RF guns for FELs

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Content:
• Motivation: Why electron source is so important for linac based FELs?
• Basic principles and challenges
• Examples: - low average current RF guns
  - medium average current RF guns
  - high average current RF guns
• comparing experimental results and designs
• future trends
• personal remark: details are important for good performance and reliable operation
• summary
One FEL key component: \( \rightarrow \) the high brightness electron source

Why electron injector is so important …. ???

\( \rightarrow \) property of linacs: beam quality will DEGRADE during acceleration

Main components of short wavelength SASE-FELs:
- **electron source**
- **accelerating sections** \( \rightarrow \) e.g. wakefields, coupler kicks
  - in between: **bunch compressor(s)** \( \rightarrow \) e.g. coherent synchrotron radiation (CSR)
- **undulator** to produce FEL radiation

Example: FLASH 1

- **RF gun**
- **Diagnostics**
- **Accelerating Structures**
- **Collimator**
- **Undulators**
- **Beam Dump**

- **5 MeV**
- **150 MeV**
- **450 MeV**
- **1250 MeV**

\( \rightarrow \) electron source has to produce lowest possible emittance !!
Why electron injector is so important …

• Why emittance must be small …

**FLASH**

- \( \varepsilon_n = 1 \text{ mm mrad} \)
- \( \varepsilon_n = 2 \text{ mm mrad} \)
- \( \varepsilon_n = 4 \text{ mm mrad} \)

**European XFEL**

- \( \varepsilon_n = 1 \text{ mm mrad} \)
- \( \varepsilon_n = 2 \text{ mm mrad} \)
- \( \varepsilon_n = 3 \text{ mm mrad} \)

• e.g. XFEL goal: slice emittance (1nC) = 1.0 mm mrad@undulator

• if even smaller emittance \( \Rightarrow \) new horizons:
  - shorter wavelength, higher repetition rate

peak power

output peak power of the
FLASH SASE2 @ 0.1 nm (GW)

output peak power of the
XFEL SASE2 @ 0.1 nm (GW)

path length in the undulator (m)

energy spread: 2.5 MeV

peak current: 5 kA

Q = 1 nC

path length in the undulator (m)
Basic principles and challenges:

**Generic Injector Layout**

Example: European XFEL

- **RF gun** (high gradient, amplitude and phase stability, 1 ↔ many ↔ cw bunches)
- Space charge compensating **solenoids** (positioning, no higher field components)*
- Photo **cathode laser** system (synchronization, laser pulse shaping in time + space)
- **Booster** cavity (synchronization, matched gradient and position**, later: high energy gain)
- **3rd harm. cavity** to linearize longitudinal phase space (synchr., matched gradient + phase)[5]
- **Laser heater** to increase uncorr. energy spread (prevent μ-bunching instability) [6,7,8]
- Detailed **diagnostics** of electron and photo cathode laser beam
- **Bunch compression** and then **further acceleration** of beam (→ wakefields)

*“Emittance compensation“ [1, 2, 3] **“Emittance conservation“ [3, 4]
Basic principles and challenges:

**Emittance budget:**

\[ \varepsilon_{tot} = \sqrt{\varepsilon_{th}^2 + \varepsilon_{RF}^2 + \varepsilon_{SC}^2} \]

- **thermal emittance** \( \varepsilon_{th} \propto \sigma_{x,y} \sqrt{E_k} \)
  
  where \( \sigma_{x,y} = \text{RMS laser spot size} \) @ cathode
  
  \( E_k = \text{mean kinetic energy of emitted } e^- \) [9, 10]

- **RF induced** emittance growth \( \varepsilon_{RF} \propto \sigma_{x,y}^2 \ast \sigma_z^2 \) [11], \( \sigma_z = \text{electron bunch length} \)

- **Space charge** induced emittance growth \( \varepsilon_{SC} \) = subject to numerical optimization, different dependencies for different photo cathode laser shapes

**High accelerating gradient at cathode**

- mitigates space charge effects
- allows to extract higher Q for fixed beam dimensions
- cathode roughness plays larger role
- reliability issues, heat load
- larger \( \varepsilon_{RF} \) for long bunches

