High Brightness Photoinjectors of Tomorrow: Physics of Beam Brightness at the Frontier

DOE Early Career: Investigation of Fundamental Limits to Beam Brightness Available From Photoinjectors

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world's highest avg current & brightness photoinjector at Cornell
Research objectives

• Goals:
  – Understand fundamental physics and technology limits to high brightness beam production in photoinjectors;
  – Cathode research:
    • Photoemission physics modeling & measurements of intrinsic mean transverse energy (MTE), response time, and quantum efficiency (QE) of non-metal photocathodes (QE ≥ 5%);
    • Explore and engineer novel photocathode materials in real-life accelerator conditions of a high average current photoinjector
  – Beam dynamics:
    • Realization of the brightness limit from the photoinjector as set by space charge and the photocathode mean transverse energy spread
    • Among the physics issues being tackled: virtual cathode instability & adaptive laser shaping for lowest emittance
Need for high brightness beams

- Powerful probes of matter
  - Colliders, fixed target experiments
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  - Small lab scale probes (e.g. ultrafast electron diffraction)

600 fs snapshots of Al melting, Dwayne Miller, U Toronto
Need for high brightness beams

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  - Colliders, fixed target experiments
  - Small lab scale probes (e.g. ultrafast electron diffraction)
- Sources of secondary beams
  - Synchrotron radiation sources: storage rings, free electron lasers, energy recovery linacs

Petra-III – world’s brightest storage ring
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![XFEL oscillator concept](image)
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Energy Recovery Linac X-ray source concept
Need for high brightness beams

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  - Colliders, fixed target experiments
  - Small lab scale probes (e.g. ultrafast electron diffraction)
- Sources of secondary beams
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- Cooling of hadron beams

coherent electron cooling being tested at BNL
What is brightness?

• 6D phase space
  – \{x, p_x, y, p_y, E, t\}

• \( \beta_{4D} = \frac{\text{flux or current}}{4D \text{ phase space volume}} \)

• Connection to:
  – Liouville theorem, beam temperature, entropy, coherence
Example: linear optics beamline of non-interacting particles
Some definitions

- **Micro-brightness**: \( \mathcal{B}_{2D}(x, p) \)
  
  - Flux: \( \mathcal{F} = \iint \mathcal{B} \, dx \, dp \)

- **Normalized emittance (phase space area)**:
  
  \[ \varepsilon_{\text{norm}} = \frac{1}{mc} \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle xp_x \rangle^2} \]
  
  - e.g. quantum limit for e\(^-\): \( \varepsilon_{\text{norm}} = \frac{\hbar/2}{mc} = 1.93 \times 10^{-13} \, \text{m} \)

- **Alternative definition of phase space area (volume)**
  
  - “Liouville’s emittance”: \( \varepsilon_{\text{Liouville}} = \left[ \frac{4\pi}{mc} \iint \left( \frac{\mathcal{B}}{\mathcal{F}} \right)^2 \, dx \, dp \right]^{-1} \)
  
  - coherence length: \( L_\perp = \frac{\hbar}{mc} \frac{\sigma_x}{\varepsilon_{\text{norm}}} \)
Linear and non-linear motion (continuous focusing channel)

- Liouville’s emittance: const in both cases
Space charge in a continuous focusing channel
Space charge in a continuous focusing channel

emittance vs distance

• But Liouville’s emittance stays const
Tricky space charge

- Beam as non-neutral plasma: 3 characteristic lengths
  - $\alpha$: beam diameter; $l$: inter-particle distance; $\lambda_D$: Debye length

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\lambda_D \gg \alpha \quad \text{YES}
\]

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\lambda_D \gg l \quad \text{YES}
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\lambda_D = \frac{\sigma v_\perp}{\omega_p} = \frac{\sqrt{k_B T_\perp / \gamma m}}{\omega_p}
\]

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\omega_p = \sqrt{\frac{e^2 n}{\epsilon_0 m \gamma^3}}
\]

-集体作用力有关

- “smooth force”
  - 6D phase space volume conserved

- “grainy forces”
  - must deal with 6N-D phase space
Information loss in phase space
Accelerator topologies

Linac

Ring

Recirculators

source

RF

beam dump
Photoinjectors = marriage of physics and technology

normal conducting RF gun

SRF gun

DC gun

plus variants…

- CW operation: max cathode fields: (DC \leq 10 \text{ MV/m}), NCRF (\leq 20 \text{ MV/m}), best promise for SRF (\leq 30 \text{ MV/m})
Physics 101: basic limit to beam brightness from photoinjectors

- Each electron bunch assumes a ‘pan-cake’ shape near the photocathode for short (≤ 10ps) laser pulses.

