



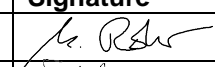
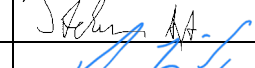
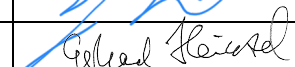
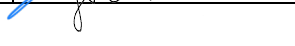
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Phase Reference Distribution System

2nd Fiber Irradiation Test Campaign

Test Report

N/Ref :	LISA-AEI-PRDS-RP-002
Title	PRDS 2nd Fiber Irradiation Test Campaign Test Report
Abstract	<p>The three LISA satellites will be subject to high doses of radiation during their nominal and extended mission lifetime.</p> <p>The PRDS backlink implementation choice is strongly dependent on the backscatter produced within optical fibers. A set of fibers has already been tested.</p> <p>This document reports on the second test campaign for a different set of fibers of different type/supplier. This second test campaign was performed to characterize these in terms of the backscatter levels in realistic conditions and to assess the compliance with the LISA requirements.</p>

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Document Change Record

Ver.	Date	Authors	Description	Pages
1	2021-04-19	J. M. Rohr	Initial release	16

Distribution List

Internal Recipient	Organization	External Recipient	Organization
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Applicable Documents

- AD 1 *LISA Mission Requirements, ESA-L3-EST-MIS-RS-001_L3*
- AD 2 *ESA Environmental Conditions, ESA-L3-EST-MIS-SP-001, ESA-TEC-SP-006666*
- AD 3 *System Engineering General Requirements, ECSS-E-ST-10C, Issue 3, 06/03/2009*
- AD 4 *LISA – Mission Analysis Guidelines, ESA-L3-ESOC-MIS-TN-001, June 2017*

Reference Documents

- RD 1 *“LISA Consortium List of Acronyms”, Jens Reiche, Version 0.001, Date: 08th February 2018*
- RD 2 *“LISA Pathfinder Technology Package- Preparation of Particle Irradiation Tests of OHARA S-PHM52 Optical Glass Windows”, Technical Note, S2-DLR-TN-3001, 11. July 2005, Issue 1, Re. 1*
- RD 3 *Total Dose Steady-State Irradiation Test Method, ESCC 22900*
- RD 4 *M. A. Xapsos, G.P. Summers, J.L. Barth, E. G. Stassinopoulos and E.A. Burke, “Probability Model for Cumulative Solar Proton Event Fluences,” IEEE Trans. Nucl. Sci., vol. 47, no. 3, pp 486-490, 2000.*
- RD 5 *LISA PRDS Fibre Irradiation Test Procedure (1st Test Campaign), LISA-AEI-PRDS-TP-001*
- RD 6 *ESCC 22900 Total Dose Steady State Irradiation Tests*
- RD 7 *LISA-AEI-PRDS-RP-001 PRDS Fibre Irradiation Test Report*
- RD 8 *LISA-AEI-PRDS-TP-002 PRDS Fibre Irradiation Test Procedure 2nd Test Campaign*

Abbreviations and Acronyms

LIG	<i>LISA Instrument Group</i>
LISA	<i>Laser Interferometer Space Antenna</i>
PRDS	<i>Phase Reference Distribution System</i>
TDI	<i>Time Delay Interferometry</i>
TID	<i>Total Ionizing Dose</i>
UCL	<i>Université catholique de Louvain</i>



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1. Introduction

The three LISA satellites will be subject to high doses of radiation during their nominal and extended mission lifetime.

Any PRDS implementation utilizing fibers is subject to Rayleigh scattering within these which results in a parasitic signal in the backwards direction. This causes a ghost beam on the optical bench resulting in undesired, excessive phase noise.

Concepts to address this exist and a previous study (see *RD 7*) has shown that for the fibers tested at that time exposure to ionizing radiation is not worsening the backscattered signal. The previous tests were performed with gamma and neutron radiation. This document reports on the second irradiation campaign testing the Nufern fibers for replacing the fibers tested in *RD 7*.

2. Test Objectives and Criteria

The main effect of ionizing radiation on optics is the production of color centers. The radiation produces electrons which populate defects in the glass matrix. These lead to absorption in the energy gap and therefore to a darkening of the optical material. Additional effects are the change of the index of refraction, the production of light (fluorescence, luminescence, scintillation), and surface effects at optical boundaries.

With regards to the backscatter it was found in previous studies that the currently measured levels (around 4-10 ppm/m of optical power reflection at 1064nm) are consistent with Rayleigh scattering that is coupled into a back-reflection mode by the acceptance angle of the fiber. Hence, it is feasible that typical fiber radiation damages might increase this level of backscatter, but no experimental studies that directly measure this are available. However, many irradiation experiments indicate that losses in PM fiber increase and under the hypothesis that the backscatter is driven by the same mechanism (Rayleigh scattering) an increase is expected. However, the fibers tested in *RD 7* did not show this behavior.

The radiation tests have the following objectives:

1. Characterize the fibers with respect to their increase of backscatter resulting from exposure to ionizing radiation. This requires that the fibers will be exposed to increasing radiation with intermittent performance measurement. There are no relevant criteria except that the results shall provide information on degradation versus radiation dose.
2. Determine the effects of annealing on the backscatter and degradation with typical optical power levels expected in LISA. Ideally the radiation damage is partly reversed by continuously sending light through the fiber with about 1mW of power.
3. Determine the capability of the fibers to sustain the applicable radiation dose without degradation beyond the required limits. If the limits cannot be achieved, alternative solutions or provisions for mitigations must be defined.

In particular, it shall be verified, if the Nufern PM1060L will have sufficiently low backscatter and that potential degradation under ionizing irradiation will not occur. The feed fiber from laser head to optical bench is supposed to use the 8.5 μm fiber from Nufern (PM1060L) as the use of the previously tested 6.6 μm fibers might result in stimulated Brillouin scattering. To decrease the required effort in development and verification of the FIOS, the PRDS shall also use these fibers if the relevant performance parameters allow the use. In addition, a fiber of 10.5 μm core diameter shall be tested in the same manner as this fiber (Nufern FUD-3561) is a candidate for use in the laser head.