**Photo cathode laser pulse shaping (in time and space):**

- relaxes requirements on cathode gradient and gives a lot of additional flexibility!
- high cathode gradient helps, but laser shaping is as important!
Low average current RF guns (<1 µA)

> Most popular S-band gun, the BNL/SLAC/UCLA gun, and its further developments → the **LCLS gun**:

LCLS Injector Setup @SLAC:

Realised design improvements:

> **Z-coupling** (reduces pulsed heating, increases vacuum pumping)

> **Racetrack to minimize quadrupole fields**

> **Deformation tuning to eliminate field emission from tuners**

> **Iris reshaped, reduces field 10% below cathode**

> **Increased 0-π mode separation to 15MHz**

> **All 3D features included in modeling** (laser port and pickup probes, 3D fields used in Parmela simulation)

## Low average current RF guns (<1 µA)

<table>
<thead>
<tr>
<th></th>
<th>a)</th>
<th>b)</th>
<th>c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>LCLS, USA</td>
<td>SPARC-LAB, Italy</td>
<td></td>
</tr>
<tr>
<td>Gun type</td>
<td>NC RF gun</td>
<td>1.6 cell NC RF Gun</td>
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<td>Experimental results or</td>
<td>exp. results</td>
<td>exp. results</td>
<td></td>
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<td>design goals/simulation</td>
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<tr>
<td>Operation mode</td>
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<td>Gaussian</td>
<td>COMB</td>
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<tr>
<td>Pulsed / CW</td>
<td>pulsed</td>
<td>pulsed</td>
<td></td>
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<tr>
<td>Cathode type</td>
<td>copper</td>
<td>copper</td>
<td></td>
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<tr>
<td>Single bunch charge</td>
<td>20-250 pC</td>
<td>up to 1 nC</td>
<td>up to ~200 pC</td>
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<tr>
<td>Single bunch rep rate</td>
<td>120 Hz</td>
<td>10 Hz</td>
<td>~1 THz</td>
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<tr>
<td>Length of bunch train</td>
<td>N/A</td>
<td>N/A</td>
<td>currently ≤4 pulses</td>
</tr>
<tr>
<td>Bunch train rep rate</td>
<td>N/A</td>
<td>N/A</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Total beam charge</td>
<td>2.4 - 30 nC/s</td>
<td>up to 10 nC/s</td>
<td>up to 4 nC/s</td>
</tr>
<tr>
<td>generated per second</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DC voltage / gap</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Cathode peak field</td>
<td>115 MV/m, 50% at emission</td>
<td>105 MV/m, 50% at emission</td>
<td>100 MV/m, 50% at emission</td>
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<tr>
<td>Beam energy at gun exit</td>
<td>6 MeV</td>
<td>~5 MeV</td>
<td>4.5 MeV</td>
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<tr>
<td>Norm. transv. emittance</td>
<td>0.3 - 0.4 for 150 pC</td>
<td>~1 for 280 pC</td>
<td>0.54 for 2×90 pC</td>
</tr>
<tr>
<td>(RMS) in [mm mrad]</td>
<td>@ 135 MeV</td>
<td>@ 147.5 MeV</td>
<td>@ ~100 MeV</td>
</tr>
<tr>
<td>Norm. transv. slice</td>
<td>0.3 - 0.4 for 150 pC</td>
<td>0.5 - 1 for 280 pC</td>
<td>N/A</td>
</tr>
<tr>
<td>emittance (RMS) in</td>
<td>@ 135 MeV (central slices)</td>
<td>@ 147.5 MeV</td>
<td></td>
</tr>
<tr>
<td>[mm mrad]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge fraction analyzed</td>
<td>95%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>RF frequency</td>
<td>2856 MHz</td>
<td>2856 MHz</td>
<td></td>
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</tbody>
</table>

**Table from F. Stephan, M. Krasilnikov (2014) [12]**

- **Collection of current photo injector parameters for**
  - LCLS
  - SPARC-LAB
- **average beam current in the nA range**
- **low emittances**
- **S-band guns**
Medium average current RF guns (1 μA < $I_{av.}$ < 1mA)

