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A COMPACT INVERSE COMPTON SCATTERING SOURCE BASED ON X-BAND TECHNOLOGY AND CAVITY-ENHANCED HIGH-AVERAGE-POWER ULTRAFAST LASERS

A. Latina, V. Muşat, R. Corsini, L. A. Dyks, E. Granados, A. Grudiev, S. Stapnes, W. Wuensch, CERN, Geneva, Switzerland
E. Cormier, CELIA, Talence, France
G. Santarelli, ILE, Palaiseau CEDEX, France

Abstract

A high-pulse-current injector followed by a short high-gradient X-band linac is considered as a driver for a compact Inverse Compton Scattering source. We show that using a high-power ultrashort pulse laser operating in burst mode and a Fabry-Pérot enhancement cavity, X-rays with flux values over 10^{13} ph/s and photon energies up to MeV are achievable. The resulting high-intensity and high-energy X-rays allow for various applications, including cancer therapy, tomography, and nuclear waste management. A preliminary conceptual design of such a compact ICS source is presented, together with simulations of the expected performance.

INTRODUCTION

The number of Inverse-Compton Scattering (ICS) sources has steadily increased over the last few years. Most ICS designs are based on storage rings due to a circular layout, which maximises the repetition rate and flux. However, the latter comes at the cost of increasingly large facilities. In the 2000's, Energy Recovery Linacs (ERLs) have garnered interest as potential drivers for ICS, and several designs based on ERLs exist [1]. However, these machines are typically based on super-conducting technology, which is not readily available in hospitals or small laboratories. Normal-conducting, low-emittance linacs can also be adapted for compact ICS designs. Linac-based ICS sources tend to offer higher brilliance due to the lower emittance obtained from the photoinjector but exhibit lower fluxes since the electron bunches are used only once.

Stemming from the R&D made at CERN in the context of X-band high-gradient multi-bunch acceleration for the Compact Linear Collider [2], this paper proposes a high pulse-current accelerator based on a photoinjector and a short X-band linac, which can deliver high-charge electron pulses and ultimately high-flux photons. Given the compactness of the linac, electron beam energies up to hundreds of MeV are achievable within a few metres, allowing for the generation of MeV photons.

Inverse-Compton Scattering

ICS is defined as the scattering of a low-energy photon from a relativistic electron resulting in a high-energy photon. Figures of merit for ICS photons are energy, bandwidth, flux, and brilliance. The following equations are derived in the Thomson regime, where the electron recoil is negligible.

Table 1: Electron Beam Parameters From the HPCI Injector at the Interaction Point

Parameter	Value	Unit
Energy	140	MeV
Bunch charge, Q	300	pC
Bunch repetition frequency, f	10	Hz
Nb of bunches per train	1000	
rms spot size at the IP, $\sigma^\star$	30	µm
Bunch length, σ_z	300	µm
Bunch spacing	1/3	ns
Normalised Transverse emittance, $\epsilon^N_{x,y}$	5	mm mrad

For an ultra-relativistic electron, the maximum achievable energy in an ICS interaction is given in a head-on collision by

$$E_X = 4\gamma^2 E_{\text{laser}}, \tag{1}$$

where γ is the relativistic factor of the electron beam and E_{laser} is the laser photon energy [3]. Assuming a round Gaussian transverse distribution for the electron and laser beams [4], the total flux of the ICS photon beam $\mathcal{F}$ can be derived by taking the time derivative of the number of the scattered photons,

$$N_\gamma = \sigma_{\text{T}} \frac{N_{\text{e}} N_{\text{laser}} \cos(\phi/2)}{2\pi\sigma_{\gamma,y}\sqrt{\sigma^2_{\gamma,x}\cos^2(\phi/2) + \sigma^2_{\gamma,z}\sin^2(\phi/2)}}, \tag{2}$$

where σ_{T} is the Thomson cross section, N_e the number of electrons in a bunch, N_{laser}, the number of photons in the laser macropulse, ϕ the crossing angle between the electron and laser beam in the $x - z$ plane, and σ_γ the source *rms* spot size at the interaction point (IP). For a high repetition rate f, the average flux is $N_\gamma f$. The average brilliance $\mathcal{B}$, given a non-diffraction limited beam, is [3]

$$\mathcal{B} = \frac{\mathcal{F}_{0.1\%}}{4\pi^2\sigma_{\gamma,x}\sqrt{\epsilon_x/\beta^\star_x}\,\sigma_{\gamma,y}\sqrt{\epsilon_y/\beta^\star_y}}, \tag{3}$$

where $\mathcal{F}_{0.1\%}$ is the flux in a 0.1% bandwidth at the Compton edge, $\epsilon_{x,y}$ are the normalised emittances, and $\beta^\star_{x,y}$ is the Twiss parameters at the IP. Peak brilliance, $\hat{\mathcal{B}}$, is the average brilliance normalised by $(\sigma_{\gamma,t} \cdot f)$, with $\sigma_{\gamma,t} = \sigma_{\gamma,z}/c$.

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From Eq. (2), flux was maximised by increasing the number of interacting particles per bunch, reducing ϕ to 2°, and minimising both electron and laser beam sizes at the IP.

