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Fiber Optic Radiation Sensing Systems for TESLA

by

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1. Motivation

With all types of electron accelerators one has to consider the emission of often intolerable high amounts of ionizing radiation at certain typical accelerator components and sections.

At TESLA (1) we have to distinguish two main radiation sources:
The first one is the dark current due to field emission in the super-conducting accelerator cavities and in the RF laser gun. Field emission in the cavities is strongly restricted to the region near the cavity iris. The electrons can leave the cavity when they are emitted at the proper phase. The dark current of one cavity can then be transmitted through and accelerated by the downstream cavities. This current is not matched to the magneto-optics, so that most of it will be lost in the following quadrupole and other downstream magnets, generating high energetic, penetrating Bremsstrahlung (X-rays) and electromagnetic showers where they hit the walls.

The second radiation source is the regular beam. Parts of the beam can be lost at different locations, dependent on the accelerator commissioning. For standard beam operation, losses are expected in the collimator systems of TESLA. Electrons distinctly away from the design trajectory will hit one of the collimator apertures, generating high energetic electromagnetic showers. Electrons can also be lost in the bunch compressors, undulators or anywhere else in the LINAC due to failures in the power supplies of the quadrupoles.

For a long and complex accelerator system like TESLA, it would be advantageous to monitor and measure on-line the local dose, especially at radiation sensitive equipment in the tunnel.

Such a radiation sensor could be realized by optical fibers. Despite of the fact that the different types of modern telecommunication fibers show strongly increased radiation hardness, 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 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.

The advantages of optical fiber dosimetry are:

- Modern fibers can be produced with identical composition and quality in great lengths, enabling the radiation control of very lengthy objects or spacious areas.
- The dosimeter sensitivity can be adjusted to the dose or dose rate of interest by selection of wavelength or fiber type. The radiation-induced attenuation (or loss) increases from the minimum around 1100 nm towards about 670 nm (red) or 450 nm (blue) by orders of magnitude. Ge-doped MM GI fibers co-doped with Phosphorus (P) show medium radiation

sensitivity, whereas the Rare Earth doped SM fibers that are used for fiber amplifiers or lasers show tremendous increase of loss.

- The dosimeter dimensions can be very small. Bare (i.e. uncabled) fibers usually have a diameter of only 0.25 mm, so that they can e.g. measure the dose in otherwise inaccessible, narrow slits.
- The length of each fiber section can exceed several kilometers. Therefore, only a few sensors are needed for the whole accelerator, even with a position resolution of several meters.

A complete fiber 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 optimize the accelerator control. Permanent dose measurements at the undulator magnets are desirable because they are made of radiation sensitive alloys.

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 fibers and could be used for rapid accelerator switch-off and fast beam loss detection (2).

2. Radiation effects on optical fibers

Radiation can change nearly all properties of optical fibers, dependent on radiation type, radiation energy, radiation dose and on fiber type.

2.1 Increase of attenuation, radiation-induced loss

The most obvious effect of ionizing radiation is an increase of attenuation. It is observable with all radiation types in all fiber types already at lowest dose values. The amount of increase of fiber attenuation during irradiation depends on the fiber properties and the manufacturing procedure as well as on most of the irradiation conditions. The manufacturing parameters are purity of the raw materials, doping of the core material, preform manufacturing process, drawing conditions, and others. The great efforts of all manufacturers in optimizing fiber quality led to fibers with strongly reduced radiation sensitivity. Nevertheless, there still exist some SM and MM GI fibers with high and only slowly annealing loss increase. Such fibers can be used for radiation dosimetry. One type, a Ge-doped MM GI fiber co-doped with P will be presented in section 4.1. Irradiation parameters are wavelength and intensity of the conducted light, fiber temperature, and radiation dose rate and dose.

The increase of the radiation-induced attenuation with decreasing wavelength (below about 1100 nm) can be used to increase the sensitivity - provided the necessary measuring equipment is available for the wavelength of interest (see sections 3.1, 3.2).

Within the range of light powers that are usually applied for fiber attenuation measurements (from about 0.1 µW to 1 mW) the attenuation increase should be (nearly) independent of light power, e.g., the fibers should not show "photobleaching". Otherwise, the fiber sensitivity would increase with increasing dose, when the fibers show increased attenuation and the light intensity decreases along the fiber.

The radiation-induced attenuation of all fibers varies with temperature. This temperature dependence could be determined and corrected for, but only with limited accuracy. Therefore, it is recommended to use fiber optic dosimeters only at the temperature at which they were calibrated. This usually will arise no problems at most of the accelerators since the temperature has to be kept constant within several degrees and the fiber calibration (used for the calculation of dose from attenuation increase) changes by less than 0.5 %/K for this fiber type at room temperature.

The attenuation increase of fibers depends on the dose rate with fibers that show relatively fast attenuation annealing after the end of irradiation. This can be explained by the fact that a considerable fraction of the loss increase already would anneal when the same dose would be obtained, with lower dose rate, in a longer time. Such fibers would be less suited for dosimetry purposes as discussed in sections 3.1, 3.2. (Ge+P)-doped MM GI fibers are available with relatively slow loss annealing (= fading of the dose information). Consequently, their attenuation increases (nearly) linear with dose.

2.2 Radiation-induced luminescence light and scintillation

During and immediately after the interaction of radiation with materials like glasses, crystals, water etc. one observes the emission of light. This effect is known as luminescence. With high energetic radiation the principal share of the luminescence light is "Cerenkov light". It is generated when charged particles penetrate transparent materials with velocities above that of the light in this material. At TESLA Cerenkov light can be caused by high energetic charged shower particles or Compton electrons released by high energetic gamma or X-rays.

