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Tip-based source of femtosecond electron pulses at 30 keV

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We present a nano-scale photoelectron source, optimized for ultrashort pulse durations and well-suited for time-resolved diffraction and advanced laser acceleration experiments. A tungsten tip of several-ten-nanometers diameter mounted in a suppressor-extractor electrode configuration allows the generation of 30 keV electron pulses with an estimated pulse duration of 9 fs (standard deviation; 21 fs full width at half maximum) at the gun exit. We infer the pulse duration from particle tracking simulations, which are in excellent agreement with experimental measurements of the electron-optical properties of the source in the spatial domain. We also demonstrate femtosecond-laser triggered operation of the apparatus. The temporal broadening of the pulse upon propagation to a diffraction sample can be greatly reduced by collimating the beam. Besides the short electron pulse duration, a tip-based source is expected to feature a large transverse coherence and a nanometric emittance. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4867185]

I. INTRODUCTION

Time-resolved electron diffraction is a powerful tool to follow structural dynamics in space and time, with “molecular movies” as the grand goal.1–3 Melting processes in metals4 and structural phase transitions in crystals5 have been studied with femtosecond electron diffraction. In these experiments, structural dynamics is initiated by laser pulses, and electron pulses serve as the probe. An electron kinetic energy of tens of kilo-electron volts provides short enough de-Broglie wavelengths to resolve atomic distances and changes thereof on the scale of milli-Angstrom. To obtain an instructive diffraction pattern, more than a full unit cell (typically several nanometers for complex materials) needs to be illuminated coherently. The transverse coherence of typical flat photocathodes is limited by their source size and electron energy spread6 and restricts imaging to full unit cell dimensions below around 20 nm.6

Of further interest is the electron pulse duration delivered by the source, which is the limiting factor for the temporal resolution in a pump-probe experiment. Experiments that operate with many electrons per pulse are typically limited by space charge broadening of the electron bunch.5–9 Coulomb repulsion is most efficient in lengthening the electron pulses within the acceleration region, where the electron cloud is still rather slow. After acceleration to higher velocities, the effects of space charge are much reduced. Rather complex experimental means such as rf-cavities,10,11 reflectrons,12 and ponderomotive light forces13 allow post-compression of space charge broadened pulses to smaller durations at the target. Experimentally, 67 fs (standard deviation, std. dev.) pulses have been achieved in this way.10 A resolution of about 100 fs is also achievable by several alternative approaches.14–20

Space charge broadening is avoided altogether when operating the electron source in the multi-shot regime, where each electron pulse contains only a few electrons and the final image is constructed from a large number of experimental cycles.21,22 In total, about 106 to 108 electrons are typically needed to obtain a diffraction pattern.2,3,10 This restricts the systems that can be investigated to such with reversible dynamics, like in many condensed matter systems, or the sample must be replaced between excitations, for example, by placing and aligning molecules in the gas phase.23–26 The effective pulse duration is then given by the arrival time difference of the electrons that contribute to the final diffraction image.21,22,27 These timing differences are mainly caused by path length and kinetic energy differences of the individual electrons. Flat single-electron photocathodes, at best technically possible conditions, cannot provide pulses with a std. dev. duration shorter than about 34 fs (80 fs full width at half maximum, FWHM).22 Shortening of the pulses and increasing their coherence thus pose two of the most urgent challenges towards atomic-scale recording of dynamics with electron diffraction.

The central idea of this work is to replace the usually flat cathode of a photoelectron source by a sharp metal tip with radius of curvature in the range of several tens of nanometers. A laser pulse triggers photoemission from the localized area of the tip apex while it is biased with a static voltage that lies just below the threshold for field emission (or slightly above it if a cw background current can be tolerated). Pulsed electron emission from these tips has been actively studied in recent years28–33 and it has been found that the emission process is controllable on the sub-femtosecond timescale.34,35 However, an ultrashort emission process alone does not necessarily yield short pulse durations at a diffraction target, as the pulse broadens during propagation due to initial velocity differences and, in the case of pulses containing many
electrons, space charge forces. In the following, we will study the electron propagation in a tip-based electron source in detail and present a design that promises a std. dev. pulse duration well below 50 fs at the target.

