FIBRE OPTICAL RADIATION SENSING SYSTEM FOR TESLA

H. Henschel, Fraunhofer-INT, Euskirchen, Germany
M. Körfer, DESY, Hamburg, Germany
F.Wulf, HMI, Berlin, Germany

Abstract

High energy accelerators generate ionising radiation along the beam-line and at target places. This radiation is related to beam losses or dark currents. The in-situ measurement of this ionising dose that is distributed over long distances or large areas requires a new monitor system. This paper presents first results and the concept of such a monitor system at the Tesla Test Facility.

1 MOTIVATION

Field emission electrons are coming out of the RF laser gun and accelerator cavities. Particles based on this dark current can leave the cavity when they are emitted in a proper phase and will be accelerated together with the bunched beam. The dark current is not well-matched to the magneto optics so that most of it will hit the vacuum chamber, cavities and collimators in front of the undulators/detectors. This mechanism produces high energetic X-rays and electromagnetic showers. The regular bunched beam can also be lost during the accelerator commissioning or standard beam operation due to power supply failures. For a long and complex accelerator system like TESLA [1] it will be advantageous to monitor and measure on-line the local dose in sections of interest, especially at radiation sensitive equipment like fast signal processing units (PCs), superconducting components, collimators and permanent undulator magnets . A new in-situ sensing system could be realised by optical fibres combined with an Optical Time Domain Reflectometer (OTDR).

2 MEASUREMENT

2.1 General Layout

The most obvious effect of ionising radiation in optical fibres is an increase of light attenuation. The radiation penetrates the fibre and creates additional colour-centres which cause a wavelength-dependent attenuation that can be measured with an OTDR (Fig.1). A short laser pulse is launched into the fibre. A fraction of the signal reaches the photo-detector by Rayleigh back-scattering and Fresnel-reflections. The light coming from fibre sections behind the exposed fibre part suffers absorption leading to an attenuation step on the OTDR trace. The height of the step is proportional to the radiation dose. Differentiation of the OTDR curve results in peaks with dose-proportional height.

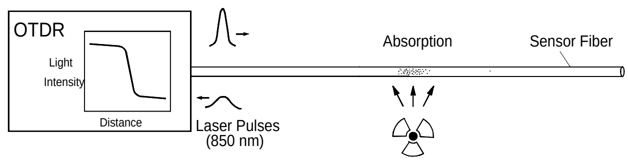

Figure 1: Principle of radiation dose measurement with optical fibres: OTDR-solution (= "distributed" sensor with local resolution). The radiation produces absorbing "colour centers". Propagation time and intensity of the back-scattered laser pulses allow determination of radiation intensity (= dose) and location of the radiation exposure.

With the known speed of light (~ 0.66 c), the measured pulse propagation time can be converted into distance, allowing the localisation of dose deposition. The shorter the laser pulse length, the better the local resolution. But reducing the pulse length leads to a reduction of the light intensity and thus of the dynamic range of the OTDR. As a consequence, the maximum sensor fibre length and/or the maximum measurable dose are reduced. The multimode fibre module of the chosen OTDR (Tektronix TFP2A) is equipped with a 850 nm laser of pulse widths (PWs) ≥ 1 ns as well as a 1300 nm laser (PWs ≥ 10 ns). Due to the wavelength dependence of the radiation-induced attenuation, the dynamic range at 1300 nm is about a factor of five higher than at 850 nm. The local resolution is also limited by the pulse broadening (= mode dispersion) that reduces the bandwidth (BW) of the selected multimode gradient-index (MM GI) fibre of 50 µm core diameter. The table below shows the broadening of laser pulses of different width by fibres with different BW along fibre sections with a length of 0.33, 1 and 5 km, respectively. To avoid excessive pulse broadening, the BW for the Tesla Test Facility (TTF; [2]) should be at least 800 MHz.

BW [MHz·km]	**Fibre Length** [km]	**Pulse Width, FWHM [ns]** with initial light pulse width of 0.2 ns	1 ns	3 ns
250	0.33	0.62	1.16	3.06
	1.00	1.77	2.02	3.48
	5.00	8.80	8.86	9.30
800	0.33	0.27	1.02	3.01
	1.00	0.59	1.14	3.05
	5.00	2.76	2.93	4.07
1500	0.33	0.22	1.00	3.00
	1.00	0.35	1.04	3.01
	5.00	1.48	1.78	3.34

The fibre that was purchased for TTF has a BW of 1100 MHz·km at 850 nm, but only 500 MHz·km at 1300 nm. The lower BW at 1300 nm is tolerable since the minimal laser pulse width of the OTDR at 1300 nm is only 10 ns, anyhow.