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3. Experimental Design

3.1. Test Method

The Total Ionizing Dose (TID) experienced during the LISA mission will be simulated using a Cobalt-60 isotope (⁶⁰Co) as a source of gamma radiation and a Proton-generator (or particle accelerator) as a source of Proton radiation.

Information on the applicable radiation environment is provided in RD5 (1st Test Campaign).

The irradiation tests will be performed in accordance with RD6 (ESCC 22900).

Each test will be performed alternating irradiation and performance test with increased radiation dose from step to step.

Annealing effects will be considered, and it will be checked re-measuring the fibers after some hours/days. Annealing in this context describes a partial recovering from a radiation induced backscatter increase of the fiber. The annealing is time dependent and is increasing with temperature. It increases with the laser power inside the optical fiber and will thus be small for the LISA backlink. Since the temperature environment for the optical fiber backlink in the LISA satellite will be around room temperature, an annealing effect on the radiation damage is expected. Optical annealing via the laser light in the fibers will also contribute to this.

To substantiate the data, a wide range of irradiation is covered in order to ensure that there are no other effects that have not yet been considered, like some steep effects that start only at a certain dosage level. This follows the approach performed in the first test campaign.

3.2. List of fibers

In this campaign 36 fibers have been tested, 18 of each type. Table 3-1 lists all fibers used in this test with the target exposures and their configuration. FC/APC connectors were chosen to connect the fibers to the performance measurement setup. These prevent that a reflection at the fibers end face enters the optical path of the backscattered signal. Two fiber types have been tested: PM1060L and FUD-3561, both supplied by Nufern. Both fiber types have been tested in three different configurations: As 4 m long "bare" fiber, as 4 m "spliced" fiber with the splice in the middle of the fiber and as a combination of two 2 m long fibers with a "connector" in the middle.

Table 3-1 List of all fibers which have been tested in this campaign including the target exposures and the configuration of the given fiber. Exposures for gamma radiation are in krad and for protons in 1/cm².

Fiber	Type	Config.	Radiation	Exposure	Comment
R1-A	PM1060L	Bare	None		Reference
R1-B	PM1060L	Spliced	None		Reference
R1-C	PM1060L	Connector	None		Reference
R2-A	FUD-3561	Bare	None		Reference
R2-B	FUD-3561	Spliced	None		Reference
R2-C	FUD-3561	Connector	None		Reference
G1-A	PM1060L	Bare	Gamma	20 – 40	
G1-B	PM1060L	Spliced	Gamma	20 – 40	
G1-C	PM1060L	Connector	Gamma	20 – 40	
G2-A	PM1060L	Bare	Gamma	20 – 40 – 60 – 100 – 1000	
G2-B	PM1060L	Spliced	Gamma	20 – 40 – 60 – 100 – 1000	



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G2-C	PM1060L	Connector	Gamma	20 – 40	
G3-A	PM1060L	Bare	Gamma	20 – 40	
G3-B	PM1060L	Spliced	Gamma	20 – 40	
G3-C	PM1060L	Connector	Gamma	20 – 40	
G4-A	FUD-3561	Bare	Gamma	20 – 40 – 60 – 100 – 1000	
G4-B	FUD-3561	Spliced	Gamma	20 – 40 – 60 – 100 – 1000	
G4-C	FUD-3561	Connector	Gamma	20 – 40 – 60 – 100 – 1000	
G5-A	FUD-3561	Bare	Gamma	20 – 40	
G5-B	FUD-3561	Spliced	Gamma	20 – 40	
G5-C	FUD-3561	Connector	Gamma	20 – 40	Bad connection
G6-A	FUD-3561	Bare	Gamma	20 – 40	
G6-B	FUD-3561	Spliced	Gamma	20 – 40	
G6-C	FUD-3561	Connector	Gamma	20 – 40	
P1	PM1060L	Bare	Protons	1e10	
P2	PM1060L	Bare	Protons	1e10	
P3	PM1060L	Bare	Protons	1e10	
P4	PM1060L	Connector	Protons	1e10	
P5	PM1060L	Connector	Protons	1e10	
P6	PM1060L	Connector	Protons	1e10	
P7	PM1060L	Spliced	Protons	1e10	
P8	PM1060L	Spliced	Protons	1e10	
P9	PM1060L	Spliced	Protons	1e10	
P10	FUD-3561	Bare	Protons	1e10	
P11	FUD-3561	Bare	Protons	1e10	
P12	FUD-3561	Bare	Protons	1e10	
P13	FUD-3561	Connector	Protons	1e10	
P14	FUD-3561	Connector	Protons	1e10	One fiber shows about 50% transmission loss
P15	FUD-3561	Connector	Protons	1e10	
P16	FUD-3561	Spliced	Protons	1e10	
P17	FUD-3561	Spliced	Protons	1e10	
P18	FUD-3561	Spliced	Protons	1e10	Only 3m long, damaged during splicing

Due to travel restrictions imposed by the Covid-19 situation we had to alter the test strategy for the proton test to a de-risking approach. Therefore, the prepared fiber spools were shipped to Université catholique de Louvain (UCL) where the fibers were irradiated. After the radiation the spools were stored for nine days until the radiation emitted by the spools was below the background radiation. Thereafter, the fibers were shipped back to AEI and the performance measurements were done (ten days after the irradiation). This resulted in a reduced amount of data generated with the protons as the fibers were only exposed up to 1e10 1/cm² instead of doing a step at half of this value and at twice the value as planned before.

3.3. Setup for Performance Measurement

Similar to the first radiation campaign, the fibers have been radiated in batches disconnected from the test setup. Afterwards, the fibers were connected to the test setup using fiber couplers and the performance was checked. This has been done with minimal delay after the radiation step to minimize annealing effects. The measurements are performed using a heterodyne Mach-Zehnder interferometer. The optical setup of the test setup is shown in the following figures: Figure 3-1 shows the laser



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preparation of the test setup. Figure 3-2 and Figure 3-3 show the test setup in “calibration mode” and “backscatter mode”, respectively.