Optical fibers transmit that fraction of the light that is emitted in the direction of the fiber axis, within an angle given by their "Numerical Aperture" (NA). The light intensity is proportional to the radiation dose rate and can thus be used for radiation monitoring and dosimetry purposes. The efforts to make use of this measuring method for TESLA are described in (2).

The light production can be increased by using special fluorescent (= scintillating) materials. This effect is widely used in nuclear physics by the "Scintillation Detectors". Some of them consist of polymers like Polymethyl Methacrylate (PMMA) which is doped with fluorescent organic molecules. Since most of the present Polymer Optical Fibers (POFs) are made of PMMA, it is easy to produce scintillating fibers. A distributed radiation monitoring system based on such fibers is presented in (3).

2.3 Radiation damage and change of refractive index

The use of radiation-induced fiber loss increase for dosimetry purposes is limited to dose values not far above 1000 Gy. The reason is that all Ge- or (Ge+P)-doped fibers show saturation effects, as shown in Fig. 4 for a (Ge+P)-doped MM GI fiber. Undoped fibers with their faster loss annealing show saturation already between about 1 and 10 Gy. Saturation begins when the colour center production rate becomes equal to their annealing rate. The generation of colour centers is the reason for the increase of attenuation. The more colour centers exist, the higher is their annealing rate (= number of "decaying" colour centers per time unit).

With undoped and Ge-doped fibers the loss begins to increase again, at dose values above 10^4 Gy (4). The reason might be that fiber loss is now dominated by new defects that are caused by radiation damage, whereas the loss at the beginning is dominated by the already existing defects in the fiber core material. Despite of the fact that the increase of loss with dose is now relatively weak, one should investigate whether this effect could be used for dosimetry at high dose values as they are expected at the undulator magnets and detectors.

Fibers doped with Ge+P do not show a new increase of attenuation above saturation up to dose values of 10^6 Gy (Fig. 4). The reason might be that the loss increase caused by radiation damage is low compared with that caused by the P atoms.

Another effect that could be applied for fiber dosimetry at high dose values is a change of the refractive index. The index changes are quite small (5), but it might be possible to make use of them by increasing the fiber length that is exposed to radiation.

3. Fiber optic dosimeter types for different TESLA sections

Dependent on the expected dose and on the respective part of the accelerator it might be advantageous to use different fiber optic dosimeter types and measuring principles.

3.1 Optical Time Domain Reflectometer (OTDR) for measurements along the LINAC

Gaebler already mentioned in 1983 that optical fibers could be used for radiation monitoring of extended areas (6 - 8). In (7, 8) he even demonstrated "the feasibility for a spatially resolving dosimetry by the means of the OTDR technique".

The OTDR principle and different realization techniques are, e.g., described in (9). Fig. 1, taken from (9), shows a block diagram of a "Single-Pulse OTDR", the type that also is used at the TESLA Test Facility (TTF).

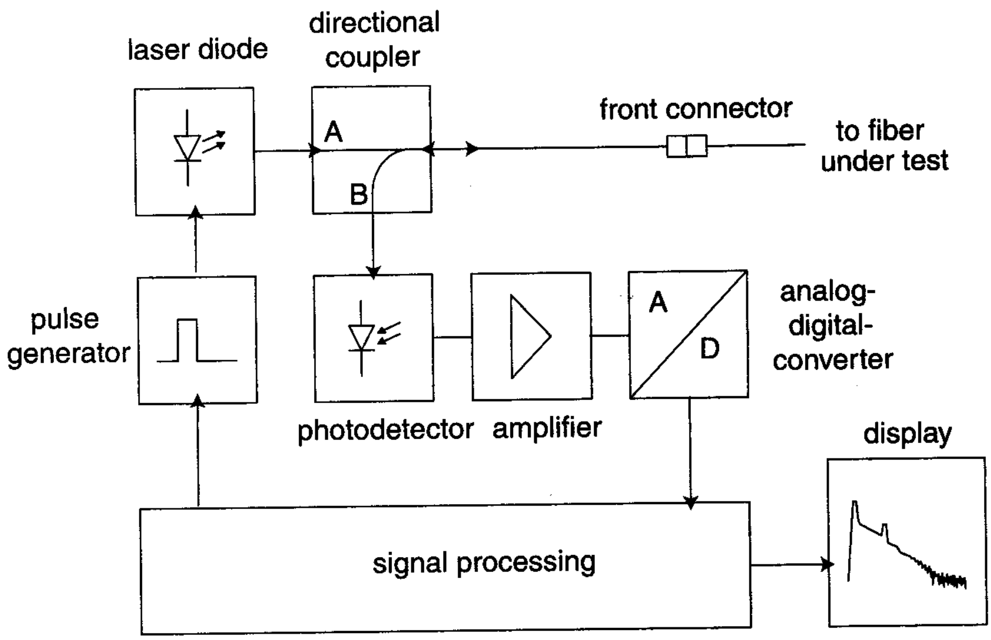


Fig. 1: Block diagram of a single-pulse OTDR.

A short laser light pulse is launched into a fiber. A fraction of the signal is reflected back to the photodetector by Rayleigh scattering and Fresnel reflections. Fiber sections exposed to radiation 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 radiation dose. The position resolution depends on the laser pulse length and on the speed of light in the fiber material (≈ 0.66 c). A pulse duration of 1 ns leads to a wave train of about 0.2 m length in the fiber.

Commercial OTDRs for SM fibers were only realized for wavelengths around 1300 and 1550 nm, whereas the also available multimode (MM) modules for such OTDRs operate at 850 and 1300 nm. These wavelengths are usual for telecommunication with MM GI fibers.

Preliminary measurements with less suited OTDRs along an accelerator section of TTF as well as at the undulator magnets were made at the beginning of year 2000. They are documented in (10).

