Rasmus Ischebeck

Diagnostics for FELs and ERLs
CERN Accelerator School: Free Electron Lasers and Energy Recovery Linacs
2016-06-08
Usage of Diagnostics: Measurement and Optimization of Beam Parameters

- Optimization of the emittance from a photocathode gun
- Figure of merit: emittance measured on screen
- Optimization of magnetic fields in the gun, and of RF parameters
• Asymmetry in the beam caused by mis-alignment
Usage of Diagnostics: Stabilization of Systems

- **Waldemar Koprek, DESY**

**FLASH/XFEL Seminar, 02.11.2010**

### Measurement

- **Macro pulse arrival time jitter**

  **With Beam Based Feedback**
  - running in ACC1 and ACC39
  - `rms = 5 fs`

  **Without Beam Based Feedback**
  - Learning Feed Forward ON
  - `rms = 74 fs`

### Performance

- Resolution of BAM ~ 10 fs for single bunch
- Can be improved to ~ 1 fs for macro pulse

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**Rasmus Ischebeck** > CERN Accelerator School on FELs and ERLs, 2016-06-08 > Diagnostics for FELs and ERLs
Figure 1: Scheme of the FBLM installed at PHIL. The red stars indicate the positions of the loss points at Sapphire plate and YAG-3 locations. In this case, two plots illustrate the typical beam losses measured by the upstream and downstream PMTs.

Although the strength of the signal detected is proportional to the beam loss intensity, it is also dependent on the type and mass of the material within which the electromagnetic shower is developed. Various beam line elements and hardware will cause the signal variations since the fiber has to be pulled around such components. This, together with the absorption of the signal by the fiber as it transmits to the detector makes difficult to extract the exact amount of the beam loss and use the FBLM to measure the absolute intensity of the losses.

The time calibration of the FBLM can be accomplished by several techniques [4]. The one, adopted by our scheme uses the beam loss signal produced by inserting a known device such as the vacuum valve, collimator, screen, etc. as the reference. Knowing the speed of light in the fiber, one can calibrate the oscilloscope display (time between the beam losses measured in seconds) to real distance along the accelerator (distance between the beam losses measured in meters). In our case, the speed of light in the fiber was measured to be $0.63 \times c$ (0.19 m/ns), where $c$ is a speed of light in vacuum. This calibration gives that every meter along the accelerator is 8.6 ns on the oscilloscope. Therefore, by measuring the time between the reference and the unknown beam loss signal and dividing it by 8.6 ns/m one can determine the location in meters from the reference to the unknown beam loss point.

As mentioned before, in some locations due to the beam line elements the fiber covers a slightly longer path than the beam line. The further measurements are done from the reference, the greater chance for the error to penetrate into the measurements. This results in the deterioration of the FBLM accuracy. Therefore, to reduce the errors in the absolute loss position measurements, it is required to have as many references as possible. Moreover, the fiber should be placed as close to the beam pipe as allowed by the geometry of the beam line components.

FBLM INSTALLATION

Fibers for the FBLM

The fiber installed at PHIL facility is made by the LEONI Fiber Optics GmbH. It belongs to the Hard Plastic Clad Silica (HPCS) fibers which combines fused silica glass core and polymer cladding consisting of a fluorinated acrylate. Numerical aperture of the HPCS fibers can go up to 0.49. This kind of the fibers are positioned as a cost-effective alternative to the silica/silica glass fibers. As far as radiation hardness is concerned, the fibers with plastic core/cladding suffer from radiation damages. Radiation damage of the optical fibers can be an issue because it will degrade the light propagation. Therefore, depending on the expected radiation level the fibers having silica glass core and cladding are preferable (e.g. AS600/660UVST, LEONI Fiber Optics) [5].

The fibers used at PHIL have a 600 $\mu$m fused silica glass core, 630 $\mu$m of optical cladding made from polymer and 950 $\mu$m Tefzel® jacket. Since the jacket surrounding the
Diagnostics at FELs — Unique Challenges

20pC, 1keV short bunch setup

Lasing off Lasing on

4.5 fs

electrons

Yuji Otake, SPring-8, Patrick Krejcik, SLAC, Bolko Beutner, PSI
Large dynamic range measurements (example)

Main principle of one of the ways to make large dynamic range measurements is to reduce a measurement to frequency measurements. Then make it work for 1 Hz and for 100 MHz and this is $10^8$ dynamic range.

