LARGE HORIZONTAL APERTURE BPM AND PRECISION BUNCH ARRIVAL PICKUP

K. Hacker, F. Loehl, H. Schlarb DESY, Hamburg, Germany

Abstract

The large horizontal aperture chicane BPM and the precision bunch arrival monitor at FLASH will be important tools to stabilize the arrival-time of the beam at the end of the linac. The pickups for these monitors will be paired with front-ends that sample the zero-crossing of the beam transient through the use of electro-optical modulators and sub-picosecond-long laser pulses delivered by the master-laser oscillator. The design of pickups for this front-end requires the consideration of the beam transient shape as well as the amplitude. Simulations and oscilloscope traces from pickups that use or will use the EOM based phase measurement and the expected limitations and benefits of each pickup are presented. In particular, the design for a 5 µm resolution BPM with a 10 cm horizontal aperture is demonstrated in terms of its capability to measure the beam energy and its sensitivity to the shape and orientation of the beam.

INTRODUCTION

A bunch arrival-time stability of 30 fs (~10 µm at v=c) is desired for pump-probe experiments and is mandatory for laser-based electron beam manipulation at FLASH and the XFEL [1]. With the accelerating LLRF goal 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 beam energy by a factor of three better than the desired energy stability of $5*10^{-5}$ and this means that the resolution for a beam position measurement in the chicane must be better than 6 µm and a longitudinal time-of-flight path-length measurement should resolve 3 µm.

A longitudinal time-of-flight energy measurement can be made with two bunch arrival monitors (BAMs): one before and one after a chicane, but a chicane 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.

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

The pickup transients from these chicane BPMs and BAMs will be paired with the sub-picosecond pulses from the master laser oscillator (MLO) from the timing and synchronization system in an electro-optical modulator (EOM) in order to sample the zero crossing of the beam transient, giving a phase measurement with an accuracy of 5-50 fs, depending on the pickup and cables used [2, 3]. Temperature dependent cable drifts are removed by installing the EOM front-end in the tunnel [4].

In this paper, a ring-shaped BAM, a button-style BAM, and a perpendicularly mounted stripline chicane BPM are analyzed with Microwave Studio simulations and measured oscilloscope traces with regard to their suitability for the EOM phase measurement technique. Measurements of the beam energy with the 10 cm wide chicane BPM pickup and an oscilloscope are analyzed with respect to their sensitivity to beam shape and orientation changes.

EOM PHASE MEASUREMENT

The EOM phase measurement [2, 3] utilizes a short 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 EOM which encodes the amplitude information of an RF pulse into the laser pulse energy. Essentially, the laser pulse samples the beam transient. The modulated laser pulse is then detected with a fast photo diode and read out by a 108 MHz, 16bit ADC that is clocked with the laser pulse at twice the repetition rate of the laser.

Since changes in the RF pulse arrival-time produce a change in laser intensity, the measurement is limited by the steepness of the beam transient slope and the precision of the laser amplitude detection. Slope changes can distort the measurement, so a feedback is used to maintain the measurement at the zero-crossing. For a particular 30 fs resolution measurement, the slope at the zero crossing was 250 mV/ps and the single-shot noise with which the laser pulse intensity was detected was 0.3% [2]. This particular measurement was done with a 10 m cable attached to the pickup, and much higher resolution is, of course, possible with in-tunnel measurements.

For the first in-tunnel tests, the EOM setup will be duplicated several times for use with two BAMs and a chicane BPM. Fiber-optic links have been sent to several key points in the tunnel in order to transport the signals without the effects of RF cable drifts and attenuation [4]. The commissioning of these front-ends will occur in September 2007.

PICKUP DESIGN

Beam pickups for the EOM phase measurement must produce a steep transient slope for maximum resolution. They must also have a minimum of ringing so that the transient of a bunch that comes earlier is not detected.

This requires the high bandwidth and voltage that are produced by short bunches, pickups with a large area exposed to the beam, and good impedance matching. Bunches that are longer than ~25 ps (RMS) will have reduced resolution because the slope of the transient becomes less steep (e.g. 50% for 25 ps).

BAM

A ring shaped pickup was originally available for the BAM prototype measurements; however, it had a critical flaw [6]. The spectral response has a notch at 5 GHz, corresponding to a quarter-length of the ring circumference, implying that the beam does not couple strongly to the second harmonic of the ring. A strong position dependence of the zero-crossing is therefore seen through a beat between the fundamental and third harmonics of the ring. This position dependence of the phase can be partially removed if the signals from both sides of the ring are combined.