- The PITZ gun, used for FLASH and European XFEL:
  - **Cs$_2$Te cathode**
    - QE~0.5-10%
  - RF-gun:
    - L-band (1.3 GHz)
    - 1½-cell copper cavity
    - RF power: ~7MW peak
    - 850 μs pulse length @10 Hz → ~1% duty cycle
    - Dry ice cleaning → low dark current
  - Cathode laser
    - $\lambda$=257nm
    - pulse trains (800 @1MHz), 10Hz rep.rate.
  - Electron bunches:
    - pC to few nC
    - $p_{max}$: ~7MeV/c
    - Bunch trains
  - **How to achieve small emittance:**
    - High **gradient** at cathode:
      - ~60MV/m (1.3GHz)
    - Cathode laser pulse **shaping**
    - Gun launch **phase** stability
    - Beam based **alignment**, trajectory optimization
    - Emittance compensation and conservation → multi parametric machine **tuning** (solenoid, laser spot size, gun phase, booster,…)

- **Graphical representation**
  - Temporal profiles
    - FWHM=(21.20±0.33)ps
    - rise time=(2.02±0.11)ps
    - fall time=(2.62±0.13)ps
  - Transverse profile
  - Laser $\sigma_{xy}$
  - Gun phase $\phi_g$
  - Solenoid $I_{main}$
  - $\min(\sqrt{\varepsilon_n x \varepsilon_n y})$ with statistics
Medium average current RF guns ($1 \mu A < I_{av.} < 1mA$)


PITZ: Measured emittance versus laser spot size for various charges w.r.t. simulations

• Measured emittance results set a benchmark on photo injector optimization
• Optimum machine parameters (laser spot size, gun phase): experiment ≠ simulations
• Difference in the optimum laser spot size is bigger for higher charges (~good agreement for 100pC)
• Simulations of the emission need to be improved

M. Krasilnikov et al., PRST-AB 15, 100701 (2012).

TABLE IV. Core xy-emittance (mm mrad) measured for various charges and gun phases. Only statistical errors are shown
Medium average current RF guns (1 µA < $I_{av}$ < 1mA)

The APEX gun at Berkeley: a NC gun for CW operation

- 186MHz:
  - reduced cathode gradient w.r.t. L-/S-band
  - low beam energy at gun exit
  + reduced RF power density on surface
  + allows longer laser pulse on cathode
    → reduced space charge density
  + good vacuum conductivity
    → high QE photo cathodes ($Cs_2Te$, $CsK_2Sb$)
    → reduces power request for cathode laser

- Commissioning ongoing successfully → table
  - dark current @19.5 MV/m → 350 nA
  - 300 µA operation (300 pC @1MHz)
  - $Cs_2Te$ lifetime (1/e) is 3 days

- Continuous extension is ongoing

Courtesy F. Sannibale
Medium average current RF guns \((1 \, \mu A < I_{av.} < 1 \, mA)\)

