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DESIGN OF A CAVITY BEAM POSITION MONITOR FOR THE FLASH 2020+ UNDULATOR INTERSECTION PROJECT AT DESY

D. Lipka*, Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Abstract

The FLASH 1 beamline at DESY will be upgraded from fixed to variable gap undulators in the next years. For this the vacuum beamline has to be adapted. This reduces the inner diameter compared to the existing chamber. The vacuum components should fit to the new dimension to minimize transitions and therefore reduce wakefields which could interact with the electron beam and disturb the SASE effect. The electron beam position in the intersection of the undulators should be detected with a high resolution and a large charge dynamic range. Cavity BPMs are known to fulfill these requirements. The existing design with 10 mm inner diameter for the European XFEL is reduced to 6 mm. Additional improvements are: widening of the dipole resonator waveguide to adapt to the dipole mode and antenna transmission. The resonator frequency of 3.3 GHz and loaded quality factor of 70 are maintained to use electronic synergies to other projects. The design considerations and simulation results of the cavity BPM are presented.

MOTIVATION

The superconducting free-electron laser user facility FLASH [1] at DESY in Hamburg routinely delivers several thousand high brilliance XUV and soft X-ray photon pulses per second. The user facility FLASH is in operation since 2005 and since 2014 the bunch train from the superconducting linac can be split between the original FLASH 1 undulator beamline and a new second beamline FLASH 2. In 2016 a significant Mid Term Refurbishment Program was started for FLASH. Its program will persist for the next years. As part of the DESY strategy process DESY 2030 [2] that was initiated 2016, a second substantial upgrade, FLASH 2020+ was proposed [3]. In April 2019 the internal conceptual design report (CDR) for FLASH 2020+ [4] was finalized. The mid and long term upgrades are described in [5].

There are several key aspects of the upgrade in 2024: the important one is in order to enhance the independence of the two beamlines and their over all operability, FLASH 1 needs to be equipped with variable gap undulators. To be able to close the undulators further a smaller inner vacuum chamber is proposed. This implies a reduction of the available Cavity Beam Position Monitor (CBPM) design from the European XFEL with an inner vacuum diameter of 10 mm [6] to 6 mm. The reduction of the diameter minimizes transition of the vacuum boundaries and therefore the impact of reduce wakefields which would interact with the electron beam and disturb the SASE production. Many institutes are developing such CBPM [7–19] to provide the beam position with the best resolution which consists of a dipole and a reference resonator. In this contribution the design considerations of both resonators are described.

* dirk.lipka@desy.de

DESIGN

For the general design the resonance frequency and quality factor have to be chosen for the dipole and reference resonator of the CBPM. Both parameters should be similar for the dipole and reference resonator to simplify the signal processing. Since the inner tube diameter is 6 mm with a cut-off frequency of 29 GHz this high cut-off this is not a limitation. To provide synergies for the already developed electronics the resonance frequency of $f = 3.3$ GHz is defined. The repetitive bunch frequency of 1 MHz allow only for a fast decaying signal, therefore a low loaded quality factor of $Q_L = 70$ is chosen which results in a bandwidth of 47 MHz. This allows a monitor production in stainless steel. The basic design is depicted from the SACLA facility [7] which was modified for the European XFEL [6]; in addition a design for the SINBAD accelerator with 34 mm diameter was developed in 2018 [19]. The quality factor and resonance frequency of the new design for FLASH 1 are similar to the European XFEL and SINBAD CBPMs for synergy but with other tube diameters and resonator thicknesses.

Dipole Resonator

The TM_{11} mode of the dipole resonator provides a signal proportional to beam offset and charge. The amplitude sensitivity is $S = \pi f \sqrt{\frac{Z}{Q_{ext}}\left(\frac{R}{Q}\right)}$ [19,20], with the line impedance $Z = 50\,\Omega$ and the normalized shunt impedance $\left(\frac{R}{Q}\right)$ and the external quality factor Q_{ext}. The antenna position defines the value of the external quality factor; a small value dominates the loaded quality factor because $\frac{1}{Q_L} = \frac{1}{Q_{ext}} + \frac{1}{Q_0}$ with Q_0 the internal quality factor (which is still relative large compared to Q_{ext} for stainless steel) and therefore increases the sensitivity too. To obtain a larger sensitivity the normalized shunt impedance can be increased by using a large resonator thickness l because $\left(\frac{R}{Q}\right) \propto l$ [21], in this design $l = 5$ mm is applied. The Eigenmode solver of the simulation tool CST [22] is used to design and investigate the resonator properties. The resulting geometry is shown in Figures 1 and 2.

