Ultrafast observation of the Lorentz transformation around a relativistic electron beam

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Femtosecond electron bunches are helpful for the development of high-quality and intense X-ray and light sources for applications in accelerator physics, such as free-electron lasers. Short electron bunches can also be applied to time-resolved pump-probe experiments involving ultrafast electron diffraction and pulse radiolysis to improve time resolutions. Electro-optic (EO) monitors are one of the techniques for analyzing the time profile of the femtosecond electron bunch [1-3] because femtosecond electron bunches generate the Coulomb field as terahertz (THz) electric fields. Diagnostics of electrons or neutrons with picosecond or femtosecond time resolution based on EO sampling would also be applied to analyze electric field and fusion reaction history [4]. Such scheme for ultrafast detection of THz electromagnetic waves can be applied to plasma diagnostics and radiations from gyrotrons or synchrotrons. EO sampling is also used in THz detection and THz applications for materials and structures [5,6].

In this presentation, demonstration of single-shot spatio-temporal detection of THz electric field around a relativistic electron beam with an energy of 35 MeV [7] with sub-millimeter and sub-picosecond resolutions based on electro-optic sampling will be reported. Furthermore, a transition between the Liénard–Wiechert potentials (LWPs) and the Lorentz transformation (LT) was demonstrated using the THz measurement system for the first time. By passing the electron beam through a metallic foil, an electric field around the electron beam was screened. After the passage of the metallic boundary, the Coulomb field was born around the electron beam, and propagated with a spherical wavefront as explained by the LWPs. In the far propagation length of ~200 mm, the wavefront forms a plane, which indicates the the LT as shown in Fig. 1. At the same time, the measurement was not for the radiation field, but the Coulomb field. Our ultrafast spatio-temporal measurement of a relativistic electric field will pave the way for experimental study of special relativity, electromagnetic radiations, and relativistic charged particle beams. This measurement scheme could also be applied to plasma diagnostics which include fields of special relativity, electromagnetic radiations, and relativistic charged particle beams.

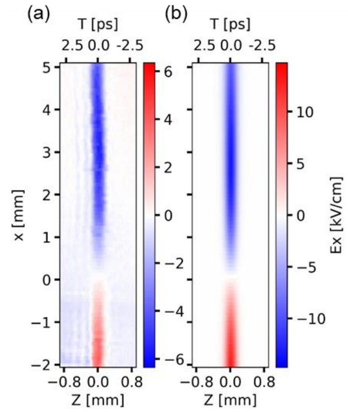

Figure 1: Comparison of the spatio-temporal profiles of (a) the experimental result and (b) numerical simulation of the LT. Axes of Z is longitudinal direction for the electron beam. The origins correspond to the beam center. Reprinted with changes from an open access reference [2].

References

[1] G. Berden, et al., “Benchmarking of Electro-Optic Monitors for Femtosecond Electron Bunches”, Phys. Rev. Lett., 99, 164801, 2007.
[2] M. Ota et al., “Ultrafast visualization of an electric field under the Lorentz transformation”, Nat. Phys. 18, 1436, 2022.
[3] M. Ota, et al., “Longitudinal and transverse spatial beam profile measurement of relativistic electron bunch by electro-optic sampling”, Appl. Phys. Express, 14, 026503, 2021.
[4] Y. Arikawa, et al., “The conceptual design of 1-ps time resolution neutron detector for fusion reaction history measurement at OMEGA and the National Ignition Facility”, Rev. Sci. Instrum., 91, 063304 2020.
[5] K. Makino, et al., “Significant Volume Expansion as a Precursor to Ablation and Micropattern Formation in Phase Change Material Induced by Intense Terahertz Pulses”, Scientific Reports, 8, 2914, 2018.
[6] V. C. Agulto, et al., “Anisotropic complex refractive index of b-Ga_2O_3 bulk and epilayer evaluated by terahertz time-domain spectroscopy”, Appl. Phys. Lett., 118, 042101, 2021.
[7] K. Kan, et al., “Time-domain measurement of coherent transition radiation using a photoconductive antenna with micro-structured electrodes”, AIP Advances, 11, 125319, 2021.