Design and Simulation of Labyrinth Seals for Space Applications

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This work was supported through the Open Space Innovation Platform under a Co-Sponsored Research Agreement funded by the European Space Agency (Contract No. 4000139889).

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

LABYRINTH SEALS IN SPACE

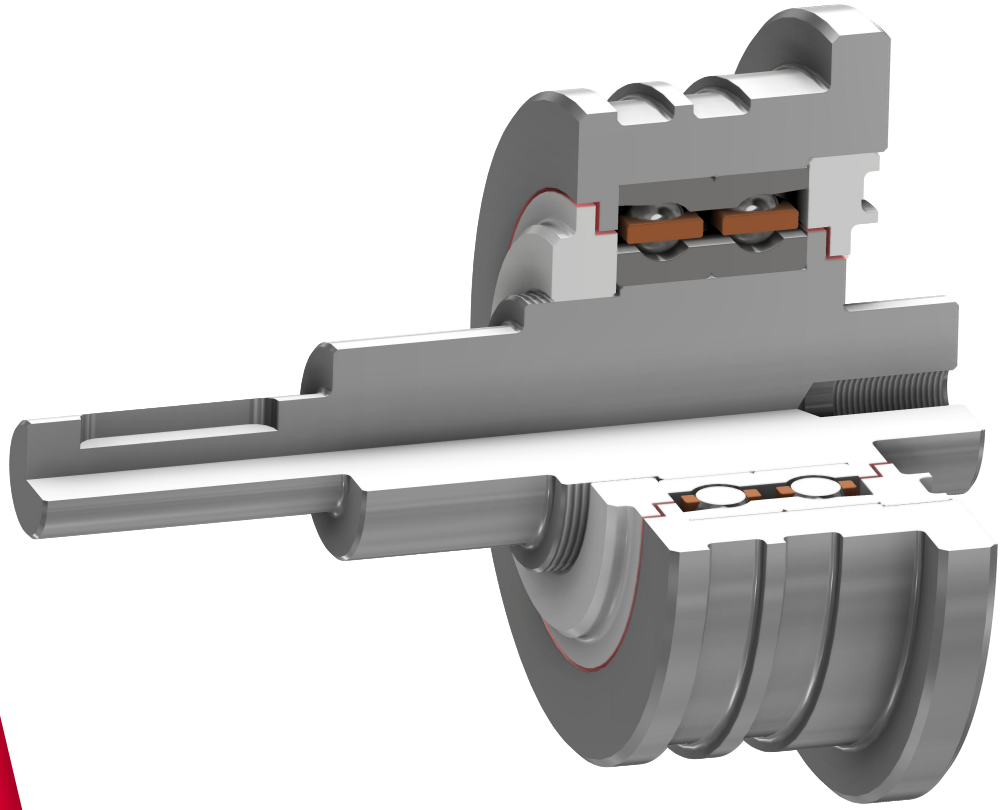
ATTITUDE CONTROL SYSTEM

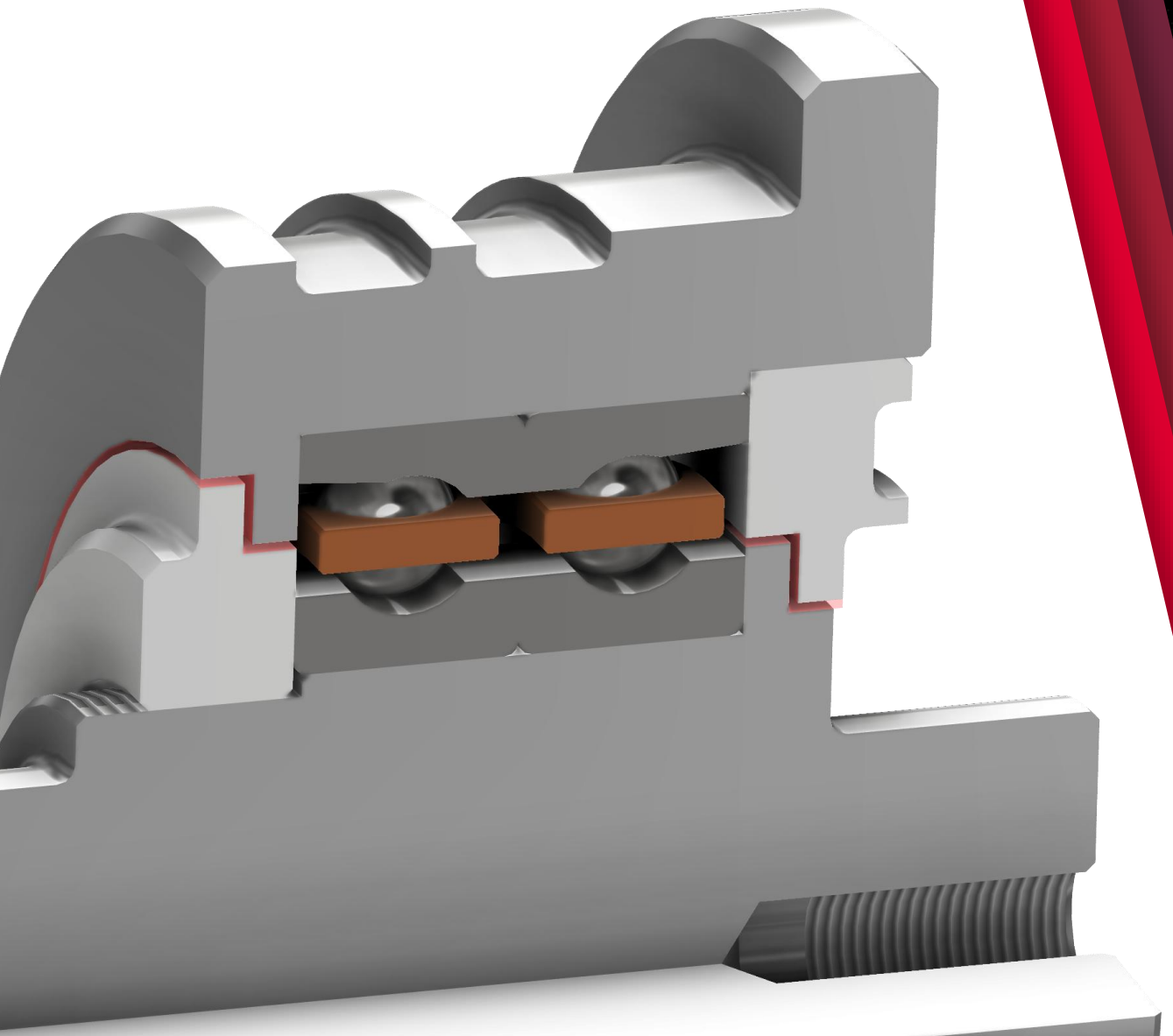
SOLAR ARRAY DRIVE MECHANISMS

COARSE POINTING ASSEMBLIES

LABYRINTH SEALS

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





LAYBRINTH SEAL RESEARCH AREAS

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

MOLECULAR FLOW

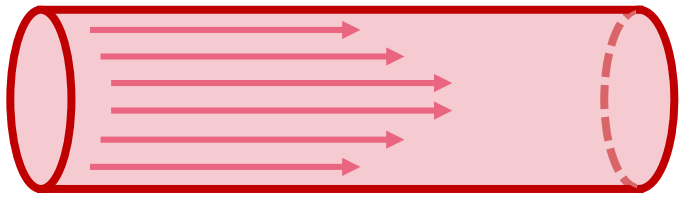
VACUUM ENVIRONMENT (UHV, XHV)

