DESIGN OF A RESONANT STRIPLINE BEAM POSITION PICKUP FOR THE 250 MEV PSI-XFEL TEST INJECTOR

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Abstract

The 250 MeV PSI X-FEL Test Injector will use resonant stripline beam position monitor (BPM) pickup as standard BPMs to reach the desired single bunch resolution in the order of 10 µm in a charge range of 10 to 200 pC. This paper presents the electromagnetic design of the pickup that was performed with Microwave Studio. The pickup was optimized in terms of the main radiofrequency (RF) characteristics - frequency, shunt impedance, unloaded and loaded Qs - of the resonant modes of interest, in order to obtain the signal characteristics required by the electronics, that samples the pickup signals directly at 5 GSamples/s [1]. Mechanical aspects of the design are also presented, with particular attention to the tuning pin solution for stripline alignment. Based on the simulated geometry, one pickup prototype was built and tested and the correct characteristics of the resonant modes were verified.

OVERVIEW

To provide the desired position resolution in the ten micrometer range along the 250 MeV PSI-XFEL injector, about 25 standard beam position monitors are foreseen to measure and stabilize the beam position within ~10% of the final beam size. The choice of a 500 MHz resonant stripline pickup and a 5 GSample/s direct sampling electronics [1] based on existing PSI designs [2] allowed a cost-efficient solution and fast prototyping of pickups and electronics as well as of the digital signal processing firmware and software. At the desired bunch charge range from 200 pC down to 10 pC, resonant striplines are superior e.g. to button pickups since they concentrate the output signal spectrally at a high signal-to-noise ratio, thus enabling higher position resolution with narrowband processing, even for single shot operation and low bunch charges [3]. The main advantage over cavity pickups is the significantly reduced cost and development time especially for the electronics, since the low Q and comparatively low frequency allow direct sampling by the 5 GSample/s Domino Ring Sampler (DRS) chip of the BPM electronics, without the need for an analog mixer scheme or a low-jitter clock distribution [1]. A schematic sketch of four resonant stripline electrodes (two per plane) is depicted in Fig. 1.

This BPM topology supports four independent TEM eigenmodes of operation $\underline{V_0} = (V_1, V_2, V_3, V_4)$:

- sum mode, or monopole mode: $V_{0,M} = \frac{1}{2}(1,1,1,1)$
- two delta modes, or dipole modes: $V_{0,D_x} = \frac{1}{\sqrt{2}}(1,0,-1,0)$ and $V_{0,D_y} = \frac{1}{\sqrt{2}}(0,1,0,-1)$
- quadrupole mode: $V_{0,Q} = \frac{1}{2}(1,-1,1,-1)$

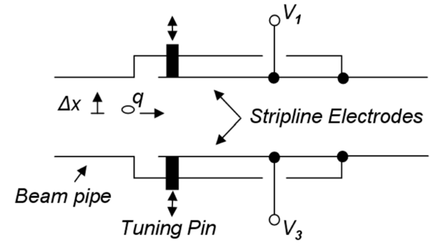

Figure 1: Resonant stripline pickup, one plane only.

The ratio of the signal voltages from opposing electrodes depends on the transversal beam position:

$$x \sim \frac{\Delta}{\Sigma} \text{ with } \Delta = (V_3 - V_1) \text{ and } \Sigma = (V_3 + V_1)$$

Each mode has a characteristic impedance and frequency spectrum that influences the BPM performance, representing the criteria for the pickup selection [4]. The pickup sensitivity, defined as the ratio of opposite voltages per beam offset in [dB/mm], is determined by the normalized shunt impedances and the loaded Qs:

$$S_x\,[dB/mm] \sim 20\,log(1 + 2s_x \cdot 1mm), \qquad (1)$$

$$s_x\,[1/mm] \sim \sqrt{2\frac{(R/Q)_{D_x}}{(R/Q)_M}\frac{Q_{l,D_x}}{Q_{l,M}}}\Bigg|_{x=1mm} \qquad (2)$$

The detection method employed is signal stretching by ringing filter, followed by direct sampling and digital envelope detection. To maintain high sensitivity of signal envelope voltage to beam position for the complete duration of the signal, the following conditions must be satisfied: at the appearance of the output signal $Q_{l,D}/Q_{l,M} \geq 1$, and the dipole and monopole frequencies must coincide, i.e. $f_D = f_M \pm 1$ MHz. The frequency of the resonant stripline pickup was chosen equal to 500 MHz, which is well in the bandwidth range of the DRS4 sampler chip. The frequency choice also enabled easy adaptation of the design already used at the SLS linac and transfer lines [2], allowing electronics development and tests with existing SLS linac pickups while the new spectrally and mechanically improved pickup was being developed.

CONCEPTUAL DESIGN AND RESULTS

Prototype Design

Figure 2 shows geometry and mechanical solutions adopted for the prototype pickup.

