INSTITUTE of ATOMIC PHYSICS
Magurele-Bucharest

PULSE and IMPULSE of ELI
("Extreme Light Infrastructure")

V. Compton Back Scattering by Polaritonic Pulse

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PULSE and IMPULSE of ELI (Extreme Light Infrastructure)

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- Marian APOSTOL, Institute of Physics and Nuclear Engineering, Magurele-Bucharest

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Coherent polarization driven by external electromagnetic fields

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ABSTRACT

The coherent interaction of the electromagnetic radiation with an ensemble of polarizable, identical particles with two energy levels is investigated in the presence of external electromagnetic fields. The coupled non-linear equations of motion are solved in the stationary regime and in the limit of small coupling constants. It is shown that an external electromagnetic field may induce a macroscopic occupation of both the energy levels of the particles and the corresponding photon states, governed by a long-range order of the quantum phases of the internal motion (polarization) of the particles. A lasing effect is thereby obtained, controlled by the external field. Its main characteristics are estimated for typical atomic matter and atomic nuclei. For atomic matter the effect may be considerable (for usual external fields), while for atomic nuclei the effect is extremely small (practically insignificant), due to the great disparity in the coupling constants. In the absence of the external field, the solution, which is non-analytic in the coupling constant, corresponds to a second-order phase transition (super-radiance), which was previously investigated.

$$E_s = -E_{int} = \hbar\omega_1\lambda^2\left|\alpha^0\right|^2 = \frac{\omega_1}{\omega_0}\lambda^2 E_f^0 .$$

$$\lambda = \sqrt{\frac{2\pi}{3a^3\hbar\omega_0}}\frac{J_{01}}{\omega_0},$$ (dimensionless coupling constant)

For numerical estimates we may take $J_{01} = \omega_0 p$, where $p = el$ is the dipole momentum of the particles, l being the distance over which an electron charge e is displaced in the polarization process. For typical atomic matter we may take, for illustrative purposes, $l = a_0 = 0.53$ Å (Bohr radius), $\hbar\omega_0 = 1$ eV and $a = 3$ Å ($p = 2.4 \times 10^{-18}$ esu). We get $\lambda \simeq 0.5$, which is insufficient for setting up the coherent state. Similarly, for atomic nuclei we may take $l = 1$ fm (10^{-13} cm), $\hbar\omega_0 = 1$ MeV and $a = 3$ Å, and get $\lambda \simeq 10^{-8}$, which is an extremely small value for the coupling constant.

- At GDR excitation we could get a maximum efficiency of 10^{-13} and therefore almost a nuclear explosion would be needed to induce a gamma laser effect.

- Direct excitation of nuclei for gamma lasers is not realistic

- Coherent gamma back scattering or the development of free electron lasers could be valuable solutions.

Infrastructure Producing High Intensity Gamma Rays for ELI Nuclear Physics, Bucharest-Magurele, Romania

The ELI-Gamma Source working group
May 31, 2010

The γ source will produce a very intense and brilliant γ beam (E_γ = 14 -16 MeV for the beginning and $E_\gamma \leq 19$ MeV latter), which is obtained by incoherent Compton back scattering of direct laser light with a very brilliant and intense electron beam ($E_e \leq 0.6$ GeV).
The scientific case of ELI presents the experiments envisaged with the γ source and suggests the parameters of the γ beam: bandwidth equal or lower than 10^{-3}, energy up to 19 MeV to access all GDR, repetition rate in the range of MHz to get about 1 event/pulse in the detector, total flux higher than 10^{13} photons/sec, peak brilliance higher than 10^{22} photons mm^{-2} mrad^{-2} s^{-1} (0.1% BW)$^{-1}$ in order to improve the ratio effect-background; the high flux and superb brilliance requires an excellent normalized emittance for the electron beam (in the range of 0.25 mm mrad).

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Ensemble of ultra-high intensity attosecond pulses from laser–plasma interaction

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ABSTRACT

The efficient generation of intense X-rays and γ-radiation is studied. The scheme is based on the relativistic mirror concept, *i.e.*, a flying thin plasma slab interacts with a counterpropagating laser pulse, reflecting part of it in the form of an intense ultra-short electromagnetic pulse having an up-shifted frequency. In the proposed scheme a series of relativistic mirrors is generated in the interaction of the intense laser with a thin foil target as the pulse tears off and accelerates thin electron layers. A counterpropagating pulse is reflected by these flying layers in the form of an ensemble of ultra-short pulses resulting in a significant energy gain of the reflected radiation due to the momentum transfer from flying layers.

