PRECISION LLRF CONTROLS FOR THE S-BAND ACCELERATOR REGAE

M.Hoffmann*, H. Kay, U. Mavric, H.Schlarb, C.Schmidt (DESY, Hamburg),
W.Jalmuzna, T. Kozak, A.Piotrowski (TUL-DMCS, Lodz)

Abstract

The linear accelerator REGAE (Relativistic Electron Gun for Atomic Exploration) at DESY delivers electron bunches with a few femtosecond duration for time-resolved experiments of material structure in pump-probe configuration. To achieve the desired 10 fs resolution, the Low Level RF controls for the normal conducting S-band cavities must provide field stability of 0.01% in amplitude and of 0.01 deg in phase. To achieve these demanding stability a recently developed LLRF controller based on the Micro-Telecommunications Computing Architecture (MTCA.4) have been installed and commission. In this paper, we report on measurement performance of the LLRF system, the achieved stability and current limitations.

THE REGAE FACILITY

The Relativistic Electron Gun for Atomic Exploration (REGAE) is an accelerator facility at DESY that will generate very low-charge (<1 pC) electron bunches of a few femtoseconds duration for electron diffraction pump-probe experiments [1] and studies on laser driven plasma acceleration [2]. It is a joint project of the CFEL partners Max Planck Society, University of Hamburg and DESY.

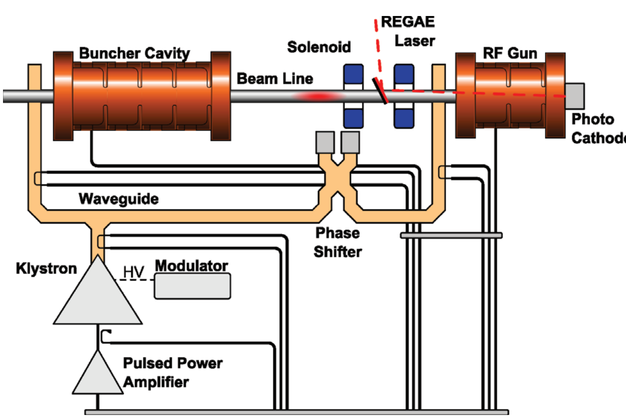

Figure 1: Overview of the RF system installed at REGAE

The bunches are generated by impinging the third harmonic (265 nm) of a commercial Ti:sapphire laser on a Cs2Te photo-cathode inside a 1.5-cell RF gun which accelerates the electrons to an energy of up to 5 MeV. After focusing and collimation by solenoid magnets a 4-cell buncher cavity induces an energy chirp by accelerating the electron bunch 90 deg off-crest. In the following drift section, the bunch is compressed by velocity bunching to pulse duration of below 10 fs rms at the sample target for the pump-probe experiments, which are carried out using a portion of the photo-injector laser. The hardware platform for the LLRF, the timing, and the laser synchronization is based on the new industry standard MicroTCA.4 released by the PICMG (PCI Industrial Computer Manufacturers Group) in autumn 2011. It will be used for the European XFEL accelerator controls [5] and has been demonstrated at FLASH.

The RF System

The RF system at REGAE (Fig. 1) consists of two normal-conducting S-band cavities operating at 3 GHz, the RF gun and the buncher cavity. The two cavities are powered by a single klystron. Through the waveguide distribution system, 3/4 of the power is sent to the RF gun, while 1/4 goes to the buncher. The phase difference of 90 deg is achieved by a remotely controllable waveguide phase shifter. The RF system at REGAE operates in a pulsed mode with a repetition rate of 50 Hz and an RF pulse length of 6 us. Waveguide couplers and probe pickups are installed to monitor the RF power and to control the electrical field in both cavities.

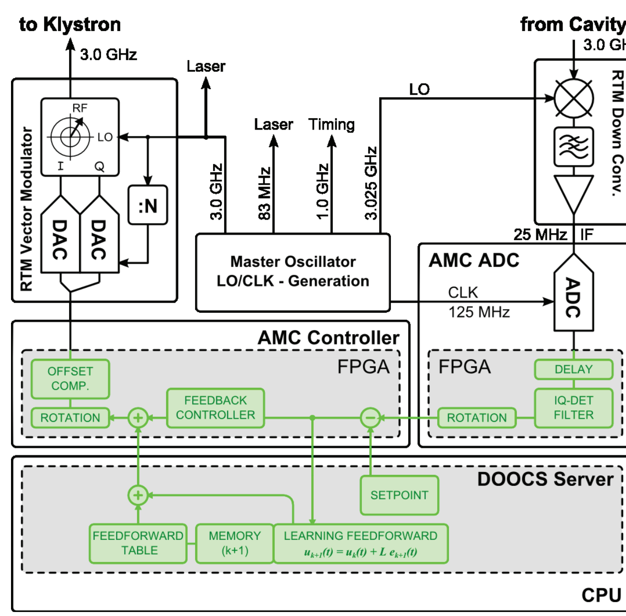

Figure 2: Overview of the LLRF system at REGAE

The Low-Level RF System

The arrival-time jitter between electron bunch and laser pulse at the target is determined by both the stability of the

