ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPG52

DESIGN OF A SINGLE MODE 3RD HARMONIC CAVITY FOR PETRA IV*

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Abstract

The upgrade of PETRA III to PETRA IV at DESY is currently in its design phase. To achieve the desired beam parameters a 3rd harmonic cavity is necessary for the accelerating system. An investigation of three types of cavity structures is conducted to find the most cost-effective and environmentally sustainable option. A high focus in this investigation is placed on the damping of higher order modes. Therefore, two of the investigated structures are so-called single mode structures. Such structures have their cavities directly coupled to RF-absorbers, allowing for damping of all resonant modes but the desired ground mode. The design considered in this paper is from a conceptual test of Helmut Herminghaus (MAMI, Mainz, DE). Taking the requirements of PETRA IV into account, the design is adapted, numerically simulated and optimized.

INTRODUCTION

With 4th-generation light the sources emittance and beam lifetime are of high importance. Intrabeam scattering and the Touscheck effect have negative effects on these characteristics, and it is desired to reduce their effect. Counteracting is possible by reducing the charge density inside a bunch through bunch lengthening. This warrants the usage of a 3rd harmonic system. Since, higher order modes (HOM) generally decrease beam quality and stability any such system needs to be designed taking their mitigation into account. For PETRA IV 24 1.5 GHz cavities are foreseen [1]. Based on the 500 MHz EU HOM damped cavity [2] ALBA has designed an active 3rd harmonic cavity [3]. The power of HOM in this cavity gets extracted and damped by so called “transdampers´´ which replace the ferrites in the initial cavity. The cavity designed by ALBA has already proven to deliver the desired bunch extension factor of 3, but it’s manufacturing is difficult and expensive. Thus, considering the number of cavities needed an alternative is sought. This alternative cavity is supposed to mitigate HOM’s while being easy and cheap to manufacture and operate and also deliver the needed bunch extension. Therefore, different so-called single mode structures are investigated, with the design focused on in this paper originating in Mainz.

THE SINGLE MODE STRUCTURE

To fulfill the requirements of the cavities for the 3rd harmonic system a proposed cavity design by Helmut Herminghaus from 1978 is reexamined. His design idea for a single mode cavity is therefore analyzed, simulated and optimized using modern available methods. He proposed a resonating structure terminated by waveguide ports so that only the accelerating mode is trapped inside the cavity. Following Ref. [4], Herminghaus called it a “single mode structure”. He showed that a cylindrical waveguide can be altered into such a cavity by changing its geometry. At the position the beam traverses the waveguide the cutoff-frequency of the $TE_{1,1}$-mode of the waveguide has to be locally lowered. This would trap the field around the changes because it can not propagate in the rest of the waveguide. In 1978 Herminghaus tested different alterations [5], measuring high quality factors. However, achieving the desired resonant frequency seemed to be the main difficulty and might be the reason this approach was not further pursued.

Modern simulation tools enable the design of a single mode cavity without the need for many prototypes. The cavity shown in Fig. 1 is derived from these earlier prototypes.

Every mode in an elliptical waveguide or elliptic cylindrical cavity has its orientation in the transverse plane fixed being either even or odd. This allows for a stronger decoupling of the ground mode in the resonator section from the waveguide section by rotating their cross-sections with respect to one another. This decoupling results in a greater difference in resonant frequency between the ground mode and the 2nd-order mode of the cavity. Therefore, the cross-sections of both the waveguide and resonator section are chosen to be elliptical and are oriented perpendicular to each other for maximum decoupling.

The 1st waveguide mode of an elliptical waveguide is the $TE_{11,\mathrm{even}}$-mode and points in direction of the semi-minor axis. The electromagnetic fields of any ideal elliptic cylindrical cavity and elliptical waveguide can be calculated according to [6]. This determines the resonant frequency for each mode. Thus, leading to the dimensions a_{wg} and b_{wg} of the waveguide for a given targeted cutoff-frequency $f_{1,1,\mathrm{even,c}}$.

The calculation of all eigenmode frequencies has to be done by simulation though since its geometry is complex and the boundary condition between the waveguide and resonator sections are not trivial.

The modes of the resonator also resonate inside the loft. Importantly almost every mode apart from the accelerating ground mode is above the cutoff-frequency of the waveguide. Thus, they will propagate out of the resonant section and importantly away from the beam-axis making it almost single mode cavity. The non-propagating modes apart from the ground mode will be discussed below.

The next step is to find a parameter set for the cavity seen in Fig. 1 that fulfills the posed requirements optimally. The waveguide length is fixed to $L_{\mathrm{wg}} = 450\,\mathrm{mm}$ since a longer waveguide no further changes the simulation results.

