BEAM PROFILE MONITORS AT REGAE [*]

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Abstract

REGAE, the relativistic Electron Gun for Atomic Exploration, is a new electron source commissioned at DESY. REGAE has been built in collaboration with university of Hamburg and Max-Planck society. This facility enables studies on structural dynamics of atomic transition states occurring on the sub-hundred femtosecond time-scale. REGAE comprises a photo-cathode inside a normal conducting 1.5 cell rf-cavity to provide up to sub pC electron-bunches of 2-5 MeV with a coherence length of 30nm. In order to produce and maintain such electron bunches, sophisticated single-shot diagnostics is desired e.g. emittance, energy, energy-spread and bunch-length measurement. REGAE's rep-rate can be up to 50 Hz. This relatively high rep-rate makes it more challenging to deal with low intensity detection especially in single-shot mode. In this contribution the conceptual ideas, the realization and results of transversal diagnostics will be presented.

INTRODUCTION

Direct observation of evolving atomic structure within several fs is a main objective at the REGAE facility. The required short electron bunches can be generated by relativistic electrons confined in low charge bunches to avoid space charge contributions. Thus, the desired time resolution for pump-probe electron diffraction experiments can be met. In Table 1 the required beam parameters at the sample position, obtained from beam optics simulations [1], are presented. Electron beam diagnostics has to be capable of characterizing such electron bunches of low intensity. For the transversal diagnostics, in particular, challenges associated with the low intensity of the beam need to be overcome.

In the range of energy of REGAE, 2-5 MeV, scintillator screens are most appropriate for electron beam diagnostics. On the other hand, within this energy range, the electron collision stopping power, which results in scintillation in a fluorescence materials, is close to minimum [2]. Therefore, a scintillator with a high photon yield for the minimum ionization loss is preferred for the purposes of transversal diagnostics. A LYSO (Cerium-dopped Lutetium Yttrium Orthosilicate) crystal is selected with a light yield of about 30 photons per keV deposited energy of the incident charged particle. The peak emission occurs about 420 nm and the decay time of the scintillator is roughly 50 ns. Apart from choosing a proper scintillator, the light collection efficiency of the diagnostic setup improves by positioning it as close as possible to the scintillator. The acceptance angle of the collecting optics is ~ 8 degrees, allowing $\sim 0.5\%$ of the scintillator emitted light to enter the setup. Based on simulation results, only ~ 70 photons per incident electron are captured by the collecting optics. Approximately 50% of those photons are vignetted, due to the lens aperture limitation. The quantum efficiency of the camera at the scintillator peak emission is $\sim 10\%$, while the number of transmitted photons per electron is ~ 3. Experimentally, it has been found that for a reasonable signal-to-noise ratio, one needs more than 1000 photons/pixel, which corresponds to ~ 290 electrons/pixel. When ICCD is employed, this number reduces to ~ 40 photons/pixel, corresponding to ~ 12 electrons/pixel, while the same signal-to-noise ratio is achieved. Although at a closer position the setup benefits of a superior light collection, by locating it farther from the scintillator, the imaging and scintillator resolutions can be improved. The current design is a compromise based on the aforementioned considerations.

Table 1: Required Beam Parameters at Sample Position.

Electron beam energy	2–5 MeV
Bunch chrage	sub-100 fC–1 pC
Bunch length	7–30 fs
repetition rate	≤ 50 Hz

EXPERIMENTAL SETUP

Along the accelerator, three transversal beam monitors and charge monitors [3] are installed. An additional screen monitor is located at the interaction point of the experiment. It is mainly used to overlap the electron and laser pump beams spatially and in addition to monitor the beam at the location of the samples. Figure. 1 illustrates the positions where the scintillator beam monitors are installed. A dipole magnet after DDC2 and before DC3 disperses the electron beam towards the DC3 scintillator monitor to serve for energy and energy spread measurements.