Eur. Phys. J. D **55**, 443–449 (2009)
DOI: 10.1140/epjd/e2009-00082-0

THE EUROPEAN
PHYSICAL JOURNAL D

Regular Article

The reflectivity of relativistic ultra-thin electron layers

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Published online 19 March 2009 –

Abstract. The coherent reflectivity of a dense, relativistic, ultra-thin electron layer is derived analytically for an obliquely incident probe beam. Results are obtained by two-fold Lorentz transformation. For the analytical treatment, a plane uniform electron layer is considered. All electrons move with uniform velocity under an angle to the normal direction of the plane; such electron motion corresponds to laser acceleration by direct action of the laser fields, as it is described in a companion paper [Eur. Phys. J. D **55**, 433 (2009)]. Electron density is chosen high enough to ensure that many electrons reside in a volume λ_R^3, where λ_R is the wavelength of the reflected light in the rest frame of the layer. Under these conditions, the probe light is back-scattered coherently and is directed close to the layer normal rather than the direction of electron velocity. An important consequence is that the Doppler shift is governed by $\gamma_x = (1-(V_x/c)^2)^{-1/2}$ derived from the electron velocity component V_x in normal direction rather than the full γ-factor of the layer electrons.

PACS. 52.38.Ph X-ray, gamma-ray, and particle generation – 52.59.Ye Plasma devices for generation of coherent radiation

Uniform Laser-Driven Relativistic Electron Layer for Coherent Thomson Scattering

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(Received 15 March 2010; published 8 June 2010)

A novel scheme is proposed to generate uniform relativistic electron layers for coherent Thomson backscattering. A few-cycle laser pulse is used to produce the electron layer from an ultrathin solid foil. The key element of the new scheme is an additional foil that reflects the drive-laser pulse, but lets the electrons pass almost unperturbed. Making use of two-dimensional particle-in-cell simulations and well-known basic theory, it is shown that the electrons, after interacting with both the drive and reflected laser pulses, form a very uniform flyer freely cruising with a high relativistic γ factor exactly in the drive-laser direction (no transverse momentum). It backscatters the probe light with a full Doppler shift factor of $4\gamma^2$. The reflectivity and its decay due to layer expansion are discussed.

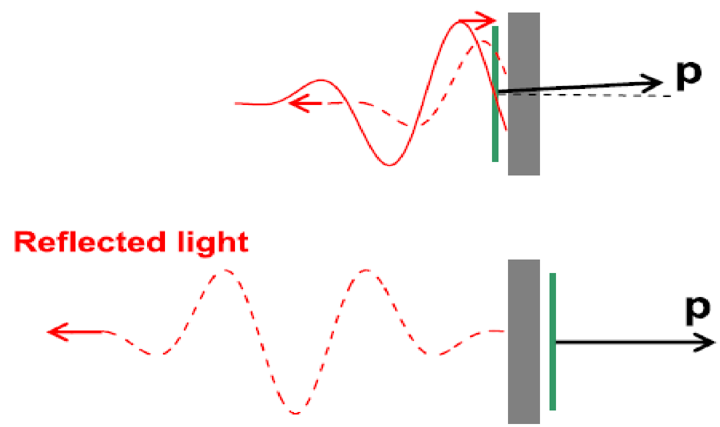

FIG. 2 (color online). Schematic drawing of electron layer (green) surfing on laser drive pulse and reflector foil (grey).

Coherent X- and gamma rays from Compton (Thomson) backscattering by a polaritonic pulse

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October 26, 2010

To be published

Abstract

It is shown that Compton (Thomson) backscattering by polaritonic pulses of electrons accelerated with relativistic velocities by laser beams focused in a rarefied plasma may produce coherent X- and gamma rays, as a consequence of the quasi-rigidity of the electrons inside the polaritonic pulses and their relatively large number. The classical results of the Compton scattering are re-examined in this context, the energy of the scattered photons and their cross-section are analyzed, especially for backscattering, the great enhancement of the scattered flux of X- or gamma rays due to the coherence effect is highlighted and numerical estimates are given for some typical situations.

