ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-WETEB9

DESIGN DEVELOPMENT FOR THE 1.5 GHz COUPLERS FOR BESSY VSR

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Abstract

The Variable pulse length Storage Ring (BESSY VSR) is a superconducting radio frequency (SRF) upgrade to the existing BESSY II storage ring at Helmholtz-Zentrum Berlin (HZB). BESSY VSR uses the RF beating of superconducting cavities at 1.5 GHz and 1.75 GHz to produce simultaneously long and short bunches. Higher power couplers capable of handling 13 kW peak power at standing wave operation, are required to provide an average power of 1.5 kW for both the 1.5 GHz and 1.75 GHz cavities. These couplers must also provide variable coupling with a range of Q_{ext} from $6{\times}10^6$ to $6{\times}10^7$ to allow flexibility to adjust to operating conditions of BESSY VSR. Here the full design development process for the 1.5 GHZ BESSY VSR coupler is presented including the design for a diagnostic prototype to ensure comprehensive monitoring of critical components during testing and cool-down.

INTRODUCTION

The required 1.5 GHz and 17.5 GHz cavities that represent the 3rd and 3.5th harmonics of the existing 500 MHz cavities within the BESSY II ring will form the BESSY VSR upgrade, creating simultaniously long and short bunches [1]. These super conducting cavities [2] will be powered by higher power couplers (HPCs), as detailed within this paper. However providing power to the cavities, though the primary function of every coupler is not the only function. The coupler must be designed to ensure that the required transmission characteristics for efficient operation are met and be able to handle the high fields and gradients associated with the operation of said cavities. In addition to this, the coupler acts as a thermal bridge and provides a transition between room and cryogenic temperatures thus must be able to withstand the differential thermal gradients and rates of thermal contraction associated with this. It also acts as an interface between ultra high vacuum and atmosphere and protects the quality of the cavity vacuum preventing performance degradation.

Thus the design of a coupler, particularly one for operation at high power with SRF is a complex and challenging one. This paper will focus on how the design for the VSR coupler has developed and in particular how VSR in terms of the high frequency and installation into an existing machine has placed significant dimensional constrains on the mechanical design.

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COUPLER DEVELOPMENT

The 1.5 GHz HPC for BESSY VSR is an adjustable coaxial coupler, with two cylindrical ceramic windows and three sets of bellows to allow for control over the position of the conical tip. This design is based on the design of the cERL injector coupler built by Cornell [3]. The coupler is designed to provide variable coupling with Q_{ext} from $6{\times}10^6$ to $6{\times}10^7$. This will allow for optimal coupling based on the operating conditions of the machine. The full technical requirements for the coupler are summarised in Table 1.

Table 1: Key Parameters for the 1.5 GHz Coupler

Parameter	Value
Central Frequency (f_c)	1.5 GHz
Bandwidth	±10 MHz
Peak Power in the coupler	13 kW
Average Operating power	1.5 kW
Q_{ext} range	$6{\times}10^6$ to $6{\times}10^7$
Q_{loaded}	$5{\times}10^7$
S_{11} (@ f_c)	≤ -30 dB
S_{11} (@ f_c±5 MHz)	≤ -20 dB

As discussed the HZB coupler is inspired by an existing coupler design that has shown reliability in operation. Nevertheless the specifications for BESSY VSR impose a higher operation frequency and thus require smaller dimensions, this represents an important challenge in the realisation of a mechanical design.

Electromagnetic Design

The RF design of the coupler was performed using ANSYS HFSS [4]. Here the initial scaled model is discussed along with the design optimisations performed to ensure the best possible response at the correct frequency, ensuring the desired Q values were reachable.

Strong coupling is characterised by strong transmission through the coupler, which can be measured through the scattering parameter S_{11}. This transmission can be controlled through the optimisation of the matching components/factors. These matching components/factors can be seen in Fig. 1 and are listed below;

