THE COMPTON BACKSCATTERING SOURCE COBRA AT THE S-DALINAC*

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Abstract

The COBRA (Compton Backscattering at a Recirculating Accelerator) source utilizes a 100 W Yb:YAG laser that is synchronized with the electron beam of the superconducting Darmstadt linear accelerator S-DALINAC for head-on collisions. The backscattered photons in the X-ray energy range can be collimated into a quasi-monochromatic beam for electron beam diagnostics and as a technology demonstrator. The first collision of the electron and laser beam is planned within the upcoming beamtime with multi-turn recirculation. During operation, COBRA will utilize stabilization systems for both beams. Later, COBRA is foreseen to be operated during energy recovery mode, serving as a demonstrator for future Compton scattering light sources. This contribution provides an overview of the COBRA source, highlighting recent upgrades to the detector setup and developments of the laser beamline.

INTRODUCTION

Intense photon beams are used in several fields of scientific and commercial applications [1, 2]. There is a need for photon beams at X-ray to γ-ray energies with small bandwidth and a high flux. Prominent examples of light sources emit synchrotron radiation through the bending of the electron beam. The energy of the photon beam is dependent on the energy of the electron beam and therefore limited by the state of magnet technology and the size of the facilities. Alternatively, the photons can be produced by **L**aser-**C**ompton **B**ackscattering (LCB), which describes the process of a relativistic electron transferring its energy onto an incoming photon. Maximum energies for the backscattered photons are reached through head-on collisions. By colliding an initial photon beam with an accelerated electron beam, the backscattered photons with an opening angle of $1/\gamma$ possess a maximum energy of $E_p' \approx 4\gamma^2 E_p$, where γ is the Lorentz factor of the electron beam, E_p is the laser photon energy and E_p' is the backscattered photon energy. There have been multiple approaches to LCB setups: The initial photon beam can be produced by an undulator in an optical cavity like at the **H**igh **I**ntensity γ-ray **S**ource (HIγS) [3]. Another possibility is an external laser system [4, 5]. The highest possible luminosity requires high currents of the electron beam at minimum emittance. **LIN**ear **AC**celerators (LINACs) offer lower emittances than competing facilities like storage rings. **E**nergy **R**ecovery **L**INACs (ERLs) [6] provide comparably high beam currents while simultaneously keeping the beam load for external power supplies minimal, if the ERL is superconducting. The electron energies can be increased with multi-turn superconducting ERLs, which can be built in a compact design and are more energy efficient [7]. The **S**uperconducting **Da**rmstadt electron **LI**near **AC**celerator (S-DALINAC) is the first superconducting multi-turn ERL in the world for which the energy recovery was demonstrated and quantified [8]. We have made steps toward preparing the infrastructure at TU Darmstadt for the world's first demonstration of a fourth-generation photon source, i.e., production of a photon beam from LCB on the electron beam of a superconducting multi-turn ERL.

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THE S-DALINAC – A MULTI-TURN ERL

The S-DALINAC (Fig. 1) is TU Darmstadt's major research instrument for nuclear spectroscopy and accelerator science [9]. It can deliver electron beams with energies up to 130 MeV and beam currents up to 60 µA at its 10 MeV injector. The electron beam is bunched at a repetition rate of 3 GHz. The S-DALINAC is a three-time recirculating LINAC, which enables its operation as a multi-turn ERL. A twice-recirculating ERL has been demonstrated with a maximum initial beam current of approximately 7 µA [8]. The lattice of the third recirculation of the S-DALINAC has been upgraded for usage in a thrice-recirculating ERL mode [10] while its feasibility has been studied via beam-dynamics simulations [11].

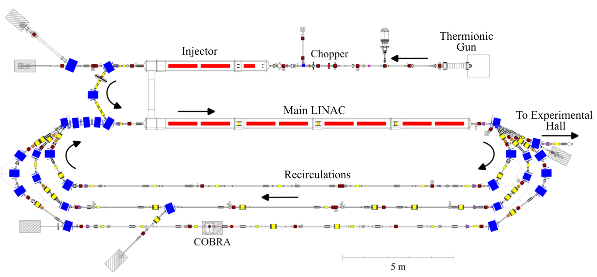


Figure 1: Floorplan of the S-DALINAC. The electron beam produced by a thermionic gun is first accelerated by the injector section and can be accelerated in the main LINAC up to four times due to the three recirculations. The COBRA setup is located in the third recirculation.

