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How Shaft Voltage Causes Bearing Damage And Lubricant Degradation

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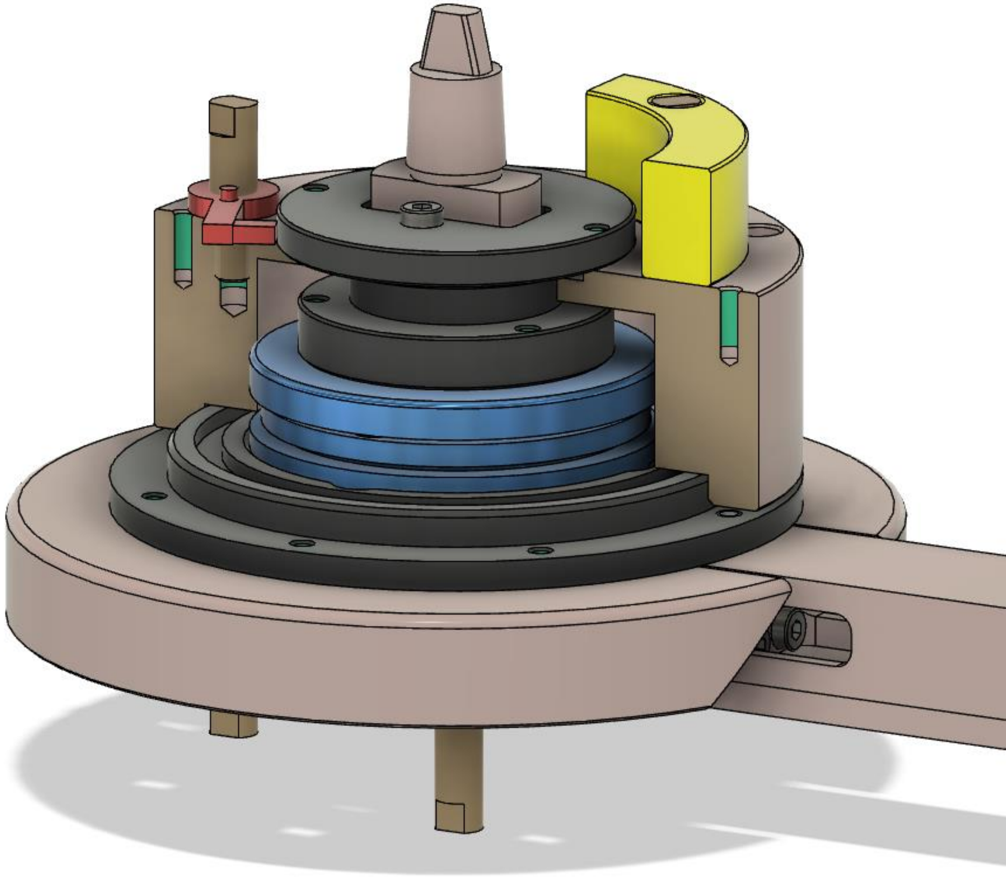

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Agenda

The Problem Of Electric Discharges In The Drivetrain

Electrical Lubricant Testing – Dual Approach

1 **Static Tests (Constant Gap): Specification Of Lubricant**
- Conductivity and Permittivity Measurement ($\kappa(\vartheta)$, $\varepsilon(\vartheta)$)
- High-Pressure Dielectric Test ($\kappa(\vartheta, p)$, $\varepsilon(\vartheta, p)$)

2 **Dynamic Tests (Variable Gap): Assessment Of Lubricant Film**
- Impedance Spectroscopy With A Lubricated Bearing
- Initial Breakdown & Discharge Distribution Test

Exemplary Test Results

Conclusions, Prospect & Discussion

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Introduction: The Problem Of Electric Discharge

- Electrified drivetrains with inverter-controlled motors often have **parasitic current flow** in their mechanical contacts
- Mechanically proven machine elements are subjected to **additional electrical load** and stray currents
- Lubricants must be **tested electrically** and optimized to minimize damage to the electric drivetrain
- Not solely a problem of e-mobility: **40%** of wind turbine generator failures are related to discharge damages

