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FINAL DESIGN STUDIES FOR THE VSR DEMO 1.5 GHz COUPLER

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Abstract

With the 1.5 GHz couplers for the Variable pulse length Storage Ring (VSR) DEMO now in the manufacturing stages, the studies that led to the final coupler design will be presented. The system specific constraints and design modifications that combat the challenges of thermomechanical stresses, higher order mode (HOM) propagation and dimensional constraints are explored. This includes S-Parameter analysis, an in-depth study of the coupling factor, and multipacting studies for the average (1.5 kW) and peak (16 kW) power.

VSR DEMO

VSR DEMO is a research and development project within the Superconducting radio frequency (SRF) group at the Helmholtz Zentrum Berlin (HZB) that aims to validate SRF technology to achieve high current (300 mA) - high gradient (20 MV/m) – continuous wave (CW) operation enabling future projects such as BESSY VSR in storage rings but also high current CW operation in other machines. This will be done using an SRF module equipped with two 1.5 GHz SRF cavities and two fundamental power couplers along with ancillary components as shown in Fig. 1. This module will be commissioned at high power at HZB, with a beam test being considered the final validation step.

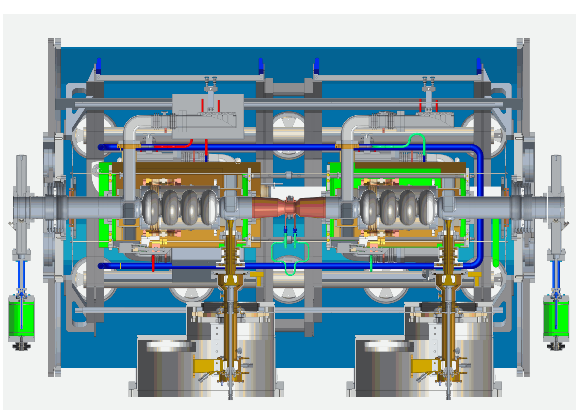

Figure 1: The VSR DEMO module showing the cold string components.

COUPLER DESIGN

The design for the VSR DEMO couplers started by scaling the well known 1.3 GHz Cornell coupler design [1,2] for operation at 1.5 GHz. This initial scaling and preliminary design changes can be seen in [3], however as the design progressed it became clear that the complex nature of VSR [4] and it cavities [5] significantly affected the design. Details of design studies relating to this are discussed in [6] and their final results are presented in this paper.

Figure 2 shows the full coupler, note the difference in coax dimensions between the warm and cold parts. The cold part has reduced coaxial dimensions to optimise coupling into the cavity and to reduce the propagation of HOMs in the coupler [7] which could cause critical damage. The warm coaxial dimensions are increased to provide better mounting and allow compressed air cooling of the warm inner conductor with sufficient flow rate to mitigate heating effects on the bellows during operation.

The coupler bellows are critical as they allow for control over the penetration depth of the coupler tip and hence the coupling level. However, bellows exposed to RF pose a heating risk. In the cold part this is mitigated by thinner copper coating and multiple intercepts. The warm bellows are more complex, in initial designs [3] temperatures of over 60 °C at peak power were observed on the bellows. The enlargement of the warm coax and the integration of compressed air cooling reduced this by 10 °C but additional steps were needed. Initially the warm bellows were almost half a wavelength long thus always saw peak field meaning more heating. By reducing the bellow length to 6 convolutions per bellow and changing their position this could be mitigated and the overall temperature on the bellows reduced to 43 °C. The reduced bellow length however limited the range of movement of the coupler tip to ± 4 mm.

The coupling level and external Q factor (Q_{ext}) is dictated by two key factors, the shape of the coupler tip and how far into the cavity it penetrates. The initial Q requirements for VSR were a range of Q_{ext} from $6{\times}10^6$ to $6{\times}10^7$. This allowed for a simpler tip than the Cornell coupler's 'pringle' tip. Initially a simple rounded tip was used [3], however, VSR DEMO requires horizontal coupler mounting and therefore the weight of the tip must be considered to avoid stresses on the cold ceramic window. A hollow open-ended tip reduces weight while avoiding an enclosed vacuum in the cold part and allowing for UHV cleaning. These modifications made a rounded tip unsuitable for VSR DEMO applications so further tip development was required. The finalised coupler tip is a hollow conical design with a wall thickness of 4 mm, which proved to be the best tip for VSR purposes.

