BEAM LOSS POSITION MONITORING WITH OPTICAL FIBRES AT DELTA*

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Abstract

The detection of ionising radiation outside the vacuum chamber of an accelerator is applied to detect local beam losses. At DELTA three different detection systems, based on the interaction of radiation with optical fibres, have been installed. The first system is based on Optical Time Domain Reflectometry (OTDR) applied to an optical fibre mounted alongside the complete vacuum chamber of the storage ring. Fibre sections exposed to radiation give rise to locally attenuated light reflection. In a second system the measurement of the radiation dose related to optical transmission in fibre loops is used to monitor radiation sensitive objects such as permanent magnet undulators. Both systems mainly provide information on a long time scale. Integration of the transmission monitor into the control system however allows the detection of increased dose rates even within a few minutes time scale. The third system is based on the emission of Cerenkov radiation in fibres. A time-of-flight technique offers real time beam loss monitoring with 2 ns time resolution. With four fibres mounted, even the spatial distribution of the radiation and therefore the beam location can be measured. The setup is used at the transfer line to increase the injection efficiency into the storage ring.

INTRODUCTION

DELTA is the 1.5 GeV electron storage ring facility operated at the Centre of Synchrotron Radiation at the Technical University of Dortmund (Fig.1). During accelerator operation ionising radiation is detected outside the vacuum chamber, mainly caused by electromagnetic cascades, generated by beam loss electrons hitting the chamber. The total dose is predominantly localised at only a few positions of the storage ring. Optical fibre radiation dosimetry offers the possibility to measure dose, dose rates, and the positions of such beam losses. Attenuation of light intensity due to radiation-induced fibre damages is exploited to localise doses over large distances by the OTDR measurement and with high sensitivity within short time intervals by the transmission measurement system. Generation of Cerenkov-light offers the possibility of detecting high dose rates on a nanosecond time scale.

Radiation induced attenuation is measured as follows: By radiation exposure of optical fibres, chemical bonds are splitted up. Radiolysis causes generation of unpaired electron states, called colour centres. Transitions between these states, stimulated by electromagnetic radiaton with frequencies from the near infrared up to the visible, result in an enhanced attenuation of the fibre [2, 3]. According to [4], the attenuation A is approximated by

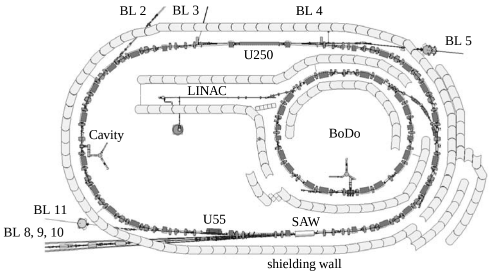

Figure 1: The DELTA accelerator complex

$$A = c(\lambda) \cdot D^f \ .$$

The constant c quantifies the radiation sensitivity of the fibre at a given wavelength, D is the dose. The dimensionless parameter f describes the linearity between attenuation and dose. A nonlinear effect is the annealing effect, i.e. the loss of accumulated dose information by regeneration processes of the colour centres. With the selected fibre [5], in this case doped with Germanium and co-doped with Phosphorus, f is nearly 1 for doses up to 1000 Gy. The radiation induced attenuation also depends on the wavelength, increasing from a minimum at about 1150 nm to shorter wavelength, i.e. the sensitivity of optical fibre dosimetry systems can be varied by wavelength-selection of the probe laser, though non-radiation-induced attenuation mechanisms, e.g. Rayleigh scattering, have to be considered [5].

OPTICAL TIME DOMAIN REFLECTOMETRY

The principle of the OTDR measurement is illustrated in Fig.2.

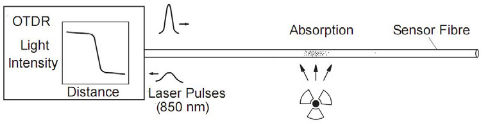

Figure 2: Principle of the OTDR measurement [6]

The Optical Time Domain Reflectometer (Tektronix) emits a 3 ns high intensity laser pulse at a wavelength of 850 nm. While Rayleigh scattering causes a constant reflection rate, the radiation induced generation of colour

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* Work supported by M. Körfer (DESY, Hamburg), W. Göttmann (HMI, Berlin)

centres results in a local attenuation of the reflected light intensity, which results in a gradual OTDR gradient. The pulse is analysed by the OTDR photodetector and the time-of-flight is converted into distance. The total dose resolution of the OTDR system turned out to be 3 Gy, allowing to detect losses after several hours of standard beam operation at DELTA. The spatial resolution is about 1.5 m. Recent measurements of the dose distribution at Delta storage ring are similar to former results presented in [6].

