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10W single-mode PM optical amplifiers in the 1.5-µm region for space applications

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ABSTRACT

MPB is developing space qualified 10 W End Of Life (EOL) optical amplifiers for longer range applications. Their design employs Polarization Maintaining (PM) Erbium and Erbium-Ytterbium Double Clad Fiber (EDF, EYDF) single-mode fibers. Absorption losses of the EDF and EYDF due to radiation in space are the major challenge to overcome. The gamma radiation tests show that the PM fibers have a greater sensitivity than standard fibers. However, in many applications, PM amplifiers show greater performances which is important for the power consumption.

Furthermore, MPB's design minimizes Stimulated Brillouin Scattering in the fibers, a major obstacle to be overcome at this power level, even for on ground applications. Moreover, the compatibility with space environment (vacuum, temperature cycling, and radiation) of the high-power optical and electronic components (isolators, laser-diode pumps, current drivers) has to be demonstrated.

The proposed optical designs compensate for radiation-induced losses, without resorting to the use of expensive radiation qualified fibers- a unique method of power recuperation through the photo-bleaching of the active fiber.

Keywords: Optical Amplifier, Optical Communication, Optical Intersatellite Link,

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1. INTRODUCTION

Proposed new space-borne large-coverage internet links, in the form of satellite constellations, are among the key drivers for significantly increased bandwidth capability of earth-orbiting satellites. In addition, the voluminous data-transfer requirements for various space missions being proposed for the Moon, Mars, deep space and Lagrange points, are enhancing the need for high-speed space data transmissions.

At present satellites rely on radio-frequency (RF) communications, which are a magnitude slower in moving data than optical fiber links. Free-space Optical (FSO) communication, or laser communication, is capable of providing the needed high-rate communication links. A key enabling technology of laser communication terminals (LCT) for space is the optical amplifier subsystem.

In addition to "real-time" telecom advantages, utilization of optical amplifier communications for downloading large volumes of acquired data from Earth Observation satellites equally will improve the magnitude and timeliness of data which is important in tracking the environment, weather, and climate change.

2. DESIGN

Major high power optical fiber amplifiers and lasers in the eye-safe -1.5 µm, are based on the cladding-pumped Yb-Er-co-doped fibers pumped into the Yb-absorption band. Our design follows this method: it is based on three stages where the first stage is using single-mode Erbium Doped Fibers (EDF). The second and third stage use double clad single-mode Erbium Ytterbium Doped Fibers (EYDF). The Polarization Maintaining (PM) version use PM-EDF and PM-EYDF.

A two-stage design has low flexibility in case of problems with a component in space and will increase the risk of more Stimulated Brillouin Scattering (see Section 3.4).

A four-stage design is more stable, however the device will take larger volume and mass, in particular when we are opting for redundant design.

Other designs are suggested in the literature. One interesting approach based on resonant cladding-pumped Yb-free Er-doped fibers was proposed in many space laboratories (NASA[1], CNES[2]). They hope to obtain higher plug-efficiency as well as power scalability due to very low quantum defect (QD) and, lower pump-induced heat deposition. We could not find recently published work showing this improvement.

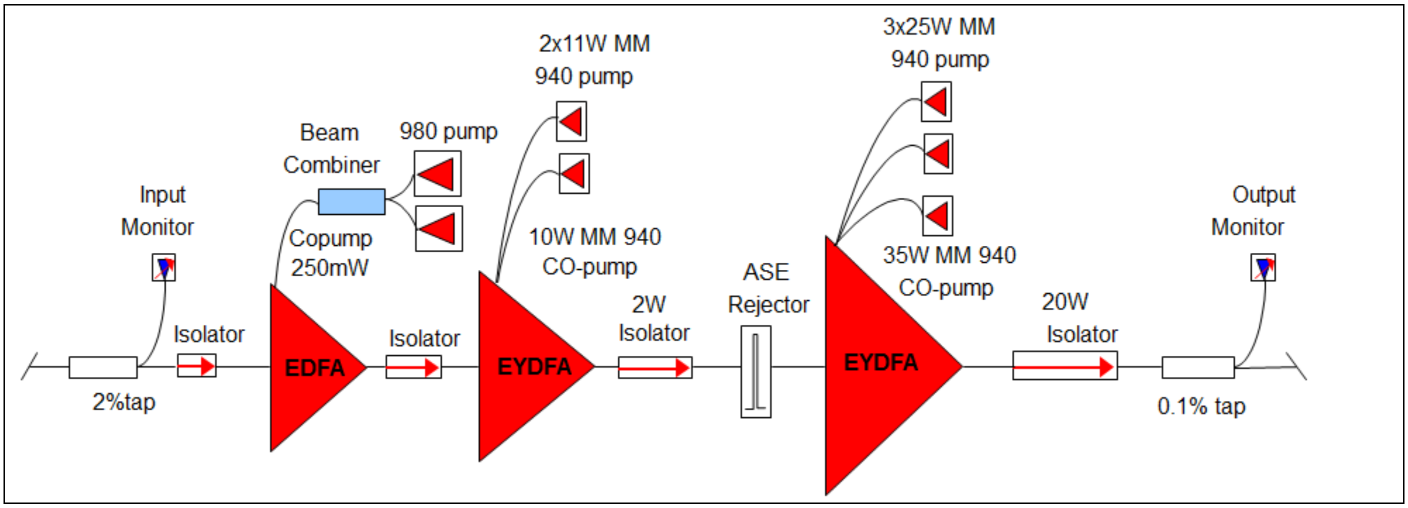

Figure 1. Schematics of the design with three stages, the calibration photodiodes at the input and output are not shown.

The nominal set is similar to the non-PM amplifier in the previous section: Source (first stage input) 1 dBm, the first stage output is 10-15dBm, the second stage output is 27-30 dBm, and the third stage output is 40 dBm. The source input can be between -3 dBm and 10 dBm. The design is flexible to permit to obtain an output level, in a continuous function, from of 1 W (30 dBm) up to 20 W (43 dBm), a factor of 13 dB in the functionality.