<table>
<thead>
<tr>
<th>Location</th>
<th>a)</th>
<th>b)</th>
<th>c)</th>
<th>d)</th>
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</thead>
<tbody>
<tr>
<td>Gun type</td>
<td>DESY (PITZ), Germany</td>
<td>1 ½ cell NC RF gun</td>
<td>NC RF gun, ⅓ wave cavity</td>
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<tr>
<td>Experimental results or design goals/simulation</td>
<td>design goals / simulations</td>
<td>exp. results</td>
<td>exp. results</td>
<td>exp. results &amp; simulations</td>
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<tr>
<td>Operation mode</td>
<td>baseline</td>
<td>baseline</td>
<td>lower charge</td>
<td>-</td>
</tr>
<tr>
<td>Pulsed / CW</td>
<td>pulsed</td>
<td>pulsed</td>
<td>pulsed and CW demonstrated</td>
<td>-</td>
</tr>
<tr>
<td>Cathode type</td>
<td>Cs₂Te</td>
<td>Cs₂Te</td>
<td>testing Cs₂Te, CsK₂Sb later</td>
<td>-</td>
</tr>
<tr>
<td>Single bunch charge</td>
<td>1 nC</td>
<td>1 nC</td>
<td>250 pC</td>
<td>10 fC to 500 pC demonstrated</td>
</tr>
<tr>
<td>Single bunch rep rate</td>
<td>4.5 MHz</td>
<td>1 MHz, 4.5 MHz later</td>
<td>20 Hz to 1 MHz</td>
<td>-</td>
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<tr>
<td>Length of bunch train</td>
<td>600 µs</td>
<td>600 µs, ≤ 800µs possib.</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Bunch train rep rate</td>
<td>10 Hz</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total beam charge generated per second</td>
<td>27 µC/s</td>
<td>6 µC/s</td>
<td>1.5 µC/s</td>
<td>up to 300 µC/s demonstrated, up to 1 mC/s possible</td>
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<tr>
<td>DC voltage / gap</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Cathode peak field</td>
<td>60 MV/m</td>
<td>~60 MV/m</td>
<td>~21 MV/m</td>
<td>N/A</td>
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<tr>
<td>Beam energy at gun exit</td>
<td>~6.5 MeV</td>
<td>~6.5 MeV</td>
<td>800 keV</td>
<td>N/A</td>
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<tr>
<td>Norm. transv. emittance (RMS) in [mm mrad]</td>
<td>(\varepsilon_{x,y} = 0.60 ) @ 25 MeV, (\varepsilon_{x,y} = 0.29 ) @ 25 MeV</td>
<td>simulated: 0.2 to 0.7 for 10 to 300 pC</td>
<td>simulated: 0.1 to 0.6 for 10 to 300 pC</td>
<td>-</td>
</tr>
<tr>
<td>Norm. transv. slice emittance (RMS) in [mm mrad]</td>
<td>1.4 for 1 nC at 17.5 GeV</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Charge fraction analyzed</td>
<td>100 %</td>
<td>95 %</td>
<td>95 %</td>
<td>N/A</td>
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<tr>
<td>RF frequency</td>
<td>1.3 GHz</td>
<td>1.3 GHz</td>
<td>186 MHz</td>
<td>186 MHz</td>
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<tr>
<td>Photo cathode laser:</td>
<td>Yb:YAG</td>
<td>Yb-doped fiber</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Laser medium</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Wavelength</td>
<td>257 nm</td>
<td>257 nm</td>
<td>266 nm and 532 nm available</td>
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<tr>
<td>Temporal pulse shape</td>
<td>flat-top, 2 ps rise/fall time, 20 ps FWHM</td>
<td>flat-top, ≤2 ps rise/fall time, ~22 ps FWHM</td>
<td>flat-top, ~1 ps rise/fall time, 50 ps FWHM</td>
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<tr>
<td>Transverse pulse shape</td>
<td>flat-top, 0.53 mm RMS</td>
<td>~flat-top, ~0.3 mm RMS</td>
<td>~flat-top, ~0.18 mm RMS</td>
<td>Gaussian, 0.05 - 0.5 mm, truncation possible</td>
</tr>
</tbody>
</table>

Collection of current photo injector parameters for

> PIZT @ DESY
> APEX @ LBNL

- high QE photo cathodes
- average beam current in the \(\mu A\) range
- low emittances
- L-band and VHF guns
- extensive photo cathode laser shaping

Table from F. Stephan, M. Krasilnikov (2014) [12]
High average current RF guns \( (I_{av.} \geq 1 \text{mA}) \)

- High current: \( \rightarrow \) high QE photo cathode (NC or SC?), high rep. rate laser, \( \rightarrow \) high duty cycle

- an interesting example for SRF gun: the 3.5 cell (1.3 GHz) SC RF gun @ HZDR:

  - gun I cavity was limited by strong field emission
    \( \rightarrow \) \( E_{\text{launch, cathode}} \) only 2.2 - 2.6 MV/m, but still …
    - first FEL operation with an SRF gun at ELBE
    - excellent life time of NC \( Cs_2Te \) cathode was demonstrated (264 C, 400 \( \mu \)A)

- Now with SC solenoid

Accelerating gradients:

- First beam operation with gun II in June 2014
- Possible future:
  Cavity design allows for additional magnetically focusing RF mode

![Cocktail and bar graph with data points](image-url)
High average current RF guns \( (I_{av.} > 1\text{mA}) \)