One distinct attenuation step appeared, e.g., in the region of Bunch Compressor 2. The encouraging results of these test measurements were the reason for the ongoing studies.

Now we use a better one of the available commercial OTDRs and a robust fiber cable instead of bending-sensitive bare fibers. Fig. 2 (lower half) shows OTDR traces obtained with the test configuration illustrated in the upper half of Fig. 2. Fiber spools of only 6 cm in diameter with 3, two and one winding(s), respectively, each separated by an unirradiated loop of 1 and 4 m length, respectively, could be clearly identified and separated with (nominal) laser pulse lengths of 1 and 3 ns, respectively. Especially the peak at about 45 m is an "artifact", presumably caused by the light reflected from the fiber end at 50 m. The measurement was made at 850 nm (i.e. with the MM module) after a dose of 440 Gy.

The best suited commercial (i.e. inexpensive) fibers are Ge-doped MM GI fibers co-doped with P. They have an attenuation of about 2.2 dB/km at 850 nm and 0.43 dB/km at 1300 nm, respectively. Since telecommunication with such fibers is only performed within distances up to 5 -10 km, the usable dynamic range of a commercial MM module of 14 - 20.5 dB (at 850 nm and pulse lengths of 1, 3 and 8 ns) is sufficient for the intended main application, i.e. the test of telecommunication fiber networks. However, when such a commercial OTDR is used for the investigation of dosimetry fibers, an attenuation increase of 15 dB is already obtained when only about 30 m of such a fiber are irradiated up to a dose of 100 Gy, or about 300 m up to a dose of 10 Gy! That means, the accelerator length that can be surveyed with one OTDR is limited by the relatively small dynamic range of a commercial OTDR.

If a high local resolution will not be necessary, one could increase the time until which the limit of the dynamic range will be reached by continuing with the 1300 nm laser diode of the MM module. The shortest 1300 nm pulse length is 10 ns, and the corresponding dynamic range is not higher than 14.5 dB (according to the manufacturer), but the radiation-induced loss at 1300 nm is only about 20 % of that at 850 nm.

Fortunately, there will be only some limited areas at TTF or TESLA with higher radiation emission, so that it could be possible to monitor a distance between 300 and 600 m with the higher resolution at 850 nm. In order to reduce the necessary number of OTDRs and thus the costs one can use, e.g., an optical 1×12 switch to measure up to about 12 fiber sections of up to 600 m length with only one OTDR. The more distant fiber sections will be, e.g., connected via fibers of distinctly lower radiation sensitivity. However, the surveyable beam line length per OTDR will be reduced by a reduction of the usable dynamic range caused by the insertion loss of the switch of at least 1 dB (loss in optimal connectors included) and the loss of the connecting fibers of 2.2 dB/km at 850 nm. Therefore, it should be possible to survey 6 accelerator sections, each with a length of 250 - 500 m at the most, i.e. 1.5 - 3 km with one OTDR.

Again the situation could be somewhat better at 1300 nm, because of an initial fiber attenuation of only 0.43 dB/km.

