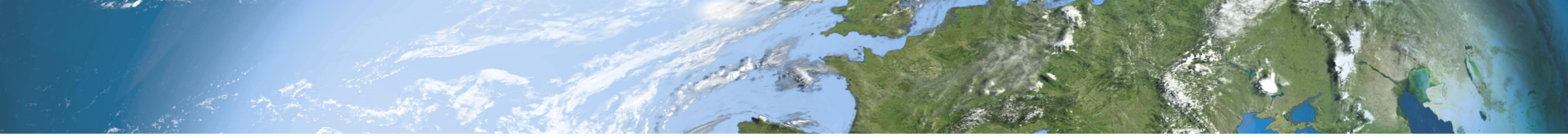

Ultra-Broadband Terahertz Time-Domain Sensing for Space Exploration

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BQ

INTEREST

Federal Ministry of Research, Technology and Space

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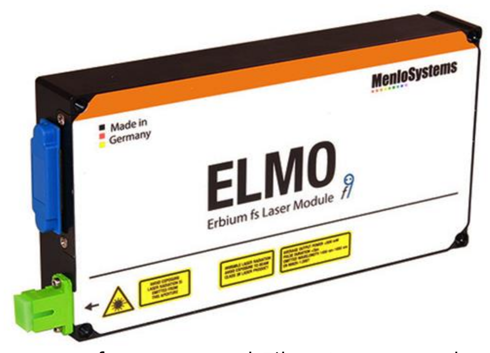
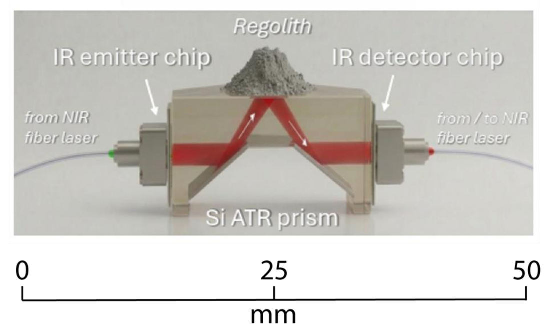
Motivation

Femtosecond lasers have in recent years been shown to be compact, robust and even space qualified [1,2], thereby so called, time-domain spectroscopy (TDS) techniques, which allow to avoid complex detector systems and/or bulky opto-mechanics of conventional instruments such as Fourier Transform Interferometers become viable options for more compact, energy/mass efficient and performant space instruments [3,6]. In this contribution we show how terahertz (THz) TDS emerges as an alternative to conventional infrared spectrometers in the spectral range of 10 – 1000 cm-1 (0.3 to 30 THz). Progress towards space qualification and chip integration is presented and future use cases such are THz TDS in attenuated total reflection (ATR) geometry are discussed.

