BEAM BASED MEASUREMENTS OF RF PHASE AND AMPLITUDE STABILITY AT FLASH

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Abstract

Beam based measurements of the phase and amplitude stability of the photo-cathode laser, the RF gun and superconducting acceleration modules are key tools for understanding and controlling these critical acceleration sub-systems. The measurements are used to identify the sources of instabilities, to determine response functions, and to optimize RF feedback parameters and algorithms. In this paper, an overview of the measurement techniques, together with some important results on the RF and laser stability currently achieved at FLASH.

INTRODUCTION

One of the most challenging tasks for the operation of high gain single pass FELs is the precision control and stabilization of the longitudinal electron bunch profile and its arrival at the FEL undulator. The acceleration RF fields prior to the bunch compression sections are sources for slow drifts and fast fluctuations. The large bunch compression factor (30-100) required to achieve peak currents in the kA range cause large bunch length variations from small changes in energy chirp rate and cause unacceptable arrival time jitter due to energy fluctuations. The RF stability is, therefore, key for successful user operation of FELs.

At FLASH and the future XFEL, the RF amplitude and phase must be controlled to about 10^{-4} and 0.01° to reduce peak current variation to the % level and to stabilize bunch arrival times to within the rms bunch duration (e.g. XFEL 60 fs). The bunch train is accelerated in superconducting TESLA-like modules operated with millisecond long RF pulses and repetition rates in the Hz range. Electron bunch trains with a frequency of MHz are accelerated during the RF flat-top. The RF pulses are controlled through the 1.3 GHz preamplifier input signal via a digital feedback system that calculates the RF vector-sum from the individual cavity pickup signals.

The complex low-level RF field regulation is fraught with difficult to identify systematic errors caused by electronics, electromagnetic noise, calibration errors, and faulty hardware. It is, therefore, of importance to develop beam based measurements that allow for validation and optimization of the RF field regulation.

RF GUN PHASE STABILITY

In the FLASH RF photo-injector, the electron beam is produced by impinging a 10 ps FWHM UV laser pulse onto a photo-cathode in the 1.5 cell L-band cavity. Laser injection phase into the cavity is at about ϕ =-38° from the RF zero-crossing. Time-of-flight effects of the non-relativistic electron bunch exiting the cathode cause a variation of the beam arrival at the following acceleration module, ACC1. The arrival-time at ACC1 changes by approximately 1 ps per 1° phase change of the RF gun. In the case of a linear energy chirp rate of 0.14%/ps impressed on the bunch by $\phi_{acc1} = 10^\circ$ off-crest acceleration in ACC1, the energy deviation already amounts to 0.14%/ϕ_{gun}. It then becomes nearly impossible to distinguish between energy variations caused by RF gun induced arrival time changes and the energy changes from ACC1 amplitude fluctuation.

To measure the gun phase stability, a current transformer (toroid) for bunch charge measurements is used. First, the gun phasing is performed by scanning the RF cavity over 360° while recording the bunch charge. The result of a scan is shown in Fig. 1. If the field gradient at the photo-cathode is decelerating when the laser pulse impinges on the photo-cathode, then no electrons exit the gun ($\phi > 0$). When the RF phase is close to the zero-crossing, half of the emitted electrons are accelerated ($\phi \approx -10^\circ$). Operation of the gun phase close to the zero-crossing makes the charge-phase dependency strongest and provides a direct measurement of the relative phase stability between the laser and the gun cavity. With a slew rate of typically 0.05 nC/deg, marked as a red line in Fig. 1, and a single shot toroid resolution of 2-3 pC, the phase jitter can be determined bunch-by-bunch with a precision of 0.05° (100 fs) [1].

Figure 2(a) shows the gun-laser phase jitter derived from the charge measurement as recorded for a period of 12 min. The rms fluctuations from macropulse to macropulse with a repetition rate of 5 Hz amount to only 0.06°. N = 30 bunches separated by 25 μs have been used. The macropulse measurement is not limited by the toroid

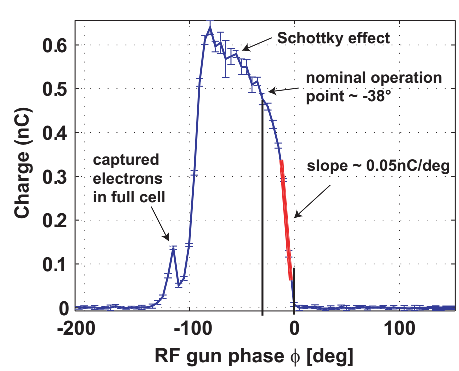

Figure 1: Charge measured by a toroid versus RF gun phase. Scans are performed for phasing the RF cavity. The nominal operation point is -38° from the point when the first electrons are detected.

resolution because the electronic noise readout limitation is reduced by $1/\sqrt{N}$.

