New Electron Source for Energy Recovery Linacs

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**ERL – Injector Prototype**

Cornell’s photoinjector: world’s brightest electron source
Outline

- Uses of high brightness electron beams
- Physics of brightness
- High brightness high current photoinjectors
- Cornell photoinjector for Energy Recovery Linac
Acknowledgements: our team & NSF for funding and more …
Need for high brightness beams

- Powerful probes of matter
  - Colliders, fixed target experiments

CEBAF 12 GeV

Add 5 cryomodules

20 cryomodules

Add arc

Enhanced capabilities in existing Halls

Add 5 cryomodules

20 cryomodules

New Hall
Need for high brightness beams

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

• Sources of secondary beams
  – Synchrotron radiation sources: storage rings, free electron lasers, energy recovery linacs
Need for high brightness beams

- **Powerful probes of matter**
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  - Small lab scale probes (e.g. ultrafast electron diffraction)
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- Cooling of hadron beams

coherent electron cooling being tested at BNL
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What is brightness?

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

- \[ \beta_{4D} = \frac{\text{flux or current}}{\text{4D phase space volume}} \]

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

- **Micro-brightness**: \( B_{2D}(x, p) \)

  - **Flux**: \( \mathcal{F} = \iint B \, dx \, dp \)

- **Normalized emittance (phase space area)**:

  \[
  \epsilon_{\text{norm}} = \frac{1}{mc} \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle xp_x \rangle^2}
  \]

  - e.g. quantum limit for \( e^- \): \( \epsilon_{\text{norm}} = \frac{\hbar}{mc} = 1.93 \times 10^{-13} \text{ m} \)

  - **geometric emittance**: \( \epsilon_{\text{geom}} = \sqrt{\langle x^2 \rangle \langle \theta_x^2 \rangle - \langle x \theta_x \rangle^2} = \epsilon_{\text{norm}} / (\beta \gamma) \)

- **Alternative definition of phase space area (volume)**

  - “Liouville’s emittance”: \( \epsilon_{\text{Liouville}} = \left[ \frac{4\pi}{mc} \iint \left( \frac{B}{\mathcal{F}} \right)^2 \, dx \, dp \right]^{-1} \)
Linear and non-linear motion
(continuous focusing channel)

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

position

momentum

transverse position
Space charge in a continuous focusing channel

- But Liouville’s emittance stays const

\[ \varepsilon(s) / \varepsilon(0) \]
Tricky space charge

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

\[
\lambda_D \gg a \quad \text{YES} \\
\lambda_D \ll a \\n\text{collective forces matter}
\]

\[
\lambda_D \gg l \\
\lambda_D \ll l \\
\text{“smooth force”} \\
6\text{D phase space volume conserved}
\]

\[
\lambda_D = \frac{\sigma v_\perp}{\omega_p} = \frac{\sqrt{k_B T_\perp/\gamma m}}{\omega_p}
\]

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

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

Linac

Ring

Recirculators/ERL

source

RF

beam dump

source
Synchrotron radiation sources

• Some approaches to light production
  
  undulators (spontaneous emission)  Free-electron-laser (oscillator)

\[ \lambda_n = \frac{\lambda_p}{2\gamma^2 n} \left( 1 + \frac{K^2}{2} \right) \]

• Desired electron beam parameters
  – Transverse phase space area (emittance) \( \sim \) wavelength
  – Energy spread \( \sim 1/\#\text{periods} \)
  – Short pulses (\( \sim \) picosecond and less)
Storage rings for hard x-rays

**APS:** circumference 1.1 km, emittance 3 nm

**ESRF:** circumference 0.84 km, emittance 4 nm

**Spring-8:** circumference 1.4 km, emittance 3 nm

**PETRAIII:** circumference 2.3 km, emittance 1 nm
Storage rings for hard x-rays

APS: circumference 1.1 km, emittance 3 nm
ESRF: circumference 0.84 km, emittance 4 nm
Spring-8: circumference 1.4 km, emittance 3 nm
PETRA III: circumference 2.3 km, emittance 1 nm

