot \vec{v} - \omega) d^3\beta
$$

where $\omega_s$ and $\omega_i$ are the scattered and incident frequency, respectively, $\theta$ is the scattering angle, and $\beta = v/c$. At high temperatures the relativistic Maxwellian must be used for $f(\beta)$.
The correction to the non-collective scattered spectrum, to first order in $\Delta \lambda / \lambda$, is given in [1]:

$$1 - 3.5 \frac{\Delta \lambda}{\lambda} + \frac{c^2 \Delta \lambda^2}{4a^2 \lambda^2 \sin^2(\theta/2)}$$

where $a = (2kT_e/m_e)^{1/2}$.

(2)

This formula yields $T_e$ and $n_e$ accurate to about 5% up to 10 keV for 90° and 50° scattering.

Matoba et al. [14] computed the fully relativistic spectrum, and also gave a correction expression valid to second order in $\Delta \lambda / \lambda$: This formula yields $T_e$ and $n_e$ accurate to about 5% up to 50 keV for 90° and 50° scattering. Zhuravlev and Petrov [15] derived an analytic expression for the relativistic case ignoring the variation in the so-called depolarization term. Selden [16] found good agreement between Matoba et al. and Zhuravlev and Petrov of 0.1% for 90° scattering at 20 keV and 1.0% at 100 keV. Naito et al. [17] derived an analytic formula accurate to 0.1% at 100 keV. Beausang and Prunty [18] derived formulae relevant to LIDAR scattering when $\theta = \pi$, see Figure 1. Differences in the various calculations mainly affected the density measurement. The $(\omega_s/\omega_i)^2$ effect can be seen in Figure 2.

4. Industrial and other low temperature plasmas

Plasmas have a wide range of applications outside fusion energy research, for example in fluorescent lighting, plasma displays, semiconductor processing, making coatings, cleaning surfaces, destroying noxious chemicals, and plasma cloaking. Thomson scattering is an attractive diagnostic option because it can make local measurements without perturbing the plasma, as can be the case for Langmuir probes.

**Figure 1.** $S(\epsilon, \pi, 2\alpha)$ versus $\epsilon$ for LIDAR scattering at $T_e$ 10, 20, 30, 40, 50 keV, courtesy Beausang [18].

**Figure 2.** The term $(\omega_s/\omega_i)^2$ is important in collective scattering as shown for the case of a laser produced gas-jet plasma, courtesy D. Froula (private communication).
Key characteristics of such plasmas are a low temperature in the 1 – 30+ eV range, and electron densities in the range of $10^{16}$ to $10^{24} \text{ m}^{-3}$, often with $n_e >> n_i$. As discussed in the reviews of Muraoka et al [19], Warner and Hieftje [20] and van de Sande [21] such parameters present a challenge for using Thomson scattering as a diagnostic, because of the low photon count rate at the lower densities, the narrow scattered line width, large Rayleigh scattering, and stray light and background plasma light. In addition for etching, chemically-reactive gases are commonly used.

The industrial plasmas are usually operated in steady-state; consequently, the approach that has been used with pulsed sources is to: integrate the signals over as many as a $10^3$ pulses; measure the Rayleigh component separately and subtract it; and have two or three monochromators in series to reduce the stray light.

Measurements have been made on: impulse breakdown plasma in atmospheric air, Uchino et al. [22]; electron cyclotron resonance (ECR) sources, Bowden et al. [23]; radio frequency inductively coupled sources, Hori et al[24]; magnetic neutral loop discharges, Sakoda et al. [25]; capacitatively coupled radio frequency sources, Wesseling and Kronast [26]; micro-discharge plasmas, Noguchi et al. [27]; neon-mercury positive column, Bakker and Kroesen [28]; atmospheric argon plasma, Zaidi et al. [29]; tin vapor discharge Kieft et al. [30]; microwave plasma torch, van der Mullen et al. [31]; and a magnetic multipole, Maurmann et al. [32].