The field regulation without a probe is particularly difficult because small variations of gun body temperature cause cavity detuning with a rate of 25 kHz/K. Thus, even for a constant forward power phase into the RF gun, the cavity acceleration phase changes by 35°/K (Q≈20000). The gun is, therefore, carefully water cooled with a temperature feedback sensor mounted in the cavity iris. The achieved temperature stability of ±0.02° is, however, still insufficient and results in peak-to-peak phase variations of ±0.7°. This variation can be determined from the reflected power phase shown on Fig. 2(b) and used to regulate the forward power [2]. As seen, in Fig. 2, the large variations of the reflected power phase do not correlate with the beam-based measurement of the cavity phase measured, therefore the combination of adaptive feed forward and feedback algorithms used was properly adjusted (see [1] otherwise). The remaining macro-pulse jitter of 0.064° (137 fs) is induced by the photocathode laser arrival time jitter.

Figure 2(c) shows the gun-laser phase across macro-pulses containing 30 bunches spaced by 25 μs. The unexpectedly large phase slope of 4.3°/ms is in contradiction to previous results. By varying the start time of the gun RF and different laser parameters, the dominant part of the slope source could be traced back to the amplifier for the

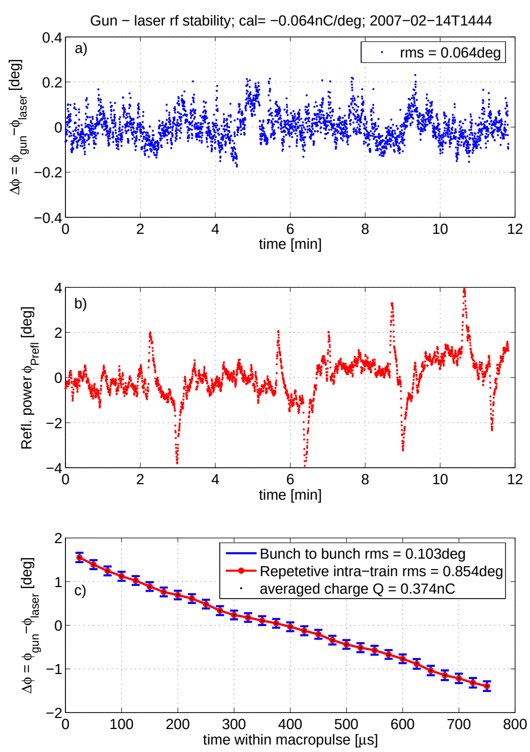

Figure 2: (a) Jitter between gun phase and laser determined from charge measurement (0.06 nC/deg) from macro-pulse to macro-pulse (5 Hz). (b) Variation of the reflected power phase with a directional coupler. c) Variation of the phase across the macro-pulse with 30 bunches spaced by 25 μs.

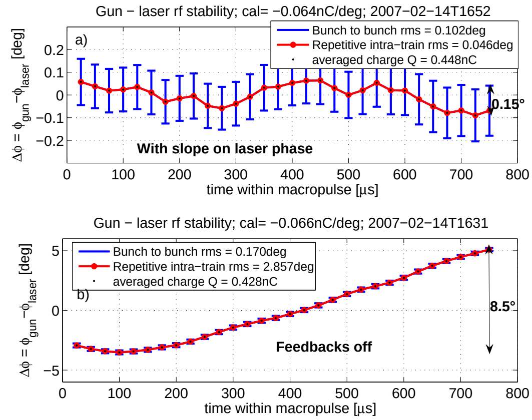

Figure 3: (a) Phase stability gun-laser when a phase slope is introduced to laser oscillator EOM. (b) All feedback algorithm for the gun are switched off.

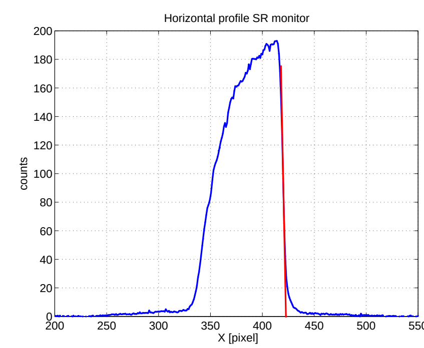

Figure 4: Horizontal beam profile from the synchrotron monitor in the first magnetic chicane.

electro-optical modulators (EOM) that actively phase lock the laser oscillator to the machine reference. To compensate for the potential laser phase slippage, a programmable fast phase shifter was installed. The results are shown in Fig. 3(a). The remaining repetitive phase error amounted to only 0.045°. For comparison, the RF feedbacks were switched off, resulting in a peak-to-peak phase drift of 8.5° from the first to the last bunch in the bunch train. This is caused by thermal heating of the gun body.

GRADIENT STABILITY OF ACC1

The beam exits the RF gun with an energy of 4.5 MeV and is accelerated in the ACC1 to 127 MeV before entering a chicane. The dispersion in the chicane is R_{16} =340 mm for 18° bending angle. Gradient variations of ACC1 cause horizontal position shifts of the beam which can be monitored parasitically using the synchrotron radiation (SR) emitted in the dipoles. A new vacuum chamber with a special SR port was installed behind the third dipole in October 2006 [3]. The SR is imaged by a telescope onto a gated, intensified CCD camera. The width and position of the gate is adjusted such that only one bunch per image is recorded.