Besides offering a short pulse duration, nanometer sharp tips are extremely bright electron sources with a large transverse coherence. This is not only beneficial for imaging crystals with large unit cell dimensions, but renders a laser-triggered tip source also interesting for other applications, like time-resolved electron microscopy. In real-space imaging, beam coherence is decisive for resolution and for the ability to focus the beam tightly on the sample. Another example would be novel electron accelerators such as dielectric laser accelerators and free electron lasers. In order to generate the required low emittance beams, a tip-based setup appears to be the only source to work directly for these applications. The device presented in the following thus may also represent the low-energy part of an electron gun for these machines.

In Sec. II, we will provide a short overview over the benefits of a tip-based electron source for diffraction experiments concerning pulse duration and transverse coherence. We will then focus in Sec. III on pulse duration by presenting simulation results for an idealized setup consisting of a tip source followed by two flat electrodes. For applications like an electron source for diffraction experiments, a modified geometry is better suited, where the tip is placed between a suppressor and an extractor electrode. In Sec. V, we will discuss this geometry in more detail. It produces electron pulse durations that are comparable to that of the tip-to-anode geometry of Sec. III. We also show how the temporal broadening of an exiting electron pulse can be significantly reduced by collimation with an electron-optical lens. We finally present a first experimental characterization of the gun without lens in DC and laser-triggered operation.

II. BENEFITS OF TIP-BASED ELECTRON SOURCES

The first advantage of a tip-based photoelectron source is the large acceleration electric field that can be generated at the apex of the tip until appreciable field emission from its surface sets in at about 2 GV/m. A high initial field, orders of magnitude larger than for flat emitters (up to 20 MV/m (Ref. 9)), helps to minimize the length of the acceleration region and therefore the overall gun dimensions. For an emitter with a finite initial energy distribution, the energy spread leads to differing arrival times of the individual electrons at the gun exit and thus contributes to the overall pulse duration. Its influence decreases for shorter acceleration distances and a tip-based setup should therefore yield a much reduced pulse duration compared to a conventional flat-cathode geometry. For a curved emitting surface, however, path length differences between electrons originating from different locations on the tip also contribute to the pulse duration, as will be discussed in Sec. III.

The second advantage of a tip-based setup is its small (virtual) source radius \( r_{\text{eff}} \), which is no longer given by the laser spot size but by the tip itself (Fig. 1). As the transverse coherence length \( \xi_{\perp} \) of an electron beam at target scales inversely proportional to the virtual source size, a significant increase in transverse coherence length compared to flat cathode setups is expected. Typical virtual source sizes for DC field emitter tips lie in the range of about one-half to a few nanometers, for tips with a radius of tens of nanometers. The virtual source size is much smaller than the geometrical source size because in field emission the tunneling process exponentially favors trajectories perpendicular to the tip surface over those under an angle. For laser-triggered emission with proper parameter settings, we expect a similar behavior, supported by very similarly looking spatial emission distributions for field emission and laser-triggered emission.

The ratio \( K \) of transverse coherence length \( \xi_{\perp} \) over beam radius quantifies the coherence properties of an electron beam. In the single-electron regime, it is a conserved quantity and can hence be employed to determine \( \xi_{\perp} \) at the gun exit. The van Cittert-Zernike theorem relates \( K \) to the virtual source size \( r_{\text{eff}} \) via \( K = \lambda / (\pi \theta_{\text{eff}}) \). Here, \( \lambda \) denotes the de-Broglie wavelength of the accelerated electrons and \( \theta \) the opening angle of the beam as observed from the detector. Typical values for nanometric field emitters lie in the range of \( K = 0.01\ldots0.1 \), in agreement with our own estimates. This value for \( K \) represents a two-order-of-magnitude improvement over flat-cathode photoelectron sources or cold-atom photoionization sources, which at best yield \( K \approx 2 \times 10^{-4} \).

Adding to the discussion above, the small virtual source size of DC field emitters results from the small initial energy spread of the tunneling electrons. For laser-triggered sources, the initial energy spread is given by the difference between the photon energy and the work function of the tip material and is generally much larger than the typical energy spread in DC operation of about 0.1 eV. However, by matching the photon energy to the work function of the tip material, the excess energy in laser-triggered operation can be minimized and we thus expect to realize transverse coherence length values significantly larger than those from flat photocathodes.
The nanometric source size results in extremely low emittance electron beams. For example, for a virtual source rms radius of 1 nm and an emission angle of 5°, the emittance of the source presented in the following is as small as ~0.1 nm (or 0.0001 mm mrad). In this work, we focus on the temporal aspects of the tip-based single-electron source, but do expect to observe significant improvements in spatial resolution and emittance in the future as well.

