FIRST COMMISSIONING OF AN SRF PHOTO-INJECTOR MODULE FOR bERLinPro*

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Abstract

Helmholtz-Zentrum Berlin (HZB) is currently building an high average current superconducting (SRF) Energy Recovery Linac (ERL) to demonstrate ERL operation with low normalized beam emittance of 1 mm·mrad at 100 mA and short pulses of about 2 ps. For the injector section a series of SRF photoinjector cavities is being developed. The medium power prototype presented here features a 1.4·$\lambda/2$ cell SRF cavity with a normal-conducting, high quantum efficiency CsK_2Sb cathode, implementing a modified HZDR-style cathode insert. This injector potentially allows for 6 mA beam current at up to 3.5 MeV kinetic energy. In this contribution, the module assembly and first cool-down and RF commissioning results of the photo-injector module will be presented and compared to the level of performance during the cavity production and string assembly process.

INTRODUCTION

The ERL bERLinPro [1] requires an injector section which generates a high current 6.5 MeV beam with a normalized emittance lower than 1 mm·mrad. This demands for an high brilliance photo-injector generating high quality beams at 100 % duty cycle. Thus, a superconducting radio-frequency photo-injector cavity design is being pursued [2] which is being realized in a staged approach. The current prototype cavity should demonstrate the required beam properties for bERLinPro and the high brilliant beam generation by implementing a normal-conducting high quantum efficiency cathode [3,4] within the superconducting and low particulate environment of SRF cavities. The latter is achieved by a modified cathode transfer system of the original HZDR design [5]. The cavity was designed at HZB, manufactured at JLab in 2013 [6], went there through several vertical and an horizontal RF test after delivery to HZB. It was finally assembled to the cold string section in early 2016 with final horizontal acceptance test [7, 8]. Table 1 gives an overview of the design parameter and the properties of the cavity as produced. The deviations are discussed in past publications [8]. The cavity's quality factor versus peak on axis field level was demonstrated to be preserved throughout the cavity production and assembly steps, see Table 2. Mid 2016 the cold string was completed by SC solenoid [9] and higher order mode (HOM) beam tube SiC absorber. Beginning of this year the module assembly and installation into a dedicated testbed to characterize this photo-injector, called Gunlab [10], was finalized. Gunlab is able to fully characterize the beam's phase space and cathode properties. A picture of the set-up at HZB's horizontal test facility HoBiCaT is shown in Figure 1.

Table 1: RF Design Parameters and the Values Estimated and Measured for the Prototype Cavity as Produced

Parameter	Design	As built
TM_{010} freq. (MHz)	1300	1300
$R/Q(\Omega)$ $\beta = 1$	150	132.5
$G(\Omega)$	174	154
P_{forward} max. (kW)	20	20
Q_{ext}	$3.6 \cdot 10^6$	$3 \cdot 10^7$
$\Delta f/\Delta l$ (MHz/mm)	1.6	1.3
E_{peak}/E_0	1.45	1.66
$B_{\mathrm{peak}}/E_{\mathrm{peak}}$ (mT/(MV/m))	2.27	2.18
E_{kin} (MeV)	3.5	2.5-3

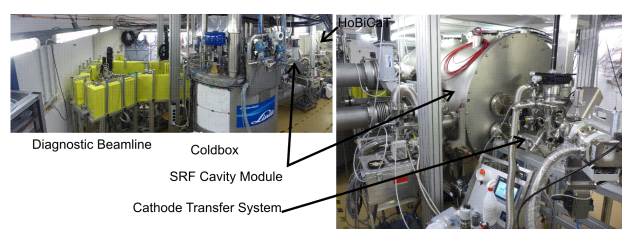

Figure 1: Pictures showing the photo-injector module with cathode transfer system (right) and the set-up of Gunlab within the HoBiCaT bunker (left).

THE SRF CAVITY MODULE

Figures 2 and 3 display the cryostat and the so-called cold string of the SRF photo-injector. On both Figures the

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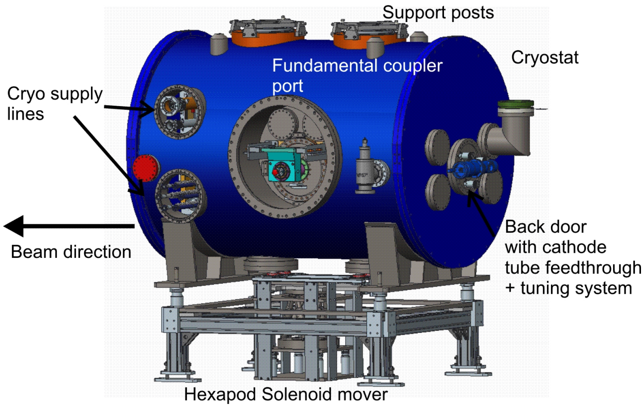

Figure 2: The photo-injector module with Hexapod solenoid mover below and fundamental power coupler ports in the center.

