ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM045

DEVELOPMENT OF SINGLE MODE CAVITY AT 1.5 GHZ FOR THE THIRD HARMONIC RF-SYSTEM IN PETRA IV

S. Karau†, M. Bousonville, S. Choroba, P. Hülsmann
Deutsches Elektronen-Synchrotron, Hamburg, Germany

Abstract

The PETRA IV storage ring currently under development at DESY will require a third harmonic 1.5 GHz RF-system to prevent negative effects on both, lifetime and emittance, caused by Touschek effect and Intrabeam scattering. These cavities lengthen the bunches and thereby reduce their charge density.

For this 3rd harmonic system, a one-cell single-mode cavity with a simple mechanical and electrical structure is under design that should also reduce Higher Order Modes (HOMs) to a quality factor less than 100. Therefore, the well-known approach of the Choke Mode Cavity was chosen, that use a radial line damper to attenuate the HOMs and a radial choke that traps the acceleration mode.

The general behaviour of the choke mode structure was simulated, discussed and optimized for the requirements of a one-cell cavity with high effective shunt impedance, high-quality factor and simple manufacturing.

INTRODUCTION

The excitation of Higher Order Modes (HOMs) of accelerating cavities can reduce the quality and stability of particle bunches. This is a particular problem on storage ring because of the short decay time during multiple runs and limits the quality of the brightness of synchrotron radiation. Therefore, single mode cavities – an accelerating cavity designed in such a way that all modes that can interact with the accelerated particles, except the desired acceleration mode, will leave the cavity through a coupling system into RF-absorber [1, 2] – are particularly well-suited for storage rings to retain the efficiency of the acceleration mode but decay all critical HOM quickly. Various approaches of single-mode cavities have been considered over the past decades with different advantages and disadvantages [1, 2, 3].

According to the voltage- and the redundancy requirements in PETRA IV a total number of 24 fundamental 500 MHz HOM damped cavities and the same number of third harmonics 1.5 GHz HOM damped cavities are foreseen [4]. The large number of cavities also ensures that operating costs are kept within limits. Each cavity of the total number of 48 cavities is driven by its own solid-state amplifier (SSA). The fundamental 500 MHz RF-system will be equipped with the reliable and well-known BESSY HOM damped cavities with three circular double ridged waveguide dampers [5]. Meanwhile ALBA has developed and manufactured a 1.5 GHz version of the 500 MHz BESSY HOM damped cavity. In the frame of a collaboration between ALBA, HZB and DESY the cavity was conditioned successfully at HZB and is already integrated in BESSY II where the desired bunch extension by a factor of three could already be demonstrated very successfully in operation with beam. The realization of the HOM damped cavity – scaled roughly by the factor three – is mechanically difficult and extremely expensive, especially by the fabrication of the smaller high-power coupler, frequency tuner, ridged HOM damper waveguides and the complicated cooling system. This is the reason to look for other alternative cavities.

One of these very simple structures is the Choke Mode Cavity which was presented in 1992 as a single-cell with a comparison to a simple pill-box [3] and was used for the design of the multi-cell C-Band accelerator cavity of SACLA X-ray laser [6, 7]. The concept of the cylindrically symmetrical structure is shown in Fig. 1 with an inner region the beam passes through and should be accelerated by the TM_{010} mode and a radial line as an outer region ending with an RF-damper that strongly reduces the quality factor of all TM modes. A serial shorted stub – named as choke – is added into the radial line to get full small band reflection at the frequency of the TM_{010} mode to avoid the damping of the desired accelerating mode.

The first development steps of a simple one-cell Choke Mode Cavity at 1.5 GHz as a possible cavity of the 3rd harmonic system for PETRA IV are the content of this paper.

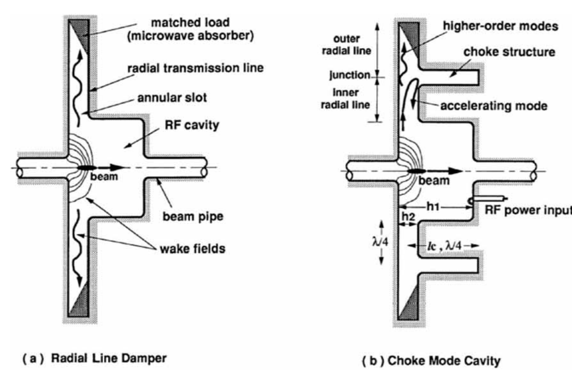

Figure 1: Concept of the Choke Mode Cavity, left without and right with the reflective choke structure [3].

