Preliminary Trials with Optical Fiber Dosimeters at TTF

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INTRODUCTION

Optical fibers are used in a wide field of applications, for instance in communication networks. Their degradation by ionizing radiation is often an unwanted effect. The main radiation effect is a wavelength-dependent increase of attenuation by absorption and scattering processes. Despite the fact that the different types of modern tele-communication fibers show strongly increased radiation hardness (1), compared with the early ones, there still exist some single-mode (SM) and multi-mode graded index (MM GI) fibers with high and only slowly annealing loss increase. Such fibers can be used for in situ local radiation dosimetry also at particle accelerators, to observe the emission of radiation along the beam line where radiation-sensitive equipment might have to be installed (2, 3). The attenuation of the optical fiber can be measured with an Optical Time Domain Reflectometer OTDR (figure1). A fraction of the incoming laser pulse will be reflected along the fiber. The scattered Rayleigh light permits the analysis of local attenuation in the fiber since the time delay can be converted into physical distance by knowing the speed of light within the fiber medium (4). Sections with higher radiation exposure attenuate the light emitted into and coming back from the fiber sections behind, leading to a step in the OTDR trace. The height of the step is proportional to the absorbed dose.
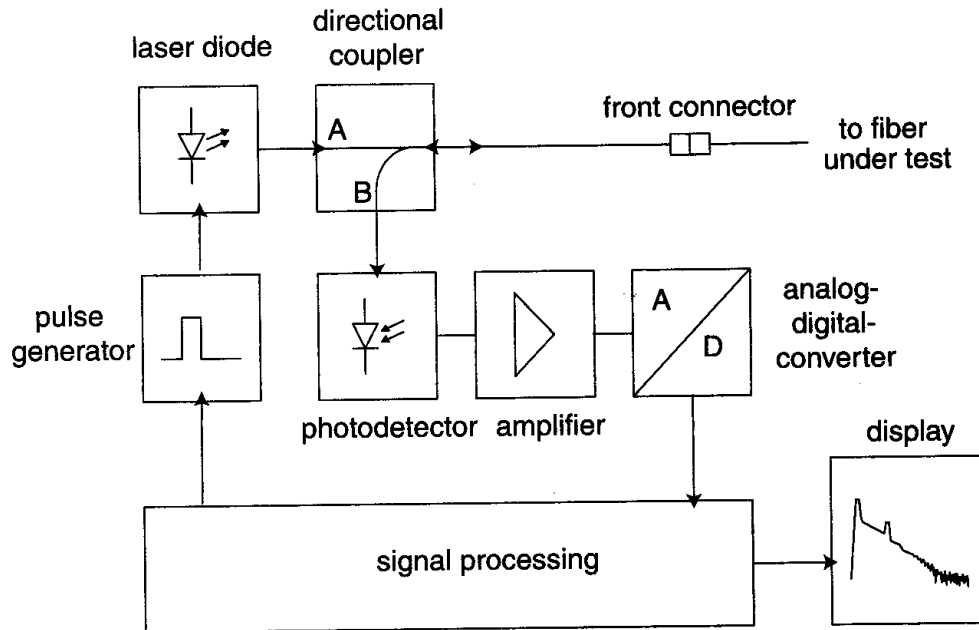
Figure 1. Operation principle of an Optical Time Domain Reflectometer (OTDR).

Particle losses in accelerators cause temporary sources of radiation. Two sources have to be distinguished at TTF. First, the dark current due to field emission in the super-conducting accelerator cavities and the RF laser gun. In the superconducting cavities the field emission is strongly located near the cavity iris and the released electrons are transported out when emitted at a proper phase. This current emerging from one cavity can then be transmitted through and accelerated by the downstream cavities. With respect to the magneto-optics the dark current is mismatched at all. The orbit, beam size and energy spread is not determined. Particle losses are located behind a single magnet or can be smeared out over the whole LINAC transfer line as well.

Second, the particle losses from the regular beam. During accelerator commissioning the location of losses is not predictable. Unfortunately, the magneto-optics is not precisely matched all the time. For standard beam operation the losses are located in the collimator system in front of the FEL undulator. The beam passes the collimator apertures and the electrons far away from the design trajectory (halo) will be absorbed. Additional losses can be obtained in bunch compressors, undulators or due to power supply failure anywhere else in the LINAC.

