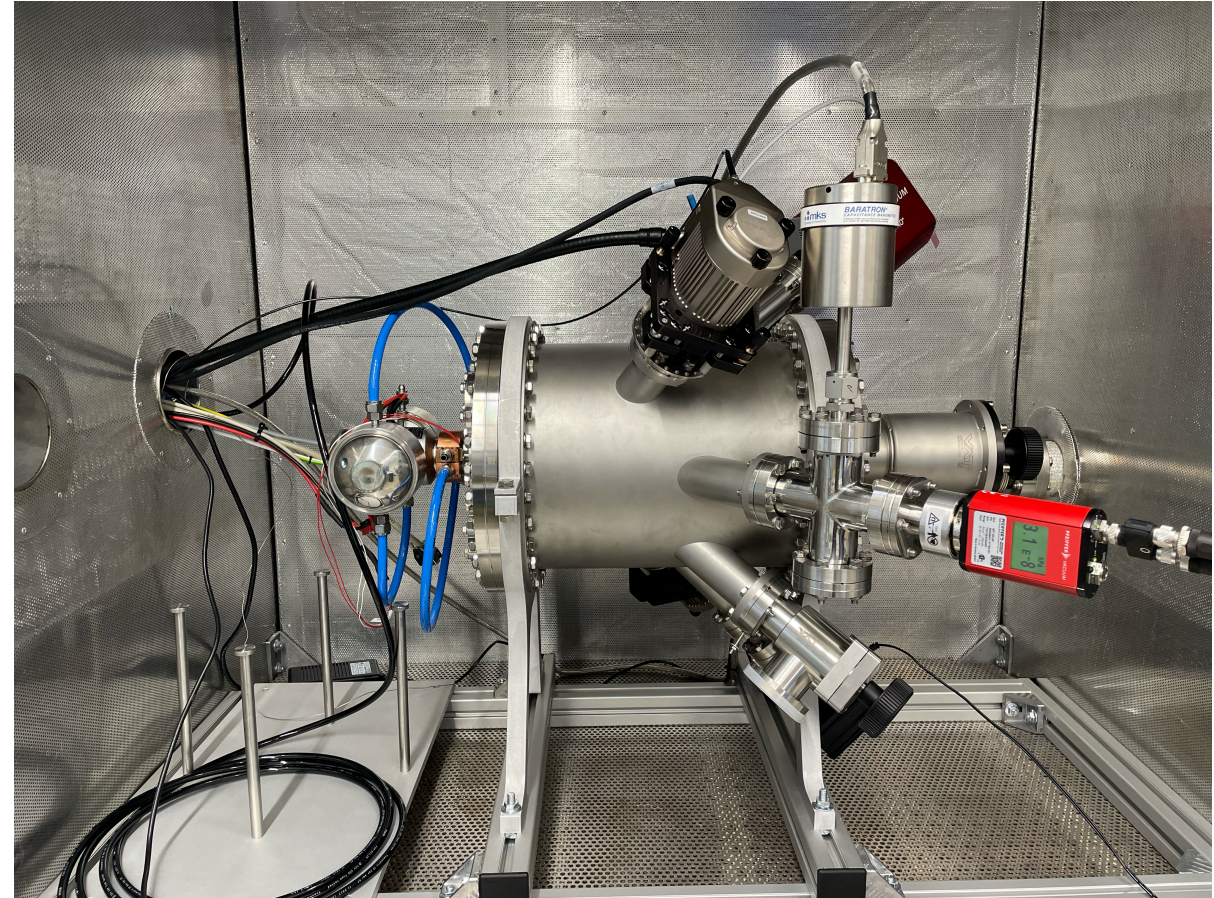


Monitoring and conditioning of cryogenic silicon mirrors for the Einstein Telescope

Markus Schulz-Ritz
16.07.2026

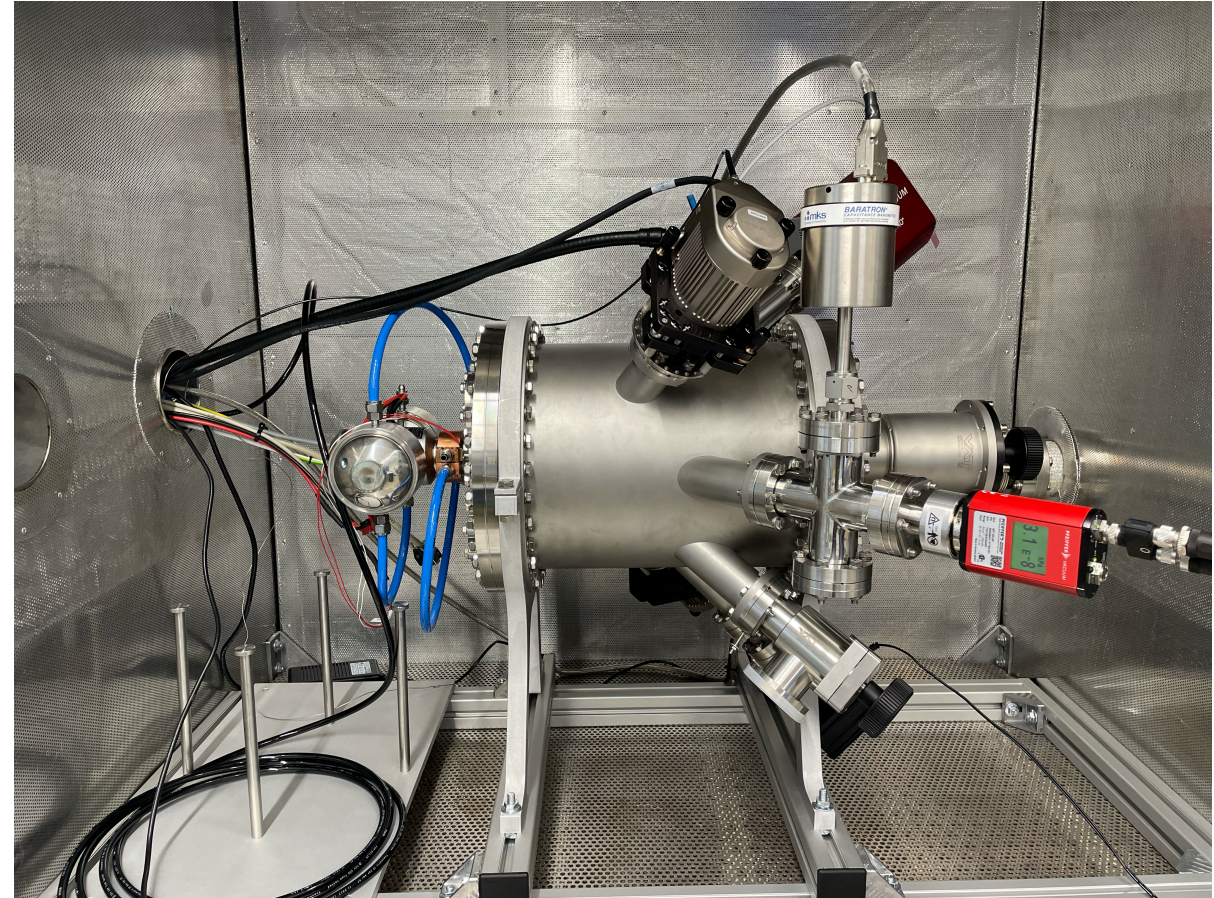


Outline

- Gravitational Waves and the Einstein Telescope
- The VINCENT Setup
- Vacuum simulations and measurements
- First tests of the conditioning methods in VINCENT
- Ellipsometry
- First ellipsometry measurements
- Outlook

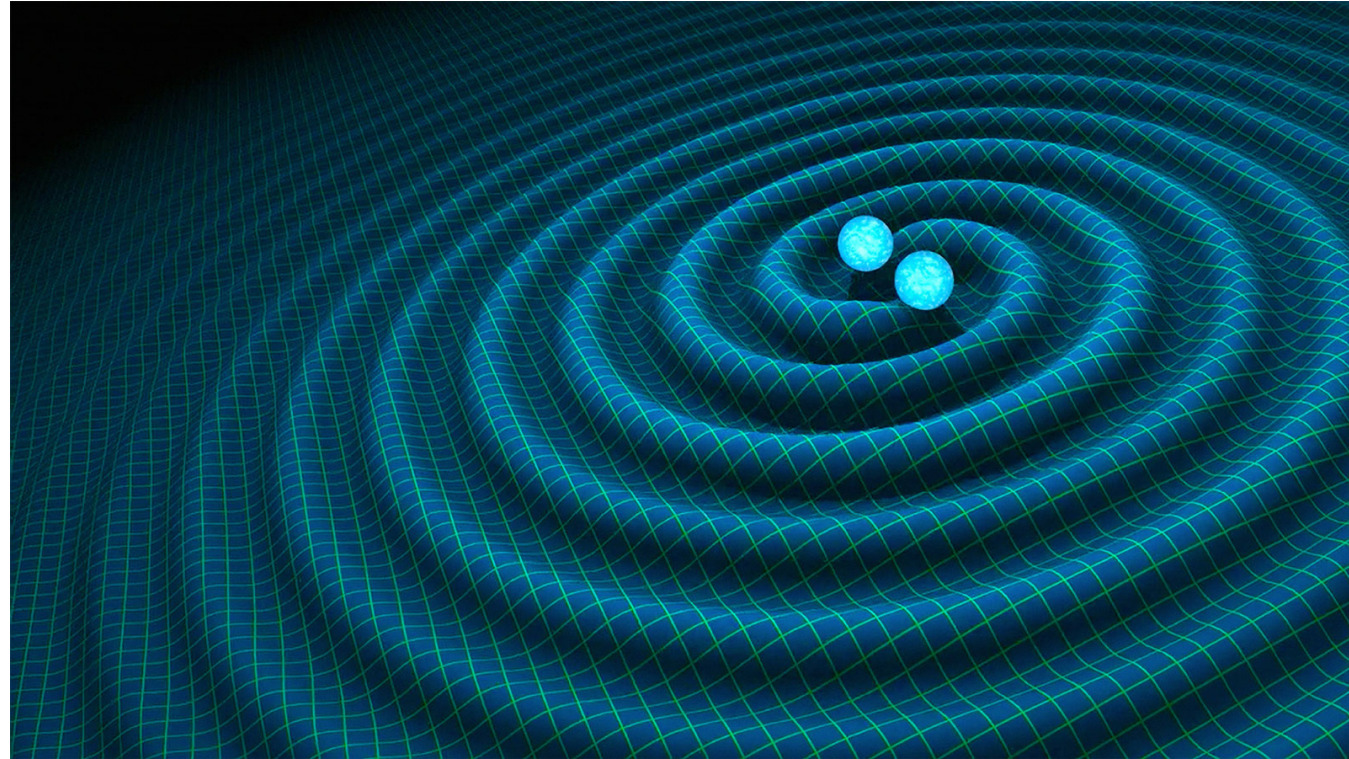
Gravitational waves and the Einstein Telescope

Markus Schulz-Ritz
16.07.2026



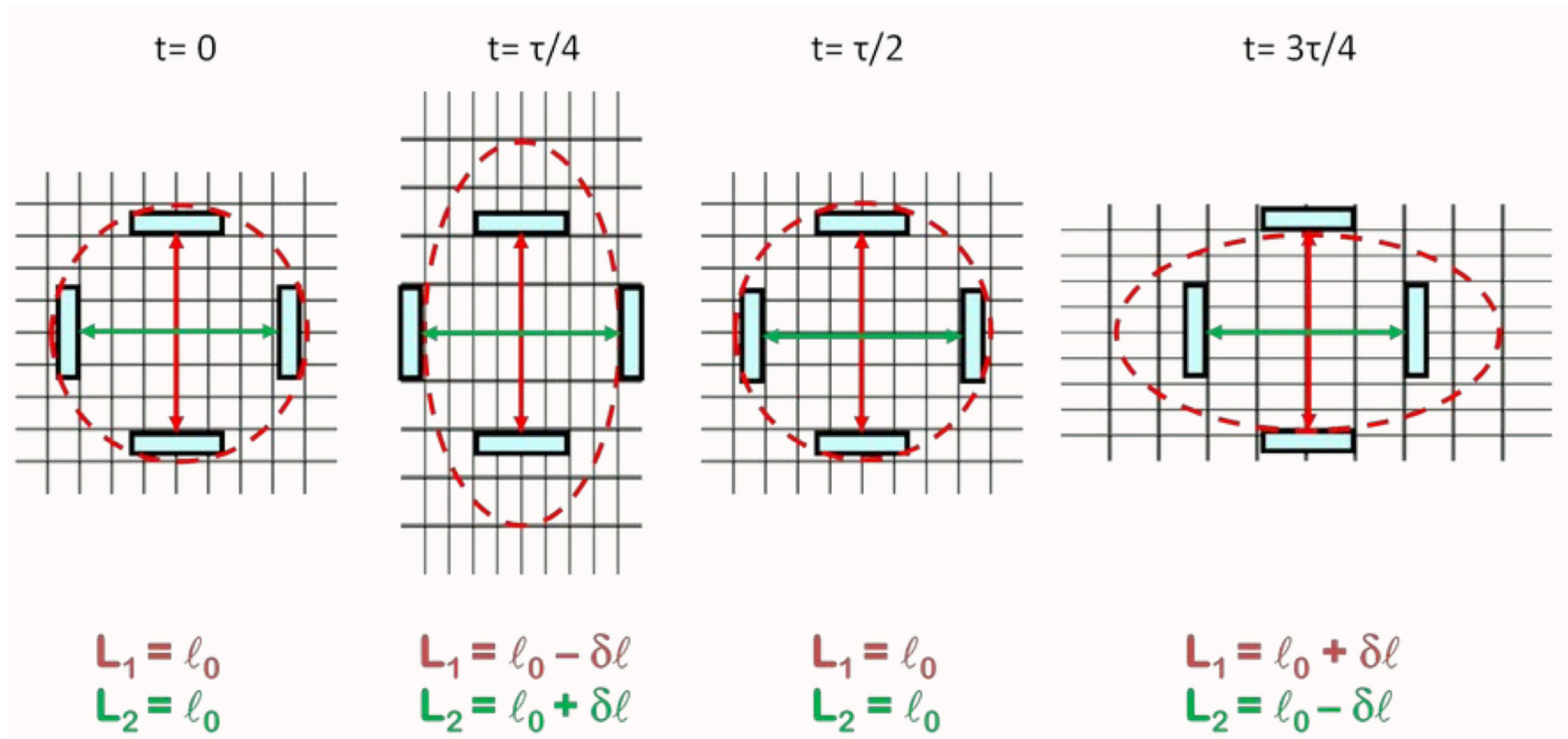
Gravitational Waves

- Predicted 1918 by Albert Einstein
- Ripples in space time
- Propagation at the speed of light
- Sources: e.g. Black Hole merger, Neutron Star - BH merger, Supernovae



https://agenda.infn.it/event/30202/contributions/168520/attachments/91271/123839/Bagnasco_ComputingForET_CCRMay2022.pdf

Gravitational Waves

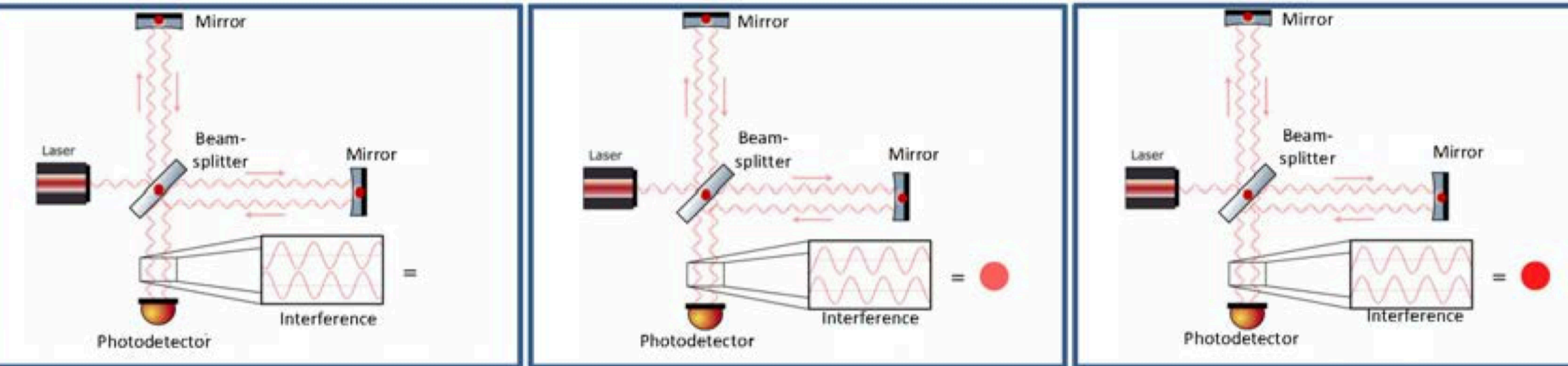


https://www.einsteintelelescope-emr.eu/wp-content/uploads/2024/05/ET-0007B-20_ETDesignReportUpdate2020.pdf

Gravitational Waves Detectors: Michelson Interferometer

■ Default for detector: destructive interference

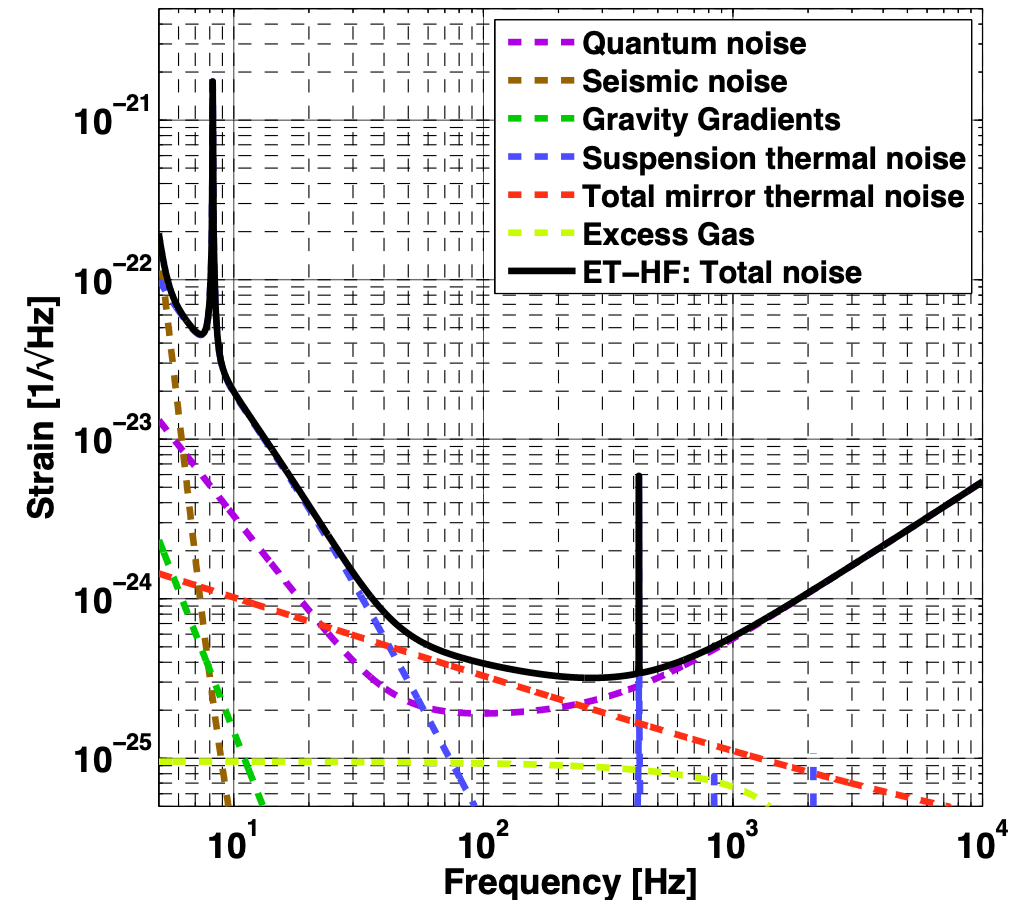
■ GW passing the interferometer: constructive interference and signal at photodetector



https://www.einsteintelelescope-emr.eu/wp-content/uploads/2024/05/ET-0007B-20_ETDesignReportUpdate2020.pdf

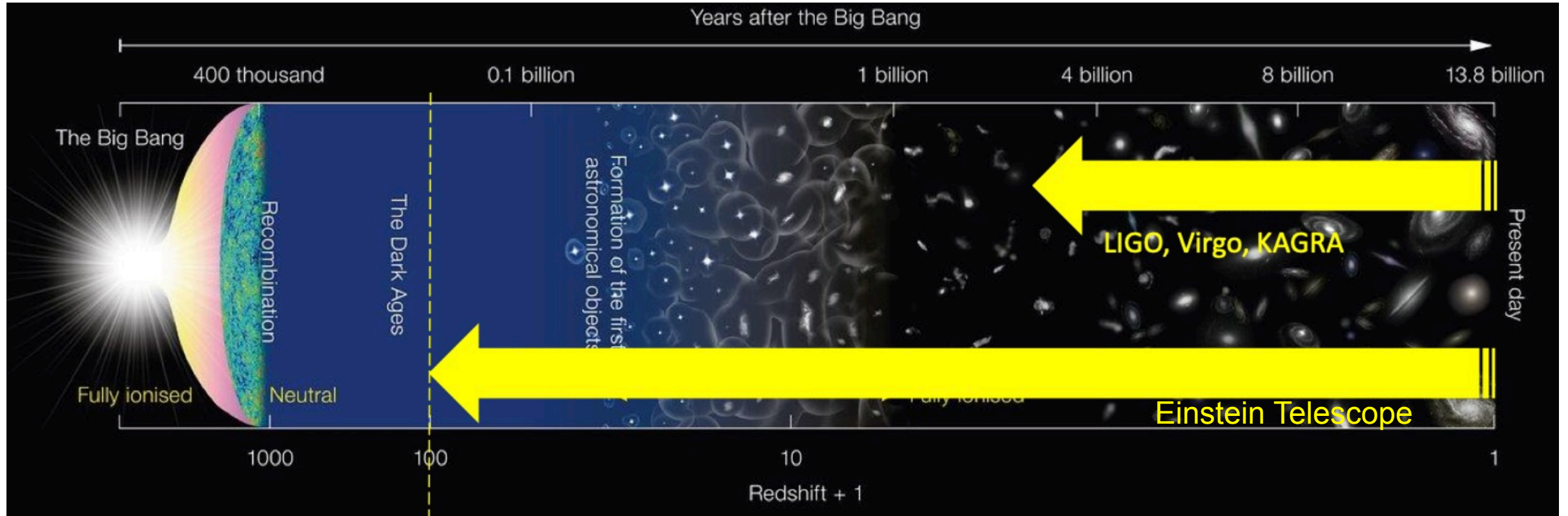
Gravitational Waves Detectors: Background sources