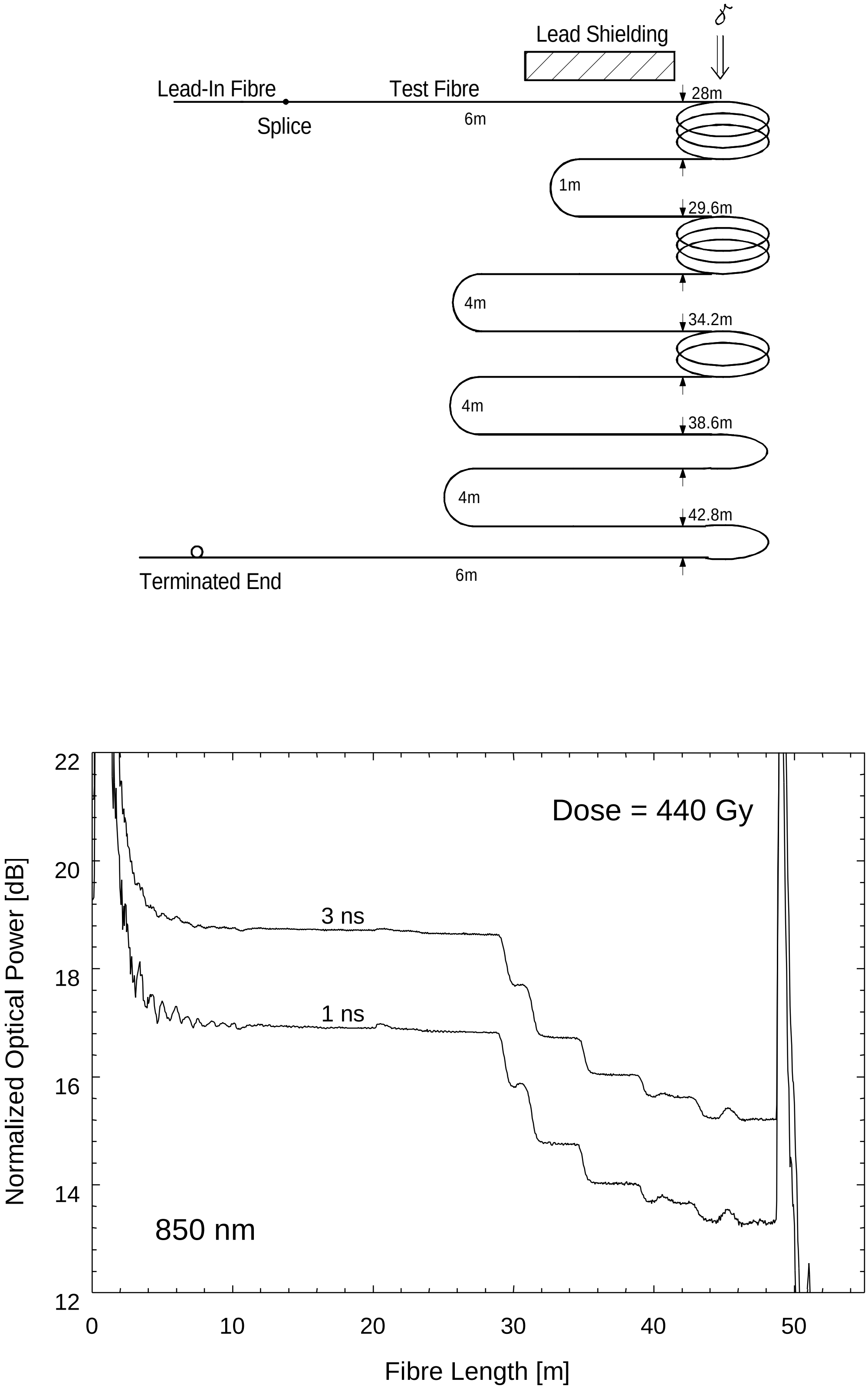


Fig. 2: OTDR traces (below) of the test fiber configuration shown above. The arrows mark beginning and end of fiber spools with three, two and one winding(s), each with a diameter of 6 cm. The measurements were made at 850 nm with OTDR pulse lengths of 1 and 3 ns, respectively, after a dose of about 440 Gy.

3.2 Multisensor optical power meter system at the undulator magnets and detectors

At the undulator magnets or in the detector area a local dose could be measured by laying a fiber meander-like through the system and measuring the attenuation with an OTDR of high local resolution.

Another solution would be to place several windings of individual fibers around the magnets or detector spots of interest and measure the transmission loss in each individual branch with the high dynamic range of a multisensor optical power meter. In order to save costs one could conduct the light of one high power LED via an $1 \times N$ power splitter to 10 -30 sensor fibers. One branch with an unirradiated fiber could be used to correct for temporal intensity drifts of the LED light source. The advantage of such a measuring system is the (principally) high measurement accuracy and the high dynamic range of the power meter. Its high sensitivity was demonstrated during the preliminary tests described in (10).

3.3 Methods for the measurement of very high dose values

In section 2.3 it was pointed out that (Ge+P)-doped fibers show permanent saturation at dose values above 10^3 Gy, whereas with undoped and Ge-doped fibers the loss begins to increase again at dose values above 10^4 Gy. If dose values of 10^3 Gy will already be reached within some days or weeks, one should investigate whether the loss increase of undoped and Ge-doped fibers above 10^4 Gy could also be used for dosimetry.

(Ge+P)-doped fibers below saturation show an increase of attenuation (A) with dose (D) of the form $A \propto D^k$ with $k \approx 0.95$, whereas Ge-doped fibers above 10^4 Gy only have values around $k \approx 0.35$ (11), i.e., the radiation sensitivity will be distinctly lower. One therefore should rather measure the increase of attenuation with an optical power meter system as described in section 3.2 than with a less sensitive OTDR.

Another method could utilize the radiation-induced change of the refractive index (n). The light velocity in the fiber material (C_{mat}) is connected to the light velocity in a vacuum (C_{vac}) by the equation $C_{mat} = C_{vac}/n$. I.e.: A change of the refractive index changes the light velocity in the fiber. A dosimeter for high dose values that is based on this effect could be a fiber optic Mach-Zehnder interferometer that consists of fibers and couplers. The light of a laser diode is split into two branches by a first coupler. One branch is exposed to the radiation, and then a second coupler recombines the two branches. Recombination of the two light paths leads to interferences that have to be analyzed. Increasing the radiation-exposed fiber length can increase the sensitivity of the device. It can be calibrated at a radiation source of known activity.

4. Properties of dosimetry fibers

For the realization of the different fiber optic radiation sensor solutions described in sections 2.2, 3.1, 3.2, and 3.3 the best-suited fiber types have to be choosen.

4.1 Fibers for OTDR and optical power meter systems

A necessary precondition for an extended, large-scale fiber optic radiation sensor system is a reasonable price for the necessary components. So it seems to be impossible to base a system on the extremely radiation sensitive Rare Earth doped single mode fibers mentioned in section 1. They still have prices up to about 30 DM/m, so that one cable along TESLA would cost more than one million DM.

A good choice seem to be Ge-doped telecommunication fibers co-doped with P. Their radiation sensitivity is distinctly higher than that of fibers which are only doped with Ge, and their radiation-induced loss anneals much slower. Consequently, they show a more linear increase of loss with radiation dose.

As with all fibers their radiation-induced attenuation increases from a minimum around 1100 nm especially towards shorter wavelengths, leading to an about 5 times higher loss increase at 850 nm than at 1300 nm.

Therefore, we propose a (Ge+P)-doped MM GI fiber of 50 µm core diameter. It should be optimized for 850 nm with respect to its bandwidth. With 50 µm diameter the bandwidth usually is distinctly higher than with the also available MM GI fibers of 62.5 or 100 µm core diameter. These show a higher "mode dispersion", i.e., an originally very narrow laser pulse from the OTDR will be broadened along the fiber, so that the local resolution of the dosimetry system will decrease. The table below shows the broadening of laser pulses with different width by fibers with different bandwidth along fiber sections with a length of 0.33, 1 and 5 km, respectively.

