The most important difference of the code applied to the SwissFEL is the use of a thermal emittance value for the 266.7 nm laser wavelength. This value is measured at the SITF.

### Table 4: Optimized SwissFEL Injector Using the Thermal Emittance

<table>
<thead>
<tr>
<th>Laser sigma (mm)</th>
<th>Gun gradient (MV/m)</th>
<th>Laser pulse length (ps)</th>
<th>Charge (pC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.38</td>
<td>100</td>
<td>9.9 (FWHM)</td>
<td>200</td>
</tr>
<tr>
<td>682 nm/mm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the case of the machine, it was necessary to dedicate a large amount of time to the optimization, considering the limited number of particles, which is a constraint in the simulations. This problem was solved by simply increasing the number of particles. However, this is only possible if the limited available CPU time can be considered. In the optimization only the mismatch parameters with respect to the design values are important. The optimization in the machine is shown in Fig. 14.

In the GUI, the method to measure the emittance can be varied. This can be repeated several times, and the standard deviation of the previous measurement is used to ensure accuracy.

When running the simulations, the Matlab-based GUI written to control the machine instead of writing an Astra input file, and do this, it’s enough to send the settings to the machine easily adapted to be applied directly to the machine. To do such an optimization is shown in Fig. 14.

As it can be seen, the code brought back the emittance measured at the SITF thermal emittance along the bunch for the SwissFEL.

### Usage of Diagnostics: Measurement and Optimization of Beam Parameters

- Optimization of one or several parameters, summarized in a figure of merit
- Manual or automatic optimization possible

### Usage of Diagnostics: Find Errors

- Errors in beam setup (alignment, phase, ...)
- Mistakes in hardware setup
Stabilization of systems
> measure parameter and automatically adjust accelerator parameters
> feed-backs
> here: beam-based feedback of arrival time, acting on RF parameters
Note the different scale on the plots!

Personnel and machine safety
> Beam loss detection by Cherenkov radiation in optical fiber
> Mapping of arrival time to position through propagation speed in the fiber

Diagnostics at FELs — Unique Challenges
> Top left: High brightness: coherent optical transition radiation spoils the usage of OTR as beam profile monitors
> Top right: Small beam diameters: beam of 14 μm rms size measured in the SwissFEL Injector Test Facility
> Bottom left: Short pulses shown in this measurement of electron phase space after the undulator at LCLS
> High accuracy requirements: Simulated dependency of the pulse length on S band phase in the SwissFEL injector
Main principal 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)

A. Freyberger, Vitali Judin, Michele Caselle

Special challenges:

- High repetition rate may destroy anything inserted into the beam
- Halo measurements require large dynamic range
- Large data sets require special processing

When designing an accelerator, we can carefully choose an instrumentation suite that lets us:

- set up the accelerator
- measure beam properties
- control the stability of the machine via feedbacks

Thus, let us distinguish longitudinal and transverse diagnostics. It is not a clear distinction, as we can transform the phase space dimensions, but it's a start.

Let's first have a look at the object of study, the beam. This beam can be represented by the particle distribution in the six-dimensional phase space, extended by transverse coordinates x and y, transverse angles x' and y', time t and energy delta.

When we speak about the longitudinal phase space, we mean the projection on these last two dimensions, and in particular the time, which is very difficult to measure with femtosecond accuracy.

No diagnostics exists for the entire distribution.
Phase space transformation with RF deflecting cavity
Reference for all longitudinal diagnostics
Shown here: installation in LCLS

Quadrupole magnets result in a phase space transformation between x and x’, and between y and y’

Beam transport
Phase advance with quadrupoles
Detection on screen
Measurements of full phase space possible! Femtosecond resolution, depending on:
— emittance
— streak strength

Skew quadrupoles couple the horizontal coordinates $x$—$y'$ and $y$—$x'$
Skew quadrupoles in dispersive sections (pictured here: bunch compressor) couple energy and transverse coordinates

Integral Measurements
> Bunch charge
> Photon pulse energy
Integral measurements
Let’s first look at diagnostics for integral properties of the beam, i.e. number of electrons / photons
Of course, many diagnostics in the next two chapters also measure integral properties
What is important here: absolute calibration

Integrating current transformer (ICT)
acts like a transformer, but the primary coil is the beam
response on secondary coil depends on the number of windings

X-ray pulse energy measurements
Photodiode (for low intensities)
Back-scattering from thin membrane
Transparent measurement of X-ray pulse energy by ionization of a gas
INSTRUMENTATION FOR MACHINE PROTECTION AT FERMI@ELETTRA


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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 a partical 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 channel of four 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 e, INFN-Roma, Rome, Italy

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Signal processing, digitization and digital data processing

- Low charge: Position-noise \(-\text{charge} = \text{const} = 15\text{pC} \mu\text{m}\)
- \(Q=135\text{pC}:\) Noise <0.8\text{µm} \text{RMS; ±1mm range}.
- Charge noise <0.1\% (<0.1pC RMS at \(Q=135\text{pC}\)).

