Status of SwissFEL

Hans-H. Braun on behalf of the SwissFEL team

27th Linear Accelerator Conference
Geneva, September 2nd, 2014
Outline

• Overview

• Injector

• Main Linac
SwissFEL in a nutshell

**ARAMIS**
- Hard X-ray FEL, $\lambda=0.1$-0.7 nm
- Linear polarization, variable gap, in-vacuum Undulators
- First users 2017
- Operation modes: SASE & self seeded

**ATHOS**
- Soft X-ray FEL, $\lambda=0.7$-7.0 nm
- Variable polarization, Apple II undulators
- First users 2020
- Operation modes: SASE & self seeded

**Main parameters**
- Wavelength from 0.1nm–7nm
- Photon energy 0.2-12 keV
- Pulse duration 1 fs - 20 fs
- $e^-$ Energy 5.8 GeV
- $e^-$ Bunch charge 10-200 pC
- Repetition rate 100 Hz

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**Diagram:**
- 1st Construction phase 2013-2016
  - Injector
  - BC1 (0.35 GeV)
  - Linac 1
  - BC2 (2.0 GeV)
  - Linac 2 (3.0 GeV)
  - Linac 3 (2.1-5.8 GeV)
- 2nd construction phase 2018-2020
  - ATHOS 0.7-7nm
  - User stations
  - ARAMIS 0.1-0.7 nm
SwissFEL building

The SwissFEL Building Site

The two passages for wild game crossing.

On the first floor the RF modulators and other supply systems are situated.

Photon Beamlines, Experiments and Preparation Laboratories

ARAMIS Undulators

Linear Accelerator

Injector

PSI campus
Swiss Light Source
Central Control Room

Situation of SwissFEL next to PSI campus
Building location (picture May 2013)
SwissFEL construction site, (picture July 2014)

**Building key figures**
- overall length: 740 m
- soil movements: 95’000 m³
- casted concrete: 21’000 m³ or 50’000 t

**Features**
- Proton cyclotrons
- Experiment hall
- SLS synchrotron
- Linac
- Undulators
- Injector
- BBQ hut
SwissFEL Injector Test-Facility

- Laser beam: \( \sigma_x = 270 \mu m \), \( \Delta T = 9.9 \) ps (FWHM), rise & falling time = 0.7 ps
- E-beams: \( Q \sim 0.2 \) nC, \( \delta_{\text{thermal}} = 0.195 \mu m \), \( I_{\text{peak}} = 22 \) A

- GUN, TDS1, S-band LINAC, X-band, BC, TDS2

- \( \sigma_z = 840 \mu m \), \( 58 \mu m \)

- Energy: \( E = 255.6 \) MeV
- \( \sigma_z \sim 1.674\% \)
- \( \Delta E = -20 \) MeV
- \( R_{56} = 46.8 \) mm
- \( \theta = 4.1 \) deg

- 3FODO: \( E = 255.5 \) MeV, \( \sigma_z = 1.665\% \)
- \( \sigma_x \sim 55 \mu m \), \( \sigma_y \sim 55 \mu m \), \( \sigma_z \sim 58 \mu m \)
- \( \sigma_{\text{mm}} \sim 0.379 \mu m \), \( \sigma_{\text{mm}} \sim 0.350 \mu m \)

- Injector building
- Beamline seen from gun end
- Commissioning crew with first beam
**Injector Emittance Achievements**  
(uncompressed beam)

Example measurements projected emittance

**High charge (200 pC):**

- **EMITTANCES / OPTICS**
  - $ex = 375.8 \text{ nm}$
  - $ey = 374.7 \text{ nm}$
  - $bx = 13.06 \pm 0.38 \text{ m}$
  - $by = 14.70 \pm 0.38 \text{ m}$
  - $ax = 1.34 \pm 0.04$
  - $ay = 1.30 \pm 0.05$
  - $Mx = 1.02$
  - $My = 1.00$

- Data saved at 2012-07-13/MKE20120713T160937.H5

**Low charge (10 pC):**

- **EMITTANCES / OPTICS**
  - $mx = 13.0 \pm 0.3 \text{ mm}$
  - $my = 15.0 \pm 0.3 \text{ mm}$
  - $bx = 13.02 \pm 0.21 \text{ m}$
  - $by = 14.72 \pm 0.50 \text{ m}$
  - $Mx = 1.01$
  - $My = 1.06$