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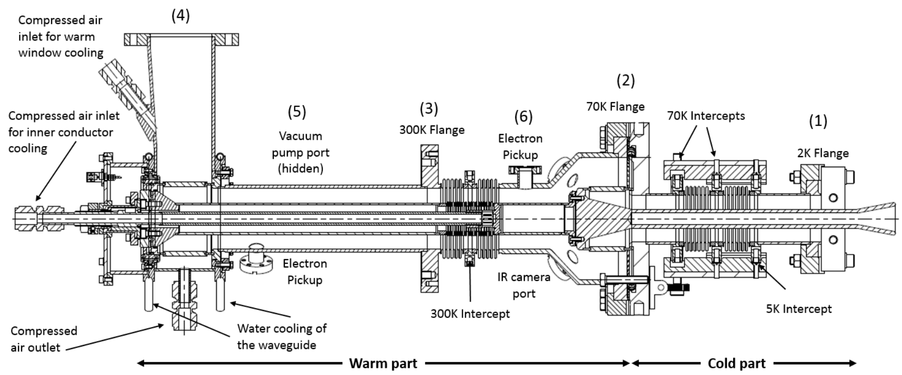

Figure 2: A labelled technical drawing of the full coupler.

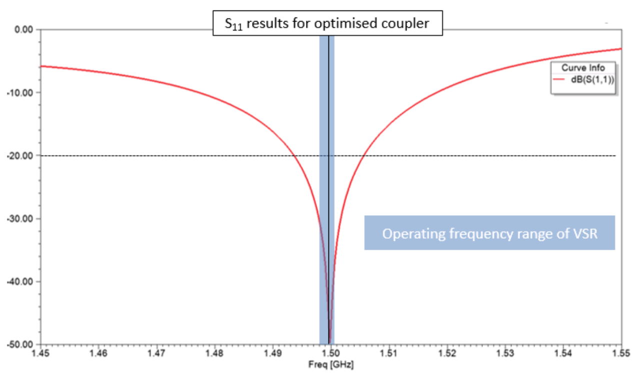

Figure 3: The S_{11} plot of the final coupler with the operational range for VSR DEMO superimposed over.

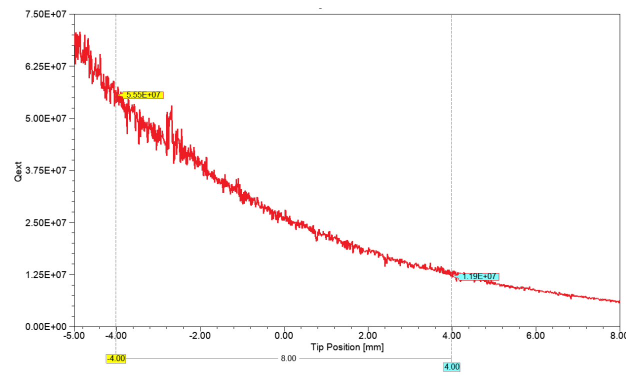

Figure 4: The Q_{ext} range achievable with a tip length of 333.9 mm and a range of movement of $\pm$ 4 mm.

S-PARAMETER ANALYSIS

The S-parameters give the level of transmitted and reflected power through the coupler, giving a measure of coupler performance. For ease of analysis S_{11}, the reflected power, is studied, the bigger the dip, the less power is reflected. A dip of -30 dB or below at 1.5 GHz, equivalent to 0.1% reflected power is the goal. Figure 3 shows the S_{11} result for the finalised coupler, here the value at the operational frequency is almost -50 dB and S_{11} remains below -30 dB across the whole operating frequency range of VSR. This simulation result will not translate fully to physical test results due to system losses, however with a simulation value of -50 dB at least -30 dB is hoped for in testing and operation.

Q ANALYSIS

In the initial plans for BESSY VSR the Q_{ext} range was set as a full order of magnitude from 6×10^6 to 6×10^7 to allow for the coupler to adjust to the behaviour of the machine, in particular to aid in low level RF factors such as the peak detuning.

To reach a full order of magnitude Q_{ext} range requires being able to move the coupler $\pm$ 6 mm however the design limits the range of movement to $\pm$ 4 mm. Figure 4 shows the Q_{ext} possible over the $\pm$ 4 mm range of movement, for a coupler with tip length 333.9 mm, measured from cold window to tip end. The available Q_{ext} range for this design is 1.19×10^6 to 5.55×10^7. However, this tip length can be changed to optimise the Q_{ext} range.

To determine the optimal range of Q_{ext} for stable operation, the data was analysed, with the aim to achieve as much of a tuning overhead as possible while maintaining an acceptable average power level. Figure 5 shows the results of the analysis, where the Q_{ext} plot is compared to that of power and detuning overhead. The desirable Q_{ext} range is indicated in this figure by the green box and is from 9.1×10^6 to 3.9×10^7 between -2 to 6 mm. Beyond 6 mm the power continues to increase, however the detuning overhead begins to flatten, so this fixes the max penetration. Therefore to optimise the Q response the coupler tip length must be increased by 2 mm to 335.9 mm.

MULTIPACTING ANALYSIS

Multipacting is the phenomena of resonant electron multiplication, where electrons are emitted due to the presence of high electric fields. These electrons are accelerated, hit another surface and force further electron emission causing an avalanche of emission leading to high power losses, heating, and performance degradation, an effect that should be avoided.

