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DESIGN OF A CAVITY BEAM POSITION MONITOR FOR THE ARES ACCELERATOR AT DESY

D. Lipka*, M. Dohlus, M. Marx, S. Vilcins, M. Werner, DESY, Hamburg, Germany

Abstract

The SINBAD facility (Short and INnovative Bunches and Accelerators at DESY) is foreseen to host various experiments in the field of production of ultra-short electron bunches and novel high gradient acceleration techniques. The SINBAD linac, also called ARES (Accelerator Research Experiment at SINBAD), will be a conventional S-band linear RF accelerator allowing the production of low charge (within a range between 0.5 pC and 1000 pC) electron bunches. To detect the position of low charge bunches, a cavity beam position monitor is being designed based on the experience from the European XFEL. It will consist of a stainless steel body with a quality factor of 70, a resonance frequency of 3.3 GHz and a relative wide gap of 15 mm to reach a high position sensitivity of 4.25 V/(nC mm) of the dipole resonator. The design considerations and simulation results of the dipole and reference resonator will be presented.

INTRODUCTION

SINBAD is a dedicated accelerator R&D facility currently under construction at DESY, Hamburg, and will host the ARES linac (Accelerator Research Experiment at SINBAD). It will consist of a normal conducting photo-injector and a 100 MeV S-band linear accelerator with beam repetition rates between 10 and 50 Hz for the production of low charge beams (0.5–30 pC) with (sub-) fs duration and excellent arrival time stability [1–3]. For dedicated user experiments bunch charges up to 1000 pC are foreseen. To observe the beam transverse position with highest precision the requirements include a resolution of 5 μm for a beam charge between 5 and 100 pC. To achieve this requirement a cavity beam position monitor (CBPM) is developed.

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 34 mm with a cut-off frequency of 6.75 GHz the resonance frequency should be smaller. 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

The TM$_{11}$ mode of the dipole resonator provides a signal proportional to beam offset and charge. The amplitude sensitivity $S = \pi f \sqrt{\frac{Z}{Q_{\text{ext}}}\left(\frac{R}{Q}\right)}$ [1] [6], with the line impedance $Z = 50\,\Omega$ and the normalized shunt impedance $\left(\frac{R}{Q}\right)$, 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 $\frac{1}{Q_L} = \frac{1}{Q_{\text{ext}}} + \frac{1}{Q_0}$ 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 $\left(\frac{R}{Q}\right) \propto l$ [7], in this design $l = 15$ mm is applied. The Eigenmode solver of the simulation tool CST [8] is used to design and investigate the resonator properties. The resulting geometry is shown in Figs. 1 and 2.

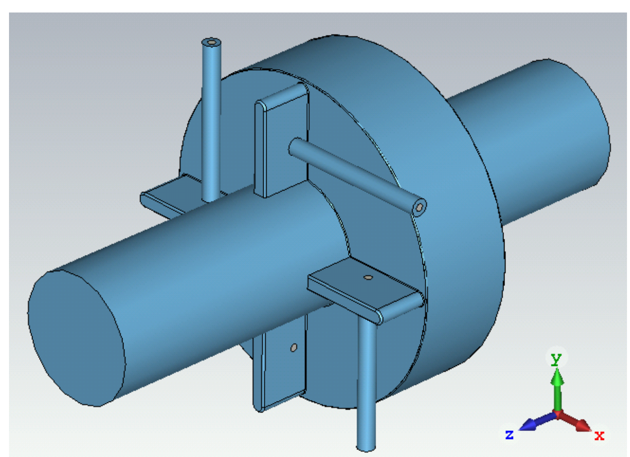

Figure 1: 3-dimensional simulation view of the vacuum part of the dipole resonator.

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

* dirk.lipka@desy.de

[1] The development of this equation is described in the appendix.

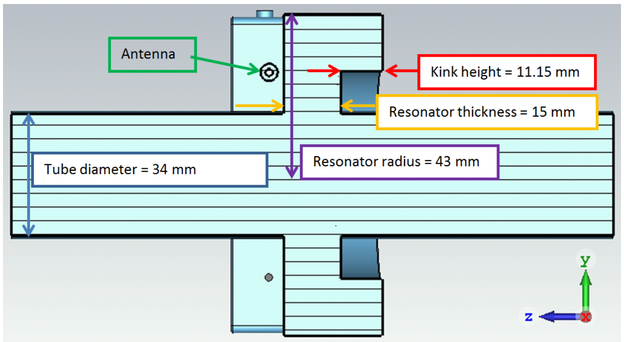

Figure 2: Cut view of the simulated dipole resonator with main design parameters.

monopole field TM_{01} is attenuated and therefore in comparison with the dipole signal negligible at the antenna positions [9].

