STATUS OF THE PERLE'S INJECTOR*

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On behalf of the PERLE collaboration

Abstract

PERLE is an Energy Revovery Linac (ERL) accelerator for electrons which aims to reach 250 MeV 20 mA cw. First brick of this accelerator is the injector, its main components are the DC photo-injector and a booster holding 4 superconducting cavities. This paper will give an overview of the injector's design, technical details about major components and the schedule of the construction.

OVERALL DESCRIPTION

PERLE [1] is under construction on the campus of the university Paris-Saclay. It aims to demonstrate the feasibility of ERLs at high power, namely 5 MW. It requires an injector which must fulfil specifications shown in Table 1.

Table 1: PERLE Injector Specifications

E (MeV)	7
Q (nC)	0.5
F_{rep} (MHz)	40
I (mA)	20
F_{RF} (MHz)	801.58
σ_z (mm)	3
ε_n (mm.mrad)	< 6

Two main components are indispensable to reach these requirements. First one is the electron source; to provide an electron bunch of 0.5 nC with an emittance lower than 6 mmmrad, a photo-injector is required, since the other classical source -a thermionic gun- cannot reach a such low emittance. In addition, the electron beam is continuously pulsed (CW) at 40 MHz therefore it excludes room temperature radiofrequency (RF) photo-injectors as several hundred of kW of RF power would be dissipated into the walls of cavity and would be very difficult to evacuate. Hence, the source of electrons must be a DC high voltage photo-injector~~.~~ This critical system was obtained during our design studies through a collaboration with Research Industry [2]. It comprises a photo-injector, a photocathode preparation chamber, and a small beamline.

Downstream of the gun, a room temperature RF cavity (buncher) compresses the bunch to the specified value at the entrance of the main accelerating module.

The second key component is the accelerating module or booster. Superconducting technology was chosen over room temperature RF cavities to limit RF power requirements and thermal losses. Design of the cryomodule is largely inspired from the ESS one, with descriptions and 3D renderings provided, while fabrication drawings are still in progress. A conceptual drawing of the injector is shown in Fig. 1.

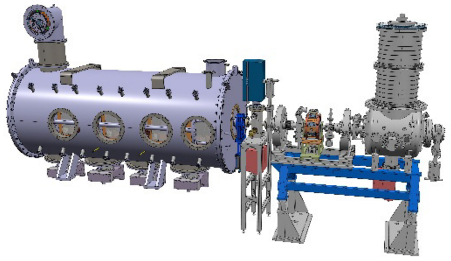

Figure 1: 3D drawing of the PERLE's injector. From right to left the gun vacuum chamber with its insulation ceramic, steerer, solenoid, laser introduction chamber, buncher, screen chamber, solenoid, valve, Faraday cup, valve and the cryomodule containing four superconducting cavities.

Details of these three main components of the injector will be explained in the following sections.

THE DC GUN

Within to a collaboration agreement between IJCLab and Research Instruments (RI) GmbH, the DC photogun as well as a Photocathode Preparation Facility (PPF) [3] were transferred from RI to IJCLab. The latter allows us to prepare materials for the photocathode such as antimonide, potassium and caesium in a glovebox under an argon atmosphere. The photocathode is obtained by deposition on a substrate and transported under vacuum thanks to a load-

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lock system to the gun [4]. A drawing of the facility is shown in Fig. 2.

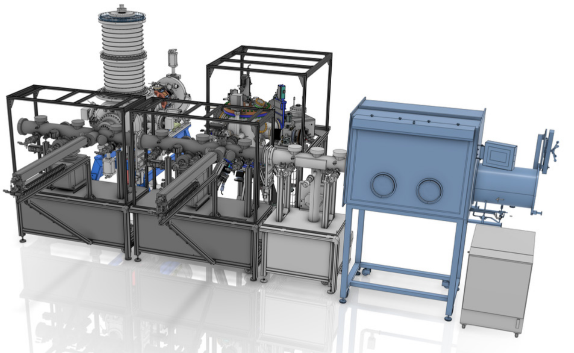

Figure 2: right, the glovebox; middle the photocathode preparation chamber and left, the gun with the insulating chamber.

