DEMONSTRATION OF A BPM WITH 5 MICRON RESOLUTION OVER A 10 CM RANGE

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Abstract

At the Free electron LASer in Hamburg (FLASH), six distinct methods to measure the energy of the electron beam have been employed in and around the first bunch compressor chicane. First results from four of the six methods will be presented here and an attempt is made to benchmark all of the measurements against one another. The design and performance of RF phase measurement and EOM sampling schemes for the BPM in the dispersive section of the chicane are also presented in this context. The BPM is required to produce sub-5 um resolution over a 10 cm range, capable of resolving $2{*}10^{-5}$ energy changes and 15 fs arrival-time changes.

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]. Arrival time jitter is primarily induced by energy dependent path-length changes in the first chicane with an R_{16} = 350 mm and R_{56} = 620 ps. With the accelerating RF goal energy stability of 10^{-4} at FLASH, the transverse position jitter in the dispersive section of the first chicane becomes 35 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.

There are two existing monitors that achieve $\sim 8{*}10^{-5}$ energy resolution: an out-of-loop vector sum of the accelerating RF [2] and a pair of photomultiplier tubes on movers [3]. The vector sum is sensitive to drifts and the photomultiplier tube measurement is shot-noise limited.

A longitudinal time-of-flight energy measurement has recently been made with two beam arrival-time monitors [4]: one before and one after the chicane, but a measurement of the beam position in the dispersive section of the chicane has an advantage in the resolution requirements 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.

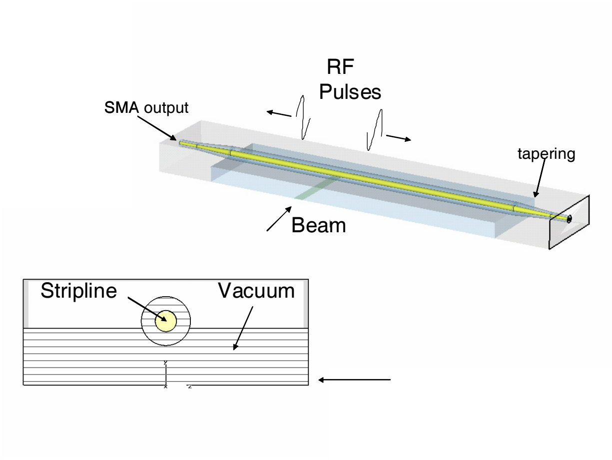

Figure 1: Top-half of the perpendicularly-mounted stripline BPM pickup.

Three different front-ends were constructed, in order to make use of a unique, perpendicularly-mounted stripline BPM pickup installed in the dispersive section of the first bunch compressor chicane (Fig. 1) [5]. The BPM needed to have a measurement range of 10 cm and a resolution of better than 5 um. This resolution was achieved with both a 10.4 GHz down-mixing scheme and an Electro Optical Modulator (EOM) sampling scheme to measure the phases of the pickup's broadband output pulses.

RF PHASE MEASUREMENT

A quick and inexpensive way to measure the phases of the RF pulses with ~5 um precision is to mix them to baseband with 10.4 GHz, as shown in Fig. 2. Since the beam transient produces pulsed signals, you don't get a DC signal out of the mixer, but instead you get a pulse with a width determined by the bandwidth of the output filter. When the phases of the pickup's pulses are adjusted with respect to the LO, so that the amplitude of the mixers' outputs is close to zero, the amplitude changes of the pulses measured at the ADCs are proportional to the phase changes of the pickup's pulses.

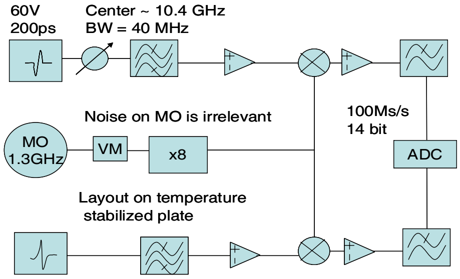

Figure 2: 10.4 GHz down-mixing scheme for a beam position measurement.