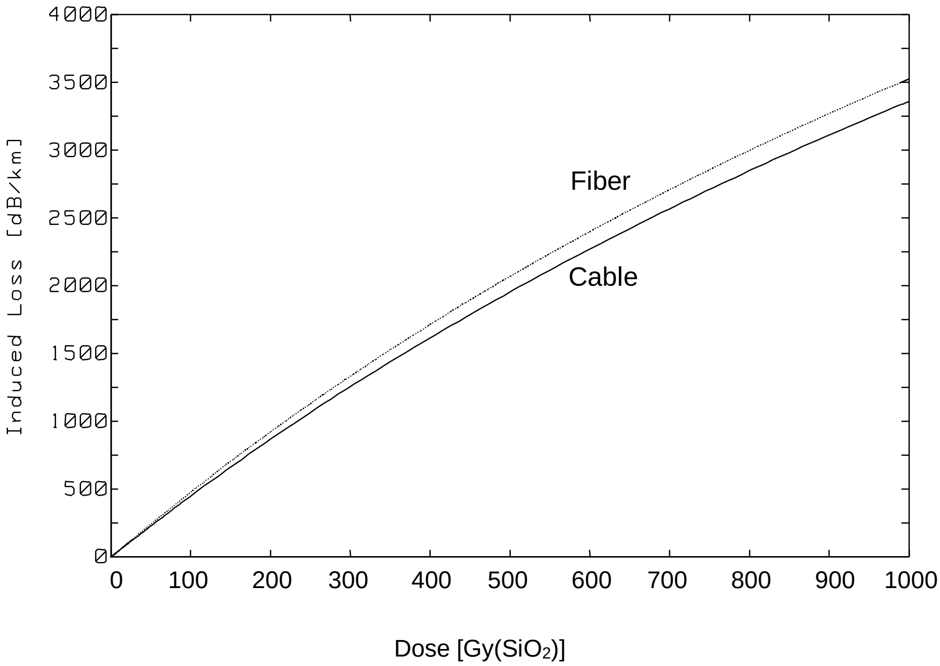
Bandwidth [MHz·km]	Pulse Width, FWHM [ns]								
	after 0.33 km with an initial pulse width of			after 1 km with an initial pulse width of			after 5 km with an initial pulse width of		
	0.2 ns	1 ns	3 ns	0.2 ns	1 ns	3 ns	0.2 ns	1 ns	3 ns
250	0.62	1.16	3.06	1.77	2.02	3.48	8.80	8.86	9.30
800	0.27	1.02	3.01	0.59	1.14	3.05	2.76	2.93	4.07
1500	0.22	1.00	3.00	0.35	1.04	3.01	1.48	1.78	3.34

To avoid excessive pulse broadening the fiber bandwidth should be at least 800 MHz·km. With a bandwidth of only 250 MHz·km 1 ns pulses will, e.g., have twice of their length after 1 km, and 3 ns pulses will have a length of > 9 ns after 5 km. I.e., more distant structures would be measured with strongly reduced local resolution. The bandwidth unit [MHz·km] means that data transfer with a frequency of e.g. 800 MHz is possible over a distance of 1 km or with only 400 MHz over a distance of 2 km, caused by the pulse broadening along the fiber.

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

The loss increase at about 830 nm of bare and cabled fiber during irradiation by a ^{60}Co gamma source, and the loss annealing after the end of irradiation are shown in Fig. 3. Both have the same radiation response (within the measurement accuracy), as expected, so that the necessary radiation dose calibrations can be facilitated by using a bare fiber. The loss annealing after the end of irradiation is a little bit faster as with the best of the so far investigated fibers. Therefore, the increase of loss with dose is less linear. Nevertheless all tests that are necessary to prove an OTDR-based fiber optic dosimeter system for TESLA can be performed with this fiber. These tests will also include the determination of the minimal detectable dose, for 850 nm as well as for 1300 nm, and with all pulse widths of interest. For TESLA one could select the best fiber samples of that type which are on stock or will be produced. It is still impossible to reproduce exactly a certain fiber sample, especially when the fibers have to be made radiation-sensitive by co-doping with P.

All fibers show a saturation of their radiation-induced loss, as already outlined in section 2.3. With (Ge+P)-doped MM GI fibers saturation sets in above about 1000 - 3000 Gy(SiO_2), as shown in Fig. 4 with a fiber made by the same manufacturer (FiberCore Jena) as that for the present investigations. This is the upper dose limit for a fiber optic dosimetry system based on measurement of the radiation-induced light attenuation. A dose of 1000 Gy is not to be expected for TESLA, as outlined in section 5, since the sensor fibers will be installed at least one or two meters away from the beam line.



