Numerical simulation of attosecond nanoplasmonic streaking

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Abstract. The characterization of the temporal profile of plasmonic fields is important both from the fundamental point of view and for potential applications in ultrafast nanoplasmonics. It has been proposed by Stockman et al (2007 Nat. Photonics 1 539) that the plasmonic electric field can be directly measured by the attosecond streaking technique; however, streaking from nanoplasmonic fields differs from streaking in the gas phase because of the field localization on the nanoscale. To understand streaking in this new regime, we have performed numerical simulations of attosecond streaking from fields localized in nanoantennas. In this paper, we present simulated streaked spectra for realistic experimental conditions and discuss the plasmonic field reconstruction from these spectra. We show that under certain circumstances when spatial averaging is included, a robust electric field reconstruction is possible.
1. Introduction

Attosecond science and nanoplasmonics are two rapidly evolving fields that involve a large number of phenomena and have an impact on many other areas of science and technology beyond fundamental physics. Attosecond science based on high harmonic generation \cite{1,2} investigates ultrafast phenomena in matter and includes areas such as production of single attosecond pulses \cite{3,4}, capturing the electron dynamics in atoms on a sub-femtosecond time scale \cite{5–7} and the probing of the molecular structure and dynamics \cite{8–10}. Nanoplasmonics is the study of collective electron excitations at metal surfaces and nanostructures, where the electromagnetic fields can be confined on the nanometre scale. The enhanced localized nanoplasmonic fields can be used for the guiding of light \cite{11,12}, for spectroscopy and biological sensing \cite{13–15}, for the control of light–matter coupling \cite{16} and for the generation of high harmonics from gas using the direct output of a short-pulse laser oscillator \cite{17}.

The nanoplasmonic fields can decay on a few-femtosecond temporal scale \cite{18}, and characterizing their temporal profile, which is generally different from the temporal profile of the exciting laser pulse, is crucial for understanding the high harmonic generation by the plasmonic enhancement process and other nanoplasmonic enhanced ultrafast phenomena. Nanoplasmonic fields can be measured by combining nano- and atto-science, as proposed by Stockman et al \cite{18}, who suggested exploiting the attosecond resolution of the streaking technique \cite{3,19,20} with the nanometre spatial resolution of the photoelectron emission microscope (PEEM) \cite{21,22}. In the experiment proposed by Stockman et al \cite{18}, electrons are ionized from a plasmonic nanostructure by the attosecond extreme ultraviolet (XUV) pulse and then accelerated by the local plasmonic field excited by a few-cycle laser pulse at nanometre-size ‘hot spots’ on the surface. Electrons are detected with an energy-resolving PEEM as a function of the time delay between the XUV pulse and the laser pulse. Since the PEEM can image the photoelectron emission, a random nanostructure can be studied and the temporal evolution of the plasmonic field at different hot spots can be detected. Compared to indirect methods based on autocorrelation previously used for characterizing the plasmonic fields \cite{22–25}, streaking offers direct access to the plasmonic electric field.

To study the local fields of the nanoantennas that have been used to generate high harmonics using the laser oscillator \cite{17}, the spatial resolution of PEEM is not needed because the photoelectron signal is a sum of signals originating from an array of identical
antennas, and a time-of-flight (TOF) detection can be employed. Moreover, for applications such as high harmonic generation by plasmonic field enhancement, a high degree of uniformity and reproducibility of the antenna array is needed. The typical size of the nanoantennas is 50–100 nm with field-enhanced regions in the gaps of the order of 10–50 nm, which is considerably larger than the spatial extent of hot spots (∼1 nm) in the experiment proposed by Stockman et al [18]. The electron escape time from the antennas is typically considerably longer than the laser period and, as we show, the regime of streaking from the antennas is between the standard oscillatory regime known from the gas phase experiments [3, 19, 20] and the instantaneous regime from a plasmonic nanosystem [18]. A numerical analysis is therefore needed in order to predict the streaked photoelectron spectra from nanoantennas.

