HIGH CURRENT PHOTOGUN FOR THE PERLE ENERGY RECOVERY LINAC*

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Abstract

PERLE is a demonstrator intended to investigate multi-turn energy recovery at high-power, under construction in Orsay (France). The electron beam is created by a DC photogun aiming to produce 500 pC bunches at 40.079 MHz to inject the ERL loop. The high intensity electron beam (20 mA) originates from photocathodes of bi-alkali material (CsK_2Sb) optically pumped by visible light. The photocathodes are grown in a preparation facility connected to the gun chamber under vacuum. This paper describes the apparatus and presents the status of its commissioning and the very first beam tests.

INTRODUCTION

Particle accelerators are exceptional instruments widely used for research and society. Progress led to accelerators at increasing energies, which require large electrical power and accelerators must now face the challenge of energy sustainability. Among the options to reduce the energy footprint of accelerators, energy recovery linacs offer an ambitious concept for machines with limited perturbations of the beam at the interaction region such as colliders, free electron lasers or Compton-based sources. In an Energy Recovery Linac (ERL), the beam, after acceleration and interaction, is recirculated and decelerated in the accelerating cavities of the linac. In such a scheme, the power of the beam is recovered to excite the superconducting radiofrequency (SRF) cavities, leading to substantial savings in electrical power to drive the RF power source [1].

PERLE, ENERGY RECOVERY LINAC

PERLE (Power Energy Recovery Linac for Experiments) is a high-power ERL demonstrator in construction in Orsay, aiming to investigate multi-turn energy recovery [2]. The electron beam is recirculated in a superconducting linac, operating at 801.58 MHz, up to three times to a maximum energy of 250 MeV. The high intensity electron beam is created by a photoinjector consisting of a DC gun, a RF buncher at room temperature and a SRF booster (7 MeV) (Fig. 1) [3]. The photogun continuously produces electron bunches at 40.079 MHz, the 20th harmonic of the RF frequency, for continuous injection into the ERL. Bunches at different energies continuously circulate in the loop before being dumped at injector energy [4].

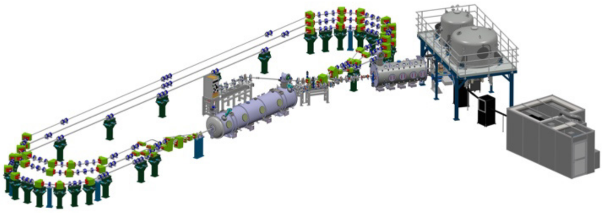

Figure 1: Layout of the PERLE energy recovery linac including injector, merger and spreader region, linac and beam dump in the 3-loop configuration.

PHOTOGUN

The electron source must provide a beam ensuring the high bunch charge and the low emittance required for injection into the ERL loop. Its main requirements are:

- high charge per bunch (500 pC) at 40.079 MHz,
- low emittance (<6 mm.mrad),
- long-term operation and reliability.

Electrons are generated by optical pumping from a photocathode illuminated by an external laser. In a DC photogun, electrons are accelerated and the beam is shaped by a strong static electric field in the gap between the cathode and a pierced anode. The gun voltage reflects a trade-off between a higher bunch charge, favouring stronger electric fields, and the risk of electrical breakdown. The gun is based on the design of the Cornell CBETA photogun [5]. It was produced, along with the photocathode preparation facility, by RI *Research Instruments GmbH* [6] and

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transferred to CNRS/IN2P3 at IJCLab (Orsay) through a collaboration agreement.

The vacuum chamber of the photogun comprises the cathode and anode, the cathode being supported horizontally by a vertical stalk, through two insulating ceramics (Fig. 2). The vacuum system consists of two ion pumps, three combined pumps (ion and NEG), two extractor gauges and a residual gas analyser (RGA).

To reach the required bunch charge (500 pC), the target operating voltage of the cathode holding the photocathode is 350 kV, generating a 7 MV/m average electric field in the accelerating gap. To provide headroom for the HV conditioning, a 450 kV / 50 mA power supply, made of four stacks, is used. To connect to the photogun, two HT resistors can be used either for conditioning (high impedance ~ 20 MOhms) or operation (low impedance ~ 5 kOhms). Columns and resistors are operated in two airtight, interconnected tanks supported by a platform (Fig. 3). Generating such high voltages require the use of insulating gases within the tanks, usually SF6 due to its high insulating capability. However, SF6 is a potent greenhouse gas with a global warming potential 23 500 times greater than CO2 over a 100-year period and suffers new EU environmental regulations. In order to replace the efficient yet harmful SF6, the PERLE photogun is operated with N2 gas at a pressure of four bars of absolute pressure.

