STRIPLINE DEVICES FOR FLASH AND EUROPEAN XFEL

M. Dehler, G. Behrmann, Paul Scherrer Institut, Villigen PSI, Switzerland
S. Vilcins, M. Siemens, DESY, Hamburg, Germany

Abstract

A prototype fast intra-bunch train feedback system is currently under development which is to be tested at FLASH. For pickups as well as kickers, stripline devices have been developed. The new pickup is based on earlier designs used in the transfer lines of the Swiss Light Source as well as in the proton cyclotron PROSCAN at PSI; in particular, the stripline electrode output coupling is intentionally mismatched in order to increase the shunt impedance seen by the beam. Two versions have been designed for a center frequency of 1.65 GHz and a loaded Q of 35. Prototypes have been fabricated and built into FLASH. The stripline kicker consists of four main elements (all in-vacuum): two stripline electrodes fabricated from extruded aluminum and two metallic ground planes, held in place by ceramic spacers. The latter reduce the mutual inductance between the electrodes and optimize the RF match for asymmetries in the RF feed. Prototypes have been built, measured in the lab, and are now in the process of being installed into FLASH.

INTRODUCTION

As part of the Swiss contribution to the European XFEL project, the Paul Scherrer Institut is developing the prototype of an intra-bunch train. The feedback system has to correct for fast transverse orbit fluctuations within the bunch train, which are due to causes as beam loading and wake fields. Each plane, horizontal and vertical, has a dedicated system consisting of two upstream pickups for the measurement, two kickers for the correction of offsets, followed by a pair of downstream pickups used to calibrate the feedback gain. The electric signal chain consists of an analog RF front end, which down converts the pickup signals to base band, a fast, FPGA based, digital processing board with ADC and DAC mezzanines for the signal conversion, and high power broad band RF amplifiers feeding the kickers. For the European XFEL, two sets of systems are foreseen, one working after the injector region at 150 MeV and the other at the end of the main LINAC at 18 GeV (For more information on the general layout see [1]).

KICKER

The bunch distance within the bunch train is 200 ns; this time period should be matched by the total latency of the feedback system. Within the latency budget, a maximum fill time of 10 ns is foreseen for the kickers – a choice, which a priori excludes alternative options such as air coils. This requirement would lead to a maximum design length of 3 meters for a strip line kicker. For the prototype, we plan to replace existing stripline kickers at FLASH with the new designs, thus to be compatible an even shorter overall length of 1 meter was chosen.

Table 1: Kicker Specifications

Active length	1000 mm
Total length	1030 mm
Beam pipe diameter	34 mm
Bandwidth	50 MHz
Kick (P = 1W/port)	1 keV/c
Input impedance (differential mode)	50 Ω
Input impedance (common mode)	61 Ω

The required bandwidth, on the order of 2.5 MHz (coming from the 200 ns bunch spacing), is no problem given the fact that latency requirements lead to a far larger value. Table 1 gives an overview of the specifications.

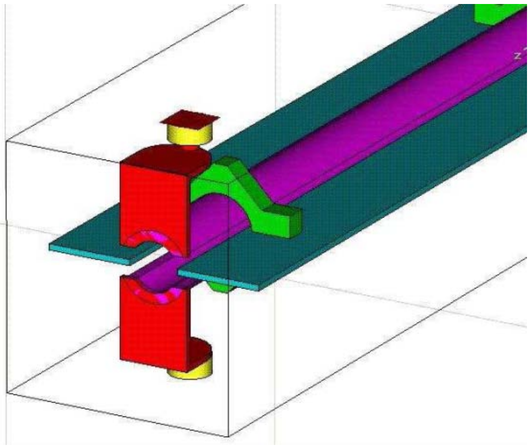

Figure 1: Front part of electrode assembly

The electrode assembly shown in figure 1 is a self supporting structure consisting of a pair of electrodes and two ground plates clamped together using ceramic spacers. The aluminum striplines are manufactured by extrusion in order to minimize twist and sag. Thus, an excellent stability and tolerance of the assembly is guaranteed.

