Status and perspectives of superconducting radio-frequency gun development for BERLinPro

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Abstract. As part of the BERLinPro study, HZB is developing an SRF photoelectron injector. The R&D will be carried out in three stages, the first of which is currently being installed at HZB’s HoBiCaT facility. It consists of an SRF cavity with SC solenoid, electron beam diagnostics and drivelaser systems.

1. Introduction
Helmholtz-Zentrum Berlin is the result of a merger between two research labs, HMI and BESSY, in the Berlin area. HZB build and operates several accelerator facilities for research with photons, neutrons and protons. Due to its expertise in the development of large scale accelerator facilities HZB is ideally suited to realize new accelerator concepts. Therefore HZB will build a demonstrator for the Energy Recover Linac (ERL) paradigm [1]. The ERL was proposed in 1965 by M. Tigner [2] and is possible today with the advent of superconducting RF technology for particle accelerators.

In order to demonstrate generation and energy recovery of a 100 mA average current and 1 mm mrad normalized transverse emittance beam HZB is currently working on BERLinPro, a fully integrated ERL test facility including all major systems found in ERLs like electron gun, booster section, merger beamline, main linac, return loop and high power beam dump.

The ultimate performance of the ERL depends on the ability of the electron source to deliver a high brightness, high-average current electron beam to the main accelerator complex. For maximum flexibility, the source must also be able to generate pulses of higher charge at lower repetition rates to meet specific experimental needs. For flexibility and performance, photoelectron injectors (or short photo-injectors) are the primary candidates. Superconducting radio-frequency (SRF) injectors have the highest potential as electron sources for ERLs, as they are able to operate at 100% duty factor and can generate significantly higher fields than (CW-operated) normal conducting (NCRF) systems. Hence SRF systems can fulfill the ERL injector requirements and provide for maximum flexibility (compared with DC sources). Most importantly, they offer the most potential for continued future improvements, so vital to the upgrade of ERL facilities.
2. Roadmap for photo-injector development

The photo-injector has three major subsystems: The cathode, the laser system to release the electrons and the initial acceleration. For the cathode, important considerations are the thermal emittance, the response time on the sub-ps scale, the photon wavelength for reasonable quantum efficiency and its longevity. The laser system must be able to provide the average and peak powers to produce high currents (of order 100 mA) at bunch charges on the order of 100 pC. At the same time, flexible pulse shaping must be included to minimize the impact of space charge on the emittance. These aspects favor longer-wavelength laser systems (e.g., 528 nm) and will impact the choice of cathode materials. For acceleration, it is vital that both a high field (for rapid acceleration to limit the impact of space charge) as well as a high voltage (to minimize the beam degradation in the subsequent drift space) can be applied.

We propose a multi-cell SRF gun operating at the ERL main linac frequency (1.3 GHz) with an embedded alkali antimonide photocathode. The number of cells is limited by the power capability of the input coupler, but should deliver at least 1 MeV/c of momentum to the photoelectrons combined with a launch field of at least 10 MV/m to overcome space-charge limited emission. The main challenges for the photo-injector system are:

- Verification of the emittance compensation scheme, optimization of solenoid location (inside or outside the cryogenic vessel of the SRF cavity) with respect to emittance performance and SRF cavity operation.
- The cathode/cavity interface, operation of a room-temperature cathode inside an SRF cavity with high accelerating field (with vacuum shield between cavity and cathode insert and RF choke), achievement of high cathode lifetime and development of a procedure for cathode changing during beam operation.
- Design of minimum beam-disruptive high power RF feeds (for power levels up to 200 kW) and HOM output coupler.

All these issues will be addressed with BERLinPro at HZB. The approach is staged, tackling one item after the other. The goals and parameters for each stage are summarized in Table 1.

Table 1. Tentative parameters of the roadmap guns.

| Parameter       | Stage A HoBiCaT gun | Stage B SourceLab | Stage C BERLinPro |
|-----------------|----------------------|-------------------|-------------------|
| Goal            | Beam demonstrator    | R&D gun           | Production gun    |
| Repetition rate | 30 kHz               | 52 MHz            | 1.3 GHz           |
| Cathode material| Pb                   | CsK₂Sb            | CsK₂Sb            |
| Drive-laser wavelength | 258 nm | 526 nm           | 526 nm            |
| Bunch charge    | 17 pC                | 77...200 pC       | 77 pC             |
| Average current | 0.5 µA               | 5...11 mA         | 100 mA            |
| Exit energy     | 0.5...2.5 MeV        | 0.5...2.5 MEV     | 1.5 MeV           |
The stage A of the R&D programme aims at setup and commissioning of an all superconducting high brightness gun. Here the cathode is Pb film which is plasma-arc deposited on the backplane of the cavity. By utilizing the backplane as the photocathode additional complications associated with introducing a normal-conducting photocathode are avoided.

