CHARGE MONITORS AT THE RELATIVISTIC ELECTRON GUN FOR ATOMIC EXPLORATION – REGAE

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Abstract

Relativistic electron diffraction requires electron bunches of extreme quality. Typical values are: electron bunch charges of 100 fC, pulse duration of 10 fs, emittance of 5 nm. In order to operate an accelerator in such conditions proper diagnostics is needed. Furthermore any possible shot-to-shot variation has to be monitored especially when it comes to the analysis of the diffraction pattern. Desired properties of electron bunches to be diagnosed include: position, charge, emittance, bunch length, energy and energy spread. In this paper the beam charge as well as dark current monitors implemented at REGAE are described with a main focus on Faraday cups.

INTRODUCTION

Electron and X-ray diffraction are complementary tools for exploring structural dynamics of matter. While in X-ray diffraction a very large number of photons traverse the probe material with a small scattering probability, the scattering cross section is some 6 orders of magnitude higher for electrons than for photons so that only a small number of electrons is required to achieve comparable results. However, the required electron beam quality is extraordinary. To study e. g. proteins a coherence length of 30 nm is required which translates into a transverse emittance of 5 nm at a spot size of 0.4 mm. In addition short bunch lengths down to 10 fs and a temporal stability of the same order are required in order to study chemical reactions or phase transitions in pump-probe type experiments. These are challenging parameters for an electron source, which demand improvements at many frontiers.

REGAE is a new linac constructed at DESY in cooperation with the University of Hamburg and the Max Planck society as an electron source for relativistic electron diffraction [1]. REGAE comprises a photocathode located inside a normal conducting 1.5 cell RF cavity to accelerate electrons to 2-5 MeV energy. Electron bunches with charges from 10 fC to 100 pC can be generated as a function of laser intensity. The fundamental harmonic of the laser is split into two parts, one part is used to generate third harmonic radiation for illumination of the photocathode, the other part can be used for pump-probe experiments. At REGAE a new scheme for an RF based laser synchronization is deployed [2]. Jitter of RF parameters transfers into time of flight variations of the electron bunch and must thus be minimized. Preliminary measurements indicate that a temporal rms stability below 50 fs has been achieved. Downstream of the gun are diagnostics stations which house Faraday cups and transverse profile measurement setups [3] as well as electron beam collimators. Solenoids are located before and after the first diagnostics station to meet beam dynamics requirements. The next important element is an S-band 4-cell normal conducting buncher cavity. It can be used to introduce an energy chirp which results in velocity bunching when the beam propagates a drift space before arriving in the target chamber. A strong dipole can be used to deflect the beam into a sideway before the target chamber. This provides the possibility to measure the energy and energy spread using diagnostics as described in [3]. In addition to the first single coil solenoid two double coil solenoids are used to prepare the beam condition on the sample. Both these double coil solenoids as well as one more downstream of the target chamber have oscillating, sine-like fields which results in zero net rotation of the beam. The third double coil solenoid installed downstream of the target chamber is mainly used to focus an

Table 1: REGAE Components

Element	Position(mm)
Cathode	0
Gun center	41
Steerer pair 1	352
Solenoid 1	550
DDC (Double Diagnostics Cross) 1	
port 1 (Faraday cup and profile monitor)	693
port 2 Collimator 1	773
Solenoid 2	930
Steerer pair 2	1192
Buncher	1360
Steerer pair 3	1654
DDC 2	
port 1 (Faraday cup, profile monitor and cathode monitor mirror)	1899
port 2 Collimator 2	1979
DaMon	2069
Spectrometer arm	2369
Solenoid 3	5025
Target chamber	5506
Solenoid 4	5987
Steerer pair 4	6317
Detector	9506
Faraday cup	9836

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ISBN 978-3-95450-127-4

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image on a fiber optic scintillator. This last screen is monitored by the REGAE diffraction pattern detector which is based on an EMCCD. Air coil steerer pairs [4] are installed at four proper positions to correct the position and angles as needed. In Tab. 1 a list of accelerator elements and their rough position is given.