The kicker is operated in differential mode with the electrodes at opposite polarity, the characteristic impedance seen by the amplifiers being 50 Ω. Phase and amplitude imbalances will show up as an additional common mode signal. This signal component itself is no problem for the beam itself, since it induces only a very minor longitudinal acceleration for the beam. The challenge lies in the mismatch at the input – for a standard electrode assembly without ground plates, the characteristic impedance is quite a bit higher – which may cause problems for the amplifier electronics. This is the reason for the additional ground plate, which, while having no influence on the differential mode, lowers the characteristic impedance of the common mode to an acceptable 61 Ω.

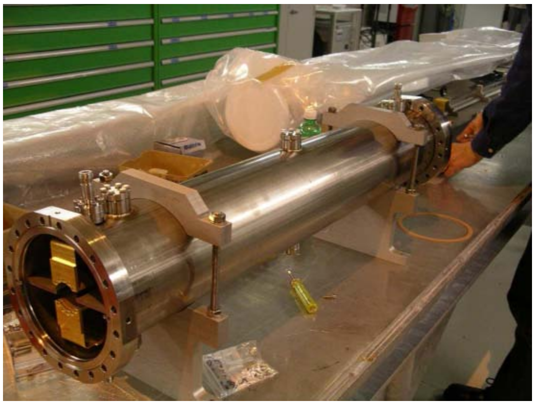

Figure 2: Photo of assembled kicker (Metallic front cap missing)

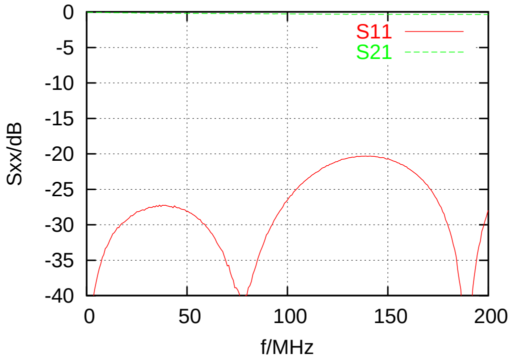

Figure 3: Measured scattering parameters

Three prototypes have been fabricated, two to be inserted into FLASH and one as a lab prototype for testing at PSI (Fig. 2). Figure 3 shows the measured reflection and transmission for the prototype. The maximum reflection within the bandwidth of interest of -27 dB is sufficient for our application. It is a little bit higher than the match of -32 dB predicted from numerical simulations using MAFIA [3], the difference probably comes from some last minute changes in the layout of the ceramics spacers.

The short range wakes and the longitudinal beam impedance were computed with CST Particle Studio [4], figures 4 and 5 show the results. The peak of the beam impedance is on the order of 700 Ω; with an average beam current of 5 mA during the EXFEL bunch train, this means a maximum wake of 3.5 kV, which is acceptable.

Currently, two prototypes of the kicker have been installed into FLASH to be tested with the beam.

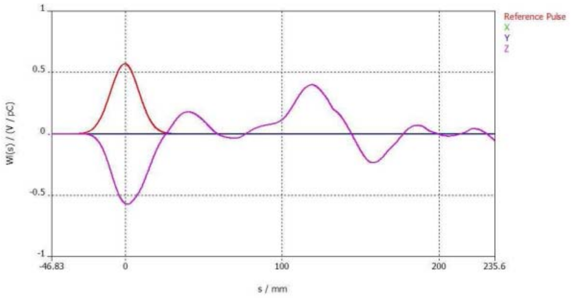

Figure 4: Short range wake field assuming a bunch charge of $Q = 1nC$ and an rms length of $\sigma = 9mm$.

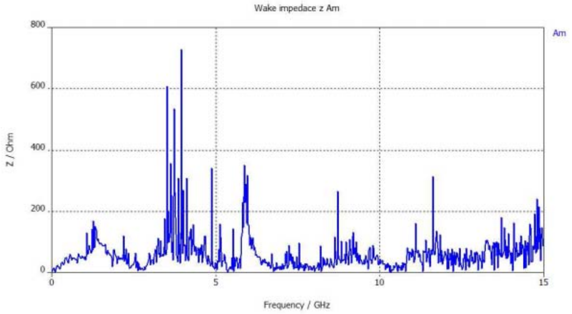

Figure 5: Computed longitudinal beam impedance

STRIPLINE PICKUPS

The conventional strip line design consists of strip line electrodes shorted on one side and perfectly matched to the output coupler. Its FIR pulse response consists of two peaks equivalent to a transfer impedance of

$$Z_T = \frac{U_{out}}{I_{beam}} = jZ_l e^{-j\omega\tau} \sin \omega\tau$$

where $\tau = l/c$ is the electrical strip line length and Z_l the characteristic impedance of the strip line and output coupler.

