The SwissFEL Project and the SwissFEL Test Facility at PSI

Paul Scherrer Institut
Sven Reiche
SwissFEL
A Compact X-ray Facility
Optimizing the FEL (Namely Brilliance)

Photon Brilliance

Electron Brilliance

Quantum Limit

\[ B = \frac{Q}{\Delta T \cdot \Delta E / E \cdot \varepsilon_x \cdot \varepsilon_y} \left( \frac{2Q}{e \hbar^3} \right) \]

Electron brightness can be much smaller but needs only to be smaller than photon brightness:

\[ \frac{\Delta E}{E} < \rho \]

\[ \frac{\varepsilon_N}{\gamma} < \frac{\lambda}{4\pi} \]

High Current   Low Energy Spread   Low Emittance
SwissFEL Design Strategy

1) Reaching 1 Ångstrom Wavelength for Atomic Resolution

2) Compact Undulator to lower Beam Energy

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

\[ \rightarrow \quad E \sim 6 \text{ GeV} \]

3) Low emittance electron beam source

\[ \frac{\varepsilon_N}{\gamma} < \frac{\lambda}{4\pi} \quad \rightarrow \quad \varepsilon_n \sim 0.3 \text{ mm mrad} \]

4) Efficient beam generation, acceleration and compression
Technology choice:

- RF photo-electron gun (2.5 cell), S-band
- 2 Stage compression at highest energy possible to minimize RF tolerances
- C-band linac (less RF stations, real estate and mains power than S-band, chirp removal after BC 2)
- X-band for linearizing phase space before BC 1
- 2 bunch operation (28 ns) with distribution to Aramis and Athos at 100 Hz
- Laser Heater to mitigate microbunch instability
PSI-developed RF Gun

- 2.5 cell copper cavity
- 2998.8 MHz (S-band)
- 2 µs pulse length
- 100 MV/m gradient
- 100 Hz repetition rate
- 40°C operating temperature

Status:
- Design finished
- Production in 2011
- Integration into test facility in 2012

Thermal analysis of cavity.

On-axis E-field
Main Linac: C-band technology

- 2050 mm long structure
- 113 cells per structure
- 5712 MHz (C-band)
- 28.8 MV/m gradient

SwissFEL will contain 104 C-band structures organized in 24 linac modules (236 MeV energy gain per module). Test stand in preparation.

Pulse compressor (SLED):
- accumulates the energy of the incoming “long” pulse and releases a short pulse
- 40 MW, 2.5 µs → 120 MW, 0.5 µs
- Q = 220'000
Undulator development (hard X-ray)

- Hybrid in-vacuum undulator
- 266 periods, each 15 mm
- Magnetic length 3990 mm
- Magnetic material: $\text{Nd}_2\text{Fe}_{14}\text{B} +$ diffused Dy
- Gap varies between 3 and 20 mm
- At a gap of 4.2 mm, maximum $B_z$ is 1 T

The SwissFEL ARAMIS beamline will comprise 12 undulators of this type. Test of prototype foreseen in injector test facility.
SwissFEL Timeline

- 2011: Parliament decision
- 2012: Start Civil Construction
- 2013: Building Ready
- 2014: Tunnel Closed
- 2015: Machine & Photon Beamlines Assembled
- 2016: First Photons (Spontaneous Radiation)
- 2017: Photon Beamlines (out of Tunnel) & Experimental Stations Ready
- 2017: First FEL Photons Pulses
- 2017: Start User Operation
Gun Optimization
(work done by Simona Bettoni)
Gun Optimization

Input Parameters

- Radius, Length, Charge
- Laser / Photo Electron Bunch
- RF Phase & Amplitude
- Solenoid Field & Position

Optimization

- Minimal Slice Emittance
- Minimal Projected Emittance
- Minimal Slice Mismatch Parameter
- Minimal Slice Energy Spread

Constraints

- Charge = 200 pC
- Peak Current > 20 A
- E > 120 MeV
- Gun gradient 100 MV/m
I try to re-optimize starting from Opt_8, but I fix \texttt{pulse_length = 10 \text{ ps}}.

