Ultra-low Charge, Ultra-high Brightness
Frontiers of Photoinjectors: Challenges and Perspectives

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Outline

• Pursuing better beams - FEL, UED/UEM
• Generation of higher brightness
• Characterizing these extreme beams
• Better machines and new science
• Summary and outlook
Pushing Science frontiers with electron beams

Linac Coherent Light Source

TEAM: Transmission Electron Aberration-corrected Microscope

1.7 km

3 m
Pushing Science frontiers with electron beams

Linac Coherent Light Source

TEAM: Transmission Electron Aberration-corrected Microscope

Enabled by EXTREME, but very different electron beams
Pushing Science frontiers with electron beams

**e-beams for XFEL**
- > ~10 GeV beam energy
- $\Delta E/E \sim 1 \times 10^{-4}$
- $10^8$-$10^9$ e- per pulse
- kA beam current
- extremely short – 10 fs
- flat photocathode
- control the collective effects

**1.7 km**

**e-beams for TEM/STEM**
- < ~300 keV beam energy
- $\Delta E/E < 1 \times 10^{-6}$
- $10^6$-$10^9$ e- per image
- pA beam current
- extremely narrow – 50 pm
- tip field-emission source
- optics, with aberration correction

**TEAM: Transmission Electron Aberration-corrected Microscope**

**Linac Coherent Light Source**

**3 m**
FEL requirement on e-beams

**SASE FEL: high gain & trans. coherence**

1D gain length

\[ L_{G}^{1D} = \frac{\lambda u}{4\pi \sqrt{3} \rho} \]

Saturation power

\[ P_{\text{sat}} \approx \rho P_{e} \]

Pierce parameter

\[ \rho = \left[ \frac{1}{16 I_{A}} \frac{K_{0}^{2} [J_{J}]^{2}}{\gamma_{0}^{3} \sigma_{x}^{2} \kappa_{u}^{2}} \right]^{1/3} \]

Geometric emittance

\[ \frac{\varepsilon_{n}}{\gamma_{0}} \leq \frac{\lambda}{4\pi} \]

Energy spread

\[ \sigma_{\eta} \ll \rho \]

**LCLS transverse profile at**

- \( z = 25 \text{ m} \)
- \( z = 50 \text{ m} \)
- \( z = 75 \text{ m} \)

Z. Huang and K.-J. Kim, PRSTAB 10, 034801 (2007)
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LCLS transverse profile at

- z=25 m
- z=50 m
- z=75 m

Photoinjectors deliver required e-beams for FEL

Cut-away view of the LCLS gun. Courtesy of E. Jongewaard

Z. Huang and K.-J. Kim, PRSTAB 10, 034801 (2007)
RF photoinjector-based MeV UED and UEM

- ultralow charge (< ~1 pC)
- ultralow emittance (< ~10 nm)
- directly serve ultrafast science
- R&D at SLAC, UCLA, Tsinghua, Osaka, BNL, DESY, LBL, Shanghai Jiaotong, SFTC, KAERI

X. J. Wang et al., PAC’03, p. 420.        P. Musumeci and R. K. Li, in ICFA Newsletter No. 59 (2013)
Beam brightness from photoinjectors

- 5-D normalized beam brightness

\[ B_{5D} = \frac{I}{\epsilon_n x \epsilon_n y} \]

- Most XFELs driven by photoinjectors
- Photoinjectors deliver excellent transverse emittance, as well as longitudinal emittance
- Most facilities operate at 0.1 – 0.5 nC
- Higher \( B_{5D} \) at lower charge, but beam diagnosis becomes more challenging
- Many new techniques for low charge (<1 pC) developed for UED and UEM

\[ B_{5D} \text{ normalized brightness (A/m}^2) \]

Using slice emittance in the calculation

emittance of low charge electron beams

• Project and slice emittance

• $\epsilon_{\text{rf}}, \epsilon_{\text{optics}}, \epsilon_{\text{sc}}, \epsilon_{\text{intri}}, \ldots$