- Data saved at 2013-06-13/MKE20130612T124958.H6

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**Example slice emittance measurement at $q_B=200\text{pC}$**

**Summary emittance measurements**  
(for uncompressed beam):

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$\sigma_{\text{laser}}$ [mm]</th>
<th>$\varepsilon_{n,x}$ [$\mu\text{m}$]</th>
<th>$\varepsilon_{n,y}$ [$\mu\text{m}$]</th>
<th>$\varepsilon_{n,\text{simulated}}$ [$\mu\text{m}$]</th>
<th>$\varepsilon_{n,\text{required}}$ at undulator [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High-charge mode (~200 pC):</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>projected:</td>
<td>0.21</td>
<td>0.38</td>
<td>0.37</td>
<td>0.350</td>
<td>0.65</td>
</tr>
<tr>
<td>core slice:</td>
<td>0.21</td>
<td>0.25</td>
<td>–</td>
<td>0.330</td>
<td>0.43</td>
</tr>
<tr>
<td><strong>Low-charge mode (~10 pC):</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>projected:</td>
<td>0.10</td>
<td>0.16</td>
<td>0.18</td>
<td>0.096</td>
<td>0.25</td>
</tr>
<tr>
<td>core slice:</td>
<td>0.10</td>
<td>$\leq 0.15^\ast$</td>
<td>–</td>
<td>0.080</td>
<td>0.18</td>
</tr>
</tbody>
</table>

*measurement limited by signal-to-noise ratio
U15 Undulator for ARAMIS beamline

**M= 17t**

**12 x U15 for ARAMIS**

Key industry partners:
- MDC Daetwyler Industries (CH)
- Bruker (D)
- Hitachi (Jp)
- Vakuumschmelze (D)

<table>
<thead>
<tr>
<th>Magnetic Length</th>
<th>3990 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period ( \lambda_u )</td>
<td>15 mm</td>
</tr>
<tr>
<td>Gap</td>
<td>3.2 4.2 4.7 5.5 mm</td>
</tr>
<tr>
<td>Undulator K value</td>
<td>1.8 1.4 1.2 1.0</td>
</tr>
<tr>
<td>Magnetic Field Bz on axis</td>
<td>1.3 1.0 0.9 0.7 T</td>
</tr>
<tr>
<td>Magnetic Material</td>
<td>NdFeB-Dy</td>
</tr>
<tr>
<td>Pole Material</td>
<td>Permendur (CoFeVa)</td>
</tr>
</tbody>
</table>
SASE lasing in in SwissFEL Injector Test Facility

Stray light related to compression ...???

E- beam
200 pC; 130 MeV

SASE scintillation.
λ=210 nm

YAG screen
Z=54.191m
### Layout and main RF systems

#### Injector
- 2.6 cell S-band RF gun
- Cu or Cs$_2$Te cathodes fed by 1 S-Band RF station
- 6 x 4m S-band travelling wave, const. gradient, 2π/3 acc. structures fed by 4 S-Band RF stations
- 1 x 1m X-band travelling wave, const. grad. harmonic linearizer fed by 1 X-band RF station (build by CERN/ELETTRA/PSI collab.)
- 1 s.w. S-band deflector from LNF

#### Linacs
- 104 (+8) x 2m
- C-band travelling wave, const. gradient, 2π/3 acc. structures with BOC RF pulse compression fed by 26 (+2) C-band RF station
- 2 x 2m
- C-band transverse deflecting structures fed by RF switch from last C-band station
## Overview RF cavities
(without TDS)