\texttt{par_start = [phi\_gun coef\_sol\_1\_a coef\_sol\_2 sigma shift\_cav1 maxB(1) coef\_sol\_1\_b];}

\texttt{path: /gpfs/homefelsim/bettoni\_s/Astra\_sim/SwissFEL\_gun/Opt\_16}

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**Projected (mm.mrad)** | **Slice (mm.mrad)**
---|---
0.23 | \(<~0.17 \text{ (average = 0.2)}\)

**Final sigma = 0.134 mm**
Reducing the Mismatch (2\textsuperscript{nd} Optimization)

Start from Opt_16\_bis, but with less parameters to vary and minimize the max mismatch calculated in range \( z = \pm 2 \) mm.

\[
\text{par\_start} = [\text{sigma shift\_cav1 maxB(1)}];
\]

path: /gpfs/homefelsim/bettoni_s/Astra_sim/SwissFEL\_gun/Opt_23

\[
\text{Position SB01} = 3.5974 \text{ m}
\]
Considering new gun with door knob coupler:
- Solenoid is shifted closer to cathode
- Allows for higher charge density
- Reduced spot size and emittance

**New optimization of shorter pulse + larger spot size**

\[\begin{align*}
\varepsilon &= 0.10 \text{ mm (not nice shape)} \\
\sigma &= 0.1 \text{ mm} \\
\sigma &= 0.2 \text{ mm} \\
\sigma &= 0.3 \text{ mm} \\
\sigma &= 0.4 \text{ mm} \\
\sigma &= 0.5 \text{ mm}
\end{align*}\]
SwissFEL Injector Test Facility

"Remind me. How much did we spend on this machine?"
SwissFEL Injector Test Facility

- Electron gun and first accelerating section (first ~50 m of SwissFEL)
- Test of components and procedures needed for SwissFEL
- Will be moved to final SwissFEL location in 2015
Keep it simple for the Federal Councillor: one button, two signals

Beam on LuAG screen in front of beam dump.

Signal from Wall Current Monitor after the RF gun.

Visit to the injector tunnel.

The Burkhalter beam:
- ~35 pC charge
- ~160 MeV energy
- ~0.5 MeV energy spread
## 250 MeV Injector Time Schedule

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### Key Events:

- **2011**
  - BC Installation
  - RF Problems
  - Priority to beam operation
  - Complete modulator repairs

- **2012**
  - Integration FINSB04 & THz diag.
  - Done
  - Re-com. RF and gun laser
  - Slice is Compression
  - FAT X-band modulator
  - Modulator assembly and diode tests
  - Assembly X-band cavity + load lock
  - Gun
  - RF commissioning
  - First potential window but schedule requires a deep verification

- **2013**
  - Integration U15 experiment
  - Production starting
  - Schedule being analyzed (critical)

- **2014**
  - Option integration alternative RF-gun
  - Possible collaboration with Diamond
  - Implementation critical
  - Priority to first SwissFEL gun
  - Concept: Three months before building ready dust free stop Facility and preparation hardware for move.
Milestones: Beam Energy

Preconditions

Gun + 4 S-Band Cavities in Operation

Beam energy $\geq 250$ MeV
(first reached on April 11)

(for bunch compression studies energy limited to $\sim 230$ MeV)

Pulsar laser
(transverse profile)
Beam optics matched and understood (using OTR screens)

Milestones: Beam Optics (M. Aiba/N. Miles)
Projected emittance

Main method: “single-quad scan” (E. Prat)
- Phase-advance scan with single quad: use last matching quad upstream of FODO section to generate phase advance simultaneously in x and y. Possible if optics at quad fulfils some conditions (matching is crucial):
  - $\beta_x = \beta_y = \beta_0$, $\alpha_x = \alpha_y = \alpha_0$ (same optics x and y)
  - $\alpha_0 \times L = \beta_0$ (L is distance to observation screen)
- Beam size measurement with screen downstream of FODO section.

Alternative method: “multi-quad scan”
- Phase-advance scan with three quads: use three quads upstream of FODO section to generate phase advance, first in x then in y, while keeping the beam size under control.
- Beam size measurement with screen downstream of FODO section.

(No longer used: “FODO scan”)

Optimization (parameter study) ongoing...

$\varepsilon_{\text{proj}}(x) = 0.45 \text{ mm mrad}$
$\varepsilon_{\text{proj}}(y) = 0.44 \text{ mm mrad}$
Slice emittance

Method:

- **Transverse deflection ("streaking"):** the bunch is streaked in the transverse deflecting cavity, then recorded on a screen downstream of the FODO section.

- **Phase-advance scan:** change optics using five matching quads between transverse deflecting cavity and FODO section:
  - Generate regular phase advance in x
  - Keep beam size under control
  - Keep longitudinal resolution constant

- **Slice analysis:** split beam into slices (use centroid from Gauss fit as reference). Beam size from Gauss fit to slice profile.

- **Transverse deflector calibration:** change deflector phase at each optics setting to obtain individual mm ↔ ps calibration for each optics setting (add the data for increased statistics).

