BEAM LOSS POSITION MONITOR USING CERENKOV RADIATION IN OPTICAL FIBERS

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Abstract

The VUV FEL in TESLA technology at DESY provides Giga-Watt output power in laser pulses. The SASE single pass Free Electron Laser (FEL) has been developed for high-brightness user applications. At the design parameters the average power of the electron beam is about 72 kW. To avoid vacuum breakdown and high radiation levels caused by electron losses a machine protection system is required. Collimators are installed upstream of the radiation sensitive undulators [1]. However, the proper operation of the collimator system needs to be measured with a beam loss monitor. Conventional radiation sensor systems are not suited for the VUV-FEL undulators, because of the restricted free space in the undulator gap. A Beam Loss Position Monitor (BLPM) based on Cerenkov light in optical fibers allows real time monitoring of loss location and loss intensity. Electrons with energies above 175 keV generate Cerenkov light during their penetration of the optical fiber. The fast response of the Cerenkov signal is detected with photomultipliers at the end of the irradiated fibers. The reconstruction of the particle loss trace in 3 space dimensions became possible with four sensors.

INTRODUCTION

Since September 2004, the VUV-FEL has been in operation and will soon used by synchrotron radiation user. The accelerator consists of an rf-laser gun, the acceleration modules, each containing eight 9-cell super conducting (SC) cavities, two bunch compressors, collimators and a 30 m long permanent magnet undulator section comprising six 4.5 m long undulator units. The final electron beam energy is 1.0 GeV. Dark current electrons caused by field emission from the normal conducting rf gun and generated in the first acceleration module are transported along the beamline. Electrons outside the phase space acceptance of the accelerator will be lost anywhere. Moreover, the electron bunches suffer unavoidable beam emittance growth from space charge effects in the gun and bunch compressors.

Lost electrons hit the vacuum chamber and create a shower of secondary particles. These showers penetrate an optical fiber and generate Cerenkov radiation. Using four parallel sensors radial to the vacuum pipe along the section of interest the electron loss traces can be determined in transversal and longitudinal direction. Thus a Beam Loss Position Monitor BLPM is used at the VUV-FEL for online analysis of particle losses. During machine commissioning and routine operation the online optimisation of collimator efficiency and studies concerning electron losses are performed.

CERENKOV RADIATION

Cerenkov radiation is emitted whenever charged particles pass through dielectric matter with a velocity exceeding the velocity of light in the medium (fiber). Cerenkov emission is immediately generated by recombination effects in the material. The response time is negligible compared to light propagation time in the fiber or rise time in photomultiplier electronics. The intensity of Cerenkov light increases inverse to the cube of the wavelength. Consequently, in the visible spectrum the blue colour dominates.

The propagation of Cerenkov light in the fiber depends on the particle shower geometry, particle and fiber properties. The shower angle with respect to the fiber axis and the shortest distance (Stoss-Parameter) between particle trajectory and the center of fiber cross-section are important for the coupling of Cerenkov light into the fiber. The modelling of Cerenkov-effects in fibers is documented in [2-5]. For electrons, the lowest energy for emitting Cerenkov light in pure quartz fibers (n=1.46) is about 175 keV. The opening angle of Cerenkov radiation in the fiber scales with the energy of non-relativistic electrons. Above 6 MeV electron energy the light intensity is given only by the number of electrons hitting the fiber and their path length inside the material.

BEAM LOSS POSITION MONITOR

Some publications about fibre optic radiation monitoring systems for accelerators based on the generation of Cerenkov light by relativistic charged particles appeared recently [6-9]. Using one fiber, a particle loss trace can be detected only within a small radial angle. Using four (or more) parallel fibers in equidistant radial space, similar to the arrangement of beam position monitor (BPM) sensors, the loss trace can be measured in transverse and longitudinal dimensions. The Cerenkov light is detected with photomultipliers (PMT's) at the end of the sensor fibers. The response of the PMT is monitored with a fast scope (ACQIRIS-Card). Measuring the time of light propagation in the fiber by

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using a trigger signal from the bunch clock, the position of the secondary shower can be determined. The scheme of the BLPM is shown in figure 1.

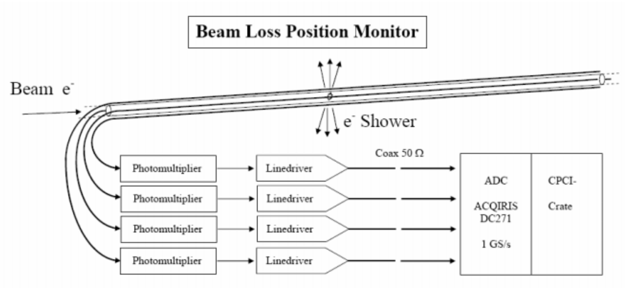

Figure 1: Scheme of the Beam Loss Position Monitor. Four fibers in equidistant radial arrangement allow the measurement of secondary particle showers along the beam line. The photomultiplier is followed by a line driver and a fast ADC (1G/s) card. The transverse loss trace can be calculated from the photomultiplier signals.

