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研究課題名（和文） Study of electron longitudinal phase space in laser wakefield acceleration via electro-optic streaking technique

研究課題名（英文） Study of electron longitudinal phase space in laser wakefield acceleration via electro-optic streaking technique

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研究成果の概要（和文）：レーザー航跡場加速(LWFA)における電子縦位相空間(LPS)のシングルショット測定のための新しい電気光学ストリーキング技術を提案した。2つのダイポール磁石で構成される「ドッグレッグ」システムの設計および製造を行った。遷移放射(TR)の測定を試み、プラズマ外の電子タイミングを測定する予備実験を行った。電子バンチのタイミング変動はわずか7fs(rms)であることを見出した。本実験結果はApplied Physics Expressに掲載された。理論研究も推し進め、計算コードを開発した。今後は、「ドッグレッグ」を実験セットアップに組み込み、電子バンチのLPS測定を計画している。

研究成果の学術的意義や社会的意義
従来の加速器では、電子バンチのLPSは高周波 (RF) Transverse Deflection Structure (TDS)で測定される。しかし、レーザー駆動の粒子加速の場合、フェムト秒の時間スケールで電子バンチを時間的にキックすることが可能なTDSを構築することは困難である。本研究は、LWFAにおける電子ビームダイナミクスの先駆的な研究となる。EO技術の創造的な応用は、中赤外からTHzまでの波長範囲でのEO結晶の分散特性の研究にも有益である。

研究成果の概要（英文）：I proposed a brand new electro-optic streaking technique for the single-shot measurement of the electron longitudinal phase space (LPS) in laser wakefield acceleration. A “dog-leg” system composed of two dipole magnet was designed and manufactured. For easier access to the overall self-field information of the electron bunches, the measurement on the transition radiations (TR) from the electron bunches are planned. I have carried out a preliminary experiment to monitor the electron timings outside the plasma. The electron bunches were discovered to have a timing fluctuation of merely 7 fs (rms). This work was published as “K. Huang et al., Applied Physics Express 15, 036001 (2022)” and selected as the spotlight paper of the journal. For the theoretical aspect: I have developed a code covering all the sessions in the LPS. For the next step, I will insert the “dog-leg” into the experimental set-up and measure the LPS of the electron bunch.

研究分野： 量子ビーム科学

キーワード： high power laser　electron accelerator　beam diagnostics　EO sampling　Longitudinal phase space

１．研究開始当初の背景

In the last 30 years, Laser Wakefield Acceleration (LWFA) [1], as an advanced accelerator concept, has invoked great interest worldwide. By focusing a high-power laser with pulse duration of a few tens of femtoseconds (fs, 1 fs = 10^{-15} s) into underdense plasma, plasma waves are generated with acceleration gradient (100 GeV/m) 3 orders of magnitudes higher than the conventional radio-frequency (RF) cavity. Recently, electrons with energy up to 8 GeV has been achieved within an acceleration length of merely 20 cm [2]. This acceleration regime shows potentials in building up a compact collider or x-ray free electron laser with cost much lower than state-of-the-art facilities. Although plasma waves can provide high acceleration gradients, the instability issue is an obstacle for application. For the optimization of the generated beams, real-time diagnostics on detailed parameters of electron bunches are necessary.