For instance use PMT and keep them working in counting mode.

Can be applied to e-beam measurements, laser, (light), X-rays.

Example: wire scanner measurements:

Courtesy of A. Freyberger (measured at CEBAF)
Diagnostics at FELs

- Integral Measurements
- Transverse Diagnostics
- Time-Resolved Diagnostics
Phase Space Transformations

Structure installed on bench before waveguide connected.
(1) Mapping of the time axis onto the vertical angle by the transverse deflecting structure, (2) variation of the horizontal phase advance between the deflector and the profile monitor by adjusting the quadrupole lenses, while keeping the vertical phase advance approximately constant such that a vertical angle is transformed into a vertical position, and (3) measurement of the horizontal beam size in several slices of the beam.
20pC, 1keV short bunch setup

Lasing off

Lasing on

X-rays

4.5 fs

Electrons

Patrick Krejcik, IBIC 2013

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Diagnostics at FELs

- Integral Measurements

- Transverse Diagnostics

- Time-Resolved Diagnostics
Integral Measurements
Current Transformer

\[ B = \frac{1}{N} \cdot I \]
Photon Pulse Energy

Faraday cup multipler: ETP 14880
-2 kV to 4 kV

Ion pulsed signal
50 Ohm

Extraction electrode
-50 V

FEL beam

Electrons
+

Faraday cup

Isolator
50 Ohm

Electron pulsed signal

Read-out electrode

Extraction electrode
+

Kai Tiedtke > CERN Accelerator School on FELs and ERLs, 2016-06-08 > Diagnostics for FELs and ERLs
INSTRUMENTATION FOR MACHINE PROTECTION AT FERMI@ELETTRA

L. Catani, INFN, Rome, Italy
D. Di Giovenale

Abstract
FERMI@Elettra is a linac-driven free-electron laser currently under commissioning at Sincrotrone Trieste, Italy. In order to protect the facility's permanent undulator magnets from radiation-induced demagnetization, beam losses and radiation doses are monitored closely by an active machine protection system. The paper focuses on the design and performance of its main diagnostic subsystems: Beam loss position monitors based on the detection of Cherenkov light in quartz fibers with multi-pixel photon counters, conventional ionization chambers with a new frontend electronics package, and solid-state RADFET dosimeters providing an online measurement of the absorbed dose in the undulator magnets.

INTRODUCTION
FERMI@Elettra is a fourth generation light source currently under commissioning at Sincrotrone Trieste. As illustrated in Fig. 1, the main components of the accelerator are a photocathode RF gun, 16 accelerating S-band sections, an X-band structure for phase space linearization, two magnetic chicanes for bunch compression, and two separate undulator sections with 7 and 10 undulators, respectively. The linac design foresees the extraction of electron bunches with a maximum charge of 1 nC at a rate of 50 Hz and the acceleration to a final energy of 1.2 GeV [1].

The maximum power carried by the beam amounts to about 60 W. While this hardly poses a direct threat to beamline components, considerable amounts of radiation can be released when a part of the electron beam strikes the vacuum chamber. Elevated radiation doses are especially undesirable in the undulator sections where they can lead to partial demagnetization of the permanent magnets with a detrimental effect on the free-electron laser process.

To avoid beam-induced damage, Fermi is protected by an active machine protection system that inhibits the extraction of charge in the photoinjector when necessary [2]. Several diagnostic systems have been developed specifically with the focus on machine protection. In the following, we give a brief overview of these systems and make some remarks on the operational experience gathered so far.

RADFET DOSIMETERS
The dose deposition in the sensitive undulator magnets is monitored by four compact integrating MOSFET dosimeters per undulator. These RADFETs (see e.g. [3]) of the type RFT-300-CC10G1 are produced by REM Oxford Ltd., have an oxide thickness of 300 nm, and allow the measurement of doses up to about 10 kGy without the application of a bias voltage during irradiation.

