FINAL ACCEPTANCE TEST OF SRF PHOTO-INJECTOR COLD STRING FOR THE bERLinPro ENERGY RECOVERY LINAC *

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Abstract

Helmholtz-Zentrum Berlin (HZB) is currently designing and building an high average current all superconducting CW driven ERL as a prototype to demonstrate low normalized beam emittance of 1 mm mrad at 100 mA and short pulses of about 2 ps. In order to achieve these demanding goals HZB started a staged program for developing this class of required high current, high brightness SRF electron sources. In this contribution we will present the current status of the module assembly and testing of the prototype SRF photo-injector cavity cold string. The steps taken to install the cathode insert system with the cavity in the clean room and the following horizontal test of the cold string as final acceptance test prior installation into its cryostat are shown. First beam in a dedicated diagnostics test stand called Gunlab are planned for this winter.

SRF PHOTO-INJECTOR FOR bERLinPro

The high average current all superconducting CW driven energy recovery linac (ERL) bERLinPro is foreseen as a prototype to demonstrate low normalized beam emittance of 1 mm·mrad at 100 mA and short pulses of about 2 ps [1]. It is currently being constructed at HZB in Berlin. In the first stage the photo-injector delivering the beam consists of a 1.4-cell superconducting cavity [2] using a high quantum efficiency (QE) normal conducting multi-alkali cathode [3] implementing a modification of HZDR's cathode insert design [4]. The medium power prototype cavity fabricated by JLab [5] utilizes CW-modified TTF-III couplers allowing an average current up to 5 mA. The purpose of this prototype is mainly to demonstrate the beam dynamics goals and the insertion of a high QE semi-conductor cathode in an SRF cavity. The final high power version is currently in its design and drafting phase. Table 1 summarizes the main RF figures of merit and parameters of operation of the first cavity and the actually achieved values estimated by combining CMM based measurements with RF simulation tools as Superfish and CST [6]. It took quite some effort to reach that stage as production proved to be challenging. This is described in several papers and not repeated here [5, 7, 8]. Here, the final cold string assembly of the cavity is described and the acceptance testing in the horizontal cavity test stand HoBiCaT [9]. In the next months the module will be completed and integrated with the diagnostic beamline of Gunlab [10] to fully study the injector beam's phase space prior to its move to the bERLinPro underground accelerator hall.

Table 1: RF Design Parameters and the Values Estimated 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
E_{peak}/E_0	1.45	1.66
$B_{\mathrm{peak}}/\mathrm{E}_{\mathrm{peak}}$ ($\mathrm{mTMV}^{-1}\mathrm{m}$)	2.27	2.18
E_{kin} (MeV)	3.5	2.5-3

THE COLD STRING ASSEMBLY

Figure 1 displays the assembly and testing steps for the gun cavity at JLab and HZB to completely monitor the performance with respect to achievable field level and surface resistance or unloaded quality factor Q_0 during the different construction steps. After helium vessel welding the cavity performed good enough in the final vertical test at JLab, and the critically coupled horizontal RF tests at HZB, to be further prepared for cold string mounting. As shown in the 3D models and pictures below the assembly comes in several stages, where the first part of cold string mounting is

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‡ E_0 is the peak on axis field. The cold string test had an administrative limit of 29 MV/m.

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

Parameter	VTA JLab	HTA HZB	Cold string HZB
E_0 (MVm^{-1})	34.9	34.5	28.5‡
E_{peak} (MVm^{-1})	58	57.3	47.3
B_{peak} (mT)	111.8	110.4	91.2
low field Q_0	$1.2 \cdot 10^{10}$	$1.1 \cdot 10^{10}$	$9.6 \cdot 10^{9}$
$\Delta f / \Delta E_0^2$ (HzMV^{-1}m)^2	-4.7	-3.7	-3.4
$\Delta f / \Delta P_{\text{LHe}}$ (Hzmbar^{-1})	-561	150	33

the most critical as it includes the assembly of the fundamental power couplers and the insertion of the cathode carrier which forms the second stage in filtering the fundamental TM_{010} mode upstream of the cathode after the choke cell.

As shown by the cut-view in Figure 2 a contact of the Niobium inner surface with the copper cathode insert had to be avoided to preserve the quality of the cavity and finally to mitigate field emission. Each assembly procedure was written in a detailed document which underwent several reviews. The clean room crew received a complete training by DESY MKS-3 colleagues and two dummy assembly tests with similar components were done to develop the procedures for this special type of cavity. This was also to further fine tune the required tooling. All work was performed in an ISO 4-5 clean room, pre-mounting all components as much as possible to only have limited steps on the rail system close to the cavity. Every connection was done under ionized N_2 overflow. All parts were ultrasonic cleaned including the couplers as below 10 kW CW power levels conditioning is not required. A thorough particle count was done at every mounting step and parts were blown off until they reached ISO 5 standards.