The High-Pulse-Current Injector

The High-Pulse-Current Injector (HPCI) consists of an S-band photoinjector, similar to that of the CLEAR test facility at CERN [5], followed by a high-gradient X-band linac with an average gradient of 35 MV/m operating at a repetition rate of 10 Hz, capable of accelerating trains of about 1000 electron bunches. Being a wakefield-dominated linac, special care was taken to control and limit the impact of both short- and long-range wakefields using strong focusing and high-order-mode damping, building on the experience made in the context of CLIC [6]. Figure 1 shows the evolution of the kinetic energy, the normalized transverse emittance, and the beam size along the HPCI injector. As visible in the figure, an energy of about 140 MeV could be reached in less than 6 metres from the cathode. A short final-focus section downstream of the linac is not included in the plot. Table 1 summarizes the electron beam parameters at the IP.

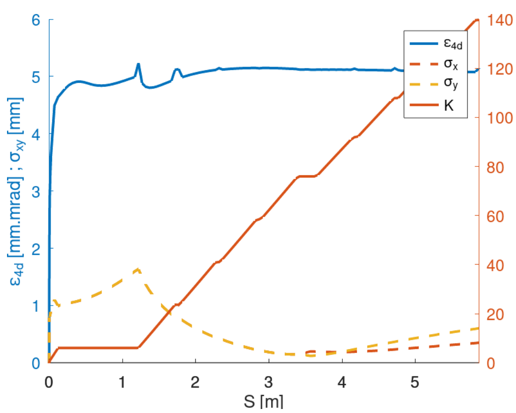

Figure 1: Evolution of the kinetic energy, normalized transverse emittance, and beam size along the HPCI injector.

Fabry-Pérot in Burst Mode

Burst mode cavities have been used for linac-based ICS sources [7]. The lower average power obtained inside the cavity significantly reduces the damage to cavity mirrors.

A four-mirror Fabry-Pérot cavity (FPC) is being considered for the HPCI-based ICS source due to its increased stability. An optimisation of the burst mode parameters and geometry was adapted from [8]. Burst mode parameters were obtained by maximising the effective energy, $\mathcal{E}_{tot} = \epsilon_{eff} U$, where ϵ_{eff} is the cavity effective gain, and U is the laser macropulse energy. The result is limited by N_e and the maximum number of injected laser pulses.

The FPC geometry was optimized numerically to obtain the configuration with the maximum macropulse energy. The cavity roundtrip length of 1 m was set to a sub-harmonic of the laser repetition rate, which matches the electron bunch spacing from HPCI. The FPC optimisation showed that an effective energy of 100 J could be achieved using GHz-repetition-rate high-power lasers, such as kW-Flexiburst [9].

PERFORMANCE ESTIMATES

The results, summarised in Table 2, were obtained using RF-Track [10], a novel CERN tracking code that simulates beam transport under the simultaneous effect of space-charge forces and wakefields. The possibility of simulating the ICS process was recently added to the code. A benchmark of RF-Track against the well-established ICS code CAIN [11] was presented in [12].

The flux of the ICS source was maximised by optimising the laser and electron beam sizes at the IP. It was found that an electron *rms* spot size of 7–13 µm corresponds to a maximum flux of 6×10^{14} ph/s, with similar requirements for the laser beam. However, a low IP beam size, $\sigma^\star$, leads to a large energy spread in the ICS photon beam. To decrease the photon bandwidth, a parametric scan of $\sigma^\star$ and ICS photon collection angle was performed. The scan showed that 5% bandwidth, as required by most applications, is obtained for a reduced aperture of 0.6 mrad and $\sigma^\star = 30$ µm. Figure 2 shows an ICS photon spectrum with a 5% bandwidth.

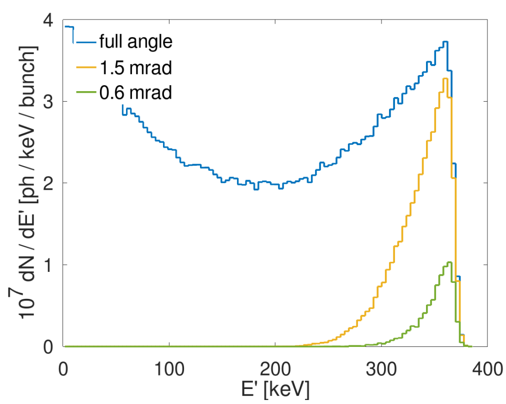

Figure 2: Scattered photon spectra from RF-Track generated by the HPCI-based ICS source. The 0.6 mrad spectrum corresponds to an energy bandwidth of 5%.

Table 2: Projected parameters of the photons generated by the HPCI-based ICS source

Parameter	Value	Unit
Energy	360	keV
Source *rms* spot size, σ_γ	10	µm
Total flux, $\mathcal{F}$	9×10^{13}	ph/s
Flux in a 1.5 mrad cone	2×10^{13}	ph/s
Average brilliance, $\mathcal{B}$	4×10^{14}	[1]
Peak brilliance, $\hat{\mathcal{B}}$	3×10^{22}	[1]

[1] ph/(s mm^2 mrad^2 0.1%BW).

CONCLUSIONS

This paper presents a conceptual design, complemented by beam dynamics and Compton scattering simulations, of

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a compact ICS source based on an S-band photoinjector, a compact X-band linac, a short final-focus section and a Fabry-Pérot cavity operating in burst mode. The proposed HPCI ICS source showed that photon fluxes in a 1.5 mrad cone of over 10^{13} ph/s could be reached, which is among the highest in the landscape of existing and designed ICS sources worldwide.

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