The dosimeters are mounted on the undulator support structure with the help of a small printed circuit board as depicted in Fig. 2. They are read out by a custom microprocessor-controlled reader unit that periodically drives the RADFETs with a constant current of 490 μA. The voltage needed to drive this current is digitized with a 24-bit ADC. Each of the four channels and communicates via an ethernet interface.

At the moment, the dosimeters have a purely diagnostic function and no direct connection to the machine protection system is foreseen. However, the reader is equipped.
Transverse Diagnostics
• Low charge: Position-noise \cdot \text{charge} = \text{const} = 15\text{pC} \cdot \mu\text{m}
• Q=135\text{pC}: \text{Noise} < 0.8\mu\text{m RMS,} \pm 1\text{mm range.}
• Charge noise < 0.1\% (<0.1\text{pC RMS at} Q=135\text{pC}).
The diagram illustrates the interaction of a primary beam with a scintillating crystal. The beam impinges on the crystal, and a virtual image is formed. The observer views the image, which is dependent on the observation angle. The graph on the right shows the dependence of the image size on the observation angle.
The multislit or a single slit scanning through the beam (or a beam scanning across the slit) does the job very well (pulsed beam only).

- well established technique
- works for space charge dominated beam
- beam profile is measured with YAG
- measures not only the emittance but the Twiss parameters as well
- enough information to reconstruct the phase space
- has been implemented as on-line diagnostics
- works with diagnostics mode only (low duty cycle, average current)

Multi-slit emittance measurements
- mask is used to cut a small beamlet(s)
- every beamlet is emittance dominated

Beam profile measurements
- intensity of beamlets (A)
- width (w)
- Displacement (d)
This can be achieved by either changing quadrupole currents or by employing several screens (multi-screen method) [6]. A long-term development of the single-screen setup is envisaged, which includes the possibility of measuring the transverse emittance of the remaining bunches in the bunch train. A longitudinal section of the electron bunch is formed by a kicker magnet and then deflected by the fast kicker magnets onto the off-axis screen [8]. The positions of the kicker magnets and the off-axis scintillation films are adjusted with respect to the beam axis and imaged under a 45° inclination [9]. The scintillation screens are made of 200 μm thick LYSO:Ce [9]. The performance of a hard X-ray free-electron laser (FEL), such as the Free-Electron Laser in Hamburg (FLASH) [7], is strongly dependent on the quality of the electron beams. Dedicated longitudinal electron beam diagnostics is essential for successful operation of modern free-electron lasers. A disadvantage of this direct time-domain method is that the transverse deflection of the electron beam may be degraded due to non-linear effects, e.g. emission of micro-bunching instabilities [4].

Excellent candidates for the measurement of the slice emittance [1] are transverse deflecting structures (TDS) [4, 5]. The electron bunch is streaked in the longitudinal direction using kicker magnets and then deflected by the fast kicker magnets onto the off-axis imaging screen. The experimental setup is described in detail in the following sections.

**Abstract**

As the FEL amplification process takes place locally, the performance of a hard X-ray free-electron laser (FEL), such as the Free-Electron Laser in Hamburg (FLASH) [7], is strongly dependent on the quality of the electron beams. Dedicated longitudinal electron beam diagnostics is essential for successful operation of modern free-electron lasers. The performance of a hard X-ray free-electron laser (FEL), such as the Free-Electron Laser in Hamburg (FLASH) [7], is strongly dependent on the quality of the electron beams. Dedicated longitudinal electron beam diagnostics is essential for successful operation of modern free-electron lasers.
Figure 1: Top view of the B1 injector merger section showing the emittance measurement system.

MEASUREMENTS

Data sets for 19 pC per bunch and 77 pC per bunch, corresponding to 25 mA and 100 mA average current when operating with the full 1.3 GHz repetition rate, were taken. Each data set consists of a measurement of the projected horizontal and vertical phase spaces, the time-resolved horizontal phase space, and the energy spread distribution. All data was taken at the end of the merger section except the energy spread data, which was measured near the entrance to the merger. From the projected phase spaces, the horizontal and vertical emittances as a function of beam fraction were computed. Similarly, from the time-resolved phase space data, the slice emittance was computed as a function of beam fraction, as well as the current profile along the bunch.