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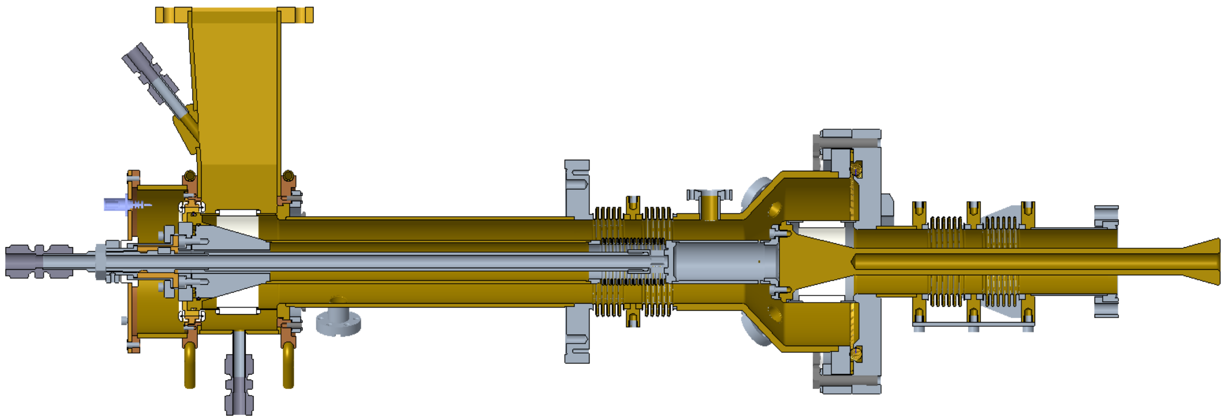

Figure 1: The finalised mechanical model of the 1.5 GHz HPC for BESSY VSR.

The length of the coupler: To ensure good transmission and to reduce reflection, the length of the coupler must be on the order of $n\lambda/2$ to ensure constructive not destructive interference.

The ratio between the inner and outer coax diameters: This ratio must set so that the coaxial impedance is as close to 50 Ω as possible.

The waveguide to coax transition at the warm window: Just inside the warm window at the waveguide to coax transition is a cone, this cone acts as a matching component and therefore to optimise the matching of the coupler the dimensions of this cone must be optimised.

The warm to cold transition at the cold window: Once again a cone within the cold window acts as the matching component and the dimensions of this cone must be optimised.

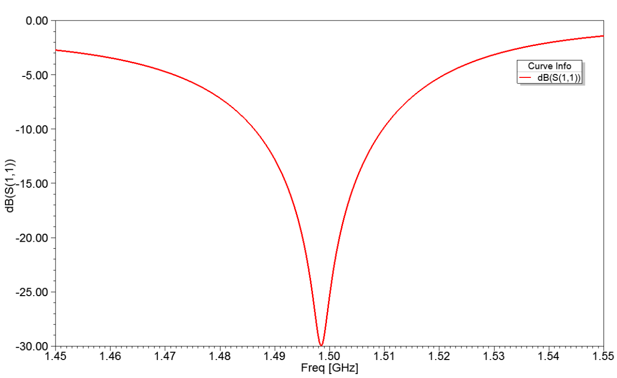

Figure 2: Plot of S_{11} for the optimised coupler.

These factors were analysed through parametric studies of the scattering parameters, which show the coupler transmission in the form of S_{11}. In the case of the VSR HPC the following S-parameter requirements were set; S_{11} must be below -30 dB at 1.5 GHz with a bandwidth below -20 dB of over 10 MHz. Through parametric sweeps it was possible to determine the ideal dimensions for the coupler to ensure good transmission. Figure 2 shows the S_{11} response of the optimised coupler.

In addition to analysis and optimisation of the matching coefficients, the electromagnetic design phase focused on creating a coupler that met the Q_{ext} range required for VSR operation. This coupling coefficient is affected by both the shape of the coupler tip and it's position in the cavity relative to the beam axis."Pringle" like tips as found in the original Cornell ERL coupler and the bERLinPro coupler [5] are designed to maximize the coupling factors. Nevertheless due to the lower specified coupling for VSR a simpler tip design would work.

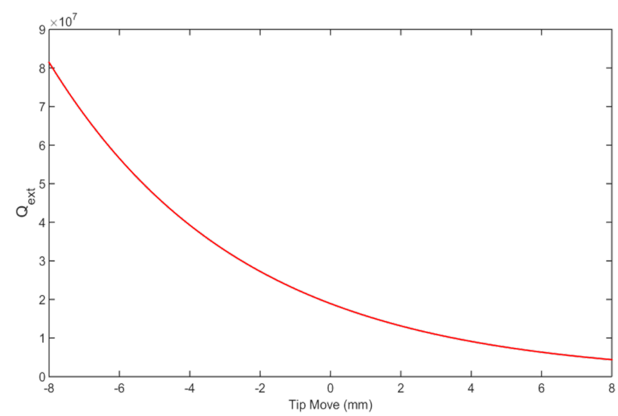

Figure 3: Plot of Q_{ext} vs Coupler tip position for an initial coupler tip design.