3. CHALLENGES

Various challenges are

- Radiation Effects on the EDF and EYDF fibers
- Stimulated Brillouin Scattering (SBS)
- Challenges in Fiber Selection
- Optoelectronics Laser diode pumps
- Photodiodes Dark Current
- Electronics with low sensitivity to radiation e.g. the 10 Amp electrical current drivers in the third stage

3.1 Radiation Effects on the Erbium, Erbium Ytterbium-doped fibers

Test with Co-60

MPB tested different kind of EDF, EDF-PM, EYDF and EYDF-PM fibers (Table 1) in three laboratories; Polytechnique/ Montreal, Alter/Spain and ESTEC/Netherlands). The first two tests at Polytechnique used Sc-46 radiation sources. The other tests were in laboratories using Co-60 calibrated sources. In all these tests we had at least one common commercial EDF fiber. The objectives of these tests were:

- Confirm the results using Sc-46 as a different source of the Co-60 commonly used
- Confirm the results using the different laboratories
- Compare the effects of the radiation dose (ESTEC1 with 363 rad/h, and ESTEC2 with 108 rad/h),

- Compare the losses of EDF and EYDF
- Compare the results of PM vs non-PM fibers

Most of the non-PM results were presented in a previous paper[3] presented at ICSO-2016. In this paper, we focus more on the progress made in high power amplifiers in particular with PM-fibers.

Table 1. Radiation Tests performed by MPB

Parameter	**Polytec-1**	**Polytec-2**	**ESTEC-1**	**ESTEC-2**	**Alter -1**	**ESTEC3**	**Alter-2**
Location	Montreal, Can.	Montreal, Can.	Noordwijk, Neth.	Noordwijk, Neth.	Sevilla, Spain	Noordwijk, Neth.	Sevilla, Spain
Radiation source	Sc-46	Sc-46	Co-60	Co-60	Co-60	Co-60	Co-60
Date	Jan. 2013	Jul.-Nov. 2013	May 2014	Nov.-Dec. 2015	Aug. 2016	Aug. 2017	June. 2018
Test Duration (Days)	20	129	12	43	23	13	23
Dose Rate (rad/h)	235	Deb:52 / Fin:18	363	108	215	344	210
Total Dose (Krad)	101.5	125.2	106.7	110.3	101	109.7	101
Measurements step*	30, 50, 100	30, 60 100,125	30, 100	100	30, 100	30, 100	10,30,60, 100
Total number of Fibers	4	3	22	25	15	15	
Standard EDF tested	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PM-EDF tested	No	No	Yes	Yes (more)	Yes	Yes	Yes
EYDF tested	No	No	Yes	Yes (less)	No	Yes	Yes+ YDF
PM-EYDF tested	No	No	No	Yes	Yes	Yes	Yes +PM-YDF

Experimental results- irradiation and photo-bleaching effect

The PM fibers are much more sensitive to radiation. For clarification, we call rad-hard fibers those that show a very low Gain loss (< 1 dB/100 krad). The fibers showing losses between 1 and 4 dB are called radiation tolerant

Table 2. Gain Loss and Recuperation of Radiation Tolerant (expensive) EDF-PM.

EDF-PM-Rad-Tolerant1: Gain before irradiation 21.5 dBm	50 krad	100 krad
After irradiation (passive during radiation)	3.04	3.92
After irradiation + 48 hours pumping	2.30	2.30
After irradiation + 144 hours pumping (6days)	1.70	1.95
After irradiation + 264 hours pumping (11days)	1.33	1.73

Table 3. Gain Loss and Recuperation of Commercial EDF-PM.

EDF-PM-COTS1: Gain Before radiation 22.12 (dBm)	100 krad
After irradiation	4.92
After irradiation + 10 minutes pumping	3.52
After irradiation + 15 minutes pumping	3.04

After irradiation + 24 hours pumping (11days)	0.77
After irradiation + 9 days pumping	0.54
After irradiation + 13 days pumping	0.51
After irradiation + 17 days pumping	0.50

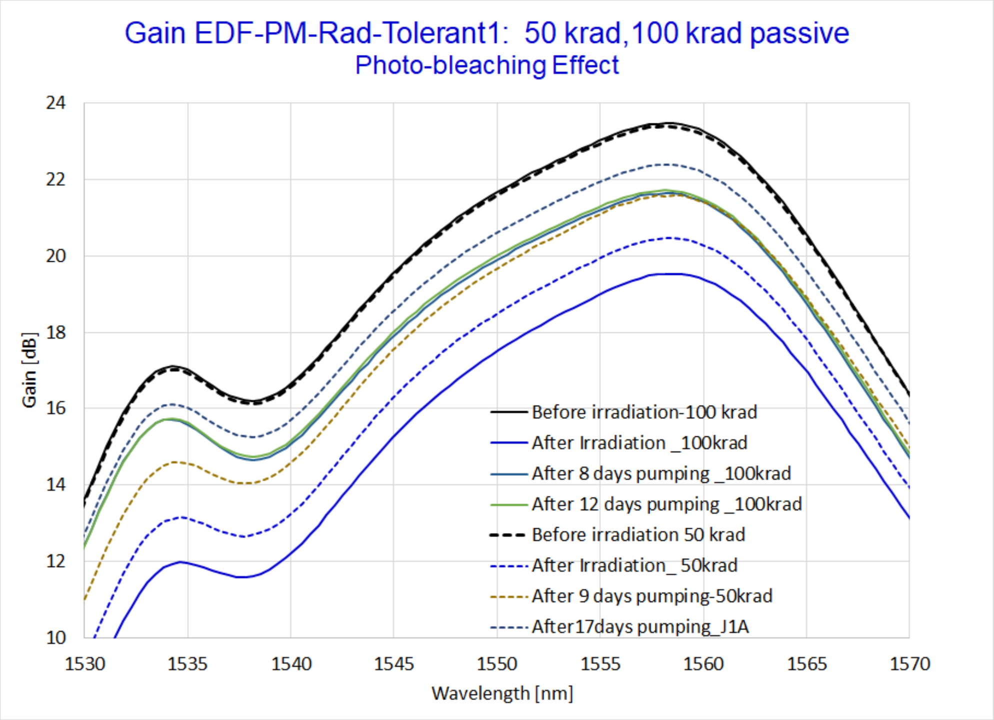

Figure 2. Radiation tolerant (expensive) EDF-PM-Rad-Tolerant1 Gain before and after radiation and post-pumping for bleaching

