The PSI X-FEL Project

&

the 100 keV Gun Test Stand

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Contents

• An X-FEL for PSI
• The Low Emittance Gun
• 100 keV Gun Test Stand
• Experimental Results
• Conclusions & Outlook

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The Status Quo at PSI
The X-Ray Free Electron Laser
A Compact X-FEL
The Swiss Light Source SLS at PSI

- SLS is a 2.4 GeV electron storage ring based 3rd generation light source
- In operation since 2001, high availability
- Delivers light to over a dozen beam lines simultaneously
- Undulator, wiggler and bending magnet radiation
- Photon energy: 1 meV - 45 keV (1 mm - 0.03 nm)
- Pulse length > 10 ps
Synchrotron Radiation Users Have Increasing Demands

- Higher (peak) brightness $\rightarrow$ single shot imaging
- Intense hard X-ray radiation ($\lambda \sim 1\text{Å}$) $\rightarrow$ imaging of molecular structures
- Ultra-short pulses ($\tau \sim 50\text{ fs}$) $\rightarrow$ time resolved imaging of fast processes
- Longitudinal and spatial coherence ("laser-like radiation from a point source")

However...

- Ultra-short pulses cannot be delivered by storage ring light sources
- Storage ring based light sources do not emit fully coherent radiation

$\Rightarrow$ New accelerator concept required
Generic Layout of an X-Ray Free Electron Laser

• High-brightness **electron gun** (high peak current, low emittance)

• **Linac** accelerates short bunches to sufficiently high energy

\[ \lambda = \frac{\lambda_u}{2\gamma^2} \left( 1 + \frac{K^2}{2} \right) \]

\[ \begin{aligned} \lambda_u & : \text{Undulator Period} \\ K \propto B_u \lambda_u & : \text{Undulator Parameter} \end{aligned} \]

• **Bunch compressors** shorten bunches to increase brightness

• Bunches radiate (incoherently) in the **undulator** and interact with emitted radiation → energy modulation → microbunching → coherent radiation \((P_\gamma \propto N_e^2)\)

• Single-pass system: SASE or seeded X-FEL → requires sufficiently long undulator section for full saturation
Two 1 Å X-FEL Projects

Linac Coherent Light Source (LCLS)
SLAC, Stanford CA, USA
- >3 km long, 14 GeV, ~300 million USD
- Construction started 2006
- Operational by 2009

European XFEL
DESY, Hamburg, Germany
- 3.4 km long, 20 GeV, ~1 billion EUR
- Construction starts 2008
- Operational by 2013
PSI is also interested in a 1 Å X-FEL, but...

- Budget constraints (~150 million EUR for SLS in 1998)
- In total 800 m length available on the PSI site

→ Is there an alternative concept for a compact 1 Å X-FEL?
**Strategy for a Compact 1 Å X-FEL at PSI**

- A low emittance electron beam significantly reduces the required beam energy

\[
\frac{\varepsilon(n)}{\beta \gamma} < \frac{\lambda}{4\pi}
\]

- A shorter linac is sufficient
- X-FEL becomes shorter and less expensive

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<th>European XFEL</th>
<th>PSI X-FEL</th>
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<tr>
<td>Beam Energy</td>
<td>20 GeV</td>
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<tr>
<td>Total Length</td>
<td>3400 m</td>
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<tr>
<td>Cost</td>
<td>1 billion EUR</td>
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<tr>
<td>Required Emittance</td>
<td>0.9 mm mrad</td>
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⇒ New challenge: generating ultra-low emittance electron beams
Accelerator Requirements

- **Low emittance electron source** (5.5 A peak current, 0.05 mm mrad normalized projected emittance)
- **Pulsed DC acceleration** (250 MV/m acceleration to 1 MeV, 15 ps RMS bunch length)
- **2-frequency RF cavity** (1.5 & 4.5 GHz SW cavity, acceleration to 3.8 MeV, ballistic compression)
- **Emittance compensation** (solenoid magnets)
- **Injector linac** (velocity bunching) & **booster linac** (acceleration to 250 MeV, TRW structures)
- **Main linac** sections (acceleration to 1080 MeV & 6 GeV in TRW structures)
- **Magnetic bunch compressors** (at 250 MeV & 1080 MeV → 50 fs RMS bunch length, 1.5 kA peak current)
Gun Requirements

