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COMPTON SOURCES OF ELECTROMAGNETIC RADIATION*

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When a relativistic electron beam interacts with a high-field laser beam, the beam electrons can radiate intense and highly collimated electromagnetic radiation through Compton scattering. Through relativistic upshifting and the relativistic Doppler effect, highly energetic polarized photons are radiated along the electron beam motion when the electrons interact with the laser light. For example, X-ray radiation can be obtained when optical lasers are scattered from electrons of tens of MeV beam energy. Because of the desirable properties of the radiation produced, many groups around the world have been designing, building, and utilizing Compton sources for a wide variety of purposes. In this review paper, we discuss the generation and properties of the scattered radiation, the types of Compton source devices that have been constructed to present, and the future prospects of radiation sources of this general type. Due to the possibilities to produce hard electromagnetic radiation in a device small compared to the alternative storage ring sources, it is foreseen that large numbers of such sources may be constructed in the future.

Keywords: Compton backscattering, Inverse Compton source, Thomson scattering, X-rays, Spectral brilliance

1. Introduction

The scattering of electromagnetic radiation by electrons was famously studied by A. H. Compton nearly 100 years ago [1]. In Compton's Nobel prize winning work, it was shown that scattered X-rays observed at an angle with respect to the incident beam direction were frequency-shifted with respect to the incident X-ray beam. Furthermore, this *Compton Effect* could be analyzed and understood by applying relativistic 4-momentum conservation to the scattering process under the photon hypothesis of Einstein. The observed frequency shifts, and their dependence on scattering angle, were in agreement with the kinematical arguments lending strong experimental support to the existence of photons.

Such arguments are largely quantum mechanical. There were prior, classical discussions of the same phenomenon associated with J. J. Thomson. If

an electromagnetic field of a given frequency passes by a classical electron, it accelerates the electron at an identical frequency. The accelerating electron re-radiates at the same frequency through the normal dipole emission process. The angle integrated power emitted may be determined by Larmor's Theorem leading to Thomson's formula for the total scattering cross section, as seen below in Section 2.2. Thomson's formula is a good approximation as long as the incident energy of the photon is smaller than the electron rest mass in the electron's rest frame (the electron recoil is negligible), a condition valid for many renderings of Compton sources. Many papers in the recent literature are rigorous in calling sources in this Thomson regime, 'Thomson sources', but many other papers utilize the broader terminology 'Compton Source', perhaps prodded by modern textbooks

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where the scattering of photons by electrons is generically called Compton scattering, in spite of Thomson's priority.

Now, if one constructs a source using the photon-electron scattering process, it is clear that the total number of scattered photons produced is proportional to the incident photon intensity. Therefore, one would like to have a high intensity laser driving the source and conversely, the source performance will in the end be limited by the possible laser intensity. Recent large gains in laser intensity, through the development of high optical power storage systems, and by the development of high intensity single-pulse laser systems, have led Compton sources out of the realm of the interesting idea and into the realm of the practical device during the last several decades.

This paper is organized as follows. In section 2 the properties of the scattered radiation are discussed and related to the properties of the incident laser beam and electron beam. A quite useful idea, pertinent as this review appears in a volume dealing with accelerator radiation sources based on electromagnetic undulators, is relating the laser beam characteristics, as much as possible, to an equivalent undulator. Radiation quality results from the field of synchrotron light sources are easily transcribed into the field of Compton sources. In section 3 the types of lasers that have been used in Compton sources are presented in two broad categories: optical cavity lasers and single (or few) pulse laser systems. In section 4 the ring-based Compton sources and in section 5 linac and energy recovery linac based sources are discussed. In section 6 some potential future projects are presented, and the review concludes with a summary.

To conclude this Introduction, in this review Compton scattering from *relativistic* electron beams will be the primary focus. Much of the discussion in this paper does translate to scattering from unbound electrons stationary in the lab frame. However, it would be a mistake to conclude that the discussion has much relevance to the interaction of intense lasers with stationary materials and/or plasmas. Indeed, there are immense and growing bodies of knowledge that deal specifically with linear and non-linear laser interactions with materials and plasma. Such items will be largely neglected in this review.

2. Properties of the Scattered Radiation

In this section various standard estimates regarding the properties of the scattered radiation are presented and related to the properties of incident laser and electron beams, along with some discussion of the limitations of the estimates. Discussions of output photon energy, flux, energy spread, pulse duration, and spectral brilliance are presented and compared to more conventional synchrotron sources. The polarization of the radiation scattered in several directions is discussed, along with the potential for rapid and controlled source polarization reversal. Similarly, there are couplings of the scattered radiation to the electron polarization variable that allow highly accurate electron polarimeters to be built. We conclude with a section on accurate computations of the distributions of scattered electrons, in both the linear and non-linear regimes, through computer calculations.

2.1. Photon Energy

One primary motivation for Compton sources follows immediately from considering the energy of the scattered radiation. Suppose, as in Fig. 1, a relativistic electron moves along the z -axis of a coordinate system aligned with the movement and a photon is incident on the electron in the x - z plane. In the general case Φ will denote the angle the incident laser beam makes with the electron beam in this plane and θ and ϕ are the usual spherical polar angles that the scattered radiation makes in the coordinate system.

Fig. 1. Scattering geometry and angle definitions.

As a specific case, consider backscattering where the photon is moving in the negative z -direction ($\Phi = \pi$). If the photon energy is E_{laser} , then by the usual relativistic Doppler shift calculation the photon energy in the beam frame is $E'_{inc} = \gamma(1+\beta)E_{laser}$ where γ and β are the usual relativistic factors for

the electron. When $E'_{inc} \ll mc^2$, that is the photon energy in the beam frame is small compared to the electron rest energy, the electron radiates with small recoil and the energy of the radiated photon is E'_{inc} . When the photon radiated in the forward direction is Doppler shifted back into the lab frame, its energy, at the so-called Compton edge, is $\gamma^2(1 + \beta)^2 E_{laser} \approx 4\gamma^2 E_{laser}$. The highest energy from the double Doppler shift is in the forward direction; the emission at an angle $\sin \theta = 1/\gamma \ll 1$ with respect to the beam direction in the lab frame is already reduced in energy to $2\gamma^2 E_{laser}$ by the same Doppler effect. Whereas a photon Compton scattered by a stationary target has its energy degraded by the process, scattering from a relativistic electron introduces the possibility of significantly enhancing the photon energy. The γ^2 dependence of the upshifting is significant and is the same as in undulator radiation, where it results from a Lorentz transformation followed by a Doppler shift.

