MOCKUP ASSEMBLY OF AN SRF MODULE: SPACEFRAME AS TOOLING AND STRUCTURAL SUPPORT FOR HIGHLY HOM-DAMPED CAVITIES

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Abstract

To support the elliptical VSR cavities featuring five protruding waveguides, a spaceframe was engineered to serve a dual purpose: providing structural support and functioning as tooling during assembly. This spaceframe facilitates cavity rotation in the cleanroom, simplifying the installation of HOM loads and fundamental power coupler components. Designed specifically for the particular cavity geometry, the spaceframe has a diameter of 1.5 m and provides axial and radial support for the cavity, along with its ancillaries, magnetic and thermal shields, and piping. A mockup assembly was conducted to evaluate the design's functionality, assessing key aspects such as rotation and railing performance, cavity support and alignment, and the mountability and stability of ancillary components.

INTRODUCTION

The variable storage ring (VSR) project has aimed at providing long and short pulses in the BESSY II storage ring using a beating scheme achieved by installing two pairs of cavities – at 1.5 GHz and at 1.75 GHz [1]. To demonstrate the feasibility of all required components and processes, the VSR DEMO module was designed. This module houses two 1.5 GHz superconducting RF (SRF) cavities with fundamental power couplers. The module design is described with a focus on the installation process in the following. For further information on the mechanical aspects of the module design please see Ref. [2]; for the cold string components, see Refs. [3] and [4]; and for the cavity, see Ref. [5].

MODULE DESIGN CONCEPT

Many elements of the VSR DEMO cold string are somewhat peculiar and present challenges during installation and operation. The most demanding components are the 1.5 GHz SRF cavities with five protruding waveguides, each terminated by a higher order mode (HOM) load at room temperature. These cavities are supported by a modular spaceframe, segmented per cavity and connected after completing the cold string assembly. Unlike the ESS monolithic frame (cf. [6]), this segmented design allows the spaceframe to serve as part of the tooling during HOM load installation.

To support the five waveguides per cavity, the spaceframe requires a 1.5 m diameter, presenting a unique design challenge. A spaceframe design was favoured over other design approaches (as compiled in Ref. [7] and cf. Ref. [8]) to maximize the position stability of the cold string during cool-down. Additionally, the spaceframe and ancillaries are designed such, that the cavity can be rotated in steps of 60° for convenient and clean HOM installation. This mounting procedure is considered the safest approach to prevent particulate contamination of the cavity. Here, the spaceframe serves as part of the tooling. And at a later stage it also supports additional subsystems, including thermal and magnetic shields, helium piping, and interconnecting cold string elements such as bellows. The frame's C-shape (rather than circular) provides necessary access for coupler installation.

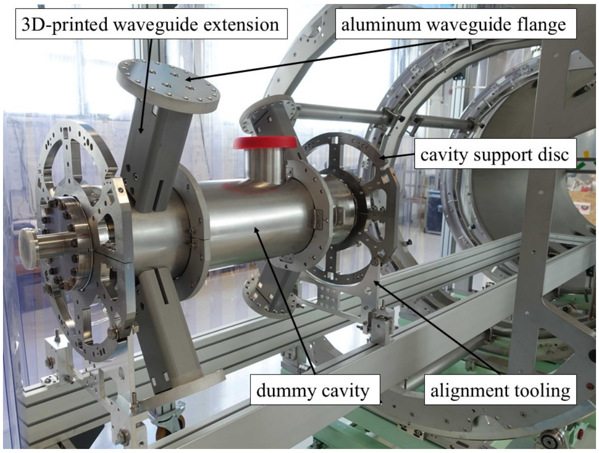

Figure 1: Dummy cavity on the installation table during alignment before installation into the spaceframe.

Once cold string and cold mass are assembled into the frame, this assembly is railed into the module. The module features ten rollers supporting the railing on the frame. When in position, support pins convert sliding bearings into fixed bearings.

Coupler warm part installation requires reaching from outside of the module into the cold mass down to the coupler cold part attached to the cavity. This installation will be performed without module doors to allow visual inspection.

INSTALLATION PROCEDURE

Installation of the cavity into the frame begins by transferring a cavity from its transportation frame onto a table with support discs, allowing sliding and alignment (cf. Fig. 1). The support discs also align the cavities in the spaceframe.

