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A HARD X-RAY COMPACT COMPTON SOURCE AT CBETA

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Abstract

Compton backscattering at energy recovery linacs (ERLs) promises high flux, high energy x-ray sources in the future, made possible by high quality, high repetition rate electron beams produced by ERLs. CBETA, the Cornell-BNL ERL Test Accelerator currently being built and commissioned at Cornell, is an SRF multi-turn ERL using Non-Scaling Fixed Field Alternating-gradient (NS-FFA) arcs. CBETA has high quality design parameters with an anticipated top energy of 150 MeV on the fourth pass. The expected parameters of a Compton source at CBETA include a top x-ray energy of over 400 keV with a flux on the order of 10^{12} ph/s. In this paper, we present anticipated parameters and potential applications in science and engineering for this source.

INVERSE COMPTON SCATTERING

Compton scattering is the process of scattering a photon off an electron at rest; in the case of inverse Compton scattering (ICS), the electron loses energy to the incident photons. In the Thomson regime, i.e., where the energy of the photons in the electron beam frame is much less than the rest mass of the electron, electron recoil is negligible, and the energy of the scattered photon in the lab frame is given by

$$E_\gamma(\Phi,\theta) \approx E_{\text{laser}} \frac{1-\beta\cos\Phi}{1-\beta\cos\theta} \tag{1}$$

where E_{laser} is the laser energy, β is the relativistic factor v_z/c, Φ is the angle between the electron and laser beams at the interaction point (IP), and θ is the angle of the scattered photons with respect to the direction of the electron beam, all measured in the lab frame. For a head-on collision between a forward moving electron beam and an incident laser beam ($\Phi = \pi$), the photons scattered in the forward direction have the highest energy, which is $\gamma^2(1+\beta^2)E_{\text{laser}} \approx 4\gamma^2 E_{\text{laser}}$, where γ is the typical relativistic factor. This energy is the Compton edge of the radiation energy range.

The total number of scattered photons, N_γ, is given by

$$N_\gamma = \sigma_T \frac{N_e N_{\text{laser}}}{2\pi\left(\sigma_e^2 + \sigma_{\text{laser}}^2\right)} \tag{2}$$

where σ_T is the Thomson cross section of 6.65×10^{-29} m^2, N_e is the number of electrons in the bunch, N_{laser} is the number of photons in the incident laser pulse, and σ_e and σ_{laser} are the *rms* sizes of the electron and laser beams, respectively, assuming both are round Gaussian distributions. In the regime where the laser spot size is sufficiently larger than the electron beam spot size at the IP, the *rms* size of the scattered photons, σ_γ, is the same as the electron spot size. For high-frequency repetitive sources, the total flux is $\mathcal{F} = fN_\gamma$, where f is the repetition rate. In the Thomson backscatter limit, the number of scattered photons in a 0.1% bandwidth at the Compton edge is given by $N_{0.1\%} = 1.5\times10^{-3}N_\gamma$, leading to the flux in a 0.1% bandwidth given by $\mathcal{F}_{0.1\%} = fN_{0.1\%}$.

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Table 1: Parameters for Electron Beam at Collision Point for Each Pass Energy

Parameter	Quantity	Units
Energy	42, 78, 114, 150	MeV
Repetition rate	1.3	GHz
Bunch charge	32	pC
β^*	1	cm
Normalized transverse *rms* emittances	0.3	mm-mrad
Bunch length (*rms*)	1.3	mm

For a non-diffraction limited beam, the brilliance of the scattered photons in a 0.1% bandwidth is given by

$$\mathcal{B} \approx \frac{\gamma^2\mathcal{F}_{0.1\%}}{4\pi^2\epsilon^N_{x,\text{rms}}\epsilon^N_{y,\text{rms}}} \tag{3}$$

where $\epsilon^N_{x,\text{rms}}$ and $\epsilon^N_{y,\text{rms}}$ are the normalized transverse *rms* emittances of the electron beam at the IP. This assumes that the laser spot is larger than the electron beam. In this approximation, the angular spread and size of the scattered photons match the angular spread and size of the electron beam at the IP. Maximizing the x-ray flux is done by maximizing the number of electrons and photons at the collision and minimizing both spot sizes - assuming a fixed repetition rate. Maximizing the brilliance at a given electron beam energy is done by maximizing the flux into a 0.1% bandwidth and minimizing the normalized transverse emittances [1].

