BEAM PICKUP DESIGNS SUITED FOR AN OPTICAL SAMPLING TECHNIQUE

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Abstract

The beam arrival-time monitor and large horizontal aperture chicane BPM at FLASH are 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 a front-end that samples the zero-crossing of the transient through the use of electro-optical modulators (EOMs) and sub-picosecond-long laser pulses delivered by the master-laser oscillator (MLO). The design of pickups for this front-end requires the consideration of the transient shape as well as the amplitude. Simulations and oscilloscope traces for pickups that use or will use the EOM based phase measurement and the expected limitations of each pickup are presented. In particular, a method to reduce the beam position sensitivity of the beam arrival-time pickup, the potential resolution of a button pickup arrival-time measurement, and the design for a 5 μm resolution BPM with a 10 cm horizontal aperture are described.

INTRODUCTION

A beam 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 beam arrival-time monitors: one before and one after the 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 arrival-time monitor and the chicane 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. A bunch length monitor and the chicane 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.

The pickup transients for these energy measurements will be paired with the sub-picosecond pulses from the master laser oscillator (MLO) from the timing and synchronization system to sample the zero crossing of the beam transient through an electro-optical modulator (EOM). The beam arrival-time monitor installed in the tunnel, a perpendicularly mounted stripline to be installed in the dispersive section of the chicane in October 2006, and button-style pickups are analyzed with Microwave Studio simulations and compared to measured oscilloscope traces with regard to their suitability for the EOM phase measurement technique. The front-ends for beam transient pickups typically filter the transient down to 2 GHz or less and utilize the ringing or amplitude of the signal to get the desired beam information, but this EOM front-end works at 10 GHz or more and samples the zero-crossing, so attention must be paid to the transient shape.

EOM PHASE MEASUREMENT

Test Bench

To date, 30 fs resolution has been achieved with the EOM phase measurement and a limited but not combined output of the ring shaped arrival-time monitor pickup [2]. It 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 electro-optical modulator (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 50 MHz bandwidth photo diode and read out by a 100 MHz, 12bit 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 RF signal 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. The slope at the zero crossing for the 30 femtosecond resolution measurement was 250 mV/ps and the single-shot noise with which the laser pulse intensity was detected was 0.3%. Shot-noise of spontaneous emission from the laser is a suspected noise source, but as of yet there is no conclusion.

Future Applications

It is anticipated that for each pickup output, the transient signal will be split for a low-resolution (large range) phase measurement and a high-resolution (small range) phase measurement. A delay-line will use the low-resolution measurement to put the high-resolution measurement in range. The phase measurement is given by the position of this delay-line plus the fine measurement given by the laser amplitude. 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.

The EOM setup will be standardized and duplicated several times for use with two or more beam arrival-time pickups and two large horizontal aperture chicane BPMs.

PICKUP DESIGN

Beam transient pickups for the EOM phase measurement must produce a steep slope for sampling of the zero-crossing with a picosecond-long laser pulse to give maximum resolution. They must also have a minimum of ringing so that the transient of a bunch that comes earlier is not detected. The bunch spacing will be 200 ns for the XFEL. A steep slope requires the high bandwidth and voltage that are produced by short bunches and pickups with a large area exposed to the beam. 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) for longer bunches. Minimal ringing can be achieved through tapering from the pickup to the feedthrough.

Position Monitor

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) [3]. It was originally proposed by [4]. 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.

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

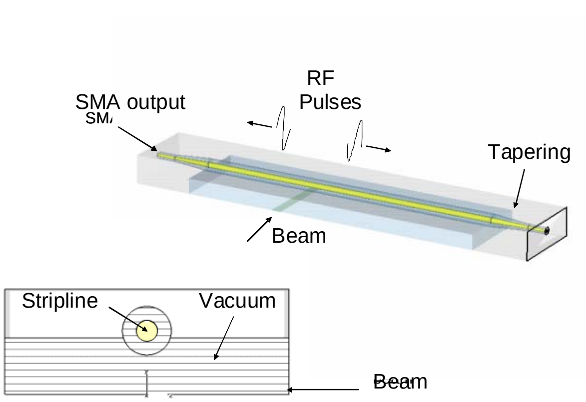

Figure 1: Perpendicularly-mounted stripline BPM pickup.

