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THE bERLinPro SRF PHOTOINJECTOR SYSTEM - FROM FIRST RF COMMISSIONING TO FIRST BEAM *

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Abstract

Helmholtz-Zentrum Berlin (HZB) is currently constructing a high average current superconducting (SC) ERL as a prototype to demonstrate low normalized beam emittance of 1 mm·mrad at 100 mA and short pulses of about 2 ps. To attain the required beam properties, an SRF based photo-injector system was developed and during the past year underwent RF commissioning and was setup within a dedicated diagnostics beamline called Gunlab to analyze beam dynamics of both, a Copper cathode and a CsK2Sb cathode as well as their quantum efficiency at UV and green light respectively. The medium power prototype - a first stage towards the final high power 100 mA design - presented here features a 1.4×λ/2 cell SRF cavity with a normal-conducting, high quantum efficiency Cs2KSb cathode, implementing a modified HZDR-style cathode insert. This injector potentially allows for 6 mA beam current and up to 3.5 MeV kinetic energy, limited by the modified twin TTF-III fundamental power couplers. In this contribution, the first RF commissioning results of the photo-injector module will be presented including dark current analysis as well as measured beam properties with an initially installed Copper cathode.

INTRODUCTION

Since the commissioning of the cryogenic system and cool-down tests [1] of the first SRF cryo-module for the bERLinPro [2] energy recovery linac within a dedicated laboratory called Gunlab [3] which was installed in parallel to the module assembly, see Figure 1, the main task was to start up RF operation, test the diagnostics instrumentation and finally transfer a photo-cathode into the cavity's half-cell back-wall opening [4]. As a first stage the implementation of a Copper cathode was done to study the particulate free transfer of a prepared cathode from the preparation chamber via vacuum suitcase into the transfer system. For the latter a dedicated set of special diagnostics was installed. This would allow a thorough preparation for the final transfer of the CsK2Sb photocathodes.

However, during the course of the measurements several technical problems were encountered and finally a limited beam program could be achieved towards the end of 2017 and beginning of 2018:

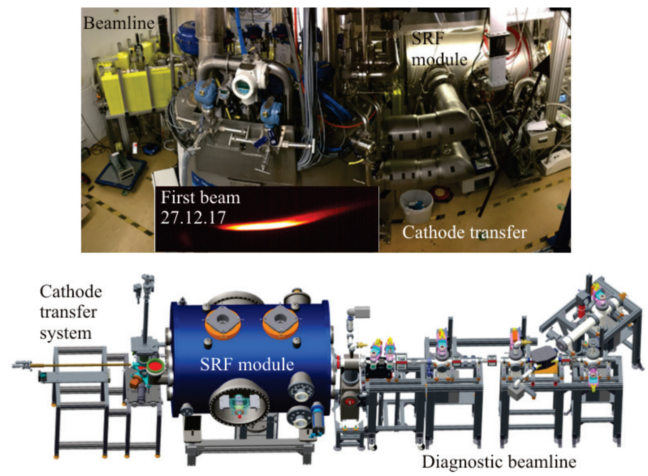

Figure 1: Overview of Gunlab housing the prototype SRF photo-injector cryo-module for bERLinPro given as picture and schematic view.

- The SC solenoid [5] showed to have several short circuits after cool-down appearing below about 100 K and thus did not allow to operate it under defined conditions. The proper setting was reached by working with a feedforward setting for the setpoint current, still leaving a residual fluctuation of current of ≈10%.
- The cryo-module had a thermal short between the 2 K return gas and a warm section. This limited in Joule-Thomson (JT) operation the available power at 1.8 K from 40 down to 20 W. To overcome this, cooling via the lower filling line was tried. As there is no dedicated phase separator in this line, the flash gas content led to gas bubbles kicking the cavity every two seconds. That type of operation did not allow fixed frequency LLRF control operation as peak detuning of 2-4 kHz were reached at a RF half-bandwidth of 30 Hz. In JT-mode with LLRF control a field stability of $\sigma_{\mathrm{phase}} \leq 0.03$ deg and relative amplitude jitter of $2{\cdot}10^{-4}$ were reached.
- The very first RF tests showed an elevated level of field emission and earlier onset compared to the data measured with a horizontal test after cold string assembly [6]. The source is still unknown yet and will be

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understood better after complete dis-assembly of the cryo-module for refurbishment.

