Advanced Beam Diagnostics Tools for the SwissFEL Project

Pavel Chevtsov
Outlook

- Introduction/ SwissFEL Project Overview

- SwissFEL Beam Diagnostics Tools

- Summary/Conclusions
SwissFEL location

Paul Scherrer Institute, near Zurich, Switzerland, Europe
SwissFEL – a hard X-ray (0.1 nm) SASE FEL at PSI, Switzerland
SASE* (Self Amplified Spontaneous Emission) FEL

- relativistic electron bunch
- a (long enough) undulator

\[ \vec{B} = \left(0, B_{u} \sin k_{u}z, 0 \right) \]
\[ k_{u} = \frac{2\pi}{\lambda_{u}} \]

*) Kondratenko, Saldin 1980
Derbenev, Kondratenko, Saldin 1982
Bonifacio, Pellegrini, Narducci 1984
SASE (Self Amplified Spontaneous Emission) FEL

- In the undulator, the bunch is modulated by its own synchrotron radiation field
- Electrons are “self-organized” in micro-bunches, which radiate coherently
- The total radiated power grows exponentially until it reaches saturation
SASE FEL performance conditions
\( \vec{B} = (0, B_{\ell} \sin k_{\ell} z, 0) \)

- A resonant condition in the undulator

\[
\lambda_0 = \frac{\lambda_u}{2\gamma^2} \left( 1 + \frac{K^2}{2} \right)
\]

\[
K = \frac{eB_u \lambda_u}{2\pi mc} \approx 0.93 \lambda_u \text{ [cm]} B_u \text{ [T]}
\]

undulator parameter

\[
x(z) = x_0 \sin k_{\ell} z
\]

\[
k_{\ell} = \frac{2\pi}{\lambda_u}
\]

**Parameters for lasing at 1 Å**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>5.8 GeV</td>
</tr>
<tr>
<td>( \lambda_u )</td>
<td>15 mm</td>
</tr>
<tr>
<td>( K )</td>
<td>1.2</td>
</tr>
</tbody>
</table>
A sufficient overlap between the electron bunch and its radiation field

A bright source with small $\varepsilon_N$ or high energy
FEL parameter for VUV FELs $\sim 0.01-0.001$

SwissFEL (0.1 nm) $\sim 0.0003$

$$L_{sat.} \sim \frac{1}{\rho}$$

SwissFEL (0.1 nm) - 45 m

$$\rho \sim \left[ \frac{I_{peak}}{\sigma_x \sigma_y} \right]^{\frac{1}{3}}$$

FEL parameter

for VUV FELs $\sim 0.01-0.001$

SwissFEL (0.1 nm) $\sim 0.0003$

$$L_g = \frac{\lambda_u}{4\sqrt{3}\pi\rho}$$
So, SASE FEL requires

- Small bunch length
- Small transverse bunch size
- Very precise beam steering through the accelerator and (long) undulator
SwissFEL – a “compact” hard X-ray SASE FEL @ PSI, Switzerland

→ building length: ~700 m
→ construction period: 2012 – 2017
**X-FEL Facilities**

<table>
<thead>
<tr>
<th></th>
<th>LCLS (USA)</th>
<th>SACLA (Japan)</th>
<th>European XFEL</th>
<th>SwissFEL (CH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start of operation</td>
<td>2009</td>
<td>2011</td>
<td>2017</td>
<td>2017</td>
</tr>
<tr>
<td>Length [km]</td>
<td>3.0</td>
<td>0.75</td>
<td>3.4</td>
<td>0.75</td>
</tr>
<tr>
<td>Beam energy [GeV]</td>
<td>13.6</td>
<td>8</td>
<td>17.5</td>
<td>5.8</td>
</tr>
<tr>
<td>Min. wavelength [nm]</td>
<td>0.15</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Peak brilliance at $\lambda_{\text{min}}$ [$10^{33}$ photons/s/mm²/mrad²/0.1% BW]</td>
<td>2.4</td>
<td>5.0</td>
<td>5.0</td>
<td>1.3</td>
</tr>
</tbody>
</table>

