

# LARGE HORIZONTAL APERTURE BPM FOR USE IN DISPERSIVE SECTIONS OF MAGNETIC CHICANES

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## Abstract

A sub-5  $\mu\text{m}$  resolution electron beam position monitor (BPM) with a 10 cm horizontal aperture is described. It will be installed in the first bunch compressor chicane of FLASH in October 2006 and is required for a bunch-to-bunch energy measurement. It utilizes a stripline-pickup mounted perpendicularly to the beam direction to generate broadband electrical-pulses travelling to the left and right of the beam direction. The arrival-times of the broadband pulses will be measured through an electro-optical technique developed for a beam arrival-time monitor. In this paper, a comparison of simulations for the beam position monitor and the beam arrival-time monitor are used in conjunction with measured results from the beam arrival-time monitor to give an estimate for the expected performance of this unique BPM.

## INTRODUCTION

Energy jitter of the electron beam becomes transverse position jitter in dispersive regions of chicanes and after chicanes it becomes longitudinal and transverse position jitter. This longitudinal position jitter, or arrival-time jitter, presents a problem for the synchronization of external lasers to the electron beam. Since the low-level RF system alone cannot provide enough energy stability, a beam-based energy feedback is envisioned to stabilize the beam compression and arrival-time of the electron beam at the end of the accelerator. A monitor required for such a feedback system could be a high-resolution, large-horizontal-aperture BPM placed in the dispersive sections of magnetic chicanes.

A beam arrival-time stability of 30 fs ( $\sim 10 \mu\text{m}$  at  $v=c$ ) is desired for pump-probe experiments and mandatory for laser based electron beam manipulation at FLASH and the XFEL [1]. For an energy stability of  $10^{-4}$  at FLASH, the transverse position jitter in the dispersive section of the first chicane becomes 34.5  $\mu\text{m}$  and results in a longitudinal position jitter of 18  $\mu\text{m}$ . A monitor for a feedback system should be able to measure the energy by a factor of three better than the desired energy stability and this means that the resolution for a beam position measurement in the chicane must be better than 6  $\mu\text{m}$  and for a longitudinal time-of-flight path-length measurement it should resolve 3  $\mu\text{m}$ .

A longitudinal time-of-flight energy measurement can be made with two beam arrival-time monitors: one before and one after the chicane, but a BPM energy measurement has an advantage given by the ratio of the  $R_{16}$  to the  $R_{56}$  terms. In the case of the first bunch compressor for the XFEL, this advantage in the required sensitivity of the monitor is a factor of six.

Standard BPMs can get better than 6  $\mu\text{m}$  single-shot resolution but they do not have the large horizontal aperture that the location in the dispersive section of the chicane requires, so a novel design must be chosen. A standard BPM could be placed on movers, but the large energy spread, space constraints, and the undesirability of bellows in a wakefield sensitive area rule out this possibility. Alternatively, an array of small, longitudinally-oriented striplines could be placed above the path of the beam to give a transverse beam profile, but experience with the multi-channel data acquisition, wire interference, calibration issues, and DC offset drifts of SEM grids suggests that this could be a difficult design to realize. Consequently, a rather simple perpendicularly mounted stripline concept was suggested, but it was noted that it could not achieve the required resolution with standard electrical processing techniques [1]. Thanks to the development of a broadband laser-based synchronization system, new optical-techniques for electrical-pulse phase measurement make the required resolution possible [2].

## VACUUM DESIGN

The design utilizes a cylindrical pickup within a cylindrically shaped vacuum chamber channel that lies over and perpendicular to the path of the electron beam (see Fig. 1). When the electron beam travels beneath this pickup, broadband electrical pulses travel to opposite ends of the pickup. The arrival times of the pulses are then measured with an optical technique and used to determine the position of the electron beam.

## General Layout

In Fig. 1, the perpendicularly mounted stripline is depicted in 3-D as well as in cross-section.

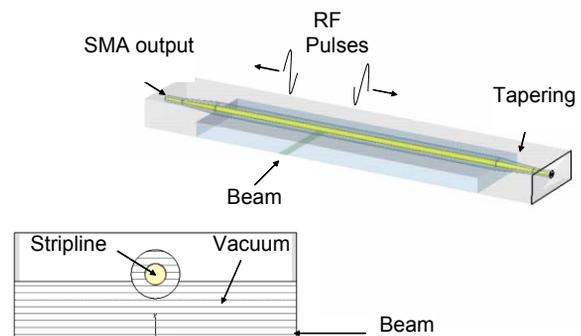


Figure 1: Perpendicularly-mounted stripline BPM pickup.

