ERL photoinjector R&D at Cornell

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world’s highest brightness & current operating cw photoinjector
Today’s talk

- Part I: ERL R&D @ Cornell
- Part II: ultimate beam brightness from DC/SRF guns
ERL development timeline

1965: M. Tigner
Nuovo Cimento
37 (1965) 1228

1986: Stanford SCA
T. Smith et al.
NIM A 259 (1987) 1

1990: S-DALINAC
(Darmstadt)

1998: BINP FEL

1999: JLAB DEMO-FEL

2002: JAERI FEL

2004: JLAB FEL Upgrade

2004: ERL-P

2005: Cornell gets $`

KEK, BESSY

Cornell ERL R&D effort

- CHESS
  - X-ray science case (XDL’11 series of 6 workshops in Ithaca, NY for diffraction limited X-rays), undulator R&D
- SRF group
  - Manufactured the first main linac 7-cell cavities, main linac cryomodule prototype
- ERL photoinjector facility
  - Operating the world’s highest current and brightness CW photoinjector
- Gun development lab
  - Laser lab, beamline diagnostics, and Mark-II gun under construction (more from Jared)
- Photocathode lab
  - Material science of high QE photocathodes, cathode engineering
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Photoemission source development

- Two accelerator facilities @Cornell to push photoinjector state-of-the-art: NSF supported 100mA 5-15 MeV photoinjector;

- New 500kV photoemission gun & diagnostics beamline (under construction): the main ‘playground’ for Jared
ERL photoinjector highlights

• Over the last year:
  
  – Demonstrated feasibility of high current operation (hundreds of Coulomb extracted with minimal degradation to QE)
  
  – Original emittance spec achieved: now getting x2 the thermal emittance values, very close to simulations (Sept 2011)
High current operation

~600C delivered (same spot)

QE before

QE after
Real-life accelerator testing for photocathodes: high average current

- CsKSB cathode after delivering ~600C.
Old Boeing RF gun record still stands!
But I bet not for long…

• ‘Dramatic accelerator physics’ – drilled a hole in the dump (1” Al) with electron beam!
• Raster wired incorrectly, (de)focusing quad setting off
• The dump is being repaired, back to Cornell in 2 weeks
6D beam diagnostics: key to success

- Transverse phase space (animation)
- Slice emittance with resolution of few 0.1ps
- Projected emittance
- Longitudinal phase space
Just last month: emittance spec achieved!

- **Keys to the result**
  - Beam-based alignment (took us a couple of months)
  - Fantastic diagnostics!! (one of the reasons we are here)
  - Fight jitters in the injector

- $\varepsilon_{ny}(100\%) = 0.4 \text{ um } @ 20\text{pC/bunch}$

- $\varepsilon_{ny}(100\%) = 0.8 \text{ um } @ 80\text{pC/bunch}$

- x2 thermal emittance! x1.3 simulated emittance
- correct scaling with bunch charge
Some proselytizing: which emittance is right to quote

- Single **RMS emittance definition is inadequate for linacs**
  - Beams are not Gaussian
  - Various groups report 95% emittance or 90% emittance (or don’t specify what exactly they report)

- The right approach
  - Measure the **entire phase space**, then obtain emittance of the beam vs. fraction (0 to 100%)

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### Graphs

**Left:**
- 20 pC/bunch
- $\varepsilon_{\text{core}} = 0.15\,\mu\text{m}$
- $f_{\text{core}} = 73\%$

**Right:**
- 80 pC/bunch
- $\varepsilon_{\text{core}} = 0.3\,\mu\text{m}$
- $f_{\text{core}} = 67\%$
But the undulator radiation in central cone is Gaussian… or is it?

animation: scanning around 1st harm. ~6keV
(zero emittance)

Spectral flux (ph/s/0.1%BW/mm²) at 50m from undulator (5GeV, 100mA, λₚ = 2cm)
Light in phase space

animation: scanning around 1st harm. ~6keV (zero emittance)

Phase space near middle of the undulator (5GeV, 100mA, $\lambda_p = 2$cm)
Emittance vs fraction for light

\[ \epsilon_x \approx 2.7 \frac{\lambda}{4\pi} \]

phase space of light

\[ \beta_x \approx 0.45 L_{\text{und}} \]

emittance vs fraction (of light!)

core emittance is \( \frac{1}{2} \frac{\lambda}{4\pi} \)

(same as Gaussian!), but

\( \epsilon(100\%) \) is much larger

Bazarov, Synchrotron radiation in phase space (in preparation)
Just how bright is Cornell ERL injector beam?

