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DESIGN STEPS TOWARDS AN ELECTRON SOURCE FOR ULTRAFAST ELECTRON DIFFRACTION AT DELTA *

D. Krieg†, S. Khan, Center for Synchrotron Radiation, TU Dortmund University, Dortmund, Germany
T. J. Albert, K. Sokolowski-Tinten, University Duisburg-Essen, Duisburg, Germany

Abstract

Ultrafast electron diffraction (UED) is a pump-probe technique to explore the structural dynamics of matter, combining sub-angstrom De-Broglie wavelength of electrons with femtosecond time resolution. UED experiments require ultrashort laser pulses to pump a sample, electron bunches with small emittance and ultrashort length to analyze the state of the sample and excellent control of the delay between them. Electrons accelerated to a few MeV in a photocathode gun offer significant advantages compared to keV electrons from electrostatic electron sources regarding emittance, bunch length and, due to the reduction of space charge effects, bunch charge. Furthermore, thicker samples and hence a wider range of possible materials are enabled by the longer mean free path of MeV electrons. In this paper, design steps towards a university-based UED facility with ultrashort and low-emittance MeV electron bunches are presented, including the transverse and longitudinal focusing schemes, which minimize space charge effects and nonlinearities.

INTRODUCTION

Ultrafast electron diffraction (UED) is a technique to explore structural dynamics of matter using, for example, the pump-probe technique with an optical pump and an electron bunch as probe. The technique has to satisfy the relevant spatial (< 1 Å) and temporal (< 100 fs) resolution requiring a very high electron beam quality. The study of, e.g. proteins, calls for a coherence length of about 30 nm. This translates into a bunch radius of 0.2 mm with a beam divergence of 12.5 µrad [1]. Moreover, short and reproducible bunch lengths down to some tens of fs are required. Recently, a design study for a university-based UED facility providing high-quality electron bunches was initiated in collaboration with the University Duisburg-Essen and the Center for Synchrotron Radiation of the TU Dortmund University which also operates the 1.5-GeV synchrotron light source DELTA. In this paper, the main limiting factors will be explained and strategies will be presented to minimize them. In addition, aspects of the radiofrequency (rf) incoupling and the laser system will be discussed.

BASIC DESIGN

In Fig. 1, a conceptual design of a UED setup is shown. A laser-excited photocathode is placed inside a 1.5-cell standing-wave cavity. A bunching cavity is used for longitudinal compression. It is operated off-crest and imprints an energy chirp onto the electron distribution such that particles at the tail of the bunch gain a higher velocity than those at the head. Solenoids compensate the transverse defocusing of both cavities. The electron source is followed by a target chamber, a detection system and the beam dump. The two main limitations for ultrashort high-brightness electron bunches are space charge effects and nonlinearities in the rf fields.

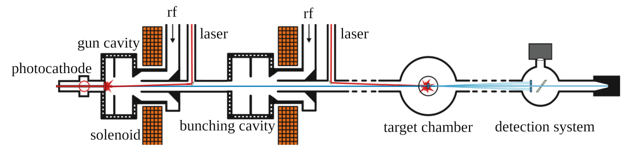

Figure 1: Conceptual UED setup comprising a photocathode rf gun, a bunching cavity, a target chamber and a detector.

SPACE CHARGE EFFECTS

The Coulomb repulsion of the electrons enlarges the bunch in all dimensions in a nonlinear way. The transverse space charge field scales as $E_r \propto r/R^2$ where r is the radial postion inside the bunch and R is the transverse bunch size. In longitudinal direction, it scales as $E_z \propto z/L$ with z being the longitudinal position with respect to the bunch center and L being the bunch length. Typically, there are $\approx 10^6$ electrons in a bunch. A high-quality electron bunch should have a small 6D phase space volume but a small volume implies increased space charge effects. Minimizing the rf-induced emittance in the photocathode gun limits the laser pulse length in practice to approximately 10° of the rf phase [2]. Furthermore, space charge forces are massively suppressed with increasing electron energy. The transverse space charge force scales as $F_\perp \propto 1/\gamma$ and the longitudinal force as $F_\parallel \propto 1/\gamma^2$ with the Lorentz factor γ [3]. Thus, the electrons have to be rapidly accelerated at the photocathode which requires a high acceleration of the order of 100 MV/m. The space charge effects are illustrated in Fig. 2. Using ASTRA [4], the acceleration of an electron bunch was simulated with and without space charge. For simplicity, an electric DC field was considered to neglect effects like the rf curvature. For both cases, the 6D phase space volume was calculated.