Initially a simple rounded tip was chosen [6] this was made hollow, similar to the Cornell design, to reduce stresses on the cold window. However a closed hollow tip would have meant a trapped vacuum which was not an option so the tip was open at the cavity end, to avoid trapped vacuums and ensure sufficient cleanability. This design with a hollow, open ended rounded tip, did not provide enough coupling to meet the requirements set out in Table 1. Hence the tip design was changed and through a rigorous design study it was found that a conical tip provides the desired level of coupling. The exact dimension of this cone were fixed

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through parametric analysis of the Q_{ext}. To ensure the full range of Q_{ext} required for VSR operation, Q_{ext} vs Coupler tip position was analysed for the different designs and plotted as shown in Fig. 3. The final tip design was then chosen such that the Q_{ext} range required was obtainable with the range of movement provided by the bellows of the coupler.

The electromagnetic design continues throughout the mechanic design phase as mechanic constrains lead to design changes that alter the frequency and transmission of the coupler. Thus throughout the mechanical design phase, there is continual parametric analysis of the electromagnetic response to ensure the design is both mechanically sound and able to provide the correct coupling response.

Mechanical Design

Figure 1 shows the final mechanical design for the 1.5 GHz BESSY VSR coupler. The realisation of a mechanical model represents one of the main project challenges due to the difficulty in matching the basic RF geometry to the fabrication and tooling techniques currently available. With VSR operating at the higher frequencies of 1.5 GHz and 1.75 GHz this means smaller scales and smaller components. For some parts this just mean unique tooling but for others it is not realisable with current techniques and so components must be redesigned and electromagnetic analysis must be re-run.

In Fig. 1 it is evident that there is a difference in coax dimensions between the warm part and the cold part. The cold part has an inner conductor radius of 10 mm and an outer conductor radius of 24.5 mm, where as the warm part has an inner conductor radius of 16.5 mm and an outer radius of 32 mm. For the cold coax part these dimensions are fixed due to the higher order modes (HOMs) in the cavity [7]. To protect the ceramic window, which could suffer a failure if too much power from the cavity is incident on it, the cold coax dimensions were optimised to decouple the HOMs and push those powers more into waveguide HOM dampers [8]. The coax dimensions that led to the greatest amount of HOM decoupling was found to be 10 mm inner radius and 24.5 mm outer radius.

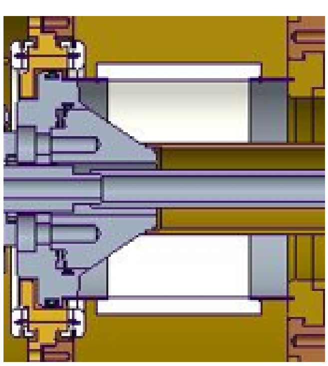

Figure 4: The new mechanical model of the cone that acts as the waveguide to coax transition, showing the split to allow for assembly.

The warm coax dimensions are affected by two mechanical factors. The first is a constraint on the maximum dimension to ≤ 64 mm which is set by the dimension of the 80 K flange. This is is fixed by the cryomodule design [9] and tooling restrictions for installation. The second factor affecting the warm coax is the need for cooling of the inner conductor bellows. As a result of the high power nature of the coupler, heating of the inner conductor bellows during operation is a risk factor that must be mitigated. Due to the level of heating and the associated complexity of a water cooling system, a compressed air cooling system is used. To ensure a flow sufficient to properly cool the bellows, without having the inner conductor pressurised, the cross sectional area for airflow must be increased. To maintain a good electromagnetic response the outer conductor radius must be increased as the inner conductor radius increases. Additional sufficient space between the inner conductor and outer conductor must be maintained so that it is still possible to assemble the coupler without the need for special tooling.

The need to create a mechanical design that is assembleable is not trivial, and has led to the redesign of several components, most noticeably the cone that acts as the matching component at the waveguide to coax transmission. Since this component it crucial to the overall transmission capabilities of the coupler the dimensions fixed by the electromagnetic design phase must be maintain wherever possible. However it must also allow for an assembly of the coupler in which the outer conductor of the warm-part is slid over the inner conductor of the cold-part without contact or damage to any components. In the initial mechanical design the radius of this cone component was too large for this assembly method, however the dimensions were essential to ensure the correct electromagnetic response. The solution can be seen in Fig. 4, in which it can be seen that cone is actually split into two parts, the lower part is now part of the inner conductor whereas the upper part forms part of the back section of the coupler that is connected to the outer conductor. This configurations allows for better assembly of the full coupler.