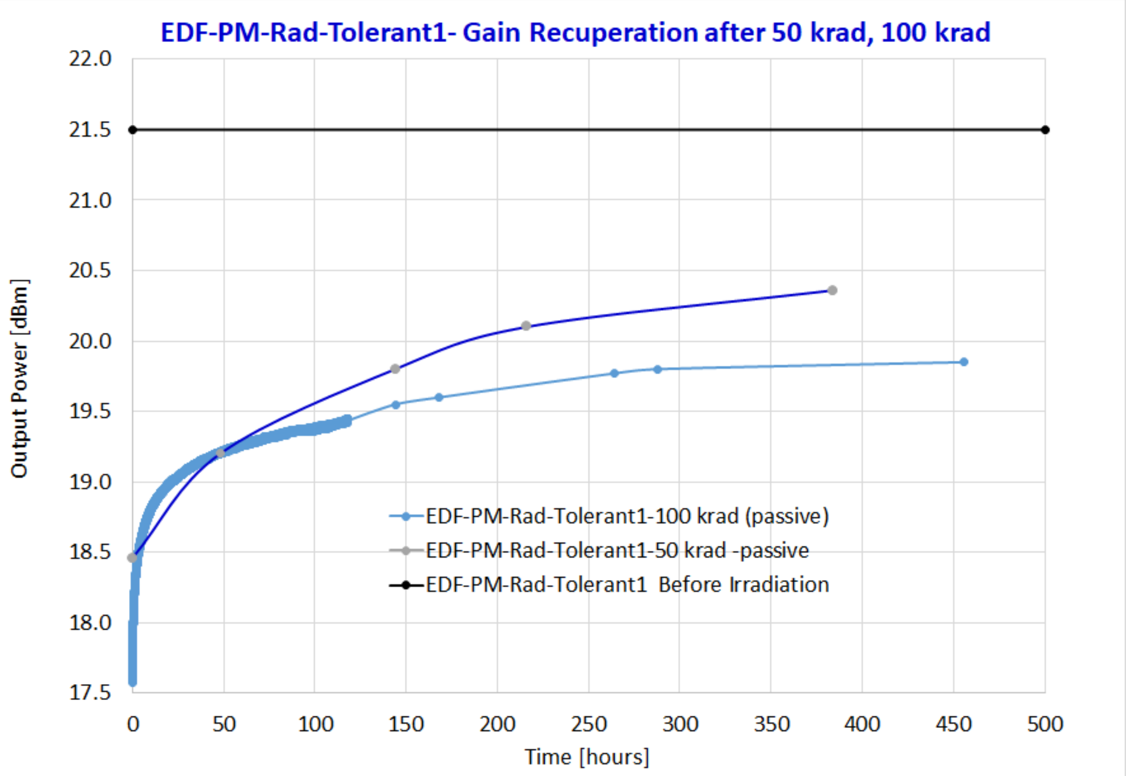

Figure 3. Radiation tolerant (expensive) EDF-PM-Rad-Tolerant1 Gain recuperation with pumping

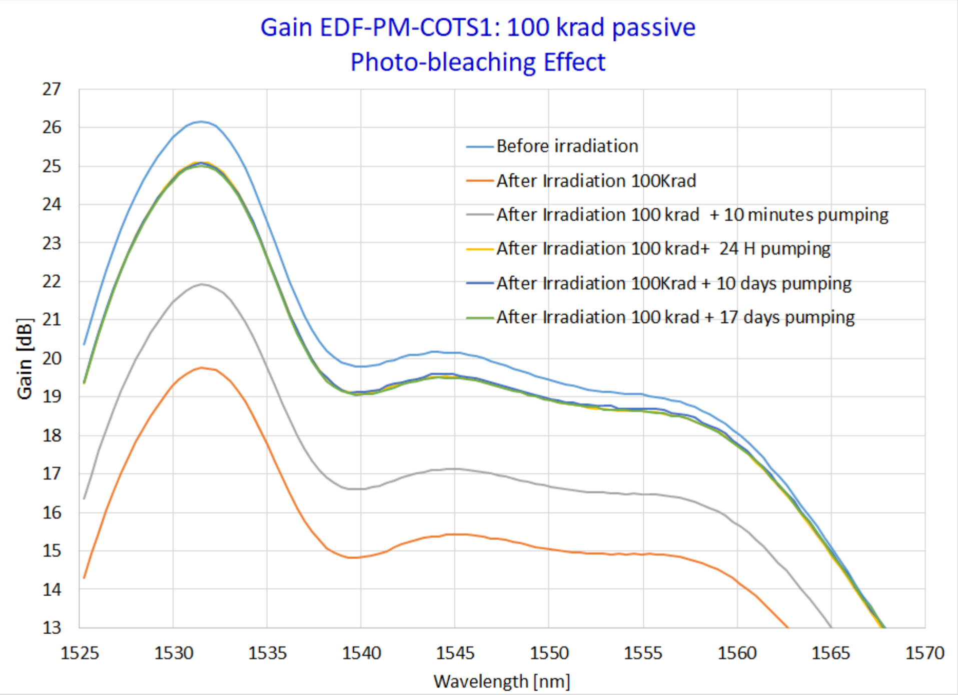

Figure 4. Commercial EDF-PM-COTS1 special core Gain before/after radiation and photo-bleaching

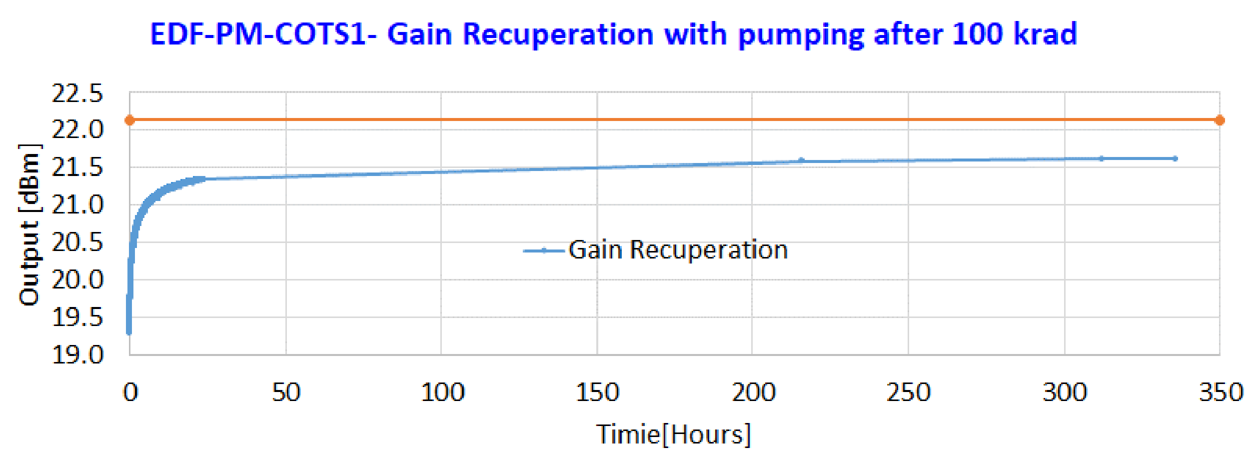

Figure 5. Commercial EDF-PM-COTS1 special core Gain recuperation by photo-bleaching