The precise location of the secondary shower with respect to the beam line layout can be figured out by movable vacuum components, e.g. OTR screens or wire-scanners. Consequently, the allocation of the accelerator layout and signal time structure can be checked. Due to the fact, that the speed of relativistic electrons in vacuum (~ c) is higher than the light propagation in the fiber (~ 0.66 c), the chronological order of detected losses generated by one bunch / halo can be mixed up. In order to keep the chronologic order of loss events, the beam needs to pass first the PMT position and afterwards the sensor fiber. In other words: with respect to the beam direction the PMT position is always upstream of the sensor position. In this case, the detected time difference t_D^* of two Cerenkov pulses in the fiber (within one trigger event) is $t_D^* = 5/2\ t_D$ with reference to the time difference t_D of two beam-loss occurrences. The time scale stretching by a factor of 2.5 implies a higher local resolution on the scope. While the scope sample rate of one nanosecond covers a distance in vacuum of about 300 mm, the in fact supervised distance is only 120 mm. In the case, that the PMT would be downstream of the sensor fiber the detected signals can be mixed up and the time difference t_D^* is a factor 5 shorter.

An important issue for analysing the data is the clear allocation of losses to a bunch clock trigger. The overlap of different Cerenkov light pulses generated by different clock triggers can be avoided when the time space of two consecutive trigger signals is larger than the time of light propagation in the total fiber length. At the VUV-FEL at DESY the time space of bunch triggers in a bunch train varies between 1 μs and 111 ns, respectively the fiber sensor length could vary between 120 m and 13 m. The sections downstream of the collimator are equipped with the BLPM system using a maximum sensor length of 36m for a beamline upstream of the undulators and 35m for the undulators itself.

Fiber Properties

The detection system needs a radiation resistant optical fiber extending the working periods without fiber replacement. Unfortunately, the highest Cerenkov intensity appears in a spectrum-range where the radiation induced losses are high. The radiation hardest commercial fibers for visible light and light of shorter wavelength are multi-mode step-index fibers with pure silica core of high OH-content. A sensor fiber with a 300 μm core diameter drawn from a Heraeus Tenevo SSU preform was used. To increase the signal to noise ratio the fiber was shielded by black Nylon buffer against ambient light. The light output of the sensor scales linear with the diameter, but a larger diameter reduces the bandwidth and limits the local resolution. The spectrum of the output signal depends strongly on the spectral attenuation of the fiber. In agreement with theoretical predictions the maximum intensity was measured in the wavelength range around 550 nm after penetrating a fiber length of 35 m.

Photomultiplier

For all fiber sensors selected photomultipliers (Hamamatsu H6780-02) are used. Every single PMT was tested to obtain the gain characteristics depending on PMT control voltage and wavelength. The relative comparison of the PMT's to each other was done with a red laser (pulse width 40 ns). The PMT output-signal was amplified depending on different control voltages to approve its linearity. To ensure that all photomultipliers are working with the same amplification the individual control voltage settings of PMT's are saved in a look-up table. A LabView Software ensures comparable output signals at different amplification levels for all PMT's in use.

MEASUREMENT

The system allows a sensitive loss measurement along the beam path. A typical loss pattern in the Temporary-Beamline Seeding is shown in figure 2. The losses are generated by an inserted OTR-screen (3SUND1). The loss shower intensity started smoothly and was rapidly increased downstream of the (first) quadrupole. The local minima in the signals are due to the transverse distance variation of the fiber with respect to the vacuum pipe center. The distances at screens, pumps and quadrupoles are increased by roughly a factor of three. An envelope curve (not shown in the plot) of the signal maxima corresponds to the loss profile with equidistant space between fiber and transverse chamber center. However, losses at places with larger fibre distances will probably lead to false detection of the shower origin.

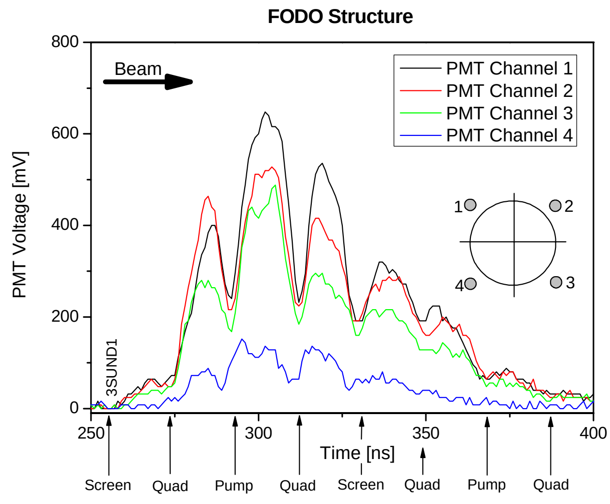

Figure 2: Cerenkov light in optical fibers detected with photomultipliers. The online monitor system allows the measurement of electron losses along the sensor. Due to bypassing the fiber at several enlarged vacuum components along the beam line (screens, quadrupoles, pumps) the transverse distance varies and influences the signal height. The minima allow the reconstruction of the beam line design. The time axis scaling is 8.2 ns/m.