One task of fiber optic dose sensors could be verified by laying the selected fiber along the accelerator section of interest and measuring the radiation dose distribution with a commercial OTDR at 850 nm wavelength where the radiation-induced fiber attenuation is several times higher than at 1300 or 1550 nm. Another task would be a continuous dose measurement at one or several or even a bigger fraction of the radiation-sensitive undulator magnets. This can be verified by laying the same fiber type meander-like through the magnet system and measuring the attenuation with a special OTDR of high local resolution, if available and/or affordable. An alternative solution would be to place

several windings of separate fibers around all magnets of interest and measure the transmission loss in each individual branch with a multi-sensor optical power meter.

The correlation between attenuation of light and local distribution of dose along the accelerator serves to find unexpected particle losses and allows an improvement of operation conditions. Information from other diagnostic tools will help to explain the reason for increased dose values.

EXPERIMENTS AT TTF

The selected sensor fibers are lying along the accelerator sections of interest (Fig. 2). One fiber runs along the LINAC. The second fiber is going to the collimator (COL) and the Free Electron Laser (FEL) undulators. Only the measurements with the first fiber were made with OTDRs. In the injector region the distance between fiber and beam position is about 0.2 m, while at the accelerator modules this distance is approximately 0.6 m. A radiation harder "forerun fiber" was installed between OTDR and ACC2. The splice to the radiation sensitive fiber caused an unwanted attenuation step. The beam starts in the RF laser gun at the entrance of the injector (82 m away from the OTDR) and travels through the super-conducting capture cavity CC, the accelerator modules ACC1, ACC2 and the bunch compressor BC2.
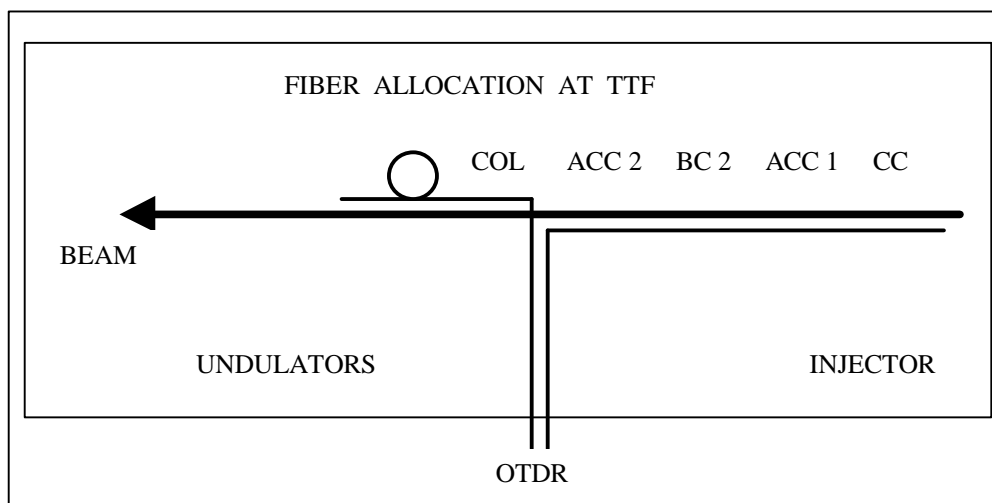

Figure 2. Schematic view to the optical fiber paths close to the beam transfer line at TTF.

