AXISYMMETRIC NUMERICAL STUDIES OF HIGHER ORDER MODE DAMPING TECHNIQUES USING RING FERRITES FOR BESSY VSR*

B. Riemann†, B.D. Isbarn, M. Sommer, T. Weis
TU Dortmund University (DELTA), Center for Synchrotron Radiation, Dortmund, Germany

Abstract

Utilizing superconducting multicell rf cavities with fundamental frequencies of 1.5 GHz and 1.75 GHz and therefore modulating the rf gradient, the upcoming BESSY II upgrade BESSY VSR aims to provide both short and long electron bunches simultaneously. However, beam induced excitation of higher order modes (HOM) inside those superconducting cavities is a major concern for beam stability in a recirculating accelerator. Thus it is important to develop and apply proper HOM damping techniques. Current design considerations involve HOM coupler which usually introduce discontinuities in the cross section while also breaking the axisymmetry. To circumvent these issues we investigate in a layout with ring ferrites as an alternative or additional HOM damping technique. We also present an alternative superstructure setup that uses two instead of four cavities for VSR.

INTRODUCTION

For the planned upgrade of the BESSY II storage ring called BESSY VSR [1,2], a total of ≈ 38 MV acceleration voltage needs to be applied in an installation space of 4 m length. Besides achievable acceleration gradients, successful installation of superconducting cavities in a high-current storage ring requires control of coupled-bunch instabilities by active [3] and passive means. The following study contains preliminary results about application of ferrite rings [4] into a four-cavity SRF system to damp its undesirable interaction with the beam by eigenmodes. After presenting the ferrite ring results, we draft an alternative cavity design using more cells, very large inner irises and less couplers, which should increase robustness of installation and operation.

FERRITE RINGS

A number of different approaches exist to damp eigenmodes in superconducting cavities. One solution being discussed for BESSY VSR is the application of waveguide dampers [5,6]. Ferrite rings [4] have the advantage to not break the cavity symmetry, which can reduce computational efforts and limit the study of asymmetries to the input couplers. For the following study, we assume that the rings made of silicon carbide have a loss angle of 0.5 rad, neglecting their detailed frequency dependencies but staying below the typical loss angles of the considered silicon carbide material in the frequency range below 12 GHz [7]. The used model is a modification of a cavity design made by A. Vélez for the $f_\mathrm{A} = 1.5$ GHz cavity [8].

* Work supported by the BMBF under contract no. 05K13PEB.
† bernard.riemann@tu-dortmund.de

Simulation Setup

Several tools exist to simulate electromagnetic fields in cavities, starting with 2D Superfish [9] using finite differences, 2.5D codes like URMEL [10] and CLANS [11] solver groups and full 3D FEM codes like COMSOL Multiphysics [12].

Although being able to solve 2.5D problems in principle, COMSOL does not allow solution of problems with cylindrical symmetry if the problem is non-coaxial respectively there is non-conducting material at $r = 0$. An inhouse-developed program for solving 2.5D cavity problems by finite elements with negligible computational overhead is working [13] but not yet ready to consider lossy materials.

Therefore, we use the COMSOL [12] 3D eigenmode solver on the provided cavity model as described in the following. To study monopole modes, the axial planes are assigned to magnetic boundary conditions. We add constrictions on the beam tube on which impedance boundary conditions are applied. For the purpose of simulating monopole modes in our context, it is sufficient to study a 45° slice of the cavity which does not significantly change the computed quantities (see Fig. 1).

Ferrite Ring Results for Original VSR Design

The scaling of modal quality factors as a function of ring distance is shown in Fig. 2. The exponential behavior for most modes indicates that only one evanescent waveguide mode is dominantly participating in the damping. The shown relations suggest that for proper damping of a 5-cell f_A cavity, more than $L^\mathrm{pip} = 0.15$ m of beam pipe length are required at each side.

