THE PHOTON BEAM LOSS MONITORS AS A PART OF EQUIPMENT PROTECTION SYSTEM AT EUROPEAN XFEL

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Abstract

For the X-ray beam transport systems, the problem of potential damage to the equipment by mis-steered photon beam emerged with advent of powerful X-ray Free-Electron-Lasers (FELs). In particular high repetition rate machines as European XFEL, where not only focused beam can produce ablation, but even unfocused beam can melt the beamline components while machine operates in multibunch mode, demand for implementation of equipment protection. Here we report on development of photon beam loss monitors at European XFEL facility. The photon beam loss monitors will react on the mis-steered photon beam and interface the machine protection system. The prototype comprises the vacuum chamber with fluorescence crystals positioned outside the photon beampath. The fast sub-hundred ns fluorescence induced by mis-steered beam can be detected by photomultiplier tube allowing for intra-train reaction of machine protection system. First tests have been carried out at FLASH and shown the feasibility of detection based on PMT-detected fluorescence. In addition to the efficient YAG:Ce crystal, the robust low-Z material as CVD microcrystalline diamonds has shown a potential to be used as fluorescence crystals.

INTRODUCTION

The high energy and high intensity accelerator facilities use the beam loss detection systems to react on losses of the particle beam and prevent radiation damage to the equipment. Different types of such beam loss monitors exist (see, for instance, [1]). The beam loss detection becomes an essential part of the machine protection system in case of superconducting linacs.

In case of photon beam transport systems, the problem of potential damage to the equipment was not considered till very recently. The total energy of a particle beam is usually much higher than the energy of produced by it photon beam. However with advent of highly brilliant X-ray Free-Electron-Lasers the potential danger of damage to the photon beam transport systems has been realised. Focused X-rays can ablate components of the beam transport systems. And in case of high repetition rate machines as European XFEL, trains of photon pulses capable to melt the beamline components even in case of unfocused beam [2]. In order to prevent such damage, we propose to introduce photon beam loss monitors reacting on mis-steered beams and interfacing the machine protection system in a way similar to electron (particle) beam loss monitors. To our knowledge the development presented in this paper is the first attempt to introduce a protection system for the photon beamlines.

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DETECTION SCHEME

The kind of potential damage to the photon beam transport system differs from those in case of a particle beam. While highly energetic particles escape the vacuum chamber of the accelerator, and beam losses are usually detected outside the vacuum, the X-ray beam, in particular of low photon energies, is potentially capable to produce highly localized damage to the vacuum chamber itself or to the components inside the vacuum. This leads to necessity of introducing a detection system reacting on losses of photon beam into the vacuum of the beamline. The possible realization of such detection will be presented in following subsections. As for electronics and interface to machine protection system, this part of beam loss detection system can be in high degree adopted from the beam loss monitors for the particle beam. In our case, the systems developed for the electron beam loss detection at European XFEL [3] will be used.

Conceptual Scheme

The conceptual scheme of proposed photon beam loss monitors is presented in Fig. 1. As discussed above, the main task of the photon beam loss monitors is to prevent hitting of the beamline components by the photon beam. To react on mis-steering of the photon beam, some 'screen' can be introduced into vacuum vessel around the nominal beam path (represented in yellow in Fig. 1). This 'screen' converts the X-rays into visible light. The conversion of photons into visible range enables relatively easy detection, since many types of detectors are available

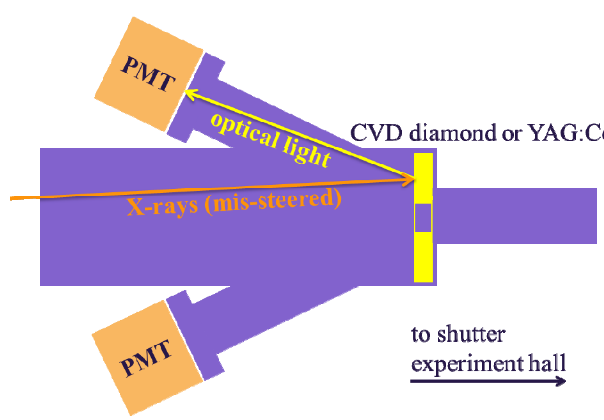

Figure 1: Conceptual scheme of the photon beam loss monitor (see text).

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and positioning of detector outside the vacuum vessel is possible. Types of converting screens will be discussed in next subsection, and a detector for visible light will follow. Among the requirements to the detection system comprising converting screen and detector of visible light is a fast response allowing to react within the pulse train and to stop machine (or reduce number of bunches in train) in order to prevent damage. The maximal repetition rate of photon pulses at European XFEL of 4.5 MHz results on desirable detection response < 220 ns. Another important issue is a radiation hardness of the 'screen' in order not to be destroyed by the X-ray beam. And finally, since the beam loss monitors interface the machine protection system, the detection scheme should provide clean, highly reliable signal of high signal-to-noise ratio.

