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OBSERVATION OF SCINTILLATOR CHARGING EFFECTS AT THE EUROPEAN XFEL

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Abstract

Scintillating screens are widely used for beam profile diagnostics at various kinds of particle accelerators. At modern linac based electron machines with ultrashort bunches as the European XFEL which is operated by DESY in Hamburg (Germany), scintillators help to overcome the limitation of standard OTR based monitors which is imposed by the emission of coherent radiation. The XFEL injector section is equipped with four off–axis screens allowing to perform online beam profile diagnostics, i.e. a single bunch out of a bunch train is kicked onto the screen and the profile is analyzed. However, during user operation a decrease of the SASE level was observed in cases that one of the of–axis screens were in use. The observation is explained by charging of scintillator screens: each deflected bunch hitting a screen causes ionization and results in electrostatic charging of the screen. The scintillator as good insulator keeps the charge for some time such that the non–deflected part of the bunch train feels their Coulomb force and experiences a kick, resulting in a drop of the SASE level. This report summarizes the observations at the European XFEL and introduces a simple model for quantification of this effect.

INTRODUCTION

The European XFEL is a free–electron laser located in Hamburg, Germany [1]. It is driven by a 17.5-GeV superconducting linac which operates at 10 Hz pulsed mode and delivers up to 2700 bunches per pulse.

The accelerator is equipped with scintillator screens in order to overcome the limitation of OTR caused by coherent effects [2, 3]. Most of the XFEL screen stations have a simple observation geometry which is introduced in Fig. 1: the electron bunch crosses the scintillator parallel to its surface normal; the light radiated from the scintillator is observed under an angle of 45°, then reflected by the mirror and focused onto a CCD via a wide–angle imaging lens. The CCD is oriented in Scheimpflug geometry in order to compensate the defocusing caused by depth–of–field effects.

In addition there is a number of screen stations that have additional so–called "of–axis" screens. In Fig. 2 the underlying scheme is plotted. The geometry for mirror, lens and CCD is the same than in Fig. 1, hence for simplicity only the is CCD depicted. Main difference is that the scintillator is slightly away from the bunch trajectory such that the majority of electron bunches pass nearby (blue dashed arrow), and only dedicated bunches will be kicked onto the scintillator

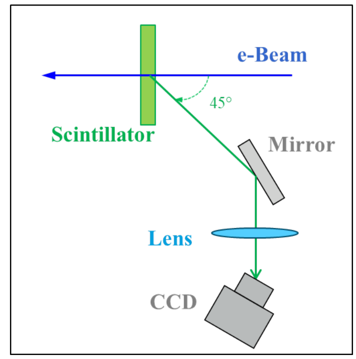

Figure 1: Standard scheme of scintillating screen monitors at the European XFEL.

(red dashed arrow) by a fast kicker magnet. The advantages of this setup are summarized in the following:

- A minimum perturbing online diagnostics may be performed by kicking only a single bunch out of a bunch train of up to 2700 bunches onto the scintillator. In addition, due to safety reasons the number of bunches which are allowed to hit a screen at 10 Hz repetition rate is restricted to a single one.
- Four off–axis screen monitors are paired together and can be operated in combination with a Transverse Deflection Structure (TDS). Besides conventional bunch profile measurements, this allows to measure longitudinal bunch profiles via streaking and to study online slice emittances in a minimum perturbing way.

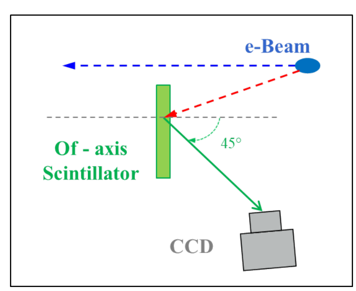

Figure 2: Of–axis screen scheme. Blue line: normal trajectory of electron bunches, red line: bunch trajectory of kicked ones crossing the scintillator.

The XFEL is operated with about 70 screen monitors, the majority is equipped with LYSO ($Lu_{1.8}Y_{0.2}SiO_5$:Ce) as scintillator material because of its good resolution as described in Ref. [4]. However, this material has other disadvantages, see e.g. Ref. [5]. Therefore the stations at which charging was observed utilize YAP ($YAlO_3$:Ce) as screen material.

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This does not mean that LYSO will not be affected by these effects, up to now it was simply no time for dedicated LYSO studies.

OBSERVATION OF SCREEN CHARGING

The influence of scintillator charging was observed at screen stations in the low–energy XFEL injector operated at a maximum beam energy of about 130 MeV. The stations are grouped close to the injector TDS at 55, 56, 58 and 59 m away from the gun, see Fig. 3. As shown in this example, from four consecutive bunch trains each consisting of three bunches, the second one is kicked onto the off–axis YAP screen of each station. In fact, bunch train length and kicked bunch are freely configurable parameters, and in standard operation the four off–axis screens are not inserted simultaneously.