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.

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 because in simulation it transmits 20% more signal amplitude and has 80% less ringing amplitude compared to the non-tapered design.

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 (Fig. 2).

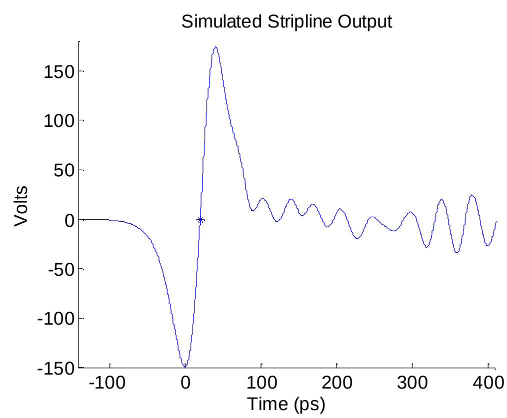

Figure 4: Simulated stripline output with a marker at the sampling location. The slope at the marker is 10 V/ps.

A similar simulation for an existing pickup also predicted such a high voltage, and when the pickup output was measured in the tunnel, the results matched the simulation within a few volts. The transient without a long cable is most interesting because the EOM front-end will be installed in the tunnel within a temperature stabilized enclosure, thus minimizing cable lengths and temperature dependent signal drifts.

The BPM's horizontal response is linear over the entire horizontal aperture and is insensitive to small changes in the beam shape. Vertical position changes and charge changes influence the amplitude of the signal but not the phase. 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. Alternatively, if the electron beam arrival-time is known, the energy spread can be measured through changes in the sum of the BPM outputs' phase measurements with a projected sensitivity of 1.5 fs/µm (Fig. 3), but this is only possible when the beam width is larger than the length.

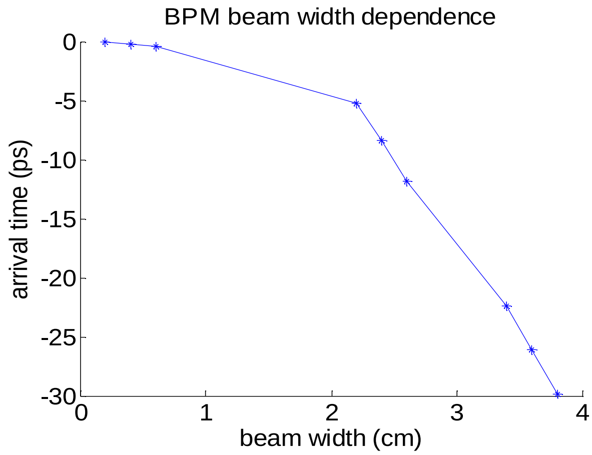

Figure 3: Energy spread measurement with BPM.

An important thing to note about pickup transients is that a measurement of the zero-crossing gives the RMS value of the beam position, in the case of the transverse stripline, or, in the case of the beam arrival-time monitor, it gives the RMS value of the arrival-time. This is different from measurements with devices that can measure the peak intensity of an electron distribution, such as synchrotron light monitors and electro-optical sampling. For non-linear, inhomogeneous compression schemes the RMS value and the peak value can differ, but for linear, homogeneous compression, they should be one and the same. About 30 fs difference between the peak and RMS values has been measured for the current compression scheme. The 3rd harmonic cavity will be installed in summer 2007 to linearize the compression.