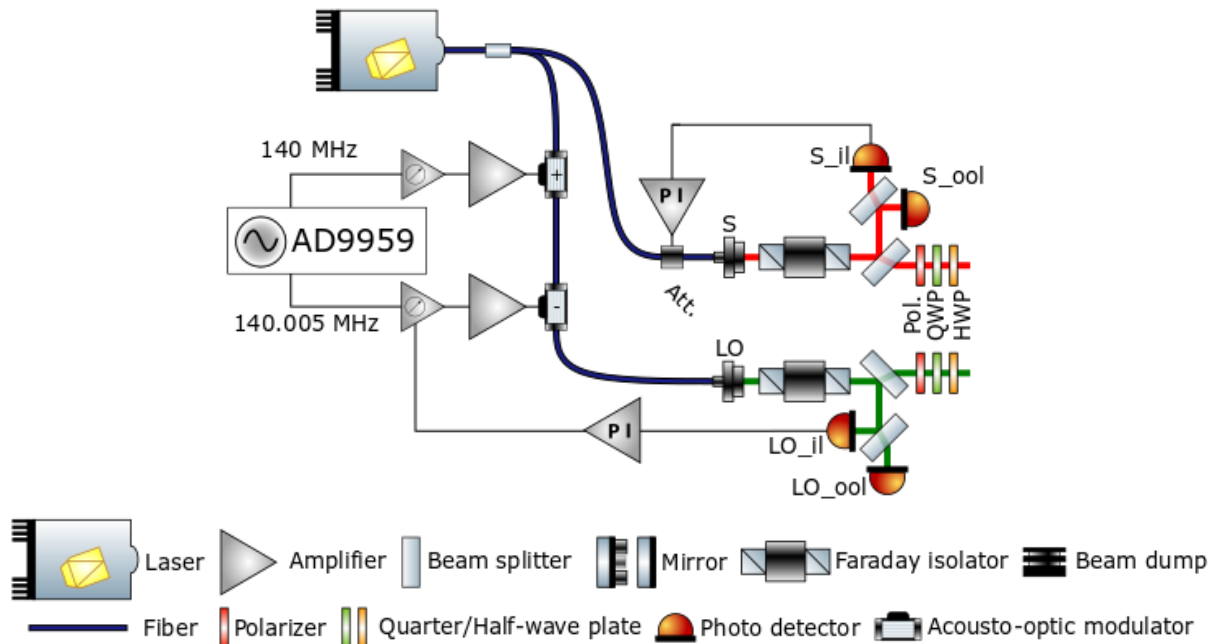


Figure 3-1 Laser preparation of the test setup. The light emitted by a Nd:YAG laser is split in two arms which are frequency shifted by 5 kHz using AOMs. Both beams are amplitude stabilized using a photo diode placed after the Faraday isolator.

The backscatter measurements were performed in several steps:

1. Connect the fiber under test to the test setup and optimize the fiber coupling.
2. Block the beam propagating to the forward end of the fiber under test (FUT-F) and optimize the contrast using the adjustable mirrors in the LO path.
3. Take calibration measurement (around 30 s), measure powers of the calibration beam on the BS x photo diodes.
4. Block the beam propagating to FUT-R and let the beam propagate to FUT-F.
5. (Optional) Optimize for contrast in the TX interferometer using adjustable mirrors.
6. Perform the backscatter measurement: Activate the temperature modulation of the fiber under test and take backscatter data (~3 min)
7. (Optional) Measure the required powers (TX, LO at the different positions) using a power meter
8. Disconnect the fiber under test.

The backscatter measurements have been performed at room temperature while the fiber coil is subject to a sinusoidal temperature modulation of ± 2 K around room temperature at a frequency of about 0.01 Hz, this modulation is achieved by detuning a PI temperature controller. This modulation was performed to achieve a worst-case estimate of the backscatter.



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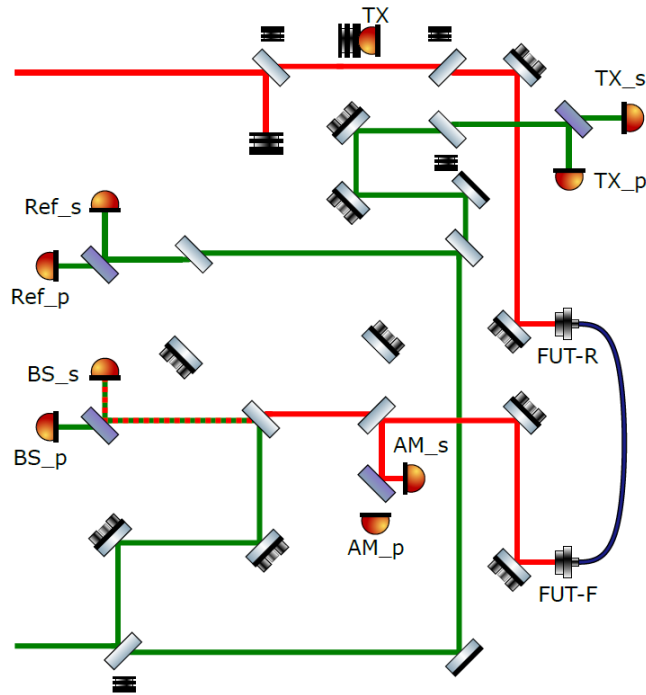


Figure 3-2 Optical paths in the calibration step.

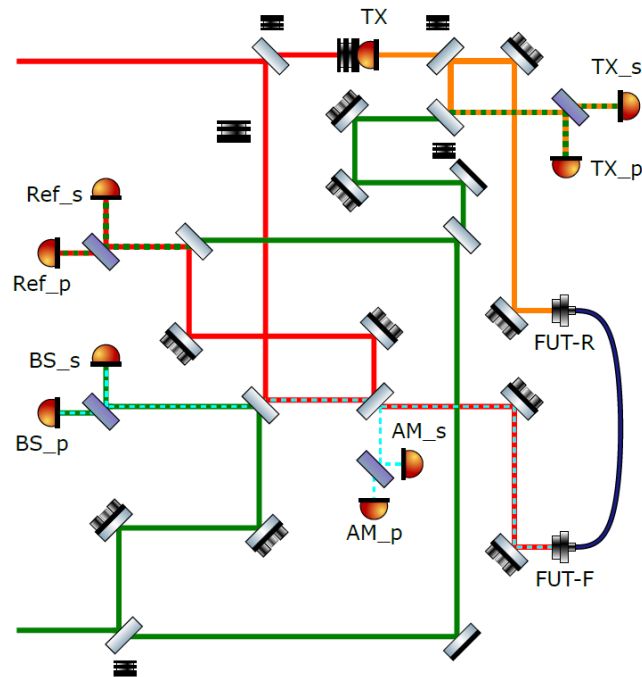


Figure 3-3 Optical paths in the backscatter measurement. The optional measurement with an amplitude modulation were not performed during this campaign.