For situations where electron recoil cannot be neglected, the scattered photon energy is

$$E_\gamma(\theta, \phi) = \frac{E_{laser}(1 - \beta \cos \Phi)}{1 - \beta \cos \theta + E_{laser}(1 - \cos \Delta\Theta)/E_{e-}}$$

where $\Delta\Theta$ is the angle between the incident and scattered photons which satisfies $\cos \Delta\Theta = \cos(\Phi) \cos(\theta) - \sin \Phi \sin \theta \cos \phi$, and E_{e-} is the initial total energy of the electron. This expression quantifies the full effect of the relativistic Compton and Doppler effects, and it should be noted that the numerator of this expression is simply the photon energy of the incident laser in the beam frame divided by γ . In the backscatter arrangement ($\Phi = \pi$), the highest energy is in the z -direction ($\theta = 0$). For side scattering arrangements ($\Phi = \pi/2$), the peak energy is shifted slightly off the electron axis. The limit $\beta = 0$ and $\Phi = 0$ recovers the original Compton formula.

As a numerical example, to obtain 10 keV photons from an one eV drive laser, $\gamma = 50$ is needed, i.e., about 25 MeV electron beam energy. For access to the same photon energy at a storage ring operating with a 2.5 cm period undulator, $\gamma \approx 10,000$ is needed; the laser radiation scattered in a Compton source may have several orders of magnitude smaller wavelength than the period of an undulator in a ring.

This example points to the fact that in principal X-rays can be produced by an accelerator much smaller than the large synchrotron storage rings.

2.2. Field Strength and Photon Flux

The number of photons produced by a laser pulse incident on an electron is proportional to the time-integrated intensity of illumination. Therefore one expects, as in the case of undulator radiation, that total photon yield is proportional to the square of the field strength. However, in the Compton case the transverse electromagnetic fields of the incident laser are accelerating the electron. Therefore, in analogy to the undulator case, the field strength parameter for a plane-wave incident laser is defined to be

$$a = \frac{eE\lambda_{laser}}{2\pi mc^2}$$

where e is the electron charge, E is the (transverse) electric field of the laser, λ_{laser} is the incident laser wavelength, and mc^2 is the rest energy of the electron (MKS units). Sometimes the definition is calculated with a local value of the electric field; the more common practice is to quote a using the peak value in the most-intense part of the laser pulse. In contrast to undulators whose field profiles are designed to be close-to-sinusoidal and flat in amplitude, laser pulses tend to be spatially dependent in both the longitudinal and transverse coordinates. Using a to denote the field strength was established in the mid 1960s, prior to the development of the K notation for undulators. This parameter, for Compton Scattering, plays a role in many ways identical to K .

For example, the bending angles of the accelerated electrons in the scattering events have amplitude a/γ , and $a \approx 1$ gives the maximum emission into the fundamental line of scattered radiation. Beyond this level, harmonic emission starts to become more dominant and relativistic accelerations of the electrons are induced by the incident laser. If $a \ll 1$, the regime of linear (in the field strength) scattering, emission is primarily in the fundamental and the spectrum of the scattered radiation follows closely the spectrum of the incident radiation, suitably upshifted in energy.

In the linear regime for backscattering, it is quite straightforward to obtain the number of photons generated by each electron. The total power radiated by a electron can be calculated by Lienard's relativistic

generalization of Larmor's Theorem to be

$$P_{rad} = \frac{\gamma^4}{6\pi\epsilon_0} \frac{e^2}{c^3} |\dot{\mathbf{v}}|^2 = \gamma^2 \sigma_T \epsilon_0 c |(\mathbf{E} + \mathbf{v} \times \mathbf{B})(\mathbf{x}(t))|^2$$

where e is the electron charge, σ_T is the Thomson cross section $8\pi r_e^2/3$, r_e is the classical electron radius, ϵ_0 is the permittivity of free space, $\mathbf{E}$ and $\mathbf{B}$ are the electromagnetic fields for the incident laser, $\mathbf{x}(t) = (x, y, \beta ct)$ is the first approximation of the orbit of the electron as it passes the laser pulse, and the relativistic Lorentz force law is used to evaluate $\dot{\mathbf{v}}$, the acceleration in the laboratory frame. The total energy radiated by the electron is

$$U_{e-} = \int P(t) dt = \gamma^2 (1 + \beta)^2 \sigma_T \epsilon_0 c \int |\mathbf{E}(x, y, (\beta + 1)ct)|^2 dt \quad (1)$$

$$= \gamma^2 (1 + \beta) \sigma_T \epsilon_0 \int |\mathbf{E}(x, y, z')|^2 dz'$$

provided the acceleration is evaluated at the correct longitudinal location in the wave by including the movement of the electron through the wave in the lab frame. Notice that the force of the magnetic field in the plane wave adds to the electric force, accounting for the $(1 + \beta)^2$ factor in Eqn. 1.

For a plane wave $\epsilon_0 |\mathbf{E}|^2$ is the energy density of the wave including both the electric and the magnetic field. If both the electron and laser transverse intensity distributions are round gaussian distributions of *rms* size σ_e and σ_{laser} respectively, then

$$U_\gamma = \gamma^2 (1 + \beta) \sigma_T \frac{N_e N_{laser}}{2\pi(\sigma_e^2 + \sigma_{laser}^2)} \hbar \omega_{laser}, \quad (2)$$

where U_γ is the total energy in scattered photons, N_e is the number of electrons in the electron pulse, and N_{laser} is the number of photons in the incident laser. It will be seen below that the average energy of the emitted photons is $\gamma^2 (1 + \beta) \hbar \omega_{laser}$.