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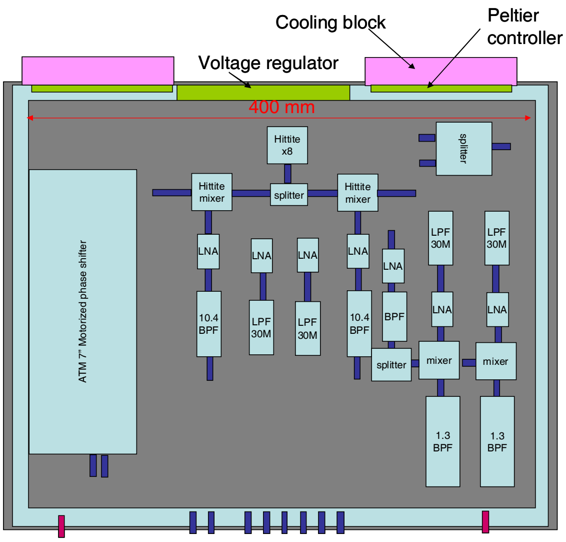


Figure 3: Chassis upper layer. including a motorized trombone phase shifter, two 10.4 GHz downconverters, and two 1.3 GHz downconverters.

The phase noise on the 1.3 GHz coming from the master oscillator (MO) is irrelevant for the performance of the position measurement because the position of the electron beam is given by the difference between the phases of the pickup's outputs; the MO jitter cancels out, since it is common to both phase measurements. MO changes do, however, affect any arrival-time measurements, because the arrival-time is given by the sum of the phases of the pickup outputs

Two phase shifters are employed: a vector modulator board that shifts the phase of the 1.3 GHz reference signal and a motorized trombone, scans of which are shown in Fig. 4. The trombone, needed to be long enough to shift the signal over the full 10 cm range of the pickup and it needed to have a position read-back. A potentiometer was used for position read-back, but due to backlash and mechanical hysteresis, it was not a reliable position reference. A linear encoder is always preferable, but it requires mechanical engineering and a board for digital processing. The mechanical hysteresis of the trombone phase shifter limited the repeatability of the measurement over larger ranges, but did not affect the measurement over smaller ranges during which the trombone did not move.

The selection of the amplifier after the bandpass filter is somewhat critical, because it determines the dynamic range of the measurement. Two different sets of amplifiers were used because one of the members of the first set broke (ZX60-14GHz), possibly due to a beam that was incident upon the pickup. This was unfortunate because, although the second set of amplifers produced a higher K-phi, or sensitivity to phase change of the MO, the position measurement became unreliable when it was benchmarked against other measures of position in the accelerator. It is suspected that the more powerful second amplifier pair caused a reduced dynamic range and non-linearities in the monitor's response.

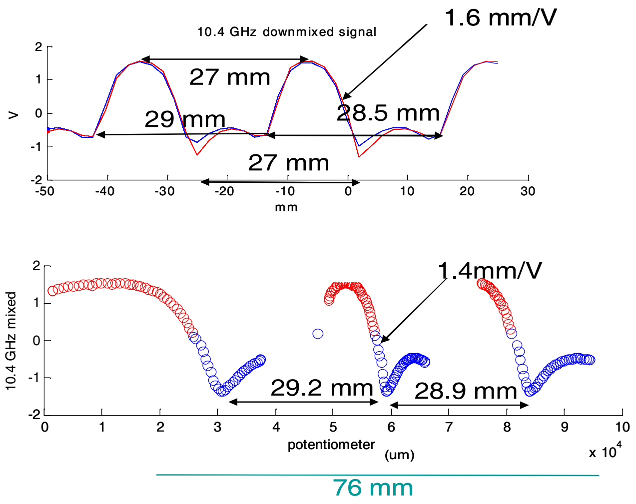


Figure 4: Fiducializing the trombone with respect to the vector modulator. The slope where the sampling takes place must be the same for both phase shifters. The bumps in the signal come from the pulse reflected by the mismatch at the output of the pickup. Their location changes with beam position.