- Realization of the PSI X-FEL depends on a novel type of electron gun

  ➡ “Low Emittance Gun (LEG) Project”
  - Electron gun with unprecedented emittance ($\epsilon_{x,y} = 0.05$ mm mrad)
  - High gradient acceleration (250 MV/m pulsed)
  - Conserve low emittance up to relativistic energies
  - Implement diagnostics capable of measuring ultra-low emittance
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Survey of Electron Sources
Field Emission
Conserving Low Emittance
Thermionic Electron Sources

- Oldest and most well known electron source → lots of experience
- Good cathode materials have low $\phi_w$ → very sensitive to vacuum conditions and contamination
- In order to get high peak current, need very high temperature and/or large cathode size → blows up source emittance

$$\varepsilon^{(n)} = \frac{\gamma r_c}{2} \sqrt{\frac{k_B T}{m_e c^2}}$$

- A priori DC source → need pulsed grid or chopper
  - Prefer smaller, pulsed, cold cathodes

Photo-Electric Electron Sources

- Irradiate cathode material with short laser pulses → electrons are released into vacuum
- Big advantage: time structure of electron bunch given by laser pulse; short-pulse laser systems are available
- High accelerating gradient → avoid materials with low work function $\Phi_w$ (dark current!)
- High peak current through use of short wavelength lasers → $E_\gamma = hc/\lambda$ is much larger than work function $\Phi_w$ → large momentum spread → large source emittance
- Use longer wavelength laser where $E_\gamma = hc/\lambda \sim \Phi_w$ → reduced current → larger cathode area required → increased source emittance

→ Need an alternative electron emission process (ideally: pulsed, cold, small emission area, low transverse momentum spread)
Field Emission

- Bring cathode material into high electric field region
- High external electric fields reduce potential barrier (Schottky effect)
  - The effective work function $\Phi_{w,e}$ is reduced
  - The potential barrier thickness is reduced
- Quantum mechanics: there is a finite probability for electrons to tunnel through the potential barrier into vacuum → **Fowler-Nordheim law**:

  \[
  J_{\text{FN}} \approx 1.54 \cdot 10^{-6} \frac{\beta^2 E^2}{\Phi_w} \exp \left( -6.83 \cdot 10^9 \frac{\Phi_w^{3/2}}{\beta E} \right)
  \]

- Since the electrons tunnel through the potential barrier → kinetic energy is lower than the effective work function $E_e < \Phi_{w,e}$
- Provided there is a very high effective electric field (several GV/m) large amounts of current can be drawn from very small areas
  - Small emission area and low transverse momenta → **low source emittance!**
Field Emission Cathodes (I)

High current density requires large effective electric field strength $\rightarrow$ geometric field enhancement and high external voltage

- Needle-tip emitters $\rightarrow$ total current insufficient

- Field emitter arrays (FEAs) $\rightarrow$ many nano-tips distributed over cathode surface
Field Emission Cathodes (II)

- FEAs with gate layer → pulsed emission

- FEAs with focusing layer → reduce divergence → minimize source emittance
Once a low emittance electron bunch has been emitted by the cathode, can its emittance deteriorate?