In this paper, we present a numerical simulation of the electron motion in nanoplasmonic fields in the gap between the antennas. We perform calculations for realistic experimental parameters of rectangular gold antennas on a sapphire substrate, organized in an array as shown in figure 1. We calculate the plasmonic fields by a finite-difference time-domain (FDTD) method and then solve the classical equation of motion of the electron in the plasmonic field for different time delays between the electron birth and the plasmonic pulse. We consider electrons ionized by the XUV pulse from gold. We use centre-of-mass analysis of the simulated streaked spectra to determine the plasmonic field, which is then compared with the field used for the calculation. We show that when spatial averaging of the initial electron position within the antenna is included, the plasmonic field can be reconstructed with high accuracy.

2. Simulations of streaking from enhanced nanoplasmonic fields

2.1. Two regimes of streaking

Attosecond streaking from nanoplasmonic fields differs from the standard streaking in the gas phase due to the field localization on a nanometre scale. Therefore, before presenting the results
of the numerical simulation, we briefly summarize the differences between ‘standard’ streaking and ‘instantaneous’ streaking.

As pointed out in [18], in the gas-phase streaking experiments, the electron ionized by the XUV pulse moves in the laser field until the laser pulse is over (figure 2(a)). The focal volume of the XUV pulse is smaller than the focal volume of the laser pulse; therefore, the electron experiences an approximately spatially uniform laser field. The electron escape time \( t_e \) from the focal volume is longer than the duration of the laser pulse. In this regime, referred to as the \textit{standard oscillatory regime}, the energy shift of the electron is determined by the value of the vector potential at the instant of the electron’s birth. The final electron velocity \( v_f \) is [20]

\[
\mathbf{v}_f = \mathbf{v}_0 + \frac{e}{m_e} \mathbf{A}(t_0),
\]

where \( \mathbf{v}_0 \) is the initial electron velocity at the time of birth \( t_0 \), \( e \) and \( m_e \) are the electron charge and mass, respectively, and \( \mathbf{A}(t_0) \) is the vector potential of the laser field at the electron’s time of birth.

A different situation occurs when the spatial extent of the field is so small (of the order of nanometres) that the electron leaves the field in a shorter time than the laser field period \( T \) (figure 2(b)). This is the \textit{regime of instantaneous emission} [18], defined by

\[
t_e \ll T,
\]

where \( t_e \) is the electron escape time from the enhanced field region. For an electron with an initial energy of \( \mathcal{E}_0 = 80 \) eV and a characteristic enhanced field dimension of 1 nm, the escape
time is $t_e = 190\text{ as}$, which is much smaller than the laser period of 2.7 fs, and therefore the streaking regime is effectively instantaneous. In the instantaneous regime the final electron energy $E_f(r, t_0)$ is related to the local electrostatic potential $\phi(r, t_0)$ at the electron’s time and place of birth by [18]

$$E_f(r, t_0) = E_0 + e\phi(r, t_0).$$

In this regime, the electron energy does not oscillate as the electron moves in the electric field, but the electron is rather ‘kicked’ by the instantaneous value of the plasmonic field.

An intermediate situation occurs in nanoantennas with a typical gap size of $\approx 30\text{ nm}$. In this case, the electron escape time is $t_e \approx 5.7\text{ fs}$, which is longer than the laser period but typically shorter than the duration of the excited plasmonic field. Consequently, the streaking regime lies between the instantaneous and the oscillatory regimes. Streaking in this intermediate regime is not amenable to a simple analytical form and will be simulated in section 2.3 by numerical integration of the electron’s equation of motion in the nanoplasmonic field.

### 2.2. Plasmonic field calculations

For the simulation of nanoplasmonic streaking in the intermediate regime, we consider an array of gold rectangular antennas placed on a sapphire substrate. The geometry and coordinates are defined in figure 1. To design antennas with resonance at 800 nm and to simulate the time-dependent plasmonic field, we used Lumerical FDTD solutions, a proprietary software implementing the FDTD method. Three-dimensional simulations were performed in the time domain with perfect-matched-layer boundary conditions, and non-uniform adaptive meshes were used in order to model accurately the antenna gap area with a mesh size of 1 nm. The total simulation time was 400 fs with a time step of 0.953 as. The convergence of the numerical calculations with respect to the mesh size and the total simulation area was checked. The optical response of gold was modelled through the fit of Johnson and Christy [26] experimental data by multi-coefficient models within the wavelength range of 600–1000 nm. The dimensions of the antennas with the resonance centred at 800 nm were calculated to be the following: height $h = 40\text{ nm}$, gap width $w = 30\text{ nm}$, length of the antenna $L = 100\text{ nm}$ and width of the antenna in the $y$-direction $l = 60\text{ nm}$.