- Maximum charge density determined by the electric field:
  \[ \frac{dq}{dA} = \varepsilon_0 E_{\text{cath}} \]

- Angular spread set by mean transverse energy (MTE) of photoelectrons
  \[ \Delta p_{\perp} \sim (m \times \text{MTE})^{1/2} \]

\[ \frac{B_n}{f} \bigg|_{\text{max}} = \frac{\varepsilon_0 mc^2}{2\pi} \frac{E_{\text{cath}}}{\text{MTE}} \]

\[ \varepsilon_{n_{\perp}} = \sqrt{\frac{3}{10\pi\varepsilon_0 mc^2}} q \frac{\text{MTE}}{E_{\text{cath}}} \]

Optimization study: SRF vs DC guns

- Vary gun geometry while realistically constraining the voltages
- Full beam dynamics with 3D space charge
- Multiobjective parallel genetic optimization

**DC gun**, 3 geometry parameters: gap, cathode angle & recess

**SRF gun**, 4 parameters: gap, cath angle & recess, pipe dia

Optimization study: SRF vs DC guns

**DC Gun**

- MTE=25meV
- MTE=120meV
- MTE=500meV
- MTE=120meV (10ps)

**SRF Gun**

- MTE=25meV
- MTE=120meV
- MTE=500meV

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Accelerator test-beds at Cornell

- Two accelerators make this CAREER work possible: NSF supported 100mA 5-15 MeV photoinjector;

- New 500kV photoemission gun & diagnostics beamline (processed to 400kV and ongoing): the main ‘playground’ for a PhD student (J. Maxson)
Two accelerators make this CAREER work possible: NSF supported 100mA 5-15 MeV photoinjector;
Accelerator test-beds at Cornell

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REER work possible: NSF photoinjector;

- Two accelerators make this CAREER work possible: NSF photoinjector;
  - NSF supported 100mA 5-15 MeV photoinjector;
  - SRF cryomodule
  - HV DC gun
  - Laser system
  - Coldbox
Accelerator test-beds at Cornell

- SRF cryomodule
- 6xRF 135 kW klystrons
- HV DC gun
- coldbox
- laser system

Two accelerators make this CAREER work possible: NSF supported 100mA 5-15 MeV photoinjector; laser system; SRF cryomodule; coldbox; HV DC gun; laser system.
Accelerator test-beds at Cornell

- 6xRF 135 kW klystrons
- SRF cryomodule
- world's brightest photoinjector!
- HV DC gun
- coldbox
- laser system
Photocathode research at Cornell: some results

- Wide selection of photocathodes experimentally evaluated for the first time (MTE, response time, accelerator performance): GaAs, GaAsP, GaN, Cs$_3$Sb, K$_2$CsSb, Na$_2$KSb

CAREER-supported journal publications related to photocathodes to date:

- Appl. Phys. Lett. 98 (2011) 224101
- Appl. Phys. Lett. 98 (2011) 094104
- Appl. Phys. Lett. 102 (2013) 034105
- J. Appl. Phys. 113 (2013) 104904
Cornell cathode facilities: low MTE, high QE, robustness

- Over in Newman Lab
- Over in Wilson Lab
- Over in Phillips Hall

- Dedicated MBE system
- Antimonide growth & analysis chamber
- Actual accelerator

Cornell Campus
Breakthrough in modeling

Simulation snapshot

- Monte-Carlo simulation tool for III-V family photocathodes
  - Fully developed for both non-layered reflective cathodes as well as layered & transmission mode structures
Modeling of photocathodes: a predictive tool in hand

- Simulations explain existing experimental data for bulk GaAs taken by our group without free fit parameters
- Next, will extend this tool to antimonides & cryogenically cooled materials

Molecular Beam Epitaxy: towards ultra-cold photoemitters

- MBE: ultimate tool for photocathodes
  - Lowest emittance cathode grown (x2 improvement over bulk GaAs!)
- Starting to “engineer” new types of MBE photocathode structures