3.2 Universality of the Photo-bleaching Effects

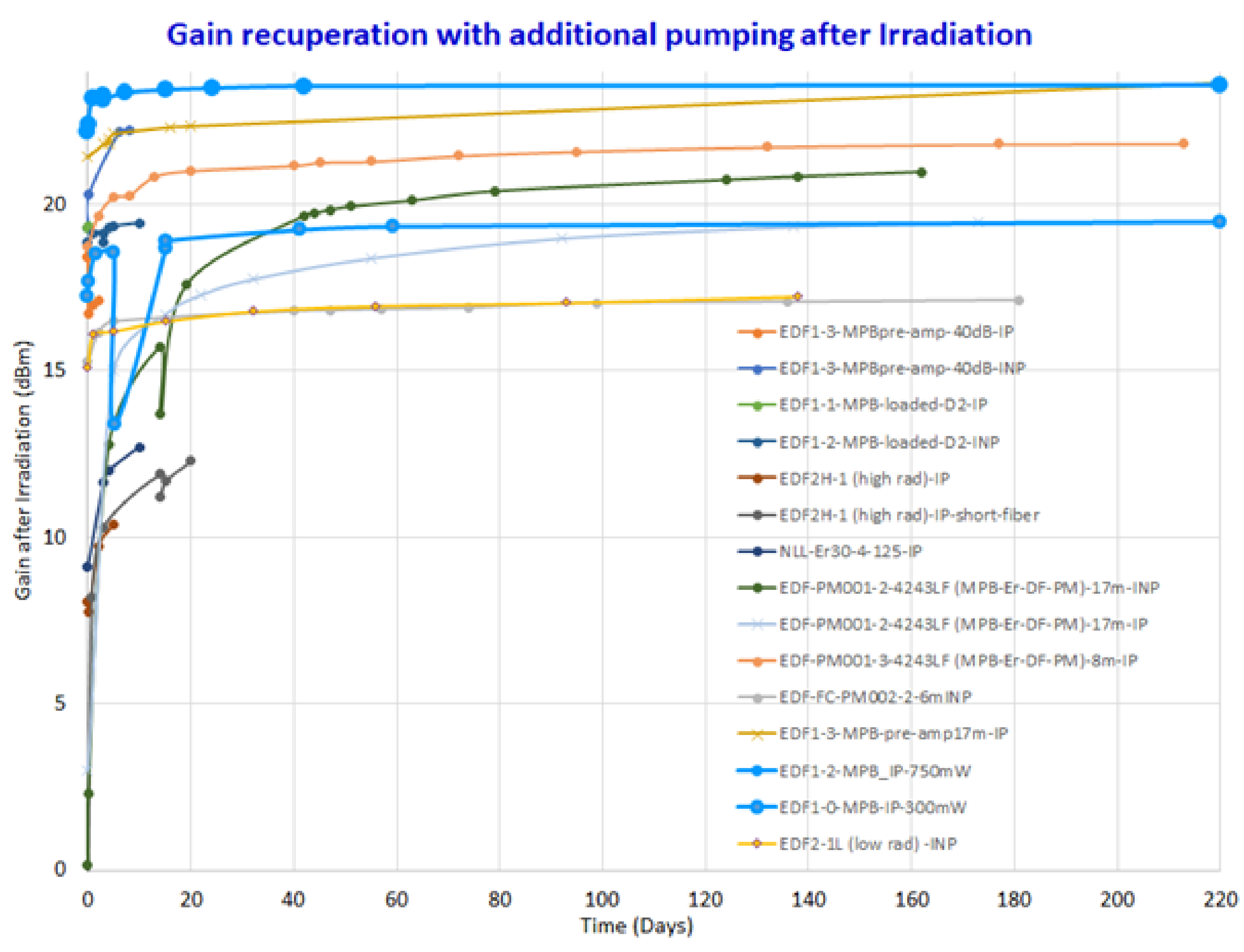

Figure 6. The effect of the additional pumping, after the irradiation on the Erbium Doped Fibers

The glitches going down are due to the annealing at 70°C. The effect of annealing was beneficial in some cases permitting a faster gain recuperation relative to the fiber that was not annealed at 70°C

3.3 Comparing the effect of TID estimated by Spenvis and Co-60

The simulation for the Total Ionization Dose (TID) for a satellite can be made using the orbit of the satellite and Spenvis code. The TID for a specific orbit is commonly traced in function of the thickness of Aluminium shield

The Co-60 emits two gammas ray at 1.17 MeV (100%) and 1.33 MeV (100%), with an average of 1.25 MeV. The gamma-ray attenuation (μ) by different materials is proportional to the material density (ρ). The mass attenuation coefficient (μ/ρ) is relatively very close for the materials

Table 4. Comparison of the attenuation by metallic shield of total Ionization Dose from Co-60 and from Spenvis

Co-60 (1.25 MeV)	**Density**	**Mass attenuation coefficient (μ/ρ)**	**Output gamma** 1mm shield	**Output gamma 5 mm shield**	**Output gamma 10 mm shield**
Unit	g/cm^3	cm^2/g	%	%	%
Spenvis	-	-	20-60	5-15	< 5
Aluminum	2.7	0.0549	98.5	92.8	86.2
Molybdenum	10	0.0516,	94.9	76.8	59.0