For transverse coherence at 1Å require

$$\epsilon_{geom} = \frac{\lambda}{4\pi} \approx 0.01 \text{ nm}$$
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Photoinjectors = marriage of physics and technology

normal conducting RF gun  

LANL RF gun

SRF gun

½ cell  Tuner  RF / HOM ports

Cathode stock  Choke filter 3 full cells

ELBE SRF gun

DC gun

Cornell gun

plus variants…

• CW operation: max cathode fields:  
  (DC ≤10 MV/m), NCRF (≤ 20 MV/m),  
  best promise for SRF (≤ 30 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
  \[ \Delta p_\perp \sim (m \times \text{MTE})^{1/2} \]

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

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

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Cornell photoinjector

- NSF-supported accelerator R&D test-bed, fully beam-operational starting 2010
  - Main goals: <1 μm normalized rms emittance (to best storage rings)
    average current 33mA @ 15MeV & 100mA @ 5MeV (demonstrate photocathode longevity)
    2-3 ps bunch length
Cornell photoinjector

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[Diagram showingCornell photoinjector components: beam dump, diagnostics, beam lines, HV DC gun, laser system, cryomodule, buncher, photocathode DC gun]
Cornell photoinjector

- main goals:
  - <1 \mu m normalized rms emittance (to best storage rings)
  - average current: 33 mA @ 15 MeV & 100 mA @ 5 MeV (demonstrate photocathode longevity)
  - 2-3 ps bunch length

Cornell photoinjector

- DC gun
- cryomodule
- buncher
- SRF cryomodule
- photocathode
- 5 m beam dump
- diagnostics
- beam lines
- laser system
- HV DC gun
Cornell photoinjector

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Cornell photoinjector

- SRF cryomodule
- cryomodule
- buncher
- photocathode
- DC gun
- 5 m
- fully beam-operational
- HV DC gun
- coldbox
- laser system
Cornell photoinjector

**Main goals:**
- ≤ 1 µm normalized rms emittance (to best storage rings)
- Average current: 33 mA @ 15 MeV & 100 mA @ 5 MeV (demonstrate photocathode longevity)
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**Components:**
- HV DC gun
- SRF cryomodule
- laser system
- coldbox
- 6xRF 135 kW klystrons
- photocathode
- DC gun
- beam dump
- beam lines
- SRF cryomodule
- coldbox
- laser system
- HV DC gun
- 6xRF 135 kW klystrons
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- world's brightest photoinjector!
Beam dynamics inside the photoinjector (80 pC/bunch)

\[ \Delta p_x \text{ (keV/c)} \]

\[ \Delta p_z \text{ (keV/c)} \]

\[ \Delta x (\text{mm}) \]

\[ \Delta z (\text{mm}) \]

\[ \sigma_x = 0.294 \text{ mm} \]

\[ \sigma_z = 0.000 \text{ mm} \]

\[ \varepsilon_x = 0.077 \text{ mm-mrad} \]

\[ \varepsilon_z = 0.000 \text{ mm-keV} \]
Getting high average current

- **Must couple ~MW RF power** into the beam without disturbing the low emittance

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

  - Re-cesiation recovers Q.E.  
  - Damage is only at the surface

- **Best prior achievements**
  - Boeing FEL RF gun 32 mA avg (25% d.f.)
  - JLAB FEL DC gun 9.1 mA avg (100% d.f.)
Highest current at Cornell photoinjector with CsK$_2$Sb

- 60 mA with > 30 hour 1/e lifetime (run the beam offset!)
- went as high as 65 mA (limited by RF processing in input couplers)

- Exceeded the 1993 Boeing results by x2!

Ion damage limited to the central area

Active area is offset from the center
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

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%

80 pC/bunch

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: 2.1±0.1 ps
80 pC/bunch: 3.0±0.2 ps

Energy spread: 0.1-0.2%
Energy Recovery Linac

- If built today, would be the world’s brightest source of continuous x-rays (x20 better than Petra-III); another x10 improvement in photoinjector brightness anticipated over the next couple of years.

- Superconducting RF cavity tests demonstrated better than spec’ed $Q_0$ inside the cryomodule (lower LHe refrigeration power).

- An entirely different concept of a new and better x-ray source using ERL configuration has been proven feasible!

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$Q_0$ of SRF cavities exceeds the spec by 50%
The End