- Newtonian Noise: mass density fluctuations around the mirror (e.g. seismic noise)
- Excess gas: scattering of the LASER light
- Quantum noise: fluctuations in amplitude of LASER intensity and/or shot noise
- Thermal Noise: brownian particle movement of in the mirror or suspensions



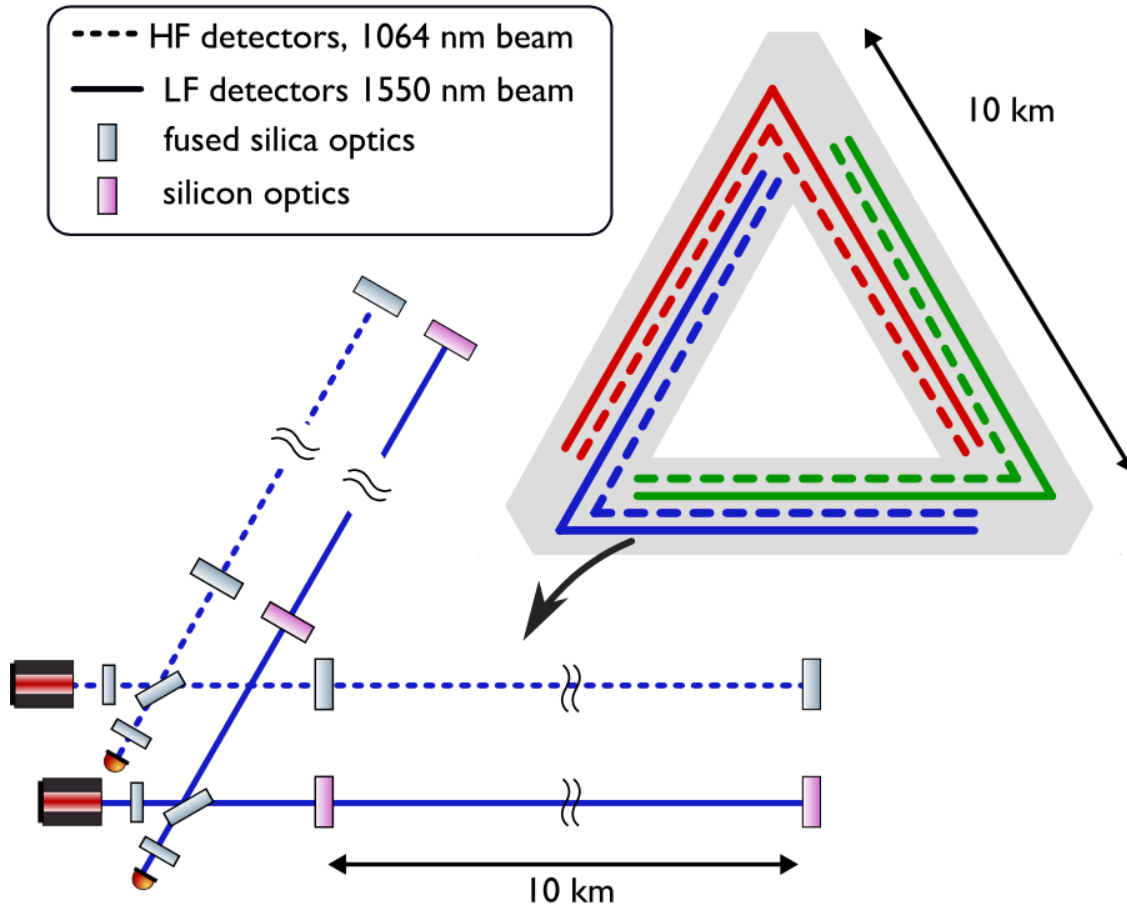
https://www.einsteintelelescope-emr.eu/wp-content/uploads/2024/05/ET-0007B-20_ETDesignReportUpdate2020.pdf

The goal of Einstein Telescope



https://agenda.infn.it/event/30202/contributions/168520/attachments/91271/123839/Bagnasco_ComputingForET_CCRMay2022.pdf

The Einstein Telescope Layout



<http://www.gwoptics.org/research/et/layout/>

First 3G GW Detector

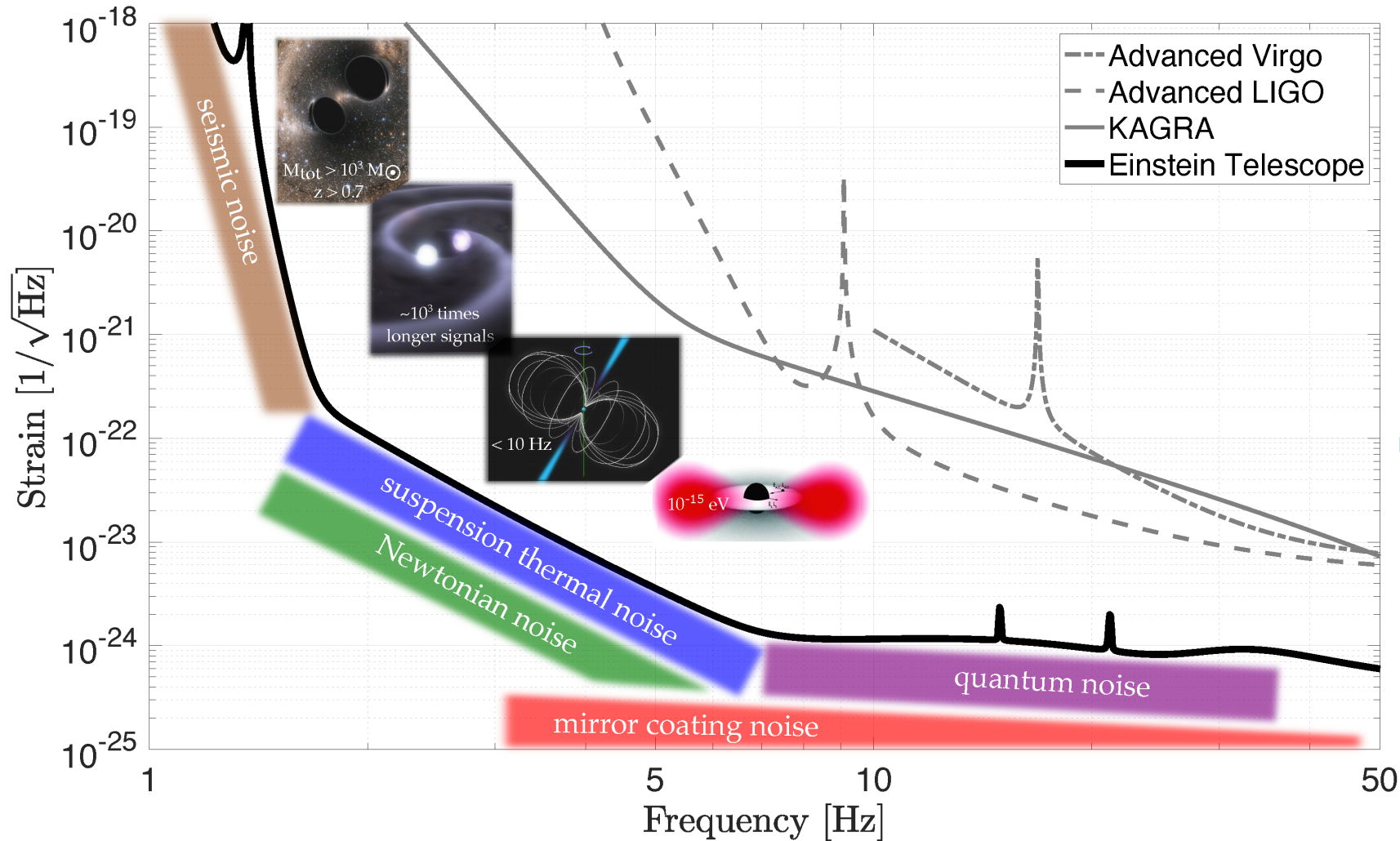
ET High Frequency (ET-HF):

- High frequency detector
- 1064nm LASER
- 200kg test mass mirror (fused silica optics)
- High power (3MW)
- Operating at 300K
- 30Hz - 2kHz

ET Low Frequency (ET-LF):

- Low frequency detector
- 1550nm LASER
- 211kg silicon test mass mirror
- Lower power (500W)
- At cryogenic temperatures (10K-20K)
- 3Hz - 30Hz

ET-LF Sensitivity



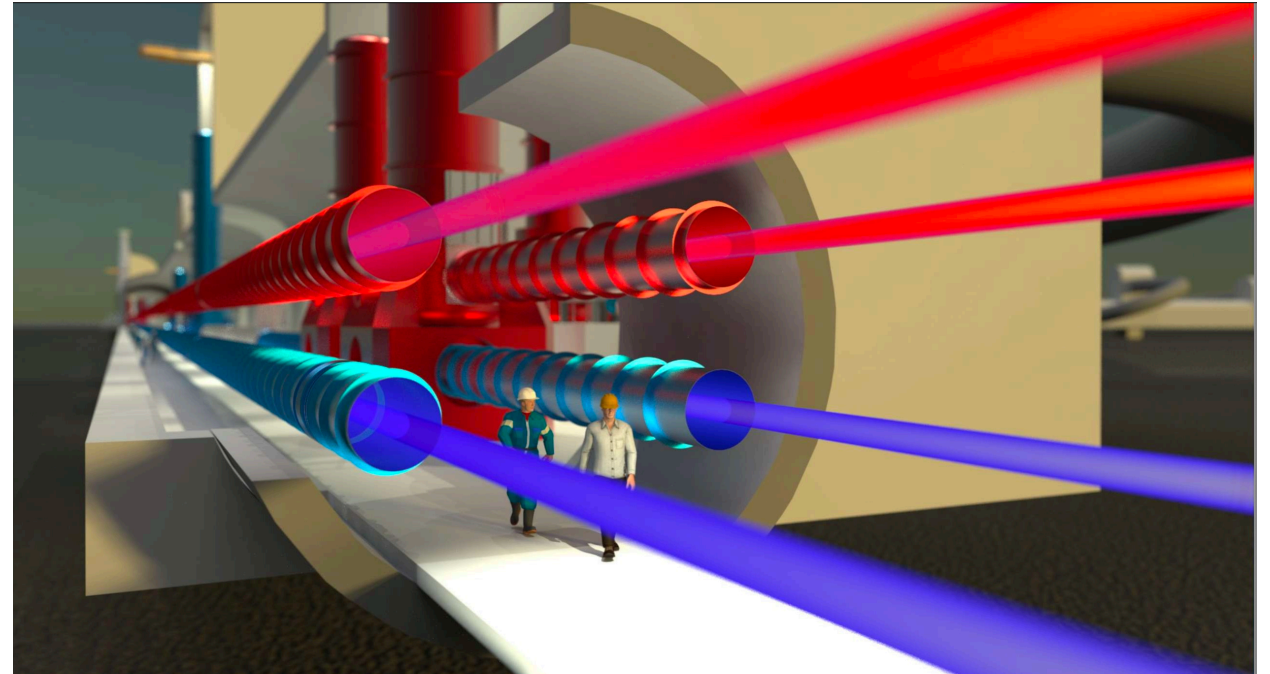
- Increase of sensitivity by factor of 10
- Dominant noise source below 10Hz:
 - Suspension thermal noise

➔ Cooling of the mirrors required

Di Pace et al.; Research Facilities for Europe's Next Generation Gravitational-Wave Detector Einstein Telescope; 2023; DOI: 10.3390/galaxies10030065

ET Vacuum

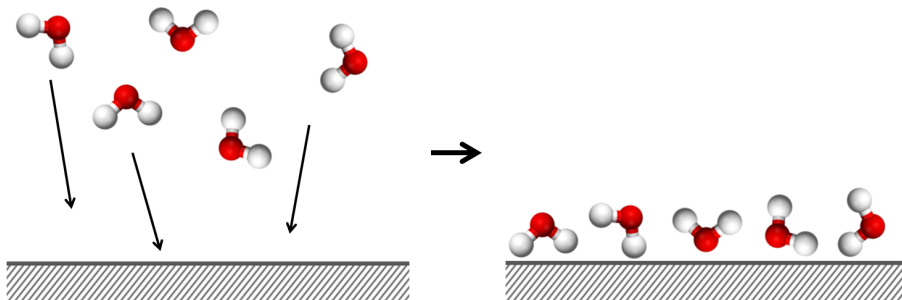
- Prevent scattering of light in the beam tube:
 - Vacuum in the beam pipes needed (10km long and 1m in diameter!)
 - $p_{\text{pipe}} < 1 \cdot 10^{-8}$ mbar
 - Vacuum in the towers $p < 1 \cdot 10^{-10}$ mbar
- Will be the largest vacuum system in the world: 120km beam line
 - ET (triangle): 100 000m³
 - Ca. 180 Towers with cryostats



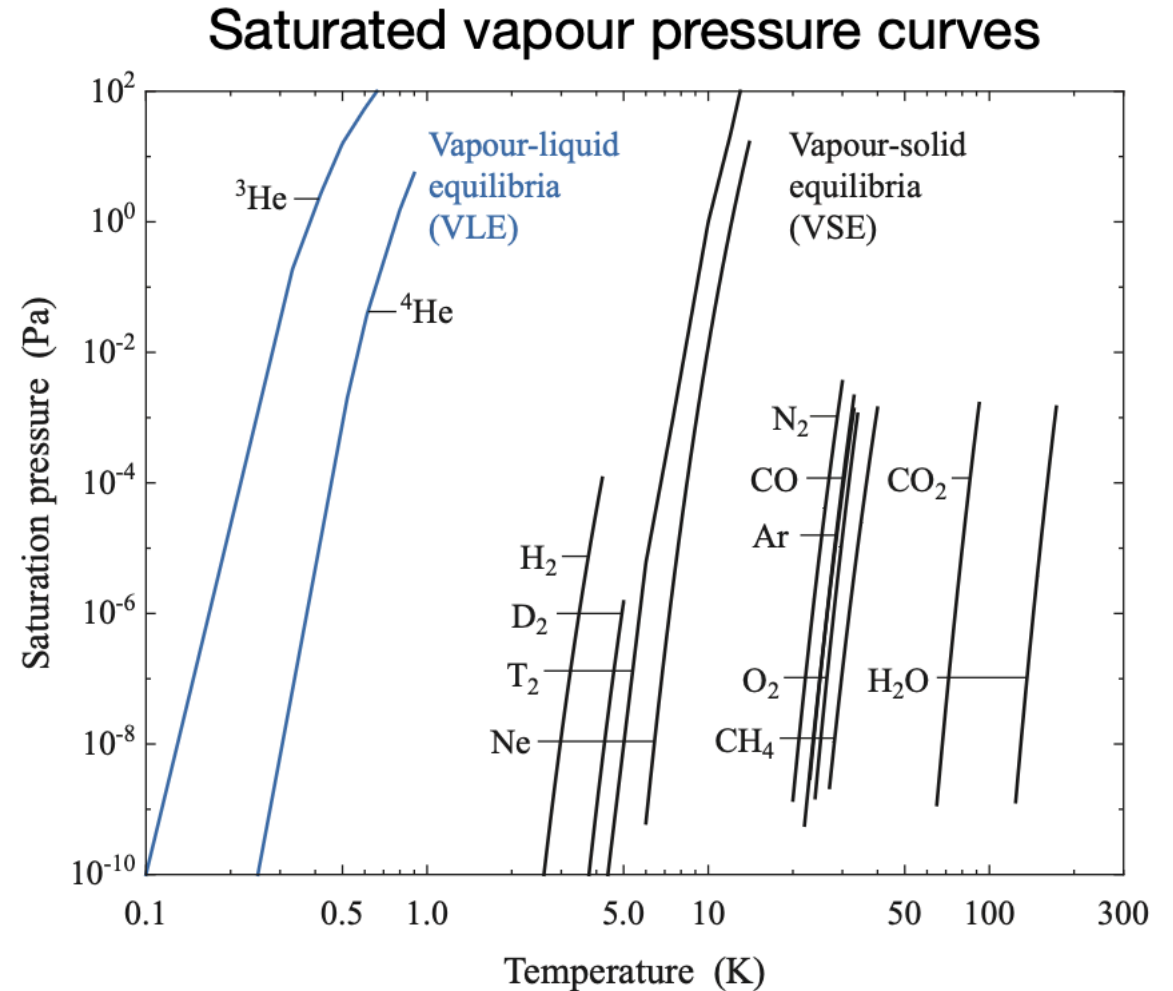
H. Lück, The Einstein Telescope, APS Sacramento, 04.2024

Frost Formation

- At 10K-20K: adsorption of most gases form ice on surfaces, even at low pressures
- At $p_{\text{H}_2\text{O}} = 1 \cdot 10^{-10}$ mbar it takes just 3h to form one monolayer of ice
- For H_2O one monolayer equals 0.3nm



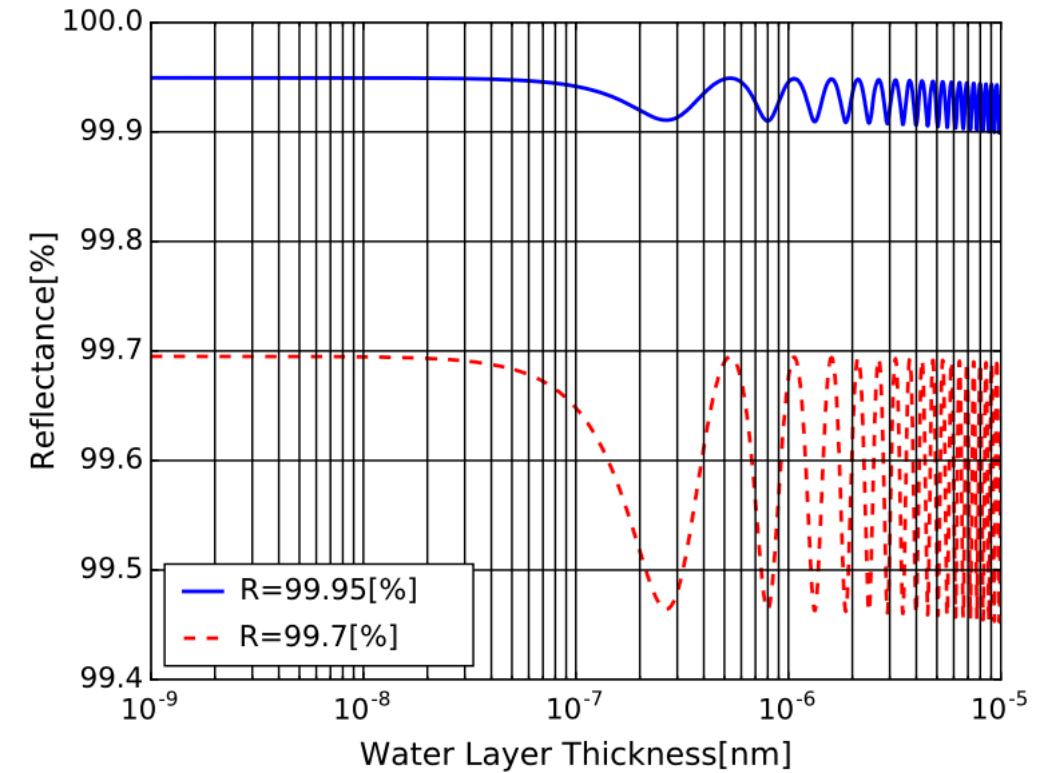
<https://chembam.com/definitions/adsorption-vs-absorption/>



S. Grohmann, ET-LF Vacuum and Cryogenics Requirements,
ET Cost-Benefit Analysis (CoBA) full immersion workshop,
Cortona, 21-24 November 2021

Frost on GW Mirrors

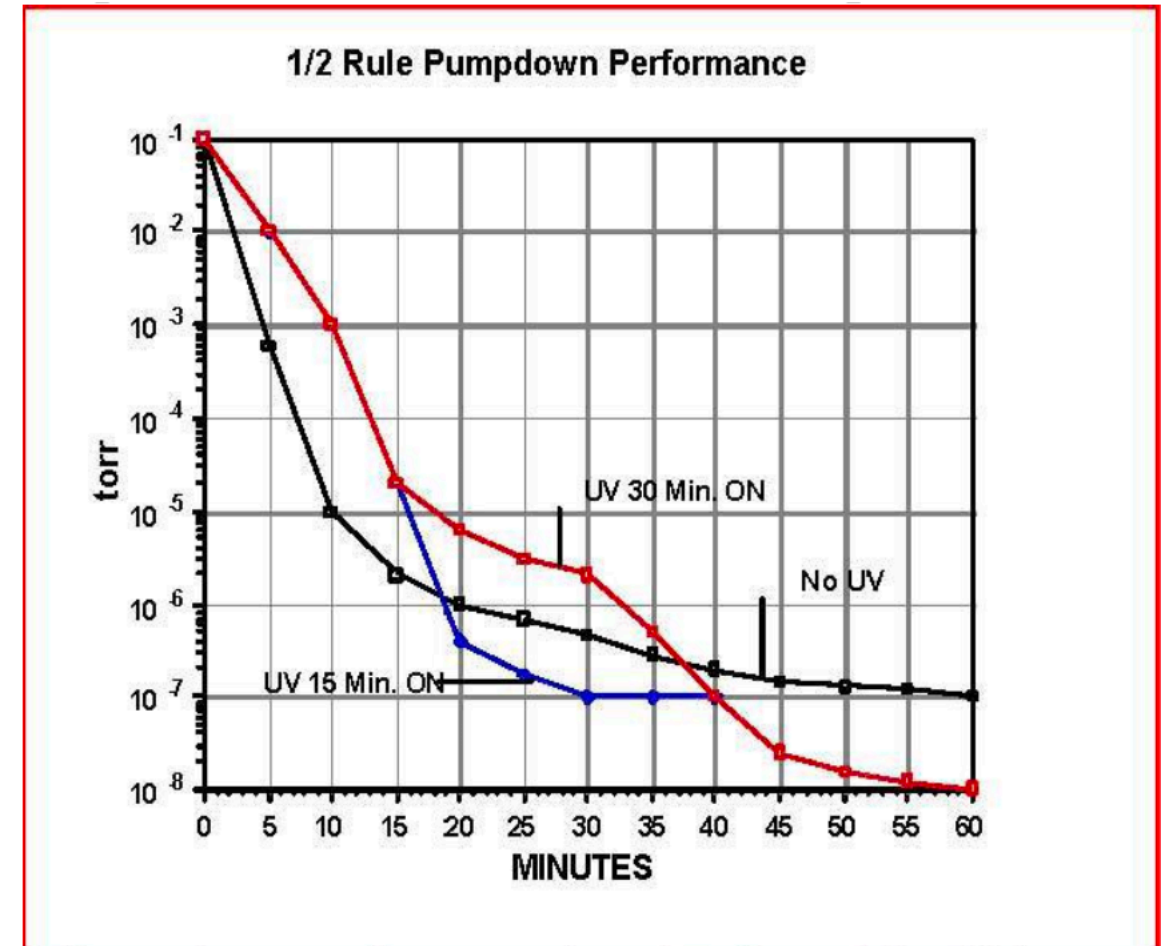
- At KAGRA:
 - Frost formation on mirror effects reflectivity!
- Thermal budget of ET: (0.1-0.5W)
 - Will be exceeded after 1-10nm of water ice
 - At $p_{\text{H}_2\text{O}} < 1 \cdot 10^{-12}$ mbar the layer thickness exceeds the limit after 1yr
 - Goal: $p_{\text{H}_2\text{O}} < 1 \cdot 10^{-14}$ mbar
- Mitigation strategies required!
- How to remove ice without heating of the mirrors?
- How to measure the ice thickness in-situ?