Tables 2 and 3 give the measured and simulated projected horizontal and vertical emittances for 19 (77) pC per bunch, respectively. The measured 19 (77) pC/bunch horizontal and vertical projected 100% emittances agreed with the GPT model to within 6 (5) % and 25 (8) %, respectively. Similarly, the measured horizontal and vertical 90% emittances agreed with GPT to within 21 (16) % and 27 (16) %, respectively. We point out that the measured horizontal and vertical 100%, 90%, and core emittances obey the expected scaling law $\varepsilon_n = \varepsilon_0 n^q$. Also of note is the fact that the horizontal core emittance for 77 pC meets the injector design specification for an ERL. In the vertical plane, both the 90% and core emittance meet this specification.

In order to satisfy the injector design requirements, it was important to verify that the emittance values were measured with an acceptable bunch length ($t \lesssim 3$ ps). The rms bunch length was computed from the instantaneous current of each bunch measured with the time-resolved merger EMS. The rms bunch lengths for the 19 (77) pC per bunch settings were measured to be $2.1 \pm 0.1$ ($3.0 \pm 0.2$) ps, respectively, while GPT gave bunch lengths of 2.2 (3.1) ps, respectively. The agreement between measurement and GPT was within 5% in both cases.

The last quantity measured was the rms energy spread. To do so, the beam was sent through the A4 straight section, followed by a single dipole and viewscreen in the C2 section. Table 4 shows the simulated and measured rms energy spread in the straight section, as well as simulated values in the B1 merger. While the energy spread was not directly in the merger section, the agreement found between measurement and simulation for emittance and bunch length lead us to conclude that the values measured in the straight section at least provide an upper bound on the energy spread in the merger, following the same trend found in the simulation data.

CONCLUSION AND DISCUSSION

The projected and time-resolved phase spaces at the end of the Cornell ERL injector merger have been measured and simulated using the space charge code GPT for 19 pC and 77 pC bunch charges. In addition, the energy spread was measured in the straight section of the machine. Overall, we found excellent agreement between measurement and simulation. For both bunch charges, the agreement between measurement and simulation was within 5%.
Profile Momenta:

- $\text{RMS}_x = 1.6896 \text{ mm}$
- $\text{mean}_x = 5.2883 \text{ mm}$
- $\text{RMS}_y = 0.62493 \text{ mm}$
- $\text{mean}_y = -3.2103 \text{ mm}$
shielding for better accessibility. The optical path length of Helmholtz and Kirchhoff of the emitting relativistic electron. The fields are propagated from valley-to-peak ratio of the phenomena of SR emission, propagation and focusing i.e. the vertical electron beam size.

Tuning' a new beam size monitor was designed and built. The monitor is based on the imaging of the vis-UV synchrotron radiation (SR) imaged onto a CCD camera for detection. The vertical beam size from vertically polarized (\(+\pi\)) was measured using this beam size monitor, \(\pm 4\) pm, was measured using this beam size monitor, \(\pm 0.5\) µm. The interferometric method of the beam size monitor is wavelength independent focal length. This enables a simpler measurement in this so-called intermediate configuration \([5–7]\). In addition to the vertical beam size the horizontal beam size, being of the order of 60µm, can be deduced from a Table 1: Toroidal Mirror Specifications.

\begin{table}[h]
\begin{tabular}{|c|c|}
\hline
Parameter & Value \\
\hline
Material & Silicon \\
\hline
\end{tabular}
\end{table}

Vertical beam size: \(4.8 \pm 0.5\) µm

Corresponding vertical emittance: \(1.7 \pm 0.4\) pm
Time-Resolved Instrumentation
bunch length of below 300 fs. Hence, we employed the RFDEF to diagnose a 30 fs electron bunch of SACLA. The bunch-length measurement system, as shown in Fig.26, comprises a C-band rf deflector (RFDEF), a beam drift space, and a high spatial resolution SCM, as mentioned in the previous section. This RFDEF operated at 5712 MHz is driven by a high-power rf source including a 50 MW pulse klystron.