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

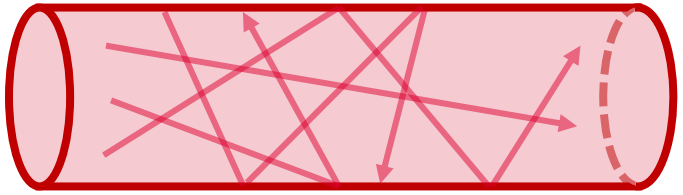
VACUUM EVAPORATION

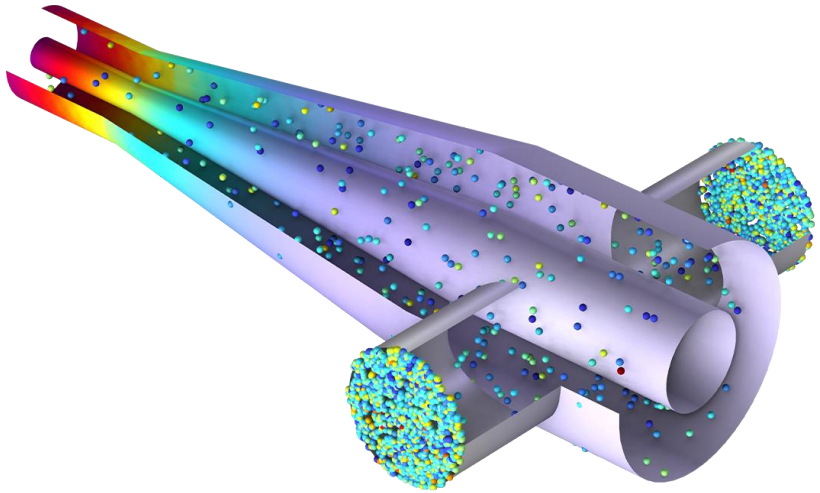
- Vacuum pressure ≤ Vapor pressure

Viscous flow



Molecular flow





EVAPORATIVE MASS LOSS

ANALYTICAL

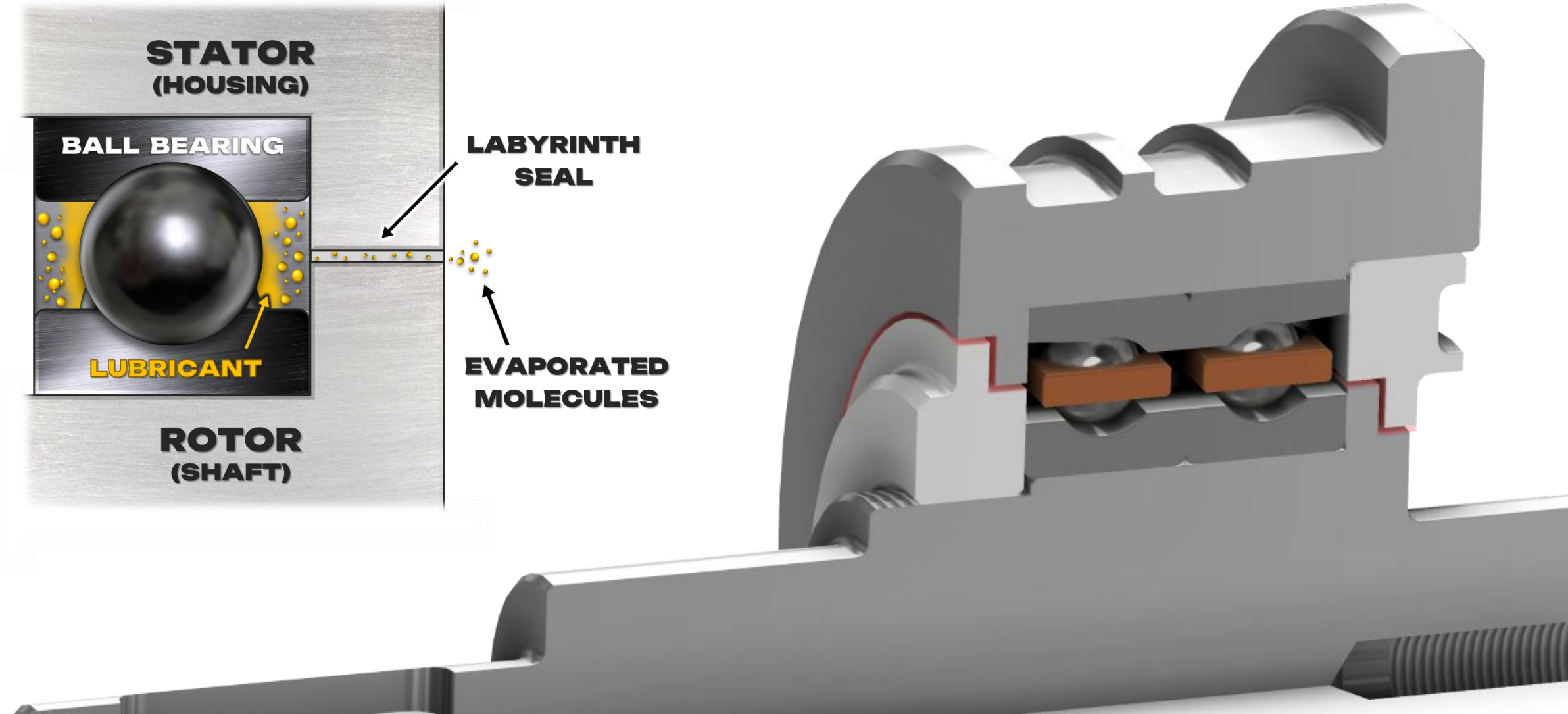
SIMULATION

EXPERIMENT

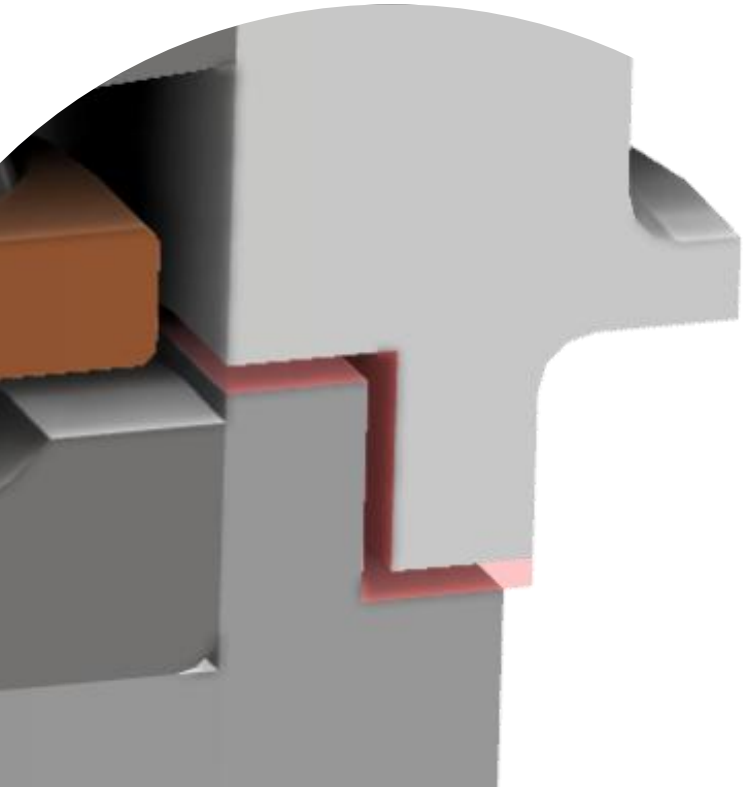
ANALYTICAL

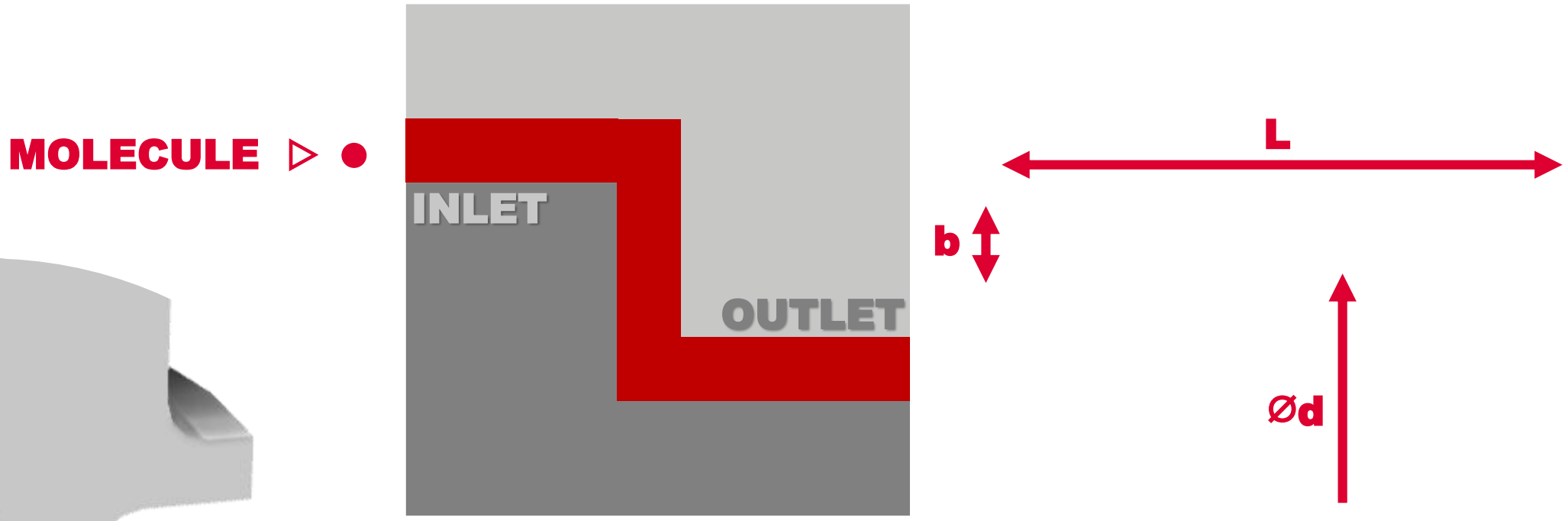
LABYRINTH SEAL

EVAPORATED MOLECULES



ANALYTICAL





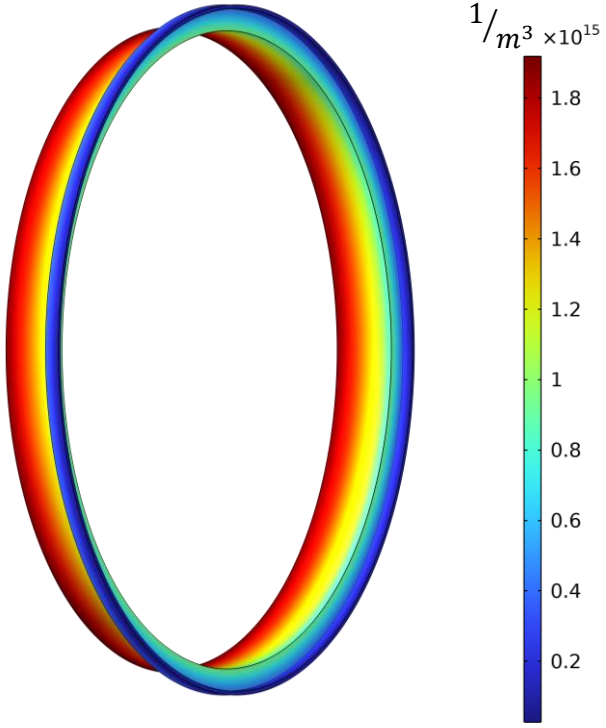
ESTL Model:

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

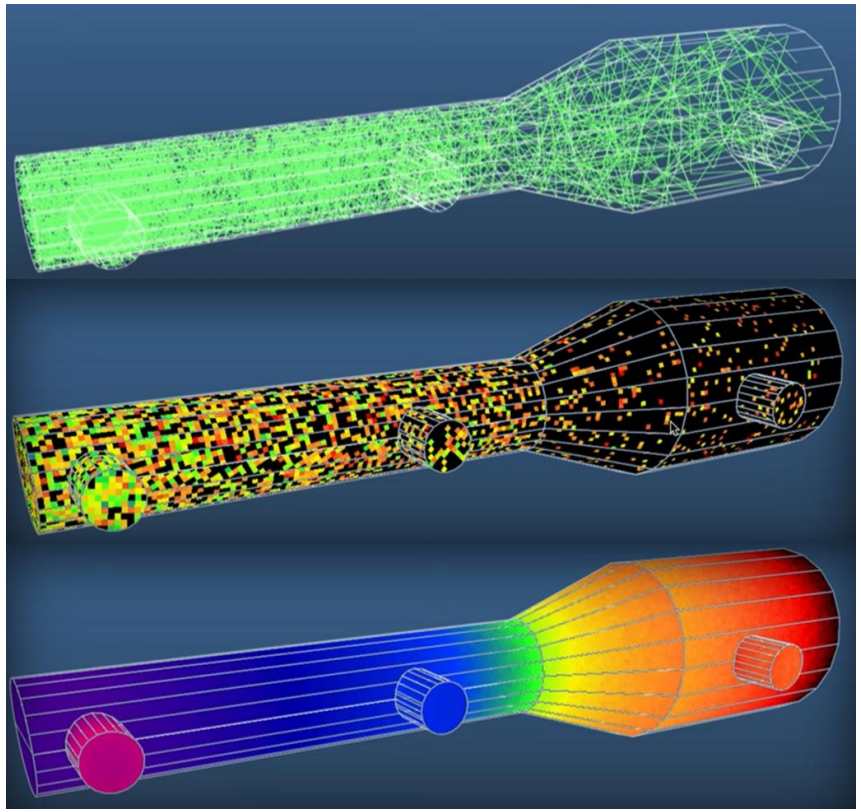
SIMULATION

COMSOL MULTIPHYSICS

- Particle Tracing module
- Molecular flow module

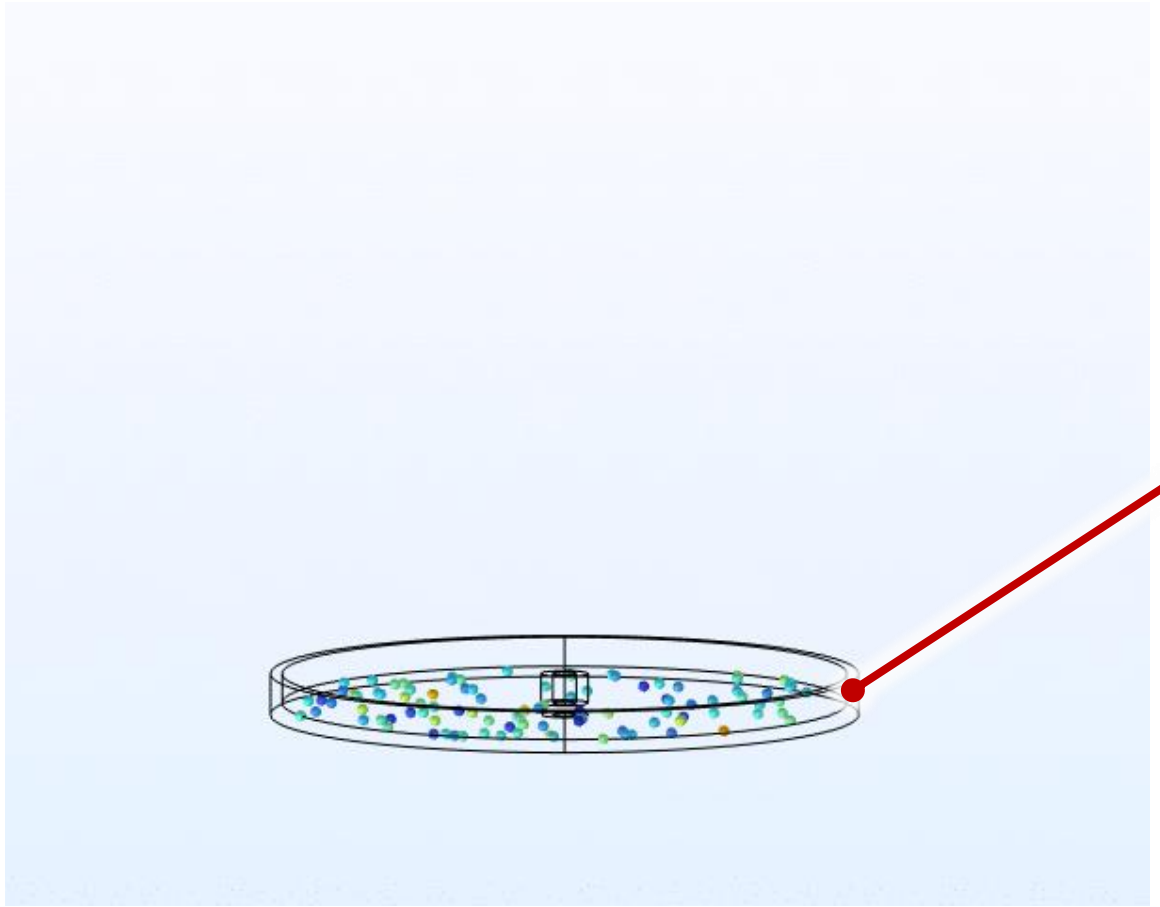


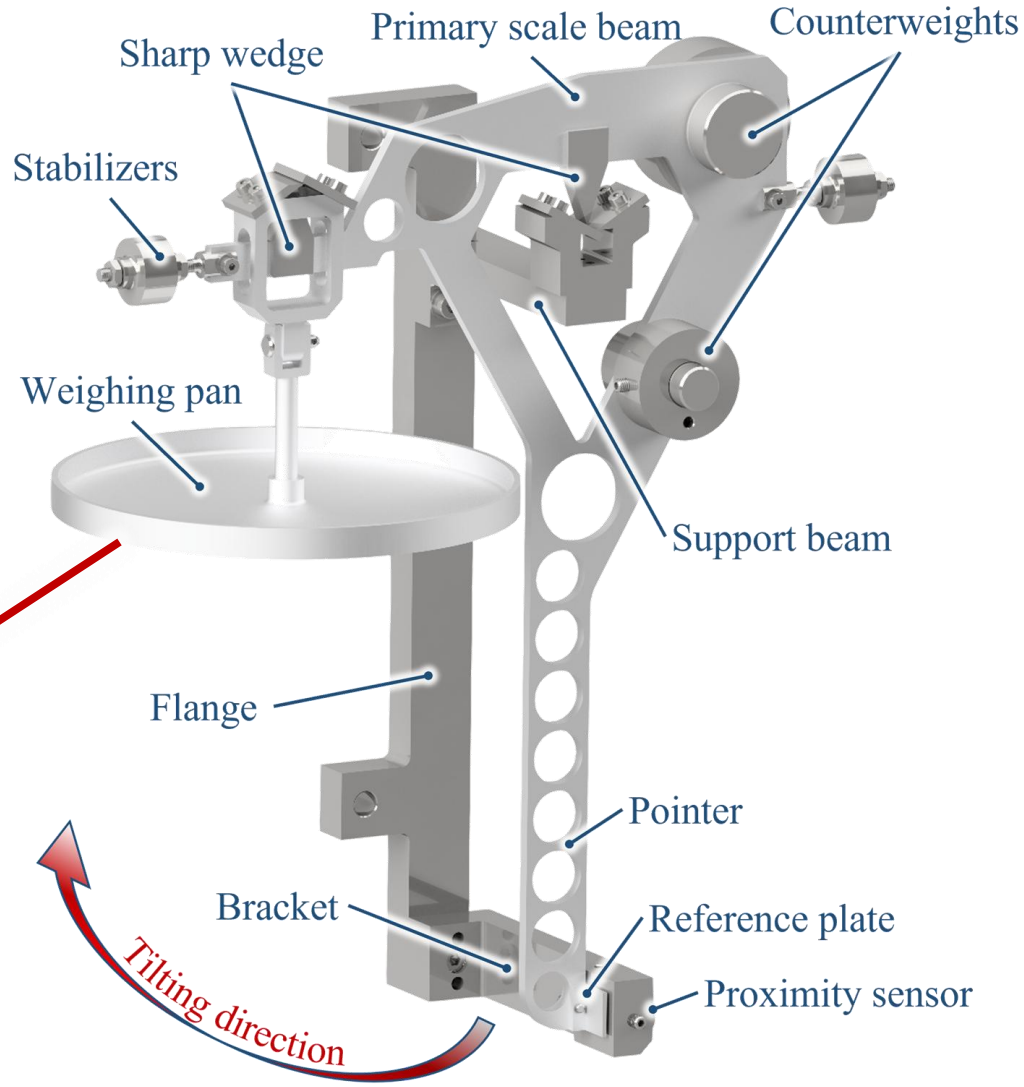
MOLFLOW+ (CERN)



EXPERIMENT

EVAPORATION TEST RIG (ETR)