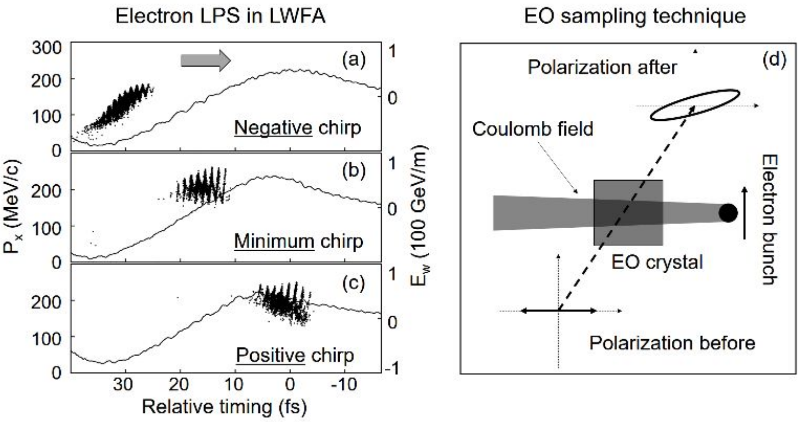

Fig. 1 (a-c) LWFA electron longitudinal phase space evolution at laser propagation times of (a) 8 ps, (b) 13 ps and (c) 21 ps. (1 ps = 10^{-12} s). The arrow in (a) shows the propagation direction of laser and electrons. Relative zero timing is defined by the peak position of the laser. Scattered points and curves illustrate the electrons and wakefield profiles, respectively. (d) Explanation of the electro-optic sampling method. The probe laser changes from linear polarization to elliptical polarization after propagating through the EO crystal due to the external Coulomb field of the electron bunch.

The longitudinal phase space (LPS) (E, t) of a high energy electron bunch is one of the most important parameters in beam physics. Since electrons in a bunch are trapped at different timings and experience different acceleration times, the LPS of the electron bunch exhibits various kinds of energy chirps (energy changes with time in a bunch). To explain it, I conducted a particle-in-cell (PIC) simulation, as shown in Fig. 1(a-c). The electron LPS rotates from negative chirp (Fig. 1(a)) to positive chirp (Fig. 1(c)). Although LPS is crucial for understanding the electron injection and acceleration process in plasma, it has not been measured experimentally due to the lack of single shot diagnostics at femtosecond level. Electro-optic (EO) sampling technique [3] was introduced into conventional accelerator research for single-shot non-destructive determination of the bunch lengths of high energy electron beams [4]. By setting the EO crystal with millimeters aside from the electron path, the electric field in the THz range acts as a DC bias inside the crystal. When a probe laser is incident simultaneously, the Pockels effect induced by the electric field causes birefringence and the temporal information of the electron bunch will be encoded to the probe laser, as shown in Fig. 1(d). I plan to measure the LPS (energy-time) information by a newly designed “EO streaking” technique in this proposal.

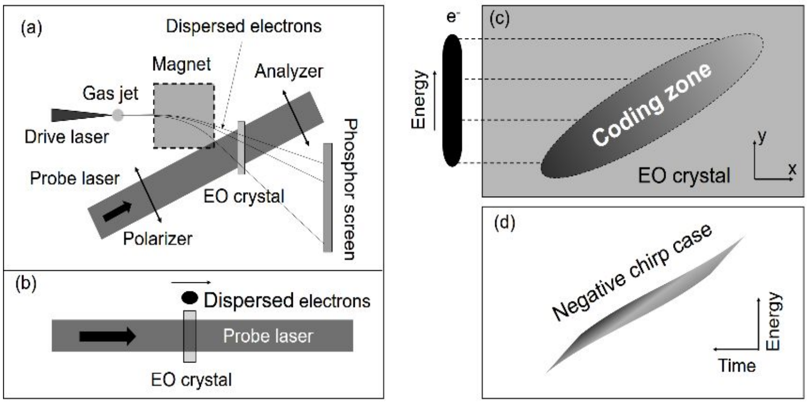

Fig. 2 “EO streaking” technique. (a) An experimental concept of the “EO streaking” technique. I plan to measure the electron temporal profile after electrons passing through a magnet. (b) Side view of (a). (c) Dispersed electrons create EO signals at different “y” positions in the crystal. (d)The EO signal is translated to the (E, t) LPS distribution after deconvolution calculation.

