

TUNABLE MONOCHROMATIC GAMMA RAY SOURCE DESIGN USING INVERSE COMPTON SCATTERING AT DARESBUARY LABORATORY*

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Abstract

Inverse Compton Scattering (ICS) is an attractive source of tunable monochromatic photons, particularly in the MeV regime that is difficult to access with other techniques. Scattering of a laser pulse from relativistic electrons can produce gamma photons in the 1-20 MeV range, which have many uses in nuclear physics and for the production of medical radioisotopes. The energy of the scattered gamma photons can be easily tuned by changing the incident electron energy. ICS sources can also be made quasi-monochromatic by using low energy spread electron and laser beams, and collimating the scattered photons. They are typically available from large synchrotron driven electron sources, but these have a lower flux in the desired bandwidth than sources based on energy recovery or linacs. A new planned ICS gamma source is under consideration as part of the proposed UK-XFEL project, which would involve part of the XFEL linac using energy recovery via return lines. A demonstrator experiment to support the UK-XFEL project is discussed here for the upgraded CLARA electron accelerator at Daresbury Laboratory, UK. The experiment will utilise a new Ti:Sapphire laser at 800 nm and scatter these pulses from 250 MeV electrons. The aim of the experiment is to fully characterise the source, including the bandwidth and flux of the collimated ICS photons, test the tunability of the output by changing the electron energy, and benchmarking the performance against ICS codes. The results will inform the design process for an ICS source at the UK-XFEL.

INTRODUCTION

ICS, the scattering of photons (typically provided by a laser) from a high energy electron beam, is an ideal source of narrow bandwidth MeV-scale photons for applications such as nuclear structure experiments, nuclear decommissioning, nuclear security or medical radioisotope production. The ICS process results in the transfer of energy from the electrons to the input laser, producing high energy upshifted scattered photons and is unique in that the scattered high energy photons can have a narrower bandwidth than those from other sources [1].

Other sources of high energy photons include synchrotron radiation, bremsstrahlung and radioactive nuclei. However, synchrotron radiation does not reach high enough energy for nuclear resonance fluorescence (> 2 MeV), and bremsstrahlung is generally too broad bandwidth to be useful for most of these applications. This is because a broad

bandwidth source would produce photons at energies which are not useful for a nuclear structure experiment, but still provide a significant radiation dose to any target.

Therefore, a high energy, narrow bandwidth, tunable source of gamma photons is invaluable for nuclear detection experiments, but currently the UK has no such dedicated source. Facilities of this type do exist in other countries, including the High Intensity Gamma-ray Source (HIGS or HI γ S) at Duke University, USA [2]; and planned at ELI-NP (Extreme Light Infrastructure - Nuclear Physics) in Romania [3]. A demonstrator experiment at Daresbury Laboratory in Cheshire, UK is being discussed. The experiment would utilise the CLARA (Compact Linear Accelerator for Research and Applications) facility's FEBE (Full Energy Beam Exploitation) upgrade. It will involve scattering pulses from a new 100 TW Ti:sapphire laser from the 250 MeV electron bunches, producing gamma rays up to 1.48 MeV. This experiment will provide data and benchmark ICS codes for the UK-XFEL project [4].

Energy of Photon Source

The energy of a scattered photon, E_γ , after an incident photon, E_{laser} , scatters from an electron with energy E_e is given by

$$E_\gamma = \frac{E_{\text{laser}}(1 - \beta \cos(\phi'))}{1 - \beta \cos(\theta) + (1 - \cos(\theta'))E_{\text{laser}}/E_e} \quad (1)$$

$\beta = v/c$ is the velocity of the electron relative to the speed of light. The energy of the scattered photon depends on the angle of the incident photon and electron, ϕ' , the angle of the incident photon and the scattered photon, $\theta' = \phi' - \theta$, and the crossing angle, ϕ . A diagram of the scattering angles is given in Fig. 1.

A head-on collision of incident photons ($\phi' = \pi$, $\phi = 0$) results in the maximum energy of the scattered photons if the photons are back-scattered opposite to the direction of the incident photons ($\theta = 0$). The maximum energy of the scattered photons is given by

$$E_{\text{max}}^\gamma = \frac{4\gamma^2 E_{\text{laser}}}{1 + X} \quad (2)$$

where $X = 4\gamma E_{\text{laser}}/m_e c^2$ is the electron recoil factor (usually small, $X \ll 1$). For example, a head-on collision of a 250 MeV electron bunch and a laser of wavelength of 800 nm would result in photons with a maximum energy of 1.481 MeV.

