PRECISION RF GUN PHASE MONITOR SYSTEM FOR FLASH

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Abstract

For RF photo-injectors, the properties of the high brightness beam depend critically on the synchronization between the RF gun acceleration phase and the photo-cathode laser pulse. At FLASH, the phase stability is determined by operating the RF of the gun close to the zero-crossing RF phase. This allows for the conversion of phase variations into charge variations which can then be read out by a toroid-based precision charge measurement system. In this paper, we discuss the limitation of this method. Resolution reduction of the charge measurement system due to electro-magnetic-interference is discussed in detail.

INTRODUCTION

The development of single pass Free Electron Lasers (FEL) operation at UV-, XUV or X-ray wavelength requires the successful understanding and operation of RF photoinjectors as the source for electron beams with high quality. In an RF photoinjector, the electron beam is produced by impinging a short laser pulse onto a photocathode that is mounted in an RF cavity. The bunched electron beam is accelerated at high gradients to overcome the strong space charge forces at low beam energies. These force also limits the available peak current from photoinjectors to about 20-100 A. To reach peak currents of several kA, as is mandatory for FELs, the beam is further longitudinally compressed in magnetic bunch compressors at higher beam energies where the space charge forces are greatly reduced. The RF stability of the photoinjector sensitively influences the beam properties and the beam quality at the FEL undulator. This paper is devoted to a measurement technique to determine the relative phase variation between the RF cavity field and the laser injection phase.

FLASH PHOTOINJECTOR

The photoinjector consists of a 1.5-cell L-band copper cavity with a Cs_2Te photocathode and a solenoid system for compensating space charge induced emittance growth. The laser beam is coupled into the cavity with a small mirror mounted at the cavity exit. To avoid time dependent RF induced kicks of the beam, the RF is fed into the cavity with a coaxial coupler. Directional RF couplers attached to the waveguide system close to the RF input allow for monitoring of the amplitude and phase of the forward and reflected power.

The gun cavity changes its resonance frequency with a rate of 20 kHz/K. The gun is, therefore, carefully water cooled with a temperature sensor mounted into the cavity iris and cooling water that is stabilized to about $\pm 0.02°$.

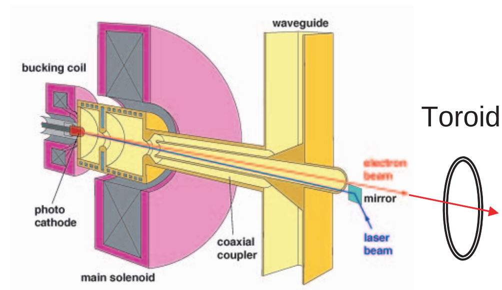

Figure 1: Scheme of FLASH RF-gun and the toroid for measuring the bunch charge emitted by the gun.

Several diagnostic elements such as YAG-screens for imaging the beam, Faraday cups to monitor the bunch charge and the dark current, a slit arrangement for emittance measurements, etc. are installed between the RF gun cavity and the first superconducting acceleration modules. For our purpose the current transformer, toroid 1GUN, which is located 0.7 m behind the RF-gun is the most interesting device (see Fig. 1).

The photo-cathode laser system is built in a master laser oscillator configuration [1]. It is comprised of an active mode-locked Nd:YLF oscillator with a repetition frequency of 27 MHz. Mode-locking is established with acousto-optic modulators (AOM) operated at 13.5 MHz and 108 MHz and an electro-optical modulator (EOM) at 1.3 GHz. The frequencies are locked to one another and are provided by the master RF oscillator. The EOM determines the precision of the synchronization of the laser oscillator to the accelerator. The laser operates in the burst-pulse mode. A pulse-picker selects, with a rate of 1 MHz, the laser pulses that are amplified in a linear chain, frequency converted from the IR to the UV, and sent to the photo-cathode. The number of laser pulses can be varied between 1 and 800.

IMPACT OF GUN RF JITTER

During FEL operation we often observe severe reduction of the SASE output power when the RF cavity gradient is changed by 0.1 % or the phase is varied by 0.1°. The reason for this critical dependence is not yet completely understood. Small changes in the energy chirp of the electron beam or differences in the beam Twiss-parameter might the main reason, beside small changes in the transverse orbit.

In addition, phase changes of the RF-gun cause a change of the arrival-time of the beam at the first acceleration mod-

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ule ACC1. Since this acceleration section is operated off-crest to provide the required energy chirp for the longitudinal compression of the bunch in a magnetic chicane, the incoming arrival-time jitter is transferred to an energy jitter. Tt is, therefore, not possible to distinguish gun-phase jitter from gradient or phase jitter of ACC1 by measuring the beam energy in the chicane without knowledge of the precise beam arrival time together with the bunch length after the chicane.