K. Hasegawa et al., Molecular adsorbed layer formation on cooled mirrors and its impacts on cryogenic gravitational wave telescopes, PHYSICAL REVIEW D 99, 022003 (2019)

UV-Cleaning

- UV photons are created by mercury lamp
- UV photons give energy to e.g. water molecules which desorb faster into the volume and get pumped
- Half rule:
 - 15min of UV cleaning for same pressure as after 30min without
 - 30min UV: one decade lower than without after one hour



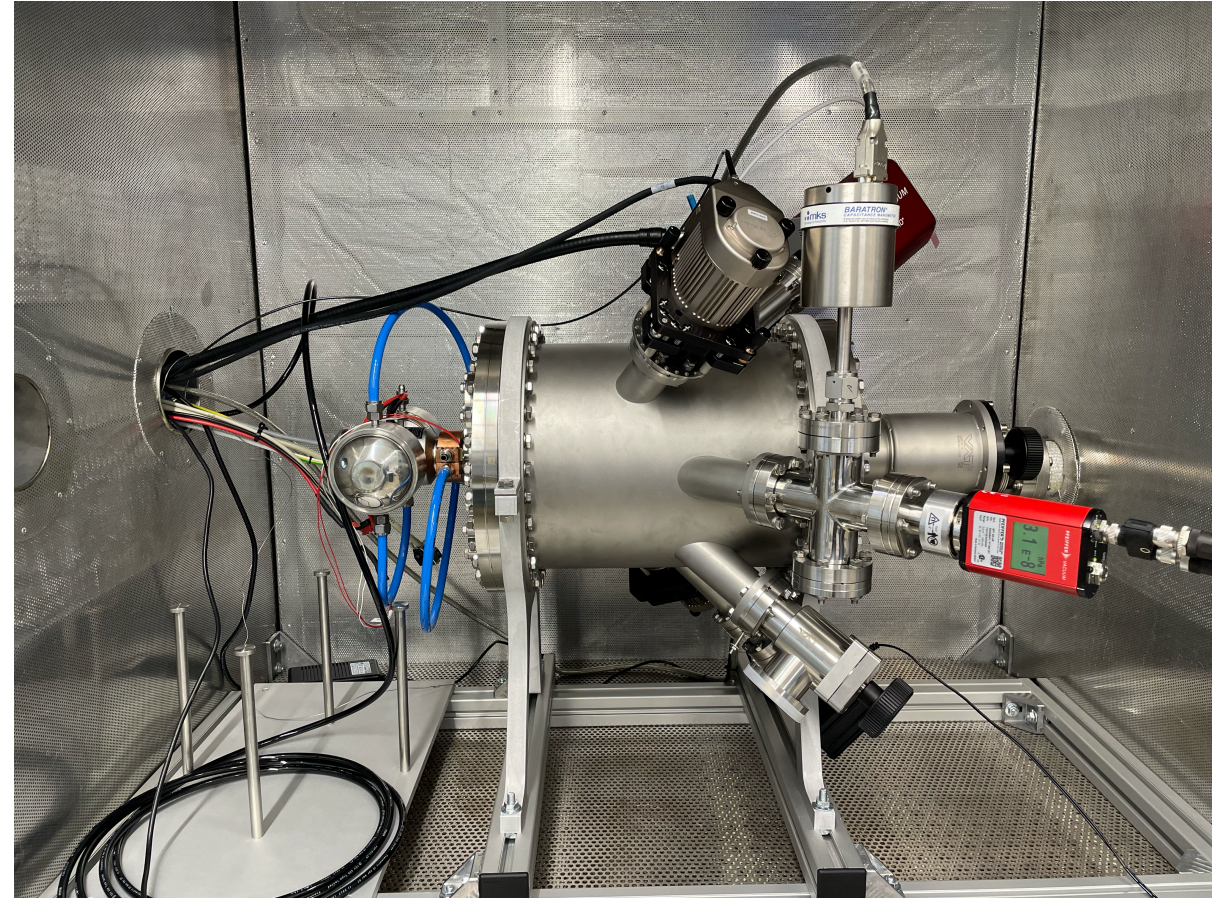
Rbd Instruments, Mini-Z Manual

UV/Ozone conditioning

- Needs dry air for ozone production
- UV photons give energy to oxygen which forms ozone
- Ozone decay needs another molecule for decay: gives energy to other molecules -> faster desorption
- Needs constant pumping and inflow of dry air

Ellipsometry

Markus Schulz-Ritz
16.07.2026

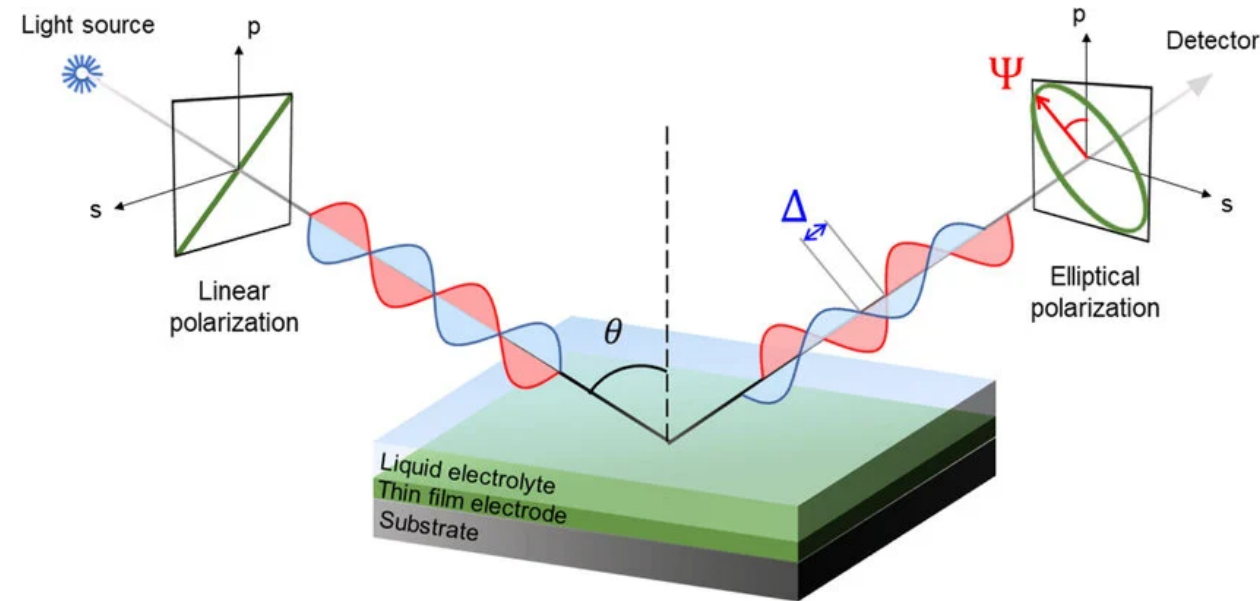


Ellipsometry

- For thickness measurement of thin films (even down to sub-nm)
- Linear polarised light becomes elliptically polarised after travelling through films with different optical properties
- Two important measured parameters:
 - phase difference Δ
 - polarisation angle Ψ

$$\tan \Psi e^{i\Delta} = \rho = \frac{r_p}{r_s}$$

- With reflection coefficients r_p and r_s



https://www.researchgate.net/figure/Configuration-in-spectroscopic-ellipsometry-for-a-determined-incidence-angle-th_fig1_359192239

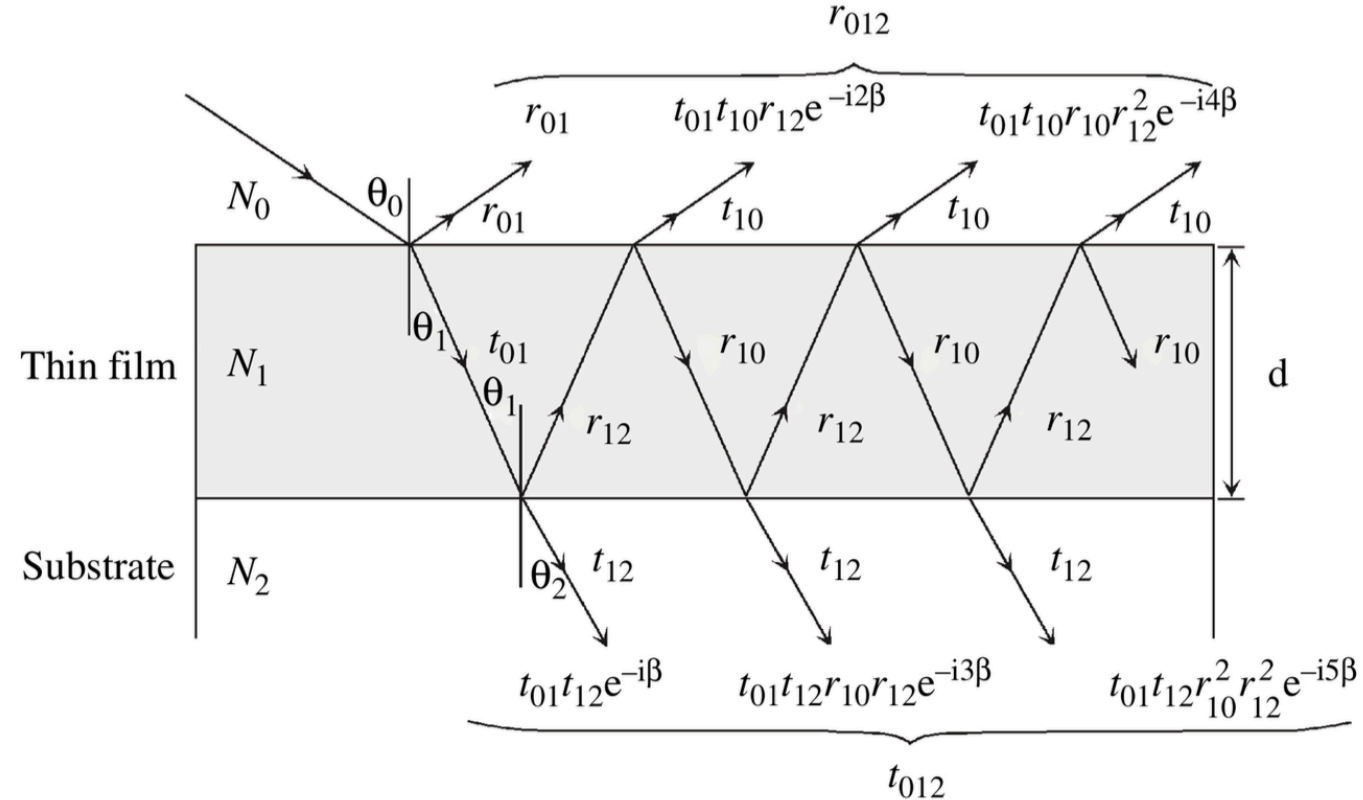
Ellipsometry - creating a model

- Need to calculate the Fresnel coefficients for each transition between two layers
- Iterative process for multi-layer stack of thin films

$$r_{012} = \frac{r_{01} + r_{12}e^{-i2\beta}}{1 - r_{01}r_{12}e^{-i2\beta}}$$

- Film thickness via phase:

$$\beta = \frac{2\pi d N_1}{\lambda} \cos \theta_0$$



Ellipsometry - creating a model

- Need optical model for the refractive index

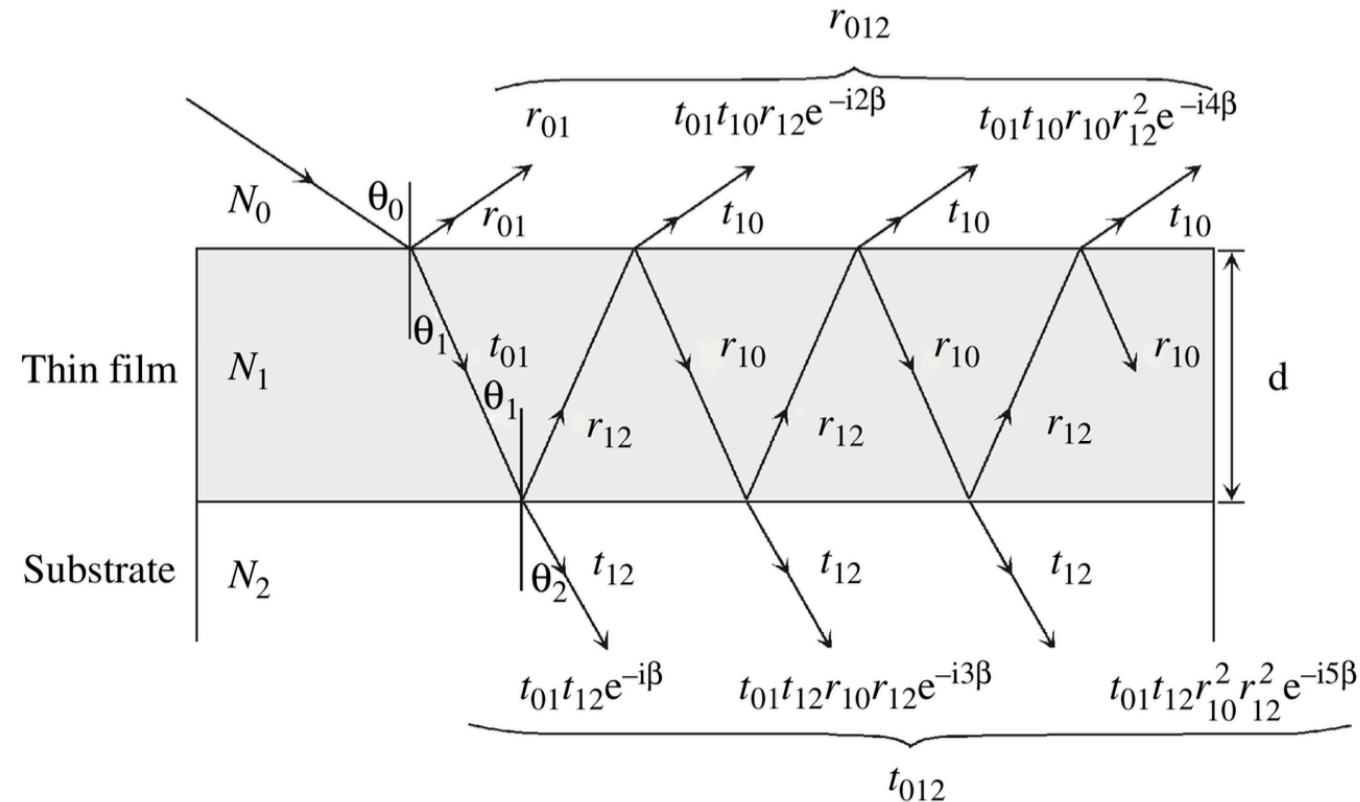
$$N(\lambda) = n(\lambda) + i\kappa(\lambda)$$

- Model used in this thesis:

- Sellmeier model: for thin transparent films with absorption resonance wavelengths C_i

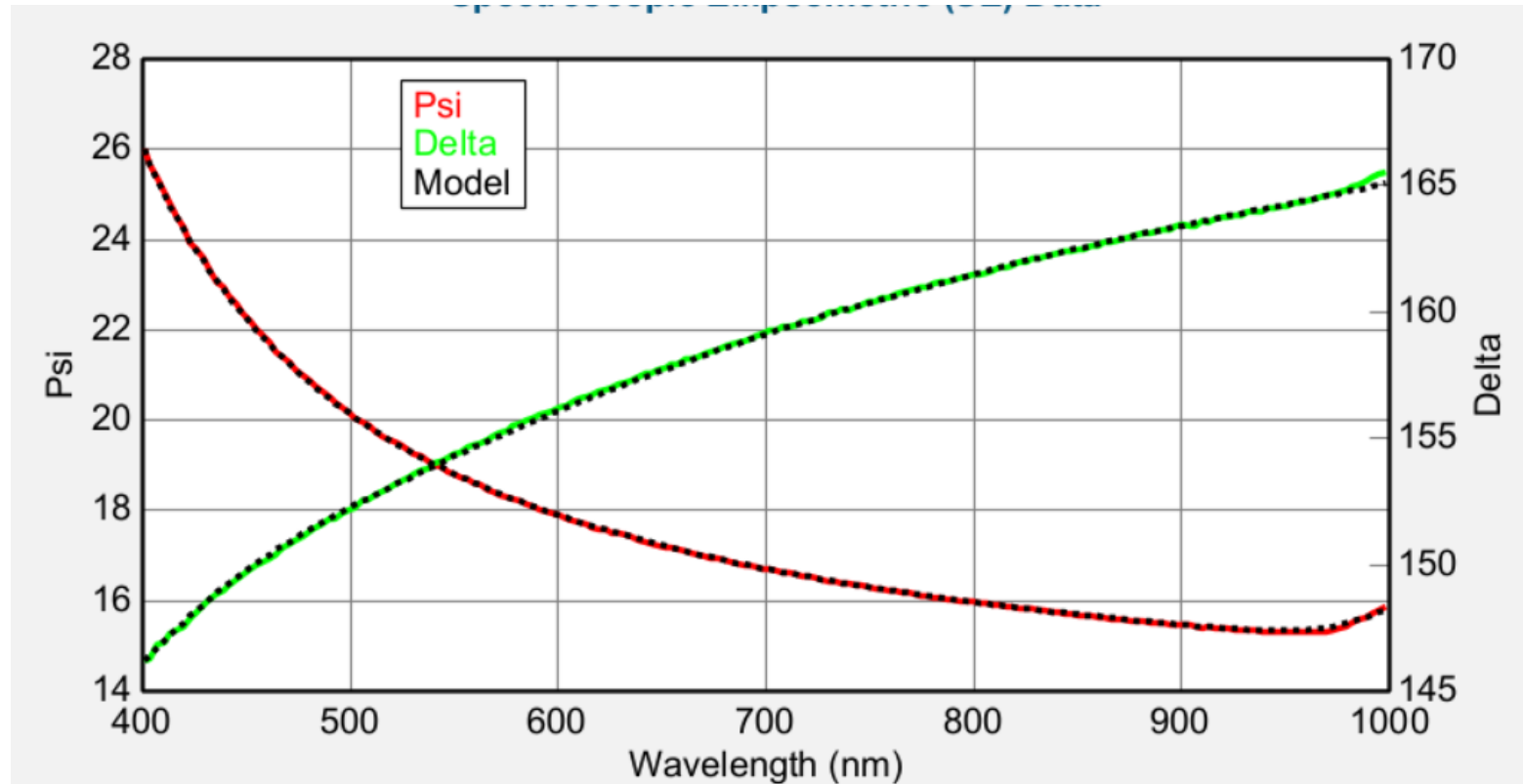
$$n^2(\lambda) = A + \sum_i \frac{B_i \lambda^2}{\lambda^2 - C_i^2}$$

- Spectroscopic Ellipsometry: usage of data from a spectral range from 400-1000nm (for our ellipsometer)