To calculate the time-dependent plasmonic field, an incident pulse polarized in the $x$-direction with a Gaussian temporal profile, a duration of 5 fs and field amplitude normalized to 1 was used in the FDTD simulation. The actual field strength for the simulation of streaking will be specified later. The calculated plasmonic field strength is normalized to the incident field. We assume that the time dependence of the plasmonic field is the same at all points in space and we decompose the total plasmonic field $E(x, z, t)$ into its spatial and temporal components: $E(x, z, t) = E(x, z)E(t)$. This assumption, supported by our FDTD simulations, is needed for the reconstruction of the electric field from the streaking process, where only one time-dependent field $E(t)$ is retrieved. Note that the XUV pulse in the streaking experiment does not affect the plasmonic field because of its high photon energy far from the resonance, and is not simulated by the FDTD method.

The spatial profile of the $x$-component of the plasmonic field $E_x(x, z)$, shown in figure 3(a), varies across the gap, with the maximum field enhancement of approximately a factor of 12 near the corner of the gold antenna. The spatially averaged enhancement in the gap region is about a factor of 6 and the field is approximately uniform in the gap. The calculated time-dependent
Figure 3. (a) Calculated plasmonic field $E_x(x, z)$ in the gap between the antennas at time 17.4 fs corresponding to maximum enhancement. (b) Temporal profile of the incident laser field (black line) and the calculated plasmonic field $E_x(t)$ at the point $x = 10$ nm, $z = 0$ nm (blue line).

fields are shown in figure 3(b). The black line shows the incident field and the blue line shows the time-dependent plasmonic field $E_x(t)$ at the position $x = 10$ nm, $z = 0$ nm. The calculated plasmonic field is longer in duration than the incident field; it lasts for more than 10 fs after the incident pulse.

2.3. Classical simulation of nanoplasmonic attosecond streaking

In the streaking experiment, the attosecond XUV pulse ionizes an electron by a single-photon process and the electron is then streaked in the plasmonic field excited by the laser pulse (figure 4(a)). At the beginning of the streaking calculation (which is two-dimensional in the $xz$-plane), the electron is born at time $t_0$ at the initial position $(x_0, z_0)$ with an initial velocity $v_0$ at an angle $\alpha_0$ from the $z$-axis. The time $t_0$ is the delay between the birth of the electron and the plasmonic field $E(t)$, where the peak of the incident pulse is at time 15 fs; see figure 3(b). The initial position is chosen at the edge of the gold antenna ($x_0 = w/2$, $z_0 = 0 - h$). We consider ionization by an XUV pulse with a central photon energy of 90 eV and a Gaussian temporal profile with full-width at half-maximum (FWHM) duration of $\tau = 580$ as. A rather long XUV pulse duration (compared to the present state of the art [4]) is chosen in order to keep sufficient spectral resolution for a streaking measurement.

The initial electron velocity $v_0$ is determined by the single-photon ionization process by the 90 eV XUV pulse and is scanned through the initial photoelectron spectrum from gold, which contains contributions from several energy bands [27]. The photoelectron spectrum used for our calculations (figure 4(b)) was obtained from a spectrum measured with a narrow line source with a photon energy of 1487 eV, corrected for energy-dependent ionization cross-sections and a convolution with the spectral content of the XUV pulse. We have found, in our preliminary measurements, that the photoelectron signal from the dielectric substrate is considerably lower than that from gold; therefore, we do not consider the photoemission from sapphire.

The XUV pulse will ionize electrons from the whole sample regardless of the field enhancement. Therefore, there will be a large background signal of electrons ionized from
Figure 4. (a) Schematic diagram of streaking in nanoantennas; the inset shows the time-dependent fields. The incident laser pulse excites the plasmonic field in the gap that has a longer duration. The XUV pulse ionizes an electron that is then streaked in the plasmonic field. The end of streaking (marked by crosses) is either when the electron leaves the gap or at the end of the plasmonic pulse, whichever is earlier. (b) The photoelectron spectrum from gold used for the calculation.