III. ACCELERATION CONCEPT WITH TWO ELECTRODES

Since the desired electron pulses shall propagate in free space in a grounded region, the final kinetic energy of the electrons is given by the tip bias. It is set to $E_{\text{kin}} = 30 \text{ keV}$, suitable for diffraction from complex materials and molecular systems. The central concept of our work is to maintain the highest possible electric field along the entire acceleration distance without exceeding critical field strengths at the tip and any other electrode surface. At the tip, the field is limited by the onset of DC field emission to $F_{\text{tip}} = 2 \text{ GV/m}$. Depending on the tip material and the allowable background (DC) field emission current during laser-triggered operation, this value might be larger, but certainly by much less than an order of magnitude.

Due to field enhancement at the sharp tip, a surface field of $F_{\text{tip}} = 2 \text{ GV/m}$ can be realized by applying a comparably moderate voltage bias between the tip and a grounded electrode at a distance of several millimeters. However, away from the tip, the field drops steeply on a length scale of a couple of tip radii. To minimize the resulting loss of acceleration, we demand that the field should nowhere drop significantly below 5 MV/m. This especially means that the surface field on any additional electrode is kept at 5 MV/m. We chose this value as such a field still can be safely applied to polished steel parts.\(^3\)

The requirement to satisfy these boundary conditions for fixed final kinetic energy $E_{\text{kin}}$ and arbitrary tip radius $R$ necessitates a setup that incorporates the tip and at least two electrodes, as first considered in Ref. 51. Fig. 2 shows this geometry, which consists of the tip placed in front of two flat electrodes at variable distances. In the first part of the setup, the distance $D$ between tip and first anode, as well as the voltage difference between these elements, are chosen to fulfill the boundary conditions on both the tip (2 GV/m) and anode field (5 MV/m). The space between the first and second anode then serves as a parallel-plate capacitor with a constant field of $F_{A12} = 5 \text{ MV/m}$ to further accelerate the electrons to the desired final kinetic energy.

Below we will show detailed simulations based on this and a more realistic geometry. Recently, Paarmann et al. performed simulations similar to ours to investigate the influence of a spectral and angular spread on the arrival time differences of single electrons in a comparable geometry.\(^52\) Apart from the lower kinetic energies considered in that study, the authors did not discuss the limitation on the surface electric fields in their setup. Thus, it remains unclear which settings would generate the shortest pulse duration while maintaining the limits on physically feasible surface fields. By restricting the surface fields to the highest reasonable values, we expect our study to yield the shortest pulse durations that can be expected from a tip-based electron source at 30 keV without active recompression after the gun. Additionally, we will, in Sec. VII, demonstrate that the values obtained in this way are experimentally feasible.

IV. SIMULATION RESULTS

Due to geometric field enhancement, the local electric field at the apex of the tip depends on the tip geometry, which is characterized by the tip radius $R$ and the opening angle $\beta$ of the tip shank. We set $\beta = 3^\circ$, a value that is consistent with the tungsten tips commonly used in our laboratory.\(^32,53\) We then performed simulations for various $R$ and scaled both $D$ and $V_{A1}$ to yield the desired maximum surface fields. All anodes are modeled as infinitely thin sheets that are permeable to electrons. In Sec. V, we will consider the experimentally realized setup with finite electrode thickness.

The timing in a tip-based setup depends on two mechanisms. First, each surface element of the tip can emit electrons with different initial velocities, given by the final energy distribution of the photoemission process. Second, the inhomogeneity of the acceleration field around the tip produces path length and timing differences between trajectories of electrons that leave the tip under various emission angles $\alpha$, Fig. 2.

To simulate the timing of the source, we assume that single electrons are emitted by one-photon photoemission with the central energy of the laser spectrum lying just at the effective surface barrier height of the tip material.\(^9,22,50\) Consequently, only photons from the high energy part of the laser spectrum promote electrons into vacuum. If we assume the laser spectrum to be Gaussian, the initial total energy distribution of the electrons can be considered as a truncated Gaussian, which is centered at $E = 0$, and where the half at negative $E$ has been removed. The width (std. dev.) of the full Gaussian distribution is taken as $\sigma_E = 0.25 \text{ eV}$. A laser spectrum of the same shape would correspond to a Fourier-limited pulse of 3 fs duration (FWHM). This is much shorter than the pulse duration that we intend to use in the experiments, so that $\sigma_E = 0.25 \text{ eV}$ can be considered as an upper limit on the initial electron energy spread at the tip.