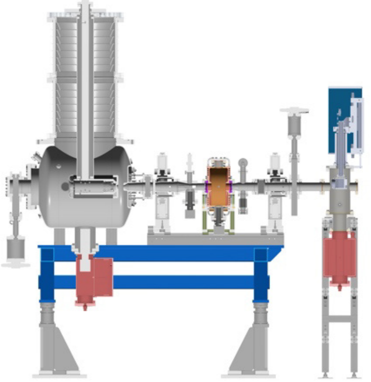

Figure 2: Cutaway view of the photogun (left) displaying the cathode held by a vertical stalk through the insulating ceramics facing the anode connected to the test beamline.

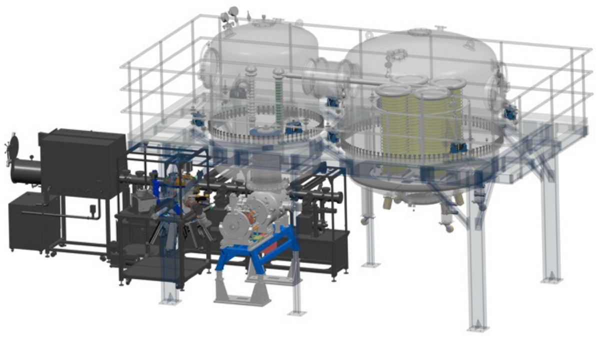

Figure 3: HV system in tanks above the electron gun connected to a short beamline (on blue frame) and linked to the photocathode preparation facility on the left.

Electrons are emitted from photocathodes of bi-alkali material (CsK_2Sb). They are deposited in a photocathode preparation facility (PPF) consisting of a molecular beam epitaxy (MBE) chamber for growth, linked via vacuum transfer lines to a glove box for precursor preparation and to the gun vacuum chamber [7]. With this unique system, photocathodes can be prepared and loaded into the gun chamber rapidly and under excellent vacuum conditions. For CsK_2Sb, the quantum efficiency (QE), that is the number of emitted electrons per incident photon, is expected to be up to 10% with green light.

Photoemission is generated by a green laser (515 nm), a customized version of the Satsuma HP laser (Amplitude). Based on Chirped Pulse Amplification, it is an infrared laser, frequency doubled and temporally stretched up to about 55 ps (FWHM). It is used at the operating frequency of the injector (40.079 MHz).

When a high intensity beam is produced, it ionizes the residual gas in the gun vacuum chamber. The resulting ions are backscattered toward the photocathode, leading to degradation of the emitting surface. To limit the resulting drop in quantum efficiency, an extreme ultra-high vacuum is essential (10^{-11} mbar or better). In addition, a small bias will be applied to the anode in order to optimize the charge lifetime [8]. Nevertheless, at high current the charge lifetime remains limited. Long-term performance will be ensured by the load-lock system for fast photocathode exchanges.

At the exit of the gun, a preliminary beamline section provides beam tuning and transport: it includes two focusing solenoids, two magnetic steerers in both planes, two button-type beam position monitors (BPMs), a beam viewer and a Faraday cup. This section is pumped by one NEG pump and two combined pumps.

COMMISSIONING

The assembly of the apparatus was initiated in 2024 in the igloo bunker at IJCLab. After high-pressure rinsing of the vacuum chamber, the photogun has been fully assembled in a clean room environment with regular particle count monitoring. All NEG pumps were activated in a separate test chamber to avoid residue in the gun. The cathode and the anode were aligned using laser trackers in a clean room with an accuracy better than 0.1 mm. The gun section was baked up to 200°C for a total duration of a week: the ultimate vacuum level reached in the gun chamber was 5×10^{-12} mbar. However, after a small leak occurred and was fixed, the operating pressure was about 2×10^{-11} mbar.

The HV system has been fully assembled and commissioned: the 4 HV columns (each of 12,5 mA, 450 kV) have been installed as well as the two HV resistors and in the horizontal adjustable interconnexion. After the vessels have been pumped down and leak checked, they have been filled with N2 gas at 3 bars of relative pressure (Fig. 4). The conditioning was performed by raising the HV progressively while monitoring vacuum activity, HV power supply current and radiation with two probes located close to the gun chamber (near the accelerating gap) and on one of the HV tanks. Initial conditioning was successfully performed until 350 kV without field emission. However, during subsequent HV ramp, some field emission was detected. Several initial sessions of conditioning helped to reduce it, yet some level remains and is still under processing.