Another consideration of BAM pickup design is the ratio between the amplitude of the transient and the slope of the transient. An optimal pickup would produce a large slope and small amplitude. Large amplitude is undesirable because it must be limited or attenuated in order to protect the EOM from damage. Attenuators reduce the signal slope and limiters have AM-PM conversion behaviour. The ring-shaped pickup produced a slope of 1 V/ps and a peak-to-peak voltage of 130 V when measured in the tunnel with an 8GHz bandwidth oscilloscope, but the EOM can only tolerate ~10 V.

The most obvious alternative to a ring is a button pickup. A Microwave Studio and oscilloscope based comparison between the button pickups in the FLASH linac yielded that, although many button pickups designed with attention to impedance matching would be adequate for an EOM phase measurement, an optimal pickup would have no "button" at all; it would consist of a simple coaxial cylinder with one end open to the beam and the other end connected to a vacuum feedthrough of the same inner and outer diameters. A type-N feedthrough was chosen for the final design because of its large diameter, enabling the pickup to achieve the same signal slope as the ring-shaped monitor, but less than half of the peak-to-peak voltage. To remove the position dependent amplitude changes, the signals from opposing buttons are combined.

Chicane BPM

The chicane BPM 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) [3]. When the electron beam travels beneath this pickup, short electrical pulses travel to opposite ends. The arrival-times of the pulses are then measured with the EOM technique and used to determine the position of the electron beam. They have been installed in both the 1st and 2nd bunch compressor chicanes at FLASH with respective horizontal ranges of 10 and 20 cm.

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

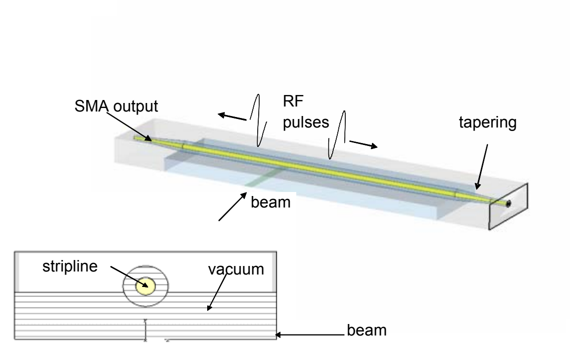

Figure 1: Perpendicularly-mounted stripline BPM pickup.

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 piece 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.

A simpler design that utilizes a type N feedthrough and does not require tapering was not possible for the first installation because the vacuum chamber height is only 8 mm. This would, however, be a good option for the XFEL where the vacuum chamber height will be 40 mm.

In a 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 and low-pass filtered to 8 GHz to match the bandwidth of the oscilloscope measurement (Fig. 2).

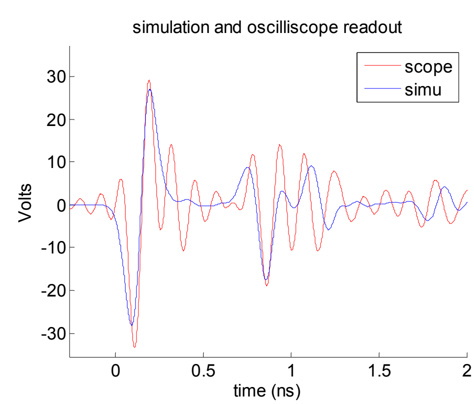

Figure 4: Simulated and measured stripline output. The ringing in the measured signal is an oscilloscope artefact. The echo with 0.6 ns delay is caused by a ceramic support at the opposite end of the stripline.

Good agreement is observed between the measured and simulated signals, except for the ringing seen on the oscilloscope signal. This ringing starts before the arrival of the electron beam and is observed only for in-tunnel measurements. It is observed for different types of pickups measured in the tunnel. If the higher frequencies are attenuated through the use of a long cable before the oscilloscope, the ringing is gone. The oscilloscope is not designed for signals with a bandwidth of much more than 8 GHz and in simulation the spectral response of the monitor is strong up to 50GHz, yielding a short >300 V peak-to-peak pulse.

The oscilloscope was attatched to either end of the stripline and used to measure the beam energy in the chicane (Fig. 5). The pickup operates as expected over the entire 10 cm aperture and the measurement was only limited by the maximum amplitude of the accelerating module on one end and by the chamber width on the other..The position resolution with the oscilloscope with an intrinsic trigger jitter of 0.5 ps rms was only 150 um, but 5 um is the expected resolution with the EOM front end.

