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BESSY VSR: SRF CHALLENGES AND DEVELOPMENTS FOR A VARIABLE-PULSE LENGTH NEXT-GENERATION LIGHT SOURCE

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Abstract

The BESSY VSR project represents an exciting alternative to diffraction limited storage rings in the development of a next generation light source. Such a system should be capable to store "standard" (some 10 ps long) and "short" (ps and sub-ps long) pulses simultaneously in the storage ring opening the door to picosecond dynamic and high-resolution experiments at the same facility [1]. This unique feature can be created by the introduction of the beating effects produced by higher harmonic SRF cavity systems (1.5 GHz & 1.75 GHz). The challenging design specifications as well as the technological demands on the SRF system make BESSY VSR a defiant project where non-standard techniques such as waveguide-damped cavities have been further developed. This talk focuses on the new SRF developments that include waveguide-damped cavities, high-power couplers and higher-order mode absorbers that must handle nearly 2 kW of HOM power. The cryomodule design and its interaction with the beam will also be discussed.

INTRODUCTION

The BESSY VSR module is designed to run CW with a 300 mA high current beam. With a quite exotic filling pattern, impedance control plays a key role when avoiding CBIs [2]. Therefore the longest low-β straight section in the BESY ring has been chosen as the only feasible module location. The cavity design was recently changed from a 5-cell to a 4-cell cavity since the available space is insufficient to accommodate the original 5-cell cavity based module design. As a result the total module voltage drops in 20% (29.71 MV) with respect to 37.2 MV originally specified for BESSY VSR. Thus a 10% reduction in the expected VSR bunch compression is obtained. That is a VSR short bunch length of 1.87 ps instead of 1.7 ps for the standard BESSY optics.

COLD STRING DEVELOPMENTS

Several recently identified important issues such as HOM power damping or incoming synchrotron light generated in the closest dipole magnet upstream to the VSR module have been studied and are presented on this paper. In addition the hard length restriction demands for unusual cavity connections. These are required to provide the system with the mechanical flexibility imposed by cooling shrinkage and, meanwhile, providing fundamental mode shielding to avoid overload of the cooling system and non-acceptable Q-value reduction. Thus designed solutions and actions taken to mitigate all such effects are presented in this paper.

Warm HOM Waveguide Loads

As a first measure to optimize the module length the number of cells per cavity (Fig.1) was decreased from 5 to 4. This variation results in a positive 15% reduction off the total HOM power and also improves the damping capabilities of the cavities. Consequently full EM validation of the new shortened cavity version by means power propagation studies through the module were performed [3].

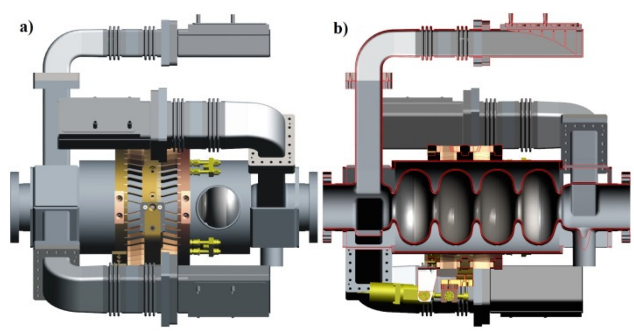

Figure 1: 4-cell 1.5 GHz cavity design equipped with He-vessel and blade tuner (a). Cut plane view showing waveguide (WG) HOM loads design details (b).

As it was designed for the VSR 5-cell cavities and presented in [4], the main HOM damping is performed by means of 20 warm water-cooled WG HOM loads. These are Silicon-Carbide (SiC) based loads with a maximum power specification of 460 W (10% overhead included) per load at room temperature. The design of these loads is being performed in collaboration with JLab [5]. The first prototypes are currently under fabrication and will be shortly tested in Jefferson Laboratory facilities. A detailed view of the load design and the calculated temperature on the absorbing tiles is shown in Fig. 2.