- The viewscreen of the first vacuum cross was lost as it broke under mechanical stress caused by a wrongly installed holding mechanism. Removing the remnants of the screen with the driving system led to a clear signal in the vacuum gauges which are installed down- and upstream the SRF cavity. Even though an increase in the cavity's intrinsic quality factor Q_0 was not observed. Unfortunately this happened during the first dark current analysis without cathode, that there is no reference whether that led to an increase in field emission.
- Before the first cathode transfer by accident a large leak was opened between the cavity vacuum system and the local clean room atmosphere. The measured pressure wave remained below 1 mbar and below the turbulent limit. An increase of the field emission level afterwards was not observed. But we believe that this potentially altered the Copper surface within the cathode channel leading eventually to an increase in secondary electron yield, a major cause for multipacting we saw during the RF operation with cathode.
- As for the first cathode transfer the laser based cathode distance measurement system was not in operation yet, a cathode position mainly based on data taken during clean room assembly and relative measurements by the capacitive sensors [1, 7] was assumed. This was cross-checked with RF simulation assisted check of the TM_{010}-π mode's frequency shift, as the cathode acts as a plunger tuner reducing the volume of the resonator. It was shown later, that the cathode was 0.6 mm into the half-cell instead of -1.0 mm retracted. This resulted in increased RF heating of the cathode surface with a following elongation, thus increased losses and a thermal runaway which finally harmed the cathode plug's holding mechanism.
- The cathode was removed, the cavity Helium processed [8] and a second transfer performed by moving the cathode surveyed by laser system, RF measurement and capacitive sensors [4] to -0.8 mm.
- As a follow-up the CsK2Sb cathode was lost within the half-cell after a so far very smooth transfer due to damaged spring in the cathode insert, probably caused by the RF heat load as discussed in the previous item.

In summary, at each change to the system, the SRF module underwent a characterization of Q_0 versus field level and measurement of dark current or radiation level to analyze and evaluate the quality of assembly steps taken. Two transfers of Copper cathodes were performed and with the second transfer a small beam program was conducted, including dark current analysis, beam momentum measurements, Schottky scans and quantum efficiency mapping of the Cu cathode and the Niobium back wall in the cathode's vicinity. Some selected aspects of this run will be shown in the following.

EXPERIMENTAL RESULTS

A complete discussion of the obtained RF properties and beam results during the last year would be beyond the scope and extend of this paper and more detailed analysis will be published in the future elsewhere. Still, some coarse overview will be given here.

RF Measurements

Figure 2 displays the mostly by Helium boil off rate measured cavity quality factor at the given stages of operation. Comparing with the cold string assembly some contamination by the final assembly or opening of the gate valves to the surrounding vacuum system given by cathode transfer system and diagnostic beam line caused an increase in field emission. Moreover, field emission is the dominant loss factor, as low field Q_0 still hints at a preservation of the quality of the global Niobium surface. Following cathode inserts, especially given the unwanted incidents mentioned before further decreased the cavity performance. Similar observations were obtained when measuring the dark current of the cavity directly using FOMs and Faraday Cup signals or monitoring the test cave's radiation sensors when the latter was not available for some reason.

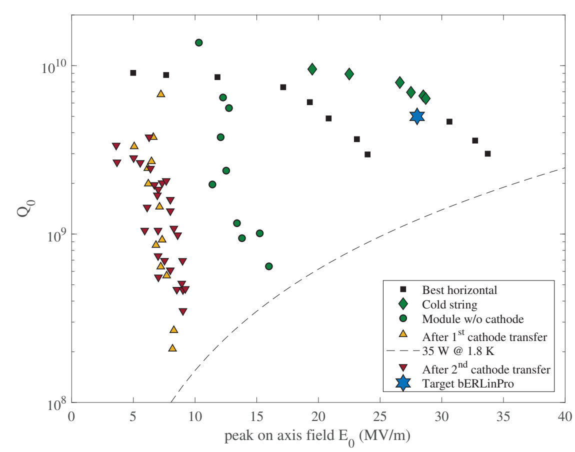

Figure 2: Intrinsic quality factor measured at each assembly or commissioning stage versus peak on axis field of the TM_{010}-π mode. All data sets except the first were measured by Helium boil off rate.

This is summarized in Figure 3. The emission onset degraded from 15 MV/m via 10 MV/m down to as low as 4 MV/m after the first cathode transfer. A performed Helium processing brought this level up to 6 MV/m. Attempts to map the several emitters via the Solenoid on the viewscreens was partially successful, that a main emitter was identified close to the cathode opening on the half-cells' backwall. Two main emitters, which form a cross like structure on the viewscreen at 7.0 MV/m with momenta of 0.86 MeV/c and 0.82 MeV/c, were responsible for about 75% of the dark current downstream the beamline.

