University of Bremen

MAPEX Bremen
Material. Process. Excellence.

SOLAR SAIL PROPULSION LIMITATIONS DUE TO HYDROGEN BLISTERING: PROGRESSION OF REFLECTANCE DECREASE

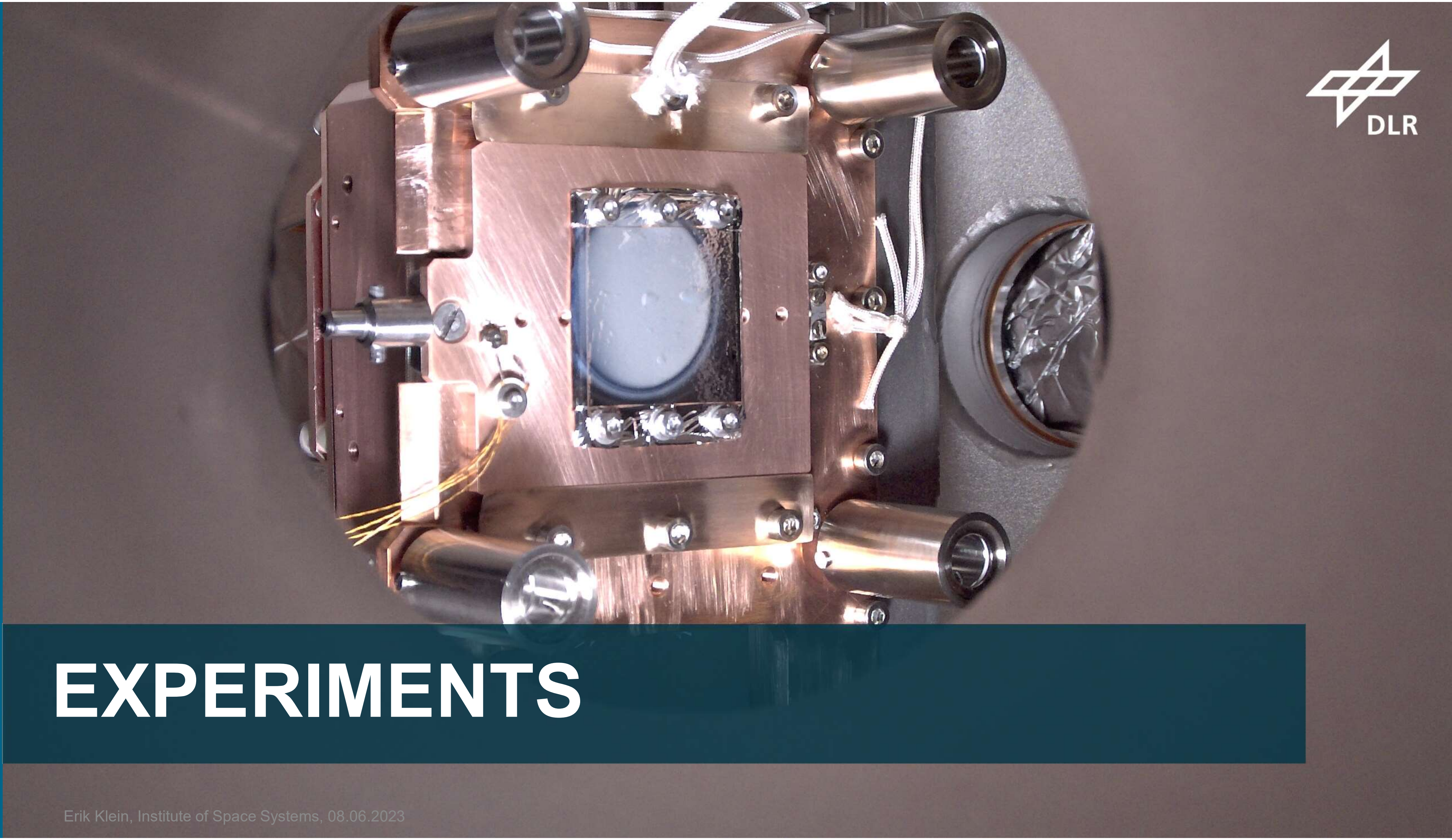
The 6th International Symposium on Space Sailing

Erik M. Klein, Patric Seefeldt, Maciej Sznajder

DLR

Introduction Content

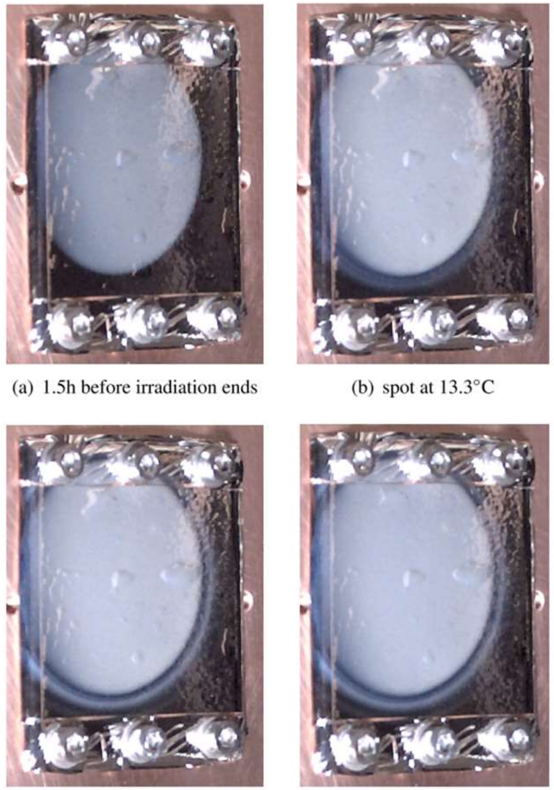
- Analysing data from the blistering study from 2022, presented on the last ISSS.
- Analysis of time-labs pictures in order to understand the change of reflectance over time.
- Attempt to model the progression over time, having only the brightness of pixels as well as measurements before and after



EXPERIMENTS

Radiation exposure

- Continuation of an hydrogen blistering study from 2020
- Irradiation of solar sail membrane, coated with aluminium, for various temperature.
- Observation of hydrogen blister formation for only certain temperature
- E.g. warm/hot aluminium coating is less likely to form hydrogen blisters



(a) 1.5h before irradiation ends (b) spot at 13.3°C

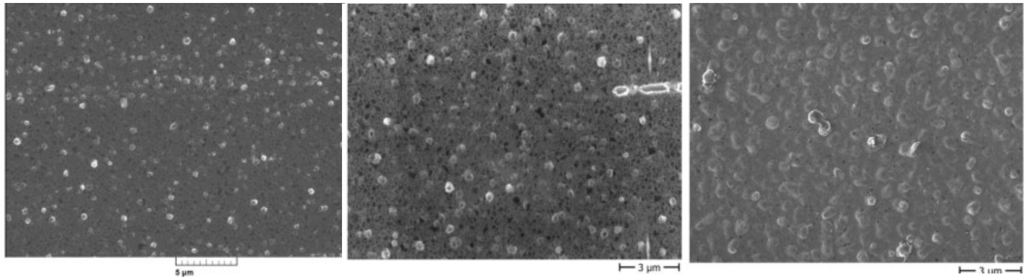
(c) spot at 75°C (d) spot at 16°C

Figure 9: Sample S1 at four different stages of the irradiation test.