The resonator has a kink to decrease the resonator diameter which bends the dipole field. This is an advantage for a smaller overall monitor transverse size. The dipole field is propagating into the four slots where the dominating monopole field TM_{01} can not propagate due to the geometry and is therefore in comparison with the dipole signal negligible at the antenna positions [23]. The thickness of the slots are increased compared to [6, 19] to provide the low external quality factor shown in Table 1.

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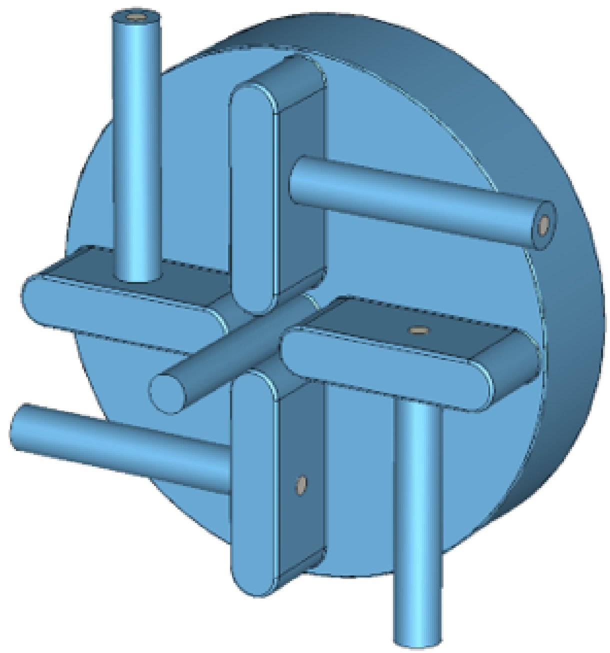

Figure 1: 3-dimensional simulation view of the vacuum design of the dipole resonator.

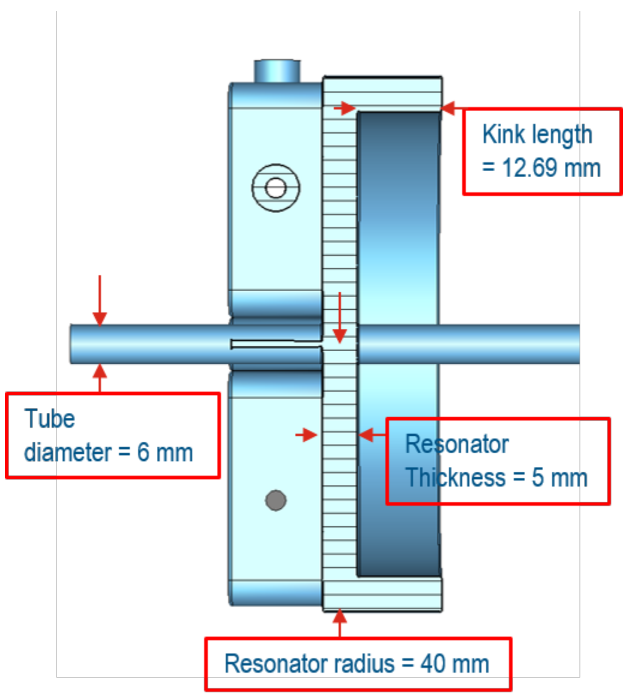

Figure 2: Cut view of the simulated dipole resonator with main design parameters.

An additional signal is generated when the beam is not parallel to the CBPM axis with a phase difference of 90° compared to the offset signal, this signal will increase with the resonator thickness [24]. To simulate the beam angle signal, the "particle in cell" (PIC) solver of CST [22] is used. The resulting relative angle compared to the offset amplitude results to be 0.62 mm/rad, this means that a beam angle of 1 rad results in the same signal amplitude as a beam offset of 0.62 mm. This value is even smaller compared to the European XFEL design with 10 mm tube diameter and 3 mm resonator thickness with the same resonance frequency and quality factor results in 0.9 mm/rad; the influence of the smaller diameter to the signal caused by the angle seems to be not negligible.