EVAPORATIVE MASS LOSS

ANALYTICAL

SIMULATION

EXPERIMENT

LABYRINTH SEAL OPTIMIZATION

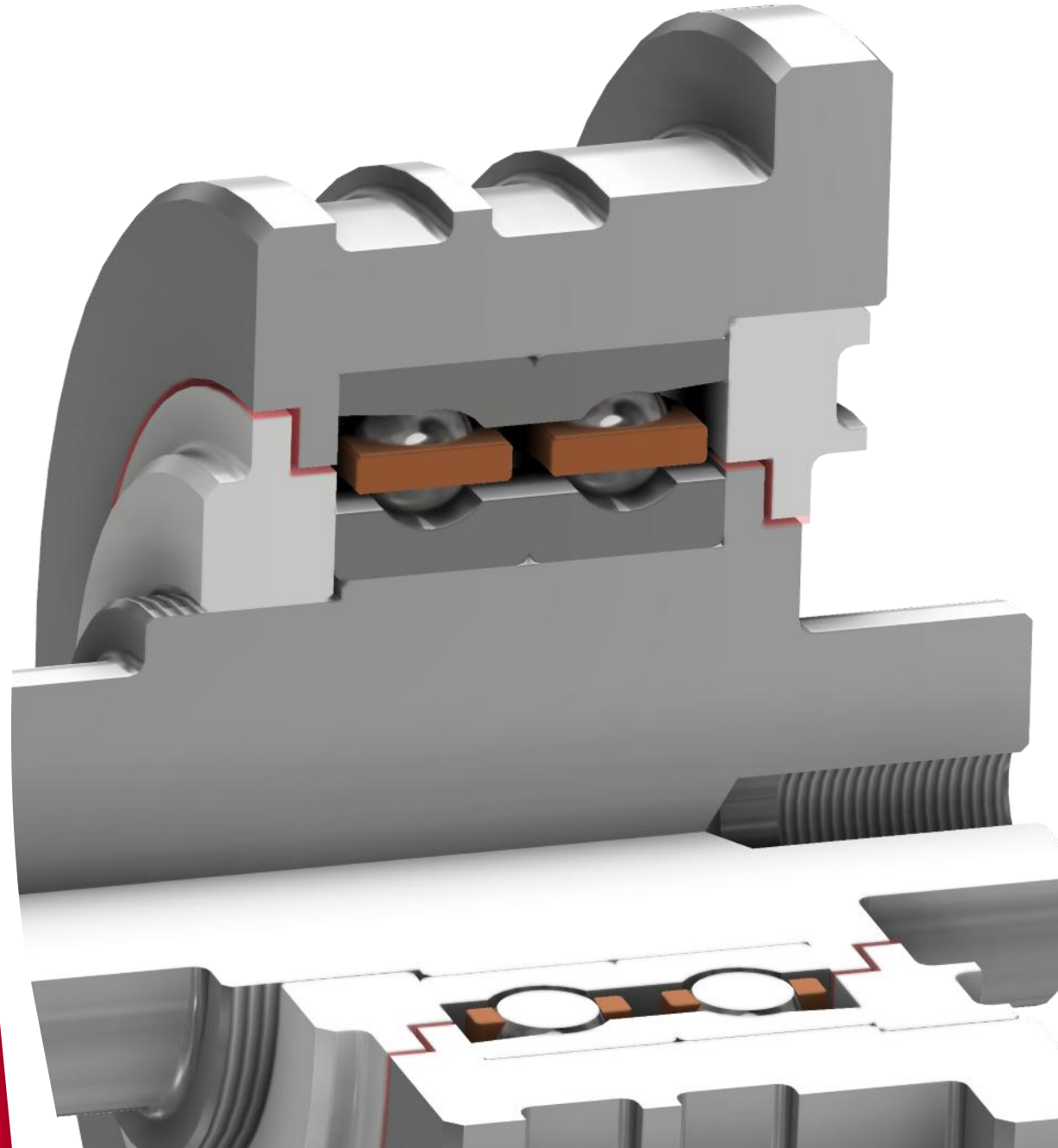
- Overall geometry

  Length, Width, Complexity

  - Geometrical modifications

    - Surface topography

      - Rotational influence

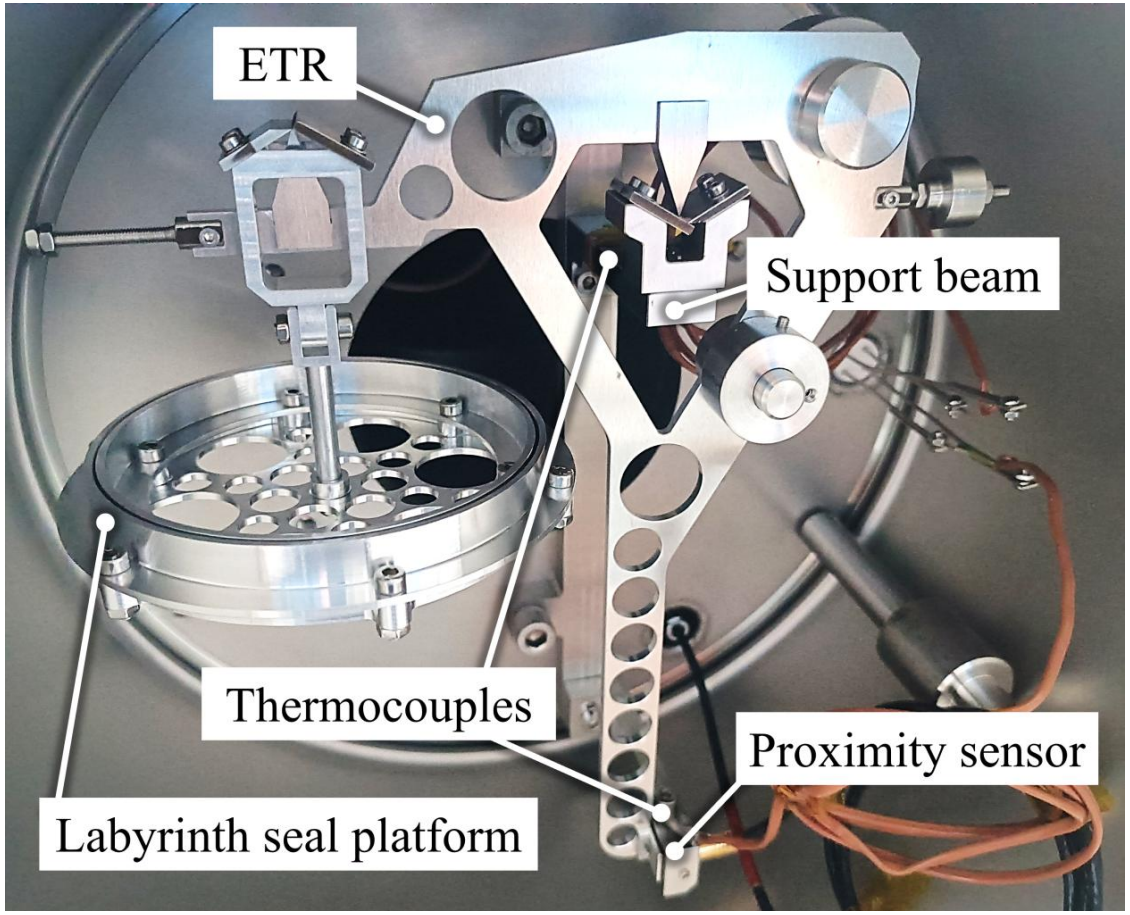


LABYRINTH SEAL OPTIMIZATION

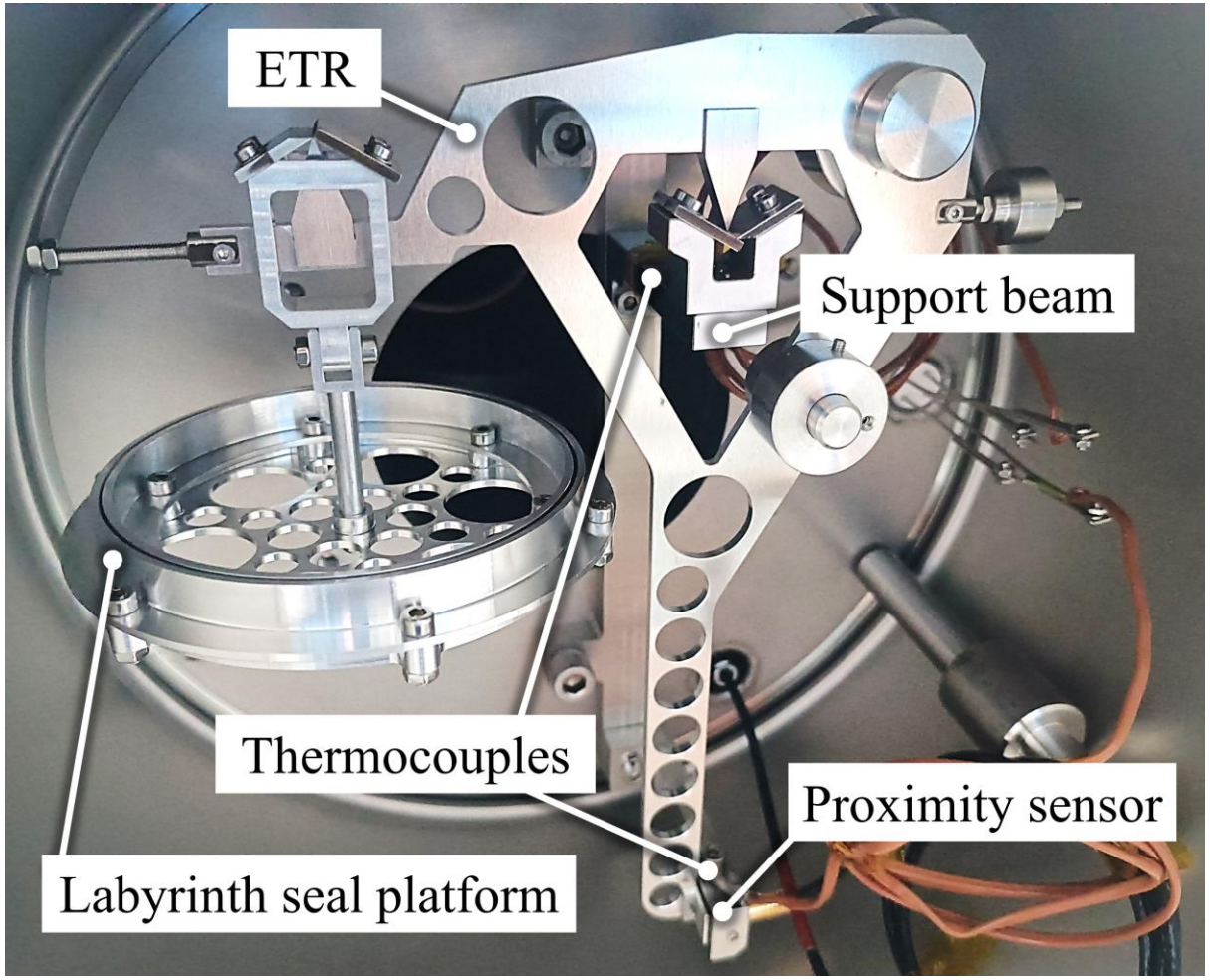
- **Overall geometry**

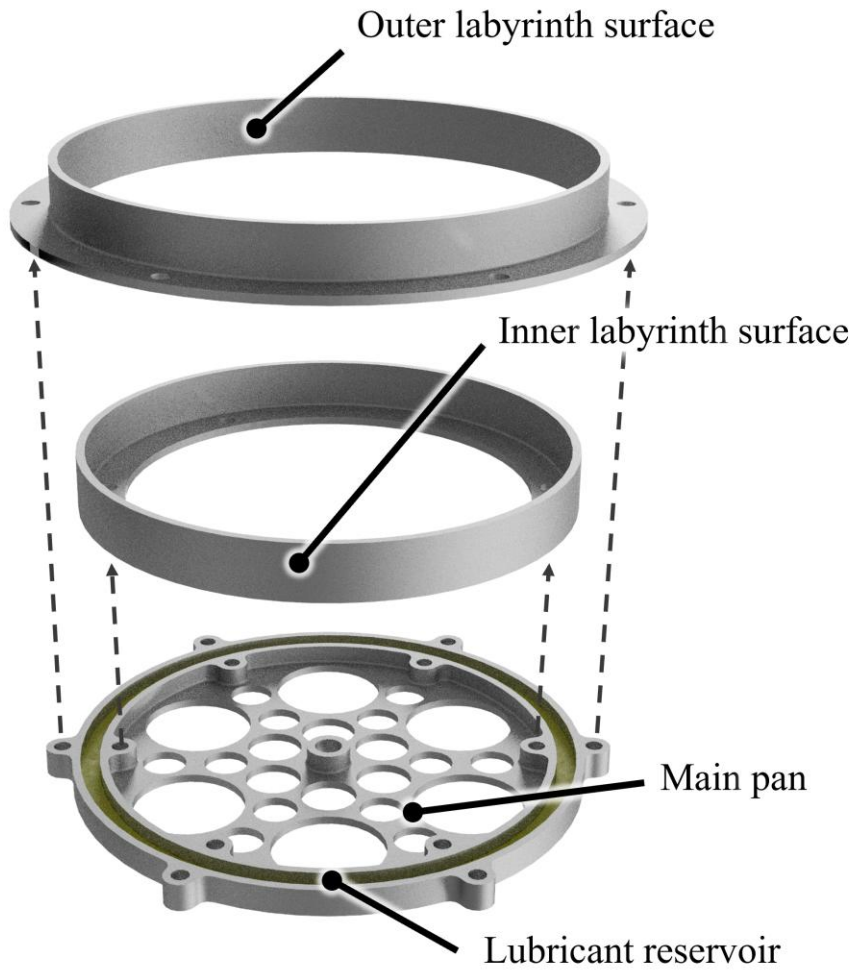
  Length, Width, Complexity

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



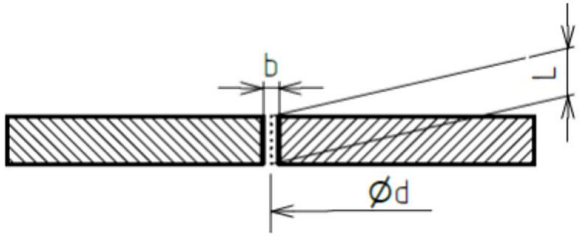
GEOMETRY


ETR
Support beam
Thermocouples
Proximity sensor
Labyrinth seal platform

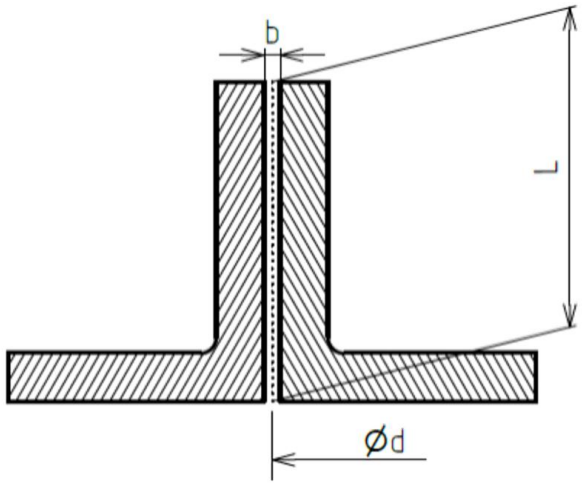