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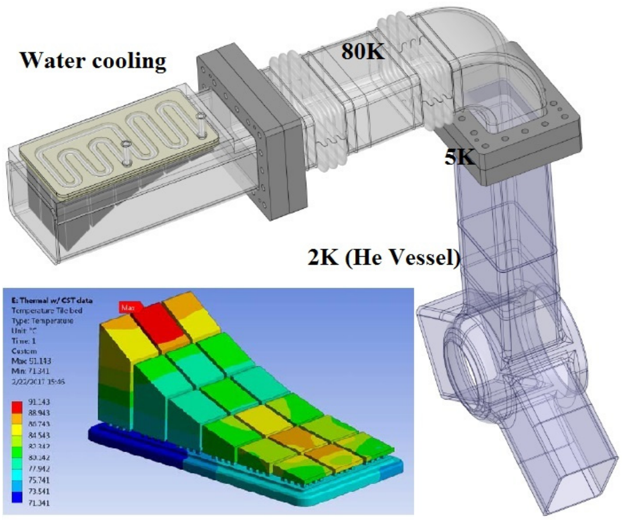

Figure 2: Water-cooled HOM WG loads with calculated temperature rise due to HOM power spectrum (courtesy of F. Fors, Jlab). T_{max} = 91°C for 460 W input power.

Warm Beam-pipe Loads

By design HOM cavity end-groups performance in terms of damping are highly efficient. They can take most of the HOM power left behind by the beam (≈ 75%). Nevertheless there is still an important HOM contribution travelling up- or downstream outwards the module, roughly amounting to 1.5 kW [3]. In order to avoid the undesired load transfer to the BESSY ring or any backwards reflection into the VSR module, a set of two new warm beam-pipe absorbers is designed (see Fig. 3). These warm loads are inspired on the SiC Coorstek SC-95 design developed by Argonne [6] fot the Advance Photon Source upgrade. As it can be inferred from Fig. 4 HZB design is extremely shortened in order to accommodate a required very steep taper, matching the BESSY to the VSR module beam pipe cross section. In addition the toroidal dielectric absorber with its cooling jacket, a bellow for length compensation and a pumping dome are included in the design. The significant amount of wakes generated by the almost step-like taper is immediately absorbed in the dielectric toroid, which furthermore effectively serves as a shielding for the bellow.

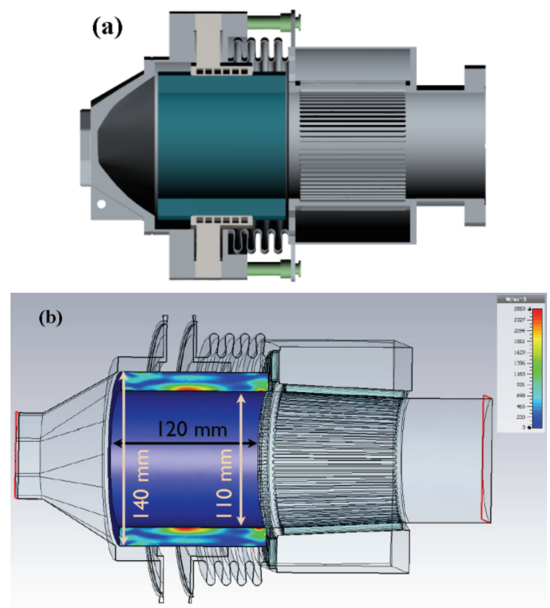

Figure 3: CAD view of the designed warm beam-pipe load (a). Sample EM eigenmode calculation of deposited power densities (b).

Synchrotron Light

Detailed calculations on synchrotron light trajectories prove the existence of a significant amount of the synchrotron light in the module environment. This light is emitted from the nearest downstream magnet section and will collide at several cold-string spots (1.8 K environment) such as cavity irises. This strong power contribution (89 W) must be controlled since just a small fraction would be sufficient to induce a quenching process and also would cause an inacceptable additional load of the cooling system. Figure 4 show a full layout of the studied BESSY VSR cold-string. To mitigate this issue new collimators are introduced. As a first pre-module measure, a warm collimator is placed at the upstream quadrupole prior to the module entrance. This is design to absorb most of the incident light power (63 W). Full absorption at this instance would put the collimator prohibitively close to the beam; therefore some light is left to travel to the bellow section in the centre of the cold-string (11 W), which is designed as a second collimator. The remaining light contribution (15 W) leaves the module without hitting the cold-string walls. The latter concept is described in the following section.

