Generation of X-Rays by Laser Accelerated Electron Beam: A Synopsis

X-ray radiation represents a powerful tool to investigate the properties of matter. Currently, promising concepts of the X-rays generation from laser plasmas are arising. The evaluated dissertation brings the new results mainly in the branch related to laser wakefield acceleration of electrons (LWFA) [1]. This approach is based on the interaction of ultrashort and ultraintense laser pulses with gaseous targets.

The fundamental idea how to generate the X-rays is to wiggle trajectories of relativistic electrons in the beam and to induce directional emission of high-frequency electromagnetic radiation thereby. Transverse oscillations either occur naturally during the acceleration process in case of betatron radiation, or they are forced by counter-propagating laser pulse in the case of Thomson backscattering.

The features of generated X-ray pulses are determined by the properties of accelerated electron bunch. A new method to calculate the betatron radiation features from the knowledge of the accelerated electron trajectories was developed. The first part of this synopsis is devoted to it. The second part introduces two novel optical injection schemes. Such approach is legitimate because the plasma electron injection into a nonlinear plasma wave accelerating phase is of a decisive influence on the final features of accelerated electron bunches and secondary X-rays.

Spectrograms of betatron radiation [2]

Theory of electrodynamics [3] states that an accelerated electron emits the electromagnetic radiation. Electric field signal emitted by relativistic electron is found

$$\mathbf{E}(\mathbf{r_O}, t) = \frac{e}{4\pi\varepsilon_0} \left\{ \frac{(1-\boldsymbol{\beta}^2)(\mathbf{n}-\boldsymbol{\beta})}{R^2(1-\mathbf{n}\cdot\boldsymbol{\beta})^3} + \frac{\mathbf{n}\times[(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}]}{cR(1-\boldsymbol{\beta}\cdot\mathbf{n})^3}, \right\}_{ret}, \tag{1}$$

where $\mathbf{r_O}$ is a position of observer, $\mathbf{r}$ is electron position, $\mathbf{R} = \mathbf{r_O} - \mathbf{r} \approx \mathbf{r_O}$, $R(t') = |\mathbf{R}| = |\mathbf{r_O} - \mathbf{r}(t')|$ is the distance between the point of emission and observer, $\boldsymbol{\beta}$ is electron velocity normalized to speed of light in vacuum, $\mathbf{n}$ is the unit vector in direction of observation, and the rest are fundamental physical constants. Index ret mean that vector quantities $\mathbf{r}$, $\mathbf{n}$, $\boldsymbol{\beta}$ and $\dot{\boldsymbol{\beta}} = \mathrm{d}\boldsymbol{\beta}/\mathrm{d}t$ are evaluated in retarded time $t' = t - |\mathbf{R}|/c$.

The formula for the frequency and the angular distribution of the radiation emitted by the relativistic electron is then written as

$$\frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}\Omega} = \frac{c\varepsilon_0}{\pi} \left| \mathfrak{F}[R(t)\mathbf{E}(t)](\omega) \right|^2. \tag{2}$$

Thus, the radiation of relativistic electron can be calculated a the Fourier transform of the its emitted electric field signal which depends only on its trajectory. Assuming that incoherent electron bunch is comprised of N_e randomly distributed electrons, the total radiation spectrum intensity is simply a sum of the contributions from single electrons [4]

$$\frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}\Omega} = \sum_{i=1}^{N_e} \frac{\mathrm{d}^2 I_i}{\mathrm{d}\omega \mathrm{d}\Omega} \approx N_e \left. \frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}\Omega} \right|_{ave}. \tag{3}$$

This assumption is always fulfilled in LWFA. The principle of betatron radiation is the transverse betatron oscillations of electrons during the acceleration phase. The electron emits radiation almost exclusively in N_p turning points of its sine-like trajectory, as it can be seen in Figure 1. Hence, there are only a few very narrow time intervals, which contribute significantly to the betatron radiation emission, while the rest can be neglected. Let us consider the signal of the radiation $\mathbf{u}(t) = \mathbf{E}(t)R(t)$ as a sum of the contributions by single peaks $\mathbf{u}_j(t)$, i.e.