Outer labyrinth surface
Inner labyrinth surface
Main pan
Lubricant reservoir

GEOMETRY

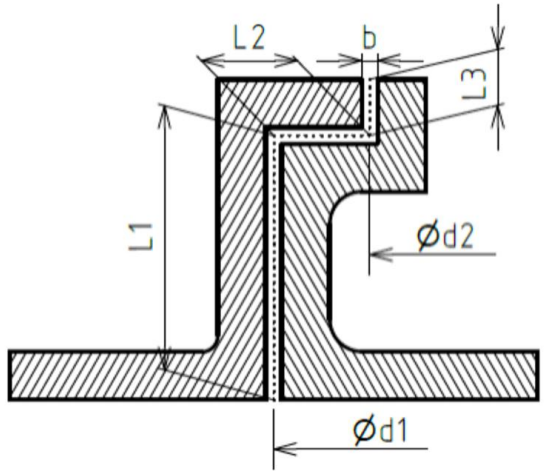
SHORT



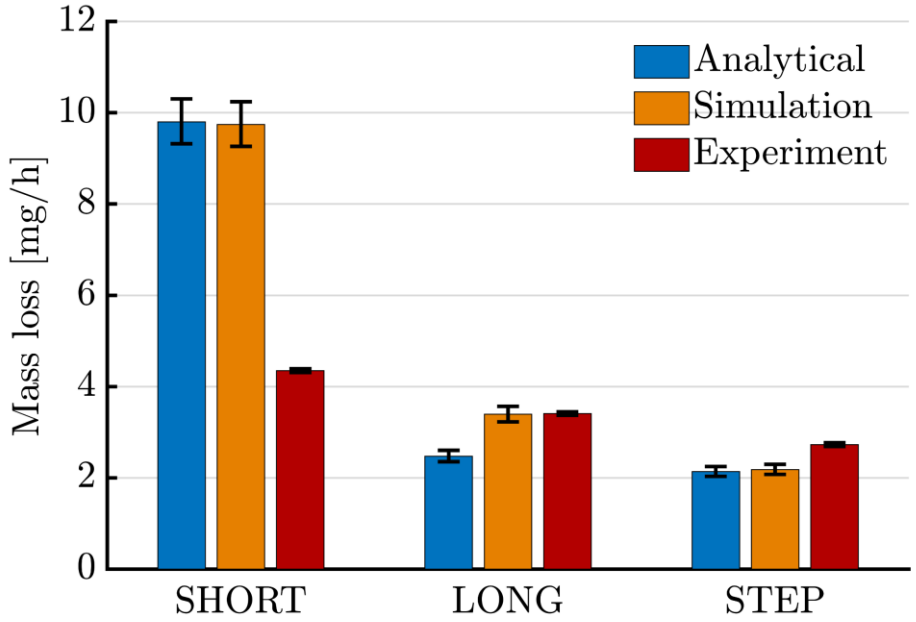
LONG



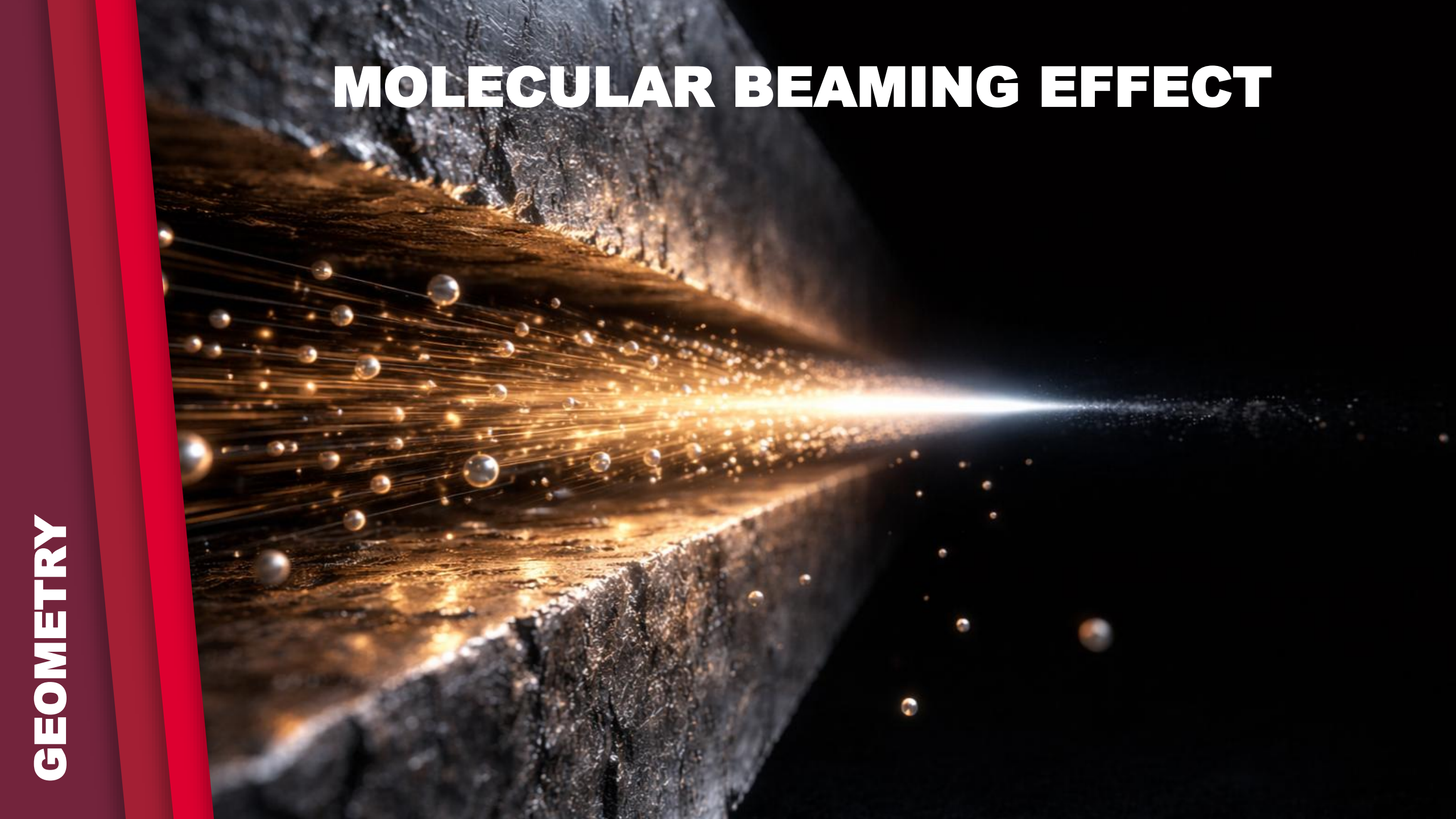
STEP



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

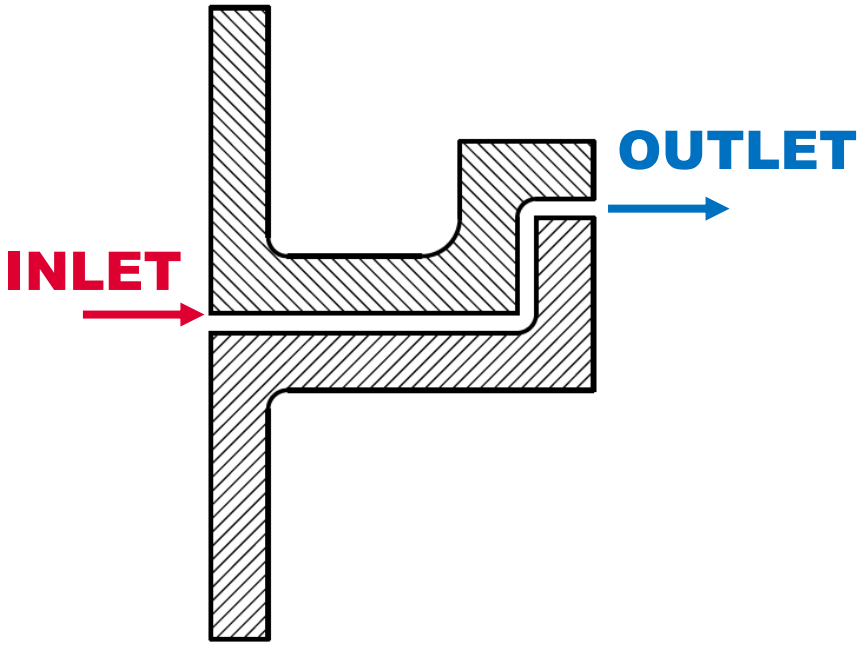


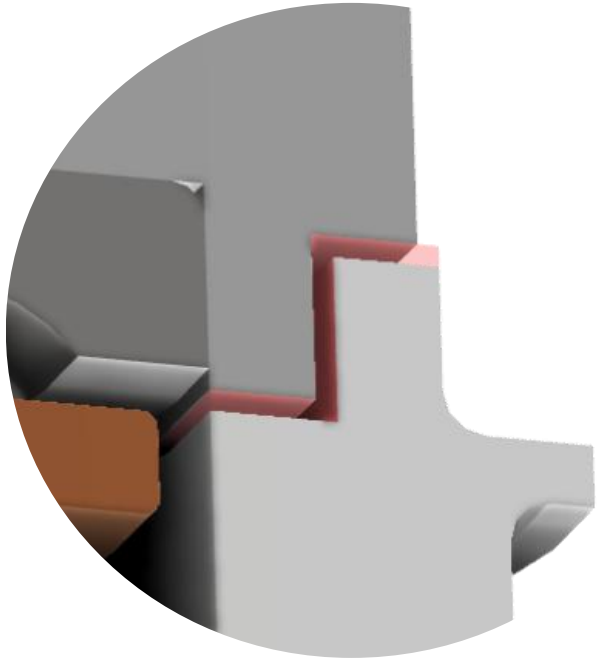
MOLECULAR BEAMING EFFECT

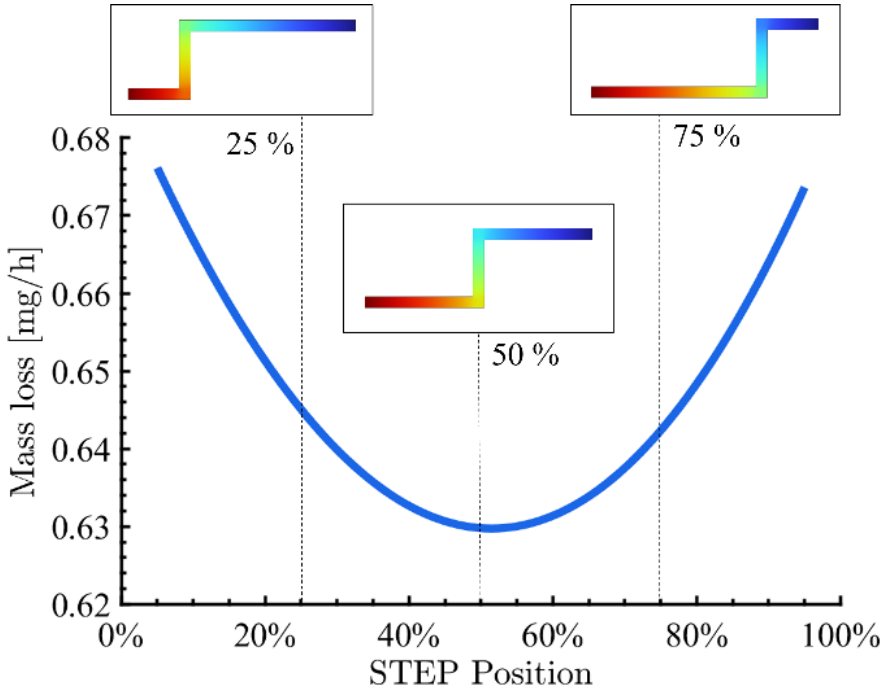


GEOMETRY

GEOMETRY







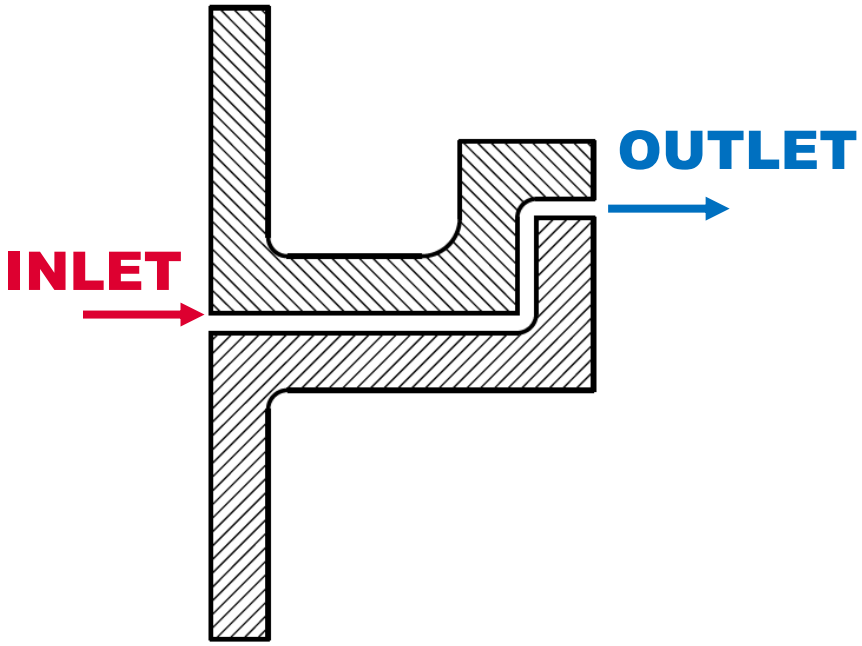
Step position (see Fig. 9)	Mass loss [mg/h]	Loss rate *
10 %	0.665	+ 5.19 %
25 %	0.643	+ 1.62 %
50 %	0.633	–
75 %	0.640	+ 1.24 %
90 %	0.662	+ 4.71 %