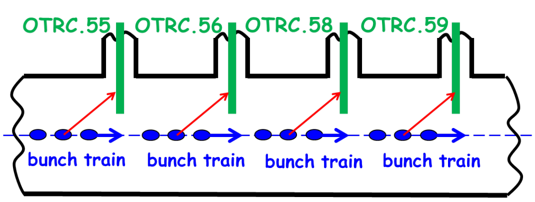

Figure 3: Off–axis screen overview at the XFEL injector: the stations are (historically) entitled as OTRC.55, 56, 58 and 59.

While the effect was observed for the first time the accelerators was operated in SASE delivery mode, and one out of four off–axis screens was inserted. An inverse relation between number of bunches on the screen and SASE level was noted: the more kicked bunches, the less output intensity of the FEL. After retracting the screen to standby position, the FEL intensity recovered to the previous level. Figure 4 shows the chronological sequence of the BPMs readings downstream of the inserted screen. The meaning of the red numbers is explained afterwards.

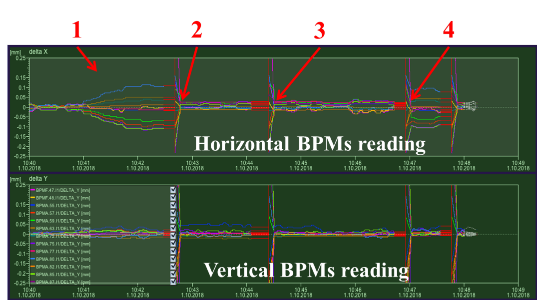

Figure 4: BPMs readings downstream the injector screen stations: 1. an off–axis screen was inserted and a bunch kicked on it; 2. the screen was retracted; 3. another off–axis screen was inserted without kicked bunch; 4. the second screen was retracted and the first one moved back in.

1. An off–axis screen was horizontally inserted and a bunch was kicked onto the screen. At the same time, the downstream BPMs measured a horizontal orbit deflection, and the FEL intensity decreased. The vertical plane was unaffected because the screen was inserted in the horizontal plane. Some time later saturation occured, i.e. the orbit deflections remained constant and the SASE level was stable.

2. The screen was retracted. Immediately, both trajectory and SASE level recovered.

3. Another off–axis screen was inserted without any bunch kicked on it. The BPM readings in both planes were unaffected.

4. The second screen was retracted and the first one inserted back to the off–axis position. The orbit deflection appeared at the same level.

The observation described before provided a strong indication that noted orbit deviation and FEL intensity drop were initiated by scintillating screens, in particular due to screen charging.

CHARGING MECHANISM

The mechanism of charging is illustrated in Fig. 5. A single bunch from a bunch train is kicked onto the screen (a) and initiates ionization inside the scintillator material. Some of the ionized electrons having enough energy leave the scintillator volume (b) and a positive charge inside the scintillator remains (c). Due to the fact that typical scintillators are very good insulators, the discharging process takes place over a very large time scale which is much longer than the charge creation from the subsequent bunch kicked onto the screen. As a result positive charges accumulate in the scintillator material. The remaining bunches from the bunch train which are not kicked feel the resulting Coulomb force

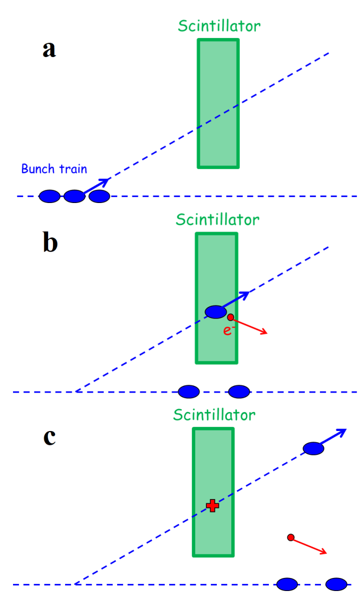

Figure 5: Illustration of the screen charging mechanism.

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and hence changeir the trajectory. The amount of deflection depends on the number of accumulated charges inside the scintillator.

It is interesting to consider the "saturation" level, i.e. the point when charging and discharging are equal in amplitude but opposite in sign. According to Fig. 4 this happened already at the first stage: the orbit deflection did not rise after a while and a rather constant horizontal deviation could be observed.