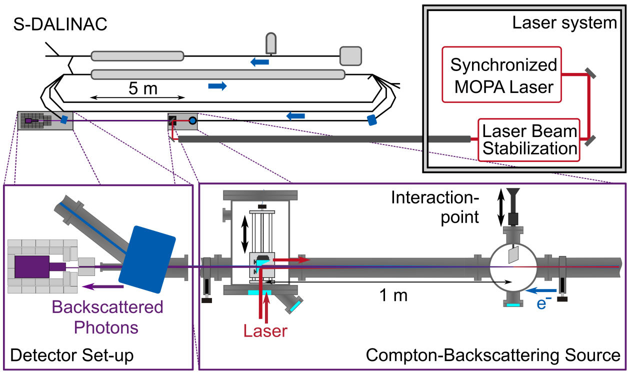


Figure 2: Layout of the COBRA setup installed in the third recirculation's straight section. Adapted from Ref. [12].

COBRA AT THE S-DALINAC

The **Co**mpton **B**ackscattering at a **R**ecirculating **A**ccelerator (COBRA) source utilizes a 100 W Yb:YAG laser, which is synchronized with the electron beam of the S-DALINAC for head-on collisions. A schematic of the setup is shown in Fig. 2. The ultrarelativistic electron beam provided by the S-DALINAC interacts through Compton backscattering with the laser beam from the external laser system. Through a transport line, the laser beam is guided from the laser laboratory to the accelerator hall. The beams collide in the **I**nteraction **P**oint (IP) in the third recirculation of the electron beamline and the backscattered photons leave the beamline at the end of the third recirculation into the detector setup.

The Laser System

The infrared laser beam with a wavelength of 1030 nm is produced by a **M**aster **O**scillator **P**ower **A**mplifier (MOPA) laser which consists of multiple components that can be seen in Fig. 3. The *SYNC-Controller* produces a pulsed laser beam that is synchronized to the master oscillator of the S-DALINAC. The pulse repetition rate can be adapted with an integrated pulse picker in a range from 0.2 to 40 MHz. Through mode locking the pulse length is as short as 0.8 ps. Inside the *TANGOR-Amplifier*, the laser signal is amplified through the process of chirped pulse amplification to reach an average power of up to 100 W.

The Laser Beam Transport Line

The laser system resides in the laser laboratory from where the **L**aser **B**eam **T**ransport **L**ine (LBTL) guides the photon beam along approximately 40 m to the IP in the accelerator hall. The complete LBTL consists of eight mirrors and is depicted in Fig. 4. The LBTL is vacuum pumped to provide stable transport. Through mechanical reinforcement of the bellows and the mirror fixtures of the LBTL a reproducible vacuum of 0.2(2) mbar could be reached. The highly reflecting (99.9 %) mirrors can be adjusted from the outside in the horizontal and the vertical direction, but a complete realignment of the transport line requires the opening and therefore venting of the system.

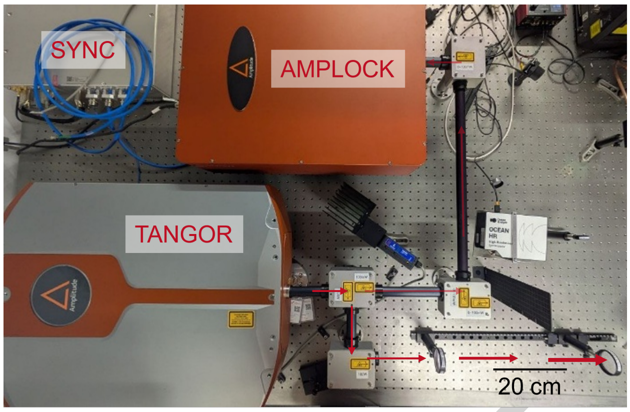


Figure 3: Labeled MOPA laser system for the external laser of the COBRA source, bought from Amplitude [13]. The path of the laser beam (red arrows) displays the small percentage of the beam used for the *AMPLOCK* and the telescope expanding the beam size for transport.

