EDURAC: A radiation tolerant frequency comb fiber laser for space applications

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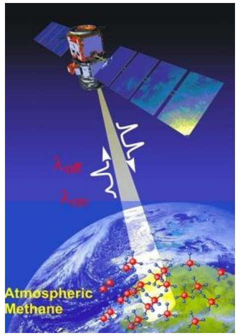
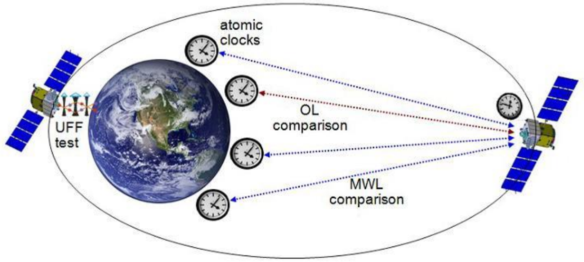
Why are we doing this? Spacecomb Applications

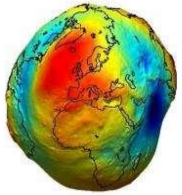


Fundamental Physics „spacetime“



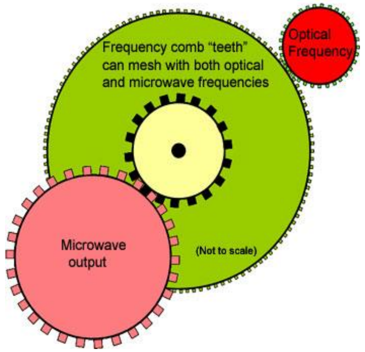
Atmospheric Trace Gas Detection „referenced LIDAR“

Gravitational Potentials „gravitational redshift“



Optical Clocks & MW „photonic microwave generation“

Reference & Time Distribution „optical clocks“



Ranging for formation flying satellites „dual comb ranging“

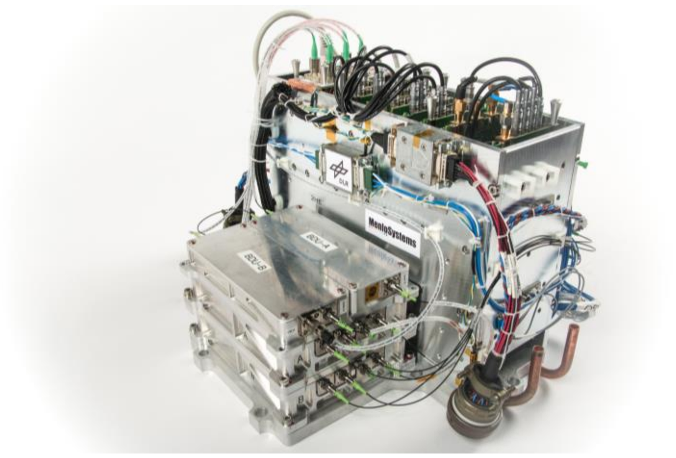
TRL of space combs before the project

Combs are not yet qualified for space environment

Environmental Sensitivity of Lasers:

- Vacuum → not a fundamental problem
- Thermal cycling → requires thermal concept
- Vibrations → damp or stabilized them
- Lifetime → pump diodes, fiber components
- Radiation sensitivity → **in particular gain fibers**

In the past years Menlo Systems has demonstrated robust comb systems flying in experimental payloads on sounding rockets up to 280 km height

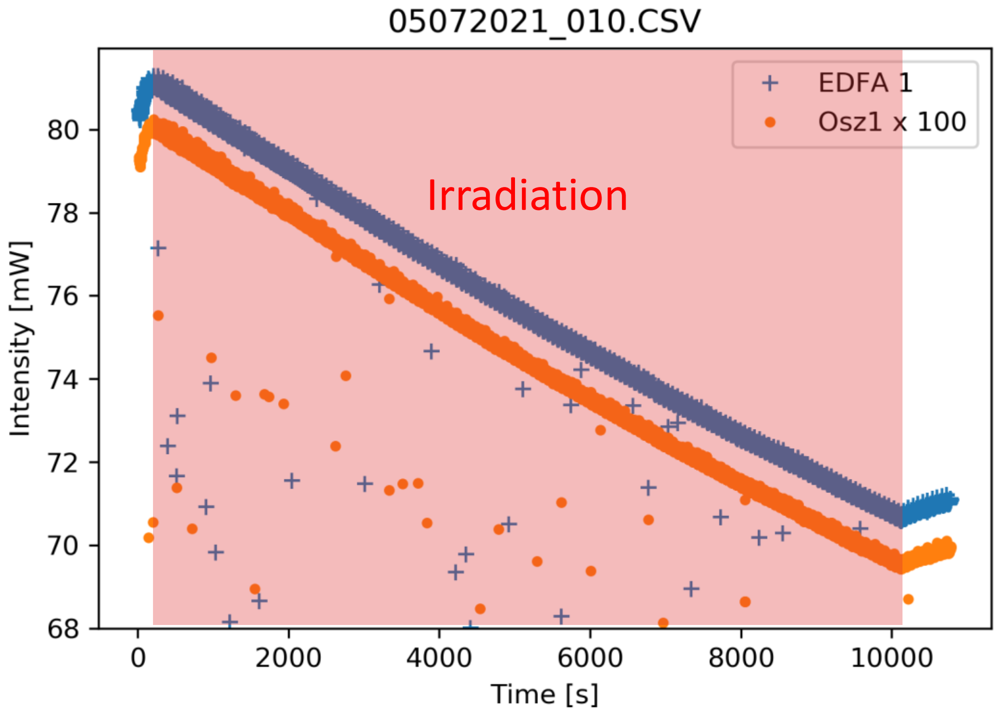


Dual Comb for Sounding Rocket

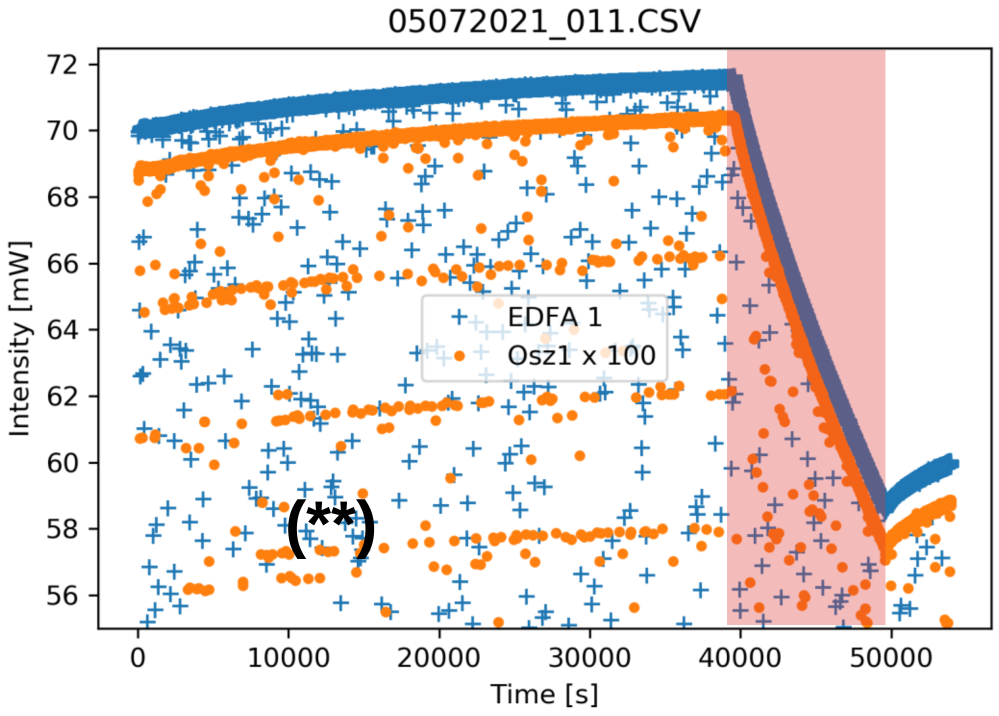
Single Comb for Sounding Rocket

Standard Gain Fiber Radiadion Hardness

Measured at INT under active laser operation
Laser power degradation is 0.6 dB at 100 Gy(*),
but significant recovery is possible



Irradiation at 10 mGy/s, 90% DC



10 hr recovery, then irradiation at 10 mGy/s, 10% DC

(*) 1 year in mid-earth orbit accumulates about 100 Gy

(**) Outlier dots are caused by laser on/off switching

Goals

1. Literature and requirements review
2. iXblue designs several generations of fiber with enhanced radiation tolerance, high gain, polarization maintaining, and low dispersion
3. Fibers are verified passive & active for function and robustness
4. Fiber oscillators are designed, manufactured and verified
5. Fiber amplifiers are designed, manufactured and verified
6. A fiber comb made from the fiber is designed, manufactured and verified
7. The comb is verified for radiation tolerance