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3.4. Radiation Facilities

The gamma irradiation was performed at ESTEC's Co-60 facility and the proton irradiation was performed at the Cyclotron Resource Centre at UCL. For both facilities the setup of the irradiation process is depicted in the following photographs.

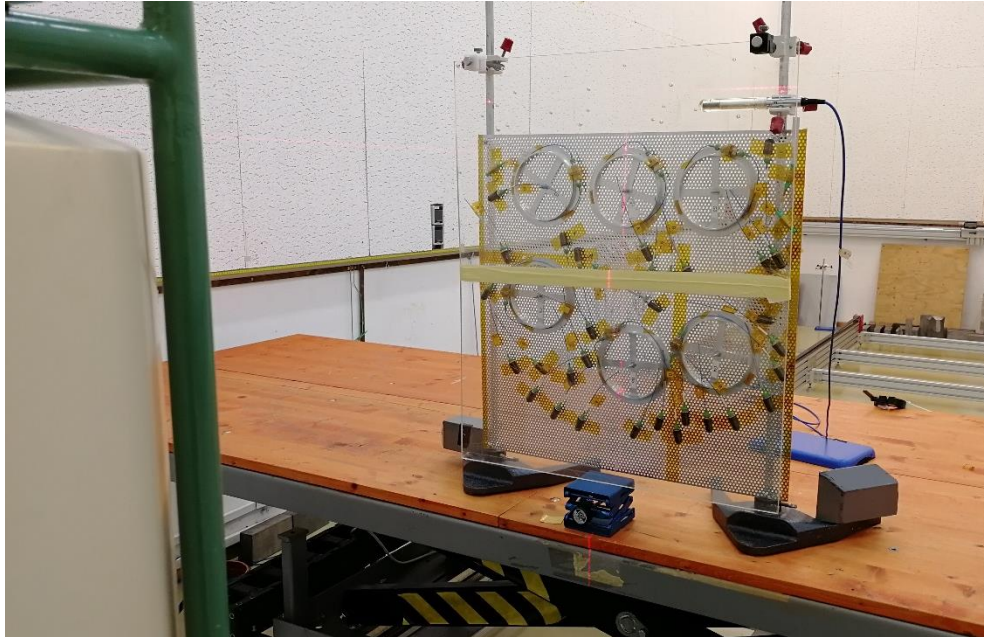


Figure 3-4 Irradiation setup for the exposure to gamma radiation at the Co-60 facility at ESTEC. On the left is the source and in the center are the fibers under test which are positioned such that the exposure is homogenous across the fibers.



Figure 3-5 Irradiation setup of the proton radiation. (Left picture) Alignment of the fiber spool to the center of the proton beam. (Right picture) Complete irradiation setup: On the left is the accelerator's exit, in the center the degraders to adjust the energy of the protons and to the right is the fiber under test (not visible here).
Photographs by UCL.



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4. Test Results

4.1. Gamma radiation

The results of the measurement for the fibers exposed to gamma radiation are depicted in the following plots (Figure 4-1 and Figure 4-2):

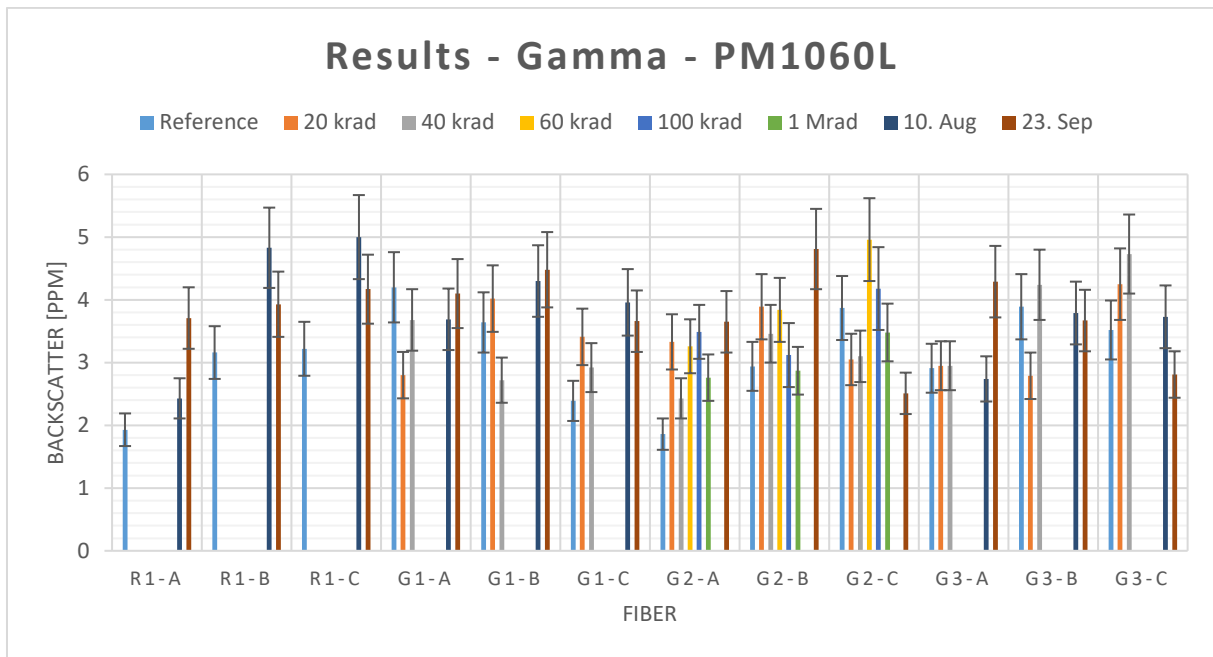


Figure 4-1 Results of the backscatter measurements of the PM1060L for the gamma radiation.

