All-optical, quasi-real-time measurement of the 3- and higher-dimensional structure of microbunched electrons from a laser-driven wakefield accelerator

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Introduction

Multi-spectral coherent transition radiation (CTR) imaging has revealed 3D structure $\rho(r)$ of microbunched electrons. Here, we present a new experiment that measures CTR spectrum together with additional wavelength-resolved CTR images. Using GPU-accelerated differentiable simulations, the reconstruction speed is improved by a factor of ~100, enabling **quasi-real-time** reconstruction. The reconstruction algorithm requires only prior information obtained from optical measurements, eliminating the need for an electron spectrometer, make it **all optical**. Our method can be further extended to reconstruct the **5D phase space** of μ-bunched electrons.

Theory

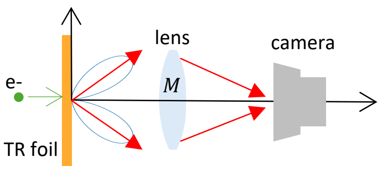

Fig.1

- Single-electron-induced transition radiation field $\boldsymbol{E}^{\mathbf{1}}(\boldsymbol{k},\boldsymbol{r})$ on the camera imaged by a lens system is given by

$$\boldsymbol{E}^{\mathbf{1}}(\boldsymbol{k},\boldsymbol{r}) = \frac{2e}{\lambda}\int_0^{\theta_{\max}} d\theta \cdot \frac{\theta^2}{\theta^2+\gamma^{-2}} J_1(k\theta r)\,\boldsymbol{e_r}$$

The 3D structure $\rho(\boldsymbol{r}')$ is encoded into total CTR field $\boldsymbol{E}^{(\boldsymbol{n})}(\boldsymbol{k},\boldsymbol{r})$ by

$$\boldsymbol{E}^{(\boldsymbol{n})}(\boldsymbol{k},\boldsymbol{r}) = \int dr'^3 \cdot Q\boldsymbol{E}(\boldsymbol{r}-\boldsymbol{r}')e^{-ikz'}\rho(\boldsymbol{r}')$$

- Form factor $\mathcal{F}(k)$ is partially measured by the CTR spectrometer

$$|F(\boldsymbol{k})| = \frac{1}{N}\sqrt{\frac{W_N}{W_1}} \approx F_z(\boldsymbol{k})$$

Methods

Electron bunches are treated as a set of macroparticles $\{p_i, i=1,2,\dots,n\}$. Each $p_i = (x_i, y_i, z_i, e_i, \gamma_i)$. The reconstruction algorithm finds best set of (x_i, y_i, z_i), to simultaneously minimize the difference between **measured** and **reconstructed**

1. Multi-λ CTR images
2. form factor $|F(\boldsymbol{k})|$

While e_i is determined by the number of macro particles we choose, γ_i follows the distribution measured by the e- magnetic spectrometer.

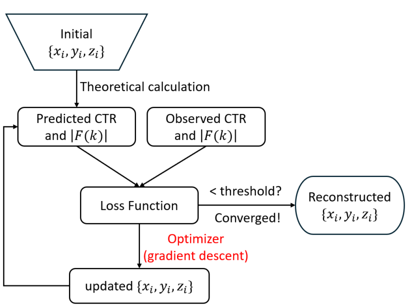

Fig.2 (reconstruction pipeline)

