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New Computer Modeling and Experimental Results on a Photoelectron Gun with Time-Dependent Electric Field

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Abstract—The paper elucidates some new computer modeling and experimental results on the design of a photoelectron gun with time-dependent electric field. The main essence of the new approach is based on the fact that the properly chosen electric field ramp ensures first–order temporal focusing of photoelectron bunch, which is principally impossible in static field previously used. This new technology allows a real breakthrough in time resolution of photoelectron guns and diffractometers intended for time-resolved electron diffraction experiments (TRED).

Key words: time resolved electron diffraction, electron bunch compression, temporal aberrations, ultrashort electron bunch, photoelectron gun.

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1. INTRODUCTION

Here we consider the problems of generating short enough electron bunches for the needs of time-resolved electron diffraction (TRED) technique which represents one of the most exciting and promising areas of the modern micro-world physics and technology. The TRED technique was proposed [1–4] to experimentally study physical and chemical transitions in solids and gases as responses to femtosecond laser excitation. The femtosecond laser pulse is divided into two fractions by a semitransparent mirror. One fraction excites the sample under investigation while the other one illuminates photocathode, thus giving birth to photoelectron bunch which, in turn, also hits the sample with a certain time delay. The electrons experience diffraction upon the crystalline lattice or separate gaseous-state molecules, so that the resultant diffraction pattern contains direct information as to physical state of the sample at a time moment being posterior to the laser excitation. In such experiments the electron bunch plays the role of a probe and therefore should be made as short as possible to ensure best temporal resolution.

It is well known that the limiting electron bunch duration in the nowadays time-analyzing photoelectron tubes operating with static electromagnetic field is mainly restricted by the first–order temporal chromatic aberration, which according to the Zavoisky–Fanchenko law [5]

$$\delta T \approx \frac{\sqrt{2m}}{eE_0}\sqrt{\delta\varepsilon_n}, \tag{1}$$

is directly proportional to the square root of the normal component of the photoelectron initial energy spread $\delta\varepsilon_n$ and inversely proportional to the electric field intensity E_0 nearby the photocathode (m and e are, respectively, the mass and charge of electron). During about 60 years, since the first Courtney-Pratt's time-analyzing image converter tube (according to the modern terminology—the streak image tube) was invented [6], the increase of field intensity nearby the photocathode has always been employed by researchers as the main way to diminish the first–order temporal chromatic aberration. As a result, temporal resolution of the most advanced streak cameras presented at the modern market constitutes about 200 fs, with the field intensity at the photocathode raised up as high as to 20 kV/mm and even more. The up-to-date situation is that electrical breakdown limitations make rather problematic a somewhat significant improvement of this result.

As we have shown in [7], the use of time-dependent electric field instead of static one can ensure temporal focusing of electron bunches at the sample. This fact is quite similar to spatial focusing of electron bunches in electron-optical devices employing spatially inhomogeneous electric fields. It is of profound importance that temporal focusing allows complete elimination of the first–order temporal chromatic aberration and, at the same time, does not impose any ultra-high constraints upon the electric field in the near-cathode region. This new approach allows a real breakthrough in time resolution of photoelectron guns and diffractometers intended for TRED experiments. It was further developed in [8–12], where we have proposed to use a special electrode biased with a quasi-linear potential ramp. An alternative approach based on the use of a cylindrical resonator was proposed in [13].

Basically, the temporal focusing principle is similar to that being employed for re-grouping electrons in klystrons. The time-depending electric field, in contrast to the static one, introduces a certain extra energy spread into the bunch, and, as a result, the particles located at the bunch' tail start to move faster compared to those located at the bunch' head. After some time of traveling inside the photoelectron gun, during which the bunch is being also spatially focused, the rear electrons overtake the front ones. This very moment determines the point of temporal focusing at which the electron probe duration becomes minimal and where the sample has to be located.