NONLINEARITIES OF RF FIELDS

The curvature of the accelerating field [5]

$$E_z(z,t) = E_0 \sin(\omega t + \varphi) \cos(k_z z), \qquad (1)$$

translates into nonlinearities in the longitudinal phase space distribution of the electrons. Moreover, there is a nonlinear-

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† daniel.krieg@tu-dortmund.de

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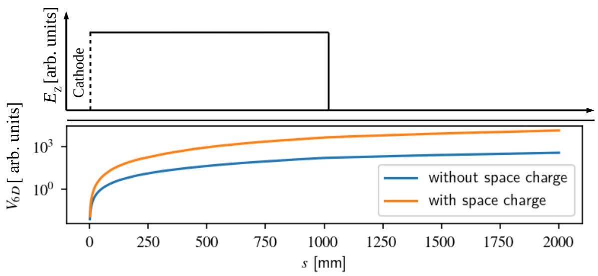

Figure 2: Electric field and phase space volume $V_{6\mathrm{D}}$ as a function of the longitudinal position s.

ity of the longitudinal compression using a bunching cavity. A longitudinal shift of the electrons in a drift space is given by the velocity difference within the bunch based on the energy chirp induced by the bunching cavity in a nonlinear way as shown in Fig. 3. The electron distribution in the longitudinal phase space is depicted at different locations. The electron bunch length in the focus is increased in the presence of nonlinear energy chirp reducing the possible temporal resolution.

LONGITUDINAL AND TRANSVERSE FOCUSING

The focusing strategy should minimize both space charge effects and nonlinearities to reduce the effective 6D phase space volume and thus improve the electron beam quality. In the longitudinal case, a small electron density at the cathode, realized by a relatively long laser pulse, and compressing the electron bunches at higher energy with a bunching cavity will suppress space charge effects. The 6D phase space volume, calculated using ASTRA simulations under variation of the laser pulse length T_L, is shown in Fig. 4. In addition, the compression capability of the gun cavity alone is very limited. As shown in Fig. 5 the region of the gun phase leading to longitudinal compression of the electron bunch is typically around 30°. Furthermore, the energy spread caused by the gun cavity is relatively small. The shift of the relative longitudinal position Δz in an electron bunch after a drift of length l is given up to third order by [6, 7]

$$\frac{\Delta z}{l} = \frac{1}{\gamma^3\beta^3}\delta\gamma + \frac{2-3\gamma^3}{2\gamma^6\beta^5}\delta\gamma^2 + \frac{2-5\gamma^2-4\gamma^4}{2\gamma^9\beta^7}\delta\gamma^3 \quad (2)$$

where β and γ are the velocity and the Lorentz factor of a central bunch particle ($z = 0$) and $\delta\gamma$ denotes the difference from γ. With Eq. (2) neglecting space charge effects and assuming that the initial electron bunch is approximately as long as the laser pulse, the required drift length to focus an electron bunch to a length of < 100 fs under variation of the gun phase φ and the laser pulse length T_L is shown in Fig. 6.

For laser pulses with $T_L \gtrsim 1000$ fs the drift space would be excessive long. Using a bunching cavity, the maximum laser pulse length is limited by the second-order rf-induced emittance which grows as the square of the bunch length limiting the laser pulse length to approximately 10° of rf phase [2].