TRANSMISSION MEASUREMENT

One out of three insertion devices at DELTA is the U55 permanent magnet undulator with variable gap. The magnets are composed of Neodynium-Iron-Boron alloy (NdFeB). Investigations of radiation effects on NdFeB revealed an irreversible demagnetisation for accumulated doses exceeding 60 kGy [7], giving an average dose per hour of 0.8 Gy/h for the U55, based on an intended lifetime of 25 years and 3000 annual operating hours. To minimize radiation effects, the magnet gap is opened to its maximum value of 300 mm during injection periods. OTDR-measurements show a high dose accumulation at the U55 position [6]. During the intended frequent injection mode at DELTA [8] the magnet gap has to stay closed, resulting in an increased dose rate at the magnets. To protect the U55 magnet structure from doses exceeding the limit, a local sensor system based on a transmission measurement has been installed at the magnets, consisting of sensor fibre loops with several turns each. The radiation induced increase of attenuation of the transmitted laser light intensity (660 nm, 20 mW) is detected by an fibre optic powermeter (Newport). The setup at DELTA is illustrated in Fig. 3.

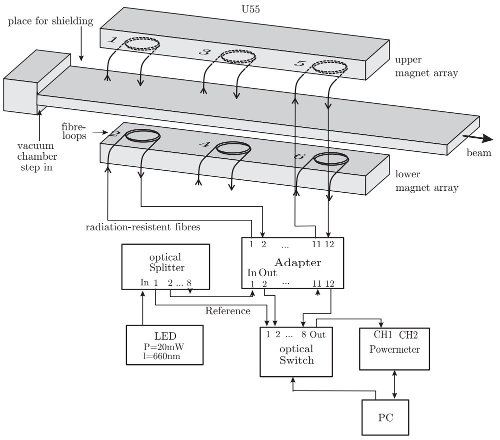

Figure 3: Setup of the transmission measurement system at DELTA [1]

The calibration of the system has been done with thermoluminescence dosimeters (TLD), which have been installed together with the fibre loops on the vacuum chamber for one week of operation. The horizontal dose distribution is shown in Fig. 4. As expected, the main part of the dose is located near the beam axis. Mainly due to the limited dose range of the available TLDs and the increase of dose error by exceeding this limitation, the accuracy of the dose measurement is about 30 %, which is sufficient to guarantee a safe operation of the U55 and similar to the accuracy of the TESLA Test Facility (TTF) system [9].

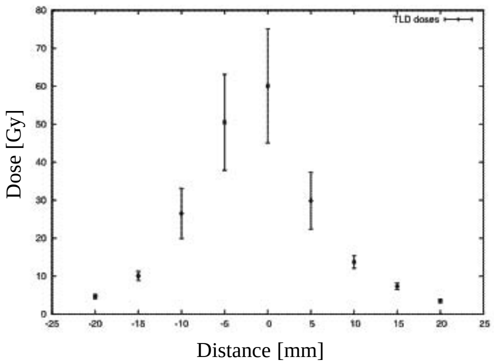

Figure 4: TLD measurement of the horizontal dose distribution on the upper side of the vacuum chamber at the entrance of the U55

The measurement system described here was developed at DESY, and for the first time operated at the TTF linac [4]. The system is capable of successively switching eight fibres to the input of the powermeter, using a MEMS fibre optical switch (Sercalo). To avoid an influence of the laser source stability on the determinated doses, the measured intensities are normalised to the laser output power. For this reason one of the fibres is directly connected to the optical switch. For an effective interlock system the dose rate must be detectable within a short time period. The systems dose resolution of 60 mGy results in a required period between two measurements of the same loop of about 5 minutes to achieve a dose rate resolution of 0.8 Gy/h. To ensure a continuous dose determination, the system is integrated in the DELTA control system (EPICS), which operates the optical switch and the powermeter [1].