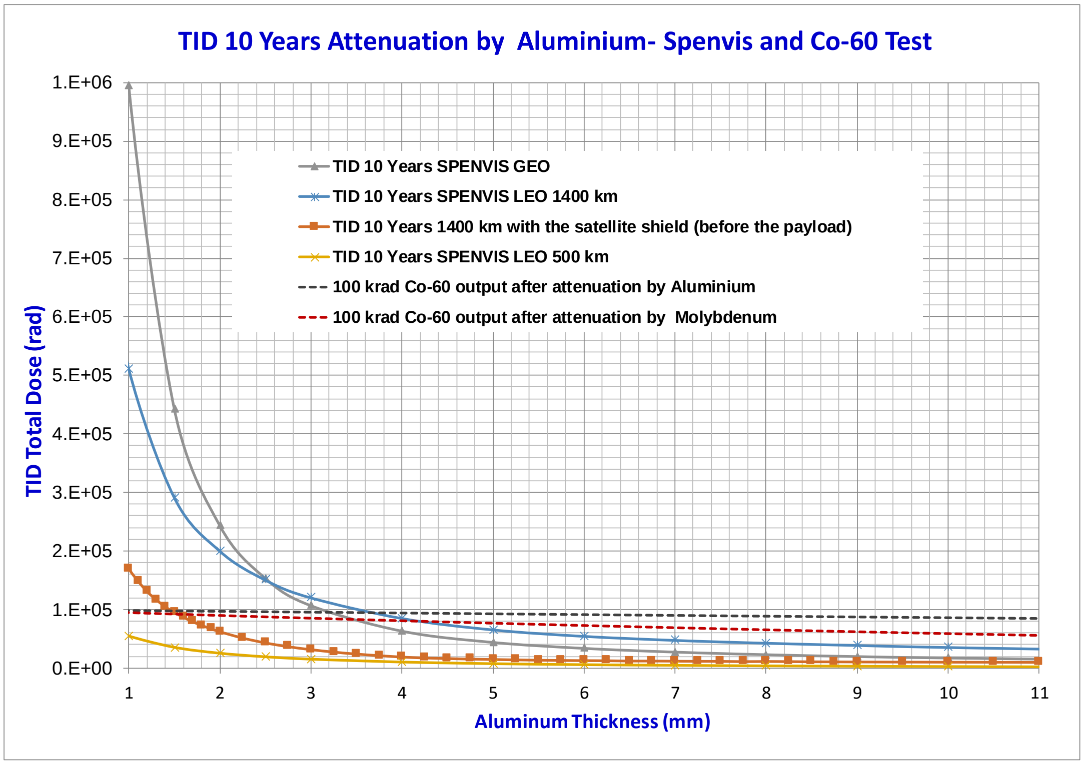

Figure 7. Attenuation by Al shield of TID as predicted by Spenvis and as estimated from the attenuation of the Co-60 gamma-ray.

3.4 Stimulated Brillouin Scattering (SBS)

Stimulated Brillouin scattering (SBS) is a resonant nonlinear optical interaction with the material that results in transmitted light being scattered back towards the input. Brillouin scattering manifests itself through the generation of a backward propagating Stokes wave downshifted from the frequency of the incident pump wave by about 20 GHz. The process of SBS can be viewed as a parametric interaction among the pump wave, the Stokes and anti-Stokes wave, and an acoustic wave. The pump field generates sound waves in the fiber which induce a periodic modulation of the refractive index due to the pressure.

The SBS signal is amplified in the backward-propagating direction, and therefore, if present, can lead to instabilities and severe impairment of the transmission quality. For a non-modulated spectrally-narrow signal launched into 20-km of standard telecom fiber, the SBS threshold is as low as about 4 mW.

However high power isolator is used in the third stage, which can block any back reflection to third stage gain fiber, therefore the risk of SBS from the delivery fiber is well limited. Beside the isolator, we also a new approach to eliminate SBS in high power level in the delivery fiber.
We apply common techniques to increase the SBS threshold. A dither is applied[4] to suppress the Stimulated Brillouin Scattering (SBS) in the third stage A 1552.3nm DFB (TEC=25C, I=62mA) 12mW is applied a dither which is modulated at 100KHz sine by direct current.

We considered the SBS issue in one channel (one DFB seed) system. For a given total output power, in a multi-channel system, the total power will be distributed on several channels, with each individual channel at a lesser power, therefore reducing the risk with SBS.

3.5 Optoelectronics - Laser diode pumps

The laser diode pumps (0.3-0.5 mW) for the first stage were tested in the 2006-2008 by Alter-Technology[5], and their compatibility with space vacuum and resistance to radiation were demonstrated.

For the second stage that requires laser diodes of the order of 10 W, the diodes were selected based on MPB experience for terrestrial and submarine applications. These diodes are not compatible with vacuum, and one the tested diode failed. According to the manufacturer one out of four diodes would likely fail in vacuum tests:

•There is Oxygen environment around the pumps that is needed to neutralize any organic vapors, which may arise from, e.g., heated epoxies or residual solvents within the sealed component housing package. If the O2 escapes (via a leak) due to non-hermeticity of the package, the organic vapors will not be neutralized and may deposit on the laser output facet, leading to catastrophic failure.

• The epoxy used to attach and bond different parts together will become softer at a relatively higher temperature in additional to outgassing in vacuum, which leads to the need for laser welded parts without epoxy

MPB could only find two suppliers for diodes hermetically closed with laser welded parts. Samples of these diodes are currently under thermal cycling in vacuum (TVAC)

For the third stage, the total power required should be more than 60 W considering the conversion efficiency between the 915-940 nm to 1550 nm range. Due to the internal heat emitted the temperature functional range of these diodes is limited (15°C to 35°C), whereas most of the clients requested a range between -35°C and 65°C.

We tried different commercial Multi-Mode Laser Diode pumps (25-30 W) selected for the third stage. Both of them had epoxy and were not hermetically closed. We could not find a laser welded -hermetically closed diode at this power rating.

The diodes successfully passed a thermal cycling test in an environmental chamber (air) [-35°C to 65°C]. However, when they were put in vacuum, one of the 3 diodes completely failed at room temperature.

Recently we purchased from a company 30W laser diodes hermetically closed, although they are not laser welded but use epoxy to attach the components:

- 3x 30 W diodes (with epoxy but hermetically closed enclosure) This is the optimal choice if these diodes pass the vacuum and temperature cycling tests.
- 6-8 x 11 W (laser welded components, hermetically closed enclosure) - This configuration has less efficiency, however, the smaller power pumps are more reliable

A European company had provided its laser diodes for space in at least two missions, over a wide temperature range in vacuum. However, they do not offer either the right size of fibers (only large diameter 250-µm cladding) or the wavelength (e,g. only 980 nm is made, where 940 nm is needed).

In addition to the Laser diodes, a special care should be given in the selection of the electronic components, such as the current drivers for the third stage (10 A). A preliminary test showed some of the models are sensitive to gamma radiations.

3.6 Photodiodes Dark Current

The dark current is related to the lifetime and damage susceptibility. There are two ways to solve this potential issue:

- Redundancy of the photodiodes
- Selection of photodiodes with low sensitivities to Radiation- According to[6] different papers there is a factor > 100, between the photodiode current increase, depending on the manufacturer and the model.