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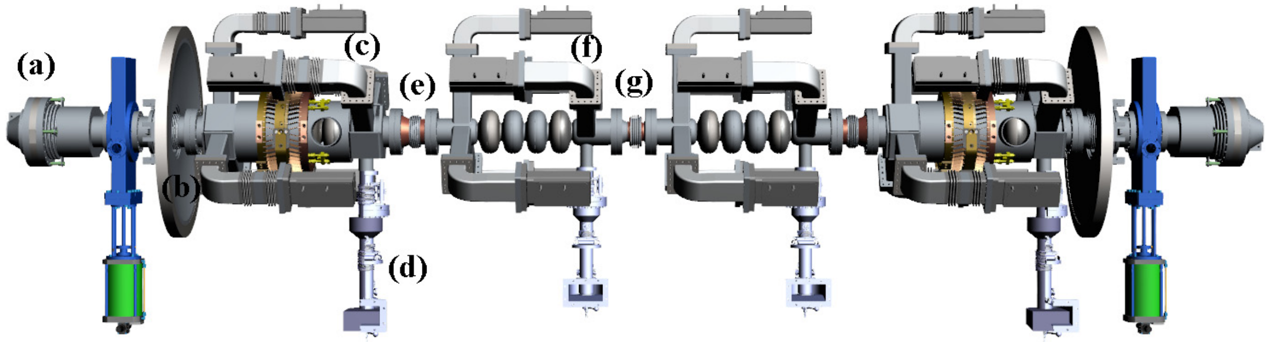

Figure 4: The BESSY VSR cold-string. Components named (left to right): Warm beam-pipe absorber including taper and pumping dome (a). Warm/cold transition bellow (b). 1.5 GHz cavity with He vessel and blade tuner (c). 1.5 GHz, 16 kW high-power coupler (HPC) (d). Non-collimating shielded bellow (e). 1.75 GHz cavity (shown without vessel and tuner) (f). Collimating shielded bellow (g).

Non-collimating Shielded Bellows

The bellow connections between cavity pairs 1/2 and 3/4 do not act as collimators but nevertheless match different beam pipe diameters (110 mm / 94 mm attached to 1.5 GHz / 1.75 GHz cavity resp.), and therefore show some tapering. Alike the central collimating bellow they are directly exposed to fundamental mode fields and therefore are also equipped with an inner shielding (cf. Fig. 5). Detailed design work on this component is in progress.

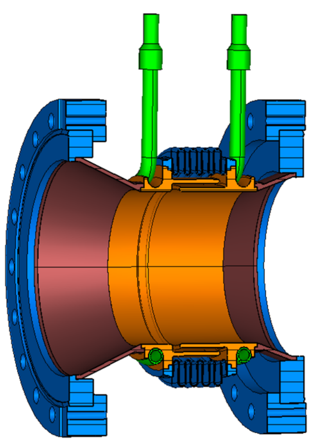

Figure 5: Draft version of the non-collimating shielded bellow with massive copper inner parts (orange), copper-plated tapers (dark red), stainless steel bellow and flange parts (blue) and cooling piping (green).

Collimating Shielded Bellow

Due to the reduced space available new multipurpose cold-string elements are currently under design. In particular the centre bellow section between the two 1.75 GHz cavities is being designed in order to also act as a collimating structure by means of its first copper plated steep taper section. The main purpose of the three bellows connecting the cavities is the compensation of thermal shrinkage while cool-down and of tuner-driven cavity length variations. They also provide the elasticity needed by the cold-string while assembling. In order to restrict the bellow lengths as far as possible it was decided to demand tight tolerances ($<$ 0.5 mm axis-to-axis; angular tilt t.b.d. after mechanical evaluation of bellow samples) for transversal deviations of the cavities from their ideal straight shape. Thus predominantly longitudinal compensation is demanded from the bellows.

There are virtually no alternatives to stainless steel bellows. Copper coating was discarded in order to avoid any risk of particulate production. This, together with the extremely short beam pipe extensions of the cavities being tolerable within the given space, raised fundamental mode field losses in the bellows unacceptably high when considering an unshielded design. Therefore an inner RF shielding was designed, which in its central part is made of massive copper and equipped with two circumferential pipes to be attached to the 5K to 8 K system. The peripheral taper parts are made of copper coated stainless steel. As a consequence low RF losses and reduced static heat flux into the 1.8 K-cooled cavities is achieved.