The process of producing the mechanical design of the 1.5 GHz HPC highlighted the challenges created when designing components for a higher operating frequency. Through this process greater insight into how these challenges may be overcome has been gained. This knowledge will be of great help during the designing of the 1.75 GHz coupler which will have even smaller components.

THERMAL ANALYSIS

Since the coupler acts as a thermal interface between the superconducting cavity at 2 K and the RF load at room temperature it is important to understand the thermal stresses and loads on it. As too high a stress will result in damage to the coupler as a whole and too high loads could result in heating of the SRF components and potentially a quench.

To ensure that there is good RF performance without too much thermal transport the coupler is fabricated from stain-

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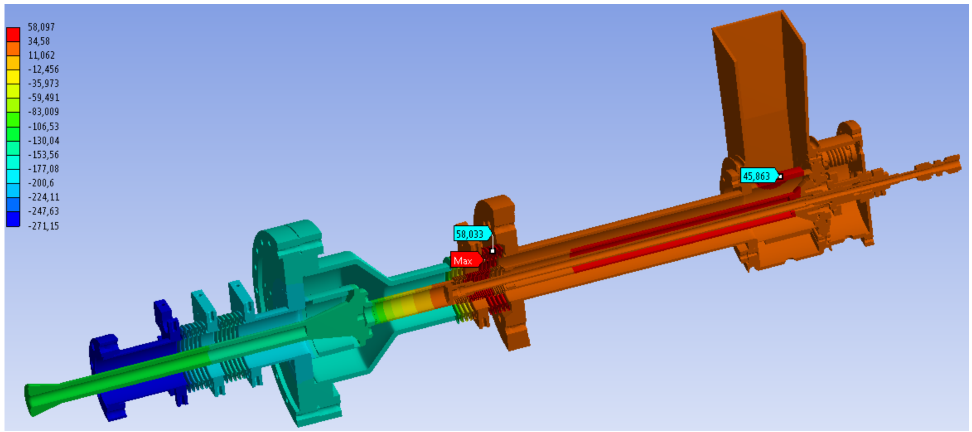

Figure 5: A temperature plot of the coupler at 16 kW operation, showing the two temperature peaks.

less steel with a thin copper coating. The thickness of this copper coating varies depending on the location in the coupler and the heat load there. For tubes and flanges including those at < 5 K a coating of 20±5 μm is required to ensure good RF transmission without significant thermal transport. For the bellows this is more complex. Copper coating of bellows results in uneven depositions on the convolutions thus the bellows coating must be at least 20 μm to ensure good RF performance but no more then 30 μm. The slightly thicker coating is permissible on the bellows as better thermal transport will avoid hot spots on the bellows.

Initial analysis was performed by studying the field within the coupler, identifying any areas of high field which could result in hotspots, and altering the design accordingly. Then the thermal load is calculated in ANSYS using the data obtained in the electromagnetic analysis. Figure 5 shows the temperature plot in °C of the coupler at a peak power of 16 kW, here it can be clearly seen that there are two points of significant heating. The first on the warm bellows at a temperature of 331 K and the second on the warm window of 319 K. Both of these peaks are manageable during safe operation of the coupler. In previous designs the bellows hotspot reached much higher temperatures, this was mitigated through altering the bellow position, reducing the number of convolutions and allowing for thicker copper coating to increase thermal transport away from the hotspot. On the warm ceramic this heating will be further mitigated by compressed air cooling and the connection to the waveguide is cooled using water.

It was through initial thermal analysis that the critical nature of the cold window was identified, and through this the cold part of the coupler faced a significant redesign. The cold window, is the only component connecting the cold inner conductor to the warm outer conductor and so acts as a thermal bridge. In initial simulations the cold ceramic window was experiencing a temperature gradient of over 100 K which would result in significant stresses. To reduce the stresses on the window, the connecting sleeves were redesigned, to provide more contact with the ceramic thus improving thermal transport and the coupler tip was made hollow to reduce the mechanical stresses. With the cold window redesign the temperature gradient is reduced to 40 K across the window and the stresses were reduced by 60% so there is no longer a risk of damage or deformation at peak power operation.

