Overview of FEL injectors

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SASE FEL Electron Beam Requirement:
High Brightness $B_n > 10^5$ A/m$^2$

\[ B_n \approx \frac{2I}{\varepsilon_n^2} \]

- Bunch compressors
- RF & magnetic
- Cathode emittance
- Pulse shaping
- Emittance compensation
FEL resonance condition implies that $e$ slips back in phase w.r.t. photons by $\lambda_r$ per period $\lambda_u$.

Amplification occurs over slippage length $L_s$

$\Rightarrow N\lambda_r \approx L_s$

$\Rightarrow \text{`slice' parameters are important}$

Courtesy Paul Emma - SLAC
FLASH @ 13 nm

\[ B_n \approx 10^{15} \left[ \frac{A}{m^2} \right] \]
Emittance Compensation

$\Rightarrow$ Controlled Damping of Space Charge Effects

$\rho = \left( \frac{I}{\gamma I_A \varepsilon_n} \right)^2$

$\varepsilon_{th} = 0.6 \mu m$

$E_{acc} = 25 \text{ MV/m}$

$\rho = 1$

$\Rightarrow$ propagation close to the “invariant envelope”$

$I = 100\text{ A}$

$I = 1\text{ kA}$

$I = 4\text{ kA}$

Potential space charge emittance growth

$\rho$ vs. $T$ [MeV]
\[ \varepsilon_{th} = 0.6 \mu m \]

Graph showing the relationship between enx and eny over Z [m] for HBUNCH.OUTnew. The graph indicates a behavior at 1 kA - 1 GeV.
500 kV pulsed thermionic gun for SCSS

Stable operation with uniform beam quality

Low thermal emittance single crystal CeB₆ (Cerium Hexaborite)

Low accelerating gradient (10 MV/m) ==> Low charge density ==> Free from dark current
Ultra-Low slice emittance gun

\[ \Rightarrow 0.05 \, \mu m \text{ @ source} \quad (0.1 \, \mu m \text{ @ undulator}) \]

### Field Emitter Array
5 \, \mu m

### gated ZrC tip
1 mm

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1x10 Hz (macro pulse)</td>
</tr>
<tr>
<td>Peak field at cathode</td>
<td>6 GeV/m</td>
</tr>
<tr>
<td>Charge per bunch</td>
<td>200 pC</td>
</tr>
<tr>
<td>Rms norm. emittance at cathode</td>
<td>0.05 mm mrad</td>
</tr>
<tr>
<td>Peak Current at cathode</td>
<td>5.5 A</td>
</tr>
<tr>
<td>Average Current at cathode</td>
<td>2 nA</td>
</tr>
<tr>
<td>Peak Current</td>
<td>0.6 A</td>
</tr>
<tr>
<td>Average Current</td>
<td>&gt; 5 , \mu A (long pulses)</td>
</tr>
</tbody>
</table>
Goals of PITZ

- test facility for FELs: FLASH, XFEL
  - small transverse emittance
    (1 mm mrad @ 1 nC)
  - long RF pulses => high average power
  - long laser pulse trains
  - high QE cathode Cs₂Te
- PITZ2 features:
  - higher gun gradient (~60MV/m)
  - flat-top cathode laser profile with shorter rise/fall time
  - emittance conservation with booster cavity

Several gun cavities (1.5-cell, L-band, 1.3 GHz) have been conditioned and operated: PITZ-guns1,2,3, BESSY-gun. Currently, gun3 cavity is under characterization.
Emittance measurements of PITZ Gun

The PITZ RF gun is developed for the operation with long RF pulses and long laser pulse trains, e.g.

measured @ PIZT: $p = 5.2$ MeV/c, $Q = 1$ nC,

- regularly obtain $2.1$ mm mrad (100% rms projected emittance)
- minimum $1.1$ mm mrad (90% rms projected emittance)

measured @ VUV-FEL(FLASH): $p = 127$ MeV/c, $Q = 1$ nC

- regularly obtain $2.1$ mm mrad (100% rms projected emittance)
LCLS Injector  Courtesy: C. Limborg-Deprey, D. Dowell

Under Construction – Commissioning starts January 2007
## LCLS Injector Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Current</td>
<td>100 A</td>
</tr>
<tr>
<td>Charge</td>
<td>1 nC</td>
</tr>
<tr>
<td>Normalized Transverse Emittance: Projected/Slice</td>
<td>&lt; 1.2 / 1.0 micron (rms)</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>120 Hz</td>
</tr>
<tr>
<td>Energy</td>
<td>135 MeV</td>
</tr>
<tr>
<td>Energy Spread@135 MeV: Projected/Slice</td>
<td>0.1 / 0.01 % (rms)</td>
</tr>
<tr>
<td>Gun Laser Stability</td>
<td>0.20 ps (rms)</td>
</tr>
<tr>
<td>Booster Mean Phase Stability</td>
<td>0.1 deg (rms)</td>
</tr>
<tr>
<td>Charge Stability</td>
<td>2 % (rms)</td>
</tr>
<tr>
<td>Bunch Length Stability</td>
<td>5 % (rms)</td>
</tr>
</tbody>
</table>

