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LASER COMPTON BACKSCATTERING SOURCE FOR BEAM DIAGNOSTICS AT THE S-DALINAC*

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Abstract

The Superconducting DArmstadt electron LINear ACCelerator S-DALINAC is a thrice-recirculating linear accelerator providing electron beams with energies up to 130 MeV and beam currents up to 20 µA for nuclear-physics experiments. A new setup for Laser Compton Backscattering (LCB) will provide a quasi-monochromatic X-ray photon beam for nuclear photonics applications, in photonuclear reactions, and for beam diagnostics. The expected energies of a LCB source at the S-DALINAC extend from about 28 keV to 180 keV with a flux of about 17 ph/s at an expected bandwidth of 0.3 % with a collimated beam. This project is aimed at accelerator physics development in the field of artificial γ-sources. In the first step it will be used at the S-DALINAC for non-destructive beam diagnostics to measure energy and energy bandwidth. Gerneral considerations for the setup are presented.

INTRODUCTION

For a wide range of applications in nuclear photonics it is necessary to have a brilliant quasi-monochromatic high-energy photon beam. Hence, the development of artificial γ-sources is important. While bremsstrahlung produced by an electron linear accelerator (LINAC) has a broadband spectrum, novel γ-ray sources use Laser Compton Backscattering (LCB) [1], where photons, produced from a laser, scatter with relativistic electrons at 180°. The scattered photons are Lorentz boosted in the direction of the electrons. LCB provides a sharp energy spectrum at 180°. In a ring accelerator, the energy distribution of the scattered photons is typically limited by the emittance to ≥ 3%. To go below this limit, the use of a LINear ACcelerator (LINAC) with LCB was proposed [2]. The γ-ray intensity and / or the experimental count rate are limited by the collision rate and the intensities of both laser and electron beam. A setup combining high electron beam currents with low-emittance beams and high repetition rates could therefore be considered as an ideal driver of an LCB source. Superconducting Energy-Recovery LINACs (ERLs) can provide such electron beams. A secondary application of LCB, useful for all kind of accelerators, is non-destructive beam diagnostic, to measure e.g. beam energy [3].

The thrice-recirculating [4] Superconducting DArmstadt electron LINear ACcelerator S-DALINAC [5] delivers energies uo to 130 MeV with average currents of up to 20 µA

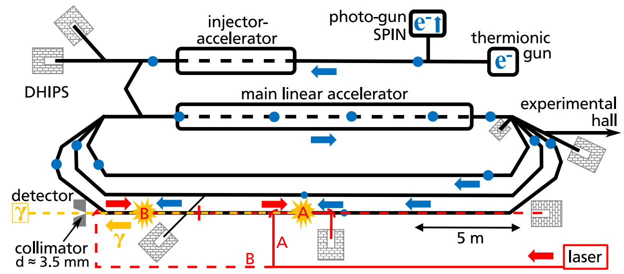

Figure 1: Schematic view of the S-DALINAC, with two (A,B) possible LCB interaction points. The 3 GHz pulsed electron beam collides with laser pulses at the third recirculation. The boosted photons will be detected behind the dipole magnet.

with 3 GHz repetition frequency. It was operated as Germany's first ERL in 2017 [6]. Current investigations are focused on multi-turn ERL operation. Figure 1 shows a floor plan of the accelerator, its sources, injector LINAC as well as the main LINAC with the three recirculation paths.

We propose to install an LCB setup in the third recirculation beam line, where the electrons may reach a maximum energy of about 99 MeV. At the proposed section, the ERL operation is not possible, however, the setup will allow the synchronization of laser pulses and electron bunches to be optimized, the beam-transport lattice to be adapted, and the transmission through the main LINAC after inverse Compton scattering to be studied. The LCB photons will be used for first applications in nuclear photonics as well as non-destructive beam diagnostics.

LASER COMPTON BACKSCATTERING

The Compton effect describes the elastic scattering of a photon with a free electron, where the X-ray photon typically loses recoil energy to the electron. The inverse process to this is Compton backscattering, where the photon is scattered off an relativistic electron at 180°, see Fig. 2. In most cases

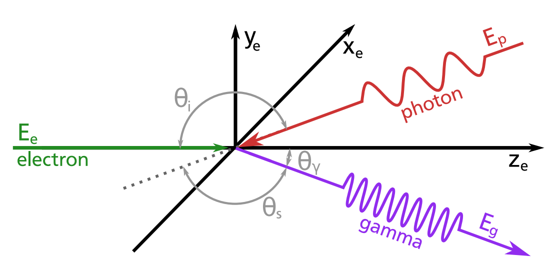

Figure 2: Schematic view of Laser Compton Backscattering.