Both processes of charging and discharging depend on the number of electrons in the volume which is affected by the bunch. On the one hand, the more electrons present in the volume, the more possibilities for ionization. On the other hand, the more vacancies present in the volume, the higher the possibility to be filled by the electrons from the vicinity. Having this in mind a differential equation is deduced for the number of positive charges:

$$\frac{dN}{dt} = -\lambda_1 N + \lambda_2 (N_0 - N), \tag{1}$$

with λ_1, λ_2 two constants of discharging and charging respectively, showing the number of disappeared/appeared charges per unit time, N the number of positive charges (vacancies) in the volume, and N_0 the initial number of electrons in the volume (when there is no charge). If the case is considered when bunches are permanently kicked onto the screen with constant frequency, and none of the parameter like charge, energy, size. . . will be changed, then Eq. (1) defines the number of charge changes per time. Basically, λ_1 and λ_2 both depend on bunch frequency, bunch energy, size or charge, on the bunch position on the scintillator and so on. The equation may easily be solved resulting in an expression for the charge–time dependency:

$$N_q(t) = \frac{\lambda_1 N_0}{\lambda_1 + \lambda_2} \left(\exp\left[-(\lambda_1 + \lambda_2)t\right] + \frac{\lambda_2}{\lambda_1} \right). \tag{2}$$

The equation is simplified by assigning

$$A_1 = \frac{\lambda_2 N_0}{\lambda_1 + \lambda_2}, \quad A_2 = \frac{\lambda_1 N_0}{\lambda_1 + \lambda_2}, \quad A_3 = \lambda_1 + \lambda_2, \tag{3}$$

which allows to rewrite Eq. (2) in the form

$$N_q(t) = A_1 + A_2 \exp[-A_3 t]\,. \tag{4}$$

Advantage is that both A_1 and A_2 contain A_3. This means that if the charging/discharging slope is measured and fitted by Eq. (4), with the help of Eq. (3) the parameters λ_1, λ_2 can be extracted.

Nevertheless it should be kept in mind that the proposed model is rather simple and has two assumptions, (1) the charge cloud is considered to behave like a point charge, and (2) the space between charge cloud and crossing bunch is assumed to be vacuum, i.e. material properties of the scintillator are not considered.

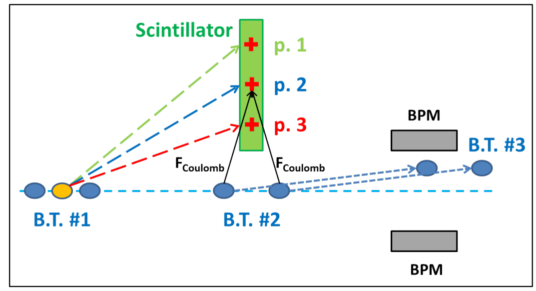

Figure 6: Measurement scheme.

MEASUREMENTS

After the first observations, a number of dedicated studies at 130 MeV with bunch charges of 250 pC was performed. The measurement scheme is shown in Fig. 6. Objective was to get an idea about the amount of accumulated charge and to fit the charge over time dependency by Eq. (4). At the beginning of the experiment, single bunches out of 3000 consecutive bunch trains (corresponding to 300 s accumulation time at 10 Hz train repetition rate) were kicked onto position 1. The downstream BPM reading was recorded simultaneously, and using the Coulomb equation orbit deflections were converted into accumulated charges. Afterwards the procedure was repeated with positions 2 and 3. The closer the charge distance to the bypassing bunch, the higher the deflection which was measured at the doenstream BPM.

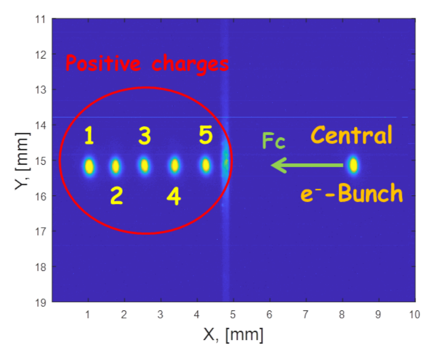

Figure 7: Bunch positions on the screen in the first measurement.

In a first measurement five positions of the bunch hitting the off–axis screen (i.e. charge positions) were selected. The bunch train consisted of two bunches, one of them was kicked and the other one deflected. In Fig. 7 the positions of the kicked bunches and the one passing by are indicated. The central vertical line represents the scintillator edge. The distances between charge positions and the bypassing bunch position were measured to 7.3 mm (position #1), 6.6 mm (#2), 5.8 mm (#3), 4.9 mm (#4), and 4.1 mm (#5). The downstream BPM was about 4 m away from the screen station.