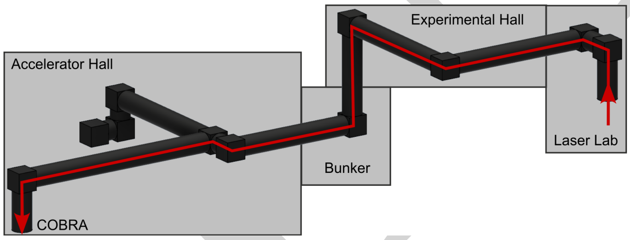
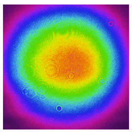
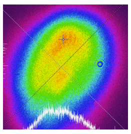


Figure 4: The laser beam transport line from the laser laboratory to the accelerator hall. The laser (red) is deflected by highly reflective mirrors. The empty path of the beamline directs to the laser driven electron photogun of the S-DALINAC. Adapted from Ref. [12]

Stability of the Laser Transport

Multiple parameters of the laser beam have been compared in front and behind the LBTL. The intensity, the beam profile and the transverse position have been measured. A comparison of the measurements is presented in Table 1. The beam profile and ellipticity depicted were measured with a beam profiler in october 2025. The picture of the profile is one snapshot and the ellipticity is averaged over one hour. For the measurement of the positional stability, the laser beam with a size of 4 mm is focused to 100 µm onto the beam profiler and for this measurement the beam stabilization system is off. In the IP the electron and the laser beam are both focussed to less than 100 µm size. We aim for a transversal 1σ jitter of the intensity maximum below 10 µm for both beams. A *Compact* stabilization system of MRC [14] is currently being commissioned to stabilize the transverse position of the laser beam in the IP. The system consists of two position sensitive detectors and two piezo-mirror actuators in form of piezo mirrors. The first actuator is positioned in the laser laboratory in front of the laser beam transport. The two detectors and the second actuator are positioned in the accelerator hall on the optical table above the coupling chamber. The capabilities of the stabilization system are currently surveyed to enable a stable

Table 1: Stability of Laser Properties throughout the LBTL

Parameter	Before LBTL	After LBTL
Intensity [12]	1.51(2) W	1.45(2) W
Intensity scaled up	100.0(14) W	96.0(14) W
Beam profile		
Ellipticity	0.87(3)	0.84(4)
max. hor. deviation	12.9 µm	369.8 µm
max. vert. deviation	35.7 µm	179.1 µm

beam transport due to mechanical stress on the transport line.

In-beamline Setup and Interaction Point

The laser beam exits the beam transport line through a vacuum window and enters the coupling chamber. The setup in the third recirculation is shown in Fig. 5. The laser beam is focused by an off-axis parabolic mirror inside the coupling chamber into the IP. The parabolic mirror is connected to a five-axes table for precise remote alignment. The sixth axis can be driven remotely by a motor. The IP is approximately 1 m upstream in the electron beamline, where the electron and the laser beam collide head-on. A hole of 1.7 mm diameter inside the mirror enables the backscattered photons to pass in the downstream direction of the electron beam. Both in the coupling chamber and at the IP a beryllium oxide screen is available that can be driven into the beam remotely and monitored with high resolution cameras. For optimal alignment a new wire scanner system is being commissioned to measure both beam positions in the IP simultaneously.

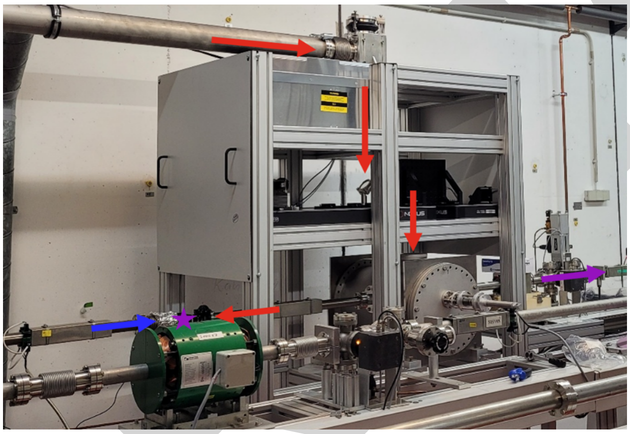


Figure 5: The coupling chamber and the setup for the IP (purple star) in the straight section of the third recirculation. The laser beam (red arrows) follows along an optical table and is focused by a parabolic mirror into the IP at a distance of 1 m where the laser light collides head on with the electron beam (blue). The backscattered photons (purple arrows) pass through the hole in the mirror to the upstream end of the straight section.