Apart from $E_{\text{tip}}$, the arrival time differences at the sample depend in a tip-based setup on the path length differences between trajectories of electrons that leave the tip under
various emission angles $\alpha$. The angular distribution of the emission sites across the electrode surface is centered around forward emission and also assumed to be Gaussian with a width of $\sigma_z = 25^\circ$ (std. dev.). This approximates the beam profiles that we observe in our laser-triggered electron emission experiments. To study the angular dependence of the time-of-flight differences between individual electrons, we cut the distribution at varying maximum emission angles $\alpha_{\text{max}}$, which would correspond to the introduction of an aperture with varying opening diameter in the experiment.

We performed particle tracking simulations with the commercially available software package CPO (Scientific Instrument Services, Inc.). We only trace rays that are emitted parallel to the surface normal of the tip, as the additional delay that results from a tilted emission is found to be negligible compared to the delays caused by $\sigma_z$ and $\sigma_E$. We define the pulse duration $\sigma_r$ for a given $\alpha_{\text{max}}$ as the standard deviation of the time-of-flight between the tip and the second anode. For comparison, we will also list the FWHM durations assuming a Gaussian distribution of the arrival times. Note, however, that the electron pulses arriving at the sample are highly asymmetric in time due to the different broadening mechanisms involved, as discussed in the preceding paragraphs. The FWHM values can therefore only be considered as approximately representing the pulse width. For each data point, we trace several thousand individual electrons, which have been sampled randomly from the above mentioned spectral and angular distributions. Coulomb repulsion effects do not arise because of the individual electron nature of the simulation.

The resulting variation of electron pulse duration $\sigma_r$ with tip radius $R$ and clipping angle $\alpha_{\text{max}}$ is shown in Fig. 3. If we only consider electrons that are emitted on the optical axis ($\alpha_{\text{max}} \leq 1^\circ$), the pulse duration is solely given by the initial velocity spread (corresponding to $\sigma_E$) and decreases with increasing tip radius $R$. This is because field enhancement at the tip apex decreases for larger $R$. Consequently, the desired surface fields at tip and anode of $F_{\text{tip}} = 2 \text{ GV/m}$ and $F_{\text{A1}} = 5 \text{ MV/m}$ are realized for a larger distance $D$ between tip and anode and for a higher voltage $V_{\text{A1}}$ at the first anode. The electrons then travel a larger fraction of the complete acceleration distance in a region where the field is higher than that in the parallel-plate stage between A1 and A2.

For finite $\alpha_{\text{max}}$, the effective path length differs between electrons emitted under different emission angles $\alpha$ and additionally contributes to the pulse duration. Path length differences dominate the pulse duration for $\alpha$ larger than $\alpha_{\text{max}} \approx 10^\circ$, so that $\sigma_r$ increases at these clipping angles with $R$ for all radii studied. Up to $\alpha_{\text{max}} \approx 5^\circ$, the pulse duration is limited by $\sigma_E$ for small $R$, so that it initially decreases with increasing $R$. At larger $R$, the effects of the path length differences again outweigh $\sigma_E$ and the pulse length starts to increase with $R$.

At $\alpha_{\text{max}} \approx 5^\circ$, the contributions of $\sigma_E$ and $\sigma_z$ to the pulse duration are approximately equal for tip radii $R \approx 100 \text{ nm}$. Additionally, a beam clipped at $\alpha_{\text{max}} = 5^\circ$ contains about 2% of the total electron current that is emitted by a tip with an angular spread of $\sigma_z = 25^\circ$. For the experiment, we thus chose $\alpha_{\text{max}} \approx 5^\circ$ as a reasonable compromise between a small pulse duration and a comparably large electron current. From the results of Fig. 3, an effective electron pulse duration of $\sigma_z = 12 \text{ fs}$ (28 fs FWHM for a Gaussian distribution) seems feasible in a tip-based setup. This is a ten-fold improvement compared to a flat cathode geometry operated at 5 MV/m, where the corresponding pulse duration would amount to about $\sigma_z \approx 130 \text{ fs}$ (300 fs FWHM) at $\sigma_E = 0.25 \text{ eV}$ (cf. Eq. (5) of Ref. 22).