- Effective brightness (for comparison)

\[ B_0 \propto I \frac{f_{x,\text{core}} f_{y,\text{core}}}{\epsilon_{x,\text{core}} \epsilon_{y,\text{core}}} \]

- Today’s 20mA ERL injector beam is as bright as 100mA 0.6nm-rad × 0.006nm-rad storage ring Gaussian beam!

- Parity in transverse brightness with the very best rings is already achieved; the result can only improve
Photocathode research at Cornell

- multalkali growth chamber with vacuum suitcase
- GaAs system with load-lock
- in-vacuum LEED/Auger

- Also on campus
  - AFM, EDX, SEM, STM, SIMS, ARPES
- + CHESS (XRF, x-ray topography, EXAFS, and much more)
Photocathode research: some results

- Wide selection of photocathodes evaluated for MTE and response time: GaAs, GaAsP, GaN, Cs₃Sb, K₂CsSb

- 10%QE in green now routine

- Just 2011 alone
  - APL 98 (2011) 224101
  - APL 98 (2011) 094104
  - APL 99 (2011) accepted
  - PSTAB (2011) submitted
  - PRL (2011) in preparation
Photocathode research: moving forward

- Exciting prospects of generating sub-thermal (ultracold) photocathodes, i.e. photocathodes with essentially zero thermal emittance;
- About to grow our first MBE III-V with tuned parameters!
Building collaboration on photocathodes for accelerators

- Collaboration with
  - ANL
  - BNL
  - JLAB
  - SLAC
  - Berkeley
- Excitement and momentum in the community;
- Cathode workshop at Cornell in 2012;
- Leading the effort on creating collaborative community-driven Internet resource;
3D laser shaping for space charge control

- Optimal 3D laser shape: practical solutions identified

 temporal – birefringent crystal pulse stacking

 transverse – truncated Gaussian

- >50% of light gets through, emittance (sims) ~20% higher than the optimal

PRSTAB 11 (2008) 040702
Appl. Opt. 46 (2011) 8488
Plenty of laser power now!

1.3GHz laser at 65W

should operate reliably at ~40W

Future outlook: towards ultimate brightness from DC/SRF guns

• Jared Maxson (part II)

Comparing DC and SRF guns
• The final answer:
  – Given a laser, photocathode, and accelerating gradient → Max. beam brightness is set!

• Take a short laser pulse, < 10 ps:
  – Beam assumes pancake distribution
  – There is a max charge density supportable!
    \[
    \frac{dq}{dA} = \varepsilon_0 E_{\text{cath}}
    \]

• Take a particular photocathode & laser:
  – Transverse momentum spread intrinsic to photoemission
  – There is a minimum emittance achievable!
    \[
    \Delta p_{x,y} \sim (m \times MTE)^{1/2}
    \]
    \[
    \epsilon_{nx,y} = \sigma_{x,y} \sqrt{\frac{MTE}{m \cdot c^2}}
    \]
• Transverse brightness:
  \[ B_{n,ave} \sim \frac{I}{\epsilon_{nx}\epsilon_{ny}} = \frac{q_b f}{\epsilon_{nx}\epsilon_{ny}} \]

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

• \( q \): (Determined by \( E_{cath} \))
  – What are the \textbf{largest gradients achievable} with existing technology, pushed to its limits?

• \( f \):
  – What are the technologies that best support \textbf{CW operation}?

• \( \epsilon_{nx} \):
  – Can we transport the thermal emittance, wrangling \textit{space charge dilution} and \textit{element abberations}?
High Brightness Sources

• A host of high brightness photoinjectors are being built for various ERL/FEL applications.

• For the Cornell ERL, we need:
  – **100 mA** average current
  – **< 1 mm-mrad** norm emittance

• Once upon a time...
  – DC guns were a viable (stable!) CW option at the time
  – Local expertise in negative affinity GaAs
  – ...so an injector was born!
• What about normal conducting RF guns?
  – Much success in for pulsed applications (SLAC, LCLS)
  – **Large field** at the photocathode
  – **Stable, pulsed** operation

• CW operation not so easy:
  – Field emission → poor vacuum
  – Poor vacuum quality → Poor photocathode lifetime
  – Lots of power, heat → Limited to lower frequency

• Can be done!
  – Dave Dowell and the Boeing RF gun
  – 1992 demonstration of 32 mA average current (running at 25% duty factor)
  – Limited by vacuum quality, and...
The Boeing 433 MHz RF Photocathode Gun

...it was a beast!
DC guns are deceptively simple:
  - HVPS, Stalk, Ceramic, and electrodes

Voltage limited by ceramic puncture
  - Field emission from HV stalk bores holes through alumina HV vacuum envelope.

