Liquid Lubricant Evaporation in Space Applications

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esa

INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN

INTRODUCTION

SPACE ENVIRONMENT

- Vacuum, Extreme temperatures, Radiation

SPACE MISSIONS

- Operation over long lifetimes (5–15 years)

MISSION–CRITICAL TRIBOLOGICAL COMPONENTS

- Bearings, gears, actuators

LUBRICATION FOR SPACE APPLICATIONS

- Solid, Fluid (oils & greases), Hybrid

MOTIVATION

LONG–LIFETIME SPACE MISSIONS

- Reliability of tribological components

FLUID LUBRICANTS IN SPACE APPLICATIONS

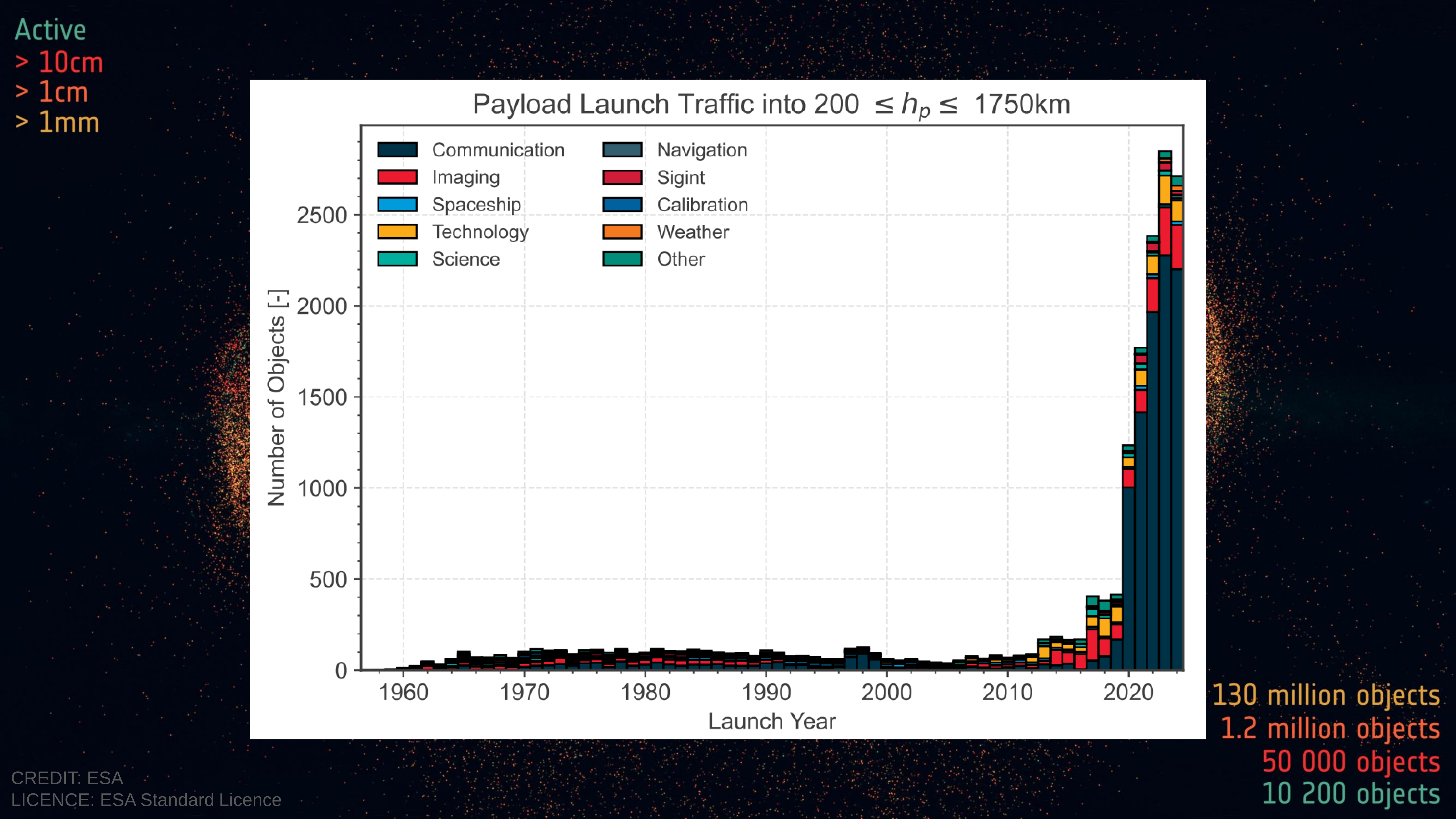
- Vacuum evaporation, Contamination

LABYRINTH SEALS IN SPACE MECHANISMS

- Evaporation mitigation by flow restriction

SPACE DEBRIS THREAT

- Non–functional satellites and fragments



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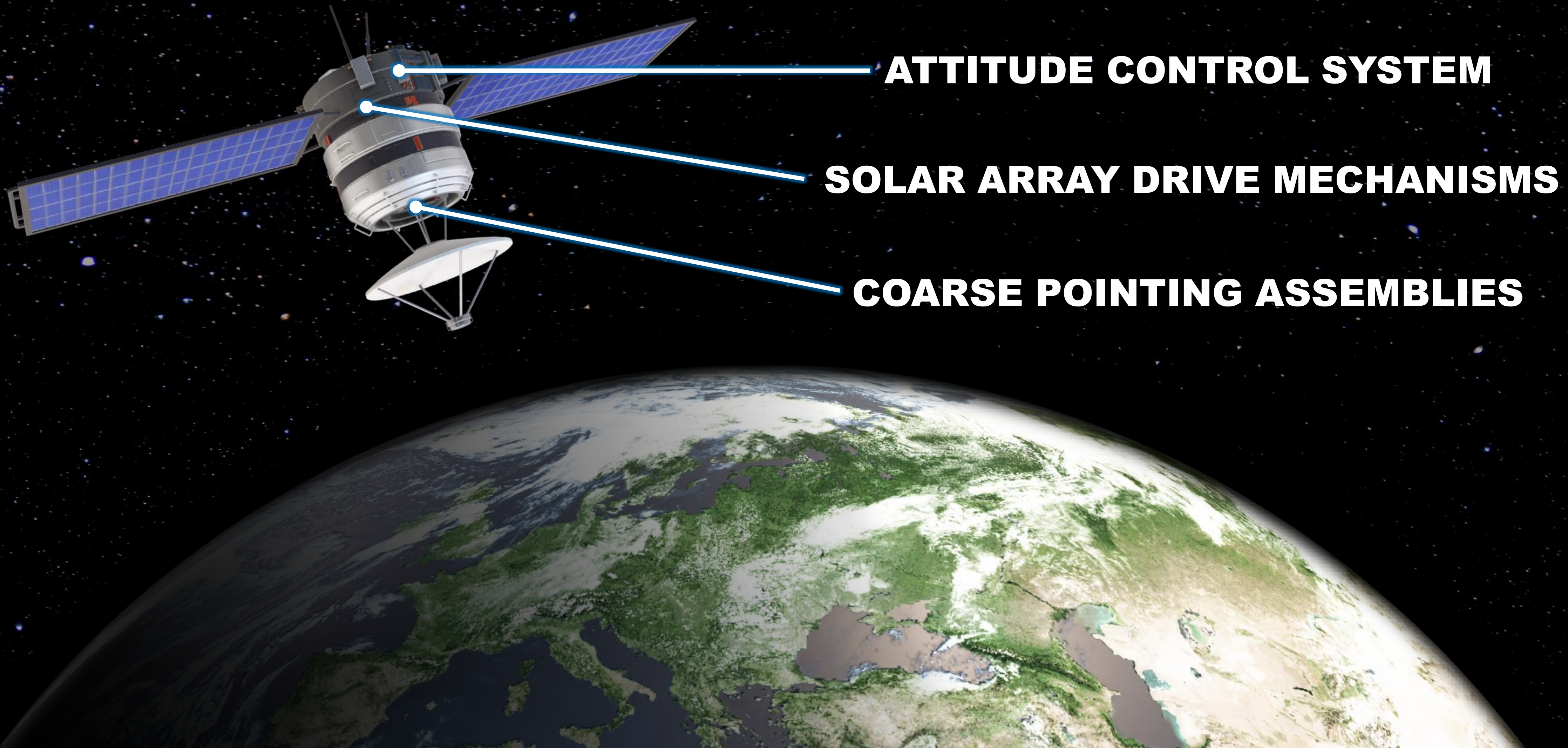
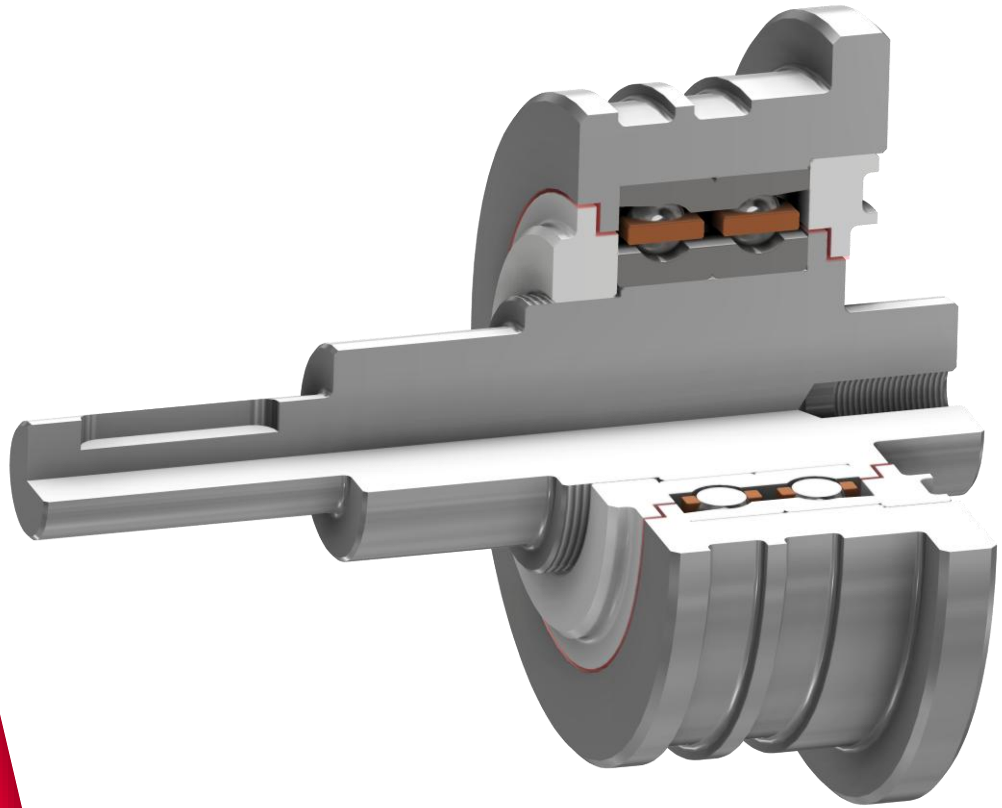
LABYRINTH SEALS IN SPACE



LABYRINTH SEALS

- Sealing lubricant evaporation
- Preventing contamination
- Design for each assembly



MOLECULAR FLOW

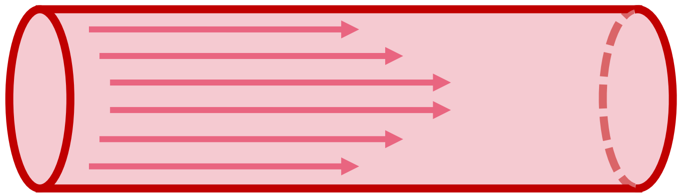
VACUUM ENVIRONMENT (UHV, XHV)

- Molecules move freely
- Primary surface collisions
- Rare intermolecular collisions

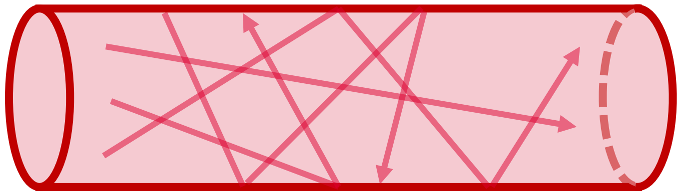
VACUUM EVAPORATION

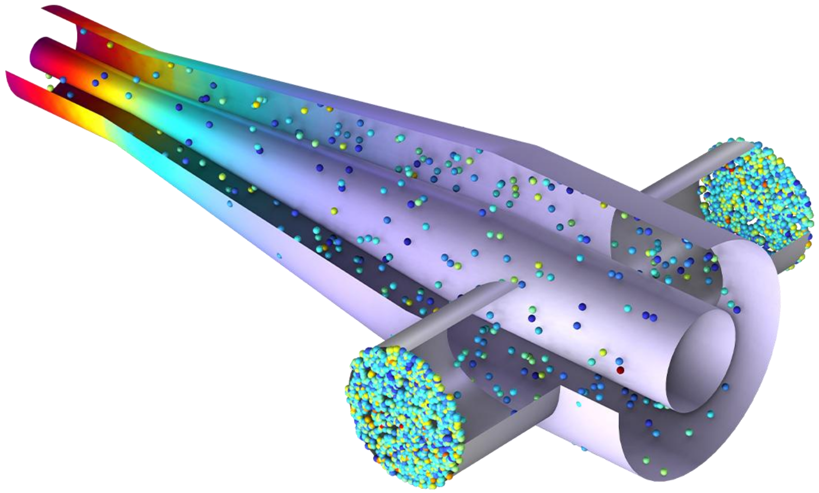
- Vacuum pressure ≤ Vapor pressure

Viscous flow



Molecular flow

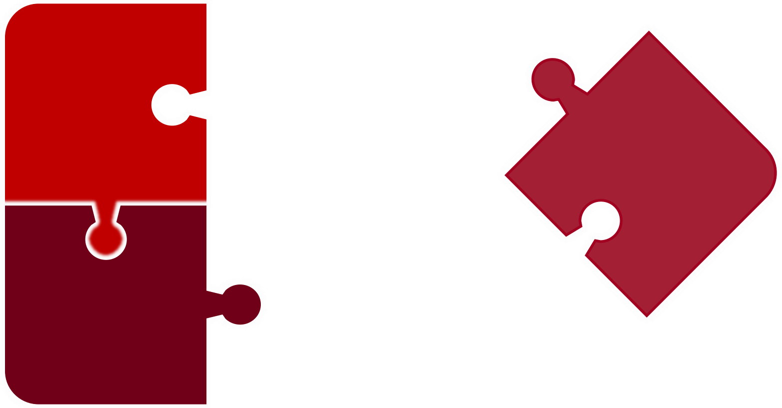




LITERATURE REVIEW

WELL ESTABLISHED | PROBLEMATIC | MISSING

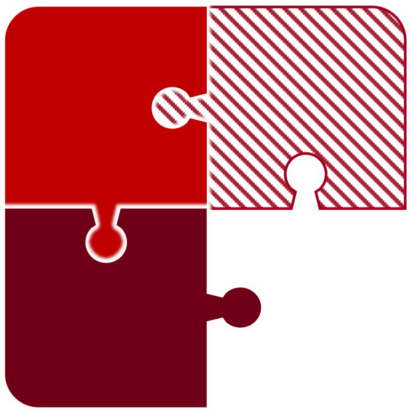
- **Liquid lubricants are essential for space mechanisms but volatile in vacuum**
- **Vacuum evaporation is commonly estimated using Langmuir models**
- **Labyrinth seals are a standard passive method to limit vapor migration**
- **Molecular flow simulations are used to support seal design**



LITERATURE REVIEW

WELL ESTABLISHED | **PROBLEMATIC** | MISSING

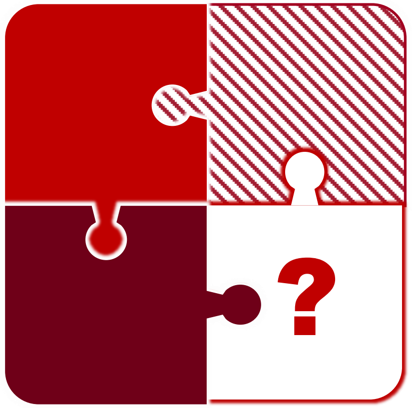
- Analytical evaporation models systematically overpredict mass loss
- Vapor pressure data show large uncertainty and poor reproducibility
- Labyrinth seal models rely on idealized, smooth geometries
- Experimental validation under space-relevant conditions is limited



LITERATURE REVIEW

WELL ESTABLISHED | PROBLEMATIC | **MISSING**

- Time-resolved evaporation measurements under high and ultra-high vacuum
- Quantified influence of surface roughness on molecular transmission
- Combined validation of experiments, analytics, and simulations
- Simple, design-oriented correction models usable in early development



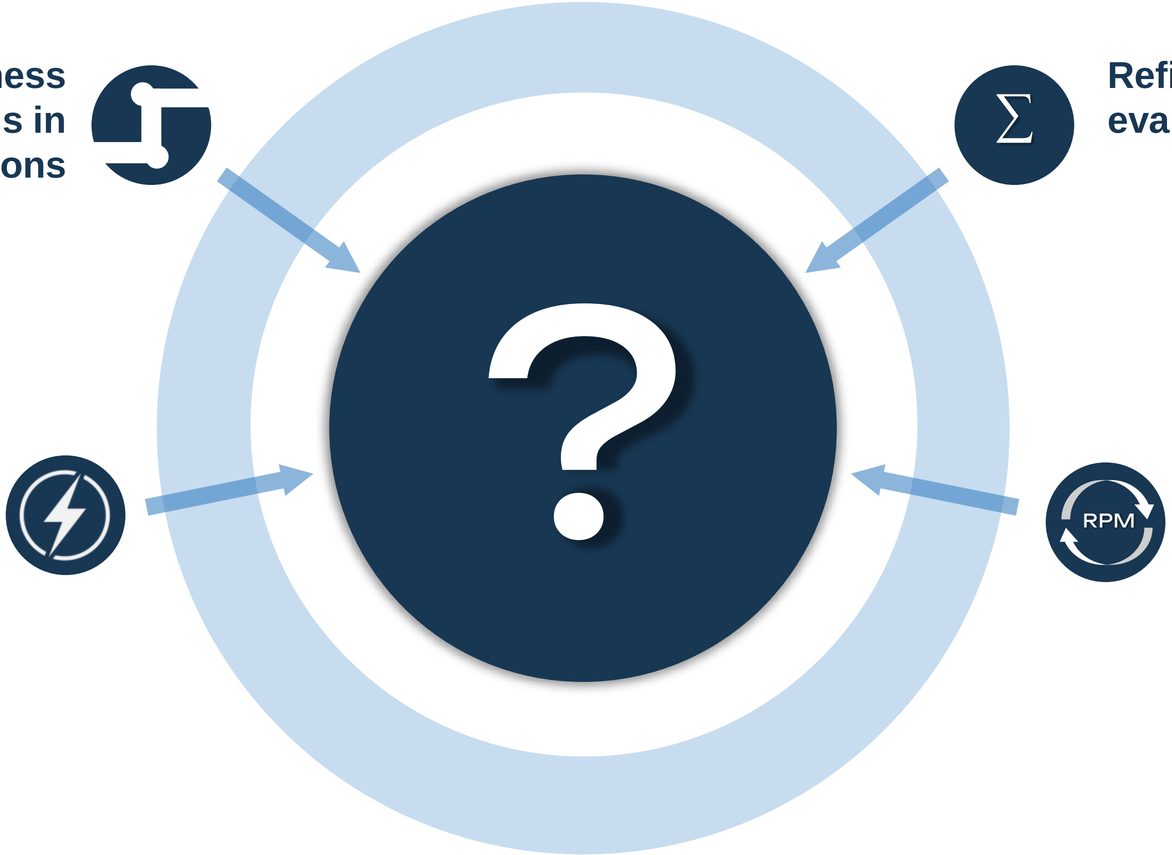
THESIS OBJECTIVES

1. **Develop an experimental method for lubricant evaporation measurement**
2. **Assess the validity of analytical evaporation models**
3. **Evaluate labyrinth seal effectiveness under vacuum conditions**
4. **Derive design-relevant insights for space mechanisms**

THESIS OBJECTIVES

Geometry and surface roughness optimization for labyrinth seals in space applications

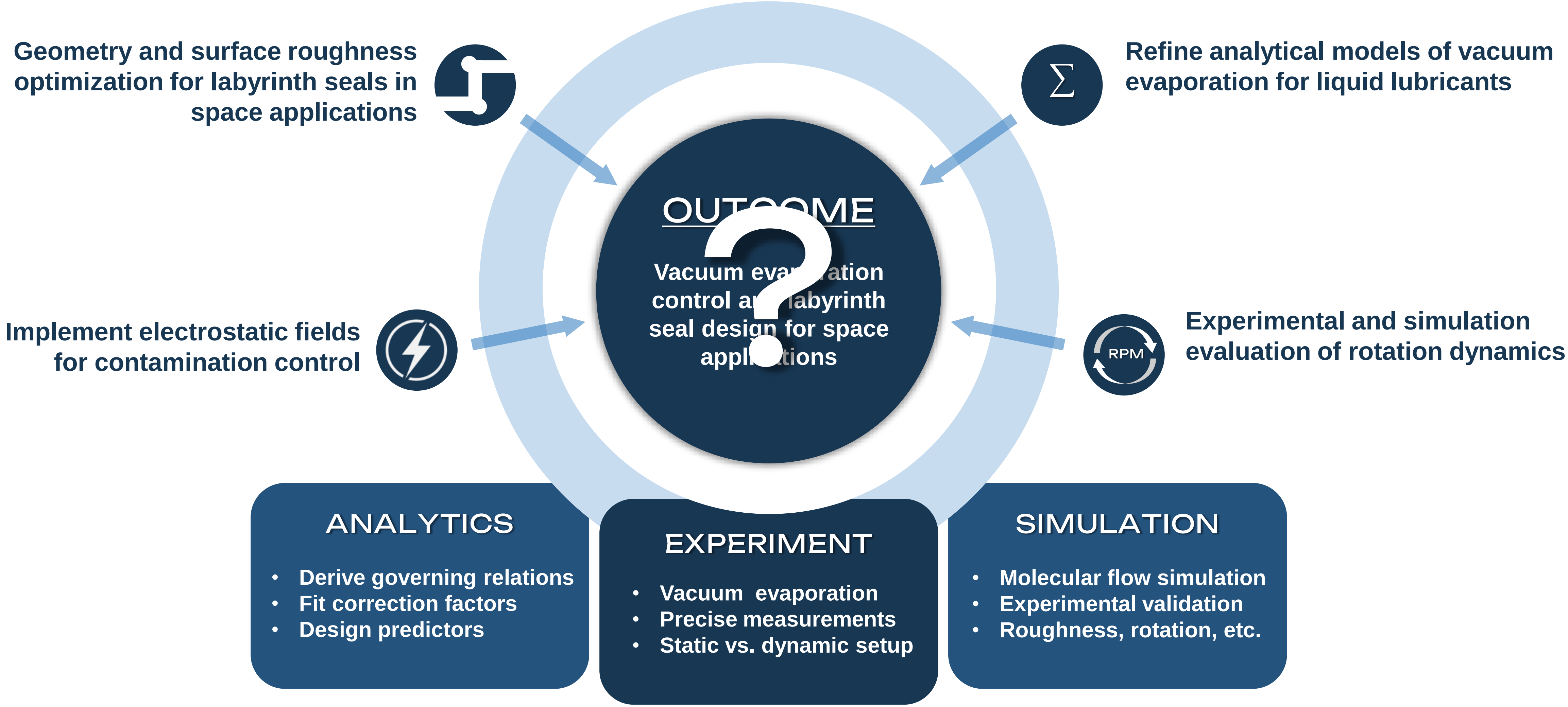
Refine analytical models of vacuum evaporation for liquid lubricants



