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ADVANCES AND CHALLENGES IN COMPTON RADIATION SOURCES*

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Abstract

Ongoing developments in Compton radiation sources are aimed toward a diversity of potential applications, ranging from university-scale compact x-ray light sources and metrology tools for EUV lithography, to positron sources for e^-e^+ colliders. Novel conceptual approaches are pursued on different routes: One research direction lies in multiplying the source's repetition rate and increasing its average brightness by placing the point of Compton interaction inside an optical cavity. High-gradient plasma-wakefield accelerators are fast becoming a practical reality, offering a new paradigm to compact all-optical Compton sources operating in x-ray- and gamma-regions. Continuing improvement in the quality of the beam of plasma accelerators promises the achievement of fully coherent Compton x-rays, thereby prompting the evolution of the Compton source to an all-optical free-electron laser.

INTRODUCTION

Passing head-on the laser focus, relativistic electrons with a velocity $v = \beta c$, where c is the speed of light and β is the relativistic factor, scatter laser photons within a narrow-divergence cone with a half-opening angle $\theta_0 = 1/\gamma$ centred along the electrons' propagation. The scattered photons emerge Doppler-shifted to the x-ray or gamma range at

$$\lambda_x \approx \frac{\lambda_L}{4\gamma^2}[1 + a_0^2 + \gamma^2\theta^2], \qquad (1)$$

where λ_L is the laser wavelength, $\gamma = \frac{1}{\sqrt{1-\beta^2}} =$ E[MeV]/0.511 is the Lorentz factor, E is the electron energy, $a_0 = 0.855 \times 10^{-9}\lambda_L[\mu m]\sqrt{I_L[Wcm^{-2}]}$ is the normalized laser vector-potential, and I_L is the laser intensity.

The maximum specific photon yield for matched counter-propagating laser- and electron-pulses, $\frac{N_x}{N_e} = \frac{N_L\sigma_T}{2\pi\sigma_L^2}$, easily can reach one photon per electron, where N_x, N_e, and N_L correspondingly are the number of Compton photons, electrons, and laser photons per pulse; σ_T =6.65× $10^{25} cm^2$ is the Thomson cross-section, and σ_L is the rms radius of the laser's focus.

The effect, credited to the scientists who discovered this radiation process, is called Thomson scattering (classic regime at $h\nu_x \ll mc^2$) or *inverse* Compton scattering (relativistic regime at $h\nu_x \geq mc^2$).

The classic interpretation of photon scattering from electrons actually is synchrotron radiation, due to the electron's oscillation in a transverse electromagnetic field similar to its motion inside a wiggler of a Synchrotron Light Source (SLS). Therefore, a Laser Synchrotron Light Source (LSLS) is another legitimate identifier name for such a radiation source.

With that in mind, a more widely recognized terminology of a Compton Source (CS) is adopted here for the entire category of sources that produce gamma rays via inverse Compton scattering, or x-rays via Thomson scattering.

The science and technology fields that study and apply CSs are far-reaching and diverse. Several unique features of CSs identify them as invaluable research instruments: Thus, due to the micrometre-scale optical period of its virtual wiggler (the laser), a CS can be configured as a relatively compact and economical device that readily will fit to university- and industrial-settings. The capability of delivering ultra-high peak brightness and pulses of femtosecond duration favours the application of a CS for single-shot tomography of fast transient processes and living objects. The natural synchronisation between the x-ray (gamma) pulses and the laser-pulses is ideal for pump-probe experiments.

While the fundamental physics of CSs is well understood, their experimental verifications still are fragmental and their potential for application is not fully utilized. Research is underway to improve this situation.

This paper reviews innovative concepts and steps towards developing compact Compton light sources wherein the CS's advantages are intensified in several directions:

One of such research directions is multiplying the source's repetition rate and increasing its average brightness by placing the Compton interaction point inside a laser cavity filled with fast-recurring laser pulses.