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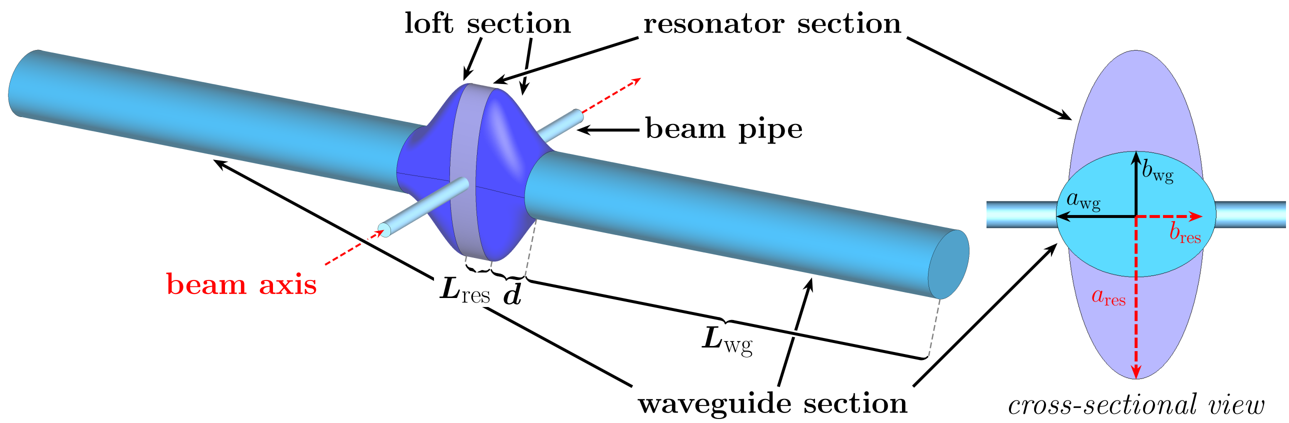

Figure 1: Structure of single mode cavity.

The targeted resonant frequency of the ground mode is $f_1 = 1.5\,\text{GHz}$. The cutoff-frequency of the lowest waveguide mode is chosen to be $f_c \approx 2\,\text{GHz}$. This decreases the probability of the ground mode coupling to the waveguide under non-ideal conditions. The chosen f_c requires that for the frequency of the 2nd eigenmode $f_2 > 2\,\text{GHz}$ must apply to ensure the coupling to the waveguide and the propagation to the dampers. Furthermore, the operating costs for each 3rd harmonic cavity needs to be reduced as much as possible. Maximizing the quality factor Q_0, the shunt impedance R_s and the transit time factor λ_{TTF} simultaneously is difficult since they respond differently to parameter changes, at times even inversely. To remedy this, a different figure of merit is proposed. Introducing the efficiency ε as the ratio of energy gain per cavity passage ΔU to the external supplied radio-frequency(RF)-power P_e. The coupling of the power supply to the cavity can be neglected since it does not depend on the cavity geometry. Therefore, we assume $P_c = P_e$. The cavity power is the sum of power losses in the cavity walls P_{loss} and the energy absorbed per bunch passage $P_{\Delta U}$. With the assumption $P_{\Delta U} \ll P_{loss}$ it follows that $P_e = P_{loss}$. The energy gain of all bunches is $\Delta U = -Q\,\underline{V}_{acc}$ [7, Ch. 2.1.1] where Q is the charge of all bunches and $\underline{V}_{acc} = \int_{-\frac{L_{res}}{2}}^{\frac{L_{res}}{2}} \underline{\vec{E}}\, e^{-j\omega\frac{z}{\beta c}} \cdot \mathrm{d}\vec{z}$ is the accelerating voltage. Thus, the proportionality

$$\varepsilon := \frac{\Delta U}{P_e} \propto \frac{\underline{V}_{acc}}{P_{loss}} \tag{1}$$

applies, and we can optimize for efficiency ε by maximizing the right-hand side of Eq. (1).

REGIONAL SENSITIVITY ANALYSIS

Optimizing the geometry of this cavity by tuning the parameters outlined in Table 1 is not straight forward. Individual influences of single parameters on the model are highly dependent on the values of the other parameters. This is due to higher-order interactions between parameter combinations and the output values. A way to estimate the influences of a parameter on the model is the regional sensitivity analysis (RSA) [8] also known as Monte-Carlo filtering. The RSA maps out the input space according to different regions of interest in the model output. Thus, the corresponding input regions are identified. For this purpose the input space is sampled, by simultaneously varying all the input parameters randomly. The parameter combinations are generated using Latin Hypercube sampling. The output is used to identify the regions of input space corresponding to the different states of the output. Analyzing these regions results in a reduction of the parameter ranges, which is beneficial for optimization.