From the assumption of one dominant waveguide mode representing each eigenmode's coupling through the beam pipe, one can estimate the needed beam pipe length for the $f_\mathrm{B} = 1.75$ GHz cavity. As the monopole waveguide cutoff frequency is ≈ 20.6 GHz, the spatial attenuation constant of

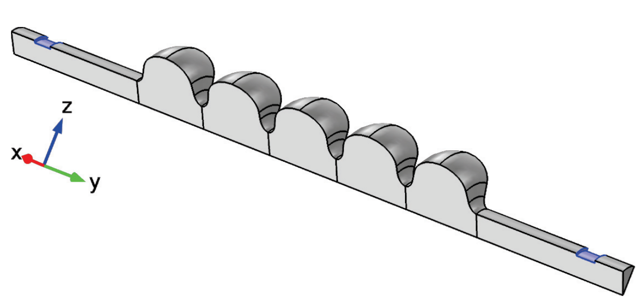

Figure 1: A rendering of the model used for computation with $L^\mathrm{pip} = 0.15$ m. The ferrite impedance boundary conditions (loss angle) are imposed on the blue-colored regions.

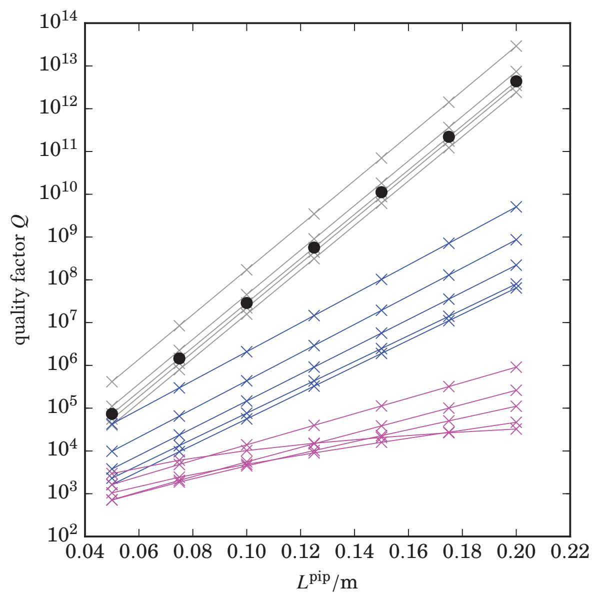

Figure 2: Scaling of Quality factors against beam pipe length for the first 3 monopole passbands in gray (1455–1500 MHz), blue (2627–2757 MHz), and magenta (3061–3226 MHz). The operational mode quality factor is denoted by black markers.

the waveguide mode will only decrease very slightly when considering f_B instead of f_A, and we will assume both distances as L^{pip} in the following.

While the resulting installation length used for damping $L^{\mathrm{pip}} < 0.2\,\mathrm{m}$ and therefore takes up less space than the HZB3 design [2], the waveguide damper contains additional space that can be reduced.

A TWO-CAVITY APPROACH

Although the current VSR cavity design has been specified for a total of four cavities [2], the physical constraints essentially consist of the overall applied voltage and all modal quality factors.

For each operation frequency, one may consider using a single cavity instead of using two cavities, so that one can create a superstructure in the form

ring ferrite – beam pipe – f_A cavity –
short beam pipe – f_B cavity – beam pipe – ring ferrite.

While this approach would require stronger intercell coupling to ensure sufficient damping, this would result anyway from using the f_B cavity with a minimal iris radius of 35 mm, which results in a large relative iris radius (corresponding to ≈ 47 mm in a 1.3 GHz cavity). Note that for the design, only the cavity-internal radii are enlarged, so that the (outer) beam pipe radius always remains at 35 mm. This is reasonable to provide sufficient attenuation of the operation eigenmode fields below the pipe cutoff frequency.

As the described installation only contains two cavities, there are no enclosed cavities in between and the mode damping installations can be reduced to the outer ends of the superstructure if sufficient mode propagation inside the cavity is ensured (by large irises). To compensate for the resulting increase in $E_{\mathrm{peak}}/E_{\mathrm{acc}}$ [14, 15], the cavity would need significantly more cells, e.g. 9 or 11.

Two N-cell Cavities with Ferrite Rings

When assuming a N-cell design, this would result in a total superstructure length of

$$\begin{aligned} L_{\mathrm{tot}} &= N(L_A + L_B) + 2L^{\mathrm{pip}} + \Delta \\ &= NL_A(1 + f_A/f_B) + 2L^{\mathrm{pip}} + 2L_A, \end{aligned}$$

where we assumed that the inner endcells of the superstructure are separated by a distance $\Delta = 2L_A = 0.2\,\mathrm{m}$.