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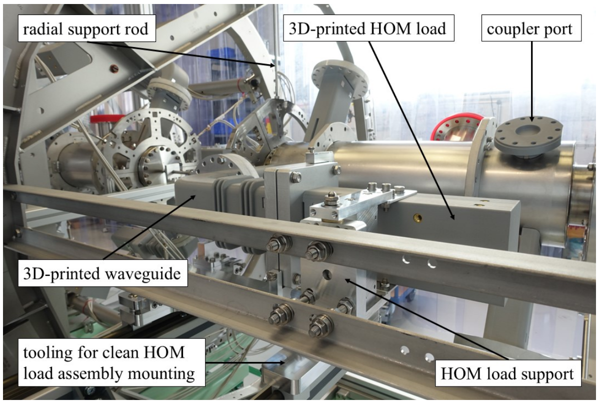

Figure 2: Rotated cavity during installation of HOM load assemblies.

The magnetic shield and tuner are then mounted, and the cavity is prealigned using the coupler flange as a vertical reference. Three radial support rods per support disc are attached, forming the connection to the frame. The cavity is disconnected from the table and the rods and pretensioned using strain gauges, followed by alignment verification.

The spaceframe then becomes tooling for coupler cold part, waveguide, and HOM load installation. The latter two parts are preassembled and will be called HOM load assembly in the following. Rotation of the frame around the cavity axis is enabled by rollers, while the frame serves as railing rim. The closed (blind-flanged) cavity is rotated by 120°. The cavity vacuum is then opened at a waveguide stud, and a HOM load assembly is flanged to the cavity (cf. Fig. 2). During this step, sliding tooling supports and moves the heavy assembly. The HOM load is secured to the spaceframe with holders, leaving one rotational degree of freedom unconstrained. Then the cavity will be turned by 60° and another pair of HOM load assemblies are installed. Finally, the cavity is rotated by 60° back to its original position. At this orientation one HOM load assembly and the coupler's cold part are mounted.

These steps inherently pose a contamination risk. First, because the clean cavity has to be opened in the presence of large elements difficult to clean. For example, the spaceframe will be carefully degreased and blown with dry ice but is too large to be cleaned in an ultrasonic bath at HZB site, and will remain a risk of contamination. Other elements such as the blade tuner will be wrapped with foil, to further reduce potential sources for particulates. Second, because the HOM loads are made of many ceramic tiles with narrow gaps between making them challenging to clean. During the turning process, particulates from the HOM load could reach the superconducting surfaces of the cavity. Therefore, cleaning of the tiles before installation is of utmost importance. To further mitigate the risk of contamination a Kapton shield is integrated in the flange between HOM load and waveguide [4].

Figure 3: Completed cold string assembly in the spaceframe.

After this step, a leak check is performed to assess the flange connections. Due to the size of the cavity with the HOM load assemblies attached, performance testing for field emitters cannot be carried out until cold sting assembly is complete. Instead, it can only be tested at a very late stage, i.e. on the completed cold string assembled into the module. Therefore, all assembly steps on the beam pipe vacuum must be executed with the highest care for cleanliness.

After these preparatory steps on the cavity, the cold string can be assembled. Opening of the cavity beam pipes is required, and highly sensitive installation steps are performed at rather poorly accessible positions. Between the cavities the collimating shielded bellows (CSB) will be installed. At the string's ends, the so-called module end bellows (MEB) will be installed (cf. Fig. 3). These components consist of length-adjustable bellows for the beam pipe, combined with a heavy flange that connects to the module door. After connecting the bellows segment to the cavity, the flange is connected to the spaceframe to support the flange's weight (cf. Fig. 4). This connection is only for temporary purpose and will be disconnected once the module doors are closed. Later, the flanges are connected to the module door.

With the cold string completed, remaining components - i.e. shields, sensors, piping, axial fixation - are mounted outside of the cleanroom. Lastly, the assembly is railed into the module (cf. Fig. 5), doors are closed, isolation vacuum pumped, and the system prepared for storage.

Positional stability of the cold string after cooldown is assessed with a laser tracker measuring from outside through

