DESIGN OF CAVITY BPM PICKUPS FOR SWISSFEL

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Abstract

SwissFEL is a 0.1nm hard X-ray Free Electron Laser being built at PSI. A photocathode gun, S-band injector and C-band linac provide 2 bunches at 28ns spacing, 10-200pC charge range, 100Hz repetition rate, and 5.8GeV maximum energy. A fast distribution kicker will provide one bunch each to one hard X-ray and one soft X-ray undulator line. For linac and undulators, first prototypes of dual-resonator cavity BPM pickups have been designed and one undulator prototype has been fabricated. The pickups were optimized for low charge and short bunch spacing in the linac. Design considerations, simulation and first test results will be reported.

INTRODUCTION

SwissFEL [1] requires three different BPM pickup types, due to the different beam pipe apertures along the machine: 38mm in the injector, 16mm in the linac, and 8mm in the undulators. The desired BPM RMS noise and drift is <1 µm for the undulators, <5 µm for the linac, and <10 µm for the injector, for a charge range from 10-200pC. For the SwissFEL undulators, we will use dual-resonator cavity BPMs due to their good achievable drift and noise level even at low charge.

At the SwissFEL injector test facility (SITF) that is operational since 2010, resonant striplines are used as "working-horse" BPMs, achieving 7 µm RMS noise down to charges of 5pC [2], while a test section at the end of the machine is used for cavity BPM tests.

For the final SwissFEL machine, we plan to use cavity BPMs in the accelerator, including injector and linac. This will allow to have a homogeneous BPM system and to be able to use the latest electronics generation for the whole machine, based on our developments for the E-XFEL BPM system [3].

Both the RF and mechanical designs of the present SwissFEL cavity pickup prototypes were largely inspired by devices developed in Japan for the XFEL/Spring-8 [4] and at DESY for the E-XFEL [5]. In particular, we plan to use the 3.3GHz working frequency of the E-XFEL undulator BPMs also for SwissFEL injector and linac pickups. This choice allows us to adapt our E-XFEL cavity BPM electronics to SwissFEL linac and injector BPM requirements with relatively small effort, thus maximizing the synergies of the E-XFEL BPM collaboration between PSI and DESY on this subject and minimizing costs and man power.

For the present SwissFEL BPM pickup prototypes, we adapted the loaded quality factor (Q) and sensitivity to the lower bunch charge range (10-200pC) and bunch spacing (28ns) of SwissFEL, since the E-XFEL BPM pickups were designed for 100-1000pC and 222ns bunch spacing.

As shown in Fig. 1, each pickup consists of two cavities having a folded shape to limit their transverse dimensions and get a more compact device. The working modes are TM_{110} (dipole) for the so called position cavity and TM_{010} (monopole) for the reference cavity. When the beam crosses the two cavity gaps it induces signals proportional to the product of charge and position offset in the position cavity, and to the charge only in the reference cavity. The beam position is then obtained by dividing the two signal amplitudes, which are available at the outside by means of properly designed couplers. In particular, the position cavity has four rectangular waveguides that couple to the dipole mode while rejecting the monopole mode that would otherwise limit the resolution of the electronics.

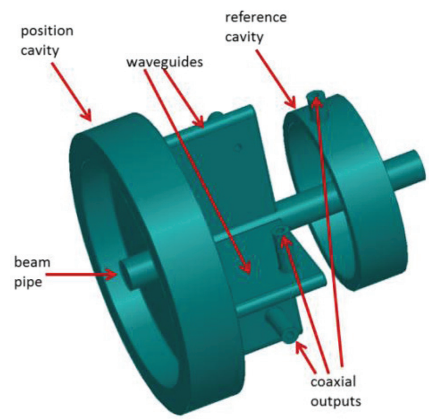

Figure 1: Cavity BPM pickup schematic view (shown: vacuum).

The waveguides are connected to the cavity volume through slots placed 90° apart from each other on one cavity side wall. Each waveguide has a transition to a coaxial line which ends with a standard type-N connector output. In the reference cavity the signal is coupled out by means of a coaxial line where the inner conductor passes through the cavity (predominantly magnetic coupling). The position and the reference cavities must have a sufficiently large distance to each other to avoid crosstalk. This distance needs to be increased with increasing diameter of the beam pipe.

In the following sections, the undulator and linac pickup design as well as lab measurements of the RF characteristics of the first undulator pickup prototypes are presented. The design of the injector BPM has not yet started.

