Towards a Low Emittance X-ray FEL at PSI


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Outline of the talk

1. Introduction to the PSI-XFEL
2. Overview innovative technologies
3. The 250 MeV injector facility

http://fel.web.psi.ch
Motivation

Switzerland contributes to the European XFEL
⇒ beamtime for Swiss users: 100-200 hours per year

But:
one would like to have 3000-5000 h/year for experiments
⇒ a national 1Å source would be needed

Drawback:
XFELs are presently too expensive to be financed as a national project within Europe
⇒ bring the cost down!

Solution:
shorter accelerator / lower beam energy
⇒ reduce beam emittance while keeping brightness
The PSI-XFEL is based on 3 innovative features:

1. **Generate a low emittance electron beam**
   - field emission from field emitter arrays (FEA)
   - or single micro tips (needle cathodes)

2. **Fast acceleration after the emission to avoid beam blow up due to space charge forces**
   - diode configuration with high applied pulsed voltage

3. **Low initial current to reduce beam blow up by space charge effects**
   - 3-fold bunch compression scheme for high electron pulse compression
Proposed layout of the PSI-XFEL

3 FEL lines covering the wavelength range $\lambda = 0.1 \text{ nm} - 10 \text{ nm}$

**XFEL Parameters:**

Target values @ undulator entrance (5.8 GeV, Q= 200 pC)

- peak current: 1.5 kA
- slice emittance: 0.2 mm mmrad (rms)*
- energy spread: $10^{-4}$
- undulator length: 30 m
- undulator period: 15 mm

* 1pC slice
International context

Peak brilliance:

- European XFEL
- LCLS
- SCSS
- PSI-XFEL (SASE)
- FLASH

Diagram showing a plot of peak brilliance (photons/s mm² mrad² 0.1% Δλ/λ) vs. photon energy (eV) and wavelength (m) for various light sources.
The PSI-XFEL Site
PSI-XFEL Construction

- SLS
- User experiments
- Photon beamlines
- Undulator (80 m*)
  *reserved space
- Electron source
- Accelerator (400 m)

SITUATION 1:3500
Variante "Aare"

plan for cost evaluation only
Project Realization Strategy

Development of the critical technology
- low emittance electron source
- high voltage generation and high gradient acceleration
- two-frequency cavity for bunch compression

Experimental verification of this technology
- Construction of a high voltage and high gradient facility
- Construction of a 250 MeV injector facility

Construction of an X-FEL
- FEL-3 / 10 nm - 1 nm
- FEL-2 / 1 nm - 0.3 nm
- FEL-1 / 0.3 – 0.1 nm

→ development after successful demonstration of the low emittance accelerator concept (2011-2016)
Experimental Verification of the Critical Technology (1)

Low emittance electron source

Challenge: sufficient current, low emittance

(5.5 A, < 0.05 mm mrad)

Possible electron sources:
1. Field Emitter Arrays (FEA)

extracted current: $I_{/\text{tip}} \sim 10 \, \mu\text{A} (\text{DC})$

2. single tip field emitter (needle cathode)

$\rightarrow$ pure field emission: 470 mA (2ns)

$\rightarrow$ emission triggered by laser: $I \sim 2.9$ A (16ps)

3. scaled photo cathode

start-up solution to give more time for the FEA development

Note: Parameters for photo emission and field emission are chosen such that the accelerator design is the same for both!
High gradient acceleration

500 kV pulser

cathode holder

gap variable
0 (4) - 30 mm

anode

max. gradient: 125 - 250 MV/m

500 kV

1 MV

Status:
- 500 kV pulser installed in test bunker
- HV tests done successfully
- start of operation end 2007
- later upgrade to 1 MV foreseen
Bunch compression scheme

2-frequency cavity for large compression:
- Off-crest acceleration with fundamental frequency leads to energy chirp for **ballistic bunching**
- Harmonic frequency flattens accelerating field and allows **pulse shape control** during rf-compression

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**Diagram:**
- 1 MeV, 5.5 A
- 4 MeV, 7 A
- 4.5 GHz:
  - 1.5 GHz: pass
  - 4.5 GHz: reject

**Graph:**
- Beam current vs. Δz (mm)
  - Fundamental only
  - Fundamental + harmonic
  - Ideal

**Result:**
- ~25 A at z = 2.6 m

**Finalization:**
- Bunch compression finalized in following accelerating structures and magnetic BC
High compression ratio and transport of the emittance in the relativistic regime to be verified

→ build 250 MeV Injector Facility

**Emittance preservation**


**Conceptual Layout (CDR):**

- 5.5 A, 0.5 - 1 MeV
  - 6 - 7 A, 3.5 MeV
  - 25 A, 3.5 MeV
  - 30 A, 30 MeV
  - 265 - 280 MeV
- 30 A, 250 MeV
- 350 A

- RF and ballistic compression

\[ \varepsilon_n \leq 0.05 \text{ mm mrad} \]

- Slice emittance
  - (1pC slice)

\[ \varepsilon_n \leq 0.1 \text{ mm mrad} \]
Location of the 250 MeV injector facility

new building

PSI West
Simulations of the 250 MeV injector

Example: Beam Envelope Tracking

growth of projected emittance and beam size:

bunch length:

- 2-f cavity
- chicane

(HOMDYN results)
Simulations of the 250 MeV injector

Example: Beam Envelope Tracking

(slice = 10 % of total charge)

emittance growth:

- Gauss, $E_0 = 1.0$ MeV
- Rectangular, $E_0 = 1.0$ MeV
- Rectangular, $E_0 = 0.5$ MeV

Simulations of the 250 MeV injector (BET results)
Simulations of the 250 MeV injector

Example: Field tolerance studies

- basic tolerance studies are done, but need to be verified
- pulser, first solenoid, and fundamental of 2-f cavity are most critical components (tolerances below $5 \cdot 10^{-3}$)
- other tolerances more relaxed
Example: Misalignment studies  all solenoids and accelerator structures randomly misaligned with ± 200 µm

beam radius:

emittance:

large emittance linked to dispersion (D > 5-10 mm)

No transverse wakes!
Summary and outlook

Proof of critical technology for PSI-XFEL
• development and experimental verification ongoing

250 MeV injector to be built
• beam dynamics simulations of the injector are well advanced
• different codes are used: envelope tracker (HOMDYN, BET), particle codes (IMPACT-T, MAFIA, GPT, CAPONE)
• S2E simulation results show feasibility of the concept (bunch compression, emittance preservation)
• basic tolerance studies are done
• alignment requirements seem not to be too tight
→ build the thing and test the concept experimentally