PHOTOCATHODE DEVELOPMENT PLAN FOR DALI MULTIFUNCTIONAL FACILITY

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Abstract

DALI is an accelerator-based terahertz (THz) light source that uses multiple superconducting accelerators to drive CW electron bunches through undulators to emit ultra-intense THz pulses, including two ELBE SRF photo injects as the e- sources for high bunch charge beamline and for the UED, respectively. It requires a versatile portfolio of photocathodes to support diverse electron gun configurations and beam parameters targets. For the SRF gun commissioning, robust polycrystalline copper cathodes and magnesium cathodes will be employed, providing reliable performance and simplified handling during initial RF conditioning. Beam commissioning and routine user operation will firstly rely on the mature Cs_2Te photocathode, chosen for their proven robust, stability and realiable quantum efficiency. To enhance operational flexibility, especially in scenarios where UV laser generation presents challenges for special user appliations, we will consider to apply high-efficiency “green” photocathode optimized for visible-wavelength drive lasers. In parallel, an ultra-low-emittance photocathode in tens of micrometers will be under investigation to meet the stringent beam quality requirements of UED applications. This multi-cathode strategy ensures reliable commissioning, user-friendly operation, and state-of-the-art beam performance across all beamlines of the new accelerator facility.

INTRODUCTION

DALI is planned as a next-generation SRF accelerator facility for multifunctional user applications. The facility aims to deliver high-quality electron beams with flexible beam parameters to support accelerator research, compact THz radiation sources, positron source and ultrafast electron diffraction [1]. Such versatility imposes demanding requirements on the electron sources. Photocathodes are a key component of photoinjectors because they directly determine operational stability and the reachable beam quality. No single photocathode material can simultaneously satisfy all operational requirements of DALI. Therefore, a diversified photocathode strategy is required.

The proposed development plan builds upon more than ten years of operational experience with the ELBE SRF gun-II at HZDR [2], together with recent collaborative developments on new semiconductor photocathodes. The goal is to establish a flexible photocathode platform capable of supporting different operation regimes within DALI.

The photocathode program focuses on three major cathode families. Metallic photocathodes are considered for gun commissioning and ultra-low emittance applications, Cs_2Te photocathodes are intended for reliable high-current operation, and bi-alkali antimonide photocathodes are being developed for high-QE visible-light operation and energy-efficient photoinjectors. In parallel, supporting technologies including cathode preparation systems, UHV transfer systems, surface cleaning techniques, and cathode characterization methods will be discussed as well.

CATHODE PLAN

The DALI facility foresees multiple operational modes requiring substantially different beam characteristics. For high-field THz radiation and compact positron source applications, stable high-bunch-charge and high-average-current operation is essential. On the other hand, UED application requires extremely low transverse emittance and high beam coherence [3].

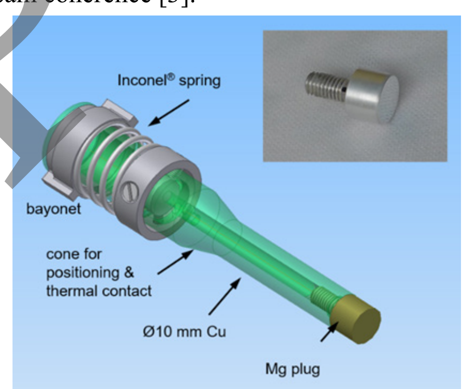

Figure 1: ELBE-style cathode with replaceable plug. The inset photo is a Mg cathode.

To satisfy these requirements, the photocathode system must provide high quantum efficiency (QE), low intrinsic emittance, long operational lifetime, compatibility with SRF environments, low dark current, and fast temporal response while maintaining high operational reproducibility. Experience from the ELBE SRF gun demonstrates the importance of reliable cathode preparation and exchange procedures in long-term SRF operation. Therefore, the DALI photocathode program emphasizes not only cathode performance itself, but also operational robustness and reproducibility.

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Figure 1 shows the ELBE-style photocathode design with a replaceable cathode plug concept developed for SRF gun operation. The cathode assembly consists of a copper stalk with a diameter of 10 mm and a photocathode plug screwed at the tip. In this example, a magnesium cathode plug is installed, as shown in the inset photograph. The cathode holder uses a bayonet-type mechanical connection combined with a spring to ensure reliable fixation, stable electrical contact, and good thermal conductivity during operation in gun. A conical interface between the cathode and its holder (cathode stalk) provides precise positioning and efficient thermal contact, which are essential for stable SRF gun performance. The replaceable plug concept allows different photocathode materials to be exchanged efficiently without changing the entire cathode design.