The quality of the beam from high-gradient plasma-wakefield accelerators driven by contemporary ultra-intense lasers already is comparable to that from conventional electron accelerators, so supporting the value of compact, all-optical CSs. Furthermore, this development aids in approaching the ultimate challenge for the next-generation CSs that are progressing towards their full coherency, thereby completing their evolution from a virtual synchrotron light sources to virtual free-electron lasers.

Progress in ultra-intense lasers hastens explorations into strong-relativistic regimes, where multiple Compton harmonics are generated.

This review is concluded by considering other enticing research possibilities in yet unexplored CS regimes, which are awaiting demonstration. They encompass extending the e-beam/laser interaction region via the channelling the beams and multiplying the Compton photon energy by colliding the laser pulses.

GAMMA-RAY COMPTON SOURCES

The competitiveness of CSs lies primarily in their relatively compact size and ability to produce ultra-high

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spectral-peak brightness exceeding that of 2nd- and even 3rd-generation SLSs while maintaining a similar spatial coherency. It is well understood that the potential for miniaturizing the radiation source reflects the short optical period of a virtual wiggler (laser) that is measured in micrometres compared with the centimetre structural scale for a static magnetic undulator. This advantage is derived directly from the undulator's expression, which is identical to Eq.(1) after substituting λ_L with the double wiggler period $2\lambda_w$ and a_o with the undulator parameter $K = 0.934\lambda_w[cm]B[T]$. Evidently, the main saver of space does not just lie in miniaturizing the insertion devise (the undulator or wiggler) but mainly the hundredfold reduction of the electron accelerator required for attaining the same photon-energy from several GeV for SLS to tens of MeV for CS.

Alternatively, using GeV-class electron accelerators, allows our moving the scattered photon energy to the MeV gamma-range that is inaccessible with conventional SLSs.

The penetration properties of gamma rays into matter are the gate to their diverse applications. Hard gamma photons propagating though dense materials prompt nuclear reactions, generating secondary kinds of radiation that is easily identifiable, such as alpha particles and neutrons, and can be used for separating isotopes. Moving towards compact gamma sources is the direction being pursued at leading nuclear-physics facilities, such as the MEGa-Ray project at Livermore National Laboratory in the United States [1], and the ELI-NP machine in Europe [2].

Fortunately, the expected fast-scaling of the CS's peak brightness with γ, $B_p \approx 1.5\times10^{-3}\frac{N_x\gamma^2}{(2\pi)^2\sigma_e^2\tau_e}\sim\gamma^5$ (or $\sim\gamma^3$ for the emittance dominated condition, $\epsilon_n > \sigma_e$, where $B_p \approx 1.5\times10^{-3}\frac{N_x\gamma^2}{(2\pi)^2\epsilon_n^2\tau_e}$) makes its gamma-ray regime not only unique in terms of spectral access, but highly competitive in the delivered brightness to the 2nd- and 3rd-generation SLSs; here, σ_e is rms radius of the electron beam, and τ_e is the duration of the electron bunch. For example, B_p>1.5×10^{21} ph/s-mm^2-mrad^2-0.1%BW* is projected for the 13 MeV ELI gamma- source.

INTRA-CAVITY HIGH-REPETITION COMPTON SOURCES

A high peak brightness and short duration pulse are essential to the CS's competitiveness and define those applications where CSs can strongly complement SLSs. However, the much higher MHz repetition rates of SLSs result in a higher average brightness, $B_{avg} = B_p f \tau_e$, and intensity. Catching up in this parameter is important for promoting CSs as the new-generation compact light-sources [3], as gamma sources for producing polarized positrons in future e^-e^+ linear colliders [4], and for metrological purposes in next-generation EUV lithography [5]. Importantly, the losses in the laser beam on Compton scattering typically are negligible and are favourable for multiple closed-loop laser pulse recirculation, so resulting in the efficient multiplication of the CS repetition rate and average power.

