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

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Abstract

A sub-5 μm resolution electron beam position monitor (BPM) with a 10 cm horizontal aperture is described. It was 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 measurements taken with an 8GHz bandwidth oscilloscope are presented.

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 (~10 μm 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 μm and results in a longitudinal position jitter of 18 μm. 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 μm and for a longitudinal time-of-flight path-length measurement it should resolve 3 μm.

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 μm 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 [2]. Thanks to the development of a broadband laser-based synchronization system, new optical-techniques for electrical-pulse phase measurement make the required resolution possible [3]. This system is being duplicated for commissioning with the chicane BPM in February 2007. Oscilloscope measurements of the beam transient from the BPM pickup demonstrate that it meets expectations.

VACUUM CHAMBER 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 used to determine the position of the electron beam.

General Layout

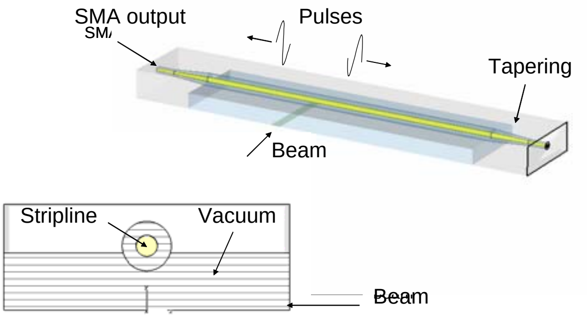

Figure 1: Perpendicularly-mounted stripline BPM pickup.

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

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

Table 1: BPM Dimensions

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 ~0.5 mm below the boundary of the beam pipe.

Construction

Considerations for the construction include:

- A ring shaped Alumina spacer is used to stabilize and align the pickup in the channel (for future designs, Vespel (polyimide) may be used).
- 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. (Parameters are adjustable for individual applications.)

OPTICAL PHASE MEASUREMENT

Beam Phase Monitor

To date, 30 femtosecond resolution has been achieved with the optical beam arrival-time 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 measurements 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 for which one can correct 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 arrival-time monitor’s optical phase measurement has shifted the focus to a tried concept.

SIMULATIONS

In the Microwave Studio simulation, a 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 (Figs. 2 and 3).

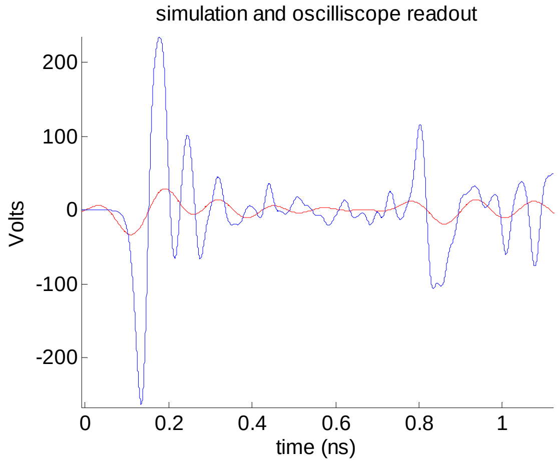

Figure 2: 50 GHz bandwidth simulation of BPM output (blue) and 8 GHz oscilloscope measurement. The reflected pulse (right) is undesired and is due to the impedance mismatch caused by the ceramic support.

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 and charge fluctuations influence the amplitude of the signal but not the position measurement.

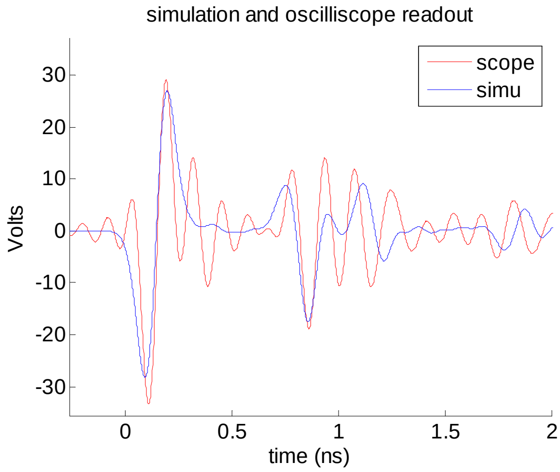

Figure 3: When the bandwidth of the simulation is the same as the bandwidth of the oscilloscope (8 GHz) good agreement is observed. The additional ringing on the oscilloscope signal is believed to be a scope artefact, but no conclusive test has been done.

The simulation did not include the 1 meter long cable between the pickup and the oscilloscope. The additional ringing observed on the oscilloscope signal is believed to be an oscilloscope artefact, but a conclusive test will be available in February 2007 when the optical front-end is commissioned.

MEASUREMENTS

The beam energy was changed through the adjustment of the accelerator section ACC1 RF amplitude and the beam position in the chicane changed as expected. The position was measured on an 8GHz oscilloscope by triggering the acquisition of the beam transient from one end of the stripline with the output from the opposite end (Fig. 4). This method should give ~150 um position resolution. The target resolution for the optical front-end is <5 um.