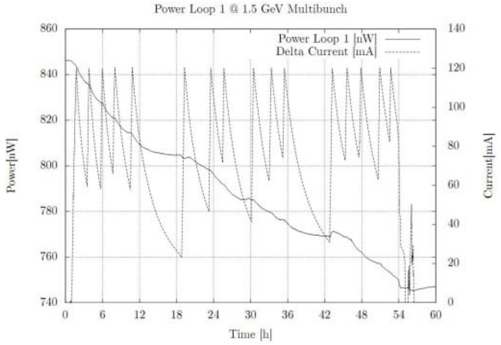

Figure 5: Intensity measurement at the upper magnet array at the entrance of the U55 [1]. Magnet gap: 300 mm during injection, closed during storage mode

In fig. 5 an intensity measurement over a period of 60 hours of beam operation in combination with the beam current is displayed. There is a correlation between the slopes of intensity and current, because the beam loss rate is proportional to the dose rate and to the decrease of intensity for constant machine parameters and outside injection phases. The dose rate for standard user operation at the upper side is at 0.8 Gy/h, i.e. the limiting value is already reached. At the lower side of the U55 the dose rate is by a factor 5 smaller, which can be explained with a non-centered beam in front of the U55. The dose rate measured at the undulator entrance during injection phases is by a factor 3 higher than in storage mode. Measurements during a simulated frequent injection mode revealed a dose rate exceeding the limiting value by a factor 3. By optimisation of the lead shielding at the U55 entrance the dose rate could be significantly lowered by a factor 2. Further shielding improvements will follow.

DETECTION OF CERENKOV RADIATION IN OPTICAL FIBRES

To improve the injection efficiency of the transfer channel between the synchrotron and the storage ring, a sensor system based on cerenkov-light emission has been built at DELTA. The system setup was developed by DESY in cooperation with the Hahn-Meitner-Institut (Berlin) and the Fraunhofer Institut (Euskirchen) [10] and designed for simultaneous realtime beam loss detection of four fibres with a single bunch resolution of 2 ns and a spatial resolution of approximately 0.12 m at the TTF. The measurement principle and basic setup for one fibre are illustrated in Fig. 6.

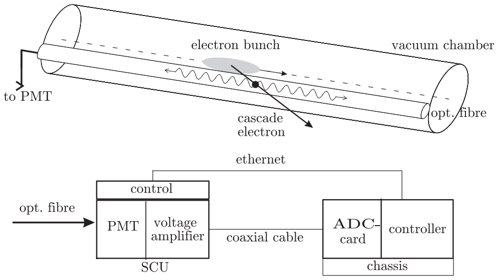

Figure 6: Principle and basic setup of the Cerenkov-light detector, displayed for one fibre [1]

Relativistic shower electrons generate Cerenkov-light, the intensity of which is proportional to the dose rate, by penetrating an optical fibre. Taking fibre attenuation-effects into account, the maximum intensity appears in a spectral range of about 550 nm. To achieve an optimum of light-intensity, radiation resistant multi-mode step-index fibres with a core diameter of 300 μm are used, with a pure silica-core and a high OH-content. The light is transformed into an intensity proportional voltage signal by a photomultiplier (PMT) (Hamamatsu H6780-20) connected to the end of the fibre. The amplified signal is recorded by a fast 4-channel ADC (Acquiris DC 271) with a sampling rate of 1GS/s per channel and stored at the controller, which operates the PMTs and amplifiers placed in the signal-conditioning-unit (SCU). With four fibres equidistantly mounted at the vacuum chamber, beam loss measurements can be obtained with transverse, and together with the time-of-flight method, longitudinal resolution. For this purpose, the data acquisition is started, when the beam enters the section. The calibration of the longitudinal position is performed with a screen inserted in the beam as target. The detector is connected to the fibres at the upstream side, i.e. the light signal has to cover the same distance as the electron bunch up to the time of beam loss. Due to the speed of the beam electrons $(v_e = c)$ and the speed of Cerenkov-light in the fibre $(v_{cer} \approx 2/3c)$, two signals generated at a distance of 1 m will be detected with a time difference of 8 ns.

SUMMARY

Three systems to measure radiation doses with optical fibres were applied to the transfer channel and the storage ring of DELTA, where the space is too small for usual dose measurement systems. The transmission measurement system was integrated into the EPICS control system, thus ensuring a continuous dose surveillance of the U55. As a consequence of the measured dose rates the shielding of the U55 was significantly improved. The Cerenkov-light detector has been installed and its functionality verified.

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