Once the electron is born its equation of motion in the plasmonic field is numerically solved. The trajectory of the electron is numerically integrated with a leapfrog algorithm with a time step of 48 as. The field that enters the equation of motion is the plasmonic field calculated by the FDTD method. The electric field strength of the incident laser pulse is taken to be $1.03 \times 10^9$ V m$^{-1}$ (corresponding to an intensity of $1.4 \times 10^{11}$ W cm$^{-2}$) and is enhanced in the gap as shown in figure 3(a). The calculation finishes when the plasmonic pulse ends or when the electron hits the gold antenna or when the electron leaves the region of the nanoplasmonic field. For this calculation, the end of the plasmonic pulse occurs when the field strength drops to 0.005 of its maximal value (which is at time $\sim 45$ fs).

To simulate the streaked spectrum that will be detected by the spectrometer, we consider an ensemble of electrons with initial energy distribution given by the initial photoelectron spectrum and we record the final electron velocity $v_f$ at the end of the simulation. A TOF detector with acceptance half-angle $\Delta \theta = 1^\circ$ is placed at an angle $\theta_0 = 20^\circ$ from the $z$-axis. The TOF detector has to be placed at an angle from the laser polarization in order to detect electrons that leave the gap and do not hit the antenna. This geometry slightly reduces the modulation of the final electron energy compared with detection parallel to the direction of the field polarization. If the direction of the final electron velocity is towards the TOF, i.e. if $\tan(\theta_0 - \Delta \theta) \leq v_{fx}/v_{fz} \leq \tan(\theta_0 + \Delta \theta)$, the electron is detected and contributes to the final streaked spectrum with a weight given by its initial spectrum. Because the relationship between the initial and the final electron direction is not known in advance, we perform calculations for
Figure 5. (a) Calculated trajectories of electrons with an initial energy of 80 eV born at times \( t_0 = 10 \) fs (solid line) and \( t_0 = 18 \) fs (dotted line). Initial electron position: \( x_0 = 14 \) nm, \( z_0 = 2 \) nm; initial angle: \( \alpha_0 = 35^\circ \); incident field intensity: \( 1.4 \times 10^{11} \) W cm\(^{-2}\). (b) Calculated time-dependent energies of an 80 eV electron for the same conditions as in (a). (c) Calculated time-dependent energies of an electron with an initial energy of 14 eV. Other conditions are the same as in (a, b).

a range of initial electron angles \( \alpha_0 \) and count only electrons that are detected. The distribution of the initial angles \( \alpha_0 \) is assumed to be isotropic.

So far, we considered only electrons ionized at a single time \( t_0 \) and did not take into account the effect of the XUV pulse duration on the final streaked spectrum. The XUV pulse duration is included in the calculation by weighting over a distribution of times of births; that is, at a given time delay \( t_0 \), the number \( N_\tau(t_0) \) of detected streaked electrons is given by

\[
N_\tau(t_0) = \sum_{t_j = -1.5\tau}^{1.5\tau} N(t_0 + t_j) I_{XUV}(t_j),
\]

where \( N(t_0 + t_j) \) is the number of detected electrons at time \( t_0 + t_j \), \( I_{XUV}(t_j) \) is the normalized intensity envelope of the XUV pulse and the index \( t_j \) runs through the duration of the XUV pulse \((-1.5\tau < t_j < 1.5\tau, \) where \( \tau \) is the FWHM duration of the XUV pulse). In this way, the number of streaked electrons at a given delay \( t_0 \) includes the contributions of streaked electrons at times around \( t_0 \) with a weight given by the intensity of the XUV pulse.

Finally, the detected streaked spectra were averaged over the initial electron z-position at the edge of the antenna.

2.4. Simulation results

To gain insights into the streaking from localized fields, we first examine trajectories of individual electrons in the gap between antennas. Figure 5(a) shows trajectories of electrons with an initial energy of 80 eV and initial angle \( \alpha_0 = 35^\circ \) ionized at two different times, \( t_0 = 10 \) and 18 fs, respectively. An electron with this energy can come from the valence band of

\[
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\]
gold irradiated by our 90 eV attosecond pulse. One can see that the plasmonic field does not significantly affect the direction of the electrons. The electron trajectory is slightly modulated mainly for the electron born at 10 fs.

