GA-assisted Single-shot 3D-charge-density reconstruction of a laser wakefield kilo-ampere electron bunch via a TR-EO detector

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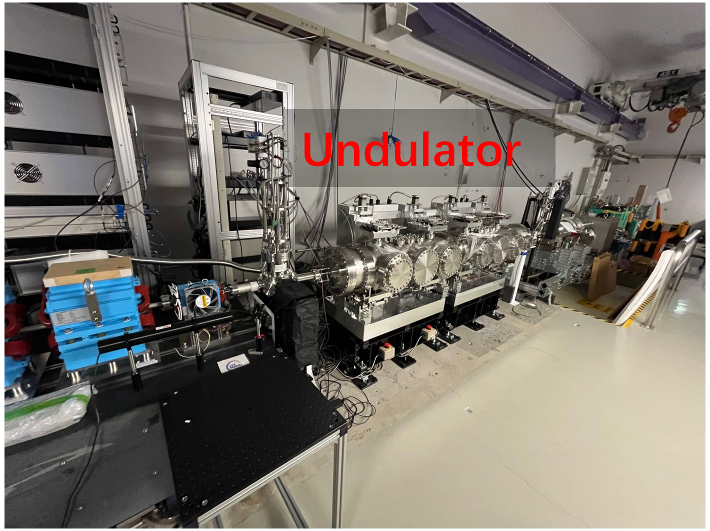
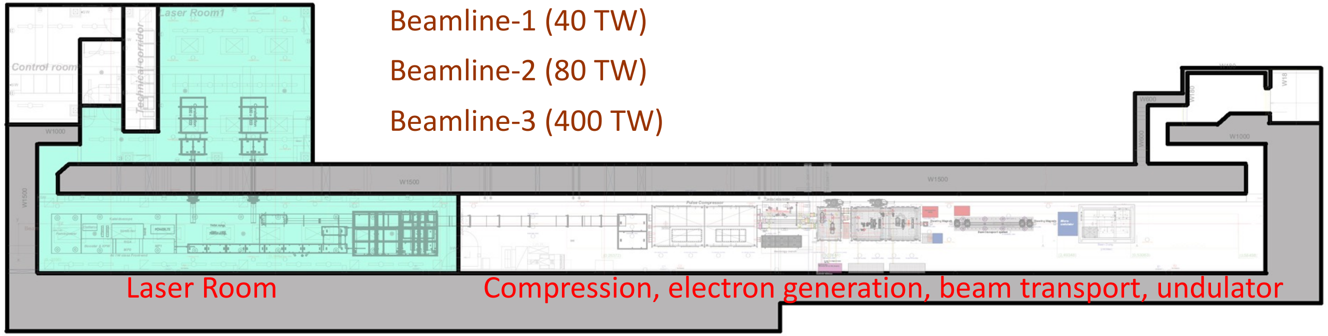
LAPLACIAN platform for laser electron acceleration





LAPLACIAN
Laser Acceleration Platform as a Coordinated Innovative Anchor

革新的研究開発推進プログラム ImPACT
Impulsing Paradigm Change through Disruptive Technologies Program

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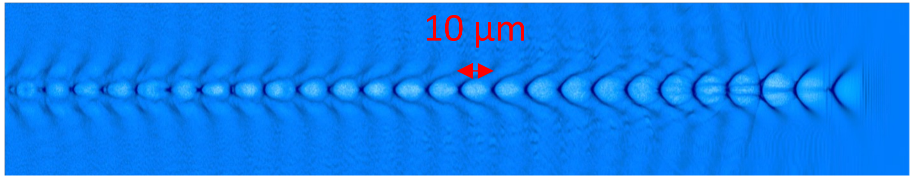
Laser wakefield acceleration (LWFA)

1 m -- 20 MeV

RF-Cavity: < 0.1 GV/m



LWFA: 100 GV/m

Present achievements of LWFA:

Maximum energy: ***7.8 GeV*** *(Berlekey)*

Smallest energy spread: ***0.4%*** *(rms) (SIOM)*

Highest repetition rate**:** ***1 kHz*** *(LOA)*

Highest charge: ***0.3 nC*** *(FWHM) (HZDR)*

FEL @ ***27 nm*** *(SIOM)*

100000 shots *(Hamburg U)*

T. Tajima and J. Dawson, Phys. Rev. Lett. 43, 267 (1979); W. P. Leemans et al., AAC (2018); W. T. Wang et al., Phys. Rev. Lett. 117, 124801 (2016); W. Wang et al., Nature 595, 516 (2021);D. Gunot et al., Nat. Photonics 11, 293 (2017); J. P. Couperus et al., Nat. Communications. 8, 487 (2017); A. R. Maier et al., PRX 10, 031039 (2020); Jens Osterhoff. DESY. 2017; T. Esirkepov, REMP code.