Three other formulas convenient for estimating source performance in the case of linear backscattering and neglecting the collision hourglass effect follow from Eqn. 2. The first is

$$U_\gamma = \gamma^2 (1 + \beta) \frac{N_e \sigma_T}{2\pi(\sigma_e^2 + \sigma_{laser}^2)} U_{laser}$$

where U_{laser} is the total energy in the incident pulse. Likewise the total number of scattered photons N_γ

is

$$N_\gamma = \sigma_T \frac{N_e N_{laser}}{2\pi(\sigma_e^2 + \sigma_{laser}^2)},$$

a formula reminiscent of the standard gaussian luminosity formula of collider theory. In the limit $\sigma_e \ll \sigma_{laser}$, by replacing the electric field with the a parameter one computes the number of photons per electron in a flat incident pulse as

$$N_{pere-} = \frac{2\pi\alpha N_\lambda a^2}{3},$$

where α is the fine-structure constant and N_λ is the number of wavelengths in the incident pulse. This result is well known in undulator theory [2–4].

The spectral energy density of the output pulse may be computed analytically in the linear Thomson backscatter limit as

$$\frac{d^2 U_\gamma}{d\omega d\Omega} = \frac{r_e^2 \epsilon_0}{2\pi c} |\tilde{E}[\omega(1 - \beta \cos \theta)/c(1 + \beta)]|^2 \times \frac{\sin^2 \phi (1 - \beta \cos \theta)^2 + \cos^2 \phi (\cos \theta - \beta)}{\gamma^2 (1 - \beta \cos \theta)^5},$$

where $\tilde{E}$ is the spatial Fourier transform of the transverse electric field of the incident laser evaluated in the lab frame, and the notation means evaluate the transform at the Doppler shifted wave number $\omega(1 - \beta \cos \theta)/c(1 + \beta)$. An integration over frequency and conversion of the solid angle to output energy using the Doppler shift formula yields the photon number density as a function of output photon energy displayed in Fig. 2, under the assumption of a single incident laser frequency. The distribution is precisely parabolic, with minimum value of β^2 at $E_\gamma = (1 + \beta) \gamma^2 \hbar \omega_{laser}$, also the average energy of the distribution. The number density grows to a value $2\beta^2$ at both the Compton edge in the forward direction, and in the backward direction where the laser frequency is not Doppler shifted. It should be noted that the average energy photon is emitted with an angle of $\sin \theta = 1/\gamma$; the energy flux of the scattered photons is largely within this angle. Comparing the integral of this curve over all energies, to the number in a 0.1% bandwidth at the Compton edge, it is

computed that

$$N_{0.1\%} = 1.5 \times 10^{-3} N_{\gamma}.$$

Therefore, the flux (photons/sec) into a 0.1% bandwidth is

$$\mathcal{F} = 1.5 \times 10^{-3} \dot{N}_{\gamma}.$$

This formula may be used to directly compute peak fluxes. In high frequency repetitive sources the average flux is $\mathcal{F} = 1.5 \times 10^{-3} f N_{\gamma}$ where f is the repetition rate.

Fig. 2. Energy distribution of scattered radiation.

2.3. Energy Spread

The energy spread in the scattered X-ray pulse has a variety of sources. Usually the energy spread delivered to a given experiment has its source in a wide assortment of phenomena. Here we shall list the possibilities and quantify the expectations regarding that particular effect. The expectations regarding any experiment should in practice be examined in a unified manner using simulations including all the details in the experimental setup.

The basic sources of energy spread are: energy spread in the electron beam, energy spread generated by the laser line-width, and energy spread due to the finite θ width of apertures defining the acceptance of an experiment. As this last source is minimized in the forward direction and the brilliance is maximum there, experiments are usually installed in the forward direction to the electron beam. The γ^2 dependence of the output radiation in the forward direction, leads to the result that the $\sigma_{E_{\gamma}}/E_{\gamma}$ generated by the electron beam energy spread is simply $2\sigma_{E_{e^-}}/E_{e^-}$. Because the entire spectrum in a given observation direction is entirely upshifted by the double Doppler shift, the relative spread in energy in the scattered particles generated by the laser line-width is the same as the laser line-width. A direct

estimate of the third source of spread is to take the opening angle $\Delta\theta$ of the detection apparatus and use the energy curve Eqn. to estimate the energy spread possible through the aperture. Finally, there is a subtle effect of finite opening angle. Due to the emittance in the beam, off center electrons moving at an angle can emit along the forward direction, at an angle with respect to their forward direction. From the angle dependence of the Doppler shift, the radiation through the aperture has lower energy than in the forward direction. This source of emittance generated energy spread is easily estimated to be

$$\sigma_{E_{\gamma}}/E_{\gamma} = 2\gamma^2 \epsilon / \beta_{e^-}$$

where β_{e^-} is the electron beta-function at the interaction point.

2.4. Pulse Length

Pulse lengths have been evaluated thoroughly in three scattering geometries: backscattering ($\Phi = \pi$), side-scattering ($\Phi = \pi/2$), and small angle scattering ($\Phi \ll 1$). The result for backscattering is that in the forward direction the scattered pulse length is equal to the incident pulse length within corrections $o(1/\gamma^2)$. This result is easily understood as both the collection of scattering electrons *and* the forward scattered radiation move in the same direction, the former at close to the speed of light and the later at the speed of light. There is no longitudinal spreading possible. More significant is the longitudinal smearing from the finite acceptance of the detector in θ . When $\theta = \pi$, the photon pulse length is equal to the incident photon pulse length without correction as both the incident and scattered radiation move at the velocity of light [5, 6].

An early application of Compton Scattering was to access short X-ray pulse lengths by having a small transverse laser spot size at the interaction point in a side-scattering arrangement ($\Phi = \pi/2$) [7, 8]. Quite general formulas for pulse length were published to cover this case [7]. For the same reason as in the $\theta = \pi$ case above, for small angle Thomson scattering the output pulse length reflects the incident laser pulse length, providing a potential path to short X-ray pulses [9]. General formulas including the corrections for finite electron bunch transverse size may be

found in this reference. Because the energy amplification is considerably reduced in small angle scattering geometries, one must start with a more substantial accelerator to get to the same X-ray energy as compared to the backscattering and side-scattering geometries.

2.5. Spectral Brilliance

Taking advantage of the correspondence with undulator radiation, the spectral brilliance of the scattered radiation is estimated by using standard undulator theory [10]. For constant intensity (flat) incident laser pulses in the linear regime the results should be reliable, but for Gaussian laser pulses better calculations must be made to obtain results good to 10%. The overall purpose of this estimate is to investigate scaling behavior.