High-Finesse Super-Cavities

Several research groups are investigating the value of the approach of using a "coherent cavity" or a "super-cavity" for a high-average-power CS. This concept is based on a well-known property of a Fabre-Perot interferometer: Thus, tuned in resonance with a continuous monochromatic beam, it builds up inside the radiation power equal to $P_c = \frac{F}{\pi}P_0$, where P_0 is the laser power outside the cavity, $F = \frac{\pi\sqrt{R}}{1-R}$ is the cavity's finesse factor, and R is the reflectivity of the cavity's mirror. A similar situation occurs when the source of illumination is a mode-locked CW laser, and the round-trip through the cavity is exactly synchronized with the pulse's repetition rate.

In the field-enhancement super-cavities designed for Compton scattering, the path of the laser beam is folded with mirrors that also focus the laser on to an electron beam delivered from a high-repetition rate accelerator. Experiments are underway in Japan [6], the United States [7], and France [8] to explore the potential of this approach towards achieving average x-ray fluxes meaningful for the aforementioned applications. The MHz repetition rate of the mode-locked CW Ti:sapphire lasers used in these sources is matched to the bunch's repetition rate in a synchrotron storage ring or a superconducting linac. With the demonstrated hundredfold multiplication of the acting laser power at the Compton IP, a 10^{12} ph/s average x-ray flux is achieved using 100-W lasers. Further progress rests on extending the technology limits for average laser-power and the quality of reflecting mirrors. Researchers suggest that the industry will progress within the next few years towards achieving a 1 kW laser power, and the mirror coating losses at only 0.005%. This will allow the demonstration of a photon flux of 10^{14} ph/s, approaching the SLS's parameters. However, the extremely low tolerances of the components' stability and alignment, the optical diffraction losses, and the lower efficiency of crossed - beam interactions (compared to counter-propagation) make this ambitious goal very challenging.

Active Laser Cavity

BNL researchers are investigating a different approach to using an optical-laser storage cavity for increasing the ICS's average power by employing a high-power 10-μm CO_2 gas laser rather than the solid-state lasers employed elsewhere. The obvious advantage of using a CO_2 laser is that it provides 10-12 times more photons per Joule than do solid-state lasers. However, the mid-infrared (IR) gas laser- and optics-technology does not favor the super-cavity approach: CO_2 lasers do not operate in a CW mode-locked regime, and mirrors typically have much higher losses there than in the 1-μm wavelength region.

*These units are used for B_p and B_{avg} throughout the paper.

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At the same time, pulsed CO_2 lasers can operate at appreciably high repetition rate, 100-Hz to 1 kHz, and at ~1 kW average power. Based on the x-ray yield already demonstrated in BNL's single-shot Compton experiments [9], an average flux 10^{12} ph/s is projected by the direct application of such lasers, even without a storage cavity. To raise this number, re-using the laser pulse ~100 times was proposed via injecting and circulating it inside an active ring-cavity [10].

Unlike the super-cavity approach, the active cavity encompasses an active element, a CO_2 laser amplifier. This intra-cavity amplifier replenishes the loss in the laser pulse's energy during beam propagation, multiple reflections, and transmission through the windows that separate the laser's medium and an in-vacuum electron-beam line from the atmosphere.

Such an active cavity experiment already is being conducted by BNL and RadiaBeam Technologies LLC. The researchers demonstrated a train of picosecond laser of a total energy 30 J, potentially available for multiple interaction with synchronized electron bunches over a time span of ~1 μs [11]. The project's next goal is combining this laser-pulse train with a photocathode electron- linac to support a cumulative Compton photon yield of 4×10^7ph/0.1%BW per a single laser-shot.