EDURAC Fiber Requirements

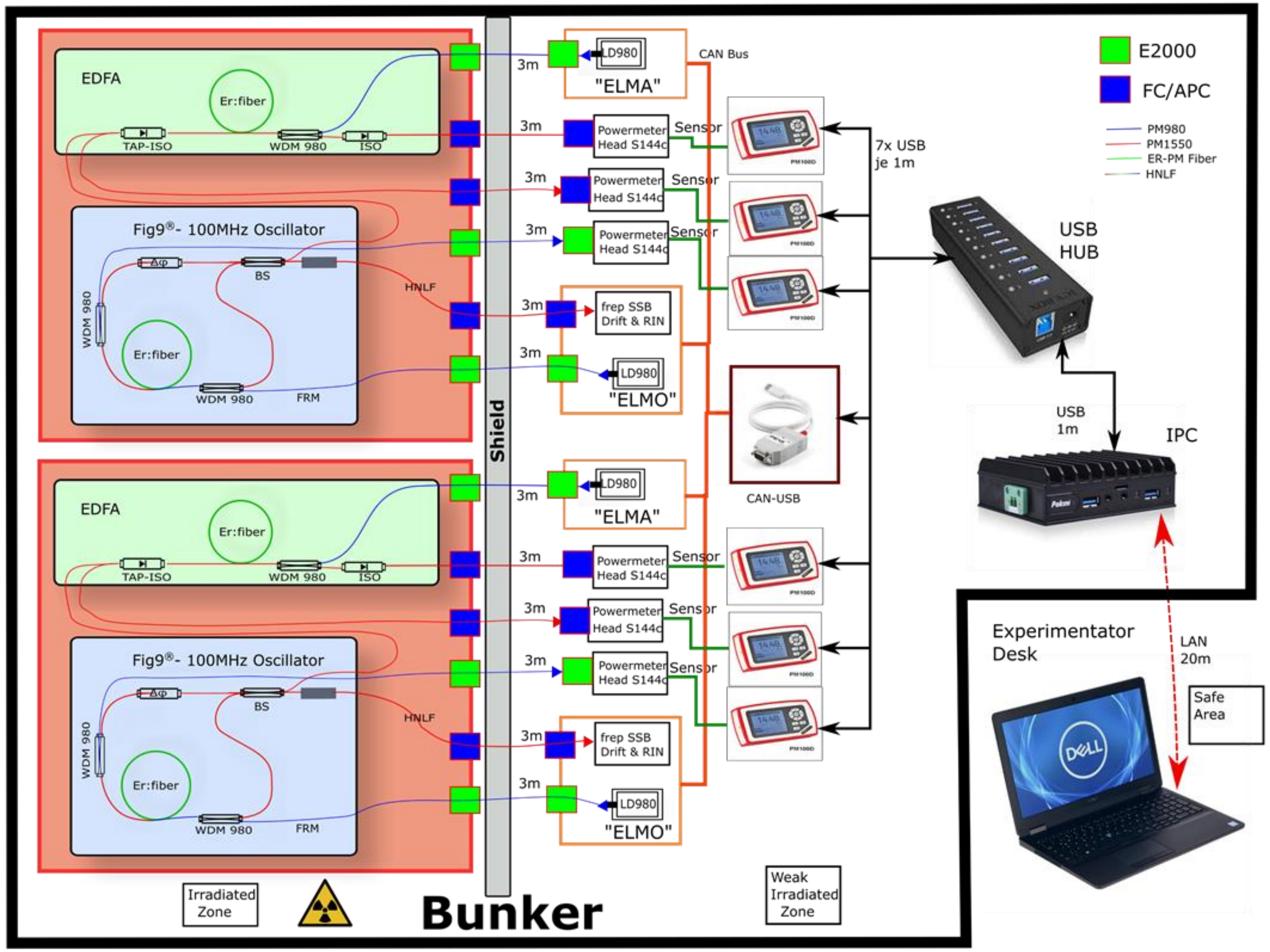
Controlled fiber parameters

- Pump Absorption @ 980 nm
- Laser Absorption @ 1530 nm
- Mode field diameter @ 1550 nm
- Background losses
- Cladding Diameter
- Coating Diameter
- Proof test level
- Group Birefringence for PM
- Fiber Dispersion @ 1550 nm
- Splice Loss to PM15 and PM98
- Radiation induced absorption (RIA)
- Radiation induced gain variation (RIGV)

Parameters in line with requirement for both generations

Active fiber laser irradiation experiments

- Femtosecond fiber oscillators and EDFAs are been placed simultanously into the irradiated zone
- Lasers are switched on/off with selectable duty cycle (DC)
- Lasers are operated and monitored remotely
- Laser power is detected at different positions (3 Powermeters/Laser):
  - oscillator out (RIGV)
  - amplifier out (RIGV)
  - oscillator remaining pump power (RIA)



Co_{60} Gamma Irradiation Experiment at INT

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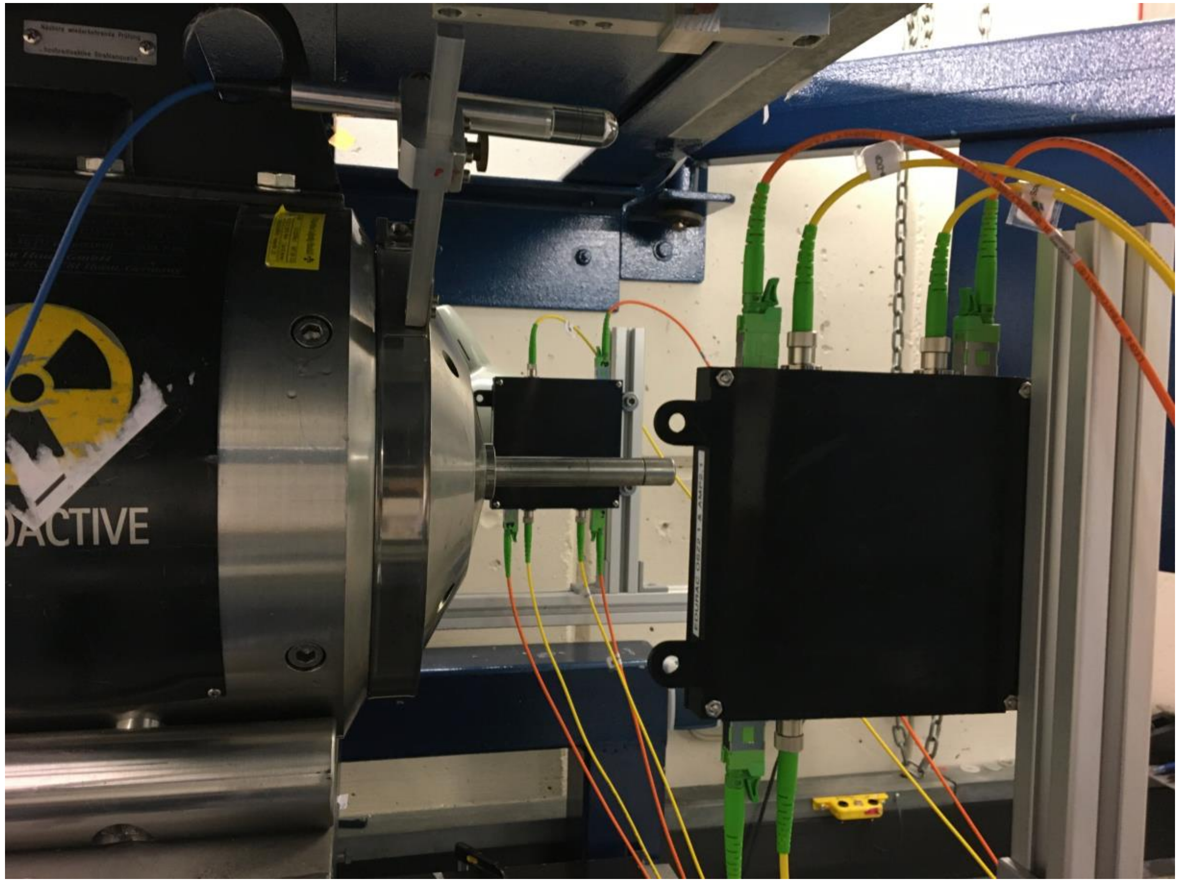
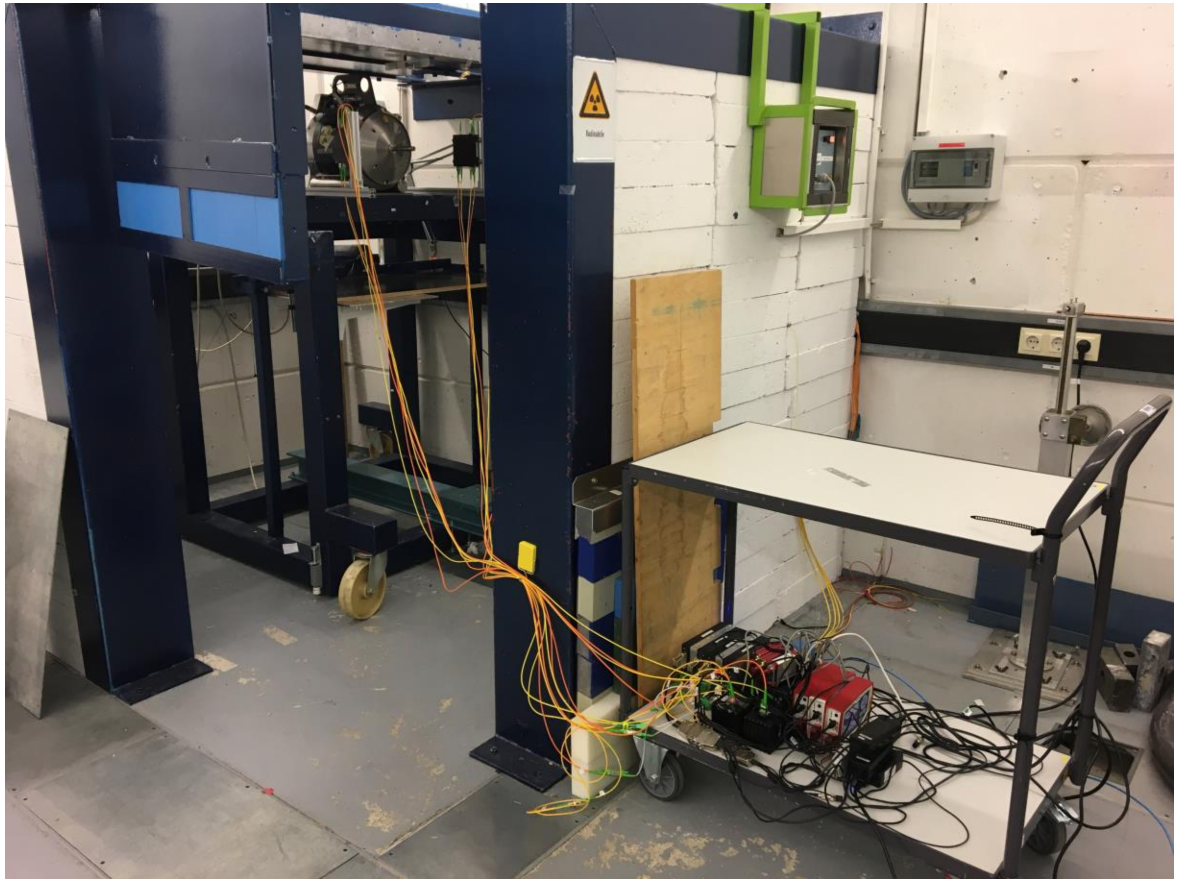


