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STATUS OF THE HIGH CURRENT 1.5 GHz SRF CAVITY PROTOTYPES FOR VSR DEMO

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Abstract

The BESSY Variable pulse-length Storage Ring (VSR) Demo project is a feasibility study aiming to provide short and long pulses simultaneously in the BESSY II storage Ring. To achieve this goal HZB has developed high current Continuous Wave (CW) Superconducting Radio Frequency (SRF) cavities operating at 1.5 GHz for 300 mA beams with large damping capabilities to cope with the HOM powers expected. This paper presents the current status, fabrication and lessons learned as results from the fabricated prototypes by Reseach Instruments (RI) and the first tests campaign carried on at SupraLab in HZB.

INTRODUCTION

Elliptical SRF cavities are well established for accelerators but mainly for low-current applications. High-current machines require efficient higher order mode (HOM) damping to avoid instabilities [1]. Standard HOM coupler antennas are limited when dealing with broad-band spectrums and high HOM powers, and beam-pipe absorbers are usually impractical when space is constrained in a synchrotron by the use of anspecific straight section like in BESSY II. Therefore waveguide loaded end-groups represent a practical solution since damping offers broadband performance, high-power capability and results into a compact solution [2].

In this paper the current status of the High current 1.5 GHz waveguide-loaded cavities development is presented. These cavities are being manufactured by Research Instruments (RI). Currently the fabrication of the first prototype is completed to the point of an “undressed” prototype cavity and has been tested for the first time in a Large Vertical Test Stand (LVTS) at HZB’s SupraLab. The results of these tests and lessons learned are presented in this work. A second prototype is currently in the last stages of “undressed” cavity fabrication and is waiting to be tested in the LVTS.

DESIGN OVERVIEW, MAIN CAVITY ELEMENTS AND MECHANICAL CHALLENGES

The cavity consists of four niobium cells with stiffening rings for pressure stability, two endgroups with HOM waveguide extensions, and a titanium Helium Vessel. Beampipe and Fundamental Power Coupler (FPC) flanges are made from NbTi, prepared for aluminum hexagon gaskets and copper RF lips. Stainless-steel flanges are joined to the Ti-made Lhe tank by by explosive bonding.

There are two end-group configurations, one with three waveguides and the other with two waveguides plus the fundamental power coupler port. In both cases the waveguides are arranged non-symmetrically (60° rotation) to extract the maximum amount of HOM power while minimizing impact on the fundamental mode. The large beam-pipe cross-section ensures broadband propagation. Waveguide (WG) extensions continue with bends and water-cooled HOM loads dissipating up to 460 W each. To prevent heat transfer back to the cavity, actively cooled flanges connected to the 5–8 K circuit were developed.

Figure 1 depicts the full cavity for illustration with ancillary components attached (Blade tuner, Funda-mental power coupler and HOM loads). For a deeper comprehension, all details on the mechanical design are discussed to the detail in [3] while the electromagnetic design and impedance considerations are discussed in [4].

Tuning is performed by a blade tuner driven by a stepper motor and piezo actuators. The required range of over 1 MHz imposes high forces and frequent operation, demanding robust components. Reliability studies revealed the need for a release mechanism to protect the cavity in case of motor failure. Finite element simulations were carried out for pressure and tuning loads. Safety margins were tight due to niobium’s low yield strength, especially at room temperature. Peak stresses were reduced by design modifications, such as larger radii at critical transitions and optimized stiffening ring positions. Waveguide flanges had to remain leak-tight at 1.8 K while allowing reliable RF contact. Initial designs with rectangular gaskets failed; instead, custom aluminum-copper composite gaskets were developed, achieving vacuum tightness and RF sealing. Integrated cooling channels in the flanges maintain superconductivity in the WG extensions. Tests confirmed stability under pressures well above operating conditions.