The nonlinearity of the longitudinal phase space distribution can be minimized alone by choosing gun- and bunching cavity parameters according to [6]. In this method, the beam is longitudinally expanded after the electron source. This enables a higher-order correction of the longitudinal focus by a bunching cavity, operated at the same frequency as the gun cavity. An alternative would be the use of an additional third-harmonic rf cavity [8, 9]. However, this method results in extra cost and requires additional space, which is not available at the currently foreseen location. For the transverse case, space charge effects decrease with larger laser spot size because of the reduced electron density. On the other hand, a larger laser spot increases the initial emittance of the electron source. First simulation studies show that the

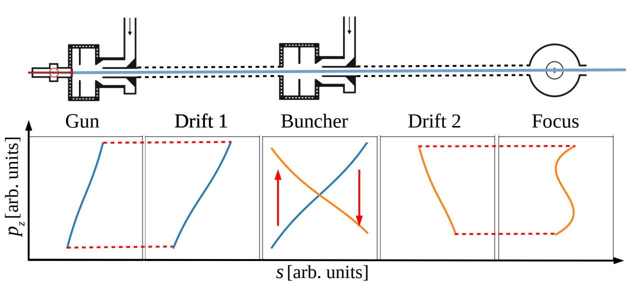

Figure 3: Schematic longitudinal phase space distributions of an electron bunch at different positions after the photocathode with a nonlinear energy chirp (bottom).

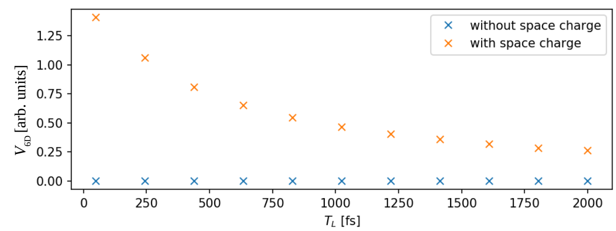

Figure 4: Space charge influence on the 6D phase space volume $V_{6\mathrm{D}}$ under variation of the laser pulse length T_L.

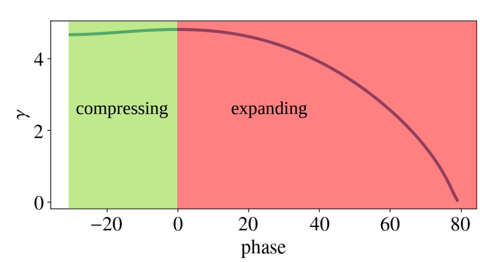

Figure 5: Lorentz factor γ of an electron accelerated in an rf electric field with a maximum gradient $E_0 = 100$ MV/m and a frequency $f \approx 3$ GHz according to Eq. (1) under variation of the gun cavity phase φ.

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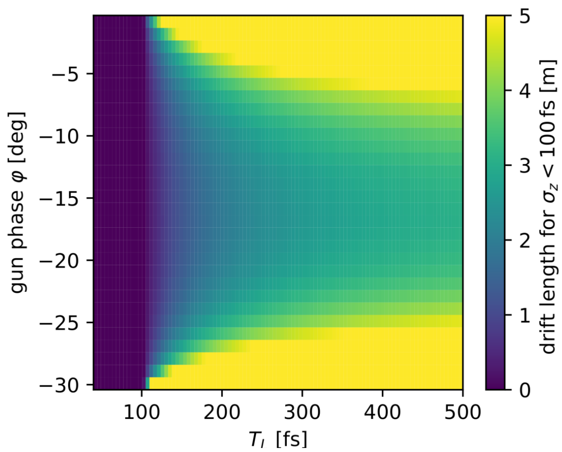

Figure 6: Required drift length for longitudinally focusing an electron bunch to a length < 100 fs under variation of the gun phase and laser pulse length.