Table 1: Parameters of the Single Mode Cavity

Parameter		Unit	Value range
Semi-major axis, resonator	a_{res}	mm	[59, 100]
Fraction of semi axes, resonator	b/a_{res}		[0, 1]
Length, resonator	L_{res}	mm	[0, 150]
Beampipe radius	r_{bp}	mm	[7, 23]
Length, loft	d	mm	[10, 100]
Smoothness, loft	s		[0, 0.45]
Semi-major axis, waveguide	a_{wg}	mm	[44, 45]
Fraction of semi axes, waveguide	b/a_{wg}		[0, 1]

Additionally, when examining ε with Q_0 and λ_{TTF} it becomes apparent that a higher quality factor seems to correlate with a higher ε while for λ_{TTF} the opposite seems to be the case, although to a smaller degree (Fig. 2). This leads to the assumption that at least for this kind of cavity, the quality factor Q_0 has a higher impact on the efficiency ε than the transit time factor. Therefore, it is valid to at least somewhat lower λ_{TTF} in order to achieve a higher Q_0.

OPTIMIZATION AND RESULTS

A candidate with high ε from the simulations in the RSA is chosen and used as a starting combination for the optimization. The optimization is then performed using it parameter

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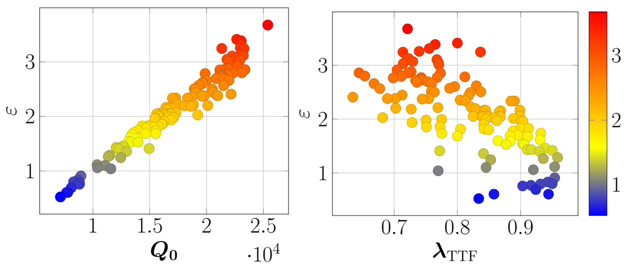

Figure 2: Relation of ε with Q_0 and λ_{TTF}.

combination as initial values and the CST internal trust region algorithm in a staggered fashion. This is done because the targets $f_1 = 1.5$ GHz, the coupling of 2nd eigenmode to the waveguide and maximizing ε are mostly independant of each other. Therefore, first the resonant frequency f_1 was tuned to be as close to 1.5 GHz as possible by tuning the most influential parameters: a_{res}, L_{res} and d. Then in the next step the other two goals are also taken into consideration. The important values of the cavity obtained from the optimization is shown in Table 2. The quality factor Q_0 is much higher than achievable with normal-conducting cavities. In Fig. 3 the 1st and 2nd eigenmodes are shown. The

Table 2: Result of Optimization

Figure of merit	**Value**	**Unit**
f_1	1.500 51	GHz
f_2	2.012 48	GHz
ε	3.384	s
V_{acc}	1.363	MV
P_{loss}	402.6	kW
Q_0	23247.3	
λ_{TTF}	0.754	
R_{s}	2.306	MΩ

maximum of the ground mode is centered around the beam axis while the 2nd mode obviously couples to the waveguide port, meaning it would be able to propagate out through the waveguide. Both of these outcomes confirm the design goals.

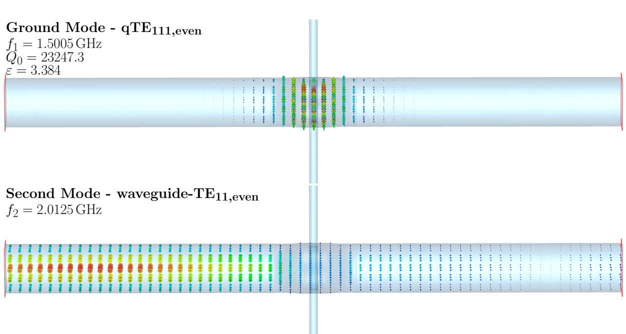

Figure 3: Electric field vector $\vec{E}$ of the first two eigenmodes of the optimized cavity.

For the given cavity geometry almost all modes, except the ground mode couple to the waveguide. Nonetheless, some do resonate inside the resonator section, e.g., the 13th eigenmode (Fig. 4). Even though this contradicts the idea

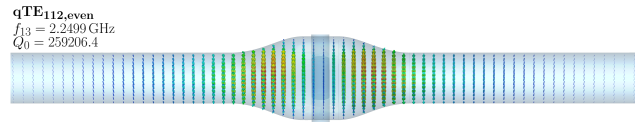

Figure 4: Electric field vector $\vec{E}$ of the 13th eigenmode of optimized cavity.

of this cavity being a single mode cavity, most if not all the modes which geometrically can not couple to the two waveguide sections do not couple to the beam. In particular the longitudinal component of the electric field of the 13th eigenmode is zero on the beam axis. Thus, this mode is not excited and is unlikely to arise inside the cavity. To gain a deeper insight in that regard, further wakefield studies of the cavity are necessary.

CONCLUSION

The cavity structure proposed by Herminghaus was examined using modern simulation, analysis and optimization techniques. The input parameter space and the parameter influences on the resulting structure were studied to gain a deeper understanding of the operating principle. A new optimization procedure was setup in order to better weigh the traditional optimization goals against each other. A suitable candidate for the 3rd harmonic system of PETRA IV was found with possibly still better ones around. Next steps are designing a coupler and the dampers as well as a tuning system. Aside from that future work will consider the kick factors of the resonating modes.

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