MANUFACTURING AND QUALITY CONTROL

The fabrication process of this cavity has been a four years process in which many compromises and modifications took place. In particular deep drawing of the cavity geometry according to specification required from several iterations. The whole system (with the exception of the presurized cooling of the waveguide flanges) was classified under low-pressure-vessel regulations but subjected to best

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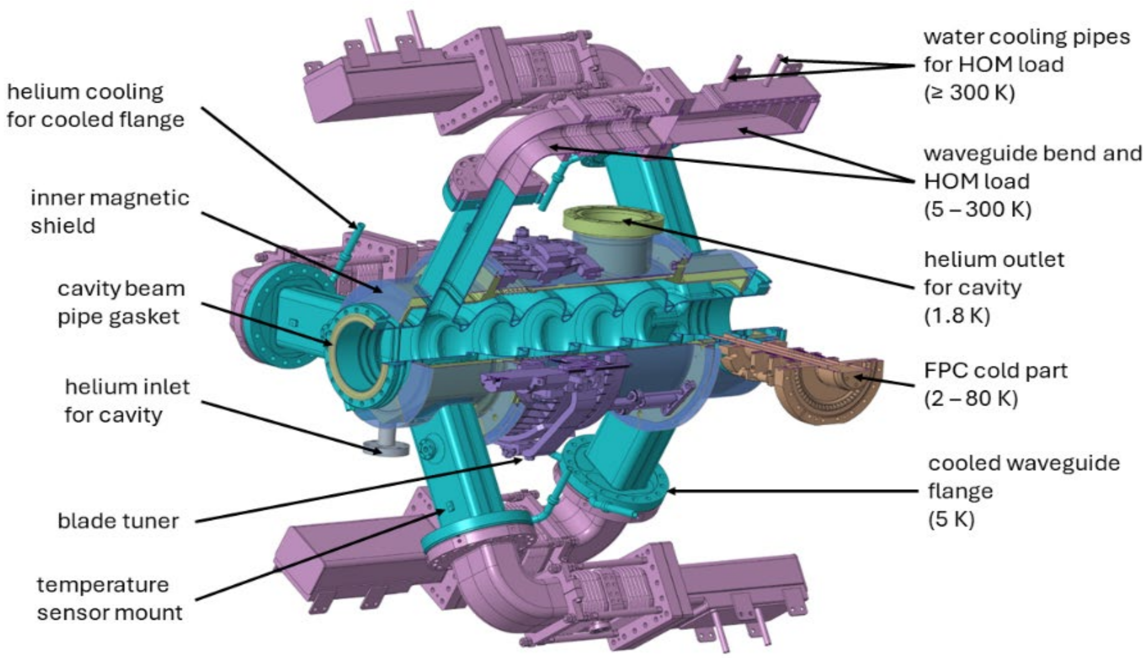

Figure 1: CAD model of the 1.5 GHz High current HOM damped cavity with ancillary components. Nb parts are depicted in light blue, Titanium in dark blue and Stainless Steel in purple.

engineering practice and to stringent quality control by an external authority (DEKRA). Tensile tests of niobium samples at different production stages provided realistic material properties, showing less degradation than expected during the bakeout process. Weldings an explosion-bonded Ti–steel transitions was qualified by inspections and pressure tests. Before performing this last step of welding the Helium Vessel the required SAT by vertical testing of the “undressed” prototype must take place. Finally and after some iterated processing, a first prototype was completed and delivered in May 2025 and went undergoing testing at HZB.

TESTING

The Cavity was installed inside the LVTS facility at HZB´s SupraLab for RF characterization (Fig. 2). The LVTS is dimensioned to be able to accomodate two nine-cell Tesla cavities simultaneously. The cavity insert positions the cavity in the bottom part of the cryostat to minimize the amount of liquid Helium required for the test and maximize the magnetic shielding to protect from ambient fields. To be able to monitor the temperature of the cavity surface during the cold tests sixtemperature sensors (Cernox type) were attached to the surface, namely on the HOM waveguide, main antenna flange (up), beampipe flange and cavity cells. The lower flange and pick-up flange were not temperature monitored (c.f. Fig. 3)

The cavity was cooled down to 1.8 K and the test took place in June 25 with the following findings:

Bulleted Lists

Absolutely no radiation indrease above the background level was observed at any time during the experiment, in strong contrast to previous test with the same cavity. Therefore a proper cavity preparation can be concluded.