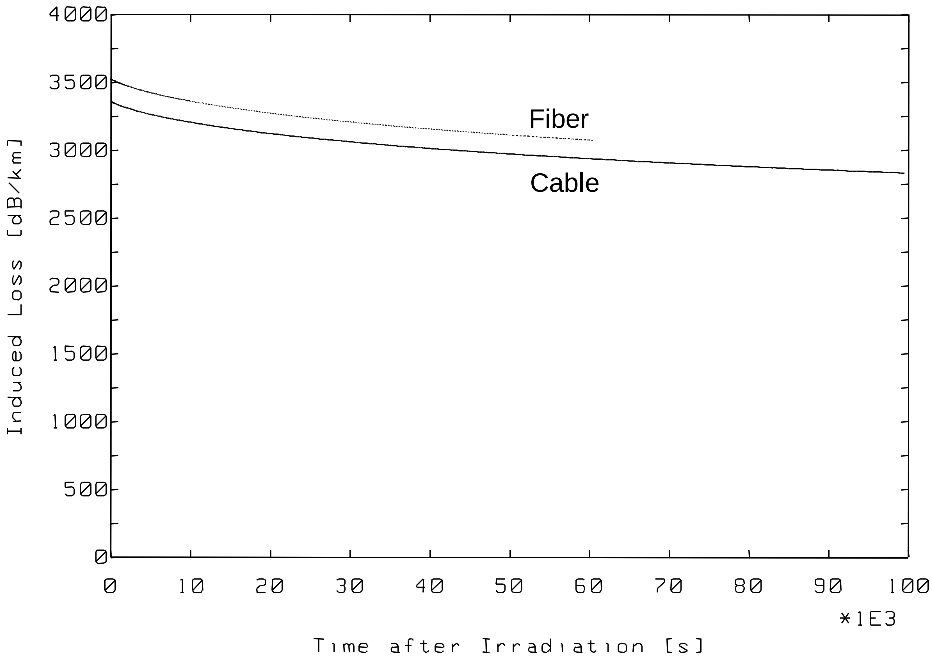


Fig. 3: Increase of attenuation during (above) and its annealing after irradiation (below) of the MM GI fiber FiberCore N1001269E and the cable (diameter 3 mm) made of this fiber. Measuring wavelength 829 nm; ^{60}Co gamma dose rate 0.047 Gy(SiO_2)/s; Room temperature.

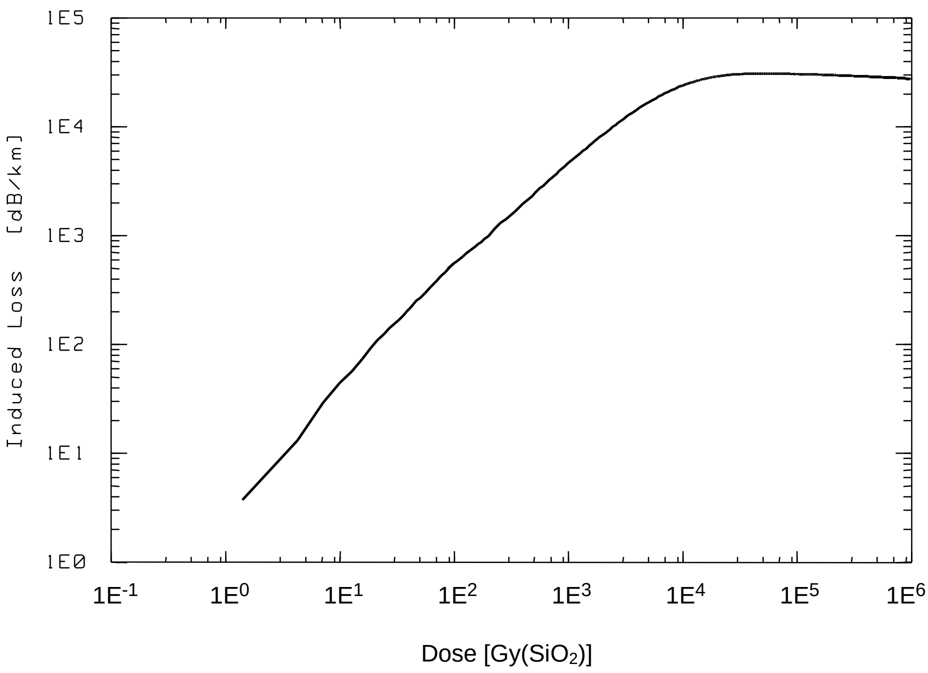


Fig. 4: Loss increase with dose of the fiber FiberCore N2900107GA during ^{60}Co gamma irradiation with a dose rate of 1.43 Gy(SiO_2)/s. Measuring wavelength 829 nm, Room temperature.

For the present investigations at TTF the first fiber cables are laid directly on the beam pipe. Therefore, the dose rate will be orders of magnitude higher at some places, especially at the collimators, and a dose > 1000 Gy could be reached within unwanted short operation periods. Since it would be inconvenient or even impossible to replace the fibers by new ones every few months, it should be carefully investigated whether they could be regenerated, e.g., by bleaching out the colour centers with laser light of high intensity, as described by Gaebler et al (12).

Some first efforts with the fiber used for the measurement of Fig. 4 have shown that regeneration of this fiber type would be very difficult or even impossible in the accelerator environment. The reason is that fibers that are suitable for dosimetry must have very stable colour centers. One meter of that fiber 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 fiber 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. 5). This is quite encouraging, but on the other hand it is obvious that it would be impossible to heat up all dosimeter fibers along TESLA up to 150 °C. These investigations will be continued with laser light of shorter wavelength and higher intensity.

