From strong-field physics in and at nanoscale matter to photonics-based laser accelerators

Martin Kozák^{1,2}, Takuya Higuchi¹, Joshua McNeur¹, Roy Shiloh¹, Christian Heide¹, Timo Paschen¹, Peyman Yousefi¹, Constanze Sturm¹, Ang Li¹, Johannes Illmer¹, Stefan Meier¹, Norbert Schönenberger¹, Philip Dienstbier¹, Alexander Tafel¹, Philipp Weber¹, Robert Zimmermann¹, Michael Seidling¹, Anna Mittelbach¹, Jonas Heimerl¹, Timo Eckstein¹, Martin Hundhausen¹, Jürgen Ristein¹ and Peter Hommelhoff^{1,3,}*

¹Department of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstraße 1, D-91058 Erlangen, Germany, EU

²now with Faculty of Mathematics and Physics, Charles University, Ke Karlovu 3, 12116 Prague 2, Czech Republic, EU

³associated with Max Planck Institute for the Science of Light (MPL), Staudtstraße 2, D-91058 Erlangen, Germany, EU

Abstract. New ways of controlling quasi-free and free electrons by means of phase-controlled ultrashort laser pulses are demonstrated: from strong-field physics in the conducting 2-d material graphene and at the surface of nanostructures, to laser acceleration of free electrons with a nanophotonic structure, and the demonstration of the longitudinal Kapitza-Dirac effect.

Twenty-five years after the broad acceptance of the recollision picture in atomic strong-field physics [1, 2], introducing optical-field-driven control over electrons, a similar level of control has not long ago been introduced to solid matter. Until recently, research on electron dynamics inside of solids has been limited to dielectrics and semiconductors [3]. We have recently shown the transition from the weak-field to the strong-field regime in the conductor graphene, a 2-dimensional layer of carbon atoms. In the strong-field regime, we observe coherent electron dynamics and quantum path interference in the form of repeated Landau-Zener transitions, known as Landau-Zener-Stückelberg interferometry [4].

Strong-field physics at the surface of nanoscale structures has been demonstrated several years ago [5]. Quantum-path interference with a very high degree of coherence is demonstrated in photoemission from metal tips [6], as well as the tell-tale plateau structure, indicating electronic recollision, from nanoscale structures with other dimensionality.

In the second part of the talk we have discussed controlling electrons in free space with the help of two-colour laser fields and with the help of dielectric, nano-photonic structures. Two-colour laser fields impinging on an electron beam in a scanning electron microscope under two different angles allow us to generate an optical traveling wave co-propagating with the femtosecond electron bunch. This way, an efficient momentum transfer from the light field to the electrons can take place. We demonstrate an acceleration gradient of 2.2 GeV/m, which is one to two orders of magnitude larger than in modern particle accelerators [7]. This represents also a demonstration of the longitudinal version of the Kapitza-Dirac effect. We furthermore show that a pulse train with individual pulse durations shorter than 300 attoseconds results [8].

* Corresponding author: peter.hommelhoff@fau.de

With laser fields properly shaped by transparent nano-photonic structures, electrons in the optical near-field of these structures can be accelerated efficiently, and in great similarity to today's particle accelerators operating principle, namely with phase-synchronous acceleration, but here at optical frequencies. The proof-of-concept experiments have been performed several years ago [9]. We showed that we can not only accelerate with gradients approaching 1 GeV/m but also deflect, focus and streak electrons [10]. Thus, we have full control over a free-space electron beam with optical forces only and may now build a miniaturized particle accelerator composed of nano-photonic building blocks. This is what the Accelerator on a Chip International Program (ACHIP) is pursuing [11].

We acknowledge funding from the Gordon and Betty Moore Foundation (Accelerator on a Chip International Program), the European Research Council (Consolidator Grant Near Field Atto), the Deutsche Forschungsgemeinschaft (Collaborative Research Centre SFB953 Carbon Allotropes and Priority Program SPP1840 QUTIF), the Bundesministerium für Bildung und Forschung (05K16WEC),

References

1. K. J. Schafer, B. Yang, L. F. DiMauro, and K. C. Kulander, *Phys. Rev. Lett.* **70**, 1599 (1993), P. B. Corkum, *Phys. Rev. Lett.* **71**, 1994 (1993)
2. K. Schafer, M. Vrakking, Zhiyi Wei, eds., Special Issue “25 years of recollision physics”, *J. Phys. B: At. Mol. Opt. Phys.* **50**, 170201 (2017); P. Hommelhoff, M. Vrakking, Symposium “25 years of recollision physics”, DPG spring meeting, March 4 – 9, 2018, in Erlangen
3. S. Ghimire, DiChiara, A. D., Sistrunk, E., Agostini, P., DiMauro, Louis F., Reis, D. A. *Nat. Phys.* **7**, 138–141 (2011); T. Paasch-Colberget al., *Nature* **493**, 70–74 (2012); M. Schultze et al., *Science* **346**, 1348–1352 (2014); Vampa, G., Hammond, T. J., Thiré, N., Schmidt, B. E., Légaré, F., McDonald, C. R., Brabec, T., Corkum, P. B. *Nature* **522**, 462–464 (2015); Langer, F., et al., *Nature* **533**, 225–229 (2016); M. Lucchini et al., *Science* **353**, 916 (2016)
4. T. Higuchi, Heide, C., Ullmann, K., Weber, H.B., Hommelhoff, P., Light-field-driven currents in graphene, *Nature* **550**, 224 (2017).
5. R. Bormann, M. Gulde, A. Weismann, S. V. Yalunin, C. Ropers, *Phys. Rev. Lett.* **105**, 147601 (2010); M. Schenk, M. Krüger, P. Hommelhoff, *Phys. Rev. Lett.* **105**, 257601 (2010); M. Krüger, M. Schenk, P. Hommelhoff, *Nature* **475**, 78 (2011); G. Herink, D. R. Solli, M. Gulde, C. Ropers, *Nature* **483**, 190 (2012); B. Piglosiewicz et al., *Nat. Phot.* **8**, 37 (2014); P. Hommelhoff, M. Kling, (eds.), *Attosecond Nanophysics*, Wiley 2015; M. Ciappina et al., *Rep. Progr. Phys.* **80**, 054401 (2017)
6. M. Förster, T. Paschen, M. Krüger, Chr. Lemell, G. Wachter, F. Libisch, Th. Madlener, J. Burgdörfer, P. Hommelhoff, *Phys. Rev. Lett.* **117**, 217601 (2016); T. Paschen, M. Förster, M. Krüger, Chr. Lemell, G. Wachter, F. Libisch, Th. Madlener, J. Burgdörfer, P. Hommelhoff, *J. Mod. Opt.* **64**, 1054 (2017)
7. M. Kozák, T. Eckstein, N. Schönenberger, P. Hommelhoff, *Nature Physics* **14**, 121 (2018)
8. M. Kozák, N. Schönenberger, P. Hommelhoff, *Phys. Rev. Lett.* **120**, 103203 (2018)
9. E. Peralta et al., *Nature* **503**, 91 (2013); J. Breuer, P. Hommelhoff, *Phys. Rev. Lett.* **111**, 134803 (2013)

10. M. Kozák et al., Optics Letters **41**, 3435 (2016); M. Kozák et al., Nature Communications **8**, 14342 (2017); M. Kozák et al., Optics Express **25**, 19195 (2017); J. McNeur et al., Optica **5**, 687 (2018); P. Yousefi et al., to be published
11. <http://achip.stanford.edu>