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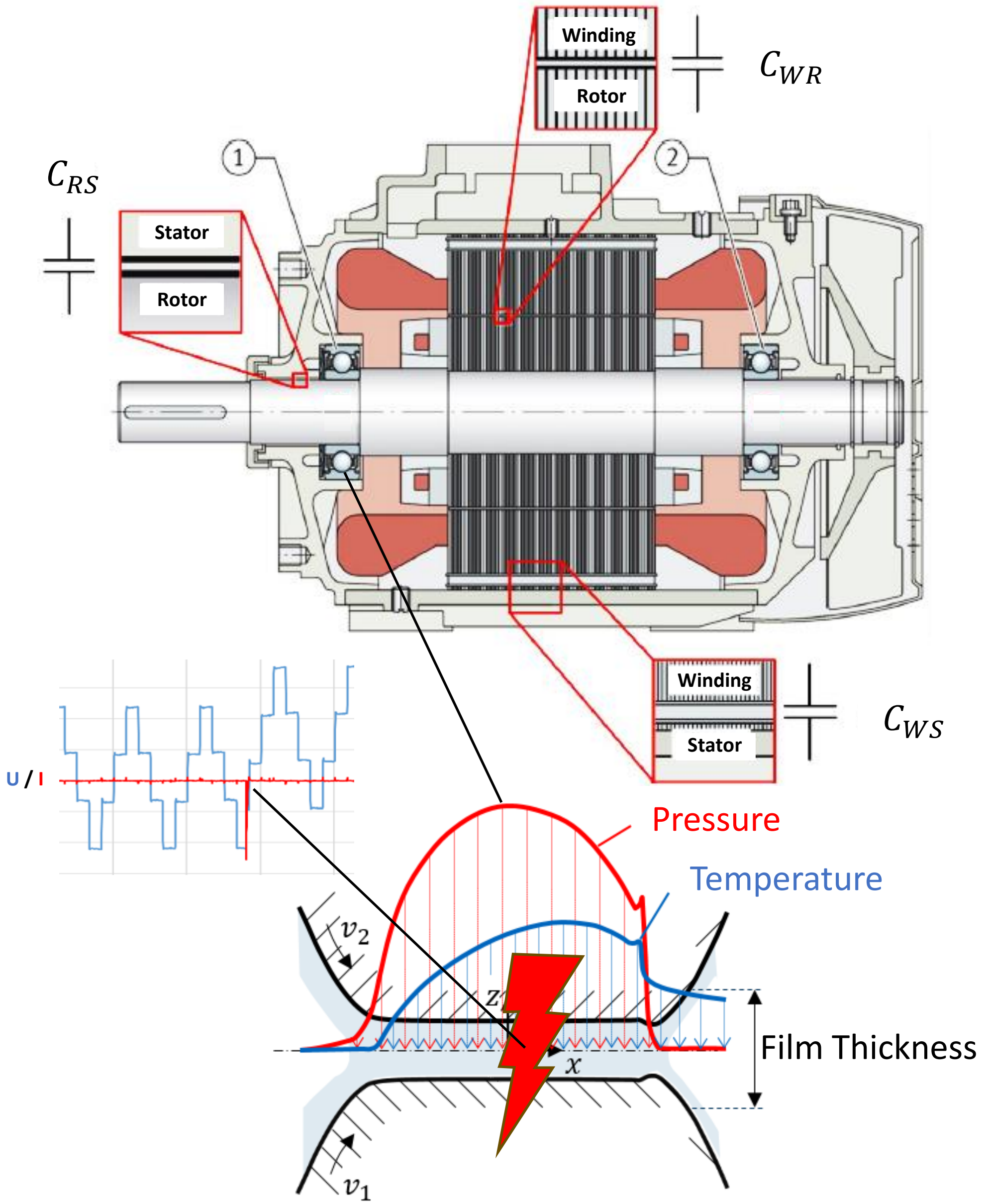
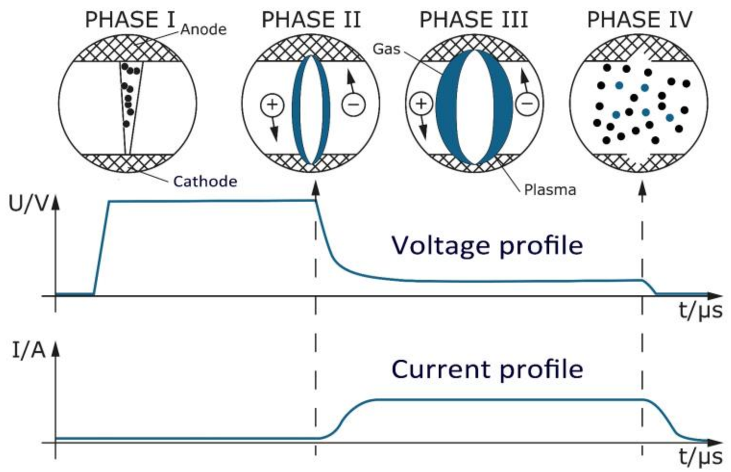
How Discharges Occur In The Electric Drivetrain