Sznajder, M.; Seefeldt, P.; Spröwitz, T.; Renger, T.; Kang, J. H.; Bryant, R.; Wilkie, W. (2020): Solar sail propulsion limitations due to hydrogen blistering. In: *Advances in Space Research*.

Proton radiation and blistering

- Recombination of protons with free electrons in the aluminium coating to hydrogen
- Test flux $1.4 \cdot 10^{12} P^{+} cm^{-2} s^{-1}$



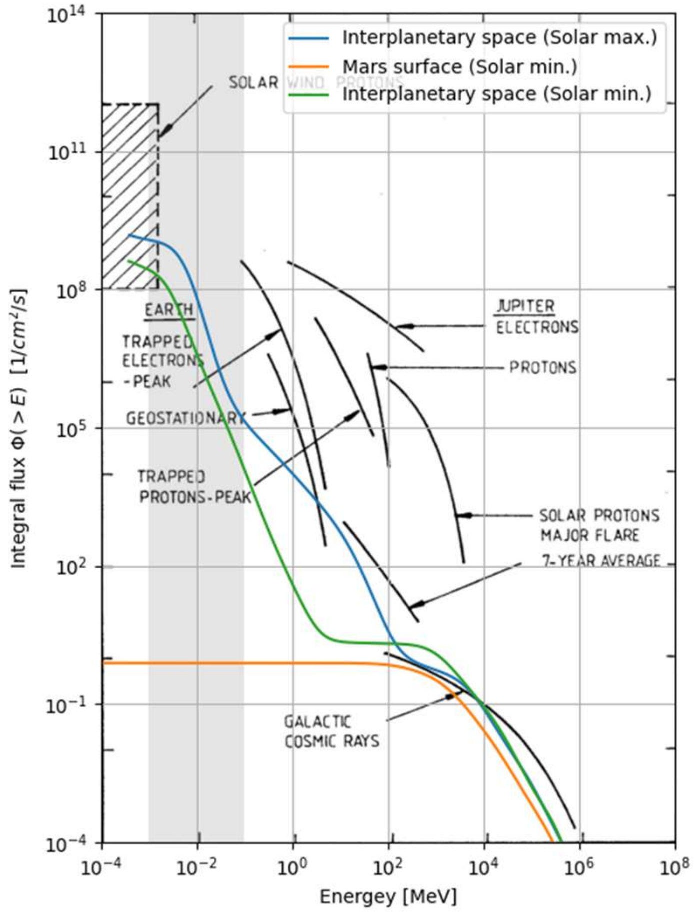
$7.8 \cdot 10^{17} P^{+} cm^{-2}$ $8.2 \cdot 10^{17} P^{+} cm^{-2}$ $1.3 \cdot 10^{18} P^{+} cm^{-2}$

- Process depends on multiple parameters:
  - Temperature (high: > 65°C partial evaporation, <65°C bubbles form
  - For low temperatures the mobility of hydrogen atoms is slow, so that bubbles grow very slow, but if temperatures increase the formation appears rapidly
  - Proton Energy (protons needs to get trapped within the aluminium layer)
  - Flux (< 2.3 x 10^{12} p^{+} cm^{-2} s^{-1} bubbles form, high flux destroys aluminium oxide lattice -> smaller and significantly less bubbles)
  - **Time**

Proton radiation spectra

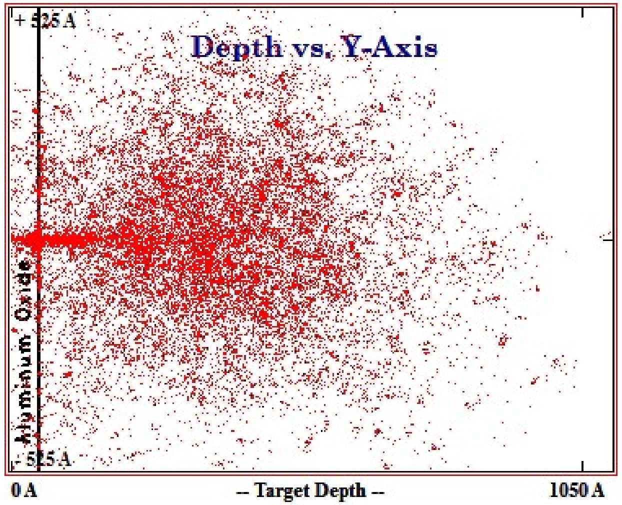
- Spectrum comparison

- Sznajder, Maciej (2023): Solar wind H+ fluxes at 1 AU for solar cycles 23 and 24. In : *Advances in Space Research* 71.11 (2023): 4923-4957.
- Klein, E. M.; Sznajder, M.; Seefeldt, P. (2022): Proton Spectra for the Interplanetary Space Derived From Different Environmental Models. In: Front. Space Technol. 3, Artikel 933340, S. 14. DOI: 10.3389/frspt.2022.933340.#
- European Space Agency (1993): Radiation Design Handbook. Hg. v. ESA Publications Division. European Space Agency.
- Matthiä, Daniel; Berger, Thomas (2017): The radiation environment on the surface of Mars - Numerical calculations of the galactic component with GEANT4/PLANETOCOSMICS. In: Life Sciences in Space Research 14, S. 57–63. DOI: 10.1016/j.lssr.2017.03.005.



Proton radiation and surface degradation

- Low energy protons get trapped in the very surface of material and therefore have the highest impact with respect to surface chages
- The penetration depth can be calculated with Bethe-Bloch equation, e.g. using Srim. Example for 2.5keV protons radiating on 100nm aluminium layer with a 5nm oxide layer.