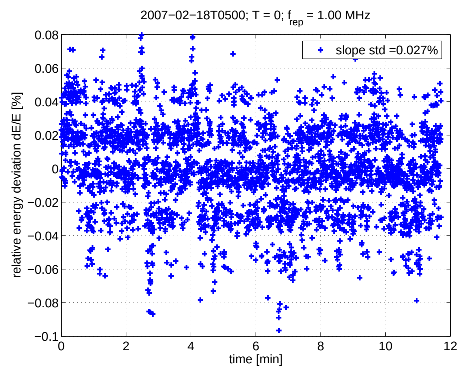

Figure 5: Energy stability of the first bunch in a pulse train.

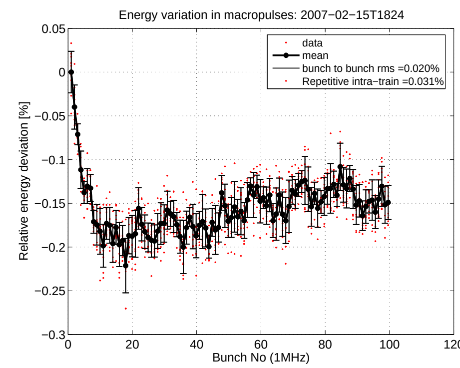

Figure 6: Energy deviation across macro-pulses.

Most of the beam energy stability measurements are carried out at 9° during FEL operation. The energy distribution of a 10 ps FWHM electron bunch with a residual energy spread of only a few keV is comprised of a steep rising edge at high energies with a low energy tail, as plotted in Fig. 4. Phase variation of the acceleration module changes the tail distribution, while gradient variations shift the entire profile. To determine the energy stability, the offset value of a linear fit on the rising edge is used. The monitor is calibrated by varying the dipole current while tracking the profile movement. The value for 18° bend angle is $dE/E=2.5\cdot 10^{-4}$/pixel.

Figure 5 shows the energy stability recorded for the first bunch in the pulse train over a period of 12 minutes. Typically, an energy stability of $2.7\cdot 10^{-4}$ is measured, where values as small as $1.5\cdot 10^{-4}$ have been recorded. This is an improvement of a factor of two compared to earlier measurements. The better stability was achieved after the removal of a faulty probe signal from the vector sum and optimal adjustment of the feedback gain.

The energy stability within macro-pulse trains of 100 bunches is shown in Fig. 6. Each individual bunch was recorded for 20 shots before the gate was shifted by 1μs. To compensate acceleration field variations caused by beam loading, charge measurements were incorporated into the low level RF regulation[4]. Besides transient effects during the first 10μs of the macro-pulse, which could not be corrected within one shift, a beam energy stability of 0.07% peak-to-peak (0.02% rms) has been achieved.

PHASE STABILITY OF ACC1

Off-crest acceleration provides an energy chirp that leads to a compression of the electron bunch in a magnetic chicane. Compression is monitored at FLASH using a diffraction radiator after the chicane and a pyro-electric sensor that records the Terahertz radiation power emitted at the radiator. When the phase of ACC1 is scanned from on-crest to about -20° the compression monitor detects, within a narrow phase range of about 4° FWHM, a large coherent signal. At $\phi_{ACC1} \approx -9°$ the monitor voltage varies strongly with the ACC1 phase and the slope of the linear

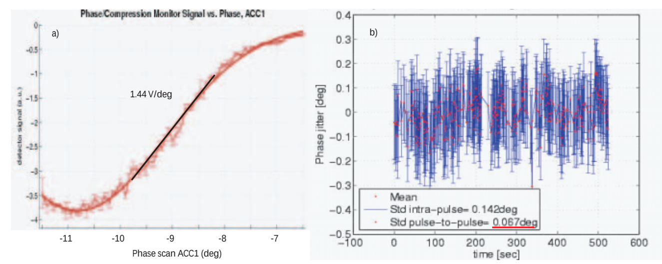

Figure 7: (a) Phase scan of first acceleration module. (b) Pulse-to-pulse phase jitter extracted signal variation of pyro-electric detector (1.44 V/deg).

fit, depicted in Fig. 7(a), provides a conversion factor for a phase measurement. The phase stability over 10 minutes is shown in Fig. 7(b) and amounts to 0.067°. Beam injection, however, is influenced by the laser and the RF gun phase, so the quoted value is an upper limit on the phase stability achieved by the low level RF regulation.

SUMMARY

We present techniques to measure the phase stability of the photo-injector RF gun and the first superconducting acceleration module. An upper limit for the phase stabilities is 0.06°, a value that is limited by laser arrival time stability. An amplitude stability of $2\text{-}3\cdot 10^{-4}$ was also measured for a single acceleration module which provides an energy gain of 120 MeV.

REFERENCES

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