![Diagram of LCLS Injector Components](image)

**Beam-to-Linac**

**Solenoid**

**Gun**
LCLS Gun

Modified from
BNL/SLAC/UCLA version

S-Band (2.856 MHz)
1.6 cell

LCLS version

• RF Dipole suppressed with dual feed
  • Quadrupole suppressed with racetrack shape
  • Solenoid Quadrupole component compensated
• Laser axial injection
• Mode separation 15MHz instead of 3.5 MHz

LCLS Gun
<table>
<thead>
<tr>
<th>Parameter</th>
<th>200 pC</th>
<th>900 pC</th>
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</thead>
<tbody>
<tr>
<td>Charge</td>
<td>200 pC</td>
<td>900 pC</td>
</tr>
<tr>
<td>Emittance</td>
<td>0.8 mm-mrad</td>
<td>2.2 mm-mrad</td>
</tr>
<tr>
<td>Energy</td>
<td>5.65 MeV</td>
<td>5.55 MeV</td>
</tr>
<tr>
<td>Energy spread</td>
<td>1 %</td>
<td>2.6 %</td>
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<tr>
<td>Pulse length</td>
<td>8 ps</td>
<td>12 ps</td>
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</tbody>
</table>
Ti:Sa LASER system

0.02 nm resolution spectrometer

200 fs resolution UV xcorrelator
Cu Cathode QE $\sim 10^{-4}$ improved by laser cleaning
**Coils Current Configuration**

- **Beam rotation ~60°**
  - $I(A) = +140, +140, +140, +140$

- **Beam rotation ~0°**
  - $I(A) = -140, -140, +140, +140$

\[
\begin{align*}
  r^* &= -\left(\frac{eB(z)}{2\gamma m\beta c}\right)^2 \\
  \theta' &= -\frac{eB(z)}{2\gamma m\beta c}
\end{align*}
\]
Movable Emittance-Meter

![Graph showing Emittance, Envelope, and Bz field with measured distances of ~200-400 mm and ~1250 mm.](image)
Gun and emittance meter in the SPARC bunker
Beam envelope along the drift
Beam rms norm. emittance along the drift
Comparison measurements – computations: envelopes

Q = 700 pC  \( \sigma = 4.35 \) psec

![Graph showing comparison of measurements and computations with envelopes.](image)
Comparison measurements–computations: emittance
Velocity bunching concept

Electron Bunch from RF injector
Initial velocity $\beta_0 \sim 0.994$ (4MeV)

Phase $-90^\circ$

$\beta > \beta_0$ (tail)

$\beta = \beta_0$

$\beta < \beta_0$ (head)

Phase $0^\circ$

Phase $90^\circ$

RF (Traveling Wave)
Phase velocity $\beta_{ph} \sim 1$
\[ \langle I \rangle = 860 \, \text{A} \]

\[ \varepsilon_{nx} = 1.5 \, \text{\mu m} \]
# Rectilinear Bunching Experiments

<table>
<thead>
<tr>
<th>Method</th>
<th>BNL</th>
<th>UCLA</th>
<th>BNL-DUVFEL</th>
<th>UTNL-18L</th>
<th>LLNL</th>
</tr>
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<tbody>
<tr>
<td>Acc. Structure</td>
<td>Ballistic</td>
<td>Ballistic</td>
<td>Velocity Bunching</td>
<td>Velocity Bunching</td>
<td>Velocity Bunching</td>
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<tr>
<td>Measurement</td>
<td>S-band</td>
<td>PWT</td>
<td>4 S-band</td>
<td>1 S-band</td>
<td>4 S-band</td>
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<tr>
<td>Measurement</td>
<td>zero-phasing method</td>
<td>CTR</td>
<td>zero-phasing method</td>
<td>Femtosecond Streak Camera</td>
<td>CTR</td>
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<tr>
<td>Charge</td>
<td>0.04 nC</td>
<td>0.2 nC</td>
<td>0.2 nC</td>
<td>1 nC</td>
<td>0.2 nC</td>
</tr>
<tr>
<td>Bunch width</td>
<td>0.37 ps (rms)</td>
<td>0.39 ps (rms)</td>
<td>0.5 ps (rms)</td>
<td>0.5 ps (rms)</td>
<td>&lt; 0.3 ps</td>
</tr>
<tr>
<td>Comp. Ratio</td>
<td>6</td>
<td>15</td>
<td>&gt; 3</td>
<td>&gt; 13</td>
<td>10</td>
</tr>
<tr>
<td>Solenoid field</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
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</table>
High average current sources

High Average Current Injector
LINAC
FEL
Undulator Radiation
Beam Dump
DC photo-electron source