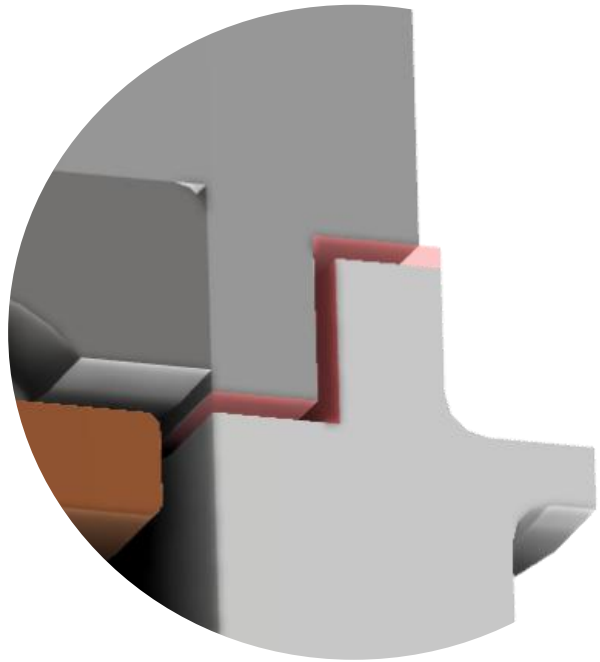
LABYRINTH SEAL OPTIMIZATION

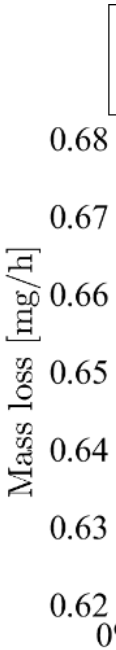
- **Overall geometry**

  Length, Width, Complexity

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







LABYRINTH SEAL OPTIMIZATION

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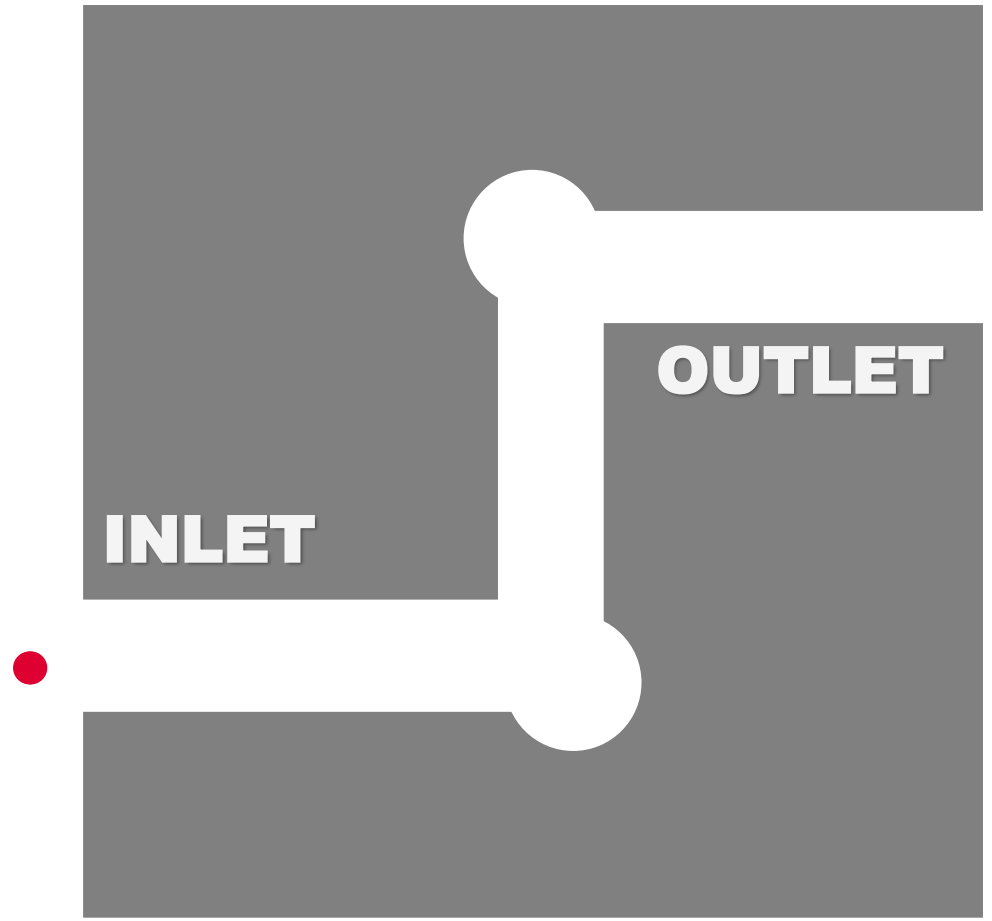
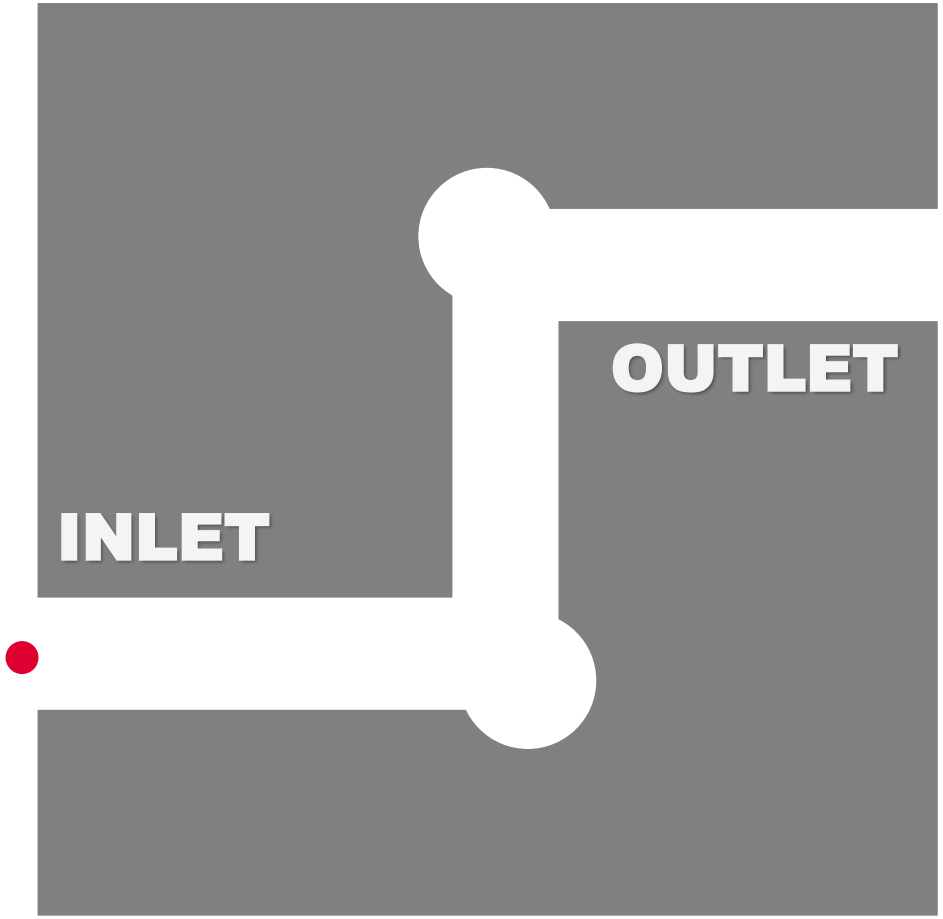
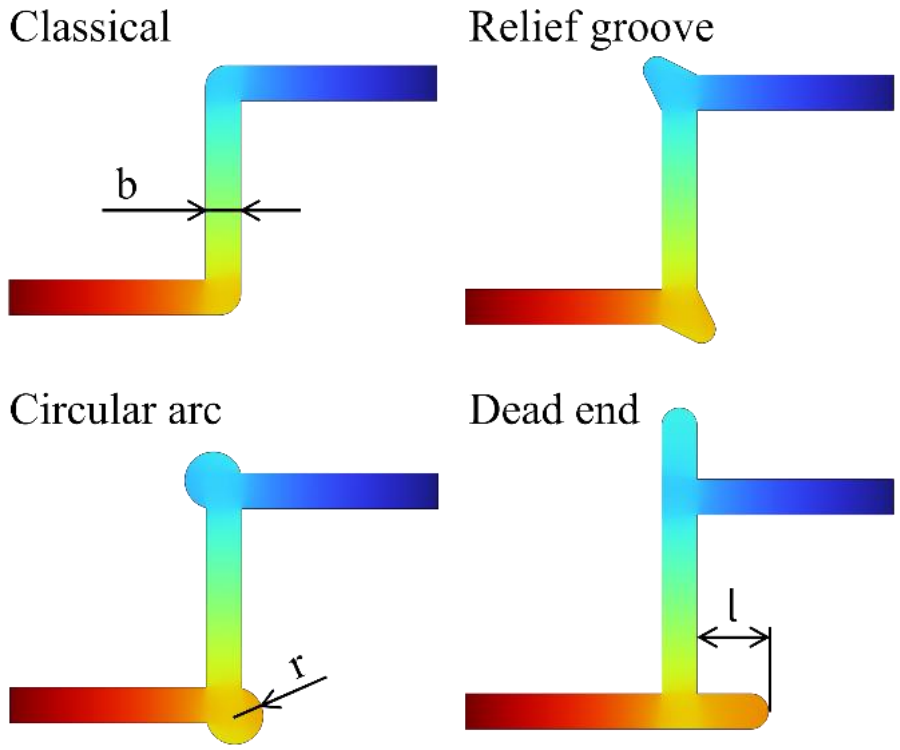


MODIFICATIONS

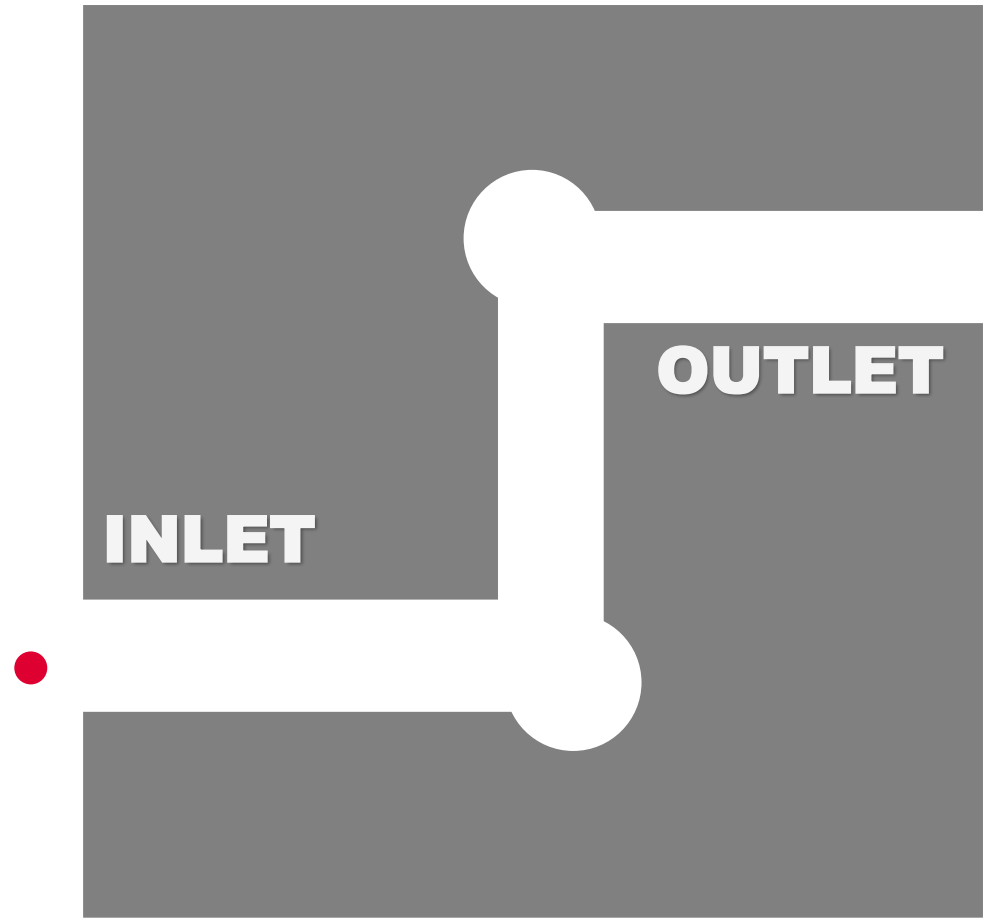




Corner geometry	Characteristic parameter	Loss reduction
Classical	–	–
Circular arc	r = b	3.8 %
Relief groove	type G*	3.9 %
Dead end	l = 2b	4.3 %