- **Capacitive coupling** of rotor, stator and motor windings
- **Potential difference** between shaft (rotor) and housing (stator) is present in the bearings
- Shaft voltage must be taken into account when operating inverters with **high switching frequencies**
- When the critical field strength is exceeded **discharge currents** flow **through the insulating lubricant film** (EHD contact)
- Similar to Electric Discharge Machining (EDM), these **high-energy breakdown events** cause **structural damage** to the metallic components and to the lubricant in the gap

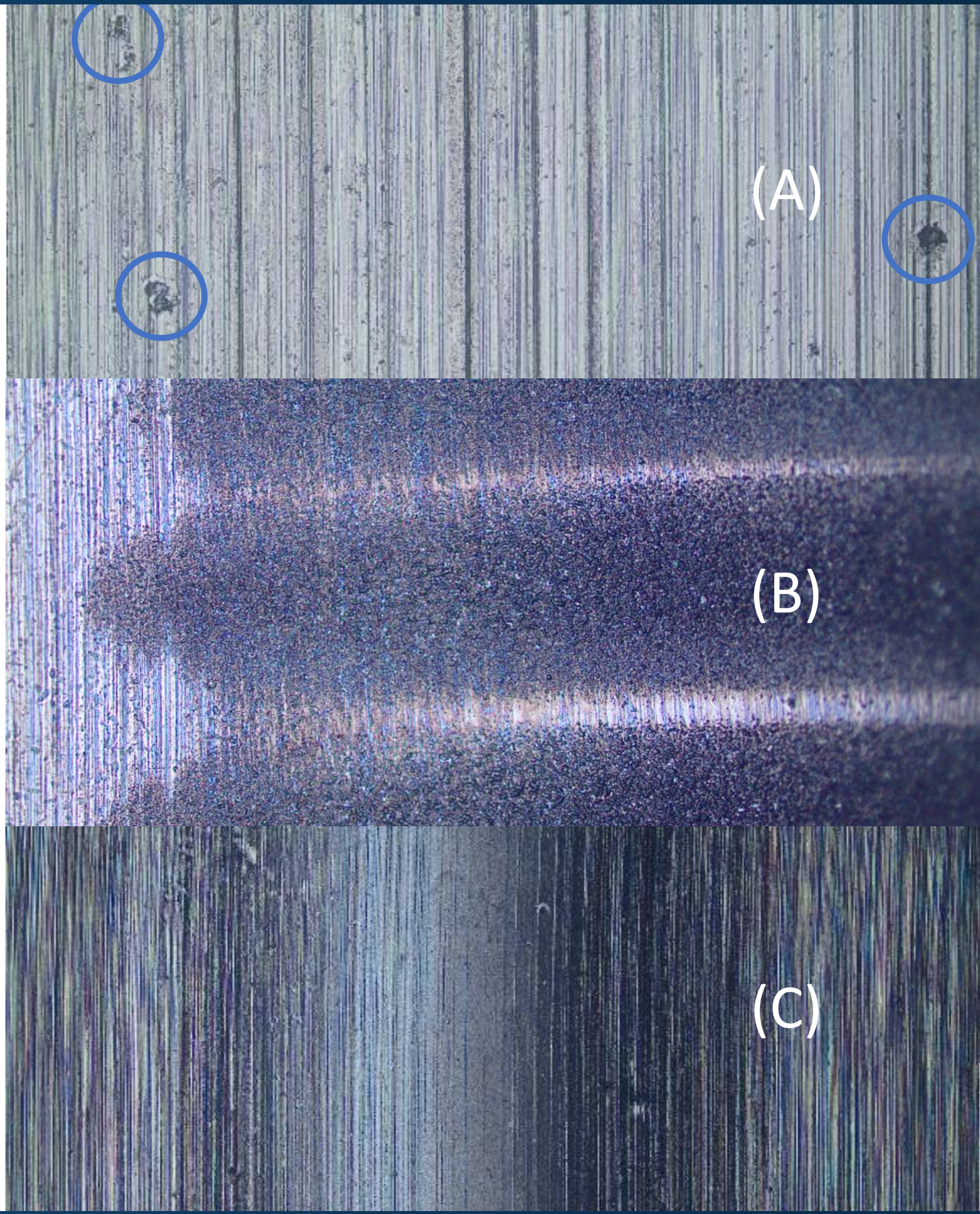


Bearing Damage Through Electric Breakdowns

- Reaching the breakdown voltage will generate an **electric arc** through the lubricant film
- **100 mA** EDM currents are sufficient to create damage in the contacts
- The spark-erosive current flow will **damage the ball and the raceways** of both the rotating and stationary ring