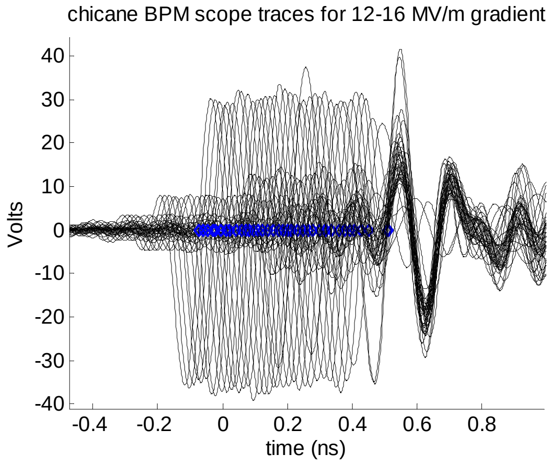

Figure 4: Beam transients for different beam energies.

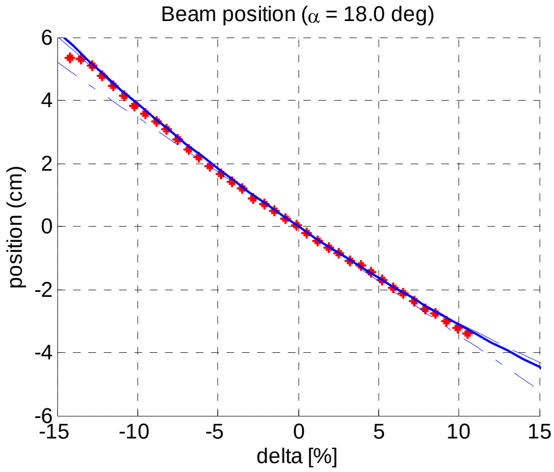

Figure 5: Beam positions for different beam energies for an angle of 18 degrees into and out of the chicane: measured (red*) and calculated R16, T166, R1666 (blue).

In Fig. 5, the measured values of the positions expected in the chicane for different beam energies (red) agree well with the calculated values (blue). The straight blue line is just the R16 term for the chicane and the curved lines include the higher order dispersion terms, T166 and R1666. The calculation was done for an angle into the chicane of 18 degrees. On the left end of the plot, the beam was clipped by the vacuum chamber and on the right end of the plot, the gradient could not be increased any more.

In Fig. 6, the phase of the 1.3 GHz accelerating RF was changed and the beam position in the chicane changed in a sinusoidal form, as expected. When the bunch is further off crest, the energy spread, and therefore the transverse position spread, of the bunch is larger, but the length of the bunch is shorter. This situation seems like it could produce a position measurement error for very off crest beams, due to the difference in the arrival times of the head and tail of the bunch, but in reality the monitor always measures the centroid.

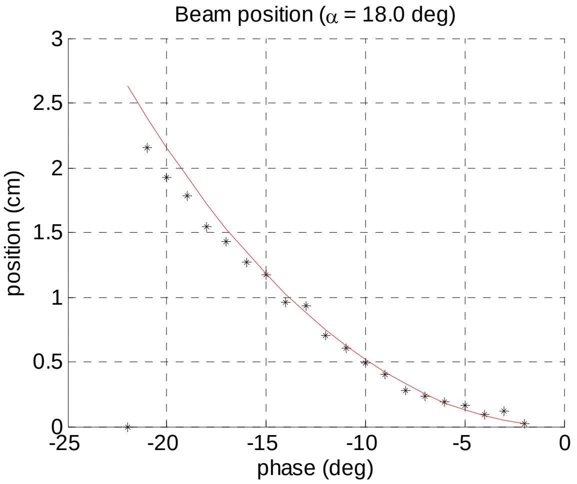

Figure 6: Beam positions for different beam energy chirps: measured (black*) and calculated (red). The phase of the accelerating RF was changed, creating a sinusoidal position change.

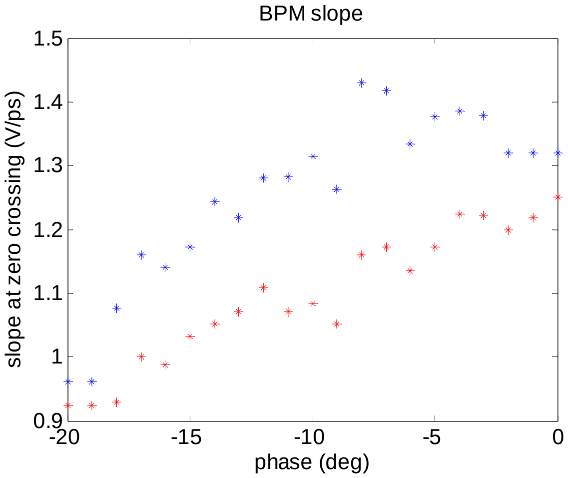

Figure 7: Slope at the zero crossing for different energy spreads. Negative phase corresponds to increased energy spread.

Fig. 7 shows the slope at the zero crossing for different accelerating RF phases. For the optical front- end, it is desirable to sample the transient as close as possible to the zero crossing because if one samples away from the zero crossing and then the bunch charge, the beam shape, or the vertical position changes significantly, then an error is introduced into the measurement from the resulting transient amplitude change. By sampling on the zero crossing the measurement is insensitive to amplitude changes. Nevertheless, it is good to see that bunch shape changes due to energy spread changes, do not drastically affect the slope of the transient.

FUTURE DEVELOPMENTS

A final version of the electro-optical front-end is expected to be completed by February 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 µm 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.

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