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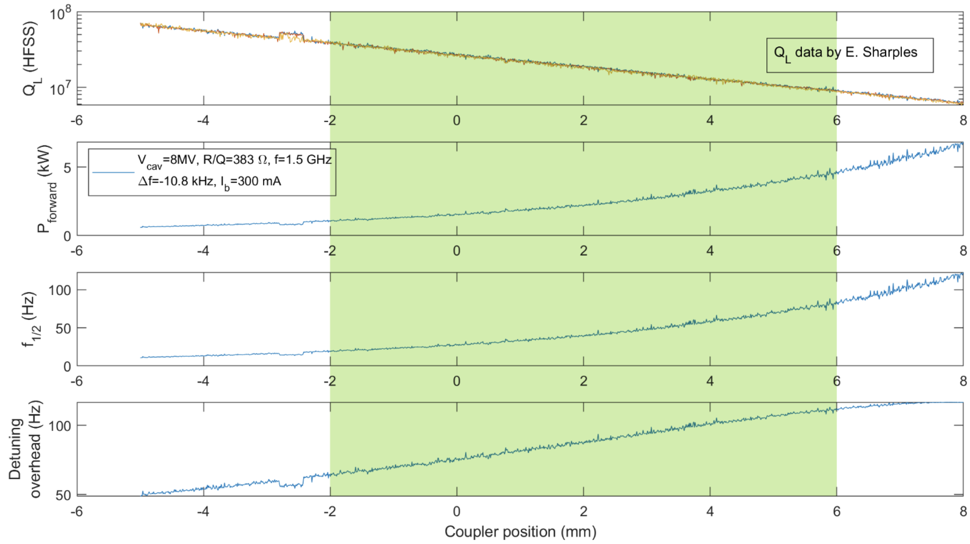

Figure 5: Plots comparing Q, power, and tuning overhead over the possible Q range of the coupler. The green box indicates the new Q range of the coupler.

The high power and high field coupled with the fine features of the design mean that multipacting is a potential risk for these couplers. Therefore, everything possible should be done to suppress multipacting. During the design this has been done by;

- Optimising the geometry of the coax for a higher impedance, to minimise resonant electron effects.
- Adding a blend radius to edges ensuring there are no sharp corners that see RF.
- Building in a DC bias that can be applied to the inner conductor to create additional fields that will shift the resonant conditions.

During the fabrication steps the potential for multipacting will be further suppressed by the coating of all ceramic windows with TiN to reduce the secondary emission yield (SEY) from 7 to 1.5, and the thorough cleaning of all RF surfaces. Finally, the conditioning of the couplers with RF will 'burn away' any final surface contaminants that could be sources of multipacting.

With the design modifications that mitigate multipacting already in place in the RF model, simulations were performed to see if multipacting is successfully suppressed. These simulations were performed at three different power levels: 1.5 kW the average power and 16 kW the peak power for VSR operation and 50 kW the power if the VSR couplers were to be used as injector couplers for the ring.

Figure 6 shows the number of emitted secondaries in the coupler for each power level, here the ceramics are coated with TiN and have an SEY of 1.5. After the initial excitement between 0-5 ns the level of emitted secondaries drops significantly for all power levels, though most significantly at the average power of 1.5 kW. For all power levels the

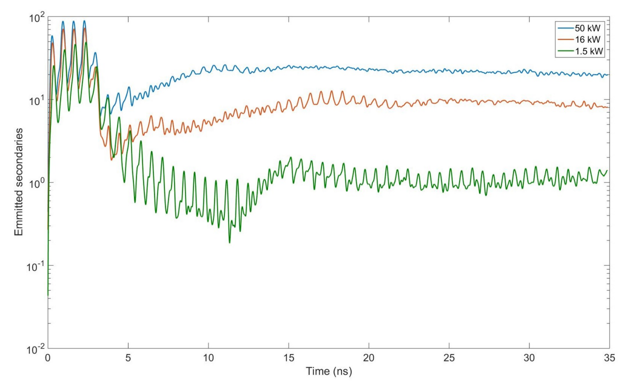

Figure 6: A log plot of the emitted secondariness in the coupler for three power levels, when windows are TiN coated.

number of emitted secondaries plateaus after 115 ns and then trends downwards. This is enough for multipacting to not be considered an issue however thorough cleaning and conditioning will still be performed and the DC bias is still built in for use if needed.

CONCLUSION

The coupler manufacture is now ongoing, the initial remote inspections have taken place and in house testing of samples is being performed now. The prototype couplers are due in house mid August 2021 with an aim to start conditioning early 2022. The next steps will be to finalise a cohesive testing plan and to follow up on the procurement and manufacture of a testing set up.

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