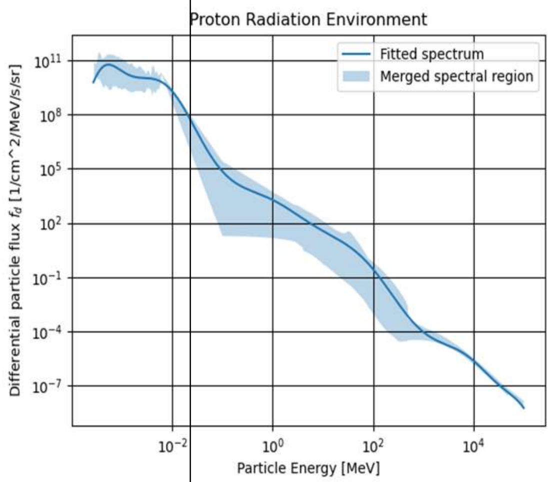


➢ J. F. Ziegler. Srim software, 2013. www.srim.org (Bethe-Bloch equation)

Proton radiation and surface degradation

- Proton energies for which the protons get stuck in the layer of interest
- Radiation tests can only be made with one particle energy
- Calculating the flux up to that energy can be used to define test conditions

$5.3 \cdot 10^8 P^+ cm^{-2} s^{-1}$



2.5keV

$$f = \int_0^{2.5keV} f_d dE = 5.3 \cdot 10^8 P^+ cm^{-2} s^{-1}$$

Test flux $1.4 \cdot 10^{12} P^+ cm^{-2} s^{-1}$

Samples

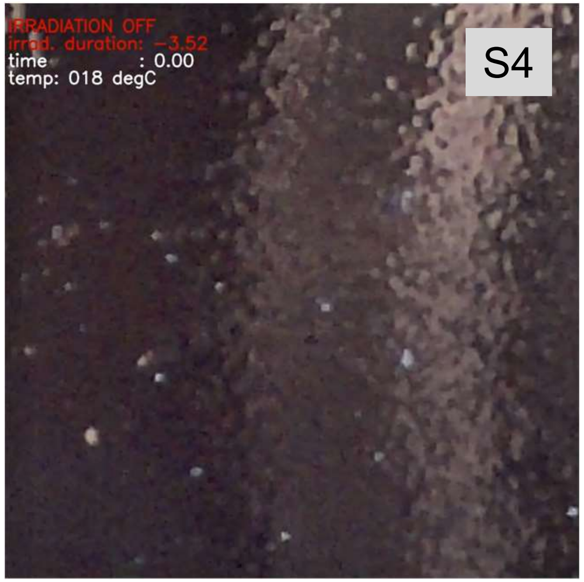
- Sample have been irradiated with the same particle fluence and flux, e.g. **acceleration factor**
- Temperatures varied from **-175 °C to 113 °C**
- Clearly, the **hotter** the samples, the **less** their reflectance has been diminished

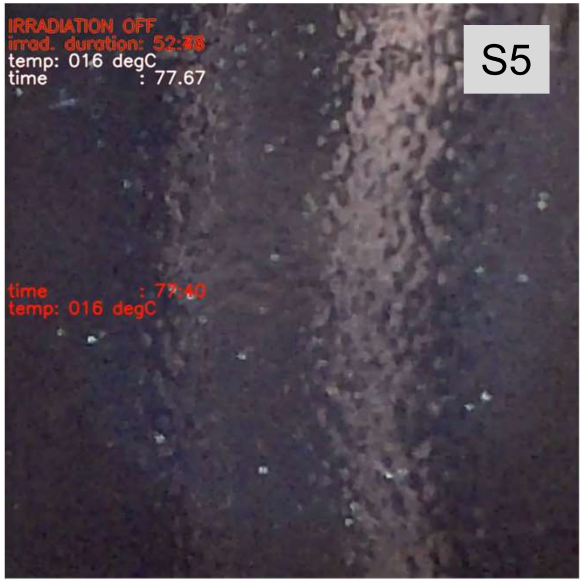
Table 2: Change of relative specular reflectance weighted with the ASTM E490 reference spectrum of irradiated samples given in %-value. As reference sample the unexposed material was used. In addition the temperature during radiation and the max. curing temperature after radiation is given

Sample	Rad. Temp. [°C]	Max. Temp. [°C]	R_S/R_{ref} [%]
S1	-176	75	73.05
S2	-100	39.3	66.94
S3	31.6	31.6	96.93
S4	75	75	90.48
S5	113	113	99.77

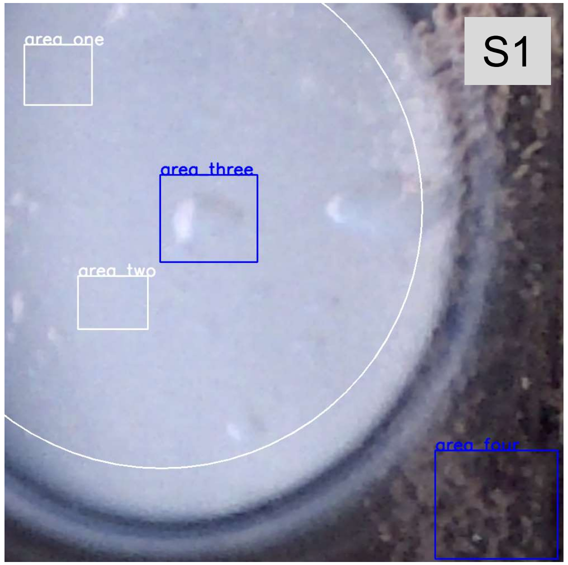
Sznajder, M.; Seefeldt, P.; Spröwitz, T.; Renger, T.; Kang, J. H.; Bryant, R.; Wilkie, W. (2020): Solar sail propulsion limitations due to hydrogen blistering. In: *Advances in Space Research*.

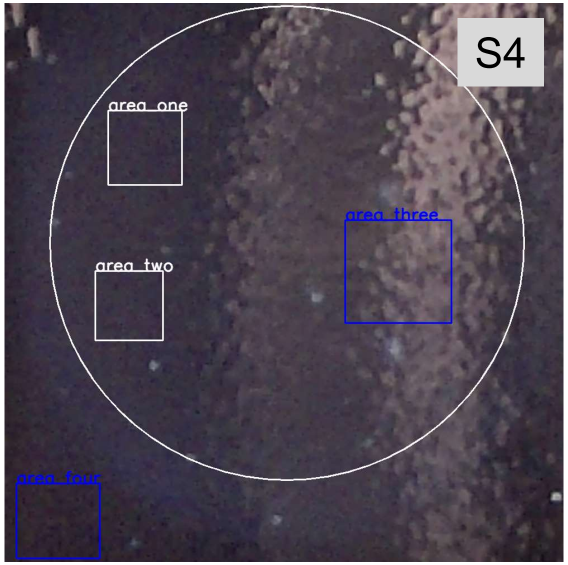
Time labs pictures during radiation

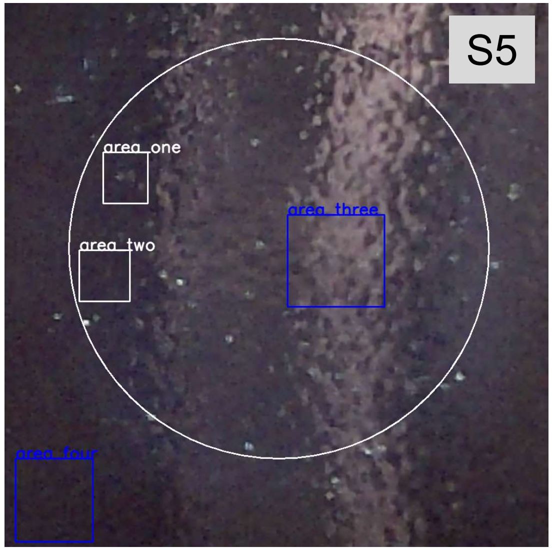




Total and specular reflectance



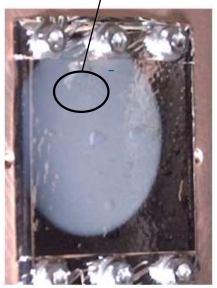




Objective

- Further evaluate the course of the blister formation over time and fluence
  - **Pristine and final** values for diffuse and specular reflectance **known**: What happens in between?
  - Especially during irradiation
  - For a given irradiation environment, e.g. **particle flux and temperature**, what is the course over time of reflectance parameters?