High-pressure CO_2 lasers operating at 1 kHz promise to raise the CS's flux to 4×10^{10} ph/s-0.1%BW. This implies B_{avg}=3×10^{10} at the photon peak energy of 6.4 keV is achievable with a 60-MeV linac. In considering the possibility of scaling the brightness with $\sim\gamma^3$ when using a 2.4-GeV linac, we can project a hard gamma-ray source at 10 MeV photon-energy with $B_{avg} \approx 2\times10^{15}$ that otherwise is not accessible in that spectral range. By possibly compressing the electron bunch to 10 fs, the attainable peak brightness of such CS source can reach $B_p \approx 2\times10^{24}$. These parameters are compiled in the column "Incoherent ICS" of Table 1.

ALL-OPTICAL COMPTON SOURCES BASED ON PLASMA ACCELERATORS

Plasma Accelerators

The pre-eminent way to miniaturizing the CS is to use the most space-efficient design for the electron accelerator. Here, lasers again offer a solution. Laser-driven plasma-wake- field electron accelerators (LWFA) deliver acceleration gradients by three orders-of-magnitude above the conventional RF accelerators due to downscaling in the period of the accelerating structure to the plasma wavelength; it is symmetric to the benefit a virtual laser wiggler over a static magnetic undulator. The latest generation of plasma accelerators operating in the "blow-out", or the otherwise-called "bubble" regime gain the reputation of offering a promising approach towards more compact and affordable next-generation energy-frontier particle accelerators [12]. The already demonstrated GeV-class centimetre-long LWFAs deliver beam qualities competitive with some RF accelerator parameters, such as the micron-scale σ_e and ϵ_n , ~100 pC charge, sub-percent energy spread; these beams can readily produce synchrotron radiation.

Radiation from a Plasma Accelerator

A variety of complementary synchrotron radiation mechanisms, as follows, are associated with LWFA.

The most straightforward approach is to send an electron beam from a compact several-centimetre plasma accelerator through a conventional undulator, thereby producing synchrotron radiation in UV-rays and soft x-rays as was proposed [13] and experimentally demonstrated [14].

At the same time, it recently was discovered that an electron bunch accelerated inside the plasma "bubble" radiates due to its betatron motion caused by transverse focusing plasma-fields [15]. Similar to other forms of synchrotron radiation, the fundamental wavelength due to the electron's betatron oscillation in a plasma column scales with γ into the x-ray- and gamma- region $\lambda = \lambda_b/2\gamma^2$, where $\lambda_b = \lambda_p\sqrt{2\gamma}$ is the betatron wavelength, and λ_p is the plasma wavelength. Inside the plasma wake field, electrons are being accelerated and radiated simultaneously, so resulting in a broad smearing in the betatron spectrum. However, the very small micron size of the electron bunch in a plasma accelerator preserves the spatial coherency, as was demonstrated by phase-contrast imaging [16]. Combined with the inherent femtosecond pulse- duration, the synchrotron radiation from the LWFA has proven to be a useful diagnostic tool and also invaluable for applied exploitations; Corde and colleagues comprehensively review this subject [17].

All-optical Compton Sources

Due to the short wavelength of the laser, CSs reach the highest photon-energy than do magnetic- or plasma-wigglers. Such approach has been experimentally investigated over the last few years, typically using ~100 TW laser beams split and synchronized for simultaneously driving LWFA electron bunches from a gas jet and bouncing Compton x-rays from these bunches [17].

An interesting realization of this approach was demonstrated in an experiment wherein the same laser beam that drives the LWFA e-beam was reflected by a foil at the end of the plasma channel to interact with the electron bunch producing Compton photons [18]. Such all-optical, ultra-compact CS is tuneable to 1-MeV at peak brightness, B_p=10^{21}.

With further progress towards the kHz-class solid-state laser drivers for LWFA combined with CO_2 lasers for Compton scattering, we can realize compact all-optical Compton light sources up to B_{avg}=2×10^{13} tunable to the 10 MeV spectral range (see entry in the column "All-Optical CS" in Table 1).