Lower beam energy:
  - Emittance dilution
  - Large charge beam instability
  - Hard to transport, sensitive to element aberrations.
• But you get:
  – Inherent CW operation
  – Excellent vacuum
  – Design simplicity, small inherent aberration.

• Overcoming ceramic puncture
  – KEK segmented insulator
  – Define voltage on each segment with metallic guard rings.
  – MK II gun @ Cornell: my PhD

• MK II will also feature:
  – Adjustable cathode/anode gap
  – Biased anode?
With ceramic puncture mitigated...
  – Still limited by UHV breakdown in beam region.

– Inherent tradeoff between energy, field at the cathode, and focusing strength.
• Also (conceptually) simple:
  – **n+1/2 cell** SRF cavity, with a photocathode at position of max gradient
  – Quarter wave resonator is another option
  – **Low RF losses** means CW operation is viable
  – Huge (>30 MV/m) cathode gradients
  – MeV beam direct from the gun!

• Practical limitations:
  – High QE photocathode load lock, puck insertion mechanism challenging
  – Lots of places for **field emission**!

• Fields only limited fundamentally by SRF quenching.
• SRF guns promise to deliver high brightness beams with only a few fundamental drawbacks.
• But how much better is better?
• Let’s consider the ultimate (ideal) gun design for both types:
  – Subject to only fundamental constraints
  – Simulate them on the same linac (ERL inj. Prototype)
  – Performance:
    • Emittance vs. Bunch charge
    • Beam envelopes
• Ultimate performance = (ultimate gun design) + (fully optimized beamline)

• Utilizing multi-objective genetic optimizer + 100 node computer cluster:
  – **Specify**: RF frequency (1.3 GHz), cathode intrinsic emittance, current (0-200mA, or 0-154 pC/bunch), beamline elements.
  – **Vary**: gun geometry, gun voltages, laser temporal profile, solenoids, SRF cavity voltages & phases
  – **Minimize**: emittance after 10m.
  – **Constrain**: fields to be within “fundamental limitations”.

• Specifics:
  – Calculate discrete set of gun geometries (Poisson/Superfish) \(\rightarrow\) export 1D field map
  – Optimizer requests from continuous gun geometry parameter set \(\rightarrow\) interpolate field map in multi-D space.
DC Gun Geometry

- Field constraint: Voltage, given a min cathode-anode gap, must be below breakdown.
• Select: 1.3 GHz, ½ cell
  – Only one (half) cell! 200mA (beam) $\rightarrow$ 400kW coupler power—tough at 1.3 GHz.

• Use optimistic field constraints (TESLA nine cell)
  • $E_{acc} \leq 25$ MV/m
  • $E_{peak}/E_{acc} \leq 2$
  • $H_{peak}/E_{acc} \leq 4.26$ mT/(MV/m)

• Majority of possible solutions were constrained by $E_{pk} (\leq 50$ MV/m).
• Equatorial radius used as the tuning parameter.
• The effect of space charge at the photocathode will be different for each gun:
  – The temporal pulse shape should have a strong effect on the final emittance:
• Optimizer can use combinations of archetypical shapes:
Beamline parameters

(a)

(b)

DC Gun

SRF Gun

$E_z$ (MV/m)

$B_z$ (100G)
• The SRF beamline is simplified:
  – NC buncher cavity is ineffective at high beam energy
  – Only one solenoid included
• **Cathode Mean Transverse Energy:**
  
  – Thermal *(intrinsic)* emittance:
    
    \[ \varepsilon_{nx} = \sigma_x \sqrt{\frac{MTE}{mc^2}} \]
    
  – 25 meV:
    
    • Lowest MTE for NEA GaAs *(room temp!)*
    • vacuum cleaved
  
  – 120 meV:
    
    • Cornell’s MTE for NEA GaAs @ 520 nm
    • *in operando.*
  
  – 500 meV

• **Note:** Initial sims request long *(~100 ps)* DC gun laser pulse length
  
  – Keep solutions, but this is hard to do!
  
