Longitudinal Electron Bunch Measurements at Free Electron Lasers

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Abstract

In this paper I present the overall idea of the longitudinal electron bunch measurements at free electron lasers using semiconductor detectors and electronic readout circuits. The proposed system will be implemented and tested at FLASH (Free-Electron Laser in Hamburg). Different aspect of detecting electron radiation and dedicated electronic hardware design are discussed in this article.

The paper is divided into 6 sections. The first one describes the general idea of the Free Electron Laser (FEL) installed in Hamburg and the role of electron bunch diagnostics. The second section is devoted to electron bunch analysis methods. It presents chosen aspects of ElectroOptic systems. The section 3 presents the conceptual view of the diagnostic system that should be connected to the FLASH control system. The section 4 highlights aspects of semiconductor detectors that can be applied to the methods described in the section 2. The next section describes electronic front-end design. It shows the most important design challenges and tradeoffs related with the detector physics. Finally, the section 6 concludes the paper.

1. FLASH

The FLASH is based on a Self Amplified Spontaneous Emission (SASE) which enables production photon beams in X-ray regime [6].

Fig 1. Conceptual view of FLASH system

Fig 1 shows the block schematic of FLASH. The whole system is composed of several major blocks. A laser driven by a radio frequency (RF) gun produces high-current electron bunches. The electrons are accelerated in resonant, superconducting RF cavities (accelerating structures, ACCs).

The detailed principle of operation of the SASE method is beyond the scope of this paper. It is sufficient to say that this process requires electron bunches with high peak current (several kA) which is not possible to obtain due to electron energy spread introduced by the accelerating elements. As a consequence two magnetic chicanes are included in the system. The bunch compression is based on the fact that electrons with different energies need to cover different distances. In other words, the electrons with smaller energies travel through a shorter path and have the opportunity to catch up with those with higher energies.

The last acceleration structure is followed by the diagnostics section. In this section a number of electron bunch measurements are conducted. One of them is described in the section 2.1 Electro-Optic Sampling.

The accelerated and compressed electron bunches go to the undulator section. Again the goal of this paper is not to present details about the principle of operation of this element. It suffices to say that in this element (made of short magnet dipoles) changes trajectory of electrons moving at relativistic velocities. The wiggling path forces electrons to release photons which then can be used in a number of experiments.

The very important aspect of an FEL is the ability to adjust the output photon wavelength by changing the energy of electrons. However, it is extremely important to have a tight control over the electron bunches going into the undulator. Their longitudinal profile (in fact peak current) is a crucial factor influencing the wavelength of the laser.

2. Electron bunch diagnostic

Preserving high quality of the electron beam going into the undulator section is very demanding even with modern technologies. The longitudinal structure of an electron bunch can be very useful source of information regarding the processes that
take place in the undulator (SASE). What is more, it is said that bunch-to-bunch measurements can be used to adjust the accelerating elements to minimize the energy spread of electrons. This idea is discussed in section 5 of this paper.

There are several techniques that can be employed in order to get the electron bunch profile. Some of them are destructive. It means that the probed bunch vanishes. Examples of this type of methods are Transverse Deflecting Structures (TDS) or coherent transition radiation (CTR). For more information about these techniques please refer to [1] or [2]. In contrast to this, there are non-destructive methods which allow the probed bunches to go through the modulator. In this paper I briefly present one of these diagnostic methods – the Electro-Optic sampling, which is based on the Pockels effect.

2.1 Electro-Optic Sampling

Fig 2. Conceptual view of Electro-Optic sampling [5]

Fig 2 shows the principle of operation of Electro-Optic Sampling. The most important part of the equipment is the Electro-Optic crystal (EO) mounted in the beam pipe just a few millimeters from the electron bunch. The electric field associated with the moving electrons traverse through the crystal introducing birefringence (double refraction).

When the laser sampling pulse passes the birefringent crystal its polarization gets slightly rotated. The magnitude of rotation is proportional to the magnitude of the bunch field. In other words, the longitudinal structure of the electron bunch is represented in the polarization modulation of the sampling laser pulse. In order to measure the longitudinal structure of the entire bunch additional element is added to the system – optical stretcher.

The analyzer (A) transfers the polarization modulation into an intensity modulation. This optical element may be constituted by a polarizer.

The overall operation of the EO Sampling technique can be seen as an imposing the longitudinal charge distribution of the electron bunch from the spectrum of the sampling laser pulse.