To be published

A photon traveling in solid matter cannot be treated as an independent entity. The interaction of photons with a crystal produces various kinds of excitations, e.g., phonons (in an ionic crystal), plasmons (in a metal), or excitons (in a semiconductor). Photons and solid-state excitations are dynamically coupled and periodically exchange energy. Thus a mixed state of two quantum-mechanical systems—the electromagnetic field and a solid-state excitation—is created inside the crystal. This state represents a coupled combination of an electromagnetic wave and a medium-polarization wave propagating through the crystal. The quantum of such a mixed state is called a polariton.

PHYSICAL REVIEW A **71**, 023804 (2005)

Propagation of nuclear polaritons through a two-target system: Effect of inversion of targets

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Laser Electron Accelerator

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(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

$$v_p = \omega_p / k_p = v_g^{\mathrm{EM}} = c(1 - \omega_p^2/\omega^2)^{1/2}$$

Such a wake is most effectively generated if the length of the electromagnetic wave packet is half the wavelength of the plasma waves in the wake:

$$L_t = \lambda_w/2 = \pi c/\omega_p . \qquad (2)$$

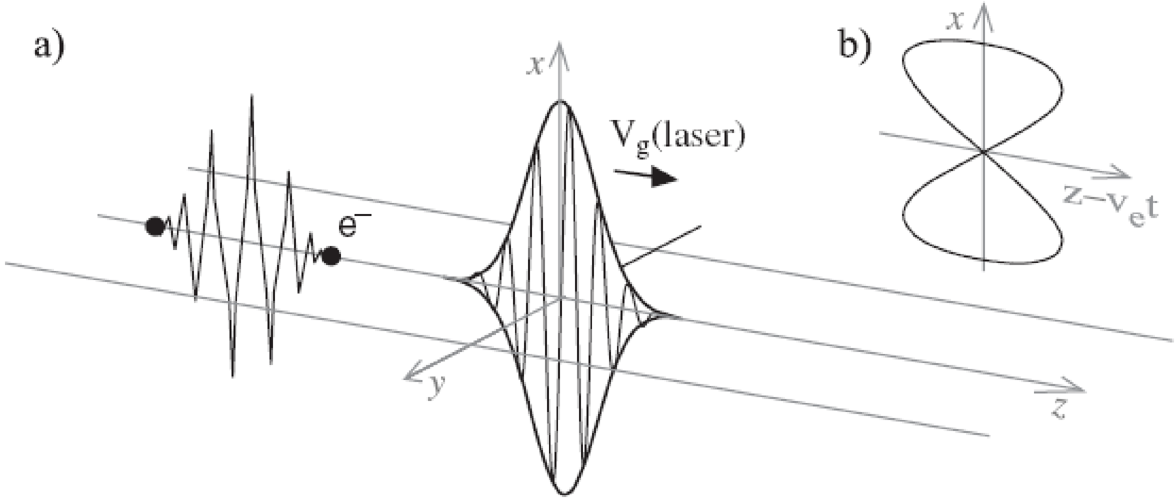


Fig. 2.3. (**a**) A relativistic laser pulse, propagating from *left* to *right* on the z-axis, has passed an electron. Its electric field points along the $\hat{x}$-direction, the magnetic field (not shown) into $\hat{y}$. The electron has moved along a zig-zag–shaped trajectory in the $\hat{x}$–$\hat{z}$-plane and stopped at rest after the passage. (**b**) "Figure of 8" electron trajectory in a frame moving with the mean forward velocity of the electron (averaged rest frame of the electron)

$$\boldsymbol{F}_{\mathrm{L}} = \frac{d\boldsymbol{p}}{dt} = -\mathrm{e} \cdot \left(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}\right).$$

$$p_x = -\frac{\mathrm{e}E_0}{\omega m_0 c} \sin(\omega t - kz) = -a_0 \sin(\omega t - kz),$$

relativistic parameter $a_0 = \mathrm{e}E_0/\omega m_0 c$,

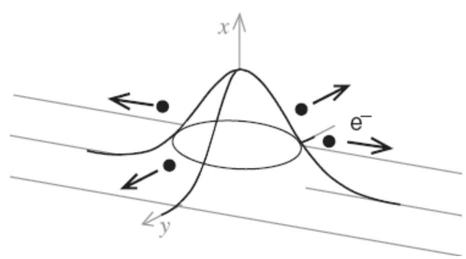
$$p_z = \left(\frac{\mathrm{e}E_0}{\omega m_0 c}\right)^2 \sin^2(\omega t - kz) = \frac{a_0^2}{2} \sin^2(\omega t - kz).$$

