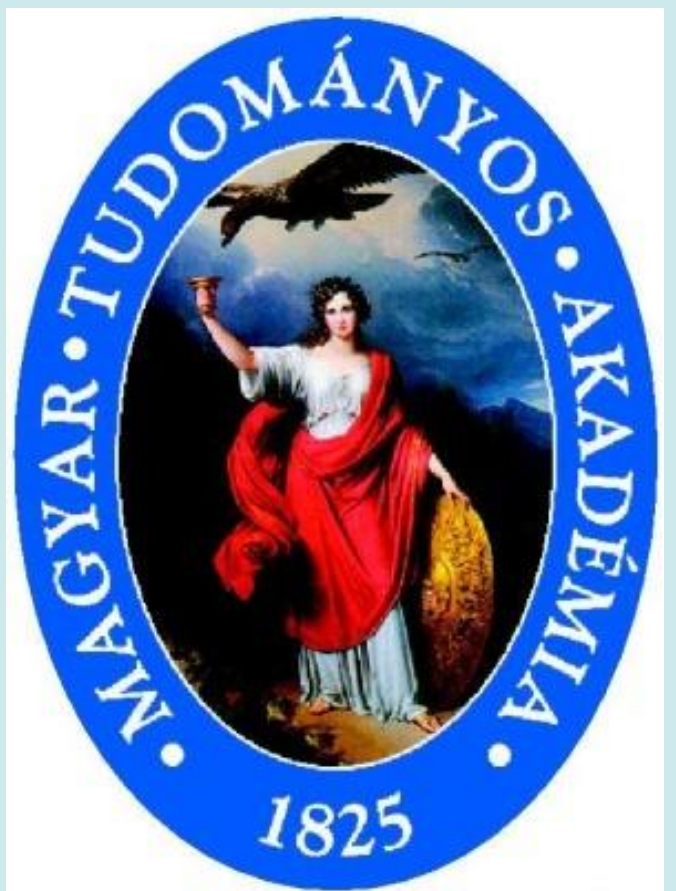


Proposal for sub-femtosecond pulse generation with controlled carrier-envelope phase

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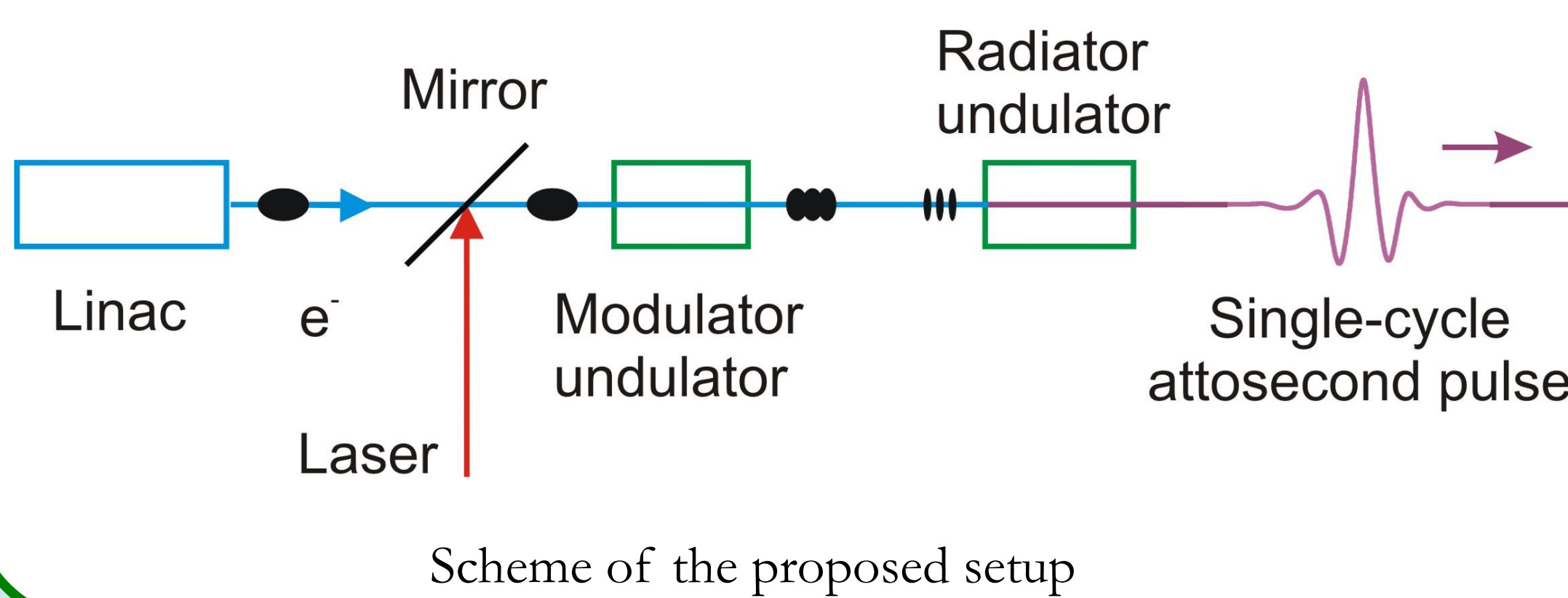