Implement electrostatic fields for contamination control

Experimental and simulation evaluation of rotation dynamics

THESIS OBJECTIVES



EVAPORATIVE MASS LOSS

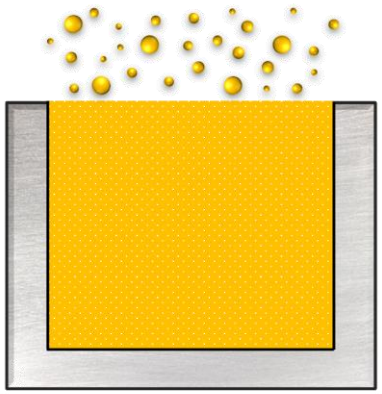
ANALYTICAL

SIMULATION

EXPERIMENT

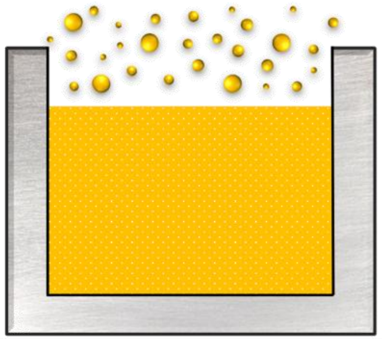
ANALYTICAL

LANGMUIR

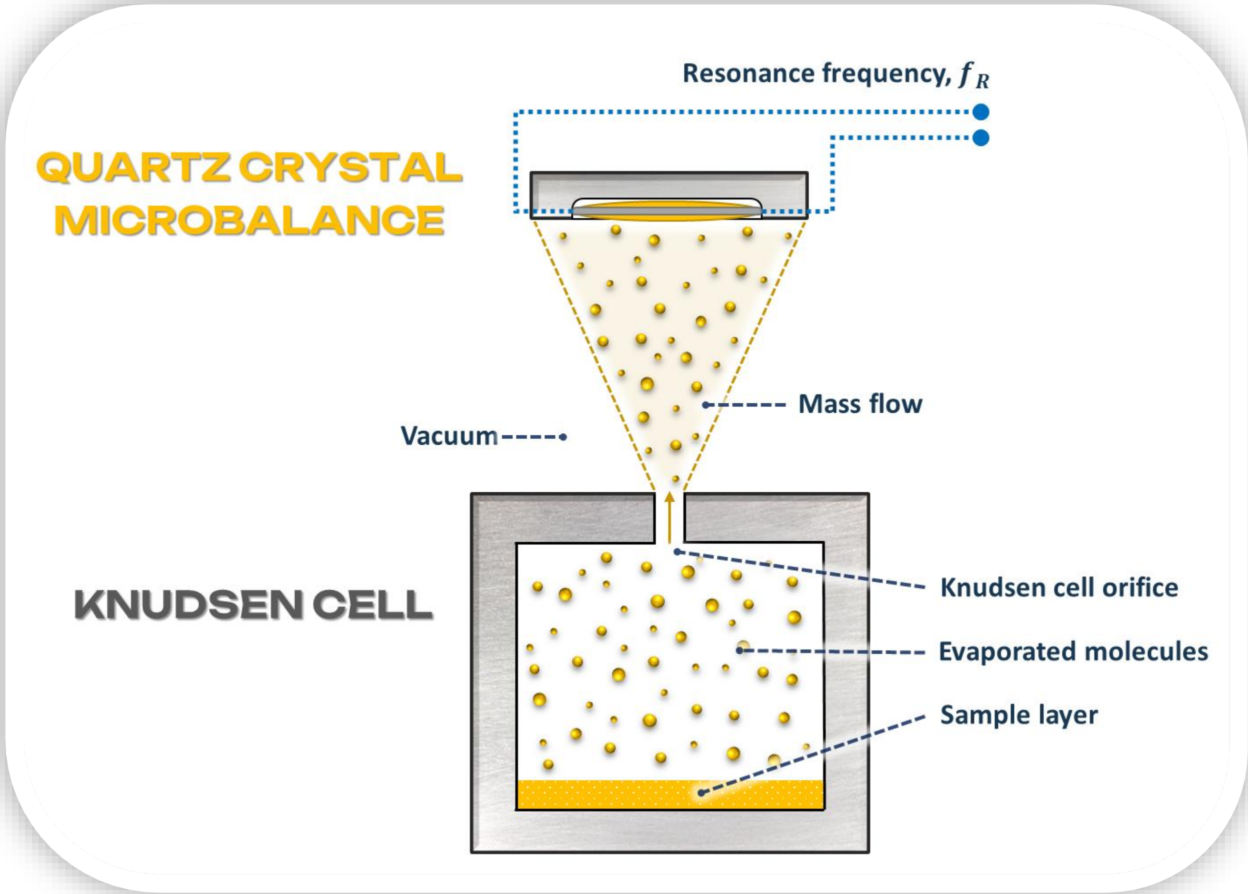


$$\frac{dM}{\text{Adt}} = (p_v - p_p)\sqrt{\frac{M_m}{2\pi kT}}$$

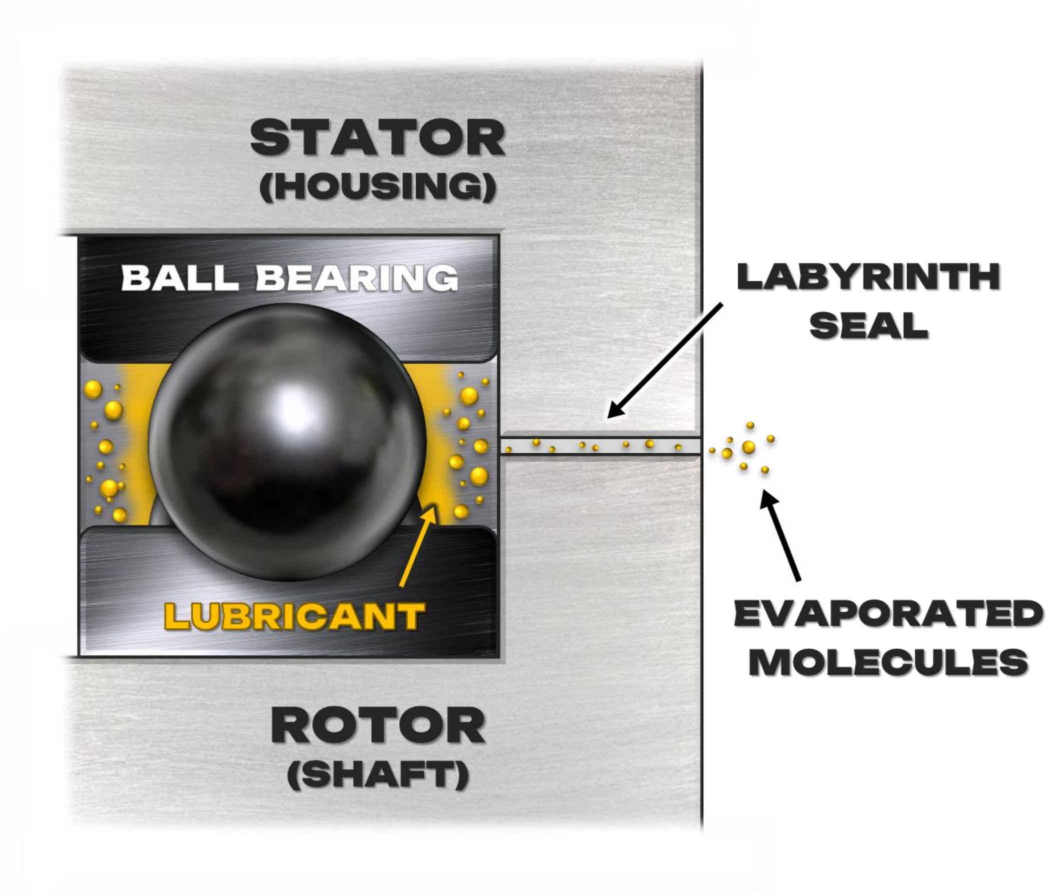
MODIFIED LANGMUIR



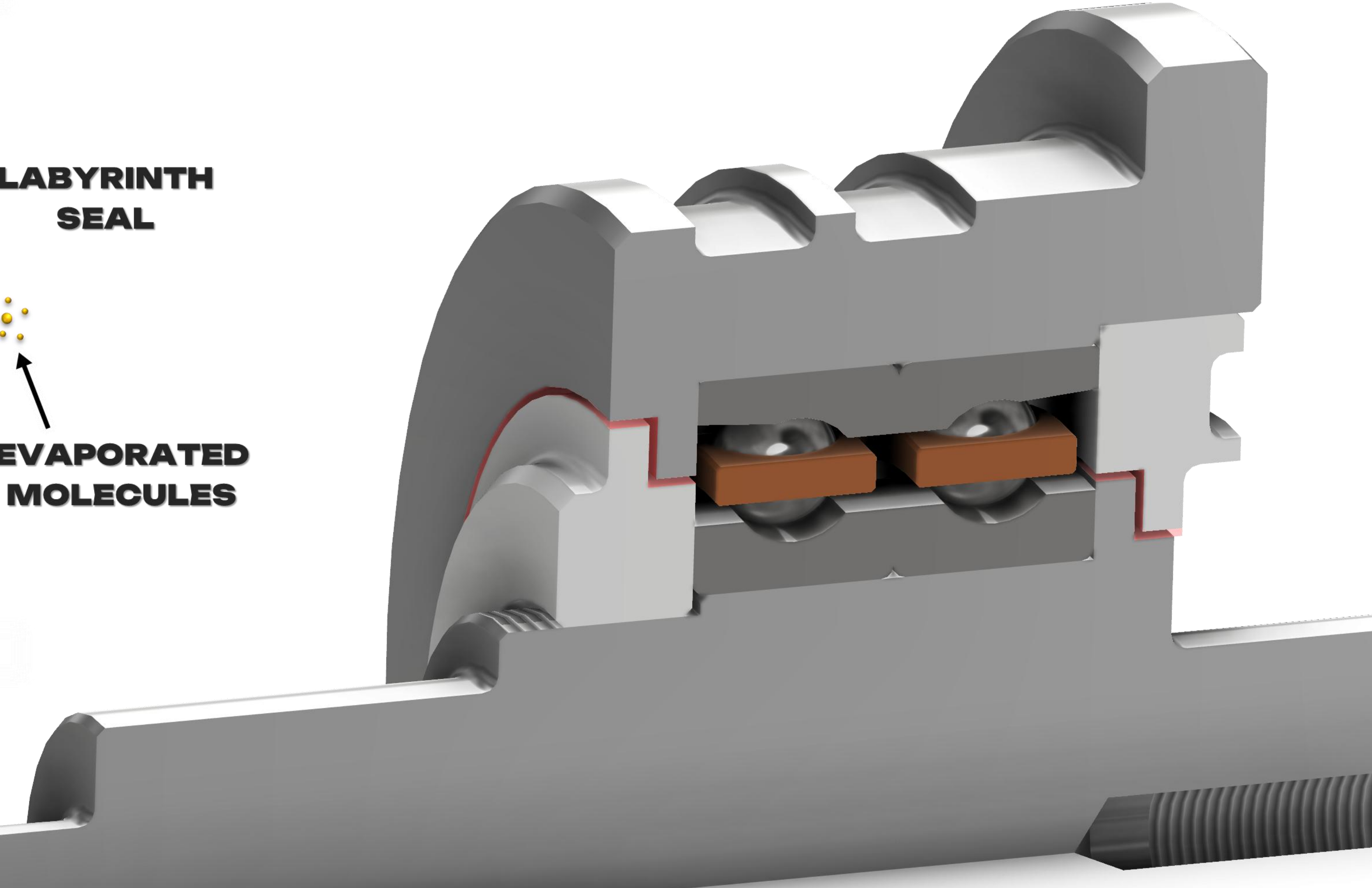
$$\frac{dm_{evap}}{dt} = -0.044\,P_s(T)\sqrt{\frac{M}{T}}$$



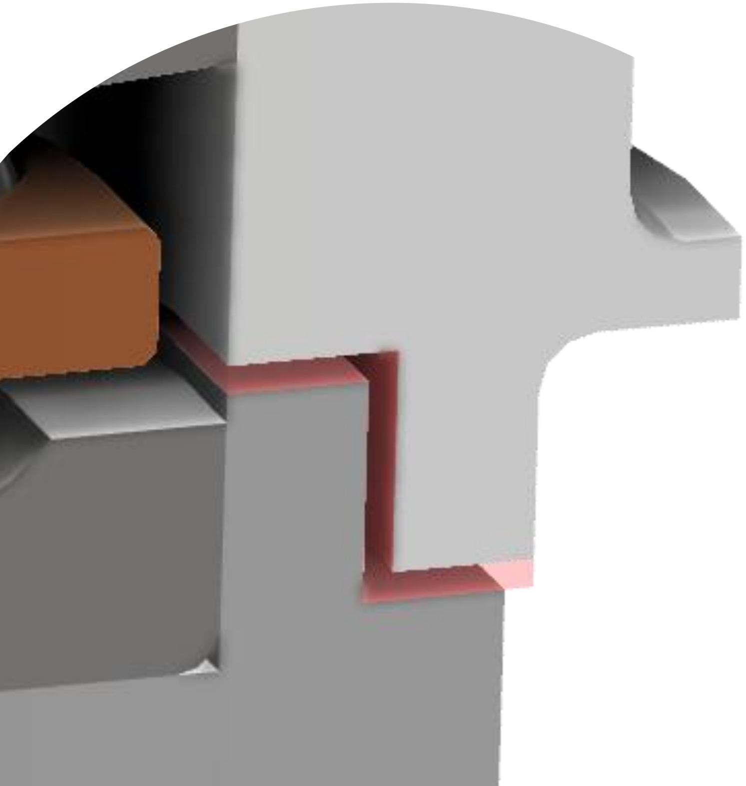
ANALYTICAL

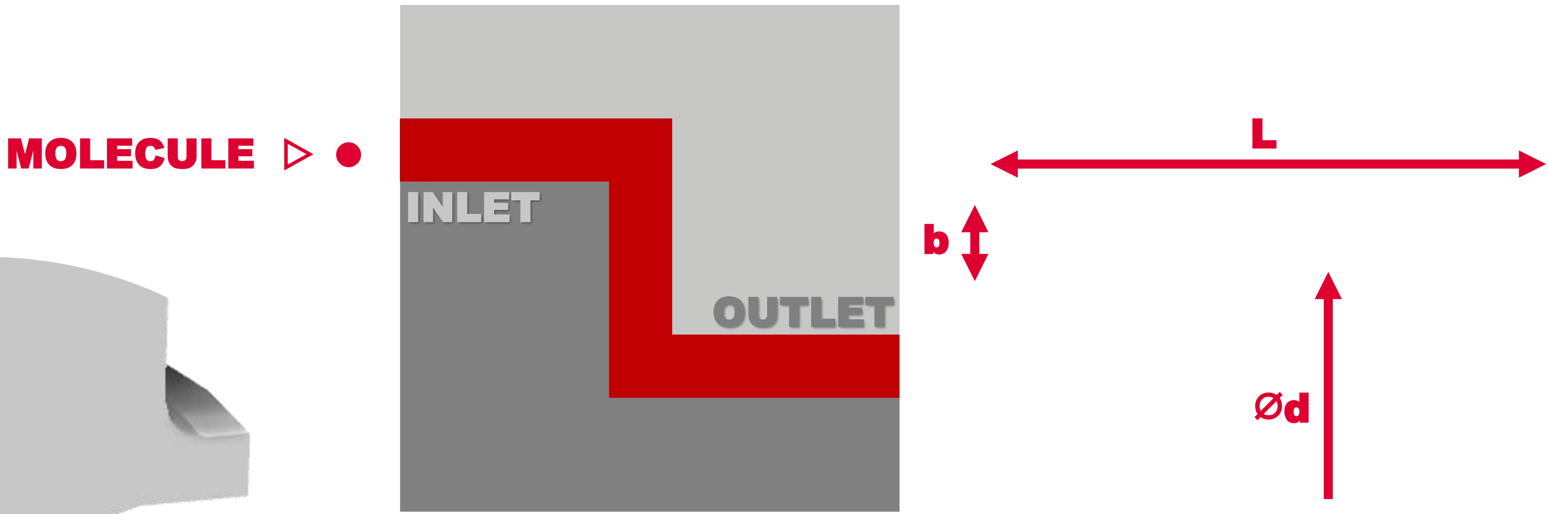


STATOR
(HOUSING)
BALL BEARING
LUBRICANT
ROTOR
(SHAFT)
LABYRINTH
SEAL
EVAPORATED
MOLECULES



ANALYTICAL





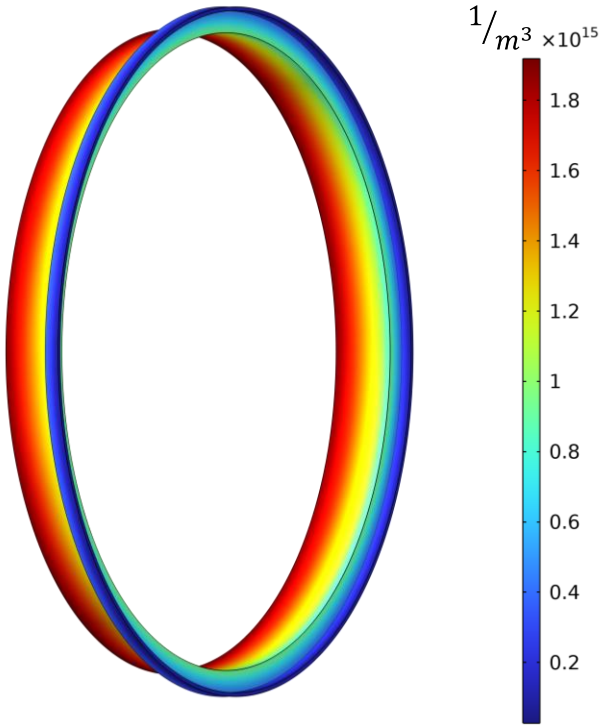
ESTL Model:

$$Q_m = 0{,}0436 \frac{P_v \pi d b \left(\frac{M}{T}\right)^{0{,}5}}{1 + 0{,}375 \cdot \frac{L}{b}} \quad [g/s]$$

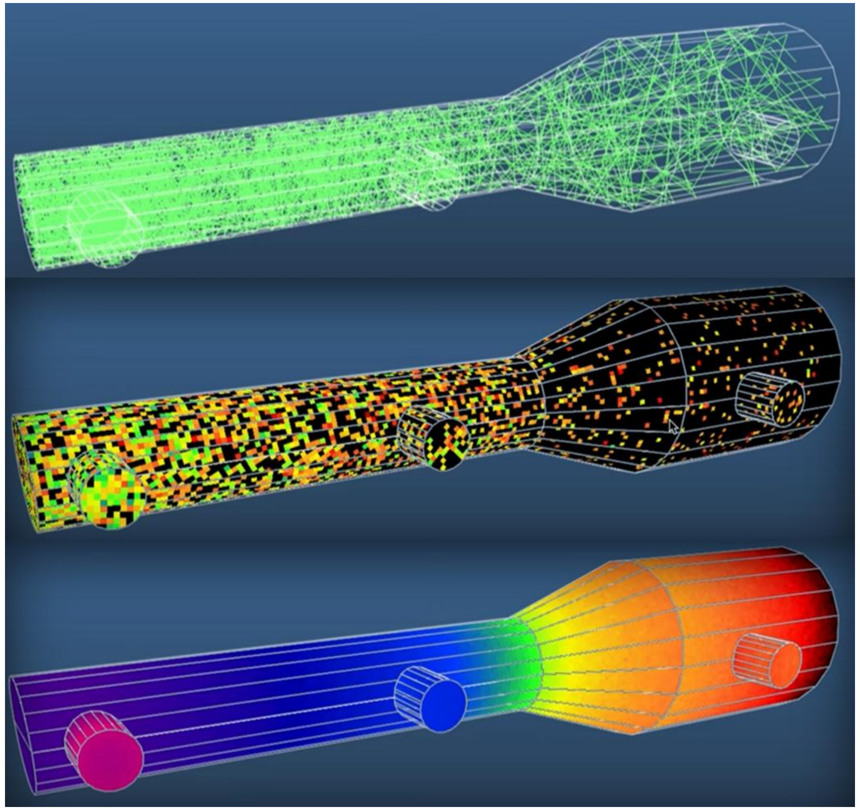
SIMULATION

COMSOL MULTIPHYSICS

- Particle Tracing module
- Molecular flow module



MOLFLOW+ (CERN)



EXPERIMENT

https://doi.org/10.1016/j.jct.2018.07.004.

EVAPORATIVE MASS LOSS

ANALYTICAL

SIMULATION

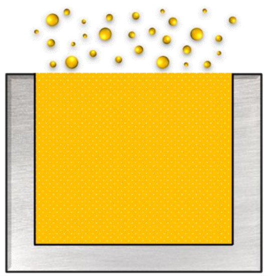
EXPERIMENT

QUESTIONS & HYPOTHESIS

Q1: How can existing analytical models for liquid lubricant evaporation in vacuum be corrected or refined using high precision experimental evaporation data?

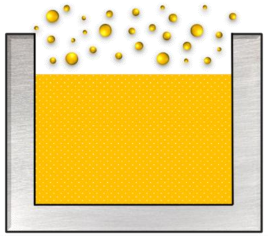
H1: Analytical evaporation models can be significantly improved using experimentally derived correction factors.

LANGMUIR



$$\frac{dM}{\mathrm{Adt}} = (p_v - p_p)\sqrt{\frac{M_m}{2\pi kT}}$$

MODIFIED LANGMUIR



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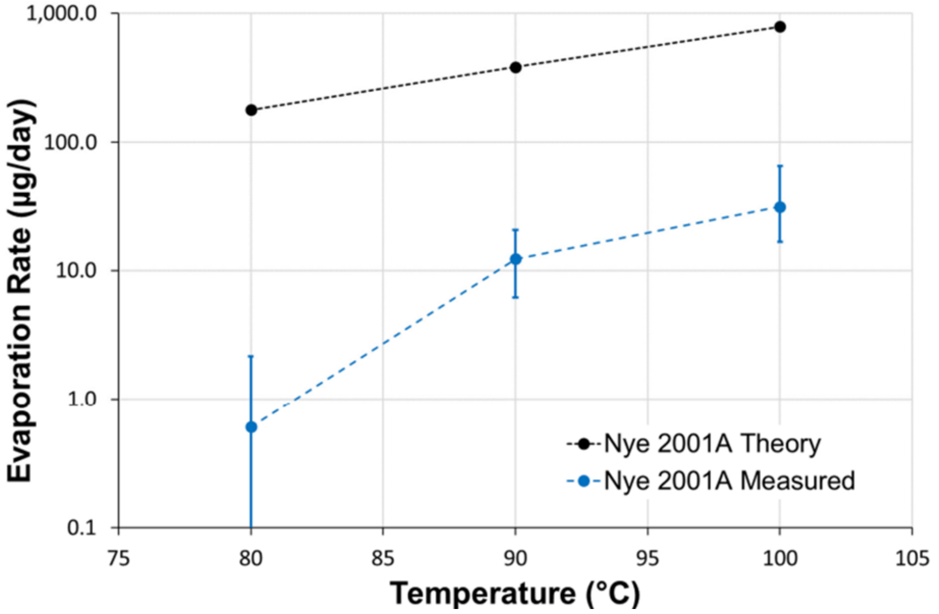
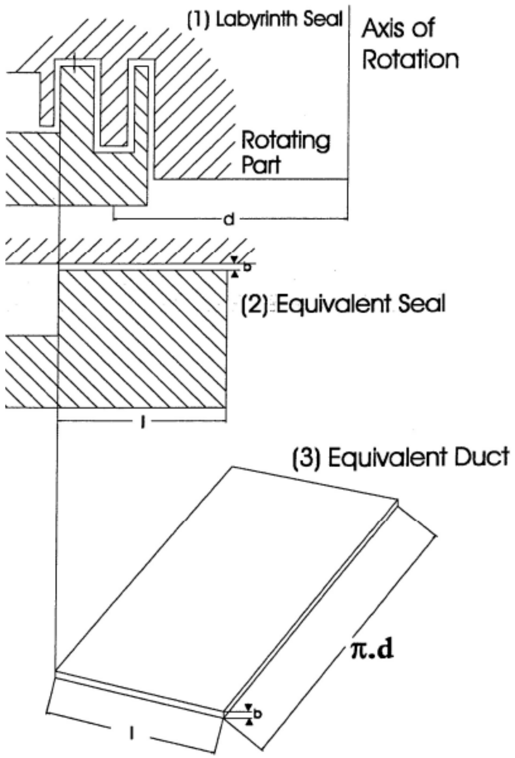


Stanley, S., Hampson M. ESA-ESTL-TM-0162 01- An Experimental Assessment of the Evaporation Lives of Space Oils. 2018

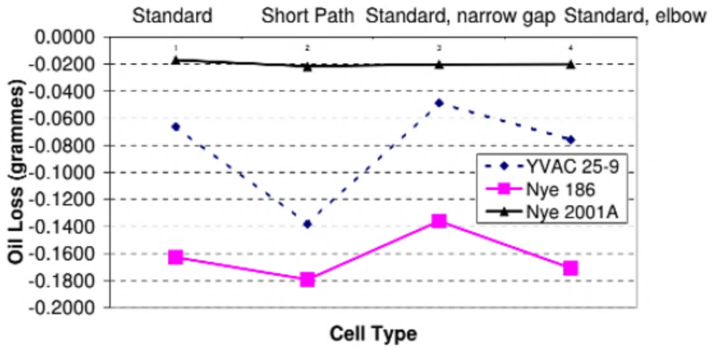
QUESTIONS & HYPOTHESIS

Q2: What is the influence of internal geometry and surface structure of labyrinth seals on the transmission of lubricant molecules under molecular flow conditions?

