A CHOKE-MODE-CAVITY WITH ADJUSTABLE COUPLER FOR THE THIRD HARMONIC RF-SYSTEM OF PETRA IV

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Abstract

The future fourth-generation synchrotron radiation source PETRA IV at DESY requires 24 third-harmonic cavities. Due to the large number of cavities, DESY decided in 2021 to launch an in-house cavity development program designed to meet several criteria: first, the cavities must be easy to manufacture; second, the cavity should be designed to prevent the excitation of higher-order modes (HOM) as much as possible; third, the HOM damping system should be as simple as possible; and fourth, the cavity should be equipped with an RF coupler that is variable during beam operation and covers as wide a range of the coupling factor as possible. The first two conditions are met only by so-called single-mode cavities. Among the few candidates for single-mode cavities, the so-called choke-mode cavity was selected as the one most likely to satisfy all four conditions. The cavity design has already been completed, and the cavity is currently under construction. This paper describes the cavity's functions and highlights several aspects, such as the operation of the variable coupler and the HOM damper power load during future PETRA IV operation.

INTRODUCTION

The future PETRA IV [1] will use 24 EU Higher-Order-Mode (HOM) damped cavities [2] for the fundamental 8.0 MV, 500 MHz RF-system. In order to reduce the influence of Touschek effect and intrabeam scattering on lifetime, 24 3rd harmonic HOM damped cavities are going to be installed to lengthen the bunches and thereby to lower their particle densities [1]. Both the 500 MHz fundamental- and the 1.5 GHz third-harmonic RF systems will consist of single-cell cavities, with each cavity fed by its own solid-state amplifier (SSA) [1]. The third harmonic cavities have to provide an overall voltage of 2.2 MV which means a gap voltage of 92 kV for each cavity.

The baseline design for PETRA IV harmonic RF consists of 24 third-harmonic cavities of the ALBA HOM-damped cavity type [3, 4]. The ALBA cavity at BESSY II (HZB) has already demonstrated that, as a third-harmonic cavity, it would be a good choice for PETRA IV [4]. However, with 24 cavities required, the number is so large that both the cost of manufacturing the cavities and the cost of integrating them into the infrastructure must be carefully considered. By "connection to the infrastructure," we mean the cooling water connection—for example, how many independent cooling water circuits need to be supplied and what are the requirements for the vacuum system. Consequently, we started in 2021 the investigation of various so-called single-mode structures [5, 6] and among them we selected the "choke-mode cavity" [5, 7]. Figure 1 shows the basic structure of the DESY-Type-Choke-Mode Cavity [8]. If you disregard the coupler and the tuner, the cavity is azimuthally symmetric and very compact in the radial direction, since no HOM-damping waveguides are required and the cavity consists of only two parts: the actual cavity body with the chokes and the back plate. Figure 1 shows only a partial view of the cavity. The complete design will be presented in THP2006, this conference [8].

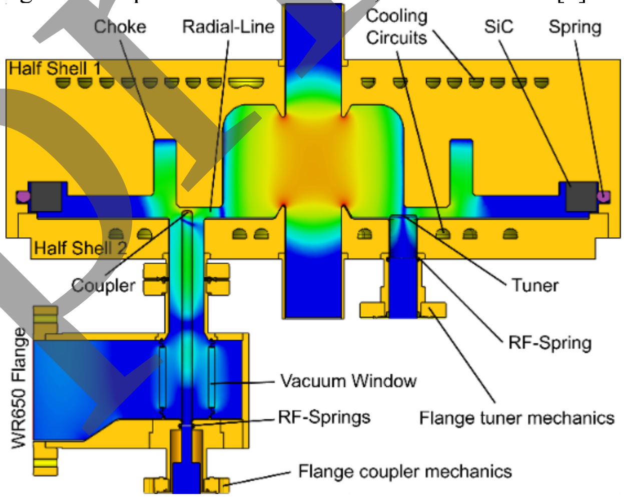

Figure 1: Sketch of choke mode cavity half shells with cooling circuits, tuner and adjustable coupler.

THE DESY TYPE CHOKE MODE CAVITY WITH ADJUSTABLE COUPLER

The Basic Principles of the Choke Mode Cavity

The cavity consists of a simple pillbox equipped with a continuous azimuthal coupling slot on its outer wall. The coupling slot opens into a radial parallel-plate waveguide that is terminated at the end with a highly damping material that serves as an HOM damper [5, 8]. This HOM damper is a SiC-ring [9-11]. All TM-modes, including the TM_{010}-fundamental mode, would be severely damped by the presence of the coupling slot if no further measures were taken. To prevent attenuation of the fundamental mode, a device known as a choke is used, whose function is to transform the short-circuit condition into the azimuthal slot for the fundamental mode.

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The presence of the azimuthal coupling slot causes all relevant transversely deflecting HOM-modes to be strongly attenuated. This includes the TM_{110} mode, which is a dipole mode that possesses the highest transverse shunt impedance. Electromagnetic models in CST Microwave Studio show that the HOM-damper works excellently up to the cut-off-frequency of the beam pipe which is about *5 GHz* (*23 mm* beam pipe radius), hence the cavity is called a single mode cavity. Above the cutoff frequency, there are again a number of modes, but these are no longer relevant for beam dynamics. In this respect, the term "single-mode structure" should not be taken literally.