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the energy of the incident photon in the electron beam frame is much less than the electron rest mass, and so the electron recoil is negligible. Therefore LCB is perfect suitable for in beam experiments at ERLs. The scattering cone is pointed in the forward direction of the electrons. The energy of the scattered photon, E_g, is given by [7]

$$E_g = \frac{(1-\beta\cos(\theta_i))E_p}{1-\beta\cos(\theta_\gamma)+(1-\cos(\theta_s))(E_p/E_e)}, \tag{1}$$

where E_p, E_e are the incident photon and electron energies, respectively, θ_i, θ_γ are the angles between the electron direction of motion and incident and scattered photon, θ_s is the angle between incident and scattered photon (can be seen in Fig. 2), and β is the electron velocity in units of speed of light. The scattered photon energy only depends, apart from the incident particle energies, on the scattering angle, shown in Fig. 3. The relation between the scattered photon energy and the scattering angle is displayed in Fig. 4. The X-ray energy may be selected by collimation, to provide a small energy bandwidth.

For the head-on collision Eq. (1) can be simplified to

$$E_g^{max} = \frac{4\gamma_e^2 E_p}{1+4\gamma_e^2(E_p/E_e)} \tag{2}$$

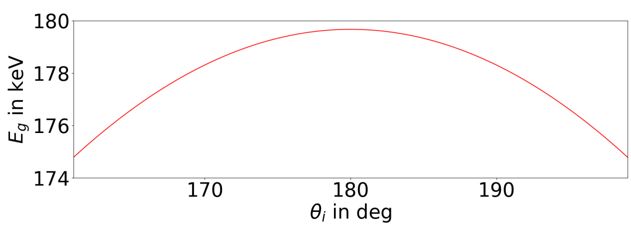

Figure 3: X-ray energy of inverse Compton scattering for 1.2 eV incident photons over the angle between laser and electron beam at 98.8 MeV

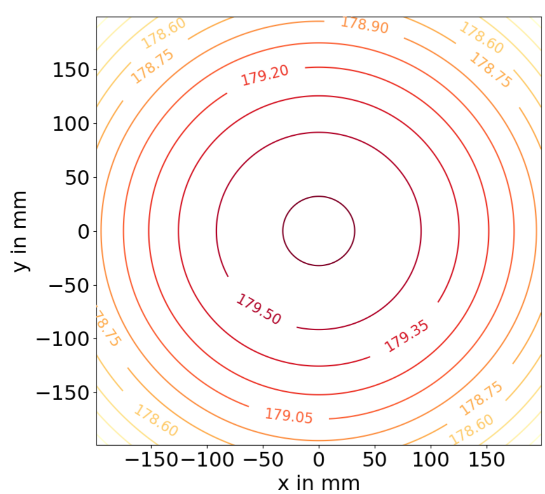

Figure 4: Scattered photon energy angle distribution on an observation plane, 10 m away from the interaction point. Photon energies are given in keV for E_p = 1.2 eV and E_e = 98.8 MeV.

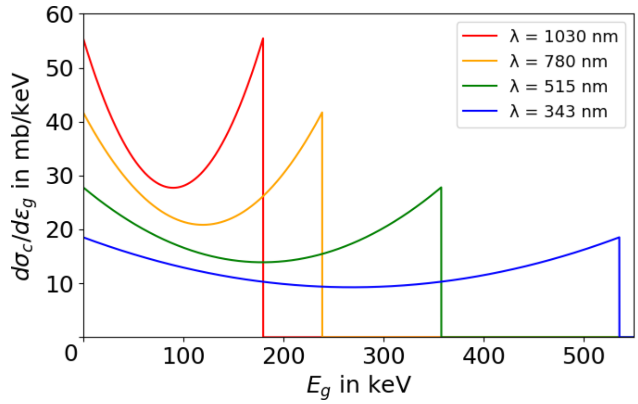

Figure 5: Energy-differential cross section of inverse Compton scattering with 98.9 MeV electrons and four different laser wavelengths.

with $\gamma_e = E_e/(m_e c^2)$. The energy differential cross section, [8]

$$\frac{\mathrm{d}\sigma_c}{\mathrm{d}\epsilon_g} = \frac{\pi r_0^2}{2}\frac{1}{\gamma_e^2\epsilon_p}\left[\frac{1}{4\gamma_e^2\epsilon_p^2}\left(\frac{\epsilon_g}{\gamma_e-\epsilon_g}\right)^2 - \frac{1}{\gamma_e\epsilon_p}\left(\frac{\epsilon_g}{\gamma_e-\epsilon_g}\right) + \frac{\gamma_e-\epsilon_g}{\gamma_e} + \frac{\gamma_e}{\gamma_e-\epsilon_g}\right] \tag{3}$$

with r_0 classical electron radius, $\epsilon_p = E_p/(m_e c^2)$ and $\epsilon_g = E_g/(m_e c^2)$, shows that lower incident photon energies result in higher cross sections, visualized in Fig. 5. This graph indicates the maximum possible energy with the cross section.

The flux $\mathscr{F}$ of the LCB X-ray can be calculated with the cross section σ_c and the luminosity $\mathscr{L}$ for the collision as $\mathscr{F} = \sigma_c\mathscr{L}$. The luminosity for a small crossing angle $\theta_i = \pi + \phi$ between incident laser and electron beam is given by [8]

$$\mathscr{L} = \frac{1}{2\pi\sqrt{\sigma_{e,y}^2+\sigma_{L,y}^2}} \times \frac{BfN_eN_L\cos(\phi/2)^2}{\sqrt{(\sigma_{e,x}^2+\sigma_{L,x}^2)\cos^2(\phi/2)+(\sigma_{e,z}^2+\sigma_{L,z}^2)}} \tag{4}$$

where B is the number of bunches, f is the collision frequency, N_e and N_L are the Number of electrons and photons per bunch, and σ are the rms sizes of the electron and the laser beam at collision point, in either x or y direction.