The measured horizontal deflection (Δx) of this BPM is shown in Fig. 8 as function of time. For each new charge position the deflection is steadily increased because the charge

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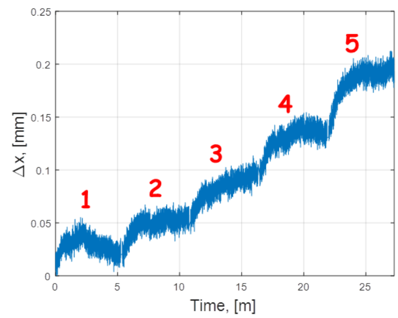

Figure 8: Horizontal bunch deflection as measured with the BPM 4 m downstream the screen monitor. The red numbers correspond to the positions of the bunch onto the screen.

from the previous position is still present, it took about 30 min to discharge the screen completely. The same measurement but the deflection converted into a deposited charge is shown in Fig. 9. As can be seen the total amount of accumulated charge was about 3 nC. Afterwards each of the five

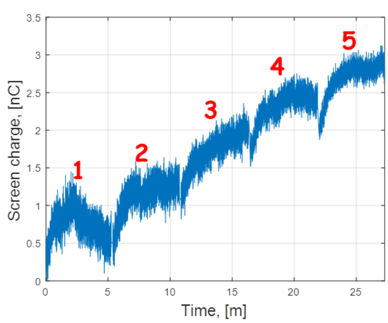

Figure 9: Accumulated screen charge as converted from horizontal bunch deflection in Fig. 8.

slopes was fitted by Eq. (4), the result is plotted in Fig. 10. The resulting λ_2 parameter indicated that each bunch created in average about 6 % of its own charge inside the scintillator. Compared to the result of a GEANT4 simulation which was in the order of about 3 %, there is a satisfactory agreement between both values.

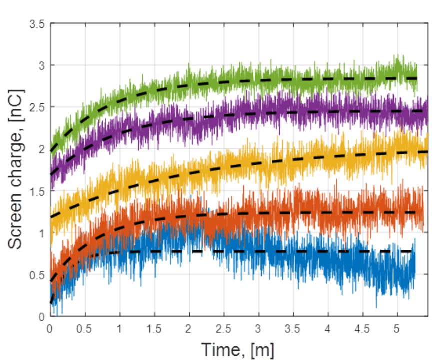

Figure 10: Fit of the charging/discharging slopes.

The second measurement was a repetition of the first one, but with only four charge positions (c.f. Fig. 11), a different injector screen station, 158 bunches passing by, and the BPM was only 2 m downstream. The corresponding distances to the central bunch amounted to 9.7 mm (position #1), 9.0 mm (#2), 8.3 mm (#3), and 7.5 mm (#4)

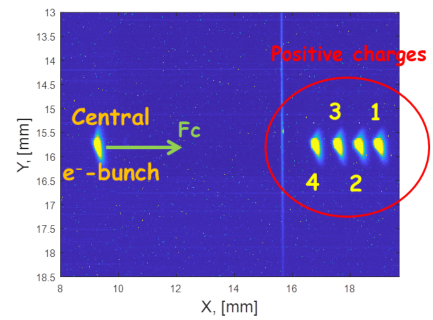

Figure 11: Bunch positions in the second measurement.

As before the orbit deflection was converted into a deposited charge, the result is shown in Fig. 12. The red lines indicate exactly that moment when the positions of the bunch onto the screen were changed. As can be seen, there are two instant drops during the 2^{nd} and 3^{rd} charge position which are considered as fast discharging (perhaps a sort of spark). Both events occurred at similar charge levels. The absence of this effect during the 4^{th} position might be explained that the accumulated charge did not reach this discharge level. Due to these effects it was refrained from further analysis by fitting with Eq. (4).

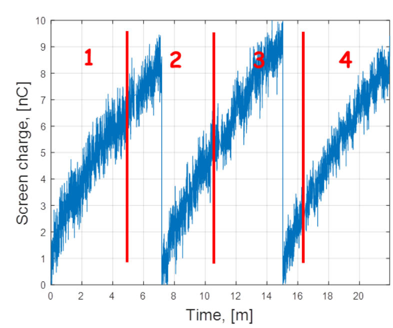

Figure 12: Accumulated screen charge as converted from orbit deflection.

CONCLUSION AND OUTLOOK

Charging and discharging effects were observed with the screen stations at the European XFEL. At present the FEL output intensity is affected by this effect, making an online diagnostics not possible for the moment. Thus, all screens are completely retracted during user operation. For the future it is planned to use scintillating screens covered by a conductive layer (Indium Tin Oxide, ITO) to get rid of the charge in a faster way. The fast discharging effect observed in the second measurement is not yet understood and requires further investigations. Additional studies with the XFEL beam and with a small laboratory test stand consisting of a few–keV electron gun and a screen station are in preparation.

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