Laser Co_{60} irradiation geometry

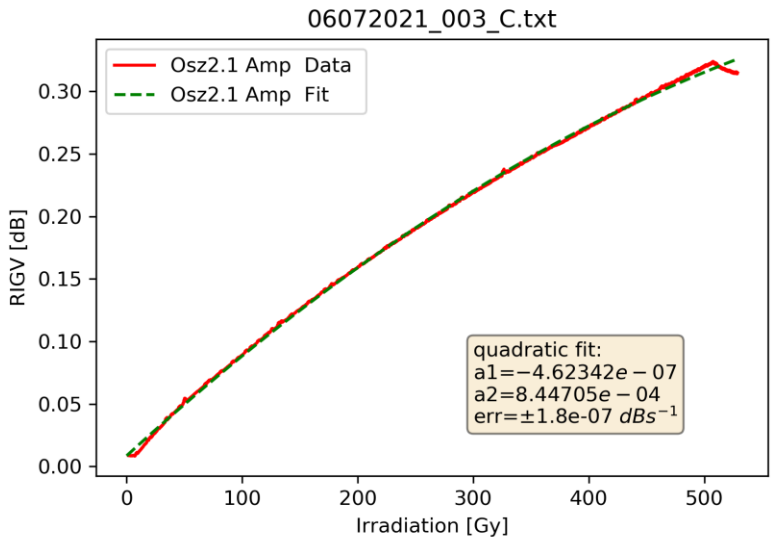


Laser controls behind lead shield

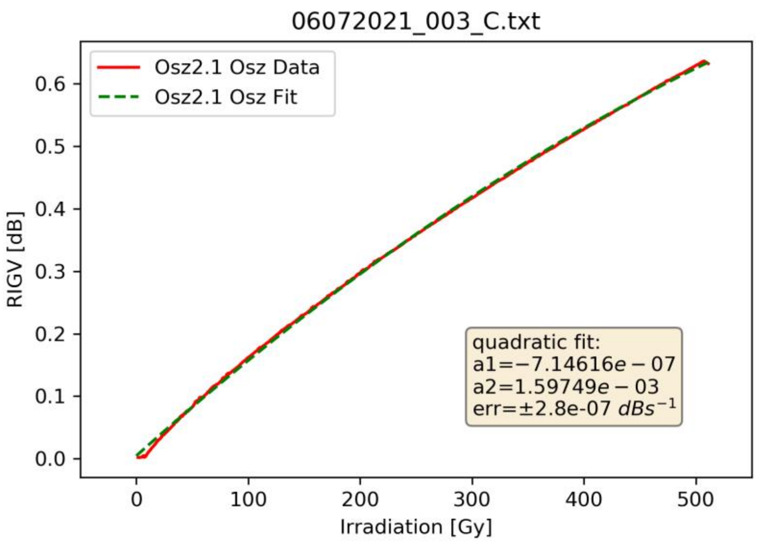
Fraunhofer
INT

RIGV of Radhard Fiber Laser operated at 90% DC

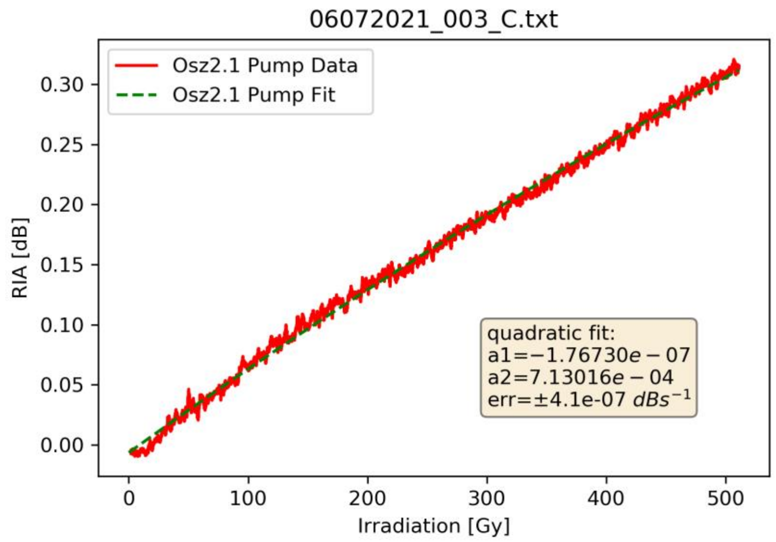
Radiation tolerant fiber laser using iXblue fibers.
Amplifier output loss is about 1/10 compared to standard fiber
Laser looses about 13% of output power after 1 kGy irradiation



Amplifier RIGV



Oscillator RIGV



Oscillator Pump RIA

Fraunhofer INT

(Higher RIGV or RIA means stronger losses)