The choke cavity (Fig. 2) can be understood as a quarter-wave impedance transformer. For $l_{ch} = \lambda_{\chi h}/4$, the choke entrance behaves as an open circuit ($\Gamma_{ch} = +1$).

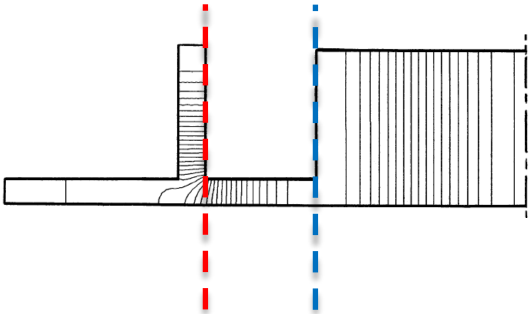

Figure 2: Schematic sketch of a choke mode cavity half [6].

$$\Gamma_{ch} = \frac{Z-Z_r}{Z+Z_r} = \frac{\frac{R-Z_r}{jZ_{Ch}\tan(\beta_{Ch} l_{Ch})}+1}{\frac{R+Z_r}{jZ_{Ch}\tan(\beta_{Ch} l_{Ch})}+1}, \qquad (1)$$

$$\Gamma_{ch} \to 1 \, for \, l_{ch} \to \frac{\lambda_{ch}}{4}$$

After transformation through the radial line over an additional quarter wavelength the reflection coefficient changes sign, yielding $\Gamma_E = -1$. Thus, the entrance of the azimuthal slot appears as an effective short circuit at the operating frequency

$$\Gamma_E = \Gamma_{ch} e^{-j2\beta_r l_r} = \Gamma_{ch} e^{-j\pi} = -1. \qquad (2)$$

Z_{ch} and Z_r are the line impedances of the choke coaxial- and radial transmission line, l_{ck} and l_r are the length of choke- and radial transmission line, R is the resistance of the SiC-ring for the TEM-mode at *1.5 GHz* and, finally, β_{ch} and β_r are the wavenumbers of the choke coaxial- and radial transmission line.

Table 1: Basic Parameters of PETRA IV

Parameter	Value
Resonance frequency f0	1.5 GHz
Shunt impedance R_{sh}	1.6 MΩ
Unloaded quality factor Q_0	19000
R_{sh}/Q_0	84 Ω

Based on the simulations with CST-MWS, the choke-mode cavity has the key parameters listed in Table 1.

The Concept of Coupler and Tuner

Simulations using CST-MWS optimized the arrangement of the coupler and tuner so that they operate as effectively as possible. Figure 1 shows that the dipole coupler is optimally positioned at a location of high electric field strength, while the tuner is optimally positioned at the location of maximum magnetic field strength. A minor drawback of this coupler and tuner arrangement is the breaking of the cavity's azimuthal symmetry, depending on how far the coupler and tuner protrude from or extend into the cavity's backplate. This results in a small parasitic power flow from the fundamental mode into the HOM damper. This parasitic power flow does not exceed about *26 W* under PETRA IV standard operating conditions

Given the simplicity of a dipole coupler in terms of adjustability, we decided to design the coupler to be movable, which essentially means that we can change the coupling factor while the cavity is in operation. Figure 3 shows the range within which the coupling factor can be adjusted. If the coupler is moved from approximately *-5.5 mm* to *+5.5 mm* (zero reference is the cavity wall), this results in a significant change in the coupling factor, ranging from approximately *0.2* to *5.0*. Meanwhile, the shunt impedance and resonance frequency change only slightly, which is a result of the optimization of the coupler's exact radial position using CST-MWS simulations.

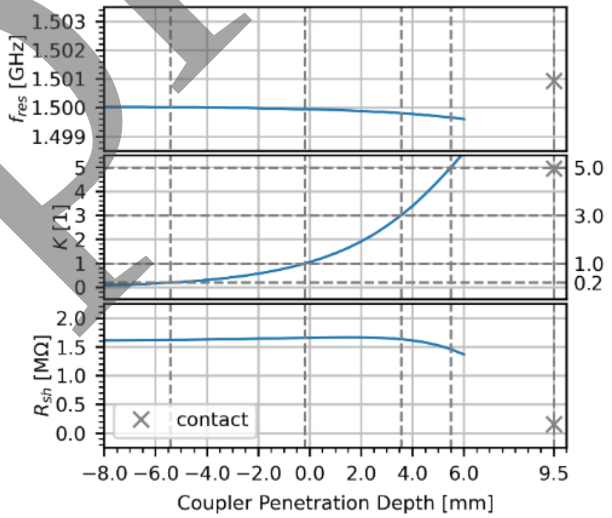

Figure 3: Shunt impedance R_{sh}, resonance frequency f_{res} and coupling factor K depending on the penetration depth of coupler. *0.0 mm* means the inner conductor is in the same plane as the cavity back wall; *+9.5 mm* means the inner conductor is in electrical contact with the opposite side of the cavity.