Britghness of pixel B

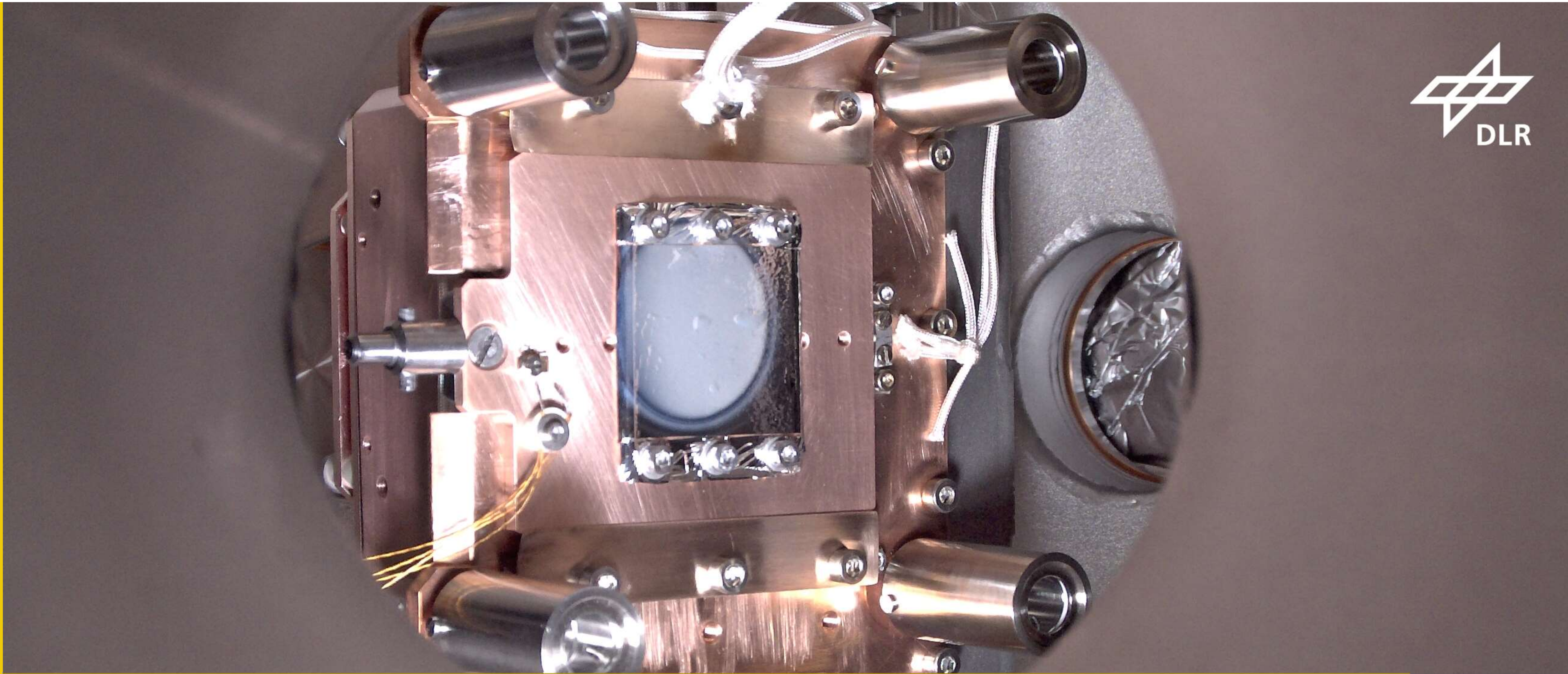


Boundary conditions, reflectance values before and after test!

Sample	Rad. Temp. [°C]	Max. Temp. [°C]	R_S/R_{ref} [%]
S1	-176	75	73.05
S2	-100	39.3	66.94
S3	31.6	31.6	96.93
S4	75	75	90.48
S5	113	113	99.77

Change of specular reflectance ρ_s as a function of fluence F.

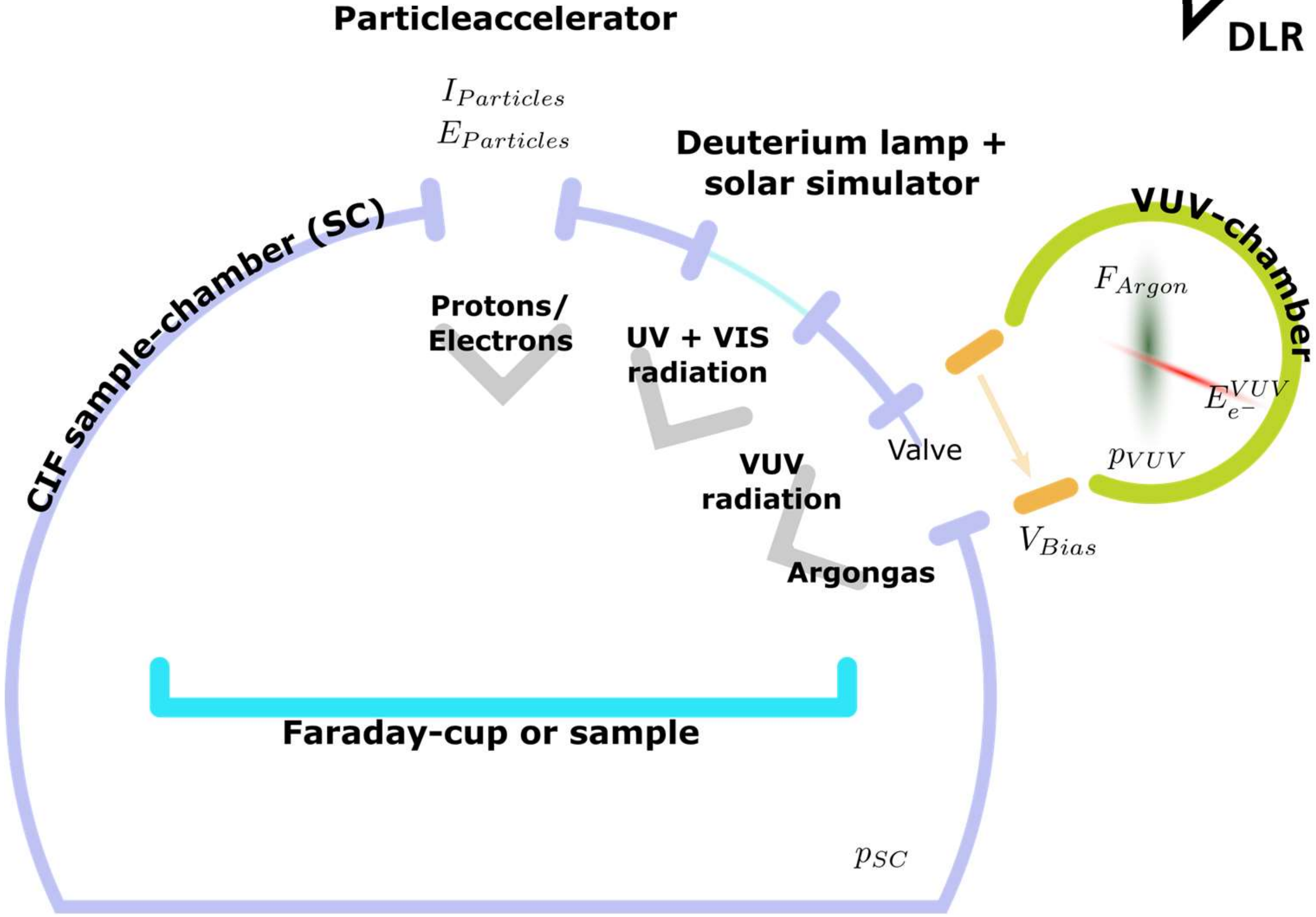
Correlation of the change of reflectance ρ_s to a mission time.