２．研究の目的

The purposes of this research are: (i) To develop an “EO streaking” technique suitable for LWFA experiments. (ii) To investigate the physical dependence of LPS distributions on key parameters such as laser intensity, plasma density, and plasma length by using the developed new technique. In conventional accelerators, the LPS of an electron bunch can be measured with a radiofrequency (RF) transverse deflection structure (TDS). Yet, in the case of laser-driven particle acceleration, it is difficult to build a stable deflection structure to temporally kick the electron bunch in femtosecond time scale. The proposed study will be a pioneering work for the investigation of electron beam dynamics in LWFA. The creative application of EO technique is also beneficial for the study of the dispersion characteristics of EO crystals in the wavelength range from mid-infrared to THz.

３．研究の方法

The electrons with different energies are dispersed in one direction via a dipole magnet. Simultaneously, the electron temporal information is measured by the EO crystal in a perpendicular direction with a probe laser. The concept design of the “EO streaking” is illustrated in Fig. 2(a). The EO crystal is placed slightly aside the electron bending plane to allow electrons passing by, as shown in Fig. 2(b). The electron energies are separated in “y” direction and the EO coding happens in “x” direction, as illustrated in Fig. 2(c). The Coulomb field of electrons with different energies might overlap in the EO crystal. A 2D deconvolution algorithm needs to be developed for the reconstruction and fitting of the original electron longitudinal bunch shape. After the deconvolution, a single shot LPS distribution will be achieved, as shown in Fig. 2(d).

４．研究成果

4.1 The design of a dog-leg magnet system

Though slightly different from the original plan, to better separate the electrons with different energies and maintain the direction, a “dog-leg” system was designed, as shown in Fig. 3(a). The electrons with different energies are illustrated by different colors. The designed magnets have length of 120 mm, magnetic field strength of 0.7 T and distance of 10 mm between each other. The photo of the magnets can be found as Fig. 3(b)). I have calculated electrons in the energy range between 295 ~ 305 MeV. The transportation of the electrons through the “dog-leg” system was calculated. The natural extra chirp induced by the system was calculated with a non-chirped electron beam. The transverse off-set of electrons with different energies at different positions can be found in Fig. 4(a-c). The timing lag introduced by the system is plotted in Fig. 4(d).

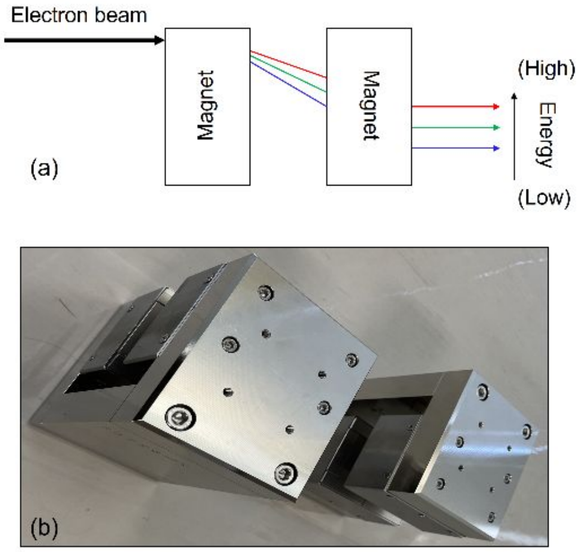

Fig. 3 (a) A concept of dog-leg magnet system to separate the chirped. electrons in space. (b) A pair of dipole magnets.