Conversion of X-rays into Visible Light

Conversion of intense X-ray radiation into visible light can be realized either by using luminescent material or by detecting thermal light. These two possibilities have its advantages and disadvantages. While luminescence response is strongly material dependent property, thermal light is less material dependent and would be induced in any material due to the temperature increase after absorption of intense X-ray pulses. Thus, in case of thermal light, one can choose almost any radiation stable material, for instance B_4C – material, which, due to high damage threshold, will be used at European XFEL for the slits and dumps in photon beamlines. In contrast to thermal light, the choices of luminescent material are much more limited. However, though not in any arbitrary material, the luminescence response reaches much higher spectral brightness, allowing, thus, for much easier detection. Taking this into account, we decided to start the development using the luminescent materials for conversion of X-rays into visible light.

The two luminescent materials have been chosen to be tested in the prototype of the photon beam loss monitors: monocrystalline YAG:Ce and polycrystalline CVD diamonds.

YAG:Ce is well known scintillator material and is widely used to convert energy of the particles and X-rays into visible light. The light yield of YAG:Ce luminescence of about 8 photons/keV is high. The fast, <100 ns, time response makes YAG:Ce attractive to applications demanding for time resolution. The yellow characteristic luminescence of Ce in YAG falls into the wavelength range corresponding to maximal sensitivity of conventional detectors as PMT. All these properties make YAG:Ce a good candidate for a fast and efficient convertor of X-rays into visible light. Indeed, the monocrystalline YAG:Ce is widely used to image X-rays at XUV/X-ray FELs as FLASH and LCLS. However, the applications of YAG:Ce at these powerful machines are limited by the damage threshold of YAG, which demands for high attenuation or / and reducing number of pulses in train. The problem of relatively low damage threshold holds for most of well-known scintillator materials, since the scintillators are usually used to detect a weak signal and have been optimized for highest possible absorption, corresponding to high-Z materials. While to reduce the damage threshold, one should aim for low-Z materials in order to minimize absorption and thus reduce the density of excitations in material. This means that new luminescent materials should be developed for high-intensity applications.

CVD diamonds: The low-Z material known for its superior properties relative to any kind of damage is diamond. The damage threshold in diamonds, exposed to X-ray beam of European XFEL, is expected to be by two orders of magnitude higher than in YAG. The monocrystalline diamonds are excessively expensive for the presented here project (in total, several tens of large, of few cm^2 surface, crystals are needed). However, polycrystalline CVD diamonds, which are available for a much lower price, are still very robust materials. The high penetration depth of X-rays in diamonds reduces the excitation density and increases single shot damage threshold, while high thermal conductivity helps to sustain long pulse trains.

The light yield of CVD diamond luminescence is known to be very weak compared to YAG:Ce luminescence, - the best reported yield in CVD diamonds is by two orders of magnitude lower than in YAG:Ce. Still, due to high intensities of FEL radiation, this yield can be acceptable, in particular taking into account that only the integral signal, without spatial resolution, is to be detected by the beam loss monitors.

Another particularity of luminescence from diamonds is its spectral signature. In YAG:Ce the spectral content of luminescence is well-defined and almost does not depend on growth conditions, due to its origin in Ce atoms which are embedded in YAG in very low concentration of typically 0.2%. In contrast, the defects responsible for the luminescence in diamonds are strongly dependent on preparation conditions. More than a hundred of different luminescent centres in diamonds have been reported.

Finally, the decay time of X-ray induced luminescence in diamonds is about 10 fs, which is even faster than in YAG:Ce.

In summary, the CVD diamonds would be preferable convertor into visible light, provided that the luminescent signal can be clearly detected. Finally, one more property of luminescence should be investigated and taken into account for applications with intense X-ray beams, namely saturation. This phenomenon is known to be limiting the signature of YAG:Ce luminescence, in particular for lower photon energies, when the penetration depth decreases and the density of excitations in material increases.