The operating principle of the RFDEF is as follows. The RFDEF is a backward traveling-wave structure at the operation rf mode of HEM11. When the electron beam is injected into the structure at an rf zero-cross phase, the RFDEF pitches the beam bunch around its center to project an image of a longitudinal bunch structure on the screen of the above-mentioned SCM. The relation between the deflection voltage, $V_y$, and the projected bunch length on the screen, $l_y$, is given by

$$V_y = \frac{l_y L_d}{k a C^2 z}.$$  

(7)

where $L_d$ is the drift length between the RFDEF longitudinal center and the surface of the SCM screen, $k a$ is the wave number of the RFDEF, $C$ is the bunch length, and $p z$ is the longitudinal momentum of the electron bunch. $V_y$ must be 40 MV in the case of $L_d = 5 \text{ m}$ to obtain a bunch-length measurement sensitivity of $200 \text{ fs} = 2 \text{ mm}$ on the screen of the SCM with a spatial resolution of less than $2 \text{ mm}$.

To realize this measurement system, a special backward traveling-wave accelerating structure with the HEM11-$(5/6)$ transverse mode at 5712 MHz was developed, as shown in Fig.27. This accelerating structure has racetrack-shape rf coupling irises to prevent rotation of the deflection plane of the HEM11 mode. The main parameters of this backward traveling-wave accelerating structure are tabulated in Table II, and the dispersion relations of the X and Y modes in a fabrication model of the accelerating structure are depicted in Fig.28. In the figure, the X and Y modes are sufficiently separated by the iris. Furthermore, even though the $(5/6)$ mode is employed, a group velocity, $v g = 0.02 c$, in the accelerating structure is achieved. These rf characteristics guarantee stable high-power rf operation of the accelerating structure.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total deflecting voltage</td>
<td>$40 \text{ MV}$</td>
</tr>
<tr>
<td>rf deflecting phase</td>
<td>0 degree</td>
</tr>
<tr>
<td>Fractional bunch length for x-ray oscillation</td>
<td>$200 \text{ fs}$</td>
</tr>
<tr>
<td>Beam energy at the deflector</td>
<td>$1.45 \text{ GeV}$</td>
</tr>
<tr>
<td>Resonant frequency</td>
<td>5712 MHz</td>
</tr>
<tr>
<td>Type of structure</td>
<td>CZ</td>
</tr>
<tr>
<td>Resonant mode</td>
<td>HEM11</td>
</tr>
<tr>
<td>Phase shift per cell</td>
<td>$5/6 \text{ rad}$</td>
</tr>
<tr>
<td>Group velocity</td>
<td>$v g = 0.02 c$</td>
</tr>
<tr>
<td>Filling time</td>
<td>$0.27 \text{ s}$</td>
</tr>
<tr>
<td>Unloaded QQ</td>
<td>11500</td>
</tr>
<tr>
<td>Transverse shunt impedance</td>
<td>$13.9 \text{ M}$</td>
</tr>
<tr>
<td>Length of structure</td>
<td>$1.72 \text{ m}$</td>
</tr>
</tbody>
</table>
Electrons flying into plane of view

32 mm
strongly on the duration of the cycle period of the dressing laser
with a magnetic bottle electron spectrometer (MBES). With an
ionized by the FEL and the generated photoelectrons are detected
with the X-ray beam in a dilute gas target. Here, Ne gas atoms are
coarsely synchronized to the X-ray pulse is spatially overlapped
technique for temporal characterization of attosecond pulses in the
to be measured.

The presence of an external optical laser
the basic principle of streaking. Photoelectron spectra generated in
Supplementary Methods.

NIR streaking spectroscopy of FEL pulses
To directly measure the FEL pulse duration we rely on the method
NIR streaking spectroscopy26,27, a well-established
nature, ultrashort duration and the inherent jitter in their arrival

new photolines, symmetrically distributed on both sides of the orig-

Figure 1 presents the experimental set-up and illustrates the
the photoelectrons in the absence of the NIR laser is distributed
FEL photon energy of
E ≈ 921 eV. Thus, each photoelectron can
1,791 eV and a binding energy of
890 eV.

Figure 1 | Experimental set-up and measurement principle at the LCLS.