**SwissFEL has the lowest beam energy (optimized for 1Å)**

**Advantages:** Compact and affordable for Switzerland

**Challenges:** More stringent requirements for the beam quality, mechanical and electronic tolerances
For availability/costs reasons the injector is **European S/X band**, whereas the linac is **US C band**

<table>
<thead>
<tr>
<th>Frequencies in MHz</th>
<th>«European»</th>
<th>«American»</th>
<th>( f_b = 142.8 )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Injector</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-Band</td>
<td>2997.912</td>
<td>2856</td>
<td>2998.8 (21( f_b ))</td>
</tr>
<tr>
<td>Already procured</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X-Band (4 x S-band)</td>
<td>11991.648</td>
<td>11424</td>
<td>11995.2 (84( f_b ))</td>
</tr>
<tr>
<td>Already procured</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Main linac</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-Band (2 x S-band)</td>
<td>5998.524</td>
<td>5712</td>
<td>5712 (40( f_b ))</td>
</tr>
<tr>
<td>requires development of klystron with PSI presently the only customer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Klystron available almost “off the shelf” Spring8, KEK, LNF are already customers</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Common sub-harmonic 142.8MHz, minimum bunch spacing 7 ns
SwissFEL Highlights
- **Two FEL Beamlines:**
  - Hard X-ray Beamline Aramis: SASE FEL (1 – 7 Å), tuning mostly by energy
  - Soft X-ray Beamline Athos: SASE FEL (7 – 70 Å), seeded FEL (10 – 70 Å), tuning by gap and energy
  - Possible future extension for another hard or soft X-ray beamline (Porthos)

- **Electron Beam:**
  - 10 – 200 pC, 2.1- 5.8 GeV, 1.5 – 3 kA, 0.15 – 0.43 mm mrad, Energy spread 300 keV

- **RF:**
  - 2.5 cell S-band RF Gun, S-band booster linac, X-band linearizer, C-band linac
SwissFEL Machine/Beam Diagnostics
Design/Development Resources
SwissFEL Injector Test Facility (SITF): 250 MeV Machine

In operations from 2010-2014
Other FEL Facilities Worldwide

- LCLS, USA
- SACLA, Japan
- FERMI, Italy
- FLASH, Germany
SwissFEL Diagnostics Challenges – Key Beam Parameters

→ low charge (10 pC) capability for all diagnostics monitors
→ high bandwidth pick-ups and detectors to accommodate for 2-bunch mode ($\Delta \tau = 28$ ns)
→ low emittance beam ($\varepsilon_n \geq 180$ nm rad) generating small transverse beam sizes
→ ultra-short bunches ($2.5 \text{ fs} < \tau < 20 \text{ fs}$) and high compression factors
→ ultra-low synchronization and timing (as well as RF) jitter tolerances
→ all monitors must be capable of being used in (beam-based) real-time feedbacks

<table>
<thead>
<tr>
<th>SwissFEL Key Parameters</th>
<th>Operation Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Long Bunch</td>
</tr>
<tr>
<td>Photon Energy</td>
<td>0.2 – 12 keV (1 Å)</td>
</tr>
<tr>
<td>Power / Energy</td>
<td>60 µJ / 2 GW</td>
</tr>
<tr>
<td>Electron Energy</td>
<td>5.8 GeV (for 1 Å)</td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>200 pC</td>
</tr>
<tr>
<td>Rep. Rate</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Bunch Distance</td>
<td>28 ns (2 bunches)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SwissFEL Key Parameters</th>
<th>Operation Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Long Bunch</td>
</tr>
<tr>
<td>Bunch Length</td>
<td>20 fs (rms)</td>
</tr>
<tr>
<td>Comp. Factors</td>
<td>125</td>
</tr>
<tr>
<td>Norm. $\varepsilon_{h,v}$</td>
<td>430 nmrad</td>
</tr>
<tr>
<td>Timing Stability</td>
<td>Jitter</td>
</tr>
<tr>
<td>Sync. System</td>
<td>&lt; 10 fs</td>
</tr>
<tr>
<td>Bunch Arrival</td>
<td>&lt; 10 fs</td>
</tr>
</tbody>
</table>
Beam Charge Monitors

Main SwissFEL requirements:

- Absolute charge (10-200 pC) measurement accuracy – 1%
- 2-bunch resolving capability
Bergoz Turbo-ICT-2

- Delivered as a fully calibrated device
- Not sensitive to the dark current due to its fast readout of the beam induced current (3 ns) at higher bandwidth
Turbo-ICT Principle

- Integration time is reduced by 25 compared to traditional ICT. Bandwidth increase is achieved by using low-loss core alloy.