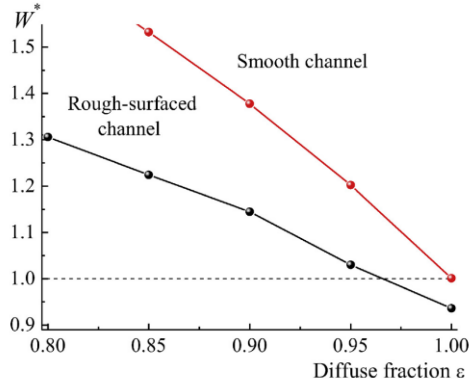
H2: Labyrinth seal geometry and surface roughness influence molecular transmission under vacuum conditions.



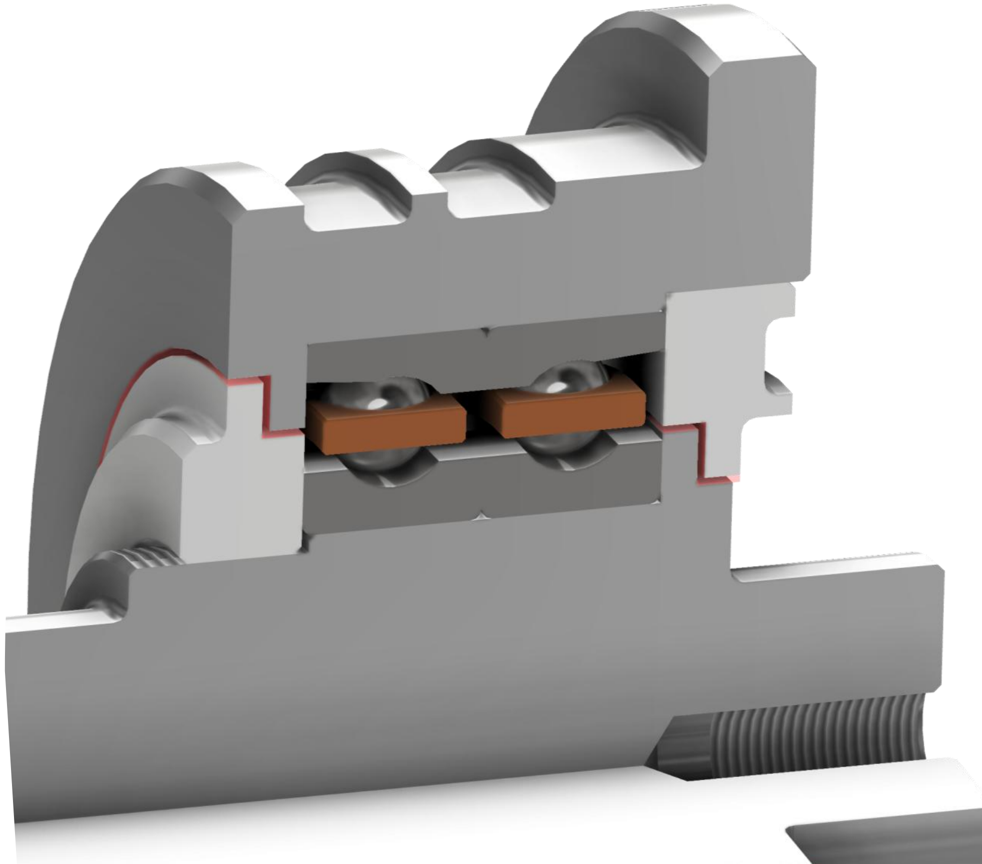
Roberts, E W; Eiden M. Space Tribology Handbook, 5th edition (v2). ESR Technology Ltd.; 2013



Anderson M, Freeman S, Roberts EW. Evaporative losses of vacuum-compatible oils through labyrinth seals. Proc 10th Eur Sp Mech Tribol Symp 2003; https://ui.adsabs.harvard.edu/abs/2003ESASP.524..265A.



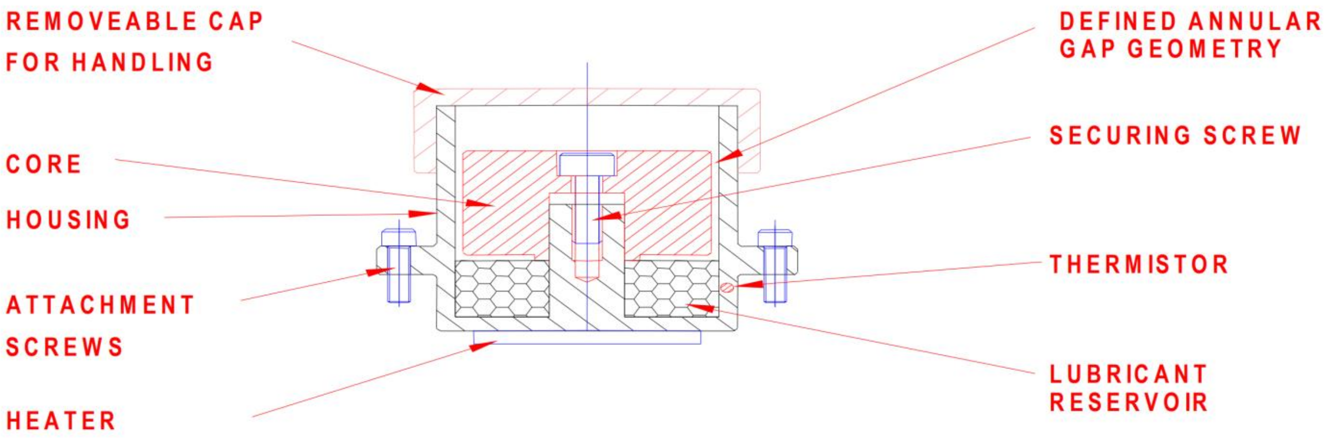
Oleg Sazhin, The effect of surface roughness on internal free molecular gas flow, Vacuum, Volume 159, 2019, Pages 287-292, ISSN 0042-207X, https://doi.org/10.1016/j.vacuum.2018.09.031



QUESTIONS & HYPOTHESIS

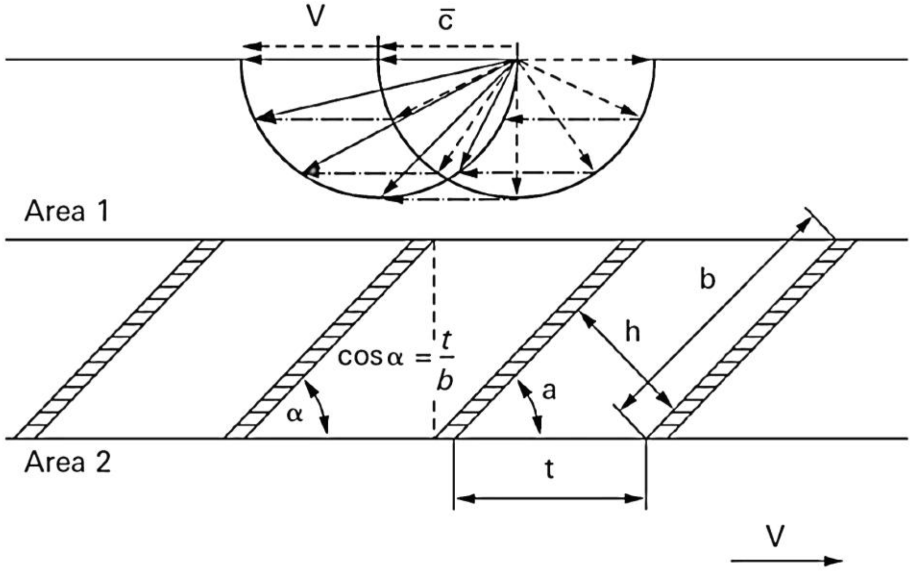
Q3: How does rotational motion of labyrinth seal components influence the molecular transport of evaporated lubricants under vacuum conditions?

H3: Surface rotation in labyrinth seals alters molecular trajectories and reduces transmission probability.



- There is no evidence from the literature that rotation is required to simulate the labyrinth seal action. This is also true considering molecular flow conditions. Therefore for simplicity, and as used by previous experimental studies, a static configuration was used.

Anderson M, Freeman S, Roberts EW. Evaporative losses of vacuum-compatible oils through labyrinth seals. Proc 10th Eur Sp Mech Tribol Symp 2003;524:255–70. https://ui.adsabs.harvard.edu/abs/2003ESASP.524..265A.

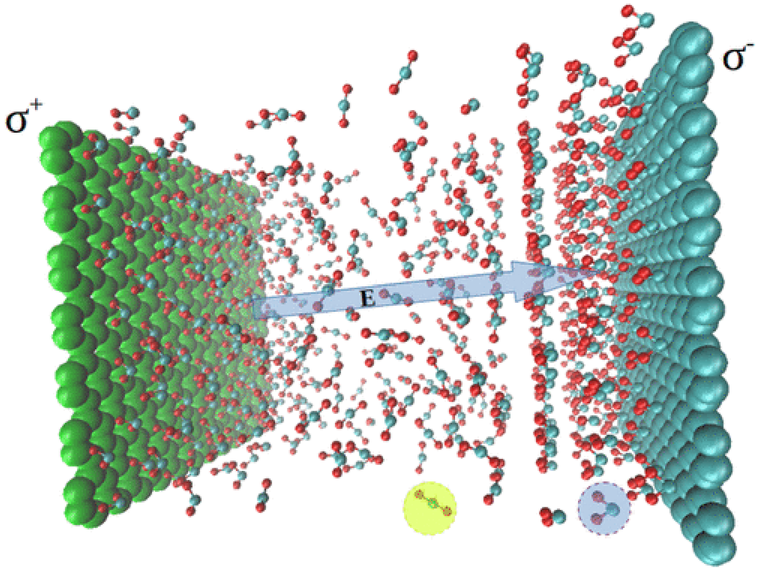


https://www.pfeiffer-vacuum.com/pl/en/knowledge/vacuum-technology/knowledge-book/4-vacuum-generation/4_9_turbomolecular_pumps/

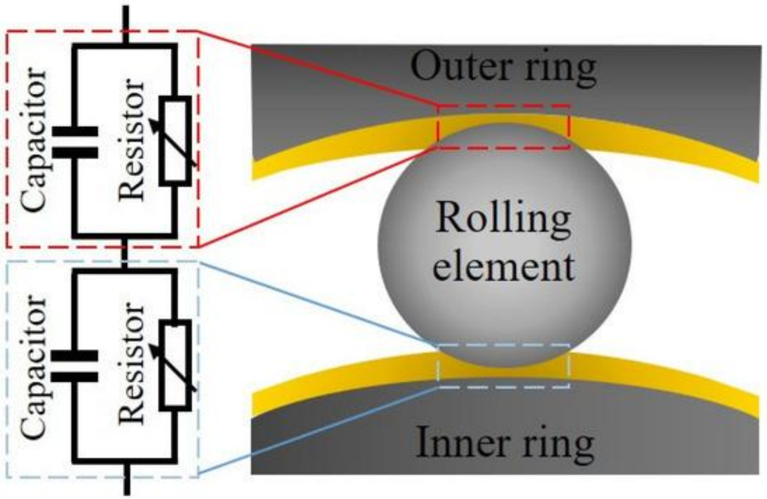
QUESTIONS & HYPOTHESIS

Q4: Can externally applied electrostatic fields be used to influence molecular transport through labyrinth seals and reduce lubricant evaporation in vacuum environments?

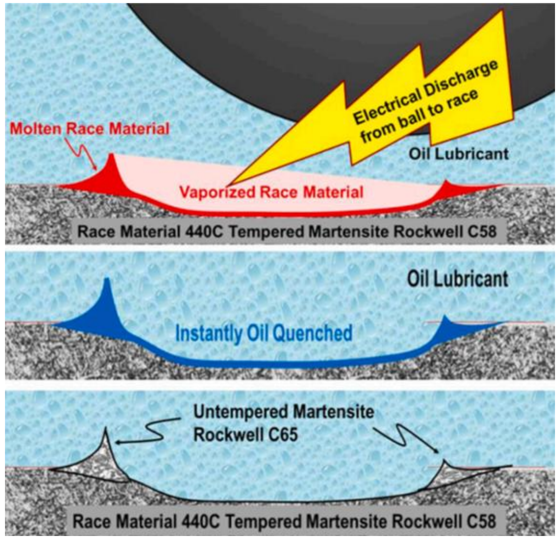
H4: Electrostatic fields can actively influence molecular transport and reduce lubricant evaporation in vacuum.



https://pubs.acs.org/doi/10.1021/acs.jpcc.9b05239



Esmaeili, K.; Wang, L.; Harvey, T.J.; White, N.M.; Holweger, W. Electrical Discharges in Oil-Lubricated Rolling Contacts and Their Detection Using Electrostatic Sensing Technique. Sensors 2022, 22, 392. https://doi.org/10.3390/s22010392



R Rejith, D. Kesavan, P Chakravarthy, S.V.S. Narayana Murty, Bearings for aerospace applications, Tribology International, Volume 181, 2023, 108312, ISSN 0301-679X, https://doi.org/10.1016/j.triboint.2023.108312

QUESTIONS & HYPOTHESIS

Q1: How can existing analytical models for liquid lubricant evaporation in vacuum be corrected or refined using high precision experimental evaporation data?

H1: Analytical evaporation models can be significantly improved using experimentally derived correction factors.

Q2: What is the influence of internal geometry and surface structure of labyrinth seals on the transmission of lubricant molecules under molecular flow conditions?

H2: Labyrinth seal geometry and surface roughness influence molecular transmission under vacuum conditions.

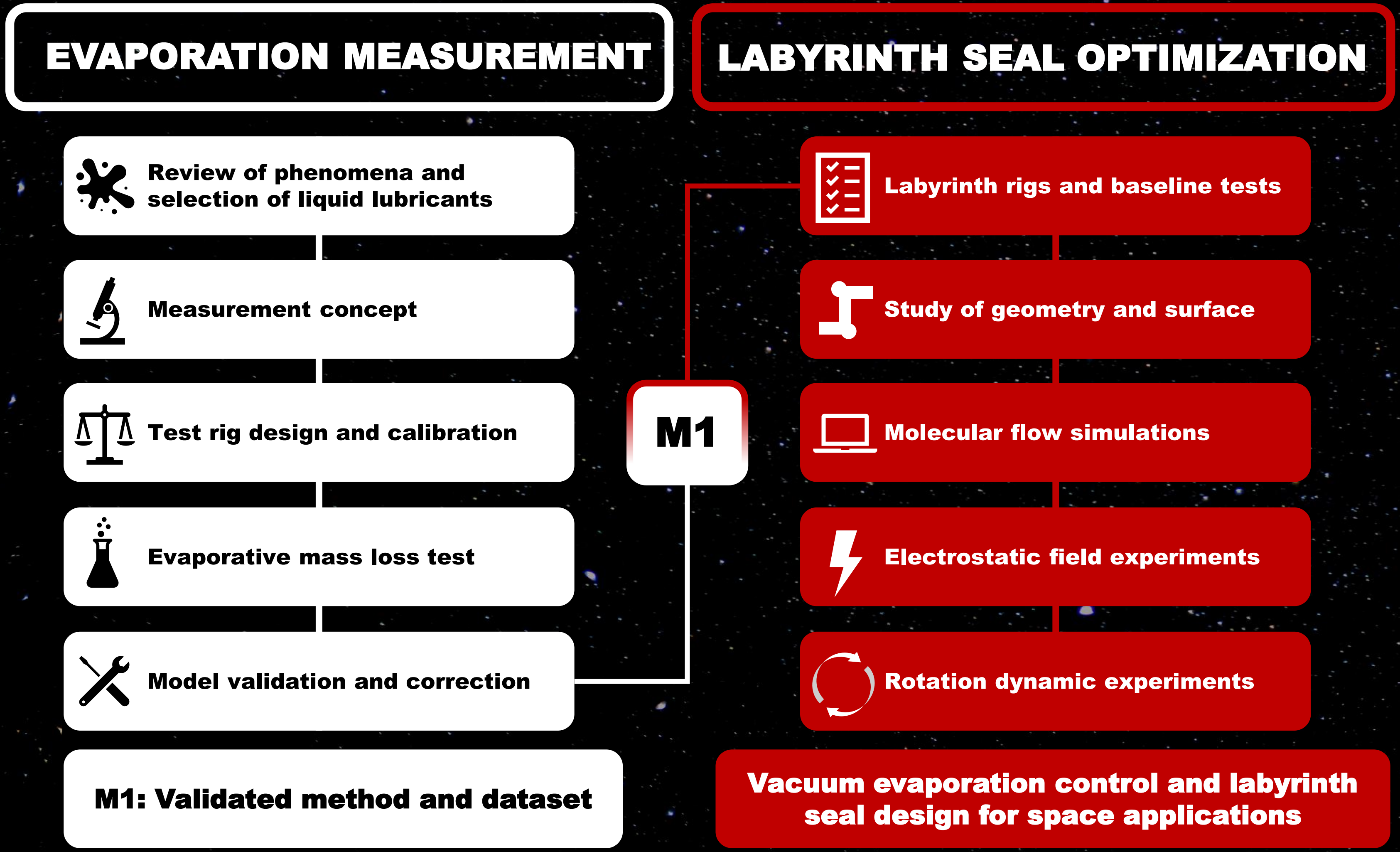
Q3: How does rotational motion of labyrinth seal components influence the molecular transport of evaporated lubricants under vacuum conditions?

H3: Surface rotation in labyrinth seals alters molecular trajectories and reduces transmission probability.

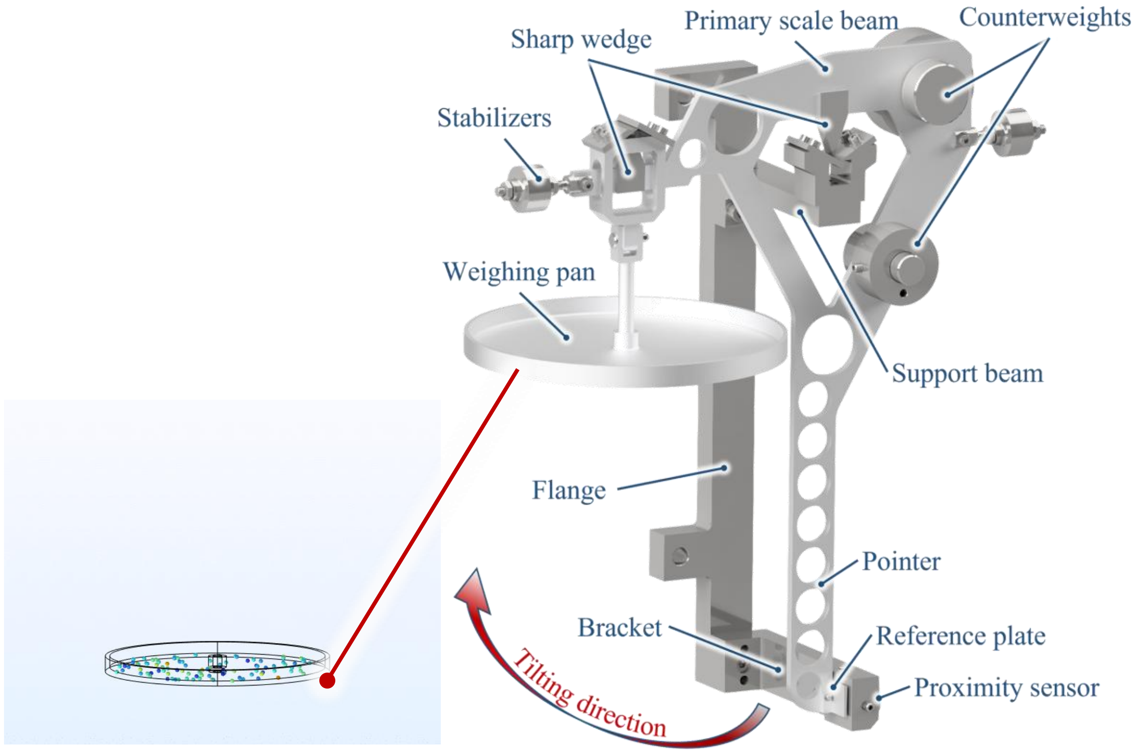
Q4: Can externally applied electrostatic fields be used to influence molecular transport through labyrinth seals and reduce lubricant evaporation in vacuum environments?

H4: Electrostatic fields can actively influence molecular transport and reduce lubricant evaporation in vacuum.

WORKFLOW


EVAPORATION MEASUREMENT
Review of phenomena and selection of liquid lubricants
Measurement concept
Test rig design and calibration
Evaporative mass loss test
Model validation and correction
M1: Validated method and dataset
M1
LABYRINTH SEAL OPTIMIZATION
Labyrinth rigs and baseline tests
Study of geometry and surface
Molecular flow simulations
Electrostatic field experiments
Rotation dynamic experiments
Vacuum evaporation control and labyrinth seal design for space applications

EVAPORATION TEST RIG (ETR)



Parameter	Value
Dimensions (W, H, D)	220x125x200 mm
Operating temperatures	-100 ÷ 150 °C
Sample weight	1 – 100 g
Weighing precision	± 0.04 mg

EVAPORATION MEASUREMENT

- **Evaporation Test Rig (ETR)**

  Vacuum chamber, High accuracy

- **Liquid lubricant selection**
- **Vapor pressure approximation**
- **Experiment vs. Predictions**
- **Correction factors**

EVAPORATION MEASUREMENT

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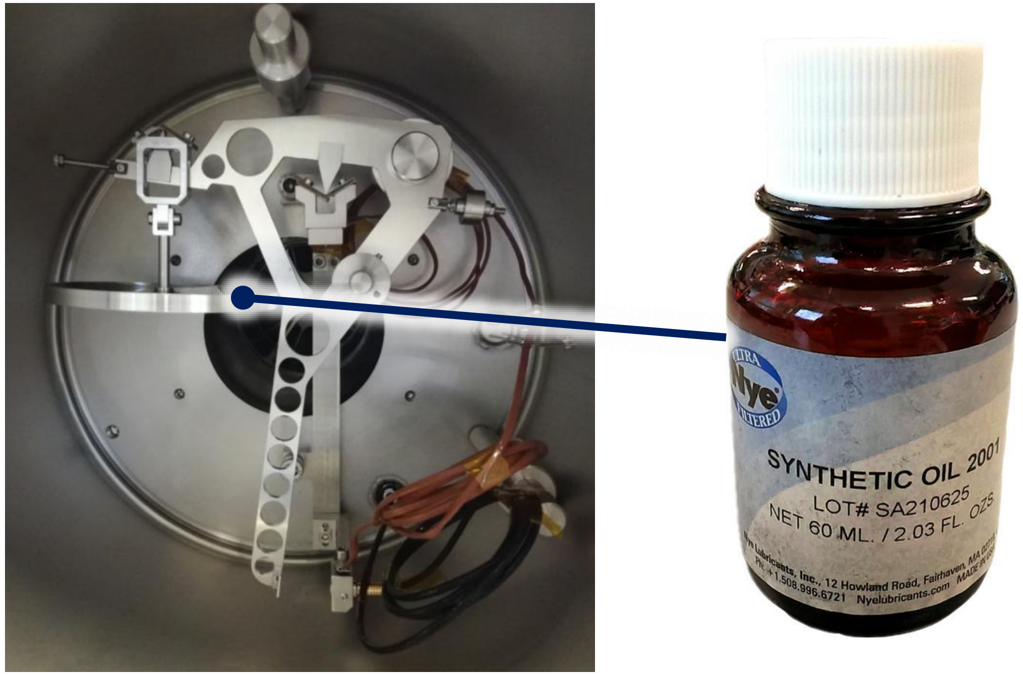
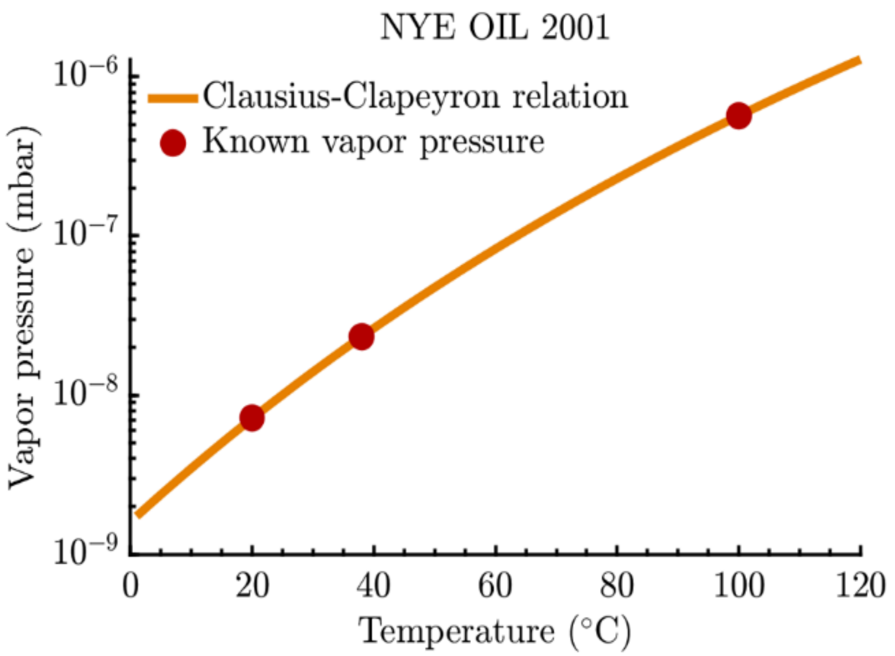
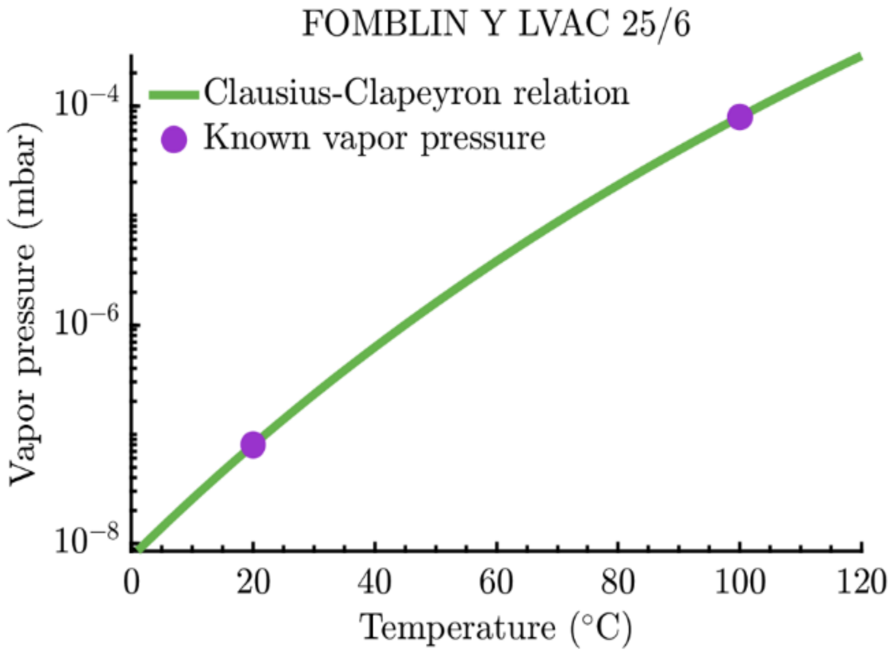