UNDULATOR CAVITY BPM

Design and Simulation Results

The design of the SwissFEL BPM system is based on the E-XFEL cavity BPMs where the pickup is developed by DESY and the electronics by PSI. Since SwissFEL

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operates at much lower beam current than E-XFEL, one of the main requirements is to maximize the monitor sensitivity. For the present SwissFEL linac and undulator BPM pickup prototypes this has been achieved by increasing the cavity gap from 3 to 7 mm, extending the waveguide length and connecting the waveguide to the beam pipe along its whole length. After readjusting the other dimensions to obtain the desired TM_{110} mode frequency at 3.3GHz with a Q of 70, HFSS simulations showed an increase of the position sensitivity to S=9.3V/nC/mm, compared to 2.89V/nC/mm for the E-XFEL undulator BPM pickup.

The improved sensitivity also lead to an increase of the beam angle sensitivity, i.e. the additional signal generated when beam and cavity have a relative dX/dZ or dY/dZ angle, where X, Y and Z are the horizontal, vertical and longitudinal coordinates. According to simulations, a pickup misalignment angle dX/dZ or dY/dZ of 1mrad gives the same output amplitude (for a centered beam) as a trajectory with 9µm offset. The undesired impact of this angle signal on the position resolution, linearity and drift will be minimized by suppressing the angle signal digitally (exploiting the fact that angle and position signal have 90° phase difference), and by survey-based and then beam based angle measurement and correction. The angle is dominated by the misalignment of the pickup, while the additional angle signal caused by betatron oscillations of the beam around its ideal trajectory is negligible.

Other properties of the pickup that may affect the performance are the leakage of the TM_{010}[6] (monopole) mode in the dipole cavity as well as the coupling between horizontal and vertical plane, e.g. due to manufacturing tolerances.

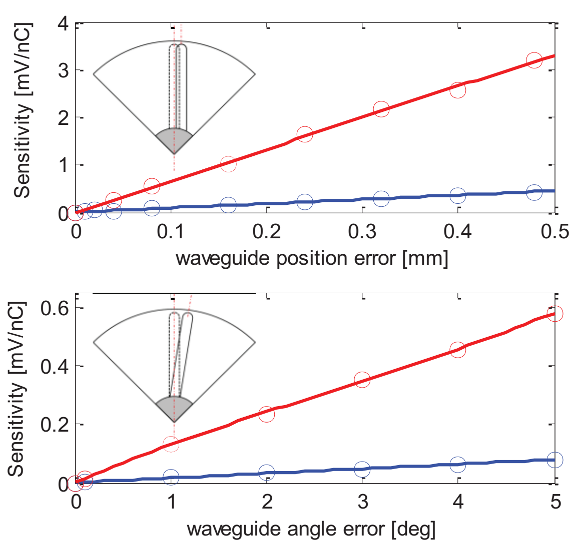

Figure 2: Simulated output signal, generated by 1nC, centred beam, due to TM_{010} coupling as a function of waveguide misalignments. Red and blue curves refer to stainless steel and copper (or copper plated) structures respectively.

Although the monopole mode leakage is minimized by the arrangement of the mode-suppressing coupling slots and waveguides, some dimensional tolerances, especially slot misalignments in position and angle may cause monopole mode leakage, where the amplitude of the leaking signal is proportional to the mechanical error, as shown in the simulation results [7] plotted in Fig. 2. The frequency of the monopole mode in the dipole cavity is around 2.5GHz, but the amplitude of the tail is still not negligible at the 3.3GHz working frequency.

For the material of the inner cavity surface, two options have been considered in the simulations: stainless steel, and copper (or copper plated steel). In the second case the common mode Q, which essentially depends on the losses at the cavity walls, is higher, and the tail amplitude at 3.3GHz is lower. As a consequence also the TM_{010} leakage is lower, as shown by the blue curve in Fig.2.

The effect of slot position and angle misalignment has been simulated also concerning the X-Y coupling. In Fig. 3 the ratio between the signal voltage at orthogonal outputs, V_X/V_Y (V_Y/V_X), due to a purely vertical (horizontal) beam position offset, is plotted as a function of the misalignment error. The allowed mechanical tolerances for a given upper limit of orthogonal coupling can be estimated from these plots.