4. EXPERIMENTAL RESULTS

The following table and figures summarize the experimental results obtained from the breadboard, respecting the size and mass of the final prototype.

Table 5. Comparison Parameters measured with 14.4W output after PM isolator, 1552nm DFB

Stage	DFB Seed	First stage output after isolator	Second stage after isolator	Third stage after isolator
Input of 1552 signal (DFB)	10mW	97mW	1.75W	14.4W
Pump Power	12mW	198mW	10.96W	51W
LD current	60mA	400mW	7A	7A

Table 6. The range of power capabilities of each stage

Stage	Input to the stage tolerated range	Input to the stage tolerated range
First stage input (DFB seed output)	12mW ±6 mW	10.8 dBm ±3dB
Second stage input (output of first stage)	100mW ±50 mW	20.0 dBm ±3dB
Third stage input (output of second stage)	1.75W±0.75W	32.4 dBm ±2dB
Third stage output	10 W ± 4.5W	40 dBm ±2dB

Table 7. Experimental efficiency at each part of the PM and standard version of the 10 W amplifier.

Prototype	PM Version	Non-PM version
Nominal output Power(W)	10	10
ErYb-doped fiber efficiency	31%	33%
Combiner efficiency signal	86%	86%
Combiner pump transmission	93%	93%
Isolator efficiency	85%	90%
940 Pump power efficiency(electrical to optical	50%	50%

Driver and control board efficiency	96%	96%
Total electrical power needed(W)	100	90
Wall plug efficiency	10.0%	11.1%

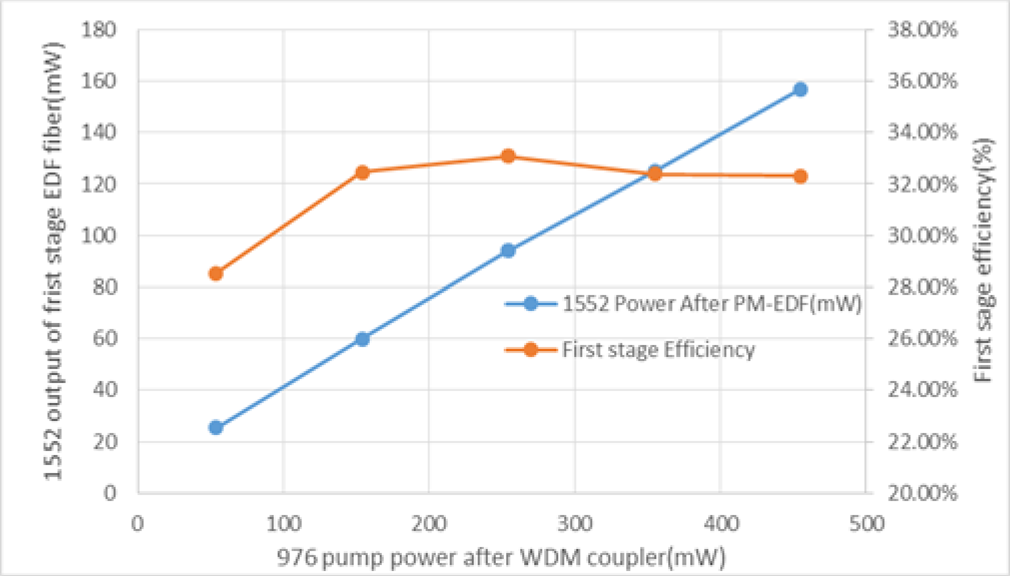

Figure 8. The first stage has 32% optical power efficiency.

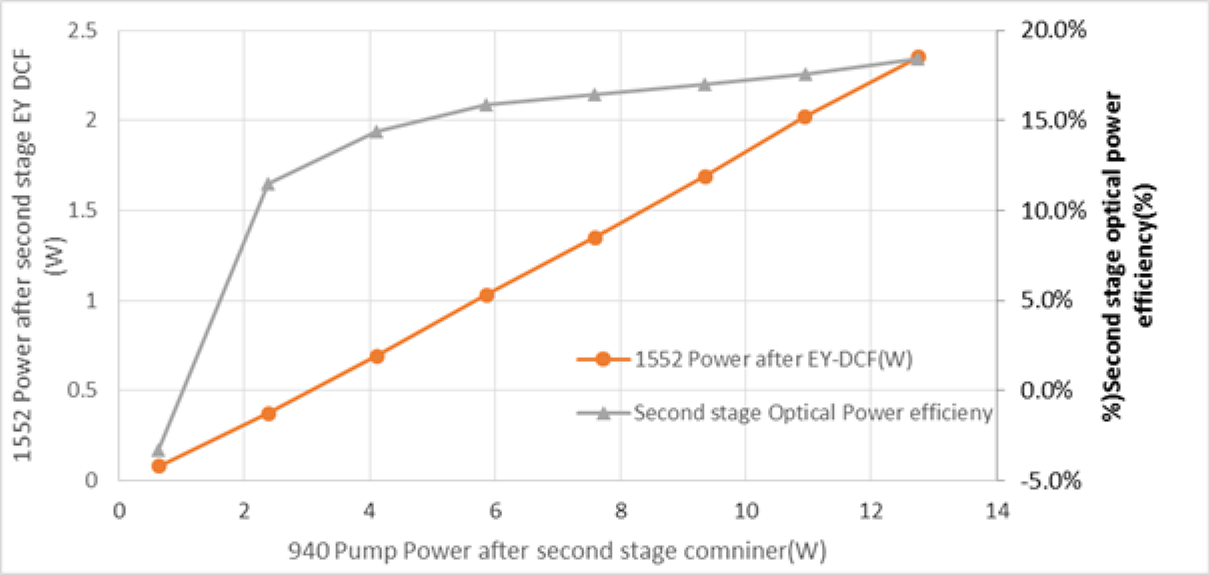

Figure 9. The second stage has 16-18% optical power efficiency in the functional region.