Detection of Visible Light

Among existing detectors for visible light, the photo-multiplier tube (PMT) is sufficiently fast for our application, with typical time response of few ns. The high sensitivity and the high dynamic range make the PMT a good candidate to be used in photon beam loss monitors. Moreover, the PMT is often used for the beam

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loss monitoring in accelerators. In latter case, the PMT faces directly the surface of the medium transporting visible light: glass or fiber transporting Cherenkov radiation, or scintillator transporting luminescence. Such geometry allows for easy optical shielding from the ambient light. For the case discussed here, namely detecting the light induced by photon beam in the luminescent screen (or screen producing thermal light), a direct contact between the screen and the PMT is hardly possible. Being located at some distance from the screen (preferable realization would be outside the vacuum chamber), the PMT, due to its high sensitivity, can 'see' even very weak light coming through the beam transport system. If light, coming from the outside of the vacuum system, can be eliminated by optical shielding of the vacuum chamber, the light, coming along the beamline, is a more challenging obstruction. In particular, being originated from the same bunches as the FEL light, bending magnet radiation of the electron dump system and spontaneous radiation in undulators (in contrast to ambient light) cannot be filter out by the nanosecond timing response of the PMT. Thus, the problem of signal to noise ratio can question the feasibility of the PMT detector in case of weak signals. Additional filtering by spectral filters is possible in case of luminescence, since the spectral response is well defined (in contrast to thermal light, which spectral response is wide and strongly temperature dependent). This possibility to clean the signal favours the luminescent screen versus the thermal one. The sensitivity range of the detector should be considered as well. Though the detectors of high sensitivity in IR range are available nowadays, they are more expensive than those for visible light and usually exhibit lower signal-to-noise ratio. This fact favours again luminescence, in particular with spectral response in the middle of visible range, versus thermal light. Lastly, since the PMTs are used for the electron beam loss monitors at European XFEL [3], implementing the same detector type for the photon beam loss monitors would be a cost effective solution allowing for easy integration.

FEASIBILITY TESTS AT FLASH

To check on proposed detection scheme comprising the luminescent screen and the PMT detector, the feasibility tests have been carried out at FLASH.

The prototype of the photon beam loss monitor, presented in Fig. 2, has been constructed in a way to optimize detection of weak luminescent (or thermal light) signal. Since both types of radiation, luminescence and thermal light, are emitted into entire solid angle of 4π sr, the closest possible distance between the screen and the detector (or lens, focusing onto detector) ensures maximal angular collection of the visible light. In the simplest case of the detector located outside the vacuum vessel, the geometry was optimized to reduce distance from the beam axis to the window flanges, where the detector is attached. The feedthroughs will allow to position 4 screens: from sides, from above and from below, in order to confine the photon beam path according to

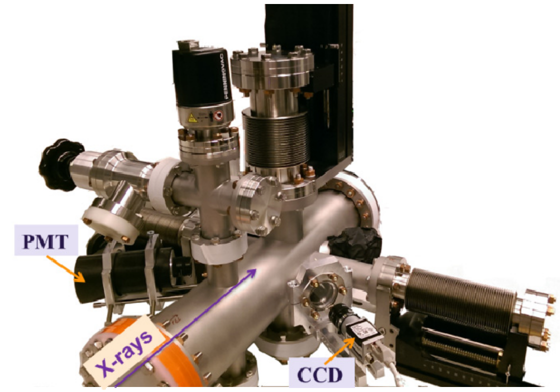

Figure 2: Prototype of a photon beam loss monitor used for the feasibility tests at FLASH.

the photon energy and the beam loss monitor location in the beamline. In tests, presented below, the feedthroughs were used only for positioning of the test samples into the beam. The HAMAMATSU R7600U-00-M4 PMT has been attached to one of optical windows directed to the luminescent screen. Due to large effective area of the PMT of 18 mm x 18 mm, no lens has been used to focus collected light onto PMT. Such a lens can increase the collection angle of the visible light and can be introduced if required. Neutral density and bandpass filters can be attached to the PMT depending on signal level and spectral content of luminescence. The PMT maximum sensitivity is in the range 300 – 500 nm. The chamber was optically shielded when the PMT was in operation. In order to check the origin of detected by PMT signal, a Basler acA640-120gm CCD equipped with RICOH FL-HC1214-2M lens has been attached to the second window flange. Images of the spot on sample, recorded with the CCD, provided a resolution of 8.5 pix / mm in horizontal direction and 12 pix / mm in vertical direction.

FLASH was operating at 7 nm (corresponding to the photon energy of 177 eV). The measurements were done behind the focus at the PG2 beamline. The spot size on sample was about 0.85 mm x 1.75 mm. The beam of an average energy of about 50 μJ per pulse has been transmitted onto the sample. The single pulse measurements have been performed with the repetition rate of 10 Hz.

Several polycrystalline CVD diamonds from different producers (from Diamond Materials, Germany, from General Institute of Physics, Russia and from TISNUM, Russia) have been investigated. The samples have been produced under different conditions and are characterized by different content of impurities as nitrogen and boron. The thickness of the CVD diamond samples were in the range 50 – 300 μm, which is much higher than penetration depth for 177 eV photons of about 0.4 μm. Thus all the XUV photons were absorbed in the samples. Similar in case of YAG:Ce with penetration depth of below 0.07 μm and the sample thickness of 500 μm. The reference YAG:Ce samples have been produced by Crytur ltd., Czech Republic, and by Academy of Science of Armenia.

