VERTICAL TESTING OF THE WAVEGUIDE-HOM-DAMPED 1.5 GHz 4-CELL PROTOTYPE CAVITIES FOR THE VSR-DEMO PROJECT*

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Abstract

The VSR Demo project aims for the validation of a cavity design suitable for the application in electron storage rings, characterized by currents of several hundreds of mA and a dense wakefield spectrum caused by inhomogeneous fill patterns. The cavities are equipped with five waveguides plus a coaxial fundamental power coupler, forming two groups of three radial extensions at either cavity end. Recently two prototypes were manufactured and are in the process of vertical testing at HZB's Large Vertical Test Stand. First tests completed with Prototype 1, covering all modes of the fundamental passband and different temperature levels, did not match the Q(E)-performance expectations, but indicate a yet unknown loss mechanism in the cavity's periphery, i.e. waveguide endgroups, beam pipe extensions, blind flanges or the coupling feedthrough. Further insights are expected from the ongoing testing program with modified coupling and with Prototype 2.

INTRODUCTION

Even though elliptical superconducting rf (SRF) cavities found a broad range of applications in a variety of accelerator designs, partially reaching large industry-scale volumes, the domain of *waveguide-damped*, elliptical multicell cavities still remains widely uncharted, once the sole proven path following from the ”Original CEBAF” waveguide-damped 5-cell 1497 MHz cavity ended in HOM damping designs with filtering couplers [1].

A comprehensive summary from 2017 (cf. [2], Table 1) about high-current SRF cavity projects, partially looking back into the early 2000's, reveals only 4 (of 16, not all of them multicell) cavity designs providing a waveguide higher-order-mode- (HOM-)damping. To the best of author's knowledge, none of those four, nor any other, got into regular operation ever since and only one, JLAB's 5-cell 1497 MHz so called ”high current” cavity successfully proved vertical testing with two prototypes [3]. This is a remarkably poor progress in view of the, at least conceptional, intrinsic simplicity and elegance of just hollow pipes providing both accelerating mode rejection – by the pipe's cutoff – and capable HOM power guiding, but it may indicate a severe risk of unexpected complications of the concept. This is unfortunate, since it seems to be ideally suite if high amounts (say $\geq 100\ W$) of average wake power need to be drained and/or if high duty cycles need to be managed, both uncomfortable for most HOM-coupler designs. Compared with dielectric beam pipe absorbers, the other alternative HOM-damping concept, waveguides excel by their modest requirements of real-estate length; a decisive property when hard length limits are given.

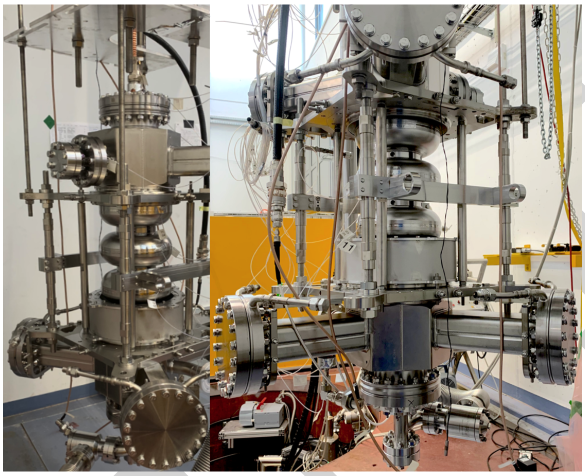

Figure 1: Second prototype of the VSR 1.5 GHz 4-cell SRF cavity in preparation of it's first vertical test in HZB's Large Vertical Test Stand, March 2026, in two opposing perspectives.

At HZB, two projects studied waveguide-damped multicell SRF cavities. The energy-recovery-linac project bERLinPro, later renamed to SeaLab [4], which recently received the notification of an imminent final shutdown, developed an rf design for a 7-cell 1300 MHz cavity with 5 waveguides and a coaxial FPC port, but did not enter into deep engineering. It nevertheless helped in the development of the so-called Variable-Storage-Ring (VSR) 1.5 GHz cavity, which followed the same concept, but needed to reduce the planned number of cells from 5 to 4, dictated by the available length found in between the magnet lattice of HZB's synchrotron light source BESSY-II. This cavity type was developed [5, 6] to act as a (primarily) passive 3rd harmonic cavity that, by lengthening the accelerating voltage's flat top and thus reducing the phase space density of bunches, should increase the synchrotron's beam's life-time in the trade off to the accessible bunch charge.