LABYRINTH SEAL OPTIMIZATION

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



LABYRINTH SEAL OPTIMIZATION

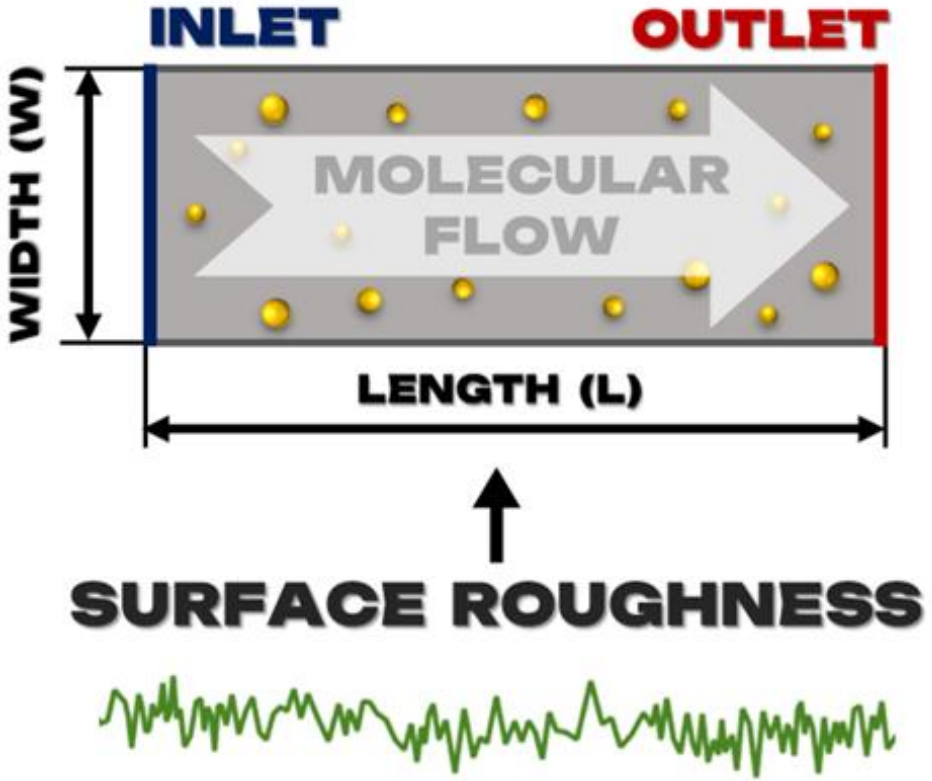
- Overall geometry

  Length, Width, Complexity

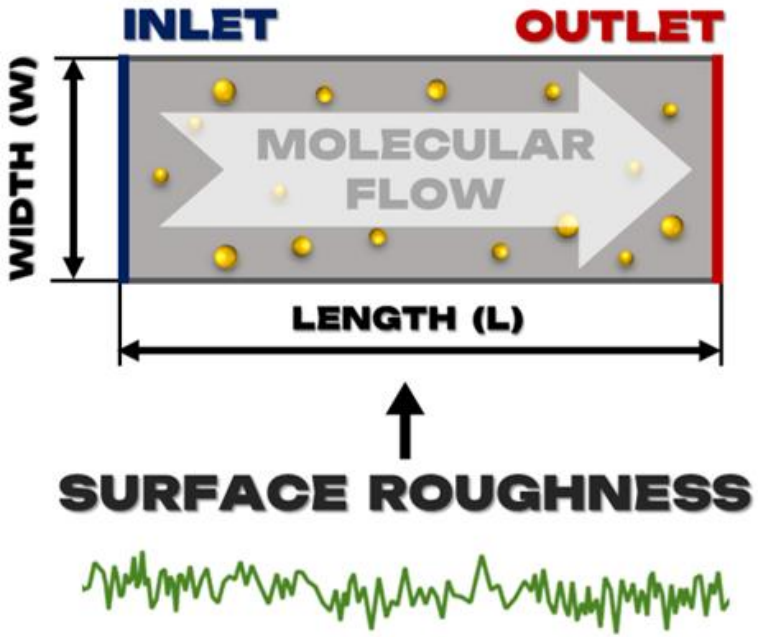
  - Geometrical modifications

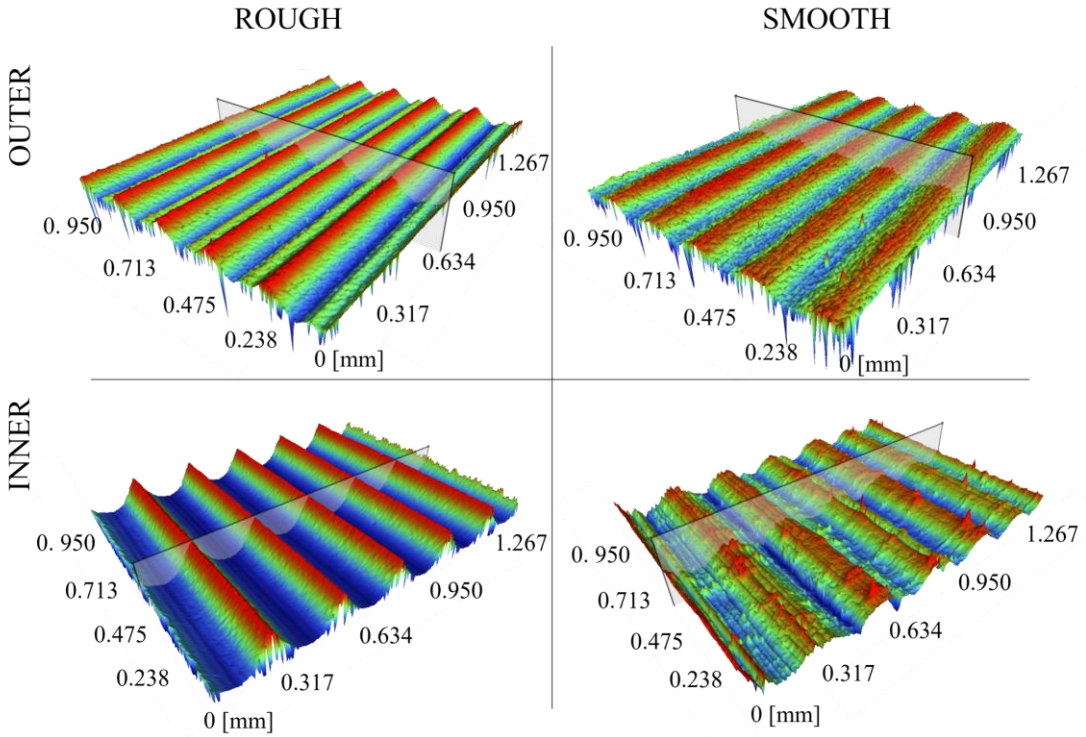
    - **Surface topography**

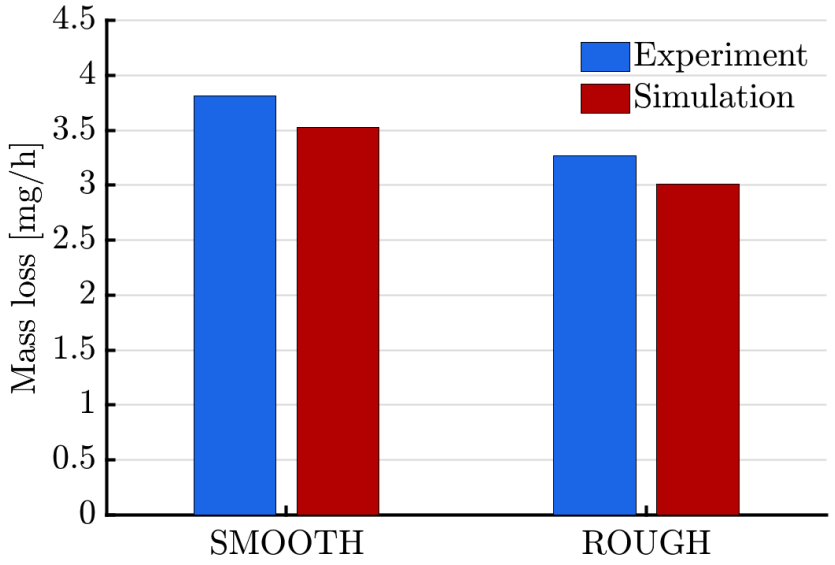
      - Rotational influence



ROUGHNESS

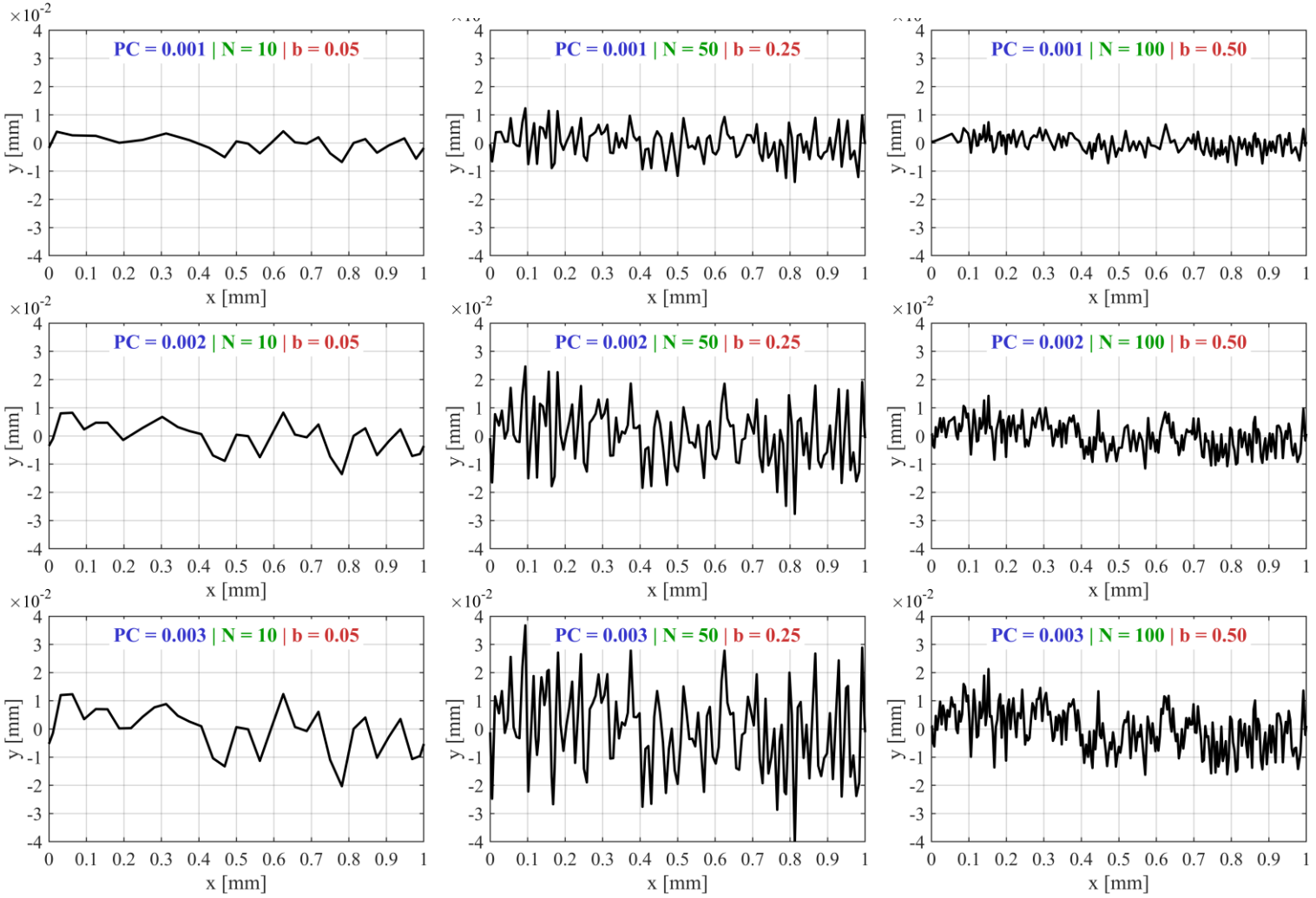

INLET
OUTLET
WIDTH (W)
MOLECULAR FLOW
LENGTH (L)
SURFACE ROUGHNESS

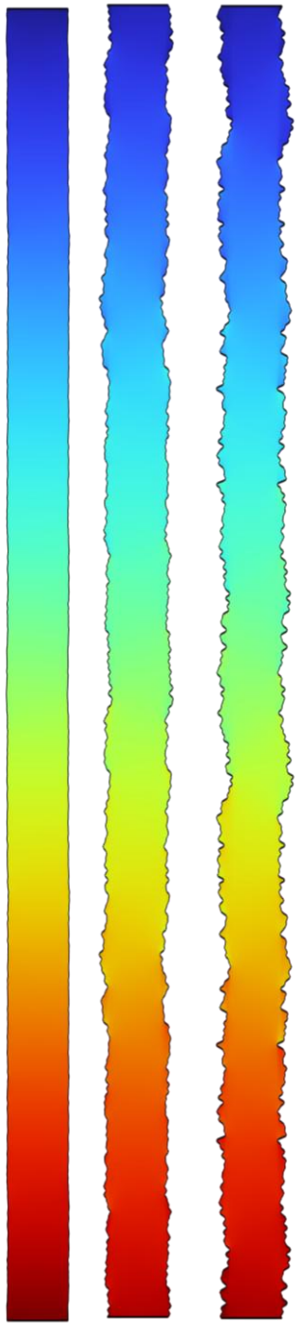

ROUGH
SMOOTH
OUTER
INNER
0. 950
0.713
0.475
0.238
0.317
0.634
0.950
1.267
0 [mm]


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

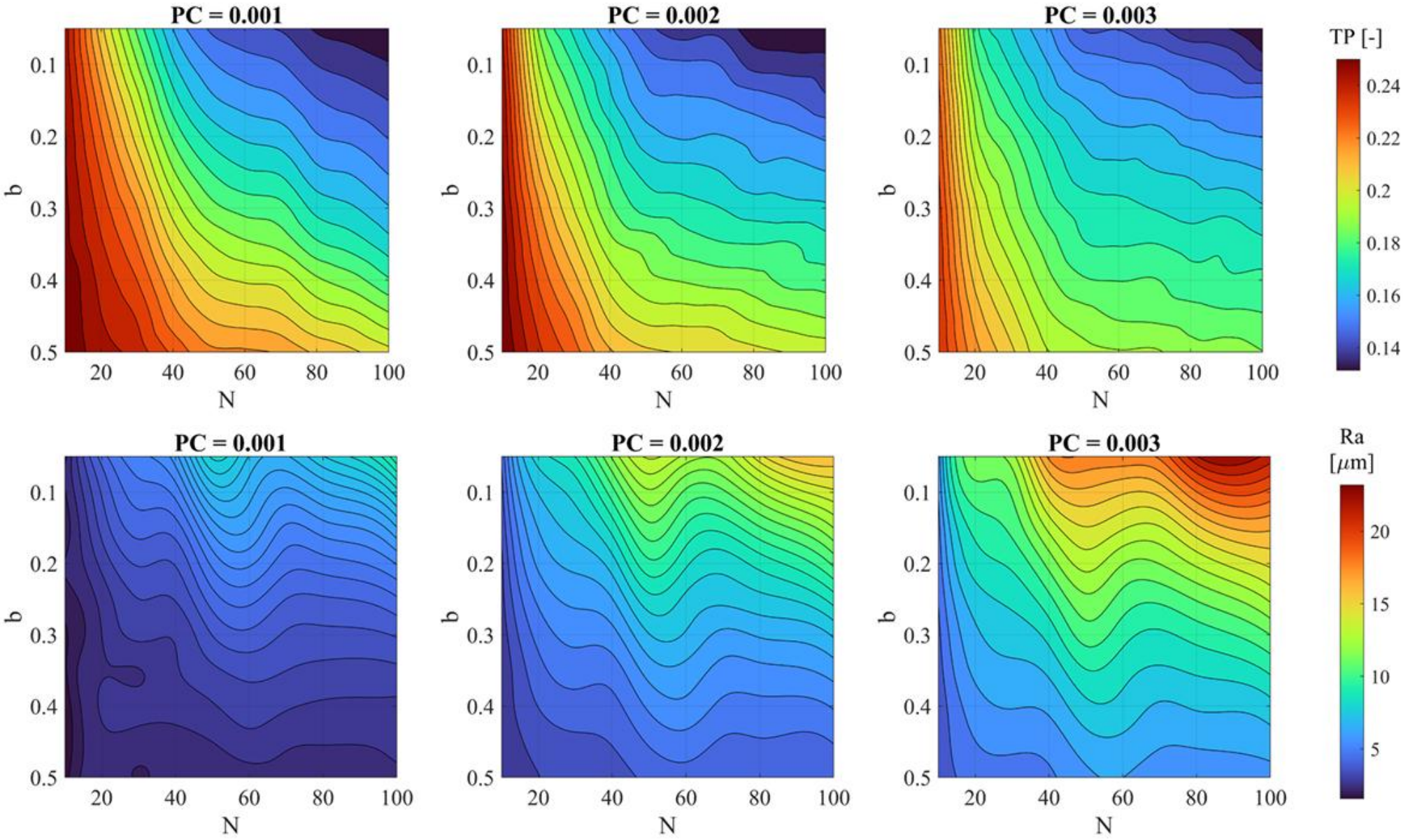
ROUGHNESS

$$z = PC \bullet \sum_{n=-N}^{N} \left(n^2\right)^{-\frac{b}{2}} \cdot g(n) \bullet \cos(2\pi(nx) + u(n))$$