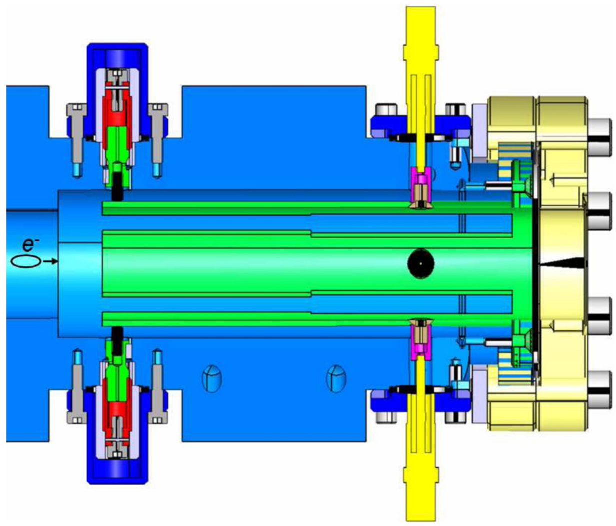

Figure 2: Pickup prototype for the PSI-XFEL Injector.

The beam pipe dimension of 38 mm was maintained as inner diameter of the stripline. To have a maximum response magnitude at the resonance, the stripline length must be equal to a quarter resonant wavelength, i.e. $l = 150$ mm. Once the overall adopted geometry was tuned, this length was reduced to 138.4 mm. A first tuning of the pickup was performed on the width of the stripline slots. Because the loaded Qs must be lower than that of the ringing filter (max. 30), but not too low to keep the spectral energy density high at 500 MHz, an initial width of 11 mm was chosen for the slots, resulting in eigenmodes with $Q_l \sim 8$. Moreover, because longer slots correspond to a closer proximity of the resonant modes, the length of the slots was made equal to the length of the stripline itself. This ensures a few MHz difference between monopole and dipole frequencies. Afterwards, according to the design described in [5], each slots was modified and the initial width of 11 mm was reduced to 9.3 mm for the first half of the stripline, which now presents two different widths. In fact, this configuration corresponds to add a capacitive load, which will only affects the electrodes at different potentials, as e.g. for the dipole mode case. Consequently the dipole and quadrupole modes will move down in frequency towards the sum mode. The final tuning of the frequency spectra was obtained by adjusting the position of the ports. The feedthroughs (50 Ω line impedance) are put in the region where the magnetic field of the modes is mostly concentrated. Simulations show a sensitivity of the port position with the frequency modes of about +1 MHz/mm in the beam direction, depending also on the geometry of the rest of the structure. The contact with the electrodes is guaranteed by means of Cu-Be screws fixed on the feedthrough antennas. Concerning the pickup alignment with respect to the beam pipe, a tolerance of 10 µm was considered for the concentricity, giving a tolerance of 5 µm for the electrical center.

Four ceramic screws of 4 mm diameter put at 5 mm from the open end of the stripline allow the alignment of the stripline (with a satisfying precision). A detailed view of the feedthroughs and tuning pins complex are shown in Fig. 3.

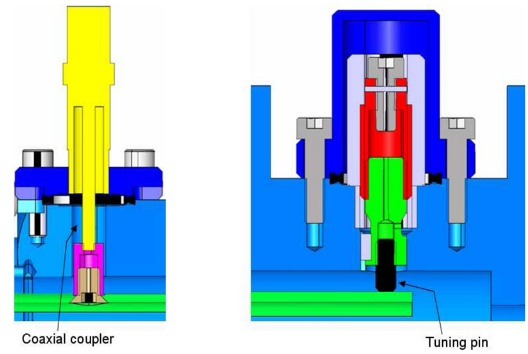

Figure 3: Details of the feedthroughs (left) and tuning pins (right).

Simulation Results, Measurements and Redesign

The BPM prototype was tested for both S-parameters and beam measurements and the results were compared to the simulations. Table 1 shows the eigenmode frequencies and their obtained Q factors. Microwave Studio was used to compute the eigenmodes both directly (second column in Table 1) and the mode group delay analysis (third column). With this method the S-parameters are obtained at first by a frequency sweep of the pickup. Then they are suitably combined to obtain the four mode reflection coefficients S_{mode}, i.e. the eigenvalues of the scattering matrix **S**. Finally, the group delay of mode reflection coefficients corrected for the single pass delay of feed lines $(dS_{mode}/d\omega) - 2\tau$ is computed. The frequency where the mode group delay is maximal is the mode resonance frequency. The agreement of the two simulation methods is better than 1 MHz for the frequencies, and also quite good for the Q factors. The condition $Q_{l,Dipole} \geq Q_{l,Monopole}$ previously described is satisfied. Since in the simulations a magnetic symmetry plane has been defined longitudinally, the two dipole modes are identical. From the shunt impedance values computed, $(R/Q)_M = 10.6\,\Omega$ and $(R/Q)_D = 44\,\text{m}\Omega$ at 1 mm, the expected sensitivity is $S = 1.57$ dB/mm. Using a model of pickup, electronics, and detection algorithm, this results in an estimated position resolution of 5.5 µm for 200 pC beam charge.