Very low noise readout of cavity BPMs results in sub-micrometer accuracy

Beams in modern accelerators are small!
...but now: COTR!
Intense light, has made all the high-energy OTR monitors at LCLS useless

Direct COTR away from the imaging system!
At the same time, observe
> Snell's law of refraction
> Scheimpflug imaging condition

Snell's law of refraction results in an angle-dependent broadening of the virtual image
Measurement of emittance by slits

Measurement of small emittances by quadrupole scan
RF deflector allows measurement of time-resolved beam properties
> slice emittance
> beam optics (matching)

At high repetition rates (European XFEL):
Kicking the beam sideways to the screen
Measurement at ERL: making use of high repetition rate beam to measure emittance by scanning beam across slits

Image from synchrotron radiation monitor

Measurement of synchrotron radiation in storage ring
> Measurement principle: interference of vertically polarized synchrotron light
> Measurement of very small beams possible, even at a large distance
> Requirement: very good knowledge of the beam shape (here: Gaussian)
Time-resolved instrumentation is especially challenging at FELs, due to the very short bunches.

Let's first look at direct time domain methods!

**Streak Camera**

Traditional method to determine pulse length

Resolution down to ~1 ps possible

Commercially available devices

A sub-picosecond time resolution can be achieved with the latest generation streak camera. Shown here: a measurement at SACLA.
Another method to achieve sub-picosecond resolution is to probe directly the transverse electromagnetic field of the electron bunches. An electro–optical crystal, i.e. one that exhibits the Pockels effect, is introduced into the vacuum chamber, and the change in birefringence is probed by a short laser pulse.

Cross–correlation with an external laser pulse
Pockels effect allows to cross–correlate coherent THz fields with laser
Reflectivity change allows to cross–correlate X–rays with laser
Measure: Bunch arrival time & Bunch length
Also known as “Electro–optical effect”
Electric field induces birefringence in crystal
Birefringence can be probed with a polarized laser
Pockels Effect can probe down to time scales of 10…100 fs
Effect is totally reversible

The setup has been transformed from an experiment to a reliable diagnostics. Shown here: electro–optical monitor at the ANKA storage ring, designed in a KIT–DESY–PSI collaboration.
Interesting detail: fast readout of the detector.
Measurement of instabilities as a function of beam current in a storage ring

Another possibility: put the electro-optical crystal in a box outside the accelerator vacuum, and transmit the EM field through cables.
→ Possibility to measure arrival time

THz Streak Camera installed at SACLA
Measurement principle: X-ray photons ionize a gas
Photoelectron spectrum is equal to photon spectrum minus binding energy
Additional electromagnetic field (THz) streaks the photoelectrons
Measurements at LCLS confirm sub-cycle pulse length

Another possibility: ignore the phase of the spectrum of the bunch, and measure only spectral amplitude
→ Stabilization for feedbacks

Reminder: bunch compression
Calculated spectrum, assuming Gaussian bunches, for different compression stages, and for different operation modes of SwissFEL. Note logarithmic scales on both axes!

Careful! Ignoring the phase of the radiation means that generally, you cannot reconstruct the bunch length from the spectrum.

Setup at LCLS
Detection of coherent edge radiation from the bunch compressor
Signal peaks at maximum compression

Similar setup at SACLA (free electron laser at SPring8 in Japan)
I will now show a comparison of CSR measurement with bunch length measurements using transverse deflecting cavity

The bunch length observed with the CSR monitor was calibrated by using the RF-deflector's data. Electron beam was bypassed through BC3. Bunch length was changed by the RF phase of the S-band accelerating structures. Estimated bunch length measurement sensitivity is about 6% at a bunch length of 170fs.
CSR intensity as a function of the RF Phase of the C-band accelerating structures before BC3. CSR intensity was linearly changed by the RF phase of the C-band (5712 MHz) accelerating structure before BC3. Estimated bunch length measurement sensitivity is less than 0.1 deg., which is better than that of the RF deflector.

Coming back to the power distribution of CSR, we see that we could improve resolution if we detect selectively near an edge.

Setup installed at the SwissFEL Injector Test Facility. Beam splitters, then using grids as edge pass filters.
Indeed, sensitivity to X-band phase changes (i.e. compression changes) increased when using only high-frequency radiation.

This detector is very fast: detection of two bunches separated by 28 ns easily possible.

Similar idea: detect different frequency components. Here: five channels separated by waveguides, for GHz frequencies (SACLA after first compression).
Dependency of different frequency signals on compression

THz spectrometer with 120 channels implemented at DESY, for FLASH

Photo of the setup
Setup CRISP4

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

E.Hass (University of Hamburg)

Parallel readout of a total of 120 channels in pyro detector arrays

Reconstruction with Kramers–Kronig relation.
Keep in mind: this is the shortest pulse compatible with the spectrum.
The spectrum in itself is also compatible with a bunch length of 4.6 billion years!

Rasmus Ischebeck > Diagnostics for FELs and ERLs

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