B. E. Carlsten, NIMA 285, 313 (1989)
Serafini & Rosenzweig, PRE 55, 7565 (1997)

• $\epsilon_{\text{rf}}$, mainly projected emittance, is much reduced for smaller beam dimensions

$$\epsilon_{\text{rf}} = \frac{eE_0}{2\sqrt{2}mc^2} \sigma_x^2 \sigma_{\phi}^2, \quad \langle \phi \rangle = 90^\circ$$

K.-J. Kim, NIMA 275, 201 (1989)

• $\epsilon_{\text{optics}}$ - chromatic and spherical aberrations

  • Chromatic: different $x - x'$ slope for different slice energy
  • Spherical: nonlinearity in slice $x - x'$ distribution – might be corrected

Beam shaping – low charge but still high charge density

- Uniformly filled ellipsoidal is ideal – linear SC forces and phase-space


Space charge forces:
- Linear
- Slice-independent

Gaussian bunch

Thermal-emittance-limited beam!

- Practical and robust in experiment – transverse shaping of ultrashort laser

Useful even for longer UV laser

P. Musumeci et al., PRL 100, 244801 (2008)
F. Zhou et al., PRST-AB 15, 090701 (2012)
Cigar-shape beams

- Pancake regime: relatively large initial spot size and intrinsic emittance
- Cigar regime – an alternative way to generate 3D ellipsoid beam
  - Tiny laser spot (10s of µm) on the cathode, hence very low $\epsilon_{\text{intri}}$
  - Long (several ps), parabolic laser temporal profile
  - Transverse SC expansion creates ellipsoidal beam, again

Transverse SC expansion, & frozen longitudinal motion.

Ideal regime for ultralow charge, nm-emittance beams!

R. K. Li et al., PRST-AB 15, 090702 (2012)
Space charge limit in emission

- **pancake**
  - Maximum surface charge density set by the extraction field
  
  \[
  \frac{Q}{\pi R^2} < \epsilon_0 E_0
  \]

  Dowell, USPAS 2010

 Courtesy of P. Musumeci

- **cigar**
  - Only charge within a radius distance from the cathode contributes to space charge field
  
  \[
  Q = J_{CL} \pi R^2 \propto \frac{V^3}{d^2} R^2 \propto (E_0 R)^{3/2}
  \]

  D. Filippetto et al., PRST-AB 17, 024201 (2014)
Collimation can improve the brightness

- Part of the beam (always) has higher phase-space density
- outside electrons help maintain the high density in the core

\[ R = \frac{B_{5D} \text{ center 50\% beam}}{B_{5D} \text{ 100\% beam}} \]

‘Good’ and ‘bad’ electrons? The bad ones make the others better.
Collimation can improve the brightness

- Part of the beam (always) has higher phase-space density

![Graph showing higher density and lower density regions in a beam](image)

- Outside electrons help maintain the high density in the core

‘Good’ and ‘bad’ electrons? The bad ones make the others better.
Higher extraction field - new gun geometry

- Brightness depends on $E_0$: $B_{5D} \propto E_0$ (pancake) and $B_{5D} \propto E_0^{3/2}$ (cigar)
- Higher $E_0$ allows more emission, also suppresses SC induced emittance growth

- 1.6 cell to 1.4 cell shifts the launching phase from 30° to 70°. Note $\sin(70°)=0.94$.
- $E_0$ roughly x2 times higher

R. K. Li and P. Musumeci, PRApplied 2, 024003 (2014)
Intrinsic emittance

Thermal emittance \[ \epsilon_n = \sigma_x \sqrt{\frac{\hbar \omega - \phi_{\text{eff}}}{3mc^2}} \]

Quantum efficiency \[ \text{QE}(\omega) \propto (\hbar \omega - \phi_{\text{eff}})^2 \]

Minimizing \( \hbar \omega - \phi_{\text{eff}} \) can reduce \( \epsilon_n \), but at the cost of QE

Dowell and Schmerge, PRST-AB 12, 074201 (2009)