Cavity Qo

For the fundamental TM010 mode (π), first observations showed a very fast degradation of the Qo value starting already at very low fields (< 1 MV/m). Even though Qo was measured 5e10 for very low transmitted powers (Pt = 0.01 W), this value quickly decayed below 1e10 when Pt reached 0.02W. This effect is shown in Fig. 4. Interestingly, the Qo value offered a better performance when the π/4 mode was under test (factor 6 higher).

This effect suggests the presence of a hidden loss mechanism which affects the intrinsic cavity quality factor. An improper cleaning after BCP that could leave some residual material inside of the cavity has been excluded as a probable cause due to the high quality factor obtained at low fields. Thus, several cavity components are currently studied as probable cause for this effect and will be discussed next.

First, the performance characteristics of the main antenna located on the upper beampipe (designed to be critically coupled) was analysed. As a result a large undercoupled behaviour was measured (beta < 0.1). This was a surprising result though detailed and consistent accurate EM calculations (CST [5]) were run to determine the proper antenna length showed high sensitivity with the penetration. Thus, because the antenna is screwed to the feedthrough

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pin, a possible partial detachment during transportation was suspected. After testing, the cavity was opened for inspection in the clean-room. The action did not reveal any indication of this effect but analysis is still ongoing to consider a possible failure of the 7/16 feedthrough connection on the liquid Helium bath side.

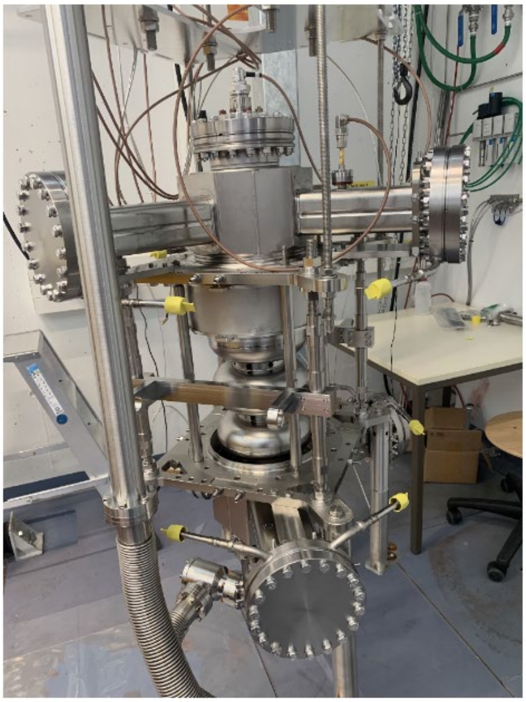

Figure 2: Picture of the naked cavity installed in the LVTS insert ready for testing.

A second theory considers the beam-pipe flanges as possible cause for a loss mechanism. As already discussed, beam-pipe flanges are fabricated from NbTi alloy to be superconducting whilst being stable enough to tolerate repeated use with hexagon gaskets. This is due the expected leaking fields reaching the flange position due to the large cavity aperture that ensures a good HOM propagation. The losses would result in a not tolerable Q decrease if the beam-pipe blind flanges would have been made out of stainless stell. Therefore, due to the superconducting properties of NbTi no relevant losses were expected at this position. Nevertheless some studies suggest this cannot be excluded [6, 7]. In fact the results obtained point in this direction since, as already mentioned, the π/4 mode shows a better performance than the Pi mode in terms of Qo. Figure 5 depicts the field distribution calculated for the different modes in the fundamental pass band. As expected the π/4 mode is the one with lower fields in the end-group region and therefore the one possibly inducing the lowest losses.