In the system used by Bowden at al. [23], an ECR plasma was operated in argon at 1 mTorr ($3.5 \times 10^{19} \text{ particles/m}^3$). The electron density and temperature determined from the fitted Gaussian spectrum ranged from $2.1 - 6.2 \times 10^{17} \text{ m}^{-3}$ and $2.4 - 3.1$ eV, respectively. In one experiment, they operated a YAG laser at 532nm and at 1 kHz repetition rate with 1 mJ pulses of duration 7 ns, and beam divergence of 0.5 mrad. To improve the signal they used spherical mirrors to reflect the laser light up to 26 times through the scattering volume. A difficulty with this approach was the relative increase in background light because of the longer duration of the measurement. The lower limit on density measurement capability was estimated as $5 \times 10^{16} \text{ m}^{-3}$. A more satisfactory approach was to operate the laser at 10 Hz repetition rate with 0.5 J pulses of 10 ns duration and a beam divergence of 0.5 mrad. The estimated lower limit on density capability was $1 \times 10^{16} \text{ m}^{-3}$.

Hori et al. (24) demonstrated the ability to measure non-Maxwellian electron energy distributions in an inductively-coupled plasma, see Fig. 3.

![Figure 3. Thomson scattering at various pressures, courtesy of Muraoaka.](image)

Sakoda et al. [25] measured the electron density ($n_e - 0.7 - 5.5 \times 10^{17} \text{ m}^{-3}$) and temperature (0.9 - 2 eV) profiles in a neutral loop discharge.

A tin vapor discharge is one of the sources under development for extreme ultraviolet lithography. During the pre-pinch phase, the electron temperature and density are, respectively, in the range of $5 - 30+ \text{ eV}$, and $10^{23} - 10^{24} \text{ m}^{-3}$. Measurements on such plasmas have been made by Kieft et al. [30].

Noguchi et al. [27] and Hassaballa et al. [32] made measurements in small scale (0.1 - 1 mm) plasmas of a micro-discharge, as used in a plasma display. A key to their success was the suppression
of strong laser stray light with the aid of a triple-grating spectrometer. The plasma parameters were \( n_e \sim 8 \times 10^{18} \text{ m}^{-3} \) and \( T_e \sim 0.5 – 1.4 \text{ eV} \).

5. Micro-instability measurements

Tynan et al. [33] have reviewed the progress in experimental drift turbulence studies, because these modes are believed to be responsible for enhanced transport in many toroidal confinement devices. Ion and electron pressure gradients drive ion and electron diamagnetic currents. However, in the absence of dissipation of the electron motion parallel to the magnetic field, any density fluctuations will be in phase with the potential fluctuations resulting in no net flow. But, in the presence of dissipation, owing to collisions or to trapped electrons, for example, a phase shift will occur and this leads to a flux. At sufficiently high pressure the fluctuations can perturb the magnetic field and lead to additional loss mechanisms.

Early studies in a tokamak by Mazzucato [34] showed scattered spectra that were consistent with drift instabilities. However, at the time, the theory of instability growth and saturation was not developed sufficiently to clearly identify whether these modes were responsible for the observed anomalous transport. Since then, there has been growing evidence that in the case of toroidal plasmas, such as the tokamak and stellarator, the ion temperature gradient instability (ITG), trapped electron modes (TEM), and electron temperature gradient instability (ETG) cause anomalous transport in the plasma core.

The modes evolve, owing to the changes in the background plasma and through 3-wave coupling, to give a broad wavenumber spectrum. At some point, the turbulent energy cascades to smaller scales and modes where it may be damped by viscosity or Landau damping. Eventually, a new equilibrium balance is reached at a balance between the destabilizing and stabilizing forces.

Substantial progress, reviewed by Hammett [35] has been made both theoretically and computationally using gyrokinetic theory coupled to the Particle-in-Cell (PIC) approach.

Experimental diagnostics measure conditions under the constraints of viewing sight-line and time and space. Because of these limitations, synthetic data, allowing for the experimental realities is constructed from the code calculations to compare with the experimental data.

An important contribution was made on Tore Supra using \( \text{CO}_2 \) laser light scattering, Hennequin [36] with the measurement of wavenumber fluctuations in the range \( 3 \text{ cm}^{-1} < k_\perp < 26 \text{ cm}^{-1} \). The measurement showed how the spectrum and decorrelation times scaled with normalized poloidal...
gyroradius. Among earlier work was the study of microturbulence on the KT-5 tokamak also using CO₂ light scattering, Chang et al. [37].