H. Schwoerer et al., *Lasers and Nuclei*,
Lect. Notes Phys. 694 (Springer, Berlin Heidelberg 2006), DOI 10.1007/b11559214

The energy of the electron is can also be expressed with help of a_0:

$$E = \gamma m_0 c^2 = \left(1 + \frac{a_0^2 \sin^2(\omega t - kz)}{2}\right) \cdot m_0 c^2 \,.$$

Now we eventually have to come up with real numbers of electron energies versus electric field and light intensity: From (2.7) follows that the kinetic energy of the electron reaches its rest energy at $a_0 = \sqrt{2}$. For a laser wavelength of $\lambda = 800\,\mathrm{nm}$, this corresponds to an electric field strength of $E_0 \approx 5 \cdot 10^{12}\,\mathrm{V/m}$ and a light intensity of $I \approx 4 \cdot 10^{18}\,\mathrm{W/cm^2}$, following from $I = \frac{1}{2} c \epsilon_0 E_0^2$. At the currently almost maximum intensity of $10^{20}\,\mathrm{W/cm^2}$ the electric field is $E_0 \approx 3 \cdot 10^{11}\,\mathrm{V/cm}$ and the mean kinetic energy of the electron amounts to $6\,\mathrm{MeV}$. This relativistic electron energy gave rise to the term relativistic optics. Nevertheless, because of the planeness and transverse infinity of the light wave, our electron is again at rest after the pulse has passed it. It was moved forward, but no irreversable energy transfer took place.



$$F_{\mathrm{pond}} = -\frac{e^2}{2 m_0 \omega^2} \cdot \nabla (E)^2 \,.$$

An irreversable acceleration of an electron in a light field can be achieved only by breaking the transverse symmetry of the light field. This is obtained in real propagating light fields or laser beams, which all exhibit a transverse spatial intensity profile

H. Schwoerer et al., *Lasers and Nuclei*,
Lect. Notes Phys. 694 (Springer, Berlin Heidelberg 2006), DOI 10.1007/b11559214

Electron Self-Injection and Trapping into an Evolving Plasma Bubble

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(Received 24 June 2009; published 25 September 2009)

The blowout (or bubble) regime of laser wakefield acceleration is promising for generating monochromatic high-energy electron beams out of low-density plasmas. It is shown analytically and by particle-in-cell simulations that self-injection of the background plasma electrons into the quasistatic plasma bubble can be caused by slow temporal expansion of the bubble. Sufficient criteria for the electron trapping and bubble's expansion rate are derived using a semianalytic nonstationary Hamiltonian theory. It is further shown that the combination of bubble's expansion and contraction results in monoenergetic electron beams.

The resulting plasma bubble follows in the wake of the laser pulse propagating with the group velocity $v_0/c \approx 1 - 1/2\gamma_0^2$ ($\gamma_0 \approx \omega_0/\omega_p$), where $\omega_p = \sqrt{4\pi e^2 n_0/m}$ is the electron plasma frequency and $\omega_0 \gg \omega_p$ is the laser frequency. Strong longitudinal (E_x) and transverse electric fields inside the bubble are responsible for acceleration and focusing of the relativistic electrons which can, under the right circumstances, be injected into the bubble from the ambient plasma. The latter process of injection and trapping is the focus of this Letter. Although several analytic and semiempirical models of the plasma bubble have recently been put forward [9,10], the complex process of trapping ambient plasma electrons into the bubble is not well understood. Understanding electron trapping or injection from the background plasma has important practical implications because the alternatives (such as, for example, using a second laser pulse [11–13]) are technically demanding. Moreover, injection into a nonevolving bubble in the most interesting case of $\gamma_0 \gg 1$ (corresponding to tenuous plasmas) that could potentially result in single-stage multi-GeV acceleration [14] requires a very large bubble size [9].