Finally, the arrival-time of the photo-cathode laser pulse also changes the arrival-time of the beam at the acceleration modules. Simulation shows that 70 % timing jitter of the laser and 30 % timing jitter originating from the gun phase change is transferred to the arrival-time jitter at the acceleration module.

To operate a longitudinal feedback system the laser arrival time, the gun RF phase, and ACC1 phase and amplitude must, therefore, be controlled.

METHOD TO MEASURE THE GUN RF PHASE STABILITY

A method has been developed to provide a beam-based measurement to control and to optimize the low-level RF regulation for the normal conducting RF-gun. The method is rather simple. Phasing of the RF-gun is done by scanning the RF cavity phase by 360°. The result is shown in Fig. 2. If the field gradient at the photo-cathode is decelerating when the laser pulse impinges on the photocathode, then no bunch charge exists the gun ($\phi > 0$). When the RF phase is close to the zero-crossing, half of the emitted electrons are accelerated, exit the cavity and can be measured by the toroid ($\phi_H \approx -10°$). The steepness of the slope depends primarily on the pulse duration of the laser pulse. Other features of the phase scan are caused by space charge, Schottky effect, travelling time from the half to the full cell, bunch lengthening effects and electron captioning in the full cell. For details see [2].

The steep linear slope of about 0.03-0.05 nC per degree

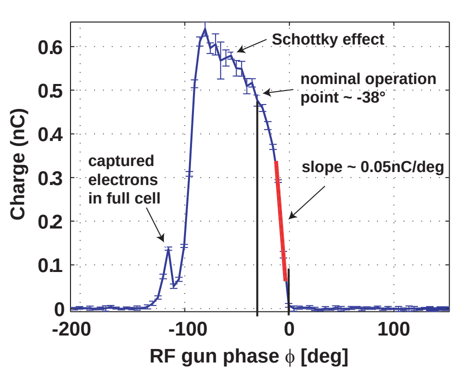

Figure 2: Charge measured by a toroid versus RF gun phase. Scans are performed for phasing the RF cavity. The nominal operation point is -38° from the point when the first electrons are detected.

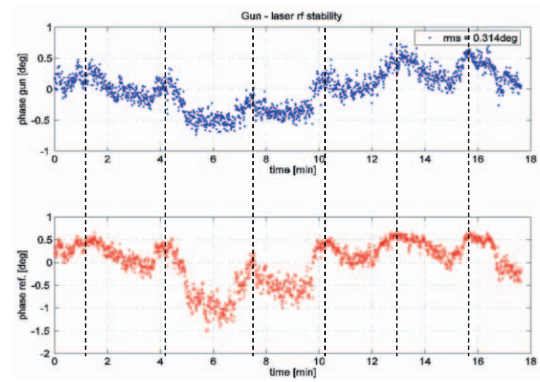

Figure 3: (a) show the variation of the phase between the gun and the laser derived from the charge measurement (0.04 nC/deg). (b) Measurement of the reflected power phase with a directional coupler.

L-band phase, marked as a red line in Fig. 2, provides through monitoring the bunch charge at e.g. $\phi = -10°$, an ultra-sensitive measurement of the relative timing jitter between the RF phase and the laser.

Figure 3(a) shows an example of the phase jitter derived from the charge variation (25 deg/nC) over a time period of 18 min. The rms fluctuations amount to 0.3 deg. The plot below shows the reflected power variation from the gun measured with a phase detector. Both are well correlated and thus the phase variation is induced by the RF gun and not from the laser system. The measured phase variation are also correlated to temperature variation of the order of $\pm 0.02\,C$ detected at gun iris. The temperature variation causes a detuning of the cavity that changing the reflected power phase. The vertical lines mark the peak phase change where shortly before of the water temperature regulation started to feeding cold water into the system.

The gun phase fluctuations severely degraded the FEL stability. Because of that, the original DSP system which

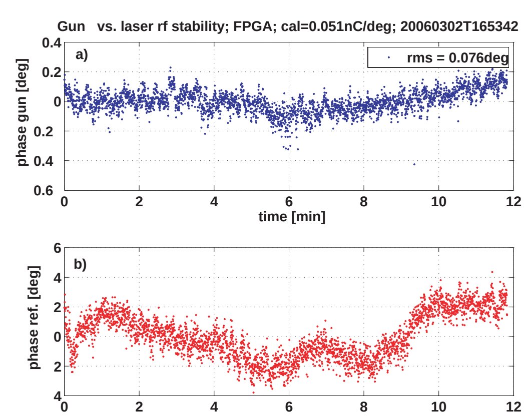

Figure 4: Gun phase versus laser arrival time stability (a), reflected power phase measurement (b). The LLRF system is upgraded to an FPGA system. Temperature variations of the RF gun are to great extend removed.

could stabilize the RF forward power only, has been replaced by an FPGA based control loop capable to process both forward and reflected power signals to stabilize the gun amplitude and phase, regardless of small temperature fluctuations[3]. The result of a phase stability scan using the FPGA is shown in Fig.4. Phase stability as small as 0.08° rms (or 170 fs) has been achieved, limited by the measurement resolution.