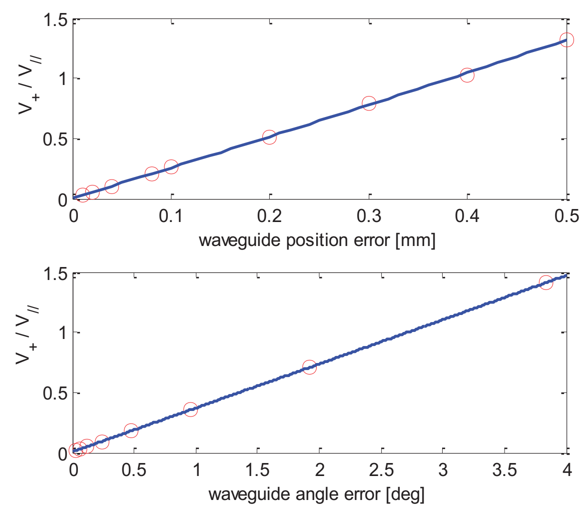

Figure 3: X-Y coupling due to position and angle error of the waveguides in the 3.3GHz undulator pickup. V_+ and $V_{//}$ are the voltages detected respectively at the orthogonal plane and at the same plane of the beam offset plane.

A 4.8GHz cavity BPM has also been considered and simulated as an alternative to the design described above. The pickup sensitivity increases with the frequency, thus a 4.8GHz pickup can give better performance at low charge operation, which would mainly be attractive for the undulator BPMs. The frequency has been chosen as the maximum to still have a safe distance to the C-band accelerating section frequency (5.712 GHz). Moreover staying below 6GHz simplifies the electronics design and minimizes drift effects that tend to increase with the frequency. A quality factor of 100 was chosen to have the same bandwidth and decay time constant as for the 3.3GHz version. For a pickup made of stainless steel the sensitivity exceeds 14V/nC/mm, while a 10% higher

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value could by achieved by copper plating of the surfaces. The common mode coupling, the orthogonal coupling and the beam angle signal are lower in the case of the 4.8GHz cavity. The main parameters characterizing the two designs are listed in Table 1.

Table 1: RF characteristics of the 3.3GHz and 4.8GHz BPM position cavities, both made of stainless steel

Frequency	3.3 GHz	4.8 GHz
Q loaded	70	100
Q external	160	232
R/Q	0.65 Ω/mm^2	1.01 Ω/mm^2
Sensitivity	9.3 V/nC/mm	14.1 V/nC/mm
TM010 frequency	2.534 GHz	3.492 GHz
Angle/position signal ratio	9 rad/mm	7 rad/mm

Prototype Measurement Results

For the 3.3GHz undulator BPM prototype four pickups have been fabricated, with the aim to both validate the simulation results and to test different manufacturing techniques.

The pickup body, made of LN316 stainless steel, is composed of three pieces, forming both the position and the reference cavities. The vacuum feedthroughs, which constitute the end part of the coaxial line outputs, are welded onto the pickup central body. Figure 4 shows pictures of the three main parts and the final assembly of the pickup.

Figure 4: SwissFEL undulator prototype: pictures of the 3 parts composing the pickup body and final assembly after brazing.

A first RF measurement of the pickup frequency and Q has been done before welding/brazing the parts together, just by applying pressure to the stacked body parts and then inserting the feedthroughs. This allowed to have an early indication of the manufacturing quality and RF tolerances. Afterwards, two prototypes have been electron beam welded and the other two brazed. Finally the frequency and Q were measured again to test the impact of the welding and brazing on the pickup RF parameters.

The measurement results are summarized in Table 2, where the numbers in black (blue) refer to the measurements before (after) the brazing or welding. For each device, the table shows the frequencies and the quality factors of both the TM_{110} polarizations of the position cavity and of the TM_{010} of the reference cavity. The undulator prototypes named UP1 and UP2 have been brazed, while UP3 and UP4 were electron beam welded. Moreover, the feedthroughs have been welded only in prototypes UP1 and UP4, while they have just been plugged into the unbrazed/unwelded and then brazed/welded main body parts of UP2 and UP3.

