

FROM Cs₃Sb TO Cs₂Te PHOTOCATHODES ON ELSA ACCELERATOR AT CEA DAM

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Abstract

The 19 MeV electron linear accelerator ELSA at CEA DAM operated as an IR-FEL in the 1990s is now a user facility that provides pulsed bremsstrahlung and Inverse Compton Scattering (ICS) X-rays. Renovation of the facility is currently under way to improve system reliability. The 144 MHz photo-injector gun is the key element for producing a low-emittance beam for the ICS X-ray source. While the refurbishment of the 144 MHz RF source has increased the photo-injector's reliability, the short lifetime of the photocathodes has become the facility's weak point. A first step toward improved beam availability for users is to replace the Cs₃Sb photocathodes with Cs₂Te, which is known to have a longer lifetime. The drawback of this material is that it requires illumination with UV light, resulting in less laser energy available for photon-to-electron conversion compared with visible-light operation. This paper will present the fabrication process, compare the two materials in terms of quantum efficiency and lifetime, and describe the laser-system upgrades needed to maintain the same electron-beam current.

INTRODUCTION

Following its operation as a free-electron laser in the 1990s [1], the facility has been repurposed as a user facility delivering electron and X-ray beams to the scientific community. A distinguishing feature of this electron accelerator is its capability to generate low-emittance, high-charge bunches, thereby delivering high-current pulse trains to users [2]. The main accelerator line employs a low-frequency (144 MHz) photoinjector designed to extract high-charge bunches from the photocathode. These bunches are produced via the interaction of a 72 or 144 MHz Nd:YAG laser with an alkali photocathode. The resulting bunch lengths are tunable within the range of approximately 20 to 100 ps. This first accelerating stage boosts the beam energy to 2.2 MeV. The second stage comprises three 433 MHz accelerating cavities. Due to limitations in the RF sources and main power supply, the duty cycle is restricted to 250 μ s pulse trains at a repetition rate of 5 Hz. Consequently, for low beam currents, the maximum achievable energy at the linac exit is 17 MeV.

The facility comprises three beamlines: one dedicated to bremsstrahlung X-rays, another to Inverse Compton Scattering (ICS) X-rays, and a third, straight-through line for electrons. A double-alpha magnet, described in [3], is employed to split the beam and direct it into the respective

lines. In 2015, a third accelerating stage was added to the X-ray beamline to boost the beam energy to 30 MeV and to enable higher beam currents, circumventing the power limitations of the second stage.

Over the past decade, evolving user demands have necessitated the delivery of continuous high-current beams five days a week. This operational mode places stringent requirements on the accelerator's reliability and availability. Consequently, essential renovations are underway to revitalize this 30-year-old facility. The initial phase involved upgrading the power sources for the first two accelerating stages with state-of-the-art high-power transistor technology [4].

Regarding electron production, alkali antimonide photocathodes on Molybdenum substrates (K₂CsSb, Cs₃Sb, K₃Sb, or Na₂KSb) have been utilized or tested for the past 30 years using a frequency-doubled laser [5, 6]. For the last 15 years, however, only Cs₃Sb on Mo substrates have been employed.

Observations indicate that while the initial quantum efficiency (QE) immediately after fabrication has remained relatively stable over the years, the lifetime of the photocathodes has deteriorated significantly due to pressure increase in the fabrication chamber and in the photoinjector. This degradation results in a drastically reduced time-averaged QE. Practically, a photocathode now survives only about 2 days while delivering a high-current electron beam. Consequently, investigating photocathodes with extended lifetimes has become imperative to ensure the reliable delivery of high-current beams to users.

Cs₃Sb PHOTOCATHODES

Mo Substrate

Material deposition on the Molybdenum substrate is performed in an ultra-high vacuum (UHV) chamber. The pressure in this chamber ranges from 2 to 5.10⁻⁹ mbar and can rise to 2.10⁻⁸ mbar during material heating. The substrate consists of a Molybdenum cylinder with a polished face exhibiting surface roughness parameters of R_a = 3 nm and R_q = 5 nm. The polished face measures 50 mm in diameter (Fig. 1).

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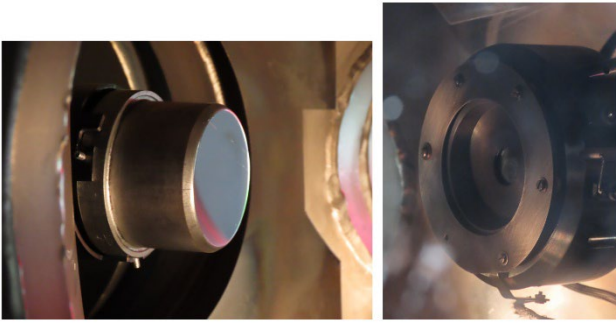


Figure 1: Molybdenum substrate on the left, oven and mask on the right.