If the output coupler is shifted from the end of the stripline toward the grounded end of the electrode, the combined impedance of the short at the end plus the coupler is transformed to a narrow band peak with a corresponding increase of output power.

Given the coupling between the strip lines, there are three different resonant frequencies inside the structure, the the monopole/sum resonance, the difference/dipole resonances and a quadrupole resonance. The central frequency of the measurement should lie in between the monopole and the dipole resonances. The bandwidth/Q factor must be chosen suitably in order to give enough overlap for the measurement.

Since this approach was already used for the design of the stripline BPMs at the transfer lines of the Swiss Light Source as well as a prototype tested at the proton treatment facility PROSCAN[2], it was decided to adapt it for the prototype of the intra-bunch train feedback system.

Current Design

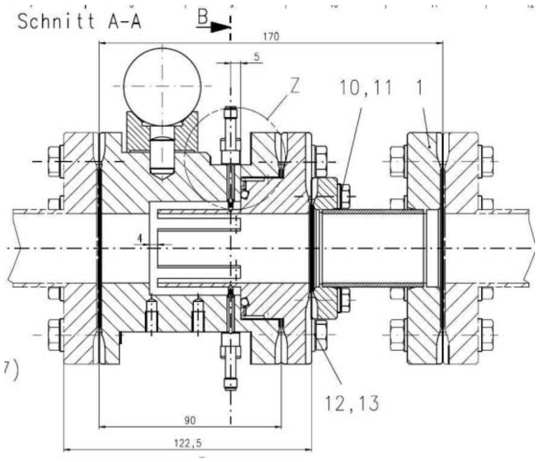

Figure 6: Cut view of stripline pickup

The center frequency was chosen as a multiple of the FLASH reference clock at 1.625 GHz. If we allow for a latency (corresponding to the roll off time of the pulse response) of 10 nsec, a quality factor of up to 50 is possible. In addition we have to keep in mind the required overlap between monopole/dipole resonances and the measurement frequency. With a difference between monopole and dipole of 35 MHz, this leads to a slightly lower limit of 45. For added security, the design goal was set to 35.

Figure 6 shows the cross section of the stripline and table 2 gives the respective specifications. The stripline is coupled out roughly 10 millimeters from the ground point, giving loaded Q factors of over 30 for the sum (monopole) and difference (dipole) modes. To avoid contact problems between the RF feedthroughs and electrodes as well at the contact surface of the vacuum tank, the inner part of the electrode assembly is gold plated.

Table 2: Specifications of Stripline BPM

Design frequency	1625 MHz
Sum resonance	1615 MHz
Shunt impedance sum mode	480 Ω
Loaded Q sum mode	32
Dipole resonance	1650 MHz
Loaded Q dipole mode	37
Sensitivity	10.1 mm

Figure 7 shows the reflection for monopole, dipole and quadrupole excitation. The minimum reflection of about 1.2 dB corresponds to an internal Q of 480. Power loss calculation using MAFIA would give Qs of 180 for a pure stainless steel device and 1200 for an ideal gold coating. Given that internal losses are relatively minor compared to the external ones, the actual value of the internal Q is anyway of negligible importance.

