Overview of Photoinjectors

→ Part tutorial
→ Part recent progress

John Power
Argonne Wakefield Accelerator Group
Argonne National Laboratory

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The ideal electron source...

...depends on your application.

SASE FEL → High peak current & low emittance

$I_{\text{micropulse}} \approx 1 \text{ kA}$

$I_{\text{avg}} \approx 1 \mu\text{A}$

High Peak Brightness

![Graph showing relationship between Gain Length and Projected Emittance](image)

LCLS
The ideal electron source...

...depends on your application

High Average Current $\rightarrow$ ERL & IR-FEL

$I_{\text{micropulse}} \sim 100 \text{ A}$

$I_{\text{avg}} \sim 10 \text{ mA-1 A}$

High Average Brightness

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The ideal electron source...

...depends on your application

High Pulsed Current $\rightarrow$ Wakefield Acceleration

$I_{\text{micropulse}} \sim 1 \text{ kA}$

$I_{\text{avg}} \sim 100 \mu\text{A}$

dielectric wakefield acceleration
The ideal electron source...

Match application $\leftrightarrow$ source

the trade offs: $\varepsilon$ vs $Q$' or $\varepsilon$ vs $I_{AVG}$ or etc.

$\varepsilon_N = 1.5Q^{0.7}$

Argonne Wakefield Accelerator

"1 $\mu$m per nC"

LCLS
The Argonne Wakefield Accelerator (AWA) Facility Beamline

**Single bunch operation**
1. \(Q=100\) nC
2. Current = 10 kAmp
3. Energy=15 MeV

**Bunch train operation**
1. 4 bunches x 25 nC (3 ns, present)
2. 16 bunches x 5 nC (12 ns, present)
3. 32 bunches x 40 nC (25 ns, future)

*World's Highest Q RF Photoinjector*
(Typical) Photoinjector Facility
The Argonne Wakefield Accelerator (Upgrade)

Q = 40 nC

Today's focus

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AWA facility upgrade (Conde) WG3
Application to linear colliders (Gai) WG3
Anatomy of an rf photoinjector
Electron emission
- Dynamics (Theory & Simulations)
- The drive laser
- The guns
- Beam characterization

Disclaimers
- biased: NCRF guns with metal photocathodes
- selective: picked a few representative examples
Adopt a standard for comparing cathodes

- Normalized intrinsic emittance of cathode per unit beam size

\[ \varepsilon_N = \sigma_x \sigma_{p_x} \quad [m - \text{rad}] \]

\[ \sigma_{p_x} = \frac{\sqrt{\langle p_x^2 \rangle}}{mc} \]

\[ \sigma_x = \frac{r}{2} \]

Position spread (we control)

- Assume e- have no momentum-position correlation at emission

\[ \frac{\varepsilon_N}{\sigma_X} = 1.4 \text{ microns/mm (rms)} \]

\[ E_{\text{int}} = 1 \text{eV} \]

\[ \frac{\varepsilon_N}{\sigma_X} = \sqrt{\frac{E_{\text{int}}}{mc^2}} \]
How to get the electrons out of the box?

- free electrons are trapped in a potential well
- electrons must overcome the work function $= (q\Phi)$

1. thermionic emission
2. photoemission
3. field emission
**thermionic emission**

heat electrons up until they go over the barrier

\[ \text{Vacuum Energy} \quad \text{Excited electrons} \]

\[ \text{Current density} \rightarrow J = AT^2 \exp \left( -\frac{\phi_{\text{eff}}}{k_B T} \right) \]

\[ \text{Thermal energy} \rightarrow E_k = k_B T \]

\[ \text{Intrinsic emittance} \rightarrow \frac{\varepsilon_N}{\sigma_X} = \sqrt{\frac{E_k}{mc^2}} \]

\[ \phi_{\text{eff}} = \phi - \phi_{\text{Schottky}} = \phi - e \frac{F_a}{4 \pi \varepsilon_0} \]

**EXAMPLE:** \( T = 1740 \text{ K} \) & \( F_a = 20 \text{ MV/m} \)
- \( J = 17 \text{ A/cm}^2 \)
- \( E_k = 0.150 \text{ eV} \)
- \( \varepsilon_N/\sigma_X = 0.54 \text{ } \mu\text{m/mm(rms)} \)

\[ J_{\text{th}} \sim (10-100) \text{ A/cm}^2 \]
thermionic emission

The High Brightness Dream:
Can we have high current & low (thermal) emittance?