The spectral brilliance is

$$\mathcal{B} = \frac{\mathcal{F}}{4\pi^2 \sigma_x \sigma_{x'} \sigma_y \sigma_{y'}} \approx \frac{\mathcal{F}}{4\pi^2 \sqrt{\beta_x \epsilon_x} \sqrt{\epsilon_x / \beta_x + \lambda / 2L} \sqrt{\beta_y \epsilon_y} \sqrt{\epsilon_y / \beta_y + \lambda / 2L}}$$

where σ_x and σ_y are the source size for the scattered radiation and $\sigma_{x'}$ and $\sigma_{y'}$ are the source angular sizes. We have followed standard practice and estimated the later as due to a combination of the intrinsic beam angles and the radiation diffraction, quantified by $\lambda/2L$, where λ is the emitted wavelength and L is the effective length of the source. In storage rings the intrinsic angles are small compared to the diffraction and the overall spectral brilliance tends to scale only inversely with the beam emittance.

Because one wishes to produce X-rays with low energy beams in some Compton sources, the beam emittances are much larger than for synchrotron sources. The opposite limit for the angular source size applies and

$$\mathcal{B} = \frac{\mathcal{F}}{4\pi^2 \epsilon_x \epsilon_y}.$$

For Compton sources with lower electron energies it is generally true that the best performance arises by having the absolute best electron beam emittance at the interaction point, and the spectral brilliance goes inversely as the square of the emittance. If this result is stated in terms of normalized emittance, notice the strong γ^2 dependence of the result.

Because brilliance is so strongly correlated with beam emittance and storage ring light sources operate at high energy, Thomson scatter sources with low electron energies will not likely achieve comparable average brilliance. With present CW linac technology, one loses at least an order of magnitude in beam average current compared to rings, and 4.5 orders from the γ^2 effect in the enhanced opening angles [11] for the same output X-ray energy. One can possibly make some of these factors up by smaller spot sizes allowed in linac-based systems; it is difficult to imagine more than one or two orders of magnitude improvement because of the present good performance of storage rings. For ring-based Compton sources even this possibility seems debatable. Consequently to be attractive in the long term, Compton sources must develop user programs not reliant on the highest average brilliance, but where substantial fluxes of narrow-band X-rays are desired.

For peak brilliance, due to the high field strengths possible in modern lasers and the fact that the electron pulse lengths can be made smaller in linacs than in rings, Compton sources more competitive to rings can be built. It remains to be seen how close they eventually will come to storage ring performance, or indeed, whether rings can eventually be exceeded.

2.6. Polarization Effects

For a linearly polarized incident laser beam, general expressions exist resolving the distribution of the polarization in plane and polarization out of plane scattering in the linear regime. Qualitatively, the polarization properties are identical to undulators for linear polarization. In the forward direction the scattered pulse has the same polarization as the incident pulse. Because of the fact that dipole moments do not radiate in the direction of the induced dipole, the polarization is also entirely in plane for $\sin \theta = 1/\gamma$ and ϕ chosen in the direction of the incident polarization. Also, because of the reversal of the photon motion, if a certain circular polarization is incident in a backscattering arrangement, the opposite circular polarization will emerge in the scattered radiation in the forward direction. The fact that circular polarization is preserved and because the circular polarization of a laser beam can be changed rapidly, Compton scattering provides a straightforward way

to obtain high energy polarized photons whose polarization is easily changed and controlled.

The scattering distributions do not depend on the electron polarization variables in the Thomson regime. However, for GeV scale electron beams with optical frequency lasers, where the full Compton effect is present, coupling to the electron polarization exists, leading to the possibility of Compton polarimeters.

In a polarimeter circularly polarized light interacts with a longitudinally polarized electron beam. As shown in QED-type calculations, the rate of scattering in the forward direction is slightly different depending on the electron polarization. By measuring the asymmetry in the rate, through measurements where beam polarization is reversed in a controlled matter, the electron beam polarization can be determined. If the recoiling electron is detected simultaneously with the forward-going scattered photon, substantial backgrounds in the measurements can be eliminated.

2.7. Harmonic Generation and Non-linear Effects

As the field strength parameter becomes of order 1 or higher, phenomena familiar from undulator theory begin to arise. Specifically, frequency red-shifting and harmonic generation become prominent [12]. For a longitudinally flat illuminating laser, computations and results are very similar to those in standard undulator theory. Here only the main differences will be summarized in the case of backscattering ($\Phi = \pi$).

At large a values, red shifting of the emitted radiation arises because the electrons are slowed down longitudinally by the laser field. A calculation entirely analogous to that in undulator theory yields a modified resonance condition

$$E_\gamma \approx \frac{4\gamma^2 E_{laser}}{1 + a^2/2}$$

where a is calculated using the amplitude of the laser field and linear polarization is assumed. As in undulators, $a^2/2 \rightarrow a^2$ in this formula for a circularly polarized incident laser.

For linear polarization, harmonics are generated. The strengths of the harmonic lines are quantified by “Bessel function factors”. These factors have the same functional form as in undulators, but the relativistic invariants in the arguments of the functions

are modified. For example

$$K \frac{\omega}{k_0 c} \frac{\sin \theta \cos \phi}{\gamma} \rightarrow a \frac{\omega}{k_0 c} \frac{\sin \theta \cos \phi}{\gamma(1 + \beta)}$$

and

$$\frac{K^2}{8} \frac{\omega}{k_0 c} \frac{\cos \theta}{\gamma^2} \rightarrow \frac{a^2}{8} \frac{\omega}{k_0 c} \frac{1 + \cos \theta}{\gamma^2(1 + \beta)^2}$$

for the Thomson backscatter case. In the formulas ω is the emission frequency and k_0 is the wave number corresponding to the lab frame periodicity of the undulator or incident laser wavelength.