* Work supported by a Cockcroft core grant and an IPAC student grant

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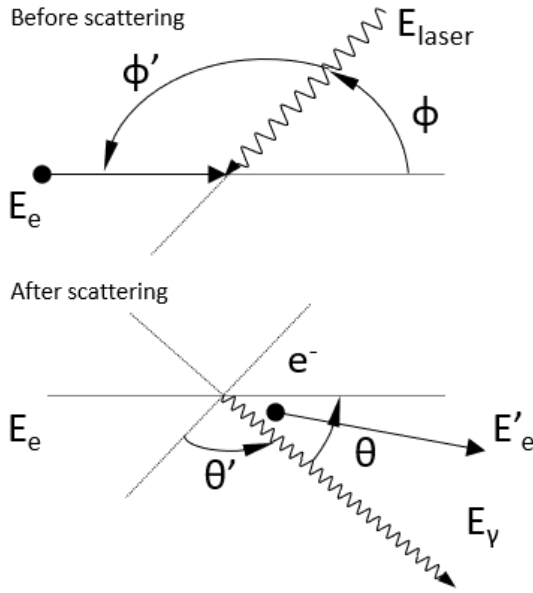


Figure 1: Geometry of scattering at the inverse Compton scattering interaction point in the lab frame of reference.

Flux of the Photon Source

The number of photons, N_γ from a collision between a laser pulse and an electron bunch is given by [5]

$$N_\gamma = \sigma_c \frac{N_e N_{laser} \cos(\phi)}{2\pi \sigma_y \sqrt{\sigma_x^2 \cos^2(\phi) + \sigma_z^2 \sin^2(\phi)}} \quad (3)$$

where σ_c is the Compton cross section which relates to the Thomson cross section, σ_T , as $\sigma_c \approx \sigma_T(1 - X)$ where $\sigma_T = 6.65 \times 10^{-29} \text{ m}^2$, $\sigma_i^2 = \sigma_{\text{electron},i}^2 + \sigma_{\text{laser},i}^2$ is the convoluted spot size of the electron beam and the laser for $i = x, y, z$, N_e is the number of electrons in the bunch, and N_{laser} is the number of laser photons in the pulse. To convert this equation into a flux the repetition rate of the scattering interactions must be included as a factor.

Bandwidth of Photon Source

The energy spread of the photons, $\Delta E_\gamma / E_\gamma$, will be influenced by the initial energy spread of the electron bunch, the energy spread of the laser photons and any variation in crossing angle or scattering angle. The bandwidth of an ICS source is given by [1].

$$\frac{\Delta E_\gamma}{E_\gamma} = \sqrt{\left(\frac{\sigma_\theta}{E_\theta}\right)^2 + \left(\frac{\sigma_e}{E_e}\right)^2 + \left(\frac{\sigma_L}{E_L}\right)^2 + \left(\frac{\sigma_\epsilon}{E_\epsilon}\right)^2} \quad (4)$$

This equation contains contributions from four sources; the collimation of the gamma source, σ_θ / E_θ , the energy spread of the electron beam, σ_e / E_e , the energy spread of the laser, σ_L / E_L , and the emittance of the electron beam $\sigma_\epsilon / E_\epsilon$.

The easiest of these contributions to vary is the collimation angle of the photons, which can be done by creating an adjustable collimator or changing the distance of a collimator

to the interaction point. This collimation contribution arises from the angular variation of the energy of the scattered photon which can be seen from equation 1.

EXPERIMENT PARAMETERS

In this experiment electron bunches from the CLARA accelerator, see Table 1, will interact with a Ti:sapphire laser, see Table 2, to produce gamma photons. This gamma beam will be collimated and detected down stream of the Interaction Point.

A layout of the experiment is shown in Fig. 2; the electron bunches and the laser pulses will interact at the IP and the scattered gamma photons will be collimated before being detected 10 m downstream. The collimator will be adjustable in size and position to allow precise measurement of the dependence of the flux at the detector with collimation. In addition the tunability of the source can be tested by varying the electron beam energy from the maximum of 250 MeV to a minimum of 150 MeV.

Table 1: Electron Bunch Parameters at the IP for the CLARA FEBE ICS Experiment

Parameter	Quantity
Electron kinetic energy, E_e	250 MeV
Repetition rate, f	1–100 Hz
Bunch charge (typical), eN_e	100 pC
Normalised <i>rms</i> emittance, ϵ_N	1 mm-mrad
<i>rms</i> bunch length, $\Delta\tau$	0.73 mm (2.4 ps)
Absolute energy spread, ΔE_e	20 keV
Relative energy spread, $\Delta E_e / E_e$	8.00×10^{-5}
Baseline parameters	
β -function at the IP, β^*	1.23 m
Electron bunch size, σ_{electron}	50 μm

Table 2: Ti:sapphire Laser Parameters for FEBE Experiment

Parameter	Quantity
Wavelength, λ_{laser}	800 nm
Photon energy, E_{laser}	1.55 eV
Pulse energy, E_{pulse}	0.10 J
Number of photons per pulse, N_{laser}	4.03×10^{17}
Repetition rate, f	1 Hz
<i>Rms</i> spot size at the IP, σ_{laser}	45 μm
Crossing angle, ϕ	0 rad
<i>Rms</i> pulse length, τ_{laser}	2.00 ps
Normalised Laser Vector Potential, a_0	8.56×10^{-3}
<i>Rms</i> spectral Bandwidth, $\Delta E_{\text{laser}} / E_{\text{laser}}$	0.03185