iXblue

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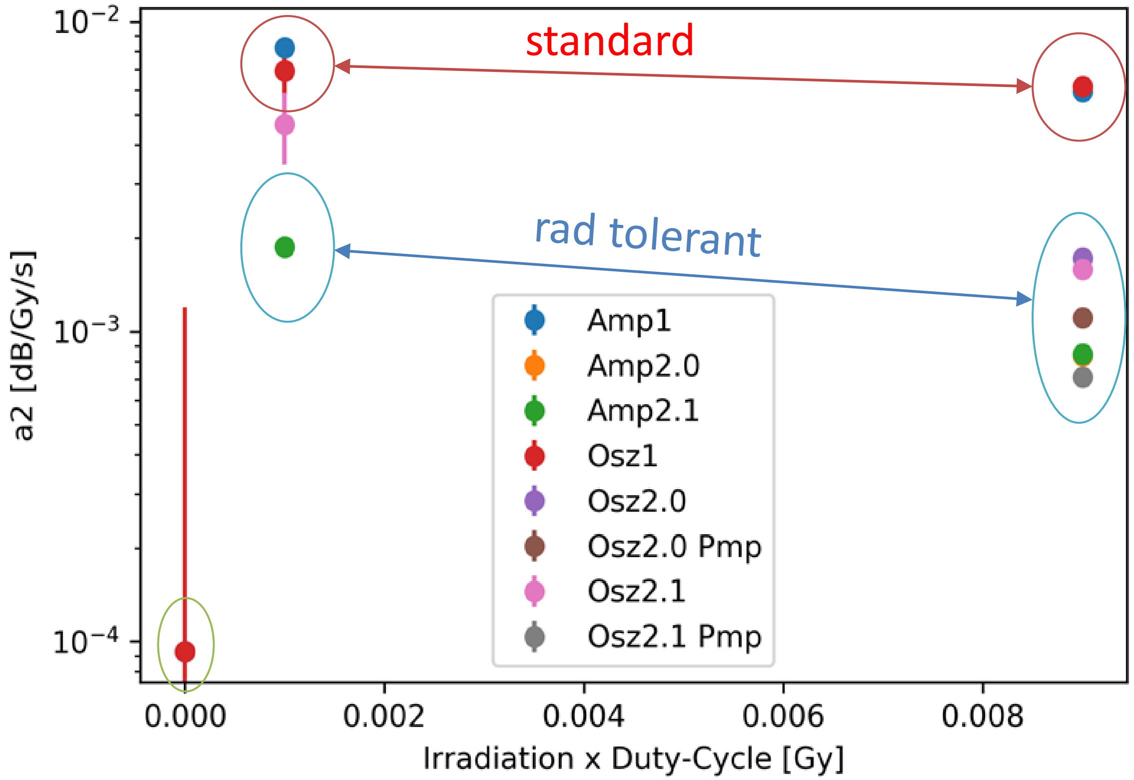
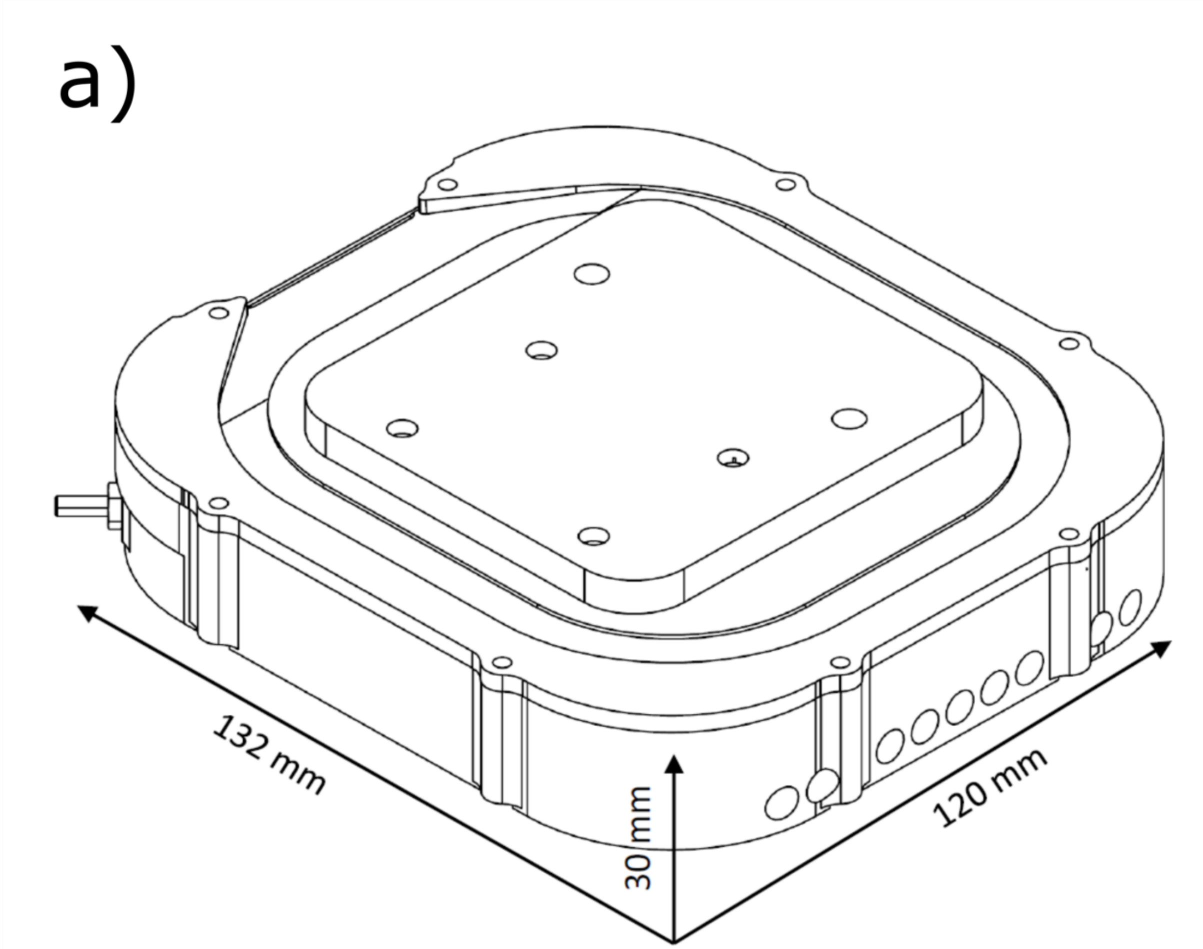
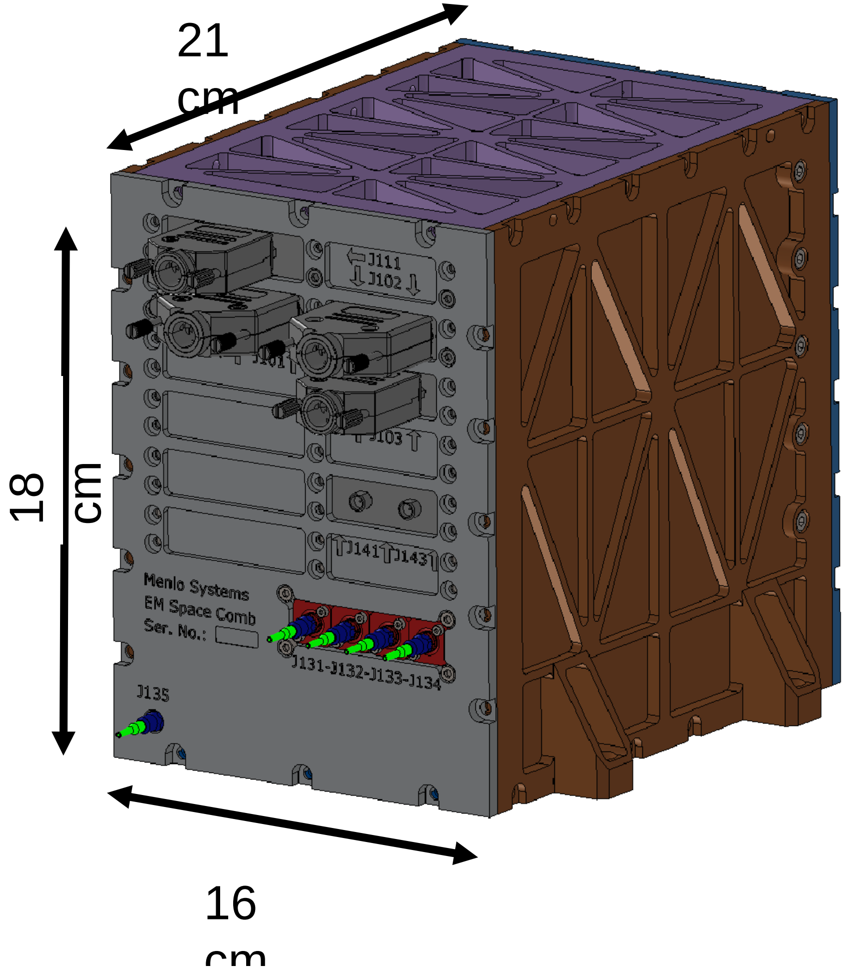
1. Fiber aging rate is 1/6 compared to standard fibers
2. Fiber ages less when active with higher DC
3. Rapid fiber recovery requires in-situ measurements
4. RIA and RIGV can be measured in active laser at the same time
5. Fiber oscillator starting behavior not always reproducible (possibly due to narrow coiling)



Goals

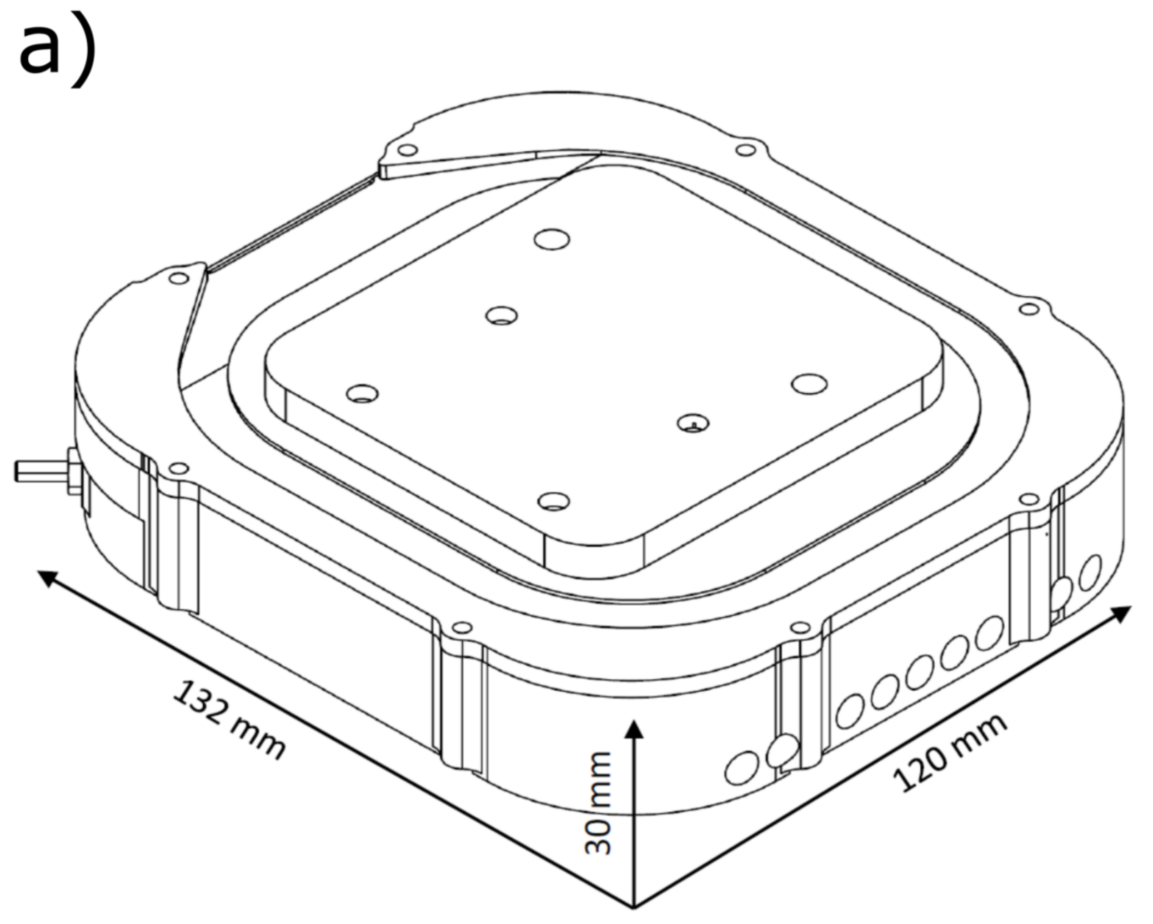
1. Fully functional comb fiber optics
2. 100 MHz in a compact package with fast actors
3. Amplifier for octave broadening
4. HNLF and waveguide doubling
5. Offset beat signal >35 dB above noise
6. Low phasenoise operation
7. Radiation tolerance