Collection of photo injector parameters for

- (DC gun @ Cornell)
- NC RF gun @ Boeing
- 3.5 cell SRF gun @ HZDR

Table from F. Stephan, M. Krasilnikov (2014) [12]

<table>
<thead>
<tr>
<th>Location</th>
<th>a)</th>
<th>b)</th>
<th>c)</th>
<th>d)</th>
<th>e)</th>
<th>f)</th>
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<tbody>
<tr>
<td>Gun type</td>
<td>Cornell, USA</td>
<td>Boeing, USA</td>
<td>4 cell NC RF Gun</td>
<td>SC RF gun, 33/2 cell elliptical cavity</td>
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<tr>
<td>Experimental results or design goals/simulation</td>
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<td>exp. results</td>
<td>exp. results</td>
<td>design goals / simulations</td>
<td>exp. results</td>
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<tr>
<td>Operation mode</td>
<td>high current</td>
<td>measurement mode</td>
<td>-</td>
<td>ELBE</td>
<td>high charge</td>
<td>ELBE</td>
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<tr>
<td>Pulsed / CW</td>
<td>CW</td>
<td>pulsed, CW possible</td>
<td>pulsed</td>
<td>CW, pulsed operation possible</td>
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<tr>
<td>Cathode type</td>
<td>alkali-Sb / GaAs</td>
<td>GaAs</td>
<td>K₂CsSb</td>
<td>Cs₂Te</td>
<td></td>
<td></td>
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<tr>
<td>Single bunch charge</td>
<td>77 pC</td>
<td>77 pC</td>
<td>1 - 7 nC</td>
<td>77 pC</td>
<td>1 nC</td>
<td>max. 77 pC</td>
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<tr>
<td>Single bunch rep rate</td>
<td>1.3 GHz</td>
<td>50 MHz, 1.3 GHz possible</td>
<td>27 MHz</td>
<td>13 MHz</td>
<td>0.1 - 0.5 MHz</td>
<td>13 MHz</td>
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<tr>
<td>Length of bunch train</td>
<td>N/A</td>
<td>0.1 to 10 μs</td>
<td>8.3 ms</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<td>Bunch train rep rate</td>
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<td>1 - 5 kHz</td>
<td>30 Hz</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<td>Total beam charge generated per second</td>
<td>100 mC/s</td>
<td>~1 μC/s</td>
<td>6.7 - 47 mC/s</td>
<td>1 mC/s</td>
<td>0.5 mC/s</td>
<td>max. 0.5 mC/s</td>
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<td>DC voltage / gap</td>
<td>500 kV / 5 cm</td>
<td>350 kV / 5 cm</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Cathode peak field</td>
<td>5 - 6 MV/m</td>
<td>4 MV/m</td>
<td>26 MV/m</td>
<td>20 MV/m</td>
<td>7.6 MV/m</td>
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<tr>
<td>Beam energy at gun exit</td>
<td>500 keV</td>
<td>350 keV</td>
<td>5 MeV</td>
<td>9.4 MeV</td>
<td>3.3 MeV</td>
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<tr>
<td>Norm. transv. emittance (RMS) in [mm mrad]</td>
<td>( \leq 0.3 )</td>
<td>( \epsilon_t = 0.51, \epsilon_r = 0.29 ) @ 10 - 12 MeV</td>
<td>5 - 10 @ 5 MeV</td>
<td>1 @ 9.4 MeV</td>
<td>2.5 @ 3.3 MeV</td>
<td></td>
</tr>
<tr>
<td>Norm. transv. slice emittance (RMS) in [mm mrad]</td>
<td>( \leq 0.3 )</td>
<td>( \epsilon_{slice,x} = 0.4 - 0.5 ) for central slices</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
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<tr>
<td>Charge fraction analyzed</td>
<td>100%</td>
<td>90%</td>
<td>90%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>RF frequency</td>
<td>1.3 GHz for buncher and booster</td>
<td>433 MHz</td>
<td>1.3 GHz</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Photo cathode laser:

- Wavelength: 520 nm, 520 nm, 527 nm, 258 nm
- Temporal pulse shape: flat-top, 20-30 ps, Gaussian, 53 ps FWHM, Gaussian, 4 ps FWHM
- Transverse pulse shape: flat-top, 2.5 mm diameter, Gaussian truncated at 35% intensity, 2mm diam., flat-top, 1-3 mm diam., flat-top, ~2.7 mm diam.
Comparison of experimental results / designs