Special tools were developed to align the cathode insert and measure the possible future cathode position with respect to the half cell's backwall. This needed to be done as no cathode was installed at that stage. Acryl glass windows were used for alignment and concentricity check with the dummy PEEK cathode.

The cathode reached its nominal position -1.5 mm behind the opening to the half cell and no contact between cathode insert and cavity was observed. This was proven by measuring the resistance between isolated insert and cavity with a multimeter.

GUN CAVITY HORIZONTAL TESTS

After pumping with a special low particle count pumpstand and leak check, the string was rolled out and equipped with magnetic shielding and the blade tuner. A testing program was started to evaluate the performance of the cavity with respect to the bERLinPro parameter space and to qualify it for further module assembly. Figure 4 depicts the measured Q_0 versus peak on-axis longitudinal field E_0 comparing the final vertical test (VTA) at JLab with two horizontal tests (HTA) at HZB still with the same antenna configuration to the cold string test. Whereas the first tests were done with RF methods using critically coupled antennas, the cold string test was limited to using the helium boil of rate to determine Q_0 as the loaded Q by the couplers was $2 \cdot 10^7$. As can be seen in the data of the 2$^{\text{nd}}$ HTA test, the cavity required some RF processing to achieve the final field level. This was observed in the past, as due to the half-cell being shorter than designed the cavity is more prone to multipacting at E_0=18 MV/m. But this can be overcome by processing and was done as well for the cold string test. All tests shown here were done at 1.8 K.

Besides that, the cavity kept its performance comparing to the final production test at JLab and the follow-up horizontal tests at HZB. These field levels allow for beam energies between 2.5-3 MeV and the Q_0 at the target of E_0=30 MV/m keeps the RF losses within 10 W, whereas exhaust chimney limit is 35 W.

To summarize, the cold string assembly was successful. To probe the cavity more, the residual resistance of the zero and π mode were determined with individual measurements by subtracting the BCS term using Halbritter's code shrimp [11]. The π-mode had 10.2 nΩ residual surface resistance, the zero-mode 9.7 nΩ. Within the error margins, it can be assumed that both, the half cell and full cell have equivalent quality factors, given that the zero-mode probes more the half cell, while the π-mode both with this field-flat cavity.

Table 2 summarizes the achieved level of performance at the different stages and it can be regarded as rather constant. Also the mechanical optimization done for low helium pressure sensitivity [12] was successful as it is close to the envisaged "0" Hz/mbar. The final value of 33 Hz/mbar is even explained by the shortened half-cell as well.

Following the RF tests, first LLRF operation of the cavity was performed and testing of the tuner's piezos and stepper motor were carried out. This work is presented in [13]. One issue observed during the tuning, and already known beforehand from the first horizontal tests at HZB, is a significant deviation of the fundamental mode's frequency from the expected frequency. The frequencies sampled during production are given in Figure 5. As the cavity geometry deviated from the beginning, an update of the frequency table relied on an estimated RF model from a limited set of CMM data. It has to be checked carefully for the final tuning, how to preserve the field flatness while still reaching the target frequency.

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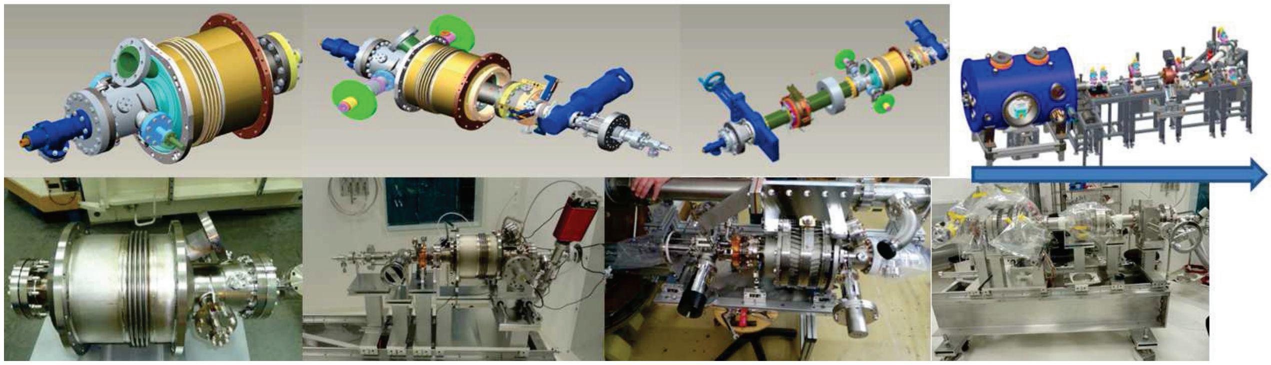

Figure 1: Order of assembly of the gun cavity from cavity in helium vessel to final module configuration and set up in Gunlab. The upper row shows the planned steps, the pictures below the achieved progress.