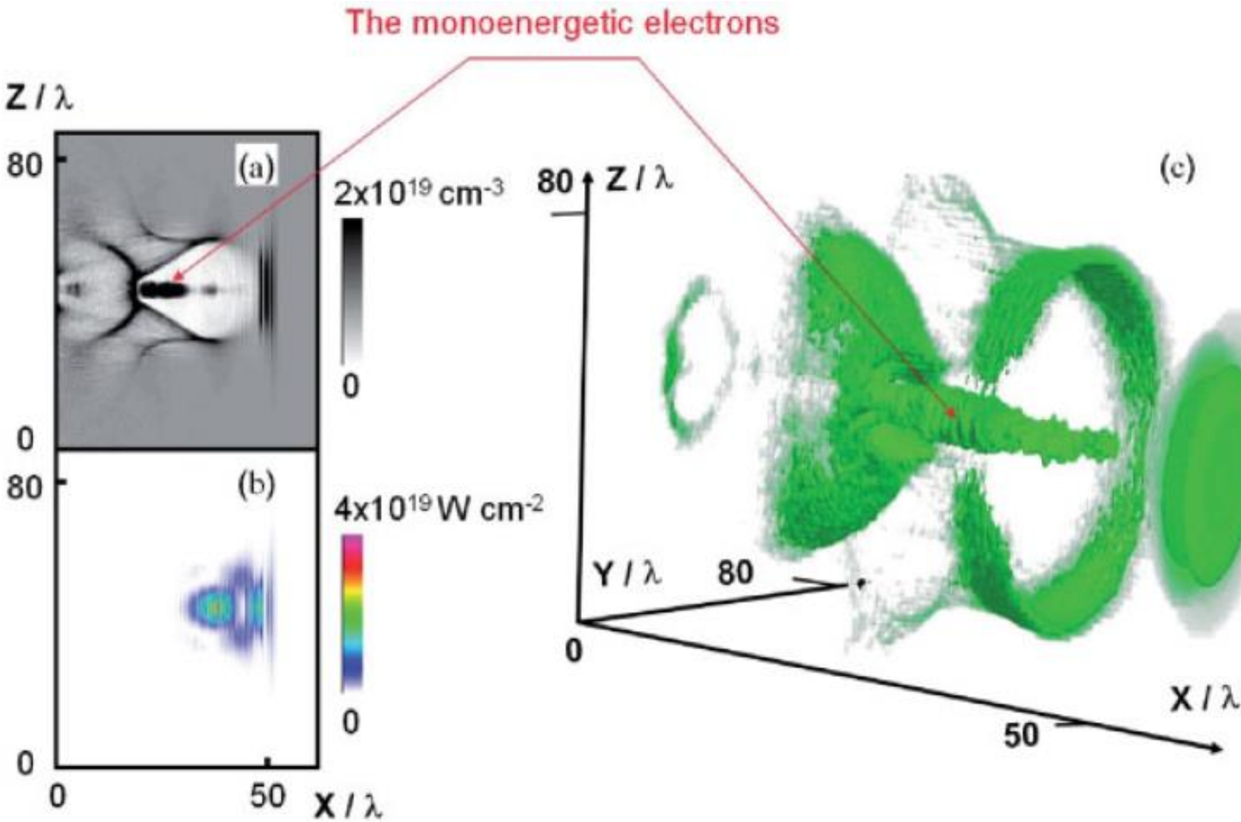


Figure 6 (online color at: www.lpr-journal.org) 3D PIC simulation results for the case $n_e = 6 \times 10^{18}\,\mathrm{cm}^{-3}$. Frames (a) and (b) show distributions of electron density and laser intensity in the XZ-plane which is perpendicular to the polarization direction and passes through the laser axis. Frame (c) provides a 3D volume view on the electron density distribution in the bubble. The image shows an isosurface at $n_e = 2 \times 10^{19}\,\mathrm{cm}^{-3}$.

Recent theoretical work has developed scalings for acceleration in the bubble regime [24]. However the main questions which remain outstanding for the further development of such sources in this regime are typically those of experimental control of the acceleration process. How can the laser and plasma parameters be adjusted to enable control of the electron beam energy, charge, energy spread, divergence, emittance and pointing? These properties have all been observed to vary more than desired – and consequently the most significant results of the research reported recently involved insights into improving the stability of these critical beam parameters.