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>S-band photogun</th>
<th>S-band cavities (injector)</th>
<th>X-band cavities (injector)</th>
<th>C-band cavities (Linacs 1)</th>
<th>C-band cavities (Linacs 2)</th>
<th>C-band cavities (Linacs 3)</th>
<th>C-band cavities (Athos linac)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz) – ( f_b = 142.8 ) MHz</td>
<td></td>
<td>2998.8 ( (21 \times f_b) )</td>
<td>2998.8 ( (21 \times f_b) )</td>
<td>11995.2 ( (84 \times f_b) )</td>
<td>5712 ( (40 \times f_b) )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase Advance</td>
<td>( \pi )</td>
<td>2( \pi/3 )</td>
<td>5( \pi/6 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active Length</td>
<td>mm</td>
<td>162</td>
<td>4070</td>
<td>750</td>
<td></td>
<td></td>
<td></td>
<td>1978</td>
</tr>
<tr>
<td>Total Length</td>
<td>mm</td>
<td>4150</td>
<td>965</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2050</td>
</tr>
<tr>
<td>Number of Cells</td>
<td></td>
<td>2.5</td>
<td>122</td>
<td>72</td>
<td></td>
<td></td>
<td></td>
<td>113</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>( ^\circ )C</td>
<td>40</td>
<td>40</td>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Maximum Gradient</td>
<td>MV/m</td>
<td>120</td>
<td>25</td>
<td>34</td>
<td></td>
<td>28</td>
<td></td>
<td>28</td>
</tr>
<tr>
<td>Operating Gradient</td>
<td>MV/m</td>
<td>100</td>
<td>14.8</td>
<td>25</td>
<td>27</td>
<td></td>
<td></td>
<td>27.5</td>
</tr>
<tr>
<td>Required Input Peak Power per structure</td>
<td></td>
<td>19 MW for 100 MV/m</td>
<td>24 MW for 16 MV/m</td>
<td>7 MW for 20 MV/m</td>
<td></td>
<td></td>
<td>27.2 MW for 27.5 MV/m</td>
<td></td>
</tr>
<tr>
<td>Klystron maximum performance</td>
<td></td>
<td>35 MW – 4.5 ( \mu s )</td>
<td>45 MW – 4.5 ( \mu s )</td>
<td>50 MW – 1.5 ( \mu s )</td>
<td></td>
<td></td>
<td></td>
<td>50 MW – 2.5 ( \mu s )</td>
</tr>
<tr>
<td>Filling Time</td>
<td>ns</td>
<td>490</td>
<td>1000</td>
<td>105</td>
<td></td>
<td></td>
<td></td>
<td>322</td>
</tr>
<tr>
<td>Number of structures</td>
<td></td>
<td>1</td>
<td>6</td>
<td>2</td>
<td>36</td>
<td>16</td>
<td>52</td>
<td>8</td>
</tr>
<tr>
<td>Number of structures per klystron</td>
<td></td>
<td>1</td>
<td>1 or 2</td>
<td>2</td>
<td>4</td>
<td></td>
<td></td>
<td>4</td>
</tr>
</tbody>
</table>
RF gun

Machined “on tune” according to HFSS
No tuning plungers
No tuning step during machining

Best design features from
LCLS and CTF/PHIN RF guns adopted

• quadrupole compensated symmetric coupler
• load lock
• $\beta=2$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HFSS</th>
<th>Measured</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$-mode freq.</td>
<td>2997.912</td>
<td>2997.912</td>
<td>MHz</td>
</tr>
<tr>
<td>$\beta$-coupling</td>
<td>1.98</td>
<td>2.02</td>
<td></td>
</tr>
<tr>
<td>$Q_0$</td>
<td>13630</td>
<td>13690±100</td>
<td></td>
</tr>
<tr>
<td>Filling time</td>
<td>485</td>
<td>481</td>
<td>ns</td>
</tr>
<tr>
<td>Mode sep.</td>
<td>16.36</td>
<td>16.20</td>
<td>MHz</td>
</tr>
<tr>
<td>Field balance</td>
<td>&gt;98</td>
<td>&gt;98</td>
<td>%</td>
</tr>
<tr>
<td>Operational temp.</td>
<td>57.7</td>
<td>53.0</td>
<td>°C</td>
</tr>
</tbody>
</table>
Programmed RF Amplitude for RF Gun to minimize heat load and dark current

$\beta_{\text{coupling}} = 2$

Amplitude modulation scheme with 150 ns flattop - fast filling and two bunch operation.