In order to describe the focusing effect mathematically, we introduce the temporal aberrations as the coefficients in the Taylor's expansion

$$T(z, \tau, \varepsilon_n, \varepsilon_t) = T_0(z) + [T|\tau]\tau + [T|\varepsilon_n^{1/2}]\varepsilon_n^{1/2} + \frac{1}{2}([T|\tau\varepsilon_n^{1/2}]\tau\varepsilon_n^{1/2} + [T|\varepsilon_n]\varepsilon_n + [T|\varepsilon_t]\varepsilon_t) + \ldots, \tag{2}$$

where $T(z, \tau, \varepsilon_n, \varepsilon_t)$ is the time moment at which the electron having left the photocathode at the initial time moment τ with axial and tangential energy components ε_n and ε_t, correspondingly, arrives at the plane $z =$ const. Similar expansion can be introduced for electron full energy

$$E(z, \tau, \varepsilon_n, \varepsilon_t) = [E|\tau]\tau + [E|\varepsilon_n^{1/2}]\varepsilon_n^{1/2} + \frac{1}{2}[E|\varepsilon_n]\varepsilon_n + \ldots. \tag{3}$$

In general case, the aberrational coefficients in square brackets are the functions of the axial coordinate z. Important theoretical result obtained in [7] is that the two first–order coefficients $[T|\varepsilon_n^{1/2}]$, $[T|\tau]$, mainly contributing the temporal broadening of electron bunch, turn to be proportional in any electromagnetic field:

$$[T|\varepsilon_n^{1/2}] = -\lambda[T|\tau], \quad \lambda = \frac{\sqrt{2m}}{eE_0}. \tag{4}$$

Obviously, the case of stationary electric field trivially gives $[T|\tau] \equiv 1$ and brings us back to the well-known Zavoisky–Fanchenko formula (1). In contrary, as it was shown in [8, 9], the multitude of time-depending electric fields (in particular, linear ramps) make it possible to simultaneously "kill" the coefficients $[T|\varepsilon_n^{1/2}]$ and $[T|\tau]$, and thus ensure the ideal (first–order) temporal focusing of the bunch at the sample.

The following pair of linear differential equations describes joint evolution of the first–order temporal and energy aberrational coefficients:

$$\frac{d}{dz}[T|\tau] = -\frac{\sqrt{m}}{(2W)^{3/2}}[E|\tau], \tag{5}$$

$$\frac{d}{dz}[E|\tau] \approx e\frac{\partial^2\Phi}{\partial t\partial z}[T|\tau] - \frac{4\pi e^2}{S(z)}J_0. \tag{6}$$

Here $\Phi(z, t)$ is time-dependent electric potential, W is average kinetic energy of electrons, J_0 is photoemission current, and $S(z)$ is local cross-section of the bunch. The initial conditions for (5) and (6) at the photocathode are obvious: $[T|\tau] = 1$, $[E|\tau] = 0$.

Again, one can see that in the case of static field the first term in the right part of (6) is zero and the space-charge repulsion, qualitatively described by the second term, can make the value $[E|\tau]$ negative. In turn, the equation (5) says that $[T|\tau] \geq 1$, so that the temporal focus can not exist. The situation is radically different

Fig. 1. General view of the photoelectron gun for electron bunch compressing.

with time-depending fields, when the first term in (6) may be intentionally chosen to compensate for the energy spread induced by the space-charge interaction and even make the coefficient $[E|\tau]$ positive. This fact leads to the principal possibility of the first–order temporal focusing.

Contribution of the second–order terms in (2) becomes most substantial at the point of temporal focusing where the first–order terms vanish. The Liouville theorem claims conservation of the phase volume in the time-energy coordinates, so that the functional determinant $D(T, E)/D(\tau, \varepsilon_n)$ is identically unit for any initial time moment τ and any initial energy ε_n. Having differentiated this equation with respect to $\varepsilon_n^{1/2}$, we obtain

$$[T|\tau]\{[E|\varepsilon_n] + \lambda[E|\tau\varepsilon_n^{1/2}]\} + [E|\tau]\{[T|\varepsilon_n] + \lambda[T|\tau\varepsilon_n^{1/2}]\} = -2. \tag{7}$$