For estimation of dose during the beam operation period Radio-Photo Luminescence dosimeters (RPLs) were placed at some (randomly) selected positions along the fiber (figure 3). The total dose accumulated over 4 month varies between up to 90 Gy in the injector and 24 Gy in the collimator region (not shown). The dose in the center of ACC1

and ACC2 is negligible. The RPLs show "fading" during accelerator shutdown times. As a result the measured dose values are lower than expected. This systematic error is less than a few percent of the total dose.
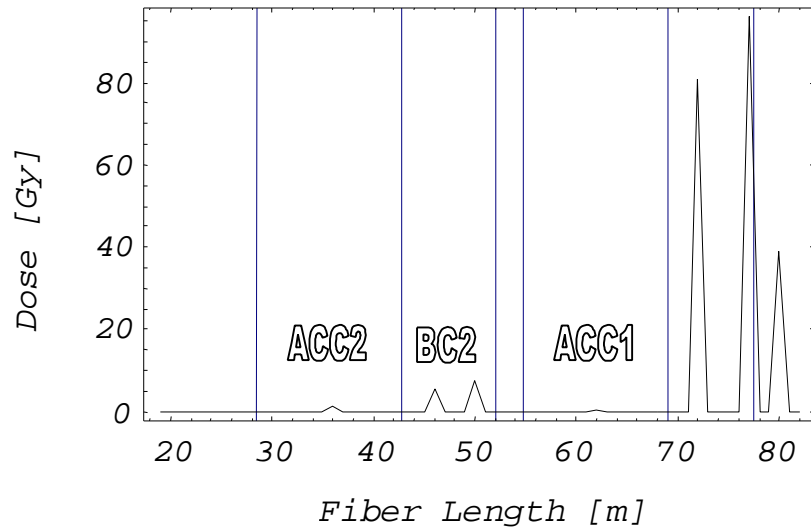

Figure 3. Total dose measured with Radio-Photo Luminescence dosimeters (RPLs) along the dosimetry fiber.

Most of the commercial OTDRs have "Multi Mode" (MM) modules for multimode graded index (MM GI) fibers as well as "Single Mode" (SM) modules for single mode (SM) fibers. The MM GI fibers are used for shorter distances (up to 10 km maximum) at 850 nm and 1300 nm, whereas SM fibers are used at 1300 nm and 1550 nm for distances up to about 300 km. Therefore the MM modules are offered with higher local resolution that is especially obtained with a shorter laser pulse duration (Fig. 1). Since the radiation-induced fiber attenuation at 850 nm is distinctly higher than at 1300 nm (5), the most promising radiation sensor solution would be a MM GI fiber connected to the 850 nm laser of the MM module.

Modern MM GI as well as SM fibers show quite good radiation hardness and are therefore less suited for radiation measurement via increase of attenuation. But there still exist MM GI fibers made with the "Modified Chemical Vapor Deposition" (MCVD) process. Here Phosphorus (P) has to be added for process optimization. The presence of P increases the radiation sensitivity by at least one order of magnitude, and loss annealing after the end of irradiation (= fading of the radiation dose information) is distinctly slower, so that such fibers are good candidates for radiation sensing purposes (5). They should be optimized (with respect to their bandwidth) for 850 nm. A higher bandwidth (e.g. 1000 MHz·km instead of usual values of 250 -400 MHz·km at 850 nm) would reduce the broadening of originally small laser pulses during propagation along the fiber and would thus enable a higher local resolution with longer fiber sections.

The measurements were usually done once a week during a period of four months with two different OTDRs. The first one (an older Advantest Q8460) was less suited since the

receiver signals for pulse durations shorter than 20 ns were dominated by noise. However, with a (nominal) pulse duration of 20 ns it is impossible to localize regions with higher radiation exposure since the "Attenuation Dead Zone" at 20 ns pulse length is about 6 m. The second OTDR was the model CMA4000 from GN Nettest. Here it was possible to perform also measurements with the shortest pulse length of 4 ns. Due to the different local resolution the measurements made with these two OTDR types were not comparable at all.

The second fiber that goes to the undulator magnets was used for a first attempt with an optical power meter. Three windings of a fiber with still higher radiation sensitivity were placed around one of the magnets. This fiber was spliced to the fiber that was intended for OTDR measurements. The light of a blue LED was coupled into this fiber branch, and the light was conducted back to the power meter with another fiber that was placed in a greater distance especially from the collimator. Blue light was used in order to increase the sensitivity, since the radiation-induced attenuation increases with decreasing wavelength. This system was extremely sensitive. Attenuation changes of 0.001 to 0.01 dB could be measured. However, if such a system should be selected for dosimetry purposes, care has to be taken that the fiber sections to and back from the sensor fiber should be as radiation hard as possible and that these fibers are placed far away from the accelerator. The reason is that such a system measures the attenuation increase in the whole fiber length of e.g. 50 - 100 m and not only in the length of about 0.5 m that is irradiated with a higher dose.