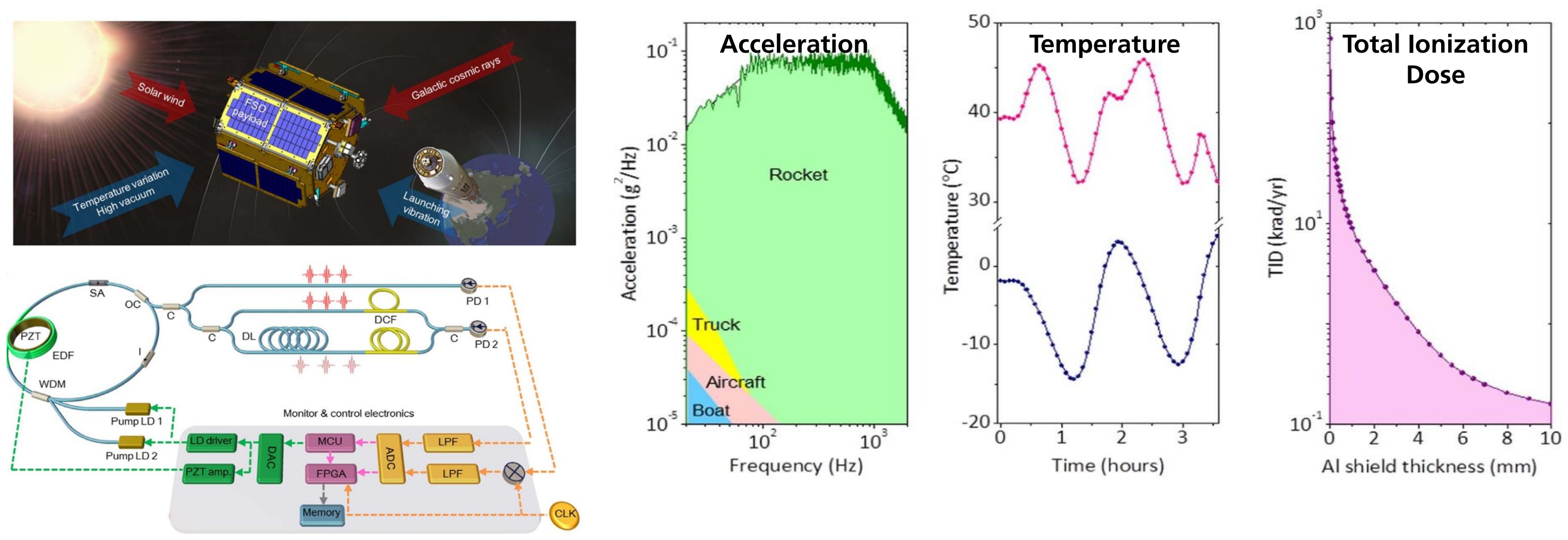


Compact femtosecond Fiber Lasers are becoming space ready [1], Credit: Menlo Systems GmbH [2]

