TRANSVERSE EMITTANCE MEASUREMENT AT REGAE*

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Abstract

A new linac, named REGAE (Relativistic Electron Gun for Atomic Exploration) has been built at DESY and operates as an electron source for ultra-fast electron diffraction. An RF photocathode gun provides electron bunches of high coherence, sub-pC charge and energies of 2–5 MeV. In order to film time-resolved structural changes of excited specimens, bunch lengths of several femtoseconds need to be created. Taking into account these critical parameters, beam diagnostics at REGAE is very challenging. The existing diagnostics consists of energy, energy spread, beam profile, beam charge and emittance measurements. For transversal diagnostics, specific approaches have to be considered to overcome complications associated with the low charge and to carry out the beam diagnostics in single shot. In this paper, the contribution of the transversal diagnostics to the measurement of the transverse emittance is presented.

INTRODUCTION

In electron diffraction experiments it is far more important to resolve atomic structural changes than observing the atomic structure of matter in a static mode. Ultra-fast Electron Diffraction (UED) paves the way towards observing the atomic motions in real time, which has a strong impact on an extensive area of science, including physics, chemistry and biology. The time scale of atomic motions is on the order of $\sim$ 100 fs. To resolve such fast processes, electron bunches of the same or shorter length are required. The generation of short electron pulses has become possible by means of femtosecond laser systems. However, the pulse length is influenced by repulsive space charge forces and the required resolution is consequently limited. RF photo injector facilities, capable of generating mega electron volt electrons, can be employed to suppress space charge effects in the relativistic regime. Besides improving the beam quality and obtaining the desired temporal resolution, a high enough number of electrons can be confined in a pulse for single shot pump-probe experiments.

REGAE is a new linear accelerator constructed and operated in the framework of the Center for Free–Electron Laser Science (CFEL) as a collaboration of Max Planck society, Hamburg University and DESY. The REGAE accelerator comprises of a photocathode located inside a normal conducting 1.5 cell RF cavity which can accelerate electrons to 2–5 MeV energy. Electron bunches of 10 fC–100 pC can be generated as a function of the injector laser intensity. A 4-cell S-band buncher cavity is used to compress the pulses down to several femtoseconds as an ultimate resolution for a time resolved diffraction experiment. According to beam optics simulations by ASTRA [1], beam parameters as a bunch charge of sub-100 fC–1 pC, transverse emittance of $\approx$30 nm rad and a bunch length of 7–30 fs is required to fulfill the objective. Sophisticated diagnostics on a shot-to-shot basis is essential to generate and maintain these electron bunches. Some major results of diagnostics, including charge, energy, energy spread and beam profile measurements, have been presented in [2–4]. In this paper, the main focus is on the transverse emittance measurements, which is an important parameter to evaluate the beam quality for the UED experiment. An ongoing emittance measurement technique at REGAE is based on the solenoid scan method [6]. Two further techniques have been examined and will be described in the following.

REGAE SETUP

In the accelerator section of REGAE, DDC1 and DDC2 are dedicated to the transverse profile diagnostics and the charge diagnostics. Faraday cups and a cavity monitor (DaMon) [5] perform charge measurements. The third station (DC3), downstream at the side, is allocated to measure the beam energy and its spread using a dipole magnet. The beam profile measurement is extended by a fourth station in the target chamber to optimize the beam conditions for the diffraction experiment. After interacting with the specimen, the electrons are directed towards a fiber optics scintillator screen, which is monitored by an EMCCD-based detector. Apart from the diagnostics elements, steerer and solenoid magnets change and modify the electron trajectories. A layout of REGAE is shown in Fig. 1.

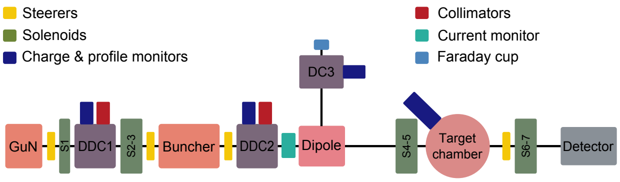

Figure 1: Layout of REGAE.