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 [10]. To simulate the beam angle signal, the "particle in cell" (PIC) solver of CST [8] is used. The resulting relative angle compared to the offset amplitude results to be 8.7 mm/rad, this means that a beam angle of 1 rad results in the same signal amplitude as a beam offset of 8.7 mm. This value is even smaller compared to the European XFEL design with 40.5 mm tube diameter of 15.7 mm/rad, although a resonator thickness of 3 mm is used[2].

Dedicated simulations are done to investigate the angle influence based on different resonator thicknesses with the same tube diameter. Here the angle signal is increased by 10 % between l = 3 mm and 10 mm resonator thicknesses. This shows that the resonator thickness is not the main contribution to the angle influence; the tube diameter influence is larger.

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. Here a smaller resonator thickness can be used because the sensitivity of the TM_{01} mode is much higher compared to the dipole signal. To compare 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 Figs. 3 and 4.

Table 1: Dipole Resonator Property Results

property	value
f	(3300.0 ± 5.8) MHz
Q_L	69.9 ± 2.3
Q_0	1264 (Stainless steel)
Q_{ext}	74.1
S	4.25 V/(nC mm)

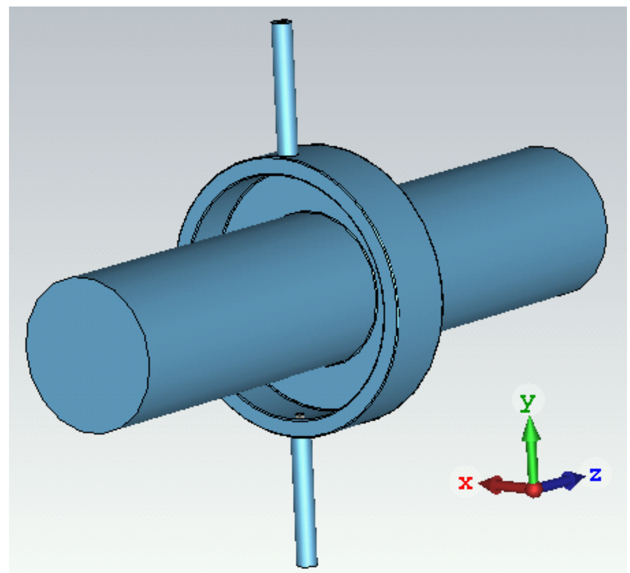

Figure 3: 3-dimensional simulation view of the vacuum part of the reference resonator.

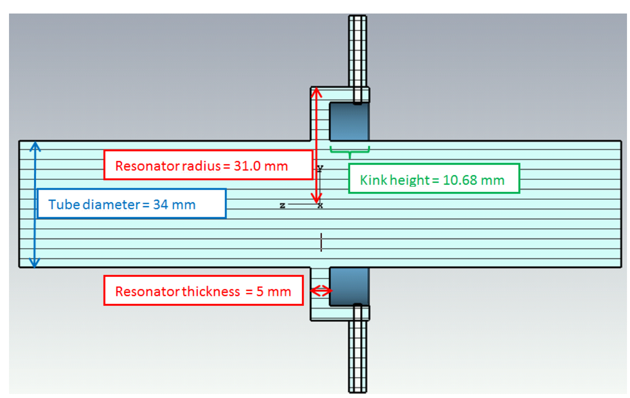

Figure 4: Cut view of the simulated reference resonator with main design parameters.

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

[2] A dipole resonator with 10 mm tube diameter and 3 mm resonator thickness with the same resonance frequency and quality factor results in 0.9 mm/rad.

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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 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 is the same as for the dipole resonator, the loaded quality factor is slightly smaller, but still within an acceptable limit. Tolerance studies with the expected mechanical deviations result in maximum possible deviations of the resonance frequency and quality factor. Here the deviation of the frequency is larger due to a higher impact of the kink thickness and length. 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

property	value
f	(3300.0 ± 13.3) MHz
Q_L	68.9 ± 2.6
Q_0	514 (Stainless steel)
Q_{ext}	79.6
S	44.5 V/nC

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. We assume that the dipole field is negligible when the resulting offset is below 0.1 µm; this corresponds to a sensitivity of $S_{\text{dipole}}(0.1\mu\text{m}) = 0.424\,\text{mV/nC}$, see Table 1. The ratio $20\log_{10}(S_{\text{dipole}}(0.1\mu\text{m})/S_{\text{reference}}) = -100.4\,\text{dB}$ 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 −100 dB requirement is fulfilled with a distance of 120 mm between both resonators, compare with Fig. 5. The antennas with the highest influence in the dipole resonator have the same orientation as the antennas in the reference resonator.