From this measurement, a second important conclusion can be drawn: the synchronization of the active mode-locked laser provides an arrival time stability smaller than 170 fs rms over a course of 10 minutes.

Since the electron charge can be detected bunch-by-bunch, the relative phase stability between gun and laser can be measured with high precision across the macro-pulse. The measurement method has been used to optimize the FPGA regulation parameter and to test adapted feed-forward algorithms to stabilize the RF field for long RF pulses (800 μs) where fast temperature changes occur [3].

RESOLUTION LIMITATIONS

Laser synchronization: the timing jitter of the laser sets an upper limit on the resolution of the gun phase measurement. We plan to measure and stabilize the photocathode laser timing relative to new synchronization laser master oscillator. With methods such as optical cross-correlation or EOMs reading out fast photo-detectors we aim for a resolution smaller than 50 fs rms[4].

Laser amplitude fluctuations: fluctuations of the laser intensity at the photocathode cause fluctuations of the detected charge. We currently measure 2 % rms charge stability. At $\phi = -10°$ the charge exiting the gun is about 0.2 nC and it fluctuates by 4 pC rms. At 43 ps/nC (0.05 nC/deg) one finds 170 fs rms resolution. We believe that by photo-detection, the laser pulse energy can be measured within of 0.5 % precision resulting in a resolution of 42 fs.

Noise of the toroid read out system: The toroid output signal passes a Gaussian-filter with 15 MHz bandwidth, a preamplifier with a gain of 70, 30-50 m long cables for signal transport out of the tunnel, and DC-blockers to avoid ground currents. A 1:1 buffered splitter feeds the signal of 0.5 V/nC into two 1 MHz ADCs. One ADC samples the baseline of the toroid signal 43 ns ahead of the current pulse while the second samples its peak. In this way, a digital high-pass filter is realized with corner frequency of 8 MHz. The upper cutoff is given by the input bandwidth of the ADC (≈40 MHz).

Determined by correlation measurements, the rms resolution of the toroid varies between 3-7 pC depending on the location. The noise spectrum is not Gaussian distributed but shows large irregular spikes leading to a much larger peak-to-peak value. The white noise spectrum is dominated by the preamplifier (2-3 nV/$\sqrt{Hz}$ about 2 -3 pC rms), followed by ADC resolution (0.4 mV or 0.8 pC rms). Noise is also generated by the DC blocker which picks 27 MHz component from the environment.

The irregular noise spikes reducing the toroid resolution originate from the switched magnet power supplies that are a major noise source at FLASH. Fig. 5 shows typical common mode noise signals from such a power supply. Switching transient bursts of several MHz repeat at a rate

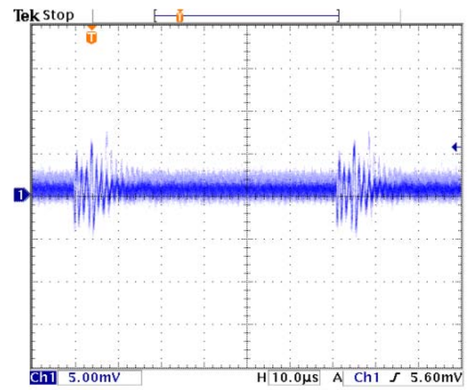

Figure 5: Common mode noise signals on the output lines of a switched magnet power supply ($I_{out} = 50$ A).

of about 15 kHz. These signals capacitively couple from the magnet coils to the beam pipe where they are picked up by the toroids. For a typical quadrupole magnet a the stray capacitance from coil to ground was 1.5 nF. To reduce this contribution, filters are installed at the chopper power supplies and when possible they are replaced by a new version with novel suppression of switching transients.

With an ultra-low noise preamplifier (330 pV/$\sqrt{Hz}$) and careful selection of bandpass filters, removing all critical switching power supplies powering nearby magnets, we where able to improve the toroid resolution to 1.5 pC, a result limited by the ADC. This corresponds to 64 fs rms phase stability measurement accuracy.

SUMMARY AND OUTLOOK

The presented technique to measure the relative phase variation between the RF gun and the photocathode laser has proven to be an important tool to control and optimize LLRF regulation. The resolution is presently limited to 170 fs, but 50 fs is achievable in the near future. 170 femtosecond is also the worst case stability of the synchronization between photocathode laser and the machine.

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