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Towards Compton FEL

The electron beam-driven plasma wakefield accelerator (PWFA) offers us an opportunity of achieving the electron beam's ϵ_n not just comparable to contemporary RF linacs and LWFAs, but even highly superior to it, reaching down to the nanometre scale compared to micrometre presently attainable. Unlike the LWFA where an accelerating cavity in plasma is produced by the *ponderomotive* electron expulsion, so resulting in the electrons being randomly heated to several MeV, in the PWFA, electrons experience negligible heating under the *Coulomb* force of the driver-bunch. Precisely injected into such "cold" plasma bubble with the micrometre-accurate laser-ionization technique named the Trojan Horse (a virtual photo-cathode) [19], the electrons can form an accelerated beam with a ultra-low emittance, ϵ_n =30 nm. The impact of this predicted beam improvement on the CS's properties could be similar to the benefit gained from using low-emittance linacs instead of synchrotrons for SLSs, a concept that resulted in the inception of 4th-generation coherent light-sources – FELs. We may well be on a verge of a similar breakthrough in CSs, which will add temporal coherency to their other attractive features.

To reach FEL-like temporal coherency, electrons must complete their micro-bunching periodical to the radiated wavelength within the laser/e-beam interaction region. The condition is achieved when the FEL gain's saturation length, L_s, fits inside the virtual-laser's wiggler defined by both the laser's double Rayleigh distance and the duration of the laser pulse. The FEL's lasing threshold is attained more easily at lower wiggling frequency with a CO_2 laser for which λ_w=5 μm, compared to the λ_w=0.4 μm for a Ti:Sapph. laser [20]. A simplified expression for L_s derived for a_0=0.5 (after [21])

$$L_s \approx 10^2 \left(\frac{I_A}{I}\right)^{1/2} \gamma^{4/3} \epsilon_n^{5/6} \lambda_w^{1/6} (1+\delta),$$

where, $\delta = 5 \times 10^2 \frac{I_A}{I} \left(\frac{\epsilon_n}{\lambda_w}\right)^{5/4} \gamma^{1/4} \sigma_\gamma^2$, and $I_A = 17\ kA$ is the Alfven current, depends upon beam's parameters: I– current, $\sigma_\gamma = \sigma_E/mc^2$ - the rms energy spread and ϵ_n. Assuming realizable PWFA parameters, σ_E=1 MeV, $\gamma = 60$, $I =$ 6 kA (0.3 nC @ 50 fs), and ϵ_n=30nm we obtain L_s =3 mm. To fit this saturation length to the double Rayleigh distance, the laser must be focused to σ_L =50 µm. Achieving $a_0 = 0.5$ will require a 1-TW laser with a of 10 ps pulse and 10 J energy, both of which are accessible parameters for picosecond CO_2 lasers [22].

With this, we anticipate FEL lasing at 7.6 Å, with N_x=3×10^9 (×100 over incoherent background), a peak power of 10 MW, and B_p=3×10^{26} (after [23]). (See entry to the column "All-Optical FEL" in Table 1.)

OTHER RESEARCH OPPORTUNITIES

Compton-scattering science continues offering unexplored territories for researchers. Let us look at a short selection of such opportunities:

Continuum of Compton Harmonics

Typical requirements on the monochromaticity of the light source limit the intensity of the laser driver, thereby assuring that the inverse Compton scattering is in a linear regime, $a_0 \ll 1$. Accordingly, only limited research has focussed on the relativistic regime when the scattered spectrum of is becoming strongly modified by the red shift due to the electron's relativistic mass change, $\overline{m_e} = m_e\sqrt{1+a_0^2}$, and by the generation of harmonics due to the figure-eight trajectory of the electrons. Meanwhile, such a highly nonlinear regime of e Compton scattering presents great fundamental- and cosmological-interest, and also could be of practical importance as a quasi-continuous source for absorption spectroscopy and material investigation. Further, it can be considered as another avenue to attaining shorter wavelengths without scaling-up an electron accelerator.