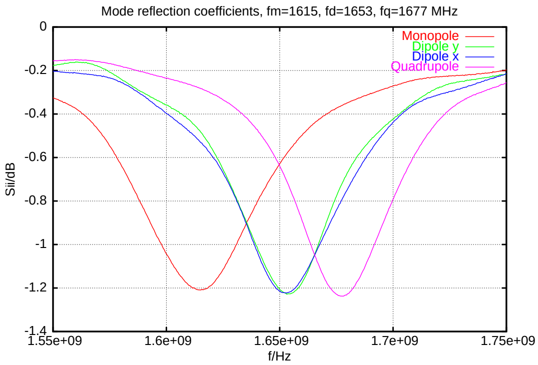

Figure 7: Measured reflection factors for monopole (all ports in phase), dipole (a pair of opposite ports in counter phase) and quadrupole excitation

Asymmetries in the structure were estimated by measuring the cross talk between the monopole and the dipole modes. As the sum (or intensity) signal also shows up as a dipole component, this corresponds to a shift of the electric center of the structure. For the devices measured, we obtained offsets up to 800 μm.

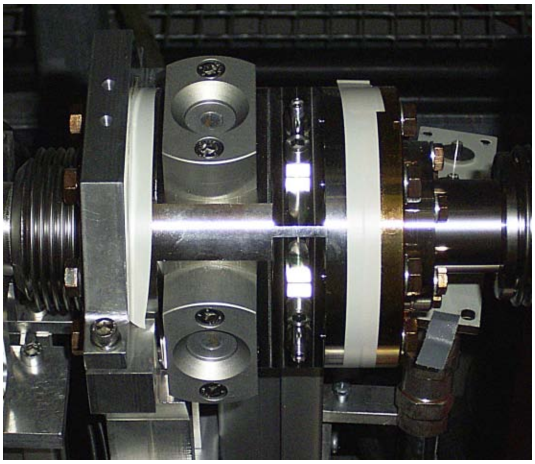

Figure 8: Stripline prototype inside FLASH

Further Developments

During the development of the stripline monitor as well as the RF front ends, the following critical aspects were observed. First, we are working at higher frequencies (compared to earlier versions), so that the quality of the contact between feedthrough and electrode can become a problem. Secondly, the difference in frequency between monopole and dipole mode creates a challenge for the development of fast latency RF front ends – phase rotations can create spurious signals in the down-converted output. A third minor, but visible effect is due to the quadrupole mode in the structure, which is responsible for quadratic nonlinearities in the measurement.

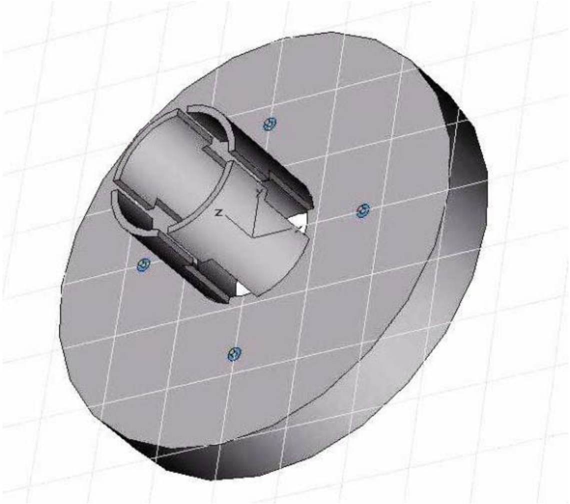

Figure 9: Electrode geometry giving equal resonance frequency for sum and difference mode.

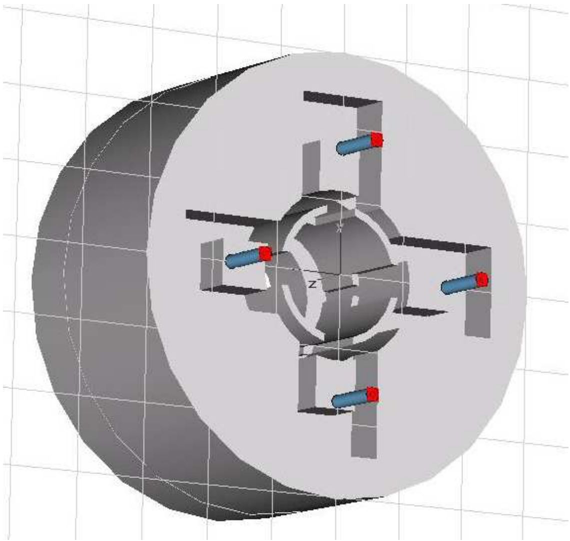

Figure 10: Coupling using a half-ridged waveguide to coaxial line transition

A new conceptual design addresses these points. The frequency difference between monopole and dipole depends on the mutual capacitive and inductive coupling between adjacent electrode, typically leading to a higher dipole frequency. If, as shown in figure 9, we add a capacitive load to the end of the striplines by widening them at their ends (which will only show an effect when the electrodes are at different potentials, as e.g. for the dipole mode), the dipole and quadrupole modes will move down in frequency toward the sum mode.