Why the electron bunch 3D charge density Q_{3D} is important for LWFA

High energy physics	⟺	Luminosity in a collider
X-ray pump-probe studies	⟺	Brightness of secondary X-ray sources
Time-resolved dosimetry	⟺	Peak dose rates of radiation

For the lasing process in an undulator

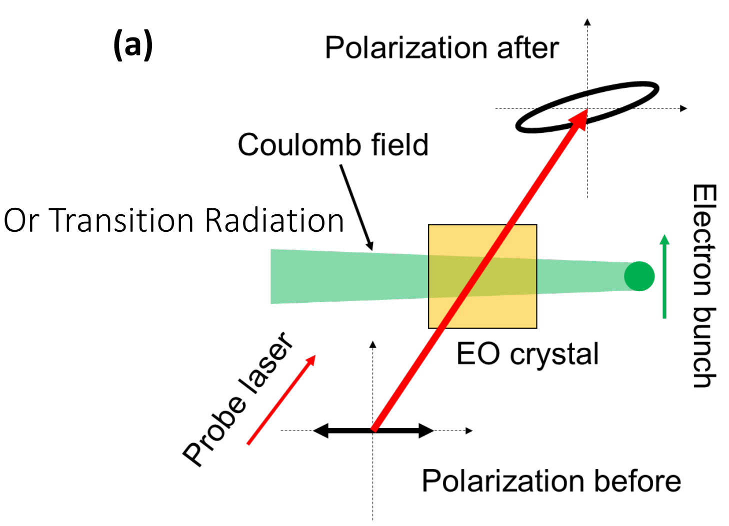
$$L_g \sim \frac{\lambda_u}{4\pi\sqrt{3}\rho} \qquad \rho \propto B_{6D} = \frac{2I}{\epsilon_n^2 \sigma_\gamma} \sim \frac{Q}{\sigma_x \sigma_y \sigma_z \sigma_{px} \sigma_{py} \sigma_{pz}} \qquad Q_{3D} \sim \frac{Q}{\sigma_x \sigma_y \sigma_z}$$

In LWFA: Not measured (B_{6D}) — Barely measured (Q_{3D})

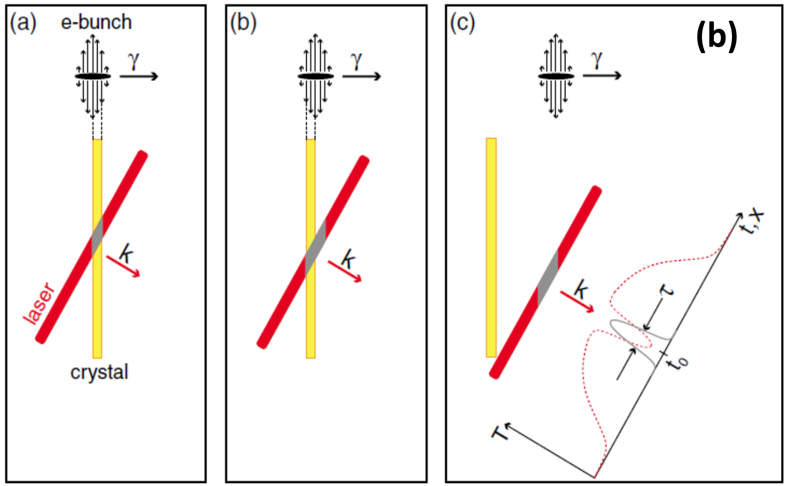
J. B. Rosenzweig et al., New J. Phys. **22 (2020) 093067**

Our approach: EO sampling

Pockels effect



EO spatial decoding



Temporal mapping relationship:

$$c\Delta\tau = \Delta\xi \, tan\theta_p$$

Merits:

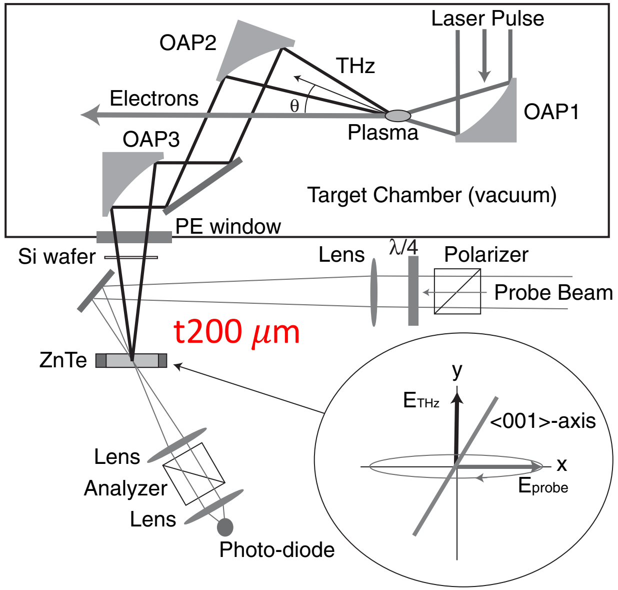
① **Non-destructive (sometimes not)**

② **Single-shot (overcome shot to shot variation exists in LWFA)**

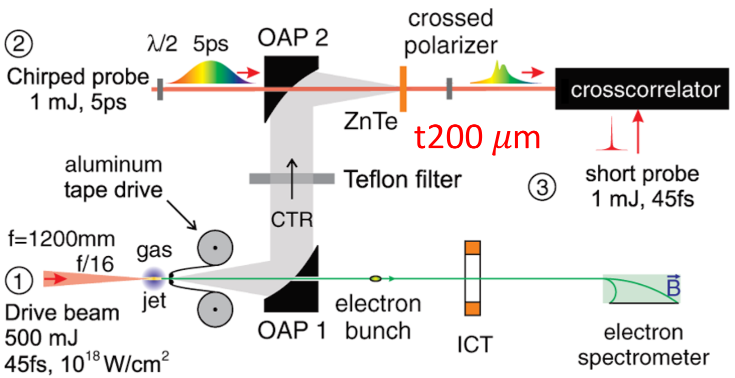
J. Shan et al., Optics Letters 25, 426 (2000); I. Wilke et al., PRL 88, 124801 (2002); A. L. Cavalieri et al PRL. 94, 114801 (2005); S. Casalbuoni et al., PRAB 11, 072802(2008); B. Steffen et al., PRAB 12, 032802 (2009); W. Wang et al., PRAB 20, 112801 (2017); K. Huang et al., PRAB 22, 121301 (2019); K. Huang et al., Sci. Reports 8, 2938 (2018) and many others…

Previous experiments in LWFA, detection on transition radiation (TR)

J. van. Tilborg et al., PRL 96, 014801 (2006)



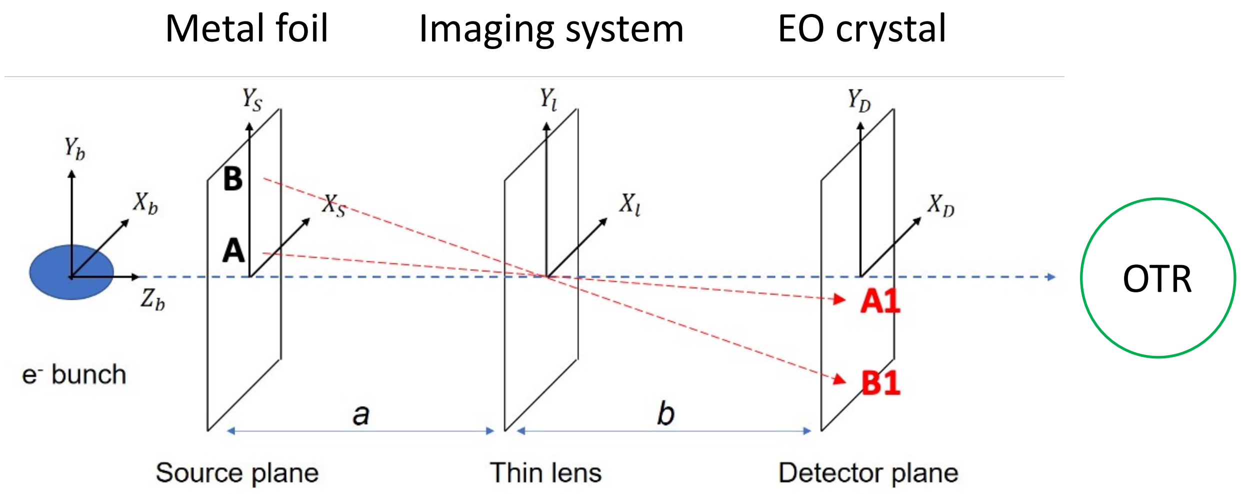
A. D. Debus et al., PRL 104, 084802 (2010)