A 10 mm diameter diaphragm is used as a deposition mask (Fig. 1). Prior to deposition, the Mo substrate undergoes a baking cycle in a dedicated oven: it is heated to 500°C with a controlled ramp rate and held at this temperature overnight to ensure thorough outgassing. Following this, the substrate is cooled and maintained at 110°C during the deposition process.

Materials

Antimony (Sb) and Cesium (Cs) are heated in alumina crucibles via a resistive filament (Fig. 2). A thermocouple in direct contact with the crucible enables precise temperature monitoring and control.



Figure 2: Sb and Cs crucibles with their heating filament.

Sb is supplied as pellets with 99.999% purity. Cs is sourced from Saes Getters in the form of cylindrical pellets (models CS/Amax/GR and Cs/BD). These pellets consist of an alloy comprising 55–60% Zirconium, 30–40% Cesium Molybdate (CsMoO_4), and 10–12% Aluminum powder. This composite material offers the distinct advantage of being air-stable, unlike pure Cs, which is highly reactive with oxygen and moisture.

Deposition Process

Sb is heated in front of a quartz microbalance to monitor the deposition rate. Once the rate stabilizes at 0.03 nm/s, the Sb crucible is aligned with the substrate, which is maintained at 110°C. Approximately 4 nm of Sb is then evaporated. During the Sb heating phase, if the chamber pressure exceeds $8 \cdot 10^{-9}$ mbar, liquid nitrogen is circulated through the double-walled cooling jacket to reduce the pressure. Once the pressure drops to $4 \cdot 10^{-9}$ mbar, Cs heating starts directly in front of the substrate. For that, the Cs crucible temperature is calibrated beforehand: the crucible is positioned in front of the quartz microbalance to establish a

deposition rate of approximately 0.003 nm/s. Since the deposition thickness is not monitored by the quartz microbalance, the termination of the Cs deposition is determined by real-time photocurrent measurements.

Photocurrent Measurement

The photocurrent is generated by illuminating the photocathode with a green He-Ne laser (< 1 mW). The resulting current is measured using a picoampere meter with a bias voltage of 100 V. Cs deposition is terminated once equilibrium between Cs and Sb is achieved, as indicated by a plateau in the photocurrent curve. Continued deposition beyond this point leads to a reduction in photocurrent due to Cs excess.

To automate this process, a detection algorithm was developed to identify the plateau. The algorithm detects the negative derivative of the photocurrent signal. To suppress false positives, multi-stage signal conditioning involving smoothing and curve fitting is applied. Implemented in LabVIEW, this algorithm demonstrates robust performance, achieving a 100% detection rate.

Quantum Efficiency and Lifetime

To measure the quantum efficiency (QE)—defined as the ratio of extracted electrons (N_e) to incident photons (N_p), as shown in Eq. (1)—the exact laser power incident on the substrate must be known. For a He-Ne laser, this power is derived by measuring the output on a test bench and accounting for the transmission losses through the viewport glass. The number of extracted electrons is subsequently calculated from the measured photocurrent.

$$Q_E = \frac{N_e}{N_p} = \frac{h \cdot c}{e \cdot \lambda} \frac{I_e}{P_{laser}} \quad (1)$$

In recent years, the Quantum Efficiency (QE) has rarely exceeded 1% immediately following the initial deposition. While a secondary or tertiary deposition of Sb and Cs can achieve QEs above 2%, these values remain significantly below state-of-the-art benchmarks.

After deposition, photocathodes are stored in a vessel maintained at pressures below $5 \cdot 10^{-10}$ mbar. However, transportation of the vessel between the fabrication laboratory and the electron accelerator frequently induces pressure spikes, leading to a degradation of the QE. Upon insertion into the accelerator, the QE typically drops to the order of 0.3%. Subsequently, due to the elevated pressure in the photoinjector ($\sim 1 \cdot 10^{-9}$ mbar) and the extraction of high-charge electron bunches, the QE degrades by an order of magnitude per day.

Cs₂Te PHOTOCATHODES

The primary motivation for this material transition was to extend the photocathode lifetime. The hypothesis was that although Cs₂Te exhibits a lower QE than Cs₃Sb immediately after fabrication—and requires UV laser excitation rather than green light—its QE would remain stable over several days.

Cs₂Te photocathodes are fabricated using the same procedure, with Tellurium (Te, 99.999% purity) replacing Sb. The major system modification involves the necessity of illuminating the photocathode with UV light. The principal drawbacks of UV illumination are the reduced optical power resulting from fourth-harmonic generation and the invisibility of the beam to the human eye, which complicates alignment and manipulation.

UV Optical System on the Fabrication Chamber

Consequently, a new optical system was installed on the fabrication vacuum chamber, utilizing a UV diode laser.