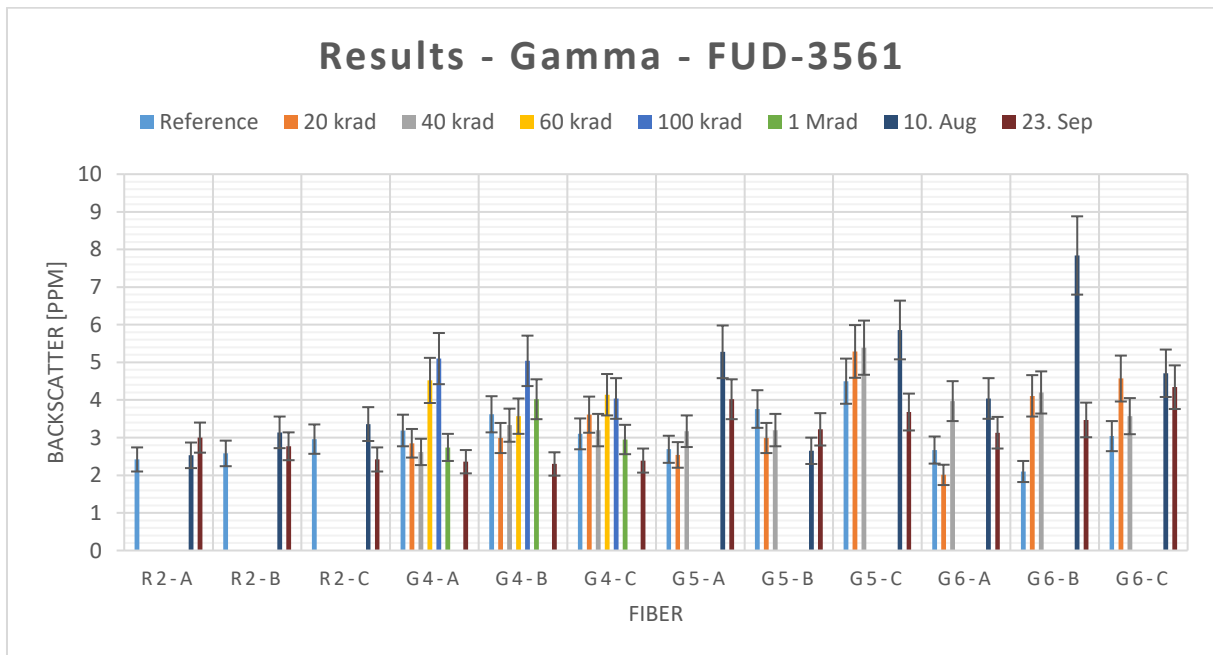


Figure 4-2 Results of the backscatter measurements of the FUD-3561 for the gamma radiation.



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For both fiber types (PM1060L and FUD-3561) the measurements show that the backscattered signal does not increase with the increase in exposure to gamma radiation. Furthermore, the measurements reveal that no annealing effects in neither direction were observed during the measurements at later times. The plotted error bars are the technical measurement error. Due to the random behavior of the scattering along the fiber the deviation between two measurements can be significantly higher.

The measured peak backscatter values are 4.3 ± 0.6 ppm for the bare fiber, 4.8 ± 0.6 ppm for the spliced configuration and 5.0 ± 0.7 ppm for the connectorized configuration using the PM1060L. Using the FUD-3561 the peak values are 5.3 ± 0.7 ppm, 7.8 ± 1.0 ppm and 5.9 ± 0.8 ppm, respectively, in the same configurations as before. For the spliced FUD-3561 the next higher observed peak over all measurements is 5.0 ± 0.7 ppm. We cannot exclude, for the measurement in question, that some dust settled on the fiber's face between cleaning and connecting it to the measurement setup. However, the measurement shows no signs of contamination and thus we cannot exclude this value.

Therefore, the length related values are <1.5 ppm/m for the PM1060L and <2.2 ppm/m for the FUD-3561 (In case one excludes the FUD-3561 measurement in question this would result in a backscatter-length dependency of <1.7 ppm/m).

The following figures, Figure 4-3 and Figure 4-4, show the average transmission measured alongside the backscatter measurements. These measurements also show no clear indication of a degradation over the increasing exposure as the transmission roughly constant. The general variance of the measurements is a result of manual optimization of the fiber coupling. G5-C shows excess transmission loss compared to the other fibers which is a result of an imperfect coupling between the two fibers.

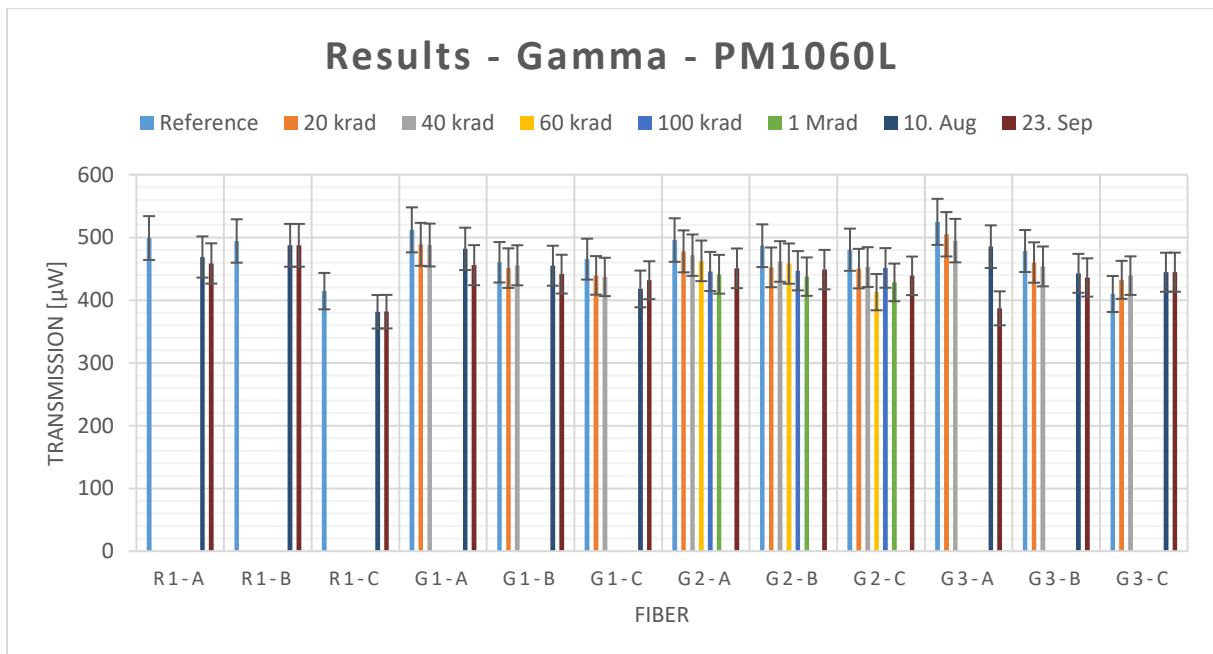


Figure 4-3 Transmission measurements during the backscatter measurements for the PM1060L fibers in the gamma test