- Typical raceway damage patterns: **craters** (A), **fluting** (B) & **grey frosting** (C)



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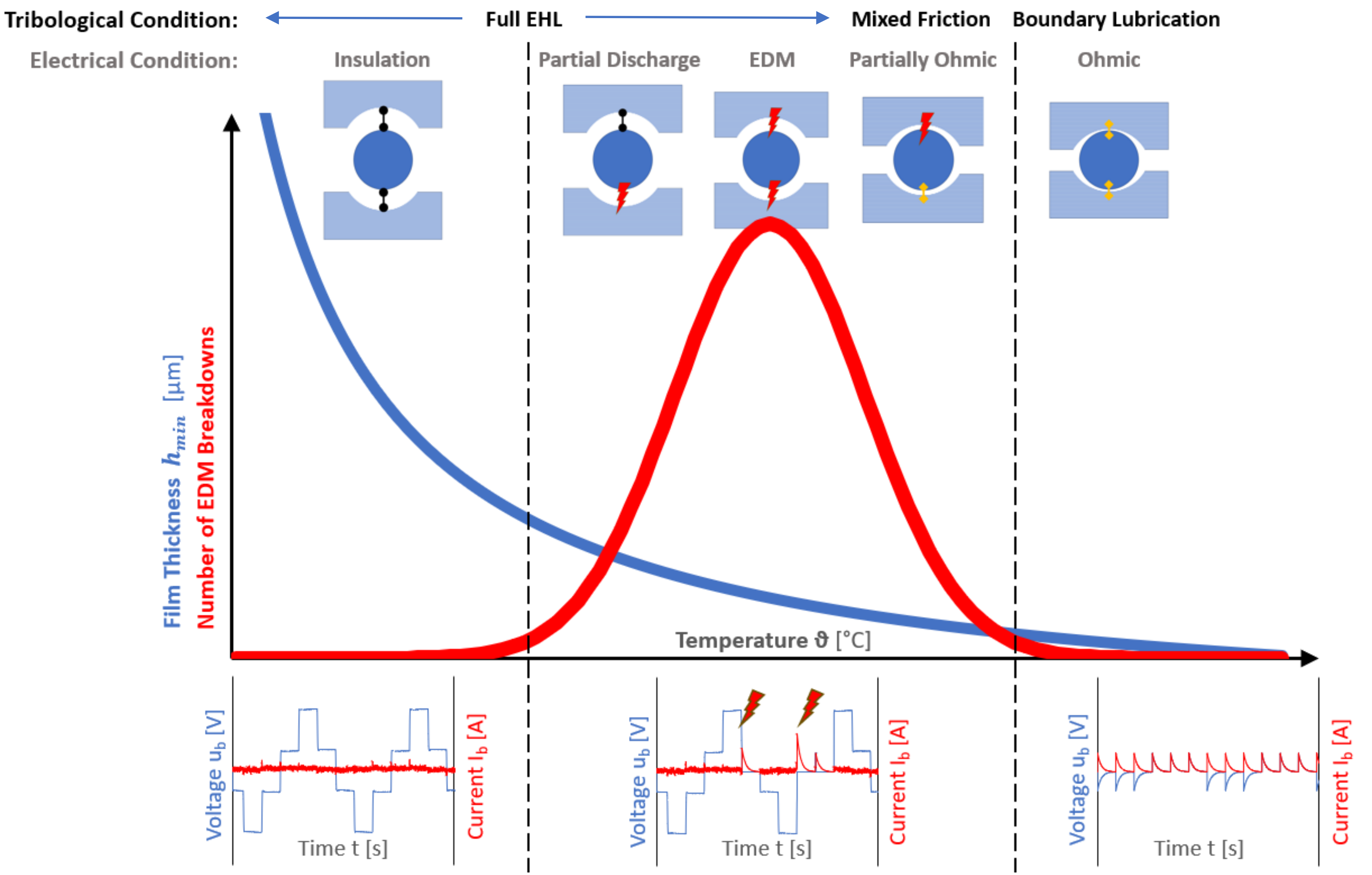
FVA Project 650: How The Breakdown Rate Relates To The Lubricating Conditions