**Space charge forces**: In high charge bunches there is a direct collective effect where the charge of the entire bunch acts on a single bunch particle.

\[
\int \int \vec{E} \, d\vec{\sigma} = \frac{1}{\varepsilon_0} \int \int \int \rho \, dV \quad \rightarrow \quad E_r = \frac{\rho r}{2\varepsilon_0} = \frac{Ir}{2\varepsilon_0 \pi r_0^2 \beta c}
\]

\[
\oint \vec{B} \, dl = \mu_0 \int \int J \, d\vec{\sigma} \quad \rightarrow \quad B_\theta = \frac{\mu_0 J r}{2} = \mu_0 \frac{Ir}{2\pi r_0^2} = \mu_0 \varepsilon_0 \beta c E_r
\]

\[
F_r = q \left( E_r - \beta c B_\theta \right) = q \left( 1 - \beta^2 \right) E_r = \frac{qE_r}{\gamma^2}
\]
Space Charge Forces (II)

- Space charge forces are repulsive and act as a defocusing lens with a strength that depends on the local charge density.
- Space charge forces lead to distortions of the bunch’s phase space distribution and to coupling between different conjugate coordinates → emittance growth.

\[ F_r = q(E_r - \beta c B_\theta) = q(1 - \beta^2)E_r = \frac{qE_r}{\gamma^2} \]

- However, at very high energies the focusing magnetic force cancels the defocussing electric force → the resulting space charge force vanishes and the phase space distribution of the bunch is “frozen”.
- Thus, emittance blow-up due to space charge forces is a concern at low energy.
- **Strategy**: Generate low emittance electron bunch and accelerate as quickly as possible to high energy in order to conserve low emittance (\( \gamma > 10 \) requires \( E_{\text{kin}} > 5 \text{ MeV} \)).
- However, no matter how quickly the bunch is accelerated, there will always be a finite amount of emittance growth due to space charge forces at low energy → compensation mechanism?
Emittance Compensation

- Bunch has longitudinal charge modulation → defocusing space charge forces are different within different slices of the bunch

- B. E. Carlsten, LANL, 1989: make use of focusing lens (solenoid) and subsequent drift section to compensate emittance blow-up due to space charge forces
- In each slice: superposition of varying defocusing force (space charge) and constant focusing force (lens) → slices rotate in phase space with different frequencies
  - At one point along drift slices overlap → emittance minimized
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Motivation Behind the 100 keV Gun Test Stand

- Gain experience with FEA as cathode in an electron gun
- What are the properties of a bunch emitted by an FEA and accelerated in a HV gap?
- Can the FEA deliver sufficient peak current?
- Do the electron bunches have a low emittance?
- What diagnostic equipment and which diagnostic techniques are required to measure ultra-low emittance?
- Investigate emittance compensation
Overview of the 100 keV Gun Test Stand

The **100 keV Gun Test Stand** consists of:

- Electron gun (DC accelerating voltage) with pulsed **FEA cathode** (exchangeable)
- In-vacuum **solenoid** magnet → beam focusing, emittance compensation
- **Diagnostics module** → benchmark FEA performance and investigate beam quality (exchangeable inserts)
- **EPICS** as digital control system → experimental control and data acquisition
- Dedicated vacuum system and diagnostics to ensure UHV conditions
- Local access control and safety system for radiation protection and HV safety
Test Stand Bunker and Control System
Test Stand Gun, Pulser and Diagnostics Module
Gun & Solenoid

- Used gated Spindt-type FEAs (Mo) from SRI International (unfocused)

- Cathode and anode electrodes (removable) define gun geometry

- Cathode is put on -100 kV DC bias, anode is grounded

- FEA pulser is on cathode potential and applies square pulses to gate layer (0 - 320 V, 5 - 100 ns)

- In-vacuum solenoid with water cooling circuit and high-\(\mu\) yoke (confines magnetic field, reduces field leak onto cathode) delivers \(B_z\) up to 200 mT on axis
Simulation & Design Optimization

- Simulations performed in 2.5D with **MAFIA** (ES/MS solver, particle tracking) and in 3D with **GPT** (tolerance studies)

- Design of cathode and anode electrodes optimized:
  - **Gap** reduced to increase accelerating gradient while keeping peak surface electric field strength manageable
  - Size of **anode iris** minimized while preventing beam scraping
  - Shape of cathode and anode optimized for minimum emittance at gun exit