Lubricant name	NYE OIL 2001	FOMBLIN Y LVAC 25/6
Lubricant type	MAC	PFPE
Kinematic viscosity (20°C)	305 cSt	276 cSt
Vapour pressure (mbar)	1.00e-8 (20°C) 2.33e-8 (38°C) 5.70e-7 (100°C)	7.98e-8 (25°C) 7.98e-5 (100°C)
Molecular weight (g/mol)	910	3300
Density (g/cm^3)	0.84	1.90





EVAPORATION MEASUREMENT

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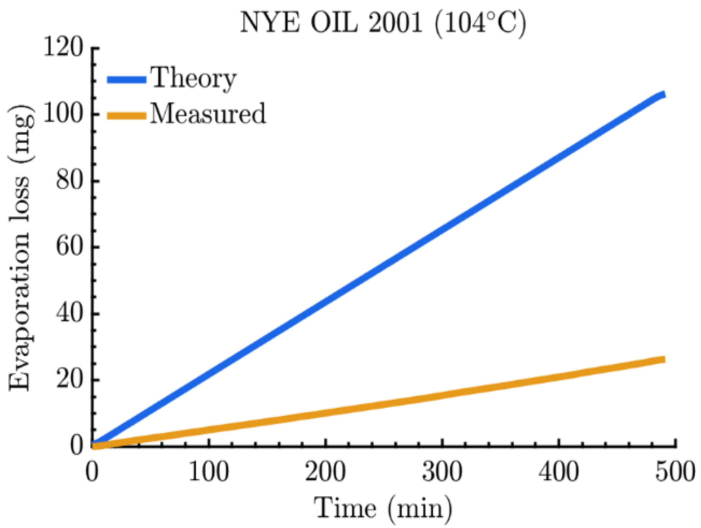
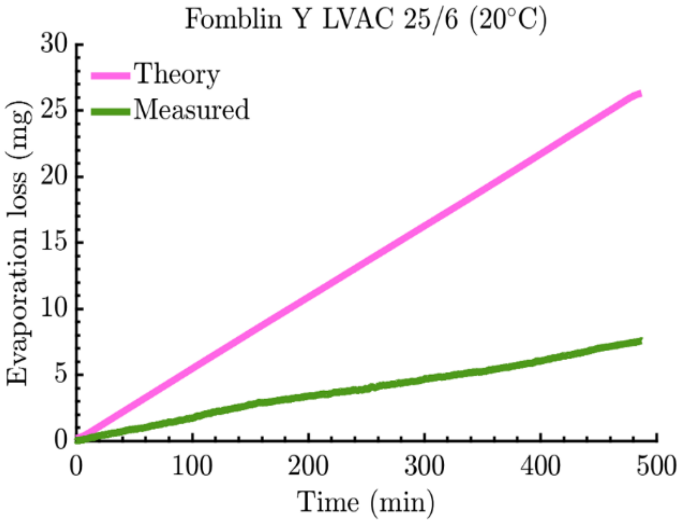
EVAPORATION MEASUREMENT





Lubricant	NYE OIL 2001	FOMBLIN Y LVAC 25/6
Operating temp.	104 °C	20 °C
Theory (mg/h)	13.0	3.0
Measured (mg/h)	3.2	0.9

- Evaporation Test Rig (ETR)
  - Vacuum chamber, High accuracy
- Liquid lubricant selection
- Vapor pressure approximation
- **Experiment vs. Predictions**
- Correction factors

EVAPORATION MEASUREMENT

- Evaporation Test Rig (ETR)
  - Vacuum chamber, High accuracy
- Liquid lubricant selection
- Vapor pressure approximation
- Experiment vs. Predictions
- **Correction factors**

Modified Langmuir Model

$$\frac{dm_{evap}}{dt} = -0.044\, P_s(T)\sqrt{\frac{M}{T}}$$

↓

$$\frac{dm_{evap}}{dt} = -0.044\, \frac{1}{\alpha} P_s(T)\sqrt{\frac{M}{T}}$$

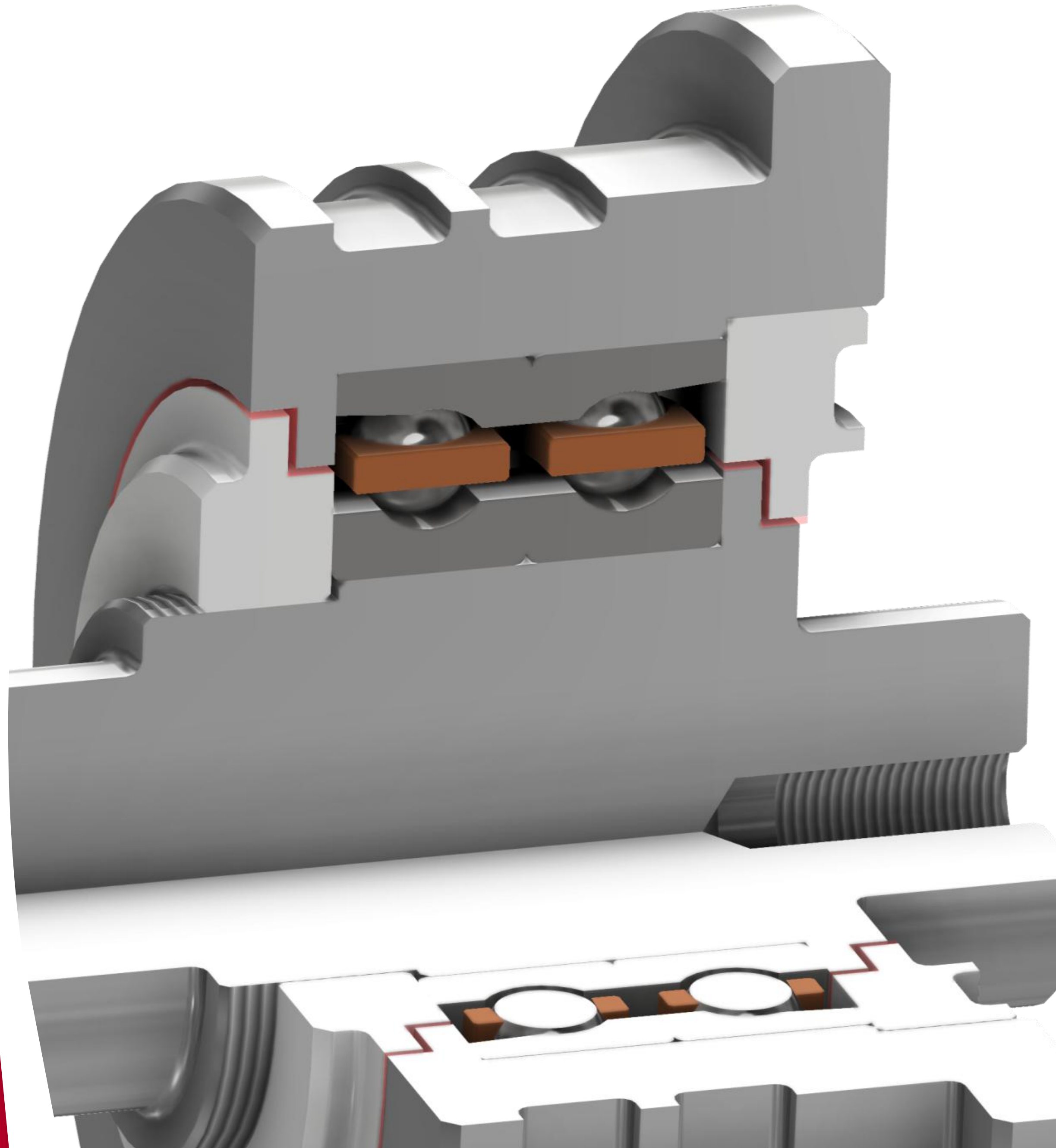
Lubricant	Correction factor α (-)
NYE OIL 2001	4.1 ± 0.3
FOMBLIN Y LVAC 25/6	3.2 ± 0.7

LABYRINTH SEAL OPTIMIZATION

- Overall geometry

  Length, Width, Complexity

- Geometrical modifications
- Surface topography
- Electrostatic influence
- Rotational influence

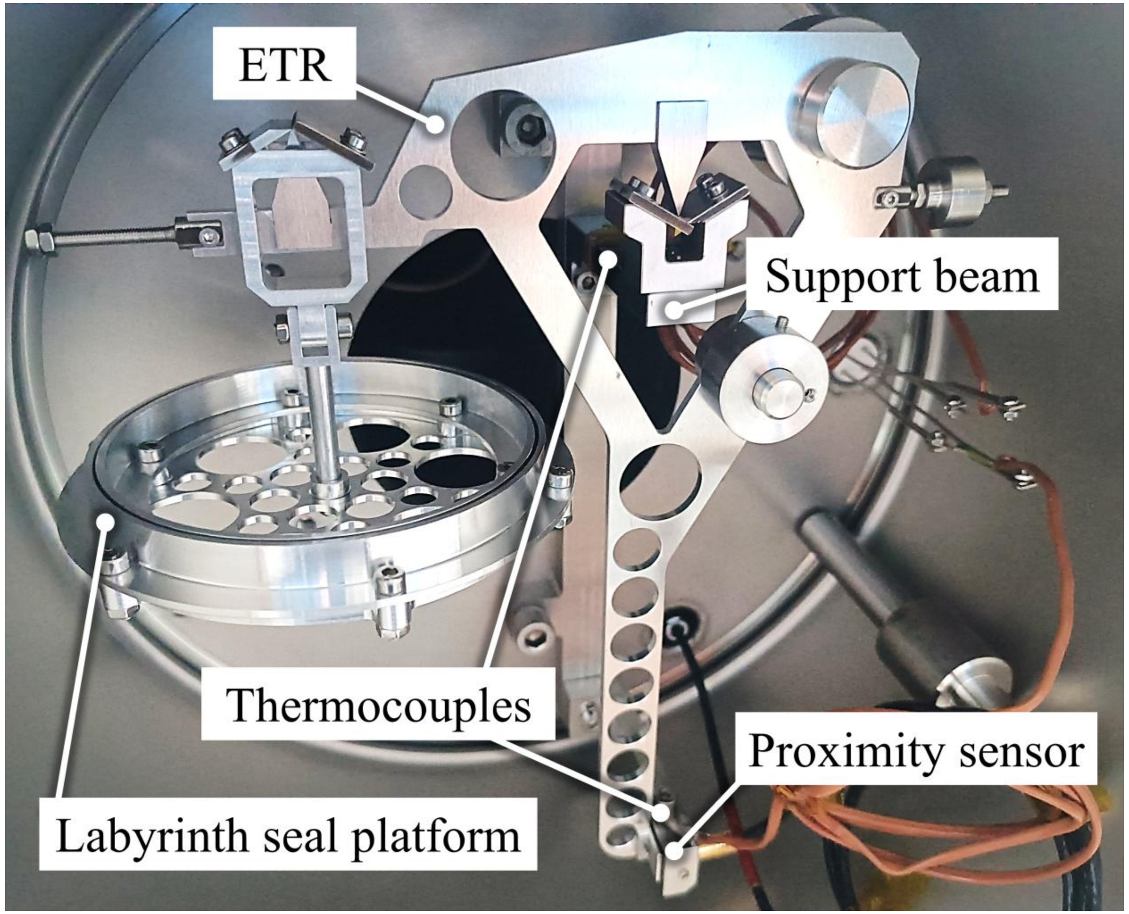


LABYRINTH SEAL OPTIMIZATION

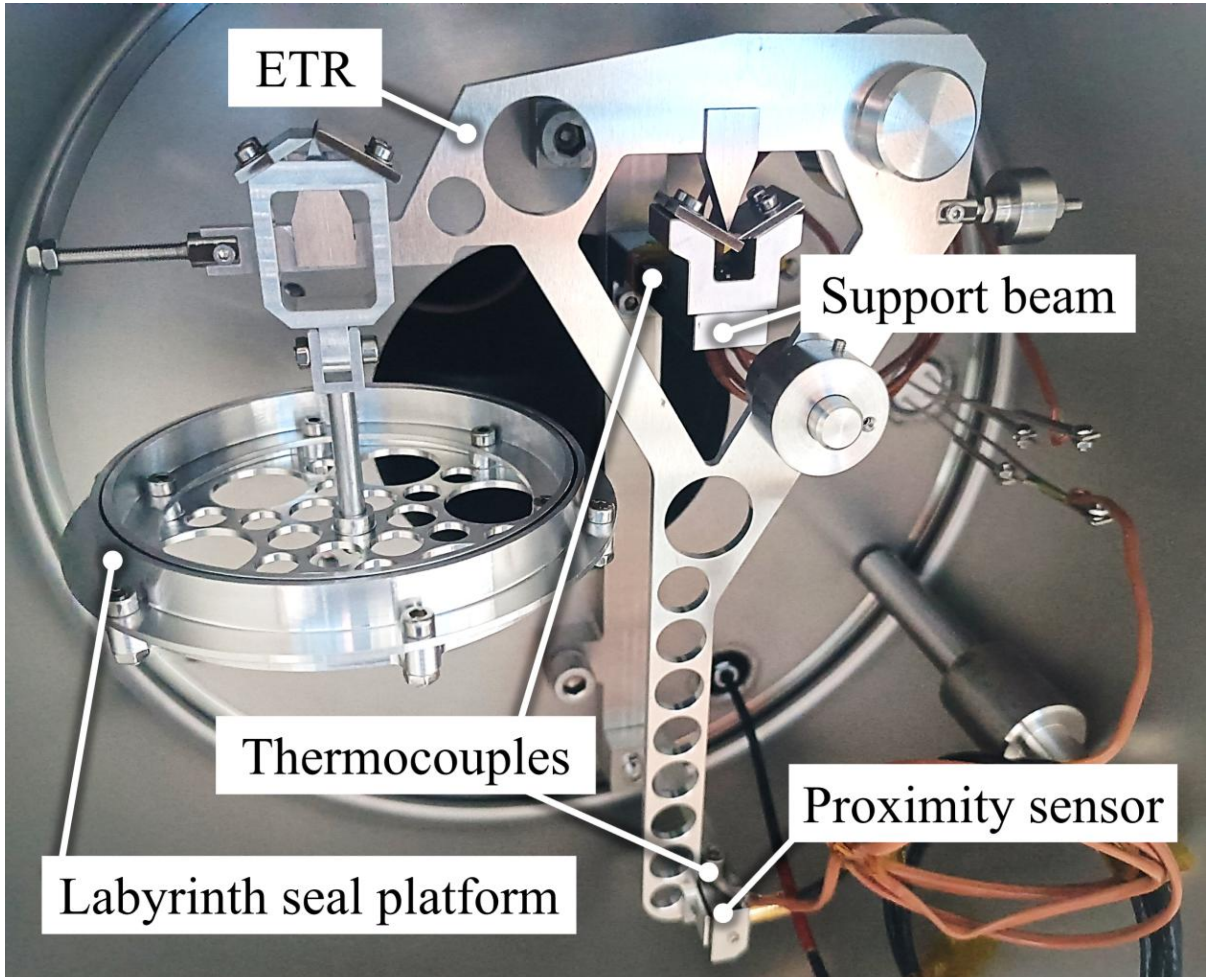
- **Overall geometry**

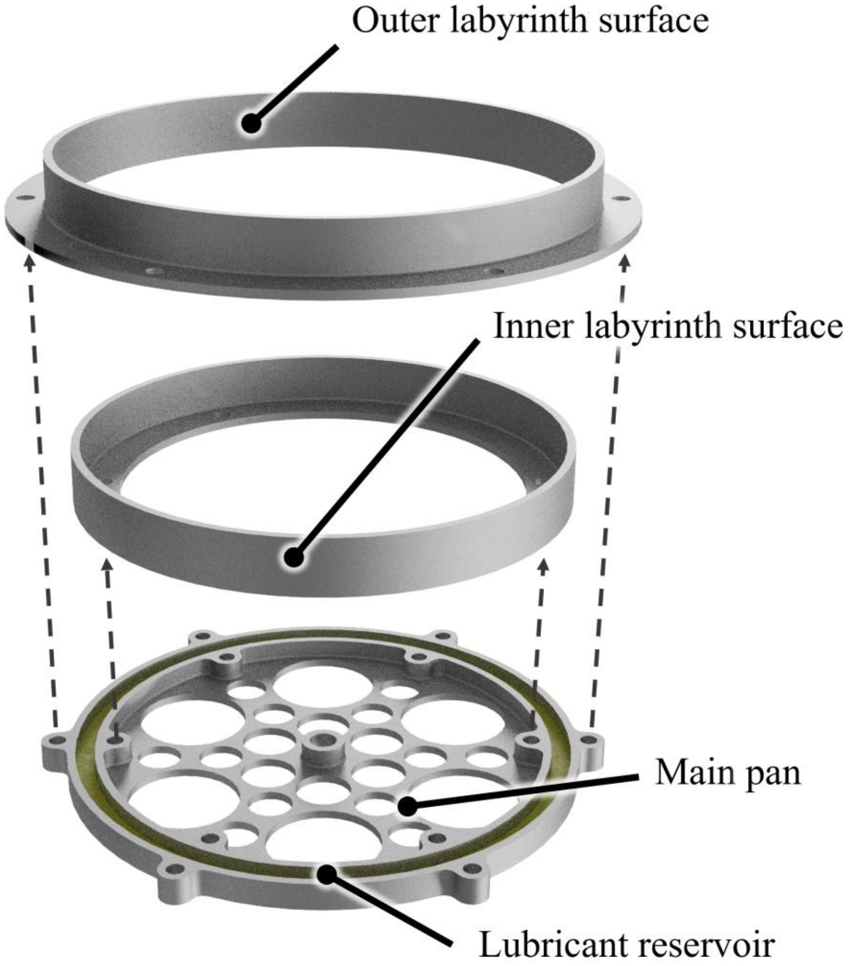
  Length, Width, Complexity

- **Geometrical modifications**
- **Surface topography**
- **Electrostatic influence**
- **Rotational influence**