Polaritonic pulse of laser accelerated electrons

Assume $\omega_p \ll \omega_0 = ck_0$; then, the group velocity

$$v \simeq c\left(1 - \frac{\omega_p^2}{2\omega_0^2}\right) \simeq c$$

The First Great Equation: Electron energy

$$E_{el} = \frac{mc^2}{\sqrt{1 - v^2/c^2}} \simeq \frac{\omega_0}{\omega_p} mc^2$$

Second Great Equation (electron flux)

$$\delta N = nd^2 \lambda_0 \frac{\varepsilon_p^2}{4mc^2 \varepsilon_0^2} \sqrt{\pi \varepsilon_{el} W_0}$$

$\varepsilon_p = \hbar\omega_p$, $\varepsilon_0 = \hbar\omega_0$ and $\varepsilon_{el} = e^2/d$,

Polaritonic pulse of laser accelerated electrons

Two Big Conclusions

Electron energy

$$E_{el} \sim \frac{\omega_0}{\omega_p} mc^2$$

Electron flux

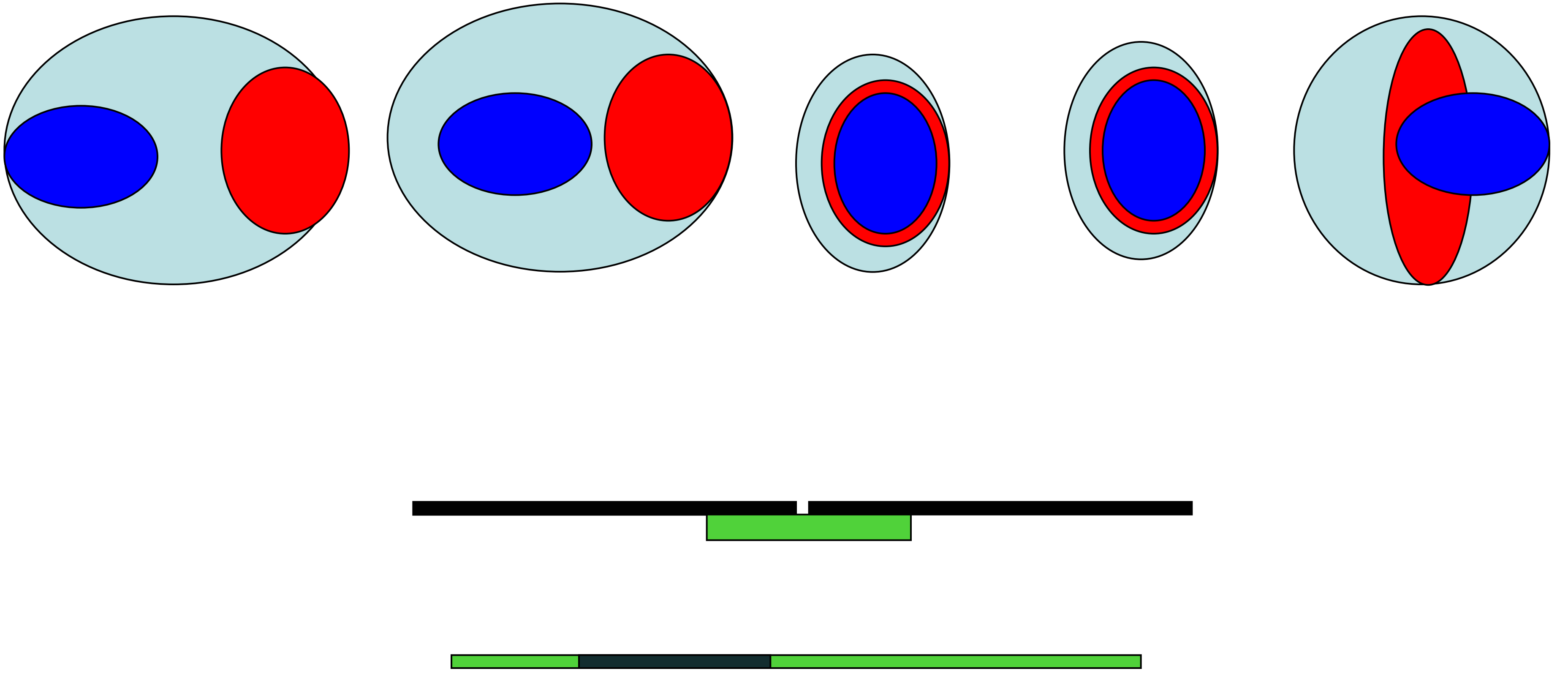
$$\delta N \sim n d^{3/2} \frac{\omega_p^2}{mc^2 \omega_0^2} \sqrt{I_0}$$