  ⇒ Signal increases by 25 and noise by $\sqrt{25}$. Hence signal over noise ratio increases by 5.

- Multiple cores could be used to catch more signal from beam. The core windings outputs are combined to optimize the power transmission from cores to front-end amplifier.

- Readout cores are coupled to a low noise amplifier. Impedance is chosen to optimize signal over noise performance.

  ⇒ readsout cores increase noise immunity.
  ⇒ decreases insertion losses in cable.
  ⇒ improves impedance matching.

- Narrow-band processing. The wide-band signal from the amplifier is converted to a 100-325 MHz single tone resonance. Apex amplitude is proportional to the bunch charge.

  ⇒ increases noise immunity.
  ⇒ decreases insertion losses in cable.
  ⇒ improves impedance matching.

Bergoz Instrumentation
Turbo ICT Installed in SITF
Beam Position Monitors
## Requirements / Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Injector</th>
<th>Linac &amp; TL</th>
<th>Undulators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pickup Length</td>
<td>250 mm</td>
<td>100 mm</td>
<td>100 mm</td>
</tr>
<tr>
<td>Inner Beam Pipe Aperture</td>
<td>38 mm</td>
<td>16 mm</td>
<td>8 mm</td>
</tr>
<tr>
<td>Position Range</td>
<td>±10 mm</td>
<td>±5 mm</td>
<td>±1 mm</td>
</tr>
<tr>
<td>RMS Position Noise</td>
<td>&lt;10 μm</td>
<td>&lt;5 μm</td>
<td>&lt;1 μm</td>
</tr>
<tr>
<td>Position Drift (per week)</td>
<td>&lt;10 μm</td>
<td>&lt;5 μm</td>
<td>&lt;1 μm</td>
</tr>
<tr>
<td>Relative RMS Charge Noise</td>
<td>&lt;0.1%</td>
<td>&lt;0.1%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Nominal Charge</td>
<td></td>
<td></td>
<td>10-200 pC</td>
</tr>
<tr>
<td># Bunches per Train</td>
<td>1-3</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Max. Bunch Train Rep Rate</td>
<td></td>
<td>100Hz</td>
<td></td>
</tr>
<tr>
<td>Min. Bunch Spacing</td>
<td></td>
<td>28 ns</td>
<td>-</td>
</tr>
</tbody>
</table>
Solution

Pickups:
• Use only cavity BPMs (based on E-XFEL/SACLA design optimized for low charge operations) to minimize manpower & to get a homogeneous system.

Electronics:
• Based on E-XFEL electronics (PSI, Swiss in-kind contribution to the European project). Small modifications are made to meet SwissFEL specs.
- Passing a pillbox-like resonant cavity the electron bunch excites several resonance modes

  -- short bunches deliver a wide spectrum of frequencies
RF-BPM (similar designs for SCSS, European-XFEL, SwissFEL)

Dual-resonator, coaxial connectors, mode-selective (3.3GHz)

Reference cavity (1 connector): 3.3GHz signal ~ bunch charge

Position cavity (4 connectors): 3.3GHz signal ~ position * charge

Visible: Vacuum, couplers

Mode-selective couplers suppress undesired other modes

Beam Position = k * (V_{Pos\_Cav} / V_{Ref\_Cav}). Factor k: Not fixed, variable via attenuator.