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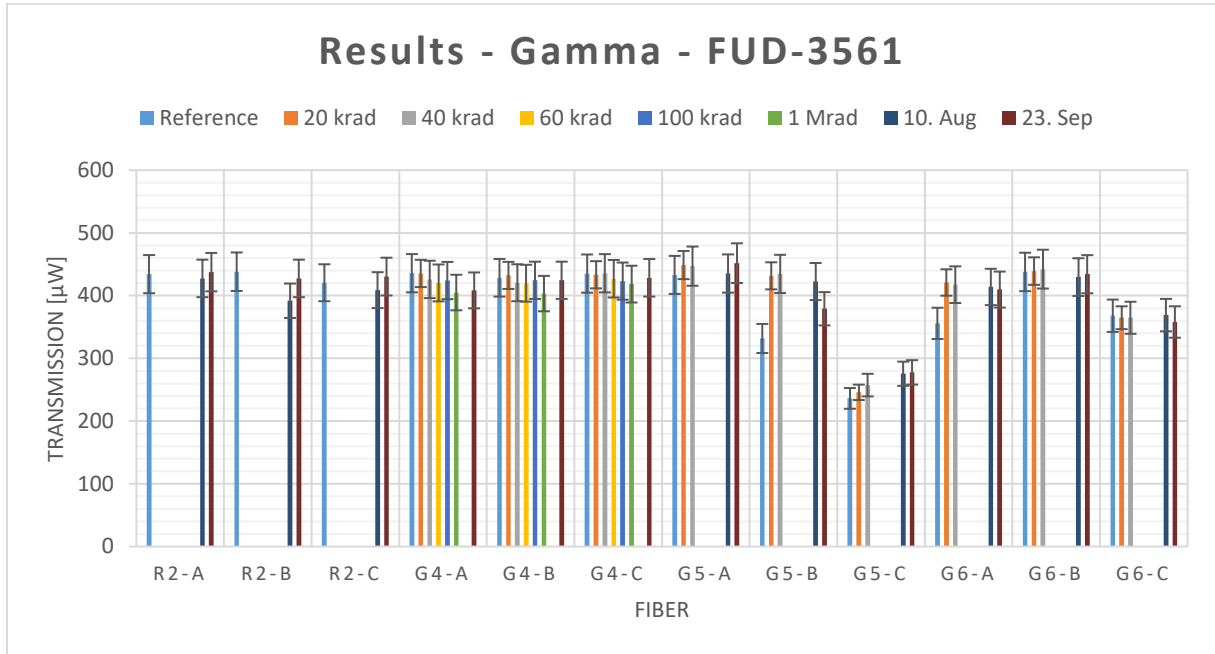


Figure 4-4 Transmission measurements during the backscatter measurements for the FUD-3561 fibers in the gamma tests.

4.2. Protons

Figure 4-5 and Figure 4-6 show the results of the backscatter measurements for the two fiber types in the protons test with a proton flux of $1e10$ 1/cm².

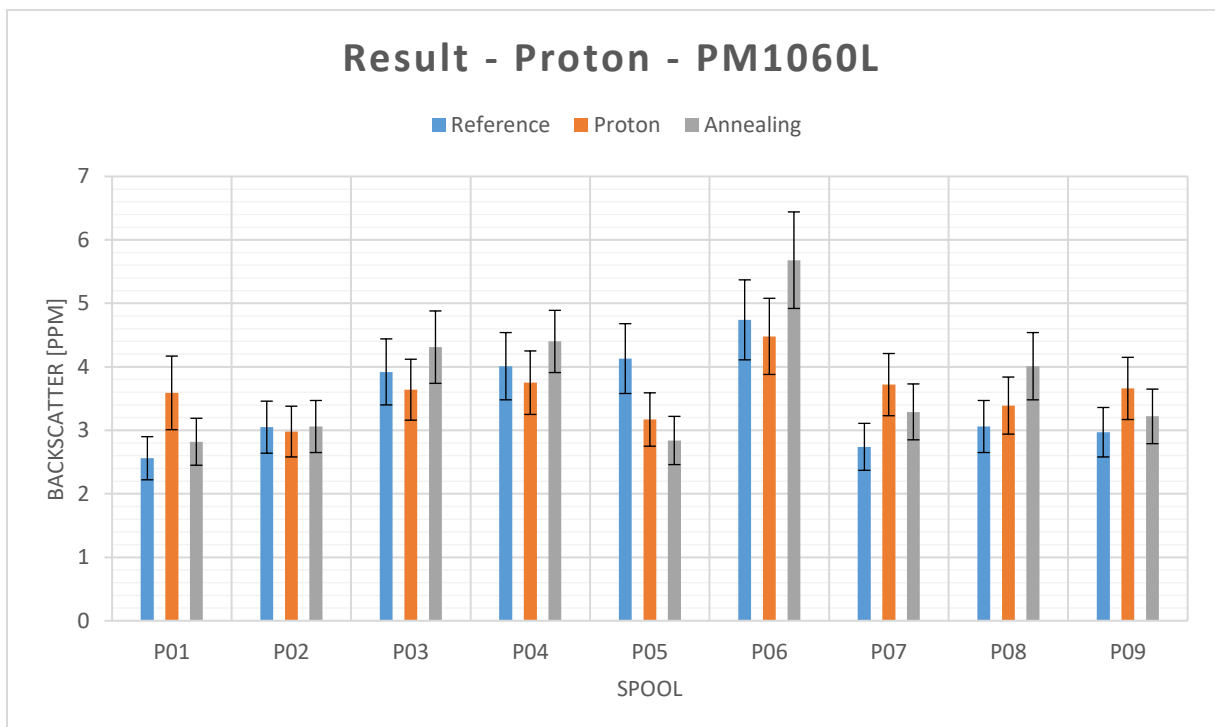


Figure 4-5 Results of the backscatter measurements with the PM1060L in the proton measurements.