While the loaded Qs measured match very well with the estimated values, the measured frequencies are larger than expected: ~ +9 MHz for the monopole and ~ +6 MHz for the dipole modes. To explain this difference, further MWS simulations were performed: imperfections of the simulated geometry explain in fact part of the frequency error. These imperfections concern an approximated geometry of the flanges at the feedthroughs and of the tank near the tuning pins, and a wrong dielectric constant value used for the ceramic alignment screws. A sum of these effects can justify ~ +6 MHz for the monopole mode and ~ +5 MHz for the dipole and quadrupole modes. The cause of remain-

Table 1: Simulated and Tested Mode Frequencies and Quality Factors

	MWS Eigenmodes			MWS S-params.			Measurements	
Mode	f_0 [MHz]	Q_u	Q_l	f_0 [MHz]	Q_u	Q_l	f_0 [MHz]	Q_l
Monopole	499.82	1067	6.3	500.31	∞	5.7	509	6.4
Dipole X	500.23	1159	7.5	501.03	∞	7.3	507	7.7
Dipole Y	500.23	1159	7.5	501.03	∞	7.3	506	7.4
Quadrupole	500.35	1145	8.2	501.39	∞	8.4	506	8.2

ing error could be identified in an imperfect stripline alignment. In the mechanical alignment procedure, a rod with the same diameter as the beam pipe away from the electrode was inserted through the pickup. The tuning screws were adjusted inwards until the torque increased and then the rod was removed. Because of the force from the tuning screws, the electrodes could be bent away from the beam pipe inner surface even further when the road was removed, reducing the capacitive load between tank and stripline. This fact is confirmed by the simulations: 0.1 mm misalignment of the all four electrodes away from the beam pipe inner surface increases the eigenmode frequencies by a few megahertz. Finally, the crosstalk measured among orthogonal dipole modes is in the order of 0.1%.
The prototype was installed at the Linac of SLS and then tested with an electron beam. Figure 4 shows the amplitude for one of the four filtered pickup electrode voltage for unknown offset beam position and 0.85 nC bunch charge.

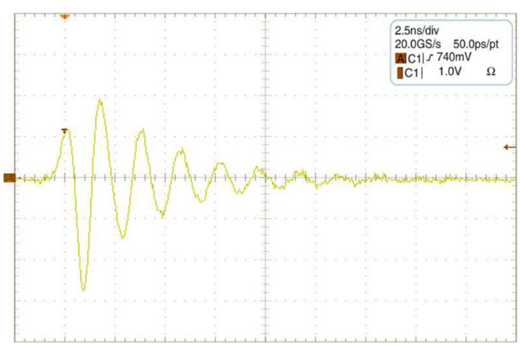

Figure 4: Lowpass filtered pickup electrode voltage at the end of cables. Filters used: Mini-Circuits SLP-1000.

Average initial amplitude is 5.25 V peak to peak. Accounting for cable attenuation and rescaling for the bunch charge of interest, the electrode voltage from fundamental resonance of monopole mode is ~2.11 V_{pp} at 0.2 nC. This is 0.7 dB more than the predicted value of 1.94 V_{pp}.
Because of the the error found in the frequency modes, the stripline was redesigned, changing in length of the electrodes by few millimeter and in widths of the slots by a few tenths of millimeter. To make the alignment of the feedthroughs easier, the gap width between bushing and inner surface of the coaxial coupler was increased from 0.5 to 1.25 mm. The mechanics of the tuning pins itself was simplified, allowing a faster mounting and minimizing in the same time the effect of the depth of the recess around the tuning pin on the fields.
The new specifications after the upgrade of the pickup are shown in Table 2. Frequencies and loaded Qs refer to MWS simulated S-parameters analyzed according to the mode group delay, and match well with the simulated values obtained by looking directly for the eigenmodes.

Table 2: Simulated Mode Frequencies and Quality Factors for the New Design Of the Resonant Stripline Pickup

Mode	f_0 [MHz]	Q_u	Q_l
Monopole	500.31	1358	6.15
Dipole X,Y	499.95	1461	7.59
Quadrupole	499.95	1493	8.71

The sensitivity decreases from 1.57 dB/mm to 1.53 dB/mm; however, the ratio $Q_{l,Dipole}/Q_{l,Monopole}$ is 5% larger. The theoretical resolution limit for the chosen BPM electronics remains unchanged at 5.5 µm. The signal levels are 0.6 dB larger.

CONCLUSIONS

The obtained results indicate that the designed resonant stripline pickup allows to reach the desired position resolution in the order of 10 µm in the PSI FEL test injector. The fabrication and the test of a prototype allowed to identify and solve, also by means of mechanics improvements, critical aspects, thus optimizing the eigenmode spectrum and resulting BPM performance.

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