GENERAL CHOKE MODE STRUCTURE

The development of the Choke Mode Cavity for the 3rd harmonic system of PETRA IV started with a review of the exemplary cavity model of the first presentation of the general idea of the Choke Mode Cavity [3]. The simple 2.867 GHz pillbox added by a radial line damper and a choke was simulated by CST Frequency Domain and Eigenmode Solver. After good agreement, the design was scaled to 1.5 GHz and the radial line damper with the choke was considered more deeply.

† simon.karau@desy.de

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM045

The radial line damper and the choke are electrically parallel plate waveguides and are supporting a TEM mode without cutoff frequency with the wavenumber $k = k_0$ of free space [8]. For an understanding of the effect of the choke a transmission line model can be used [9]. The load impedance of the parallel plate waveguide at the junction of the choke is the addition of the load impedance of the damper and the choke impedance. When the length of the choke is $\lambda/4$ the short is transformed into an open and the impedance is infinity independent of the damper impedance. This is used to get full reflection at the resonance frequency of the acceleration mode TM_{010}. The infinity impedance will be transformed again along the length back to the cavity and will be a short after a length of $\lambda/4$.

The parallel plate waveguide structure was separately simulated by CST Frequency Domain Solver – neglecting the radial increasing of the width – with two magnetic walls. The s-parameters are given in Fig. 2 and show full reflection at 1.5 GHz and its third resonance with a second full reflection at 4.4 GHz. The beam-pipe of PETRA IV will have a diameter of 46 mm and the first circular waveguide modes TE_{11} and TM_{01} will have the cutoff frequencies 3.82 GHz and 4.99 GHz. Accordingly, all critical HOMs with resonance frequency higher than approximately 5 GHz can be damped by excitation of beam-pipe modes and only the first and second full reflection frequencies must be regarded.

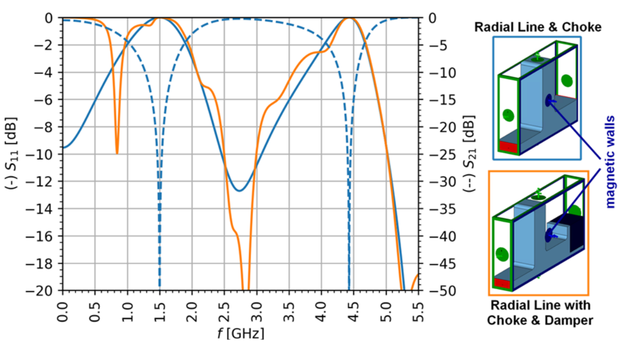

Figure 2: Simulated S-Parameters of parallel plate waveguide models of the radial line with a choke (2 ports) and of the structure with an exemplary damper (1 port).

To get an example of the mode damping by the radial line structure, a simple pillbox with length of 100 mm – very next to the half-wavelength at 1.5 GHz – was simulated alone and with the radial line damper with a choke. Because the damper material and structure have not yet been selected an exemplary damper was used and rough optimized by simulation of a parallel plate waveguide model, again with two magnetic walls by CST. Therefore, the idea of a single ring of Silizium Carbid (SiC) of the 5.712 GHz cavity of SACLA x-ray FEL [7] was adopted. The exact material parameters of SiC vary widely between manufacturing techniques and frequency [10]. In order to make rough considerations possible before actual material measurements, rough values of the permittivity of $\varepsilon_r = 20$ with $\tan\delta_E = 0.25$ were used for the simulations, neglecting the frequency dependency. The matching of the simulated parallel plate waveguide model of the radial line structure with the SiC-ring damper is shown in Fig. 2.

The 100 mm pill-box was simulated by CST Eigenmode Solver alone and with the radial line structure. The modes were assigned by the electric and magnetic fields, verified with analytically calculated resonance frequencies and are shown in Fig. 3 together to get an overview of the reduction of the quality factor by the radial line damper structure.

All critical TM modes are strongly reduced, as examples $Q_0(TM_{110})$ is reduced from about 31,900 to 14 and $Q_0(TM_{020})$ from about 38,300 to 460 at 3.402 GHz. The quality factor of the acceleration mode TM_{010} is reduced from about 25,400 to 21,700 which corresponds a reduction to 85% and the effective shunt impedance $R_{sh,eff}$ (European definition) in the axis direction from 2.485 MΩ to 1.960 MΩ which corresponds a reduction to 79%. The reason for these reductions is the energy of the standing wave in the choke structure, which increases the losses of the cavity without being a part of the accelerating electric field.

The TE modes can generally not interact with the beam but the most of them are also reduced by the radial line structure – except the TE_{0nq} modes which have no current flow in the cavity wall into the axis direction and therefore cannot excite the TEM mode of the radial line. Other very small reductions are found on $Q_0(TM_{310})$ and $Q_0(TE_{122})$ with resonance frequencies next to the second full reflection of the choke at 4.4 GHz.