Mazzucato et al. [38] made localized measurements, enabled by the toroidal curvature of field lines, at 280 GHz of fluctuations on NSTX. The results are consistent with the behavior of ETG modes, see Fig. 4. Rhodes et al. [39] employed the backscattering of 94 GHz waves on DIII-D using the second harmonic resonance as a beam dump, to study instabilities in the range 0 to 40 cm⁻¹.

6. Energetic ions, high energy density plasmas, and burning plasma measurements

6.1. Energetic ions

Energetic ions, with energy \( E_i > T_i \), derive from two main sources: heating by neutral beams and radio-frequency waves (RF); and from fusion. In the case of RF heating, the ions are accelerated from a background distribution to give a high energy tail. In the case of beams and fusion the ions start at an energy \( E_{i0} \), and then slow down by collisions, initially with electrons and then with other ions. In general, \( v_i < v_i < v_e \) for thermal ions, fast ions and electrons respectively. Suggestions for using scattering of electromagnetic radiation to measure the alpha particle distribution function were made by Hutchinson et al. [40] for CO₂ laser light, and by Woskov [41] for millimeter waves.

To date, the experimental tests have involved measurements of ions resulting from neutral beam injection. A major problem with using 10.6 µm light is the requirement for the very small scattering angle < 1° needed to obtain a sufficiently high value of \( \alpha = 1/k\lambda_D \). Nevertheless, a system has been installed on JT-60U with an improved CO₂ laser with high energy (≈17 J), high repetition rate (15 Hz), and improved S/N ratio, Kondoh et al. [42].

A successful approach has been to use longer wavelength radiation in the millimeter range, where there are essentially no limitations on scattering angle: the ion feature always dominates, thereby allowing the scattering geometry to be selected to meet other objectives. In this frequency range, the challenge is the relatively strong ECE raising the background noise. The first gyrotron-based fast ion measurements, coming from neutral beams, were made on JET, Bindslev et al. [43] Subsequently, a similar system was deployed to measure beam ions on TEXTOR, Bindslev et al. [44] The system used a 200 kW, 110 GHz gyrotron source of 0.2 s duration at a scattering scattering angle of 150° to 170°. The gyrotron was operated with a train of up to 100, 2 ms duration pulses with an adjustable time delay between pulses to temporally track fast ion evolution during the plasma shot, see Fig. 5.

Measurements have also been made on ASDEX-U, Korsholm et al. [45]. A 77 GHz system to measure both the bulk and tail ion distribution has been designed for the LHD stellarator by Nishiura et al. [46].
6.2. High energy density plasmas

The development of very high power lasers for inertial fusion made it possible to create high energy density plasmas in the laboratory. Ultraviolet probe lasers may be used for densities less than $10^{21}$ m$^{-3}$. For higher densities X-ray lasers (He-alpha, Ly-alpha and K-alpha radiation) have been used (Fig. 6.) for both non-collective and collective scattering measurements, Boehly et al. [47] and Glenzer and Redmer [7].

![Figure 6. Scattering spectrum (blue dots) from isochoically heated beryllium. Elastic and inelastic components are observed from both the titanium He-alpha and Ly-alpha probe X-rays (left). The spectrum is well fit with synthetic scattering spectra (red line). These results characterize the solid density plasma regime with an error bar of about 10%, courtesy Glenzer [48].](image)

6.3. Burning plasmas

Thomson scattering systems are being considered to measure core (LIDAR), edge, and divertor electron temperature and density in ITER, Walsh et al. [49]. Relativistic effects must be included because $T_e$ up to 40 keV is anticipated.

In fact, finite velocity effects should also be taken into account for very energetic fusion ion products, and energetic beam ions, such as the 1 MeV deuteron beams ($v_{th}/c = 0.03$) proposed for ITER. To first order in $\omega/\omega_i$, the correction factor is given approximately by

$$\left(1 + 2\frac{\omega}{\omega_i}\right) \approx \left[1 + 4\sin(\theta/2)\right]^{V_{th}^2/c^2}$$  

Building upon the experience measuring beam ions, Bindslev et al. [50] have proposed to use a 60 GHz gyrotron, which is below the fundamental ECE resonance, to measure the fusion alphas in ITER. The measurement would be made in the presence of the beam 1 MeV deuterons. For both types of diagnostic, a major challenge will be in developing components that can handle the harsh ITER environment.

The National Ignition Facility (NIF) will include both the capability for high-energy and ultra-short laser produced X-ray probing of the plasmas, Glenzer and Redmer [7].

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