Introduction

- Generation of waveform-controlled single- or few-cycle electromagnetic pulses down to the extreme ultraviolet (EUV) wavelengths is of considerable interest [1].
- Generation of carrier-envelope phase (CEP) stabilized fs pulses in the VIS-NIR wavelength range is well established, however there are no reliable techniques available for CEP control of **attosecond pulses**.
- We propose a robust method for producing CEP-controlled half-cycle – few-cycle pulses in the EUV–VUV spectral range[2-3].

The proposed setup

- The scheme of the proposed setup is shown in the figure below.
- Method is based on
 - ultrathin electron layer generation,
 - coherent undulator radiation.
- We used the General Particle Tracer (GPT) [4] numerical code for simulation of microbunching by inverse free electron laser (modulator or nanobuncher undulator).
- We calculated the temporal shape of the electric field of the radiation generated in a second undulator (radiator undulator).



Production of ultrathin electron layers

The shortest microbunch length parameters

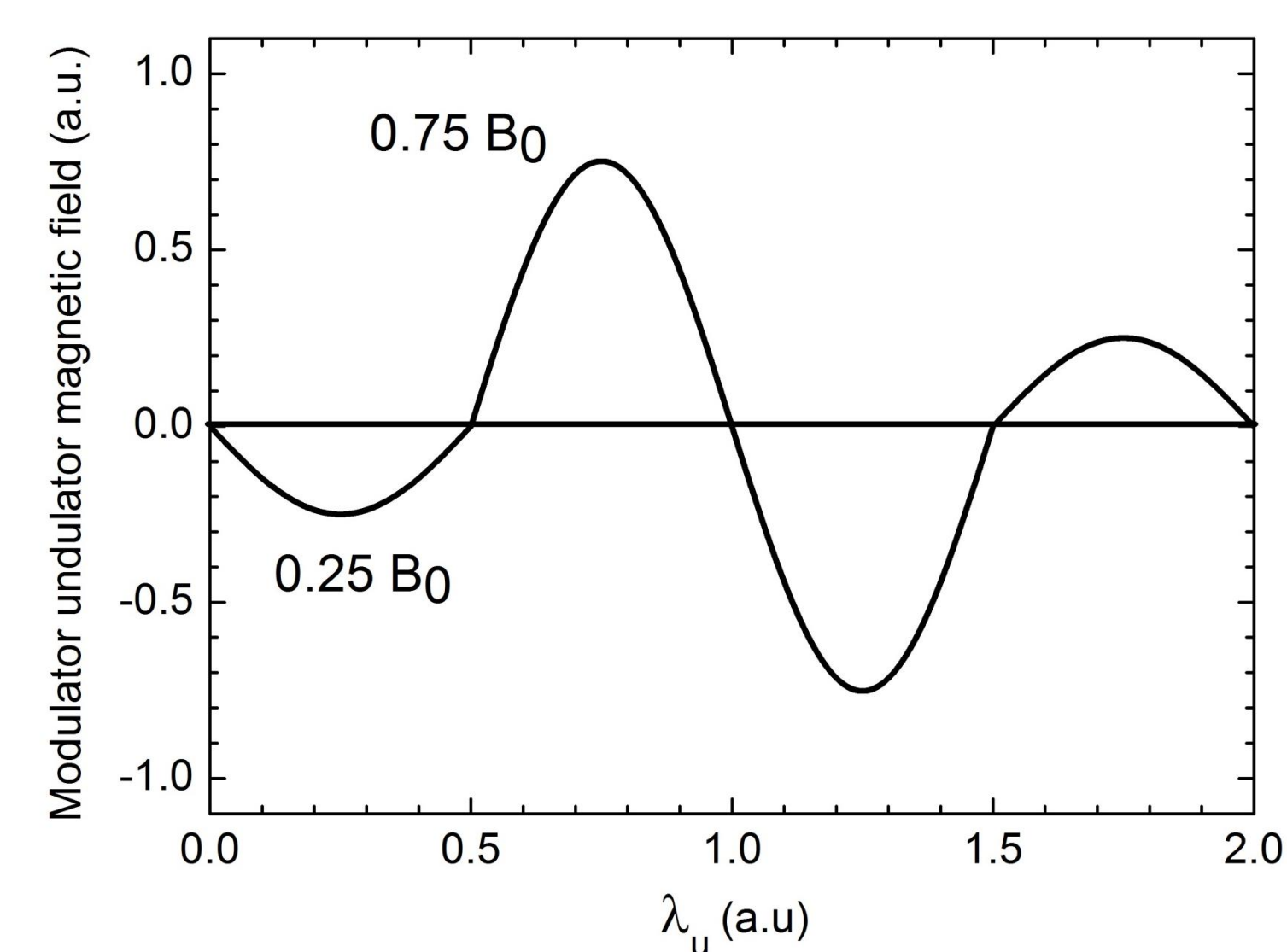
- Thus far the shortest microbunch length was about 800 nm [5].