ICS AT CBETA

CBETA, the Cornell-BNL (Brookhaven National Lab) ERL Test Accelerator, is an SRF multi-turn ERL using Non-Scaling Fixed Field Alternating-gradient (NS-FFA) arcs, seen in Fig. 1 [2]. This machine is currently being built and commissioned at Cornell. The FFA arcs are made of permanent Halbach magnets and have an energy acceptance from 42 to 150 MeV. The electron beam is injected at 6 MeV, before accelerating up to 150 MeV in 4 passes; the intermediate energies of 42, 78, and 114 MeV occur after the

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Table 2: Parameters for Scattering Laser at Collision Point

Parameter	Quantity	Units
Wavelength	1	µm
Average power	81	kW
Repetition rate	1.3	GHz
Spot size	25	µm
Pulse duration (*rms*)	5.7	ps

first, second, and third pass, respectively. CBETA has high quality design parameters throughout the acceleration of the beam, making it a potential option for a Compton light source.

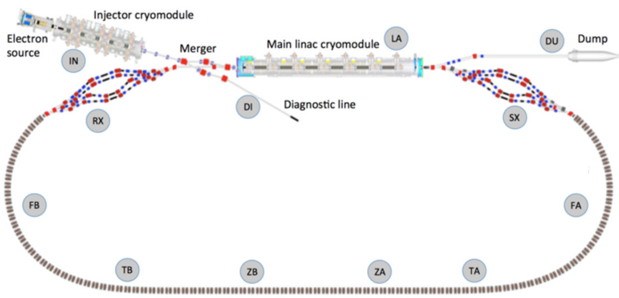

Figure 1: Layout of CBETA.

Using the CBETA design parameters, we can approximate the electron beam parameters achievable for each pass in a bypass line parallel to the ZA/ZB straight section; these parameters are given in Table 1, with each of the four energy options given. In Table 2, we give parameters for a laser similar to one utilized in a recent Compton backscattering experiment [3]. Using the formula presented in the previous section, we can estimate the anticipated x-ray parameters using Tables 1 and 2; these parameters are given in Table 3.

Table 3: Anticipated Parameters for x-ray Beam at Collision Point

Parameter	Quantity				Units
	1st Pass	2nd Pass	3rd Pass	4th Pass	
Energy	33.5	116	247	427	keV
σ_γ	6	4.4	3.7	3.2	µm
$\mathcal{F}$	1.3×10^{12}				ph/s
Average $\mathcal{B}$	3.7×10^{12}	1.3×10^{13}	2.8×10^{13}	4.9×10^{13}	ph/(s-mm^2-mrad^2-0.1%BW)
Peak $\mathcal{B}$	3×10^{19}	2×10^{20}	4×10^{20}	8×10^{20}	ph/(s-mm^2-mrad^2-0.1%BW)

APPLICATIONS

From the values in Table 3, it becomes clear that a Compton source at CBETA is capable of an extremely large energy range, with the upper limit exceeding that typically found at synchrotron sources. It achieves this with an average flux on the order of 10^{12} ph/s for all energies, an average brilliance on the order of $10^{12} - 10^{13}$ ph/(s-mm^2-mrad^2-0.1%BW), and a peak brilliance on the order of $10^{19} - 10^{20}$ ph/(s-mm^2-mrad^2-0.1%BW).

One particular application which this energy range is well-suited for is high energy x-ray diffraction, typically performed using x-rays 50-150 keV and higher. The advantages of this approach include access to high momentum transfers, high penetration of x-rays allowing experiments to be done in air and transmission geometry, reduced photo-absorption at higher energies (allowing samples with heavy elements), and reduced radiation damage in samples [4]. Another application of such a high energy, high flux source is spectroscopy in high energy atomic physics.

A number of other x-ray techniques include phase contrast imaging, absorption radiography, K-edge subtraction imaging, radiotherapy, and computed tomography. These techniques are used in a large number of fields, including medicine, cultural heritage, material science development, national security, and industry.

CONCLUSION

As we move forward with this design effort, the target parameters may be changed to allow for a wider potential user community and more reliable operation. However, based on the initial parameters presented here, ICS at CBETA promises to be a remarkably flexible and capable hard x-ray source when fully developed.

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