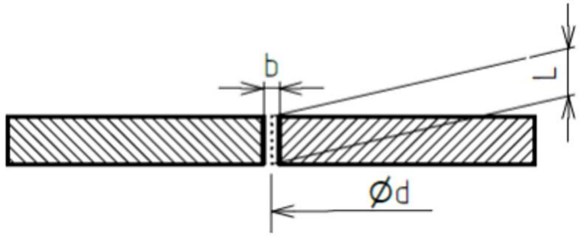


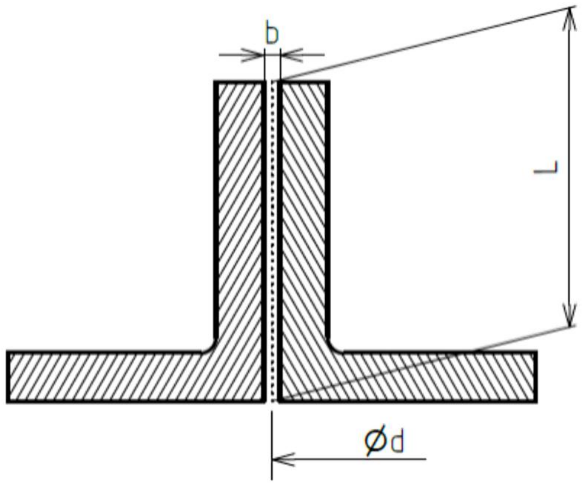
GEOMETRY

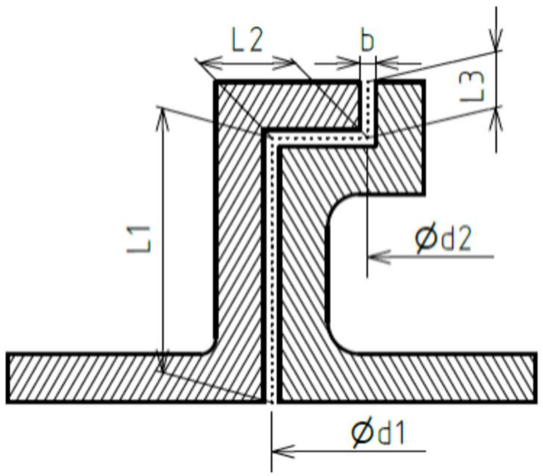

ETR
Support beam
Thermocouples
Proximity sensor
Labyrinth seal platform


Outer labyrinth surface
Inner labyrinth surface
Main pan
Lubricant reservoir

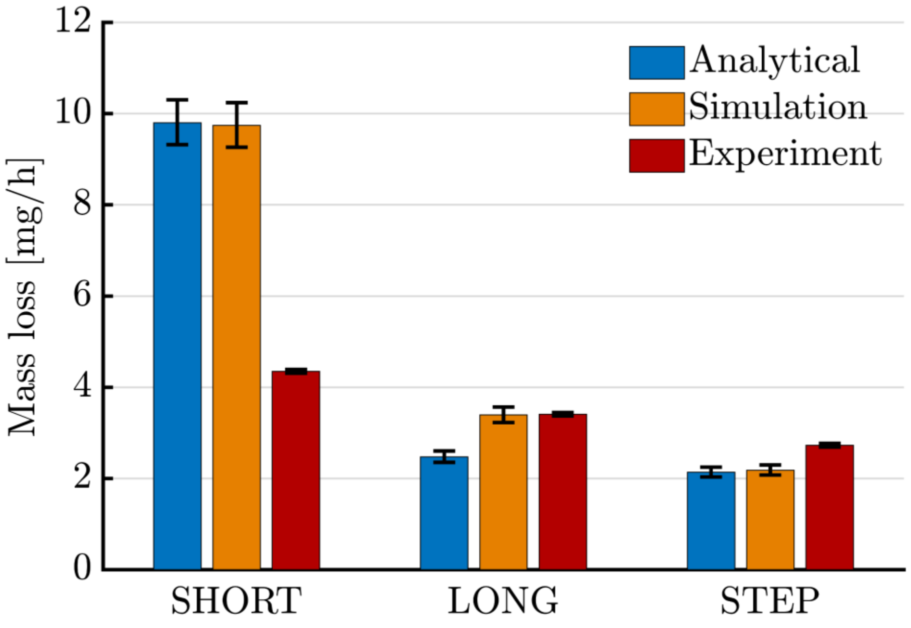
GEOMETRY



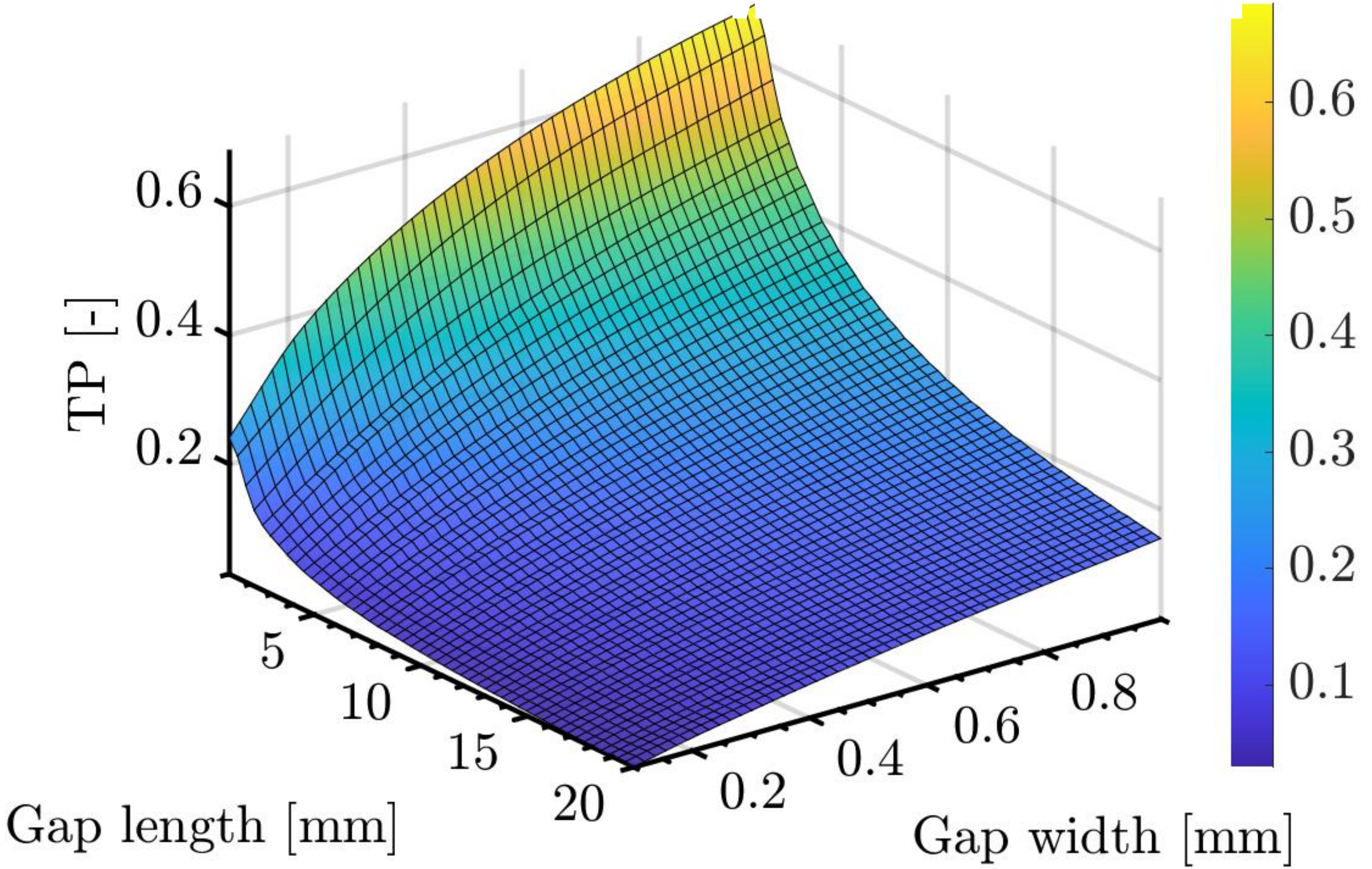




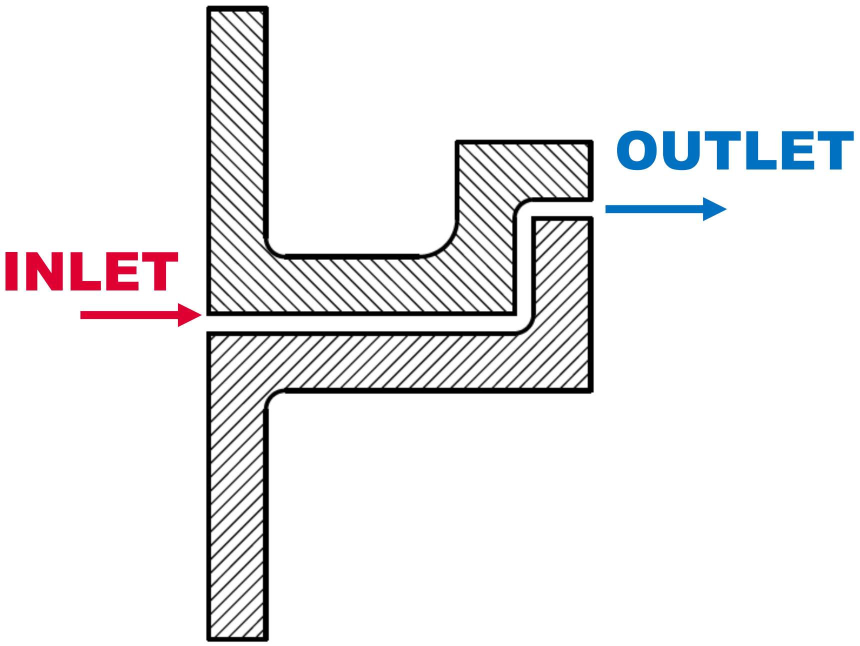
Labyrinth	Width [mm]	Diameter [mm]	Length [mm]
SHORT	b = 0.5	d = 86.5	L = 1.5
LONG	b = 0.5	d = 86.5	L = 10
STEP	b = 0.5	d_1 = 86.5	L_1 = 8.25
		d_2 = 92.5	L_2 = 3.00
			L_3 = 1.75

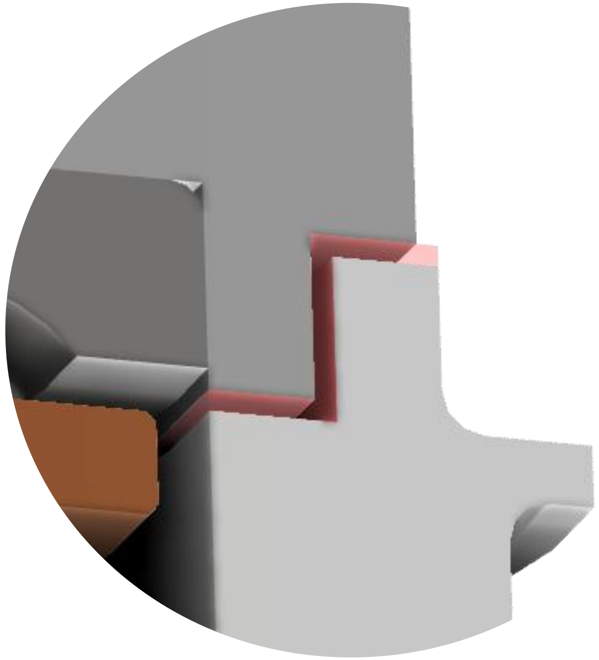


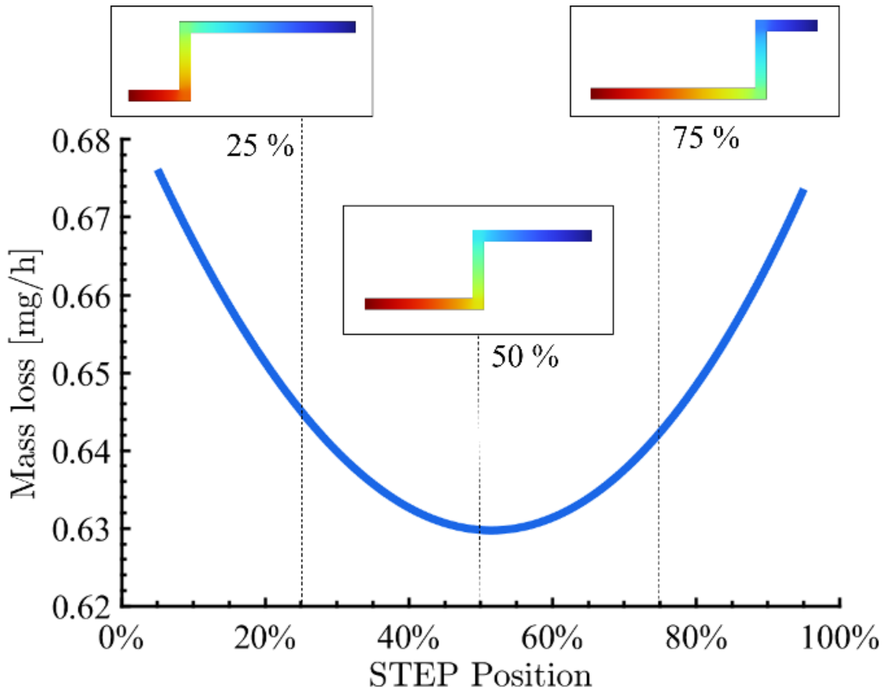
GEOMETRY


TP [-]
0.6
0.4
0.2
5
10
15
20
Gap length [mm]
0.2
0.4
0.6
0.8
Gap width [mm]
0.6
0.5
0.4
0.3
0.2
0.1

GEOMETRY





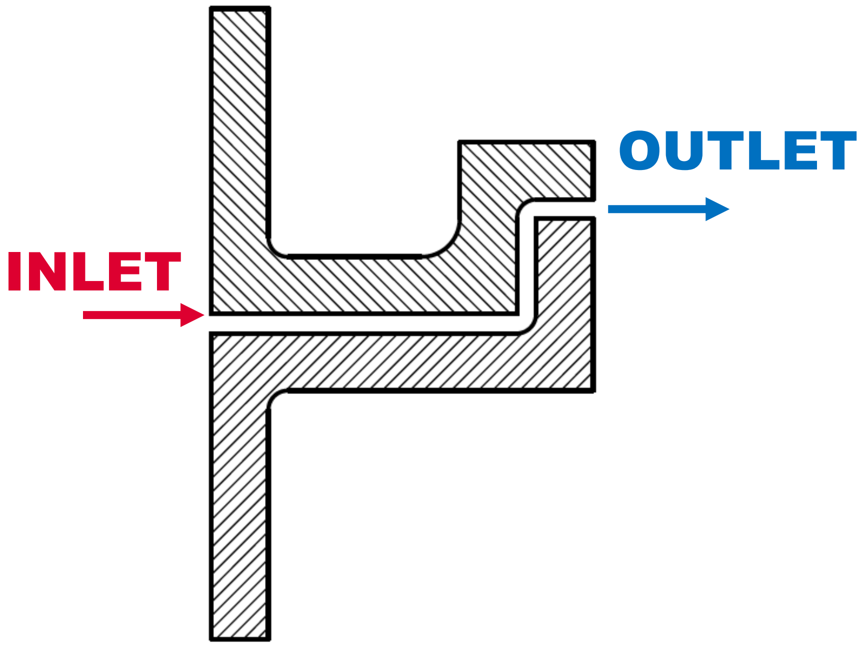


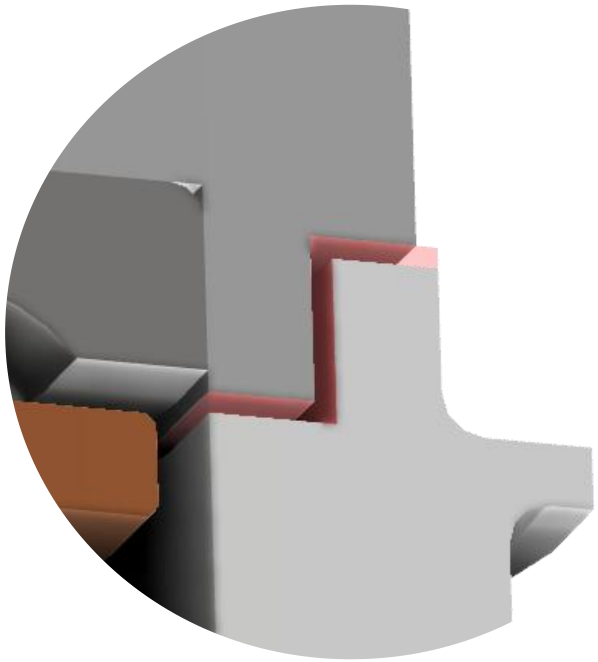
Step position (see Fig. 9)	Mass loss [mg/h]	Loss rate *
10 %	0.665	+ 5.19 %
25 %	0.643	+ 1.62 %
50 %	0.633	–
75 %	0.640	+ 1.24 %
90 %	0.662	+ 4.71 %

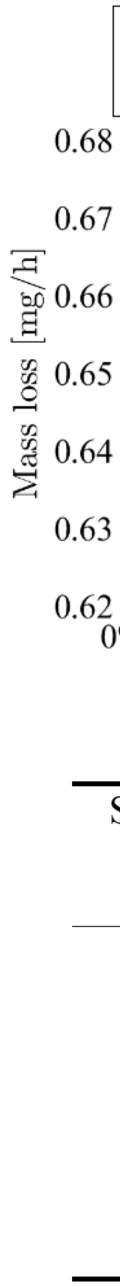
LABYRINTH SEAL OPTIMIZATION

- **Overall geometry**

  Length, Width, Complexity
- **Geometrical modifications**
- **Surface topography**
- **Electrostatic influence**
- **Rotational influence**

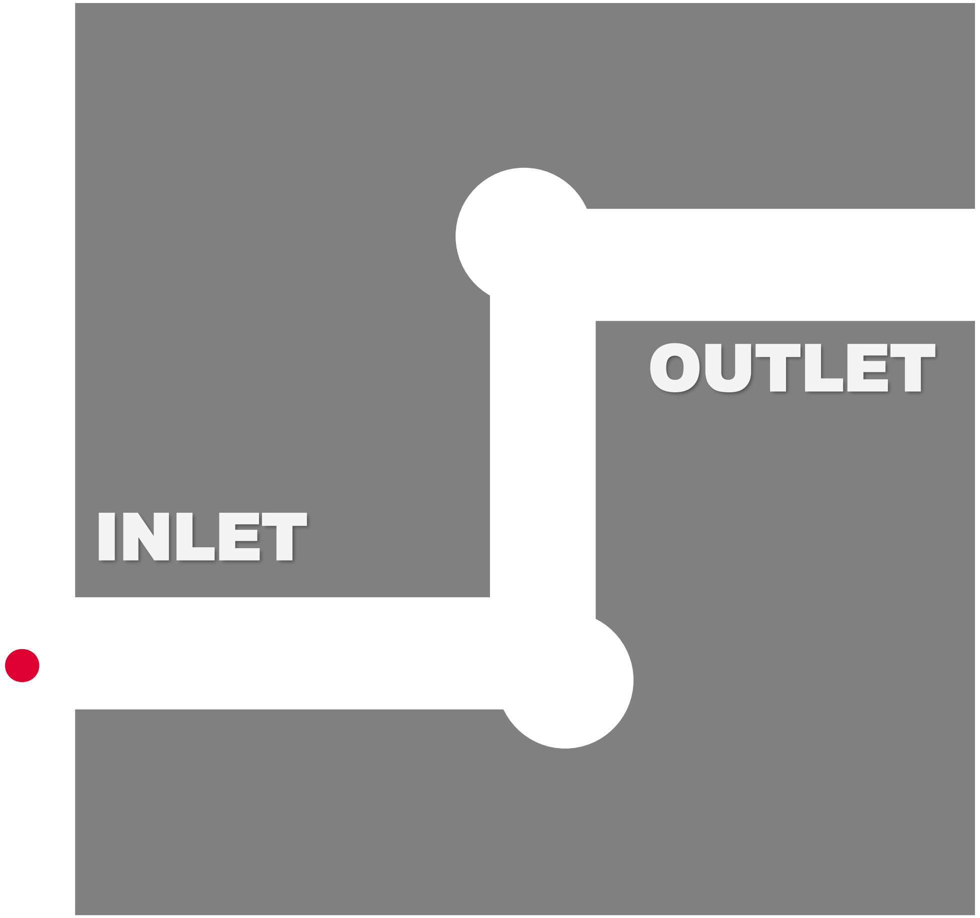




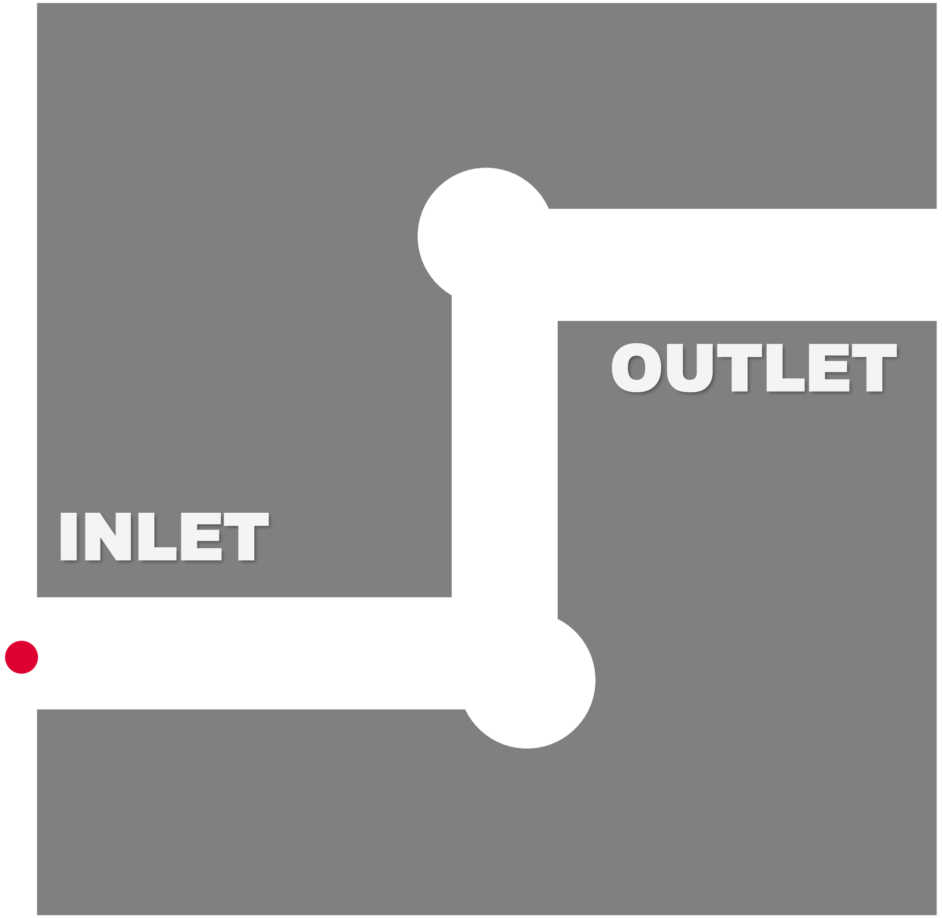


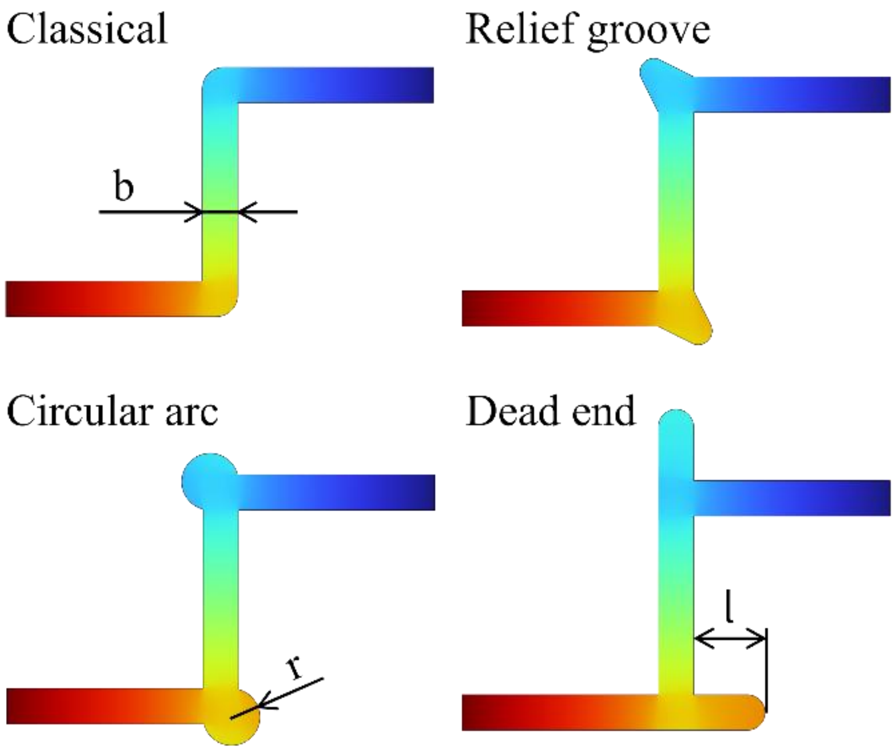
LABYRINTH SEAL OPTIMIZATION

- Overall geometry
  - Length, Width, Complexity
- Geometrical modifications
- Surface topography
- Electrostatic influence
- Rotational influence



MODIFICATIONS





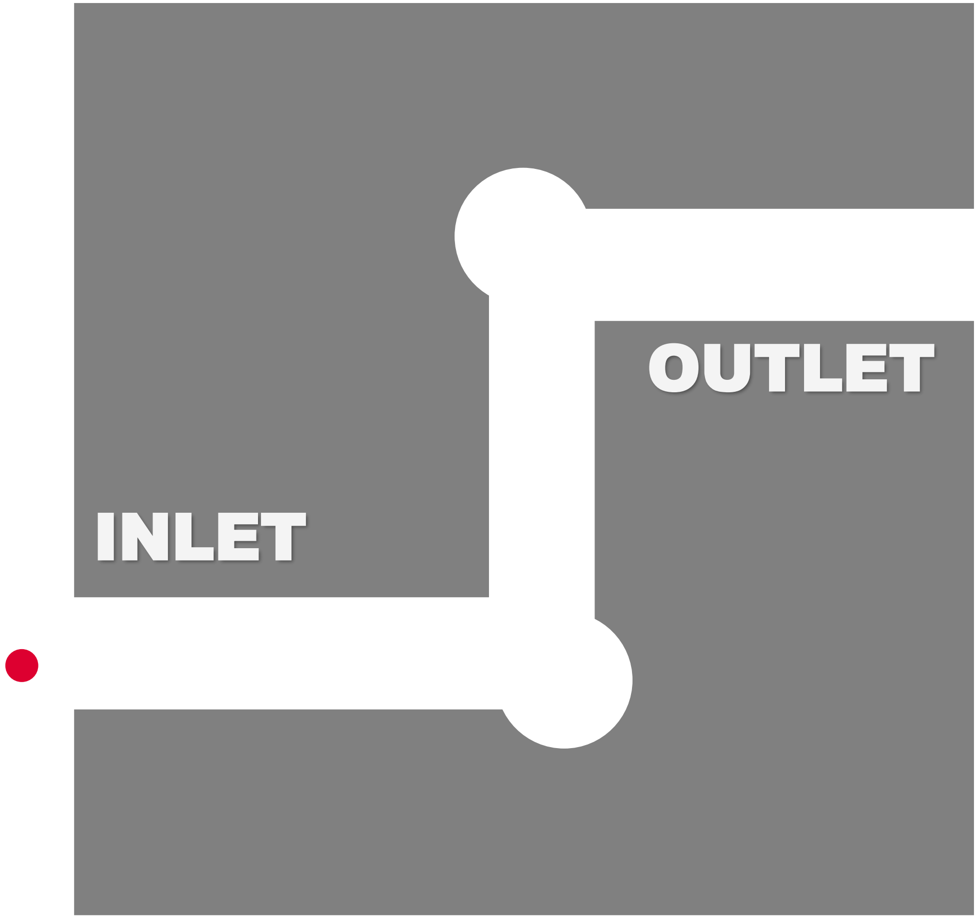
Corner geometry	Characteristic parameter	Loss reduction
Classical	–	–
Circular arc	r = b	3.8 %
Relief groove	type G*	3.9 %
Dead end	l = 2b	4.3 %

LABYRINTH SEAL OPTIMIZATION

- Overall geometry

  Length, Width, Complexity

- **Geometrical modifications**
- Surface topography
- Electrostatic influence
- Rotational influence