SUMMARY

The CBPM is designed for the ARES accelerator to fulfill the requirements. For the dipole resonator, a wide gap was selected for high sensitivity, resulting in a still tolerable beam angle influence. Tolerance studies are performed and show that the required resonance frequencies and loaded quality factors can be achieved without tuners. The distance between

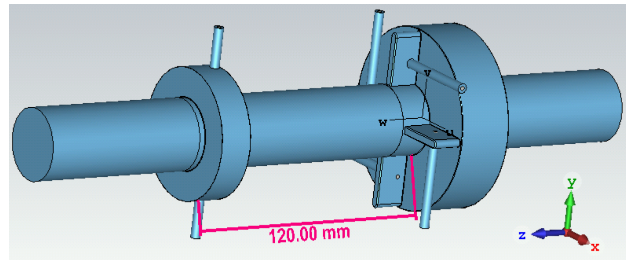

Figure 5: 3-dimensional simulation view of the vacuum part of both resonators with distance.

both resonators are defined to get a negligible influence of the reference to the dipole resonator.

APPENDIX

The development of the sensitivity equation is following. The voltage on an integration path in a cavity is defined to be $U(x,y) = \mid \int E_z(x,y,z)e^{\left(\frac{i\omega z}{c}\right)}dz \mid$ with E_z the field inside the cavity and the loss factor $k(x,y) = \frac{|U(x,y)|^2}{4W_{\text{tot}}}$. The total energy loss in one resonance mode can be expressed in terms of the loss factor of a beam of charge q to be

$$W_{\text{mode}}(x,y) = q^2 k(x,y) \tag{1}$$

and is distributed to the external and internal losses

$$W_{\text{mode}}(x,y) = \left(\sum_i^{\#\text{Ports}} \frac{Q_L}{Q_{\text{ext,Port}\,i}} + \frac{Q_L}{Q_0}\right) W_{\text{mode}}(x,y). \tag{2}$$

Here one needs to consider that each port has its own external quality factor. For a dipole mode two $Q_{extPort}$ are connected to the same mode; these external quality factors have usually the same value

$$\sum_i^{2\,\text{Ports}} \frac{1}{Q_{\text{ext,dipole}\,i}} = \frac{1}{Q_{\text{ext,Port1}}} + \frac{1}{Q_{\text{ext,Port2}}} \tag{3}$$

and therefore the common external dipole quality factor is

$$\frac{1}{Q_{\text{ext,dipole}}} = \frac{2}{Q_{\text{ext,Port}}}. \tag{4}$$

The output power on one port results to be

$$P_{\text{Port}}(x,y,t) = \frac{Q_L}{Q_{\text{ext,Port}}} W_{\text{mode}}(x,y)\frac{2}{\tau}e^{-\frac{2t}{\tau}} \tag{5}$$

with the decay time $\tau = \frac{Q_L}{\pi f}$. With equation (1) it can be rewritten to

$$P_{\text{Port}}(x,y,t) = \frac{2q^2\pi f k(x,y)}{Q_{\text{ext,Port}}}e^{-\frac{2t}{\tau}}. \tag{6}$$

The voltage on a port can be expressed with $U^2(x,y,t) = P_{Port}(x,y,t)Z$ with Z the impedance of the port, usually 50 Ω, and is for this case

$$U(x,y,t) = qe^{-\frac{t}{\tau}}\sqrt{\frac{2\pi f Z}{Q_{\text{ext,Port}}}k(x,y)}. \tag{7}$$

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The loss factor can be expressed to be

$$k(x,y) = \frac{\omega}{2}\left(\frac{R}{Q}\right)(x,y) \tag{8}$$

with the geometric dependent normalized shunt impedance of the mode [7]. The resulting sensitivity is the charge normalized voltage at $t = 0$

$$S = \frac{U(x,y,t=0)}{q} = \pi f \sqrt{\frac{2Z}{Q_{\mathrm{ext,Port}}}\left(\frac{R}{Q}\right)(x,y)}. \tag{9}$$

For the dipole mode the term $\frac{2}{Q_{\mathrm{ext,Port}}}$ can be replaced by $\frac{1}{Q_{\mathrm{ext,dipole}}}$ (compare with equation (4)) which is the case in [6]. In the presented design two antennas are used in the reference resonator therefore equation (9) can be applied in the similar way like the dipole resonator. Usually the reference resonator has only one antenna therefore equation (3) reduces to one term such that the common external quality factor is the same as the single port external quality factor.

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