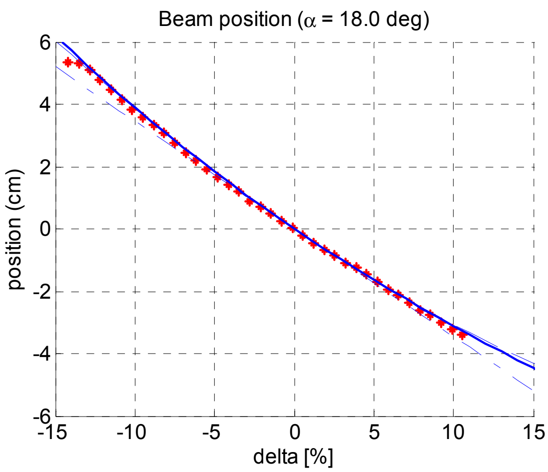

Figure 5: Calculated and measured beam position. The measurement points are shown in red and the calculated positions using R16, T166, and R1666 for the bunch compressor are shown in blue.

The pickup also responds as expected to changes in beam width (Fig. 6) and transverse tilt (Fig. 7). If the nominal beam width (4 mm FWHM) changes by a factor of 2, the slope at the zero crossing will change by less than 10%. A 200 um position measurement error is predicted by simulation and measured for a 4 mm (FWHM) wide beam tilted by 5 degrees. This means that the signals from the top and bottom pickups must be combined to remove this effect.

An error that cannot be removed would be caused by a longitudinally (XZ) tilted beam with a significant charge distribution asymmetry. In simulation, a 4 mm (FWHM) wide asymmetric Gaussian beam with the center-of-charge shifted horizontally by 1 mm relative to the peak will cause the BPM to show a 170 um absolute position error if the beam is tilted by 0.2 rad in the XZ plane. This kind of tilt would be expected for off-crest operation. As long as the beam distribution or orientation does not change dramatically, it does not have any influence on the BPM's functionality in an energy feedback.

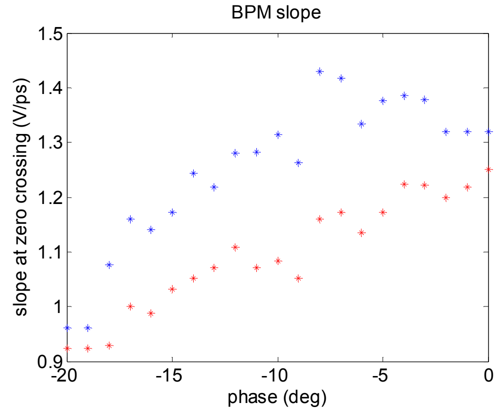

Figure 6: The slope of the transient at the zero crossing depends weakly on the beam width. The two different sets of points represent data from the left and right output of the monitor. The beam width was changed by varying the accelerator phase from nominal by ±10°.

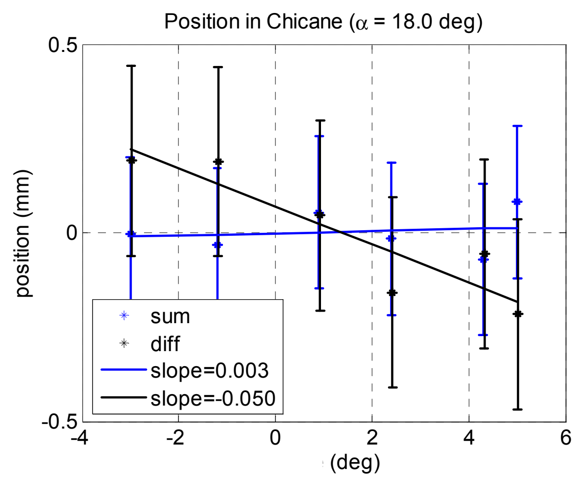

Figure 7: A transverse tilt of the electron beam would cause a measurable error unless the signals from the top and bottom pickups are combined.

SUMMARY

- EOM technique makes high resolution phase measurements possible.
- Optimal pickups for the EOM technique must maximize the slope and minimize amplitude, ringing, and transient distortions.
- Pickups perform as expected in tests with beam.

REFERENCES

[1] X-FEL Technical Design Report Sect. 4.8 2006.
[2] F. Loehl et. al., "Beam Arrival-time Monitor", EPAC'06, Edinburgh, June 2006.
[3] F. Loehl et. al., This conference WEPB15.
[4] F. Loehl et. al., This conference WEPB16.
[5] K. Hacker et. al., "BPM with Large Horizontal Aperture", EPAC'06, Edinburgh, June 2006.
[6] K. Hacker et. al., "Beam Pickup Designs Suited for an Optical Sampling Technique", FEL'06, Berlin, June 2006.