This spectrum can be measured using spectrometers based on pixel cameras which are discussed in the section 4.

3. The complete diagnostic system

Let us now concentrate on a possible application of this kind of measurement system.

The most obvious solution seems to be acquiring data to facilitate off-line data analysis. The novelty of the proposed system is to use the pre-processed data from the detectors to control the electron acceleration elements. The two mentioned solution can be applied at the same time. However these two data paths differ significantly.

Fig 3. Conceptual of the electron diagnostic system

Fig 3 shows schematically the proposed architecture of the system. Its operation can be summarized as follows. A pixel camera made of semiconductor diodes produces small amounts of electrical charge (current) upon stimulus in form of radiation. This element is described in more details in the next section of this paper. Since the charge generated in the array of diode is considerably small, the short current pulses need to be amplified and shaped to enable and facilitate further data processing. As a consequence a dedicated analog Integrated Circuit (IC) is required – Analog Front-End. This element together with the detector diodes constitutes the major part of the proposed system and is presented in the section 5. Finally, a Field-Programmable Gate Array (FPGA) together with set of Analog to Digital Converters (ADCs) is used to process incoming data and send to other systems.

Let us now consider the requirements for both data paths. The off-line analysis using a PC requires sending the whole information included in the radiation spectrum. Nevertheless, it is not necessary to do analyses in the real time. On the other hand, signal for accelerator control (ACC control) needs to be delivered quite fast and what is more important with minimized latency. One needs to take into account limited transfer rate of connections, etc. As a consequence the FPGA included in the system plays also a role of a Digital Signal Processor. The most important characteristic features of the radiation spectrum (from the accelerator control point of view) need to be extracted and fed forward.

In this paper I focus mainly on the analog part of the system. Hardware implementation of the data
processing algorithms or digital communication interfaces is beyond the scope of this paper.

4. Basics of detector physics

In this section I focus on some aspects of semiconductor detectors that can be used in the mention diagnostic techniques, e.g. to probe the spectrum of laser pulses (EO) or coherent radiation (CSR, CTR).

In principle, the detector is a semiconductor element that transforms the energy of a photon (other particles are out of the scope of this project) into an electrical value.

The absorbed radiation produces electron-hole pairs in the semiconductor volume. This charge is then swept by an electrical field applied to the sensor. This way a short current pulse is generated. The total charge of (in other words current pulse) is proportional to the radiation energy. In fact, the semiconductor detector is constituted by a reverse biased diode, where the mobile carriers are produced in its depletion region.

A series (line or pixel array) of semiconductor detectors together with a reflective blazed grating form a spectrometer (see Fig 1).

To generate the electron-hole pair, the absorbed energy needs to exceed the material bandgap. So in case of Si, mobile carriers are produced when this energy exceeds 1.12eV (for photons). As a consequence wavelengths below 1.1\( \mu \text{m} \) can be detected. In order to change the frequency band of the spectrometer, one needs to use different semiconductor material. In FLASH, diode arrays made of InGaAs are also considered. This kind of sensor is able to detect radiation with wavelength between 0.9 and 1.8\( \mu \text{m} \).

With the growing detector thickness energy absorbed by the semiconductor volume also rises. Thus, the charge signal is increased.

When the carriers are generated in the semiconductor volume, they begin to scatter. But after some time (of order of picoseconds in Si) their movement becomes non-ballistic, i.e. dependent only on local electric field. Even without an external voltage a p-n junction forms a depletion region and so called “in-built” potential. Applying an additional reverse voltage leads to spreading of the depletion region. When the width of this region is less than the silicon thickness we say that the diode is partially depleted. The more common situation is that the depletion region reaches the diode contact – a fully depleted diode. The reverse voltage that creates a fully depleted diode (depletion voltage) can be expressed as:

\[
V_d = \frac{Ned^2}{2\varepsilon},
\]  

where \( \varepsilon \) is the dielectric constant, \( N \) – dopant concentration, and \( d \) – thickness of the bulk.

The time needed to collect the generated charge is dependent on applied reverse voltage. When this voltage is higher or equal to \( V_d \), the collection time can approximated with the following formula [3]

\[
t_c = \frac{d^2}{\mu V},
\]

where \( \mu \) is the carrier mobility and \( V \) is the applied voltage. This parameter is important in case of experiments that require very fast readout.