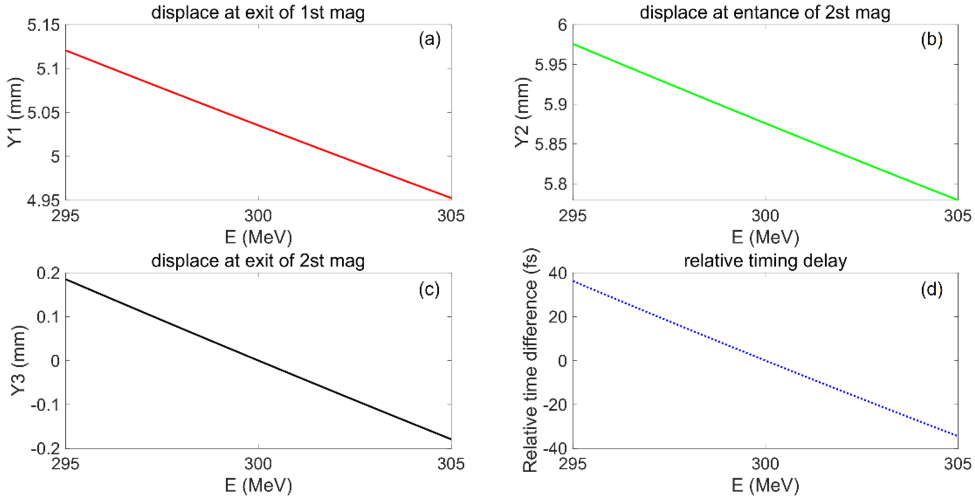

Fig. 4 The calculation of the electron propagation inside the dog-leg system. (a), (b) and (c) show the transverse off-set caused by the bending magnet at the positions of {exit of the magnet 1, entrance of the magnet 2, exit of the magnet 2}, respectively. (d) shows the relative timing delay caused by the overall system.

4.2 The theoretical calculation for the demonstration of the feasibility of this "EO-streaking" technique

A full calculation from the "dog-leg" to the EO signal generation was conducted with a self-made calculation code. The electron beam was considered to have a temporal chirp of + 3 fs/MeV. Each electron energy slice possesses a slicing bunch duration of 30 fs. Fig. 5(a) shows the calculated 2D EO signal by a transverse energy-chirped electron bunch. The timings of the peaks are then achieved at each electron energy and plotted out in Fig. 5(b). By subtracting the extra timing delay introduced by the dog-leg system, the original temporal energy chirped is reconstructed, as illustrated in Fig. 5(c). By this theoretical calculation, I demonstrated that this method can be used to reconstruct the LPS of the electron bunch.

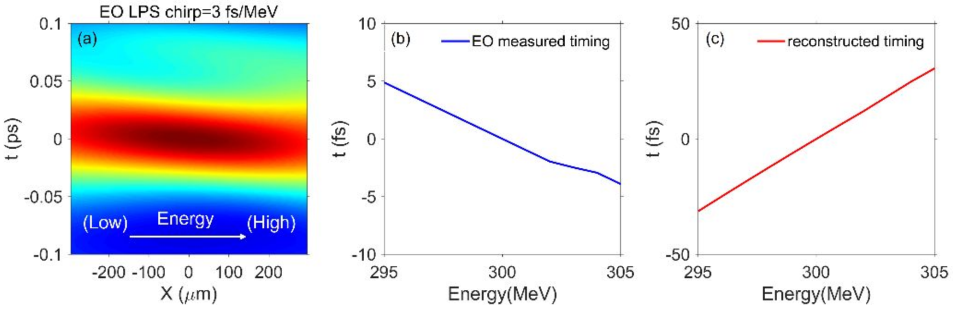

Fig. 5 (a) The EO signal generated by a chirped electron bunch. The electron energy distributes from left (low) to right (high) in the horizontal direction. (b) The peak timings of different electron energies in the EO signal. (c) The reconstructed timings of each electron energy considering the extra timing delay introduced by the "dog-leg" system.

4.3 Preliminary experiment of measuring the electron timing outside the plasma.

Though the theoretical calculation had been finished, due to the limited laser machine time and the complexity of the set-up, the final experiment measuring the LPS of the electron bunches was not conducted yet. As a preparation to achieve the final goal of measuring the LPS of the electron bunch, I carried out a preliminary experiment to monitor the electron timings outside the plasma. The experiment was conducted at the LAPLACIAN (Laser Acceleration Platform as a Coordinated Innovative Anchor) platform at the RIKEN SPring-8 Center, Japan. The experimental set-up can be found in Fig. 6(a). By performing EO spatial decoding on the transition radiation (TR) created by the electron bunch, I measured the temporal information of the electron bunch from LWFA in a single shot. The electron bunches were discovered to have a timing fluctuation of merely 7 fs (rms) [5], as shown in Fig. 6(b). This is, for the first time, a real-time demonstration of the electron jitter at femtosecond level in LWFA research. In a near-cross-polarization detection where the signal is proportional to the field strength of the TR, oscillations appeared in the signal, indicating that the electron bunch had a duration of < 50 fs (rms), as shown in Fig. 6(c). This work was published as "K. Huang et al., Applied Physics Express 15, 036001 (2022)". The paper was selected as the spotlight paper of the journal. Recently, this work was specially selected as the highlight of 2022 by the Japan Society of Applied Physics.