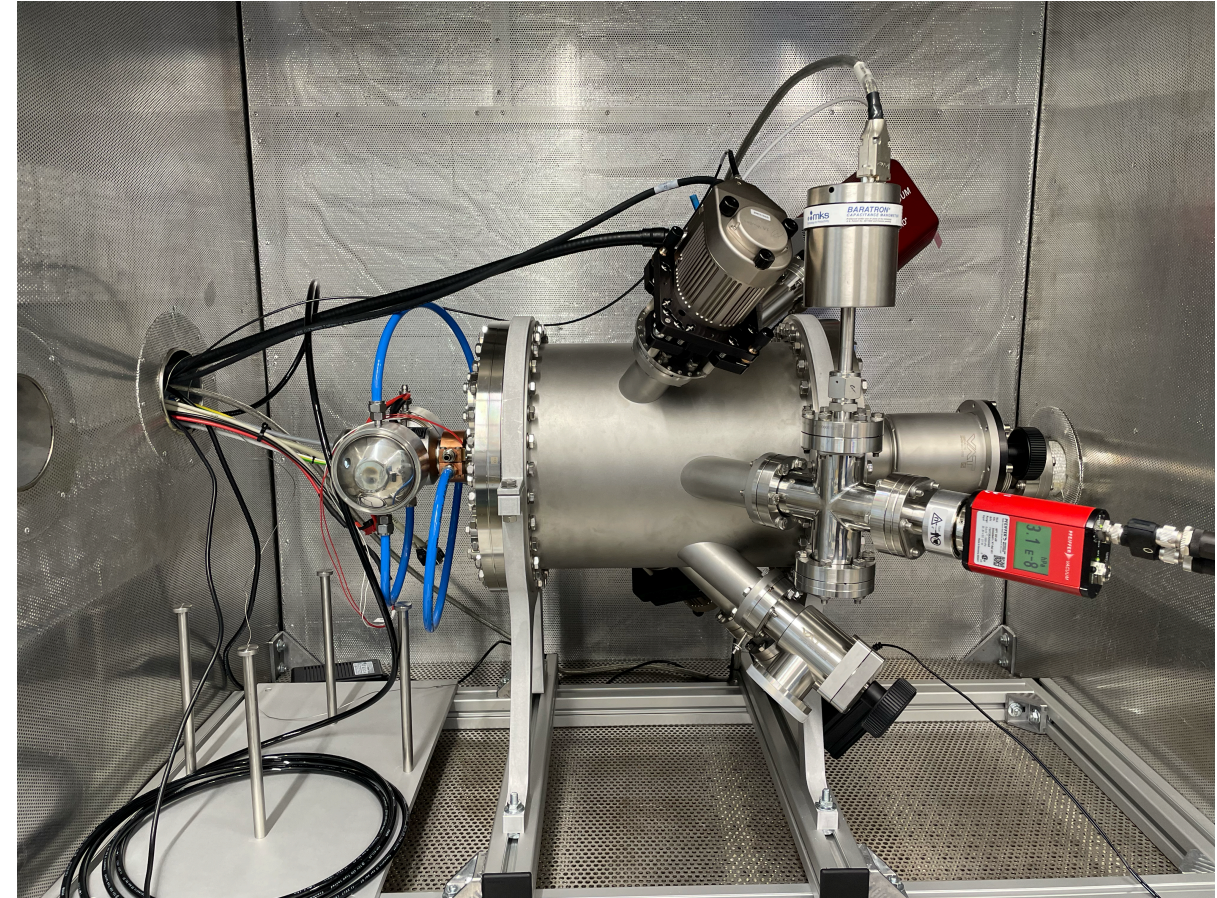
Ellipsometry - creating a model

- Spectroscopic Ellipsometry: usage of data from a spectral range from 400-1000nm (for our ellipsometer)



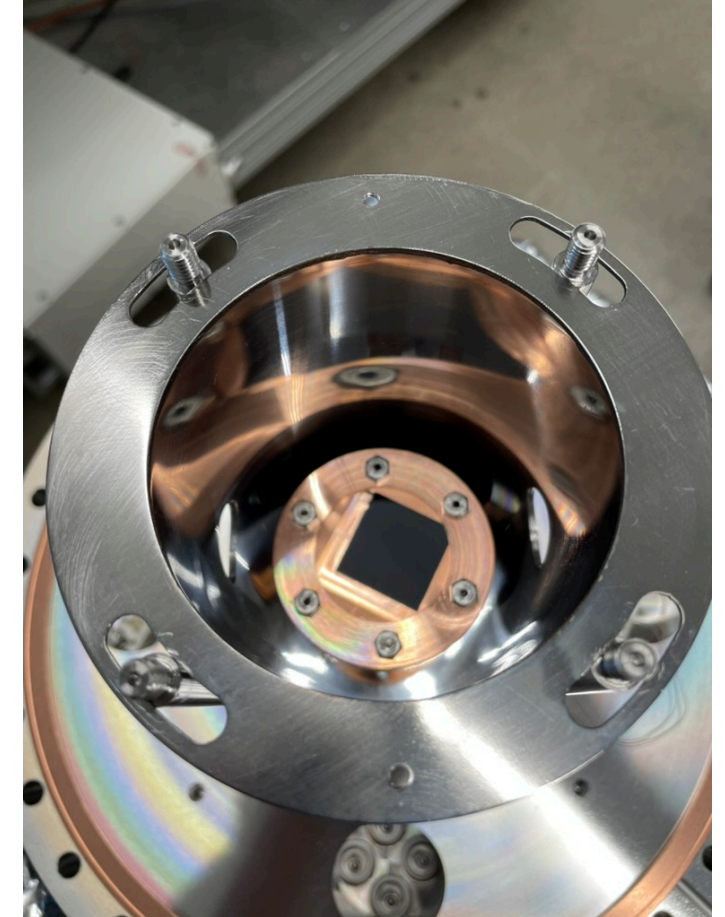
The Vacuum, surface monitoring and Cleaning experiment (VINCENT)

Markus Schulz-Ritz
16.07.2026

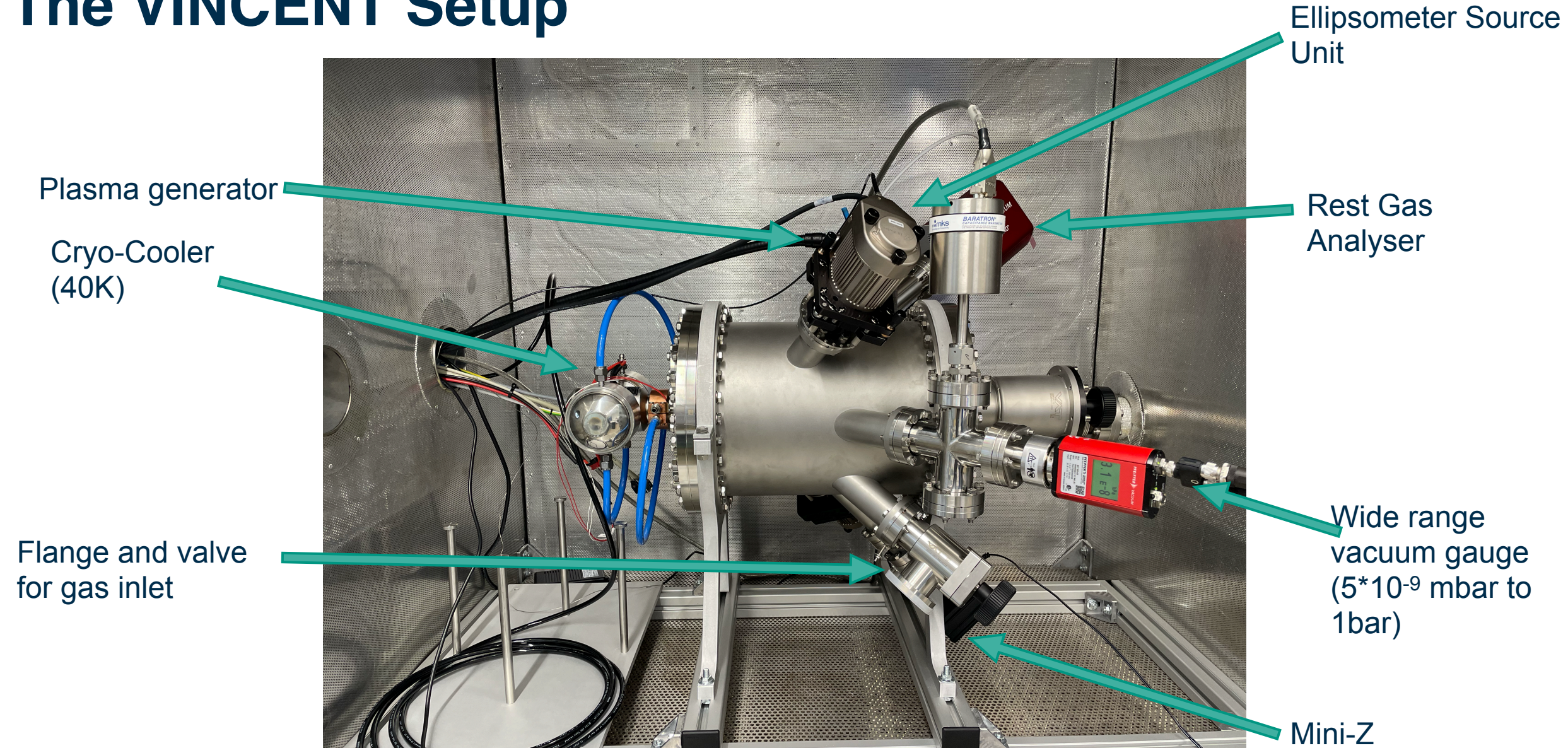


The VINCENT Setup: Goal

- Needed: test facility for controlled freezing of different gases (CO₂, Nitrogen, Water, ...) onto cryogenic surfaces
- Monitoring techniques for monitoring of desorption and adsorption of different gases required:
 - Spectroscopic Ellipsometry
 - Quartz Crystal Micro Balance (QMB)
- Investigate non thermal conditioning methods:
 - Argon Plasma Cleaning
 - Ozone Cleaning
 - UV-Cleaning
- In-situ cleaning of cryogenic mirrors (future extension):
 - Non-thermal Field Emission Electron Source (ca. 200eV)



The VINCENT Setup



Design of the gas inlet

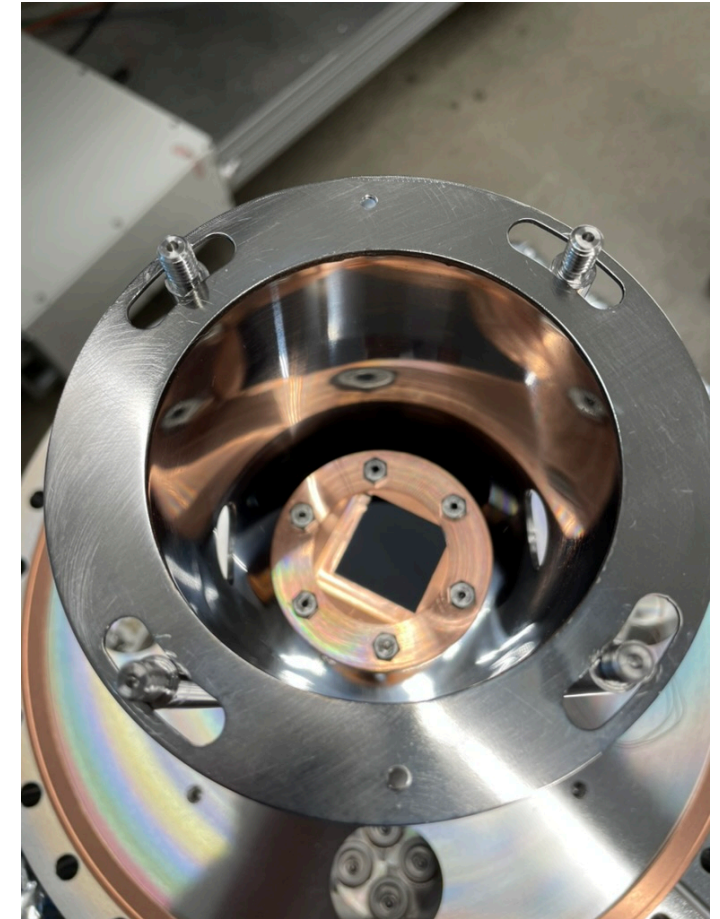
- In a vacuum tank the pressure depends on the leak rate (inflow of gas) as well as the pumping speed:

$$p_{\text{VINCENT}} = p_0 + \frac{Q_{\text{GF}}}{S_{\text{eff}}}$$

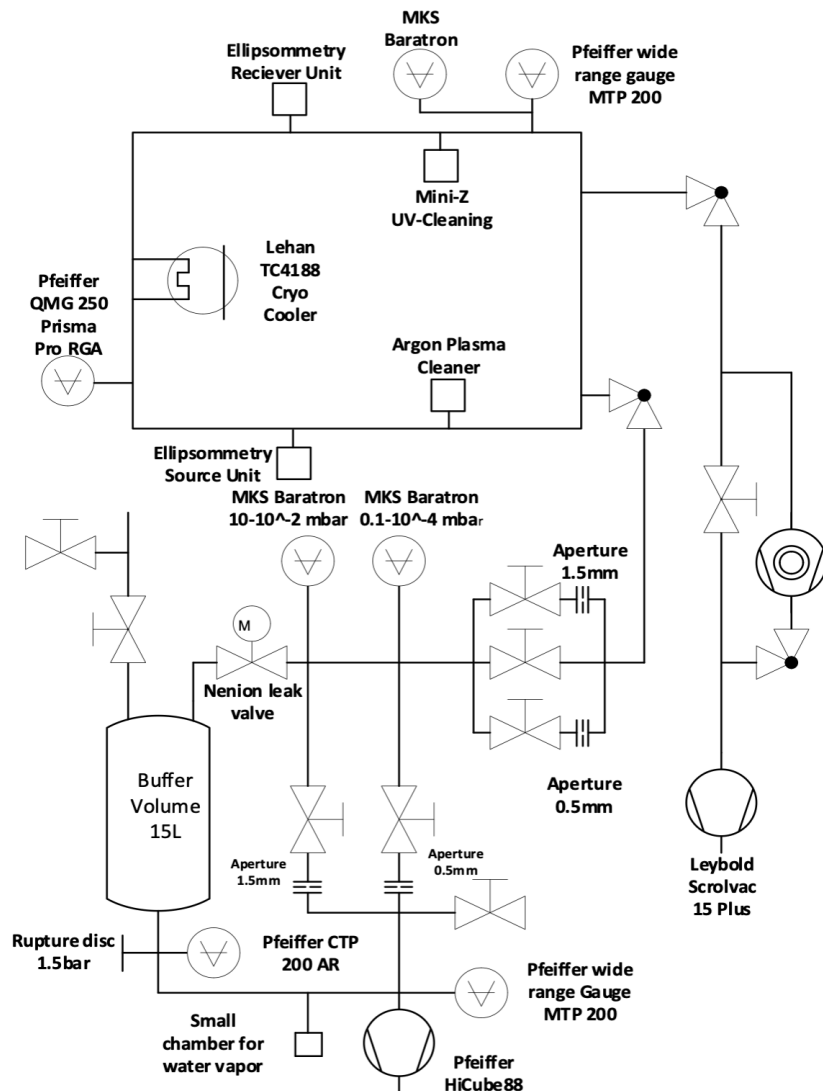
- At a pressure of $1 \cdot 10^{-8}$ mbar in the recipient without gas inflow: 90s for first monolayer

$$Q_{\text{GF}} = \left(\frac{4}{145.5} \cdot \frac{a k_B}{\tau \alpha_0} \cdot \sqrt{T M} - p_0 \right) \cdot S_{\text{eff}}$$

- Assuming a pumping speed of 7400 L/s an inflow of $2 \cdot 10^{-4}$ mbar*L/s is required (with Nitrogen)
- Corifice, 1.45mm = 0.196L/s
- Corifice, 0.5mm = 0.023L/s

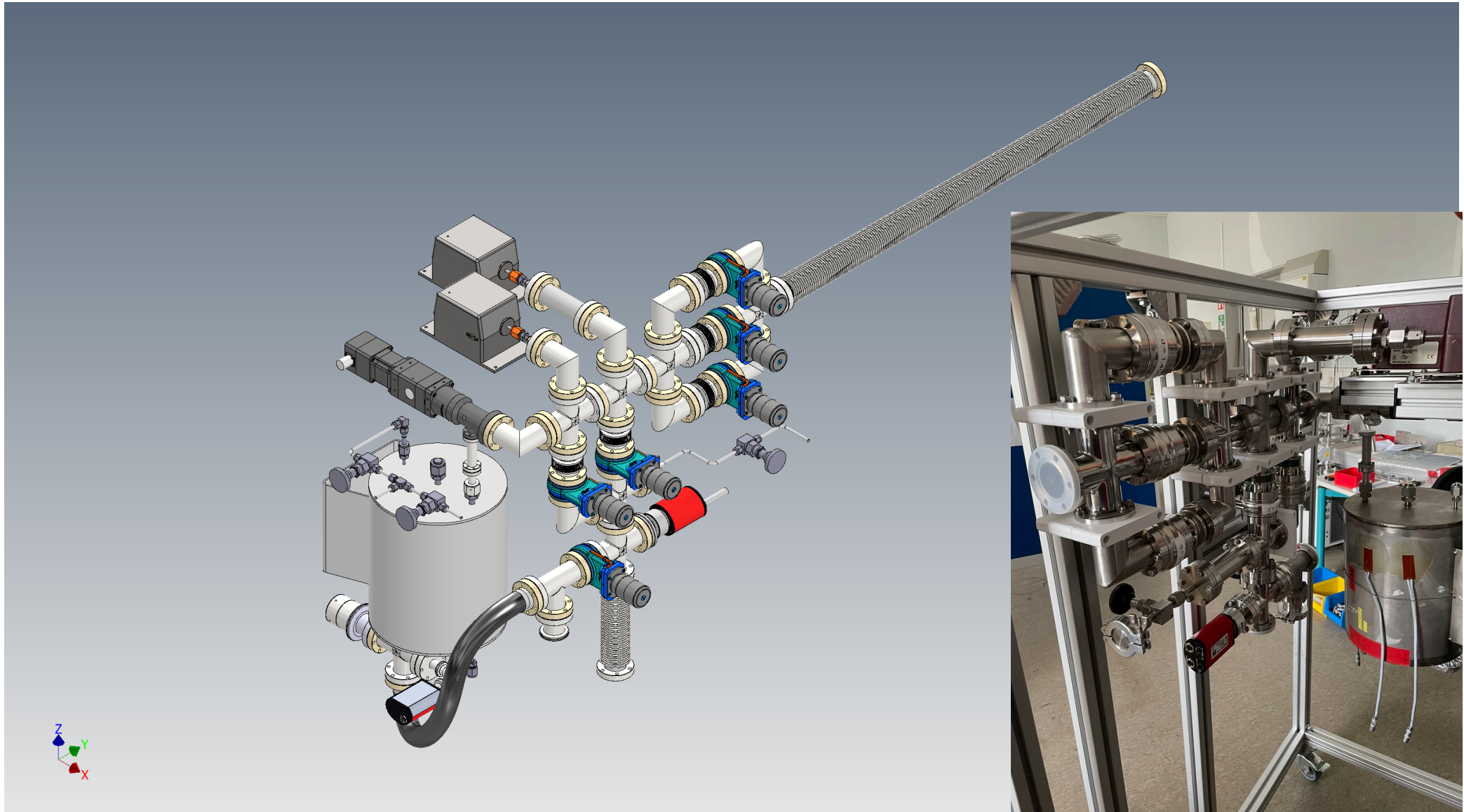


Design of the gas inlet



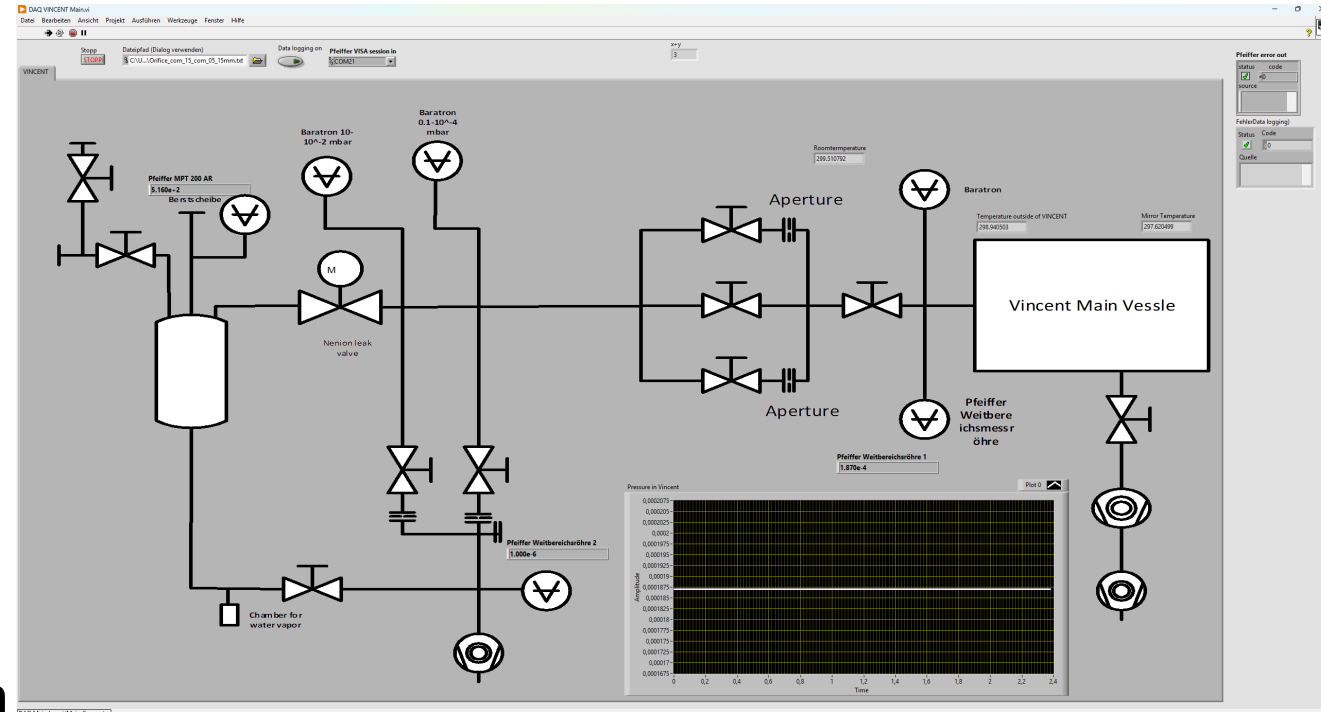
- Requirements:
- Leak valve
 - Buffer volume for gas storage
 - Pump for evacuation
 - Vacuum gauges for pressure monitoring
 - Orifices for calibration of the gas inlet (0.5mm and 1.45mm)
 - Rupture disc to prevent damage to the buffer volume