beam leaves to the left whereas the cathode is inserted from the right side. The Solenoid is moved from outside the cryo-module by a Hexapod system from PI through special feedthroughs [9]. The core part of the injector consists of a beam dynamics optimized 1.4·λ/2 cell 1.3 GHz SRF cavity [2] with twin CW-modified TTF-III fundamental power couplers (FPC) [11] allowing 20 kW forward power fed to the cavity at loaded Q of $3.6{\cdot}10^6$ to accelerate 6 mA average beam current to 3 MeV kinetic energy. The cavity is shielded versus magnetic flux by two cold magnetic shields and is tunable by a Cornell injector style blade tuner with four piezo stacks for fine tuning and detuning compensation [12]. Attached to the opening of the half-cell is the cathode insertion scheme with fundamental mode suppressing choke cell and coaxial Petrov filter, cathode tube, 80 K gaseous helium cathode cooler and cathode tuning and positioning tripod system.

Upstream the cavity is followed by a 4 K conduction cooled SC solenoid for emittance compensation [13], an 80 K cooled SiC HOM absorber of modified Cornell injector style [14] and gate valve with cold to warm bellow based beam-line transition. Further, two steering magnets are installed each deflecting in both transverse planes to allow steering of the beam as close as possible to the cathode, also to compensate for earth magnetic field effect of the beam [15]. This is crucial as the outer magnetic shield mainly covers the SRF cavity parts. The cryostat is thermally shielded by an 80 K cryo-shield operated as well as the other sub-systems at this level with gaseous helium.

The module is cooled by two 80 K circuits for thermal shield and cathode cooler and FPC and HOM respectively. One 4 K circuit cools the inner FPCs heat stations and the solenoid magnet. Another 4 K line fills the cavity helium vessel for cool-down from below. Finally, there is the 1.8 K helium inlet and outlet connected to 2-phase-line and helium gas return pipe.

To analyze the cavity state at all levels of operation, the cryostat was equipped with 18 Cernox$^{\text{TM}}$ and 21 PT-100 temperature sensors. To monitor the cathode position, the cathode tuning system is outfitted with three capacitive sensors [16] which track the relative movement of the tripod tuner with μm resolution. The final expected cathode position was determined during clean-room assembly of the cold string with a dummy cathode stock [8].

FIRST COOL-DOWN AND RESULTS

In April this year a series of first cool-down attempts were undertaken to understand the dynamics of this process for the module and also interaction and crosstalk between the cooling circuits. This is especially important to determine the proper cryo-plant's controller settings to allow slow cool-down to about 180 K, followed by fast cool-down through the regime of Hydrogen Q-disease [17] down to about 70 K. By this, also the ideal reference temperature sensor to steer the cool-down was determined.

An example of such a cool-down after parking the module between 180-200 K using mainly the 80 K cooling circuits is depicted in Figure 4. The cavity is slowly cooled to 180 K using a lower beam tube (close to helium vessel end-plate) installed Cernox sensor as reference to control the cryo-plants valve settings. The sensor in the helium inlet shows typical oscillation with the arrival of cold gaseous helium. Also, it was studied how the cathode tuner would move under cold conditions. From installation of the cold mass into the module it was observed, that a total movement of below 100 μm was achieved. Data during cool-down of the 80 K cathode cooler showed an as expected linear relation between movement (most probably by shrinkage) and temperature as given in Figure 5. As the position change of each sensor is of similar slope, no large tilt of the cathode stock within the half-cell back-wall opening is expected. It is planned to continuously monitor these sensors during the first cathode insertion together with the TM_{010} and choke cell eigenmode frequency which will help to reconstruct the current position during transfer into the cathode channel. Further, a survey of the installation process using additional optics at the Laser beam port will be implemented.

OUTLOOK

The SRF module is currently being cooled-down for full RF commissioning and subsequent beam operation. The cavity quality factor by monitoring helium losses at the 1.8 K level, field emission and operating field level will be measured at each step where the cavity inner RF surface might experience contamination. In extension to Table 2 measurements will be taken after opening the gate valve to the beam line and after first insertion of a metal cathode and first transfer of a semi-conductor cathode into the cavity. During beam operation, these cavity properties will be continuously observed to detect any degradation with time.

Currently, a second cavity of the version presented here is being built at Research Industry and is being processed

§ E_0 is the peak on axis field. The cold string test had an administrative limit of 29 MV/m, quench was not reached yet.