Whilst the VSR project first was de-scoped to present and test a 2-cavity demonstrator module, this endeavor now also is stopped. We are still aiming for the completion of both prototypes, which have been build and processed by Research Instruments, Bergisch-Gladbach, Germany with

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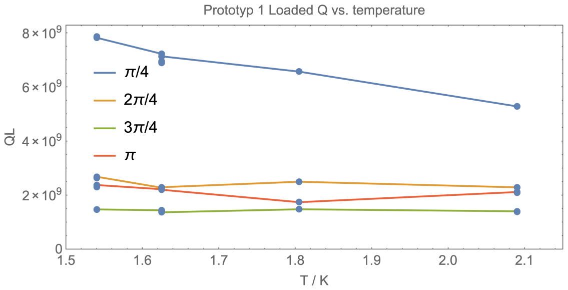

Figure 2: Results of vertical testing of prototype 1 at different temperature levels, November 2025, for all 4 passband modes at small signals. Only the $\pi/4$-mode shows a significant temperature dependence, which gave reason to assume that non-superconducting losses dominate the low Q values seen for the other modes.

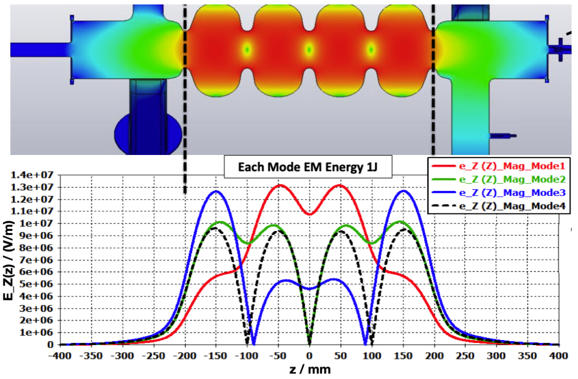

Figure 3: On-axis longitudinal E-field distribution of all 4 passband modes as simulated by CST (cf. studies reported in [6]). The strong field centralization is specific to the $\pi/4$-mode (red, "Mode 1"), which in all experiments consistently showed best Q values.

closing the helium tanks after successful vertical testing. This also will bring a subsequent horizontal testing in reach.

EXPERIMENTAL

Here we report about the recent first vertical testing (cf. Fig. 1) of the second prototype ("VSR-P2") of the VSR-cavity, which followed a sequence of tests of the first prototype VSR-P1 [7], none of which resulted in Q0-values for the accelerating π-mode significantly better than $2.0 \cdot 10^9$ (cf. Fig. 2). Consistently through all tests of VSR-P1, Q-values of the $\pi/4$-mode exceeded those of the other three modes ($2\pi/4$, $3\pi/4$, π) of the fundamental passband by factors of 3 to 5. As simulations revealed (cf. simulated field distributions in Fig. 3), it is a particular feature of the $\pi/4$-mode to extend high field strengths in the two middle cells only, whilst fast decaying is found in the two boundary cells.

In view of the results mentioned, three hypothesis were formulated in order to explain losses with peripheral locations: a) poor rf performance of the two beam pipe niobium-titanium blind flanges (one of which carries the main antenna, the other the vacuum pumping flange); b) dielectric or ohmic losses in the main antenna or its feedthrough; c) improper shielding of ambient magnetic fields.

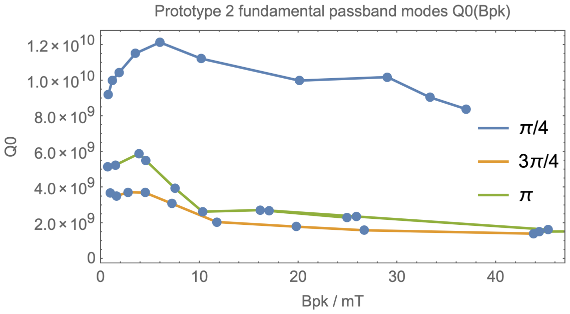

Figure 4: Q0 of three modes of the fundamental passband measured at Prototype 2 at 1.8 K versus peak magnetic surface field.

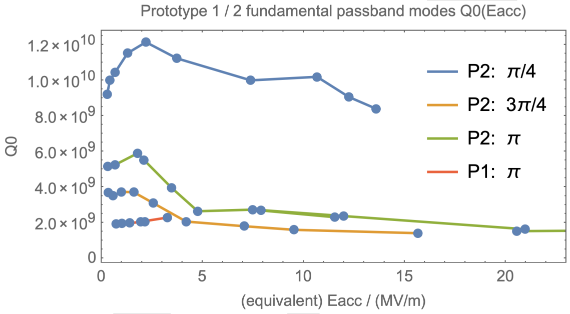

Figure 5: Q0 of three modes of the fundamental passband measured at Prototype 2 and the π-mode of Prototype 1, both at 1.8 K versus accelerating field strength. The addition "(equivalent)" refers to a field integral evaluated for the non-π-modes without a transit-time factor.