NO!
Higher current means higher emittance

$\sigma_x$ (mm)

$J \times \pi \sigma_x^2$

$I$ (µamp)

$\varepsilon_{\text{norm}}$ (mm-mrad)

$\varepsilon_{\text{norm}}$ (mm-mrad)

$J$ (A/cm²)

$\varepsilon_{\text{norm}}$ (mm-mrad)

$T$ (K)

$\Delta t$ eq $\left(\frac{W - AV}{kT}\right)$

for this example: CeB6 ($W=2.39$ eV); $F=20$ MV/m; $\sigma_x=0.2$ mm; $T=1743$ K

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**photoemission**

### Quantum Efficiency (QE)

\[ \text{QE} = \frac{\text{Number of photoelectrons}}{\text{Number of photons}} \]

\[ Q[nC] = QE[\%] \times E_{\text{laser}}[\mu J] \times \frac{\lambda_{\text{laser}}[nm]}{124} \]

### Classes of photoemitters

- **metallic photocathode**
  - Cu, Mg, Pb, Nb (bare metal)
  - CsBr:Cu, CsBr:Nb (coated metal)

- **semiconductor photocathode**
  - Cs\(_2\)Te, Cs\(_3\)Sb, K3Sb, (PEA, mono-alkali)
  - K\(_2\)CsSb, Na\(_2\)KSb, (PEA, multi-alkali)
  - GaAs(Cs), GaN(Cs), (NEA)

### Ideal Photocathode

1. high QE
2. low intrinsic emittance
3. fast response time
4. vacuum robust
photoemission theory

Spicer’s 3 step model
1. A photon is absorbed and an electron is excited
2. Electron migrates to the surface
3. Escape through the barrier

Spicer does not do emittance

3 step model applied to photoinjectors…
1. Dowell and Schmerge¹
   1. metals (zero field and temp)
   2. predicts $\varepsilon_{\text{INTRINSIC}}$ and QE
2. Jensen²
   1. metal and semiconductors
   2. predicts $\varepsilon_{\text{INTRINSIC}}$ and QE
   3. thermionic, photo, and field emission

\[
E_{\text{excess, metal}} = \hbar \omega - \phi_{\text{eff}}
\]

(picture from: Masao Kuriki, ILC school)

photoemission in metals
[Dowell and Schmerge]

- Theory predicts ‘Quantum Efficiency’ and ‘Normalized intrinsic emittance of cathode per unit beam size’
- is in good agreement with experiment
**photoemission in metals**
[Dowell and Schmerge]

The High Brightness Dream:
Can we have high QE & low intrinsic emittance?

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**Graph:**

- **QE** vs. **Photon wavelength (nm)**
- **emptance** vs. **micron/mm(rms)**

- **excess energy**

- **Yes** → Can increase charge with laser intensity
- **No** → High QE means high emittance
photoemission in semiconductors
[e.g. CsTe]

\[ E_k = \frac{1}{2} \left( \hbar \omega - E_G - E_A - \phi_{\text{eff}} \right) \]

\[ \frac{\varepsilon_N}{\sigma_X} = \sqrt{\frac{2E_k}{3mc^2}} \]

\[ \frac{\varepsilon_N}{\sigma_X} \]

[excess energy]

[excess energy]
The ideal cathodes: High QE + visible/IR lasers

- **K$_2$CsSb**
  - Successfully used in rf gun (Boeing Gun: still holds record for highest average I)
  - 10% at 543 nm

- **GaAs:Cs**
  - Used in DC guns
  - Ultra-low thermal emittance (0.22 μm/mm(rms)) near bandgap (880 nm), but slow response
  - 5.6% at 532 nm (fast response!)

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**Challenge:**

- Vacuum robustness

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**Figure:**

- Graph showingQE as a function of photon energy and wavelength.
- Formula for $kT_{\perp}$ (meV) = 309.2 - 0.3617 $\lambda$ (nm).
- Measurement of 25 meV.