Simulation results of microbunching

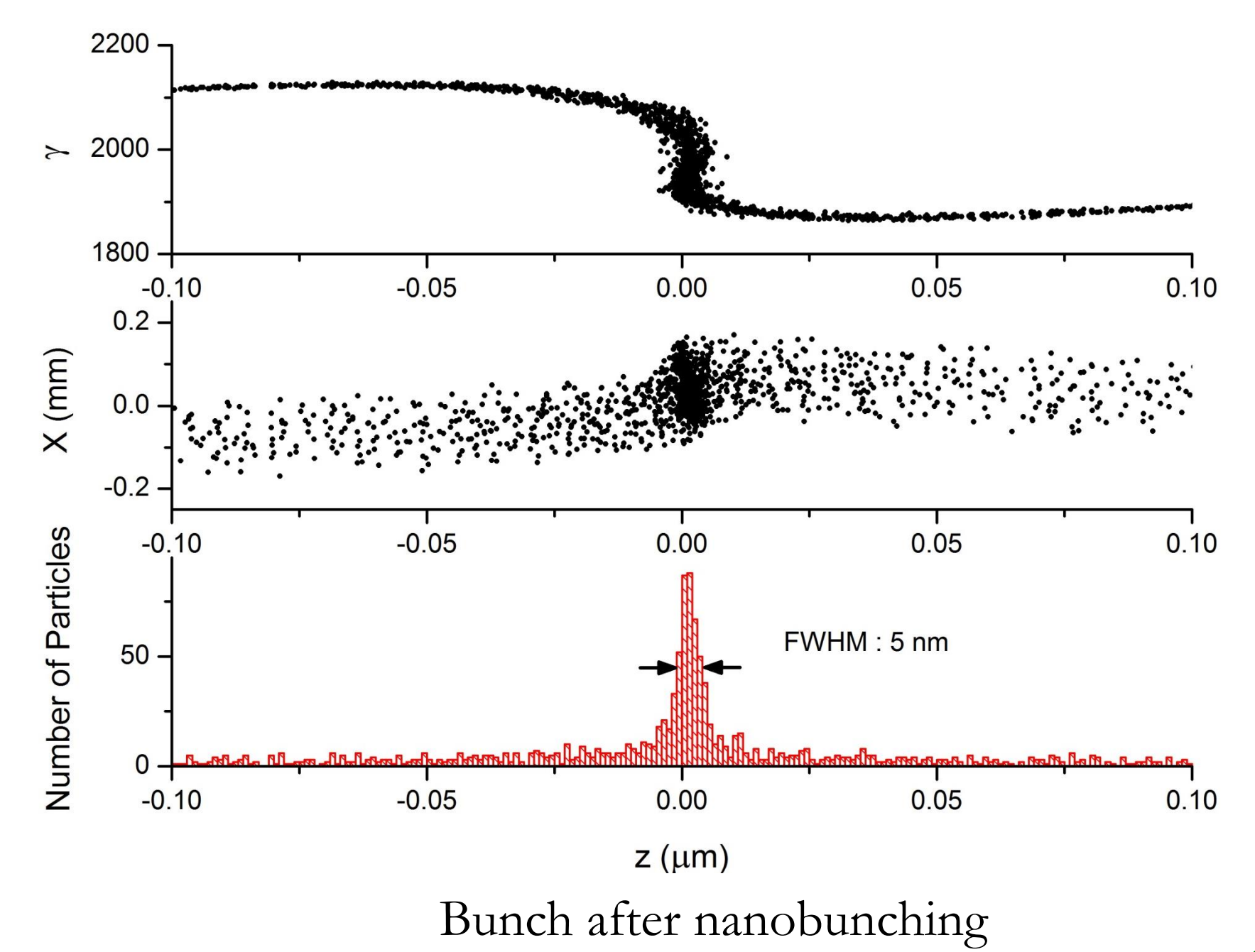
- We used the parameters of the electron bunch created by the accelerator of FLASH II in DESY, Germany.
- In order to produce shortest microbunch length we used
 - Short laser wavelength: 516 nm,
 - high modulator laser power,
 - the undulator period length satisfies the resonant condition:

$$\lambda_u = \frac{2\gamma^2 \lambda_1}{1 + K^2/2}$$

- and the 2 period modulator undulator, where the magnetic field distribution is shown in the figure below :



The starting parameters (FLASH II)	
Parameter	Value
E-beam energy	1000 MeV
E-beam intrinsic energy spread (1σ)	0.05 %
E-beam charge (total pulse)	≈ 0.25 nC
E-beam pulse length (1σ)	≈ 30 μm
E-beam normalized emittance	1.4 mm mrad
E-beam radius	30 μm
Undulator period length	2.08 m
Laser wavelength	516 nm
Laser power	10 TW
Laser beam size inside buncher u.	0.7 mm



Calculation method of the electric field and results

- During the radiation process the acceleration, velocity and position of the macroparticles were followed numerically by taking into account the Lorentz-force equation:

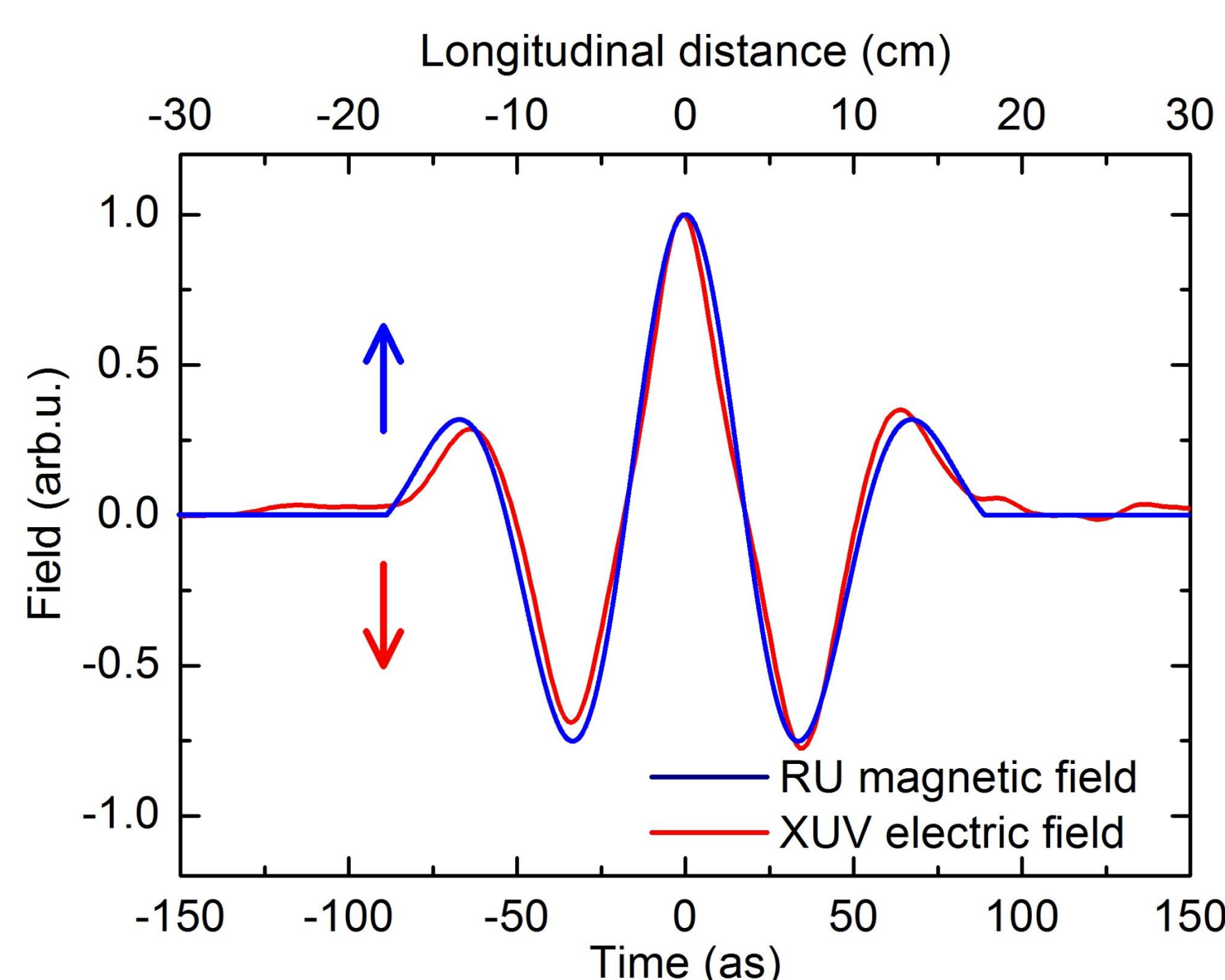
$$\frac{d(\gamma m \vec{v})}{dt} = q \vec{v} \times \vec{B}(z(t))$$

- We are interested in the temporal shape of the ultrashort pulses emitted by the extremely short electron microbunches in the radiator undulator. We calculated it in a plane 8 m behind the middle of the radiator undulator according to [6]:

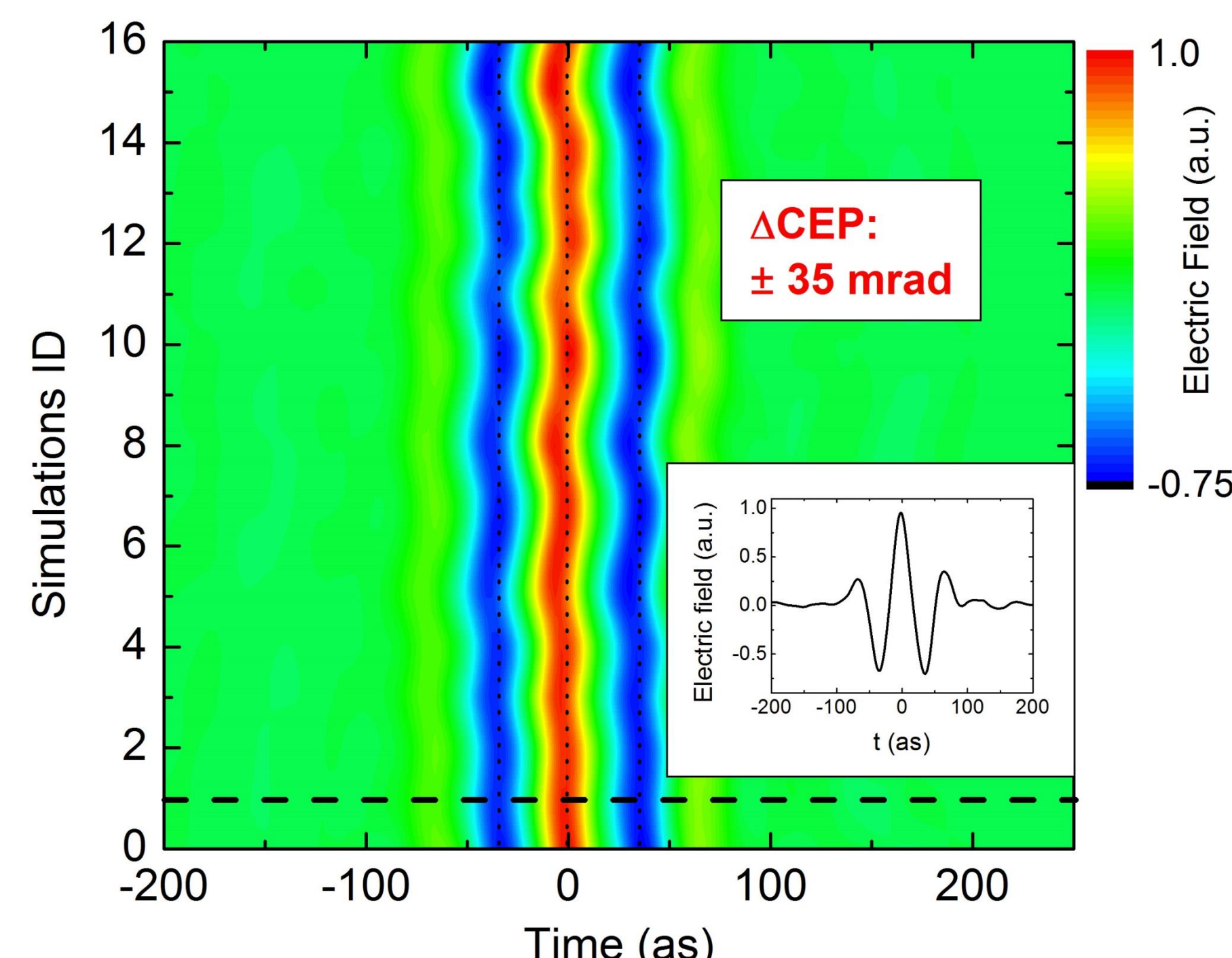
$$\vec{E}(\vec{r}, t) = \left[\frac{q \mu_0}{4\pi} \frac{\vec{R} \times \left((\vec{R} - R\vec{\beta}) \times \dot{\vec{v}} \right)}{(R - \vec{R} \cdot \vec{\beta})^3} \right]_{ret}$$

γ	λ _u	B _u	λ _r	Δt _r	E _r
1000	3.6 cm	151 mT	20 nm	80 as	3 nJ
2000	14.2 cm	38 mT	20 nm	80 as	27 nJ
2000	12.1 cm	71 mT	20 nm	80 as	49 nJ
2000	32.0 cm	17 mT	45 nm	150 as	89 nJ
2000	42.7 cm	13 mT	60 nm	225 as	116 nJ
2000	7.1 cm	66 mT	10 nm	36 as	6 nJ