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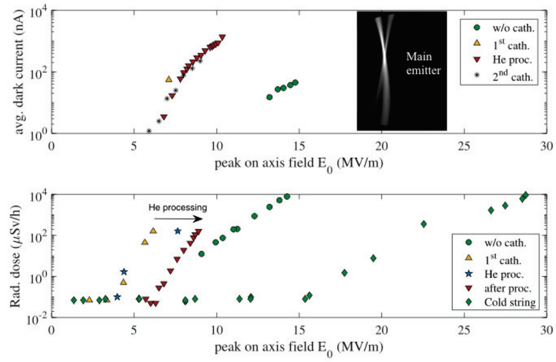

Figure 3: Average dark current measured with a Faraday Cup versus peak on axis field at the given settings. The lower plot shows the corresponding radiation level and change in field emission onset after the assembly stages and Helium processing performed after removal of the first Cu cathode.

RF-Energy Calibration

Before first cathode transfer, the field in the cavity, so far given by RF field measurement based on antenna calibration performed during cavity production, was cross-checked with momentum measurements of dark current. Figure 4 shows in the insert a FOM image of projection of the cathode iris opening with the SC solenoid. Some distinct emitters were visible and their energy measured using the steerer magnets in the cryo-module and beam-line. This result was compared to tracking simulation performed with CST PIC. It was found that the field level was underestimated by about 20%.

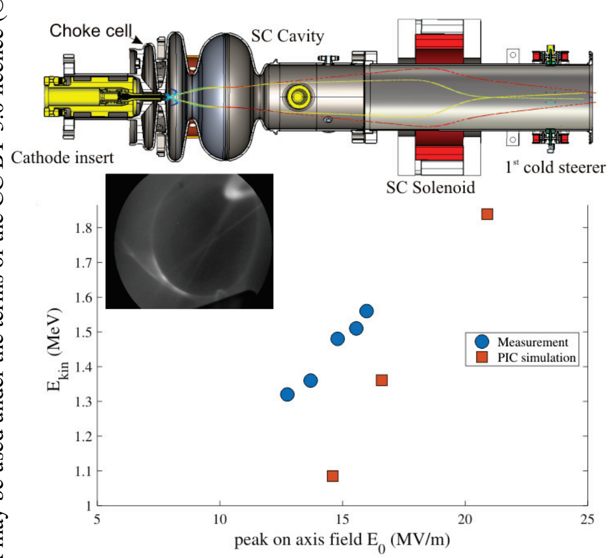

Figure 4: Measured and simulated energy gain of a field emitter located on the cathode iris opening. The inserts show a viewscreen signal of the by Solenoid focused emission area and the reconstruction by CST PIC simulation (top).

Longitudinal Beam Dynamics

After the second Copper cathode transfer the beam energy was measured using a dipole magnet, steerer and dedicated scanner magnets to obtain more insight about emission phase and the longitudinal phase space in general. The data were taken in LLRF operation. Here it showed, that Multipacting appeared far off from the predicted field level in the region of the HZDR-style coaxial cathode insert [9]. Suppressing this effect with the dedicated bias high voltage (DC bias) helped, but still the field was limited to 9 MV/m. Given such a low

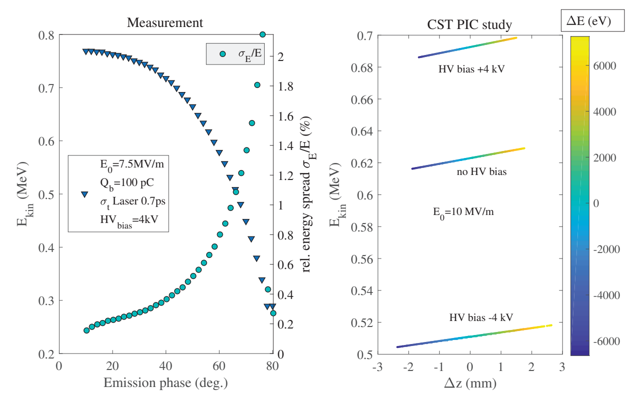

Figure 5: Measured beam energy and relative energy spread at nominally 7.5MV/m. Reconstruction by CST PIC simulation hint at higher field level (longitudinal phase space in left column).

field, the resonator was designed for about 30 MV/m [10], the emission phase is rather low and the contribution of the DC bias to the acceleration needs to be taken into account. Figure 5 shows a phase scan at 7.5 MV/m. As demonstrated with the dark current, simulations including the DC bias level showed again, that the field is underestimated. For further analysis besides cathode position, DC bias level also the field flatness and cavity shape need to be taken into account.

OUTLOOK

The module is currently inspected to determine the thermal short. In the following it will be fully refurbished including a new cavity which was recently vertically tested [11] and a new solenoid. The damaged cavity will be measured by bead-pull and optically inspected to better reconstruct the obtained measurements and also decide for future options how to repair this resonator. It is planned to have the module back for RF tests towards end of this year. An installation into bERLinPro is foreseen for 2019.

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