To derive (7) we have used the proportionality condition (2) along with similar condition

$$[E|\varepsilon_n^{1/2}] = -\lambda[E|\tau]. \tag{8}$$

At the point of temporal focus $[T|\tau] = 0$, and (7) takes simpler form

$$[E|\tau]\{[T|\varepsilon_n] + \lambda[T|\tau\varepsilon_n^{1/2}]\} = -2, \tag{9}$$

which shows that (1) the full energy spread can not be made zero, and (2) the first–order and the second–order temporal aberrations can not vanish simultaneously. These two conclusions are closely connected with the quantum limitation of electron-bunch compression. Indeed, suppose that we have designed a photo-electron device with the second–order chromatic aberration given by the coefficient $[T|\varepsilon_n]$ being also eliminated.

The formulas (8) and (9) give $[E|\varepsilon_n^{1/2}] \times [T|\tau\varepsilon_n^{1/2}] = 2$, and for the product of energy and temporal spreads at the focal point we obtain

$$\delta E \times \delta T \approx [E|\varepsilon_n^{1/2}]\delta\varepsilon_n^{1/2} \times [T|\tau\varepsilon_n^{1/2}]\delta\tau\delta\varepsilon_n^{1/2} = 2\delta\tau\delta\varepsilon_n \geq 4\pi\hbar \tag{10}$$

since the initial temporal and energy spreads of the laser-induced electron bunch should meet the Heisenberg uncertainty correlation $\delta\tau\delta\varepsilon_n \geq 2\pi\hbar$.

2. COMPUTER MODELING AND EXPERIMENTAL RESULTS

In order to confirm the principal possibility of temporal focusing of photoelectron bunch with the use of time-depending electric fields, an experimental prototype of the photoelectron gun shown in Fig. 1 was simulated, designed, manufactured, and tested at the Photoelectronics Department of Prokhorov General Physics Institute, RAS. The first experimental results on the bunch compressing obtained with the use of this photoelectron gun were published in [14] Since that we have increased the high voltage change rate on the time-focusing electrode from 1.5 kV/ns to 2.8 kV/ns and the streak speed from 60 ps/25 mm to 30 ps/25 mm.