* m.hoffmann@desy.de

accelerating field and the synchronization of the laser. For achieving values in the 10 fs range, the field must be stabilized to 0.01% in amplitude and 0.01 deg (at 3 GHz) in phase by the LLRF system. To control the electric field of the two cavities, the real and imaginary parts of the field are measured using an intermediate frequency (IF) sampling scheme. As shown in Fig. 2, the RF signal from the cavity at 3 GHz is down-converted in an RF mixer with a local oscillator (LO) at 3.025 GHz to an IF of 25 MHz and sampled by an ADC with a sampling rate (CLK) of 125 MHz. The sampled data is preprocessed by a delay stage, IQ detection filter, and rotaton matrix on the ADC board. Afterwards the data is send to the LLRF controller. In the FPGA-based controller (Xilinx Virtex 5), the detected cavity field is compared to a given set-point. The error signal is used to generate the appropriate feed-forward signal through a model-based iterative-learning control algorithm (learning feed-forward) and a feedback signal through an intra-pulse proportional-feedback controller. The feed-forward and feedback signals are added and sent through two DACs, using an RF vector modulator and a pulse power amplifier to drive the klystron.

The Timing System

In order to avoid 50Hz distortions from the mains in power supplies, the machine trigger is synchronized to the zero crossing of the 50 Hz. This is realized within a master timing module [4], which then delivers the trigger for the LLRF, the high power RF, the diagnostic tools, and for the amplifier system of the laser. In addition, the trigger has to be synchronous to the continuous machine frequencies from the master oscillator and the laser repetition rate. To achieve this, a base frequency (f_B) whose zero crossing lines up with all other zero crossings is generated and the trigger is shifted in steps of periods of f_B. In this case, 1 kHz is taken as f_B because it is the lowest frequency in the system [3]. Tab. 1 is listing the values of most relevant frequencies at REGAE.

Table 1: REGAE frequencies

Main RF	f_{RF}	2.9979 GHz
LO for down-conversion	f_{LO}	3.0229 GHz
IF from down-conversion	f_{IF}	24.983 MHz
ADC clock	f_s	124.91 MHz
Reference input timing	f_T	0.9993 GHz
Laser osc. repetition rate	$f_{Ti:Sa}$	83.275 MHz
Laser ampl. repetition rate Timing base frequency	f_{las} f_B	1.0009 kHz

The Laser Synchronization System

A commercial Ti:Sapphire laser system is used to generate the electrons in the RF gun by frequency-tripling the 810 nm to 270 nm and to carry out the electron diffraction pump-probe experiments at the end of the beamline. The synchronization system (Fig. 3) locks the laser repetition rate to the RF master oscillator. This is accomplished by extracting the 36th harmonic of the 83.275 MHz laser pulses with a photodiode and a narrow bandpass filter, centred at 3 GHz.

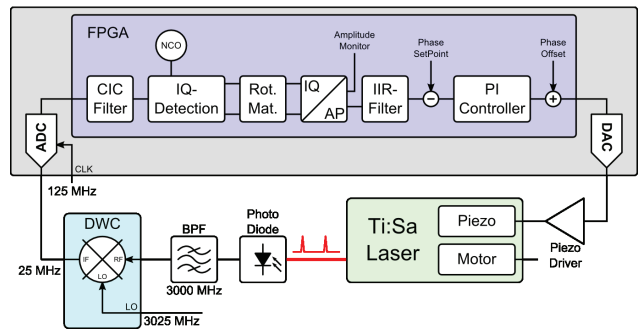

Figure 3: Layout of the digital laser synchronization system at REGAE.

The synchronization system will use the same hardware and IF sampling scheme like for the LLRF system [6]. The signal from the photodiode is down-converted, sampled and preprocessed (CIC filter, IQ detection filter, rotation matrix). The phase of the 3 GHz signal is extracted and applied in a feedback loop, which acts on a piezoelectric actuator within the laser cavity, changing frequency and phase of the optical pulse train in order to synchronize it to the master oscillator. The laser also incorporates a stepper motor for coarse tuning. In the first run of REGAE and during the measurements reported in this paper, the feedback was accomplished by a simple analog controller.

MEASUREMENT METHOD

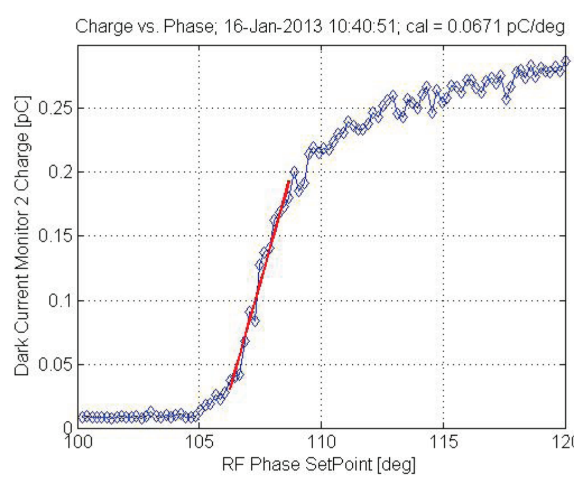

Figure 4: Charge measured versus RF gun phase during a phase scan. The linear fit (red) shows the region with the highest sensitivity (0.0671 pC/deg).