FARADAY CUPS

As the most ordinary tool to measure charges REGAE uses the well-known principle of a Faraday cup. The design of the Faraday cups – adopted from FLASH – employs a copper block which at the same time is used as a holder for a scintillator thus enabling simultaneous charge measurements and transversal diagnostics. Since at the low charge levels required at REGAE beam position monitors are not available this setup turned out to be very helpful for machine operation from the very beginning. The charge collected on the copper block is transfered via a 50 Ω resistor to ground. The voltage pulse over the resistor is measured with a fast ADC.

The Faraday cups at REGAE achieve a relatively good lower charge detection limit by employing proper electronics. REGAE has four Faraday cups, each of which can be used to measure the electron beam charge as well as dark current if the selected cup is equipped with an amplifier. For electron beam charge measurements the cups yields voltage pulses of about 5 ns length and a height of 33 mV/pC (with 50 Ω impedance) resulting in a large dynamic range of a few tens of fC to 100 pC.

In Fig. 1 a sample voltage signal of a Faraday cup is shown which corresponds to a sub-pC charge. This is an average over 5 shots, the error bars show the standard deviation of the signal. Dark current pulses are as long as the width of the RF pulse which is typically 4 μs long. A dark current voltage signal is shown in Fig. 2. In total a trace of 10 μs (500 points at 50 MHz) can be recorded at each RF pulse in this operation mode. The charge in each bin of 20 ns is below 100 fC in the presented case; the noise level – in front of the pulse – is correspondingly small. A study of the dependence of the dark charge on the gradient of the gun is shown in Fig. 3. For this measurement the first Faraday cup upstream of the buncher is used. No collimator was used to reduce the dark current. In the lower plot of Fig. 3 a Fowler-Nordheim analysis [5] of the measurement is presented. Since the voltage signal shows no clear plateau – as a result of the on-set of the emission and of the response function of the electronics – an effective current as integrated charge divided by RF pulse length has been used for this analysis. In order to accelerate electrons to 5 MeV gradients of not more than 80 MV/m are needed which would mean less than 6 pC dark charge over 4 μs pulse length. If the detection of the electron beam is gated fast down to a ns level the contribution of the dark charge is negligible (a few fC in the worst case). Unfortunately most detectors have exposure times of at minimum a few μs therefore when operating at sub-pC electron bunch charge collimators are required to reduce the background due to dark charge.

Special care has to be taken with open-loop outputs, because open outputs load with a high electrostatic voltage. Here closing the outputs with an attenuator, e. g. 0.5 dB helps. At REGAE each Faraday cup can be selected with a PXI multiplexer board. The input impedance of the digitizer board should be 50 Ω. For accurate measurement selection of an appropriate voltage range is needed. In order to deduce the bunch charge an integration over the pulse length is performed which results in a number that is proportional to the charge. When a cup is used for dark current measurement on the other hand the amplification factor has to be taken into account.

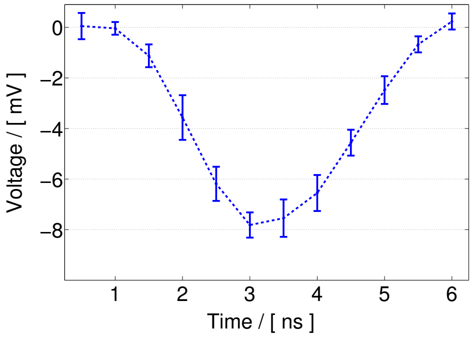

Figure 1: Voltage signal from Faraday cup in bunch charge mode. An average over 5 shots is shown, the sample rate is 2 GHz.

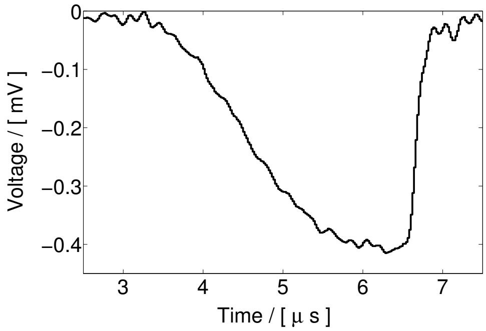

Figure 2: Voltage signal from Faraday cup in dark current mode. A single shot with a sampling rate of 50 MHz is shown.