In the 3-D depiction, only the upper-half of the BPM is shown, since the lower-half is identical. The beam is represented by a thick line underneath the stripline. The central portion of the stripline is tapered on both ends from a 3 mm diameter to an SMA sized connector pin. The vacuum feedthroughs to SMA connectors are at the ends of the stripline.

Standard stripline designs do not have tapering from the pickup to the feedthrough, but instead have a larger radius pickup connected at a sharp angle to a smaller SMA connector sized feedthrough. The tapered design was chosen to improve the broadband transmission of the beam transient signal because it is undesirable to have an overlap between the signals of individual bunches within the macro-pulse and because the resolution of the optical phase measurement is improved by more broadband transient transmission.

### Dimensions

Key dimensions of the BPM are listed below in Table 1.

Table 1: BPM Dimensions

Component	Dimension	Specification
Pickup	Radius	1.5 mm
Pickup Center	Height	5 mm
Channel	Radius	3.45 mm
Chamber	Half-height	4 mm

The ratio of the stripline pickup radius to the stripline channel radius was chosen based on a coaxial-cable impedance matching model. If the stripline channel were closed instead of open to the underlying beam pipe, the impedance would be 50 Ohms. Since the stripline channel is only a partial cylinder, the pickup assembly has closer to 60 Ohms impedance in both simulation and laboratory tests. This was the optimal configuration for coupling to the beam and throughput.

The height of the pickup assembly above the center of the beam pipe was also optimized through a simulation. The best coupling and throughput was achieved for a position where the bottom of the pickup was  $\sim 0.5$  mm below the boundary of the beam pipe.

### Construction

Considerations for the construction include:

- A ring shaped ceramic spacer is used to stabilize and align the pickup in the channel.
- A mini-bellows design for the connection from the pickup to the feedthrough accommodates thermal expansion of the pickup
- With flanges, the length is 130 mm and the width of the central chamber is 135 mm. Both of these parameters are adjustable for individual applications.

## SIMULATIONS

### Beam Position Monitor

In the Microwave Studio simulation, a 50 GHz bandwidth (FWHM) Gaussian pulse was applied to the monopole mode of a waveguide port in order to simulate the electron beam. The output signals of the SMA connector ports were scaled according to a 1 nC electron bunch charge (Fig. 2).

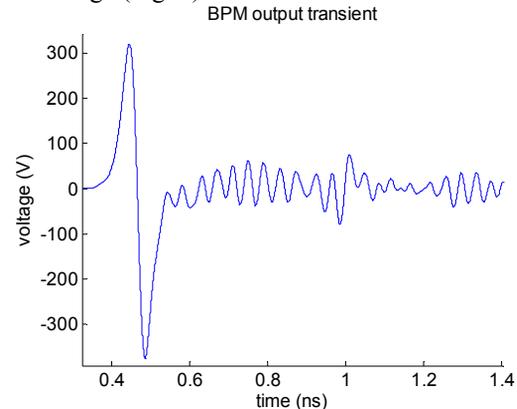


Figure 2: Simulation of BPM output. A clean inductive signal with minimal ringing is predicted.

The BPM response is linear over the entire horizontal aperture and is insensitive to small changes in the beam width and shape. Vertical position changes influence the amplitude of the signal but not the position measurement.

### Beam Phase Monitor

In order to develop confidence in the simulation, a comparison was made with measurements of transients from beam arrival-time monitors, or phase monitors, installed before and after the first chicane (Fig. 3). A phase monitor consists of a ring electrode connected to two SMA connector sized feedthrough pins in the horizontal plane and residing in a, so called, thick flange.

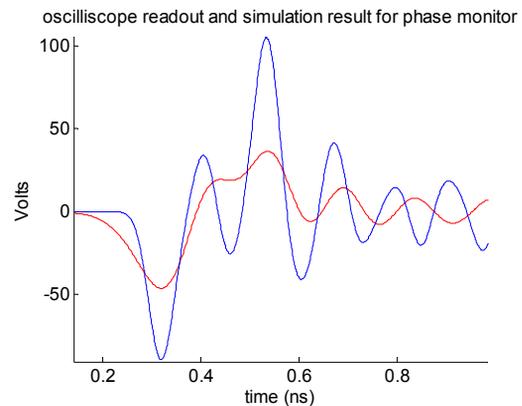


Figure 3: Simulation and Measurement of Phase Monitor Output. The lower amplitude curve was measured with a 7 GHz bandwidth oscilloscope and the larger amplitude curve was simulated.