MATHEMATICAL MODELLING

Complex Irradiation Facility

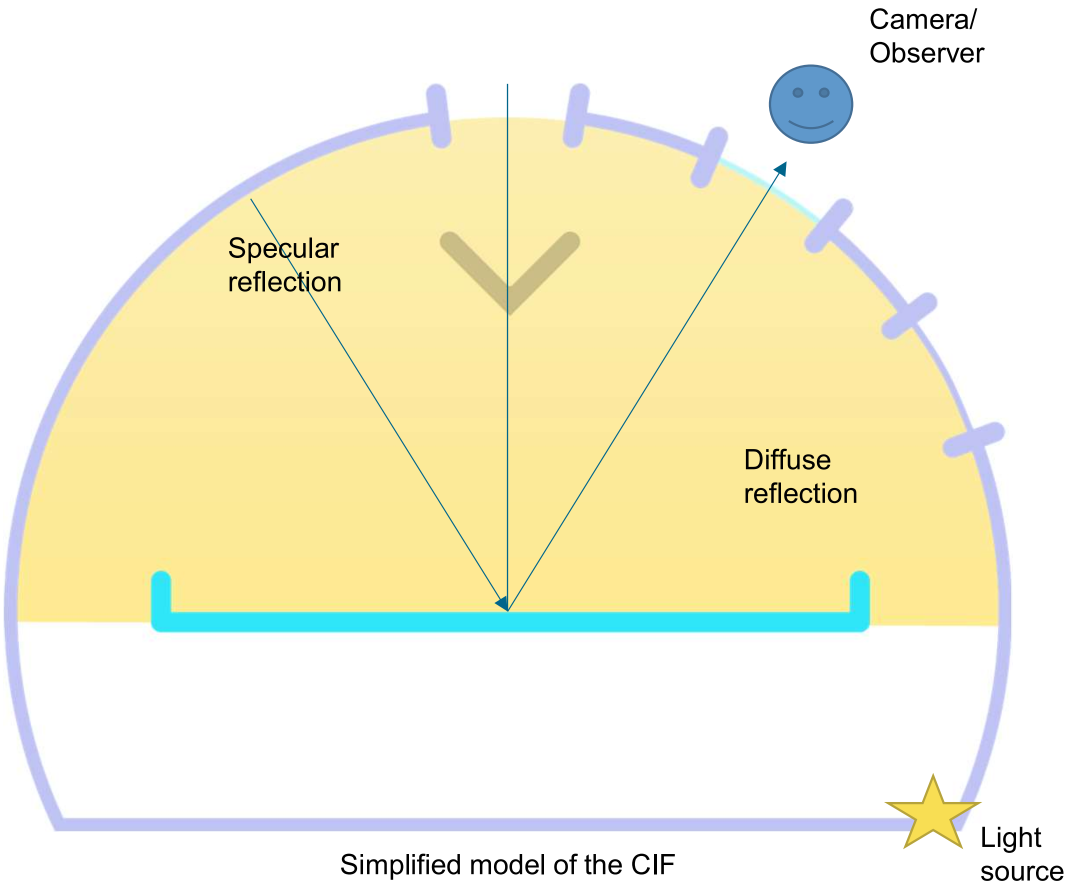
- Samples have been irradiated solely with **2.5 keV protons**
- Sample have been held at **constant** temperatures



Sketch of the working principle of the CIF. Next to particle source and sample chamber, essential process parameters, such as current IP articles and energy EP articles of the charged particle beams, are displayed. Depiction not to scale.

Modelling approach

- Perceived brightness is comprised of **specular** and **diffuse** reflected light
- The **light source**’ brightness is **constant**
- Hence, change in **perceived brightness** has to be accounted to change of thermo-optical properties: **reflectance** and **absorption**



Simplified model of the CIF

Modelling approach

- Brightness of pixel

$$B = \left[\rho_s I_i + \rho_D \cdot \frac{\cos(\Theta)}{\pi} \mathrm{G}\right] \frac{\rho}{\rho}$$

$$= \rho \left[s I_i + (1 - s) \cdot \frac{\cos(\Theta)}{\pi} \mathrm{G}\right]$$