Following the usual undulator estimate the flux factor into the n th harmonic (n odd) is

$$F_n(a) = \frac{n^2 a^2}{(1 + a^2/2)^2} \left\{ J_{(n-1)/2} \left(\frac{na^2}{4(1 + a^2/2)} \right) - J_{(n-1)/2} \left(\frac{na^2}{4(1 + a^2/2)} \right) \right\}$$

where J denotes the Bessel function of integer order. The strength of the higher harmonics grows with much higher powers of the field strength than the fundamental, eventually dominating the emission.

The scattered radiation pattern is modified at large scattering angles, θ of order $1/\gamma$ or greater; again the relativistic invariants in the scattering process are changed. This effect is usually ignorable because most of the scattered radiation emerges at small angles.

For non-flat illumination pulses the situation is considerably more complicated. Because of the electron slowdown and red-shifting, the spectrum emitted becomes broad, exhibits interference structures, and is generally maximum at the maximum red shift within the pulse [13, 14]. Semi-analytic techniques have been found to be useful in calculating the case of Thomson scattering. Recently, similar calculations have been completed quantifying the full Compton case [15, 16].

2.8. Computer Computations and Simulations

It should be said at the outset of the discussion that highly accurate and quantitative computer codes exist presently that predict the scattered radiation when linear, or low intensity scattering is considered [17]. As most existing sources reside in the linear regime, there is no immediate need to go further.

These codes include effects such as longitudinal pulsing and electron pulse length effects, transverse profiles in the electron and laser beams, hourglass effects and 3-D diagnostics for the emerging pulses. As time progresses, one expects that similar capabilities will soon exist for high intensity scattering $a \approx 1$ and higher.

3. Drive Laser Configurations

Before discussing individual source designs and performance, it is worth reviewing progress in drive lasers. The discussion is broadly organized under the topics of optical cavity-based drive lasers and single (or few) pulse systems. The former class tend to be deployed in high average power sources in storage rings and the latter in high peak power sources at the end of linacs.

3.1. Optical Cavities

In an optical cavity a CW or pulsed laser beam is stored for long periods at high intensity in an arrangement where the laser beam power distribution is enclosed and circulates. The cavity is designed so that the intensity is greatest at the collision point. Standard confocal spherical mirror systems and Fabry-Perot arrangements have been deployed in Compton sources. In the future, it is expected that more advanced optical storage devices will be developed allowing smaller ultimate spot sizes and larger circulating power.

3.1.1. Cavity Parameters

The main parameters of interest in an optical cavity designed for Compton sources are the potential circulating power and the beam spot in the collision region. The former quantity tends to be limited by residual absorption and mirror heating. The latter quantity can be limited by the wavelength of the power. Up to the present however, scattering configurations have had relatively long Rayleigh Range [18], and the transverse focussing of the laser beam is not as extreme as it might be. Because the Rayleigh range is usually much longer than the longitudinal extent of the interacting electron and laser bunches, hourglass effects from the photon beams can usually be neglected. Parameters, and some typical dimensions are given in Table 1.

Table 1. Typical Optical Cavity Parameters

Quantity	Dimesions
Wavelength	200 nm-10 μm
Circulating Power	0.1-200 kW
Spot size	50 μm -500 μm
Rayleigh Range	5 cm-5 m

3.1.2. Externally Excited

Table 2 gives data on the optical cavities of Compton sources for various projects that are energized by coupling an external laser into the optical cavity. Most arrangements of this type utilize a high-finesse Fabry-Perot storage cavity. Individual projects will be described in detail in the subsequent text. The present state-of-the art is at the 10s of kW level and development was stimulated by the desire to build more capable polarimeters.

Table 2. Externally Excited Optical Cavities

Location	Wavelength	Input Power	Circulating Power	Spot Size <i>rms</i>
Jefferson Lab	1064 nm	0.3 W	1.5 kW	120 μm
TERAS	1064 nm	0.5 W	7.5 W	0.9 mm
Lyncean	1064 nm	7 W	25 kW	60 μm
HERA	1064 nm	0.7 W	2.0 kW	200 μm
LAL	532 nm	1.0 W	10 kW	40 μm

3.1.3. Self Excited

Several projects have used self excitation of the optical cavity field by free electron laser (FEL) action on the optical mode of the optical cavity [19]. At Orsay, an early intra-cavity experiment was performed at an infrared free electron laser driven by an RF linac, yielding 10 keV Thomson scattered X-rays. At the UVSOR ring, this arrangement was used on a storage ring FEL. At Duke University and Super-ACO, optical klystrons were used to generate UV light in a high average power storage ring FEL. A single undulator FEL can produce higher FEL power if the gain is adequate. Scattering from subsequent bunches of the beam producing the FEL light is used to produce γ rays. A nuclear physics user program has been ongoing at Duke taking advantage of the polarization properties of the γ s. In a similar arrangement at Jefferson Laboratory's IR Demonstration

(IR DEMO) FEL, X-rays were produced by Thomson backscattering from the subsequent bunches in the same beam that was amplifying the high average power IR radiations. Table 3 quantifies some of the performance characteristics of the circulating radiation. All these installations used confocal spherical mirrors to form the optical cavity. The spot size is calculated by $\sqrt{Z_r \lambda / \pi}$.

Table 3. Self Excited Optical Cavities

Location	Wavelength	Circulating Power	Spot Size	Rayleigh Range
Orsay	5 μm	100 W	mm	0.7 m
UVSOR	466 nm	20 W	250 μm	0.4
Duke Univ.	545 nm	1.6 kW	930 μm	5 m
Super-ACO	300 nm	190 W	440 μm	2 m
Jefferson Lab	1 μm	100 kW	150 μm	1 m

3.2. High Power Pulsed Laser Systems

The technological breakthrough of chirped pulse amplification [20–22] has become a common technique for circumventing optical damage and non-linear effects during the amplification of short optical pulses in solid-state laser media. This advance has led to unprecedented laser powers and intensities with the current records in the Petawatt range. Terawatt and Petawatt laser pulses with durations ranging from picoseconds down to femtoseconds have been produced by a number of systems and are even commercially available [23].