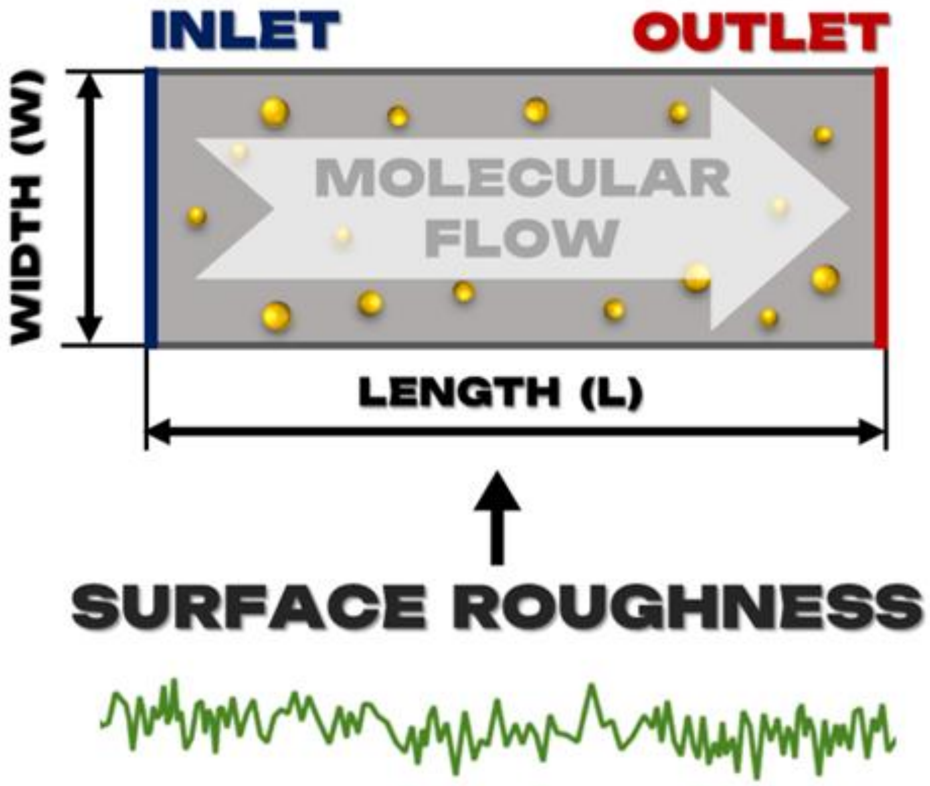


LABYRINTH SEAL OPTIMIZATION

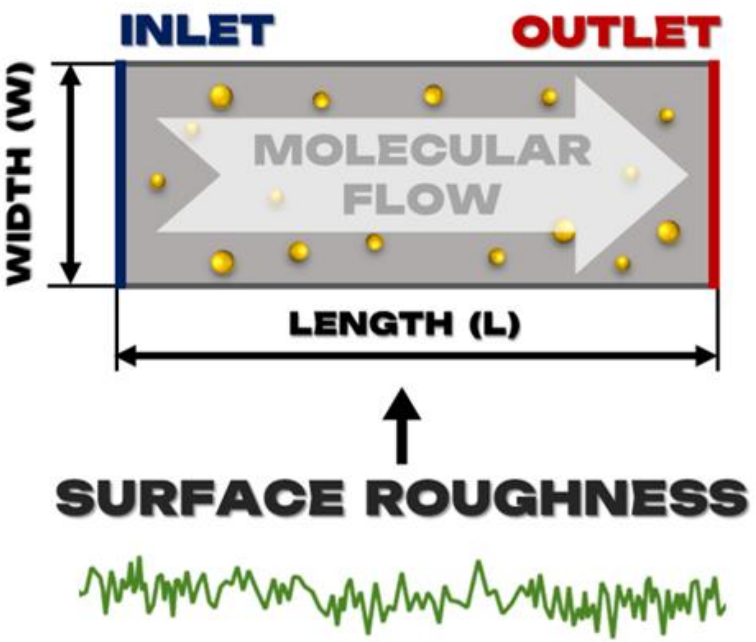
- Overall geometry

  Length, Width, Complexity

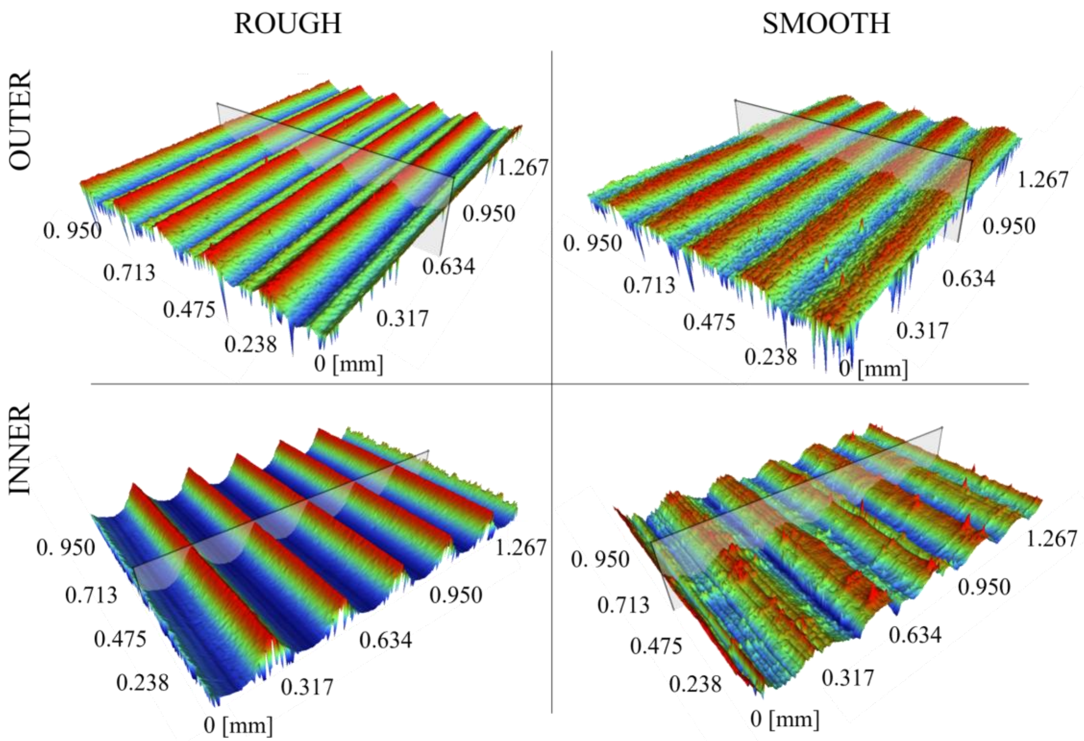
- Geometrical modifications
- Surface topography
- Electrostatic influence
- Rotational influence



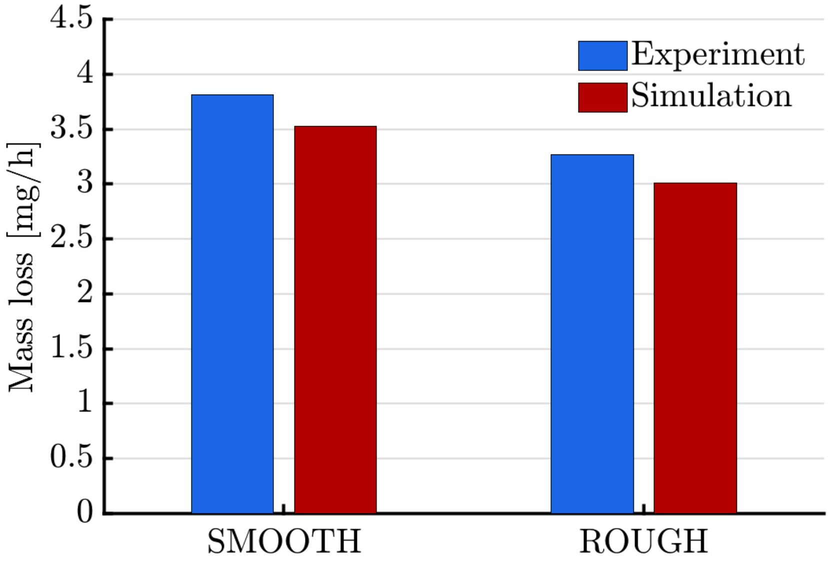
ROUGHNESS



INLET
OUTLET
WIDTH (W)
MOLECULAR FLOW
LENGTH (L)
SURFACE ROUGHNESS

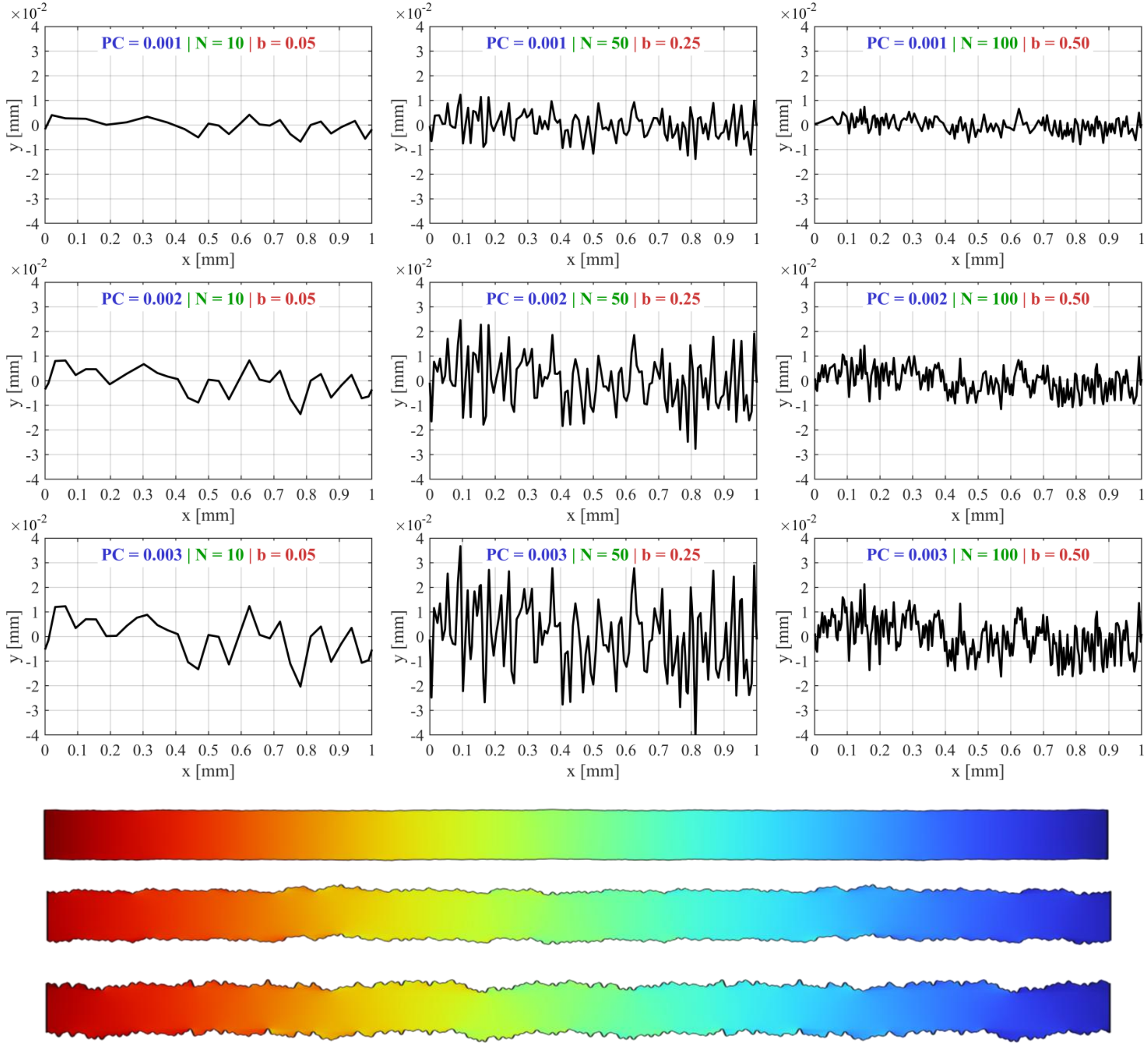


ROUGH
SMOOTH
OUTER
INNER
0. 950
0.713
0.475
0.238
0 [mm]
0.317
0.634
0.950
1.267

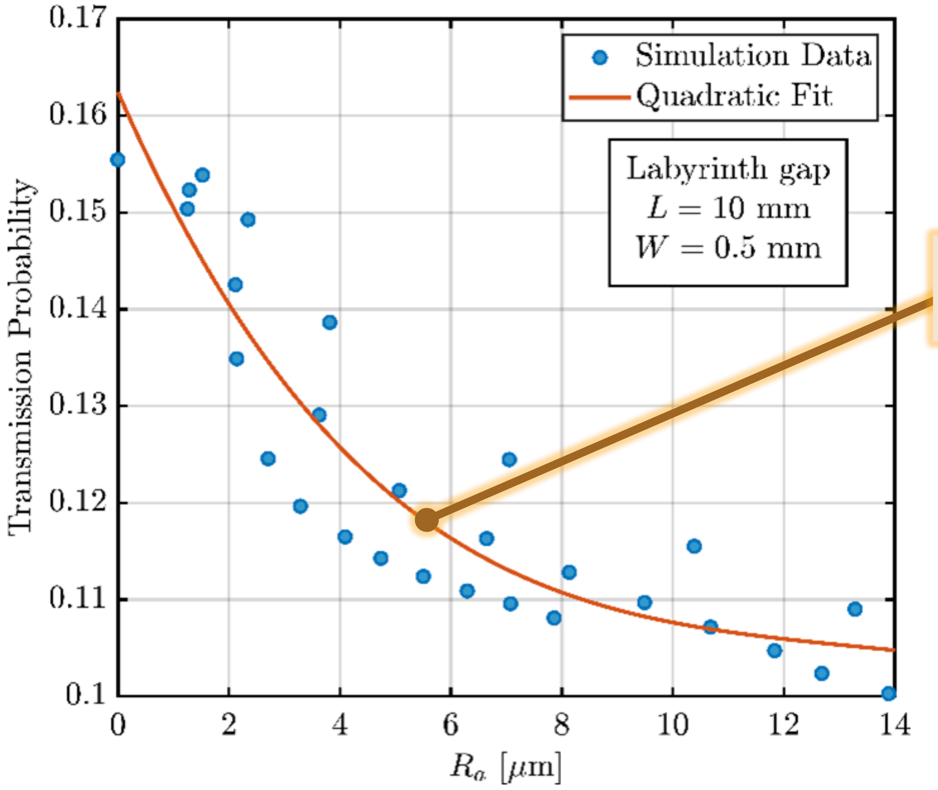


Mass loss [mg/h]
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Experiment
Simulation
SMOOTH
ROUGH

ROUGHNESS


PC = 0.001 | N = 10 | b = 0.05
PC = 0.001 | N = 50 | b = 0.25
PC = 0.001 | N = 100 | b = 0.50
PC = 0.002 | N = 10 | b = 0.05
PC = 0.002 | N = 50 | b = 0.25
PC = 0.002 | N = 100 | b = 0.50
PC = 0.003 | N = 10 | b = 0.05
PC = 0.003 | N = 50 | b = 0.25
PC = 0.003 | N = 100 | b = 0.50
×10^-2
y [mm]
x [mm]

ROUGHNESS



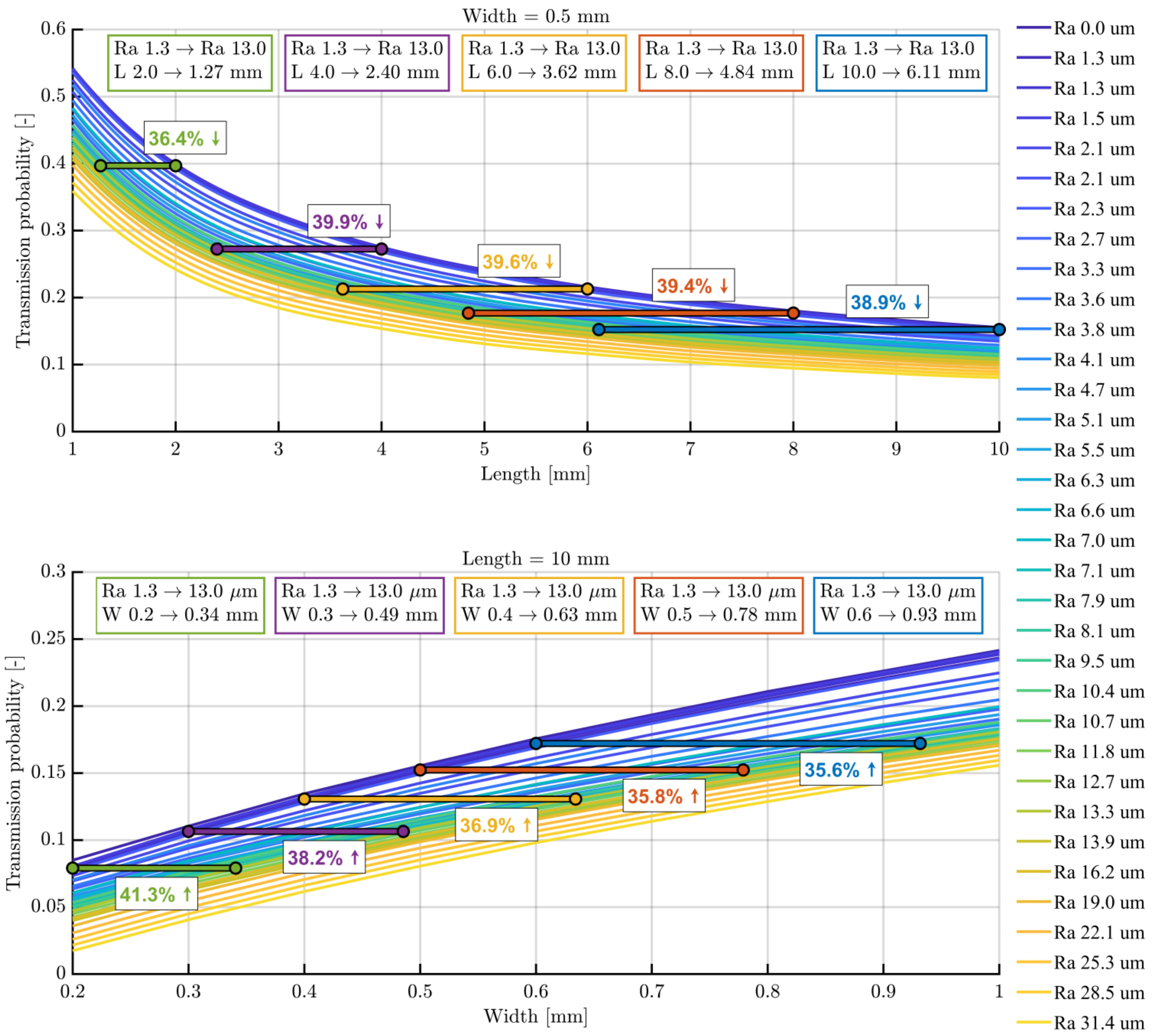
Transmission probability correction model

$$TP_{corr} = A(W,L) \cdot Ra^2 + B(W,L) \cdot Ra + C(W,L)$$

	SMOOTH	ROUGH	Roughness influence
Experiment	3.8 mg/h	3.3 mg/h	– 13.2 %
Simulation	3.5 mg/h	3.1 mg/h	– 11.4 %

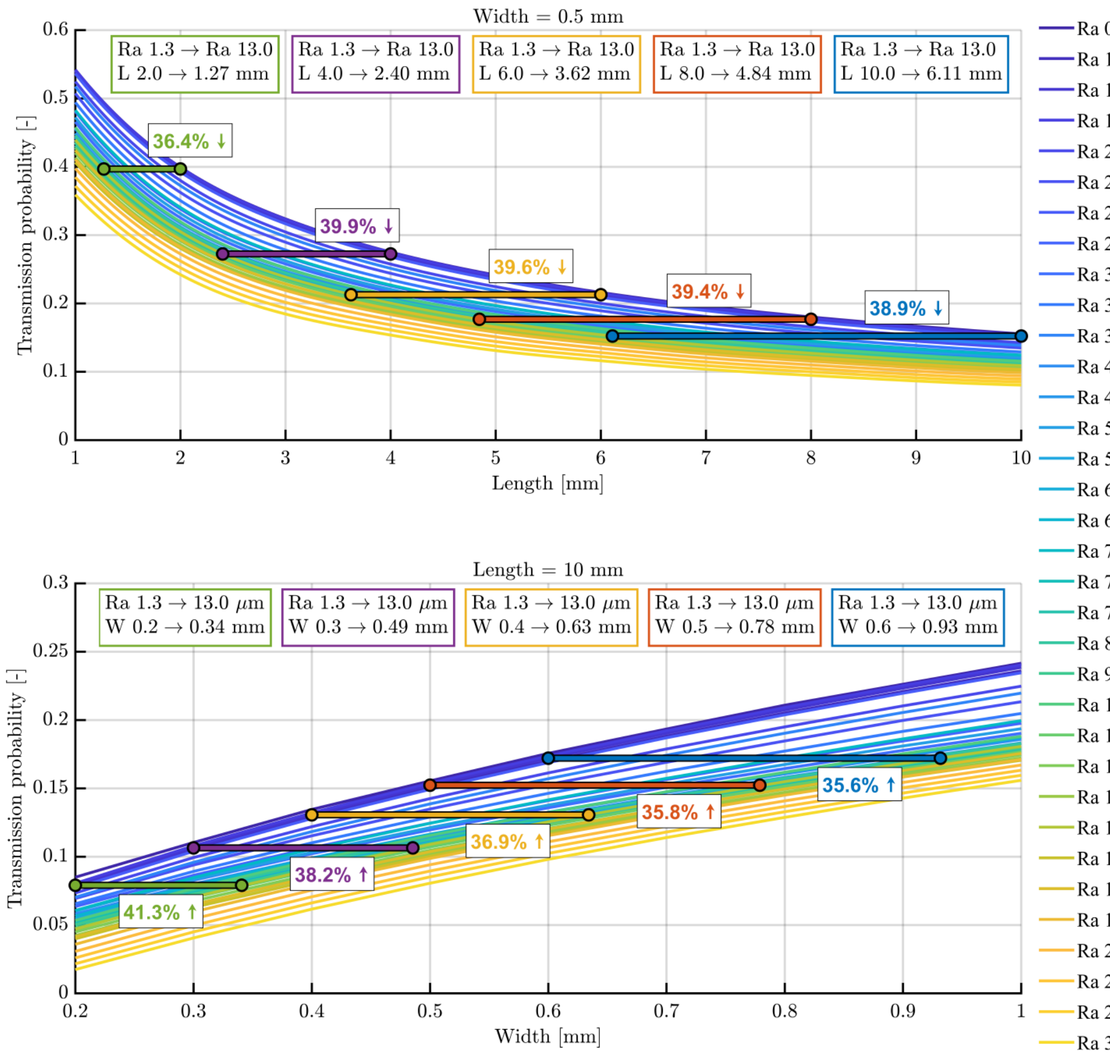
1. **Determine the surface roughness Ra**
2. **Identify the channel dimensions (W, L)**
3. **Obtain polynomial coefficients $A_{W,L}$ $B_{W,L}$ $C_{W,L}$**
4. **Calculate corrected transmission probability (TP_{corr})**

ROUGHNESS


Width = 0.5 mm
Ra 1.3 → Ra 13.0
L 2.0 → 1.27 mm
Ra 1.3 → Ra 13.0
L 4.0 → 2.40 mm
Ra 1.3 → Ra 13.0
L 6.0 → 3.62 mm
Ra 1.3 → Ra 13.0
L 8.0 → 4.84 mm
Ra 1.3 → Ra 13.0
L 10.0 → 6.11 mm
36.4% ↓
39.9% ↓
39.6% ↓
39.4% ↓
38.9% ↓
Transmission probability [-]
Length [mm]
Length = 10 mm
Ra 1.3 → 13.0 μm
W 0.2 → 0.34 mm
Ra 1.3 → 13.0 μm
W 0.3 → 0.49 mm
Ra 1.3 → 13.0 μm
W 0.4 → 0.63 mm
Ra 1.3 → 13.0 μm
W 0.5 → 0.78 mm
Ra 1.3 → 13.0 μm
W 0.6 → 0.93 mm
41.3% ↑
38.2% ↑
36.9% ↑
35.8% ↑
35.6% ↑
Transmission probability [-]
Width [mm]
Ra 0.0 um
Ra 1.3 um
Ra 1.3 um
Ra 1.5 um
Ra 2.1 um
Ra 2.1 um
Ra 2.3 um
Ra 2.7 um
Ra 3.3 um
Ra 3.6 um
Ra 3.8 um
Ra 4.1 um
Ra 4.7 um
Ra 5.1 um
Ra 5.5 um
Ra 6.3 um
Ra 6.6 um
Ra 7.0 um
Ra 7.1 um
Ra 7.9 um
Ra 8.1 um
Ra 9.5 um
Ra 10.4 um
Ra 10.7 um
Ra 11.8 um
Ra 12.7 um
Ra 13.3 um
Ra 13.9 um
Ra 16.2 um
Ra 19.0 um
Ra 22.1 um
Ra 25.3 um
Ra 28.5 um
Ra 31.4 um