RESULTS

The data presented here originate from a TTF operation period of 4 weeks. The dose calculated from the OTDR measurements necessarily must be smaller than that measured by RPLs during four months. Fig. 4 shows curves that were measured after the end of each week. At the left side (beginning) the later measured curves are normalized to that one measured at first in order to remove unavoidable offset shifts that occur when the sensor fiber is disconnected and connected again to the OTDR one week later. After about 28 m where the forerun fiber is connected to the sensor fiber one sees the splice loss of about 0.3 dB. All curves show a small increase of attenuation (= change of the slope) in the middle of BC2, whereas the two lower curves show a strong increase of attenuation "upstream" and "downstream" of ACC1. In the injector region (≥ 73 m) the radiation dose (= slope of the OTDR trace) seems to vary. Immediately above 73 m the dose seems to be higher and close to that behind ACC1 (52 - 55 m).
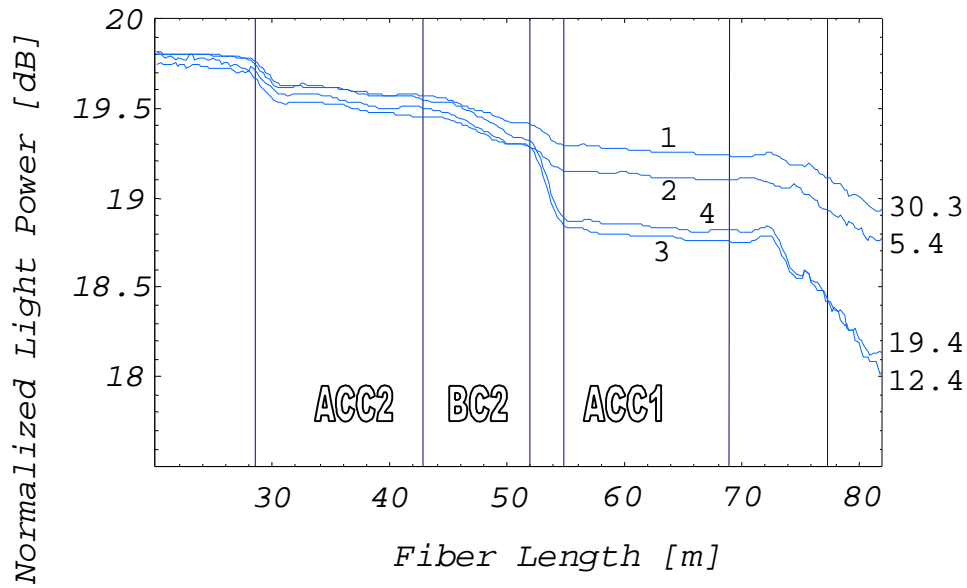
Figure 4. Increase of fiber attenuation along the beam path. At the far-left side the curves are adjusted to the first measurement.

During the second week the accelerator was in a "normal" condition and we see a moderate increase of attenuation between curves 1 and 2. In the third week the dark current reached unacceptable high values. As a result one sees a stronger increase of attenuation between curves 2 and 3. During week four the accelerator was switched off in order to do some necessary improvements. Curve 4 was measured after the end of this week, and we see a slight annealing of the fiber attenuation. Such an annealing during accelerator switch off times has to be considered when one intends to determine total dose values.