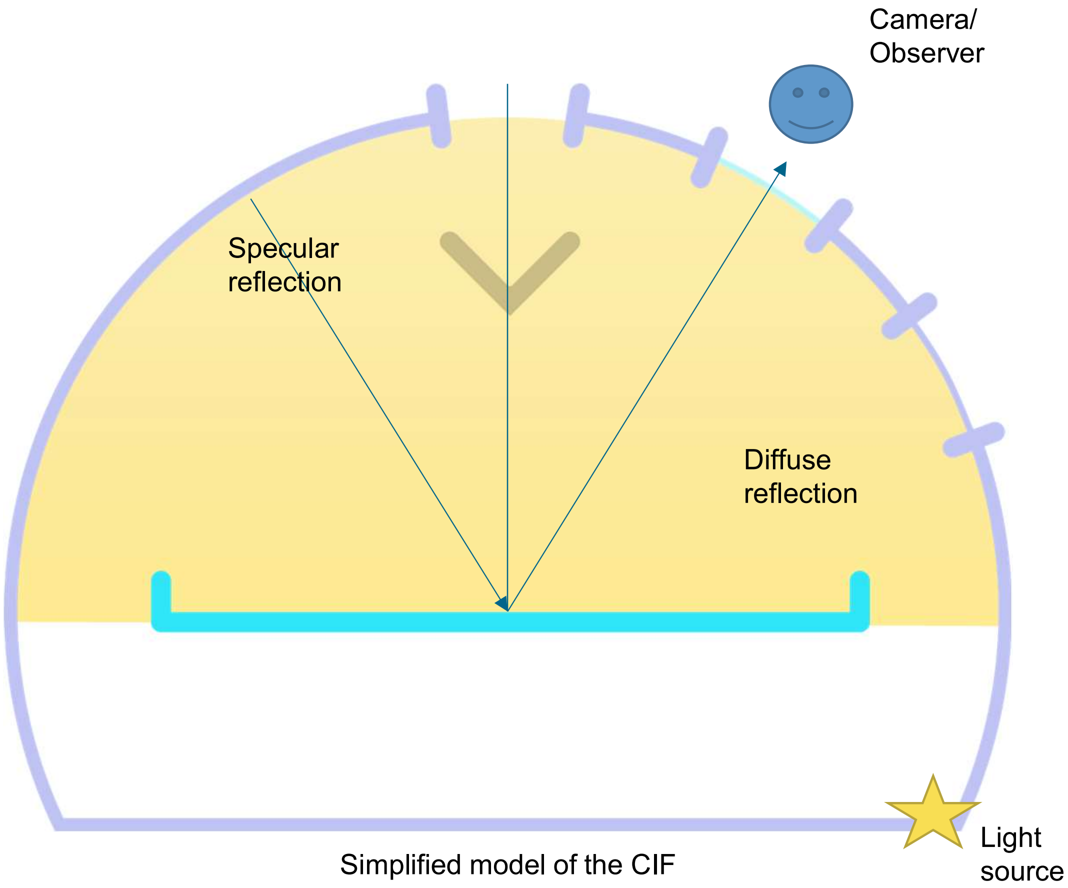
⇒From start and end values derive division of B between ρ_s und ρ_D

- Approach for fitting function

$$B = C_1 + C_2 \cdot (1 - e^{C_3 F})$$

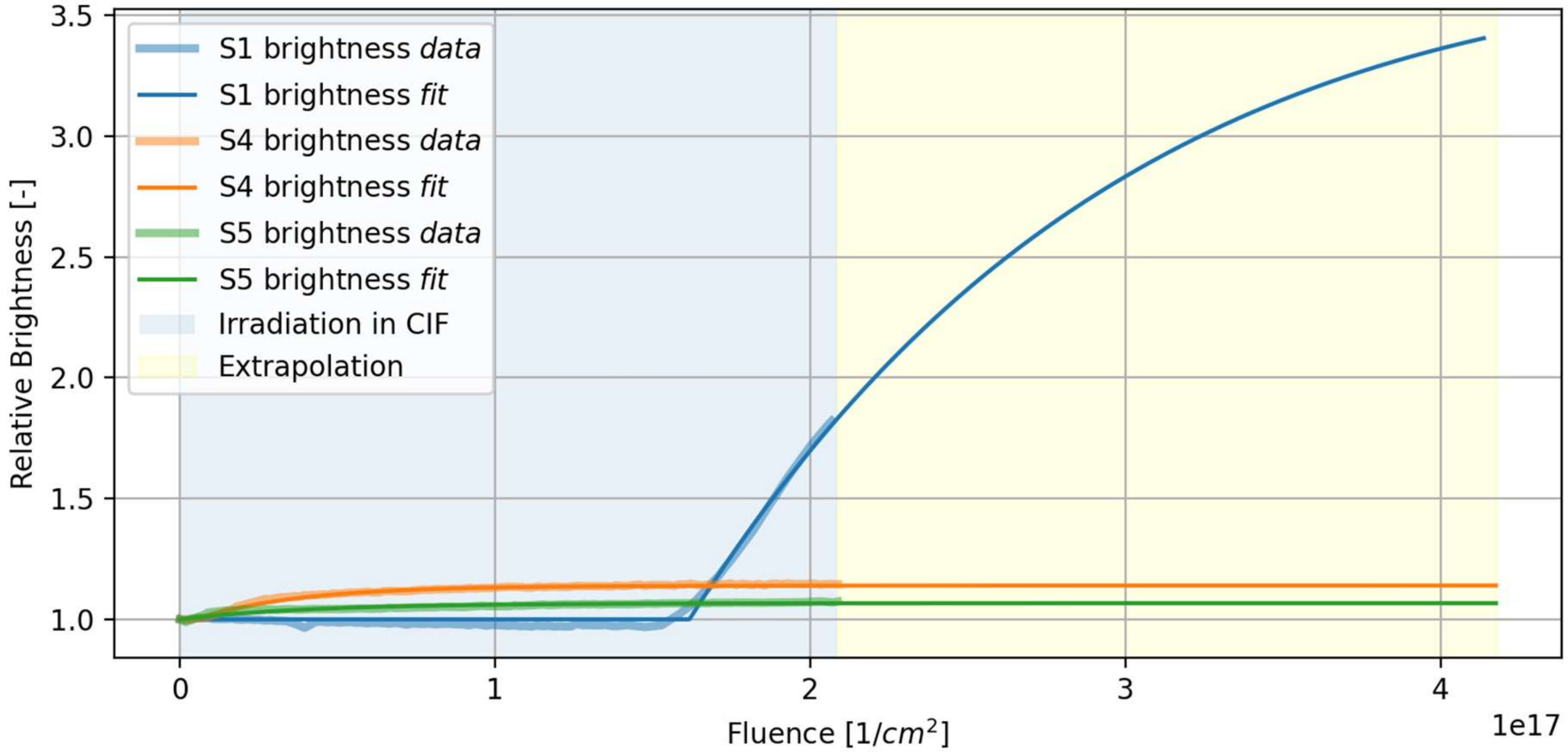
Compare with

➢ B. Dachwald et al. (2005), Potential Solar Sail Degradation Effects on Trajectory and Attitude Control AIAA Guidance, Navigation, and Control Conference and Exhibit 15 - 18 August 2005, San Francisco, California



Simplified model of the CIF

Results Pixel Brightness



Specular and diffuse reflection fitted to observed brightness data

Modelling progression of reflective properties

- Using the same fitting function for reflectance d

$$\rho_D = \rho_{D_0} + \Delta\rho_D\left(1 - exp\left(-\frac{F - F_0}{F_H}\right)\right)$$