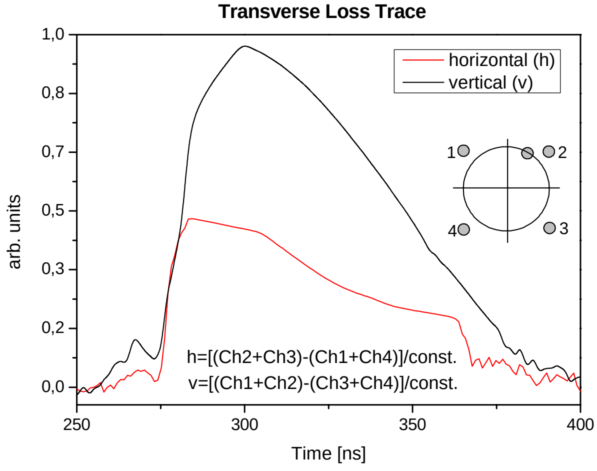

Figure 3: Transverse particle loss trace along the beam line. The envelope of the calculated horizontal and vertical loss trace is shown. Losses are dominated in the first quadrant of the vacuum chamber.

The transverse loss traces are calculated from the PMT signals. In figure 3 the minima due to local shielding have been omitted. Then the envelopes reveal the loss trace for both planes. With respect to the beam direction the losses are on top (vertical) and on the right side (horizontal) of the beam path. The loss trace amplitude for each plane is different because of the asymmetric beam halo (measured by profile monitors). In an untypical case, that the signals measured at the four fibers are equal in amplitude and time the loss trace in figure 3 would become zero. So, by observing the PMT signals and the loss trace one can easily figure out the transverse position of the loss shower.

The same principle of the BLPM System with four fibers was also adapted to an optical fiber dosimeter system based on the Optical Time Domain Reflectometer [10] technique.

CONCLUSIONS

A real time sensing system measuring the local origin of electron losses and collimator “leaks” has been developed and operated during the VUV-FEL commissioning and routine operation run. The advantages of an optical fibre BLPM system are:

- It enables the operator to control radiation emission in transverse and longitudinal dimensions.
- The losses can be measured in narrow slits, which are inaccessible for conventional online dosimeter systems. The radiation hard bare fibre is shielded with nylon and has a diameter of only 800 µm.
- Beam losses can be tuned continuously.
- Malfunction of active components (rf, magnets) and operator errors can be verified by electron losses.
- Fast switch off for machine protection system is possible.

REFERENCES

[1] V.Balandin, N.Golubeva and M.Körfer, Studies of the collimation system for the TTF FEL , Nucl. Instr. and Meth. A483, 340-344, 2002
[2] G. Anzivino et al, Quartz fibre calorimetry – Monte Carlo simulation, Nucl. Inst. Meth. A357 (1995) 380-385
[3] P. Gorodetzky et al, Quartz fibre calorimetry – Monte Carlo simulation, Nucl. Inst. Meth. A361 (1995) 161-179
[4] Yao-Cai Wang et al, Passive optical fibre sensor based on Cerenkov effect, SPIE Proceedings 1572/74 (1991) 32-37
[5] B.L.Pruett et al, Gamma-Ray to Cerenkov-Light Conversion Efficiency for Pure-Silica-Core Optical Fibers, SPIE Proceedings 506 (1984) 10-16
[6] T. Kawakubo et al, Fast-response beam loss monitor, Proceedings of ICANS-XV, 15th Meeting of the International Collaboration on Advanced Neutron Sources, November 6-9, 2000, Tsukuba, Japan
[7] R. Naka, et al., Radiation Distribution Sensing With Normal Optical Fiber, IEEE Trans Nucl. Sci., Vol. 48, No. 6, pp. 2348-2351, 2001
[8] R. Nishiura, N. Izumi, Radiation Sensing System Using an Optical Fiber, Mitsubishi Electronic ADVANCE, pp. 25-28, Sept. 2001
[9] E. Janata, Determination of location and intensitiy of radiation through detection of Cerenkov emission in optical fibers. Part 1. method and experimental, Nucl. Instr. Meth. Phys. Res. A 493, pp. 1-7, 2002
[10] H. Henschel, M. Körfer, J.Kuhnhenn, U.Weinand, F.Wulf, Fibre optic radiation sensor systems for particle accelerators, Nucl. Instr. and Meth. A526, 537-550, 2004