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[References: I. Bazarov, J. Appl. Phys. 103, 054901 (2008)]
## Properties of Photocathodes

<table>
<thead>
<tr>
<th>Cathode Type</th>
<th>Cathode</th>
<th>Wavelength &amp; Energy, $\lambda_{opt}$ (nm), $\Delta \lambda$ (eV)</th>
<th>Quantum Efficiency (electrons per photon)</th>
<th>Vacuum for 1000 h Operation (Torr)</th>
<th>Ge+ Gap Energy + Electron Affinity, $E_G + E_A$ (eV)</th>
<th>Thermal Emittance (microns/mm (rms))</th>
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</thead>
<tbody>
<tr>
<td>PEA: Mono-alkali</td>
<td>Cs$_2$Te</td>
<td>211, 5.88</td>
<td>0.1</td>
<td>$10^{-9}$</td>
<td>3.5 [42]</td>
<td>~1.2 [35]</td>
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<td></td>
<td></td>
<td>264, 4.70</td>
<td></td>
<td></td>
<td></td>
<td>0.9</td>
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<tr>
<td></td>
<td></td>
<td>262, 4.73</td>
<td></td>
<td></td>
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<td>0.9</td>
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<tr>
<td></td>
<td>Cs$_3$Sb</td>
<td>432, 2.87</td>
<td>0.15</td>
<td>?</td>
<td>1.6+0.45 [42]</td>
<td>?</td>
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<tr>
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<td>K$_2$Sb</td>
<td>400, 3.10</td>
<td>0.07</td>
<td>?</td>
<td>1.1+1.6 [42]</td>
<td>?</td>
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<td>Na$_3$Sb</td>
<td>330, 3.76</td>
<td>0.02</td>
<td>?</td>
<td>1.1+2.44 [42]</td>
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<td>Li$_3$Sb</td>
<td>295, 4.20</td>
<td>0.0001</td>
<td>?</td>
<td>?</td>
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<tr>
<td>PEA: Multi-alkali</td>
<td>Na$_3$Ks</td>
<td>330, 3.76</td>
<td>0.1</td>
<td>$10^{-10}$</td>
<td>1+1.1 [42]</td>
<td>?</td>
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<td>(Cs)Na$_3$Ks</td>
<td>390, 3.18</td>
<td>0.2</td>
<td>$10^{-10}$</td>
<td>1+0.55 [42]</td>
<td>1.1</td>
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<td></td>
<td>K$_2$CsSb</td>
<td>543, 2.28</td>
<td>1</td>
<td>$10^{-10}$</td>
<td>1+1.1 [42]</td>
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<td>K$_2$CsSb(O)</td>
<td>543, 2.28</td>
<td>0.1</td>
<td>$10^{-10}$</td>
<td>1+0.4 [42]</td>
<td>~0.4</td>
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<tr>
<td>NEA</td>
<td>GaAs(Cs,F)</td>
<td>532, 2.33</td>
<td>0.1</td>
<td>?</td>
<td>1.4 ± 0.1 [42]</td>
<td>0.8</td>
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<tr>
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<td>GaN(Cs)</td>
<td>860, 1.44</td>
<td>0.1</td>
<td>?</td>
<td>?</td>
<td>0.7</td>
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<td>GaAs(1−x)Px</td>
<td>260, 4.77</td>
<td>0.1</td>
<td>?</td>
<td>1.96±0.1 [44]</td>
<td>0.8</td>
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<tr>
<td></td>
<td>x=0.45 (Cs,F)</td>
<td>532, 2.33</td>
<td>0.1</td>
<td>?</td>
<td>1.96±0.1 [44]</td>
<td>0.49</td>
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<tr>
<td>S-1</td>
<td>Ag–O–Cs</td>
<td>900, 1.38</td>
<td>0.01</td>
<td>?</td>
<td>0.7 [42]</td>
<td>0.7</td>
</tr>
</tbody>
</table>

*Normalized intrinsic emittance of cathode per unit beam size*


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Electron emission

Dynamics (Theory & Simulations)