Furthermore, the existence of the radial line structure also creates new modes, but most of them have a very small quality factor and have no field in the beam-line and are not shown in Fig. 3. A special case is a critical mode at 406 MHz which is a mixture of the evanescent TM_{01} mode of the pill-box and the TEM mode of the radial line structure which is marked as TM_{010} subharmonic in Fig 3. Its electric vector field is shown in Fig. 4 – together with the acceleration TM_{010} mode – and should not be disregarded during the design of such a single-mode cavity.

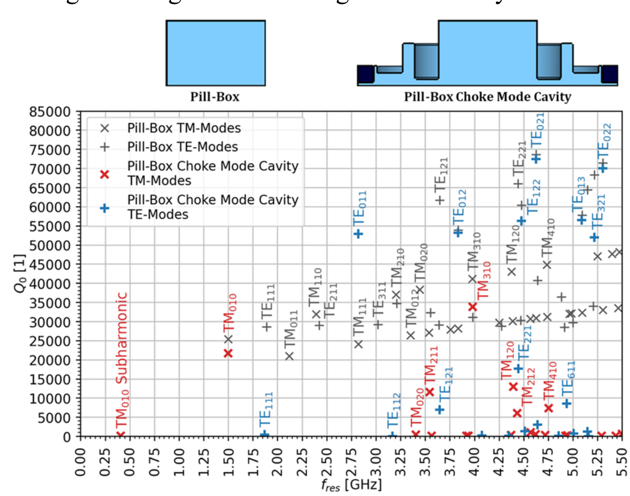

Figure 3: Cutting plane of the 100 mm pill-box alone and with a radial line damper structure and an overview of simulated resonance modes with $Q_0 \geq 100$.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM045

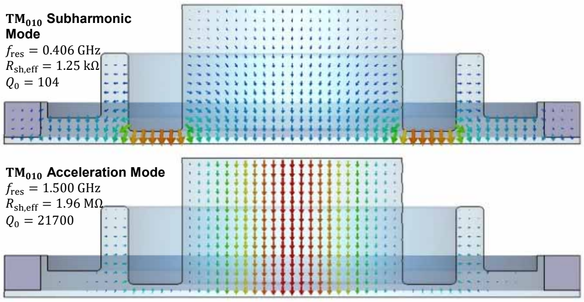

Figure 4: Electric vector field of the TM_{010} acceleration and subharmonic modes of the pill-box Choke Mode Cavity.

NOSE-CONE CHOKE MODE CAVITY

After an analysis of the radial line structure on an ideal half-wavelength pill-box, the effect of the beam-pipe should be considered. The acceleration mode TM_{010} of the pill-box would excites the evanescent TM_{01} mode of the beam-pipe which expands the length of the axial electric field. Therefore, the length of the pill-box must be reduced to get again the perfect Transit Time Factor, which decreases the quality factor.

For an optimization of the cavity with the beam-pipe noses at the transitions between cavity and beam-pipe were introduced which increase the stored energy. To further reduce the losses, the edges of the cavity should be rounded, but the junction between an optimized nose-cone and the radial line damper should be on the back side of the cavity – to ensure that all TM modes can excite the radial line efficiently – and only the front side could be rounded. This rounding was optimized together with the distance between the noses, their length and angle to get a maximum effective shunt impedance $R_{sh,eff}$ in the axis direction of the acceleration TM_{010} mode. The optimized nose-cone alone and with the radial line structure was simulated by CST Eigenmode Solver. Due to the rounding and particular due

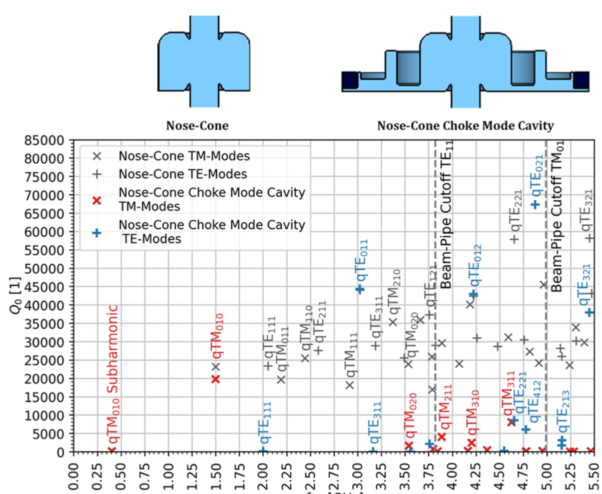

Figure 5: Cutting plane of the nose-cone alone and with a radial line damper structure and an overview of simulated resonance modes with $Q_0 \geq 100$.

to the noses, the resonant modes no longer consist of only one TM or TE waveguide mode, but more complex hybrid modes. Nevertheless, these modes each correspond to a mode of the ideal pill-box and can be compared with them. These modes are shown in Fig. 5 called as qTM and qTE (quasi-TM and quasi-TE following the naming of the quasi-TEM modes of PCB microstrip lines).