Fundamental mode field patterns incident from either of the neighbouring cavities were computed, resulting in 1.46 W total loss if a gradient of 20 MV/m is assumed. Neglecting any others losses would result in cavity Q-values of better than $2 \cdot 10^{11}$; thus not implying significant cavity performance limitations.

On the other side it is unavoidable that such a structure develops a set of own eigenmodes. The beam relevance of which was computed both with eigenmode and wake computations in CST [7]. Above beam pipe cut off – 2.441 GHz for the TM_{01} mode with 47 mm beam pipe radius – a set up with two cavities attached was used. After tuning of the shielding labyrinth it was possible to adjust the frequencies of the relevant three modes in a way that none of the dominating spectral lines of the BESSY beam current, which are harmonics of 250 MHz, is hit (cf. Table 1). This holds even if the bellows are shortened or stretched by up to 2 mm.

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Table 1: Collimating Shielded Bellow Modes

mode	1	2	3
f/MHz	422	2155	3923
(R/Q)/Ω	15.8	4.25	0.73
Q	497	1490	1038
P/W (20 mA single puls)	6.70	9.16	2.9
f(-2mm)/MHz	416	2125	3976
f(+2mm)/MHz	423	2135	3784

Even if those modes are detuned with respect to the beam harmonics in case of the standard fill pattern, they will be excited in case of the single-pulse mode with its rather broad spectrum. The 5th line of Table 1 applies to those worst conditions, which together with the fundamental mode power and the synchrotron light deposition defines the load power used in the thermal computations shown in Fig 6b. Figure7 shows EM calculations on different modes.

Rectangular Waveguide Gaskets

Tightening the cavity-waveguide connection under all conditions including immersion into supra-fluidic LHe during cavity tests is a non-trivial issue. The application of full-copper VATSeal© [8] gaskets, are foreseen. Those are currently under experimental testing, showing encouraging results.

Gap-free Beam-pipe Gaskets

Standard CF gaskets, providing vacuum tightness and RF connection with a single knife-edge contact, are characterized by a small circumferential slit interrupting the inner beam pipe surface. Such geometries are prone to trap RF modes of non-negligible beam impedance, especially meaningful if coinciding with prominent lines of the beam spectrum. Attempts to reduce the effect by narrowing the slit, though in principal reducing the impedance, make the resonance frequencies very sensitive against geometrical uncertainties. Therefore it was decided to apply modified CF-like gaskets with an additional lid at the inner radius, that fully fills up any gap between either side of the flange connection. Appropriate pumping is ensured by some gaps, interrupting the lid and evenly distributed around the inner circumference. The lid thickness has to be carefully manufactured in order to assure even RF contact and maintenance of the knife-edge vacuum gasket.

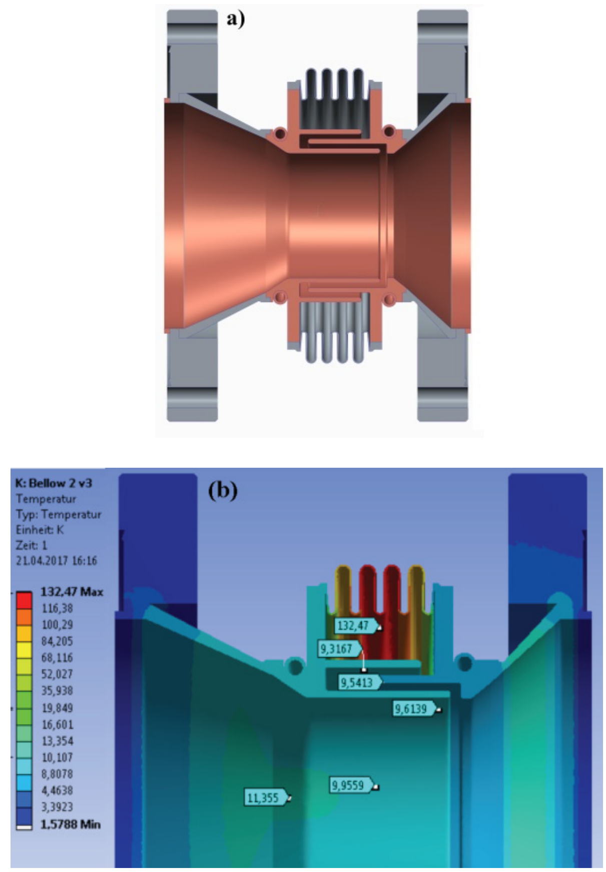

Figure 6: CAD view of the collimating shielded-bellow design (a). Cooling channel are 5…8 K intercepts. Temperature distribution induced by the incident light. The 11.35 K light green area corresponds with the synchrotron light impact point. Heat load on the below section is a result of the fundamental model leaked power (b).