All issues connected with the introduction of a normal-conducting cathode film or stock into the SRF cavity are mitigated to stage B of the programme. For BERLinPro, the baseline cathode material is currently CsK₂Sb, due to the high QE achievable at visible wavelength [3]. Intense activity with regards to cathode preparation and characterization will be unfolded before suitable high QE cathode can be introduced to the gun in Stage B. For the last stage C the goal is to accelerate 100 mA of current to 1.5 MeV, so the development of suitable high average power RF couplers is the main focus of R&D activities in this stage.

3. SRF cavity development

The cavity was designed at HZB based on a microwave model by J. Sekutowicz. The cavity itself was fabricated and tested at Jefferson by P. Kneisel. As the cavity was designed without a tuning scheme special emphasis was laid on the mechanical design to lower the detuning by deformation of the cavity, such improve the expected field stability and thus allow meaningful studies of the beam parameters. The backplane stability is supported by a stiffening spider, long flat bars attached to the backplane.

![Cavity parts](image1)

**Figure 1.** Cavity parts (left three photos) and fully assembled cavity (right).

4. Pb cathode deposition

The Pb cathode is deposited on the large-grain Nb half-cell back-wall by means of plasma arc deposition. At the setup at the Andrzej Soltan Institute the cavity vessel is installed in a 30 degree angle to the plasma source in order to avoid the formation of droplets while still allowing a high Pb deposition efficiency [4]. After up to 16 cycles of about 5 minute deposition time with 30 minutes pause in between a Pb cathode with a thickness of about 0.5 µm and 3 mm diameter has been formed. During the pauses between deposition cycles the cavity is given time to cool down. The spot is located within a single-crystal lattice domain to have isotropic thermal contact between Pb film and backplane. After deposition and visual inspection of the film, the cavity volume is filled with Ar gas. Then the cavity is sent back to Jefferson Lab for the final BCP and high pressure rinsing treatment, following final vertical tests and assembly of the RF input and pickup couplers.
5. Summary of vertical tests at JLAB

The cavity was tested several times during construction, cleaning and before and after deposition of the Pb film at the vertical test area (VTA) and Jefferson Lab [5]. The cavity was first tested after assembly and welding of the cells, tuning and BCP-high pressure water rinsing treatment. The resulting quality factor $Q$ versus peak electric $E_{\text{peak}}$ data is shown in figure 1.

![Figure 1](image1.png)

**Figure 1.** Quality factor $Q$ versus peak electric $E_{\text{peak}}$. See text for explanation.

During test #1 the field flatness between half and full cell was only 66%. Further tuning and another BCP treatment resulted in an improvement of the field flatness to 94% and quality factor $Q_o$ exceeding $10^{10}$ levels for peak electric fields $E_{\text{peak}} \leq 35$ MV/m (see test #2). Test #3 was done after mounting of the LHe vessel. There was no significant change in performance noticed. The performance drops in $Q_o$ for field levels above 35 MV/m due to slight field emission. After this test the cavity was sent to A. Soltan Institute for deposition of the Pb film. After deposition and visual inspection the cavity was sent back to Jefferson Lab for final treatment steps. Visual inspection of the Pb spot there showed a yellowish color of the Pb film hinting at contamination with Pb yOx. During further treatment steps the film was accidentally lost. Again, the cavity was sent to A. Soltan Insitute for coating. After another round of BCP and high pressure rinsing test #4 indicated partial recovery of the performance.

6. Additional systems

The cavity will be installed together with a superconducting solenoid in the cryovessel of the HoBiCaT facility. HoBiCaT is a test facility at HZB including a complete range of infrastructure necessary for performance tests of superconducting RF systems and cavities [6]. The electron beam diagnostics beamline has all elements required to measure the projected beam emittance, monitor charge transmission and measure the energy and energy spread of the bunches from the SRF gun. The beamline elements are derived from the diagnostics setup for the FZD/ELBE SRF photo-injector [7].
The photocathode drive-laser is developed by Max Born Institut (MBI) and consists of a diode-pumped Yb:YAG oscillator with a diode-pumped regenerative amplifier. We want to use the 4th harmonic of YAG to illuminate the Pb photocathode with 258 nm laser photons. The quantum efficiency of Pb at this wavelength is close to $5 \times 10^{-4}$ [8]. The laser pulse length will be 2...3 ps FWHM, with pulse energy of 0.15 µJ. The repetition rate is 30 kHz.

7. Outlook
First beam from the all superconducting gun in HoBiCaT is expected for early Spring 2011. In parallel cathode preparation and characterization facilities are setup to be ready by 2013 to start operation of a SRF gun cavity with NC cathode insert and high QE photocathode.

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Figure 3. Setup of the gun cavity in the HoBiCaT test facility with electron beam diagnostics beamline.