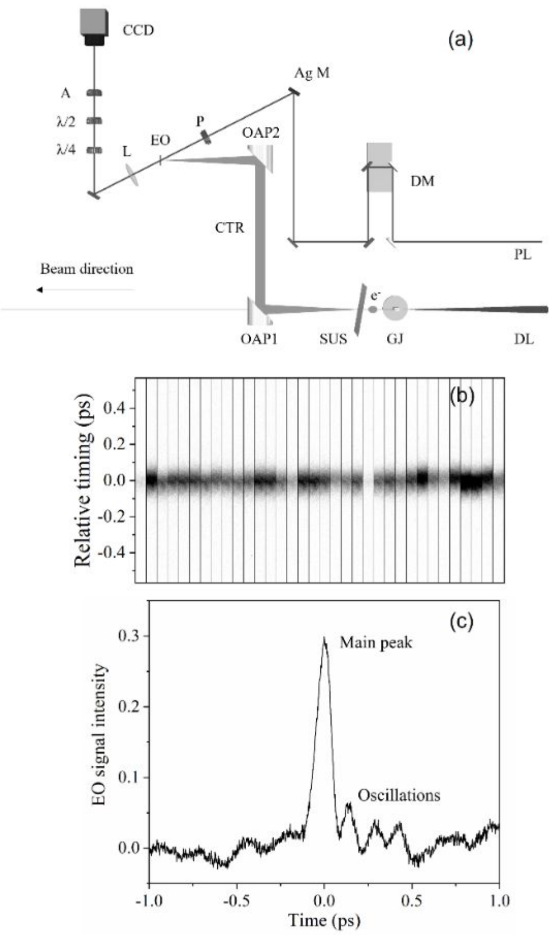

Fig. 6 (a) The experimental set-up of monitoring the electron timing outside the plasma. (b) The electron timing signals of consecutive 34 shots. (c) The EO signal with near-cross-polarization detection.

For the next step, I will insert the "dog-leg" into the experimental set-up. The longitudinal chirped electron bunch will be transformed to a transversely chirped bunch. The TR created by such a bunch will be imaged to an EO crystal for the EO sampling. By using the calculation code which I have developed, the original temporal chirp information of the electron bunches will be reconstructed.

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５．主な発表論文等

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２．論文標題 レーザー航跡場加速における電気光学サンプリングによる非破壊単発電子タイミング診断	５．発行年 2022年
３．雑誌名 加速器	６．最初と最後の頁 124～130
掲載論文のDOI（デジタルオブジェクト識別子） 10.50868/pasj.19.3_124	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 -

１．著者名 黄　開	４．巻 99
２．論文標題 電気光学サンプリング技術によるレーザー航跡場加速電子の時間特性評価	５．発行年 2023年
３．雑誌名 プラズマ・核融合学会誌	６．最初と最後の頁 33~39
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 有
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３．雑誌名 Applied Physics Express	６．最初と最後の頁 026001～026001
掲載論文のDOI（デジタルオブジェクト識別子） 10.35848/1882-0786/acb892	査読の有無 有
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１．著者名 Huang Kai、Jin Zhan、Nakanii Nobuhiko、Hosokai Tomonao、Kando Masaki	４．巻 15
２．論文標題 Experimental demonstration of 7-femtosecond electron timing fluctuation in laser wakefield acceleration	５．発行年 2022年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.35848/1882-0786/ac5237	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 -

〔学会発表〕　計8件（うち招待講演　4件／うち国際学会　3件）

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黄　開

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2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関