Readout Electronics and Software

A PXI system from ADLINK (currently ADLINK-3950, in future a faster ADLINK-3980), as digitizer board a NI-5152PXI (National Instruments) [8] and a 500MHz-Multiplexer board NI-2593PXI are used. The digitizer NI-5152PXI has a 300MHz analog bandwidth. The sampling rate is 2 Gc/s in TIS-Mode (i. e. with 0.5 ns sample distance resulting in 11 points at the length of 5 ns, in total 1000 points are recorded). The measurement precision is 8 bits. With a sampling rate of 2 Gc/s the signal jitters naturally with 0.5 ns. This jitter is due to the asynchronous clock

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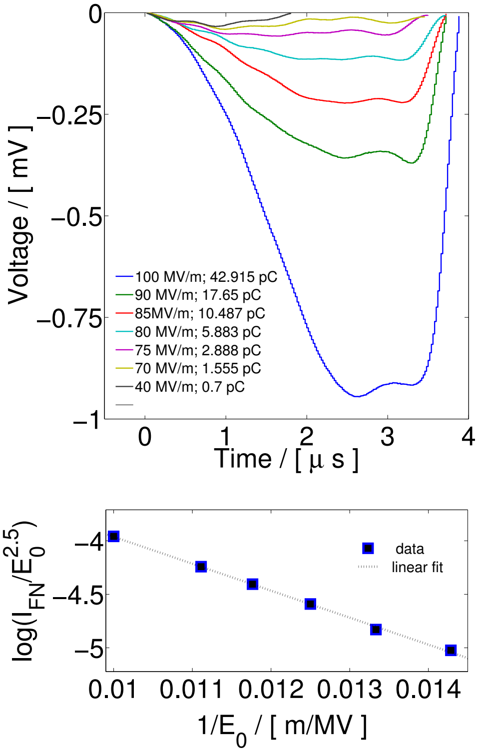

Figure 3: Dependence of the dark charge on the gradient in the gun cavity. Five shots are averaged for each data point. The sample rate is 50 MHz. In the lower part a Fowler-Nordheim plot is shown.

of REGAE and the digitizer board. It could be avoided by using the external REGAE clock for the digitizer. Tracking the peak of the voltage pulse and defining the integration interval dependent on the peak position relaxes the effect of this jitter. The analysis software is created with LabVIEW 2010 at MS WinXP. As control system environment the Three-fold Integrated Network Environment TINE [6] is used. The server software which runs at the PXI controller acquires the pulse, and permanently calculates and archives the bunch charge, transmits the data to the client and receives commands from the client (e. g. switching the voltage range or switch between the four Faraday cups). Pulse arrays are acquired continuously with the Multi Record Acquisition Mode, i. e. the acquisition of data blocks with multiple trigger events without restarting the hardware. The client is also written in LabVIEW. The client panel shows the pulse trace and a history of the calculated bunch charge. The control of the voltage acquisition range and the selection of the Faraday cup is implemented too. In order to perform some long term machine studies a data archiving is prepared. It includes a central archive for a long and a local history for fast archiving. The latter is limited to one month storage. The central archive is used for average values and the fast local history for every shot.

CAVITY MONITOR

A Cavity monitor called DaMon [7] developed by the Machine Diagnostics and Instrumentation group (MDI) at DESY has also been installed at REGAE. REGAEs fundamental RF frequency of 3 GHz is not a harmonic of the monopole mode of the installed cavity (which is designed as dark current monitor for a resonance frequency of 1.3 GHz). Therefore dark current cannot be measured with this device at REGAE. Instead bunch charges of 10 fC to 50 pC can be diagnosed. Two electronics branches are used to measure the bunch charge each more suitable for a defined range of charge. The agreement with Faraday cup results and independent calibration results from PITZ measurement gives confidence on the measured values of both monitors.