- The drive laser
- The guns
- Beam characterization
Transverse emittance growth

\[
\varepsilon_N = f(\varepsilon_{\text{THERMAL}}, \varepsilon_{\text{rf}}, \varepsilon_{\text{sc}}) \approx \sqrt{\varepsilon_{\text{THERMAL}}^2 + \varepsilon_{\text{DYNAMICS}}^2} \quad \varepsilon_{TH} \left\{ \text{Lowest possible emittance} \right\}
\]

- Linearize all forces and apply emittance compensation
  [B. E. Carlsten, NIM, A285, 313 (1989)]
- Nonlinear forces (rf multipole fields, rf curvature, solenoidal aberrations, nonlinear space charge, etc.) dilute slice emittance

The Dynamics Lesson

[Image: Figure courtesy of S. Lidia (USPAS)]
**Emittance compensation**

reduces projected emittance due to slice-dependent linear focusing forces

**Examples…**

1. linear space-charge forces (dominant)

2. linear rf energy-dependent forces

Note → most guns operate in the space charge dominated regime since we are interested in high charge applications
**Beam envelope theories for photoinjectors**
for the optimized AWA drive beamline

Emittance compensation in space-charge regime [Carlsten 1989],
General envelope theory with newly found criteria [Wang et al. 2007]

Invariant envelope in constant acceleration/focusing channel with a simple matching condition [Serafini and Rosenzweig (1997)]; [Wang 2006]; **double minima in drift** [Ferrario 2000, PRL2007]

Q = 40 nC

$\varepsilon_N$ [\(\mu \text{m}\)]

$\varepsilon_X$ (\(\mu \text{m}\))

$10^* \sigma_X$ (mm)

24 \(\mu \text{m}\)

0.6 mm

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Simulations for photoinjectors

Simulations are the workhorse of the photoinjector field

- 1980s
  - 1000’s of macroparticles
  - Searched for solutions by hand
- 1990s
  - 100,000s of macroparticles
  - Local optimizers
- 2000s
  - Global Optimizers
  - Realistic laser profiles
- 2010s
  - Parallel Codes (1:1 particle)
Global Optimizers
Multiobjective genetic algorithms

Schematic of the dc gun injector layout.

22 parameters scanned
{longitudinal positions, accelerating gradients and phase, dc gun voltage, solenoid fields, buncher cavity gradient, laser spot size and length, bunch charge}
Realistic Laser Profiles

- More accurate simulations $\rightarrow$ better understanding $\rightarrow$ improved beams

measured laser profile

Monte carlo generated macroparticle distribution
Parallel Sims
1:1 particle rep

Simulations with billions of particles are now achievable.

Large numbers needed to control the numerical shot noise and avoid overestimating the microbunching instability.
Electron emission
Dynamics (Theory & Simulations)
The drive laser
The guns
Beam characterization
The trade-off: cathodes and lasers

J = (100-500) A/cm² (semiconductors)
J = 10000 A/cm² (metals)

- State-of-the-art
  - Near IR laser and visible = 25 W
  - UV laser = 2W
Ti:Sa CPA x3 + excimer + shaping

The AWA Drive Laser

LASER OUTPUT
248 nm, 1.5 – 15 mJ
1.5 - 26 ps FWHM, 10 Hz

Ti: Sapphire Amplifier (regen + 2 linear amps)

532 nm pump

x2 --- Quanta-Ray 170

x2 --- Quanta-Ray 230

Millenia V

Ti: Sapphire Oscillator

532 nm pump

532 nm pump

744 nm seed

248 nm 1.5 mJ

248 nm 15 mJ

248 nm 15 mJ

birefringent crystals

Transverse Pulse Shaping

Longitudinal Pulse Shaping

iris

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laser pulse shaping
linearize the space charge forces

tri-Gaussian

beer can

1990s

2000s

2010s

Generated ellipsoidal beam in blowout regime
$Q=20 \text{ pC} \ (35 \text{ fs} \rightarrow 300 \text{ fs})$

[generated ellipsoidal beam image]

[P. Musumeci et al. PRL 100, 244801 (2008)]
Flat-top for low emittance at the AWA