*W. Schaff, IVB, et al. (2013) in preparation*
Getting high average current

- **Ion back-bombardment**: a sure killer of sensitive photocathodes

- **Best prior achievements**
  - Boeing FEL RF gun 32 mA avg (25% d.f.)
  - JLAB FEL DC gun 9.1 mA avg (100% d.f.)
Robust photocathodes at Cornell

May 25, 2013

2000 Coulomb delivered from Na$_2$KSb

Beam current (mA)

Time (hours)
Practical lifetimes for ~100 mA operation

- Lifetime good enough to operate for ~ week without interruption at 65 mA!
- Highest avg current so far 75 mA (limited by RF processing in input couplers)
- Exceeded the 1993 Boeing results by >x2!

Ultralow emittance: many ‘tricks’ needed to get there

- 6D phase space diagnostics!
- ‘Virtual accelerator’: 3D space charge, 3D RF cavity field models, quads, dipoles, etc.
- Beam-based alignment via beam response matrices from fieldmaps
- Improved 3D laser shaping
- And many others…

*Phys. Rev. ST-AB 15, 024002 (2012)*  
*Phys. Rev. ST-AB 14, 032002 (2011)*  
*Phys. Rev. ST-AB 14, 112802 (2011)*  
*Nucl. Instr. Meth. A 614, 179 (2010)*  
...
Emittance results after ‘merger’

20 pC/bunch

80 pC/bunch

Normalized rms emittance (horizontal/vertical) 90% beam, E ~ 8 MeV, 2-3 ps rms

0.22/0.15 mm-mrad

Normalized rms core* emittance (horizontal/vertical) @ core fraction (%) 0.14/0.09 mm-mrad @ 68%

0.49/0.29 mm-mrad 0.24/0.18 mm-mrad @ 61%

20x the brightness at 5 GeV of the best storage ring (1nm-rad hor. emittance 100 mA)!

Similar to the best NCRF guns emittance but with > 10^6 repetition rate (duty factor = 1)

Measured time-resolved phase space distribution

20 pC/bunch

80 pC/bunch

2.1±0.1 ps

3.0±0.2 ps

Energy spread: 0.1-0.2%
Measured time-resolved phase space distribution

20 pC/bunch

80 pC/bunch

GPT: $\sigma_t = 2.2$ ps, data: $\sigma_t = 2.1$ ps

GPT: $\sigma_t = 3.1$ ps, data: $\sigma_t = 3.0$ ps

Energy spread: 0.1-0.2%
To the fundamental brightness limit...

- Fundamental limit to emittance compensation?
  - ~90% final emittance can be due to thermal (cathode) emittance according to simulations; ~70% according to the latest measurements

- Main physics issues for reaching cathode emittance
  - 'virtual cathode' instability → longitudinal breaking of the bunch at the cathode
  - control of non-linear space charge forces → better 3D laser shaping

- Fundamental limit to the lowest cathode emittance (from beam physics point of view)?
  - Set by 'disorder-induced-heating' to cryogenic temperatures (depends on beam density)

'virtual cathode' instability

`\( kT \text{[eV]} \)`

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Key CAREER Crew

Siddharth Karkare  
PhD student  
CAREER 100% support

Dr. Luca Cultrera  
Research Associate  
CAREER 50% support

Jared Maxson  
PhD Student  
(NSF PhD fellowship)  
(will be supported by  
CAREER 100%  
starting 2014)
Support & Our Team

• NSF DMR-0807731 for ERL R&D support
  – 2 M$/year funds the photoinjector and gun development providing a unique accelerator test-bed and infrastructure
• DOE DE-SC0003965 CAREER grant
  – 0.15M$/year mostly supporting the CAREER personnel and some of the photocathode work
Summary

• World’s brightest high rep rate electron source at Cornell, e.g. can be used to drive x-ray FELs and ERLs (if a 5 GeV ERL were built today, x20 better beam than Petra-III and x200 than APS); another x10 straightforward improvement in photoinjector brightness anticipated over the next few years;

• New parameter space for accelerators, new beam physics challenges in view;

• Photocathode research in full steam, photoemission physics insights now drive new material selection;

• Virtual photocathode instability and new adaptive laser shaping work starting now as the new photoemission gun comes online;

• Future beyond 2014 (the current NSF grant) is uncertain;