V. EXPERIMENTAL SUPPRESSOR-EXTRACTOR GEOMETRY

In the experiment, we realized a slightly different electrode geometry that also satisfies the above mentioned boundary conditions and generates high initial acceleration. The tip apex is sandwiched between a suppressor anode placed about $D = 500 \text{ nm}$ behind the tip apex and an extractor electrode in front of the tip, Fig. 4. The suppressor anode allows a reduction of $F_{\text{tip}}$ to the desired value just below the onset of field emission by simply varying the applied voltage $V_e$. The surface fields at the suppressor and extractor are then given by the distance $d$ between suppressor and extractor as well as by the voltage bias of the tip-suppressor unit with respect to the grounded extractor. Compared to the geometry of Fig. 2, this configuration allows the generation of the optimum surface fields at tip and anode for larger distances between tip and suppressor and provides better optical access for the laser beam used for photoemission.

We have simulated the electron pulse duration in the same way as for the idealized setup of Sec. III. We slightly relaxed the boundary conditions of the surface electric fields at the two electrodes and allowed fields of up to about 8 MV/m. The voltage on the suppressor and the distance $d$ between suppressor and extractor have been adjusted accordingly. For a tip radius of 50 nm and a tip voltage of $V_{\text{tip}} = -30 \text{ kV}$, we arrive at $d = 6.7 \text{ mm}$ and a suppressor voltage of $V_e = -33.4 \text{ kV}$. For higher $\alpha_{\text{max}}$, the pulse duration is again dominated by path length differences between off-axis and on-axis rays. When clipping the beam to $\alpha_{\text{max}} = 5^\circ$, the simulated pulse duration at the exit of the extractor electrode amounts to $\sigma_z = 9 \text{ fs}$ for $\sigma_E = 0.25 \text{ eV}$ and $\sigma_z = 12 \text{ fs}$ for $\sigma_E = 0.5 \text{ eV}$. Considering subsequent field-free
propagation, the pulse duration at a distance of 50 mm from the extractor will be $\sigma_d = 14\,\text{fs}$ at $\sigma_\theta = 0.25\,\text{eV}$ and $\sigma_r = 17\,\text{fs}$ at $\sigma_E = 0.5\,\text{eV}$.

VI. SPATIAL AND TEMPORAL COLLIMATION

Due to the inhomogeneous acceleration field at the tip apex, electrons that leave the tip away from the tip axis acquire non-vanishing radial velocity components during acceleration and exit the gun under an angle with respect to the electron-optical axis. As the absolute energy gain after acceleration is the same for all electrons, the axial velocity of these electrons is smaller than for those on axis. Hence, the electron beam further stretches in time during propagation to the sample.

Recent results on the temporal distortions in magnetic lenses offer a way out. The longitudinal expansion can be greatly reduced by collimating the electron beam either by a lens element placed behind the gun or with a lens that is integrated in the gun design, like a coil wrapped around the acceleration region.

For diffraction experiments with our source, we aim to produce a collimated electron beam. A magnetic lens is placed behind the electron gun at 31 mm from the gun exit. Fig. 5 depicts the effect of such a lens on pulse duration and beam diameter. While traveling through the lens, the electrons spiral around the optical axis so that outer electrons travel longer distances than inner ones and the pulse length initially broadens faster (thick lines) than without lens (thin lines). After collimation, the ongoing lengthening slows down significantly and is only governed by the on-axis velocity differences due to the initial energy spread after photoemission. At a distance of 250 mm behind the gun exit, a handy position for a diffraction target, we expect a pulse duration of $\sigma_r = 17\,\text{fs}$ (41 fs FWHM), only about twice as large as at the gun exit. Without the field of the magnetic lens, the pulse would have broadened to $\sigma_r = 34\,\text{fs}$ (80 fs FWHM). Thus, a carefully designed magnetic lens will allow the generation of extremely short, collimated electron pulses at such a distance from the gun that provides ample space for the diffraction or microscopy sample.