$$\mathbf{u}(t) = \sum_{j=1}^{N_p} \mathbf{u}_j(t), \tag{4}$$

vojtech.horny@atlas.cz

where N_p is number of peaks. Each contribution can be written as

$$\mathbf{u}_j(t) = \begin{cases} \mathbf{E}(t)R(t) & |t - t_j| < \Delta t \\ 0 & \text{otherwise,} \end{cases} \tag{5}$$

where t_j are the times of the signal peaks and Δt are the widths of the considered peaks. These widths has to include the whole peaks and cannot overlap each other. It is shown, that the spectral intensity of the radiation is similar as in the equation (2)

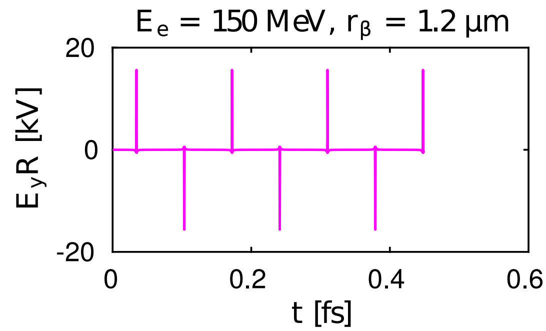

Figure 1: *Emitted signal radiated by a typical electron observed on axis at one meter distance.*

$$\frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}\Omega} = \frac{c\varepsilon_0}{\pi} \sum_{j=1}^{N_p} |\mathfrak{F}[\mathbf{u}_j(t)](\omega)|^2 = \sum_{j=1}^{N_p} \left.\frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}\Omega}\right|_j . \tag{6}$$

It means that the calculation of the radiation emitted by a single electron can be simplified to the calculation of the sum of the contributions to the radiation emitted in N_p turning points of its sine-like trajectory.

Thus, the long time interval can be replaced by several much shorter time intervals. This is particularly helpful when high energy radiation is expected and the length of the signal due to huge sampling rate places high demands on the memory. The total radiation emitted by a bunch containing N_e electrons can be written as

$$\frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}\Omega} = \sum_{i=1}^{N_e} \sum_{j=1}^{N_{p,i}} \left.\frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}\Omega}\right|_{ij} = \sum_{k=1}^{N_P} \left.\frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}\Omega}\right|_k , \tag{7}$$

because all the contributions to the total radiation by all electrons are summed up and it does not depend on the order of the summation.

Moreover, a quantity of radiated energy per unit frequency and per unit solid angle received during certain time interval $t \in [\tau - \Delta\tau, \tau + \Delta\tau]$ can be introduced as

$$\left.\frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}\Omega}\right|_{t\in[\tau-\Delta\tau,\tau+\Delta\tau]} = \sum_{k|t_k\in[\tau-\Delta\tau,\tau+\Delta\tau]} \left.\frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}\Omega}\right|_k \approx \frac{\mathrm{d}^3 I}{\mathrm{d}t \mathrm{d}\omega \mathrm{d}\Omega} \tag{8}$$

and the spectrograms of the betatron radiation can be constructed. The calculations presented indicate that generated X-ray pulse durations are typically shorter than the driver laser pulse duration. Furthermore, a mechanism to generate X-ray pulses shorter than 3 fs is proposed (as will be shown later in Figure 4). We believe that this method represents a useful tool to investigate or to tailor the betatron X-ray pulse temporal profiles and it can be used to design sources for future applications such as probing of ultrafast fundamental physical processes such as electron transfer, lattice vibrations, phase transitions, chemical reactions, or a spin dynamics.

Novel optical injection schemes

The X-ray pulse features such as duration or intensity are determined the the length and charge of accelerated electron bunch. And those properties depends mainly on the injection process, i.e. how are the background plasma electrons trapped in the accelerating phase of the laser-driven nonlinear plasma wave called the bubble. The fundamental motivation for using alternative injection techniques is to separate the wakefield generation and the electron injection into this wakefield in order to stabilize the produced electron beam properties. In optical injection configurations, an additional injection pulse injects the electron bunch into the bubble in a controlled manner.

