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Bremsstrahlung vs. Thomson scattering in VUV-FEL plasma experiments

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Abstract

We determine the spectral photon yield from a hot dense plasma irradiated by VUV-FEL light in a Thomson scattering experiment. The Thomson signal is compared to the emission background mainly caused by bremsstrahlung photons. We determine experimental conditions that allow for a signal-to-background ratio larger than unity. By derivation of the Thomson and the bremsstrahlung spectrum from linear response theory we present a consistent quantum statistical approach to both processes. This allows for a systematic treatment of medium and quantum effects such as dynamical screening and strong collisions. Results are presented for the threshold FEL-intensity as a function of density and temperature. We show that the account for quantum effects leads to larger thresholds as compared to previous work.

Keywords: Thomson scattering; Bremsstrahlung; Free electron laser; Plasma diagnostics; Threshold intensity; Dielectric function; Dynamic structure factor

1. Introduction

Thomson scattering is a well-established technique for experimental investigation of plasma parameters. Examples can be found in Refs. [1–6]. Observables like particle density, temperature, composition, and degree of ionization can be spatially and temporally resolved by analysis of the scattering spectrum [7]. Until recently, coherent light sources have been available only for the visible and near UV part of the electromagnetic spectrum. Due to small critical density $n_{\mathrm{crit}} = \omega^2\epsilon_0 m_e/e^2 \approx 10^{20}\ \mathrm{cm}^{-3}$ of free charge carriers for optical probes, the applicability of Thomson scattering using coherent sources has been limited to targets of relatively low density.

Glenzer et al. [8,9] have shown and explored the possibility of X-ray Thomson scattering in solid density targets using the Ti He-α line at 4.75 keV as probe light [10]. A new alternative emerged with the development of VUV-free electron lasers (VUV-FEL), providing pulses of coherent radiation in the far (vacuum-) ultraviolet. At the moment, the VUV-FEL at DESY Hamburg operates at 32 nm wavelength [11], corresponding to 38 eV photons. With this coherent light source, dense matter up to solid densities of $10^{23}\ \mathrm{cm}^{-3}$ can be penetrated, see Refs. [12,13]. Under these conditions, the Thomson spectrum permits the determination of electron temperature and density directly from the position and height of collective resonances, i.e. plasmons, showing up in the scattering signal [9]. First experiments will be performed in the near future at the VUV–FEL facility at DESY at $\lambda = 32$ nm FEL wavelength, while in later stages of the project, wavelengths from 13 nm (VUV–FEL) down to 0.1 nm (X-FEL) will be available.

Due to the large number of free charge carriers at the temperatures and densities considered, thermal bremsstrahlung emission, resulting from inelastic free–free scattering, contributes significantly to the emission background. Therefore, experimental conditions such as scattering angles, spectral properties of the probe and the detector have to be chosen as to obtain a maximum signal-to-background ratio. *Background* is to be understood as bremsstrahlung radiation, whereas *signal* corresponds to the photons having undergone Thomson scattering.

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So far, classical formulas for the bremsstrahlung emission level going back to Kramers [14] have been used to determine threshold intensities of the external source to overcome the background due to bremsstrahlung [15,16]. The Kramers result, given below in Eq. (19), is derived from the assumption of Keplerian trajectories of the emitting electron in the Coulomb field of an ion and integration over all initial velocities weighted with the Maxwellian velocity distribution function. Quantum features are only accounted for in a semiclassical way: the velocity integral extends over velocities v, fulfilling the condition $mv^2/2 \geq \hbar\omega$, i.e. the kinetic energy has to be larger than the photon energy. Further quantum properties, such as the finite photon momentum as well as the quantum mechanical nature of the scattering process are not accounted for. By comparing the Thomson signal strength at the laser wavelength $\lambda = 14.7$ nm to the bremsstrahlung photon yield calculated from Kramers formula, Baldis et al. found threshold intensities of 10^{13} W/cm^2 for typical values of free electron density $n_\mathrm{e} = 10^{22}$ cm^{-3} and temperature $k_\mathrm{B}T = 100$ eV [16].

In this work, we evaluate threshold conditions (intensities) using improved expressions for the bremsstrahlung spectrum. As usual, corrections to Kramers formula for bremsstrahlung are described by the so-called Gaunt factor [17]. In the simplest approach it is obtained by taking into account collisions between electrons and fixed ions in Born approximation. In dense plasmas, many-particle effects as dynamical screening become important. Moreover, strong collisions have to be accounted for. We show in this paper how the Gaunt factor can be derived from linear response theory [18] in a general way. Within this framework, modifications of the emission spectrum beyond Born approximation can be included in a systematic manner [19] as will be discussed later.

We then apply our formulas to determine the threshold intensities for a broad range of experimental parameters (wavelength, spectral properties of detectors, and different materials), relevant for future experiments at DESY. Furthermore we compare Thomson and bremsstrahlung photon yield over a finite spectral range. Thereby, and by taking improved expressions for the bremsstrahlung cross section, we show that even higher thresholds have to be reached in order to obtain a Thomson signal above the bremsstrahlung level at-least near the plasmon resonances. These peaks are much lower than the central peak, being essentially an ion feature.