Experiment

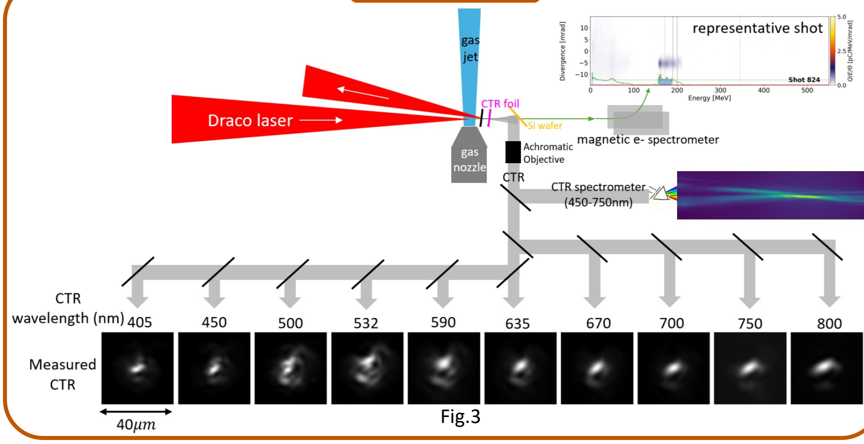

Fig.3

Results

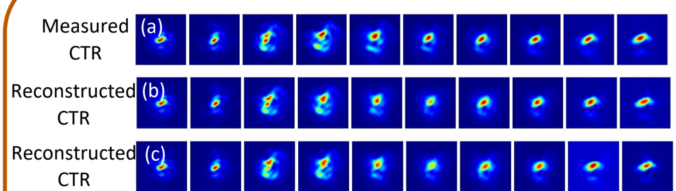

Fig.4

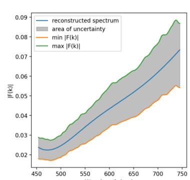

Fig.5

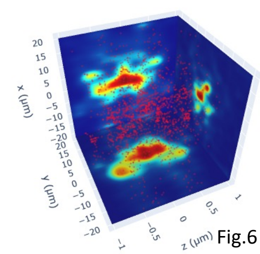

Fig.6

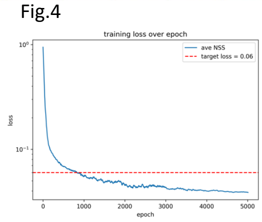

Fig.7

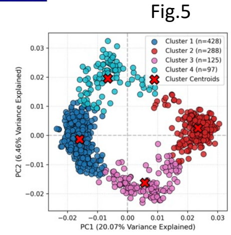

Fig.8

A representative reconstruction of electrons 3D structure is shown in Fig.6, the electrons are in a $40\mu m \times 40\mu m \times 2\mu m$ box. The reconstructed CTR images and form factor $|F(\boldsymbol{k})|$ are shown in Fig.4(b), and Fig.5, respectively. It takes about ~20s (1000 epochs) for the loss to decrease to a reasonable level in Fig.7. The reconstruction is not unique, we obtained ~900 different reconstruction and classified them into 4 groups by principal component analysis followed by K-means clustering. Fig.4(c) shows the CTR from a cluster-averaged electrons, indicating the same level of fidelity. the reconstruction algorithm captures the dominant structural features of the electron distribution.

Discussion

1. We revealed the 3D structure with more accuracy than before. The loss function is smaller compared to previous results. This is mainly attributed to more wavelength-resolved CTR images.
2. The reconstruction algorithm is robust and applies to other shots.
3. In a previous run data set, we found that less/more input charge than nominal charge leads to reconstruction with artifacts, meaning that by observing the artifacts, we can deduce the total charge of electrons. we also use Generative Neural Network to initialize the seed solution, and to reduce the number of parameters to fit. This method performs at the same level of that of gradient descent method presented here.

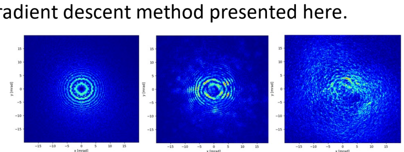

Fig.9

Outlook

1. The interference of two CTR sources could reveal the divergence, shown in Fig.9. A future upgrade could be observing this interferometry at the same time, enabling single-shot 5D reconstruction.
2. Our reconstruction framework is implemented in PyTorch and can be integrated with Cheetah for end-to-end differentiable beam-dynamics modeling.
3. The algorithm is sensitive to initial guess. A pretrained Neural Network could be used for inspiring the initial guess, which requires more experimental data and synthetic data to train the network.

Reference

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