Arrival-time Monitor

The arrival-time monitor pickup is a ring electrode in a thick flange with two SMA feedthrough sized pins attached to the ring in the horizontal plane. The frequency response of the ring shows a notch at 5 GHz which corresponds to a quarter-length of the ring circumference, implying that the beam does not couple strongly to the second harmonic of the ring. A position dependence of the output signals is therefore seen through a beat between the fundamental and third harmonic of the ring. This problem reflects the original intended use of the pickup in a lower-resolution RF down-mixing phase measurement that was not affected by the transient shape. For the EOM phase measurement the two outputs were combined to remove this effect (Fig. 3). The, so called, cold-combiner that was designed for a toroid-based charge measurement crossed the output pins of the SMA connectors in a circular void and terminated one of the arms of the cross with 50 Ohms [4].

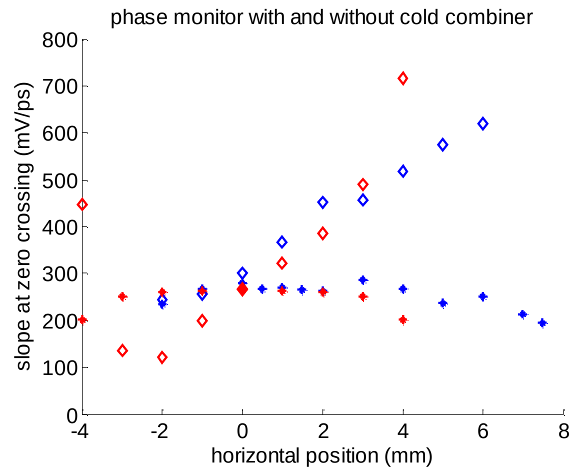

Figure 3: Slope at zero-crossing of arrival-time pickup with (star) and without (diamond) combiner. Simulation (red) and oscilloscope (blue) results are shown.

The output from the monitor was measured with an 8 GHz bandwidth oscilloscope and simulated with a Gaussian 'beam' in Microwave Studio. Simulation and oscilloscope results agree well when cable, bandwidth, and combiner attenuation are taken into account (Figs. 3 and 4).

Button Pickups

Button pickups are installed in a few locations in the FLASH linac. Their output amplitude is proportional to the button size and distance from the beam and it can be comparable to that observed from the ring shaped pickup. Buttons can be more desirable than the ring electrode due to the lack of a notch in the frequency response that causes zero crossing changes with beam position changes. No detectable change of the transient zero crossing occurs for beam position changes. Buttons also produce a steeper, very linear slope with a lower peak-to-peak voltage.

Measurements of the beam transient with button pickups at FLASH were conducted with an 8 GHz bandwidth oscilloscope inside the tunnel and steep slopes of 1-2 V/ps were observed. The large changes in the slope due to beam position changes make the challenge of measuring on the zero crossing more critical. If the slope changes prove to be unworkable, a combiner could again be used.

The main problem with the pickups that were measured was that the signal was still ringing 200 ns after the transient with an amplitude that was 0.7% of the peak voltage. This would be a problem for the 200 ns XFEL bunch spacing because 10 fs resolution requires almost 10 times less ringing amplitude (Fig. 5).

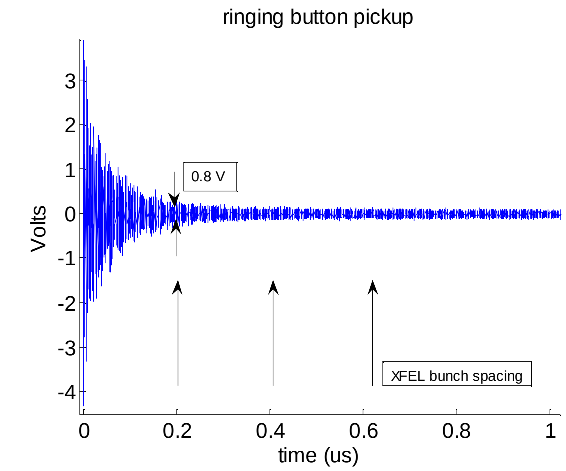

Figure 5: Ringing of button pickup with 120 Volt peak to peak transient. The ringing must be smaller than 10 mV by the time a new bunch comes for a 10 fs resolution phase measurement.