2.2 Radiation Effects on Optical Fibres

The amount of attenuation during irradiation is determined by the fibre properties as well as by the irradiation conditions, e.g. the radiation dose, dose rate and fibre temperature. The high purity of the modern fibre raw materials has reduced their radiation sensitivity. However, if the core material of Germanium (Ge)-doped MM GI fibres is co-doped with Phosphorus (P), their radiation-induced attenuation increases significantly so that these fibres are suitable for dosimetry purposes.

The precondition that an optical fibre can be used for dosimetry is that it shows a high increase of attenuation with dose and very slow annealing (= fading) of this radiation-induced attenuation after the end of irradiation (at "normal" conditions). Such fibres show *nearly* linear increase of attenuation (A) with Dose (D)

$$A = c \cdot D^f, \qquad \text{(c = constant, in dB/m·Gy)}$$

i.e., exponent f is not far below "1". Fig. 2 shows the increase of attenuation of such a fibre (in dB/m) as a function of dose, measured at 850 nm with OTDR pulse lengths of 1ns and 3ns, respectively. Exponent f is equal to 0.875, i.e. nearly 1. Usual MM GI fibres show relatively fast attenuation annealing and therefore distinctly lower radiation sensitivity and an exponent f far below 1. As a consequence their increase of attenuation (or measured dose) strongly depends on the dose rate (i.e. the time to reach a certain dose).

2.3 Results

The data presented here originate from a TTF operation period of 17 days. The measurements were done with a laser wavelength of 850 nm and 3 ns pulse length. The accumulated dose versus fibre length is shown in Fig.3.

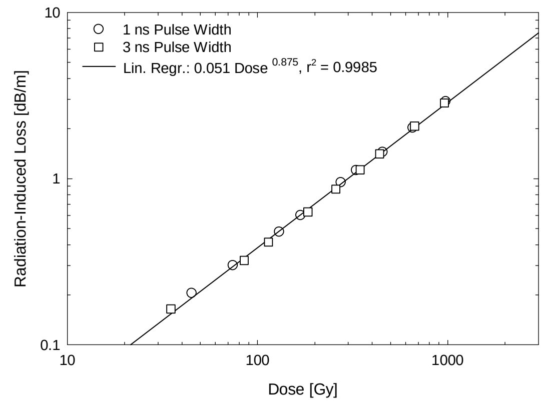

Figure 2: Loss increase with dose of the (Ge+P)-doped MM GI fibre FiberCore N2900107GA during ^{60}Co gamma irradiation. Measurements were made with the 850 nm multi-mode module of the OTDR and pulse lengths of 1 ns and 3 ns, respectively.

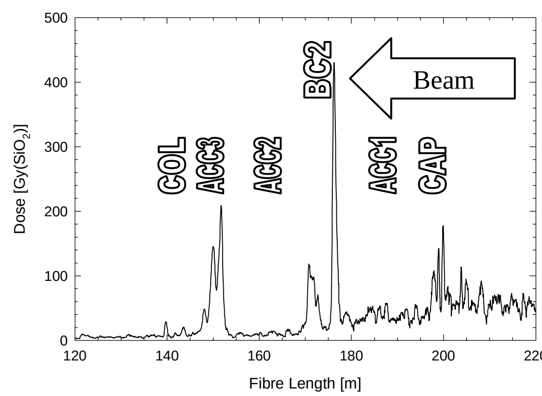

Figure 3: Dose versus fibre length at TTF. The direction of the beam is opposite to the fibre scaling. The beam passes through the capture cavity CAP, the accelerator modules ACC #, the bunch compressor BC2 and the collimator in front of the undulators.

The highest dose deposition was located at bunch compressor BC2, whereas the accelerator modules ACC1 and ACC2 have relatively low radiation levels due to the shielding by the cryogenic tanks. The dose at the temporary beam-line ACC3 (without cryogenic tank) is significantly higher, because the fibre was lying directly on the vacuum pipe. The minim um detectable dose is less than 3 Gy with a distance resolution of 0.6 m. Above 180 m the back-reflected light intensity reached the noise level, i.e. the end of the dynamic range of the OTDR.