Transverse Phase Space

emitNY=1.29 (um)  
emitNY=1.52 (um)
Spatial Profile: Beercan

- **Clipped Gaussian**
  - simple
  - flexible
  - lossy

- **Π-shaper**
  - simple
  - fixed
  - low loss (5%)


- **Deformable Mirror/ Microlens array**
  - complex (computer genetic algorithm, $$)
  - flexible
  - low loss

H. TOMIZAWA, SPring-8
Longitudinal Pulse Shaping (frequency domain)

How it works:
1. The stretcher generates the Fourier Transform of the input pulse
2. A mask is used to modulate the amplitude and phase
**SPARC:** Shaping in IR (Dazzler) + Stretching in UV

- **IR Dazzler** (Acousto-optic Programmable Dispersive filter) adopted by many photoinjector projects: LCLS, TESLA X-FEL, SPARC:
  - limited rise time in UV ~3 ps (finite bandwidth of the non-linear crystals)
- **IR Dazzler + UV Stretcher**
  - Fastest Rise time in UV ~1.4 ps

C. Vicario, SPARC-LS-09/001
Longitudinal Pulse Shaping (Time Domain)

- A series of short discs can be stacked together to make a long cylinder

- Rise time limited by the "seed", typically very short
Pulse Stacking with birefringent crystals

\[ \Delta t = L \left( \frac{1}{v_{ge}} - \frac{1}{v_{g0}} \right) = L \frac{\Delta n_g}{c} \]

2\(^n\) pulses for \(n\) crystals

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J. G. Power and C. Jing AAC08
Flat-top for low emittance at the Argonne Wakefield Accelerator

FWHM = 1.5 ps

10.4 mm 5.2 mm 2.6 mm 1.3 mm

4 crystal set

16 stacked Gaussians

FWHM = 21 ps

streak camera measurement

αBBO crystals at ANL
Electron emission
- Dynamics (Theory & Simulations)
- The drive laser
- The guns
- Beam characterization
The peak vs average trade-off

High Peak Brightness

High Average Brightness

Gradient challenges
- NCRF → cooling
- HVDC → field emission
- SRF → ~50 MV/m (potential)

*Figure adapted from: D. Dowell and J.G. Power; Workshop on High Average Power & High Brightness Beams 2009 (UCLA)
**classes of photocathode guns:**

**low duty cycle guns**

Gun dynamics \(\rightarrow\) *Modern guns realize nearly perfect rf and magnetic fields*

- **LCLS**
  1. Eliminates the dipole and quadrupole rf fields (Dual RF feed and racetrack shape)
  2. Eliminated **beating between 0 and \(\pi\) modes** during rf fill
  3. Eliminated quadrupole fields in solenoid

- **PITZ**
  1. **Coaxial coupler:** a fully symmetric design of cavity and RF coupling
  2. a careful laser pulse shaping (transversely and temporally)
classes of photocathode guns:

**CW guns**

Challenge for CW NCRF gun: **cooling** (wall losses)

- VHF gun (LBNL)
  1. 187 MHz (20 MV/m)
  2. excellent vacuum: compatible with most cathodes due to
  3. status
    1. gun is fabricated
    2. rf conditioning late August
    3. first cathodes by September
classes of photocathode guns:

- **State of the art**
  - High Current capabilities (>10 mA)
  - exceptional vacuum (allows GaAs:Cs cathodes)

- **Future directions**
  - higher Q $\rightarrow$ Increase $E_{\text{cathode}}$;
  - $>10$ MV/m (or $>500$ kV) $\rightarrow$ 1 nC

---

**Darsbery/ALICE**
- $350$ kV
- $I_{\text{avg}}=6.5$ mA
- $\varepsilon_{XN}=1.5$ $\mu$m @ $Q=80$ pC
classes of photocathode guns:

**Jlab** (C. Hernandez-Garcia)
Q>7000 Coulombs with a single GaAs wafer (at 1-8.5 mA CW; 2004-07)

**Cornell** (L. Bazarov)
Iavg=20 mA DC
300 kV

**JAEA/KEK**
>500 kV (a segmented insulator to mitigate field emission problem)
classes of photocathode guns:

- Potentially the best of both worlds
  - **Higher gradient** than HVDC (~50 MV/m)
  - **Excellent Vacuum** (may allow more cathode choices)

