Design of a Cavity Beam Position Monitor for the FLASH 2020+ Undulator Intersection Project at DESY.

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Abstract

- FLASH 1 beamline at DESY will be upgraded from fixed to variable gap undulators, for this the vacuum inner diameter will be decreased
- To minimize transitions and reduce wakefields which could interact with the electron beam and disturb the SASE effect beam pipe diameter will be decreased
- The electron beam position in the interaction 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

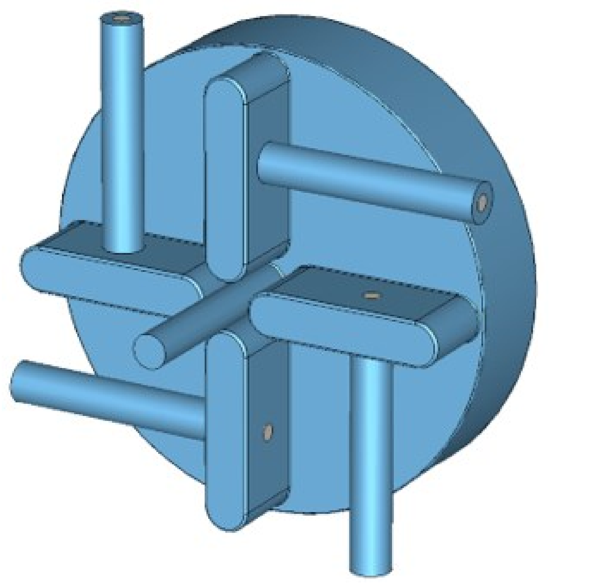
- FLASH [1] user facility in operation since 2005
- A significant Mid Term Refurbishment Program was started for the next years [2-5]
- One key aspects of upgrade in 2024 FLASH 1 needs to be equipped with variable gap undulators. To be able to close the undulators further a smaller inner vacuum chamber 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
- 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.

General Design

- Resonance frequency and quality factor should be similar for the dipole and reference resonator to simplify the signal processing.
- To receive a reliable resonance field with this tube diameter a resonance frequency of f = 3.3 GHz is defined.
- The relative low beam repetition rate would allow to use a long ringing signal to analyze the waveform. Therefore a relative high quality factor with a long decay time could be applied. But the voltage amplitude and following the sensitivity would be small 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 [4] which was modified for the European XFEL [5].
- The quality factor and resonance frequency of the new design are similar to the European XFEL CBPMs for synergy but with other tube diameter and resonator thickness of the dipole resonator.

Dipole Resonator

- TM_{11} mode of the dipole resonator provides a signal proportional to beam offset and charge.
- The amplitude sensitivity $S = \pi f \sqrt{\frac{Z}{Q_{ext}}\left(\frac{R}{Q}\right)}$ [19,20], with the line impedance Z = 50 Ω and the normalized shunt impedance *(R/Q)*, is increased by a relative small external quality factor Q_{ext}.
- The antenna position defines the value of the external quality factor; a low value dominates the loaded quality factor because $1/Q_L = 1/Q_{ext} + 1/Q_0$ with Q_0 the internal quality factor (which is still relative large compared to Q_{ext} for stainless steel).
- To obtain a larger sensitivity the normalized shunt impedance can be increased by using a large resonator thickness l because (R/Q) ∝ 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 the Figures.
- Includes a kink to decrease the resonator diameter which bends the dipole field; 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} is attenuated and 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 Q_{ext}
- 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 value is even smaller compared to the European XFEL design with 10 mm tube diameter of 0.9 mm/rad, although a resonator thickness of 3 mm is used.
- The Table shows the property results. 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 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.