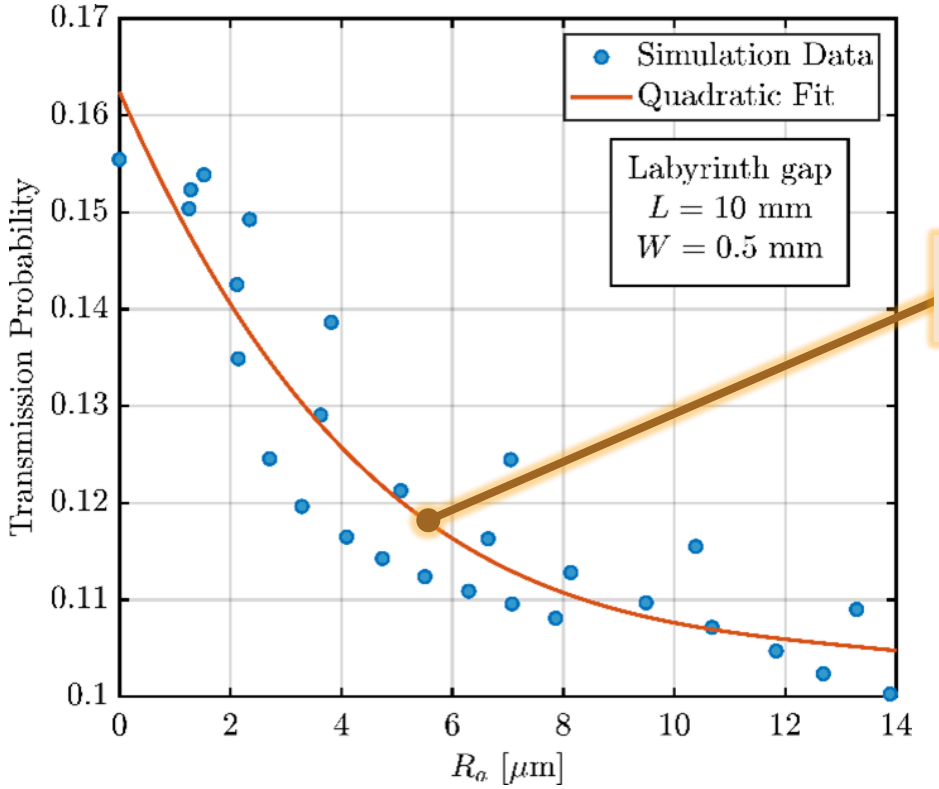




ROUGHNESS


PC = 0.001
PC = 0.002
PC = 0.003
b
N
0.1
0.2
0.3
0.4
0.5
20
40
60
80
100
TP [-]
0.24
0.22
0.2
0.18
0.16
0.14
PC = 0.001
PC = 0.002
PC = 0.003
Ra
[μm]
20
15
10
5

ROUGHNESS



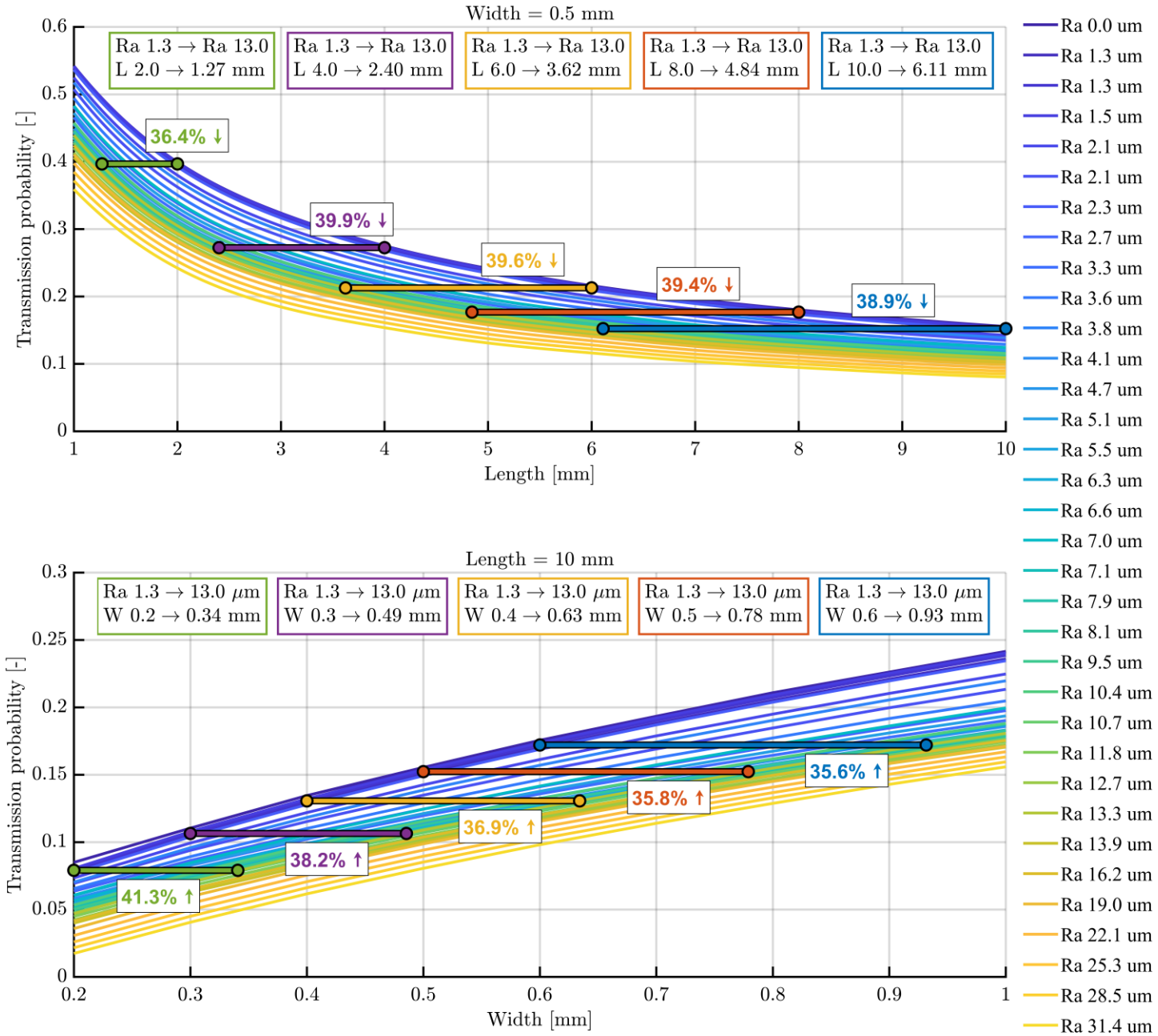
Transmission probability correction model

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

	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

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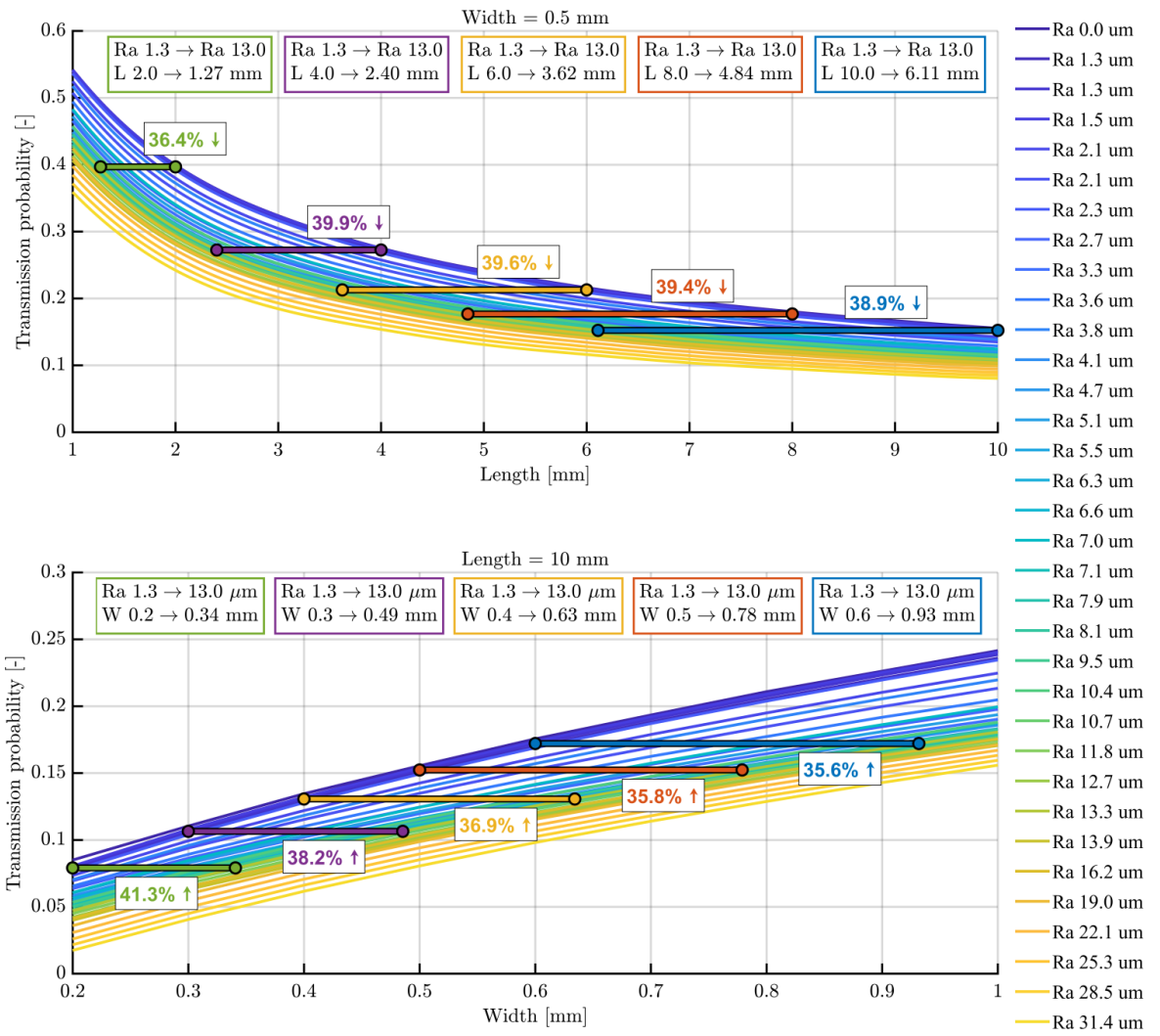
- Overall geometry
  - Length, Width, Complexity
- Geometrical modifications
- **Surface topography**
- Rotational influence