*The identical frequencies of the position and reference cavities modes minimize the impact of the frequency dependent gain drift on the position readings.
SwissFEL Beam Position Monitor System

- BPM38 (stainless steel)
- BPM8 (copper-steel hybrid)
- Electronics (BPM16+38)
- BPM16
- Feedthrough: PSI design, produced in CH (BC-Tech).
- Feedthrough Test Adapter
Cavity BPM Signal Processing Electronics as a Modular Topology of SwissFEL Diagnostics Systems

Based on the latest FPGA technology (Kintex-7/Artix-7)
### SwissFEL Beam Position Monitor System

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Injector, Linac, TL</th>
<th>Undulators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pickup Name (Number = Aperture in mm)</td>
<td>BPM38</td>
<td>BPM16</td>
</tr>
<tr>
<td>Pickup Length</td>
<td>250 mm</td>
<td>100 mm</td>
</tr>
<tr>
<td>Resonant Frequency</td>
<td>3.2844 GHz</td>
<td>3.2844 GHz</td>
</tr>
<tr>
<td>Quality factor</td>
<td>40 (low-Q)</td>
<td>40 (low-Q)</td>
</tr>
<tr>
<td>Quantity Installed in Machine (Phase 1)</td>
<td>7</td>
<td>111</td>
</tr>
<tr>
<td>Position Range</td>
<td>±10 mm</td>
<td>±5 mm</td>
</tr>
<tr>
<td>RMS Position Noise</td>
<td>&lt;10 μm</td>
<td>&lt;5 μm</td>
</tr>
<tr>
<td>Position Drift (per week)</td>
<td>&lt;10 μm</td>
<td>&lt;5 μm</td>
</tr>
<tr>
<td>Relative RMS Charge Noise</td>
<td>&lt;0.1%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td># Bunches per Train</td>
<td>1-3 (Test: SITF 1-2)</td>
<td></td>
</tr>
<tr>
<td>Min. Bunch Spacing</td>
<td>28 ns</td>
<td>-</td>
</tr>
</tbody>
</table>

**Beam Tests:** sub-μm position resolution and ~ 10 fC charge noise
smaller $Q_L$ for higher damping rate

\[ Q_L = \frac{\omega W}{p_0 + p_{ext}} = \frac{\omega W}{-\frac{dW}{dt}} = \frac{\omega}{2\alpha} \]
Beam Position Monitor Project Outcome
Standard SwissFEL Beam Diagnostics Electronics

Examples of PU & Detectors
- Cavity BPM
- Schottky diode
- Turbo ICT
- BAM pick-up
- LAM PD

Front Ends (specific / generic)
- PAC FE Unit
- EO BAM / LAM Front Ends

Generic Digital Back End with FW / SW and CS Interfaces
- Mezzanine 16 bit ADC
- Mezzanine 12 bit ADC
- Mezzanine 12 bit ADC
- Mezzanine 16 bit ADC
- digital interfaces to FE electronics
- ADC function control
- ADC stream interface
- diagnostic specific applications
- communication backbone
- generic SW (embedded CPUs)
- communication interfaces
- timing receiver

Control system
- client applications
- timing system
Transversal Beam Diagnostics Monitors
Wire Scanners
Wire Scanner Characteristics

Typical Electron Beam Size: 5-500 µm

Number of Wires per Frame:
- 3 + 3 (spare or different resolution)
- 3 possible wire separation (to speed-up the scan time)
- X, X-Y& Y scan in sequence

Wire Specifics and Resolution:
- W (Tungsten) wires
- Diameter = 5-25 µm
- Resolution (RMS)= 1.5-6.5 µm

Encoder Resolution:
- 0.1 µm (absolute position)
Technical Realization

- 3 different pins to allocate the wire
- 3 different wire separations
- 3 different scan times

Spring to maintain the wire tension constant
It was demonstrated that in the wire velocity range 0.2-2 mm/sec the wire vibration is below the intrinsic resolution limits.