The scintillator screens are movable and are placed in the beam-line with 45 degrees declination. The reflective component of the scintillator emission is captured and transported by the optics and imaged on the detector, which is either a normal CCD (see Table 2) or a home-made ICCD [4]. Two telescope stages can be moved into the optics beam line to alter the image magnification and consequently the field of view. During normal operation at REGAE, the beam charge changes between tens of fC up to 1

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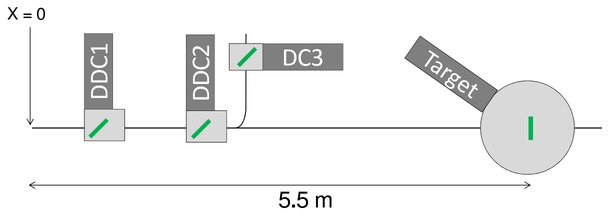

Figure 1: Layout of transversal diagnostics at stations DDC1, DDC2, DC3 and the interaction point (target). The longitudinal position of the photo-cathode is also shown. The spacings between the stations are scaled to the real distances, but the size of the elements is exaggerated.

Table 2: Specification of the Applied CCD, JAI BM-141, in the Transversal Diagnostics.

CCD sensor	ICX285AL
Active pixels No.	1392(h) × 1040(v)
Pixel size	6.45 μm
Frame rate (full frame)	~30 frames/sec
Gain	-6 to 24 dB

pC. Having the option to switch between ICCD and CCD in the diagnostic setup, the transversal diagnostics can monitor electron bunches with a wide range of charge, while achieving a sufficient quality of the signal. Once operating with low charges, the ICCD amplifies the intensity and improves the signal-to-noise ratio significantly. The signal-to-noise ratio is defined as the ratio of averaged signal to averaged background which describes the visibility of the signal on the detector. The intensification factor for each individual diagnostics station differs by a small amount as a consequence of different light transmission through the optics. Figure. 2 shows the signal-to-noise ratio of signal on the ICCD with respect to the signal-to-noise ratio achieved by a CCD at DDC1 station. Comparing signal-to-noise ratios on both CCD and ICCD, one can infer that, the signal enhancement by ICCD is not well-behaving and alters with charge. There is a point where the intensification of the intensity degrades. At the same point the ratio of ICCD SNR to CCD SNR drops. In other words, this behavior indicates saturation in MCP channels of the intensifier.

EXPERIMENTAL RESULTS

LYSO Scintillator Decay Time

The decay time of the scintillator, defined as the time interval between excitation and $1/e$ decay of the emission, is a property of the crystal that should be investigated in order to adjust a proper timing for diagnostic. The LYSO crystal decay time is quoted as 50 ns, but depending on the method of crystal growth and impurities of the material, some scintillator features, including the decay time, vary significantly [5]. Therefore, the decay time of each crystal needs to be measured. REGAE operates with a maximum repetition rate of 50 Hz. Electron bunch length is sub-ps, which sits somewhere on $\sim 4\mu s$ long RF pulse that is responsible for dark-current contribution. In order to remove this component from the beam profile, a fast gated image intensifier is employed, with a timing window that can be reduced down to 50 ns. Although this interval is still much longer than the sub-ps electron beam, the scintillator emission, which is monitoring the transversal beam profile lasts longer than the scintillator decay time.

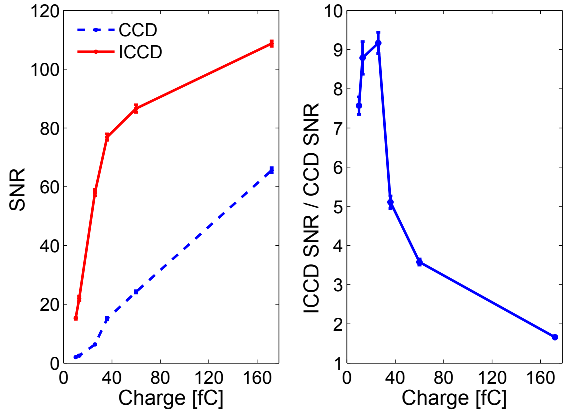

Figure 2: Signal-to-noise ratio (SNR) of the electron beam profile on the CCD and the ICCD as a function of charge (left) and ratio of the ICCD SNR to the CCD SNR (right) at DDC1. Normally, the dynamic range of CCD is not that wide to obtain such large SNR values. The data are acquired with lower camera gain to avoid saturation on the CCD and then are scaled to the maximum camera gain.

The decay time of LYSO was measured as follows: The image intensifier gating window, which is set to 50 ns was moved in steps of 10 ns until the end of the emission. The consequent variation in intensity of the monitored beam forms an exponential profile of the decay, shown in Fig. 3. From an exponential fit of the data, the decay time was found to be 45 ± 5 (syst.) ± 1 (stat.) ns. The precision of the scan steps is limited to 10 ns, adding to the systematic uncertainty in the measurement. The obtained decay time is very close to the one quoted in literature. The behavior of the decay shows that, in order to capture the full scintillator emission, the image intensifier's time window should be extended up to about 200 ns.