Comparing the measured single bunch emittance

- Notice the different charge fractions analyzed
- Notice that the values are measured at different beam energies and with different measurement methods

Comparing the “Average Injector Brightness” \[ B_{injector} = \frac{Q_{bunch} \cdot NoP \cdot RR}{(\varepsilon_{n,x} \cdot \varepsilon_{n,y})} \]

- Design average currents and measured single bunch emittances have been used.

Lower RF frequency yields higher \( B_{injector} \) due to higher \( I_{injector} \)

Figures from F. Stephan, M. Krasilnikov (2014) [12]
Future trends: Photo cathode laser pulse shaping → towards 3D ellipsoid

**Main idea:** minimize the impact of the space charge on the transverse emittance.

- **Potential of 3D ellips. for all FELs:**
  - 30-50% lower av. slice emittance
  - Better longitudinal compression
  - Reduced beam halo
  - Less sensitivity to machine settings

→ **German-Russian collaboration:**
  - IAP (Nizhny Novgorod) builds laser
  - Installation at PITZ starts autumn 2014
Future trends: Higher average currents

➢ Photo cathode **laser** developments:
  - Laser **pulse shaping** (time + space) requires significant overhead in laser **peak power**
  - **High average beam currents** in addition require **high average laser power**

➢ Extensive developments needed to overcome e.g. **thermal lensing** + **pulse heating** and to allow **stable and reliable operation 24/7** (often specific requests for planned application)

➢ **Photo cathode** developments needed to relax the laser requirements:
  - **High quantum efficiency at visible wavelength** (‘cathodes for green light’)
    ➢ less power needed at basic laser wavelength, allows to omit second conversion stage
    (laser pulse deformation, sensitivity on laser power)
  - **Reliable and robust, low thermal emittance**
Future trends: A plasma based electron source

> two-component gas plasma cell [e.g. H(13.6 eV) and He(24.6 eV)]

→ beam driven plasma wave in H → accelerating gradients >10GV/m

→ witness electron bunch by very local laser ionization of He inside plasma wave

> emittance estimate inside plasma cavity:

\[ 0.03 \, mm \, mrad \] for 2 pC bunch, but \( I_{peak} \)=300 A

> Difficulties: synchronization, energy spread, extraction of bunch from plasma, …

(e.g. hydrogen)
Details are important: here contact cathode ↔ cavity

**original watchband design**
- cavity backplane
- cathode plug
- robust spring
- severe damage on peaked nose (part of the gun), mainly when running at high peak power and long pulse length

**contact stripe design**
- cavity backplane
- cathode plug
- spring insert can be exchanged
- originally: breaking of leaves, limited electrical contact
  - gold coating + electro polishing seems to help

**“watchband reloaded”**
- cavity backplane
- cathode plug
- robust spring
- equalized radii
- still to be tested in experiment!

Courtesy S. Lederer
Details are important: here water flow simulations + tests

- Gun5 has: RF pick ups, elliptical irises, circular cell shape, more&smaller cooling channels → internal water distribution → test

First geometry with reverse flow

Current geometry with correct flow

Courtesy S. Philipp, V. Paramonov
References


+ references listed on individual slights
Summary

> The electron source is one of the **key components** of FELs.

> Different FEL facilities (average beam current, beam quality, linac type, ...) need different electron sources **→ no universal solution**!

> Different types of electron source have been developed successfully for the specific demands of „their“ FEL **→ from nA to mA beam currents**!

> Common issues: **stable and reliable**
  - RF design,
  - photo cathode laser system,
  - synchronization,
  - diagnostics, ...

> For high **“Average Injector Brightness”** \((\frac{\text{average current}}{\text{emittance}^2})\) lower RF frequencies seem to be beneficial.

> Ultimate beam quality requires **3D ellipsoidal electron bunches** (→ laser pulse shaping).

> **Higher average beam current** get increasingly important (e.g. for ERLs).

> **Plasma acceleration** might offer interesting options in future.