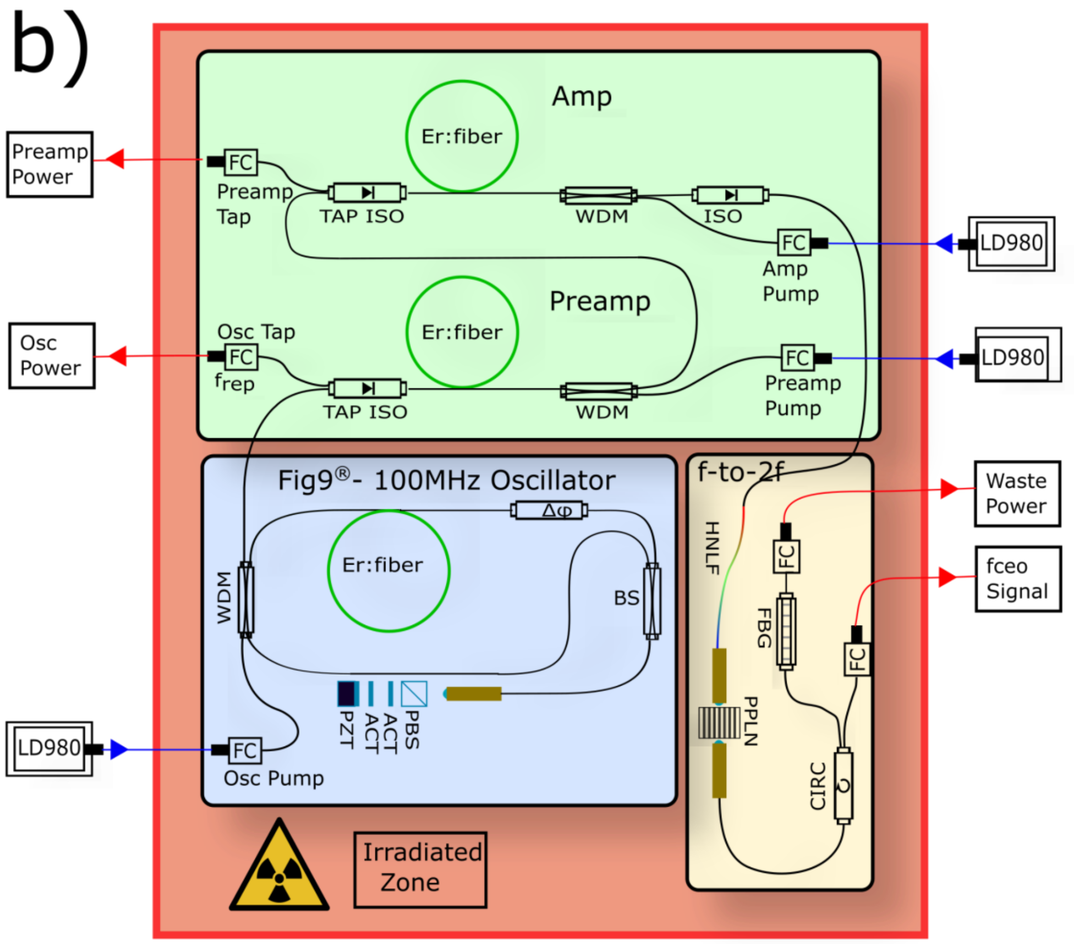




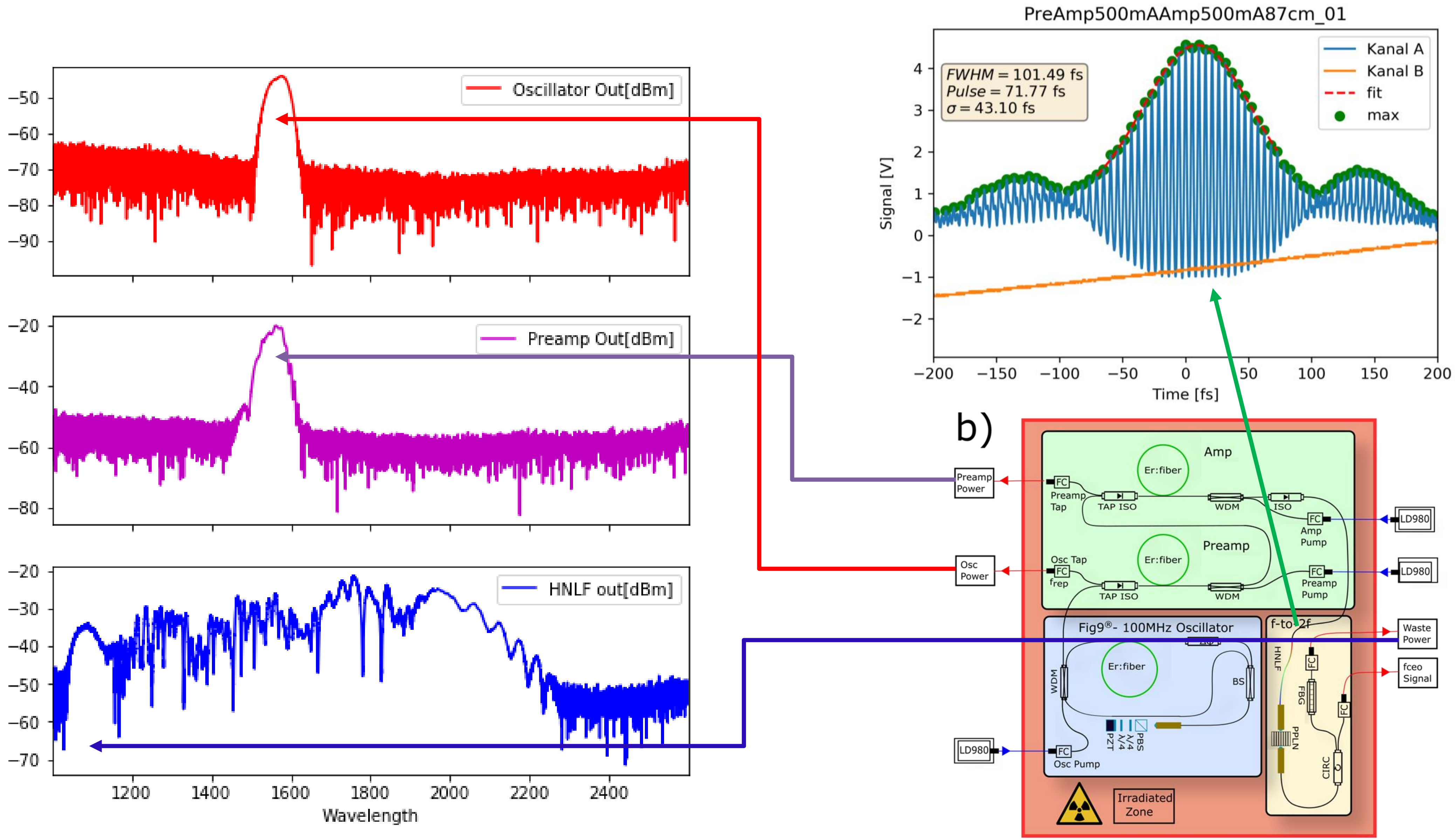
Next generation space comb for IOD project COMPASSO