A few button pickup designs were simulated to look for ways to reduce or characterize the sources of the ringing. It was noted that for a large amplitude output, the pickup pin needed to be long or have a large button attached to it. For a long pin or a large cylindrical button, the transient amplitude was good, but the ratio between the transient amplitude and the ringing was bad. For a short pin without a button, there was practically no ringing, but the transient amplitude was insufficient (Fig. 6). More work needs to be done to understand and optimize the design.

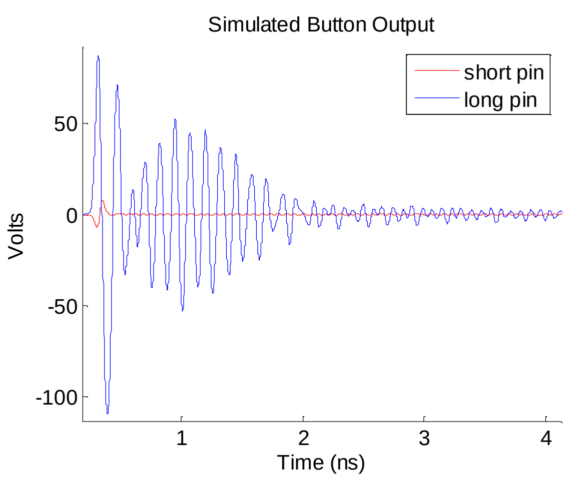

Figure 5: Button pickup with a long or short pickup pin. The long pin is more like a pickup in a cavity BPM.

EOM DAMAGE

The EOMs in the front-end are damaged by high voltages and care must be taken to preserve the steep slope of the transient while protecting the electronics from high voltage. Following a voltage surge through the arrival-time pickup caused by electron beam spray or incidence, the EOM's Lithium Niobate crystal was rendered opaque to the laser light. No limiter was in place and the damage occurred over less than a minute.

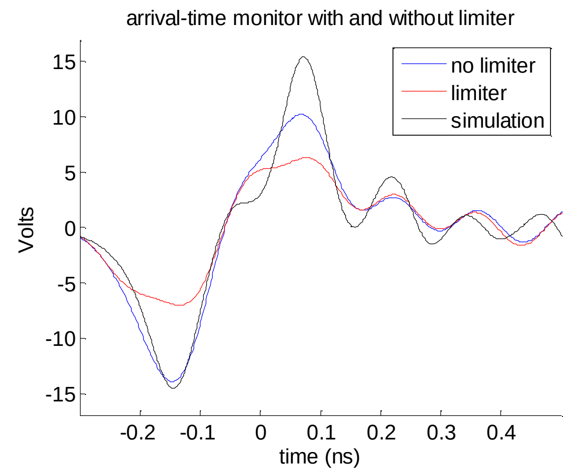

Figure 7: Limited and combined ring output from oscilloscope measurement and simulation including attenuation and dispersion from the cable, splitter, and combiner.

The Agilent N9355C 26.5 GHz bandwidth limiter that was in place throughout most tests of the EOM setup (Fig. 7) appeared to protect the EOM crystal from standard beam operation. With the limiter in place, even extreme off axis kicks from the transverse deflecting cavity upstream did not appear to damage the EOM. A conclusive study of the long-term effects of high voltage with the limiter has not, however, been done. The temperature dependent drifts of the limiter have also not been studied and are of interest even though the component will be used in a temperature controlled enclosure in the tunnel. It has also not bee used, long-term, in the tunnel, where 120 Volts peak to peak have been measured from the combined ring pickup.

SUMMARY

- EOM technique makes high resolution phase measurements possible.
- Optimal pickups for the EOM technique must maximize the slope and minimize ringing and transient distortions.
- EOMs must be protected from high voltage.

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] K. Hacker et. al., "BPM with Large Horizontal Aperture", EPAC'06, Edinburgh, June 2006.
[4] Manfred Wendt, personal communication.