Table 2: Measured frequency and quality factor of the position and reference cavity working modes of the four prototypes, before (black) and after (blue) brazing (UP1 and UP2) or electron beam welding (UP3 and UP4)

BPM #	Position cavity				Ref. cavity	
	f_{S31} [GHz]	Q_{S31}	f_{S42} [GHz]	Q_{S42}	f [GHz]	Q
UP1	3.3005	64.1	3.3010	64.7	3.3010	62.0
	3.3008	63.9	3.3004	65.4	3.3009	68.7
UP2	3.3002	65.4	3.2995	66.0	3.2995	65.0
	3.2990	71.7	3.2998	70.4	3.3010	73.0
UP3	3.3006	64.9	3.3021	63.7	3.2984	72.0
	3.2969	68.2	3.2970	68.5	3.2935	72.0
UP4	3.2999	64.7	3.2999	63.6	3.2984	72.0
	3.2985	66.0	3.2978	68.7	3.2925	74.0

Before the brazing/welding process, the measured frequencies deviated -1.6 to +2.1MHz from the design values, which is very well acceptable. This means that the mechanical tolerances are well in the range of specifications for all four prototypes. The position cavity quality factors are 6 to 9% lower than expected, which may be caused by imperfect electrical contacts of the loosely assembled body pieces before welding/brazing. The reference cavity measured quality factors are in a larger range of values, being between 62 and 74. A reason for that could be the larger sensitivity of Q to the coupler insertion position and to the VSWR of the feedthrough, as the analysis of dimensional tolerances has pointed out.

The brazing has not caused any significant change of the frequencies, while the electron beam welding caused a still negligible shift of -4 to -6MHz, with the exception of the position cavity of the prototype UP4, where the frequency change has been smaller. Due to these results, and considering that the electron beam welding is a technique which only few companies can provide, we favour brazing for the future series production.

The quality factors measured after brazing or welding are generally higher than before, because of the improved electric contacts, and are still within the desired range of ±10%.

LINAC CAVITY BPM DESIGN

For the linac BPMs, we are aiming for <5µm RMS noise and drift at 10-200pC, compared to <1µm for the undulators. Another difference is that the linac BPMs must be able to measure independently the position of two bunches with 28ns spacing. To reduce the bunch-to-bunch crosstalk and to simplify the digital suppression of this crosstalk in the BPM electronics, we reduced the Q value to ~40 while keeping the working frequency at 3.3GHz.

Table 3: RF characteristics of linac BPM position cavity

Frequency	3.300 GHz	Sensitivity	7.1 V/nC/mm
Q loaded	39	TM010 freq.	2.252 GHz
Q ext	83	Angle/position signal ratio	4.3 rad/mm
R/Q	$0.19\ \Omega/\mathrm{mm}^2$		

Comparing the geometries of this pickup with the 3.3GHz version for the undulators, the main differences, for the position cavity, are the larger size of the beam pipe aperture (16mm), and the shorter length of the waveguides (reduced from 25 to 14mm, for a more cost efficient machining of the body parts). Both modifications cause a reduction of the R/Q and thus of the resolution at low charge that mainly depends on this value. The shorter waveguides have a positive impact on the beam angle sensitivity, that is ~2 times lower, as well as on the common mode coupling, due to a larger frequency separation between TM_{010} and TM_{110}. The X-Y coupling benefits from the larger pipe diameter. For the same error in the waveguide position or angle, the ratio $V_{+}/V_{//}$ is reduced by a factor 4 (position) and a factor 2.3(angle) compared to the undulator pickups (see Fig. 3). Table 3 reports the main parameters obtained from the simulations.

A further consequence of the larger beam tube diameter, for a given cavity distance, is a larger coupling between the working modes of position and reference cavity. Therefore the distance between the cavities was increased by 10mm to 60mm for the linac pickup with respect to the undulator 3.3GHz prototype. The residual cross coupling signal produces an equivalent position offset of 150nm in the position cavity.

CONCLUSIONS AND OUTLOOK

The development of cavity BPMs for the SwissFEL project is in progress at PSI. So far, a 3.3GHz and a 4.8GHz version for the undulator and a 3.3GHz version for the linac have been designed. The 3.3GHz undulator prototype has been fabricated, and the linac prototype is currently in production.

Measurement results for frequency and Q are in good agreement with our expectations. To validate RF properties and to measure the performance at low charge, we plan to make also beam test of the SwissFEL pickup prototypes. The tests will be performed at the SwissFEL test injector facility, where a BPM pickup test area with space for four cavity pickups (two of them on motorized X-Y movers) is available. We intend to use the E-XFEL cavity BPM electronics that already has been proved to work successfully [8].

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