TR from plasma/metal vaccum boudary —— TR imaging / EO sampling ——→ Relative longitudinal profile

(TR were partially collected, ZnTe 200 μm faces the first absorption valley around 4 THz, Absolute current file not discussed, TR transmitted through the crystal were not analyzed further)

Concept of such a TR-EO detection, and more…



EO sampling basically measures the TR field information. Much more can be achieved with such a mesurement

1. Optical TR (OTR) can be used simultaneously to achieve the transverse profile at μm level. Such spatial resolution is difficult for phosphor screens (Lanex, DRZ…)
2. Transverse electron profile need to be measured at the source plane for absolute current measurement

$$E_{image} = g_{\perp}^{bunch}(x, y) * E_0$$

3. EO sampling measures the field of TR. The image of TR field has spatial frequency distribution. One needs to know the spatial point where EO decoding signal is analyzed.

$$E_{image}(x, y, \omega)$$

Our study on the LAPACIAN platform

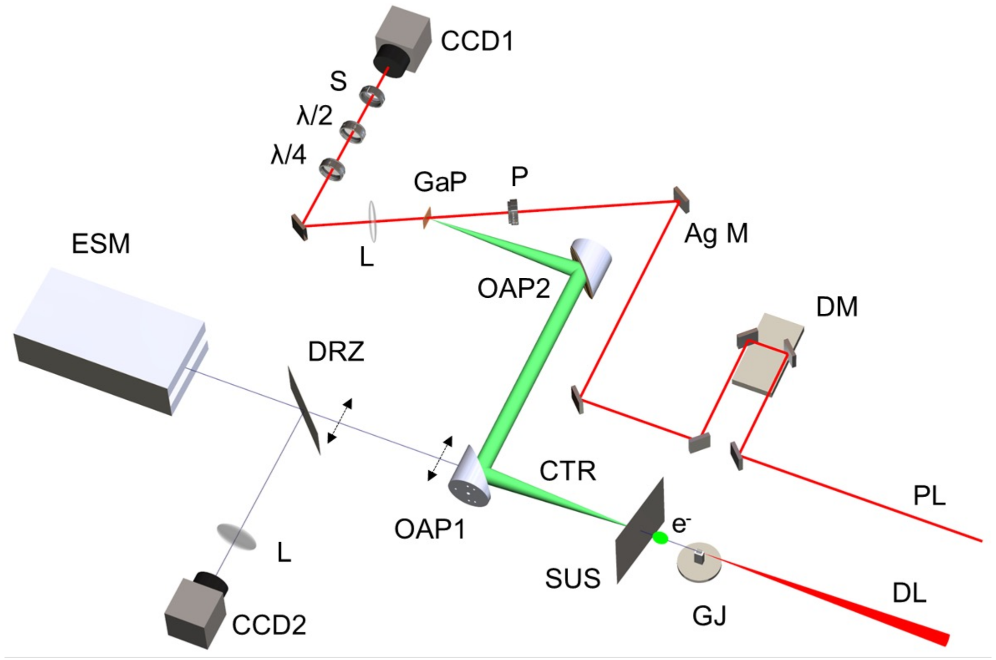
Electron <u>timing fluctuation</u> outside the plasma

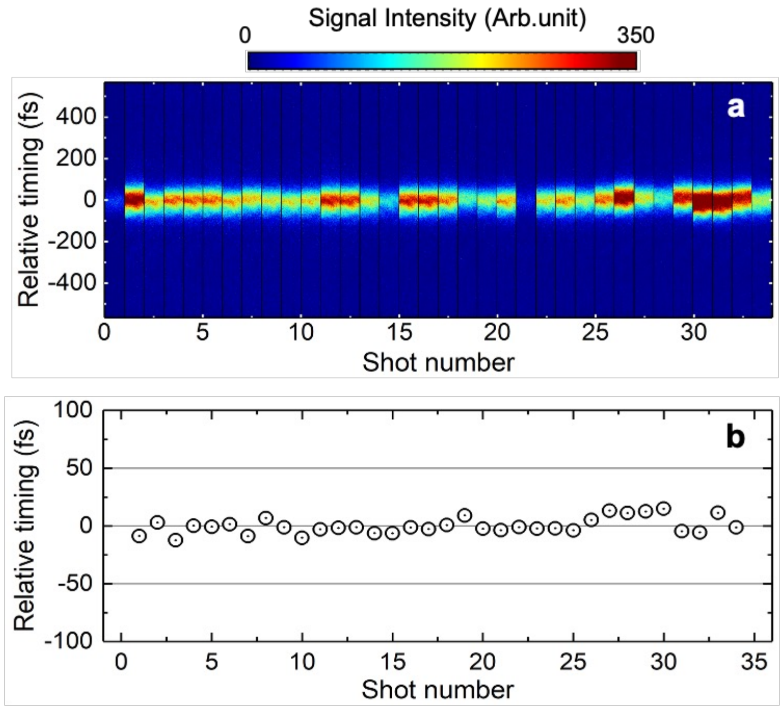
Electron <u>3D charge density</u> reconstruction via experimental measurement of OTR and EO signal. Numerical effort of TR imaging and EO spatial decoding. Genetic Algorithm