Examples for pulses generated by undulator



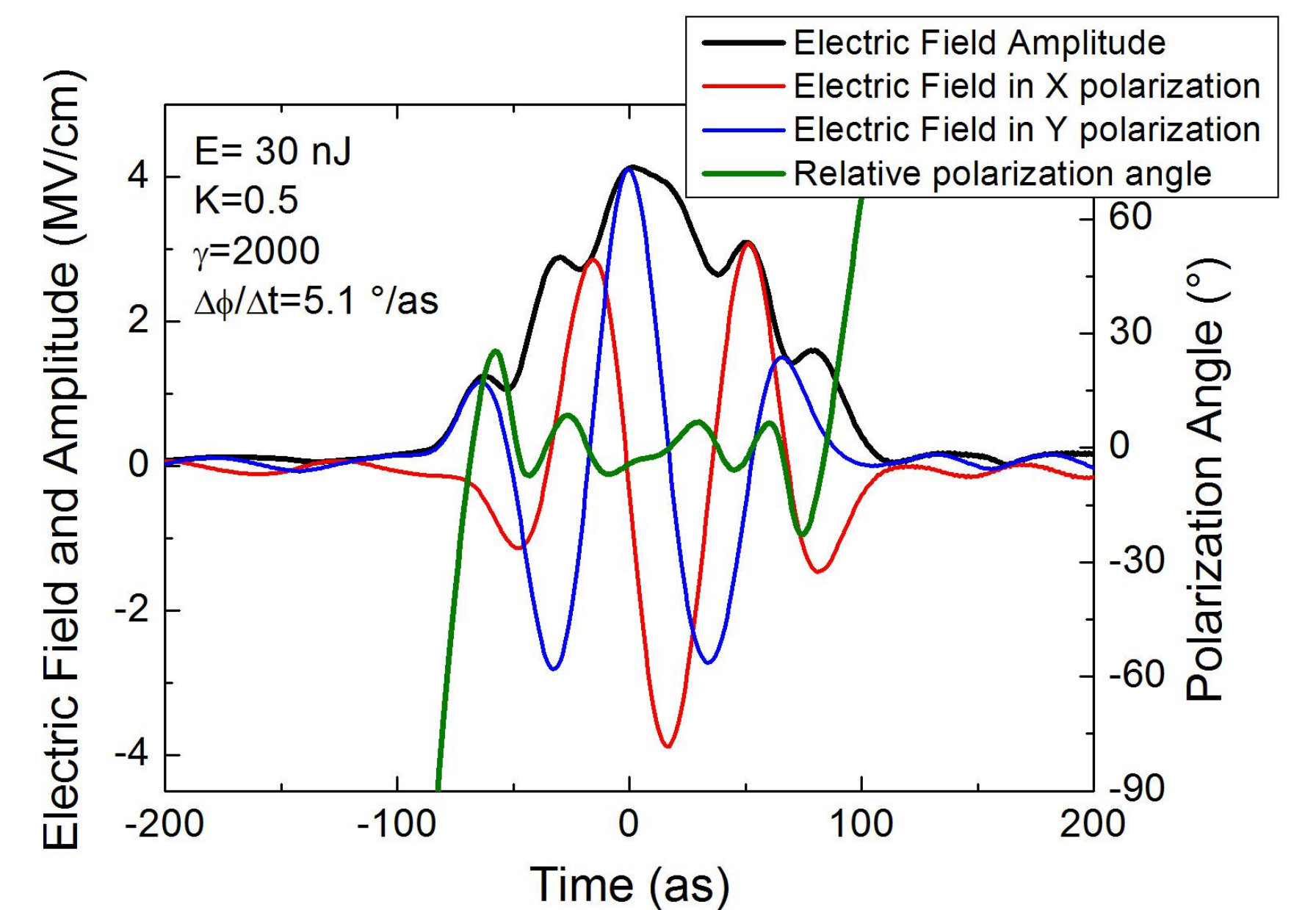
Magnetic field distribution of radiator undulator (blue line) and the electric field of the generated attosecond pulse (red line).