Al:Si wires of 12.5 micrometer thickness are possible candidates for the undulator areas.
Beam Loss Monitors
Localized BLMs (wire scanner support)

- Must provide online beam size measurements by recording losses due to wire insertions

- Requirements
  
  - Full beam loss event / bunch: 10...200 pC
  - Wire scanner operations: 0.1...20 pC
  
  Operational requirements:
  - Synchronized DAQ @ 100 Hz
  - Interface to Machine Protection System (all BLMs)
  - Ability to resolve 2 bunches
Optical Fiber Based Systems

- Scintillating Plastic Optical Fibers (POF)
- Flexible
- Cost effective

- Clear waveguides can be used to carry signals out of the accelerator tunnel

- Radiation resistant (>20% trans. scint. loss) > 400 Rad for various scintillating POF

  → radiation hard (1 MRad) versions also exist
Optical Fiber Based Systems

- POF fibers for SwissFEL – Saint Gobain Crystals
  - 1 mm diameter polystyrene scintillator fibers
  - Characteristic signal decay time $\sim 2.7$ ns
  - Emission wavelength: visible
  - Photon yield in plastic scintillator: 8000/MeV
  - $1/e$ length $\sim 3.5$m
  - Core refractive index 1.5-1.6

- Can differentiate signal from the dark current

- Can detect wire losses down to the input bunch charge of 1pC
Localized BLMs

- Wire
- ∆z
- Scintillating POF
- Waveguide POF
- Detector
- LED
- Beam Pipe
Localized BLMs

Fast PMT - Hamamatsu H10720

Provide 28 ns bunch resolution
Distributed BLMs (for machine interlocks)

Based on Cherenkov radiation generated by lost particles in long optical fibers (quartz) installed along the accelerator.

\[ t = \frac{\Delta z}{c} + \frac{\Delta z}{\frac{2}{3}c} = \frac{5}{2} \frac{\Delta z}{c} \]
Example: beam loss distribution in SITF

- Losses at bunch compressor
  - $Q = 210\text{pC}$
  - Beam energy = 200MeV
  - Distance (Wire-BLM) = 6m

- Losses due to 25um W wire
Transverse Profile Imagers
- SR/DR/ER monitors
- OTR
- Scintillator Screens
Optical Transition Radiators as 2D Transverse Profile Monitors

Schematic Set-Up and Main Properties of OTR as Screen Monitors

- OTR is generated when relativistic charged particles pass the boundary of two media with different dielectric (optical) properties.

- OTR screen could be a thin metal foil or silicon wafer (with Al layer).

- OTR is radiated in forward and backward direction with an opening angle of $1/\gamma$.

- Incoherent Optical TR provides good linearity for profile measurements.

- Surface quality of OTR screen affects profile imaging quality (beam size).
Optical Transition Radiators as 2D Transverse Profile Monitors

The PROBLEM:

Coherent OTR has been observed for highly brilliant electron beams

- Coherent OTR was first observed at LCLS
- SACLA and FLASH validated COTR observations

So, to measure profiles with wire scanners? but it is very slow...

Another option – to use scintillator screens (also affected by the COTR) and try to suppress the generated COTR.
Scintillator Screens as 2D Transverse Profile Monitors
(YAG or LuAG scintillator crystals)
Schematic Set-Up and Main Properties of Scintillators as Screen Monitors

- electrons passing the scintillator crystal excite atoms and molecules, which then scintillate: re-emit the energy in the form of light
- visible light from scintillator crystals is radiated in $4\pi$
- photons are created along the beam pass through scintillator crystal - a “light column” is formed
- scintillator crystals are very sensitive and radiation resistant
- multiple scattering in scintillator crystal increases beam divergence
- thickness of scintillator crystals and observation angles affect resolution
- COTR is formed at the border scintillator/vacuum
COTR Suppression: Temporal Separation with Scintillator & Gated CCD

- OTR is an instantaneous process
- Scintillation has a “long” decay time
- Coherent OTR produces in case of micro-bunching
- Scintillation is not sensitive to micro-bunching

![Diagram showing electron bunch arrival at screen, OTR decay time, and scintillation decay time](image)
COTR Mitigation Tests @ FLASH using Scintillator and ICCD (Minjie Yan et al., FLASH, Hamburg)

no delay at ICCD
- COTR and CSR on OTR screen
- COTR and CSR on scintillator (LuAG screen)