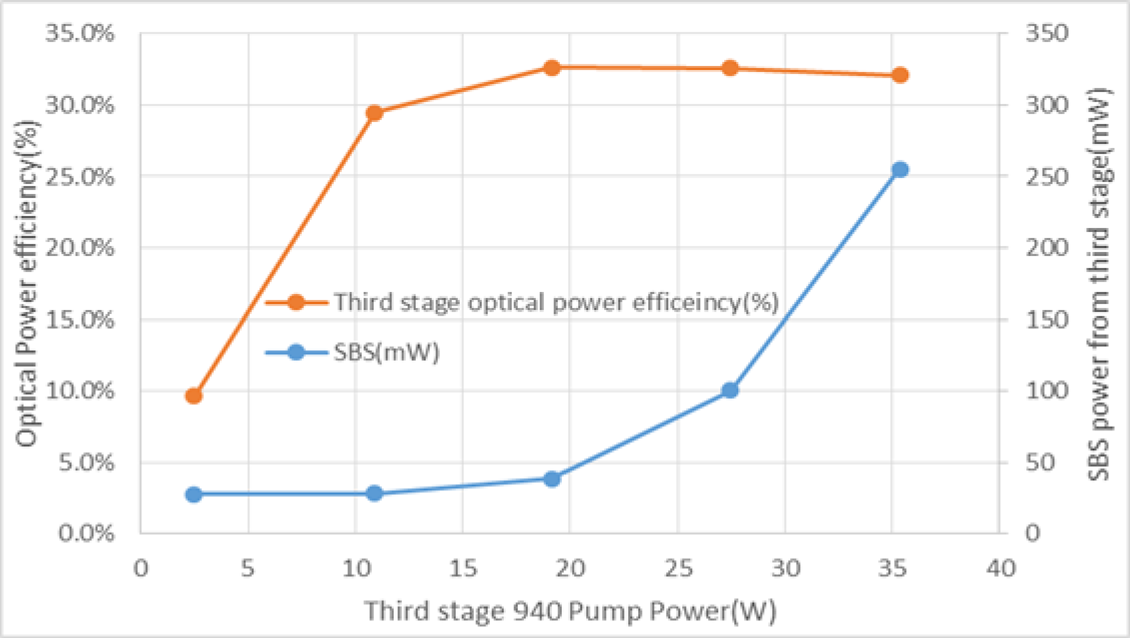

Figure 10. The second stage has 16-18% optical power efficiency in the functional region.

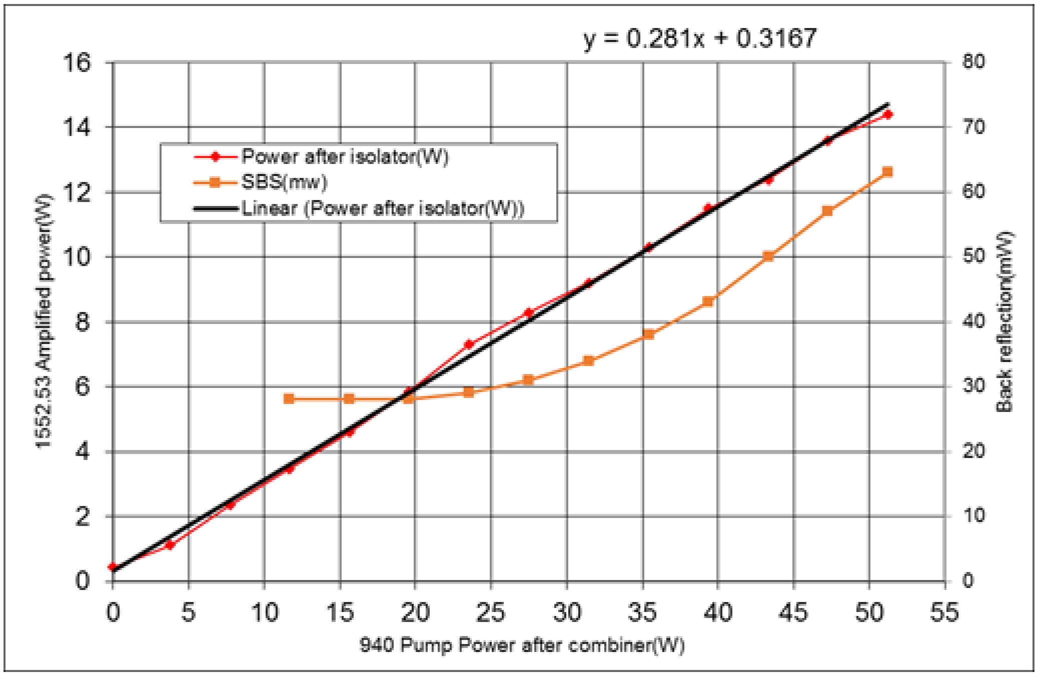

Figure 11. Third stage Optical power efficiency and SBS after one High power isolator.

MPB demonstrated the feasibility of 41.5 dBm (14.4 W) output PM-amplifier at 1552.5 nm.

The optical power conversion efficiency of the first stage is 32%, the second stage 18 % and the third stage is 33% is. The second stage fiber length is 6m, which seems to be too long. The efficiency of the second stage will be increased with an optimal fiber length.

The third stage gain fiber is a large core fiber which has high SBS threshold, so the final pigtail fiber (a few meters) is a major contributor of entire SBS. The high power isolator could dramatically reduce the SBS, therefore increasing the total output power to 14.4W. The Optical power efficiency reaches 33%.

5. MODELING AND SIMULATION

The modeling uses ANSYS for the Finite Element Analysis to the mechanical response to vibration and pyroshock as well as the thermal balance of the prototype

The following Tables and Figures present the results of the simulation

Table 8. Summary of the 10 W amplifier PM design

Parameter	MPB 20 W
Enclosure Dimensions	277.5x216.5x32 (Thickness 5 mm)
Mass	3.7 kg
Power to dissipate (at 20C)	60W
T_{min} (C) / Component limiting T_{min}	25/ Base plate
T_{max} (C)/ Component limiting T_{max}	45/2nd Stage Pumps

Table 9. Simulation results of the resonance frequency of the 10 W PM prototype

Mode	Frequency (Hz)		Mode	Frequency (Hz)
1	668.3		6	2405.7
2	983.1		7	3146
3	1525.9		8	3319.2
4	1908.3		9	3370.8
5	2225.3		10	3751

Table 10. Random Vibration PSD Spectrum used in the simulation Based on ESA ECSS-E-HB-32-25A

Frequency [Hz]	G Acceleration [G²/Hz]
20	.2
100	1
300	
2000	.04
Total	23.28

Pyroshock simulations were performed based on the Soyuz dispenser. The stress and displacement and results for the unit are shown below. This is an example: taking Soyouz, (ECSS-E-HB-32-25A, Chapter 7, subsection 7.4.4.5, Page 65),