Such nonlinear studies are hindered by the lack of facilities that provide the necessary combination of a high-brightness electron beams and relativistic-strong lasers ($a_0 \geq 1$). The ATF user facility at BNL presents one of a few such opportunities where, in 2006, the 2nd-harmonic CS was demonstrated [24]. Recently, the BNL-UCLA collaboration observed the 3rd harmonic and the mass-shift effect at a_0=1-1.4 [25]. For the yet- unexplored $a_0 \gg 1$ regime, numerous harmonics will be generated increasing in intensity up to the critical harmonic number $n_c \cong \frac{3}{4} a_0^3$, [26] and thus yielding a Compton continuum. With the planned ATF upgrade to the 500-MeV electron linac and a_0 =10 from a CO_2 laser, [27] the harmonic continuum will be extended to 3 MeV gamma rays reaching $n_c \simeq$1000.

Channelled Compton Source

Plasma channels are known to confine both electrons, and especially laser beams, over distances much exceeding the Rayleigh length. By utilizing longer and more energetic laser pulses, this advance offers an opportunity for two-orders of magnitude higher photon yields than calculated for the interaction of in-vacuum laser/electron beams [28]. Although the separate parts of this process have been tested, the combined laser/e-beam Compton interaction in a channel has not yet been reported. Experiments are required to verify the viability of this concept and especially the effects of possible instabilities in the electron bunch and modulation in plasma on the CS' performance.

Colliding Laser Pulses

A relativistic electron co-propagating with a focused laser beam can acquire considerable energy, up to $= \gamma_0(1+a_0^2)$, [29] on the way to the focus plane. This is due to ponderomotive acceleration, but it returns to the initial γ_0 state moving out of focus; no net acceleration results. Compton scattering can answer the question of how to use this transient energy when the electron is inside the laser's focus. A counter-propagating laser beam

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Table 1: Comparative Parameters of SLSs and Prospective CSs

Parameter	Source					Measure
	3rd SLS (NSLS II)	4th SLS (LCLS)	Incoherent CS* (with RF linac)	All-Optical CS** (with LWFA)	All-Optical FEL***	
Wavelength	1-10	1.3-44	10^{-3}-1.8	10^{-3}-1.8	7.6	Å
Electron Energy	3	14	0.06-2.4	0.06-2.4	0.03	GeV
Peak Brightness	2×10^{23}	2×10^{33}	3×10^{18}-2×10^{24}	3×10^{18}-2×10^{24}	2×10^{27}	****
Average Brightness	3×10^{21}	3×10^{22}	3×10^{10}-2×10^{15}	3×10^{8}-2×10^{13}	10^{17}	****
Pulse Duration	200,000	50-400	10-100	10-100	50	fs (FWHM)
Repetition Rate	5×10^{6}	120	10^{5}	10^{3}	10^{3}	Hz

* Estimated parameters for the example of the Active Cavity CS discussed in Section "Active Laser Cavity".
** Estimated parameters for the example of All-Optical CS discussed in Section "All-optical Compton Sources".
*** Estimated parameters for the example of Compton FEL discussed in Section "Towards Compton FEL".
**** ph/s-mm^2-mrad^2-0.1%BW

can serve as a probe. The Compton photons produced could be blue-shifted without needing an additional accelerator or plasma. In addition to its practical application as a feasible mode of access to the hard x-ray- and gamma-region, the proposed experiment will answer fundamental questions about the validity of the underlying theory; it also will mimic cosmological effects at the beginning of the Universe that still are sending us a message in the form of hard gamma-rays.

CONCLUSIONS

Next decade shall see maturation of the CS technology towards compact Compton-light sources that will complement contemporary 3rd and 4th -generation synchrotron light sources. Several such technical opportunities are summarized in Table 1. Extending the Compton scattering research into the yet experimentally unexplored territory of relativistic-strong laser fields, colliding-, multi-colour-, and plasma-guided-beams might offer new insights on the way of fundamental- and applied-utilization of the Compton effect.

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