The lower layer of the chassis contains the voltage regulator, the clock generator that turns the 108 MHz machine reference into a NIM-level square-wave clock signal for the Struck 14-bit ADC, and two relays to control the DC motor. Two rectangular aluminium bars support the 4 mm thick aluminium plate that holds the RF components. The rectangular bars are each elevated by a plastic post and a metal post upon which a Peltier element is fixed and sandwiched between the post and the bar.

The Peltiers and temperature controllers are essential for the drift stability of the position measurement. Without them, the phase measurement drifts by as much as 100 um when someone enters the climatized room containing the chassis. With the temperature control, this disturbance can be limited to 20 um, as shown in Fig. 5.

On a hot summer morning, the 30 m cable from the tunnel became warm and caused the 20 um drift seen in Fig. 5. On a cool foggy day with no one in the lab, the drift is absolutely flat. The chassis could easily be installed in the tunnel, right next to the pickup, thereby removing these drift problems. This would also reduce the amount of noise picked up on the long cables.

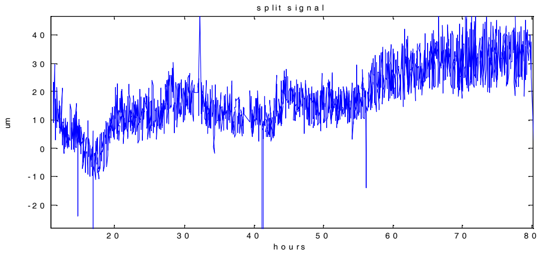


Figure 5: RF front-end drift performance from split signal. The disturbances at 18 and 44 hours were caused by people in the room. The step up at 58 hours was caused by the summer sun coming up. The rms jitter is <5 um, giving a measure of the resolution.

Many scans of the accelerating gradient were done, one of which is shown in Fig. 6, as well as scans of the accelerating phase, the injector RF gun phase, and the laser phase, all of which (with the first set off amplifiers) yielded correct measurements of the arrival-time and position changes in the bunch compressor. Correlation of beam jitter and drift over several hours with the photomultiplier monitor was 63%, while correlation with the out-of-loop vector sum was only 40%.

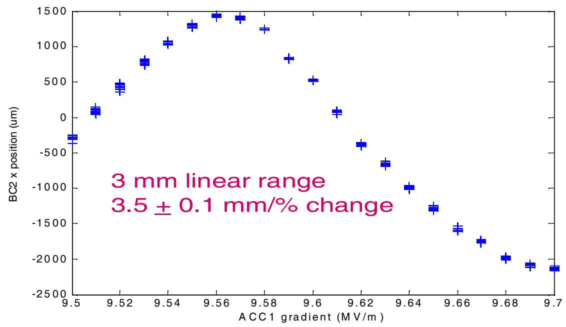


Figure 6: Position change measured in the first bunch compressor as a function of accelerating gradient, with an off-crest beam (7 deg). The linear part of the signal gives a correct measurement of beam position change.

Because the linear range of the 10.4 GHz measurement is only 3 mm, an additional 1.3 GHz phase measurement is used to provide a coarse reference for the fine 10.4 GHz measurement. If the beam moves out of the linear range of the fine measurement, the coarse measurement provides information to tell a phase shifter how to return to the optimal sampling point for the fine measurement. A parasitic machine drift measurement in Fig. 7 shows the 1.3 GHz measurement, the 10.4 GHz measurement, and the PMT measurement for changes in steps of 160 um.

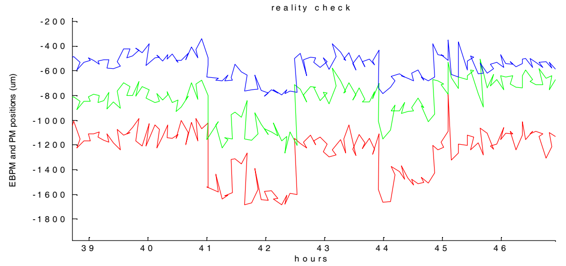


Figure 7: Parasitic measurement with 10.4 GHz front-end (top), 1.3GHz front-end (middle) and PMT (bottom).