- Solenoid settings for minimum emittance at gun exit

**Macro-particles**: 20,000
Active emitter radius: 100 μm
Pulse from: Gaussian, cut-off at ± 3 \( \sigma_t \)
Pulse length \( \sigma_t \): 20 ps
Total bunch charge: 5 pC
(peak current \( \dot{I} = 100 \) mA)
Initial energy: \( \gamma_0 = 1.0001 \)
(corresponds to 50V gate voltage)
Gun Optimization Results

\[ \epsilon^{(n)}_{\theta} (\theta) \]

At gun exit (40mm)

\[ g = 11 \text{ mm} \]

\[ \hat{E} = 20 \text{ MV/m} \]

\[ \theta = 65^\circ \]

\[ \hat{E} (g) \]

Normalized Transverse RMS Emittance [mm*mrad]

Electrode Angle [deg]

Peak Electric Field Strength [MV/m]

Gap Size [mm]

MAFIA results

1/x fit

\[ \epsilon_u (n) \]

3 of 5: 100 keV Gun Test Stand > Gun & Solenoid
Solenoid Design Results

- Magnet iron yoke confines field → no bucking coil required at cathode
- Beam sufficiently focused throughout diagnostics section

Magnet iron yoke (high $\mu$)

1000 Copper windings (max 6.83 A/mm$^2$)

$B_z = 210$ mT

$B_z(z)$
Solenoid: Emittance Compensation

- Tuning range sufficient for emittance compensation
- Global emittance minimum at location of YAG screen and inserts

\[ \epsilon^{(n)}_u (B_{sol}) \]

\[ z = 219 \text{ m} \]

\[ \epsilon^{(n)}_{\text{min}} (z) \]

\[ z = 183 \text{ mm} \]
Tolerances

- Import fields generated by MAFIA ES and MS solvers into GPT
- Apply transverse displacement or rotation around vertical axis to simulate misalignment
- Observe resulting emittance increase → determine alignment tolerance

- In order for emittance growth to remain < 5 % require:
  - transverse displacement “shift” < 0.6 mm
  - rotation around vertical axis “tilt” < 25 mrad tilt

⇒ Started design of 3D mover motor system to correct for misalignment of cathode with respect to anode/solenoid
Diagnostics: Measuring Charge-Time Structure

- A coaxial Faraday cup (> 4 GHz BW) can be driven into the beam
- Fast oscilloscope (2 GHz, 20 GS/s) measures collected current
- Integration of current signal over pulse length gives total bunch charge
Diagnostics: Imaging the Bunches

- Two screen monitor systems with dedicated zoom optics and CCD camera

- YAG: crystal (0.3 mm) at 45° angle driven into beam laterally → measure beam size at location of inserts

- P43 phosphor: Coating on vacuum window at the end of the diagnostics module (movable) → measure beam size and image beam image at various longitudinal positions
Diagnostics: Measuring Transverse Properties (I)

- Various measurements methods → compare methods, benchmark accuracy
- Measure transverse bunch properties: Insert obstruction, image emerging beamlet(s) downstream → calculate bunch properties at location of obstruction

- Inserts have to fully stop beam outside hole/slit → 100 μm tungsten masks
- 2 lateral inserts (hor/ver) with mask holders; each holds three different masks
Diagnostics: Measuring Transverse Properties (II)

- **Single slit mask** (20 μm): together with beam size at location of the slit this gives **emittance**
- **Slit array mask** (20 μm, 170 μm pitch): measure divergence within different beamlets and beam envelope → **emittance, phase space ellipse**
**Diagnostics: Measuring Transverse Properties (III)**

- **Pinhole array mask** (50 μm, 320 μm pitch): corresponds to using a horizontal and vertical slit array in one single shot

![Pinhole array mask diagram](image)

- **Pepper-pot** (50 μm, 320 μm pitch): like pinhole, but allows longitudinal sampling

![Pepper-pot diagram](image)
Simulations for Diagnostics

- Track particles through slit/pinhole arrays (MAFIA)
- Simulate screen monitor image and phase space reconstruction
  ➔ Optimized insert dimensions
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FEA Lifetime