EMITTANCE MEASUREMENT, SHADOW IMAGE

In order to install diffraction samples, commercially available transmission electron microscopy (TEM) grids are used to support the thin films. Such objects with repeating structure can be used to measure the beam divergence and subsequently the beam emittance. The technique resembles

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the pepper-pot method, where small slits (or holes) in the pepper-pot plate cut the incident beam into small pieces, each with a very low charge. This makes the pepper-pot method more suitable for emittance measurements in a space charge dominated regime [7]. On the contrary, with the TEMs, the opening areas through which the beam is transmitted are larger, which makes this method more practicable for low charges. The technique has been employed at the Pegasus facility at UCLA to measure emittances of ultra-low charge (< 1 pC) beams [8]. The projection of the edge of each grid bar contains information characterizing the beam quality. The trace-space of a charged particle beam is sheared in a drift which results in a modification of the distribution at the edge. During the propagation of the transmitted beam only the particle positions change while the divergence remains unchanged. The width of the distribution, $\sigma_{x'}$, represents the spread of the trajectory slopes and describes how much the electrons cross over the borders of a bar edge which causes the sharp edge to become blurred. Subsequently, the entire intensity profile of both edges can be described as [8]:

$$F(x) = erf(\frac{x + Ma/2}{\sqrt{2}L\sigma_{x'}}) - erf(\frac{x - Ma/2}{\sqrt{2}L\sigma_{x'}}), \qquad (1)$$

where M is the magnification of the image, a is the bar width and L is the length of the drift. Using $\sigma_{x'}$ as a fit parameter, the best agreement between measurement and fit is achieved, from which the geometrical trace-space emittance is obtained.

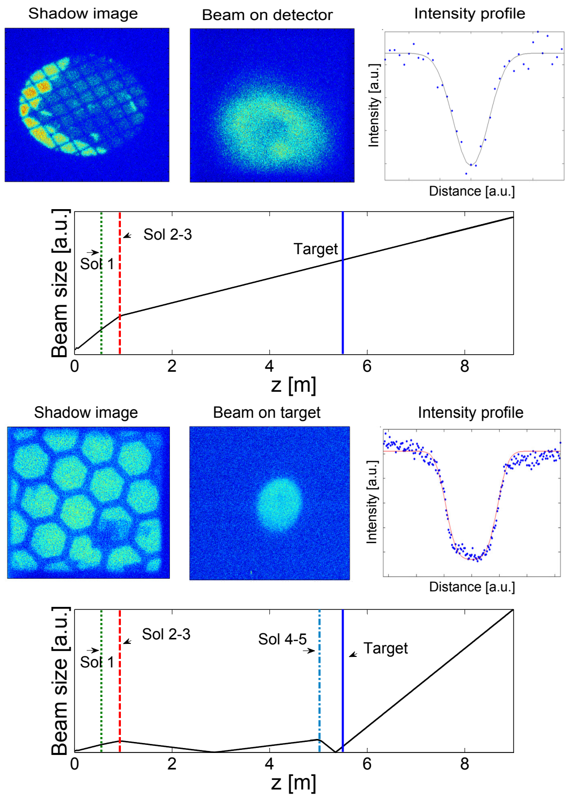

Figure 2: The first (top) and the second (bottom) configurations to create shadow images.

With this approach two different configurations have been tested. In the first configuration, the current of solenoid 2-3 (cf. Fig. 1) was adjusted so that the beam was brought to the target with a small diverging angle, without any further focusing. The beam momentum was 4.36 MeV/c and the charge was 250 fC. Moving the sample holder transversally the scintillator screen could be replaced by a hole that contained the TEM grid. The beam passed through the mesh and drifted further up to the fiber optics scintillator monitor, where the shadow image was created. A layout of the setup is depicted in Fig. 2. One major concern in this setup is the possible overlap of the projected intensity profiles of neighboring edges. As remedy the shadow image needed to be enlarged. Hence, in the next arrangement, solenoid 4-5 was used to apply a sharp focus just before the sampling target (see Fig. 2). Although the beam envelope was slightly spoiled due to space charge at the focusing point, the shadow image was significantly magnified. The beam momentum was 2.8 MeV and the bunch charge varied between 100–540 fC.

EMITTANCE MEASUREMENT, DIFFRACTION PATTERN

Analyzing diffraction patterns is another approach to measure the beam emittance. A criterion to determine the quality of a diffraction pattern is the ratio of the size of the non-diffracted spot, x_0, to the distance of a diffracted beam spot to the center, x_{diff}, which is represented by the diffraction ratio $R = x_0/x_{diff}$. If the ratio is minimized, the overlap of diffraction spots is avoided and the intensity of the spots is maximized. The position of the diffraction spot or the diffraction offset, follows the ordinary optics of a kicked central ray. In the following space charge forces are neglected. Following the development of a beam between the diffracting target and the detector, the minimal theoretical diffraction ratio is reached when the phase advance between the two points becomes 90° and is then given by:

$$R_{min} = \frac{\sqrt{\epsilon}}{x'_{diff}\sqrt{\beta_t}\underbrace{\sin{(\Delta\phi)}}_{=1}} = \frac{\epsilon}{x'_{diff}\sigma_t} \qquad (2)$$