EOM PHASE MEASUREMENT

A measurement of the pickup outputs' phases was also done with EOMs and pulses from the optical synchronization system's MLO. It was done with an older design than the one depicted in Fig. 8, but the concept was the same: Optical Delay Lines (ODLs) shift the arrival-time of a few picoseconds-long laser pulse with respect to the arrival of an RF pulse coming from the pickup. The RF and optical pulse meet up in an Electro Optical Modulator (EOM), wherein the voltage induces a change in the amplitude of the laser pulse. This modulated laser pulse is impinged upon a photo-detector whose output is sampled by an ADC that is clocked by the very same laser pulse train. When the timing of the laser pulse is adjusted so that the sampling occurs at the zero crossing of the beam transient pulse and when the EOMs are installed near a high voltage (>60 V), short-pulsed (<200ps) source, this method consistently produces <6 fs resolution phase measurements [5].

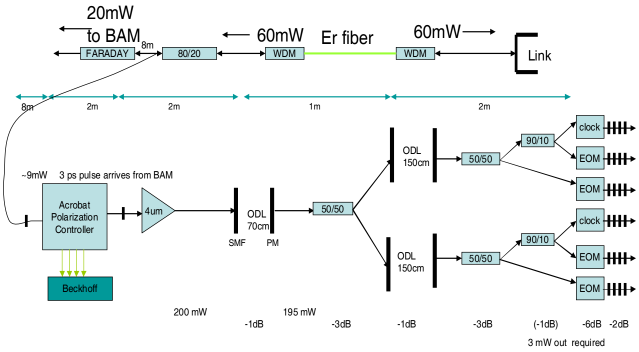


Figure 8: Schematic of EOM BPM. An 8 m long, thermally insensitive patchcord connects a near-by length stabilized fiber-link to the BPM chassis, whereupon the polarization is adjusted and the signal is amplified to 200 mW. The arrival of the laser pulse at 4 EOMs is adjusted with ODLs.

In the EOM BPM measurements presented here, a 30 m cable separated the BPM front end from the pickup in the tunnel, attenuating the signal and reducing the potential resolution by a factor of ~3. Nevertheless, the 15 fs resolution achieved was sufficient to reach the 5 um resolution goal for the monitor. An in tunnel installation of the monitor, using the layout shown in Fig. 6, will be completed in the coming weeks, thereby achieving maximum resolution.

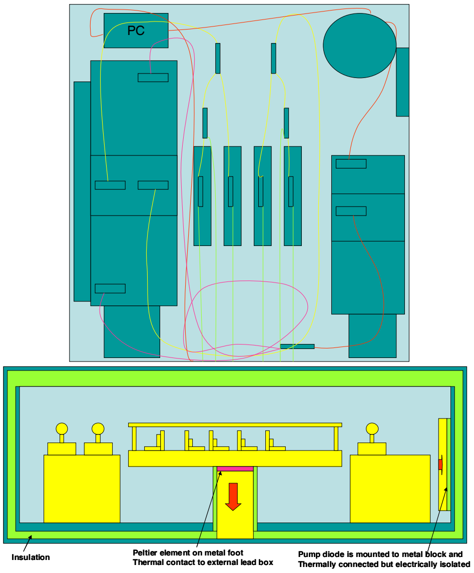


Figure 9: Physical layout of EOM BPM chassis. Top-view with fiber routing and side-view with thermal concept.

As in the RF chassis design, Peltier elements were used to stabilize the chassis temperature; this is illustrated in the side view of the chassis in Fig. 9. The heat from each Peltier is sent to the external chassis, which has contact to a large lead enclosure. The internal chassis is insulated from the external chassis with foam. Temperature stability of 0.005 degrees C can be achieved with this setup.

The monitor was calibrated by moving the delay lines over a small range and measuring the change in the amplitude of the laser light. The calibration for the out-of-tunnel setup was 65 femtoseconds per % modulation for SASE conditions, giving an arrival-time resolution of about 15 femtoseconds and a position resolution of about 4 um.

ENERGY MEASUREMENT BENCHMARKING

There are two existing monitors against which these new energy measurements can be compared: an out-of-loop vector sum (VS) of the accelerating RF [2] and a pair of photomultiplier tubes mounted on movers after the second bend of the chicane (PMT) [3]. The vector sum is limited by drifts and the photomultiplier tube arrangement is limited by shot noise to $\sim 5{*}10^{-4}$ energy resolution.