In addition to computational analysis, further thermal analysis will be performed on the prototype couplers during the testing and commissioning phase. This testing is designed to mimic the temperatures and thermal gradients experienced by the coupler during cool down. These significant temperature changes over a relatively short period of time could potentially cause damage to certain components, which should be checked during the testing phase and preventative measures should be taken.

DIAGNOSTIC PROTOTYPE

Due to the critical nature of certain components within the coupler it is essential to monitor them during the prototyping and testing phase to ensure there will be no failure during operation of BESSY VSR. To this end two diagnostic prototypes will be produced, which incorporate more diagnostics than will be found in the final series coupler. This diagnostic prototype can be seen in Fig. 6, with all diagnostic types and positions labelled.

These prototypes will be used to identify the optimal positioning of sensors in the final series coupler. Since the cold window is the most critical component within the coupler, and was shown to be susceptible to heating issues in simulations, four CF 16 ports for infra red (IR) sensors will be placed around the window, angled so as to identify the hotspots. These ports however are not compatible with operation in the cryomodule, as they do not allow for the flange connecting the coupler to the module to be mounted. Therefore these prototypes can only be used for testing in the test box. For module testing and coupler conditioning additional outer warm conductors with PT100s in place of the IR ports will be used. This alternative outer warm conductor will undergo high power conditioning with the whole coupler on the RF test-box before being integrated into the module to reduce secondary emissions and identify

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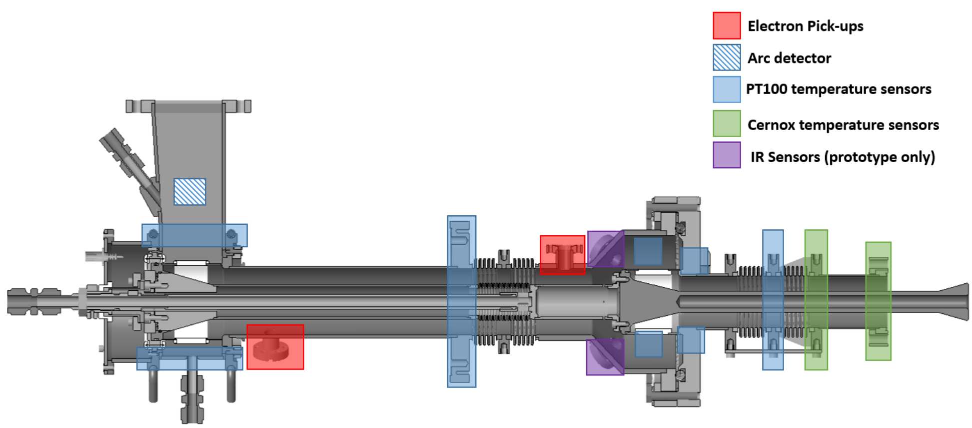

Figure 6: A view of the diagnostic prototype showing the position and type of sensors throughout the coupler.

whether the anti-multipacting bias will be needed during operation.

In addition to the careful monitoring of the cold ceramic during testing, two sample ceramic windows have been ordered for temperature and stress testing prior to the fabrication of the prototype. These two sample windows, will be of two different designs, one similar to the warm window design with the connecting supports joined to the ends of the ceramic, and one in the form of the cold window with the supports over lapping the ceramic. In each case the supports will be extended to allow for mounting. These windows will undergo leak testing, thermal shocking, visual inspection and re leak tested. The aim of the tests is to confirm the suitability of the two designs for integration within the coupler.

CONCLUSION

The detailed development of the 1.5 GHz BESSY VSR higher power coupler design, from initial electromagnetic design to thermal analysis and the full mechanical model has been presented here along with a discussion of proposed diagnostics and testing. Special emphasis has been put on the challenges in the mechanical design that arise from the smaller scaling as a result of the higher frequency and how these can be solved or mitigated. Techniques and mechanical modifications to aid with tooling developed during this design process will be used when designing the 1.75 GHz coupler. The coupler tender for the 1.5 GHz and 1.75 GHz coupler was started in May 2019 with fabrication of the 1.5 GHz prototypes to begin in late September. With continuing design development for the 1.75 GHz BESSY VSR coupler running in parallel to ensure all components will be ready for VSR commissioning.

ACKNOWLEDGEMENT

The authors would like to thank our colleague A. Tsakanian for their valuable input and help. They would also like to acknowledge the discussion and support of our SRF group colleagues along with those working on the BESSY VSR project.

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