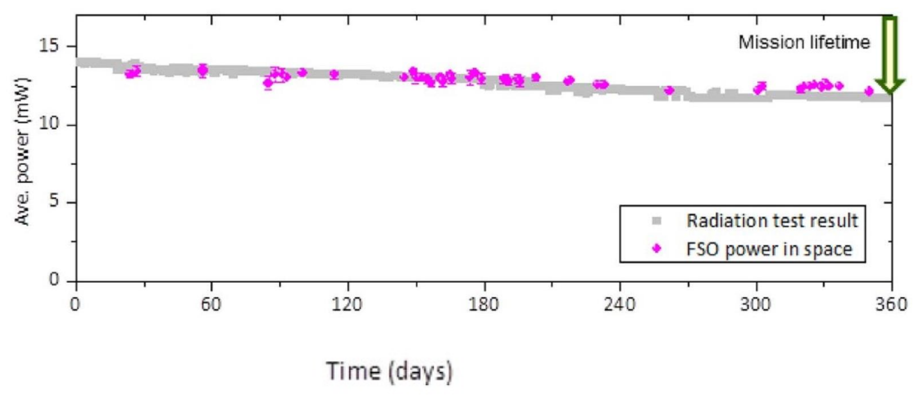


Vision:
fully integrated Time-Domain Infrared Spectrometer

Short Pulse Lasers In Space

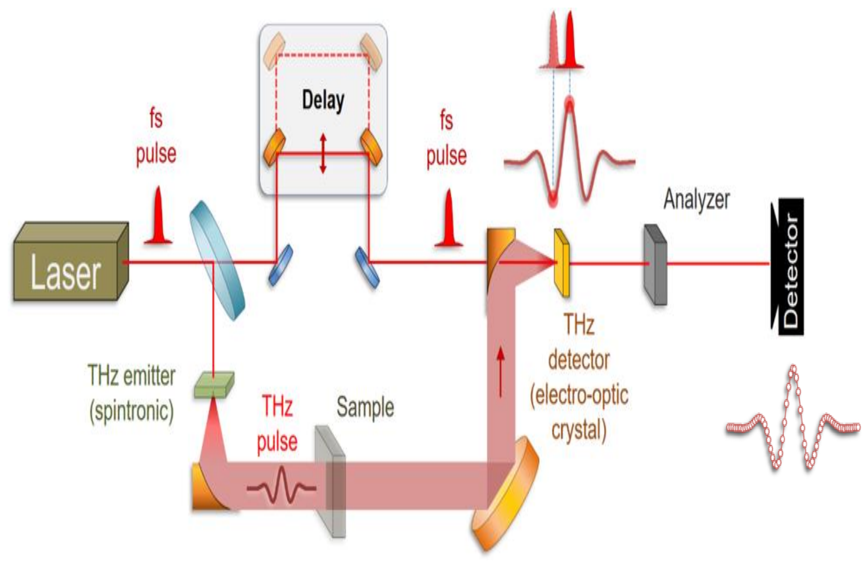


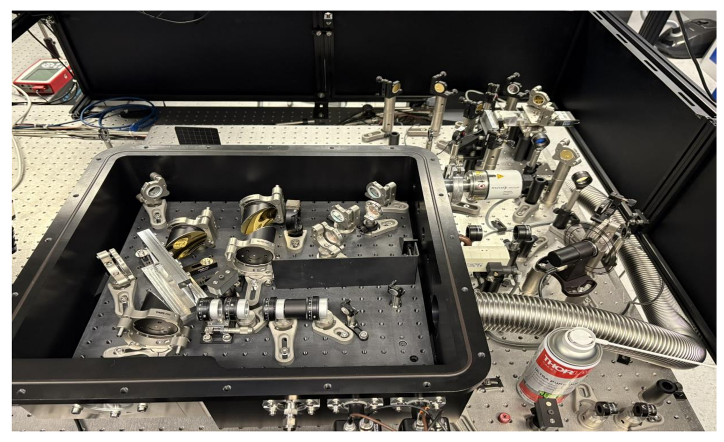
A demonstration mission showed that stable operation of a femtosecond fiber laser over a period of 12 months in low earth orbit is feasible [1].



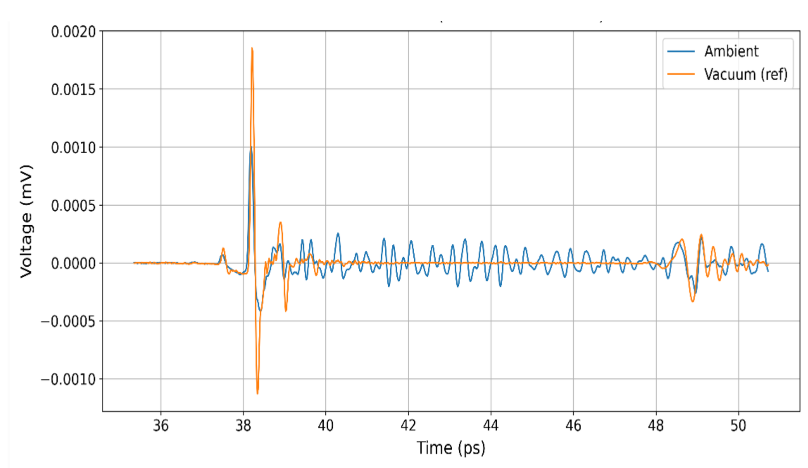
- Degradation of the average power of ~9% over 1 year due to radiation damage.
- 5mm thick Aluminum shielding would yield a stable performance over 65 years.

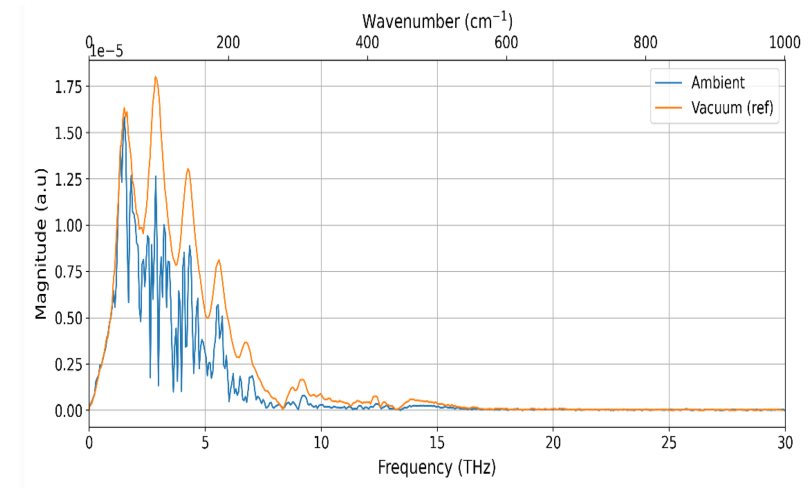
New in-vacuum THz-TDS Setup





- Enabling measurement in vacuum with up to 10^{-3} mbar
- Bandwidth (work in progress): 15THz