The acceleration qTM_{010} mode of the Choke Mode Cavity with nose-cone optimization has a quality factor of about 19,800 and an effective shunt impedance in the axis direction of 1.704 MΩ, which are again 85% of the quality factor 23,200 and 78% of the effective shunt impedance 2.194 MΩ of the nose-cone without the radial line structure. Also, a qTM_{010} subharmonic is found at 405 MHz with a quality factor of 106 and an effective shunt impedance of 1.3 kΩ. The most modes with resonance frequencies next to the second full reflection of the choke are damped by excitation of traveling modes of the beam-pipe. The remaining qTM mode with the highest quality factor $Q_0(qTM_{321}) \approx 8{,}000$ cannot interact with the beam because it has no electric field in the beam-line. The only critical higher order qTM mode that is not strongly reduced is the qTM_{020} with a remaining quality factor of about 1,600 and an effective shunt impedance of 2.8 kΩ at 3.542 GHz. A possible reason of the smaller reduction – in comparison with the pill-box model – can be a less efficient excitation of the radial line by the mode because of field displacement caused by the nose. Another reason can be the difference of the matching between 3.402 GHz and 3.542 GHz which is found in the simulation of the parallel plate waveguide of the radial line damper structure shown in the Fig. 2 – with a matching of 4.3 dB in comparison of 5.5 dB – which should be carefully considered during the design of the practical damper system.

CONCLUSION

The general approach of the Choke Mode Cavity was examined in more detail with simulations of a simple pill-box example, whereby the radial line structure was also analyzed separately – with certain neglection. The first development steps for a practically usable 1.5 GHz single-cell Choke Mode Cavity as a possible single-mode cavity for the 3rd harmonic system of PETRA IV have been taken and strong damping of almost all critical HOMs was reached by simulations.

The next design step is the development of an appropriated coupler and tuner system, for which various approaches are currently being considered. Another important step is the selection of a vacuum-suitable material and structure of the damper, which is also sufficiently attenuate at the low frequency of the TM_{010} subharmonic mode that is created by the choke structure. In addition to a SiC-ring, other vacuum-suitable dampers are possible or an array of coaxial loop current probes with external dampers could be used. After that a prototype should be created and measured.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM045

REFERENCES

[1] R. M. Sundelin *et al.*, "Parallel Coupled Cavity Structure", *IEEE Trans. Nucl. Sci.*, vol. NS-24, pp. 1686-1688, 1977.

[2] H. Herminghaus *et al.*, "Beam Blow-up in Race Track Microtrons", *Nucl. Instrum. Methods,* vol. 163, pp. 99-308, 1979.

[3] T. Shintake, "The Choke Mode Cavity", *Jpn. J. Appl. Phys.*, pp. L 1567-L1570, 1992.

[4] PETRA IV, "PETRA IV Conceptual Design Report", DESY, Hamburg, https://bib-pubdb1.desy.de/record/426140/files/DESY-PETRAIV-Conceptual-Design-Report.pdf

[5] F. Marhauser and E. Weihreter, "First Tests of a HOM–Damped High Power 500 MHz Cavity", in *Eur. Part. Accel. Conf.*, Lucerne, Switzerland, 2004.

[6] T. Shintake *et al.*, "HOM-Free Linear Accelerating Structure for e+e- Linear Collider at C-Band", in *Proc. Part. Accel. Conf. Int. Conf. High Energy Accel.*, Dallas, USA, 1995.

[7] T. Inagaki *et al.*, "High-gradient C-Band Linac for a Compact X-Ray Free-Electron Laser Facility", *Phys. Rev. ST Accel. Beams*, vol. 17, p. 080702, 2014.

[8] D. M. Pozar, "*Transmission Lines and Waveguides*", Microwave Engineering, John Wiley & Sons, Inc., 4th ed., 2012, pp. 102-110.

[9] H. Zha *et al.*, "Choke-Mode Damped Structure Design for the Compact Linear Collider Main Linac", *Phys. Ref. ST Accel. Beams*, vol. 15, p. 12200, 2012.

[10] Y. Takeuchi *et al.*, "Rf Dielectric Properties of SiC Ceramics and their Application to Design of HOM Absorbers", in *Proc. PAC'05*, Knoxville, Tennessee, May 2005, paper WPAT010.