Table 1: Dipole Resonator Property Results

f	(3299.6 ± 9.4) MHz
Q_L	70.2 ± 2.3
Q_0	585 (Stainless steel)
Q_{ext}	79.7
S	3.42 V/(nC mm)

In Table 1 the property results are summarized. The resonance frequency and loaded quality factor are investigated with mechanical tolerances. When all geometric tolerances are taken into account and will add linearly to a difference of the design value, a maximum deviation is obtained; the results are shown in Table 1 too. The values show that the deviation of the resonance frequency is expected to be small compared to the bandwidth and therefore no tuners are necessary for the production of the resonator.

Reference Resonator

The reference resonator is used to measure a charge dependent signal to normalize the dipole signal and define the direction of the offset by RF phase comparison between both resonators. For proper data processing the phase of the dipole and reference resonator signals the resonance frequency and loaded quality factors should be similar. Therefore the goal values of the resonator are equal to the dipole resonator. The design of the reference resonator is shown in Figures 3 and 4.

Two antennas are foreseen to add a symmetry to the design and be able to get a second charge output. A kink is used for the reference resonator too; this bends the monopole mode into it and the antenna can transfer the signal to a perpendicular port (compared to the beam direction). This is useful for a compact longitudinal mechanical size of the CBPM. The size of the antenna is adapted to the inner diameters of a N-connector to avoid reflections from the feedthrough and minimize influences from the antenna to the external quality factor. The kink high is smaller compared to the resonator thickness to decrease the external quality factor to the desired value.

In Table 2 the resulting reference resonator properties are summarized. The resonance frequency and loaded quality factors are almost the same as for the dipole resonator. Tolerance studies with the expected mechanical deviations result in maximum possible deviations of the resonance frequency and quality factor. Here the deviations are comparable to the dipole resonator. Therefore this design can be produced without tuners for the reference resonator as well.

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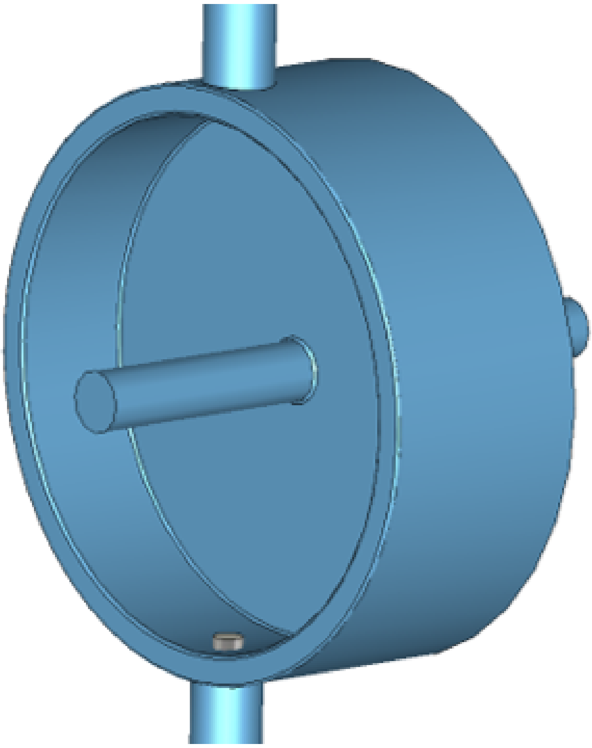

Figure 3: 3-dimensional simulation view of the vacuum design of the reference resonator.