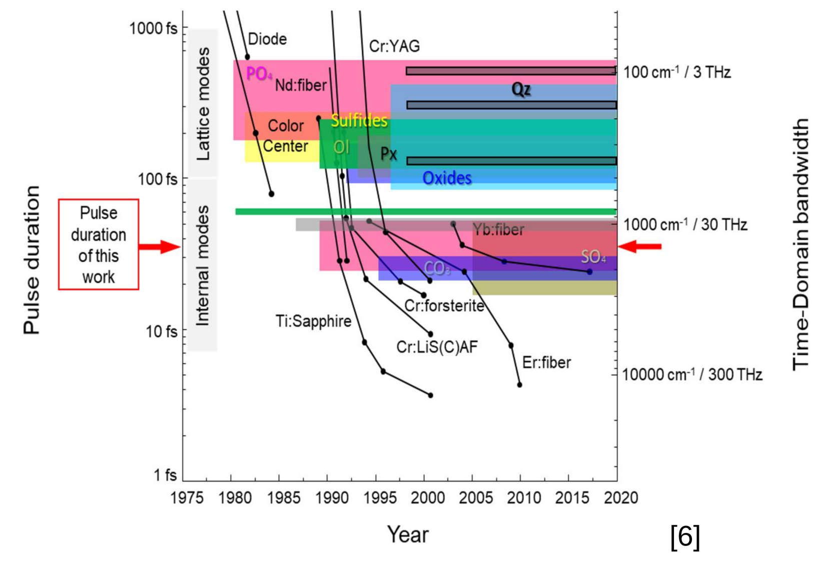


Measurement bandwidth $\Delta\nu$ defined by pulse duration δ for Gaussian pulses (time-bandwidth product)

$$\Delta\nu \cdot \delta = 0.44$$

- Spectral resolution f_{res} determined by time-scan window $\Delta\tau$

$$f_{res} = \frac{1}{\Delta\tau}$$

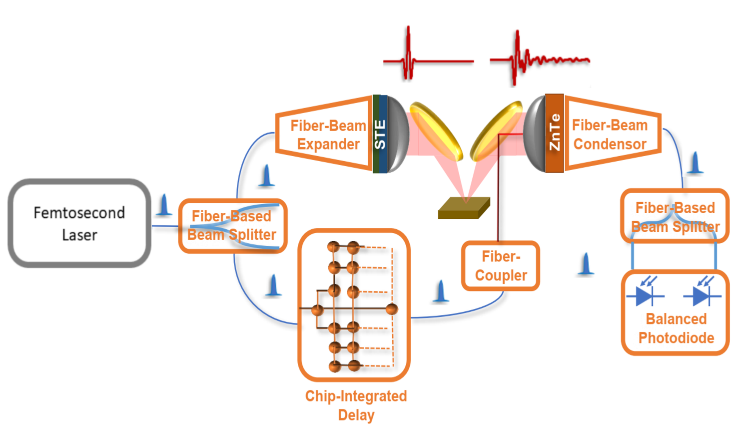


[6]

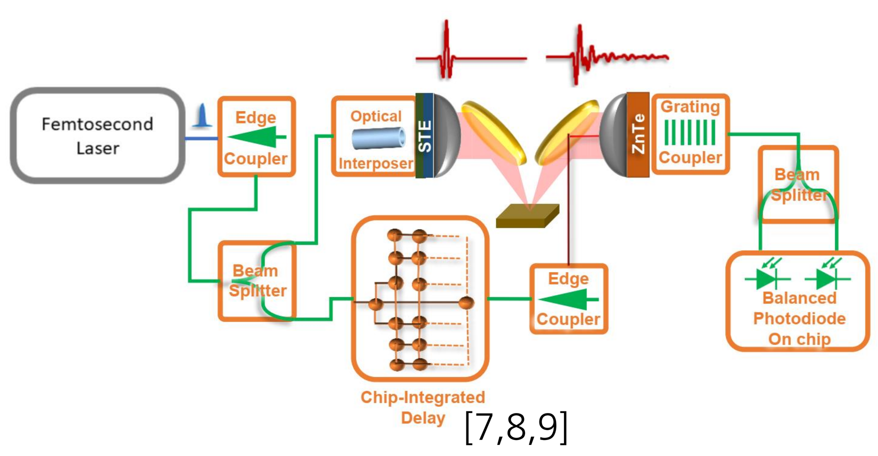
- A pulse duration of 30 fs yields a frequency bandwidth of 30 THz, assuming a 10^{-6} dynamic range
- A resolution of 100 GHz requires a time-scan window of 10 ps.