**Cu:** 0.35 mm-mrad/mm w/ mid-10^{-5} QE @ PSI

<table>
<thead>
<tr>
<th>Cathode field (MV/m)</th>
<th>Quadratic component (nm/mm²)</th>
<th>( \epsilon_{\text{int}}/\sigma_t ) (nm/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>49.9</td>
<td>724 ± 84</td>
<td>428 ± 16</td>
</tr>
<tr>
<td>34.8</td>
<td>505 ± 137</td>
<td>370 ± 25</td>
</tr>
<tr>
<td>16.4</td>
<td>321 ± 105</td>
<td>346 ± 25</td>
</tr>
</tbody>
</table>

**Cs_3Sb:** 0.21 mm-mrad/mm w/ 7×10^{-5} QE @ Cornell

- Effects of surface roughness
- Tuning extraction field and photon energy independently
- Limitation due to laser damage of the cathode and demand on laser power
- Explore more exotic emission mechanism
- Don’t forget the temporal response of the photo-emission

Prat, PRST-AB 18, 063401 (2015)
Cultrera, arXiv:1504.05920
Measure nanometer emittance

Knife-edge, single-shot emittance measurement

R. K. Li et al., PRST-AB 15, 090702 (2012)

Relies on high spatial-resolution measurement of low charge beams

- Low charge ≠ low charge density
- SC effects should be carefully evaluated

S. G. Anderson et al., PRST-AB 5, 014201 (2002)

Solenoid scan using very low charge

25 aC×120 shots

2 mm

5 μm rms
Imaging single electrons

Optimized phosphor screen + high collection optics + Electron Multiplying CCD (EMCCD). Achieved Single electron detection capability!

R. K. Li et al., J. Appl. Phys. 110, 074512 (2011)

CMOS direct detection detector

- Single e- sensitivity
- Excellent PSF (<10 um)
- Fast readout (>400 fps)
- Radiation hard (yrs lifetime) at 300 keV
- Commercialized for electron microscope

Revolutionary impact on cryo-EM

Y. G. Shi et al., 10.1126/science.aac7629

Courtesy of D. Contarato & P. Denes
Femtosecond bunch length measurement

How to measure only 5 MeV, <10 fs beams?

- 10 fs UED, external injection
- Beam is only short within a few cm

Study the spectrum of CTR (Compare 1 THz and 5 THz)

- Use Bolometer
- Strong dependence on transverse spot size
- Can be limited by rf phase and amplitude jitter

C. Behrens et al., Nature Commun. 5, 3762 (2014)

R. K. Li et al., JAP 110, 074512 (2011)
X. H. Lu et al., PRST-AB 8, 032802 (2015)
Time-of-Arrival monitor

Bunch arrival-time monitor (BAM)

- sub-10 fs for 20 pC beams (FLASH, ELBE, and SwissFEL), similar BAM at LCLS
- Cone-shape can be optimized for lower beam charge (REGAE)
- But, there is extra jitter due to the regen and user laser

Optical cross-correlation

- Direct measurement between pump (optical laser) and probe (x-ray).
- Same principle could work for e-beams. (Cesar & Musumeci et al.)
FELs enabled by a few pC, <30 nm-rad, kA electron beams

- Single-spike SASE $\sigma_z \sim 2L_c$: sub-fs pulses
- Compact FELs

1 pC-case studies

Y. Ding’s talk, TUA01, Generating Femtosecond to Sub-Femtosecond X-Ray Pulses at Free Electron Lasers

- more challenging diagnostics and beam control (especially at existing facilities)
- Consider collective effects: wakefields, LSC, CSR ($\delta_{CSR} \propto I \sigma_z^{-1/3}$)
Acknowledgement

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• Colleagues at SLAC, UCLA, and Tsinghua University


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Summary and outlook

- We can produce ultrahigh brightness with ultralow beam charge
- Charge density still high – require beam shaping and collimation
- Control the photoemission process – emittance and current density
- New techniques/detectors to measure these beams – both in x-y and in time
- Energy spread not discussed here but critical for micro-bunching and harmonic-generation for FELs, and chromatic effects in UEMs
- Merging FEL and TEM beams – ultrafast, ultra-narrow and ultra-stable
- High brightness, high precision frontier of photoinjectors
- Understand and control each e- nicely, and use it for good science.

Thank you for your attention!