Pressure data during the conditioning was analysed: the pressure decay after each vacuum burst occurring during HV tests was studied to estimate the pumping speed capacity in the gun. Right after each burst, the pressure as a function of time, P(t), can be approximated to an exponential decay $P(t)=P_0 \exp(-t/\tau)$, with τ the time constant of the vacuum system, assuming that the pumping speed remains constant over a short duration (~hundreds of s). Measurements from the RGA indicate that this time constant mostly corresponds to CH4. The pumping capacity (C) is determined by $C=V/\tau$ with a gun volume V~335 L. Data showed a decay time about 6-7 s, translating into an effective pumping capacity for CH4 about 48-56 L/s. Calculations performed with MolFlow indicate an effective pumping capacity for CH4 of 57 L/s, in agreement with our estimate.

Figure 4: Photograph of the electron gun, below the HV platform and tanks, connected to the photocathode preparation facility (left) and to a short beamline (blue frame) ended with a Faraday cup (not yet shielded).

The photocathode preparation station was fully assembled, that is the glove box with load-lock system and motorized substrate transfer, MBE deposition chamber and a low-power green laser for measuring the photocurrent. The two alloys of Cs and K with In and Sb were prepared in argon atmosphere inside the glove box, since Cs and K ignite with oxygen. Then the air-stable indium compounds were loaded into evaporators in the MBE chamber. Initial deposition yielded a photocathode of QE= 3% (515 nm), despite degraded vacuum conditions in the MBE. After restoring a good pressure (2×10^{-11} mbar), a second photocathode was grown, with QE~6.5 % with excellent dark lifetime (>1000 hours). Detail can be found in [7].

A clean room to host the laser in the bunker together have been commissioned. The laser has been commissioned: diameter is Dx=2.1 mm and Dy=2.2 mm at 80 cm from the laser output. At 40.079 MHz, the maximum power is about 1.4 W at the laser output. A power upgrade will be done to reach 500 pC. From the laser room, light is transported to the gun via two periscopes over a total distance of 13 m. Two laser interface enclosures are attached to the photogun for the laser beam to enter and exit the gun.

Command-control and safety systems have been commissioned. A 7 kW Faraday cup has been purchased (NTG): it was installed at the termination of the test beam line and a lead shielding has been be built around it.

The photocathode was transferred from the MBE to the gun chamber 26 days after its growth, as the QE was measured to be 5.5%. Preliminary beam test was done May 11, 2026 at limited high voltage (200 kV), to avoid potential field emission. Beam was seen on a YAG viewer located ~0.9 m downstream of the photocathode (Fig. 5). After initial beam tuning, profile measurements were done (at 10 Hz): σ_x = 1.25 mm and σ_y = 1.37 mm. A beam of 2.5 mA was measured in the Faraday cup on the very first day. Commissionning is underway to characterize the beam and increase its intensity progressively in the Faraday cup.

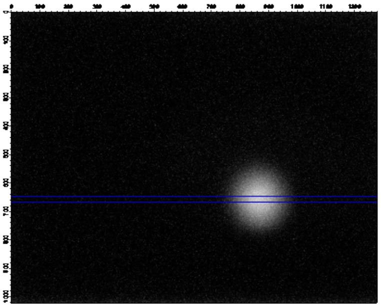

Figure 5: First beam test of the PERLE photogun where electrons are visualized on a YAG screen.

CONCLUSION

The PERLE accelerator, under construction in Orsay (France), requires an electron beam with high current and low emittance to inject into the ERL loop. A DC photogun has been assembled and commissioned. A very preliminary test in May 2026 produced some beam originating from a lab-grown photocathode of CsK_2Sb. Under these conditions (limited high voltage and beam power), the beam intensity was limited, yet the system was proven to be fully operational and bodes well for future operation, including successful operation of the HV system with N_2.

The next steps will be devoted to curing the HV limitation and producing new photocathodes. Beam studies will be carried out to investigate charge lifetime and beam intensity. The existing laser power will have to be upgraded to meet PERLE specifications. In parallel, the RF buncher is being ordered. The booster should be available in 2028 to allow the commissioning of the injector. The linac of the ERL is under manufacturing such that commissioning of PERLE with 1 recirculation loop could start around 2029. The upgrade to 3 recirculation loop is foreseen after 2030.

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