Ideally there are no carriers in the depletion region without presence of radiation of appropriate energy. However, thermal excitation can cause the electron-hole generation. This phenomenon is called dark current and is strongly dependent on lattice impurities and temperature.

Other important aspect of a semiconductor detector is capacitance. In case of strip/pixel capacitance the fringing capacitance dominates. The impact of the detector capacitance on the readout process is discussed in the next section.

5. Front-end electronics

The radiation is absorbed and transformed into an electrical signal in the detector. However, the charge generated in the detector is relatively small (in orders of \( 10^{17} \) C). The role of the front-end electronic element is to amplify and shape the signal.

![Fig 4. Conceptual view of the electronic front-end (above) and simplified signal shapes (below)](image)

One of the most popular architecture of front-end electronics is presented in Fig 4. It can be divided into 2 main parts: a preamplifier with feedback capacitance (Charge Sensitive Amplifier, CSA) and a shaper. Let us now have a closer look at principle of operation of these elements taking the most basic structures.

5.1 Preamplifier

Let us consider an ideal amplifier schematically shown in Fig. 4. The current pulse generated in the detector flows into feedback capacitor (\( C_d \)) and \( C_T \) which is a sum of the detector capacitance, input transistor capacitance, and parasitic capacitance of detector-front-end connections:
\[ i_d(s) = v_m s C_T + (v_m - v_{amp}) s C_f \quad (3) \]

Taking into account that \( v_{amp} = -K_0 v_m \), we can rewrite the same equation as

\[ \frac{v_{amp}(s)}{i_d(s)} = -\frac{1}{s (K_0 + 1) C_f + C_T}. \quad (4) \]

Assuming that the input current signal is a delta-like function \( (i_q(t) = Q_{in} \delta(t)) \), we get the time domain representation:

\[ v_{amp}(t) = \frac{K_0}{(K_0 + 1) C_f + C_T} Q_{in}. \quad (5) \]

The important aspect of CSA is the fact that its output voltage is independent of the \( C_T \) if

\[ (K_0 + 1) C_f \gg C_T. \quad (6) \]

Obviously this is only a very simplified model of a CSA. While designing a real amplifier one needs to take into account issues like bandwidth of the core amplifier and amplifier saturation.

### 5.2 Shaper

The goal of shaping electronics is to: improve signal to noise ratio by filtering the CSA output; add more gain; form pulses to avoid pile-ups.

Let us consider the basic structure shown in the Fig. 4. Assuming that integrator and differentiator time constants are equal \( \tau \), the output voltage signal of the front-end electronics can be expressed as [3]:

\[ v_{out}(t) = \left( \frac{t}{\tau} \right) e^{-t/\tau}. \quad (7) \]

A noise bandwidth can be controlled by changing the CR-RC time constant. However, the signal amplitude is also affected.

In a simple CR-RC structure, the signal goes back to the baseline value relatively slow. In order to allow higher signal rates one can add additional integrators to form a CR-RC\(^n\) structure. However, this enhancement goes at the cost of silicon area which in case of multichannel ICs is crucial.

This paper gives only a general idea of principle of operation of the front-end analog circuit. Aspects of fast signal processing like pulse pile-ups or voltage undershoot needs to be taken into account by a designer.

Apart from circuit design decision, the front-end IC designer needs take care of electronic noise while preparing the final layout. The book by Gryboś [4] is a rich source of examples and guidelines regarding designing and implementing this kind of systems in deep submicron technologies.

### 6. Conclusions

Careful analysis of the desired system revealed several tradeoffs and design challenges.

The complete diagnostic system has to ensure fast analog readout, digitalization of the signals, and seamless interaction with other systems (mainly control systems). On the top of that, a special attention needs to be paid to the quality of the readout signal (impact of noise).

In order to get the desired parameter of the detector, one needs to take the following factors into consideration: semiconductor material (to detect proper wavelength), the detector thickness (to get appropriate charge), and reverse bias voltage (to collect charge in wanted time). Additionally, one may want to take into account the ambient temperature in order to minimize the dark current.

Finally, the analog readout circuit seems to be the most challenging part. Designing a well optimized multichannel IC taking into account noise performance is very demanding. Therefore in the first stage of the diagnostic system development an existing ASIC will be used (Beetle chip [7]). It does not meet all the requirements (especially in terms of latency). However this IC should be useful for prototyping and idea validation.

### Bibliography


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