VII. EXPERIMENTAL PERFORMANCE

We test the validity of our particle tracking simulations by comparing the results to experimental DC-field-emission patterns of the source for various voltage settings, without the magnetic lens. The whole setup is mounted in a vacuum chamber with a base pressure of $2 \times 10^{-8}\,\text{Pa}$. To avoid electrical breakdown, the suppressor anode is fabricated from stainless steel and polished to optical quality. In field emission mode, we successfully generated electron beams with energies up to 30 keV while stably operating the critical part of the setup without any surface breakdown. To study the influence of the suppressor electrode on the electron emission from the tip, we first used a tungsten tip with the [110]-direction pointing forward. Residual atoms on the tip surface were removed by field evaporation during positively biased operation, so that the tip with a radius of $R = 50\,\text{nm}$ was atomically clean. Electron emission from the tip then happened preferentially from the two low-work function planes {310}, which span an angle of $26.6^\circ$ with the tip axis, Fig. 6(a). This allows the measurement of the magnification of the tip surface on the detector by determining the distance between the two electron beamlets. Figs. 6(b)–6(e) depict
field emission patterns for various tip voltages \( V_{\text{tip}} \). The extractor anode, which would otherwise clip the electron beam, was removed for these measurements and the whole emission pattern can be observed at a grounded microchannel plate detector placed 72 mm away from the tip. For each of the four tip voltages \( V_{\text{tip}} \), the suppressor voltage \( V_s \) was adjusted to yield a tip field slightly above field-emission threshold. Increasing the magnitude of \( V_{\text{tip}} \) and \( V_s \) then increases the approximately homogeneous field between suppressor and detector. This leads to the observed focusing of the emitted electron beam (Figs. 6(b)–6(e)).

Fig. 6(f) compares the distances between the experimental emission spots with results from the particle tracking simulations. The excellent agreement indicates that our simulation results, including the values derived for the pulse duration, are trustworthy. The observed narrowing of the electron beam at higher \( V_{\text{tip}} \) additionally confirms that a reduction of path length differences for off-axis rays is possible by placing the tip in a plate-capacitor setup.

Experiment and simulations can also be compared by extracting the experimental values of \( R \) and \( D \) from the numerical simulations. This is done by adjusting the model geometry so that it reproduces a tip field of \( F_{\text{tip}} = 2 \) GV/m for all experimental voltage settings. For another tip mounted in the setup the values for \( R \) and \( D \) (\( R_{\text{sim}} = 215 \) nm, \( D_{\text{sim}} = 584 \) μm) obtained in this way agree well with scanning electron microscope measurements of the tip and optical measurements of the electrode setup removed from vacuum (\( R_{\text{exp}} = 200 \pm 30 \) nm, \( D_{\text{exp}} \approx 560 \) μm). This further corroborates the validity of our pulse duration calculations and also confirms that the assumed \( F_{\text{tip}} = 2 \) GV/m at field emission threshold is correct.

VIII. FEMTOSECOND OPERATION

The setup of Fig. 4 was successfully run in femtosecond-laser triggered operation with an [110]-oriented tip (cf. DC emission spots in Fig. 6). We used laser pulses from a titanium:sapphire oscillator (~800 nm central wavelength, ~10 fs pulse duration, 80 MHz repetition rate), which were focused to a waist radius of 8.5 μm (1/e² intensity) at the tip, yielding a peak intensity of \( I_{\text{peak}} = 1 \times 10^{11} \) W/cm². The setup was operated at \( V_{\text{tip}} = -8.00 \) kV and \( V_s = -8.25 \) kV, corresponding to \( F_{\text{tip}} = 1.6 \) GV/m. The quadratic dependence of the photocurrent on the laser intensity, shown in Fig. 6(g), indicates a two-photon emission process, as expected for a mean photon energy of about 1.55 eV and an effective reduction of the work function of tungsten (4.35 eV) by 1.5 eV due to the Schottky effect. The average number of electrons per pulse at the detector was \( 1.4 \times 10^4 \). The main reason for the low electron number in these measurements was the use of a tip in [110]-orientation. Therefore, the extractor anode clipped most of the emitted electrons that propagated predominantly in off-axis directions (cf. Figs. 6(b)–6(e)).