- **Mismatch parameter:** determined for each slice, checked against central slice and design optics.
Milestones: Compression (B. Beutner)

First demonstration of bunch compression (April 18, Jaguar laser)

Bunch length (rms from Gauss fit) reduced from 3.6 ps to 200 fs.

BC angle $4.07^\circ$ ($R56 = -46.19$ mm rad$^2$)

$\phi$: phase in FINSB03/04
$\tau$: bunch length

$3.6 \text{ ps} \rightarrow 200 \text{ fs (rms)}$
Fighting the Coupling (M. Aiba)

- **Motivation:**
  - Asymmetric emittance in hor. and ver. plane persists
    - Solved partially by FINSB01 BBA: typically 0.4/0.6 → 0.4/0.5 μm
    - The remaining asymmetry because of coupling? Let’s try to correct

- **Correction:**
  - General optics correction approach
    - \( \vec{P} = S \vec{C} \rightarrow \vec{C} = S^{-1} \vec{P} \)
      - \( \vec{P} \): Beamparameters to be corrected
      - \( \langle xy \rangle, \langle x' y \rangle, \langle x'' y \rangle \)
      - \( S \): Sensitivity matrix
      - \( \vec{C} \): Corrections
  - Sensitivity matrix taken from the machine

- **Knobs:** \( \vec{C} \)
  - Quad correctors of gun solenoid: FIND1-MCQR10 / FIND1-MCQS10
  - Solenoid pairs (increase one of them and decrease the other) of FINSB01 and FINSB02:
    - FINSB01-MSOL10 + FINSB01-MSOL20
    - FINSB02-MSOL10 + FINSB02-MSOL30
  - (Two skew quad correctors available in addition for SwissFEL)
Fighting the Coupling (M. Aiba)

- Beam results:
  - Coupling correction

Typical emittance measured with correction:

(Emittance underestimated due to screen saturation, but full symmetry is achieved)

- What we learned:
  - Coupling correction works
    - Suggests lower field in the first solenoid and higher in the second
  - 100 or 200 μm orbit displacement in S-band has some impact on the emittances (up to 0.1 μm increase)
Best Emittance Measurements (Logbook)

EMITTANCES / OPTICS
- ex = 354 ± 3 nm | ey = 430 ± 8 nm
- bx = 6.58 ± 0.08 m | by = 38.72 ± 0.71 m
- ax = -0.66 ± 0.01 | ay = -0.19 ± 0.01
- Mx = 1.07 | My = 1.02

COUPLING TERMS
- e1 = 343 nm | e2 = 439 nm
- coupling factor = 1.0105
- x-y = -1.309e-09 ± 3.169e-11 m^2
- x-yp = -3.607e-11 ± 2.114e-12 m
- xp-y = -2.21e-10 ± 4.496e-12 m
- xp-yp = -7.069e-12 ± 1.56e-13

Data saved at 2012-06-04/MKE20120604T175609.h5
Slice emittance better than prediction with Astra:
• Cut of halo particles?
• Lower thermal emittance (currently matched to LCLS results)

To be studied

consistency of emittance measurement
Summary

SwissFEL

• Final permission by Swiss government in fall 2012 (very likely)
• 5 years of construction and commissioning
• 1 hard X-ray line (1-7 Å) in 2017 / 1 soft X-ray line (0.7-7 nm) in 2019
• Option to add one more hard and soft X-ray beamline

Gun Optimization

• Improvement upon „Massimo“ working point
• Door know Coupler allows for better emittances: more current from cathods to reduce required compression in linac (stability and microbunch instability)

SwissFEL Test Injector

• Major milestones achieved in April this year
• X-band and „controlled“ compression end of this year
• Unknown coupling limits current emittance optimization.
Acknowledgement

SwissFEL Beam Dynamics

- Simona Bettoni (Injector/Gun Optimization, Microbunch Instability)
- Bolko Beutner (RF Tolerances, Bunch Compression)
- Masamitsu Aiba (Beam Based Alignment, Feedback)
- Natalia Miles (Linear & non-linear beam optics)
- Eduard Prat (Diagnostic Optics, FEL self-seeding)
- Frederic Le Pimpec (Dark current studies, collimator)
- Sven Reiche (FEL performance, SwissFEL lattice)
- Thomas Schietinger (Section head, Commissioning Leaders)

Thanks to BD Alumnis (Anne Oppelt, Yujong Kim), BD Students, SwissFEL Diagnostics and RF Group, STFC Beam Dynamics group and, in particular,

- Marco Pedrozzi (Head of SwissFEL Test Injector)
- Hans Braun (SwissFEL Project Leader)