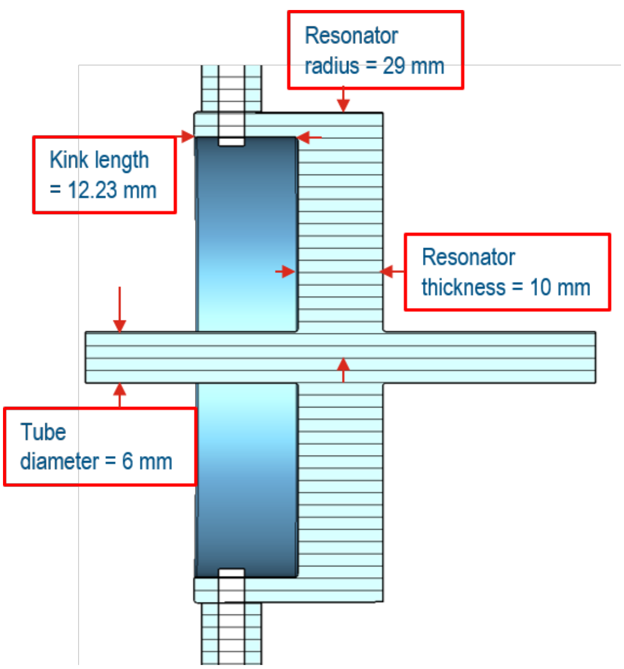

Figure 4: Cut view of the simulated reference resonator with main design parameters.

Compound of Both Resonators

Joining both resonators results in the complete CBPM. But the strong monopole field of the reference resonator at the same resonance frequency can influence the dipole field. To minimize this influence the distance between both resonators has to be specified. Assume that the dipole field is negligible when the resulting offset is below 0.1 µm; this corresponds to a sensitivity of $S_{dipole}(0.1\,\mu m) = 0.342\,mV/nC$, see Table 1. The ratio $20\log_{10}(S_{dipole}(0.1\,\mu m)/S_{reference}) = -106.9\,dB$ defines the maximum transmission for any combination between the ports of both resonators. Since the dipole antennas are not arranged in a symmetry plane, the transmission to the reference resonator are not the same for all antennas. Here one needs to identify the plane with the highest influence. In the present design the maximum transmission requirement is fulfilled even with the shortest distance between both resonators due to the small diameter of the pipe, see Figure 5.

Table 2: Reference Resonator Property Results

f	(3300.0 ± 9.3) MHz
Q_L	70.0 ± 2.9
Q_0	551 (Stainless steel)
Q_{ext}	80.2
S	75.8 V/nC

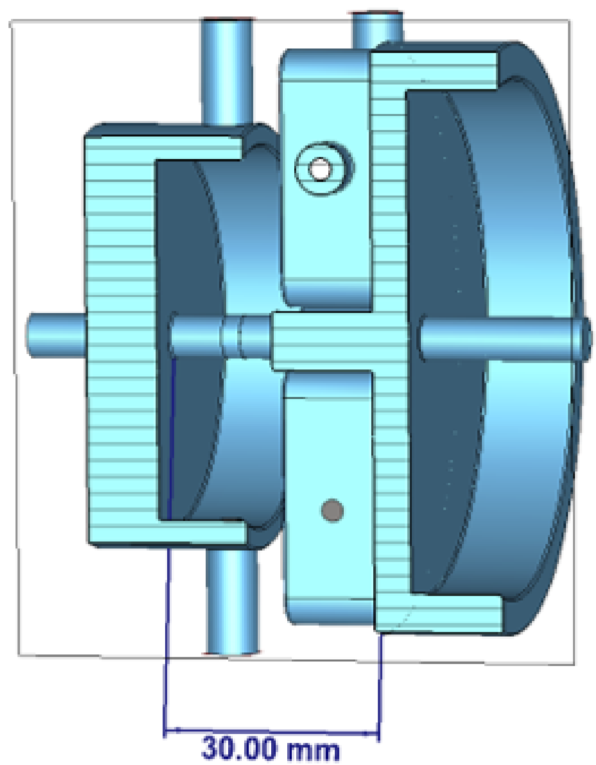

Figure 5: 3-dimensional simulation view of the vacuum design of both resonators with their proposed distance.

SUMMARY

The CBPM is designed for the FLASH 2020+ Undulator Intersection Project. In comparison to former designs the

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dipole resonator got a larger slot thickness to match with the small external quality factor and the antenna dimensions are similar to N-connectors to avoid additional reflection since small deviation in the feedthrough would influence the resonator properties. Tolerance studies are performed and show that the required resonance frequencies and loaded quality factors can be achieved without tuners.

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