100 ns delay at ICCD
- no signal from OTR screen
- Scintillation light only from LuAG screen

COTR Suppression: Temporal Separation with Scintillator & Gated CCD
COTR Suppression: Spatial Separation – Central Mask in Imaging System

- OTR is emitted at an angle $\Theta \sim 1/\gamma$
- at beam energies > 1 GeV: $\Theta < 0.5$ mrad

- scintillation light is emitted in $4\pi$
- central mask in imaging system successfully suppresses COTR intensity

COTR Mitigation @ SACLA using Scintillator and Spatial Mask (S. Matsubara et al., Spring8, Japan)
COTR Suppression: Spatial Separation – SwissFEL Profile Monitors

- entire screen (large RoI) can be observed without depth-of-field issues by following Scheimpflug imaging principle
- detector (CMOS sensor) is tilted by 15° for 1:1 imaging to avoid astigmatism
- use YAG or LuAG scintillator crystals instead of OTR
- observation of beam profile according to Snell's law of refraction
- beams can be imaged, which are smaller than scintillator thickness

\[
\frac{\sin \beta}{\sin \alpha} = n_{scint}
\]
COTR Suppression: Spatial Separation – SwissFEL Profile Monitors

COTR Mitigation for SwissFEL Screen Monitors

COTR suppression tests at LCLS (full compression, 20 pC)
Bunch Compression Monitor
Bunch radiation spectrum

\[
\frac{dU}{d\lambda} = \left( \frac{dU}{d\lambda} \right)_0 \left( N + N(N - 1) |F(\lambda)|^2 \right)
\]

where

\[(dU/d\lambda)_0\]

is emission spectrum of one electron

and

\[F(\lambda) = \int_{-\infty}^{\infty} S(z) \exp \left( \frac{-2\pi i}{\lambda} z \right) dz\]

is the bunch form factor.
Coherent Radiation Based Diagnostics

Bunch radiation spectrum

\[ \frac{dU}{d\lambda} = \left( \frac{dU}{d\lambda} \right)_0 \left( N + N(N-1)|F(\lambda)|^2 \right) \]

where

\( (dU/d\lambda)_0 \)

is emission spectrum of one electron

and

\[ F(\lambda) = \int_{-\infty}^{\infty} S(z) \exp\left( \frac{-2\pi i}{\lambda} z \right) dz \]

is the bunch form factor

Fig. 1 Plot of Power vs. Wavelength for Injector CSR Port

\[ 4\sigma = 0.4° \]

\[ 4\sigma = 0.7° \]
SwissFEL **BC-1** THz Compression Monitor

- **use of coherent edge radiation** from 4th BC-1 dipole (non-invasive)
- **two signal paths** for observation of different spectral (THz-) ranges for sensitivity to different bunch lengths
- **use of THz high pass filters and broadband Schottky diodes**
- **ND-filters for intensity adjustment** (bunch charge range: 10 – 200 pC)
- **read-out electronics similar to button-type BPM RF front end**

![Diagram of THz compression monitor](image)

**Spectral range of CER and THz filters for BC-1**

- Spectral power [W/Hz]
- Wavelength [μm]
- Frequency [THz]

[Graph showing spectral range and raw signals from Schottky diodes]
SwissFEL BC-1 THz Compression Monitor

- quasi-linear behaviour of Schottky diode signals within the nominal operation range of BC-1 compression monitor (10 – 200 pC)

- SwissFEL operation modes with 2-bunches (@ 28 ns bunch distance) and low charge (10 pC) are feasible with Schottky diodes

stability requirement of phase FB
### Table 1 - Commercially Available Room Temperature THz Detectors