Design of the gas inlet



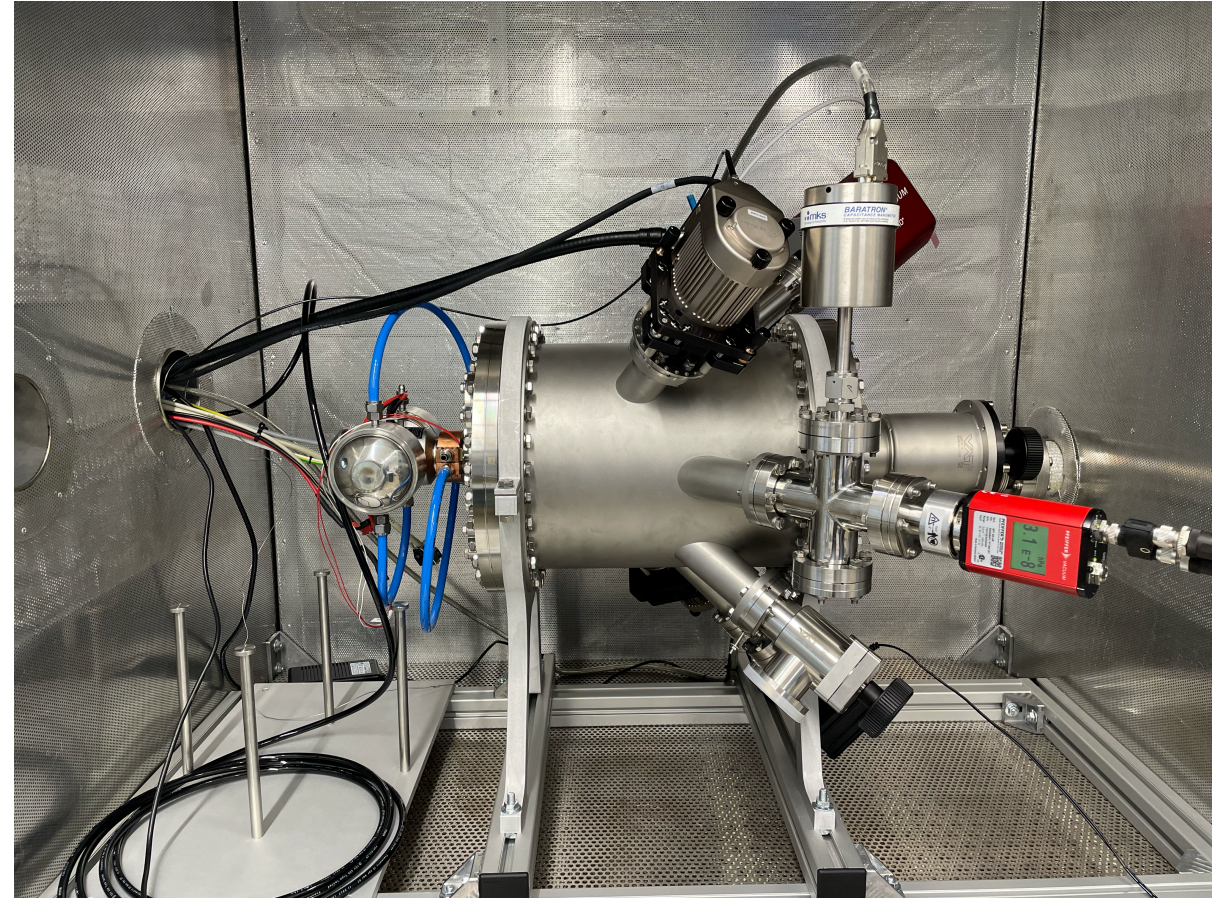
The data acquisition of VINCENT

- Readout of all vacuum gauges
 - 3x Pfeiffer
 - 3x MKS Baratron
- Temperature readout of three PT100 sensors (mirror, wall temperature, room temperature)
- For the temperature readout of the mirror temperature: adjusted resistance to temperature conversion



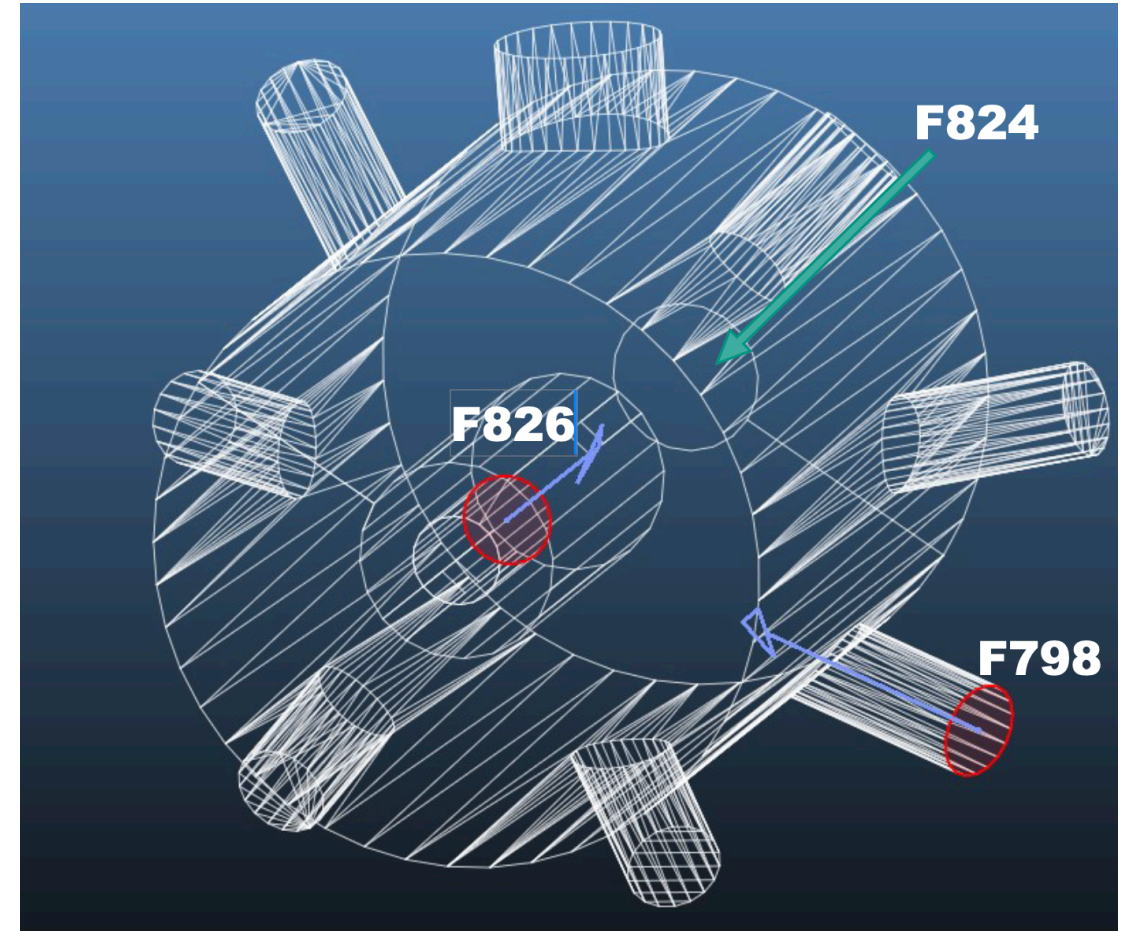
Vacuum simulations and measurements

Markus Schulz-Ritz
16.07.2026



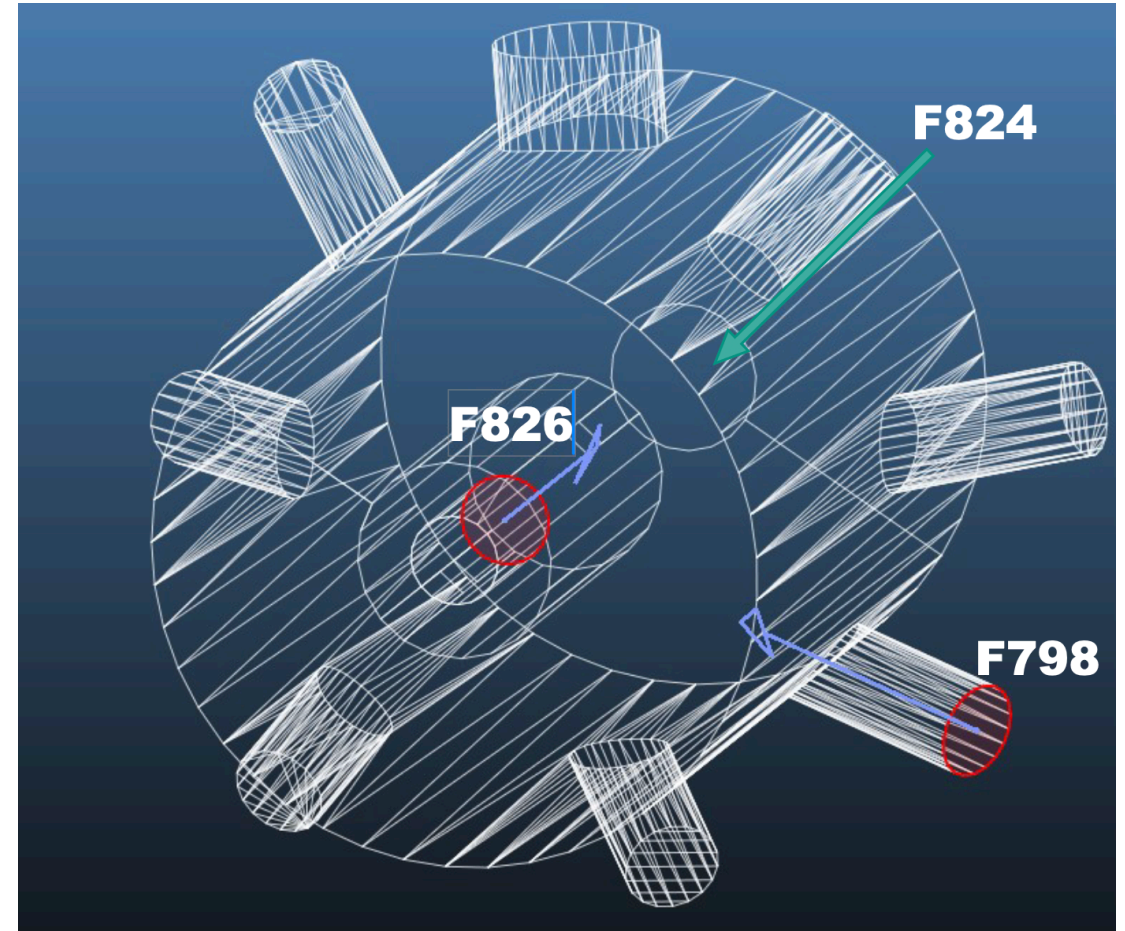
Molecular Flow+ (MolFlow)

- Molecular Flow+: Monte Carlo tool for molecular flow regime of gas particles (no interaction between gas particles)
- Usage of facets (polygons)
- Allows setting the values for each facet for different
 - Sticking coefficient/pumping speed
 - Temperature
 - Outgassing rate
- Simulates each particle flowing through the vacuum system, with random reflection at the corresponding facets



Simulation of the VINCENT main volume

- Four important facets
 - F824: fore-vacuum
 - F826: mirror
 - F798: gas inlet
 - F792: pressure readout
- Inflow of gas at F798 as calculated for gas inlet and $a = 1$
- F826: varied from $a = 0 \dots 1$
- F824: set to effective pumping speed of 72L/s
- All other facets no outgassing and $a = 0$
- Each simulation had at least $7 \cdot 10^6$ particles

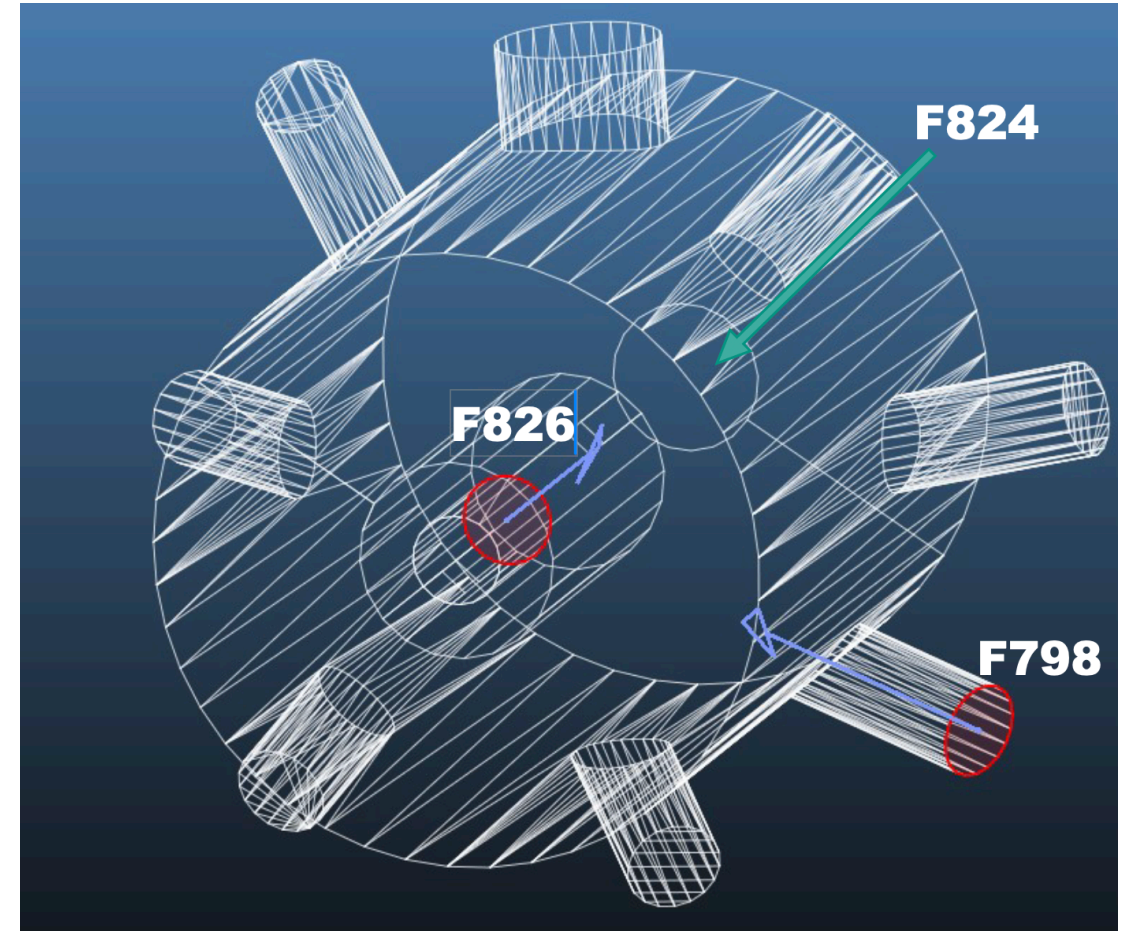


Simulation of the VINCENT main volume

- Time to form one monolayer on the mirror:

$$\tau = \frac{aD_{798}F}{A_{826}Q_{PV}}k_B T$$

- D_{798} : desorption at F798
- A_{826} : absorption at F826
- Q_{PV} : gas inflow
- F : area of the mirror facet
- a : sticking coefficient
- τ : time for one monolayer to form
- T : temperature of the gas



Simulation of the VINCENT main volume

Results:

Sticking coefficient At F826	Simulated ML formation time in s with nitrogen	Simulated ML formation time in s with water
0	0	0
0.4	885.30	993.19
0.8	535.48	601.00
1	443.83	504.74
1 and no top	-	220.09

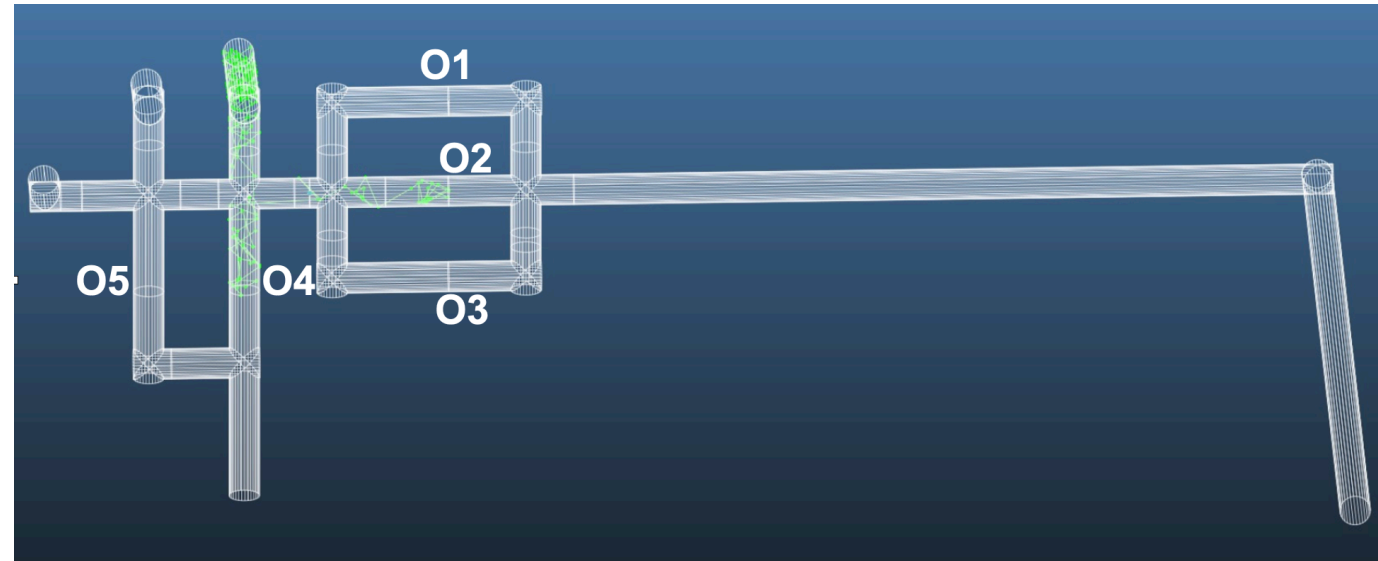
- Formation time decreases as expected with increasing sticking coefficient
- No top on cryo-shield: significant reduction of ML formation time
- All simulated times much higher than expected compared expectation (90s)
- Indicates pressure difference between outside and inside the cryo-shield
- Correction factor for pressure:

$$p_{\text{cryo}} = p_{\text{gauge}} \cdot \frac{H_{826} \cdot F_{792}}{H_{792} \cdot F_{826}}$$

Simulation and calibration measurement of the gas inlet conductance

- Gas flowing from the buffer volume to VINCENT (one orifice)
- Evacuation of VINCENT through the combination of two orifices
- Comparison with calculated values and measured
- Conductance in simulation:

$$C = S_{F1} \cdot \frac{A_{F2}}{D_{F1}}$$



Simulation and calibration measurement of the gas inlet conductances

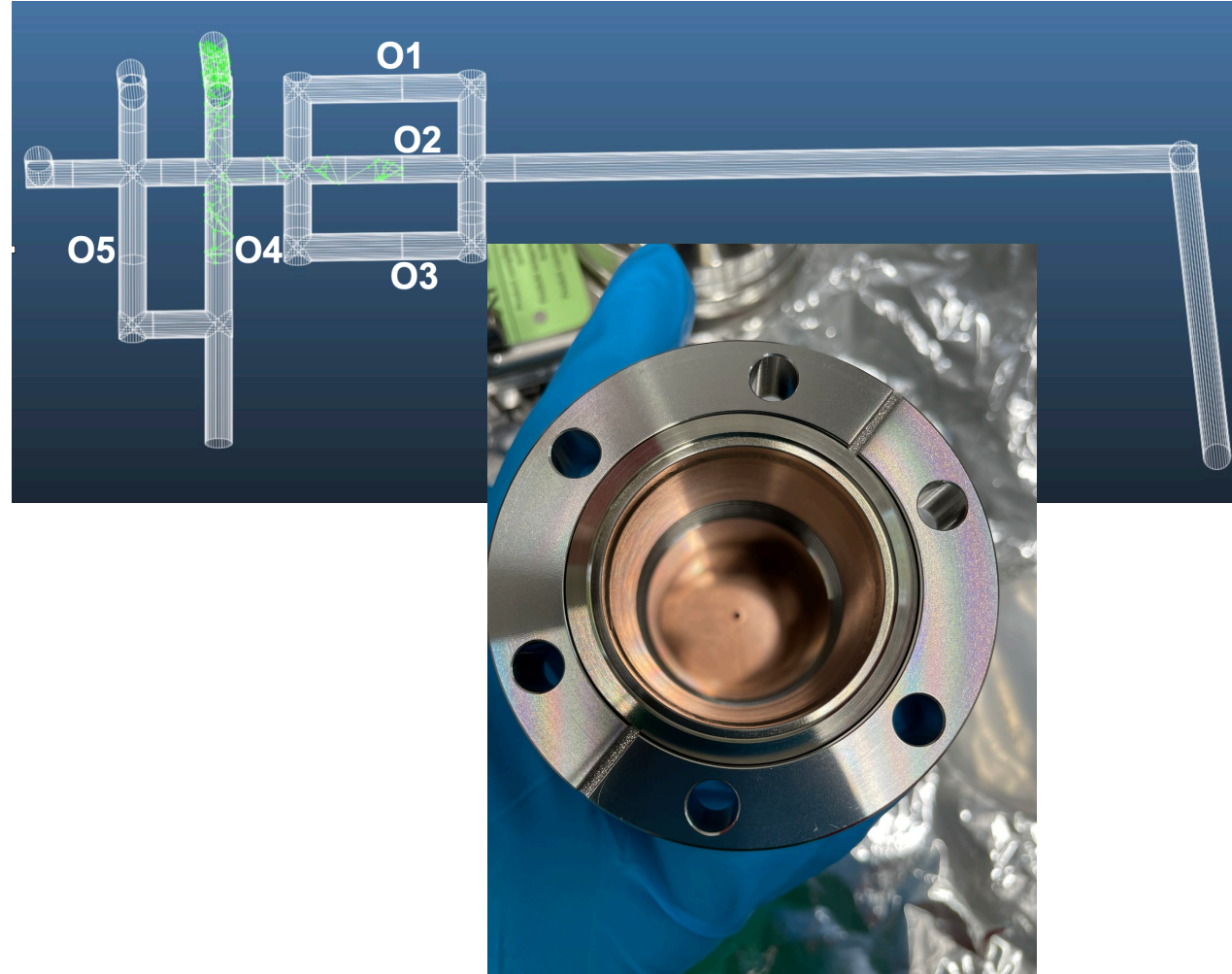
- Initial orifice design: one dimensional
(O1&O4: $d = 1.45\text{mm}$, O3&O5: $d = 0.5\text{mm}$)