Contact problems at the electrode are eliminated completely by magnetic coupling using a half ridged wave guide, as shown in figure 10, which is followed by a transition to the coaxial feedthrough, which is easy to manufacture.

Nonlinearities stemming from the quadrupole mode are addressed as follows. The normal approach is to align the couplers with the electrodes, which leads to a homogeneous coupling to all modes. Now let us rotate the coupling slots by 45 degrees with respect to the stripline line. In this case, the coupler will see the average field (or voltage) of the two adjacent electrodes. The sum mode with equal voltage on all electrodes will couple the strongest, followed by the dipole mode. The quadrupole mode has alternating polarities on the electrodes, therefore the average is zero at the coupler and its nonlinear contribution is suppressed at the output. Damping of the quadrupole will be purely due to conductive losses inside the structure.

Table 3: Modal spectrum of improved design including internal losses (Material stainless steel)

Mode	frequency	Q factor
Monopole	1637 MHz	17
Dipole	1641 MHz	48
Quadrupole	1640 MHz	305

Table 3 lists the frequencies and Q factors for the modes. At first glance, the fact that sum and difference modes have different loaded Qs may look like a drawback. However, filtering the electrode signals down to the more restricted bandwidth of the difference signal will suppress part of the strongly dominating sum signal. The level of the difference signal will not be affected, the overall sensitivity of the system is effectively increased.

An alternative time domain technique would be to use a wide bandwidth front end to sample the signals, starting i.e. a few nanoseconds after the initial maximum, where the wide bandwidth sum signal has already decayed with respect to the difference signal. Figure 11 shows the respective signals.

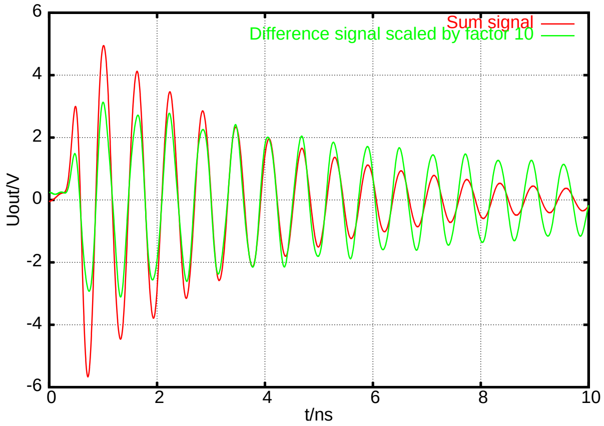

Figure 11: Sum and difference signals using signals from two opposite electrodes for a 1 nC bunch at 1 mm offset as computed with CST Particle Studio. Both signals were low pass filtered to eliminate signals from higher order resonances. To improve visibility, the difference signal was scaled up by a factor 10.

CONCLUSION AND OUTLOOK

As of the submission of the article, three prototypes of the stripline BPMs were built into FLASH and first tests with RF front end have been performed. In discussions between PSI and DESY, it has been decided, that cavity BPMs are going to used for the final system at the European XFEL, so further development of these devices (for this application) has been suspended for now.

Prototype stripline kickers are assembled and have been installed into FLASH. The final version will still need minor revisions to accommodate the differing size of the vacuum chamber and device length at the European XFEL.

REFERENCES

[1] B. Keil et al., “Design of an Intra-Bunch-Train Feedback System for the European X-Ray FEL”, DIPAC07, May 20-23 2007, Venice, Italy, in press.

[2] M. Dehler, “Resonant strip line BPM for ultra low current measurements”, DIPAC05, Jun. 6-8 2005, Lyon, France, pp. 284, http://www.JACoW.org.

[3] MAFIA rel. 4.0, http://www.cst.de

[4] Microwave Studio, http://www.cst.de