The architecture of most tabletop chirped pulse amplification Ti:Sapphire laser systems contains an ultra-short, band-width limited Kerr-lens mode-locked [26–28] master oscillator with MHz repetition rate, followed by a pulse stretcher and either regenerative amplifiers or multi-pass pre-amplifiers which are used as a front-end system for multi-pass power amplifiers. The pulses are then passed through a one to one imaging single grating stretcher to obtain a pulse-width of hundreds of picoseconds before they are injected as seed either in the regenerative amplifier, which is pumped by a diode-pumped, intra-cavity doubled, Q-switched Nd:YLF laser or in a multi-pass pre-amplifier respectively. The power amplifier contains large aperture Ti:Sa crystals, pumped from both ends (relay imaged) using two spatially optimized frequency doubled Nd:YAG lasers operating at 10 Hz, and amplifies

the pulses to several joules in a bow-tie configuration before recompression.

For the Compton sources the number of generated X-ray scales linearly with the number of incident photons and therefore increasing power of the laser available systems from TW to PW leads to an improvement of three orders of magnitude when we assume that the pulse duration and the beam size are unchanged. Within the next few years laser performance is expected to increase by about an order of magnitude and up to three orders of magnitude may be gained at the planned Extreme Light Infrastructure (ELI) facility [24] and High Power laser Energy Research facility (HiPER) [25].

High-brightness electron beams in combination with high-intensity lasers are capable of producing hard X-ray photons hence they are also candidates as gamma ray sources for high-energy physics applications such as nuclear resonance fluorescence [29], or the production of polarized positron beams for an e⁺/e⁻ collider [30].

4. Ring Based Compton Sources

Compton Sources based on electron storage rings have had three basic arrangements. In the first arrangement, a low power laser is scattered directly from the stored electron beam. The earliest experiments were of this type [31–33] and were stimulated by the desire to produce gamma rays. Work in Japan was especially prominent, even to the present [34, 35].

During the early period a wide variety of gamma ray energies were produced at various rings [36]: 5–80 MeV at Adone [31], 100–1600 MeV at Novosibirsk [37], 180–320 MeV at Brookhaven [32], 1–40 MeV at Tsukuba [38, 39] and 350–1500 MeV at ESRF [40].

For example, up 1–10 MeV photons were observed in scattering a 1 W Nd-YAG laser off electrons in the TERAS storage ring at the Electrotechnical Laboratory [33] in the mid 1980s. Later gamma ray beams were produced in a parasitic nuclear physics installation on the Spring-8 synchrotron light ring. Eventually, 2×10^4 photons/sec were produced by direct illumination of 3 W [39] at TERAS, and 2.5×10^6 photons/sec were produced for 5 W laser input at Spring-8. Because of the extremely high electron beam energy of the Spring-8 ring, 2.4 GeV photons could be produced [35].

The second arrangement is to have the electrons collide with an intra-cavity FEL beam. Projects at the UVSOR storage ring [41], Duke University [42], and Super-ACO [36] developed Compton gamma-ray sources on this basis. In the first experiments in these devices, production rates were not highly increased because due to low electron bunch currents in the rings. For example, the group at the UVSOR electron storage ring [41] produced up to 25 MeV gamma rays at rate of 2×10^6 photons/sec with 20 W circulating power. More recently, the FEL power limitation has been overcome by top-up injection of replacement electrons into the rings, allowing much higher intra-cavity power. It should be noted that most high power FELs have been designed around optical resonators with concentric spherical mirrors.

Duke University continues to operate its FEL as the High Intensity Gamma Source (HIGS) user facility for nuclear physics research [43]. The performance of the Compton source has improved along with the FEL performance [44]. A photograph of the beam-line where Compton scattering takes place is shown in Fig. 3, looking along the electron beam motion. In the foreground is the first undulator for the OK-4 optical klystron. This is followed by the buncher magnet and the gain stage of the optical klystron. The Compton interactions take place at a location between the upstream undulator and buncher magnet. The inset in the photograph shows the γ ray collimator that sits approximately 53 m downstream of the interaction point. Some present day performance parameters are up to 100 MeV γ rays, highest total measured production rate of more than 10^{10} photons/sec, at 9 MeV, lasing at 545 nm and with 1.6 kW circulating power in the FEL.

Fig. 3. Duke University collision beam-line and gamma ray collimator.

The first experiments on Compton scattering took place at existing electron storage rings. The rings, at GeV-scale energies, are not small. As GeV scale energies are needed to produce MeV or higher photons by Compton scattering, there is a nice match for producing gamma rays. But instead suppose the goal is to produce X-rays, where not so much electron beam energy is needed. One is led naturally to small low energy rings [45].

In the third arrangement of ring Compton sources, a coherent optical beam stored in a high-finesse high average power optical cavity is collided with electrons in a storage ring. As an example, the TERAS ring Compton source flux was increased and order of magnitude by installing a long-axis Fabry-Perot cavity [46]. Such an arrangement has two interesting advantages compared to the intra-cavity arrangement. First is that the circulating optical power, and more specifically its transverse intensity distribution, becomes decoupled from the electron beam. This circumstance allows higher intensities at the collision by designing in a small photon beam waist at the collision point. A related second advantage is that one may consider geometries for the optical cavity different from confocal spherical mirror geometries. In particular, one may concentrate on those resonators designed to maximize the circulating optical power. In addition, as pointed out in Ref. [45], there is cooling of the electron beam by the Compton emission in some regimes, allowing the damped beam emittance and electron spots to be much smaller than they otherwise would be.

Following this general plan, a compact Compton X-ray source has been built and demonstrated by Lyncean Technologies, a California company formed to commercialize X-ray sources based on Compton scattering. A schematic of the ring and optical cavity appears in Fig. 4. Recently this device has produced 10^{11} photons/sec full flux from a $50 \mu\text{m}$ source size in the energy range 10-20 keV [47]. It is expected that an average spectral brilliance of 5×10^{11} photons/(sec $\text{mm}^2 \text{mrad}^2$ 0.1% bandwidth) will eventually be achieved. This source has been used in phase contrast imaging experiments [48] and in determining protein structures [49].

Fig. 4. Schematic drawing of the Lyncean compact light source illustrating the laser-electron pulse interaction. The storage ring has a footprint of approximately 1 m by 2 m.

