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Compact FEL-driven inverse compton scattering gamma-ray source

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ABSTRACT

Many research and applications areas require photon sources capable of producing gamma-ray beams in the multi-MeV energy range with reasonably high fluxes and compact footprints. Besides industrial, nuclear physics and security applications, a considerable interest comes from the possibility to assess the state of conservation of cultural assets like statues, columns etc., via visualization and analysis techniques using high energy photon beams. Computed Tomography scans, widely adopted in medicine at lower photon energies, presently provide high quality three-dimensional imaging in industry and museums. We explore the feasibility of a compact source of quasi-monochromatic, multi-MeV gamma-rays based on Inverse Compton Scattering (ICS) from a high intensity ultra-violet (UV) beam generated in a free-electron laser by the electron beam itself. This scheme introduces a stronger relationship between the energy of the scattered photons and that of the electron beam, resulting in a device much more compact than a classic ICS for a given scattered energy. The same electron beam is used to produce gamma-rays in the 10–20 MeV range and UV radiation in the 10–15 eV range, in a ~4×22 m^2 footprint system.

1. Introduction

Compact tunable X-rays sources associated with various imaging techniques have been developed and used in a large number of areas ranging from spectroscopy, radiology, medical and biological applications to security, aerospace industry and cultural heritage science. In particular, the field of applications in Geo-archeology is very wide. It goes from very small archaeological findings like prehistoric teeth and old jewelry, to large artifacts and burial objects wrapped inside soil blocks,[1] possibly involving considerable sizes. Depending on the nature and composition of the artifacts inside the soil blocks their tomographic analysis may require very penetrating and high power sources of X-rays to gamma-rays [1–5], in combination with detectors capable of providing good resolution imaging for this type of radiation. Methods of X-ray production presently include Inverse Compton Scattering (ICS) facilities [6] and synchrotron radiation sources from insertion devices in electron storage rings.

Contrast imaging of massive sculptures would profit [7] from radiation sources more powerful than the X-ray Computed Tomography (CT) industrial instruments operating in the 450 keV range. In fact, the efficacy of transmission imaging techniques like radiography and tomography depends on the attenuation processes occurring within the object to be imaged. The Beer-Lambert law [8] characterizes this attenuation through a transmission function T=exp(-τρμ), involving the cross section of physical processes such as photo-electric absorption, Compton scattering and pair production. Here τ is the thickness of the sample, ρ is the mass density and μ is the mass attenuation coefficient, which depends upon both the photon energy and the sample composition [9]. Transmission data are given in Table 1 for 20 MeV gamma-rays passing through a 10 cm thickness of different materials of interest to cultural heritage studies. For many of them the transmission is large.

In this paper we discuss a system, based on ICS, to produce gamma rays up to 20 MeV, minimizing the electron beam energy and total footprint. In the proposed scheme, the electron beam interacts with its own radiation emitted in an ultra-violet (UV) Free Electron Laser (FEL), as shown in Fig. 1, making UV and gamma rays available from the same system.

It was mentioned above that a diversity of applications can be found in very different research fields, see for example [10] and references therein. Specific case studies can be identified, for example, on the basis of the energy content of the scattered light. At low photon energy

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[1] Soil blocks resulting from archaeological excavations may contain different kinds of artifacts of interest in cultural heritage.

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Table 1
Transmission of 20-MeV gamma-rays through a τ=10-cm thickness of different materials.

Sample	Z	ρ [g/cm^3]	μ [10^{-2} cm^2/g]	T [%]
Al	13	2.72	2.17	55.4
Fe	26	7.87	3.22	8.0
Cu	29	8.96	3.41	4.7
Ag	47	10.49	4.61	0.79
Au	79	19.32	6.14	7.1×10^{-4}
Pb	82	11.35	6.21	8.7×10^{-4}
Bone	–	1.92	2.07	67.2
Concrete	–	2.30	3.44	45.3
Calcite	–	2.71	2.28	53.9

$$\lambda_r = \lambda_u \frac{1-\beta_z}{\beta_z} \approx \frac{\lambda_u}{2\gamma^2}(1 + a_u^2). \tag{3}$$

Here $a_u = K_u = eB_0\lambda_u/(2\pi m_e c) = 93.4B_0[T]\lambda_u[cm]$ is the helical undulator parameter ($a_u = K_u/\sqrt{2}$ for a planar-polarized undulator), B_O the undulator central magnetic field, e the electron charge. In terms of the electron energy the energy of the FEL photons is:

$$E_r = \frac{hc}{\lambda_r} = hca_{FEL}\frac{\gamma^2}{\lambda_u}, \tag{4}$$

where we define $a_{FEL} = 2/(1 + a_u^2)$ for on axis undulator radiation.