Option a) was discarded after test results with niobium-coated flanges (here shown in Fig. 2) similar to those before; option b) by extended care in the preparation of the cable connectors mounted on the 1/2"-semi-rigid coaxial rf power cables and by equipping the region with additional thermal sensing, none with beneficial effects or insights; option c) by a magnetic field measured below 0.8 µT in the cryostat when the cavity and the supporting frame was inserted. The latter value is above an ideal-world-aim of less than 0.5 µT, but not able to justify the observed Q-value reduction. In lack of alternative proposals a test of Prototype 2 was seen as the best option to gain any additional understanding.

Prototype 2 was first tested in March 2026 at HZB's Large Vertical Test Stand at 1.8 K with outcomes shown in Figs. 4 and 5, the latter also including a π-mode result from Prototype 1. As it can be clearly seen from both plots, the Q privilege of the $\pi/4$-mode is a property of both prototypes, indicating towards a systematic cause found in the cavity's structure or its processing. The shape of the Q(E)-curves with an Q increase from smallest to modest field strengths, a maximum and a monotonous decrease towards high field strengths strongly reminds to results attributed to the so-called "Q disease" [8], even though the cooling curves (cf. Fig. 6) illustrate a fast cooldown with cooling rates higher than 1 K/min and without any holding pause at intermediate

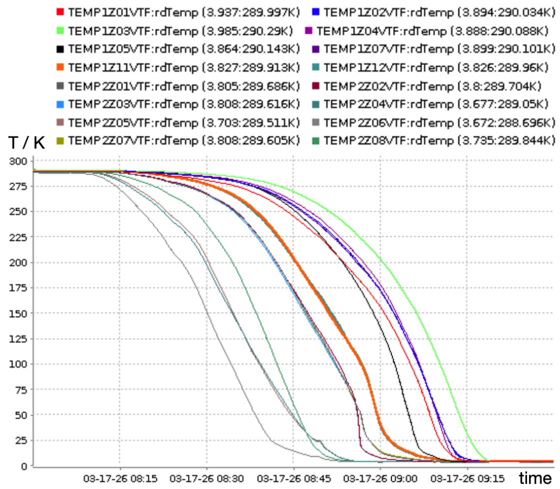

Figure 6: Cool down curves of all 16 Cernox-type temperature sensors. Sensors are mounted in a way that the above shown list represents the top-to-bottom physical arrangement. Cooling starts with the lowermost sensors getting embedded in the supply of cold helium gas first. The entire cooling concluded within an hour.

temperature levels. Q-disease is attributed to hydrogen accumulation in the bulk niobium, which routinely is cured by a vacuum baking around 800 °C for several hours. Current oven parameters of the process, as it was applied to both prototypes, foresee a temperature holding period of 3.0 hours. In view of the additional radiative shield, which is generated by the vacuum vessel bellow (which is for geometric reasons carried with the undressed cavity since the final cell welding), this may be too short for full thermal equilibration. Temperature sensing during the oven runs happened at the outer side of the titanium tank elements welded to the endgroups, which may cause strong temperature differences to innermost surfaces.

Therefore, an insufficient baking of one or both end cells, either by coverage from the bellow or impacted by the large thermal capacity of the tank endgroups, remains as a plausible hypothesis to explain the observed Q(E). Other suspicions speculate about thermocurrent generation during the cooldown, since several material interfaces are intrinsically part of the cavity construction (titanium tank elements partially in explosion bond to stainless steel and welded to niobium endgroups, equipped with niobium-titanium flanges with copper made rf lids and aluminium/magnesium vacuum gaskets) and may be driven during cooldown by an inhomogeneous temperature distribution, thus causing local flux trapping.

CONCLUSIONS

With the results of the first vertical test of Prototype 2, a more concise phenomenological picture of the Q(E) performance of the VSR cavity was established. Consistently through all tests with both cavities, the $\pi/4$-mode results in Q-values by a factor of 3 to 5 higher than those of the other three fundamental passband modes. Cause and location of their additional losses remain unresolved, but only a few qualified assumptions are still consistent with the set of observations. For further clarification we aim for a repeated and extended 800 °C oven run as part of a re-processing and -testing campaign.

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