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>NEP W/Hz$^{1/2}$</th>
<th>Responsivity V/W</th>
<th>Response Time (seconds)</th>
<th>Operating Temp (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golay cells [3]</td>
<td>$10^{-10}$</td>
<td>$10^5$</td>
<td>$10^{-2}$</td>
<td>300</td>
</tr>
<tr>
<td>Schottky diodes [5]</td>
<td>$10^{-12}$</td>
<td>$10^3$</td>
<td>$10^{-12}$</td>
<td>10-420</td>
</tr>
</tbody>
</table>
Summary
<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity and Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Position Monitors</td>
<td>$7 \times \text{BPM-38} / 111 \times \text{BPM-16} / 27 \times \text{BPM-8}$ (all cavity-type BPMs)</td>
</tr>
<tr>
<td>Screen Monitors</td>
<td>$10 \times$ high sensitivity, high resolution SCM for meas. at 100 Hz, $14 \times$ SCM for observation and control room support at 10 Hz</td>
</tr>
<tr>
<td>Wire Scanners</td>
<td>$23 \times \text{WSC}$ along LINACs, TLs and ARAMIS Undulators</td>
</tr>
<tr>
<td>Synchrotron Radiation Monitors</td>
<td>$1 \times \text{BC-1} / 1 \times \text{BC-2} / 1 \times \text{Collimator}$ ($10^{-4}$ energy spread res.)</td>
</tr>
<tr>
<td>Beam Charge Monitors</td>
<td>$4 \times \text{Turbo-ICT-2}$ (~ 4% absolute), $145 \times \text{BPMs}$ (0.1% relative)</td>
</tr>
<tr>
<td>Beam Loss Monitors</td>
<td>38 scintillating monitors (high sensitivity), 8 distributed Cherenkov monitors</td>
</tr>
<tr>
<td>Dose Rate Monitors</td>
<td>32 Rad FET dose rate monitors (FERMI-type)</td>
</tr>
<tr>
<td>Bunch Arrival Time Monitors</td>
<td>$4 \times \text{BAMs}$ (in front of LH, BC-2 &amp; collimator, behind ARAMIS undulators)</td>
</tr>
<tr>
<td>Gun Laser Arrival Time Monitor</td>
<td>$1 \times \text{LAM}$ at photo-injector gun</td>
</tr>
<tr>
<td>Compression Monitors</td>
<td>$1 \times \text{BC-1 (THz)} / 1 \times \text{BC-2 (FIR)} / 1 \times \text{Collimator (FIR to visible)}$</td>
</tr>
<tr>
<td>Transverse Deflectors</td>
<td>$1 \times \text{S-band}$ (behind BC-1 at 450 MeV providing 15 fs time resolution), $1 \times \text{C-band}$ (behind LINAC-3 at 5.8 GeV providing ~ 2 fs time resolution)</td>
</tr>
</tbody>
</table>
References

- Vacuum tank
- Mineral cast support frame
- Array of 1060 permanent magnets
- Positioning mechanic:
  - μm precision
  - Tons of magnetic force
- 4m
### U15 parameters

<table>
<thead>
<tr>
<th>Type</th>
<th>Hybrid - In Vacuum</th>
</tr>
</thead>
<tbody>
<tr>
<td># units</td>
<td>12</td>
</tr>
<tr>
<td>Period</td>
<td>15 mm</td>
</tr>
<tr>
<td># periods</td>
<td>266 (including ends)</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>3990 mm</td>
</tr>
<tr>
<td>K-values</td>
<td>1.8 1.4 1.2 1.0</td>
</tr>
<tr>
<td>GAP</td>
<td>3.2* 4.2 4.7 5.5 mm</td>
</tr>
<tr>
<td>Bz max</td>
<td>1.27 1 0.85 0.7 T</td>
</tr>
<tr>
<td>Br</td>
<td>1.25 T</td>
</tr>
<tr>
<td>HcJ</td>
<td>≥2400 kA/m</td>
</tr>
<tr>
<td>Magnet size</td>
<td>WxHxT=30x20x2.25 mm</td>
</tr>
<tr>
<td>Pole size</td>
<td>Wb/Wt/HxT=20/15x16.5x3 mm</td>
</tr>
<tr>
<td>Max GAP</td>
<td>20.0 mm</td>
</tr>
<tr>
<td>ΔGAP</td>
<td>0.3 μm</td>
</tr>
</tbody>
</table>

*Minimum magnetic GAP (Vacuum GAP=3mm)
Robot adjusting magnet positions in the SwissFEL undulator
Thank You!