Metallic Photocathodes for Gun Test and UED

Metallic photocathodes provide exceptional robustness and compatibility with SRF gun. Although their QE is relatively low compared with semiconductor cathodes, they remain attractive for applications requiring excellent beam quality and operational simplicity.

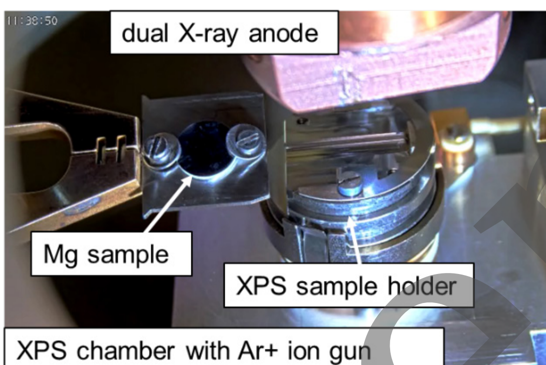

Figure 2: Clean Mg sample with Ar^+ ion and study surface with XPS (PHI 5600).

Metallic cathodes offer several important advantages for SRF photoinjectors. Their surfaces are generally stable under UHV conditions, they exhibit low dark current under high RF field, and they can tolerate handling and vacuum fluctuations better than semiconductor cathodes. In addition, their fast photoemission response and excellent compatibility with high-gradient RF operation make them highly suitable for beam commissioning. Copper and magnesium are considered primary candidates for gun commissioning and UED operation. Copper cathodes typically exhibit QE values on the order of 10^{-5} at 258 nm illumination, while magnesium cathodes can reach QE values approaching 10^{-3} under similar ultraviolet excitation conditions [2].

For UED applications, low intrinsic emittance is particularly important. Nanostructured or patterned metallic cathodes may provide opportunities to optimize beam emission characteristics and improve transverse coherence. Therefore, future studies will investigate surface engineering techniques and structured cathode geometries.

A part of the development program concerns surface treatment and cleaning methods for copper and magnesium cathodes. Surface contamination and oxide layer strongly influences QE and dark current performance. Several cleaning techniques, including laser cleaning, thermal treatment, and ion cleaning, will therefore be systematically studied. Initial X-ray photoelectron spectroscopy studies combined with Ar^+-ion sputtering have already demonstrated controlled surface modification of magnesium cathodes (see Fig. 2) [4]. The extensive operational experience gained from the ELBE SRF gun provides an important foundation for these developments and reduces the technical risks associated with implementing metallic photocathodes in DALI.

Cs_2Te for High-Current Operation

Cs_2Te photocathodes are currently the most mature semiconductor photocathodes for SRF gun operation at HZDR. Since 2019, they have been routinely operated in the ELBE SRF gun and have demonstrated reliable high-current performance under regular user operation. Typically, one or two cathodes are consumed per year, and operational lifetimes exceeding 1000 hours have been demonstrated. Extracted charges up to approximately 50 C per cathode have been routinely achieved under user operation conditions.

One of the main advantages of Cs_2Te is its relatively high QE in the ultraviolet spectral range combined with comparatively robust operation in SRF environments. Typical QE values exceeding 1 % at 258 nm can be achieved, allowing efficient beam generation at moderate laser power. The cathodes can support stable high-average-current operation over extended periods while maintaining acceptable operational lifetime.

The in-house preparation process developed at HZDR starts with diamond turning of copper substrates, followed by thermal baking at approximately 300°C to remove rest gases on surface. Subsequently, tellurium and cesium are sequentially evaporated onto the substrate surface. During cesium coating, the substrate temperature is maintained at 120°C until the maximum photocurrent is reached. Figure 3 presents the QE evolution of a Cs_2Te photocathode operated in the ELBE SRF gun system. The photocathode was prepared on a copper substrate, transported to the accelerator hall and operated in gun for about five months. The photocathode initially reached QE values close to 6% in the preparation chamber. After transport and insertion into the SRF gun, the QE gradually decreased over time due to cathode aging and operational effects, but still remained at a level above 3 – 4% during gun operation. The inset images on the right side show spatial QE maps measured at different stages of operation. These maps reveal the evolution of the photocathode surface uniformity over time. Although some degradation and non-uniformity appear during operation, the overall emission profile remains sufficiently homogeneous for stable beam generation.