INTERACTION POINT

First design options of the interaction point were investigated. Head-on collision can be realized using parabolic mirrors, off-axis or on-axis, or to inject the laser into the beam pipe at the dipole magnets at the end of the straight part of the recirculation. Another option under investigation is about introducing a small angle between laser and electron

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beam, as in Fig. 3 shows that the X-ray energy decreases only slightly.

Here two of the possible designs are sketched. The corresponding positions at the accelerator are presented in Fig. 1 and marked with A and B. The first one (A) is shown in Fig. 6:

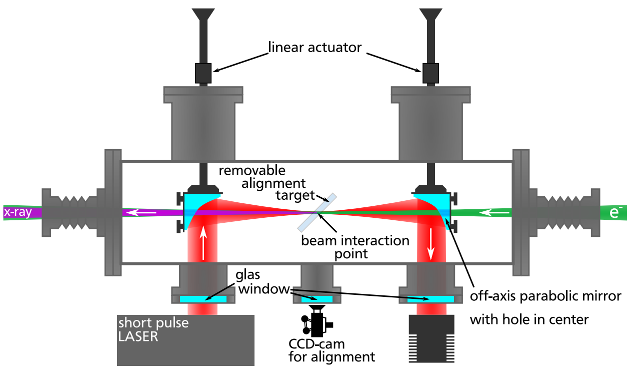

Figure 6: One of the possible preliminary designs of an interaction point for LCB at the S-DALINAC. This chamber would be located at the third recirculation beamline. Concept adapted from [9].

The electron beam is focused into the chamber from the right and leaves on the left. At the other side the laser enters the chamber at the bottom left window, is reflected and focused by an off-axis parabolic mirror (with hole in the middle for the electron beam) onto the interaction point. Another mirror collects the laser beam and separates it from the electron beam. With this design the laser collides head on with the electron beam, making it easier to adjust the overlap, and maximizes the scattered photon energy. For adjusting the beam, a removable target is installed at the interaction point. The scattered photons will leave the chamber on the left side with the electron beam, to get separated from the electrons at the next dipole magnet, in the recirculation beamline.

Another possible design for the interaction point (B), see Fig. 1, foresees the laser to enter the electron beamline at the dipole magnet at the end of the straight section, where also the scattered photons were separated from the electrons. This option would make it easier to align the two beams with each other. But for this the interaction point has to be located at the last few meters of the straight beamline, right in front of the dipole magnet. To get a small focal spot size of the laser beam, the focusing needs to be so strong that the laser beam diverges into the electron beampipe before it can exit at the opposite end of the recirculation section. An aperture has to be designed to avoid the laser hitting the walls of the beam tube and other objects inside.

Further investigations of the interaction point are in progress. The estimated beam parameters of the scattered photon beam can be seen in Table 1, with the corresponding electron and laser parameters. The energy and the energy spread is sufficient for the desired non-destructive beam diagnostics at the S-DALINAC. The calculated flux is rather low and has to be improved over time. Nonetheless, already at this implementation stage, the flux is expected to allow the electron beam energy and energy spread to be monitored in an non-destructive way within a few minutes of data taking. For low-lying collective excitations in heavy nuclei a higher flux has to be established within the future. This will be achieved with new electron source for higher electron bunch charges and introducing a optical cavity at the interaction point to amplify the pulse energy even further.

Table 1: Parameters of the S-DALINAC, the Possible Laser System and Calculated Performance of the LCB Source

Parameters	**Values**
Maximum electron energy (E_e)	98.8 MeV
Error of electron energy (ΔE_e)	29.6 keV
Electron beam current (I)	10 µA
Electron bunch Charge (q)	3.3 fC
Electron beam size ($\sigma_{e,rms}$)	100 µm
Laser Wavelength (λ)	1030 nm
Photon energy (E_p)	1.2 eV
Error photon energy (ΔE_p)	0.62 meV
Laser Pulse energy (E_{pulse})	0.5 mJ
Laser Repetition rate (f_{rep})	200 kHz
Laser Beam size ($\sigma_{L,rms}$)	100 µm
Energy scattered photon (E_g)	179.7 keV
Energy distribution width (ΔE_g)	325 eV
Energy width ($\Delta E_g/E_g$)	0.6 %
Scattered photon flux	17 ph/s

CONCLUSION AND OUTLOOK

General analytical calculations on LCB have been presented to determine which laser system the project has to aim for. To finalize the interaction point design electron and laser interaction simulations have to be done in detail. Nevertheless the simplest setup to adjust and achieve LCB at the S-DALINAC is preferred. A background measurement at the accelerator hall is in progress, to quantify the peak to background level that can be expected. The procurement procedure for the laser system is in progress and will be last until end of 2019. A laser lab for high power lasers has to be prepared and in combination with this a laser transfer line will be established.

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