second effect dominates down to around 5 μm which is a realistic spot size. Solenoids will compensate the transverse defocusing of the rf cavities, especially the gun cavity. The beam rotation with an angle φ_L around the beam axis, the refractive power $1/f$ and the emittance growth $\varepsilon_{\mathrm{sol}}$ induced by the solenoid,

$$\varphi_L = \frac{e}{2p_z}\int B_z dz, \quad (3)$$

$$\frac{1}{f} = \left(\frac{e}{2p_z}\right)^2 \int B_z^2 dz = \left(\frac{e}{2p_z}\right)^2 F_2, \quad (4)$$

$$\varepsilon_{\mathrm{sol}} = \frac{e_2\sigma^4}{3\sqrt{2}p_{z0}^2}\underbrace{\int \frac{-B_z'' B_z}{2}dz}_{F_3} + \frac{e^4\sigma^4}{24\sqrt{2}p_{z0}^4}\underbrace{\int B_z^4 dz}_{F_4}, \quad (5)$$

depend on the on-axis magnetic field B_z of the solenoid [2, 10]. The emittance growth $\varepsilon_{\mathrm{sol}}$ and thus the integrals F_3 and F_4 in Eq. (5) should be small. Typical field distributions yield values of $F_3/F_4 > 1 \cdot 10^4\,\mathrm{T}^{-2}\mathrm{m}^{-2}$ [10]. The term B_z'' describes the „curvyness“ of B_z. A longer solenoid with smaller field and reduced curvyness leads to smaller emittance growth, as shown in Fig. 7. For two solenoids of different length with the same F_2, the value of F_3 was calculated. The defocusing focal length of an rf gun cavity

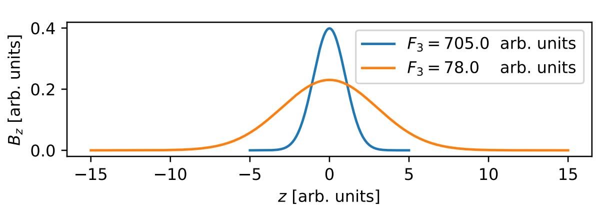

Figure 7: Two different shapes of solenoid field B_z, resulting in the same F_2 and different F_3, see Eqs. (3) and (4).

is approximately given by

$$f_{\mathrm{rf}} = -\frac{-\beta\gamma mc^2}{eE_0\sin(\phi_e)} \quad (6)$$

with E_0 being the maximum gradient and ϕ_e being the gun exit phase [5, 11]. A typical value for a gun operated at a peak field of 100 MV/m and accelerating the electrons on crest with an energy of 6 MeV results in $f \approx 12$ cm [11]. Thus, the refocusing solenoid should be located immediately after or even around the gun cavity. To avoid an increase of the emittance by magnetic fields from the solenoids at the cathode, a bucking solenoid could be needed, especially if a refocusing solenoid with a more extended magnetic field is employed.

LASER AND RF SYSTEM

The rf incoupling should produce as little as possible perturbations in the electric field of the cavity. There are in principal two options, a lateral incoupling like at LCLS [12, 13] or coaxial incoupling like at REGAE [7], PITZ or FLASH [14]. The second option promises less perturbations [11] while those of lateral incoupling could be reduced by an elliptically shaped pillbox [12, 13]. The (sufficiently small) perturbations are only significant if the electron bunch is off-axis or has a large transverse size but in a UED scheme this should not be the case. As a conclusion, from the point of field perturbations both options are coequal. The disadvantage of the coaxial incoupling is the requirement of another laser incoupling with a larger distance between the last mirror and the cathode. On the other hand, the angle between laser and cathode is smaller, no additional laser-pulse shaping is required and the outcoupling of the reflected laser is positioned outside the gun cavity. With a focus on stability a single Ti:sapphire laser system will feed the photocathode and pump the sample.

CONCLUSION AND OUTLOOK

As main limiting factors for a high-quality electron beam, space charge effects and rf-induced nonlinearities were discussed. In order to minimize space charge effects, the photocathode laser pulse will be longer than 1 ps and the electrons will be compressed with a bunching cavity. To suppress nonlinearities, a scheme as described in [6] will be applied. Another option is to use a harmonic cavity which, however, would require additional space and cost. Once a decision on the gun cavity has been made, the exact components and parameters resulting from the longitudinal and transverse focusing strategies and the rf incoupling can be worked out. A further important issue is the overall synchronization system with a jitter that must be significantly smaller than the lengths of the pump pulse and electron bunch.

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