⇒Using begin and end reflectance values as well as change of brightness

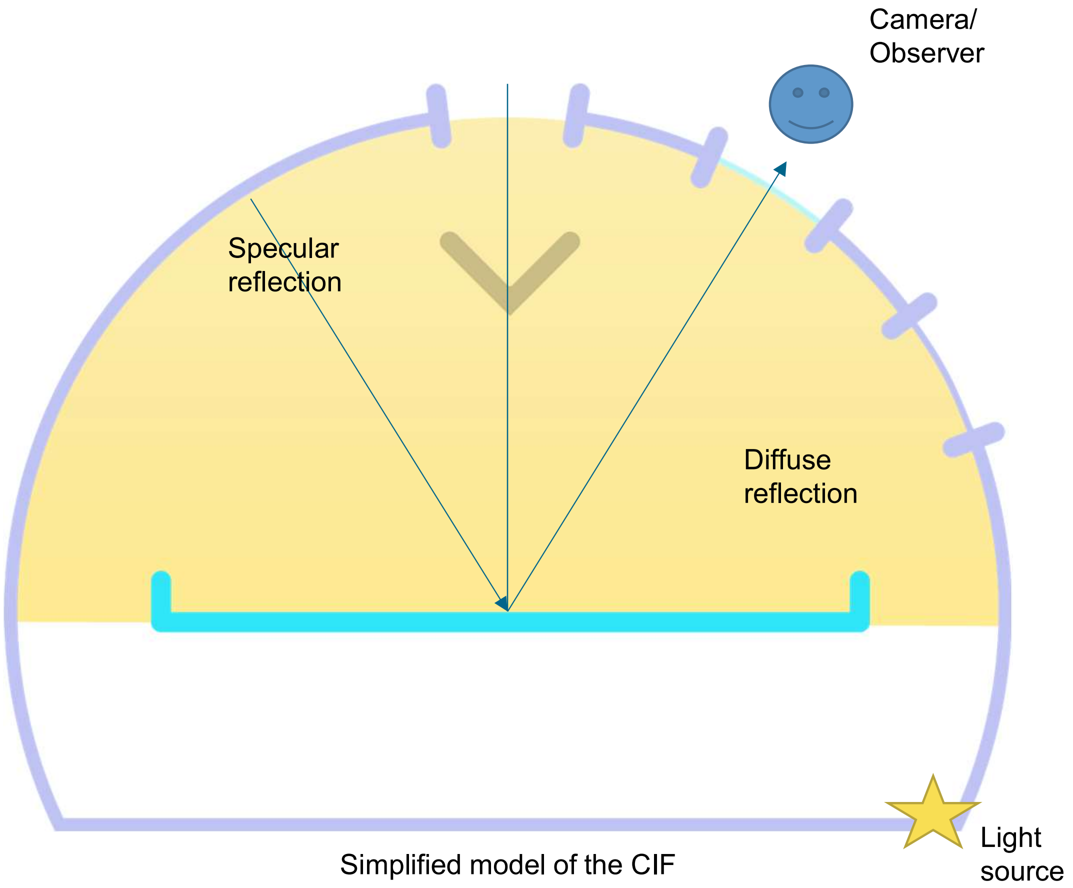
- If absorption α is not changing it is simple

$$\Rightarrow \quad d\rho_s + d\rho_d = 0$$

- However, if alpha is changing (Sample S1)

$$\Rightarrow \quad d\rho_s + d\rho_d + d\alpha = 0$$

⇒Additional relation for change of reflectance or absorptance is needed!



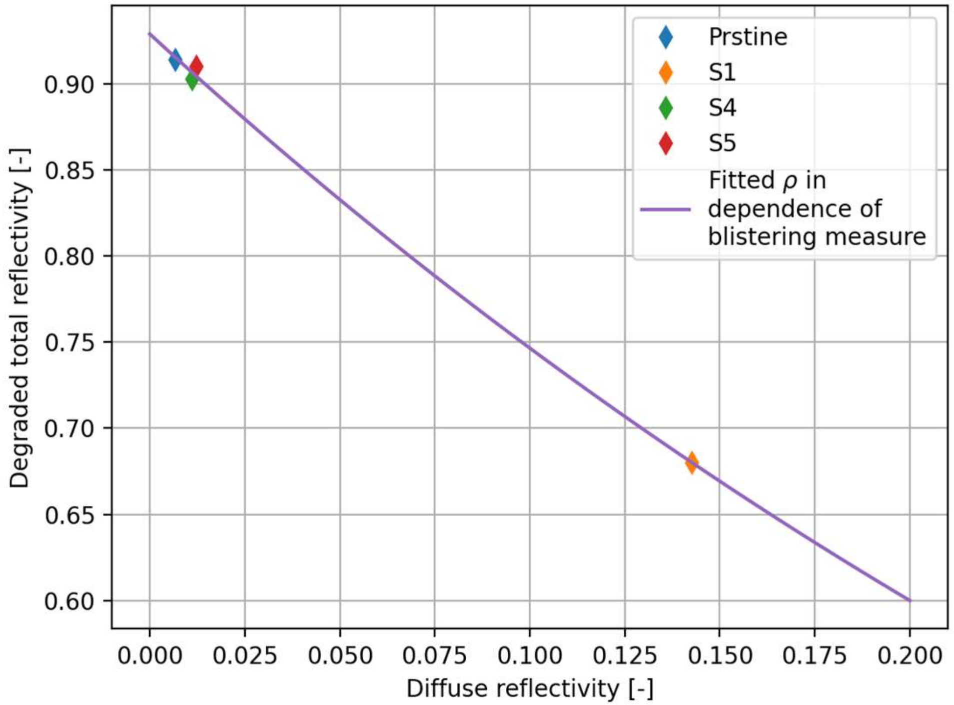
Simplified model of the CIF

Total reflectance modelling

- Total reflectance degradation in terms
- Assuming that the loss in total reflectiv to the blistering phenomena, there is a reflectivity
- Equation for the fitted reflectivity

