Snapshot Imaging of Ultrafast Electron Pulses

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Ultrafast Electron Source for Diffraction and Imaging

Rose criterion: \[ \text{Shot noise} = \frac{1}{\sqrt{N}} \leq \frac{\text{constrast}}{\# \text{ of grey scale levels}} \]

Need \( \sim 100 \text{ e}^-/\text{pixel} \)

\( 10^7-10^9 \) detected electrons for an image

\( 10^5-10^7 \) detected electrons for a diffraction pattern

Pulse compression:

What affects the compressibility?

a) Initial phase space
b) Nonlinear effects from electron optics

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Projection Shadow Imaging Technique

Laser beam: 266nm, 50fs
Electron beam: 30keV

d: Projection distance, 5mm
L: Camera distance, 16.5cm
Magnification: L/d~33
Extraction field strength: 0~0.4 MV/m

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1) Photoemitted electron pulses cast shadow images. The density profile at the center of the bunch is extrapolated for analysis.

2) Ballistic expansion with the low-density electron bunch

3) Superlinear expansion with the high-density electron bunch, due to the space charge effect

Analytical Fitting Function:

\[ F(s) = F_{\text{pre}}(s) + \frac{x_0}{Ls} A \left( \frac{\exp \left[ -\frac{(s x_0 - L z_0)^2}{2(s^2 \sigma_x^2 + L^2 \sigma_z^2)} \right]}{\sqrt{\frac{1}{\sigma_x^2} + \frac{s^2}{L^2 \sigma_z^2}}} \right) \]

- \( \sigma_z \): the longitudinal length,
- \( z_0 \): the center of mass,
- \( A \): proportional to electron sheet density.


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1) Power-law scaling relationship between longitudinal width and number of electrons

\[ \sigma_z \big|_{t=100\text{ps}} = \sigma_0 \cdot \Sigma^\gamma, \text{where } \gamma \approx 0.5 \]

2) The power-law is consistent with different experimental conditions (Extraction field strength, \( F_S \) and laser fluence, \( F \))

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Single-electron Photoemission Model

**Step 1: Photon absorption**

**Step 2: Electron transport to the surface**

**Step 3: Emission**


Selection in the momentum space

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Virtual Cathode Effect

Space charge field of early emitted electrons
1) limits the quantum efficiency
2) affects the phase space of ultra-short electron pulse

Photoelectron density saturates with the increasing of the laser fluence


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Fast Multipole Method (FMM)

1) FMM encloses all the particles into the cube box with proper size and calculate the pairwise interaction using the local and far multipole expansion.
2) Efficiency of calculation is close to $O(N)$ and computation time is significantly reduced.

Photoemission Simulation with Multi-particle Interaction

1) Momentum space selection based on Three-step Model
2) Electron transport without scattering
3) Image-charge distribution
4) Space charge field calculated using FMM

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He Zhang, Martin Berz, Nucl. Instr. and Meth. A, 645, 338 (2011)

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1) Electron bunch profile

**a)** Non-gaussian profile at the birth, while the front profile agrees with shadow image very well.

**b)** With the electron bunch evolving, the shape is more close to Gaussian shape.

**c)** The peak number of electrons reaches ~$10^8$ e\textsuperscript{-} at the beginning, while only ~$7 \times 10^6$ e\textsuperscript{-} are able to escape.

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Photoemission simulation predicts the power law dependence of electron bunch width on the number of electrons with the exponent $\sim 0.56$
Conclusion

Four aspects of photoemission and space charge effects as high-brightness ultrafast electron source:

1) Virtual cathode effect

2) Power-law scaling of bunch size with number of electrons

3) Non-linear phase space distribution

4) Initial phase space broadening

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