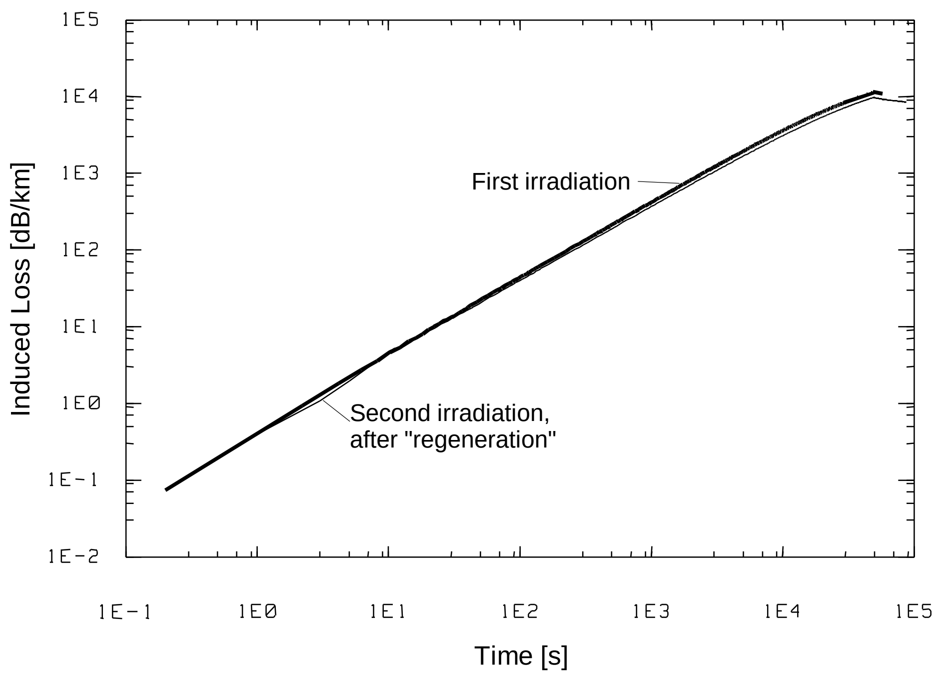


Fig. 5: Behavior of a fiber "regenerated" by heating and high power laser light during a second identical irradiation.

4.2 Fibers for luminescence light systems

Such fibers should meet the following requirements:

- The amount of light generated per unit fiber length should be as high as possible to increase the detection efficiency;
- A high percentage of the generated light should be conducted to the detector(s) at one or both fiber ends;
- The initial as well as the radiation-induced fiber attenuation should be as low as possible especially in the UV and in the visible wavelength range since the intensity of the Cerenkov light increases with $1/\lambda^3$ (λ = wavelength);
- The fiber bandwidth should be high in cases where the place of the light generation should be determined with high accuracy.

The best choice would be multimode step index (MM SI) fibers with undoped SiO_2 core of high OH content. They show the highest transmission in the UV and the lowest radiation-induced loss increase. Investigations of the Fraunhofer-INT have shown that their radiation sensitivity can be reduced dramatically especially in the wavelength range 450 -700 nm by a special high pressure hydrogen treatment, so that the decrease of the radiation detection efficiency during longer operation periods should be reduced.

The light yield per unit length increases with the fiber diameter. Usual core diameters are 100 µm, 200 µm, 300 µm, 400 µm and 600 µm. However, the fiber bandwidth decreases from about 20 MHz·km with a core diameter of 200 µm to values around 9 MHz·km for 600 µm. The bandwidth reduction (i.e. the pulse broadening) would be critical when longer accelerator sections shall be surveyed with one sensor fiber.

The conduction of a higher fraction of the generated light to the detector(s) can be achieved with fibers of higher Numerical Aperture (NA). The NA value increases with increasing difference between the refractive index values of core and cladding of the fiber. Fibers with a Fluorine-doped SiO_2 cladding have NA values around 0.2, whereas fibers with a polymer cladding can reach NA values of 0.37 - 0.4.

Details of a Cerenkov light detection system for TTF and TESLA can be found in (2).

4.3 Fibers for interferometer systems

For the realization of a fiber optic Mach-Zehnder interferometer, it is necessary (like in all interferometers) to superimpose two light components with fixed phase difference, (nearly) equal intensity and identical states of polarization. Hence, one has to use a single mode (SM) fiber with a cut-off wavelength below that of the used laser diode so that only one propagation mode is available. Identical and constant states of polarization can be ensured by the use of a polarization maintaining (PM) fiber. The light intensity from the irradiated branch should not decrease significantly during longer operation periods. Therefore the irradiated fiber length should be kept as short as possible. One of the radiation harder PM fibers that were developed for space applications (part of fiber amplifiers or fiber lasers of Free Space Laser Communication Systems) could be useful. On the other hand, it is not known so far whether radiation-resistant fibers would show smaller refractive index changes so that their irradiated length would have to be increased.

5. Concept of an OTDR dosimetry system at TESLA

Considering the data of sections 3.1 and 4.1, a proposal of a measurement system will be explained. The selected MM GI fiber has a linear region at least up to 1 kGy with a sensitivity of about 5 dB/(km·Gy). The actual estimation of the accumulated dose along the beamline is predicted to be 10 Gy/a so that the end of the linearity range along the beamline would be reached only after 100 years of operation. This value is not well known and is still under investigation.

Depending on the dynamic measurement range of the OTDR of only about 15 dB for the shortest pulse lengths, the maximum value of the product of fiber length and service life must be less than 15 dB/(5 dB/km·Gy)/10 Gy/a = 300 m·a. I.e., the OTDR traces shown in Fig. 2 will reach the noise level after one year of operation with a (homogeneously irradiated) fiber length of 300 m or after 2 years with 150 m. During longer accelerator shut down times part of the radiation-induced loss will anneal instead of growing further. Taking that into account, the maximum fiber length could be about 600 m when the fibers can be replaced by new ones every year or 300 m when the replacement can only be performed every two years. Fiber replacement would not be necessary when it would, e.g., be possible to anneal the radiation-induced loss by frequently injection of high intensity laser light, as described in section 4.1.

Instead of surveying the whole accelerator length or at least longer parts up to about 5 km length with one OTDR, the fiber sensor system has to be separated into sections of about 250 -500 m length. These sensor fiber sections can be connected with the OTDR via fibers of distinctly lower radiation sensitivity. In order to reduce the costs several of these sections could be read out with only one OTDR by means of an optical switch.

The local dose in specific positions (e.g. collimators) can be much higher than the average dose distribution. The beginning and the end of a sensor should not be placed in this region. If the sensor is connected with the system on one side only, the measurement behind a strongly irradiated area is impossible. Therefore, the sensor fibers should be connected with the ODTR system on both sides. This gives the possibility to measure behind a dark area.

For a given update rate of five minutes (which is the minimum of measurement time), a maximum of 12 sections can be measured in 1 h.

Based on these assumptions, the measurement set up for a group of six sections (covering an accelerator length of $\leq$ 3 km) is shown in Fig. 6. Up to about 10 of such configurations would be necessary to inspect the whole length of TESLA.