2.4 Fibre Regeneration

For the present investigations at TTF the fibre cables are laid directly on or near to the beam pipe. Therefore, the dose rate at some places will be orders of magnitude higher, especially at BC2, than at electronic equipment one or two meters away. A dose > 1 kGy could be reached within unwanted short operation periods. Since it would be inconvenient or even impossible to replace the fibres by new ones every few months, it should be carefully investigated whether they could be regenerated, e.g. by bleaching out the colour-centres with laser light of high intensity, as described by Gaebler et al. [3]. Some first efforts with the fibre used for the measurements of Fig. 2 have shown that regeneration of this fibre type would be very difficult in the accelerator environment. The reason is that fibres that are suitable for dosimeter must have very stable colour-centres. One meter of that fibre was irradiated up to 4000 Gy(SiO_2). The residual attenuation about one hour after the end of irradiation, when the regeneration tests began, was 11.2 dB. Injection of 830 nm and 670 nm laser light with intensities up to about 100 mW and 200 mW, respectively, only led to a loss reduction to about 7.7 dB. Only a temperature increase up to 150 °C, together with injection of the 830 nm laser light, led to a final loss of only about 2.3 dB.

After cooling down, the fibre was irradiated a second time and showed (after subtraction of the residual loss of 2.3 dB) the same loss increase as during the first irradiation (Fig. 4). This is quite encouraging, but on the other hand it is obvious that it would be impossible to heat up all dosimeter fibres along TESLA up to 150 °C. These investigations will be continued with laser light of shorter wavelength and higher intensity.

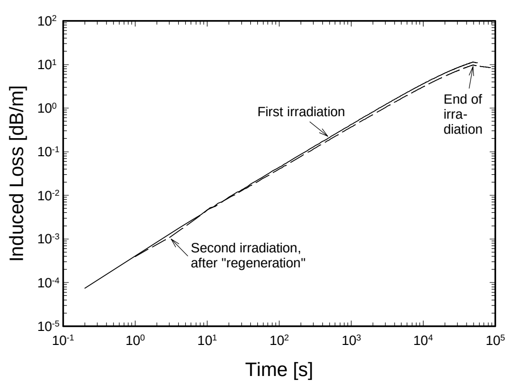

Figure 4: Behaviour of a fibre "regenerated" by heating and high power laser light during a second identical irradiation.

CONCLUSIONS

A new in situ sensing system that observes the local origin of radiation in accelerator sections of interest can be realised by optical fibres. The advantages of optical fibre dosimeters are:

- they enable the operator to control radiation emission at very lengthy objects or in spacious areas.
- they show identical properties (i.e. radiation sensitivity) over greater sensor lengths and of different sensor sections because of the identical composition and high quality of modern fibres.
- the dosimeter sensitivity can be adjusted to the dose or dose rate of interest by selection of fibre type or measuring wavelength. The radiation-induced attenuation increases from a minimum around 1100 nm towards about 670 nm or 450 nm by orders of magnitude.
- the dose can be measured in inaccessible, narrow slits due to very small dosimeter dimensions. Bare (i.e. uncabled) fibres usually have a diameter of only 250 µm.
- the length of each fibre section can exceed several kilometres. Therefore, only a few sensors are needed for the whole accelerator, even with a position resolution of several meters.

A complete OTDR-based fibre optic radiation detection and measuring system covering all parts of TESLA could help to find locations with an unexpected high dose as well as places with lower dose levels where the signal processing electronics could be installed. One could get an estimate of the lifetime of these electronic systems from the measured dose rate, and could optimise the accelerator control.

Permanent dose measurements, with a different sensor type, at the undulator magnets are desirable because they are made of radiation sensitive alloys. Here we need no local resolution (i.e. an OTDR) since the measurements are made at known position(s).

A separate fast radiation detection system is needed in cases of dangerous high radiation emission somewhere along the beam line. It shall be based on the generation of luminescence light in optical fibres and could be used for rapid accelerator switch-off and fast beam loss detection.

REFERENCES

[1] R.Brinkmann et al., (Editors), TESLA Technical-Design-Report, Tesla-Report 2001-23, March2001

[2] D. A. Edwards et al., TTF Conceptual Design Report, TESLA-Report 95-01.

[3] W. Gaebler, G. Sulz, D. Bräunig, "Radiation Effects Testing of Optical Fiber Waveguides", SPIE Vol. 404: Optical Fibers in Adverse Environments, pp. 132-140, 1983.