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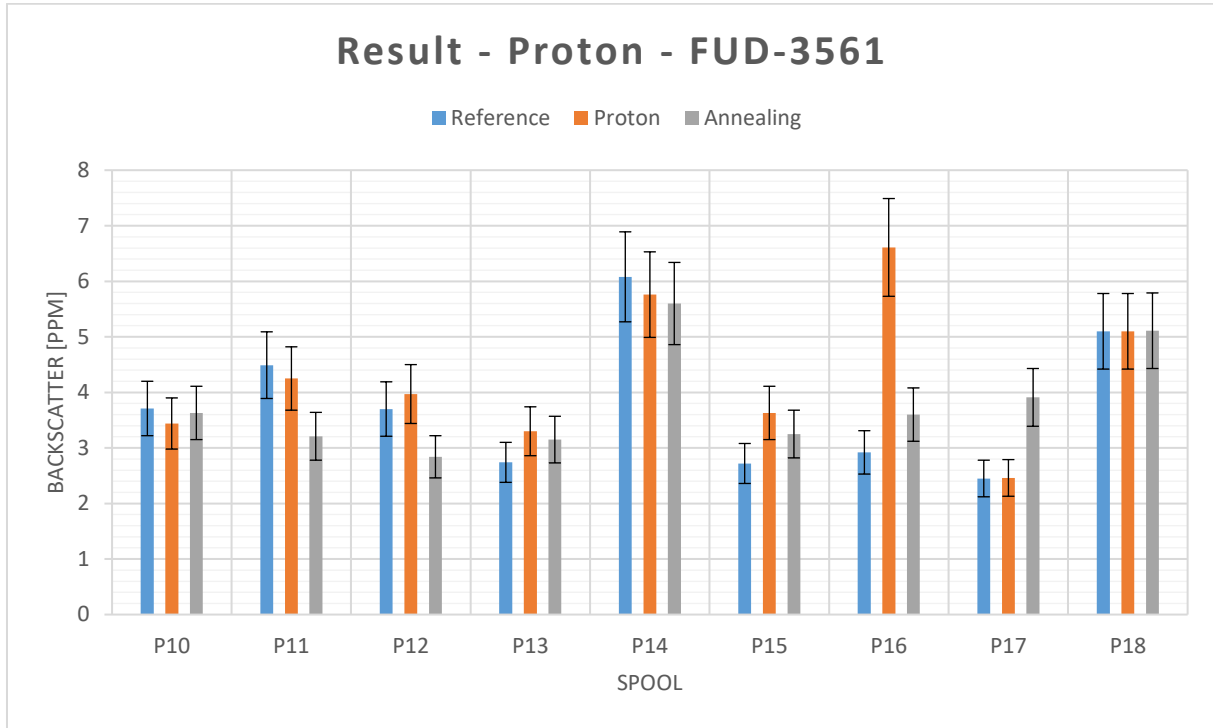


Figure 4-6 Results of the backscatter measurements with the FUD-3561 in the proton measurements.

The measurements reveal again no indication of a change in the backscatter parameters with peak values at 4.3 ± 0.6 ppm for a bare PM1060L, 4.0 ± 0.5 ppm for a spliced and 5.7 ± 0.8 ppm for a connectorized configuration. For the FUD-3561 in the different configurations the backscatter values are 4.5 ± 0.6 ppm, 6.1 ± 0.8 ppm and 6.6 ± 0.9 ppm, respectively. These values are the maxima of all proton-related measurement in the different configurations.

This results in length-related numbers of <1.7 ppm/m for the PM1060L and <1.9 ppm/m for the FUD-3561 in the proton measurements. The values measured with the imperfect configuration used in P14 which had excessive loss was still below other measurements in terms of backscatter.

The deviation in the results of the proton measurements and the gamma measurements is a result of the random scattering process. The changes of the backscattered power due to the changing of the scattering conditions (including the interference conditions between different color centers) results in a larger variance of the measured backscatter values.

Figure 4-7 and Figure 4-8 show the results of the transmission measurements belonging to the backscatter measurements above. Apart from the low transmission of P14, no peculiarities were observed, the transmitted power remained unchanged.



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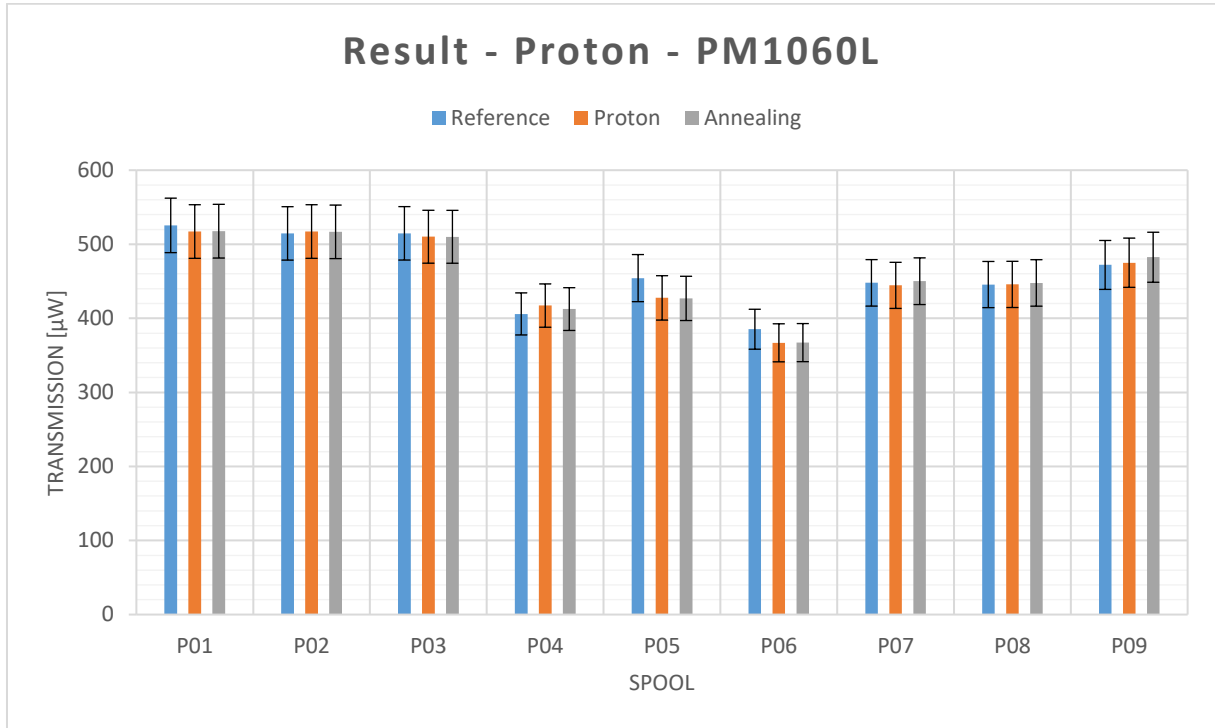