Diagnostic of Low Charge Electron Bunches

With a proper optics and a good scintillator, any bunch of more than 5 electrons/μm^2 (this translates to 200 electrons/pixel in reference to Table 2) can be diagnosed by a stand alone CCD achieving a reasonable signal-to-noise ratio. However for the required REGAE ultra low charge bunches at REGAE, ICCD can be used to monitor the beam profile with an excellent signal-to-noise ratio. The most sensitive existing charge monitor at REGAE is a cavity

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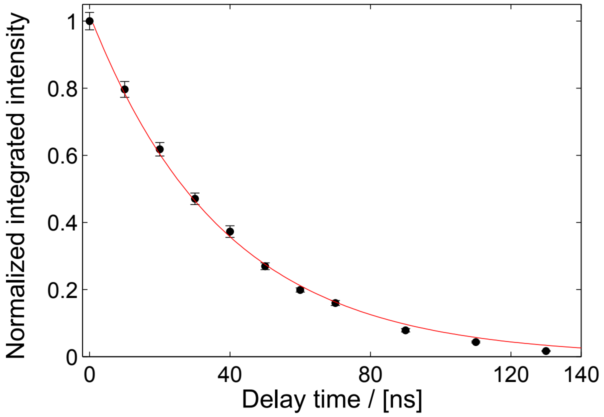

Figure 3: Decay time of LYSO scintillator. The onset time corresponds to the time where the maximum intensity starts to drop.

monitor (DaMon) [6] that measures charges down to 10 fC. This sensitivity is already beyond the requirement of REGAE. As shown in Fig. 4, at 10 fC the ICCD diagnoses the beam with signal-to-noise of ~16 in a single shot. In order to have a better impression of the correspondence of the reported SNRs to the signal quality, the related shots are also shown in Fig. 4.

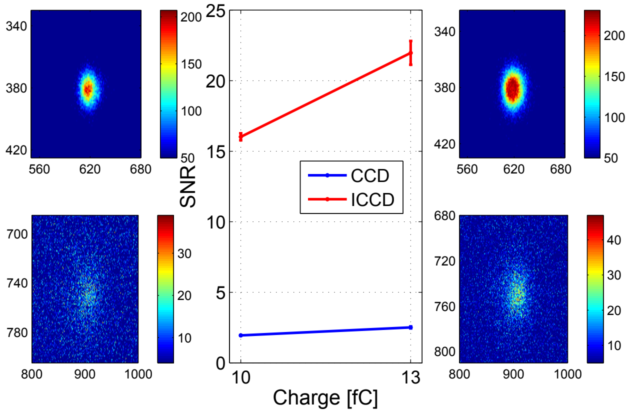

Figure 4: Signal-to-noise ratio of the monitored beam on a CCD (bottom) and an ICCD (top) starting from the minimum charge read-out by DaMon.

The rms of the beam profile size is around 150 μ m. Considering a charge of 10 fC, measured by Damon, one can calculate the corresponding charge in each pixel of the detector. For the CCD detector the obtained value is 70 electrons per pixel. The electron beam distribution, which is monitored by the scintillator is broadened due to the scintillator's resolution. In case the scintillator would widen the beam considerably, the quoted number of detected electrons per pixel would change by a large factor. In addition to the scintillator resolution, the imaging resolution is limited by the point spread function of the optics. Combining the emission spread from the scintillator and the point spread function, the overall resolution of the beam profile monitor can be acquired. Using GEANT4 [7], the passage of electrons through the scintillator and consequent fluorescence emission was simulated. The outcome of the simulation is used as an input file source in Zemax, where the generated photons from GEANT4 are traced through the entire optics setup, and finally imaged on the detector plane. The monitored beam in the simulation shows a resolution of ~ 30 μm. After de-convolution of the spread function from the monitored beam distribution, the broadening of the initial electron distribution is found to be negligible compared to the beam size. In other words, the measured size of the beam profile, 150 μ m, represents the actual size of the electron beam.