Detector

At the end of the straight section the electron beam is deflected in a dipole magnet and recirculated back to the LINAC where the electron beam's energy can be recovered when operating in the ERL mode. The high-energy LCB photons, pervade the magnetic dipole field and exit the magnet through a window on the back toward a suitable photon spectrometer. Before detection, the beam can be collimated through a lead collimator. Since the energy distribution of the beam of backscattered photons depends on the scattering angle, the collimator will leave a quasi-monochromatic beam depending on the size of the aperture. Different detectors have been evaluated for the COBRA source and offer varying advantages. With a measurement of a calibration source, the efficiency and resolution of the detectors were determined. The complete COBRA setup was initially equipped with a **L**ow **E**nergy **P**hoton **S**pectrometer (LEPS), which is a semiconductor detector utilizing a germanium crystal. The LEPS is specialized for low energies and displays a resolution and therefore a peak width of 0.87(1) %. To ensure the alignment of the electron and the laser beam position and the stable production of backscattered photons, the efficiency of the chosen detector is important. The LEPS has an efficiency of 8.6(6) %. A detector based on a modern high-resolution scintillator has been evaluated for providing a higher efficiency (10 % for a Lanthanbromide measuring at 79 keV) with the added benefit of being more resistant to high count rates from background radiation (up to 20 kHz during a background measurement [12]) and increased timing performance for synchronization of a coincidence gate with the laser oscillator of 40 MHz. Furthermore, a scintillator does not need to be cooled with liquid nitrogen, which will lower maintenance periods and preparation time for each measurement. Weighing the advantages of the detectors, the choice was made to use a scintillation detector, at least for the upcoming commissioning of the COBRA source.

CONCLUSION

This contribution presents the current status of the COBRA source setup. Advances have been made in the beam transport line and with a scintillation detector offering higher efficiency and flexibility. With the completed laser transport line to facilitate high intensity transmission, the COBRA setup will be commissioned within the upcoming beam time. First goal will be the stable superposition of the electron and the laser beam, including surveying of the capabilities of the laser stabilization system. The COBRA setup will be able to demonstrate X-ray production first during traditional multi-turn and in the future during energy recovery operation at the S-DALINAC.

REFERENCES

[1] A. Zilges *et al.*, "Photonuclear reactions – From basic research to applications", *Prog. Part. Nucl. Phys.*, vol. 122, no. 103903, 2022. doi:10.1016/j.ppnp.2021.103903

[2] N. Pietralla, "Photons and nuclear structure", *Eur. Phys. J. A*, vol. 60, p. 108, 2024. doi:10.1140/epja/s10050-024-01285-8

[3] H. R. Weller *et al.*, "Research opportunities at the upgraded HIγS facility", *Prog. Nucl. Phys.*, vol. 62, pp. 257–303, 2009. doi:10.1016/j.ppnp.2008.07.001

[4] L. Liu *et al.*, "The SLEGS beamline of SSRF", *Nucl. Sci. Tech.*, 2024. doi:10.1007/s41365-024-01469-3

[5] P. Tracz, "ELI-NP gamma beam system — New facility for nuclear physics research", in *2017 IEEE 21st International Conference on Pulsed Power (PPC)*, pp. 1–4, 2017. doi:10.1109/PPC.2017.8291290

[6] M. Tigner, "A possible apparatus for electron clashing-beam experiments", *Nuovo Cim.*, vol. 37, 1965. doi:10.1007/BF02773204

[7] P. Williams, "A route to greener Big Science", *Nat. Phys.*, pp. 479–480, 2023. doi:10.1038/s41567-022-01933-0

[8] F. Schliessmann *et al.*, "Realization of a multi-turn energy recovery accelerator", *Nat. Phys.*, vol. 19, no. 4, pp. 597–602, 2023. doi:10.1038/s41567-022-01856-w

[9] N. Pietralla, "The Institute of Nuclear Physics at the TU Darmstadt", *Nucl. Phys. News*, vol. 28, pp. 4–11, 2018. doi:10.1080/10619127.2018.1463013

[10] M. Meier *et al.*, "Development of a setup for laser-Compton backscattering at the S-DALINAC", in *Proc. IPAC'23*, Venice, Italy, pp. 2139–2142, Sep. 2023. doi:10.18429/JACoW-IPAC2023-TUPL168

[11] F. Schliessmann *et al.*, "Studies on a Triple-Turn Energy-Recovery Mode at the S-DALINAC", *J. Phys.: Conf. Ser. 2687*, no. 032023, 2024. doi:10.1088/1742-6596/2687/3/032023

[12] M. Meier, "Entwicklung und Aufbau der Laser-getriebenen Compton-Rückstreuquelle COBRA für Strahldiagnose am S-DALINAC", Ph.D. thesis, TU Darmstadt, 2024. doi:10.26083/tuprints-00027694

[13] Amplitude Laser, https://amplitude-laser.com/

[14] MRC Systems, https://mrc-systems.de/