Single-shot monitoring of electron bunch timing outside plasma

Experiment

EO crystal: GaP 100 μm
Probe duration: not optimized
Mixture gas: $(H_2:N_2)=(99:1)$



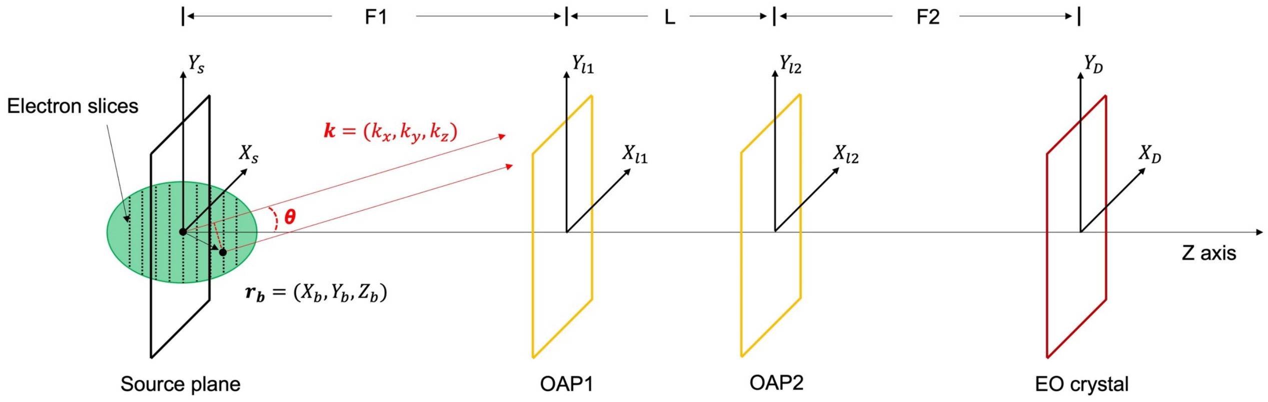


Extremely small fluctuation (outside plasma)
Standard deviation: 7 fs

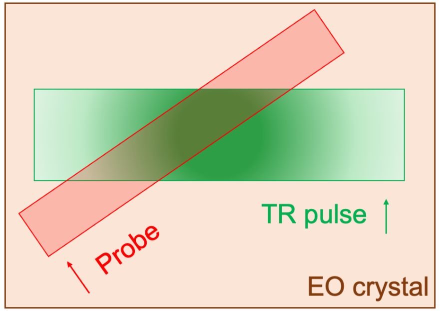
Kai Huang et al Appl. Phys. Express 15. 036001 (2022) (Monthly Spotlight and Annual Highlight)

Numerical effort of examining the calculation model

Calculation of TR imaging



Calculation of EO



Many issues have been dealt with:

1. Multi-color imaging (0 - > 200 THz). Huygens-Fresnel, step by step OR Fraunhofer
2. Multi-electron-energy. Weight of each energy component. Energy chirp can be neglected for short bunch
3. Temporal elongation of probe laser
4. Transverse TR distribution
5. Temporal distortion of TR in EO crystal
6. Formulation of the phase retardation considering the angle between the probe and the TR
7. Code vectorization for speeding up the GA calculation
8. Other issues.

K. Huang et al., arXiv:2308.11853 [physics.acc-ph], submitted to PRAB

Summary

3D TR imaging calculation (SI unit)

EO spatial decoding calculation

Integrated code for genetic algorithm

OTR and EO sampling measurement (single-shot)

↓

Electro-optic 3D snapshot of electron bunches at any position in the beam transport line
Timing jitter, 3D size, absolute current, charge density

Next:

1. Shorter probe laser; Thinner EO crystal; Try new EO crystal species; Detailed EO crystal property investigation at high frequency range
2. Analysis on the overall 2D EO signal. Try to optimize the method for $Q(x, y, z)$ reconstruction
3. Machine learning on the overall detection system

Thank you for your attentions

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