These changes of fiber attenuation can be seen more clearly in the next figures. Figure 5 shows the difference between the curves measured after weeks 2, 3 and 4, respectively, and after week 1. In Fig. 6 one sees the difference in attenuation between subsequent weeks. One can clearly recognize the fiber loss annealing during week 4 (curve 4 - curve 3).
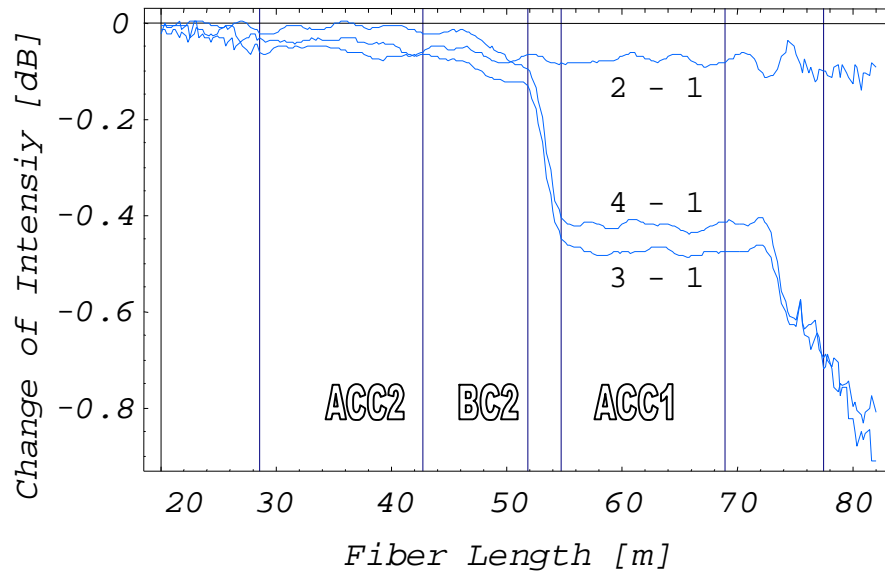
Figure 5. Difference of fiber attenuation at the end of weeks 2, 3 and 4, respectively and of week 1 as a function of fiber length (= accelerator position).
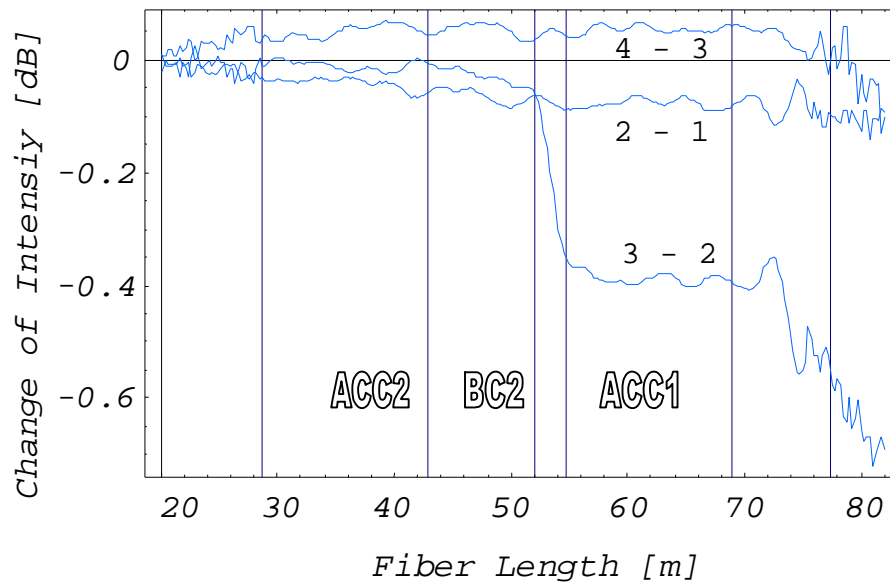

Figure 6. Difference of the fiber attenuation between subsequent weeks as a function of fiber length (= accelerator position).

CONCLUSION

The first measurements at TTF have shown that fiber optic radiation sensing systems for TESLA (6) are possible, but that one should look for a better suited OTDR, with better local resolution, and that one should use a fiber cable instead of a bare fiber. These are bending sensitive, so that it could happen that attenuation steps like these of Fig. 4 are also caused by sharper fiber bends instead of only by radiation exposure.

Further tasks that should be tackled are:
- Development of a measurement procedure and a data evaluation software;
- Development of a dose measurement system for the undulators and, especially, for places where very high dose values are to be expected (7);
- Integration of the fiber optic radiation sensing systems into the control system of TTF and TESLA;
- Regeneration of sensor fibers that have reached their saturation dose limit by high power laser and/or thermal annealing (7).

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