Towards Space-Qualified TDS

Fiber Platform

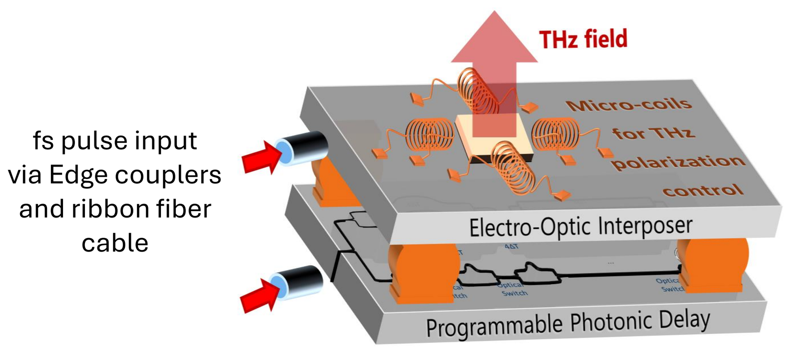


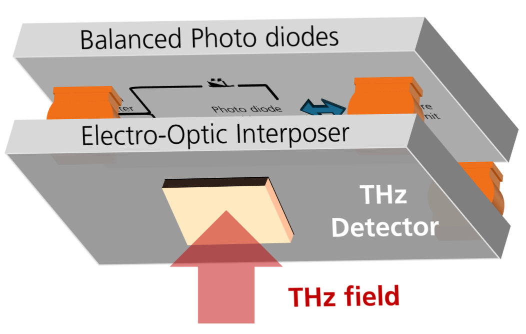
Waveguide Platform

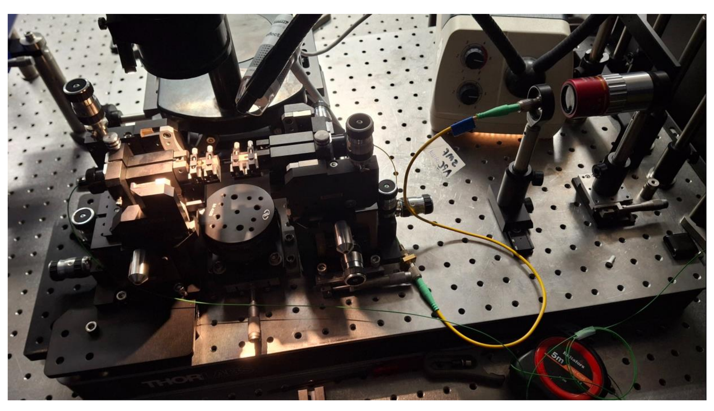


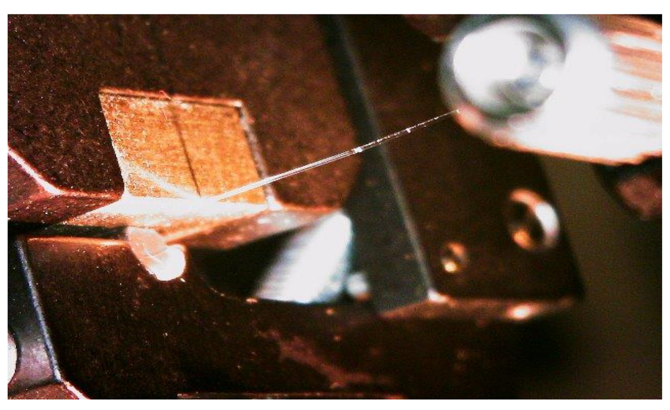
[7,8,9]

THz TDS system 3D packaging:

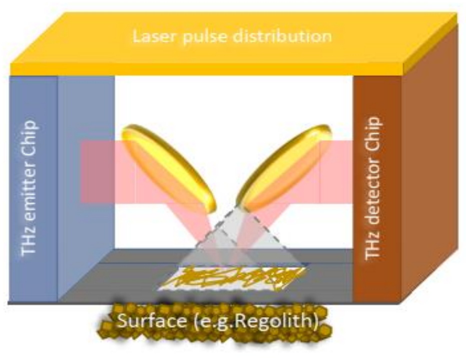


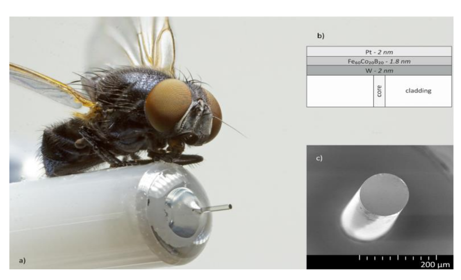






- ➢ Space qualified THz TDS
- ➢ Broad Bandwidth: 30 THz
- ➢ Compact Size: < 1000 cm^{-3}
- ➢ Low Weight: < 5 kg



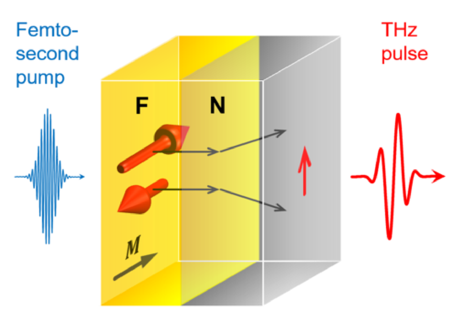


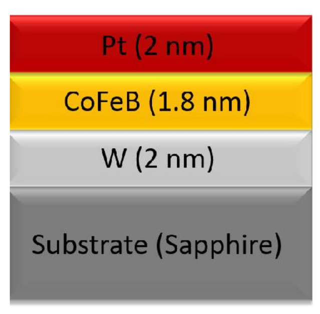
[4]

Goal for 2028: THz-TDS spectrometer for the moon @TRL6*

*TRL - Technical Readiness Level

Space-Ready Spintronic-THz Emitters

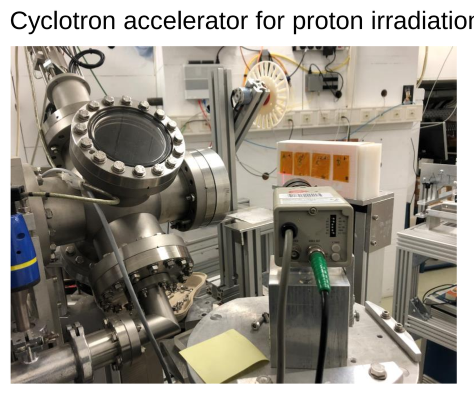




[5, modified]

Co60 source for γ- irradiation

Cyclotron accelerator for proton irradiation



Radiation hardness tests of the ultrabroadband spintronic THz emitters (STE) were successful [3].

[1] J. Lee, K. Lee, Y. Jang, et al., "Testing of a femtosecond pulse laser in outer space," Scientific Reports, vol. 4, pp. 5134 (2014)
[2] Menlo Systems GmbH, priv. com.
[3] O. Gueckstock et al, "Radiation hardness of ultrabroadband spintronic terahertz emitters: Enroute to a space-qualified time-domain gas spectrometer,"Appl. Phys. Lett. 124, 141103(2024).
[4] Felix Paries, et al. "Fiber-tip spintronic terahertz emitters," Opt. Express 31, 30884-30893 (2023)
[5] Schulz, Dominik, Benjamin Schwager, and Jamal Berakdar. "Nanostructured spintronic emitters for polarization-textured and chiral broadband THz fields," *ACS Photonics* 9.4, 1248-1255 (2022).
[6] Y.Ha, S. G.Pavlov, M. D.Rabasovic, et al., "Time-Domain Raman Spectroscopy: An Emerging Technique in Space Exploration?," Journal of Raman Spectroscopy 56, 916-919 (2025).
[7] S.A. Charania and D. Plettemeier,"*Ultra-High resolution tunable chip-integrated photonic delay line for THz Time-Domain Spectrometer*. 2025. 16th German Microwave Conference (GeMiC), Dresden, Germany, 286–289 (2025).
[8] Y. Ha, J. Woeste, D.A. Azih, et al. „Deterministic Compressed Sensing in Time-Domain Spectroscopy," Applied Spectroscopy (2026)
[9] "Verfahren und Vorrichtung zur Zeitbereichsspektroskopie mit reduzierter Stützstellenerfassung", German Patent 10 2024 118 136. (2026)

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