Radiation Tolerant Fiber Comb Design

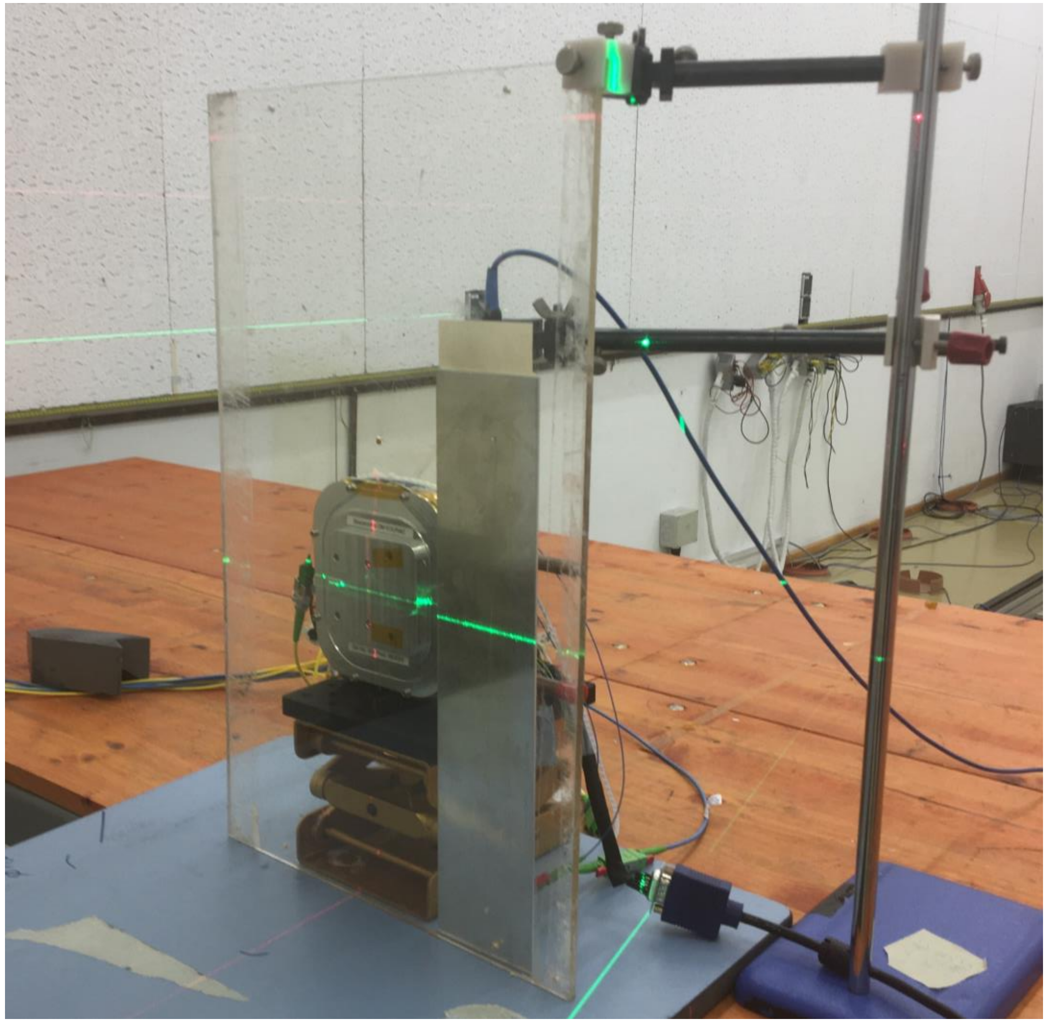




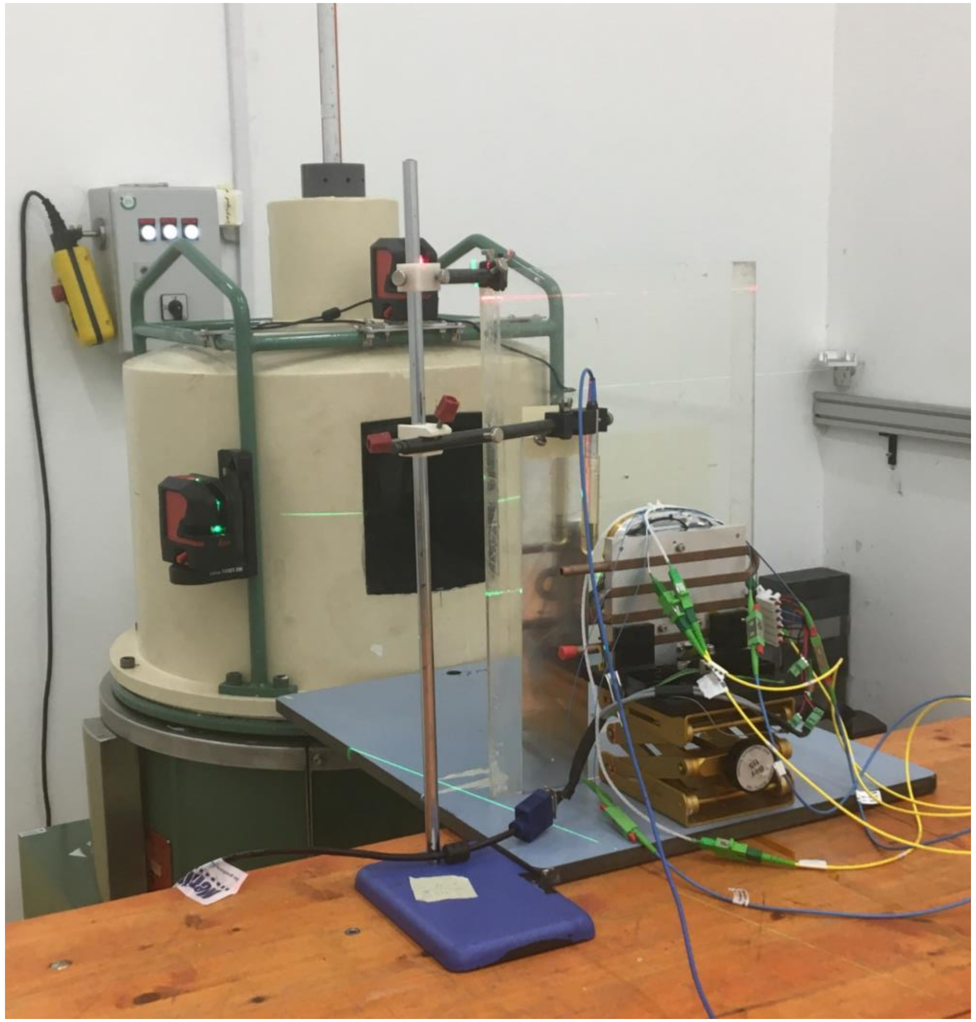
Fiber Comb Characterizations



Co_{60} Gamma Irradiation Experiment at ESTEC



Laser Co_{60} irradiation geometry



Co_{60} source and the specimen

Fiber Comb Irradiation Experiment

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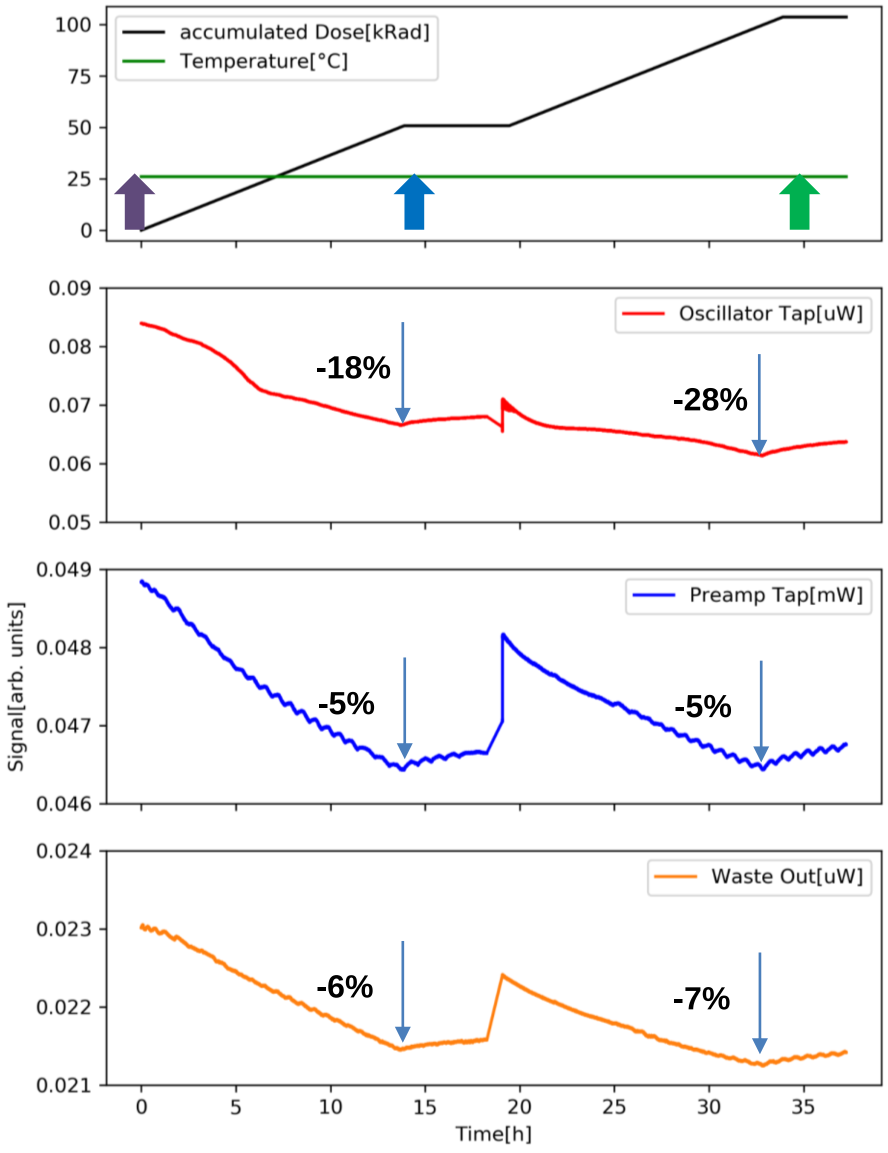