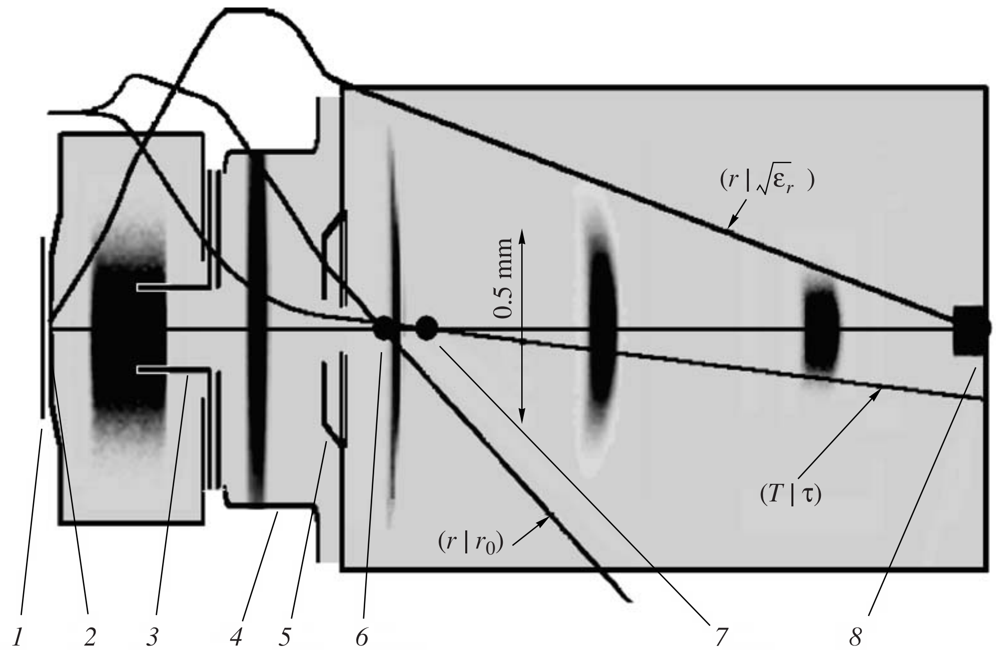

Fig. 2. Structural scheme of the photoelectron gun. *1*—photocathode, *2*—grid, *3*—compressing electrode, *4*—spatial focusing electrode, *5*—anode, *6*—the point of crossover, *7*—the point of temporal focus, *8*—image receiver (CCD). The electron distributions in different time moments are imposed (scaled-up with respect to the electrode dimensions).

The main aims of new experiments, some results of which are presented below, were, first, to confirm the "old" ones, and second, to advance at least a little further using the improved time-compressing electrodynamics and streak speed. As before, all calculations were made with ELIM/DYNAMICS [15] and MASIM 3D [16] software packages. The structural scheme of the photoelectron gun is shown in Fig. 2.

The picosecond laser illuminates a 1 mm × 0.05 mm slit-shaped area of the photocathode 1 and produces a photoelectron bunch which is then accelerated by the 3 kV/mm electric field in the gap between the photocathode and the fine-structure grid 2. Having passed through the grid, the electrons get into the area of the time-depending field governed by the electrode 3 which is supplied with electric voltage ramping from 0.9 kV to 1.9 kV during 350 ps. The ramp generator is synchronized with the laser pulse to ensure a controllable delay between the photoemission and ramp starting time moments. During the bunch' traveling in the time-depending field, the energies of the front and rear electrons become different, and, as shown in Fig. 2, the coefficient $[T|\tau]$ starts to decrease. Eventually, this coefficient, as well as $[T|\varepsilon_n^{1/2}]$, vanishes at the point of temporal focus 7 located in the field-free region downstream the anode 5. The electrode 4 serves to adjust spatial focusing of the electron bunch so that the image plane coincides with the position of CCD image receiver 8 whilst crossover 6 is located rather close to the point of temporal focusing.

The electrode voltages and switching moments have been found as result of numerical optimization and are presented in table. The two second-order temporal aberration coefficients at the temporal focus take the values $[T|\varepsilon_n] = -0.79$ ps/eV, $[T|\varepsilon_t] = 5.6$ ps/eV and determine the bunch compression limits.

The calculated values of voltages and times

Mesh voltage	3000 V
Initial voltage on the time-focusing electrode	960 V
Final voltage on the time-focusing electrode	1960 V
Start of the linear electric ramp	570 ps
End of the linear electric ramp	920 ps
Voltage of the electrode 5	2110 V
Anode voltage	9000 V

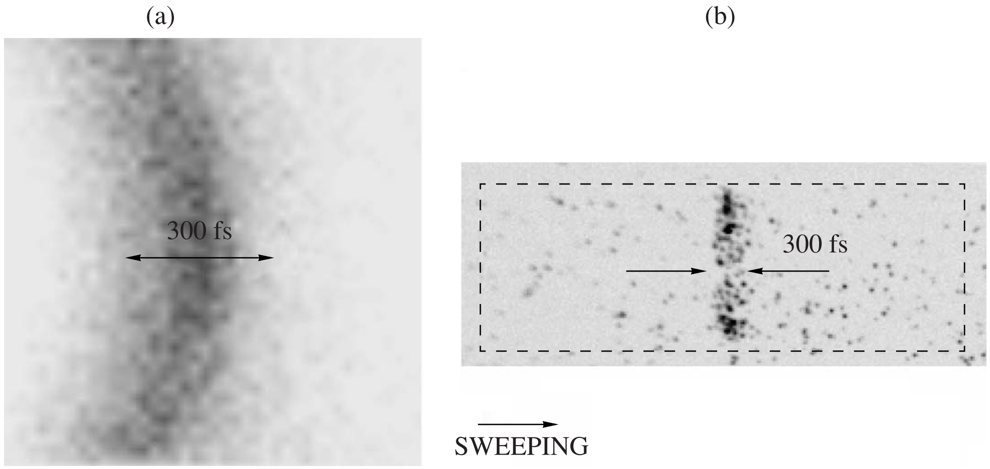

Fig. 3. The swept image of the electron bunch compressed down to 300 fs duration. (a) computer simulation, (b) experiment.