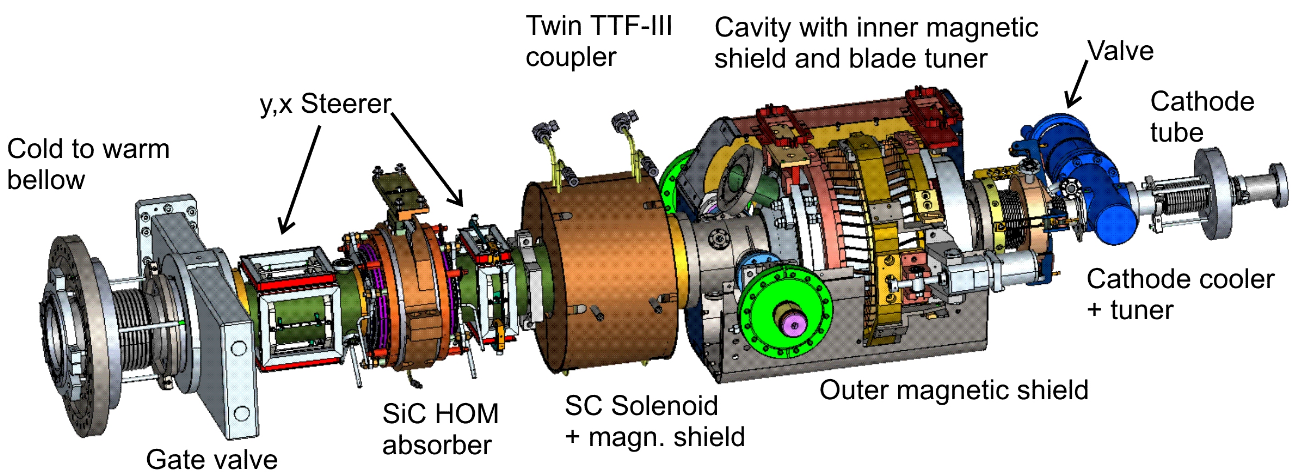

Figure 3: Overview of the complete cold string of the photo-injector cavity with ancillaries and adjacent parts.

Table 2: Achieved RF Figures of Merit During the Different Test Stages at JLab and HZB

Parameter	VTA JLab	HTA HZB	Cold string HZB	Module
max. E_0 ($\mathrm{MVm^{-1}}$)	34.9	34.5	28.5[§]	-
E_{peak} ($\mathrm{MVm^{-1}}$)	58	57.3	47.3	-
B_{peak} (mT)	111.8	110.4	91.2	-
low field Q_0 ($E_0 \leq 15$ MVm−[1])	$1.2{\cdot}10^{10}$	$1.1{\cdot}10^{10}$	$9.6{\cdot}10^{9}$	-
$\Delta f/\Delta E_0^2$ $(\mathrm{HzMV^{-1}m})^2$	-4.7	-3.7	-3.4	-
$\Delta f/\Delta P_{\mathrm{LHe}}$ ($\mathrm{Hz\ mbar^{-1}}$)	-561	150	33	-
$\Delta f/\Delta l$ (Hz/tuner step)	-	-	2.3 (1.8 K)	3.8 (300 K)

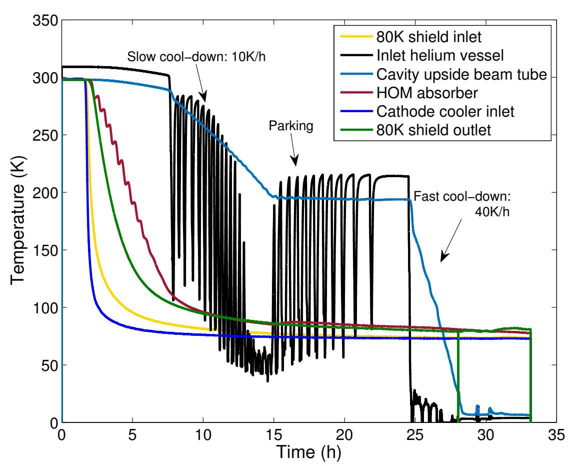

Figure 4: Temperature curves with time of the first cool-down filling all circuits. The system was parked between 180-200 K before this step was taken.

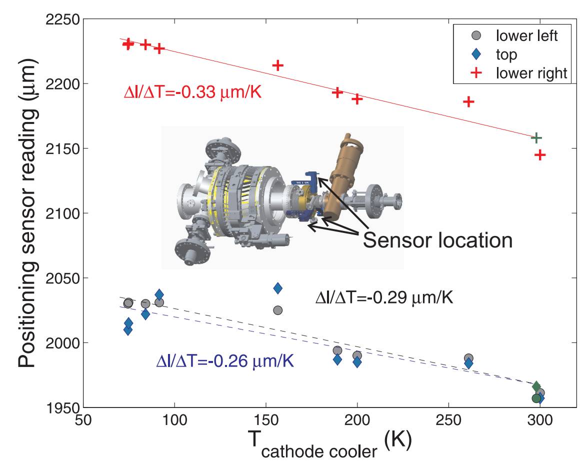

Figure 5: Change of the relative cathode holder position during cool-down from room temperature to 80 K helium gas level of the cathode cooler measured by capacitive sensors. Green data points show the position after warming up to 300 K.

by chemistry and tuned to design frequency and field flatness [18]. It will serve as a back-up in case this cavity discussed here fails during the following operation and foreseen cathode exchanges.

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