Shorter RF pulses
→ Thermal load reduction from 3 to 0.9 KW
→ Dark current reduction
→ Less RF breakdown

J.-Y. Raguin et al., "The Swiss FEL RF Gun: RF Design and Thermal Analysis", in Proc. LINAC 2012, Tel-Aviv
U. Ellenberger et al., “The SwissFEL RF Gun: Manufacturing and Proof of Precision by Field Profile Measurements”, THPP114, this conference
M. Schaer et al., “Study of a C-Band Hybrid Electron Gun for SwissFEL”, TUPP112, this conference
S-band Structures for Injector

Main Linac Design Requirements

Minimize investment + operation cost
Preserve emittance for one or two bunches
Longitudinal wake of Linac 3 has to compensate residual energy chirp from bunch compression
Transverse wakefield must allow for two bunches spaced by 28 ns
Design should facilitate assembly and installation
Minimize sources of transverse and longitudinal jitter
Linac design choices

Choices

- Normal conducting, C-band frequency, profit from KEK-JLC-C & Spring8/SACLA development
- High shunt impedance structure design with moderate gradient of 28MV/m
- Structure manufacturing tolerances tight enough to allow “on tune” fabrication, → no tuning provisions, no tuning step in production process
- High Q BOC (=barrel open cavity) RF pulse compressor
- Waveguide distribution and BOC mounted on girder → pre-assembly with most components before transport in tunnel
- Klystron modulator with solid state HV switches → compact design, very good pulse flatness, small pulse to pulse jitters
- Optical fiber reference distribution, high performance digital LLRF
- Precise cooling water temperature regulation with local smart controllers incl. LLRF as T sensor
- Ø16mm vacuum pipe → low power, air-cooled quadrupoles; high resolution cavity BPMs
cost optimization pulsed n.c. linac for SwissFEL

Cost vs. gradient for S-band with 45 MW klystron, S-band with 80 MW klystron and C-band with 50 MW klystron

Advantage of C-band is in real-estate needs and electricity consumption
SwissFEL Main Linac building block

C-band- Klystron Toshiba E37212
5.72 GHz, 50 MW, 3 μs, 100 Hz

<table>
<thead>
<tr>
<th>Main LINAC</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td>LINAC modules</td>
<td>26</td>
</tr>
<tr>
<td>Modulator</td>
<td>26</td>
</tr>
<tr>
<td>Klystron</td>
<td>26</td>
</tr>
<tr>
<td>Pulse compressor</td>
<td>26</td>
</tr>
<tr>
<td>Accelerating structures</td>
<td>104</td>
</tr>
<tr>
<td>Waveguide splitter</td>
<td>78</td>
</tr>
<tr>
<td>Waveguide loads</td>
<td>104</td>
</tr>
</tbody>
</table>

BOC pulse compressor

four 2 m long C-band structures, 28 MV/m
0.22 GeV energy gain per module (+10% overhead)

9 m
Waveguides and RF Pulse compressor integral part of girder
⇒ complete preassembly outside of tunnel

Key industry partners
TEL-Mechatronics
VDL
MHI
CML
Assembly of First Linac Module
Structures are machined “on tune”
no provisions for dimple tuning!

Specifications:
- Phase adv.: $\frac{2\pi}{3}$
- Filling Time: 322 ns
- $\text{vg/c: } 3.10\% - 1.19\%$
- $R/Q: 7.23 \text{ k}\Omega - 8.70 \text{ k}\Omega$
- $Q: 10035 - 9950$
- Iris radius (20°C): 7.244 mm – 5.436 mm

J.-Y. Raguin and M. Bopp,
"The Swiss FEL C-Band Accelerating Structure:
RF Design and Thermal Analysis",
proc. LINAC 2012, Tel-Aviv
First 2 m C-band structures

- 5 structures have been brazed so far

- High power results for first structure:
  - conditioned to 52 MV / m
  - Break-down rate at 52 MV / m
    \( \approx 2 \times 10^{-6} \)
  - At nominal 28MV/m, break-down rate negligible

R. Zennaro et al., “Measurement and High Power Test of the First C-Band Accelerating Structure for SwissFEL”, MOPP119, this conference
C-band structure with BOC pulse compression in RF power test area

Nominal $E_{\text{acc}}=28\text{MV/m}$
Achieved $E_{\text{acc}}=52\text{MV/m}$
Assembly & brazing set-up for series production
2 m C-band structure: longitudinal field distribution
BOC Pulse compressor
whispering gallery mode

RF design:
✓ Single cavity
✓ Whispering gallery mode with analytical solution
✓ Intrinsic high $Q > 200000$

Mechanical design:
Simple and robust design:
✓ Inner body from a single piece
✓ Two brazing steps
✓ Machined on tune