The gun is based on the design of the Cornell CBETA photogun [5]. The photocathode is set on a cathode connected to a rod brought to a negative high voltage accelerating the electrons to the nominal kinetic energy of 350 keV. The accelerating gap is 50 mm between the cathode and the anode which can be biased to prevent degradation of the photocathode lifetime due to ion back bombardment. The electric field on the photo-cathode is roughly 7 MV/m. At the exit of the gun, a beamline section provides beam tuning and transport into the booster. In addition to the buncher (see below), it includes focusing solenoids, two magnetic steerers in both planes, two button-type beam position monitors (BPMs) and a beam viewer. This section is pumped by one NEG pump and two combined pumps. At the end of this section there is a Faraday cup bought to the NTG company to measure the current. Now, most of this small beamline is installed and connected to the control room. We succeeded to reach 360 kV in 2 days with a dummy photocathode puck showing the good quality of the gun, namely the cleanliness of the surface state and a good vacuum of around 10^{-11} mbar. An active photocathode with a CsK2Sb deposit will be transferred to the gun for the first beam tests.

THE BUNCHER

A critical component in the PERLE injector is the buncher cavity. The electron beam that emerges from the electron gun elongates due to space charge, and must be compressed from an initial length of approximately 10 mm to about 3 mm. To match the specifications, a single-gap resonant cavity is proposed since it is enough to fulfill the specifications at reduced-cost with respect to alternative models as multi-cells for instance. The final RF model is shown in Fig. 3. The shape is quite simple, with the re-entrant nose as its most distinctive feature, enhancing the shunt impedance. For the coupling, a magnetic loop connected to a feedthrough was chosen, since the required power is estimated to be below 2 kW. Beam dynamics simulations indicated that the optimum peak electrical field is around 0.8 MV/m, corresponding to an RF power of 0.9 kW. This provides a comfortable margin to operate the cavity and adjust the electrical field if needed. Reflected power is expected to be negligible as the coupling factor will be very close to one. Likewise, with the phase set close to -90° relative to peak, the power delivered to the beam will also be minimal.

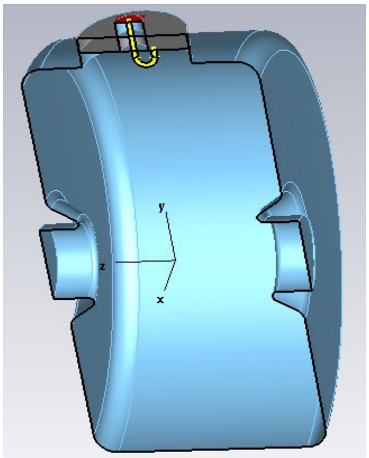

Figure 3: 3D electromagnetic design with CST, showing the longitudinal view of the buncher along the beam axis.

The Q_0 is roughly 30 000 and R/Q is 326. Beam loading has been investigated. Since this is a bunching cavity, the phase is set to -90° relative to the peak. However, a reactive component remains, causing frequency detuning of the cavity and requiring additional power to maintain the same accelerating voltage. It has been calculated to be 33 kHz requiring 1.5 kW instead of 0.9 kW. While it is manageable with the spare RF power, one may also adapt the temperature of the cavity to cancel this frequency shift. Indeed, the cooling of the cavity will be performed by a chiller which can change the operating temperature by ± 10 °C. Since the variation of the resonant frequency for this cavity is in the order of 12 kHz/°C, a frequency shift of around 30 kHz can be corrected. Technical drawings have been completed; mechanical design is shown in Fig. 4.

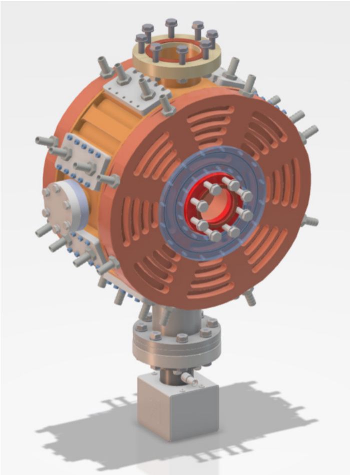

Figure 4: technical drawing of the buncher cavity; top, coupling port; bottom vacuum port with a combined NEG ionic pump.

The material of the cavity is in OFHC copper divided in three main pieces while connecting flanges are in stainless steel. Cooling channels are drilled in vertical walls and are dimensioned to mitigate 2 kW of dissipated power. A vacuum port is also mandatory due to the high level of vacuum required for a long lifetime of the photocathode in the nearby photogun. A grid is machined in the cavity wall in order to prevent the RF wave to leak to the pump. Now, a call for tender is under way for a whole construction, from the initial machining to the brazing. Delivery is expected by the end of 2026.

THE BOOSTER

The specifications for PERLE's beam performance imply that the booster must use superconducting technology, with niobium as the state-of-the-art material. RF power is another key design parameter. The booster must increase the beam energy from 0.35 MeV to 7 MeV at 20 mA, corresponding to roughly 120 kW of RF power. This is too high for a single power coupler, so a multi-cell cavity is not feasible. The solution chosen is four single-cell cavities, allowing each coupler to handle a manageable RF load.