This measurement system can be optimized due to the requirements of the dose monitor system. The local computer is connected with the control system via the Ethernet. The IEEE- 488-bus connects the PC, the ODTR and the optical switch. Depending on the capacity of the Ethernet, the PC might be replaced by an Ethernet to IEEE-488-interface.

If a higher update time for each sensor can be tolerated, more than six sensors could be connected with one ODTR.

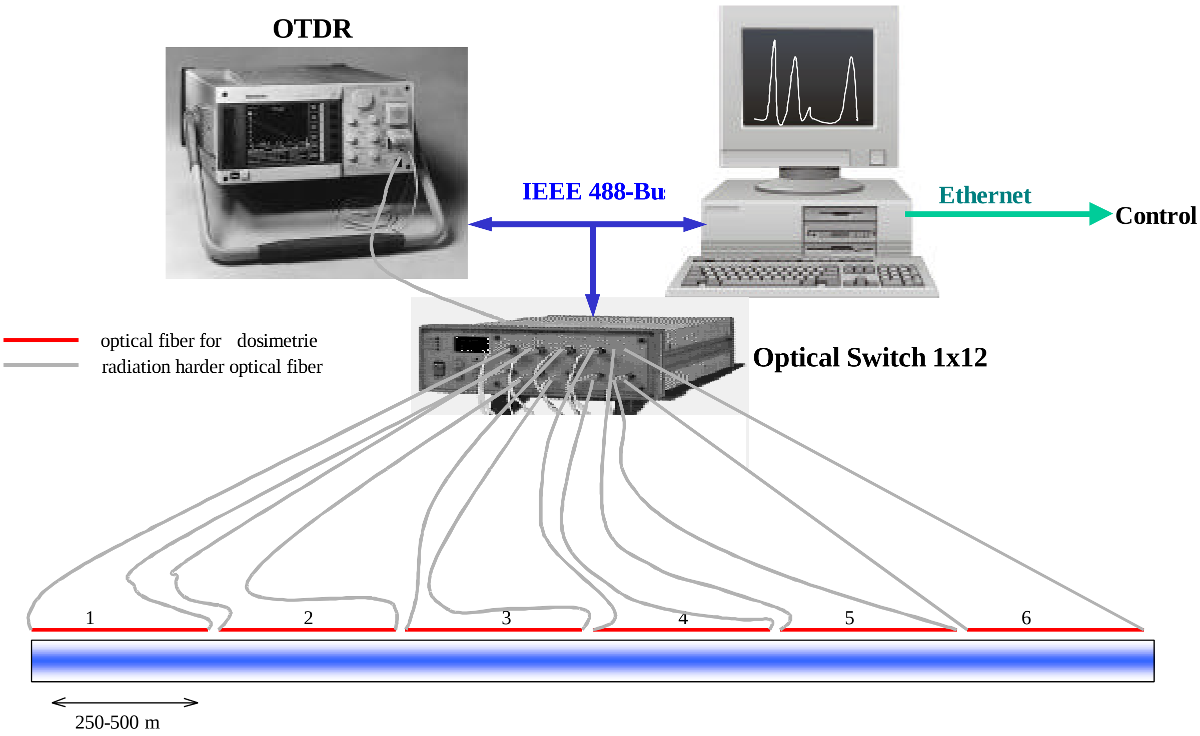


Fig. 6: Measurement set-up for a group of six sensor sections.

6. Conclusions

The preliminary tests at TTF (10) have shown that fiber optic radiation sensing systems for TESLA are possible. Different solutions are feasible for specific radiation measuring and monitoring purposes.

The main task would be a continuous dose measurement along the whole accelerator system. This can be verified by a certain number of OTDRs, each of them surveying an accelerator section of 1.5 - 3 km length. Sensitivity and operation time (before fiber replacement) can be adjusted by selection of wavelength and/or fiber type. The local resolution can be improved by selection of shorter pulse lengths - at the expense of dynamic range and surveyable accelerator length per OTDR.

A system based on the generation of luminescence (Cerenkov) light in optical fibers could be used for rapid accelerator switch-off in cases of dangerous high radiation emission somewhere along the LINAC.

The diameter of uncabled fibers of only 0.25 mm (unprotected) or 0.5 mm, respectively, allows, e.g., their insertion into the small gap between beam tube and undulator magnets. If the measuring range of the fibers of 1 - 3 kGy would already be reached there within a short time, the dose might be measured via the change of the refractive index of the fibers (interferometric) instead of via the increase of attenuation. Such a system could principally be applicable up to dose values of several MGy.

The present study at TTF is essentially focused on the installation of a prototype OTDR system. It is built up of a better one of the available commercial OTDRs and a fiber type that still can be found among the telecommunication fibers. Tasks to be solved are the dose calibration of the selected fiber (energy dependent), the development of the data evaluation software and the integration of this radiation sensing system into the control system of TTF. The experience gathered with this prototype system can be used for designing and planning a whole system of this type for TESLA.

In parallel it will be investigated whether it would be possible to "regenerate" the installed fibers in cases where the dynamic range of the OTDRs or the linearity range of the fibers is exceeded. This shall be tried by injection of high intensity laser light of shorter wavelength and/or heating up the fibers.

Furthermore, the development of a more "conventional" fiber optic dose measurement system for the undulator magnets and detectors will begin soon.

For TESLA it should be tried to obtain better suited OTDRs, with distinctly higher dynamic range. The best solution would be an improved version of that selected for the prototype system. Another task would be the careful selection of optimal dosimetry fibers out of a manufacturer's regular production, as well as the development of an interferometric fiber optic sensor for the high dose values expected, e.g., at the collimators and the detectors.

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