- Copper gaskets: 2mm thick

- Need to simulate short tubes, rather than 2D orifices

- Recalculation of orifice conductance with

$$C_{ST} = C_{\text{orifice}} \cdot \frac{14 + 4\frac{L}{D}}{14 + 18\frac{L}{D} + 3\left(\frac{L}{D}\right)^2}$$



Simulation and calibration measurement of the gas inlet conductances

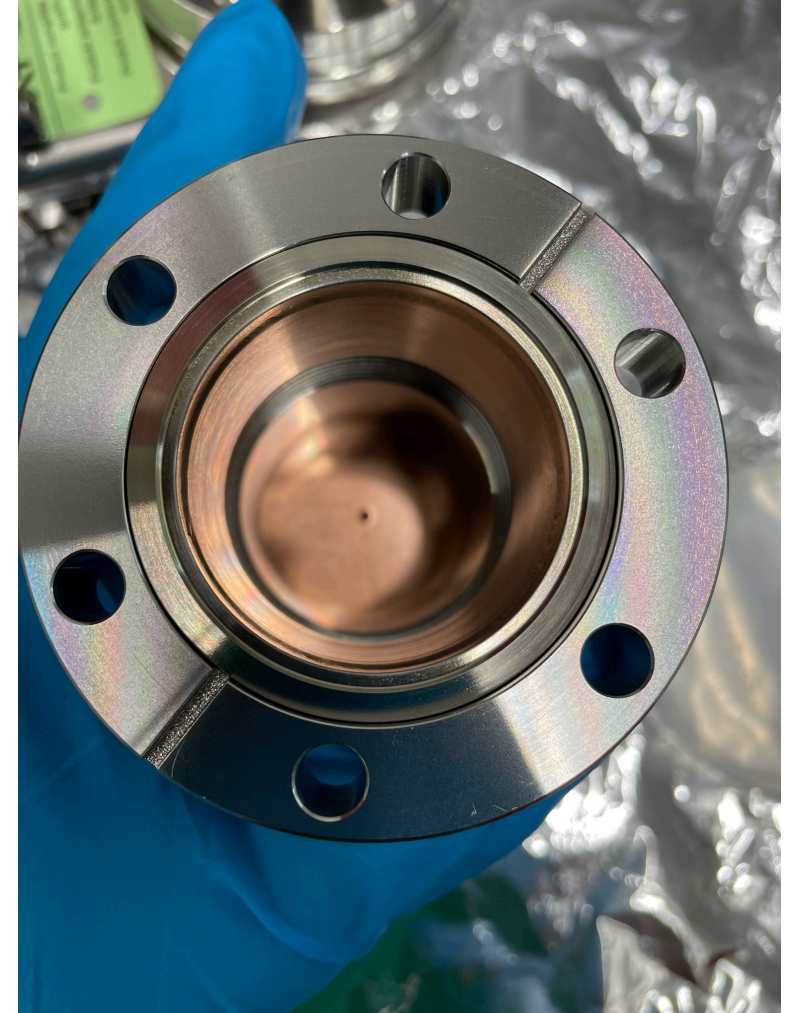
- Calibration possible by measuring the pressure during pump down

$$p(t) = p_0 \cdot e^{-\tau \frac{s_{eff}}{V}} + p_{min}$$

- Conductance can be calculated by

$$C = \frac{S \cdot V}{S\tau - V}$$

- Different orifice sizes allow different pump down paths: comparison between paths allows for conductance calibration



Simulation and calibration measurement of the gas inlet conductances

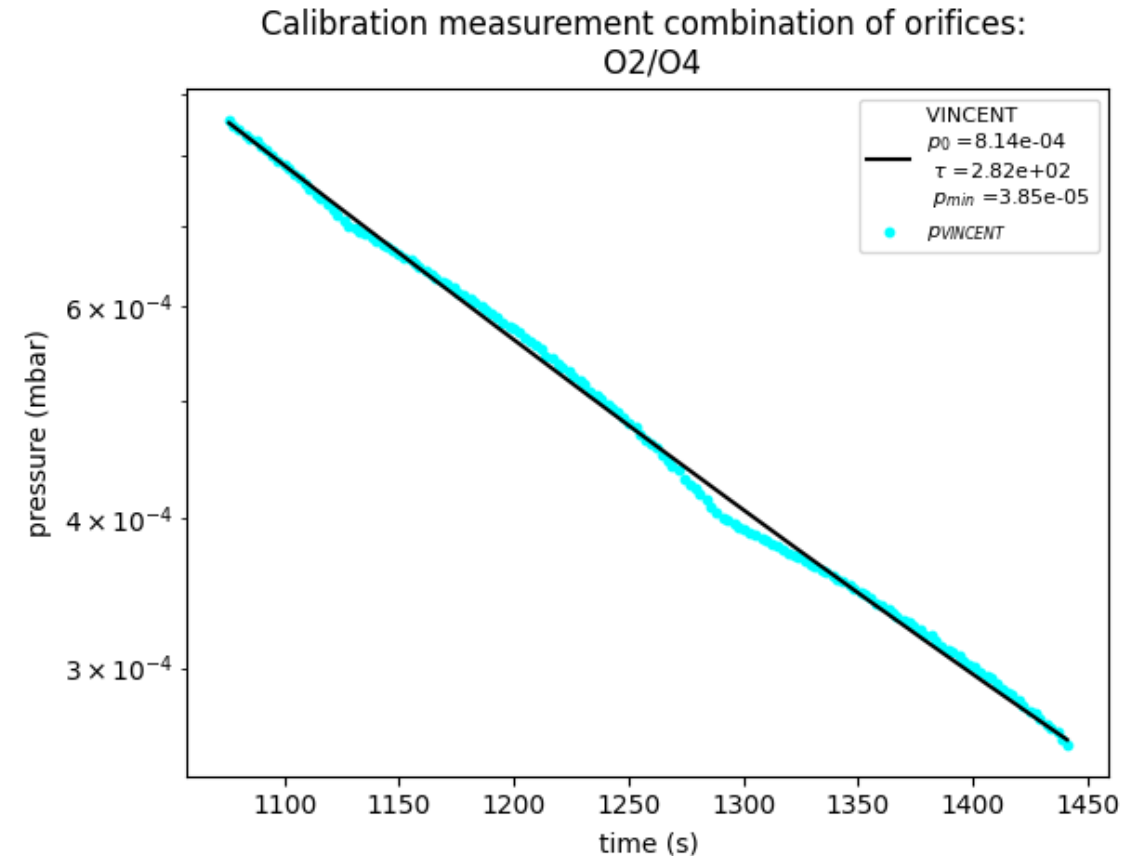
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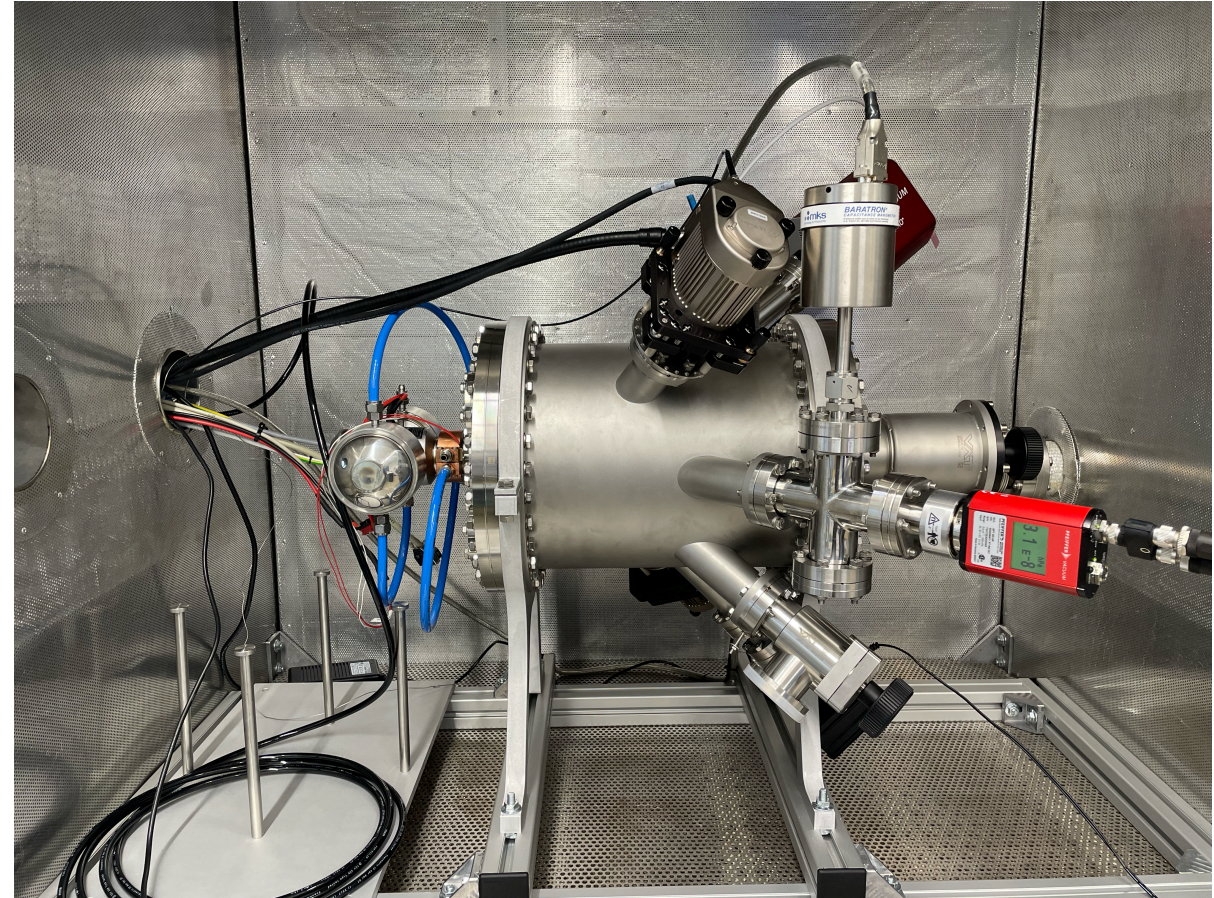
Simulation and calibration measurement of the gas inlet conductances

Combination of orifices	Calculated conductance in L/s	Simulated conductance in L/s	Measured conductance C + Cerrsys in L/ s
O1/O4	$4.15 \cdot 10^{-2}$	$3.66 \cdot 10^{-2}$	$3.94 \cdot 10^{-2} \pm 4.25 \cdot 10^{-4}$
O1//O4 + O5	$4.28 \cdot 10^{-2}$	$3.85 \cdot 10^{-2}$	$3.30 \cdot 10^{-2} \pm 1.61 \cdot 10^{-4}$
O2/O4	$8.18 \cdot 10^{-2}$	$7.34 \cdot 10^{-2}$	$6.52 \cdot 10^{-2} \pm 8.13 \cdot 10^{-4}$
O2/O5	$5.15 \cdot 10^{-2}$	$4.32 \cdot 10^{-3}$	$4.86 \cdot 10^{-3} \pm 9.89 \cdot 10^{-5}$
O3/O5	$2.58 \cdot 10^{-2}$	$2.18 \cdot 10^{-3}$	$3.21 \cdot 10^{-3} \pm 6.85 \cdot 10^{-6}$

- Values for calculation, simulation and measurement are similar, deviation of up to 20% can be expected
- Acceptable for first test BUT:
- Needs further investigation: include different geometries of the orifices for improved calculation and simulations

Test of the Conditioning Methods

Markus Schulz-Ritz
16.07.2026



Baking and cryo-cooler test

- Goal pressure: $1 \cdot 10^{-8}$ mbar before turning on the cryocooler

- Baking for 3 weeks at 100°C
 - Limitation due to cryo-cooler

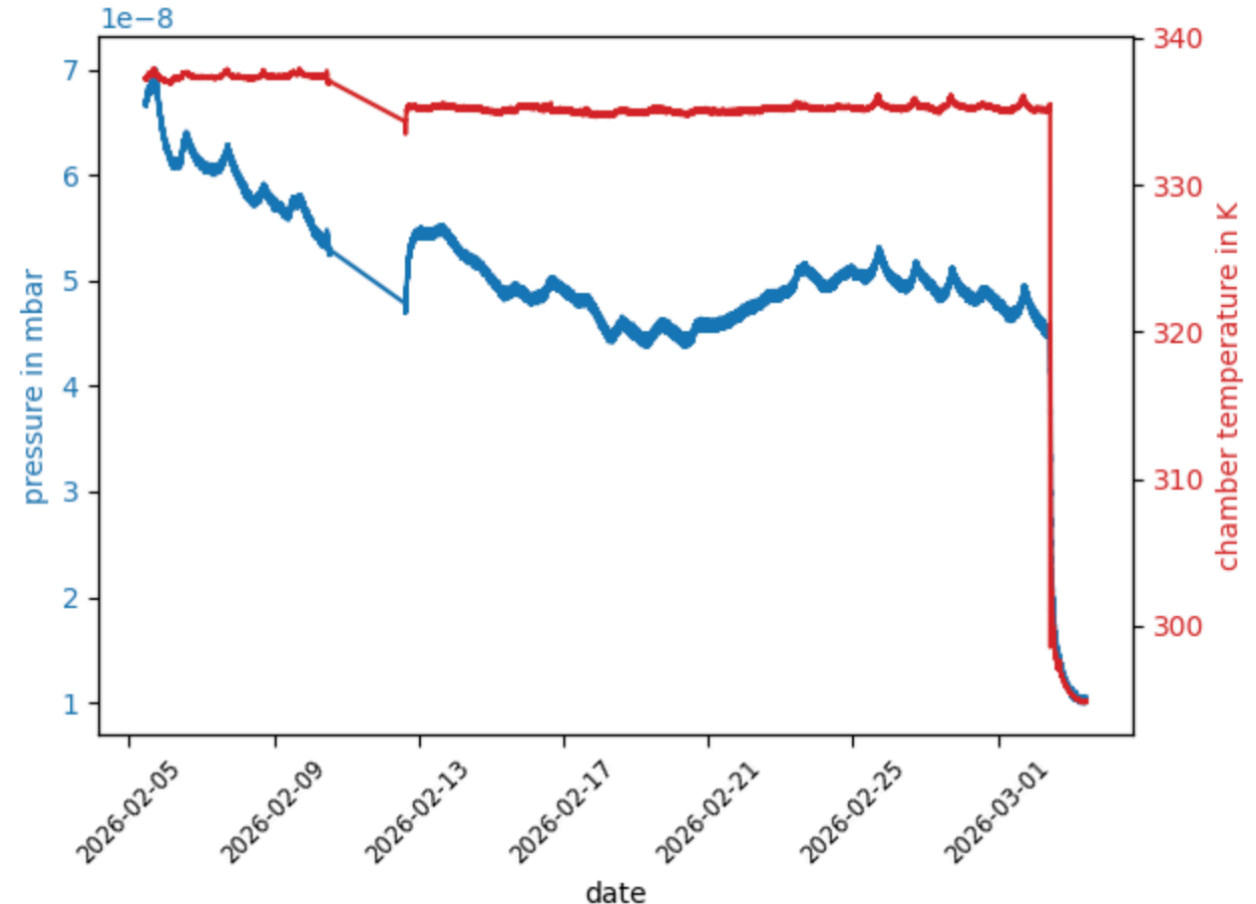
- Before baking: $5.8 \cdot 10^{-8}$ mbar

- After baking: $1.2 \cdot 10^{-8}$ mbar

- Cryo-cooler: $< 5 \cdot 10^{-9}$ mbar

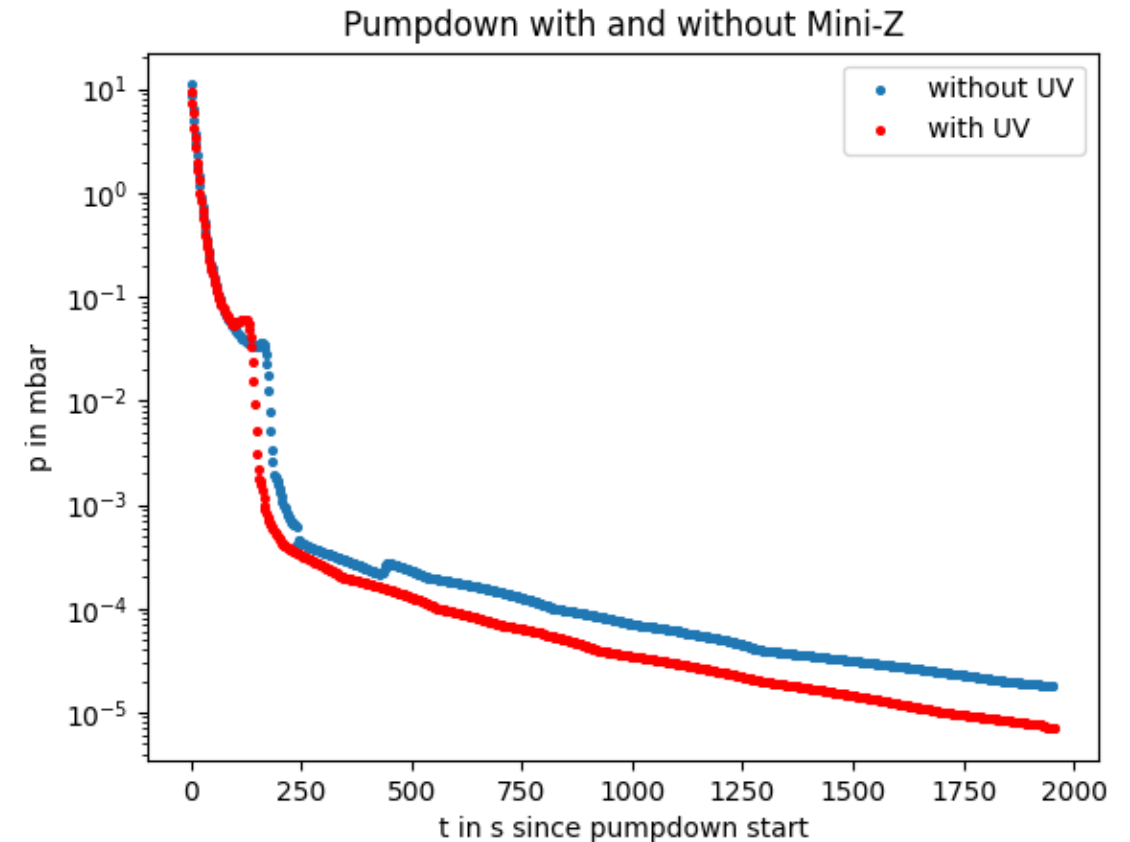
- Cryo-cooler and RGA: $1.2 \cdot 10^{-8}$ mbar

- Opened up VINCENT afterwards



UV-cleaning

- Same pressure ($4.06 \cdot 10^{-5}$ mbar) reached after 1360s with Mini-Z on
- Without Mini-Z: 1950s
- UV-cleaning reduces pump down time
- Data does not entirely confirm half rule of pump down for UV-cleaning

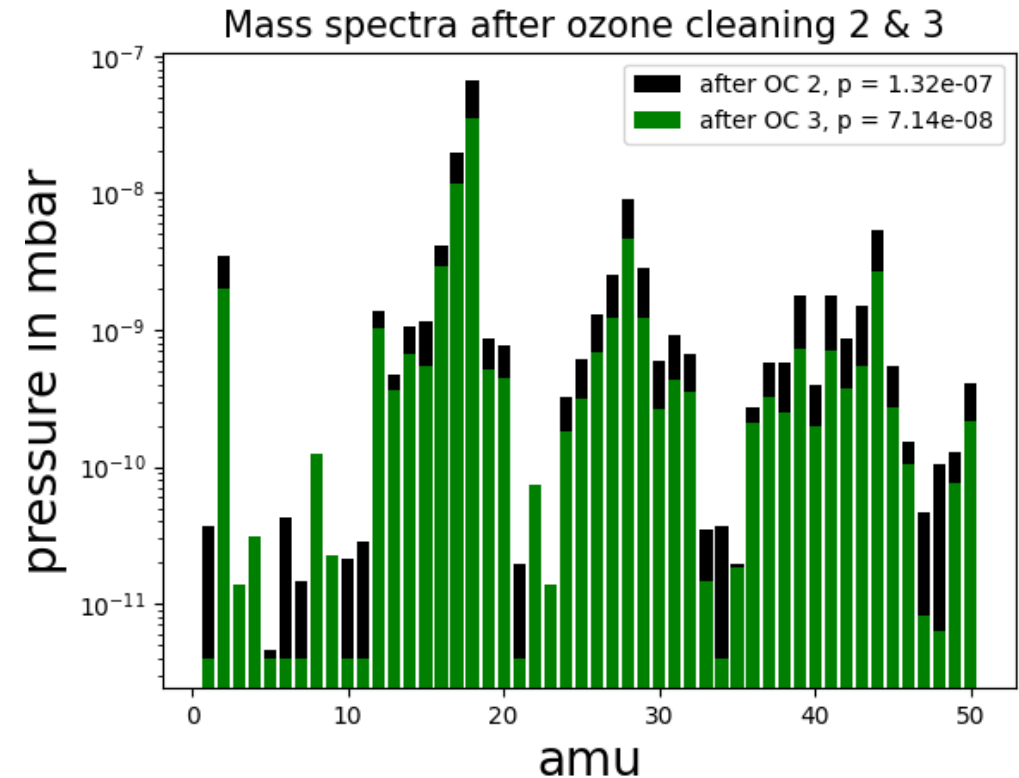
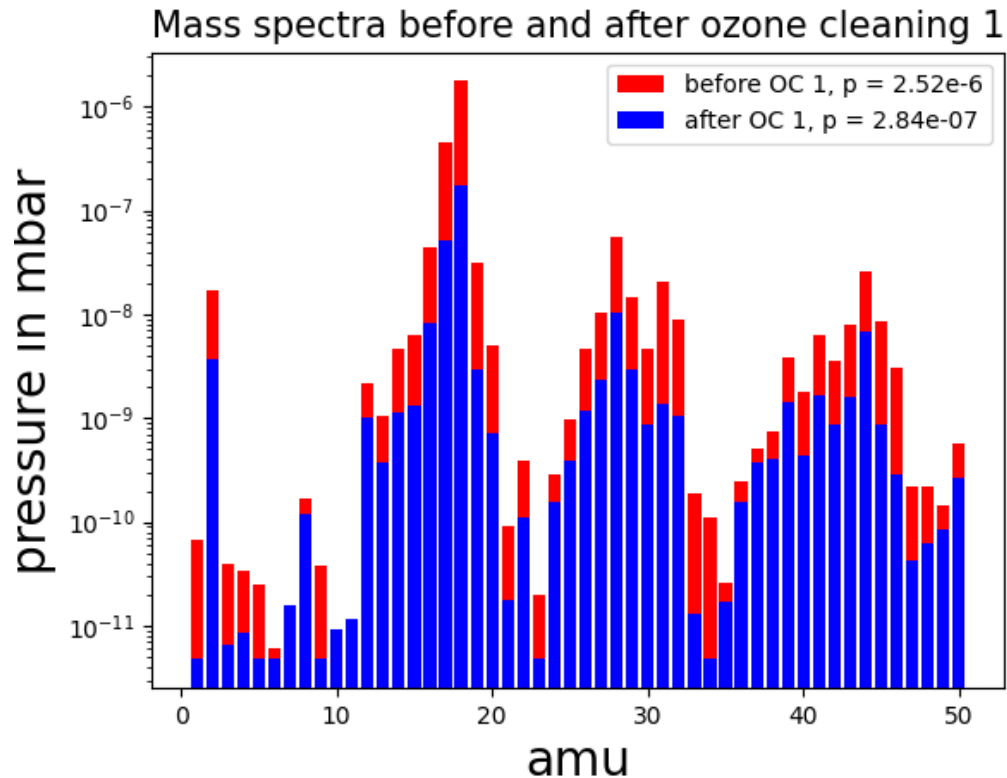