More information can be obtained from time-dependent electron energies, shown in figure 5(b) for the same conditions as in figure 5(a). The streaking regime is not instantaneous and the electron energy is modulated as the electron propagates in the plasmonic field. The situation is also different from the standard gas phase streaking because the modulation of the electron energy does not go to zero with time, when the electron leaves the enhanced field in the gap before the end of the plasmonic pulse. When the electron is born early ($t_0 = 10$ fs; solid line) it will leave the enhanced field region before the end of the plasmonic pulse (at time 21 fs), and there is no direct relationship between the final and the initial electron energy. Electrons born at longer delays ($t_0 = 18$ fs; dotted line) leave the field at later times, in this case at 29 fs. At this time (29 fs) the plasmonic field is already small (see figure 3(b)), and the amplitude of the electron energy oscillation is low. Therefore, the standard oscillatory regime of streaking is being approached.

For comparison, figure 5(c) shows the time-dependent energies of a slower electron with an initial energy of 14 eV, which might originate in inner shells of the substrate (other conditions are the same as those for the 80 eV electron). In this case, the electrons spend a longer time in the enhanced region because they are slower. For both times of birth shown, the oscillation amplitude of the electron energy goes down with time. Therefore, the regime of streaking is almost the standard regime. The energy of the electron born at $t_0 = 10$ fs (which is at the peak of the field) oscillates and the final energy is roughly the same as the initial energy (14 eV) because the vector potential at the time of birth is zero. The energy of the electron born at 18 fs, which corresponds to the zero value of the field, and therefore a maximum of the vector potential, is shifted to a final value of 12 eV.

One can see that electrons born early in the pulse ($t_0 \lesssim 15$ fs in our case) are streaked in the intermediate regime. For electrons born later, the regime approaches the standard oscillatory regime, because the electrons leave the enhanced field region towards the end of the plasmonic pulse. Furthermore, the streaking regime depends on the electron initial energy. Electrons with a low initial energy spend a longer time in the region of enhanced field and therefore the oscillatory regime is approached at shorter delays. However, the modulation of the electron energy is lower for slower electrons [19, 20].

We now turn to a simulation of the streaked spectra from which the plasmonic field can be reconstructed. Figure 6(a) shows the simulated streaked spectra from gold with electrons originating at a single position at the face of the antenna ($x_0 = 15$ nm, $z_0 = 23$ nm). The final electron energy is modulated and contributions from the valence band (energies around 80 eV) and the 5p band (energies around 30 eV) can be recognized. There are oscillations in the electron energy in the simulated spectra for short time delays (< 10 fs), resulting from the fact that the electron leaves the enhanced field region before the end of the plasmonic pulse. These ‘ghost’ oscillations, which are a consequence of the intermediate regime, do not correspond to the full oscillations of the plasmonic field. The ghost oscillations at early delays are suppressed when the streaked spectra are averaged over the initial electron $z$-position, as shown in figure 6(b). Here, the initial position of the electron was varied in the range of $z_0 = 1$–39 nm and the initial $x$-position was kept at 15 nm. The oscillations at early times are smeared out because of different contributions of electrons born at different heights, and the simulated streaked spectra resemble the streaked spectra in the standard oscillatory regime.
3. Electric field reconstruction

The plasmonic field is reconstructed from the simulated streaked spectra by a centre-of-mass analysis [19]. For the analysis, we assume that the streaking is in the standard oscillatory regime and the final electron velocity is related to the vector potential of the field at the electron’s time of birth by (1). The assumption of the standard regime of streaking is justified by the fact that at later delays the standard regime is approached and even at early delays the spatially averaged streaked spectra closely resemble the standard streaked spectra. We now further assume that the plasmonic field has only an x-component and the angle between the initial electron velocity and the polarization direction is $\theta_0$. Taking the square of (1) and solving for $A$ yields

$$A(t_0) = \frac{\sqrt{2m_e}}{e} \left( \sqrt{E_f(t_0)} - E_0 \cos^2 \theta_0 - \sqrt{E_0} \sin \theta_0 \right),$$

where $E_f = m_e v_f^2 / 2$ is the final electron energy which is obtained by calculating the centre of mass of the streaked electron spectra

$$E_f = \frac{\sum E N(E)}{\sum N(E)},$$

where $N(E)$ is the number of electrons with the final energy $E$ and the summation is performed over the valence energy band of gold. The plasmonic electric field is then obtained by differentiating the vector potential (5) with respect to time $t_0$ and will be compared with the plasmonic field used for the calculation (figure 3(b)).