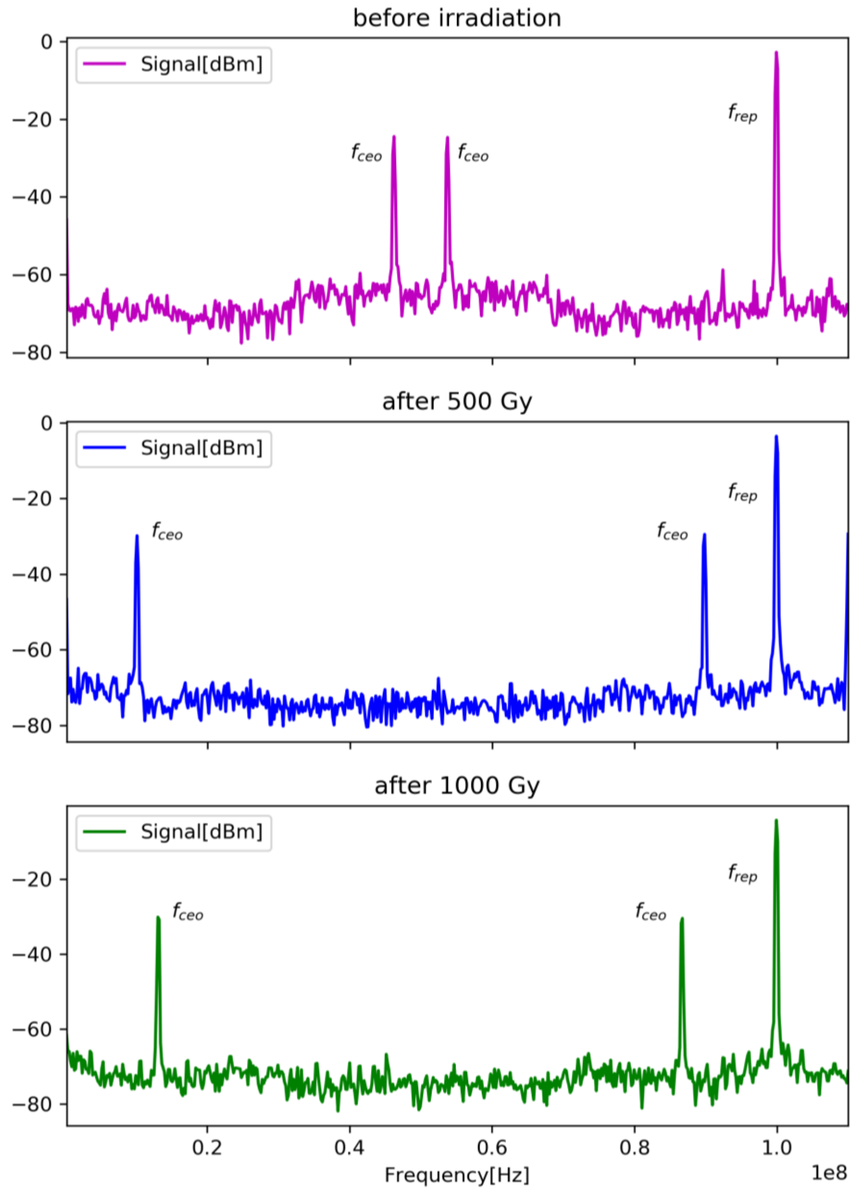

Signal of comb frequencies is not affected by irradiation

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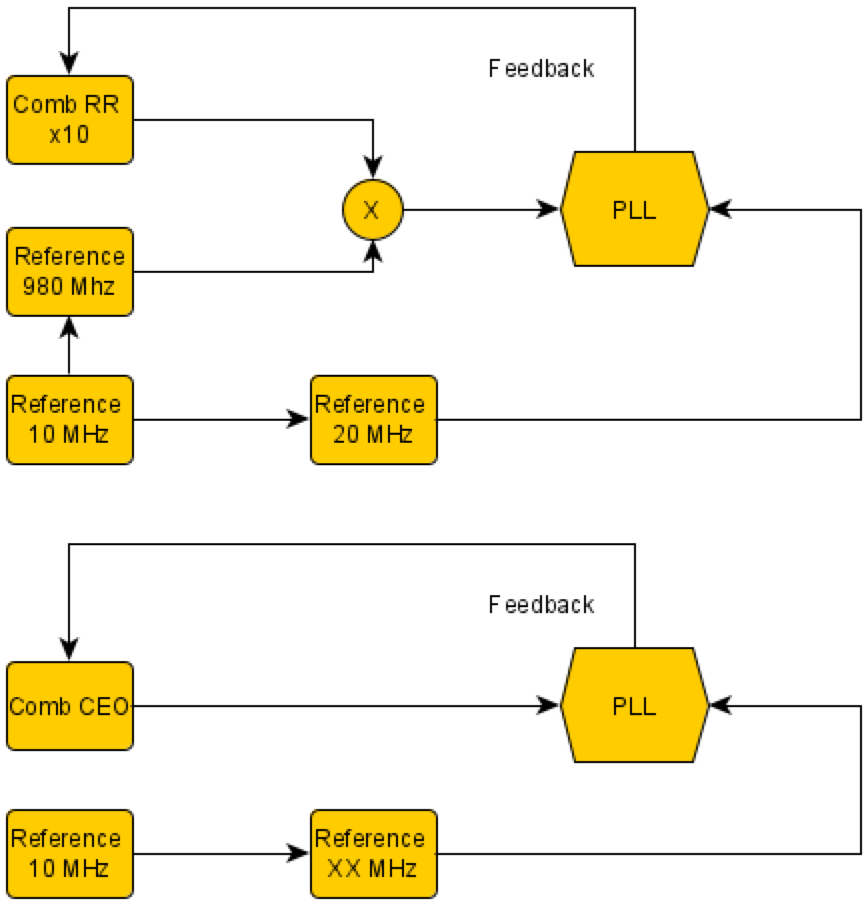
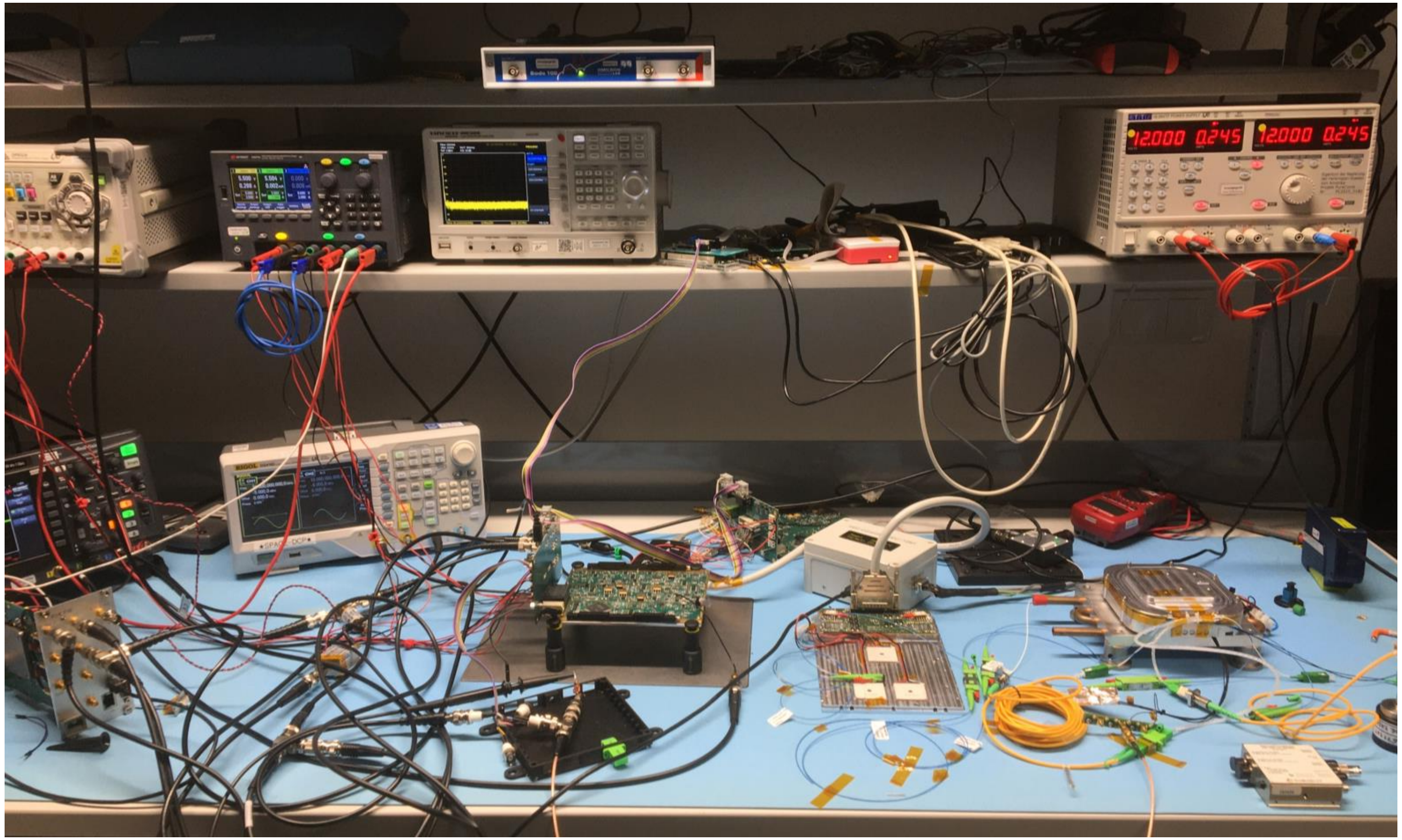
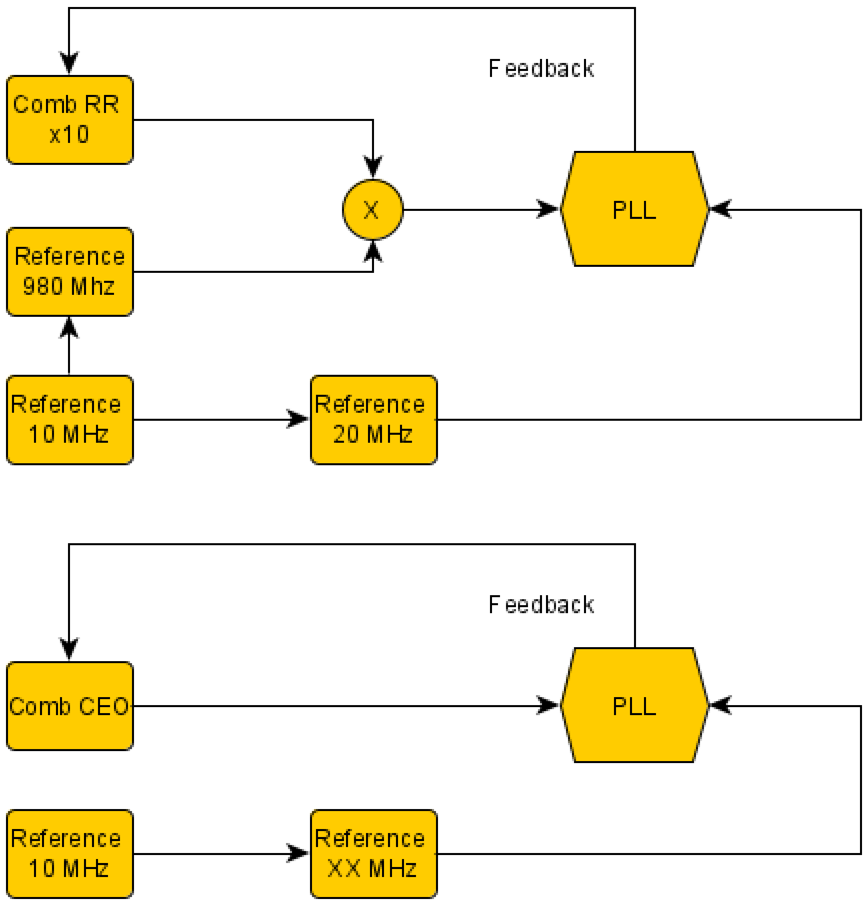
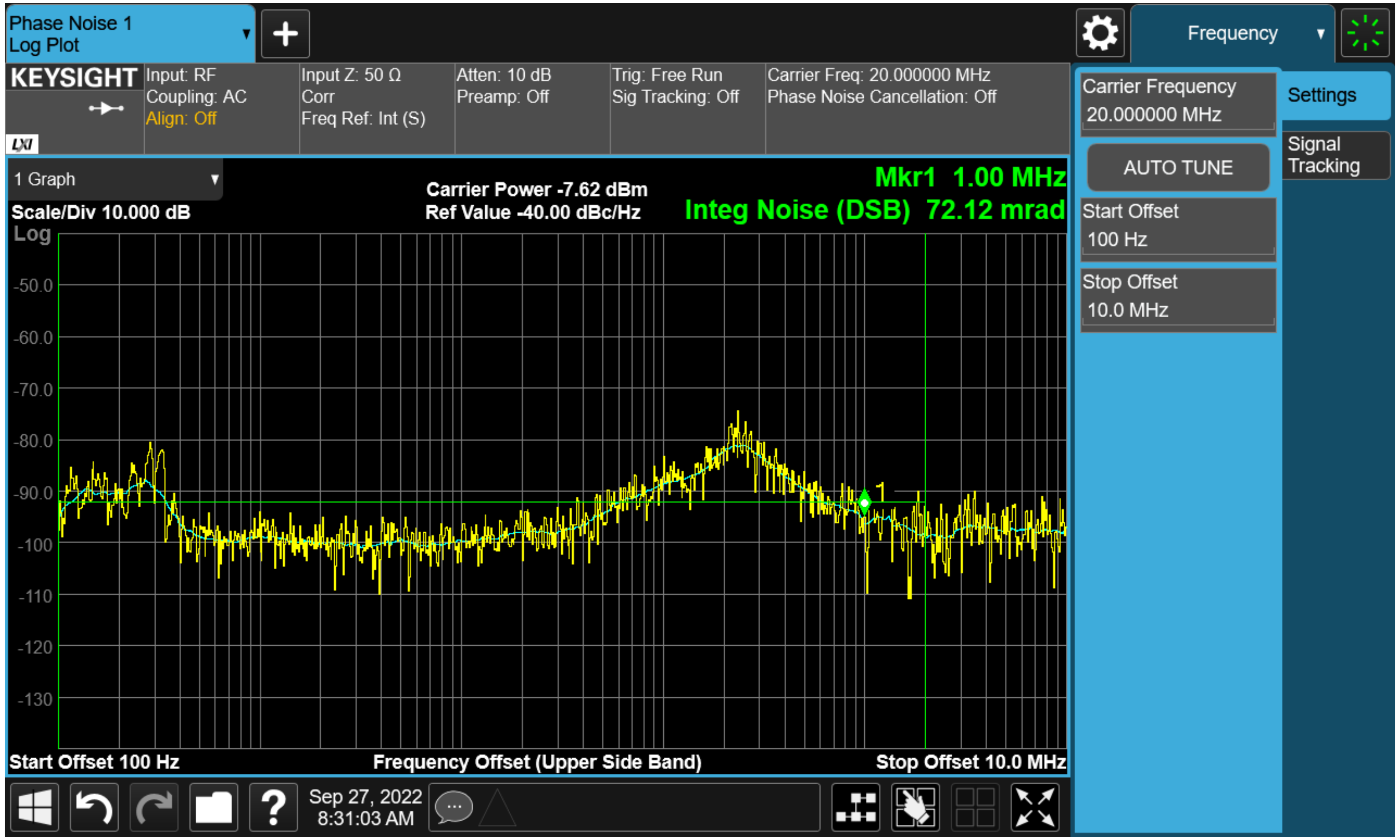