GAMMA SOURCE CHARACTERISTICS

The gamma beam produced at the IP will be collimated through an aperture before being characterised by a HPGe detector. The flux of the source at the detector will be chosen so that after collimation roughly 1000 photons reach the detector per electron bunch/laser pulse crossing. This value

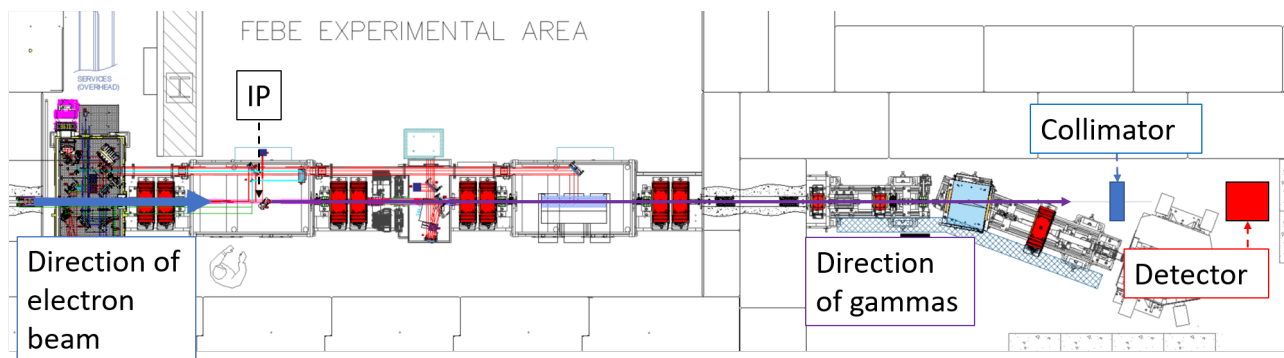


Figure 2: Experimental layout of FEBE experimental area, IP and locations of collimator and detector.

is chosen so that the detector can fully characterise the source, assuming that the detector has an efficiency of roughly 0.1%, the detector will typically collect energy from a single photon per interaction. The source parameters are shown in Table 3 and the spectral density of the source is shown in Fig. 3. The spectral density and flux of the source was calculated using the ICARUS code [1].

Table 3: Simulation Summary for ICS Experiment

Parameter	Value
Collimation angle, θ_{col}	0.070 mrad
Max gamma photon energy, E_{max}^{γ}	1.481 MeV
Source bandwidth, $\Delta E_{\gamma}/E_{\gamma}$	3.17 %
Flux at detector	1000 ph/s
Uncollimated flux	5.83×10^5 ph/s

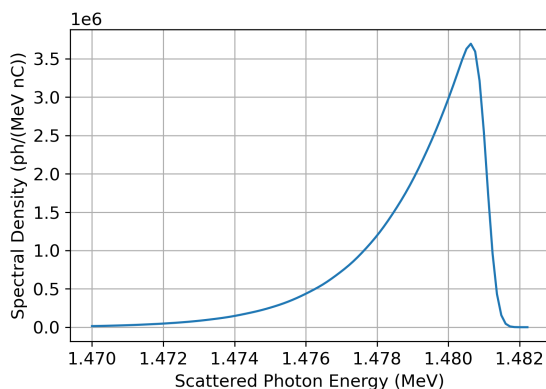


Figure 3: Spectral density of ICS spectrum from FEBE parameters calculated using the ICARUS code.

The main parameter chosen to keep the flux on the detector at 1000 photons/s is the aperture diameter, i.e. the collimation angle θ_{col} . Increasing θ_{col} will increase the flux and decreasing it will decrease the flux. If required, the electron bunch charge can be reduced from 100 pC to 10 pC to reduce the flux, allowing a larger aperture to be used. If the source is not collimated the total flux is predicted to be 5.83×10^5 ph/s, this would make the source the highest flux ICS gamma source in Europe.

The bandwidth of the gamma source is dominated by the spectral bandwidth of the laser, resulting in a gamma bandwidth of 3.17 %. This is due to Ti:sapphire lasers having an intrinsic large spectral bandwidth due to their short pulse length and the discussed experiment using a Ti:sapphire laser currently being procured for the FEBE upgrade. As this is a demonstrator experiment for characterising the source this is not a detriment, but for a user facility a laser with a lower spectral bandwidth should be used such as Nd:YAG.

CONCLUSION

In conclusion, a demonstrator experiment is being discussed to use inverse Compton scattering to produce monochromatic, tunable gamma rays at the Daresbury Laboratory's CLARA facility. The bandwidth and energy of the produced gamma rays will be comparable to those produced at HIγS [2] and ELI-NP [3], albeit with lower flux as a compromise to characterise the photon energy. This experiment will provide technical data for the UK-XFEL project and confirmation of the simulation code.

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