Such an enormous variation of coupling factor would not be thinkable by using a stub-matching technique. An adjustable coupler has different advantages:

If the cavity operates actively detuned with beam for minimum RF-power consumption an optimized coupling factor has to be applied depending on the beam current. If beam current changes, the coupling factor can be adjusted accordingly.

The variable coupling factor helps to decouple the resonator from the beam. Due to the synchronous phase of -102.8 degrees, both the beam and the RF generator generate the gap voltage. At a coupling factor of $K = 3$, the contributions to the gap voltage are roughly equal. When $K \geq 3$, the RF- generator dominates. The decoupling from the beam, combined with an increase in K, results in a decrease in impedance which lowers the risk of an excitation of coupled bunch instabilities.

POWER LOAD FOR THE HOM-DAMPER

We will calculate here analytically [12] as well as by simulations with CST-MWS [13] the HOM power load at all frequencies in standard operation at PETRA IV. The analytical method is based on an approach developed by R. B. Palmer in 1987 at SLAC [12] to calculate the overall energy loss of ultra relativistic, very short bunches during their passage through a cavity. Using simulations with CST-MWS, we have determined that B. Palmer's method also works for long bunches, as long as they are ultra relativistic [8]. According to [12] the HOM-power radiated into the load is given by

$$\begin{aligned}\Delta P_{HOM} &= (k(\sigma_l) - k_{acc})\frac{T_0}{N_b} I_b^2 \\ &= \left(\left(\frac{1}{4\pi\varepsilon_0 a}\sqrt{\frac{g}{2\sigma_l}}\right) - \left(\frac{\omega_0}{2}\frac{R_{sh}}{Q_0}\right)\right)\frac{T_0}{N_b} I_b^2 ,\end{aligned} \quad (3)$$

where T_0 is the revolution time, Nb is the total number of circulating bunches and I_b is the beam current. This numbers can be found in Tables 2 and 3. $k(\sigma_l)$ is the overall loss factor of all modes [12] depending on the bunch length σ_l (FWHM for Gaussian bunches) including the fundamental. The meanings and numbers of the symbols are shown in Tables 2 and 3. Since we are interested in the HOM-power exclusively, we have to subtract the loss factor into the fundamental k_{acc} [14] from the overall loss factor $k(\sigma_l)$, as shown in equation (3). because the RF power from the fundamental mode will be rejected by the choke and will be not dissipated by the HOM-damper. The numbers needed here are given in Table 2.

Table 2: Basic Parameters of PETRA IV

Parameter	Value
Circumference of PETRA IV	2304 m
Kinetic Energy of electrons	6 GeV
Revolution time T_0	7.69 µs
Revolution frequency f_r	130.122 kHz

According to Table 4 the highest HOM-radiation takes place in the brilliance mode with *960* bunches. Together with the highest possible parasitic power flow of about *26 W* from the fundamental mode we have an overall power flow into the SiC-HOM-damper ring of about 90 W. We are now interested in the steady-state temperature that settles in the SiC-ring. Since the ring is held in position by only a spring [8,11], it has minor thermal contact only with the Cu environment in the cavity. The ring can therefore only dissipate most of the heat through radiation.Simulations with ANSYS [8,15] have clearly shown heating the SiC-ring with *90 W* we find a core temperature

$$T < 300°C \ . \quad (4)$$

and this is well within acceptable limits. Thanks to the very smooth (roughness < *0.6* µm) surfaces inside the cavity, the heat is distributed very evenly within the water-cooled cavity.

Table 3: Cavity Parameters, Number of Bunches, Beam Currents and Bunch Lengths in Different Operational Modes of PETRA IV

Parameter	Value
Gap length g	93.5 mm
Beam pipe radius a	23 mm
Long. bunch length brilliant mode σ_l	13.7 mm
Long. Bunch length timing mode σ_l	19.3 mm
Number of bunches N_b in brilliant mode	960
Number of bunches N_b in timing mode	80
Beam current I_b brilliant mode	200 mA
Beam current I_b timing mode	80 mA

Table 4: HOM-Radiation into the HOM-Damper under Different Operational Conditions

Operational Mode	Beam current I_b	Number of Bunches N_b	ΔP_{HOM}
Brilliant	200 mA	960	64 W
Timing	80 mA	80	56 W

CONCLUSION AND OUTLOOK

The cavity is currently under construction, and once it has been assembled at DESY, it will be baked out and vacuum-tested there. Conditioning will be done at DESY and cavity operation with beam is planned at DELTA in Dortmund.By selecting a dipole antenna as the coupler, it was relatively easy to make the coupling factor adjustable during cavity operation. The coupling factor K ranges from *0.2* to *5.0*. Cavity operation with a beam in DELTA will demonstrate the extent to which this coupling factor range can be utilized.

Analytical calculations and simulations using CST-MWS have shown the HOM power that the HOM damper must dissipate in the worst-case scenario during PETRA IV operation.

Simulations using a water-cooled cavity model with ANSYS have further shown the maximum temperature that develops in the SiC-ring under the installation conditions in the cavity and it turned out that the temperature is well within acceptable limits.

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