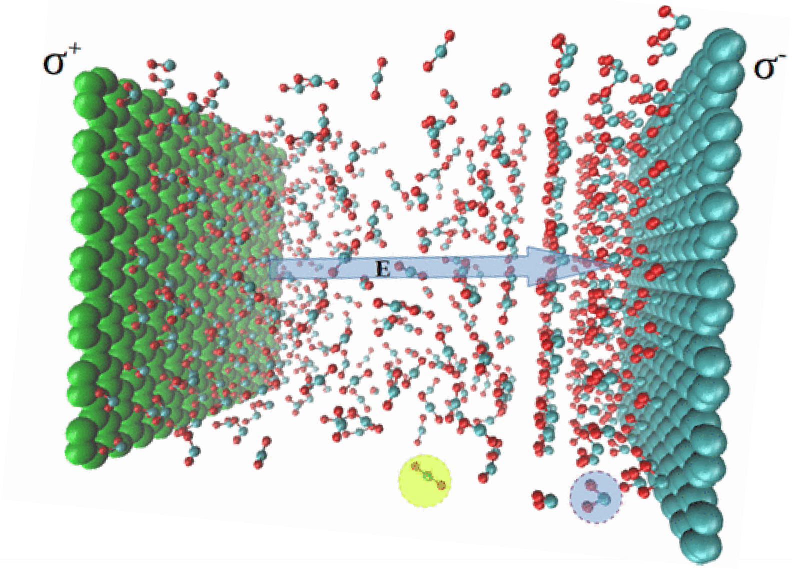
LABYRINTH SEAL OPTIMIZATION

- Overall geometry
  - Length, Width, Complexity
- Geometrical modifications
- Surface topography
- Electrostatic influence
- Rotational influence

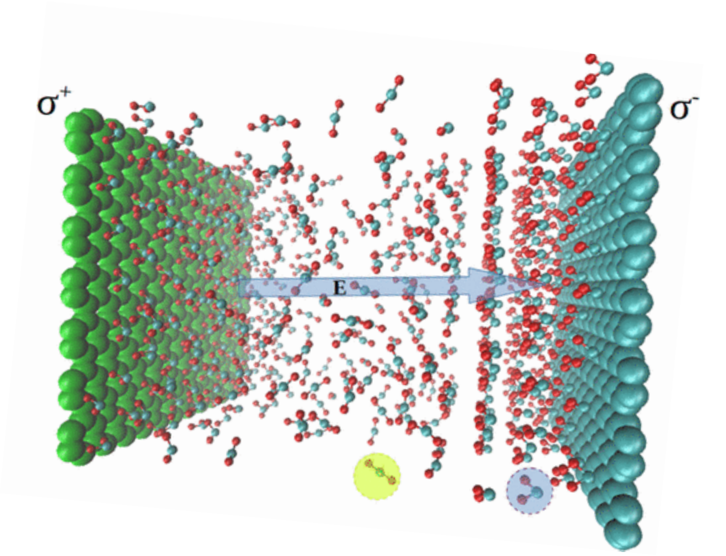


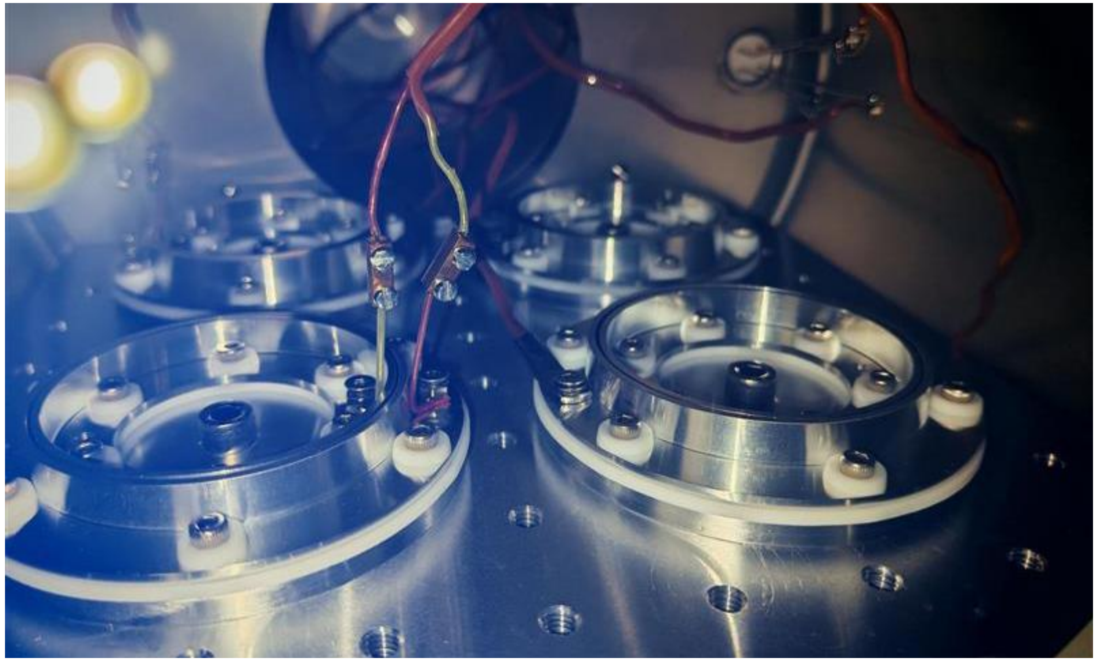
LABYRINTH SEAL OPTIMIZATION

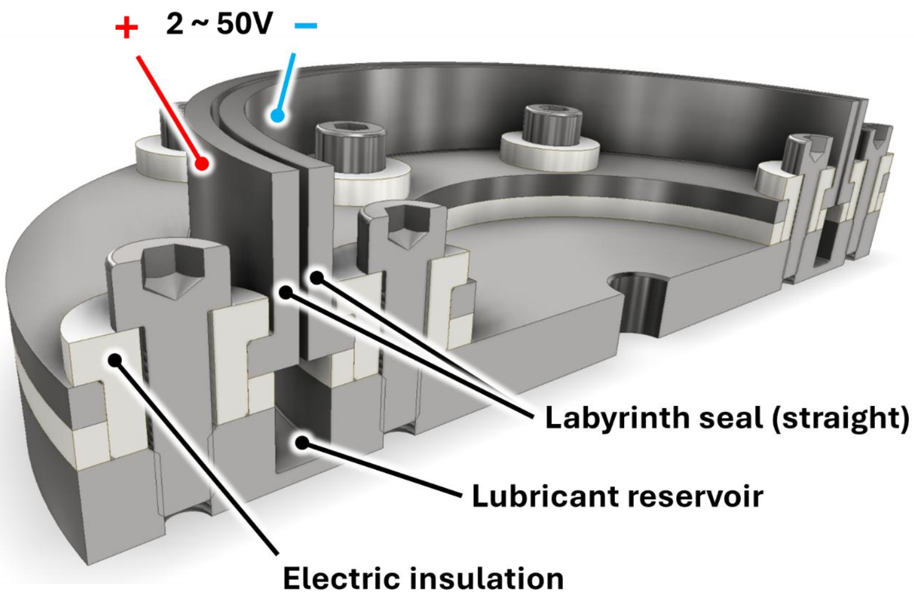
- Overall geometry
  Length, Width, Complexity
- Geometrical modifications
- Surface topography
- **Electrostatic influence**
- Rotational influence



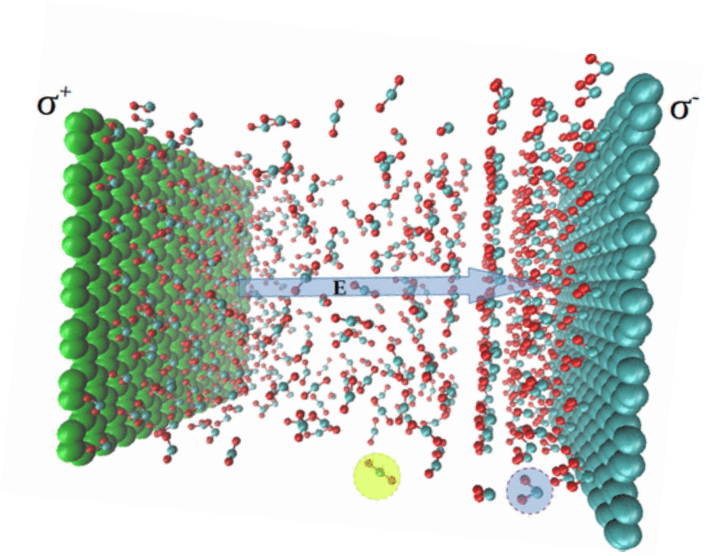
ELECTROSTATIC







ELECTROSTATIC

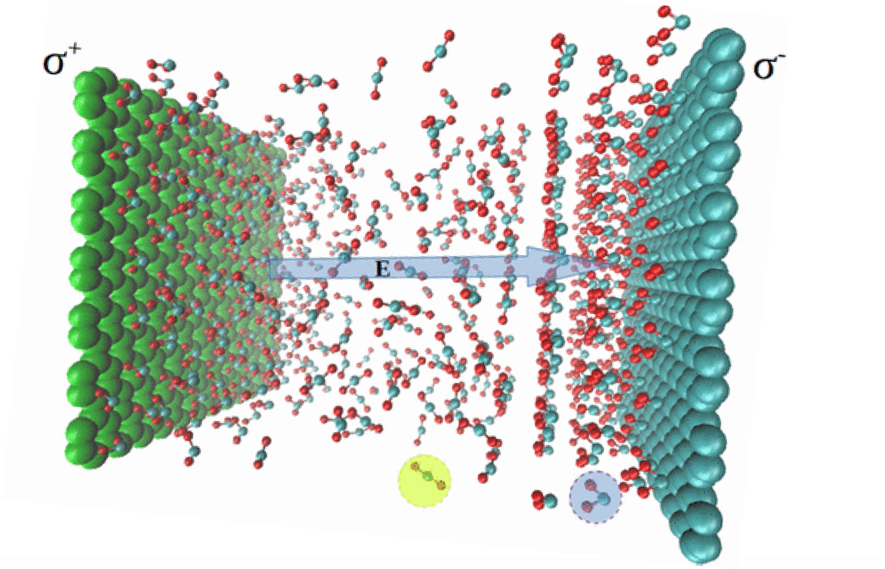


Lubricant	Type
Fomblin YLVAC	Perfluoropolyether (PFPE)
Nye 2001	Multiply-alkylated cyclopentane (MAC)
EMIM-TFSI	Ionic liquid (IL1)
OMIM-TFSI	Ionic liquid (IL2)

	Mass loss [mg/h]		Electrostatic influence
	0 V	50 V	
PFPE	0.361	0.343	– 5.0 %
MAC	0.085	0.087	+ 2.0%
IL1	0.055	0.053	– 2.7 %
IL2	0.040	0.037	– 7.4 %

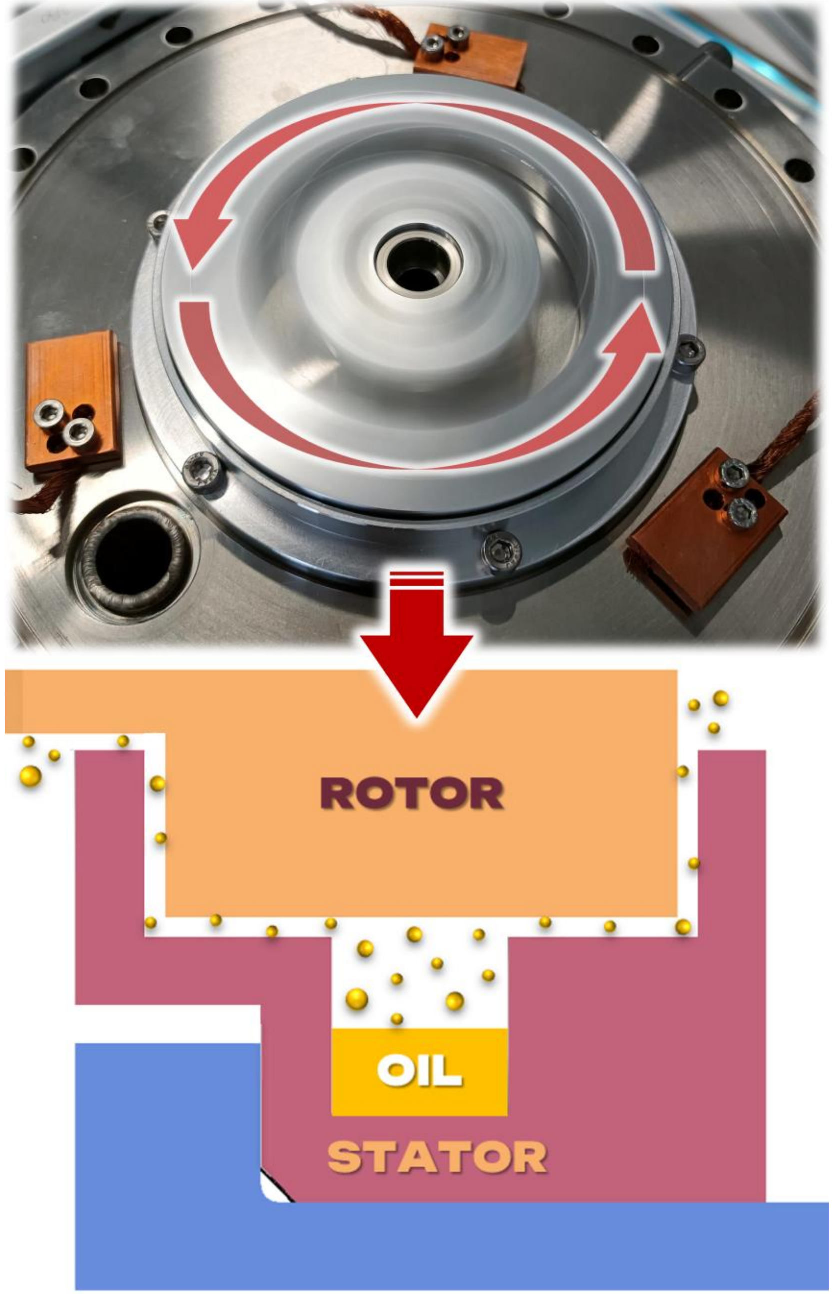
LABYRINTH SEAL OPTIMIZATION

- Overall geometry
  - Length, Width, Complexity
  - Geometrical modifications
  - Surface topography
  - **Electrostatic influence**
  - Rotational influence

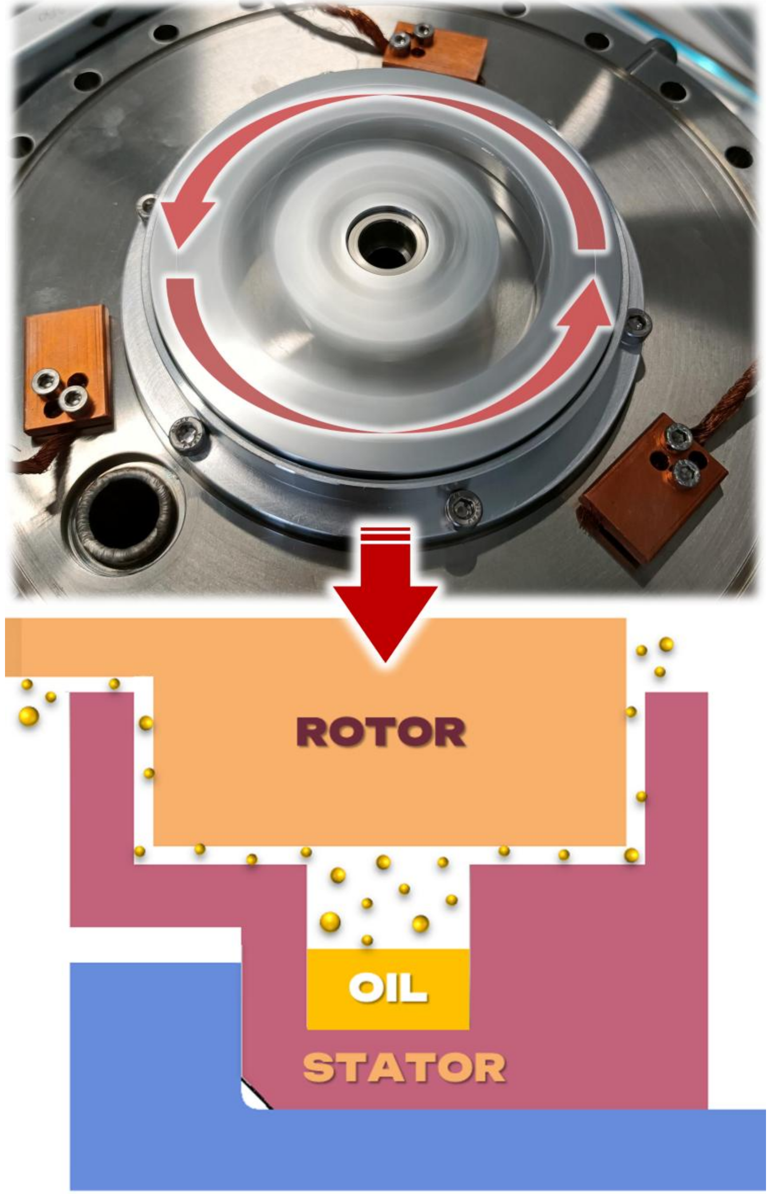


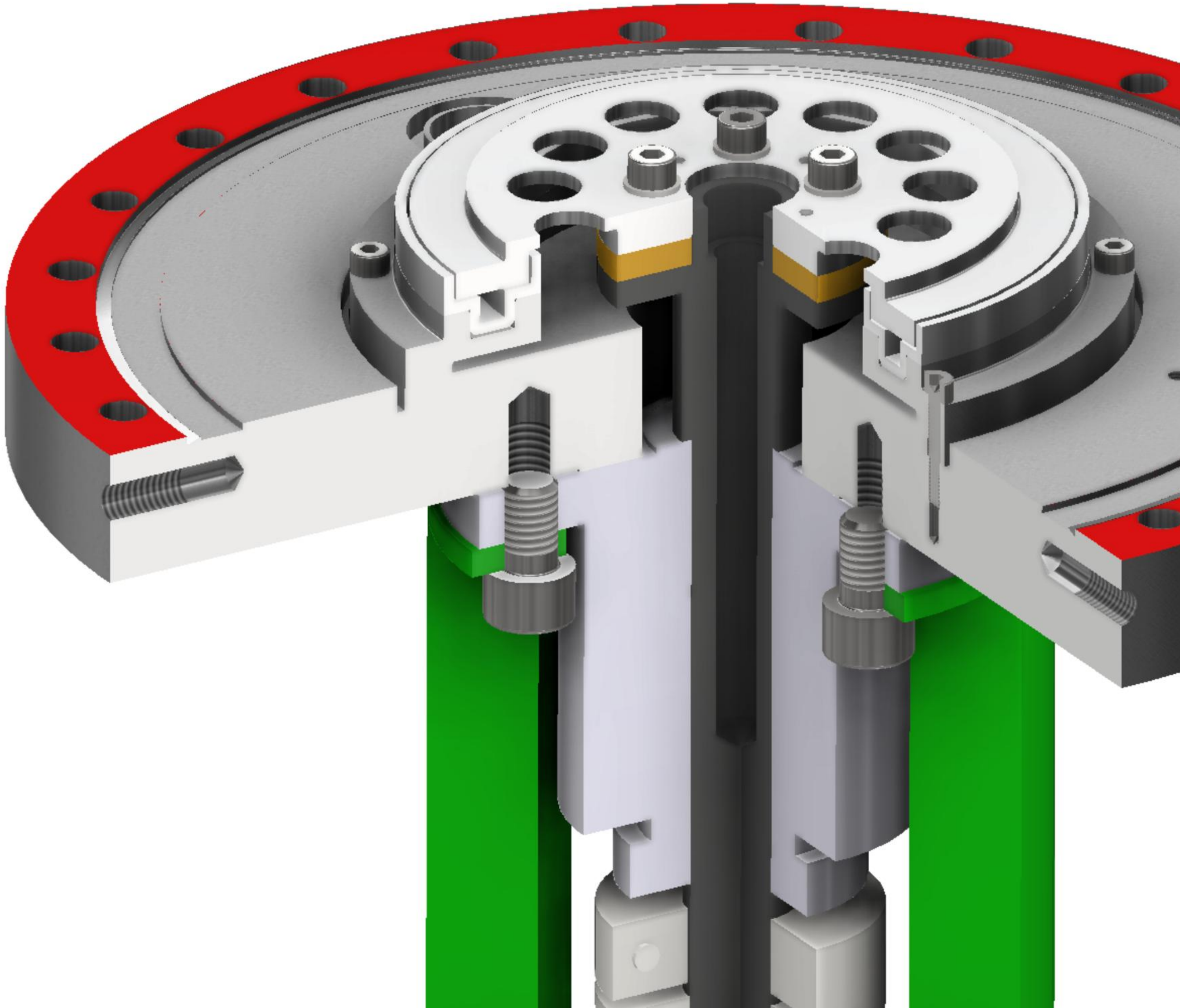
LABYRINTH SEAL OPTIMIZATION

- Overall geometry
  - Length, Width, Complexity
  - Geometrical modifications
  - Surface topography
  - Electrostatic influence
  - Rotational influence