Efficiency coefficient

$$\eta = \frac{W_{el}}{W_0} = n d^2 \lambda_0 \frac{\varepsilon_p}{4\varepsilon_0} \sqrt{\frac{\pi \varepsilon_{el}}{W_0}} \ll 1$$

Polaritonic pulse of laser accelerated electrons

- Experiment



In conclusion, we may say that the polaritonic pulses of electrons transported by laser radiation focused in a rarefied plasma may serve as targets for coherent Compton backscattering in the X-rays or gamma rays energy range, therefore as a means for obtaining an X-ray or gamma ray laser. The coherent scattering, which enhances considerably the photon output and ensure its coherence, is due to the quasi-rigidity of the electrons in the propagating polaritonic pulse, which ensures (within certain limits) the stability of this interacting formation of matter and electromagnetic radiation. The energy and cross-section of the Compton (Thomson) backscattering was re-examined in this paper in the context of the coherent scattering by polaritonic pulses, and the (pulse) duration of the backscattering emission was also estimated. Similar ideas have been advanced recently, especially for laser-driven accelerated electron mirrors.[26]-[32]

To be published

Radiation therapy potential of intense backscattered compton photon beams

Weeks, K. J.
Nuclear Instruments and Methods in Physics Research Section A, Volume 393, Issue 1-3, p. 544-547.

For close to 100 years radiation treatments of cancer have used photon radiation produced by the bremsstrahlung process. Free-electron-laser (FEL) technology can produce backscattered Compton photons and this provides an opportunity to investigate a new spectrum of photons. In contrast to bremsstrahlung, the energy spectrum of the backscattered Compton photons is peaked at the high energy. The beams also have small divergence and hence are highly focused. Dose is calculated using Monte Carlo modeling and the results show that the energy distribution can improve the relative tumor to normal tissue dose distribution especially for deep tumors. It is found that fluxes on the order of 10^{11} photons/s are required. The small divergence means that precision small field treatments can be done without collimation and also opens up the possibility of activation applications. These properties may be exploited to advantage in the future. This paper reviews the medical therapy potential and discusses benchmarks for FEL performance which are important to future backscattered Compton therapy applications.

DOI: 10.1016/S0168-9002(97)00561-5

Med Phys. 1997 Mar;24(3):417-23.

The Compton backscattering process and radiotherapy.

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Abstract

Radiotherapy utilizes photons for treating cancer. Historically these photons have been produced by the bremsstrahlung process. In this paper we introduce Compton backscattering as an alternate method of photon production for cancer treatment. Compton backscattering is a well-established method to produce high-energy photons (gamma rays) for nuclear physics experiments. Compton backscattering involves the collision of a low-energy (eV) photon with a high-energy (hundreds of MeV) electron. It is shown that the photons scattered in the direction opposite to the direction of the initial photon (backscattered) will have the energy desired for photon beam therapy. The output of Compton backscattering is a high-energy photon beam (gamma-ray beam), which is well collimated and has minimal low-energy components. Such gamma beams may be used for conventional high-energy photon treatments, production of radionuclides, and generation of positrons and neutrons. The theoretical basis for this process is reviewed and Monte Carlo calculations of dose profiles for peak energies of 7, 15, and 30 MeV are presented. The potential advantages of the Compton process and its future role in radiotherapy will be discussed.