For $N = 9$, achieving acceleration voltages of 20 MV on 0.9 m (gradient: 22.22 MV m^{-1}) is close to the design limit of the original TESLA cavities [16], which do not use large iris diameters. It is therefore necessary to increase the number of cells even further. The length can be found for different values of N in Fig. 3.

Two N-cell Cavities with Waveguide Couplers

As has been stated in the first section, ring ferrites take up more space than waveguide couplers for the considered frequencies. Therefore, it might be possible to use waveguide couplers with the presented two-cavity approach. The necessary pipe space is replaced with L_A resp. $L_B = f_A/f_B$ for each cavity, so that

$$L_{\mathrm{tot}} = (N + 4)L_A + (N + 2)L_B$$

The installation length can again be observed in Fig. 3.

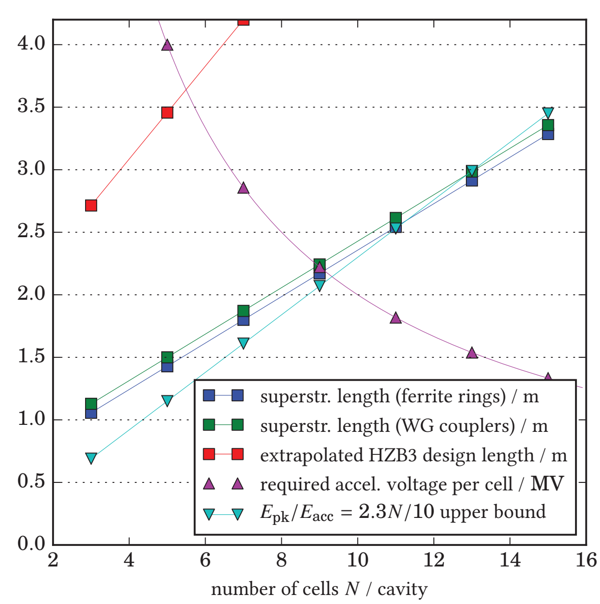

Figure 3: Scaling of some figures of merit for two-cavity N-cell structures. The $E_{\mathrm{pk}}/E_{\mathrm{acc}}$ bound is extrapolated from the HZB design goal ≤ 2.3 for 2 × 5 cells [2].

ISBN 978-3-95450-147-2

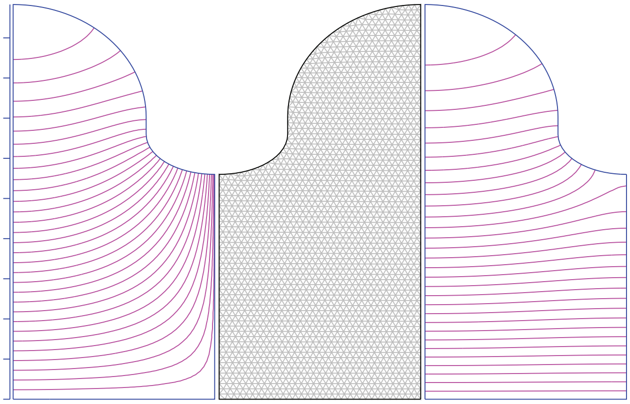

Figure 4: Mesh and electric field lines from a simulation [9] of a rectangular-wall shaped cavity with an iris radius of 56 mm, a π-mode frequency of 1502.6 MHz, a passband extending to a 0-mode frequency of 1350.0 MHz, $R/Q = 27.35\,\Omega$ per cell and $E_{\mathrm{peak}}/E_{\mathrm{acc}} = E_{\mathrm{peak}}/(E_0 T) = 2.833$.

Two $N \geq 15$-cell Cavities

The aforementioned calculations, and the fact that the $E_{\mathrm{pk}}/E_{\mathrm{acc}} \leq 2.3$ bound is imposed on the two 1.5 GHz cavities in the original design [2], result in a 15-cell cavity having a $E_{\mathrm{pk}}/E_{\mathrm{acc}} \leq 3.45$ bound. This is achievable e.g. by the elliptical cavity design shown in Fig. 4. This design has a very large iris radius of 56 mm resulting in a relative passband width of $2(f_\pi - f_0)/(f_\pi + f_0) = 0.107$.

With this inner cell design for a 15-cell A cavity, a operation mode quality factor of 5×10^7 and an input power of 10 kW [2], a total voltage of 20.25 MV is possible. Scaling the inner cell design for the f_{B} cavity is also feasible, as no further constraints apply due to the large iris. As R/Q scales with f [14], it should therefore also be possible to generate sufficient acceleration voltage for the f_{B} cavity.