Though plausible, this possibility is still surprising since losses were computed in EM simulation (CST) considering the surface resistance (Rs) of the NbTi flanges a factor 1000 higher than the one expected for Nb. Therefore the loss generated by the beam-pipe flanges would not be expected to reduce the overall Qo significantly. In order to get deeper insights on this problem the decision to coat the beam-pipe flanges with Nb has been taken. Once the coating is implemented the cavity will be again closed at HZB facilities and RF tests repeated. Of course, this problem only applies in the case of the validation by cold measurements in the LVTS since blind flanges will not be present in operation.

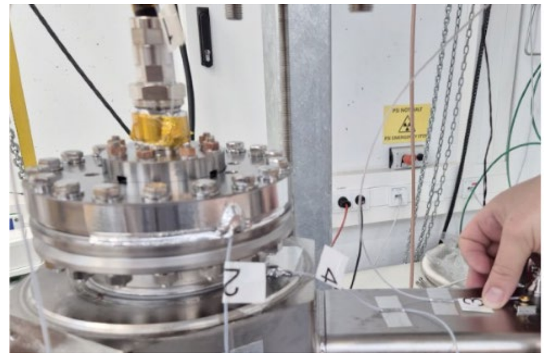

Figure 3: Picture of the temperature sensors installed on the 7/16 feedthrough (1), Nb-Ti flange (2), HOM waveguide (3) and Ti Vessel (4).

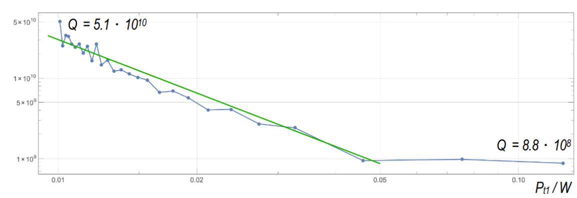

Figure 4: Log-Log-representation of Qo vs. transmitted power results splits roughly in a straight decay and a field-independent part at higher field strengths.

Temperature

Finally, the observation of the temperatures generated during the tests showed a steep increase of the signal coming from sensors located on the main antenna feedthrough and its neighbouring flange when high incident power levels, being > 45 dBm at the feedthrough. Even though this result could partially support the theory of the NbTi being responsible, the signals measured show partially very steep responses (≤ 1 s) and an oscillatory behaviour in sensors 1 and 2 and thus the possibility of cross talk between RF and sensors cabling cannot be neglected.

NEXT STEPS

The next step is to perform the coating of the beam-pipe flanges for the first prototype to investigate the possible losses introduced by NbTi. In addition a new critically coupled antenna will be produced to increase the coupling factor. The refurbished components will be installed in the cavity at HZB facilities to be able to get a deeper understanding of the technical problems seen during the first test campaign in a following test. Even though a high pressure

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rinsing of the cavity would be recommendable this won't take place since HZB does not have an optimized HPR for this task. The geometry of the cavities with the HOM waveguide extensions force the implementation of a tailored procedure with specific components which for the moment only the vendor (RI) is capable of executing. This step is proved to be crucial since any remains of the chemistry or cleaning procedure in the waveguides will lead to immediate performance degradation.

Meanwhile the LVTS will be scrutinized to investigate the possible cross-coupling between RF and temperature sensors cabling.

CONCLUSIONS

The current status in the development of HOM damped High current cavities at HZB is presented. The results showed that even though the fabricability of this type of cavities represents a challenge from the engineering and fabrication point of view, it is doable and good results can be achieved. Nevertheless, some questions still remain open with respect to the loss mechanism present in the cavity. Also the coupling of the antenna must be resolved as well as understanding the strange temperature behaviour observed. All these aspects are expected to be resolved soon and therefore be able to move into the next step where the Helium vessel will be welded and horizontal testing at HoBicat will take place

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