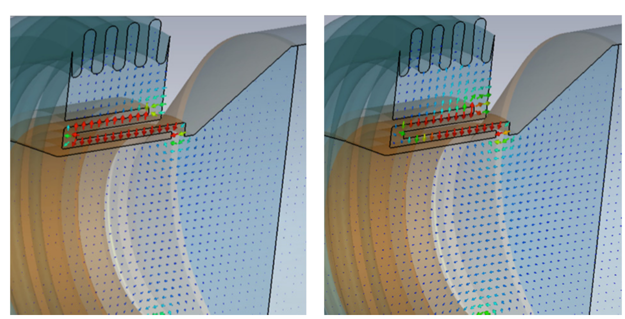

Figure 7: E-field patterns of modes 1 (left) and 2 of the collimating shielded bellow. Mode 2 changes its orientation close to the 180° bend of the labyrinth whereas mode 1 keeps its orientation over the entire length.

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Impedance Calculations

Since all of the presented elements could be a potential source for unexpected extra impedances with harmful effects on the beam quality, special care is taken on the impedance calculations for the whole VSR cold-string. Therefore wake-field full string computations are performed in CST [7] to determine the possibility of introducing harmful instabilities. The different components are in addition carefully analysed through its eigenmode spectrum to determine their feasibility with respect to HOM resonances and collision with synchrotron frequencies. Figure 8 shows a calculated impedance spectrum for the designed VSR string. In addition, a collaboration with Rostock University is established in order to perform further studies on the concatenated string by means of the **S**tate **S**pace **C**oncatenation technique (SSC) [9].

In order to validate the numerical results and discard unexpected sources of impedance HZB will fabricate a first prototype of the collimated-bellow component for beam tests at BESSY II. Further test of different elements such as the warm beam-pipe absorber are also foreseen.

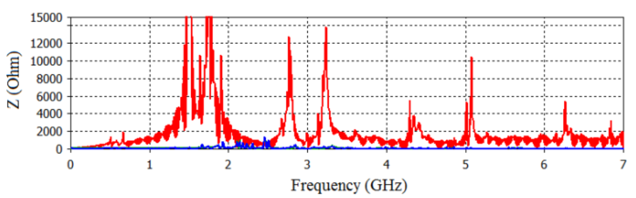

Figure 8: Calculated longitudinal (red) and transverse (blue) impedances for the full BESSY VSR cold-string. Beam harmonics are multiples of 500 MHz and 250 MHz for the “Baseline” and “Extended” baselines [3].

High Power Couplers

All independent 3 and 3.5 harmonic cavities will be equipped with a 16 KW CW HP coupler [10]. The couplers are required to provide variable coupling in the range of $6{\cdot}10^6$ to $6{\cdot}10^7$ to allow for optimal coupling based on the machine operating conditions. Additionally this allows for safe parking of the cavities when not in use. The design of this coupler is currently under development at HZB and it is based on the Cornell Injector coupler design [11]. With the main design modification being the change from the Cornell “Pringle” type tip to a rounded antenna tip, better suited for the coupling level for VSR. The basic RF design of coupler can be seen in Figure. 9.

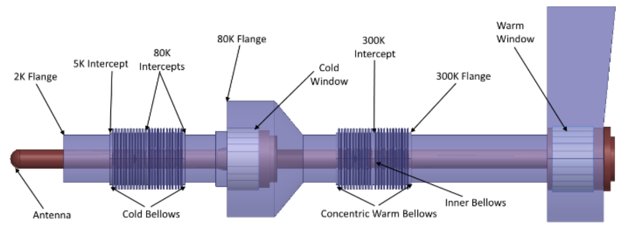

Figure 9: Basic RF design of the 1.5 GHz coupler showing the vacuum and inner conductor. Temperature intercepts and components are clearly labled.

The BESSY VSR high power coupler incorporates three sets of bellows to provide variable Q coupling by allowing mechanical control of the penetration depth of the coupler tip. These bellows additionally act as temperature intercepts for the coupler. By compression and expansion of the bellows the coupler tip can be moved forward and backwards. Simulations were performed for compression and expansion of the bellows of up to 10% (approximately ±8 mm) to investigate how this effected the response of the coupler.