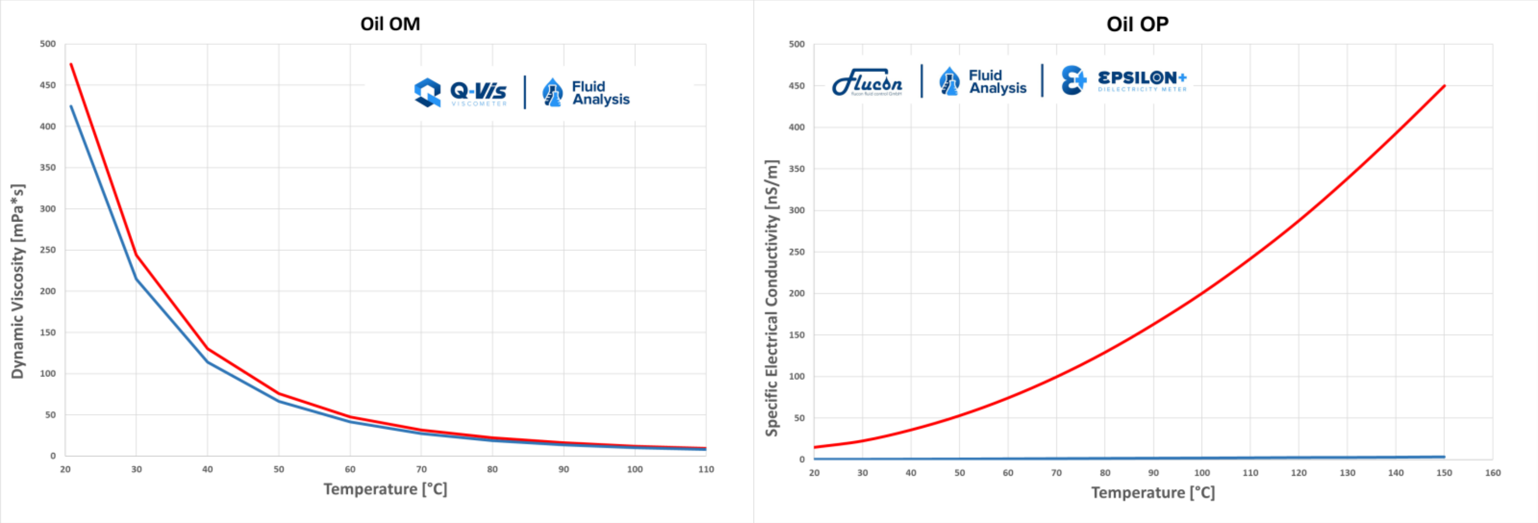


MEGT

FVA sharing drive innovation

Electrically Caused Lubricant Degradation

- With each breakdown, oils and greases are locally subjected to **high temperatures** (> 10,000°C)
- Lubricant becomes **oxidized** and **discolored**
- Contamination with **soot and metallic wear particles**
- **Viscosity**, **lubricity** and **dielectricity** are often affected



▪ Before / ▪ After 24 H Breakdown Test

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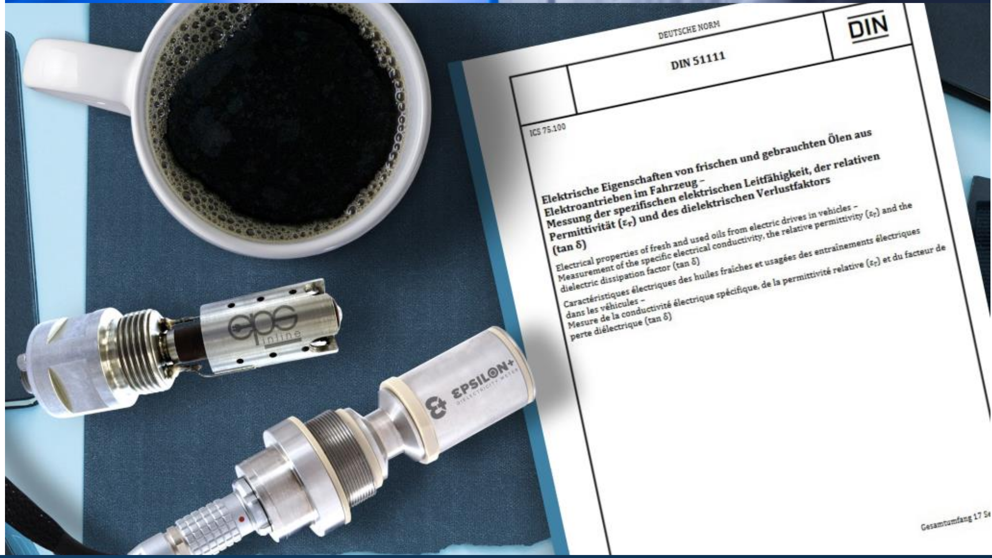
Key Factors For Electric Discharge Prevention