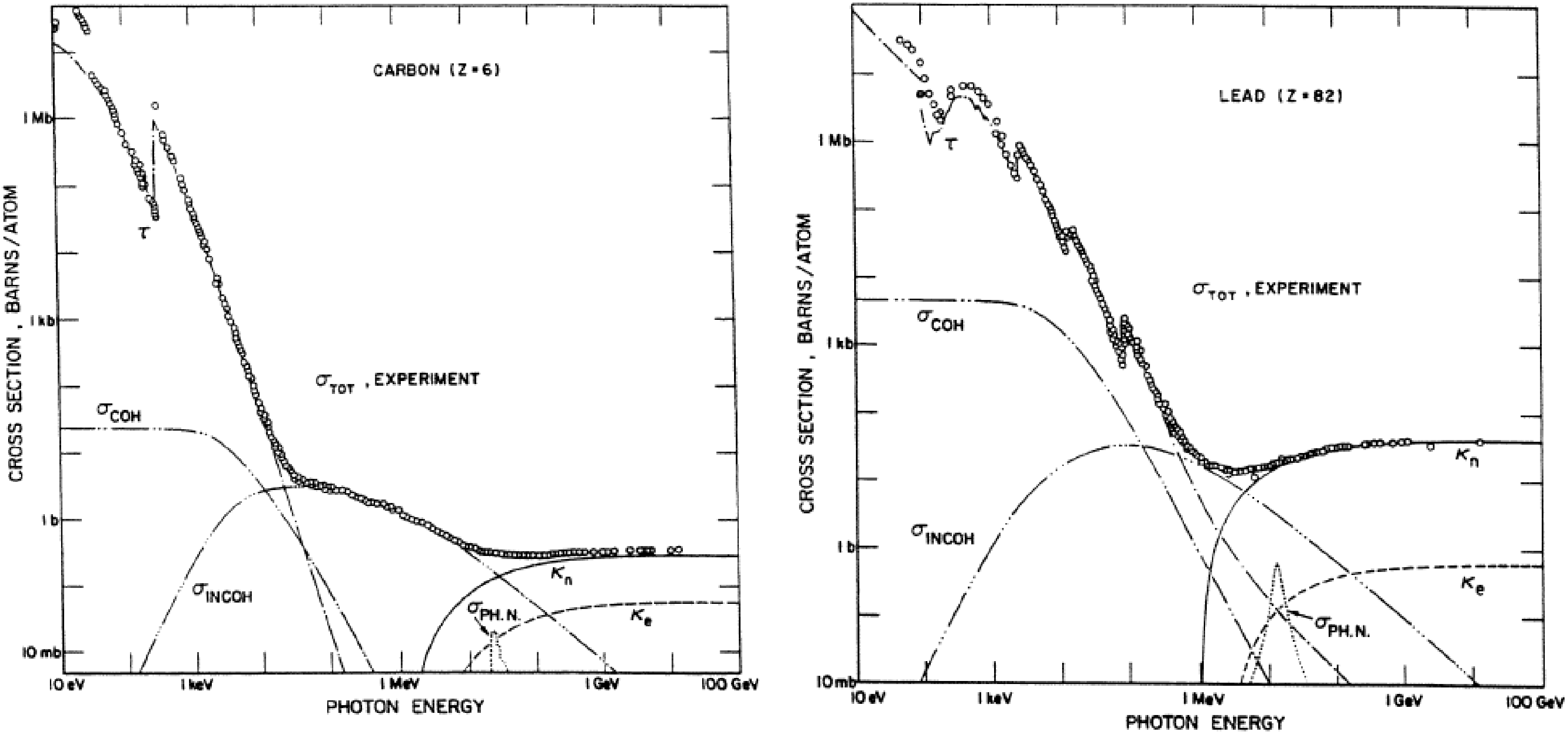

Figure 2. Contributions of atomic photoeffect, τ, coherent scattering, σ_{COH}, incoherent (Compton) scattering, σ_{INCOH}, nuclear-field pair production, κ_n, electron-field pair production (triplet), κ_e, and nuclear photoabsorption, $\sigma_{PH.N.}$, to the total measured cross section, σ_{TOT} (circles) in carbon over the photon energy range 10 eV to 100 GeV. The measured σ_{TOT} points, taken from 90 independent literature references, are not all shown in regions of high measurement density.

Phys. Med. Biol. 44 (1999) R1–R22. Printed in the UK PII: S0031-9155(99)74209-0

TOPICAL REVIEW

Review of photon interaction cross section data in the medical and biological context*

J H Hubbell†
11830 Rocking Horse Road, Rockville, MD 20852, USA

Thank you for your attention

Self-organization and polarization of a mixture of oil and zeolit granules subjected to a high intensity electric field induced by a Corona discharge