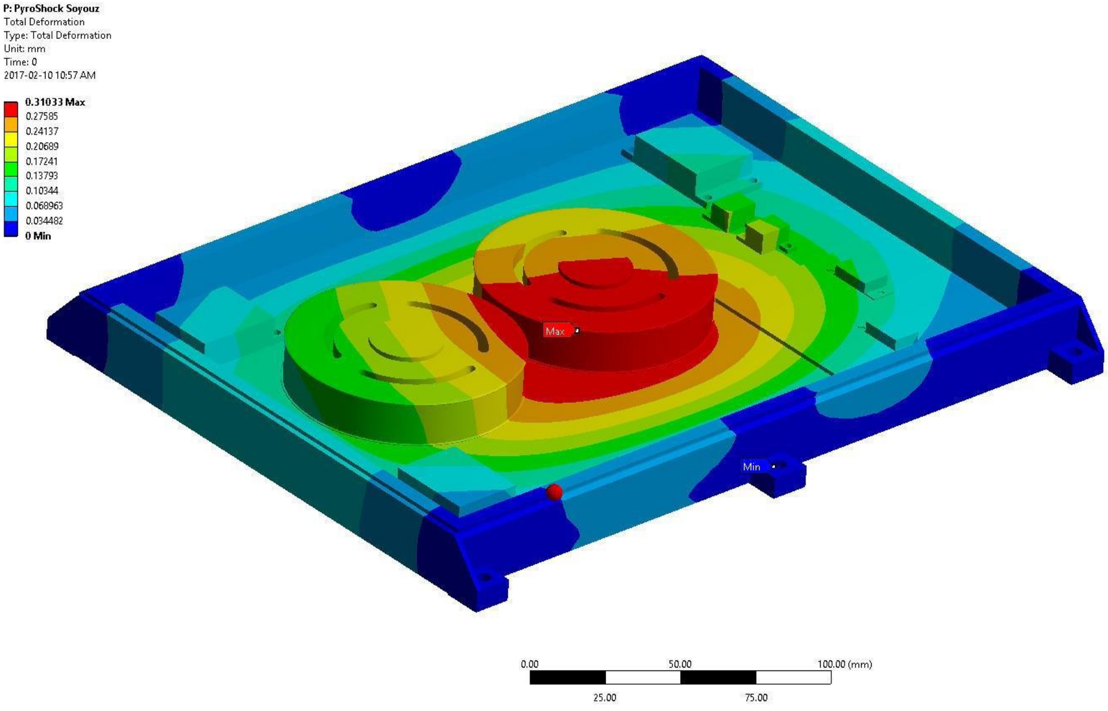

Figure 12. Displacement Contour – Soyuz Y-Excitation

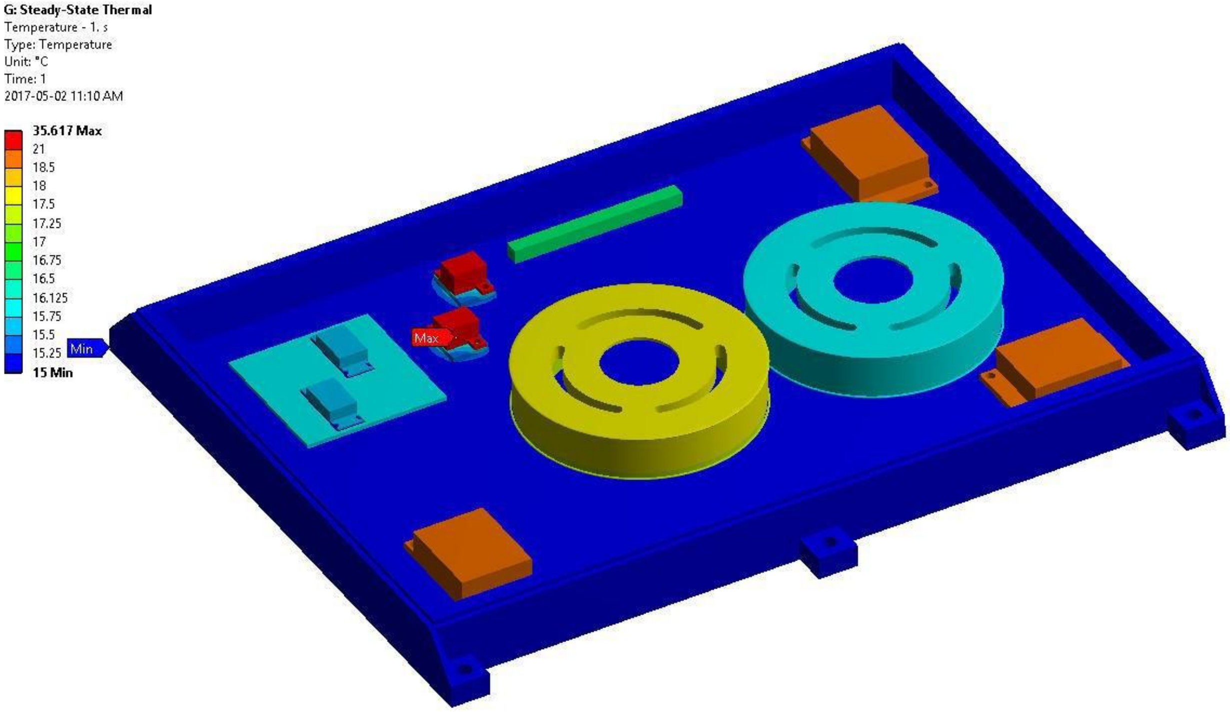

Figure 13. Steady-State Temperature for 3rd Stage Constant Temperature Condition (assuming radiator contact temperature is 15C)

6. CONCLUSIONS

The conclusions are summarized in the following table

Effect of Gamma radiation on the EDF, EYDF (PM or non-PM) adsorption - This effect is larger on PM fibers. Using rad-hard Fibers is an expensive solution, to our knowledge, there is no rad-hard EDF-PM (< 1 dB loss /100 krad). We are using commercial rad-tolerant fibers.

For the high power laser diodes, in particular during the third stage, their long-term compatibility with vacuum is challenging – we are testing hermetically closed boxes using epoxy. For the second stage, the diodes are hermetically closed with laser welded components.

The stimulated Brillouin Scattering (SBS) is controlled by an efficient fiber core along with heat dissipation and efficient isolator preventing the light from going back in the fiber. The SBS is the main limiting factor of I getting higher power than 14.5 W.

The Photodiode dark current increases under radiation (gamma and protons), which reduces the lifetime. We can solve this issue by selecting a model with low sensitivity to radiation and using redundancy.

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