This will be avoided in future laser-triggered experiments by using a tip in [310]-orientation, where emission is centered around the tip axis. Fig. 7 shows DC field-emission patterns from such a tip in the experimental setup of Fig. 4, again with the extractor electrode removed to record all emitted electrons. We conclude from the emission patterns that about 7% of the emitted electrons will be transmitted when limiting the beam to a maximum emission angle of \( \theta_{\text{max}} = 5° \), which should produce a pulse duration of \( \tau = 9 \) fs (21 fs FWHM) at the gun exit. In a different experiment but using the same laser system, we have observed a maximum electron current of 2000 electrons per pulse in stable emission from a [310]-oriented tip. A current of one electron per pulse at the

FIG. 6. Experimental performance of the tip-based electron gun. (a) Top view of a ball model of the crystal structure at the tip apex. The color encodes the relative distance of the tip surface from the surface of an idealized, hemispherical tip apex. The position of the two low-work-function planes (310) and (130), which predominantly emit electrons in field emission, is highlighted. (b)–(e) Field emission patterns for various voltage combinations \( V_{\text{tip}} \) and \( V_s \), measured 72 mm behind the tip. The position of the beamlets that originate from the (310) planes is indicated by black circles. Here, the kinetic energy is not fixed at 30 keV but given by \( eV_{\text{tip}} \). The color scale is linear (blue smallest, red highest count rate); no background is subtracted. (f) Comparison of the distance between the (310) emission spots on the screen (crosses) to that obtained from particle tracking simulation (circles), for a tip with \( R = 50 \) nm and \( D = 0.75 \) mm. (g) Laser-triggered electron emission: Dependence of electron current on the incident laser power together with a quadratic fit.

FIG. 7. DC field emission from the setup of Fig. 4, equipped with a tip in [310]-orientation. To detect all electrons, the extractor anode has been removed for these measurements and the electrons are directly accelerated towards the MCP detector. (a) Field emission originates predominantly from the (310)–site at the tip apex, leading to a well defined, central electron beam. Comparing the size of the emission pattern for tip and suppressor voltages of \( V_{\text{tip}} = -294 \) V and \( V_s = 0 \) V in (a) and \( V_{\text{tip}} = -26 \) kV and \( V_s = -27 \) kV in (b) again illustrates the focusing of the beam due to the larger absolute value of \( V_s \) in (b). The color scale is linear (blue smallest, red highest count rate); no background is subtracted. The white areas are due to damaged channels of the MCP detector.
source translates into 0.02 electrons per pulse at the sample. This would allow the acquisition of a time-resolved diffraction snapshot within minutes using a MHz laser system. It is likely that the high acceleration field at the tip will allow using few-electron instead of single-electron pulses without compromising the pulse duration too much. This would make the effective flux of the source comparable to flat single-electron emitters.\textsuperscript{6,22}

The shortness of the electron pulse duration at the sample can be measured by optical streaking.\textsuperscript{55} If the streaking laser is swept over the electron beam profile, it should be also possible to determine and optimize the residual phase front curvature partially compensated by the magnetic lens arrangement.

**IX. SUMMARY AND CONCLUSION**

We have presented the concept of a tip-based, pulsed electron source that may find various applications in time-resolved electron diffraction and microscopy experiments. In addition, it may serve as a source of future electron accelerator devices. The use of a point-like electron emitter promises a large transverse coherence of the electron beam and a rapid acceleration of emitted electrons in the large electric field at the tip apex. The latter helps to minimize pulse broadening due to an initial velocity spread of the electrons and thus yields a reduced pulse duration compared to flat cathode designs. A beam emittance in the (sub-)nanometer range is realistic.

For a 5\textdegree{} beam acceptance and an initial electron energy width of $\sigma_E = 0.25$ eV, a pulse duration of $\sigma_t = 9$ fs standard deviation (21 fs FWHM) directly at the gun exit is expected. The further broadening of the electron pulse between gun and sample can be reduced by collimating the beam with a well-designed electrostatic or magnetic lens behind the gun exit. The remaining broadening is entirely governed by the differences in absolute velocities that originate from the initial kinetic energy spread. A pulse duration of $\sigma_t = 17$ fs (41 fs FWHM) at a sample placed 250 mm from the lens will be feasible. First laser-triggered operation of the gun has also been demonstrated. In the near future, we plan to attach our source to an existing single-electron diffraction beamline\textsuperscript{56} and to an existing dielectric laser acceleration experiment.\textsuperscript{38,57}

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