The parameter space affordable with already commercially available sub-100-TW laser systems was investigated. Therefore, the results can be soon exploited in universities, research institutes, hospitals or industrial companies.

Optical injection scheme in it original configuration [5] uses the injection pulse orthogonally intersecting the wakefield at a certain distance behind the drive pulse. Consequently, a part of electrons gain the momentum kick large enough to get trapped in the linear wakefield. The optical injection techniques developed steadily within last two decades; the various modifications in number of injection pulses, their polarization or propagation direction were suggested.

Orthogonally crossed pulses (OC3P) [6]

The first of new optical injection schemes introduced in the evaluated dissertation is a certain redesign of an original Umstadter's scheme [5]. This redesign reacts on the progress of the laser technology and physical understanding within the two decades. The proposed scheme is shown in Figure 2. Most importantly, both pulses actually crosses each other, contrary to [5], where the injection pulse interacted with a plasma wave dragged by a main pulse. From the perspective of experiment, it was recently shown that it is feasible to perfom the temporal and spatial synchronisation of both pulses [7].

The new scheme can operate on a highly non-linear regime of LWFA. It was found that the injection pulse is supposed about hundred times weaker than the drive pulse to provide the quasimonoenergetic (energy spread of 4%) high charge (tens of pC) electron bunches.

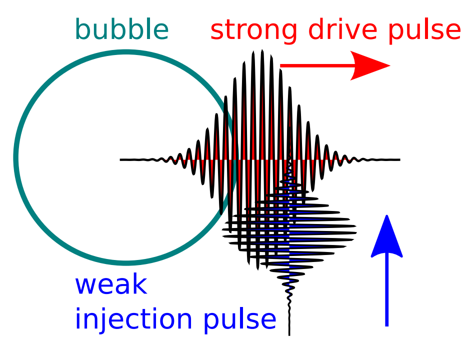

Figure 2: *Scheme of orthogonally crossed pulses with parallel polarizations (OC3P).*

Three different injection mechanisms were identified; these are shown also in Figure 2. Trapped electron groups lie in different collection volumes and evolve differently in the phase space before being trapped. It results in the higher value of transverse emittance. The dominant injection mechanism called *crossing beatwave injection* was investigated theoretically. It was found that its principle is not in direct exchange of momentum between the electron and the injection pulse due to time averaged ponderomotive force action, but in the stochastic nature of the relativistic motion equation of a single electron in the combined field of both laser pulses. It was shown that the presence of the injection pulse, albeit it is very weak, changes the differential equation solution tremendously.

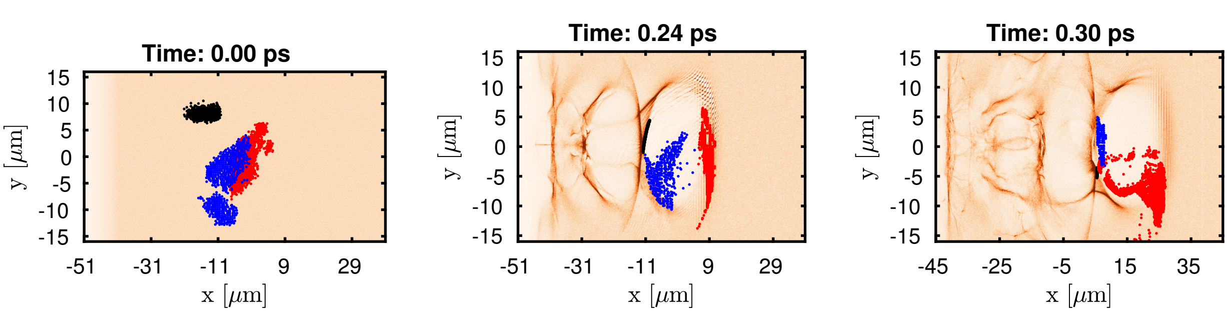

Figure 3: *Positions of electrons trapped by different injection mechanisms (points) and electron density profile (shades of orange). From PIC simulation. Red – crossing beatwave injection, blue – injection by a laser field preacceleration, black – induced self-injection.*

The significant number of electrons initially located in the region where both pulses overlap are expelled in direction opposite to addition vector of both pulses propagation vector. Consequently, these electrons find themselves in the off-axis part of the bubble. Despite their initial longitudinal momentum is in direction opposite to plasma wave propagation, they are trapped, as it was shown by the numerical simulations of electron motion within the bubble.