ϵ is the geometrical emittance, β_t denotes the beta function at the target and $\Delta\phi$ is the phase advance between target and detector. x'_{diff} and σ_t are diffraction angle and beam size at the target location, respectively. The correct phase advance is adjusted by minimizing R. The focusing scheme, chosen for the measurements, employs a solenoid between target and detector. The beam focus is thus close to the detector plane. For various magnet settings, the diffraction ratio, R, is calculated and the pattern associated to the minimum value is selected. Introducing the Bragg relation into Eq. 2, the geometrical and the normalized emittance are written as:

$$\epsilon = \frac{R_{min}\,\sigma_t\,h}{d\,m_0\,c\,\gamma\beta}, \quad \epsilon_n = \frac{R_{min}\,\sigma_t\,h}{d\,m_0\,c} \qquad (3)$$

With h, d and m_0 as Planck's constant, lattice spacing and electron rest mass and $\gamma\beta$ as relativistic Lorentz parameters.

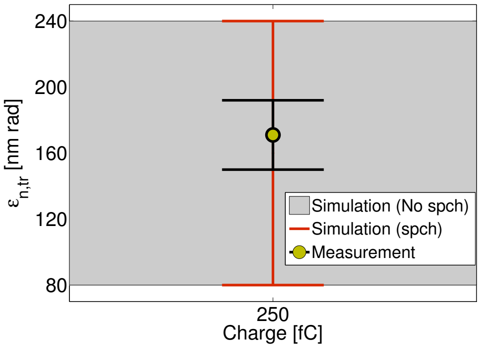

Figure 3: Measured and simulated normalized emittance from shadow image, first configuration.

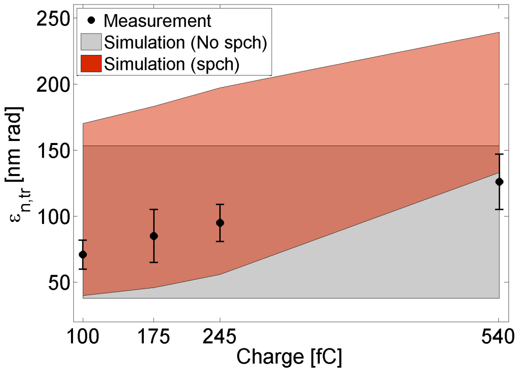

Figure 4: Measured and simulated normalized emittance from shadow image, second configuration.

MEASUREMENT AND SIMULATION RESULTS

During the time of the measurements, the size of the laser beam on the photocathode could not be precisely determined, thus the setups were simulated for a range of different laser sizes. In the first configuration of the shadow image measurement, the beam is partially covered by small pieces of diffraction samples and the analyses could not be applied across the complete beam profile, (see Fig. 3). This problem will be resolved by installing grids fully dedicated to these measurements free from any samples. In the second configuration, the simulations show that due to the steep focusing before the target, the emittance grows within the drift space, while in the analysis of the measured data space charge induced emittance growth is ignored. Therefore, the emittance is underestimated (see Fig. 4). Finally, a moderate magnification is of interest, such that the space charge effect is minimized and does not affect the evaluation of the emittance.

According to Eq. 3, the normalized emittance is derived directly from the parameters of the diffraction pattern, i.e a knowledge of the beam energy is not required. This points out a fundamental advantage of this method as compared to all other methods. The measurements and simulation results are shown in Fig. 5. The beam charge and momentum are 270 fC and p=3.7 MeV, respectively. The measured emittance agrees with the simulation results within the uncertainties. Hence, potentially both techniques can be developed for performing single shot, online emittance measurement at REGAE. Further improvements of the experimental conditions would enhance the accuracy of such measurements.

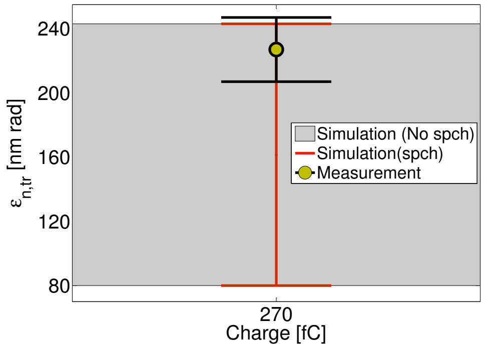

Figure 5: Simulations and measurements of the transverse emittance, using diffraction pattern.

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