For the design of the RF cavity, since the electron beam reaches very quickly the speed of light, we adopted an elliptical shape which is the state of the art to accelerate relativistic particles. Furthermore, to take advantage of the ongoing R&D in the PERLE project, we chose the end cell of the PERLE five-cell cavity of the ERL linac as a starting point. The only big change required was to remove the flat central section in order to achieve the target frequency. Regarding the fundamental power coupler, again we used the same model as the one for the 5-cell cavity for the PERLE linac, which was adapted from the SPL's power coupler. The final RF design is shown in Fig. 5.

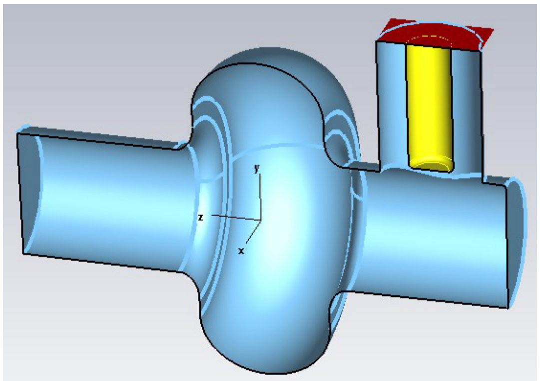

Figure 5: 3D electromagnetic model of the booster's cavity with the input coupler made with CST microwave studio.

The choice of the value for the external quality factor, Q_{ext}, was a trade-off between nominal current requirement and RF power cost effectiveness at lower current. Indeed, the commissioning of the injector will be first initiated at reduced current, around 5 mA. Hence the Q_{ext} was set at $1{,}7.10^6$ instead of 7.10^5 allowing us to reduce significantly the RF power consumption at 5 mA, while limiting the increase for 20 mA operation. To reach the nominal energy of 7 MeV, it requires a modest accelerating electrical field of 8.2 MV/m. Therefore, we aim at a Q_0 of only 10^{10} which should be reachable with standard chemical and HPR treatment. The bare cavity is fabricated from bulk 250-RRR Niobium. Niobium sheets (4 mm thick) are used in the manufacturing process. The cavity contains four ports: two beam pipes, the high-power coupler port and the pick-up port. The helium vessel, fabricated from 5 mm-thick grade 2 titanium and equipped with a titanium bellow on the tuner side, fully encloses the beam pipes to protect the cavity from thermal loads.

The cryomodule which houses the four cavities will be largely inspired from the ESS spoke cryomodule design [6]. Technical drawings are almost completed, a 3D model is shown in Fig. 6.

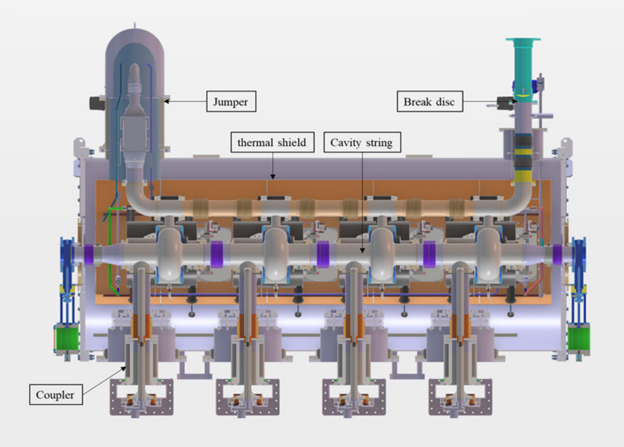

Figure 6: cross-sectional view of the cryomodule.

Each cavity is surrounded by a helium tank, ensuring its cooling at low temperatures. The cavities are also equipped with magnetic shields designed to reduce the detrimental effects of the Earth's magnetic field on the quality factor of the superconducting cavities. The cavities are connected to each other by bellows, which provide mechanical flexibility and facilitate assembly. At each end of the cavity string, there is a warm-to-cold transition, consisting of a beam pipe diameter reduction (from DN130 to DN100), a valve, and a bellow. These transitions help to limit thermal transfers between room temperature and the 2 K cavities. They are actively thermally anchored to the thermal shield to optimize cryogenic performance.

CONCLUSION

Construction of the PERLE's injector is under way. The electron source is on the verge to start and other major components are designed. Calls of tender will start this year and we expect a commissioning in 2029.

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