5. Linac and Energy Recovered Linac Based Compton Sources

Jefferson Lab constructed an X-ray source based on intra-cavity Thomson Scattering of the high average power infrared radiation in the IR DEMO free electron laser [50] off the FEL electron beam [51]. Because of the short electron bunch length in the FEL, a high peak flux of sub-picosecond X-rays can be made. 3.5 keV to 18 keV X-rays were produced at a peak brightness of 10^{10} photons/(sec mm² mrad² 0.1% bandwidth). As in the storage ring sources, this device also produced a high average flux of 10^9 photons/sec because the repetition rate was 37 MHz and higher. This result was an early demonstration of the fact that SRF linacs provide a means to high average flux sources. This work was a natural follow on to similar prior work on a pulsed linac at Vanderbilt University [52].

Jefferson Laboratory's nuclear physics program based on the CEBAF accelerator [53] uses laser Compton scattering from several GeV electrons for measuring the longitudinal polarization of the electrons [54]. Although a Compton source of photons mainly for diagnostic purposes, measurement time for a given accuracy in the polarization measurement is proportional to the number of photons scattered, and the designs of the optical cavities evolved in a direction similar to the ring Compton sources. One desires high finesse optical cavities built to have a small spot where the interaction takes place. The electron beams being probed have 50-200 μ m beam

size, so the requirements are not so extreme as some of the other applications. The polarimeter optical cavity takes a 300 mW Nd:Yag laser up to 1.5 kW inside the optical cavity. By scanning the laser beam transversely it was determined that an electron beam size of 75 μ m and a photon beam size of 120 μ m were achieved. An interesting observation is that the count rate in the polarimeter is sensitive to the electron beam size, and provides useful beam optics feedback during the operation of the CEBAF accelerator. These workers report a 3% stability in the power in the optical cavity measured over 10 hours.

Brookhaven National Laboratory created a high peak flux of 8×10^{18} photons/sec at an experiment at the Accelerator Test Facility [5]. In the experiment 7.6×10^6 X-ray photons were detected within a 1.823 Å spectral window in a 3.5 ps pulse. A 600 MW CO₂ laser interacted in a head-on collision with a 60 MeV, 140 A, 3.5 ps electron beam. Both beams were focused to a 32 μ m spot. A schematic of the experiment and a photograph of the scattering chamber for the experiment appears in Figs. 5 and 6. The precision mirror mounts evident in the center of the photo hold the focusing mirrors for creating small laser spot at the interaction point.

Fig. 6. Scattering chamber for Brookhaven National Laboratory Thomson scattering experiment. Mirror position adjustment in the foreground.

Workers from UCLA, Brookhaven, and Daresbury Laboratory have been performing measurements of energy and angular distributions of the Brookhaven National Laboratory ATF Compton source [55]. Spectral and angular information of the Compton sources was obtained using only an X-ray imaging device and foils with K-edges in keV energy

Fig. 5. Brookhaven National Laboratory high flux Thomson scattering experiment [5].

range. First, beam parameters are chosen such that on-axis photons are above the K-edge for a given material and absorption is very strong; there is very little transmission. Photons observed off-axis are red-shifted, fall below the K-edge and are transmitted creating a ring pattern. By analyzing the transmission in various beam conditions experimental results for the bandwidth and the double differential spectrum of angle and energy of Compton photons generated at the Brookhaven National Laboratory Accelerator Test Facility (BNL ATF) have been obtained.

A photo of the scattering chamber appears in Fig. 7. The $10.6 \mu\text{m}$ incident laser pulse enters through the NaCl window on the right and is focused down to the center of the chamber by a 90 deg off-axis paraboloid (OAP), where it interacts with the counter-propagating e-beam coming from the left. X-rays and e-beam exit through a 3 mm hole in the OAP and electrons are subsequently dumped by a dipole spectrometer. In the diagnostic area the X-rays are analyzed using foils with K-edges near the central X-ray energy (7 to 9 keV), such as iron and nickel. A remotely controlled pinhole allows 1 mrad selection of scattered photons. Flux is measured by a remotely insertable silicon diode detector and is routinely 1×10^8 photons/shot. A micro-channel plate detector images the Compton X-rays.

Fig. 7. Scattering chamber for Brookhaven National Laboratory Compton source during recent experiments.

At Daresbury laboratory, a multi-10-TW laser has been installed at Daresbury Laboratory to drive a Compton X-ray source [56, 57]. Polarized X-ray pulses will be generated through collisions of laser pulses with electron bunches delivered by the energy recovery linac commissioned at the ALICE facility. The spectral peaks of the emission range from 0.4 to 12 Å, depending on the electron bunch energy and the scattering geometry. X-ray pulses containing up to 10^7 photons per pulse will be created from head-on collisions, with a pulse duration comparable to the incoming electron bunch length.

Side scattering collisions will also be available; in this case the laser pulse transit time defines the X-ray pulse duration. X-rays generated by the

interaction of the table top laser with the electron bunch have been modelled by Monte Carlo simulation showing that brightness in excess of 10^{21} photon/(s mm² mrad² 0.1% bandwidth) will be obtained in back scattering geometry [58]. Called COBALD, this source will be initially used as a short-pulse diagnostic for the ALICE electron beam and will address the extreme challenges of photon/electron beam synchronization, which is a fundamental requirement for all conventional accelerator and laser wake-field-acceleration-based sources. Initial results have recently been presented [59].

Lawrence Livermore National Laboratory has been constructing a Compton Scattering γ ray source for nuclear resonance fluorescence measurements [60]. In their recent experiments, an electron pulse of around 500 pC originating in a high accelerating gradient RF photocathode gun is accelerated in a previously available linac to just over 100 MeV. The electron pulse collides with a 532 nm laser pulse of energy 150 mJ, yielding γ energies up to 0.9 MeV. The photon yields were about 10^5 photons per pulse and a peak brightness of 1.5×10^{15} photons/(sec mm² mrad² 0.1% bandwidth) was measured at 478 keV.

6. Future Proposals

As a result of its recent work [60], the LLNL group anticipates upgrading their linac both to allow higher output photon energy reach up to 2 MeV, and to improve the brilliance of the output photon beam [61]. Presently, the (normalized) beam emittance out of the gun is known to be good and it is seriously degraded by the linear accelerator, which will require a new design/upgrade to improve overall performance. Because of the strong emittance scaling of the brilliance, factors of 10^3 improvement of the brilliance are anticipated.