A pair of BAMs: one before the bunch compressor and one after the bunch compressor can make a time-of-flight energy measurement [4].. In Figs. 10 and 11, the two-BAM energy measurement is juxtaposed against the PMT and EOM BPM energy measurements. Good agreement is seen between the three monitors, except for a larger jitter measured by the two BAMs. The RF downstream of the bunch compressor is the likely source for this jitter. The two-BAM measurement required a correction for off-crest operation after the bunch compressor.

Fig. 12 shows the correlation between the RF BPM, PMT and VS. The correlation of the RF BPM with the PMT is 63% in Fig. 12 and the correlation of the EOM BPM with the PMT is 83% in Fig. 10. The improved correlation is likely due to the difference of the EOM BPM and RF BPM's resolutions. The EOM BPM has 4 um resolution while the RF BPM has 5 um resolution.

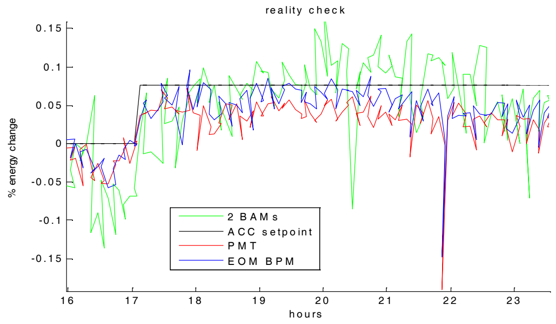


Figure 10: Four different measurements of the beam energy in the first bunch compressor: 2 BAMs longitudinal time-of-flight, and the setpoint of the accelerator gradient

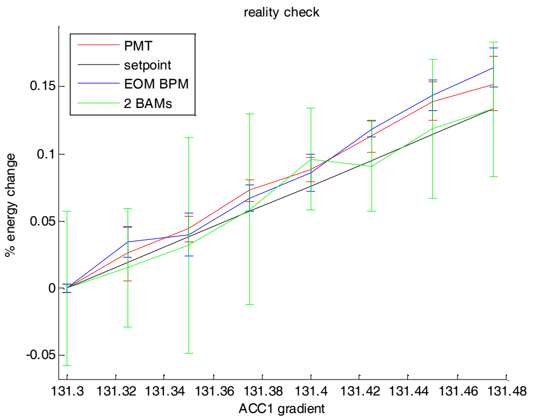
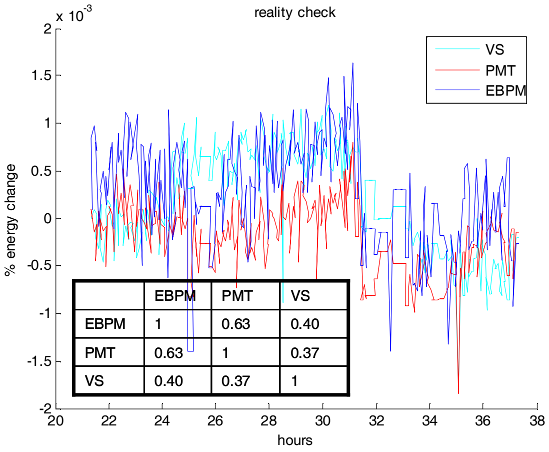


Figure 11: Comparison of EOM front-end, PMT, and difference of 2 BAMs over a 0.1 % energy change. Each point is averaged over 20 shots. Only small scan ranges were permitted, due to user operation.



	EBPM	PMT	VS
EBPM	1	0.63	0.40
PMT	0.63	1	0.37
VS	0.40	0.37	1

Figure 12: Comparison of RF vector sum (VS), RF, photomultiplier tubes (PMT) and RF BPM (EBPM) energy measurements. The table shows the correlation between the different monitors.

CONCLUSIONS

- EOM technique makes high-resolution phase measurements possible.
- RF techniques can meet the position resolution targets in the bunch compressors for less effort and expense.

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