The present work is organized as follows: in the first section we review the basic physics of Thomson scattering and bremsstrahlung and how they can be expressed in terms of the dynamic structure factor and the dielectric function, respectively. Since these two quantities are related to each other via the fluctuation–dissipation theorem [20], we are able to describe both processes on a common and consistent basis.

We then compare the emission level due to bremsstrahlung to the Thomson signal whose strength is proportional to the flux of incoming photons, i.e. the power density of the external source. Thereby, we find expressions for the threshold power density as a function of particle density and temperature. In the last section we discuss our results for various sets of experimental parameters relevant for future experiments at the VUV-FEL.

2. Thomson scattering and bremsstrahlung

The central quantity of interest is the spectral power density $\mathrm{d}P/\mathrm{d}V\,\mathrm{d}\lambda\,\mathrm{d}\Omega$, i.e. the rate of energy radiated per unit scattering volume $\mathrm{d}V$, wavelength $\mathrm{d}\lambda$, and solid angle $\mathrm{d}\Omega$. The total spectral power density is the sum of the corresponding quantity for every radiative process in the plasma. In this work we focus on Thomson scattering and bremsstrahlung, i.e.

$$\frac{\mathrm{d}^3P_\mathrm{tot}}{\mathrm{d}V\,\mathrm{d}\lambda\,\mathrm{d}\Omega} = \frac{\mathrm{d}^3P_\mathrm{Th}}{\mathrm{d}V\,\mathrm{d}\lambda\,\mathrm{d}\Omega} + \frac{\mathrm{d}^3P_\mathrm{br}}{\mathrm{d}V\,\mathrm{d}\lambda\,\mathrm{d}\Omega}. \tag{1}$$

To unambiguously identify the Thomson signal, we require that the Thomson power density is at least equal to the bremsstrahlung level,

$$\frac{\mathrm{d}^3P_\mathrm{Th}}{\mathrm{d}V\,\mathrm{d}\lambda\,\mathrm{d}\Omega} \geq \frac{\mathrm{d}^3P_\mathrm{br}}{\mathrm{d}V\,\mathrm{d}\lambda\,\mathrm{d}\Omega}. \tag{2}$$

The Thomson spectrum is given by the intensity of the probe laser I_L and the Thomson scattering cross section $\mathrm{d}^2\sigma_\mathrm{Th}/\mathrm{d}\omega\mathrm{d}\Omega$. To account for the finite spectral bandwidth of the detector, one has to convolute each power spectrum with a detector function $G(\lambda)$. In practice, this is only relevant for the Thomson signal since the bremsstrahlung spectrum is slowly varying in the relevant frequency region. The Thomson power spectrum reads

$$\frac{\mathrm{d}^3P_\mathrm{Th}(\lambda)}{\mathrm{d}V\,\mathrm{d}\lambda\,\mathrm{d}\Omega} = I_\mathrm{L}\int \mathrm{d}\overline{\lambda}G(\lambda-\overline{\lambda})\frac{\mathrm{d}^2\sigma_\mathrm{Th}(\omega_{\overline{\lambda}})}{\mathrm{d}\Omega\,\mathrm{d}\omega} = I_\mathrm{L}\overline{R}(\lambda). \tag{3}$$

We have introduced the response function $\overline{R}(\lambda)$, where the bar denotes the convolution with the detector function. Note that we assume an optically thin plasma, thus radiation transport is neglected. Also, due to the short pulselength of the VUV-FEL (20–120 fs), we neglect the heating of the plasma due to the probe beam.

The bremsstrahlung spectrum does solely depend on the plasma parameters density and temperature, so that, with a suitable formula for the bremsstrahlung spectrum, which we will abbreviate by the notation $\mathrm{d}^3P_\mathrm{br}/\mathrm{d}V\,\mathrm{d}\lambda\,\mathrm{d}\Omega \equiv j(\lambda)$ in the following, Eq. (2) defines a threshold intensity

$$I_\mathrm{thresh}(\lambda) = \frac{j(\lambda)}{\overline{R}(\lambda)}. \tag{4}$$

We will now briefly describe how expressions for the Thomson scattering and the bremsstrahlung spectrum can be obtained from a common starting point, i.e. the dielectric function of the plasma.

2.1. Thomson scattering

The cross section for Thomson scattering in a plasma can be given in terms of the dynamic structure factor (DSF), $S(\boldsymbol{k},\omega)$:

$$\frac{\mathrm{d}^2\sigma_\mathrm{Th}(\boldsymbol{k},\omega)}{\mathrm{d}\Omega\mathrm{d}\omega} = \left(\frac{\mathrm{d}\sigma(\Omega)}{\mathrm{d}\Omega}\right)_\mathrm{Th}\frac{k_1}{k_0}S(\boldsymbol{k},\omega), \tag{5}$$