Beam Profile Monitor as a Charge Monitor

The prominent performance of transversal diagnostics at low charges raises the idea of employing them as charge monitors. They are remarkably sensitive for monitoring low charge bunches, to which the charge monitors are "blind". Thus the charge of each electron bunch and the projected distribution of the same bunch can be monitored at every transversal diagnostic station.

The existing charge monitors in the accelerator, DaMon and Faraday cups, are used as references to calibrate the screen monitors for charge measurements. Both the integrated intensity over the signal on the CCD and the charge as a function of the laser power behave linearly and consistently. Therefore, one can find a relation between the integrated counts on the screen monitor and the corresponding charge that is read-out by a charge monitor. The charge calibration should be carried out for every configuration of optics, in each diagnostic station, because the optical setups, and consequently the light transmission through the optics are not identical. Figure. 5 shows the charge calibration in one of the screen monitors, located at DDC2, when a CCD is used. The most sensitive charge monitor, DaMon, is also located close to the diagnostics station and is used as the calibration reference. If the detector is calibrated for the number of photons per area an absolute calibration of the screen monitor is derived, in which the number of photons in a confined area of the detector represents the electron beam charge in the same area. Using a source with a known photon distribution, the normal CCD was calibrated relative to the number of photons.

When the diagnostics station is switched to ICCD mode, it functions more efficiently in terms of sensitivity to low intensity, however calibrating this setup as a charge monitor is not straightforward. As previously mentioned, the intensifier unit response to the charge value changes, and the integral of intensity versus laser intensity is not linear. Figure. 6 shows the charge growth as a function of the laser intensity measured by DaMon and the calibrated ICCD monitor. Due to saturation of the ICCD for higher charges (more than 40 fC), the charge values measured by the monitors, are not in very good agreement. Thus, cal-

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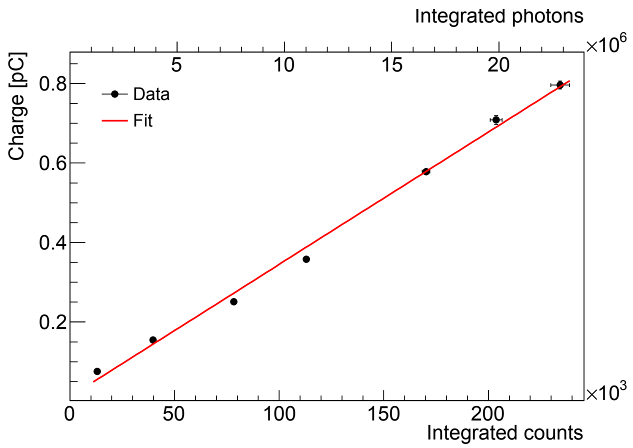

Figure 5: Charge calibration of the DDC2 screen monitor. The data points are described by a first degree polynomial $y = a + bx$, with parameters a=0.012 and b=3.33$\times10^{-6}$ determined by a fit. The upper horizontal axis shows the corresponding photon number within the area of the beam.

ibration of the ICCD monitor should be re-performed for low charges.

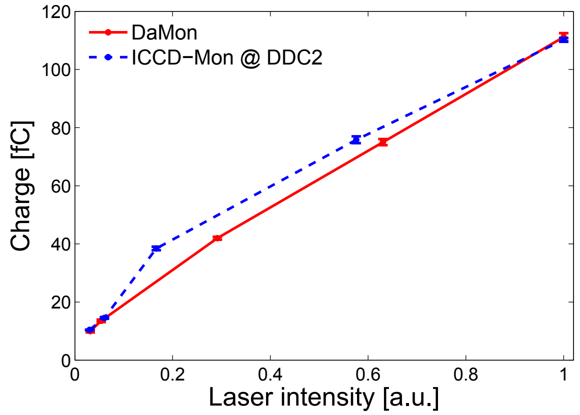

Figure 6: Charge, as a function of the laser intensity, measured by the ICCD (dashed line) and DaMon (solid line) monitors located at DDC2.

CONCLUSION

Beam profile monitors for REGAE have been designed and are in use for daily operation. Beam parameters such as emittance [8], the energy and the energy spread have been measured by means of the transversal diagnostic. The setup comprising the scintillator crystal, optics and detectors, has been evaluated as a sensitive monitor for characterizing the transversal profile of ultra-low charge electron beams. The screen Monitors are well calibrated in CCD mode and they provide the projected distribution of electrons in the bunch. Further studies are required to obtain a more precise charge calibration with the in ICCD mode.

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