  – Subsequent run: constrain pulse to <10 ps
Emittance Performance

**DC Gun**

- MTE=25meV (filled blue circles)
- MTE=120meV (green squares)
- MTE=500meV (red diamonds)
- MTE=120meV (10ps) (green squares)

**SRF Gun**

- MTE=25meV (filled blue circles)
- MTE=120meV (green squares)
- MTE=500meV (red diamonds)

Y-axis: rms normalized emittance (μm)

X-axis: charge per bunch (pC)

(a) DC Gun

(b) SRF Gun
Optimal Gun Geometry:

- **DC Gun:**
  - $\alpha \approx 0$, $g = 9$ cm, $V=470$ kV
  - Pushed for *max field* over focusing.
  - Cathode recess unimportant.

- **SRF gun:**
  - $\alpha = 2.3$, $g = 4.4$ cm
  - $r_{pipe} = 0.9$ cm, $r_{cath} = 0.4$ cm
  - $r_{pipe}$ and cathode recess seemed unimportant.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>dc gun</th>
<th>SRF gun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>80 pC</td>
<td>80 pC</td>
</tr>
<tr>
<td>Laser spot size (rms)</td>
<td>0.35 mm</td>
<td>0.21 mm</td>
</tr>
<tr>
<td>Laser pulse (rms)</td>
<td>10 ps</td>
<td>9 ps</td>
</tr>
<tr>
<td>Thermal emittance (rms)</td>
<td>0.17 μm</td>
<td>0.10 μm</td>
</tr>
<tr>
<td>Cathode field (t = 0)</td>
<td>5.1 MV/m</td>
<td>16.6 MV/m</td>
</tr>
<tr>
<td>Kinetic energy after the gun</td>
<td>0.47 MeV</td>
<td>1.91 MeV</td>
</tr>
<tr>
<td>Buncher peak field</td>
<td>1.2 MV/m</td>
<td>…</td>
</tr>
<tr>
<td>SRF cavities1,2 peak (E_z)</td>
<td>20, 22 MV/m</td>
<td>11, 6 MV/m</td>
</tr>
<tr>
<td>SRF cavities1,2 phase</td>
<td>-25, -37°</td>
<td>-60, -40°</td>
</tr>
<tr>
<td>Solenoid1 peak field</td>
<td>0.038 T</td>
<td>0.094 T</td>
</tr>
<tr>
<td>Solenoid2 peak field</td>
<td>0.023 T</td>
<td>…</td>
</tr>
<tr>
<td>Transverse emittance (rms)</td>
<td>0.21 μm</td>
<td>0.15 μm</td>
</tr>
<tr>
<td>Bunch length (rms)</td>
<td>0.89 mm</td>
<td>0.86 mm</td>
</tr>
<tr>
<td>Longitudinal emittance (rms)</td>
<td>8.2 mm keV</td>
<td>9.2 mm keV</td>
</tr>
<tr>
<td>Kinetic energy</td>
<td>12.4 MeV</td>
<td>10.3 MeV</td>
</tr>
</tbody>
</table>
...But can it be done?
• **Space charge energy chirp @ photocathode:**
  – leaves a nasty chromatic aberration through the solenoids!
  – Far more *prominent in DC case*. Must anti-chirp with buncher!

• **Space charge dominated emittance evolution:**
  – Difficult to quantify analytically!
  – Precise knowledge of orbits and phases (read alignment, calibration, and sims) required to compensate!
  – Just beyond state of the art

• **Recent alignment run @ Cornell ERL injector:**
  – Sim: 1.1 x thermal; Measured: 2x thermal.
• For cool cathodes, optimization suggests comparable DC/SRF performance.
  – SRF beamline clearly more forgiving.

• Critical areas for preserving beam brightness *common to both SRF/DC*:
  – Space charge dynamics: simulating vetting/agreement
  – 3D laser pulse control

• Both technologies must be concurrently pursued!

• Beamline collaboration a natural consequence
• BNL a leader in SRF gun development.
• Cornell’s construction of the MK II DC Gun:
  – Adjustable cathode/anode gap → “dial-in” a field!
  – Segmented insulator: pushing the voltage limits.
  – Full 6D phase space characterization:
    • Understand implications real beam orbit and optics on phase space growth
    • Induce & study space charge instability at photocathode: how longitudinal breakup impacts the transverse phase space.
Summary

Part I
• Cornell ERL photoinjector project has achieved beam brightness that exceeds that of the best existing storage rings;
• Diverse and aggressive program to improve beam brightness and injector performance further;

Part II
• Two potent technologies for high current low emittance photoinjectors discussed;
• “The proof of the pudding is in the eating”
  – Exciting time to push both DC and SRF guns to their ultimate limit (as set by photocathode & peak electric field)
Acknowledgements

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