- Gun sustains **stable DC HV** of 100 kV

- **Lifetime issue**: FEAs are extremely sensitive to HV breakdown (after HV arc FEA is usually destroyed due to bridge between tips and gate layer)

- SRI FEAs operated at 40 kV
  - At higher accelerating voltage more severe damage to FEA (**ion back-bombardment**, **HV arcs**)

- SRI FEAs gate voltage limited to < 200 V
  - At high gate voltages instabilities in emission are observed (**tip to gate emission** → local vacuum degradation → can induce HV breakdown)
**FEA Performance: Peak Current & Bunch Charge**

- Exponential increase of field emitted current with gate voltage as predicted by **Fowler-Nordheim law**

  ➤ Emission current very sensitive to gate voltage

- $\hat{I} (U_g)$

- $\hat{I} = 2 \, \text{mA}, Q = 100 \, \text{pC}$ (in 100 ns)

- Maximum performance given by stable emission of FEA and not by space charge limit of cathode

  ➤ Emittance dominated beam?
Beam Images & Profile Measurements

- Hot spots and non-uniformities discovered in the transverse beam image
- Verified beam size independent of bunch charge → emittance dominated beam

Focused beam

\[ \sigma_x = (0.833 \pm 0.006) \text{ mm} \]

Defocused beam

\[ \sigma_x = (2.92 \pm 0.03) \text{ mm} \]
Solenoid Scan (I)

- Measure downstream beam size (P43) as a function of solenoid current

\[ \sigma_x = (0.843 \pm 0.006) \text{ mm} \]
\[ \sigma_y = (0.925 \pm 0.010) \text{ mm} \]
Solenoid Scan (II)

- Model solenoid lens and express beam size as a function of solenoid current

\[
M = M_d M_{sol} = \begin{pmatrix}
\cos \phi - L \sqrt{k} \sin \phi & \frac{1}{\sqrt{k}} \sin \phi + L \cos \phi \\
-\sqrt{k} \sin \phi & \cos \phi
\end{pmatrix}
\]

where \( \phi = \sqrt{k \cdot l} \)

\[
\sigma = \sqrt{\frac{\epsilon}{\beta_s^2 M_{11}^2 - 2\alpha_s M_{11} M_{12} + \frac{1 + \alpha_s^2}{\beta_s} M_{12}^2}}
\]

- A fit for \( \sigma \) as a function of \( I_{sol} \) returns emittance and Courant-Snyder parameters at the solenoid location

\[
\alpha_x = (-3.932 \pm 0.028)
\]
\[
\beta_x = (0.194 \pm 0.001) \, \text{m}
\]
\[
\epsilon_x = (2.614 \pm 0.175) \, \text{mm mrad}
\]
Alternative Emittance Measurement: Single Slit Method

- Measure beam size at location of the single slit insert (YAG screen) \( \langle u^2 \rangle \)

- Measure beamlet width \( \sigma_u \) downstream of a horizontal or vertical slit (P43) \( \langle \tilde{u}'^2 \rangle = \frac{\sigma_u^2}{L^2} \)

- If the linear correlation between divergence and position is removed, emittance becomes a simple product of beam size and uncorrelated divergence spread

\[
\varepsilon_u = \sqrt{\langle u^2 \rangle \langle \tilde{u}'^2 \rangle - \langle uu' \rangle^2} \quad \rightarrow \quad \sqrt{\langle u^2 \rangle \langle \tilde{u}'^2 \rangle}
\]

\( \varepsilon_x = (2.41 \pm 0.19) \text{ mm mrad} \)

→ Good agreement with solenoid scan results
Emittance Measurements with a Pinhole Array (1)

- Measure **beamlet images** downstream of the pinhole array (P43 monitor)
- Calculate histogram of beamlet images and subtract background
Emittance Measurements with a Pinhole Array (II)