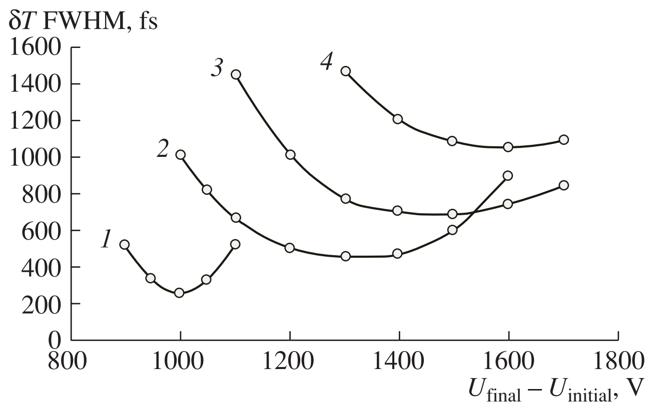

Fig. 4. Elynch temporal spread vs. the voltage ramp amplitude for different numbers N of electrons in the bunch: *1*—no space charge taken into account, *2*—$N = 1000$, *3*—$N = 2000$, *4*—$N = 3000$.

In order to measure the resultant bunch duration we used dynamic deflector placed hear the temporal focus, which sweeps the electron bunch across the image receiver plane with the velocity exceeding that of light by factor 3. The simulated and experimental swept images are shown in Fig. 3. With the initial duration of the laser pulse being $\delta\tau = 7$ ps, we achieve temporal compression down to 300 fs FWHM.

3. SPACE-CHARGE REPULSION SIMULATION

We have seen that the space-charge term in equation (6) may be, in principle, compensated by temporal compression in the time-depending field, which is obviously impossible in any static system. However more accurate computational analysis is needed to determine the residual space-charge effect on the bunch duration because of two factors which are not described by introducing the simplified term into equation (6). These factors are: (1) space-charge distribution non-homogeneity over the bunch cross-section and (2) the stochastic Boersch effect. In our computer simulations we used effective fractal method of Coulomb field calculation, which is close to the Barnes-Hut' approach [17] having been first proposed for numerical solution of the N-body problem in celestial mechanics. Accuracy of the method was essentially improved by taking into account dipole and quadrupole electric moments of the charged particle clouds.

Having calculated the bunch widening for different numbers of electrons constituting the bunch, we tried to compensate the effect of space-charge repulsion by increasing the voltage ramp amplitude. Figure 4 shows that, for a certain number of particles, one can find the optimal 'force' of the temporal lens to make the bunch as short as possible. For instance, the bunch of 1000 electrons is widened up to 1ps unless the compensation applied. However with the voltage ramp increased by approximately 300 V, the bunch duration rises only by 150 fs.

4. CONCLUSIONS

Briefly summarized, the main results of this work are as follows.

(1) Theoretical milestones of our studies on temporal compressing of photoelectron bunches with the use of time-depending electric field are elucidated and discussed.

(2) Recent experimental results on photoelectron bunch compressing with the use of the newly designed photoelectron tube with 2.8 kV/ns electric field ramp are presented and compared with the results of computer simulation.