UV/Ozone conditioning

- 3x 1h UV/Ozone conditioning
- Pressure inside VINCENT: 100mbar
- dry air flowing through VINCENT
- 1 day of pumping in between conditioning cycles
- Recording mass spectra between each cycle

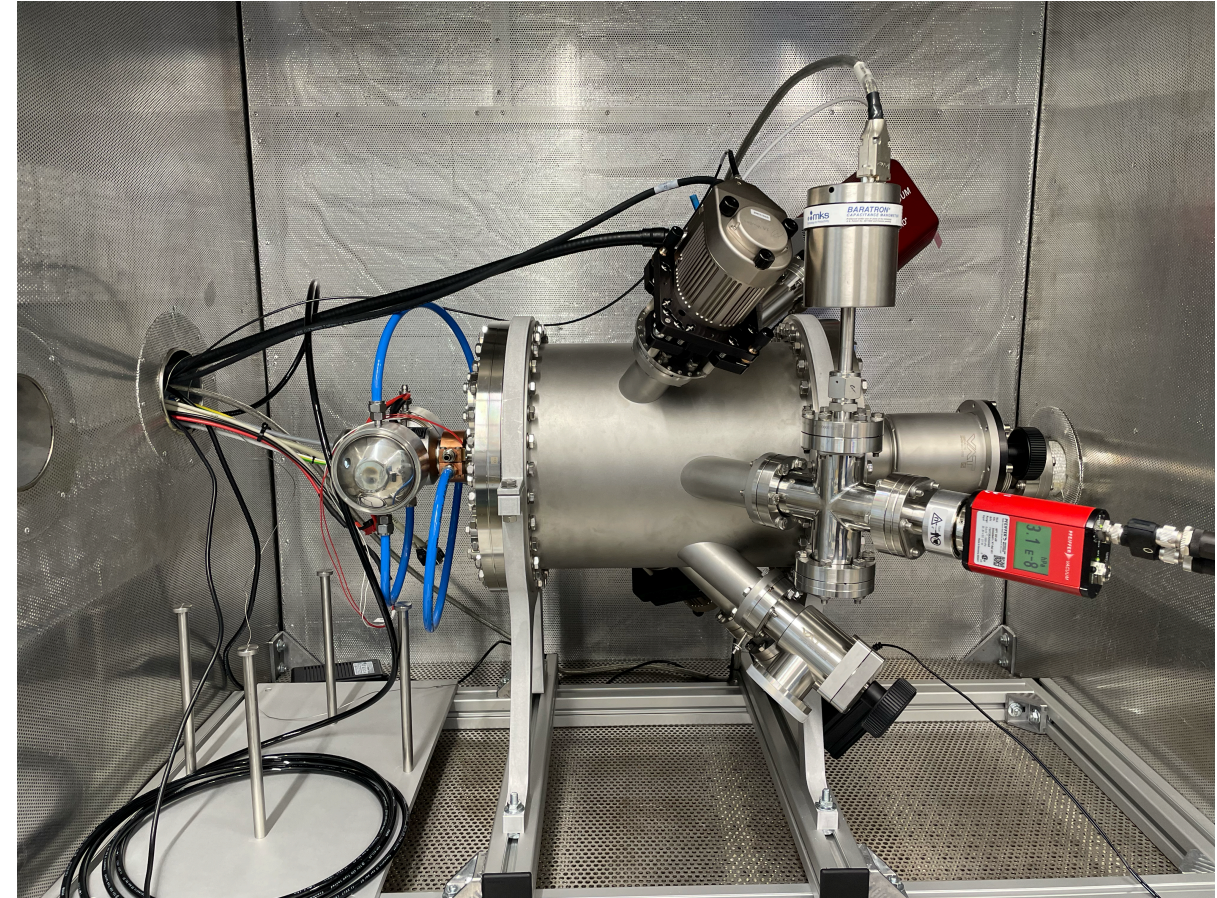
UV/Ozone conditioning

Reduction of a factor greater than 35 in pressure and water



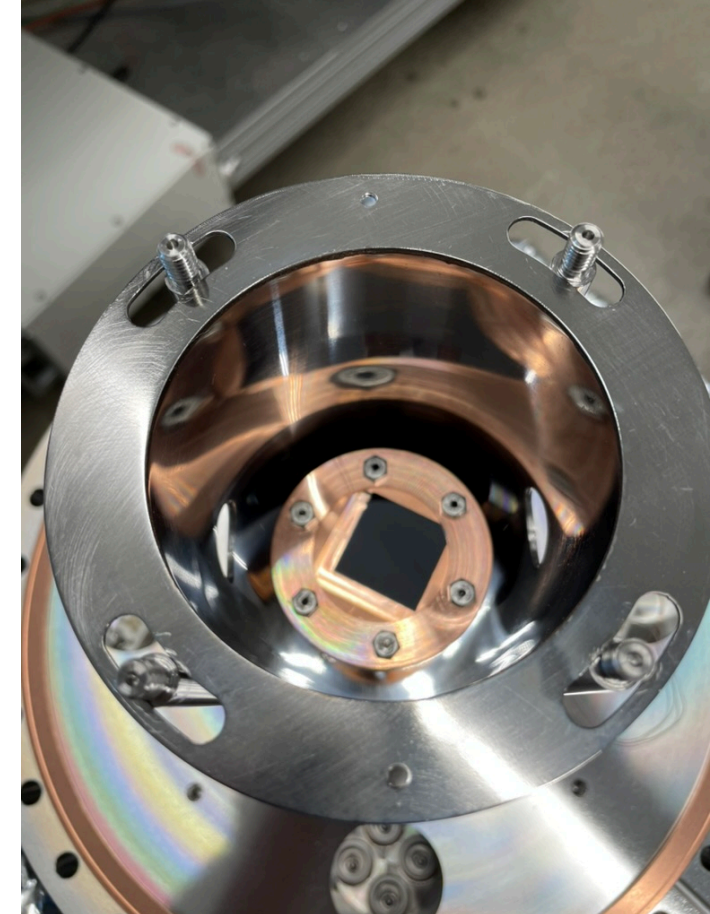
Ellipsometry measurements

Markus Schulz-Ritz
16.07.2026



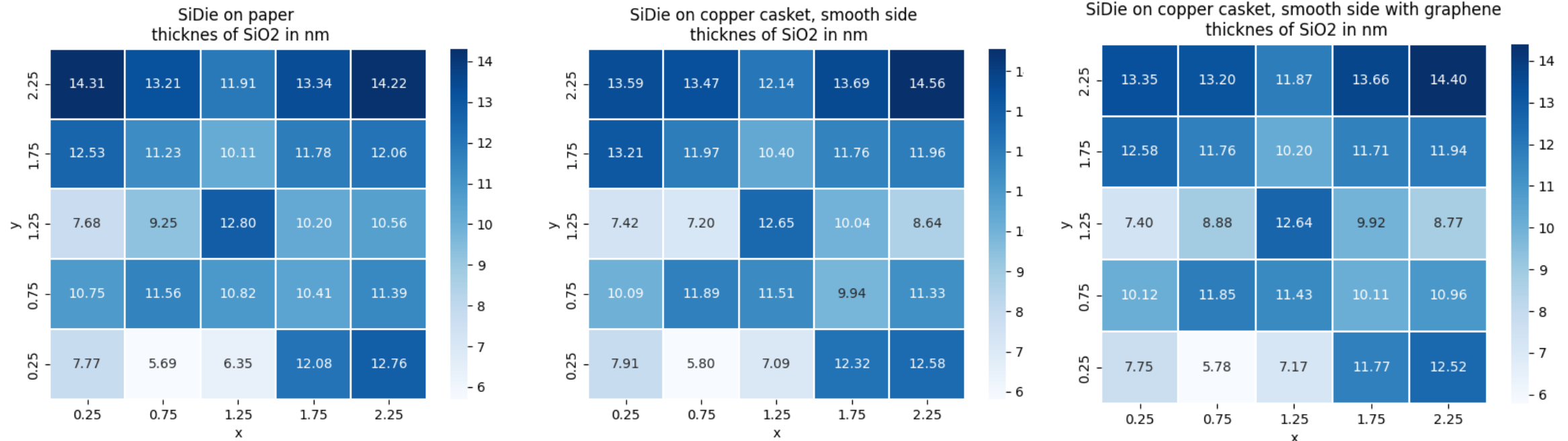
Ellipsometry Measurements:

- Model for ice growth experiments: Si-INTER-SiO₂-ASW (amorphous sold water)
- Before ice growth measurements: need to know the thickness of SiO₂ on the waver
- Makes fitting the model easier later on
- Waver on copper: if not roughened: backside effects!



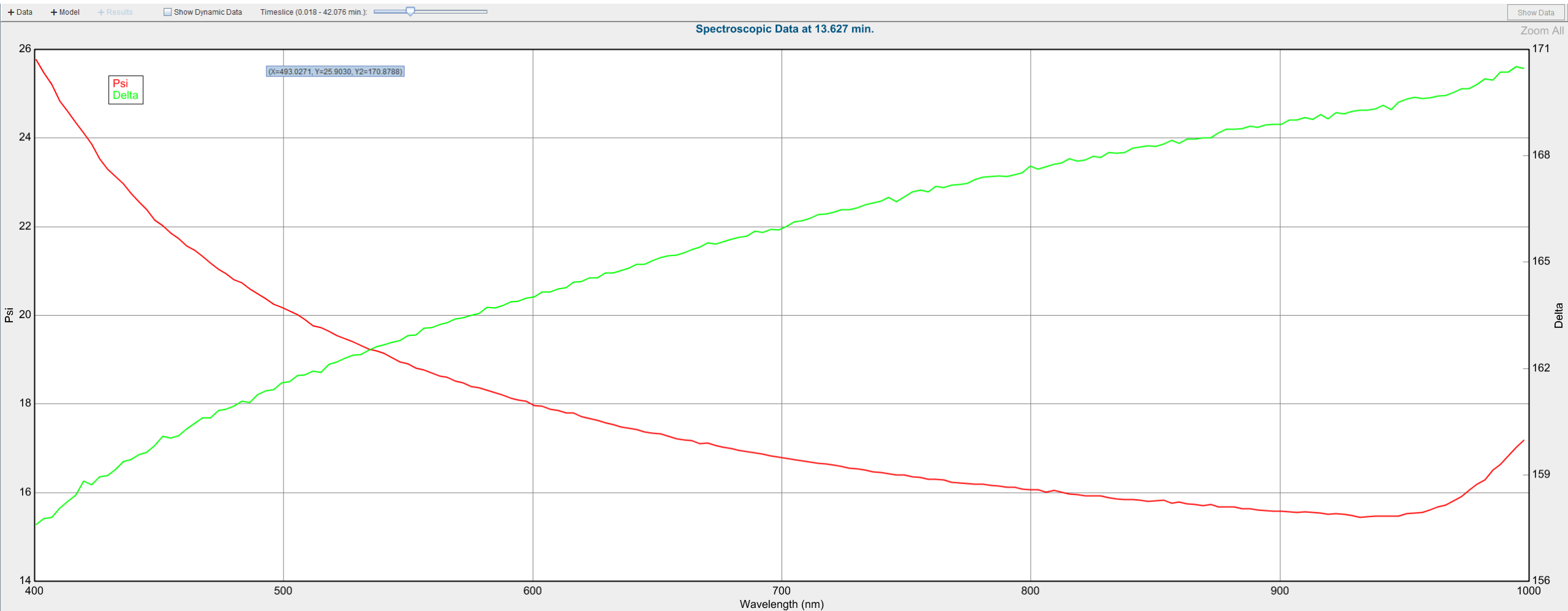
Ellipsometry Waver planarity

- SiO₂ - thickness is varying greatly !
- Tested on different surfaces for backside reflection mitigation
- Need roughening of backside or calibration waver for ice growth measurements



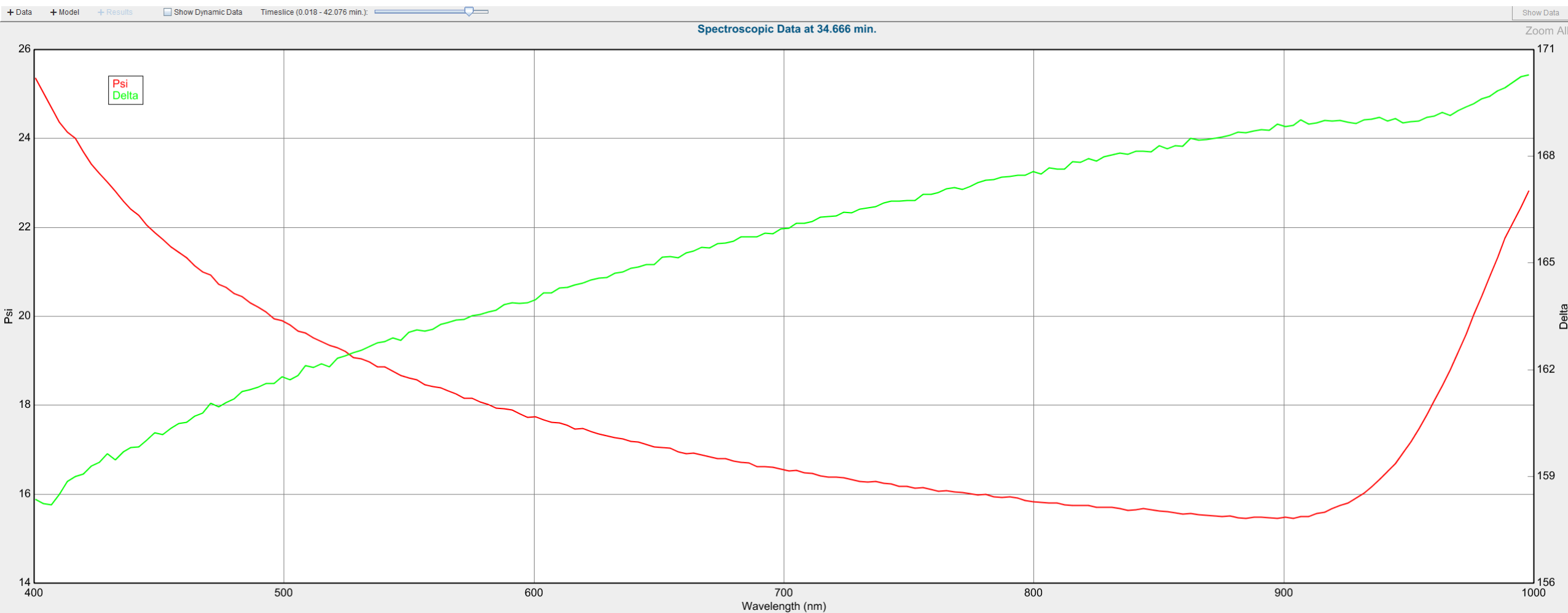
Ellipsometry Waver possible backside effects

Also rising delta after 900nm with lower temperature for SiDie without roughening:
200K



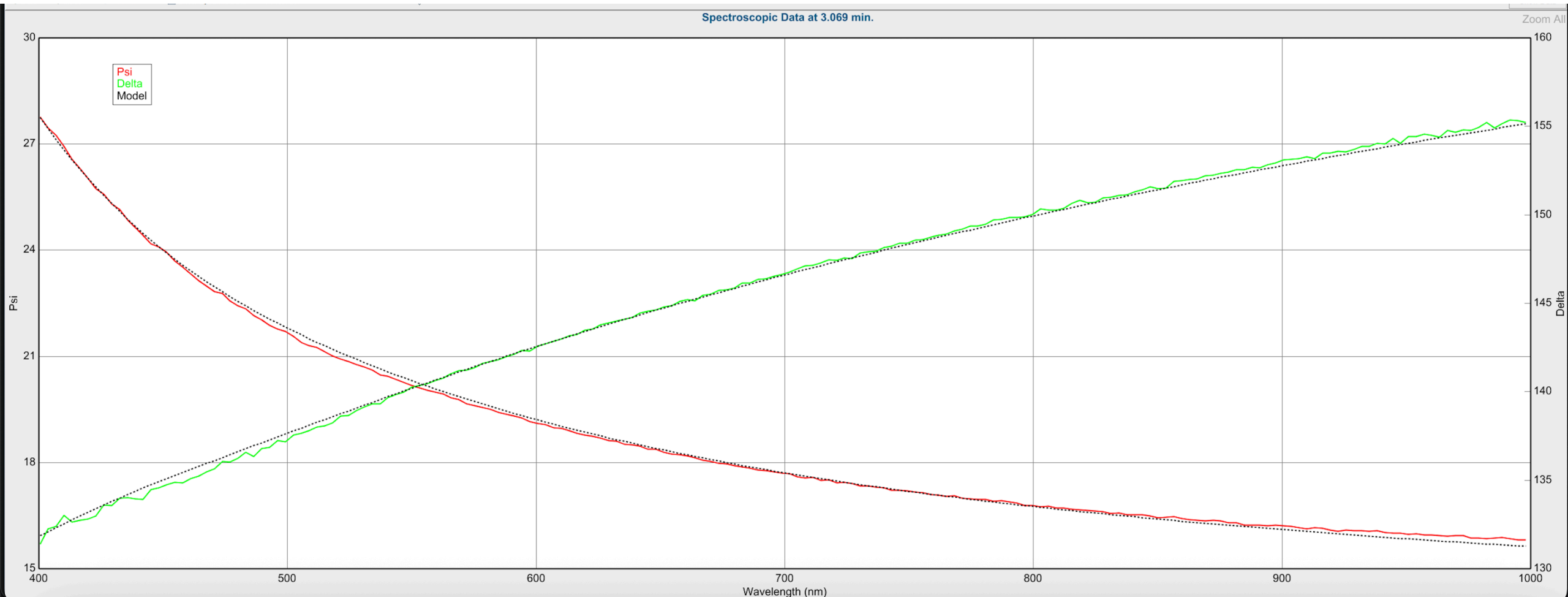
Ellipsometry Waver possible backside effects

Also rising delta after 900nm with lower temperature for SiDie without roughening:
50K



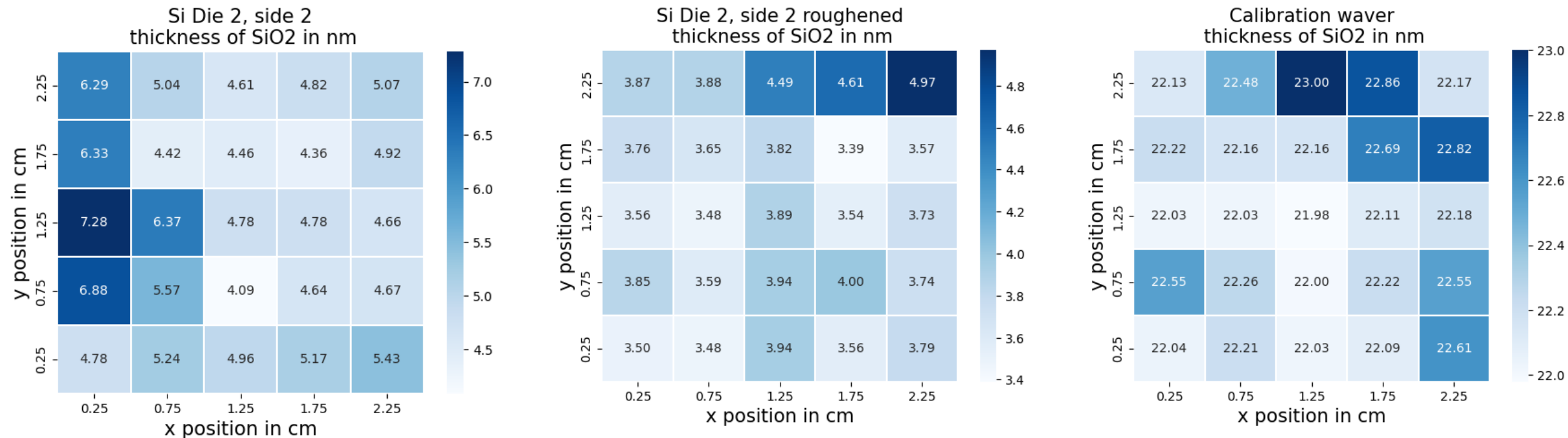
Ellipsometry Waver possible backside effects