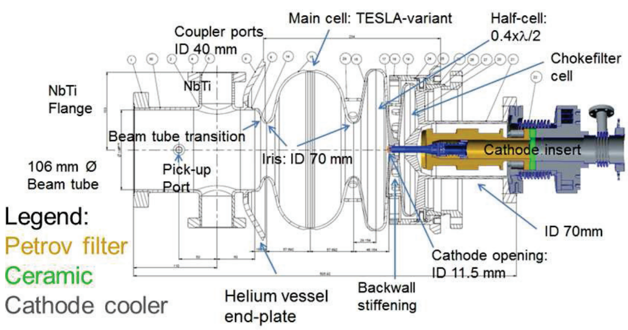

Figure 2: Cut view of the SRF gun cavity layout including the cathode insert with Petrov filter and cathode cooler unit.

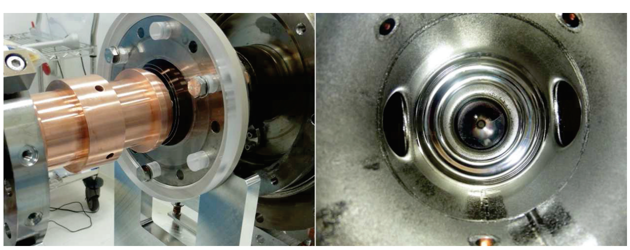

Figure 3: Left: Assembly and alignment of Petrov filter with acryl window. Right: Concentricity check by PEEK dummy cathode.

OUTLOOK

The cold string assembly is finished and the cold mass will be completed the next few weeks. Following the latter the gun will be installed into the cryostat and Gunlab will be commissioned, including RF tests, the diagnostic beam line, the cathode laser system, the cathode transfer system and the cryogenics supply chain. It is foreseen to have first beam delivered by the end of this year or early next year from a copper cathode with an UV laser. Insertion of a semi-conductor CsK_2Sb cathode will follow in a second step.

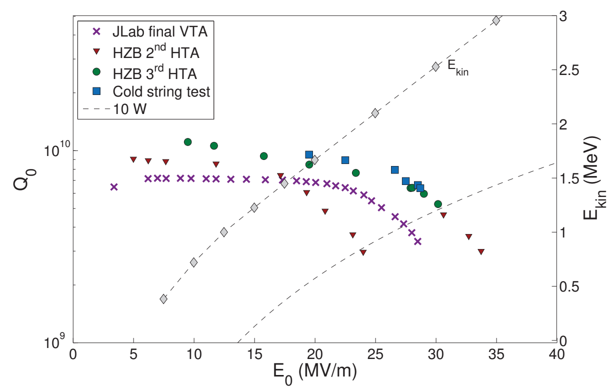

Figure 4: Unloaded quality factor Q_0 versus electric on axis peak field E_0 at 1.8K for the prototype gun cavity of the last VTA test at JLab (violett crosses) and first horizontal tests at HZB (red triangles, green circles) compared to the Q_0 of the cold string. The corresponding kinetic beam energy with field is displayed by grey diamonds as reference, as well as the 10W dissipated power line (dashed black).

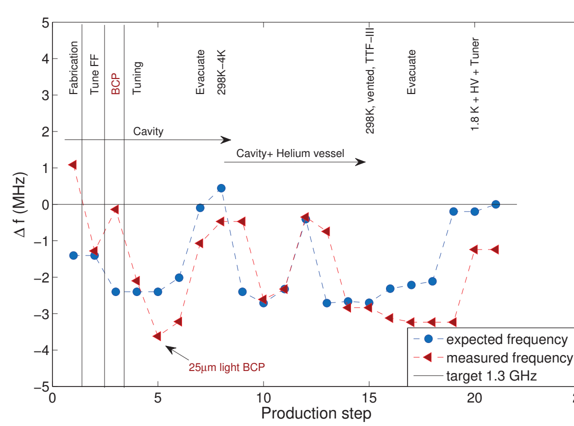

Figure 5: Comparison of the expected frequency of the TM_{010}-π mode for the cavity processing and assembly steps to the actual achieved ones.

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