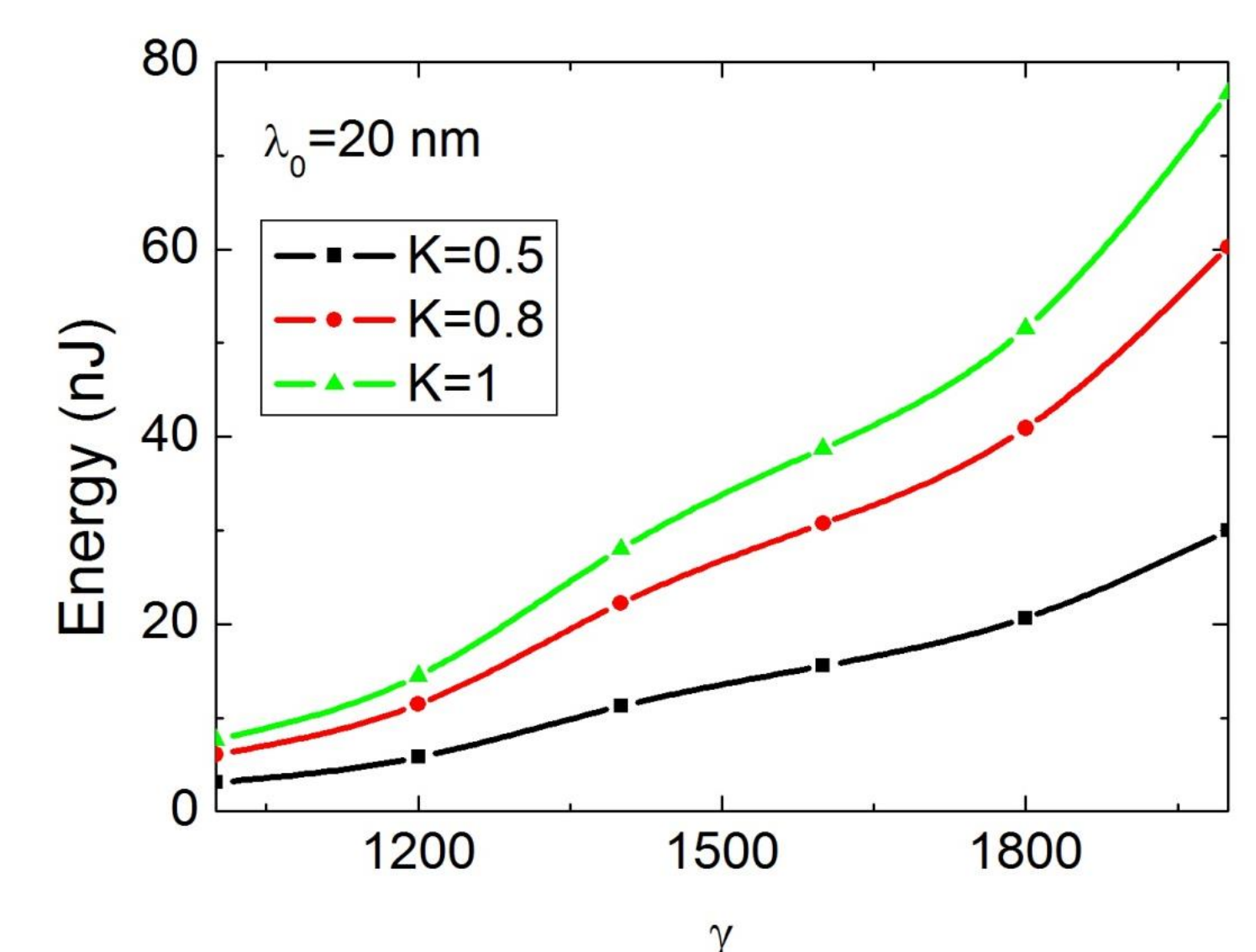
CEP-controlled XUV waveforms with same simulation parameters, but different runs (γ = 2000).

Generating circularly polarized attosecond pulses

- We calculated the radiation characteristics using helical undulator to generate circularly polarized pulses.



Single-cycle circularly polarized attosecond pulse generation.



Circularly polarized pulses energy dependence on γ and K.

Conclusion

- A robust method for producing CEP-controlled half-cycle –few-cycle pulses in the EUV–VUV spectral range was proposed
- Shorter than 10 nm microbunch length can be achieved by using a two period undulator with high modulator laser power.
- A few tens of nJ pulse energy can be achieved, these CEP stable pulse can be used in pump – probe measurements.
- The CEP fluctuation is smaller than **± 35 mrad**.
- Generation of attosecond pulses as short as **36 as** is possible by the proposed method.
- These pulses can be used as seed in SASE FEL.
- Using helical undulator for radiator it is also possible to produce circularly polarized pulses.

References

- [1] F. Reiter et al., Phys. Rev. Lett. **105**, 243902 (2010)
- [2] Tibai et al., arXiv:1304.6495
- [3] Tibai et al., Phys. Rev. Lett., **113**, 104801 (2014)
- [4] <http://www.pulsar.nl/gpt/>
- [5] W.D. Kimura et al., Phys. Rev. Lett. **92**, 054801 (2004)
- [6] J. D. Jackson: Classical Electrodynamics 3rd ed., Wiley, ISBN 0-471-30932-X

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