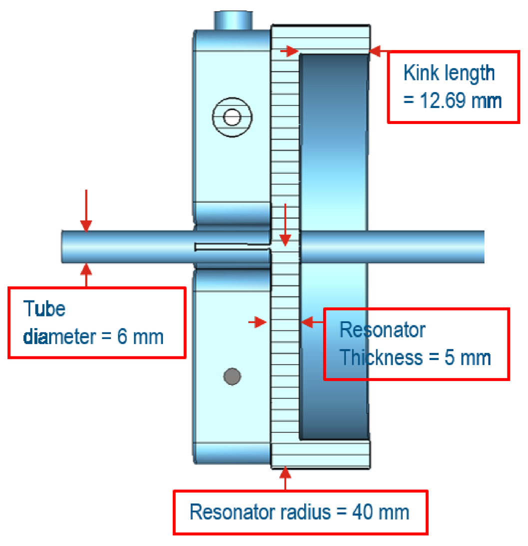


Table 1: Dipole Resonator Property Results

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)

Reference Resonator

- Reference resonator to measure a charge dependent signal for normalization and for the direction of the offset
- Phase of the dipole and reference resonator signals should be similar. Therefore f and Q_L are equal to the dipole resonator.
- Two antennas are foreseen to add a symmetry to the design; a kink is used for the reference resonator; this transfers the signal to a perpendicular port which is useful for a compact longitudinal mechanical size
- The size of the antenna is adapted to the inner diameters of a N-connector to avoid reflection from the feedthrough and minimize influences from the antenna to the Q_{ext}
- The Table shows the resulting reference resonator properties.
- Tolerance studies show that the deviation of the frequency is comparable to the dipole resonator. But the maximum deviation of dipole and reference signal is still smaller than the bandwidth.
- Therefore this design can be produced without tuners for the reference resonator as well.

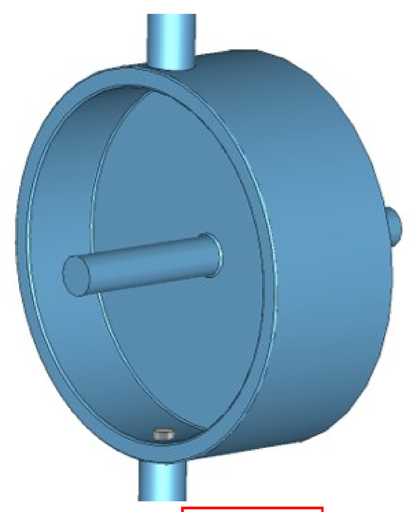
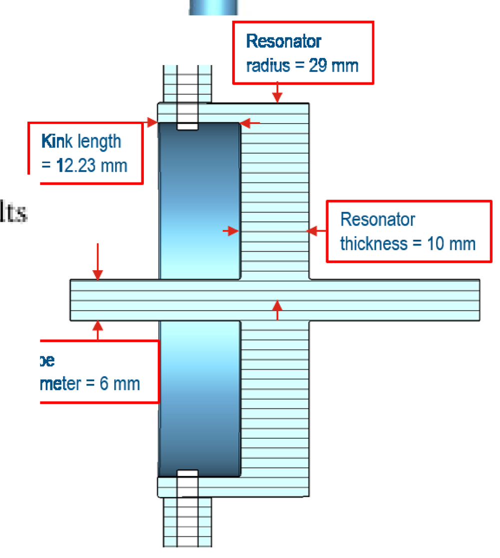


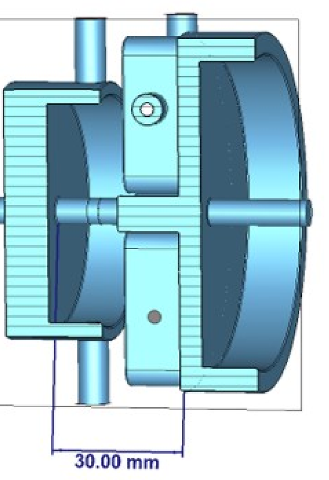
Table 2: Reference Resonator Property Results

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



Compound of Both Resonators

- Joining both resonators results in the complete CBPM; the strong monopole field of the reference resonator 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; corresponds to a sensitivity of S_{dipole}(0.1 µm) = 0.312 mV/nC. The ratio 20 $\log_{10}(S_{dipole}$ (0.1 µm) / $S_{reference})$ = -106.9 dB defines the maximum transmission for any combination between the ports of both resonators.
- 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



Summary

- The CBPM is designed for FLASH 2020+ with smaller beam pipe diameter
- In comparison to former designs the 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 in stainless steel.
- The distance between both resonators are defined to get a negligible influence of the reference to the dipole resonator.

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