The output from the monitor was measured with a 7 GHz bandwidth oscilloscope and simulated with a 7 GHz

(FWHM) bandwidth Gaussian 'beam'. The simulation did not include the 30 meter long cable between the pickup and the oscilloscope. This would account for some of the attenuation. The general shape of the beam transient exhibits a bump on the rising edge of the inductively shaped curve. The sharpness of the bump was exaggerated by the 7 GHz simulation because the frequency cut-off in the simulation is gradual, but in the scope, it is more abrupt.

The position of the bump is beam-position dependent and it would be desirable to re-design the monitor to minimize this effect. Nevertheless, it enhances the monitor's unintended functionality as a BPM, yielding a measured 3  $\mu\text{m}$  horizontal resolution over a millimeter range [3] and a large non-linear position response over the entire aperture in simulation.

## OPTICAL PHASE MEASUREMENT

### *Beam Phase Monitor*

To date, 30 femtosecond resolution has been achieved with the optical beam phase monitor measurement [3]. It utilizes a broadband optical pulse ( $< 1$  ps) from a master laser oscillator that is locked to the 1.3 GHz reference of the machine. The light pulse travels via fiber optics through an electro-optical modulator (EOM) which encodes the amplitude information of an RF pulse in the light pulse. Essentially, the light pulse samples the RF pulse. The modulated light pulse is then detected with a 50 MHz bandwidth photo diode and read out by a fast ADC that is clocked at twice the repetition rate of the laser and generated from the laser pulse itself. The method has only recently been tried and many possibilities for improving the resolution are still open.

Since changes in beam arrival-time produce a change in laser intensity, the measurement is limited by the steepness of the RF signal slope and the detection of the laser amplitude. Slope changes can distort the measurement, so it is best to measure at the zero crossing of the signal for an accurate phase measurement.

### *Beam Position Measurement*

For the chicane BPM, the average of two outputs' phase measurement can also be used to measure the beam arrival-time, as long as the energy spread is constant. The difference of the two outputs' phase measurements gives the position. Alternatively, if the arrival time is known from the phase monitor, the energy spread might be measured with the BPM.

It is anticipated that for each BPM output, the RF signal will be split for a low-resolution (large range) phase measurement, and the other output for a high-resolution (small range) phase measurement. A delay-line will use the low-resolution measurement to put a high-resolution measurement in range. The position of this delay-line plus the fine measurement given by the ADC gives the beam position. This delay line must have sub-micrometer resolution over 10 cm and be adjusted between macro-

pulses (10 Hz) in order to keep the system measuring the beam transient at the zero crossing, thereby reducing the systematic errors of slope variation caused by beam charge fluctuations or transverse profile shape changes.

The slope variation from charge fluctuation scales linearly and should amount to no more than 3 percent, an amount that can be corrected for with a toroid charge measurement. The shape dependence can be monitored with a synchrotron light monitor after the second bend of the chicane.

Interferometric schemes using either a CW laser or the master laser oscillator were also considered for this monitor, but the success of the optical phase measurement has shifted the focus to a tried concept.

## FUTURE DEVELOPMENTS

The BPM will be installed in October of 2006 and a final version of the electro-optical front-end is expected to be completed by January 2007. The incorporation of the chicane BPM, upstream BPMs, the phase-monitor, and a bunch length monitor into an FPGA based bunch-to-bunch energy feedback will follow.

The phase monitor and the BPM can distinguish the energy jitter that results from injector timing jitter from the energy jitter caused by the acceleration RF phase and amplitude jitter. The bunch length monitor and the BPM can distinguish the RF amplitude jitter from the RF phase jitter. BPMs before the chicane can be used to remove incoming orbit jitter from the chicane BPM's energy measurement.

## CONCLUSIONS

- The BPM is expected to have sub-5  $\mu\text{m}$  resolution.
- It will have a 10 cm horizontal range for this first application in the first bunch compressor.
- It will be used in a bunch-to-bunch energy measurement.
- It will use an optical phase measurement developed for a beam arrival-time monitor.
- First results from the beam arrival-time monitor optical phase measurement give a sub-30 fs resolution with many options still open for improving the system's resolution.

## ACKNOWLEDGEMENTS

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## REFERENCES

- [1] Manfred Wendt, personal communication.
- [2] X-FEL Technical Design Report Sect. 4.8 2006.
- [3] F. Loehl et. al., "Beam Arrival-time Monitor", EPAC'06, Edinburgh, June 2006, <http://www.jacow.org>