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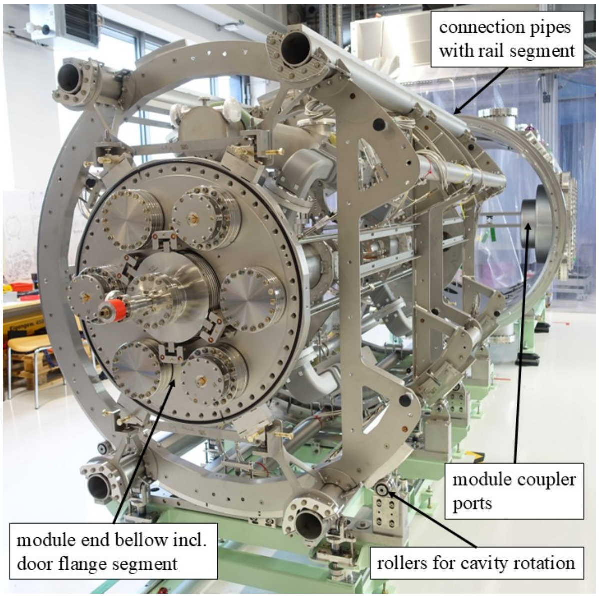

Figure 4: Side view of the (partially) assembled cold mass.

a window flange onto a target placed on the support discs, i.e. references the cavity flange position. This requires a viewing axis through all layers of the cold mass, and a correction of the media (air, glass, vacuum) if absolute position measurement is required (cf. Ref. [9] for more information).

MOCKUP ASSEMBLY AND FINDINGS

Given the peculiar assembly procedure, a high-scale mockup assembly of cold string components was performed. This is to assess functionality of support and tooling, mountability, and clean room compatibility of assembly procedures. The latter two were evaluated without practical proof, but the assessment was more realistic on physical components than in CAD model investigations.

The cavity was resembled by a stainless-steel dummy built from two pipes inserted into one another (cf. Fig. 1). The dummy cavity has hence a beam pipe and a vessel for the cooling medium. Waveguides, HOM loads, and coupler ports were simulated by 3D-printed parts and aluminum flanges, allowing verification of fit and tooling requirements but not the full weight. To connect the cavities, a CSB prototype plus a pipe segment was used. The only original parts used for the assembly were the MEBs.

Midway through, the VSR DEMO project was terminated (excluding the completion of cavity production), halting plans for cold testing of the mockup assembly. Installation steps were performed with cleanliness and magnetic hygiene protocols in place, though several cold mass installations (e.g., MLI, shields, piping, sensors) were skipped.

Key observations of the mockup assembly include:

- The C-shaped spaceframe deflects asymmetrically under load, causing cavity rotation that requires correction.
- Cavity in spaceframe rotation can be executed precisely. Repeatability and reproducibility of cavity position before and after rotation are within laser tracker accuracy of 0.02 mm.
- Axial positioning of the cavities lacks clear reference in the spaceframe, risking CSB misalignment (only 2 mm bellows compensation capability). A clearer positioning scheme is necessary.
- Axial rods anchoring the cavity are prone to vibrate. This could pose challenges during operation. Adjusting rod dimensions and appropriate pretension may resolve this.

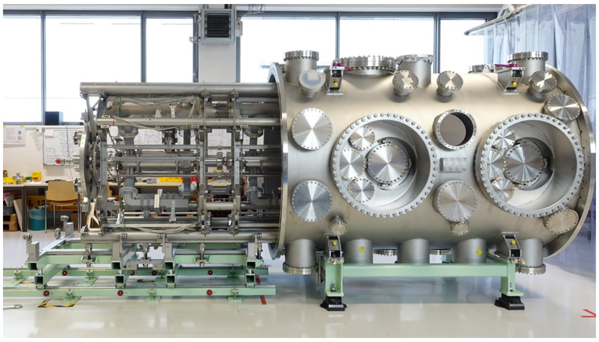

Figure 5: Cold mass - as assembled during the mockup - prepared to be railed into the module.

A mockup assembly is essential both to assess installation steps and to minimize the duration of a future cleanroom assembly.

OUTLOOK AND RECOMMENDATIONS

Although CAD analysis shows sufficient access, we recommend mockup testing of coupler warm part installation, which involves reaching from outside the module through multiple shields to connect to the cold part. This step is critical and may be limited by space or tool clearance.

The extreme thermal gradient between 1.8 K at SRF cavities and 300 K at HOM loads over a short distance (<1 m) remains a major engineering challenge. Effective mitigation of thermal shortcuts and ensuring mechanical stability under these gradients requires further investigation. Thermal gradients on the spaceframe could also cause cavity deflection, amplified and distorted due to the C-shape.

Moving forward, we recommend:

- Finalizing robust alignment strategies and axial references;
- Adopting improved tooling to minimize particulate risk during clean assembly steps;
- Studying vibration damping options for axial fixation rods;
- Full-scale testwise mounting of the coupler interface through all module layers.

These findings and recommendations provide insights for future SRF module designs under similar spatial and thermal constrains.

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