When the FEL photon energy (4) replaces that from the laser in Eq. (1), i.e., $\hbar\omega_{ph} = E_r$, the scattered photon energy reads:

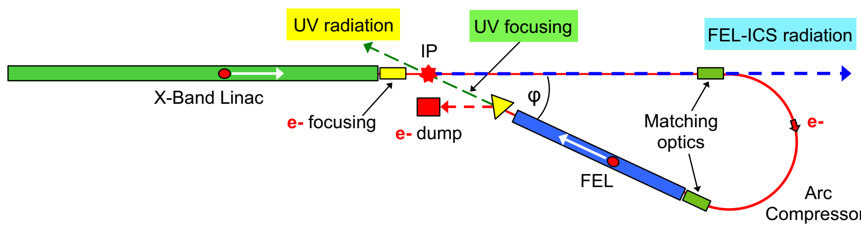

Fig. 1. FEL-ICS scheme with an electron beam return arc. Two photon energies are simultaneously available to experiments. Quadrupole triplets provide overlap control at the IP and beam properties matching for arc and undulator. The return arc provides longitudinal bunch compression for improved FEL performance. The system footprint is about 4×22 m^2.

(up to few MeV), the aforementioned contrast imaging of massive objects in Geo-archeology [7] would greatly benefit from such an intense and compact source, and this was actually the driving case of this work. At photon energies in the 1–10 MeV range, photons propagating though dense materials prompt nuclear reactions, generating e.g. alpha particles and neutrons, which can be easily identified and used for separating isotopes [11]. At photon energies higher than 10 MeV, the proposed scheme would approach the specifications for an elastic photon-photon scattering source for frontier experiments in QED [12]. Even if all these examples were equivalently considered in the presence of an external laser, it is undoubtedly demonstrated below that a higher electron beam energy would be required at the interaction point, for the same output photon energy, and therefore a longer, more expensive electron linear accelerator. Moreover, as a by-product of the proposed scheme, a naturally synchronized UV beam with large fraction of coherent photons, and at 100 fs duration level would be provided by the FEL, which is ideal for pump-probe experiments.

2. Energy scaling for FEL-ICS radiation

In an ICS process, a relativistic electron transfers a fraction of its energy to an incoming photon, scattered in the electron direction of flight, with a Doppler upshifted frequency. The wavelength of the scattered radiation is

$$E_s = a_C\gamma^2\hbar\omega_{ph}, \tag{1}$$

where $\hbar\omega_{ph} = E_L$ is the incoming laser photon energy, γ the Lorentz factor and

$$a_C \approx \frac{2(1 + \cos\varphi)}{1 + (\gamma\theta)^2} \le 4. \tag{2}$$

Here φ is the collision angle and θ the observation angle. The upper limit corresponds to on-axis radiation in head-on collisions. The scattered photon energy exhibits a quadratic dependence on the electron energy.

With our FEL-ICS scheme, we introduce a stronger γ-dependence by making the relativistic electron beam interact with its own UV radiation produced in an FEL [13]. The on-axis FEL radiation wavelength is related to the axial electron velocity β_z and the undulator period λ_u as [14]:

$$E_s = a_C\gamma^2E_r = a_C a_{FEL}hc\frac{\gamma^2}{\lambda_u}. \tag{1'}$$

The scattering efficiency, defined as the fraction of the electron energy transferred to the scattered photons, reads

$$\eta \equiv \frac{E_s}{E} = a_C a_{FEL}\frac{\lambda_C}{\lambda_u}\gamma^3, \tag{5}$$

having introduced the Compton wavelength $\lambda_c=hc/m_ec^2$=2.4×10^{-12} m. While the scattering efficiency in the ICS case scales linearly with beam energy, the cubic energy dependence in Eq. (5) provides compactness to the system, as lower electron energy is required for a given photon energy. Additional flexibility in the UV energy and thus in the FEL-ICS radiation is available as they are tunable via the undulator parameter K_u, typically ranging from 1 to 5 in an out-of-vacuum APPLE-II type device [15] or Delta undulator [16].

The collision angle φ at the Interaction Point (Fig. 1) is different from zero to allow room for optical components. Some reduction on the scattering efficiency via the impact parameter a_C and the length of the collision overlap is acceptable for an interaction angle up to φ=25^0, assumed in the FEL-ICS baseline design.

3. A baseline FEL-ICS system and its components

3.1. Description of the baseline design

A single-pass conceptual layout providing a strong source of multi-MeV photons is shown in Fig. 1. The main characteristics of the system are summarized in Table 2 and discussed in the following sections. Trains of electron bunches from an X-Band Linac are focused at the IP where they collide with FEL radiation produced by earlier bunches. A return arc guides the electrons into an FEL undulator. The return arc is designed to act as a bunch length compressor [17,18], raising the electron bunch peak current from 35 A to 500 A for an improved FEL performance. The FEL operates in the high-gain SASE regime [14,19] and is long enough to reach saturation. The emerging UV radiation is focused at the IP, where high-energy gamma-rays are produced via Compton interaction with the trailing bunches. The 180° original arc deflection in Ref. [17] is extended to 205° to produce collisions at the 25° design interaction angle.