Calibration waver at 50K



Ellipsometry Wafer planarity - solved

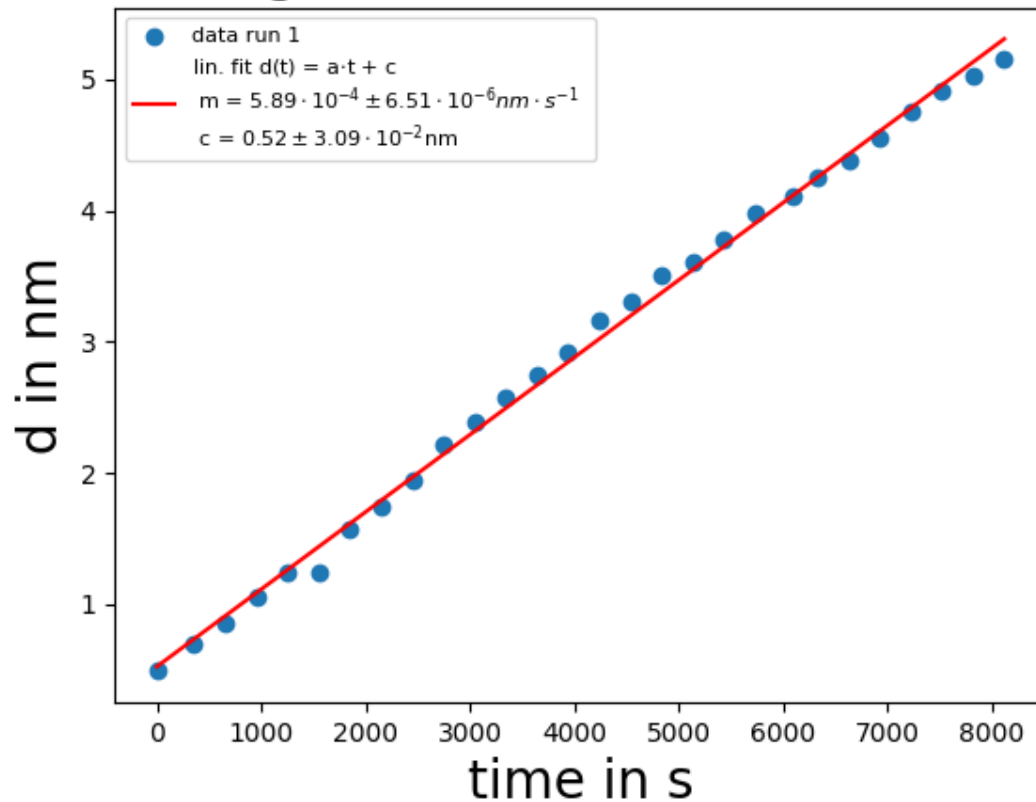
- SiDie with roughened backside and calibration wafer display better planarity



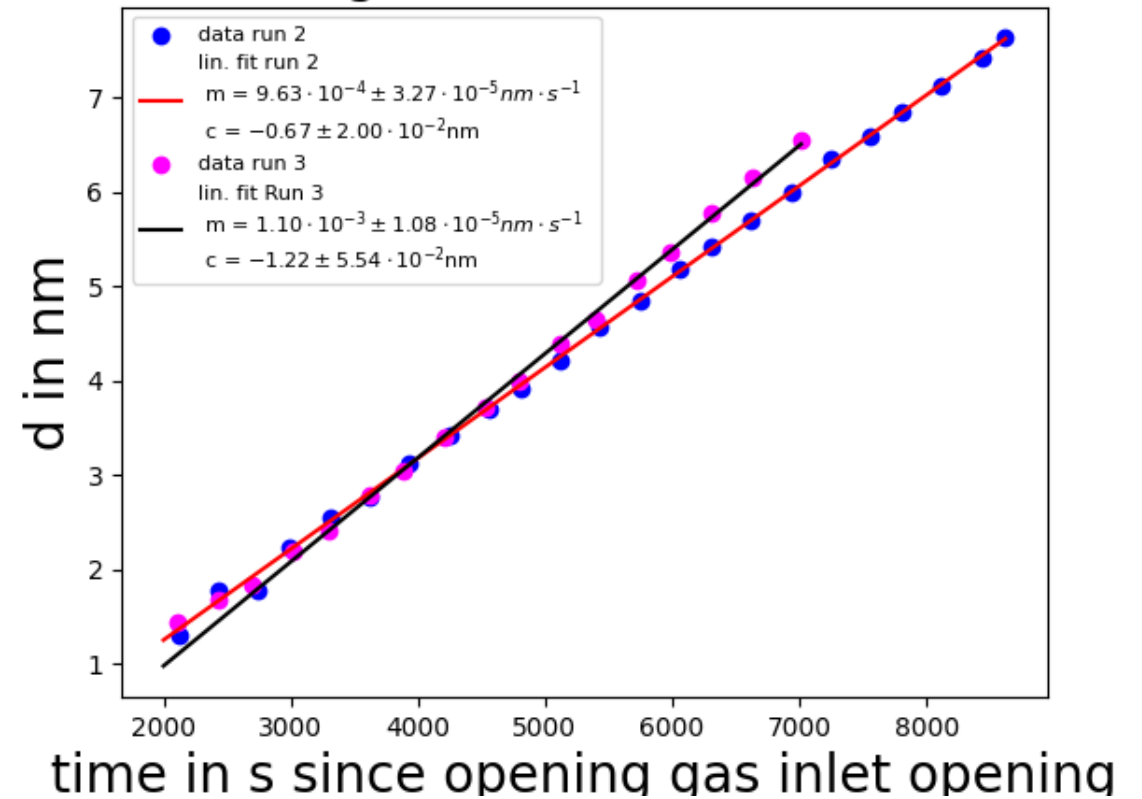
Ice growth measurements

- Three ice growth measurements
- Pressure at $3.4\text{-}4.4 \cdot 10^{-8}$ mbar
- Only used data after pressure stabilised

Water ice growth on SiDie at $3.4 \cdot 10^{-8}$ mbar



Water ice growth on SiDie Run 2 and 3



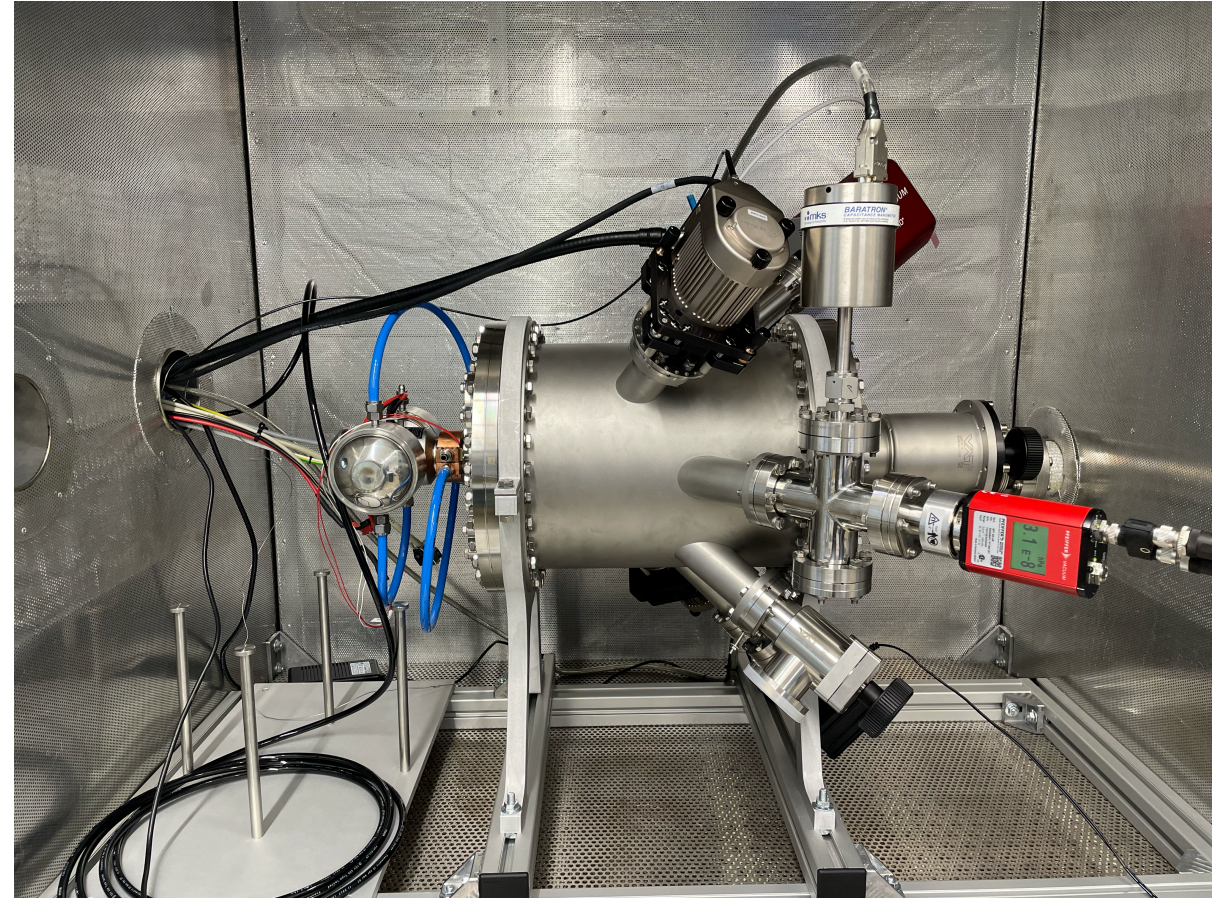
Ice growth measurements

- Monolayer formation times deviate from expected formation times at the corresponding pressures
- Expected times calculated using the measured pressure and the pressure for 90s ($3.6 \cdot 10^{-8}$ mbar)
- Comparing formation times between expectation with and without cryo-shield hints at cryo-shield responsible for deviation

Run number	τ_m in $\text{s} \cdot \text{ML}^{-1}$	τ_{err} in $\text{s} \cdot \text{ML}^{-1}$	$\tau_{\text{expect, no CS}}$ in $\text{s} \cdot \text{ML}^{-1}$	$\tau_{\text{expect, CS}}$ in $\text{s} \cdot \text{ML}^{-1}$	p_m in mbar
Run 1	514.47	6.26	84.87	791.83	3.2×10^{-8}
Run 2	314.77	1.18	69.22	645.89	4.4×10^{-8}
Run 3	274.72	2.97	62.86	586.56	4.8×10^{-8}

Conclusion and outlook

Markus Schulz-Ritz
16.07.2026



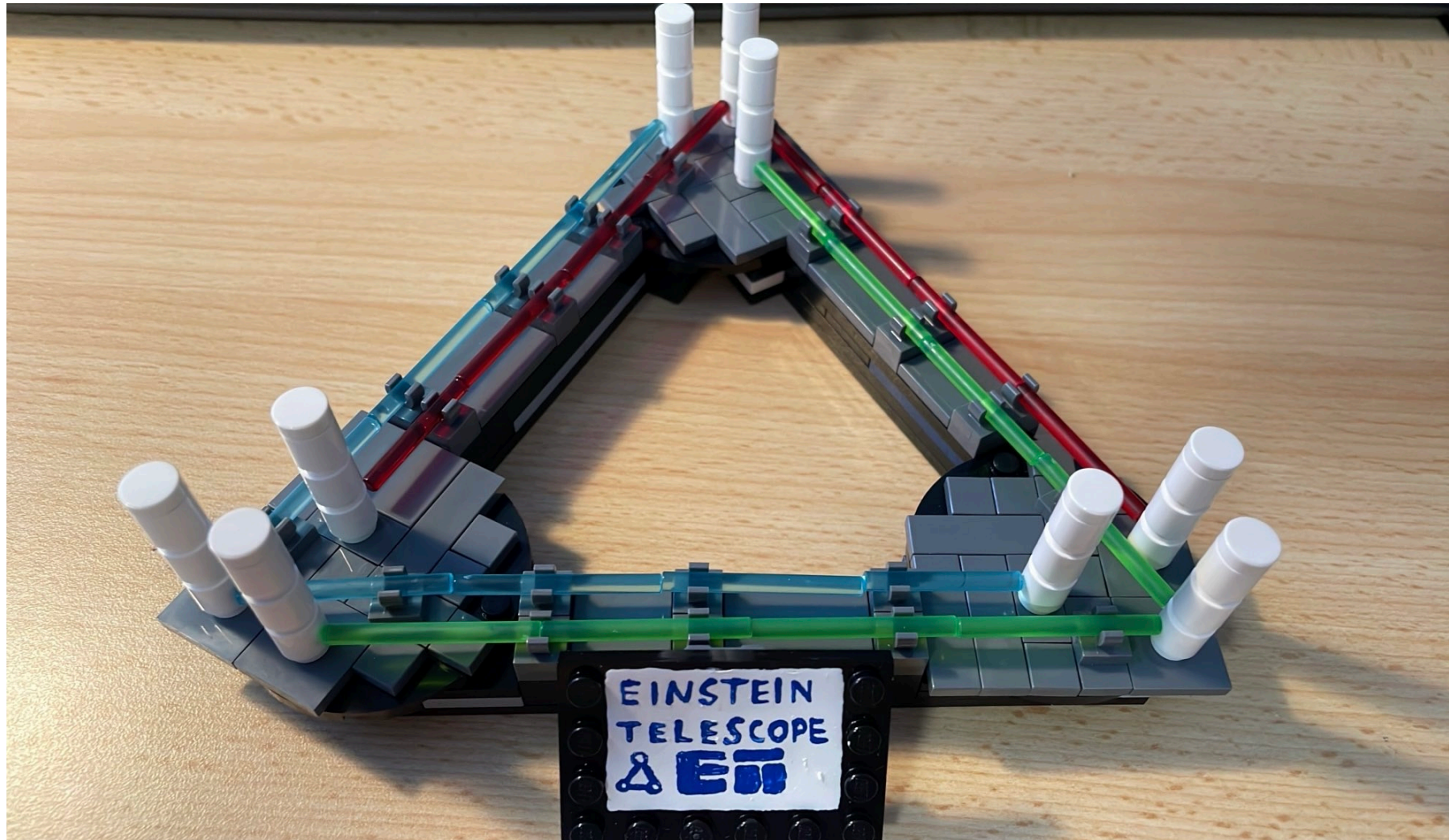
Conclusions

- Design, commissioning and first test of a gas inlet for VINCENT
- Initial test of UV-cleaning indicate usefulness for faster pump down
- UV/ozone conditioning showed reduction of total pressure by a factor greater than 35
- Ellipsometry installed and tested: ice growth measurements possible in sub-nm range
- Ice growth rate deviates from expectation, but deviation can be partially explained
- Need for further investigation of deviations from expectations as well as possible systematics

Outlook

- Future extensions:
 - New Cleaning Method: field emission electron source (with R. Schreiner at OTH Regensburg and R. Cimino at INFN-LNF)
 - Implementation of Quartz Crystal Micro Balance (test at cryogenic temperatures)
 - Two stage cryo-cooler

Thank you for your attention!

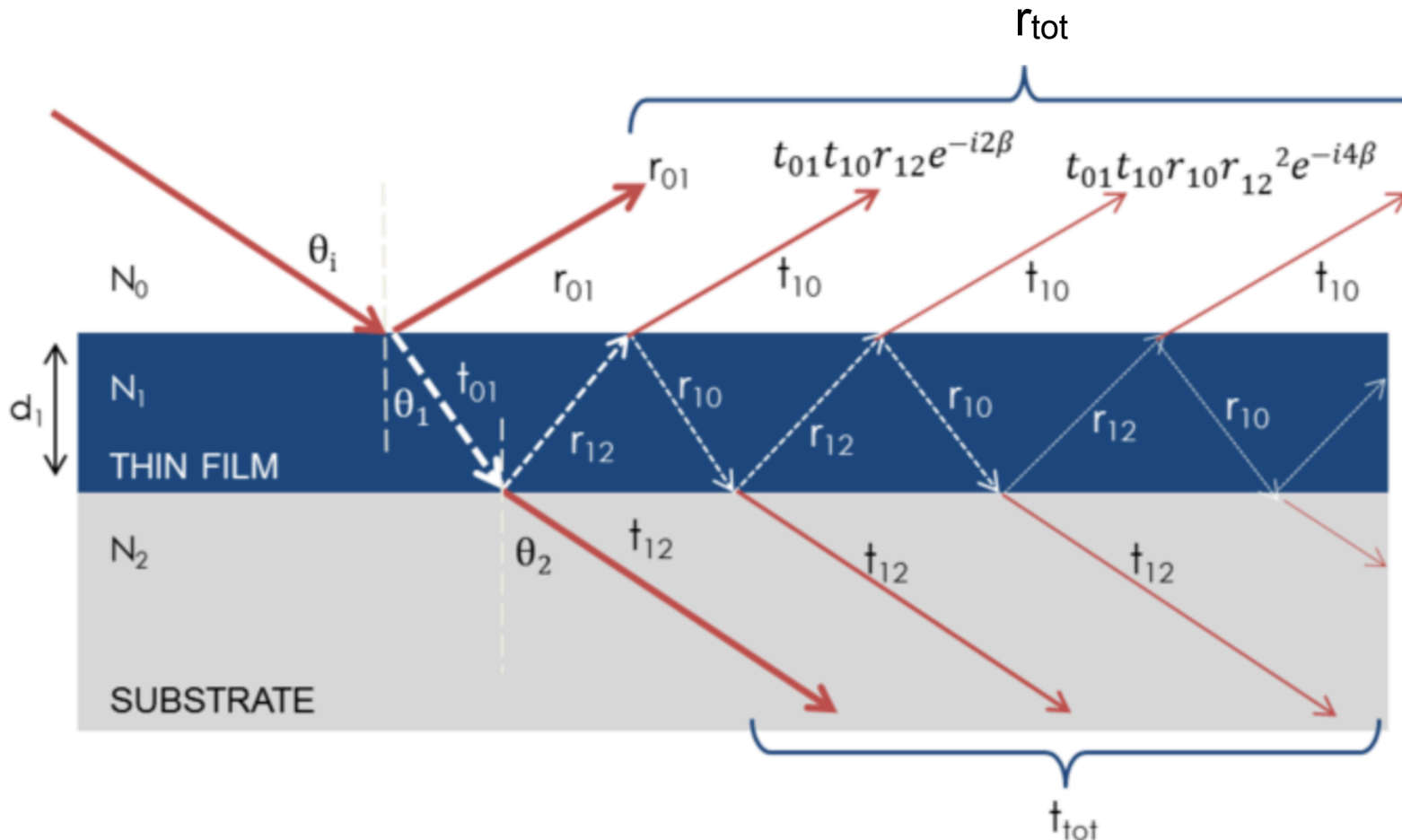


Backup Slides

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16.07.2026

Ellipsometry

Reflected intensity calculated by fresnel coefficients



$$r_p \equiv \frac{E_{rp}}{E_{ip}} = \frac{n_t \cos \theta_i - n_i \cos \theta_t}{n_t \cos \theta_i + n_i \cos \theta_t}$$

$$t_p \equiv \frac{E_{tp}}{E_{ip}} = \frac{2n_i \cos \theta_i}{n_t \cos \theta_i + n_i \cos \theta_t}$$

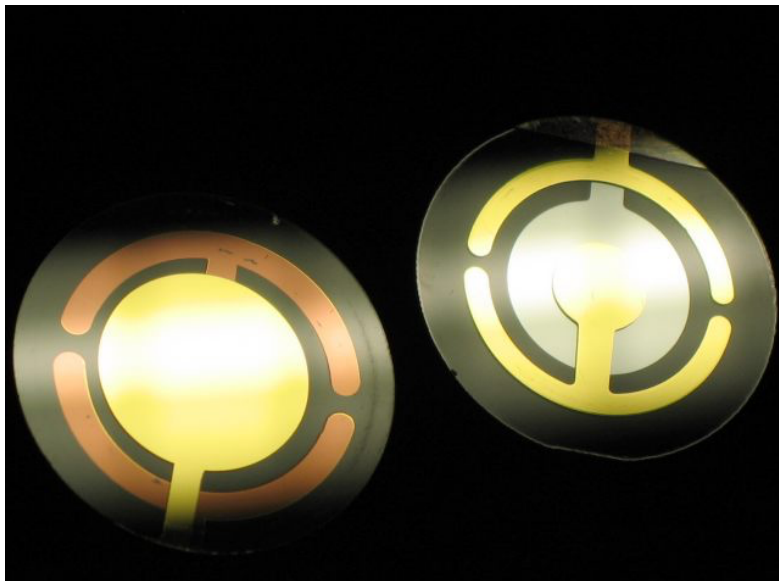
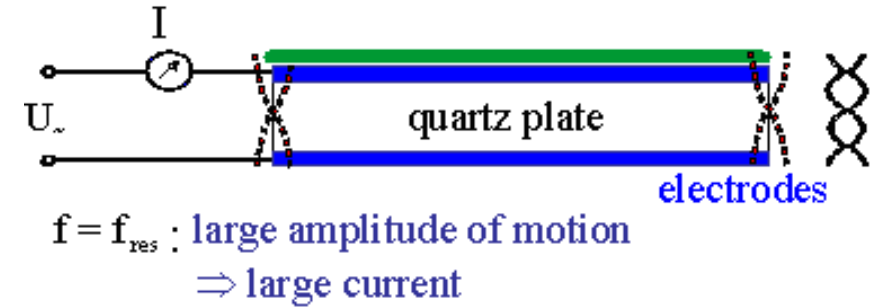
$$r_s \equiv \frac{E_{rs}}{E_{is}} = \frac{n_i \cos \theta_i - n_t \cos \theta_t}{n_i \cos \theta_i + n_t \cos \theta_t}$$

$$t_s \equiv \frac{E_{ts}}{E_{is}} = \frac{2n_i \cos \theta_i}{n_i \cos \theta_i + n_t \cos \theta_t}$$

Both Images from:
<https://qd-europe.com/be/en/product/short-introduction-ellipsometry/>

Quartz Crystal Micro Balance

- Uses piezo-electric effect
- Small mass differences lead to change in vibration frequency



Both Images from:
https://en.wikipedia.org/wiki/Quartz_crystal_microbalance