- **Divergence centroid** for each bunch slice is given by shift of beamlet image centroid with respect to pinhole position.
- **Divergence spread** of each bunch slice is given by width of beamlet image.

\[
\frac{(d_i - d_0)}{L} \longrightarrow x'_i
\]

\[
\frac{w_i}{L} \longrightarrow \sigma'_i
\]
Emittance Measurements with a Pinhole Array (III)

- Divergence centroid and spread for each slice gives phase space distribution

\[
\bar{u}'_m = \frac{\langle u_m - m w \rangle}{L} \quad m \in \mathbb{N}_0
\]

\[
\sigma'_m = \sqrt{\langle (u_m - m w)^2 \rangle / L^2 - (\bar{u}'_m)^2}
\]

- Using intensity weighted averages, calculate second order moments of distribution

\[
\langle u^2 \rangle = \frac{\sum_{m=1}^{N} I_m \bar{u}_m^2}{\sum_{m=1}^{N} I_m}
\]

- Second order moments of distribution \(\rightarrow \epsilon, \beta, \alpha\)

\[
\epsilon_x = (2.846 \pm 0.262) \text{ mm mrad}
\]

\[
\beta_x = (0.592 \pm 0.027) \text{ m}
\]

\[
\alpha_x = (-1.17 \pm 0.061)
\]

\(\Rightarrow\) Good agreement with other emittance measurement results
Reconstruction of Transverse Phase Space Density

- Drift between pinhole and screen is given by a simple mapping
  \[
  \begin{pmatrix}
  u_0 \\
  u'_0
  \end{pmatrix}
  \rightarrow
  \begin{pmatrix}
  u_0 + L u'_0 \\
  u'_0
  \end{pmatrix}
  \]

- Invert this function to map every pixel in the CCD image to an area in phase space

- Relative beamlet intensity → phase space distribution density

\[
\alpha_x = (-1.17 \pm 0.61)
\beta_x = (0.592 \pm 0.027) \text{ m}
\epsilon_x = (2.846 \pm 0.262) \text{ mm mrad}
\]
Emittance Studies I

- Emittance independent of bunch charge $\rightarrow$ emittance dominated beam (transition to space charge dominated beam expected at $\sim 190 \text{ pC}$)
- HV breakdown causes **FEA surface damage** $\rightarrow$ non-uniform emission $\rightarrow$ emittance increase

![Graph showing RMS Emittance $\varepsilon_x$ vs. Bunch Charge [pC] before and after HV breakdown]
Emittance Studies II

Emittance dominated beam → source emittance conserved → estimate source divergence:

• Measured normalized transverse emittance: $\epsilon_x = 1 \text{ mm mrad}$
• $E_{\text{acc}} = 40 \text{ keV}$
• $U_g = 173 \text{ V}$
• $\sigma_x = 0.3 \text{ mm}$ (Gaussian beam emerging from FEA with $r = 0.5 \text{ mm}$)

\[
\sigma_{x'} = \frac{\sigma_{\gamma \beta_x}}{\beta} = \sigma_{\gamma \beta_x} \sqrt{\frac{m_e c^2}{2eU_g}} \approx \frac{\epsilon_x^{(n)}}{\sigma_x} \sqrt{\frac{m_e c^2}{2eU_g}}
\]

$\Rightarrow \sigma_{x'} = 130 \text{ mrad}$
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Conclusions & Outlook

- Test stand has been successfully commissioned and is fully operational
- Different measurement techniques deliver compatible results
- Test stand allows benchmarking of FEA cathodes in terms of performance and transverse beam properties
  - SRI FEAs do not deliver sufficient amounts of current
  - Experimental evidence for increased source divergence (and hence increased source emittance) due to lack of focusing layer
- PSI has started in-house development of new FEAs optimized for use in an electron gun
  - Focusing layer → reduce source divergence → minimize source emittance
  - High tip density → increase bunch charge
  - Metallic substrate → reduce bulk resistance → increase peak current
- Test stand will be used to benchmark PSI FEAs → optimize FEA design
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