A Japanese group has also completed significant design work on a facility for resonance fluorescence detection of nuclear isotopes [62]. Their plans are based on using an energy recovered linac with beam parameters similar to those achieved already at the Jefferson Lab FEL, but with a 700 kW average power laser interacting with a beam focussed to 20-40 μ m. This device should produce a high average flux of 10^{13} gammas/sec. The group has also completed a direct Compton scattering experiment at the TERAS ring with a 40 W laser as a proof-of-principal for the isotope detection method.

The PLasma Acceleration and MONochromatic X-ray generation (PLASMONX) project is a new installation in Frascati involving an extremely high peak power Ti:Saph laser with 6 J, 20 fs pulses (0.3 PW) [63]. The laser will be scattered from beam from the existent SPARC electron photo-injector allowing for advanced laser/e-beam interaction experiments, at up to 150 MeV beam energy. The beam lines to the interaction chamber with the laser have been designed with the goal of achieving 510 μ m electron spots in collision. Given the high power and small spots, it is expected that high- a phenomena will be prominent in the output from this device.

A completely new ring-based source is being investigated at Thales/CEA company in France [64] in collaboration with workers from Laboratoire de l'Accélérateur Linéaire (LAL). The electron ring will be somewhat larger than the Lyncean device, but the accelerator still fits within a 7×10 m footprint. The optical cavity, of Fabry-Perot type, fits around one of two high field bends in the ring design, which is otherwise fairly conventional. A circulating power of 10 kW has been demonstrated as part of the ILC positron source program, with prospects of eventually achieving between 100 kW and one MW [65] and a pulsed laser beam has been stored. This result guides the the work in Reference [62] above [66]. Electron beam energies up to 70 MeV and photon output energies up to 90 keV are envisaged.

Workers at Massachusetts Institute of Technology have proposed to build a Compact ultra-bright X-ray source based on Compton Scattering [67]. There are two principal novelties in their approach. First is applying an optical cavity of advanced design, allowing the circulating power in the incident photon beam to be both higher, at the one MW level, and at the same time focused down to a small spot of a few μ m. This allows one to access a values, although still in the linear regime, much larger than other optical cavity sources. Second, and in contrast to other linac based sources, their source would be based on a superconducting RF (SRF) linac, allowing high CW accelerating gradient, and on new compact low frequency spoke accelerating systems that may be operated at 4 K temperature. From an operating viewpoint the device will look more like a ring source; the high flux comes from low bunch charge scattering but at a very high repetition rate of 100 MHz. The high brilliance of the device comes from low posited

emittance growth in the gun and linac anticipated because of the low bunch charge of 10 pC.

Duke University has plans to upgrade their pioneering γ source [44, 68]. The HIGS facility is planning for a new, high-flux Compton source by colliding the storage ring electron beam with a high-power laser beam inside a high-finesse Fabry-Perot cavity with circulating power of 10-100 kW. This Compton source will be operated to produce gamma-ray beams in the energy range of 1 – 25 MeV, with a projected total flux of 10^{11} – 10^{13} γ /second. The high-finesse cavity will be installed in the middle of their FEL straight section; the gamma-ray capabilities enabled by the FELs, in particular in the energy region above 25 MeV, will be retained.

6.1. R&D Topics

Because the X-ray flux is proportional to the laser pulse energy, continued R&D into high average power laser systems will benefit Compton Source facilities based on both storage rings and linacs. At the same time, there must be development of stable laser storage cavities capable of delivering pulses approaching 10 mJ. In the case of linac-based systems, these cavities should ideally provide the ability to make few-micron laser spot sizes at the collision point. Use of non-gaussian cavity modes, which allow use of mirrors with on-axis apertures for the electron beam, has the potential to improve the performance of both types of Compton source. Both flux and brightness will benefit from brighter electron beams. This is particularly important for linac sources for which, unlike ring sources, there is no dilution of the emittance by recirculation for millions of turns. However, a multi-collision linac-based Compton source would require careful optical design to preserve beam quality. To achieve flux that is comparable to that projected for storage-ring Compton sources, linac-based systems must include energy recovery and a high-brightness, CW gun, which requires development of gun and cathode technology. CW SC rf linac cavities operating at 4K are essential in order to reduce operating costs.

Once a detailed machine design is in hand, optimized collision beam optics (both electron and drive laser) and X-ray beamlines must be designed to match the unique characteristics of the scattered radiation. One anticipates that to achieve the

best performance ideas from particle physics collider design will be fruitfully employed.

7. Summary

A large number of Compton sources exist presently. These devices can reach output photon parameters that are easily calculable, and unique in many aspects. For example, tunable polarized γ ray sources have been built using this technique, as have X-ray sources of various sorts and geometries. Key to source performance are attaining large laser power in small beam spots, and having a high quality electron beam to scatter from. A host of new ideas, new scattering geometries, and new applications point to new developments in this field in the future.

There have been two major directions in Compton source development, mainly related to the type of laser used to drive the scattering events. The first line of development, most suitable for high average flux devices, has converged on scattering from radiation stored in high finesse optical cavities. This approach may become overwhelmingly attractive in the future, if continued progress on optical storage cavities is made. Sources with circularly polarized incident lasers can be used as polarized electron beam polarization monitors, and this application has spurred the development of externally driven optical storage cavities.

The second line of attack is to apply the latest high peak power lasers to obtain scattered pulses of the highest peak brilliance possible. Synchronized high-brightness, relativistic, electron beams and high-intensity lasers have become significantly more commonplace during the last decade, opening new possibilities for the generation of X-rays. At several laboratories, high peak brilliance Compton sources have been proposed, or are being designed, commissioned or operated for high flux generation of polarized X-rays. Additional characteristics include tuneability, short pulse durations (ps down to fs range), and high fluxes within a narrow spectral bandwidth.

Compton sources are playing an increasingly critical role for advanced applications in frontier fields like radiological imaging [69], phase-contrast imaging [70–72] radiotherapy [73], X-ray spectroscopy [74], particle accelerator diagnostics [75–77], and national security [78–80]. The existence of new compact high flux X-ray machines based on

Compton scattering is stimulating commercial activity. Perhaps this beginning will lead to a multitude of compact light sources in the future.

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