- Challenges
  - No magnetic field near cathode (emittance compensation solenoid)
  - warm (LN2 temperature) normal **conducting photocathode** in an SRF environment
  - **Cathode contamination** onto superconducting surface

(BNL) ERL R&D Gun (I. Ben-Zvi)

\[ \text{I}_{\text{avg}} = 0.5 \text{ A} \]

704 MHz, T=2.5MeV

\[ Q = 0.7 \text{ nC} \Rightarrow \varepsilon_{X_N} = 1.4 \mu \text{m}, \sigma_Z = 6 \text{mm} \]
classes of photocathode guns:

**Rossendorf/ELBE** (J. Teichert)
I = 1 $\mu$A *(demonstrated)*
Cs2Te in SRF gun *(demonstrated)*

**HZB/BERLinPro gun** (T. Kamps)
initial: Pb/Nb cathode, $I_{avg}=15$ $\mu$A
final: CsK2Sb cathode, $I_{avg}=100$ mA

**Naval Post Graduate School Prototype**
500-MHz quarter-wave cavity *(J. Lewellen)*
$I_{avg}=10$ mA, $T=1.2$ MeV, $Q=10$ pC-1 nC
Commissioning soon??

Electron emission
Dynamics (Theory & Simulations)
The drive laser
The guns
Beam characterization
Evolution of beam quality
**LCLS transverse emittance**

Asymmetric UV beam on the cathode \(\rightarrow\) creates a tail on the e-beam in the injector \(\rightarrow\) degrades the emittance

- \(Q=250 \text{pC}\)
- \(\varepsilon_x: 0.58 \rightarrow 0.4 \mu\text{m}\)

*Measured at 135 MeV with Quad Scan technique*  
*courtesy P. Hering & B. White*
Pepper pot phase space measurements at AWA

- Measuring the emittance directly out of injector
- Single shot measurement

Recovered Phase Space

\[
\begin{align*}
\epsilon_x, \epsilon_y, \Sigma, \Delta_x, \Delta_y, \beta_x, \beta_y, \\
\end{align*}
\]

Pepper Pot Beamlets on screen

Calculate rms size
4D phase space measurement at AWA

Pattern rotation indicates X-Y coupling

Simulation of Pepper Pot diagnostic, 10 million particles

Non-zero off block diagonal terms indicates X-Y coupling

$\Sigma_{4D} = \begin{pmatrix}
\langle x^2 \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle \\
\langle xx' \rangle & \langle x'^2 \rangle & \langle x'y \rangle & \langle x'y' \rangle \\
\langle yx \rangle & \langle yy' \rangle & \langle y'^2 \rangle & \langle y'y' \rangle \\
\langle y'x \rangle & \langle y'x' \rangle & \langle y'y \rangle & \langle y'^2 \rangle
d\end{pmatrix}

\varepsilon_{4D} = \sqrt{\text{det}(\Sigma)}
Longitudinal Phase Space measurements

- Deflecting cavity
  - streaks vertically
  - resolution = 50 fs

- Spectrometer
  - disperses horizontally
  - resolution 1 keV

Q=20 pC

Measured

Simulated

$\sigma_z = 300$ fs

$\varepsilon_{Z,N} = 0.5$ mm-mrad

slice $\sigma_E = 0.03%$
Longitudinal phase space measurements

- **Spectrometer**
  - disperses vertically

- **Aerogel**
  - prompt light
  - resolution = streak camera (2 ps) + optical transmission line

---

J. Ronsch, DIPAC09

⇒ streak camera resolution limited ⇐

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Where we’ve been...

- Photoinjectors are now in use at major user facilities: LCLS, FLASH, XFEL,
- Rapid improvement in all major subsystems: Cathodes, Theory and simulation, Laser technology, Gun, Diagnostics

Looking forward...

- High average current guns beginning to turn on: {SRF guns VHF guns}
- New brightness frontiers {Laser Beam shaping, New photocathodes}
acknowledgements

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