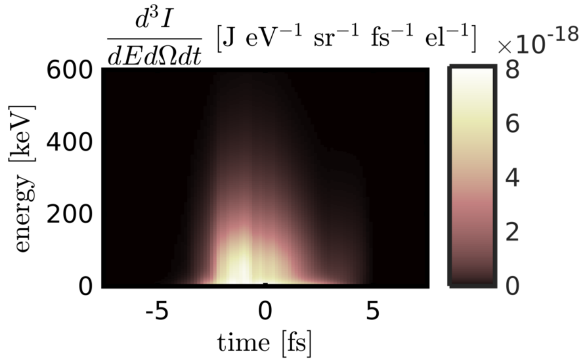

Figure 4: *Betatron radiation in OC3P case. Electrons accelerated up to 530 MeV with 8% energy spread emits synchrotron-like 2.6 fs long X-ray pulse with critical energy 54 keV.*

The parameter scan showed that the highest quality beams can be delivered, when the injection pulse intensity is only 1% of the drive pulse intensity, both pulses meets *in time*, the waist size of both pulses is the same and their mutual polarizations are perpendicular. This scheme provides shorter electron bunches than the one with counter-propagating injection pulse. Consequently, very short secondary X-ray pulses are emitted as shown in Figure 4.

Injection by a preceding pulse [8]

The second new scheme is the injection by slightly weaker preceding injection pulse. It fully avoids the potential issues with the temporal and spatial synchronization of both ultrashort pulses. Thus, its crucial advantage is relatively easy implementation in comparison with all the other optical injection schemes. It also predicts the generation of high charge ultrashort electron bunches.

This injection mechanism is in a certain way inspired by standard self-injection. The preceding injection pulse intensity must be strong enough to form its own bubble. As the collection volume for the transversely self-injected electrons in nonlinear bubble regime is a ring around laser propagation axis [9], the delay between pulses is chosen in such a way that this ring coincides with the electron sheath of the first bubble. Thus, the value of the optimal delay was derived based on this geometrical motive. Such configuration increases the electron density in a region where electrons could be potentially injected to bubble dragged by the main pulse.

Within this scheme, the injection is induced by the bubble expansion, similarly to standard self-injection. Such an expansion can occur due to stochastic nature of the bubble dynamics, but such a scheme would not be stable. Therefore, the wave breaking is achieved in a controlled manner at a density up-ramp at a vacuum plasma transition.

Such a localized injection leads to quasi-mononenergetic electron spectra and potentially to a good reproducibility. This scheme was investigated by means of 3D PIC simulations. The snapshot of the injection process is shown in Figure 5. The injected electrons (black) lying initially at the ring around the propagation axis located at the transition between the end of the density ramp and the homogeneous plasma are at first disturbed by the injection pulse and after that trapped in the bubble dragged by the main pulse (isosurfaces of electric field E_y are shown in red).

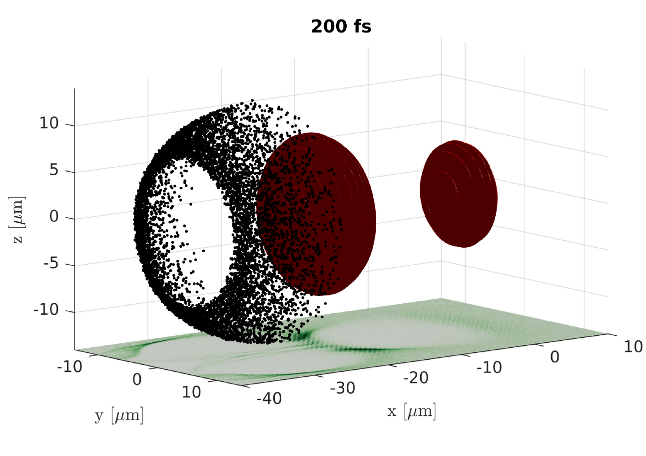

Figure 5: *Injection by a preceding pulse.*

The following parameters were chosen to demonstrate the scheme: laser wavelength 0.8 μm, waist size