Despite these successes, several technical challenges remain. The most critical concern is the possible contamination of the SRF cavity by cesium during cathode operation in gun. Future development efforts will focus on reducing contamination risks inside the SRF gun environment, as well as improving QE reproducibility, extending operational lifetime and studying cathode degradation mechanisms.

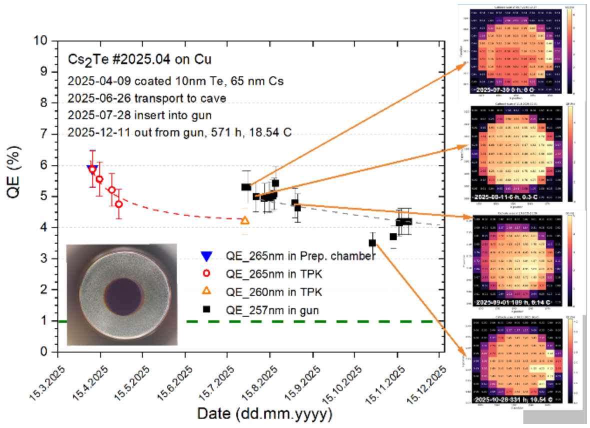

Figure 3: The QE history of a Cs_2Te photocathode used in the ELBE SRF Gun.

Na-K-Sb Photocathodes

Bi-alkali antimonide photocathodes represent one of the most promising options for high-efficiency photoinjectors. Compared with Cs_2Te, these cathodes can operate efficiently with visible-light, significantly reducing the required laser power and relaxing the request of ultraviolet laser optics. In addition to their high QE in the visible spectral range, bi-alkali antimonide cathodes may also offer lower thermal emittance compared with many conventional photocathode materials. Furthermore, unlike Cs-containing photocathodes, Na-K-Sb photocathodes do not require cesium in their composition. This feature is particularly attractive for SRF gun applications. By eliminating cesium from the material, Na-K-Sb cathodes may reduce the contamination risk for the SRF cavity.

A collaborative program between HZDR and HZB has been initiated to develop Na-K-Sb photocathodes for DALI. Recent laboratory experiments demonstrated QE values exceeding 5% at a wavelength of 520 nm. The first beam generation using such a cathode in the SEALab SRF gun has already been successfully demonstrated, confirming the feasibility of integrating these materials into SRF injector environments [5].

However, bi-alkali photocathodes are significantly more sensitive to vacuum conditions and contamination than metallic or Cs_2Te cathodes. Their preparation requires precise control of stoichiometry during growth, careful substrate preparation, and extremely clean handling conditions. Within the DALI development program, Na-K-Sb cathodes will continue to be prepared and characterized at HZB. Additional work is therefore required to develop reliable cathode transfer system. The long-term objective is to establish a reliable visible-light photocathode platform suitable for routine accelerator operation.

SUPPORTING TECHNOLOGIES

In addition to photocathode material development, DALI requires a comprehensive supporting technologies for photocathode preparation, transport, characterization, and operation. The planned infrastructure includes dedicated cathode preparation chambers, ultra-high-vacuum transport systems, load-lock exchange mechanisms, surface characterization tools, automated QE distribution tracking, and photocathode lifetime monitoring diagnostics. A precise cathode transfer system is especially important for the safe transport of activated photocathodes between preparation chambers and SRF injectors without exposing them to contamination.

The collaborative work on SRF photoinjector cathode transfer systems with LCLS-II and MSU/FRIB already provides a strong technological basis for implementing such infrastructure at DALI [6]. In parallel, advanced diagnostics including X-ray photoelectron spectroscopy, scanning electron microscopy, optical microscopy, and beam-based characterization techniques will provide the possibility to correlate cathode surface properties with electron beam performance. Such an integrated infrastructure is essential for achieving reliable long-term operation and for accelerating future photocathode research and optimization.

CONCLUSION

The DALI multifunctional facility requires a flexible and reliable photocathode strategy capable of supporting a broad range of accelerator applications. Based on extensive operational experience from the ELBE SRF gun and ongoing collaborative developments, a diversified photocathode program has been proposed. Together with dedicated preparation, transport, cleaning, and diagnostic infrastructure, these developments will establish a versatile photocathode plan for DALI.

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