Phasenoise supports high quality optical clock beyond 1E-15 accuracy

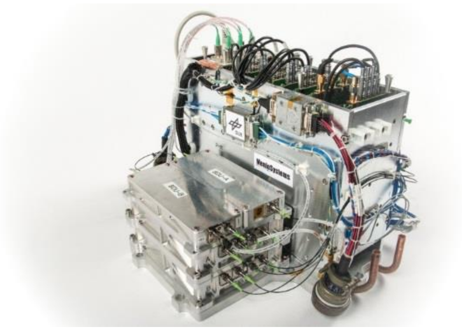
Phasenoise of the Offset Beat Note

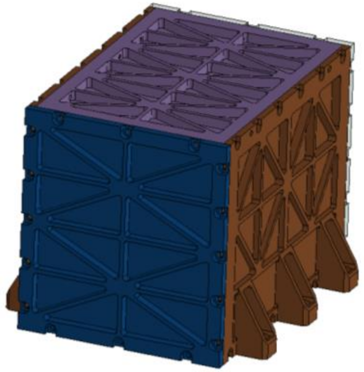


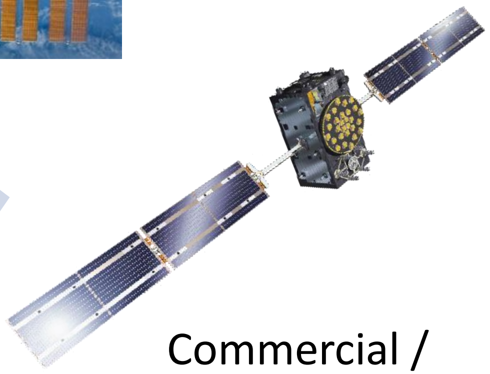


Phasenoise supports high quality optical clock beyond 1E-15 accuracy

Spacecomb Development







Laboratory Comb
2010
- Greatest Flexibility
- Highest Performance

FOKUS I
2014
- 24 kg / 21 L / 90 W
- Robust & compact
- **Texus 51&53 flight 2015/16**

FOKUS II
2018
- 10 kg / 7 L / 50 W
- Dual Comb
- Vacuum compatible
- Ultra-Low-Noise actuator
- **Texus 54 flight 2018**

OPUS / ROSC
2018 - 2022
- Robust and compact systemintegration
- 7 kg / 6 L / 40 W
- Space suitable optics module
- Electronics prepared for qualification

COMPASSO IOV
2024+
- In-Orbit-Demonstration of an Iodine Clock on ISS

Commercial / Science Missions
2028+
- COMPASSO targets Galileo 2nd Generation

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Project Manager‘s View

1. Project exceeded original duration by 33% (1 additional year of 2) ✓
2. Some reasons for delayed progess:
   a) Technical problems in fiber engineering and amplifier design ✗
   b) Restricted laboratory access due to Covid ✗
3. Project goals have been achieved ✓
4. Project cost stayed within budget (tbv) ✓

Engineer‘s View

1. Fiber requirements have been achieved ✓
2. Comb functionality has been achieved ✓
3. Radiation toleranced has been achieved ✓

Scientist‘s View

1. Radiation tolerant fiber laser and first RT fiber comb! ✓
2. In-situ measurement technologies for RIGV and RIA developed ✓
3. New split amplifier design developed ✓
4. New technologies for fiber dispersion design at iXblue ✓

Company View

1. Spacecomb Roadmap has been significantly advanced ✓
2. TRL of fiber optical frequency comb has been increased ✓
3. Our visibility to the space community has been improved ✓

Project Officer‘s View

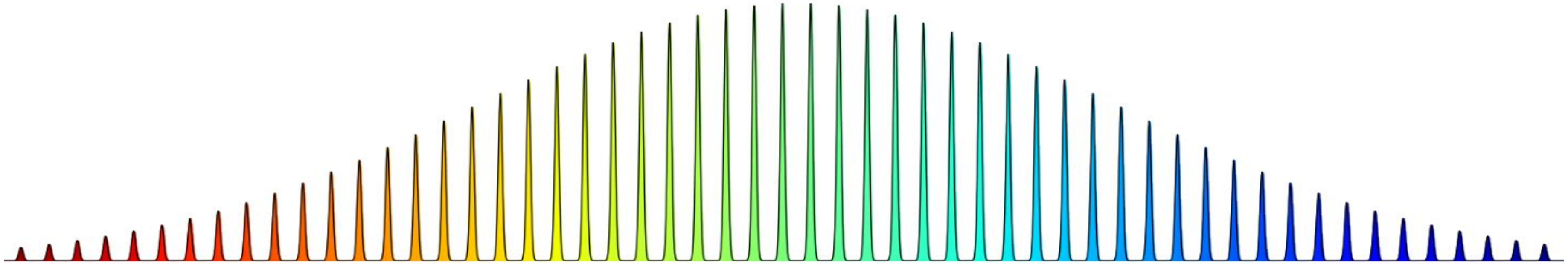
1. ?

Project Deliveries: Documents, no Hardware

Documents delivered (Technical Data Package):	Author/Source:
1. Review of Literature	Menlo, iXblue
2. Technical Requirements Review	Menlo, iXblue
3. Preliminary Test Plan	Menlo
4. Optical Fiber Test Results 1&2 Generation	iXblue
5. Oscillator Manufacturing Report 1&2 Generation	Menlo
6. Amplifier Manufacturing Report 1&2 Generation	Menlo
7. Manufacturing Report of Stabilized OFC	Menlo
8. Test Results for Stabilized OFC	Menlo
9. Technology Development Roadmap	Menlo
10. Technical Data Package	Menlo

Pending Documents by 10/11/2022:	Status
1. Final Presentation	this file
2. Abstract	prepared for review
3. Brochure	missing template
4. Technology Achievement Summary	template in the contract
5. Summary Report	tbd
6. Executive Summary Report	tbd

Thank you for your time



Thanks to the collaborative efforts by

iXblue:	**G. Melin, B. Cadier, Th. Robin**
INT:	**J. Kuhnhenn, R. Wolf, U. Weinand**
ESTEC:	**A. Costantini, I. McKenzie (ESA)**

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