R. Zennaro et al., "C-band RF pulse compressor for the SwissFEL", Proc. IPAC 2013, Shanghai

U. Ellenberger et al., "The SwissFEL C-Band RF Pulse Compressor: Manufacturing and Proof of Precision by RF Measurements", FEL 2014, Basel

A. Citterio et al., “C-band Load Development for the High Power Test of the SwissFEL RF Pulse Compressor”, this conf. MOPP118
Prototype modulator from Scandinova

K2-3 for PSI C-band: 50 MW, 370kV / 344A / 3µs / 100 Hz

Design of C-Band K2-3 Modulator
Based on K2-series: new control system, new mechanical layout.
Achieves excellent pulse shape and an rms stability of 13 ppm.

50MW Klystron and K2-3 Modulator
K2-3 FOR C-BAND AT 50 MW-LEVEL, DESIGNED FOR 20 PPM STABILITY

Klystron Voltage & Current Pulses
366kV / 325A / 3.5µs / 100Hz

Recorded Stability on Pulse Middle section
Average over 0.5 µs

Stab = 119 uV / 9.51 V
= 13 ppm RMS

Peak to Peak 74 ppm
Mechanical Layout of the new prototype Modulator

The Modulator consists of the following mechanical units:

1. Modulator tank, housing the oil immersed pulse transformer, HV divider and current measurement
2. 12 Pulse Power Modules (IGBT modules), including pre-magnetisation circuits
3. Modulator control, HV earthing, cap bank discharge, oil supervision and water manifold
4. 19” rack housing the active PFC power supplies and focus power supplies
5. 19” rack housing the precision boost converter, control system, klystron auxiliary power supplies
6. 400VAC / 50Hz Mains input and distribution cabinet
Type-µ modulator prototype for PSI C-band

Measured pulses on demonstrator modulator

(Resistive load, no perveance; pulse parameters like overshoot not optimized)
Reference distribution and LLRF

First results with I-Tech/PSI s-band (2.9988GHz) link prototype

Influence of temperature, humidity variations and mechanical vibrations are compensated by group delay control. Further drift reduction expected.

A. Hauff et al., “SwissFEL C-band LLRF Prototype System”, this conf. TUPP111

Z. Geng et al., “Architecture Design for the SwissFEL LLRF System”, this conf. THPP113
Principle of the temperature regulation units

Principle:

- Mixing ratio of ~ 1:10 improves temperature stability in stabilized circuit by factor of 10 compared to supply water
- A linearly regulated heater is used in a regulation loop to improve the stability further
- Temperature sensors are used as monitors when RF is turned off
- LLRF-based temperature measurement is used as an additional monitor during RF operation

Prototype system commissioned in spring 2013
BOC temperature stabilization

Temperature stability (T-sensor based): ≈3 mK rms
BOC frequency stability (LLRF based): ≈ 300 Hz
BOC temperature stability (LLRF based): ≈ 3 mK rms
Energy recovery for SwissFEL

Toshiba E37212 klystron with high T collector developed for SwissFEL
SwissFEL layout

Beam trajectories of the straight and deflected beam. The color rectangles represent the corresponding magnet’s field region: Kx – Kicker magnet, Dx – Dipole magnet, S – Septum magnet, Q – Quadrupole magnet.

**Kicker system**
- Number of kickers: 2
- Kickers type: In vacuum, resonant
- Total deflection angle: 1 mrad (vertical)
- Deflection stability: ±80 ppm pk-pk
- Total magnetic length: 1.5 m
- Line field integral: 10 mT.m
- Deflecting current: 500 A pk-pk

**Septum**
- Number of septa: 1
- Septum type: Lambertson, DC
- Total deflection angle: 35 mrad (horizontal)
- Deflection stability: ±10 ppm pk-pk
- Total magnetic length: 1.0 m
- Line field integral: 350 mT.m

Two bunch operation
Resonant Kicker Concept

Main Linac

Illustration of bunches separation scheme using a resonant deflecting magnet. $\vec{I}$ is magnet current, $\vec{B}$ is the magnetic field and $\vec{F}_e$ is the deflecting force.

Simplified electrical circuit

Deflecting current build-up

Achieved kicker (prototype) stability – $< \pm 15$ ppm pk-pk

Challenge:
get 6 GeV of Linac put here until LINAC 2016 conference