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The signal from all the samples has been detected by both PMT and CCD detectors. The PMT high voltage has been set to 340 V in case of YAG:Ce and to 600 V in case of diamonds. In both cases the neutral density filter on the PMT was attenuating the signal by two orders of magnitude. The signal from YAG:Ce was of the same level and spectral content for the samples from different producers, while the signal from CVD diamonds differs strongly from sample to sample. The light yield in diamonds has been estimated 2 – 3 orders of magnitude lower than in YAG for the measurement conditions.

The CCD was used to check on the origin of the signal. While moving the samples through the beam, both PMT signal and CCD images were taken simultaneously. The PMT signal was appearing only when the beam spot was seen by CCD on the sample. An example of simultaneous measurements by PMT and CCD is presented in Fig. 3. One can see the clear signature of luminescence in one of the CDV diamond samples.

This is a very encouraging result demonstrating that not only luminescence from YAG:Ce, but from polycrystalline CVD diamonds as well, can be used for the photon beam loss monitors. Indeed, for the presented system, even by several magnitude lower signal can be clearly detected due to possibility of increasing the gain of PMT by more than order of magnitude and removing two orders of magnitude attenuation filters from the PMT.

The fluctuations of the PMT signal have been observed. By correlating the PMT signal with the FEL intensity measurements by the gas monitor detector (Fig. 4), it can be demonstrated that the fluctuations reflect the SASE fluctuations. The amplitude of fluctuations in the PMT signal is lower than in gas monitor detector, which indicates some degree of saturation in diamond luminescence. The saturation effects are to be investigated, and present measurements indicate even higher saturation in YAG:Ce. At higher photon energies of the European XFEL operation range, the density of excitations will be by several orders of magnitude reduced resulting much higher saturation threshold.

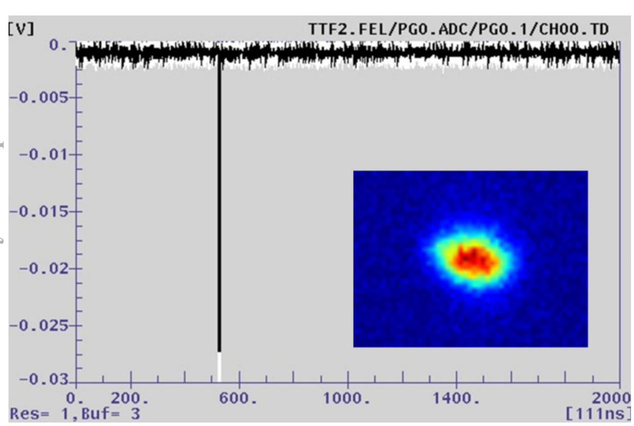

Figure 3: Signal from the CVD diamond, recorded with PMT (main pannel), and simultaneously recorded by CCD image (insertion).

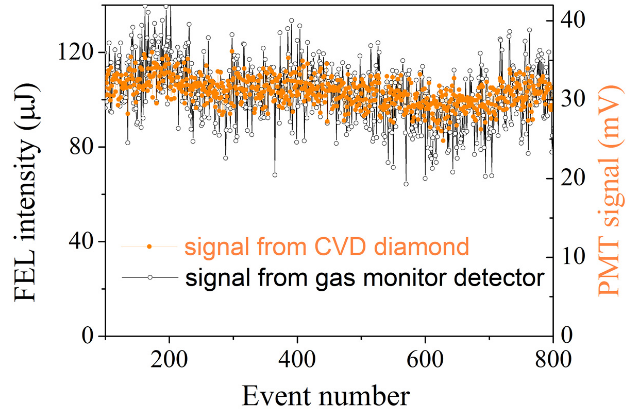

Figure 4: Signal from the CVD diamond measured with PMT compared to the signal from gas monitor detector.

CONCLUSION

The concept of novel photon beam loss monitors for the European XFEL is proposed. The induced by mis-steered X-ray beam luminescence in CVD diamonds can be detected by PMT, interfacing the machine protection system. The feasibility of such a detection has been proved at FLASH.

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REFERENCES

[1] K. Wittenburg, "Beam Loss Monitoring and Control", in *Proc. 8th European Particle Conf.*, Paris, 2002, pp. 109-113.

[2] H. Sinn, *et al.*, "Technical Design Report: X-Ray Optics and Beam Transport", XFEL.EU TR-2012-006, 2012.

[3] A. Kaukher, *et al.*, " XFEL Beam Loss Monitor System ", in *Proc. 15th Beam Instrumentation Workshop*, Newport News, 2012, pp. 35-37.

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