UV light from a 265 nm, 12 mW diode with a 130° emission angle is focused onto the photocathode to produce a 10 mm diameter spot. A beam splitter is used to monitor the UV power. After transmission through the beam splitter and the viewport glass, approximately 270 μ W reaches the photocathode (Fig. 3).

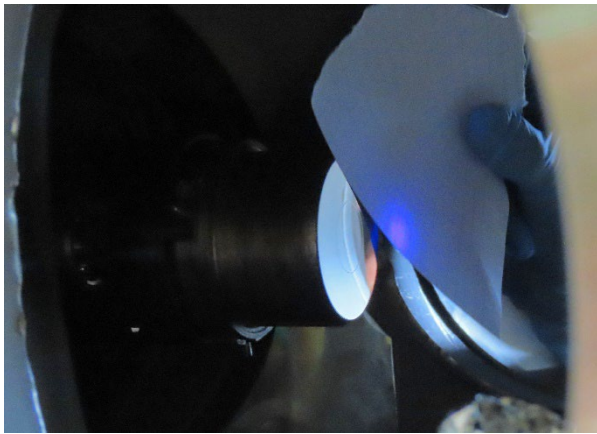


Figure 3: UV light on the photocathode.

Description of the Laser System

The laser system comprises two independent 1064 nm oscillators capable of delivering pulses at 72 or 144 MHz. A Pockels cell is employed to select specific pulses from the oscillator train. The amplifier chain consists of four Nd:YAG amplifiers: three operated in double-pass configuration and one in single-pass. Another Pockels cell protects the frequency-doubling crystal from excessive peak energy. The pulse train then passes through a KTP crystal for type II second-harmonic generation. Finally, a Pockels cell at the output of the laser table cleans the beam by gating out unwanted pulses. The resulting laser beam is transported over a distance of 25 meters to the injection table in the accelerator bunker.

On the injection table, the 532 nm laser beam undergoes type I frequency doubling via a BBO crystal to generate UV radiation (266 nm). Several optimizations were implemented to maximize the conversion efficiency:

- **Beam Pointing Stabilization:** A closed-loop pointing control system was implemented to compensate for beam pointing errors accumulated over the 25-meter transport path between the laser room and the case-mate.

- **Motorized Alignment:** Motorized mounts were installed to automate the phase-matching adjustment of the crystal and to control the final steering mirror directing the laser onto the photocathode.
- **Beam Visualization:** A laser spot visualization system was added with a UV camera. However, since this system observes the reflection on a metallic surface, it does not allow for precise measurement of the beam profile.

These adjustments have enabled a 10% green-UV conversion efficiency, ensuring sufficient illumination of the photocathode.

Quantum Efficiency and Lifetime

Only six photocathodes have been fabricated since the material transition. The first exhibited a QE of 7%, while the second reached 15%, a value consistent with state-of-the-art Cs₂Te photocathodes. Further optimization of the Te layer thickness is still required to maximize this yield.

The most significant advantage of these Cs₂Te photocathodes for our high-current electron accelerator is their extended lifetime. Not only are the photocathodes transferred to the accelerator while retaining high QE, but the efficiency also remains stable over several months, even during the emission of high-current electron beams for user experiments (Fig. 4).

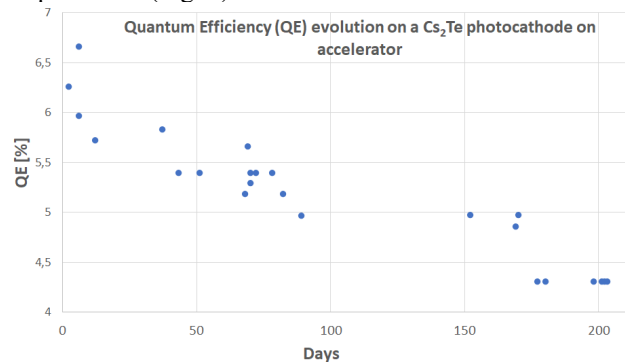


Figure 4: Evolution of Quantum Efficiency (QE) measured on a photocathode during accelerator operation.

CONCLUSION

The ELSA accelerator is a user facility delivering high-current electron beams. The transition from Cs₃Sb to Cs₂Te was driven by the need to extend photocathode lifetime, while maintaining equivalent beam currents despite the reduction in laser power caused by frequency doubling.

Thanks to a post-fabrication Quantum Efficiency (QE) of 15% and a 10% frequency-doubling conversion efficiency in the laser system, a five-fold increase in electron current was achieved, successfully meeting user demand. However, the most significant advancement lies in the photocathode lifetime: we successfully maintained a single Cs₂Te photocathode in operation for six months, whereas the previous Cs₃Sb technology would have required at least ten replacements for the same operational period.

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