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The method, which was choosen to determine the synchronization of the photo-cathode laser and the stability of the RF gun phase is described in [7]. Fig. 4 shows a so called phase scan. While the phase of the RF gun is sweeped, the bunch charge is measured with the dark current monitor system (DaMon) [8]. Due to its high charge resolution of below 1 fC, the DaMon at REGAE is used as a sensitive charge monitor. The red line in the plot marks the range of the RF phase, where the bunch charge is strongly dependent on the RF gun phase. With a steep linear slope of about 0.067 pC/deg it provides an sensitive measurement of the relative timing jitter between the RF gun phase and the photo-cathode laser. Obviously it can not be distinguished, if the measured jitter is induced by jitter of the RF gun phase or the timing jitter of the laser. Limitations of the measurement technique are the intensity fluctuations of the laser on the photo cathode and the resolution of the DaMon. The charge instability due to laser power fluctuations is about 1.9%, resulting in 3.2 fC charge variation at a measurement phase of 108.5 deg and 169 fC bunch charge. With 13.8 fs/fC (0.0671 pC/deg) the resolution is limited to about 44 fs rms. The resolution of the DaMon is about 0.83 fC rms, which corresponds to 11.6 fs rms.
By reference tracking (feeding the 3 GHz reference from the MO to one down-converter channel), the resolution of the RF phase measurement is determined to be below 18 fs rms at full detection bandwidth of 25 MHz. Due to the cavity bandwidth of about 400 kHz, the short pulse length of 6 us, and a 1 us latency in the control loop we are not able to get a stable intra-pulse proportional-feedback in operation. The learning feed-forward is used to reduce repetitive distortions and slow drifts in the system, which are mainly caused by temperature variation in the water system of the cavity.

FIRST RESULTS AND FUTURE PLANS

Fig. 5 shows two measurementes over a time periode of 10min. Both plots show the phase jitter of the RF gun measured by the probe antenna and derived from the charge variation at a measurement phase of 108.5 deg. In the upper graph, the learning feed-forward is off and both signals are well correlated, therefore the phase variation is strongly dominated by the RF gun. In the lower graph, the learning feed-forward is on and the phases are stabilized below 0.06 deg rms (55 fs). The residual jitter is primarily due to the measurement setup, caused by laser power fluctuation. The jitter due to the RF gun phase and the laser synchronization cannot be determined precisely. An estimate can be given by $\sqrt{(55\,\mathrm{fs})^2 - (44\,\mathrm{fs})^2} = 33\,\mathrm{fs}$ rms.
Due to the missing fast feedback, all jitter contributions from the klystron chain, like additive noise from the vector modulator, pre-amplifier or klystron, are not suppressed. To reach the required synchronization of 10 fs in long and short term, further steps have to be performed. In the next half year a hardware upgrade is scheduled to the new single cavity RF control system [9]. This new hardware scheme will allow to reduce the controller latency by 500 ns and will have higher FPGA processing power, which allows higher sampling rate and more sophisticated feedback operation to reduce actuator induced jitter. In addition, a drift calibration scheme and an RF interferometer based distribution system is planed to reduce long term phase drifts of the RF system. Furthermore a Laser-to-RF converter will be installed to perform drift free laser synchronization. In addition a photodiode is installed close to the photo cathode to remove laser induced charge fluctuations from the measurements.

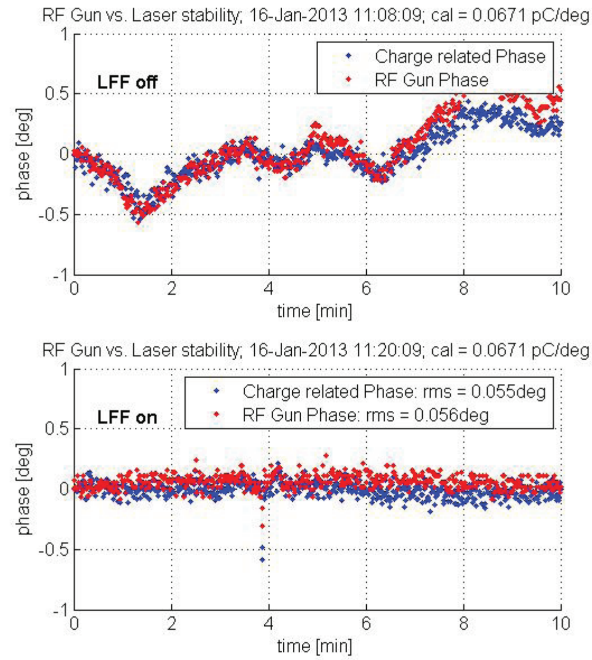

Figure 5: RF gun phase versus charge related phase with learning feed-forward turned off (top) and on (bottom).

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