To quantify the accuracy of the electric field reconstruction, we use a root mean square (rms) field error defined by [28]

$$\varepsilon = \left( \int_{-\infty}^{+\infty} |E_1(t) - E_2(t)|^2 \, dt \right)^{1/2},$$

where $E_1(t)$ and $E_2(t)$ are the two normalized complex electric fields to be compared. A value of $\varepsilon = 0$ corresponds to a perfect reconstruction; larger values of $\varepsilon$ corresponds to less agreement between the two fields. The maximum value of $\varepsilon$ for normalized fields is 2, which corresponds to fields that differ only in sign ($E_1 = -E_2$).
Figure 7. (a, c) Centre of mass of the final electron energy as a function of the
time delay, for the streaked spectra from gold integrated over the energy range
60–110 eV. (b, d) Reconstructed electric field (red) compared with the original
field (black). (a, b) The single-electron initial position $x_0 = 15 \text{ nm}$, $z_0 = 23 \text{ nm}$.
(c, d) Initial electron position averaged over the $z$-dimension.

Figure 7(a) shows the centre of mass of the final electron energy (6) as a function of the
delay between the XUV pulse and the plasmonic pulse for the streaked spectra from gold for
a single initial electron position. To calculate the centre of mass, the spectra were integrated
over the energy range 60–110 eV. There are ghost oscillations in the centre of mass at early
delays, which will present a problem for the electric field reconstruction. These oscillations are
suppressed when the simulated spectra are averaged over the initial electron
$z$-position, as can be seen from figure 7(c). This is due to the different contributions of electrons born at different
heights.

The plasmonic electric field is reconstructed from the oscillations in the centre of mass by
differentiating (5). Both the reconstructed field and the original field used for the calculation are
shown in figures 7(b) and (d). The original field is normalized to have the same maximum as the
reconstructed field in order to facilitate a comparison of the temporal profile. The amplitude
reconstruction will be addressed later. For the single initial electron position (figure 7(b)),
the falling edge of the plasmonic pulse is reconstructed well, but there are ghost oscillations
at the beginning of the pulse and the rms field error is $\varepsilon = 0.27$, indicating a rather poor
reconstruction. When averaging over the initial electron $z$-position is included (figure 7(d)),
the ghost oscillations are reduced and the field is reconstructed with good accuracy ($\varepsilon = 0.10$).
Although the regime of streaking is intermediate and the spectrum is broad, the spatial averaging
of the initial electron position helps to remove the ghost oscillations at early delays and the
reconstructed field follows in time the original field.

The amplitude of the reconstructed electric field in figure 7(d) is $3.2 \times 10^9 \text{ V m}^{-1}$, which
is a factor of 3 larger than the amplitude of the incident laser pulse. A larger field amplitude is
expected as the plasmonic field inside the gap is about six times as much as the incident field.
In the case of broad spectra from gold, the reconstructed field amplitude depends on the choice
of energies used for calculating the centre of mass and varies between enhancement factors of
2 and 6. The magnitude of the reconstructed field also decreases as the XUV pulse duration is
increased and would be larger for shorter XUV pulses.
4. Summary and conclusions

We have numerically analysed attosecond streaking from gold nanoantennas on sapphire. The regime of streaking from the antennas is between the standard oscillatory regime and the instantaneous regime and depends on the electron energy and dimensions of the antennas. For the investigated case, the regime is closer to the standard oscillatory regime. However, for early time delays, the resulting streaked spectra from antennas can contain ghost oscillations because of the electron leaving the enhanced field region before the end of the plasmonic pulse. These oscillations do not follow the plasmonic electric field. When spatial averaging of the initial electron $z$-position is included in the calculation, the ghost oscillations can be reduced and the field can be reliably reconstructed. The spatial averaging will be automatically present in an experiment; therefore, the measured streaked spectra from nanoantennas are expected to be very similar to streaked spectra in the standard oscillatory regime.

The plasmonic field can be retrieved from the streaked spectra by a centre-of-mass analysis, which reconstructs well the temporal profile, but the amplitude can be slightly underestimated. For electrons from gold, the spurious oscillations at early delays are suppressed by spatial averaging and the rms field error is $\varepsilon = 0.10$, indicating a rather reliable reconstruction. One can see that although the regime of streaking is intermediate because of the finite dimensions of the enhanced field, field reconstruction should be possible and experiments are feasible to determine the plasmonic field.

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