Figure 4-7 Transmission measurements for the PM1060L fibers during the backscatter measurements.

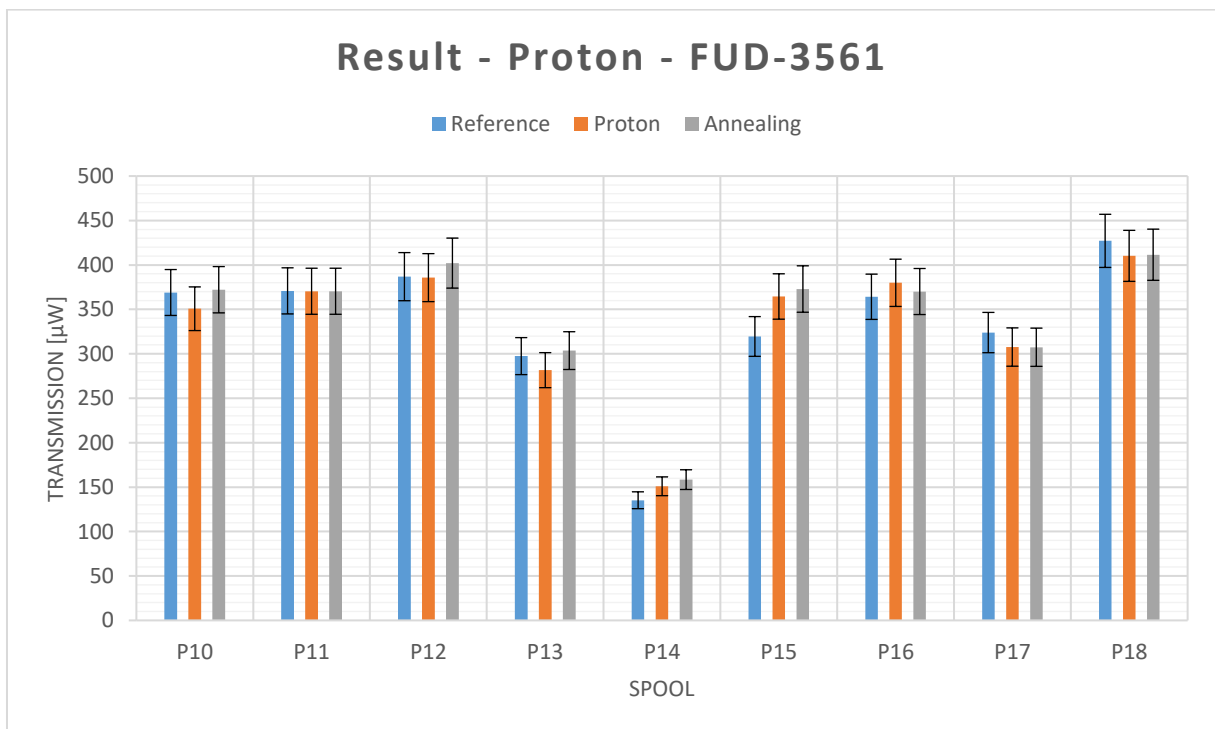


Figure 4-8 Transmission measurements for the FUD-3561 fibers during the backscatter measurements



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5. Conclusion

Combining the results of the gamma and proton test we can conclude that both fiber types (Nufern PM1060L and Nufern FUD-3561) are not degrading under the tested doses of ionizing radiation. Both types show no changes in backscattering nor transmission behavior.

On the conservative side we observe that we can expect less than 1.7 ppm/m of backscattering for the PM1060L and less than 2.2 ppm/m for the FUD-3561. Both fibers show less backscatter than the previously tested Fujikura fibers (< 7 ppm/m, *RD7*). Therefore, we can expect a gain in performance by changing the backlink fiber from the Fujikura one to the Nufern PM1060L. Although the performance is better than the performance of the Fujikura fiber the FUD-3561 is not a candidate for exchange in the backlink as this fiber is a multi-mode fiber and thus only used in the laser head. By comparing the results of the bare fibers to the results of the spliced / connectorized fibers we obtain that a splice or connector adds on average about 1 ppm of additional backscatter.

Therefore, the test criteria stated in chapter 2 and *RD8* are achieved: We verified that the backscatter level does not change over the exposure to ionizing radiation and obtained an upper level of backscatter to expect when using the tested Nufern fibers, as given above (criterion 1). Furthermore, we found no annealing effects in either direction. As the backscatter remained constant an improvement was not expectable and no degradation of performance after annealing was found (criterion 2). Due to the restrictions imposed by the outbreak of Covid-19 an alteration of the test was necessary and thus criterion 3 could only be fulfilled for the gamma test as no over-testing was performed for the proton test.

Acknowledgement

We would like to express our gratitude to Linda Mondin, Alessandra Costantino and Nancy Postiau for support in organizing and running the irradiation of the fibers at ESA's Co-60 facility and the proton source of UCL. Furthermore, we thank ESA (contract number 8586/16/NL/BW) and DLR (project reference numbers 50 OQ 0601, 50 OQ 1301 and 50 OQ 1801) for funding of this project.