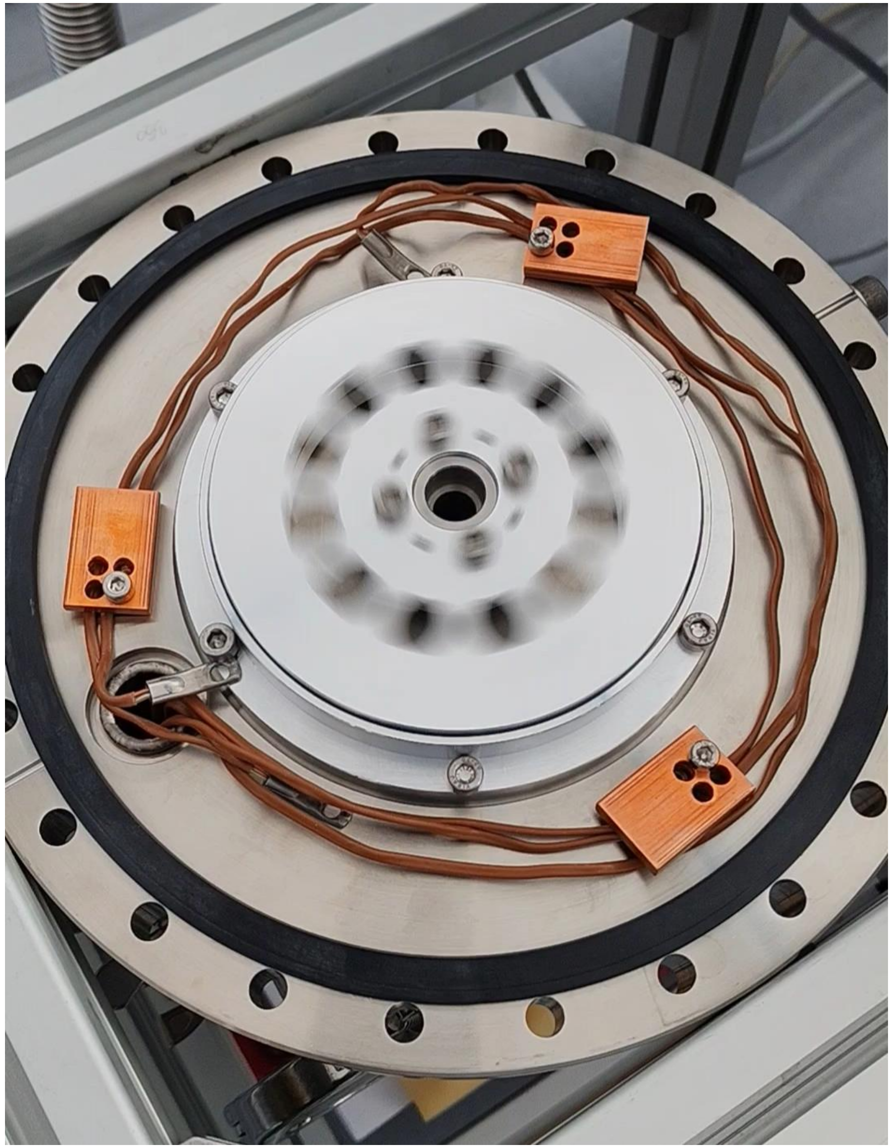


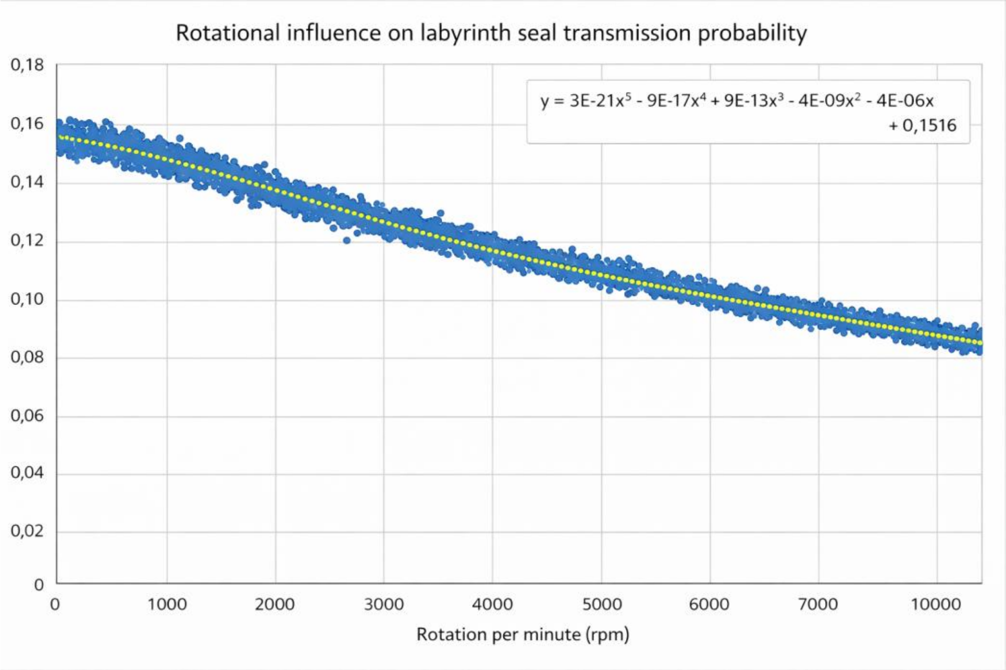
ROTATION





ROTATION





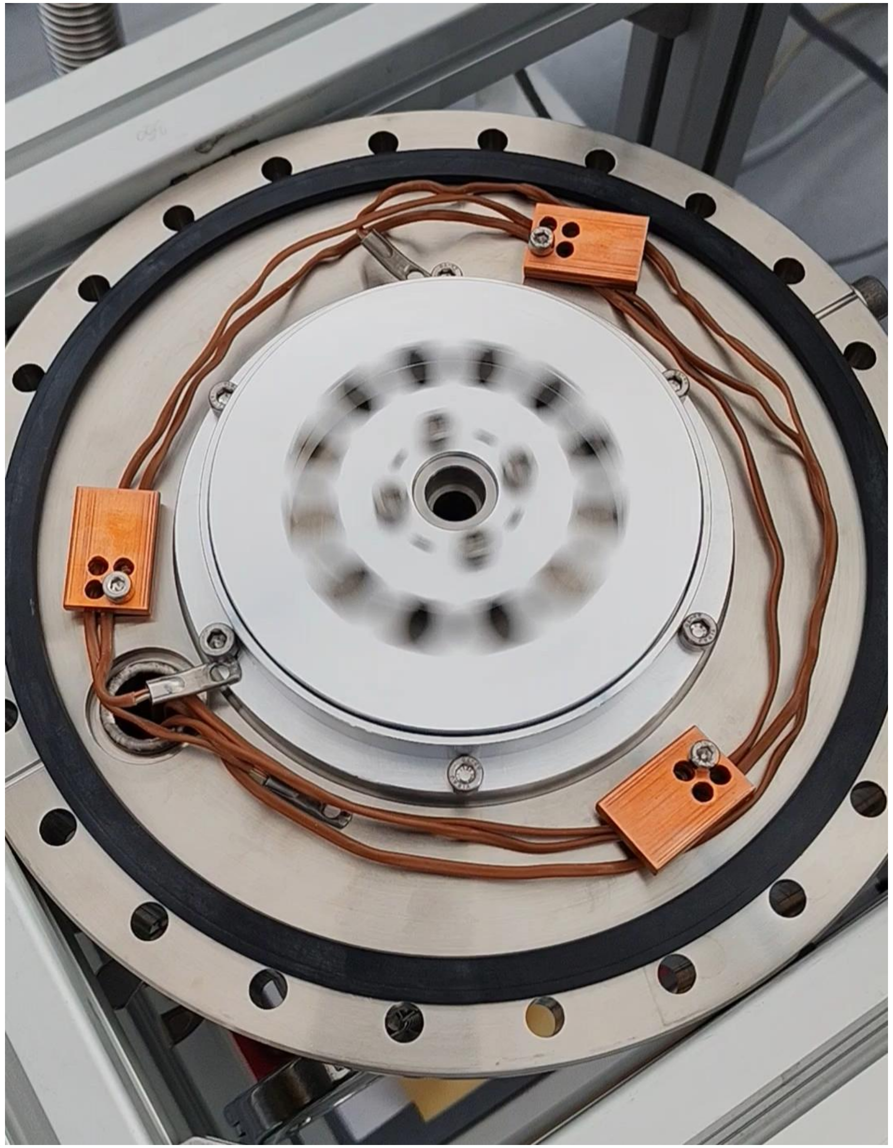
	0 RPM	2000 RPM	Spin influence
Simulation	0.178 mg/h	0.161 mg/h	– 9.05 %
Experiment	0.188 mg/h	0.168 mg/h	– 10.6 %

LABYRINTH SEAL OPTIMIZATION

- Overall geometry

  Length, Width, Complexity

- Geometrical modifications
- Surface topography
- Electrostatic influence
- Rotational influence



CONCLUSION

- Analytical Evaporation models require experimental calibration
- Simulation align with experiments for complex seals
- Stepped seals provide best sealing
- Molecular beaming increases oil loss
- Roughness affects transmission probability
- Local modifications boost efficiency
- Electrostatic field mildly affect ILs and PFPE
- Rotation influences transmission probability

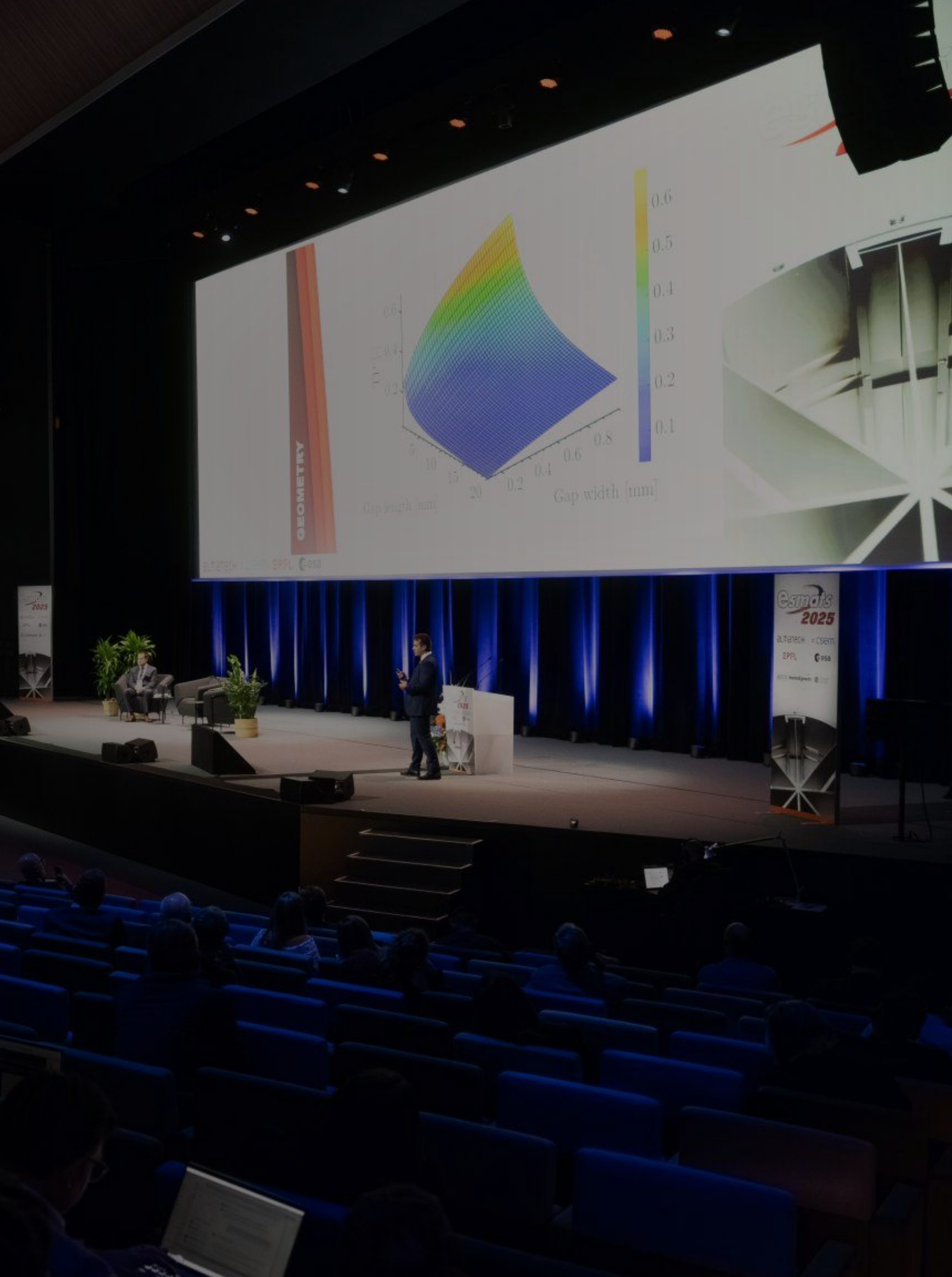
PUBLICATIONS

- **POUZAR, J.**, KOSTAL, D., SPERKA, P., KRUPKA, I., HARTL, M. Experimental study of space lubricant evaporation in a high vacuum environment. Vacuum, 2024, 219(A), 112758. ISSN 0042-207X. https://doi.org/10.1016/j.vacuum.2023.112758

- **POUZAR, J.**, KOSTAL, D., WESTERBERG, L. G., NYBERG, E., KRUPKA, I. Labyrinth seal design for space applications. Vacuum, 2025, 232, 113882. ISSN 0042-207X. https://doi.org/10.1016/j.vacuum.2024.113882

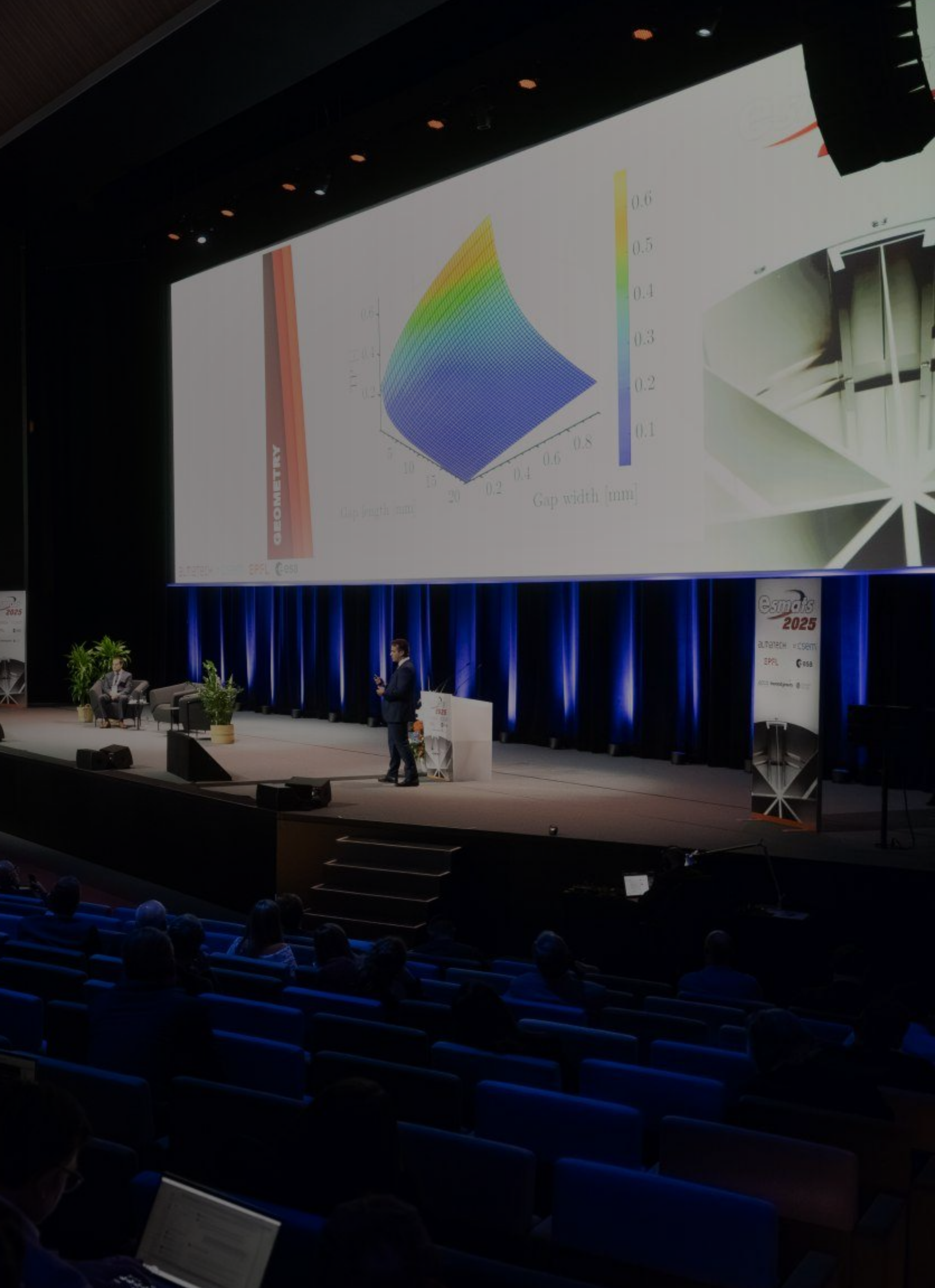
- **POUZAR, J.**, KOSTAL, D., WESTERBERG, L. G., NYBERG, E., POLACEK, T., JURIK, K., KRUPKA, I. Influence of surface roughness on molecular flow through labyrinth seals for space applications. Results in Engineering, 2025, 28, 107905. ISSN 2590-1230. https://doi.org/10.1016/j.rineng.2025.107905

- **POUZAR J.**, KOSTAL D., WESTERBERG L.G., KRUPKA I. Labyrinth seal design for enhanced sealing of evaporated lubricant molecules in space mechanisms. 21st European Space Mechanisms and Tribology Symposium (ESMATS), 2025. https://www.esmats.eu/esmatspapers/pastpapers/pdfs/2025/pouzar.pdf



CONFERENCES

- **9th International Tribology Conference, Fukuoka 2023, Japan**
- **49th Leeds Lyon Symposium on Tribology, Lyon 2024, France**
- **21st European Space Mechanisms and Tribology Symposium (ESMATS), Lausanne 2025, Switzerland**



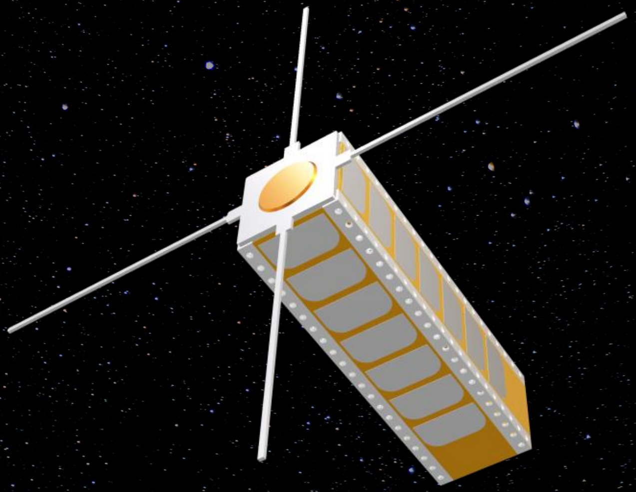
INTERNSHIPS

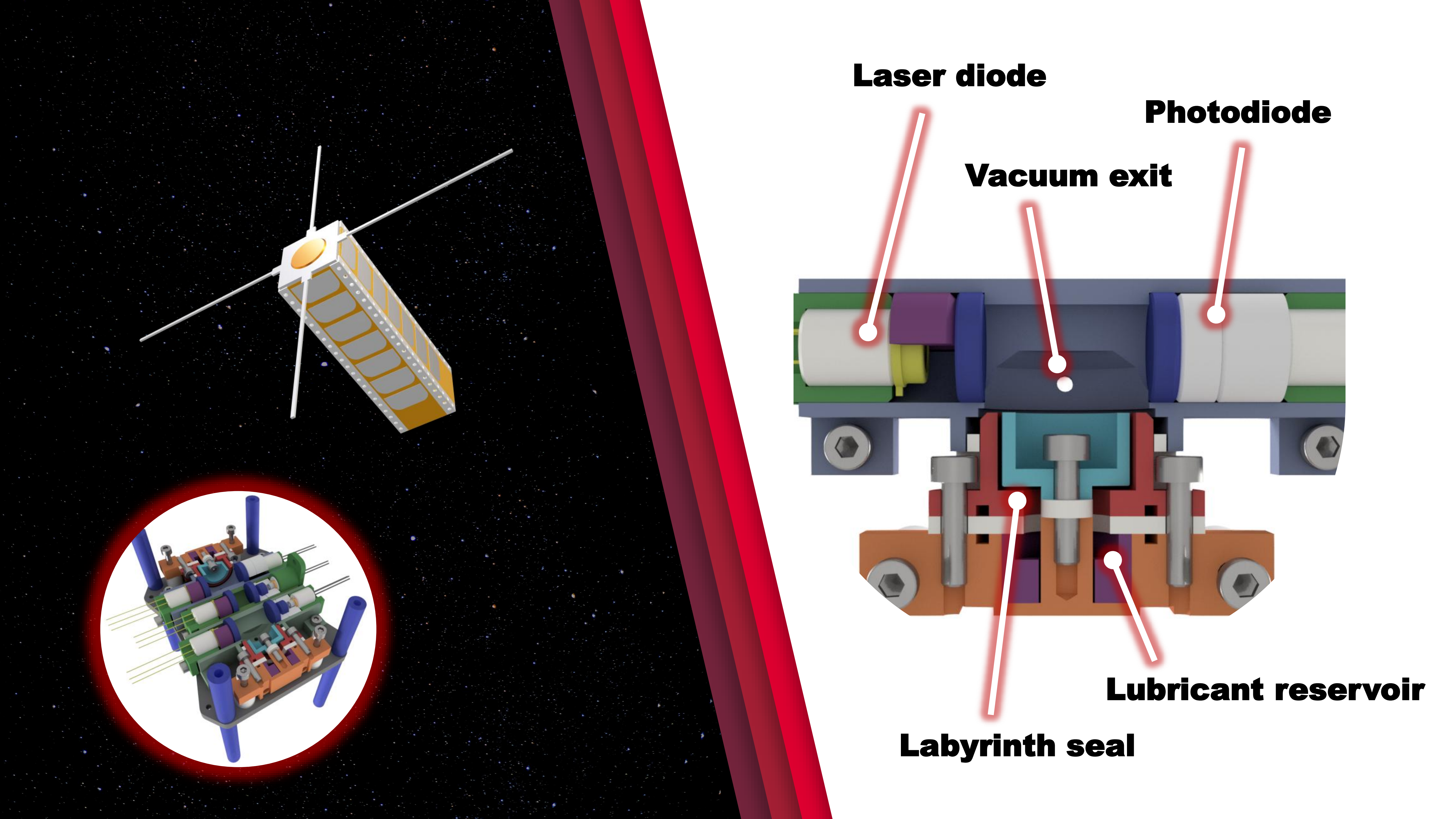
- **04/2023 – Luleå University of Technology**
  - Luleå, Sweden
- **05/2024 – STFC ASTeC, Daresbury Laboratory**
  - Daresbury, United Kingdom

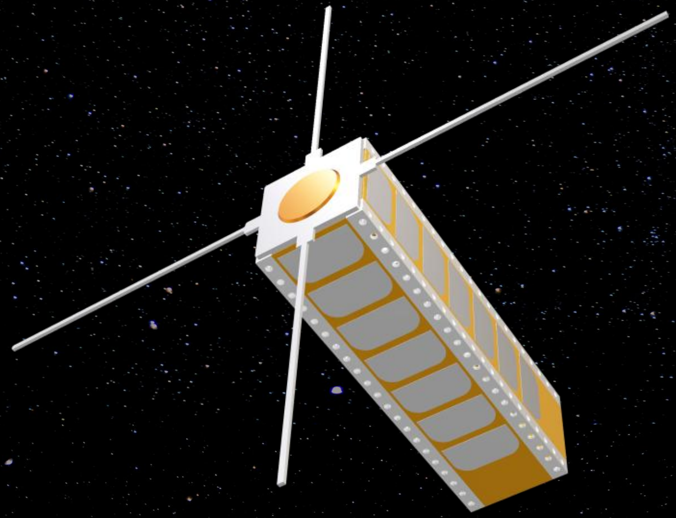
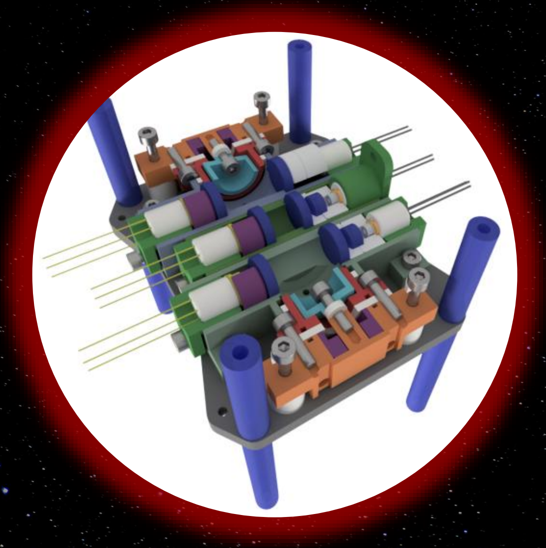
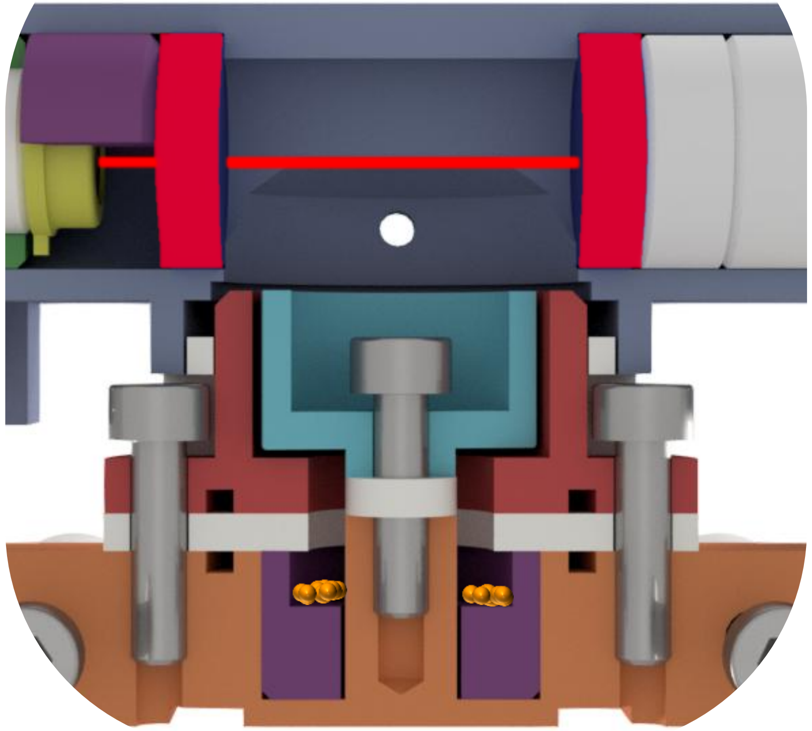
ACTIVITY PLANNING

3U CubeSat mission

- **Initiative of:** Czech Aerospace Research Center, Spacemanic CZ, Brno Observatory
- **BUT is developing 1U structure to host two experiments –** Labyrinth seals in 0.5U
- **Launch planned for end-2026 (HSO, 500km)**




Laser diode
Photodiode
Vacuum exit
Lubricant reservoir
Labyrinth seal

THANK YOU FOR YOUR ATTENTION

Josef Pouzar

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