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REFERENCES

1. Lobastov, V.A., Srinivasan, R., and Zewail, A.H., Four-Dimensional Ultrafast Electron Microscopy, *Proc. Nat. Acad. Sci. USA*, 2005, vol. 102, no. 20, pp. 7069–7073.
2. Siwick, B.J., Dwyer, J.R., Jordan, R.E., and Dwayne Miller, R.J., An Atomic-Level View of Melting Using Femtosecond Electron Diffraction, *Science*, 2003, vol. 302, pp. 1382–1385.
3. Siwick, B.J., Dwyer, J.R., Jordan, R.E., and Dwayne Miller, R.J., Femtosecond Electron Diffraction Studies of Strongly Driven Structural Phase Transitions, *Chemical Physics*, 2004, vol. 299, pp. 285–305.
4. Williamson, J.C., Dantus, M., Kim, S.B., and Zewail, A.H., Ultrafast Diffraction and Molecular Structure, *Chemical Physics Letters*, 1992, vol. 196, no. 6, pp. 529–534.
5. Zavoisky, E.K. and Fanchenko, S.D., Physical Basis of Electron-Optical Photography, *The Reports of USSR Academy of Sciences*, 1956, vol. 108, no. 2, pp. 218–221 [in Russian].
6. Courtney-Pratt, J.S., *Research*, 1949, vol. 2, p. 287.
7. Monastyrskiy, M.A., Andreev, S.V., Greenfield, D.E., Tarasov, V.A., and Schelev, M.Ya., Theoretical and Computer Study on the Possibility of Subfemtosecond (Attosecond) Temporal Focusing of Photoelectron Probing Bunches with Quasi-Stationary Electromagnetic Fields, *Proc. SPIE*, 2003, vol. 4948, pp. 305–310.
8. Andreev, S.V., Greenfield, D.E., Monastyrskiy, M.A., Tarasov, V.A., and Schelev, M.Ya., Formation of Sub-Femtosecohd Photoelectron Bunches in Time-Dependent Electric Field, *Proc. SPIE*, vol. 5398, pp. 1–15.
9. Monastyrskiy, M., Andreev, S., Greenfield, D., Bryukhnevich, G., Schelev, M., and Tarasov, V., Computer Modeling of a Subfemtosecond Photoelectron Gun with Time-Dependent Electric Field for TRED Experiments, *Proc. SPIE*, 2004, vol. 5580, pp. 324–334.
10. Andreev, S., Greenfield, D., Monastyrskiy, M., and Tarasov, V., Spatial and Temporal Focusing of Femtosecond Electron Bunches in Time-Dependent Electric Fields, *Nuclear Instruments and Methods in Physics Research, Series A*, 2006 (in press).
11. Greenfield, D., and Monastyrskiy, M., New Approach to the Problem of Coulomb Interaction in Electron and Ion Bunches, *Nuclear Instruments and Methods in Physics Research, Series A*, 2006 (in press).
12. Andreev, S., Greenfield, D., Degtyareva, V., Monastyrskiy, M., Tarasov, V., and Schelev, M., Computer Modeling of Image Intensifiers and Photoelectron Gun for Time-Resolved Electron Diffraction Experiments, *Proc. SPIE*, 2007, vol. 6636, no. 663601.
13. Fill, E., Veisz, L., Apolonski, and Krausz, F., Femtosecond Electron Gun for Diffraction Experiments, *Proc. SPIE*, 2006, vol. 6194, no. 61940J.
14. Andreev, S., Bryukhnevich, G., Greenfield, D., Lozovoi, V., Monastyrskiy, M., Schelev, M., Serdiuchenko, Yu., Tarasov, V., and Vorobiev, N., The Results of Computer and Experimental Studies on Compressing the Ultrashort Photoelectron Bunches with Time-Dependent Electric Fields, *Proc. SPIE*, 2007, vol. 6279, no. 627970.
15. Degtyareva, V.P., Monastyrskiy, M.A., Schelev, M.Ya., and Tarasov, V.A., Dynamics of Electron Bunches in Subpicosecond Streak Tubes, *Nuclear Instruments and Methods in Physics Research, Series X*, 1999, vol. A 427, pp. 225–229.
16. Monastyrskiy, M.A., Greenfield, D.E., and Tarasov, V.A., MASIM 3D Package for Precise CPO Calculations Based on Perturbation Technique, *Software Demonstrations Abstract Book* (‘CPO-7’ International Conference, Cambridge, UK, 2006), p. 23.
17. Barnes, J. and Hut, P., A Hierarchical O(N log N) Force-Calculation Algorithm, *Nature*, 1986, vol. 324, pp. 446–449.