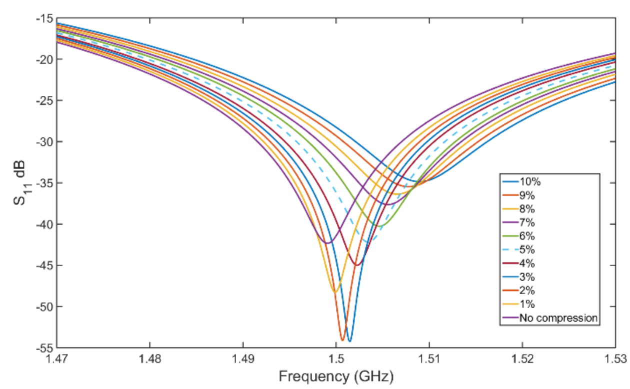

Figure 10: Change in S_{11} as the bellows are compressed by 10%.

Figure 10 shows the bandwidth and frequency of the S_{11} response increase as the bellows compress. Due to resonance conditions introduced by the bellows, the magnitude of the response increases for initial compressions of 1-3%, then decreases with further compression. For compression of up to 5% the response remains below -30 dB at 1.5 GHz. Behaviour from expansion is similar with expansion of up to 5 % remaining within the S_{11} specifications [12]. This allows for movement of the tip by ±4 mm.

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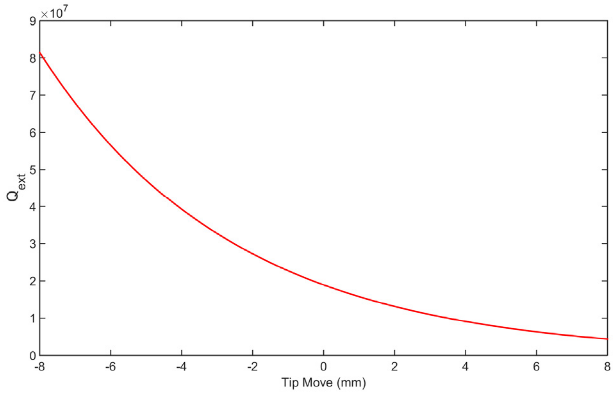

Figure 11: The change in Q as the coupler penetration depth changes. This corresponds to compression and expansion of the bellows by 10%.

Figure 11 shows that the bellows allow for a tunable range of Q_{ext} of $9.24{\cdot}10^6$ to $3.8{\cdot}10^7$ for 5% expansion and compression (±4 mm). Though the desired coupling range has not been met, these results are promising for initial coupler plus cavity simulations. With further tuning we should to be able to tune Q_{ext} over a full order of magnitude to give a coupling range of $6{\cdot}10^6$ to $6{\cdot}10^7$.

Initial thermal tests have been performed and show some hot spots however these can be mitigated by integrated cooling. Further thermal analysis is planned to analyse heating of the coupler for all operational modes to ensure no breakdown can occur when the coupler is operational

Prototypes and Testing

As it was previously introduced, the new development of several string components and damping techniques (WG damped cav.) makes the fabrication of prototypes necessary in order to validate the designs. To this end a 5-cell copper WG-damped cavity is currently in the last welding stage of the fabrication process at Research Instruments (RI) (Fig. 12). In addition a niobium single-cell cavity loaded with one side WG dampers is being delivered by RI (Fig.13). As inferred from the picture the WG ends of the Nb single-cell prototype are closed with Nb blind flanges in order to fit into HZB small vertical test stand. These cavities are planned to be shortly tested and will serve as validation of the design techniques developed by HZB.

CONCLUSIONS

The present status of the VSR cold string and the new developments done in order to deal with HOM power and synchrotron light concerns are presented on this paper. Results show the feasibility of fulfilling the challenging space constrains while keeping reliable SRF operation and beam standards. New techniques are presented and prototypes fabricated. Future RF tests and beam tests will be performed to validate these results.

Figure 12: View of the stacked 1.5 GHz 5-cell copper cavity during bead-pull tests at Research Instruments (RI).

Figure 13: View of the fabricated Nb 1.5 GHz single-cell cavity.

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