<table>
<thead>
<tr>
<th>operation mode</th>
<th>CW</th>
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<tbody>
<tr>
<td>pulsed / CW</td>
<td>CW</td>
</tr>
<tr>
<td>single bunch charge</td>
<td>122 pC</td>
</tr>
<tr>
<td>single bunch rep rate</td>
<td>75 MHz</td>
</tr>
<tr>
<td>DC voltage / gap</td>
<td>350 kV / 10.57 cm</td>
</tr>
<tr>
<td>average current</td>
<td>9.1 mA</td>
</tr>
<tr>
<td>norm. trans. emittance (rms)</td>
<td>~ 8-10 mm mrad @ 10 MeV</td>
</tr>
</tbody>
</table>

Long operating experience
High average current
Low accelerating gradient
==> Low charge density
Multivariate Optimization of Cornell Injector

Results for 800 pC:

opt. laser parameters:

1.6 mm rms spot size
17 ps rms pulse duration
Superconducting RF photoinjectors

Main Advantage:

Low RF Power Losses & CW Operation

Problems and Open Questions:

- Emittance Compensation ?
- High Peak Field on Cathode ?
- Cathode Materials and QE ?
FZR (since 1998)  
\[ f = 1.3 \text{ GHz} \]
\[ \text{Cs}_2\text{Te} \leftarrow E_{\text{RF}} \]

BNL (since 2002)  
\[ f = 1.3 \text{ GHz} \]
\[ \text{Nb} \leftarrow E_{\text{RF}} \]

IHIP PU (since 2001)  
\[ f = 1.3 \text{ GHz} \]
\[ \text{Cs}_2\text{Te} \leftarrow E_{\text{DC}} \]

BNL/AES (since 2004)  
\[ f = 703.75 \text{ MHz} \]
\[ \text{Alkali}+ \leftarrow E_{\text{RF}} \]
FZR Rossendorf

normal-conducting cathode inside SC cavity

<table>
<thead>
<tr>
<th>pulsed / CW</th>
<th>CW</th>
</tr>
</thead>
<tbody>
<tr>
<td>single bunch charge</td>
<td>1-20 pC</td>
</tr>
<tr>
<td>single bunch rep rate</td>
<td>26 MHz</td>
</tr>
<tr>
<td>length of bunch train</td>
<td>-</td>
</tr>
<tr>
<td>bunch train rep rate</td>
<td>-</td>
</tr>
<tr>
<td>average current</td>
<td>≤ 130 μA</td>
</tr>
<tr>
<td>norm. trans. emittance (rms)</td>
<td>2.5 mm mrad @ 4 pC, 900 keV</td>
</tr>
<tr>
<td>gun type</td>
<td>3.4 cell gun, Goals</td>
</tr>
<tr>
<td>------------------</td>
<td>---------------------</td>
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<tr>
<td>operation mode</td>
<td>ELBE</td>
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<tr>
<td>pulsed / CW</td>
<td>CW</td>
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<tr>
<td>single bunch charge</td>
<td>77 pC</td>
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<tr>
<td>single bunch rep rate</td>
<td>13 MHz</td>
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<tr>
<td>average current</td>
<td>1 mA</td>
</tr>
<tr>
<td>norm. trans. emittance (rms)</td>
<td>1.5 mm mrad @ 9.5 MeV</td>
</tr>
<tr>
<td>rf frequency</td>
<td>1.3 GHz</td>
</tr>
</tbody>
</table>
Splitting Acceleration and Focusing

- The Solenoid can be placed downstream the cavity
- Switching on the solenoid when the cavity is cold prevent any trapped magnetic field
HOMDYN Simulation

- $Q = 1 \text{nC}$
- $R = 1.69 \text{ mm}$
- $L = 19.8 \text{ ps}$
- $\varepsilon_{th} = 0.45 \text{ mm-mrad}$
- $E_{\text{peak}} = 60 \text{ MV/m (Gun)}$
- $E_{\text{acc}} = 13 \text{ MV/m (Cryo1)}$
- $B = 3 \text{ kG (Solenoid)}$
- $I = 50 \text{ A}$
- $E = 120 \text{ MeV}$
- $\varepsilon_n = 0.6 \text{ mm-mrad}$

$I_\text{peak}$ = 60 MV/m (Gun)
$E_{\text{acc}}$ = 13 MV/m (Cryo1)
$B$ = 3 kG (Solenoid)
Quantum Efficiency of Lead at 300 K measured @ BNL

![Graph showing quantum efficiency of lead at 300 K measured at BNL, with different deposition methods and wavelengths.](image)
Schematic diagram of a secondary emission amplified photoinjector
Lot of R&D ongoing on technical issues: Laser and Cathodes, Advanced Diagnostic, High duty, quasi-CW operations, SC RF gun, higher frequencies ultra-high gradients (X and W-band).

Within next year more experimental data will be available on RF compression and pulse manipulation for Ellipsoidal Beam and Blow Out Regime.

Progress in plasma injection.