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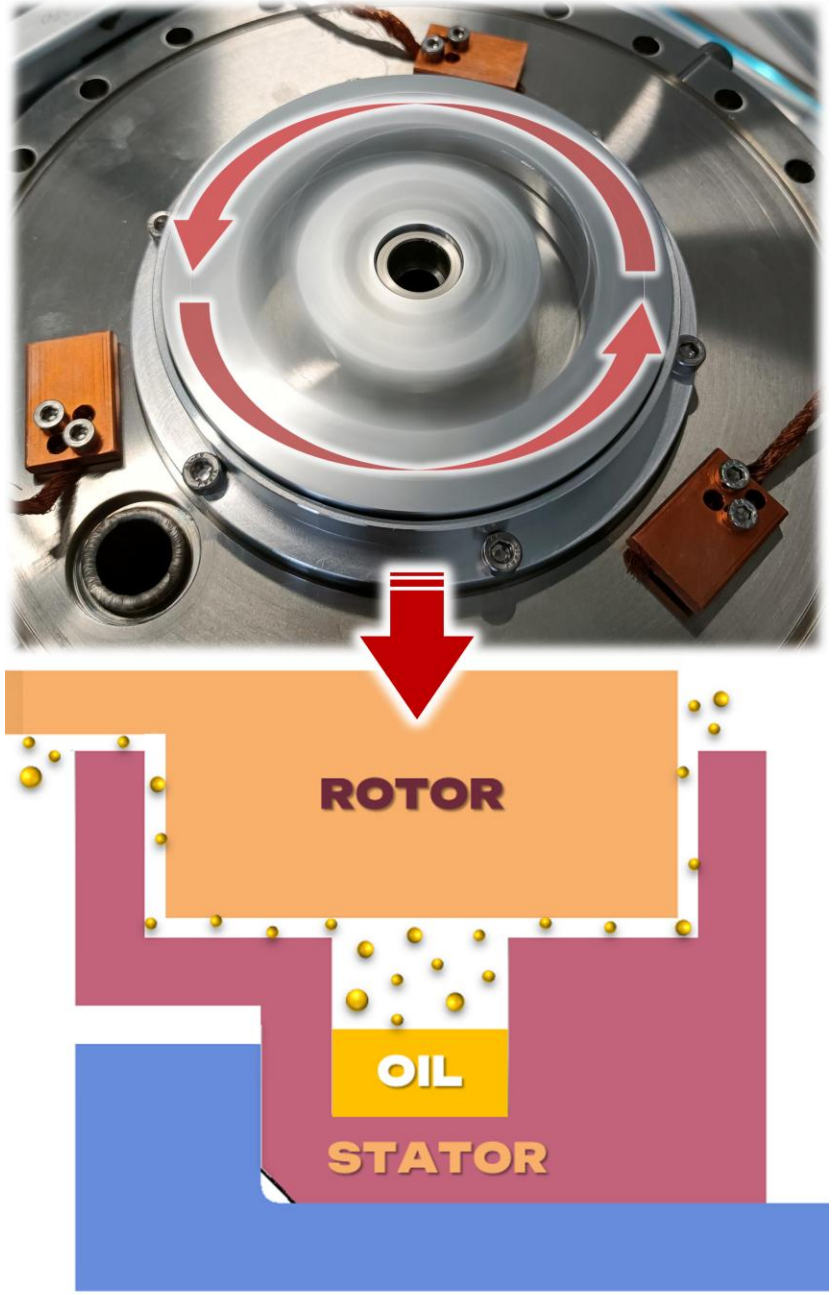
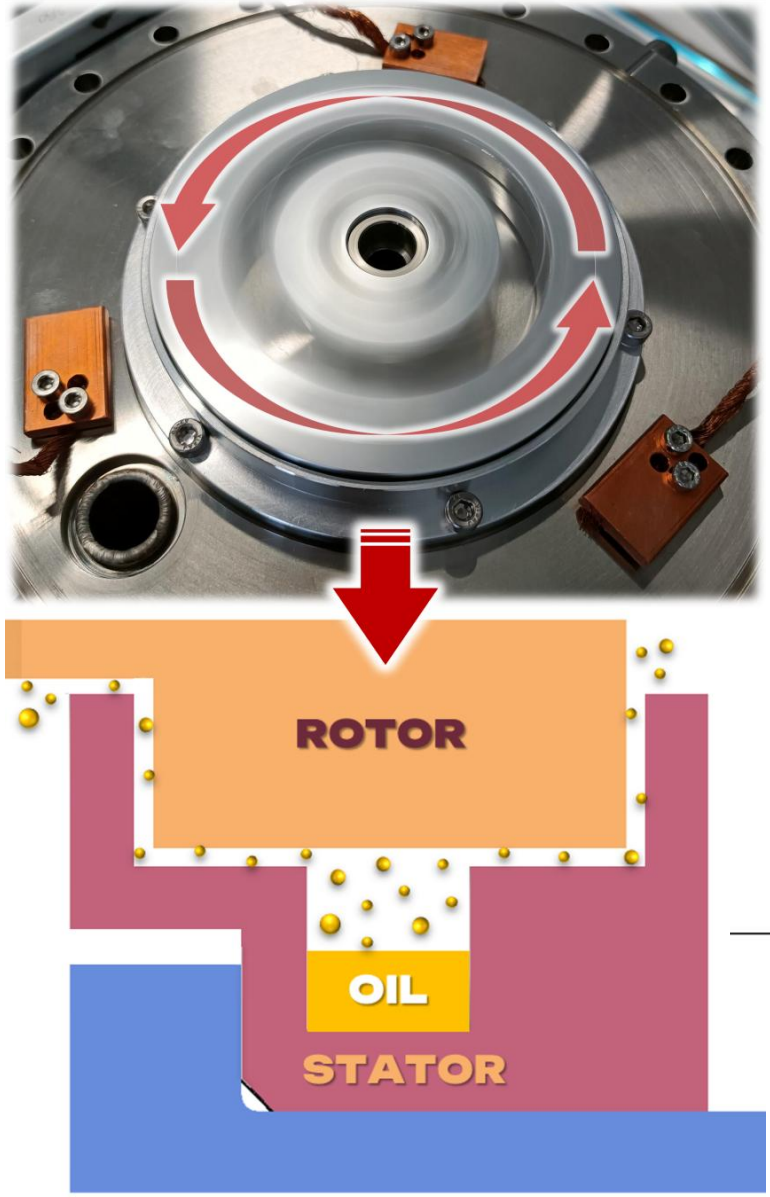
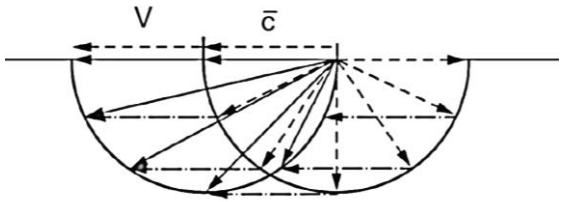
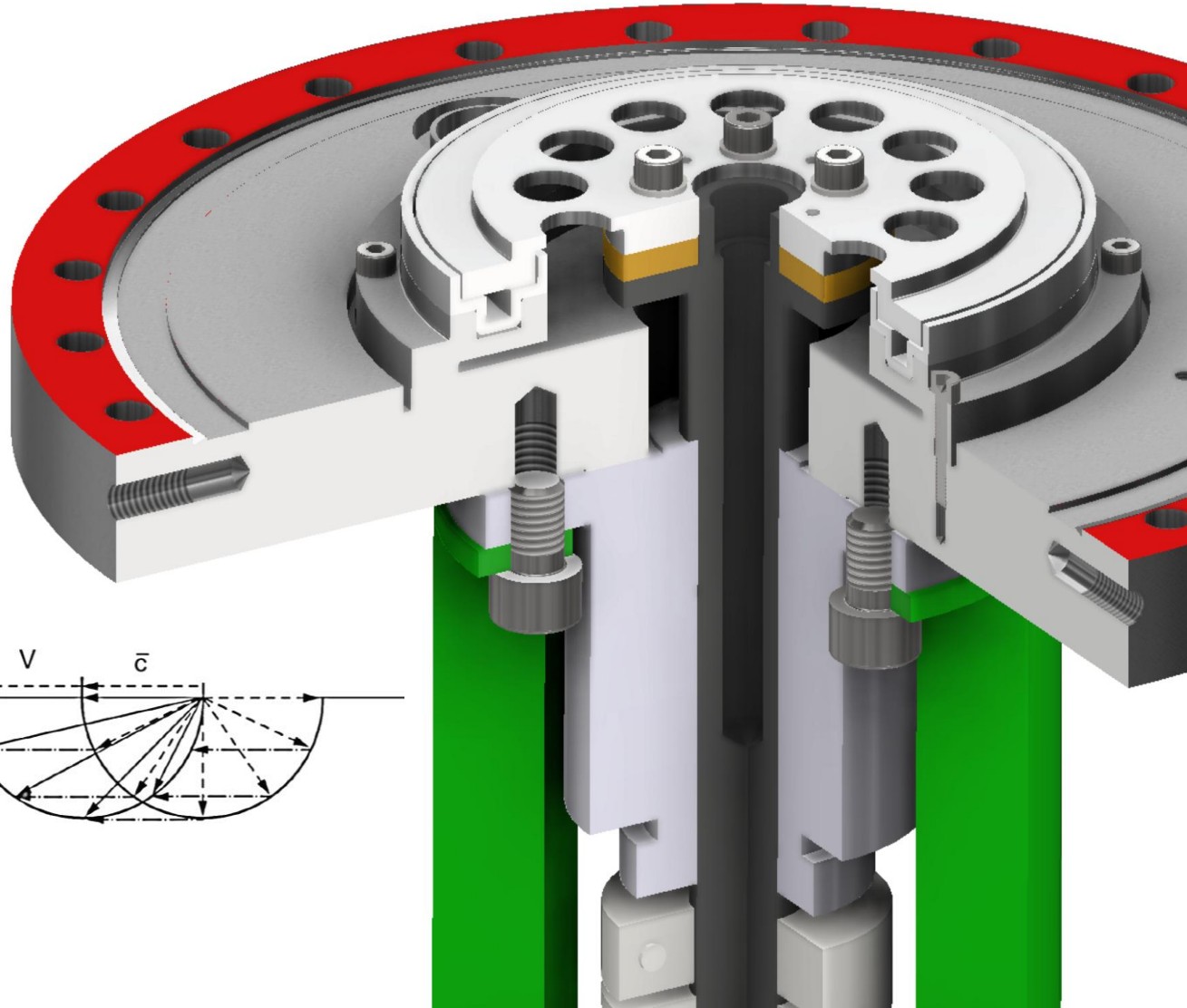


ROTATION







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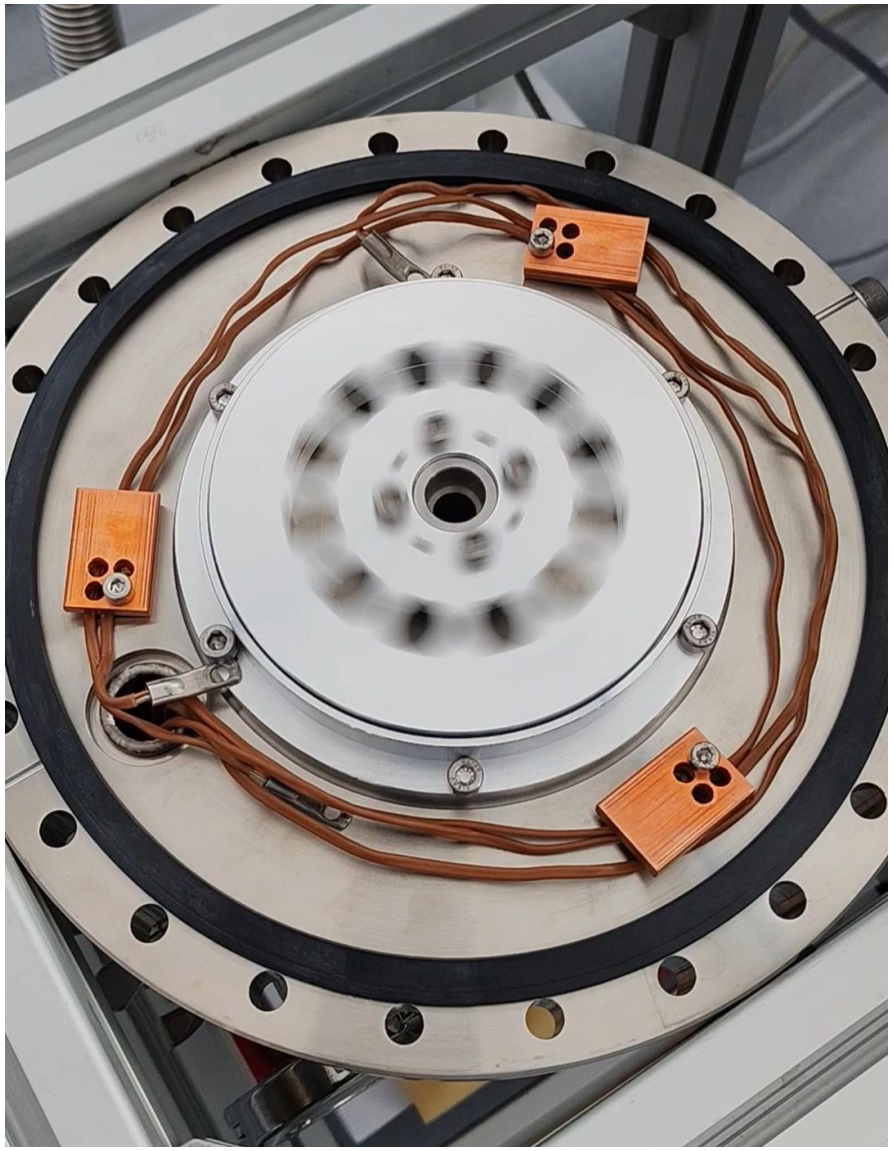
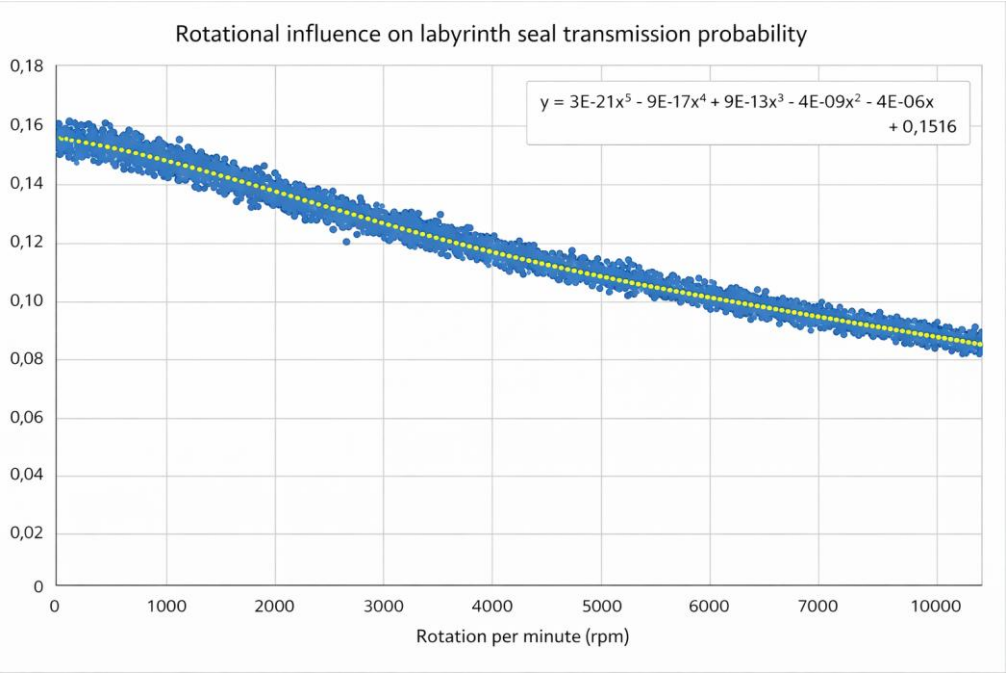




	0 RPM	2000 RPM	Spin influence
Simulation	0.178 mg/h	0.161 mg/h	– 9.05 %
Experiment	0.188 mg/h	0.168 mg/h	– 10.6 %

LABYRINTH SEAL OPTIMIZATION

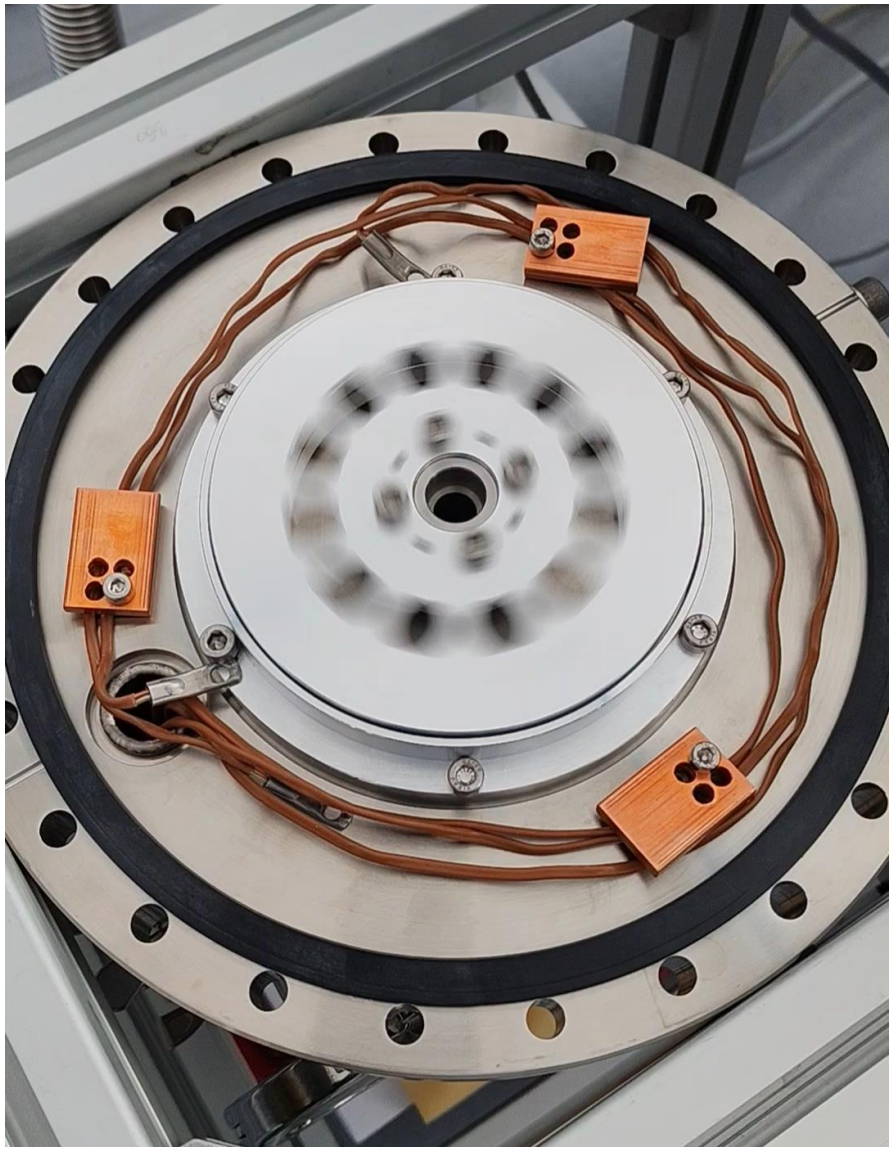
- Overall geometry

  Length, Width, Complexity

  - Geometrical modifications

    - Surface topography

      - Rotational influence



CONCLUSION

- 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
- 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

THANK YOU FOR YOUR ATTENTION

Josef Pouzar

This work was supported through the Open Space Innovation Platform under a Co-Sponsored Research Agreement funded by the European Space Agency (Contract No. 4000139889).

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