SUMMARY

A ferrite ring design was investigated for HOM damping of the four VSR cavities described in [2]. For this specific purpose, ring ferrites seem to be equivalent or slightly better than waveguide dampers.

The proposed design of a two-cavity 15-cell superstructure with its large intercell coupling is likely to have the following advantages compared to the four-cavity design.

- More robust field stability against perturbations.
- Posessing less "trapped modes", also due to the low number of end structures, which will decrease quality factors of higher-order modes.
- Deviating less from single-cell study results, again due to low number of end structures.
- Being tunable with higher precision.

For at least one of the proposed installations, further studies need to be performed to optimize the respective superstructure and validate sufficient damping of eigenmodes that can possibly interact with the beam in an undesirable manner, following many of the steps discussed in [17].

REFERENCES

[1] G. Wüstefeld et al., "Simultaneous long and short electron bunches in the BESSY II storage ring", in *Proc. IPAC'11*, THPC014 (2011) http://accelconf.web.cern.ch/accelconf/ipac2011/papers/thpc014.pdf

[2] A. Jankowiak, J. Knobloch et al. (ed.), "BESSY VSR, Variable pulse length Storage Ring, Upgrade of BESSY II", Technical Report (June 2015), http://dx.doi.org/10.5442/R0001

[3] M. Ruprecht, "Calculation of Coupled Bunch Effects in the Synchrotron Light Source BESSY VSR", Ph.D. Thesis, Humboldt-Universität zu Berlin, Berlin, Germany, 2016. URN: urn:nbn:de:kobv:11-100237038

[4] L. Merminga, "Recirculating and Energy Recovery Linacs", In: A.W. Chao and M. Tigner (ed.), *Handbook of Accelerator Physics and Engineering*, 3rd printing (World Scientific, 2009).

[5] T. Galek et al., "Aspects of SRF Cavity Optimization for BESSY-VSR Upgrade", in *Proc. IPAC'15*, MOPWA032 (2015), http://accelconf.web.cern.ch/AccelConf/IPAC2015/papers/mopwa032.pdf

[6] A. Vélez et al., "HOM Damping Optimization Design Studies for BESSY VSR Cavities", in *Proc. IPAC'15*, WEPMA013 (2015), http://accelconf.web.cern.ch/AccelConf/IPAC2015/papers/wepma013.pdf

[7] Measurement of losses for SC-35 material from F. Marhauser, transmitted by A. Neumann and B. Isbarn, personal communication (2016).

[8] A. Vélez, personal communication (HZB, 2016).

[9] K. Halbach and R.F. Holsinger, "SUPERFISH - a computer program for evaluation of RF cavities with cylindrical symmetry", Part. Acc. **7**, pp. 213–222 (1976).

[10] U. Lauströer, U. van Rienen and T. Weiland, "URMEL and URMEL-T user guide", DESY report M-87-03 (1987), http://cds.cern.ch/record/177734

[11] D.G. Myakishev and V.P. Yakovlev, "CLANS2 - A code for calculation of multipole modes in axisymmetric cavities with absorber ferrites", in *Proc. PAC'99*, pp. 2775–2777 (1999), http://inspirehep.net/record/517532

[12] COMSOL Multiphysics 5.2, COMSOL, http://www.comsol.com

[13] B. Isbarn et al., "Yacs – Progression towards isoparametric 2.5D finite elements", in *Proc. IPAC'16* (this conference), WEPOY060 (2016).

[14] T.P. Wangler, *RF Linear Accelerators*, second edition (Wiley, 2008).

[15] E. Haebel and A. Mosnier, "Large or Small Iris Aperture in SC multicell cavities ?", Proc. SRF91, pp. 823–835 (Hamburg, 1991), http://accelconf.web.cern.ch/accelconf/SRF91/papers/srf91f23.pdf

[16] B. Aune et al., "Superconducting TESLA cavities", Phys. Rev. ST Accel. Beams **3**, 092001 (2000).

[17] N. Valles, "Pushing the Frontiers of Superconducting Radio Frequency Science: From the Temperature Dependence of the Superheating Field of Niobium to Higher-Order Mode Damping in Very High Quality Factor Accelerating Structures", Ph.D. thesis, Cornell University (2014).