9.5 μm, pulse length 25 fs, drive and injection laser pulses strength parameters $a_0 = 4$ and $a_1 = 2.5$. The mutual delay between pulses was 65 fs which corresponds to the plasma period; both pulses are linearly polarized. A uniform electron gas with density 3×10^{18} cm^{-3}. The best results are predicted for an experimentally feasible initial linear ramp length 20 μ long. At the time of 3.6 ps of the simulation, energy, relative energy spread, charge, and transverse emittance of the trapped electron bunch in the simulation are 269 MeV, 9%, 188 pC, and 1.63 π·mm·mrad, respectively. Optically injected electrons are well separated from the dark current. The bunch length is 1.8 μm.

This acceleration scheme has yet another beneficial side effects. The intensity of the drive pulse decrease due to the dispersion is slower when the injection pulse is present. The cause of this effect is that the drive pulse does not propagate in a homogeneous plasma anymore, but rather in the channel with the density profile perturbed by the injection pulse. Whereas the central part of the drive pulse propagates in the very low-density plasma located in the rear part of the bubble generated by the injection pulse; the edges are cut by the electron streams of which the front bubble is comprised.

Conclusion

The evaluated dissertation is devoted to the generation of hard X-rays from relativistic electrons accelerated by laser wakefield acceleration mechanism in conditions achievable with currently available 100-TW class laser systems. These X-ray sources represent a conceptual upgrade in the features of delivered X-rays because of their tiny source size and short pulse duration. The expected high impact applications are X-ray phase-contrast imaging and sampling of fundamental physical processes such as chemical reactions or phase transitions. However, they cannot yet compete with conventional sources based on synchrotrons and undulators, mainly because of their poorer stability, reproducibility, and tunability.

The features of the generated X-ray pulses are set by the quality of accelerated electron beams. The injection of the electron bunch into an accelerating phase of a plasma wave is presumably the most important process which determines its final properties, such as the energy spread or the emittance. Therefore, two novel optical injection schemes were proposed. Both these schemes of the injection by the perpendicular and by the preceding weaker pulse provide high charge (tens of pC) and short length (fs) electron bunches. This is advantageous for the generation of short and relatively intense X-ray pulses by mechanisms of betatron radiation and Thomson backscattering.

Another significant result of this dissertation is a new method to calculate the properties of the betatron radiation and even to construct its spectrograms. The method is based on the theory of retarded potentials which are calculated from the trajectories of accelerated electrons.

It takes advantage of the fact that the electron oscillates transversally in the accelerating plasma wave in the wiggler regime and, thus, emits radiation almost exclusively in the turning points of its sine-like trajectory. X-ray pulses shorter than 3 fs can be delivered.

References

[1] E. Esarey et al., *Reviews of Modern Physics*, 81(3):1229, 2009.
[2] V. Horný et al., *Physics of Plasmas*, 24(6):063107, 2017.
[3] J. D. Jackson, *Classical electrodynamics*, Wiley, 1999.
[4] S. Corde et al., *Reviews of Modern Physics*, 85(1):1, 2013.
[5] D. Umstadter et al., *Physical Review Letters*, 76(12):2073, 1996.
[6] V. Horný et al., *Physics of Plasmas*, 24(10):103125, 2017.
[7] G. Golovin et al., *Physical Review Letters*, 121(10):104801, 2018.
[8] V. Horný and M. Krůs, *Proceedings of the 44th EPS Conference on Plasma Physics*, P1.205, 2017.
[9] C. Benedetti et al., *Physics of Plasmas*, 20(10):103108, 2013.