In Fig. 4 a measurement of charge versus laser intensity is shown. At the extreme low charges of a few tens of fC the Faraday cup measurement picks up dark current which is always there independent of the laser intensity. The cavity monitor is insensitive to dark current at REGAE [7], instead it shows its superior sensitivity at this very low charges.

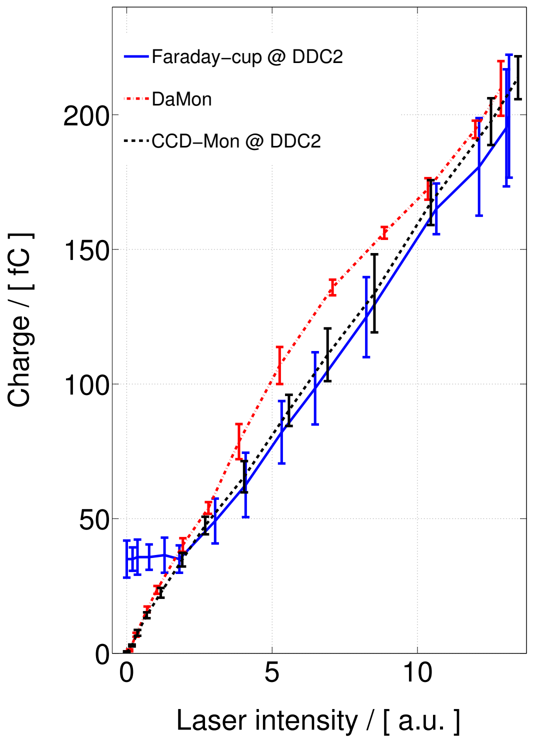

Figure 4: Comparison of charge measured with DaMon, Faraday cup and a calibrated CCD-Monitor at DDC2 as function of the laser intensity. An average of 10 shots for each measurement point is shown.

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CCD-BASED CHARGE MONITOR

Extensive calibration of scintillator radiance combined with propagation function and CCD calibration can be used to calibrate the screen monitors in the ultra-low-charge regime [3]. In practice this semi-theoretical approach is corrected by cross calibration of the CCD signal with other monitors like the cavity monitor where these still give decent signals. Assuming linearity this can be extended to ultra-low-charges down to the fC level (see Fig. 4). The profile monitors at REGAE use very sensitive photon detectors giving the possibility to resolve bunches that have a few tens of electrons per a moderate pixel size of a CCD. When this sensitivity is combined with a careful calibration, which is the case for REGAE, the transverse distribution recorded with the profile monitors yields a precision of a few electrons per pixel which contains more valuable information than a charge integral. For all cases that are foreseen at REGAE this monitor gives the charge distribution with a precision down to a total charge of 10 fC of the entire bunch.

CONCLUSION

Two destructive as well as one non-destructive charge monitor at REGAE provide information on the charge as well as on the transverse distribution down to the fC level with high precision. Generally during routine operation of an accelerator but especially during the commissioning of a new electron beam line a tool to find the beam, i. e. charge, is needed. Here Faraday cups can be used to detect any charge down to some 10 fC. The qualitative characterization of the charge level by Faraday cups is independent of a precise synchronization and, to a high extent, independent of the electron beam optics. Faraday cups present therefore ideal tools to tune a machine for the early steps. For the next steps and for more precise measurements the DaMon can be used which reads the charge, at the current REGAE layout, only downstream of the second diagnostics cross. For total electron beam charges in the fC level screen monitors can be used requiring synchronized laser, RF and CCDs as well as proper electron beam optics. Dark charge issues are very essential in ultra-low charge operation. Faraday cups that are equipped with additional amplifiers provide ultra sensitive means to measure dark charge which in turn can be used to further optimize machine settings. These three monitors fulfill thus all requirements on this type of diagnostics at REGAE.

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ISBN 978-3-95450-127-4