In general, one can discern two distinct cases of dressed
period to the duration of the X-ray pulses that generate the photo-
will

their

electron bunch instead of the X-ray pulse itself. To date, no direct
provide only indirect evidence, as they are working on the generating

irradiation. In this way, the electron spectra are signi-

sideband regime

= −

Δ

E(Δt) = −πc

IR(Δt)

When the duration of the X-ray pulses is shorter than the period

Δ

τ

X-ray < 1), measurements belong to

Δ

Δ

E(Δt) = −πc

IR(Δt)

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ARTICLES
NATURE PHOTONICS
8
−

9
−

4

−

8

9

0

4

8

Delay (fs)

X-ray pulse

Infrared pulse

Vacuum chamber AMO

MBES

Ne
Spectral Techniques
a) Off-crest acceleration

b) Magnetic chicane
c) 

d) Low energy, high energy
Relative Bunch Length Monitor

Pyroelectric detector good from 100GHz to light (response is not flat)

Si window transmits from mm-wave to ~1 micron.

Can also use mm-wave diodes for BC1 (< 1 THz)
Relative Bunch Length Monitor

- Need shot to shot non-invasive bunch length monitor.
- Diffraction aperture and broadband (pyroelectric) detector.

Joe Frisch
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Physics

Electron Beam

Bending Magnet (4th Chicane Magnet)

Perforated Mirror

View Port (Fused Silica or Silicon)

Terahertz Lens (Tsurupica)

Pyro-electric Detector or Diode Detector

Mirror

FWHM ~160fs
Det Nr. 19 / THz filter: 0.6 THz high pass

N = 0.8 % → 0.00161 V

-44.85 * x
1x diagn. noise → -0.022°

Det Nr. 8 / THz filter: 0.26 THz high pass

N = 0.6 % → 0.00238 V

-15.464 * x
1x diagn. noise → -0.065°
Detector Signals

- **Purpose:** bunch compression monitor
- **Location:** BCM after BC1
- **Front-end:** E-XFEL button BPM RFFE
- **12 bit ADC (500MS/s), 1 ch/detector**
- **Digitization of S&H output**
- **EVR + IOC per location**

**Fast MCT:**
- **Location:** CDR port after BC2
- **Front-end:** RFFE with some adaptation
- **Digitization of S&H output**
- **12 bit ADC, 1ch/detector**
- **EVR + IOC per location**

**Slow MCT:**
- **Location:** BCM after BC2
- **Front-end:** Commercial
- **12 or 16 bit ADC (tbd)**
- **Integration of digitized signal**
- **EVR + IOC per location**

---

Schottky Diodes

MCT

Fast MCT raw signal
Accelerating voltages of 238 MHz generated by the simulation results in output frequencies greater than 3, 6, 12, and 24 GHz.
Each stage acts as dispersive element + filter for next stage

- Parallel readout
- 4 Stages cover one order of magnitude in $\lambda$
CRISP4: Setup Specifications

Engineered version

2 Grating sets

\[ \text{Short} = 544 \mu m \]
\[ \text{Long} = 45435 \mu m \]

Mirror set

Set alignment

Ring mirror

Line focus

Inside vacuum vessel

Avoid IR absorption

S. Wesch (DESY)

THz Bunch Profile Monitoring


Stephan Wesch
Setup

CRISP4

- Five consecutive gratings as prefilter and dispersive devices
- Wavelength coverage from \(5.5\) to \(440\) \(\mu m\) with two sets of gratings
  - Set one: \(5.5\) to \(44\) \(\mu m\)
  - Set two: \(44\) to \(440\) \(\mu m\)
- One order of magnitude for four gratings
- Parallel readout of 120 channels for one set of gratings

E.Hass (University of Hamburg)
Profile: TDS - CRISP4 Comparison

Long wavelengths extrapolation fit with:

\[ F_l(\lambda) = \exp(-A \lambda^2 B) \]

Short wavelengths cut at minimal CRISP4 range:

\[ F_l(\lambda < 5 \mu m) = 0 \]

Average currents agree
Total bunch lengths agree
More pronounced trailing spike
Large local energy spread!

S. Wesch (DESY)
THz Bunch Profile Monitoring
BIW 2012, Newport News 15 / 20

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