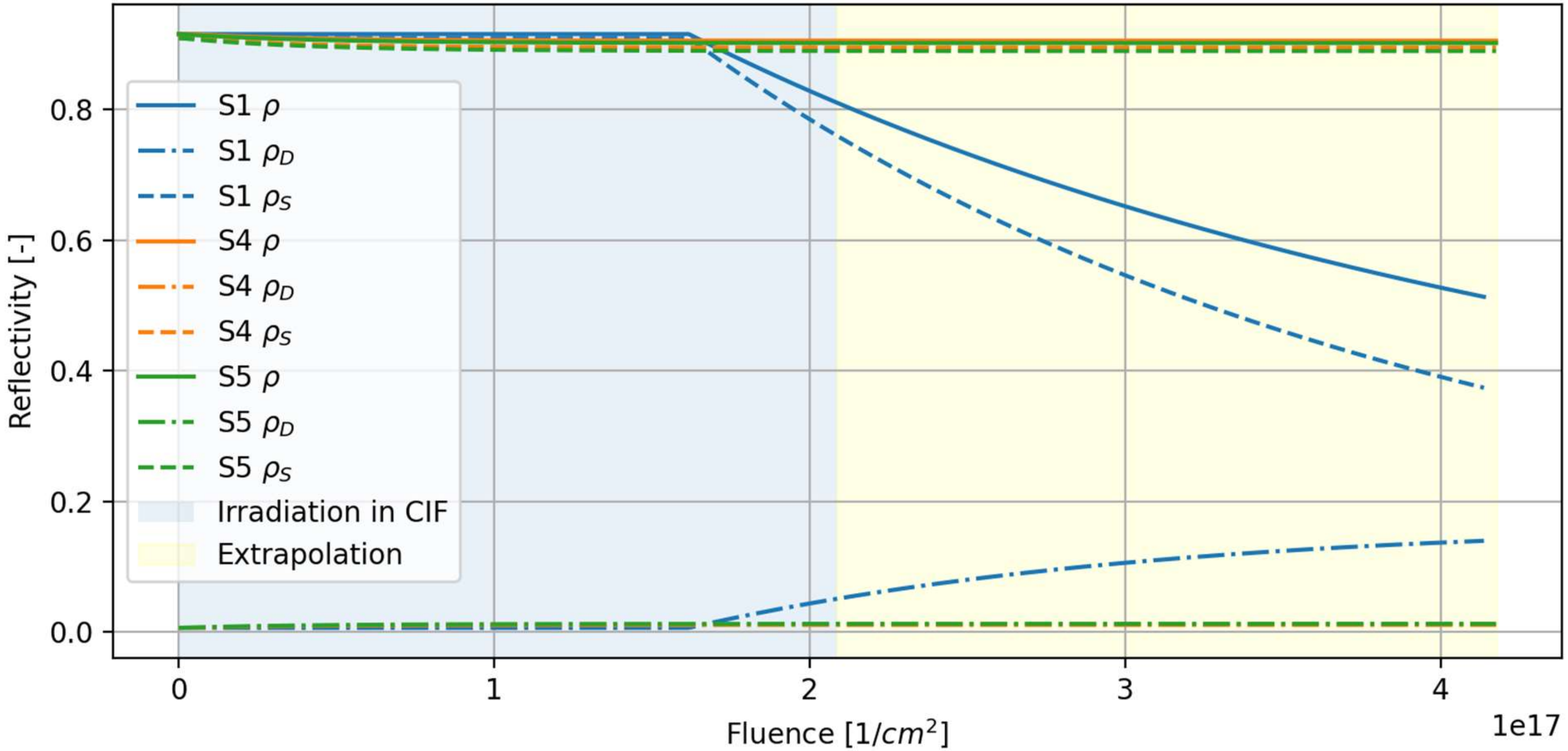
$$\rho = \rho_0^{a_1 \rho_D^2 + a_2 \rho_D + a_3}$$

$$\Rightarrow \alpha = 1 - \rho$$



Connection between diffuse and total reflectivity

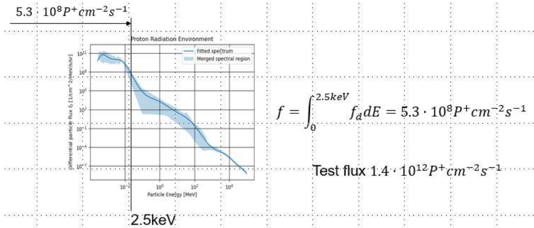
Results change of reflectance by fluence

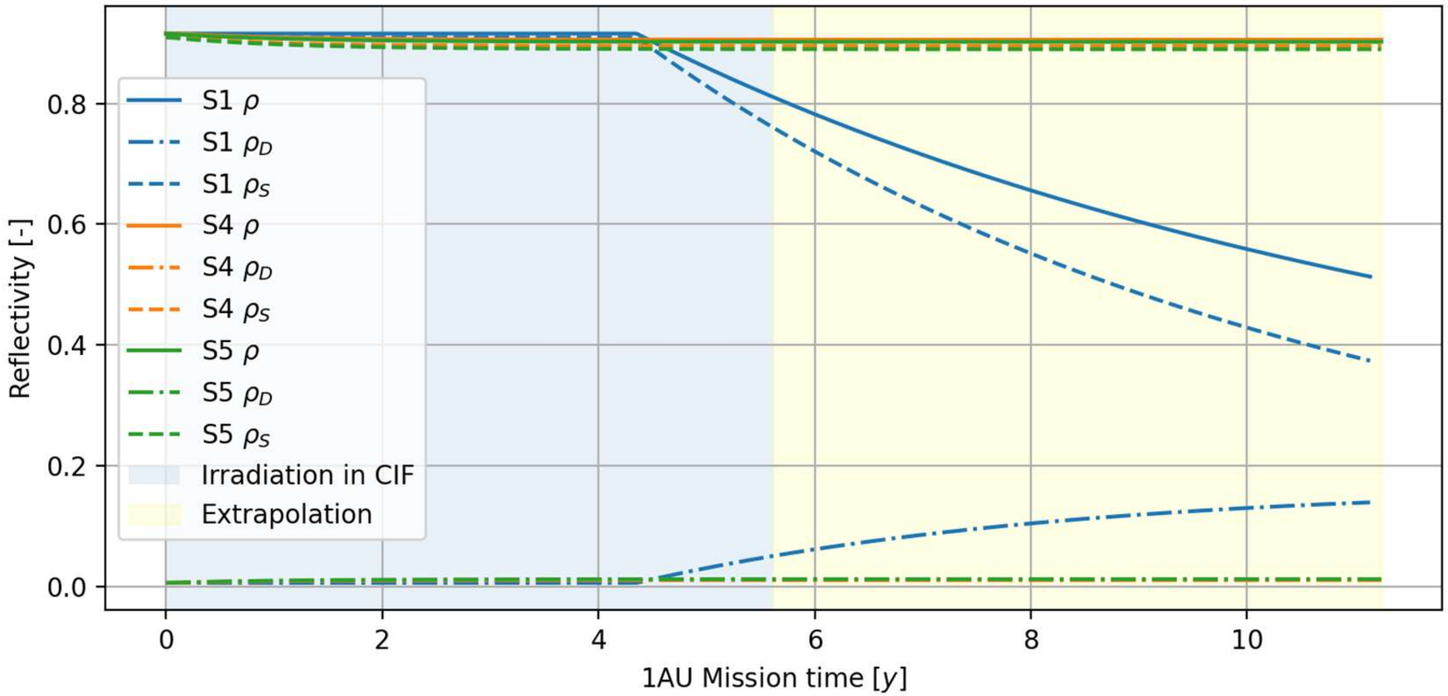


Reflectivity change over mission time at 1AU. Reference flux (1keV <= E <= 100keV), to convert fluence to time, taken from Klein, E. M.; Sznajder, M.; Seefeldt, P. (2022): Proton Spectra for the Interplanetary Space Derived From Different Environmental Models. In: Front. Space Technol. 3, Artikel 933340, S. 14. DOI: 10.3389/frspt.2022.933340. Further acceleration factor (~1700) will have influence on degradation.

Results change of reflectance over time

$$f = \int_0^{2.5keV} f_d dE = 5.3 \cdot 10^8 P^+ cm^{-2} s^{-1}$$





Conclusion

- We were able to derive (preliminary) results for the change of reflectance of aluminized solar sails as function of fluence and time for different temperatures.
- The previous assumptions of the radiation flux in space seem to be too conservative or over even simply overestimated. What seemed to happen in days now looks more to happen within years.
- It looks like there is a kind of saturation in the process. Rather that specular reflectance decreases further and further, it looks like a limit value is reached that depends on the temperature.
- Blistering must not be considered a show stopper for solar sailing, but it has influence on the performance. It can be controlled by keeping your sails warm an cozy.