- Breakdown tendency of a lubricated electric drive depends on multiple important parameters:
- **Lubricant properties**
  - Dielectricity (AC resistance & dielectric constant)
  - Viscosity & pressure-viscosity coefficient (affecting the film thickness)
- **Operating conditions**
  - Temperature
  - Speed
  - Load
  - Run time
  - Contact geometry & running smoothness (shaft concentricity, vibrations etc.)
- **New test methods are needed** for the assessment of future lubricants



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DUAL APPROACH

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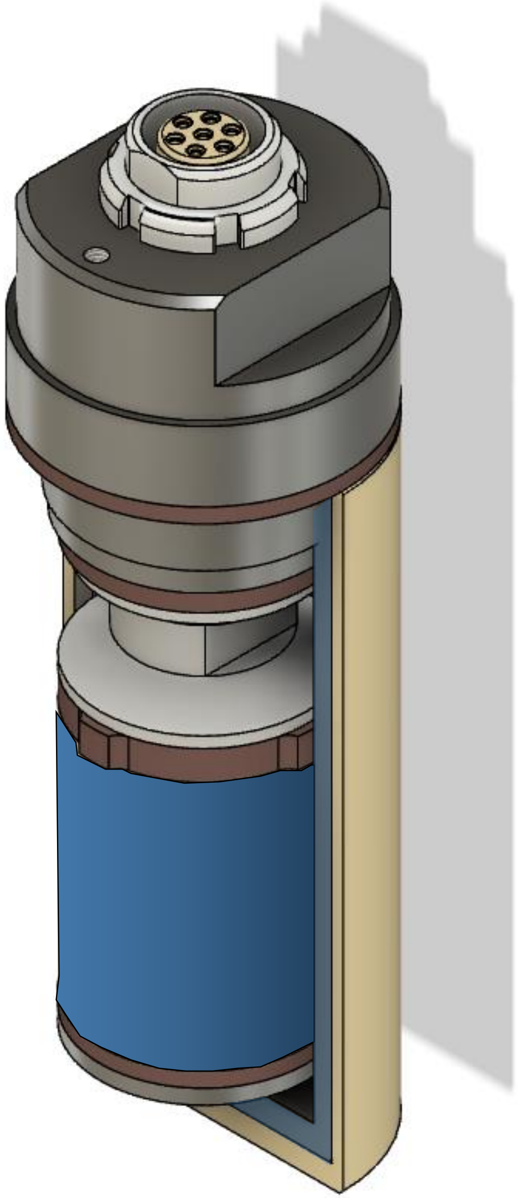
1 Static Electrical Lubricant Tests

- **Static test: constant electrode gap** (d = 1 mm)
- **Electrical characterization** of oils and greases in a tubular capacitor cell
- Measurement of the electrical fluid properties as functions of the temperature at variable frequency
  - **specific electrical resistivity** ρ (ϑ) & **specific electrical conductivity** κ (ϑ)
  - **relative permittivity** ε_r (ϑ)
  - **dielectric dissipation factor** *tan δ* (ϑ)

  @ 50°C, 100°C, 150°C for oils

  @ 50°C, 80°C, 100°C for greases
- New test standard for EPSILON+ Dielectricity Meter: **DIN 51 111:2024-02**
- Dielectricity should be specified in all lubricant data sheets!



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1 Static Electrical Lubricant Tests

- **High-pressure lubricant test** with special tubular capacitor (d = 1 mm)
- κ, ε_r & *tan* δ as substance-specific properties **up to 1.4 GPa** at variable temperature
- Additional **high-pressure viscometry** with a high-shear torsional transducer to determine dynamic viscosity η (ϑ, p) and pressure-viscosity coefficient α_p
- Validate dielectric results from the bearing with **Hamrock-Dowson's film thickness h_{min}**

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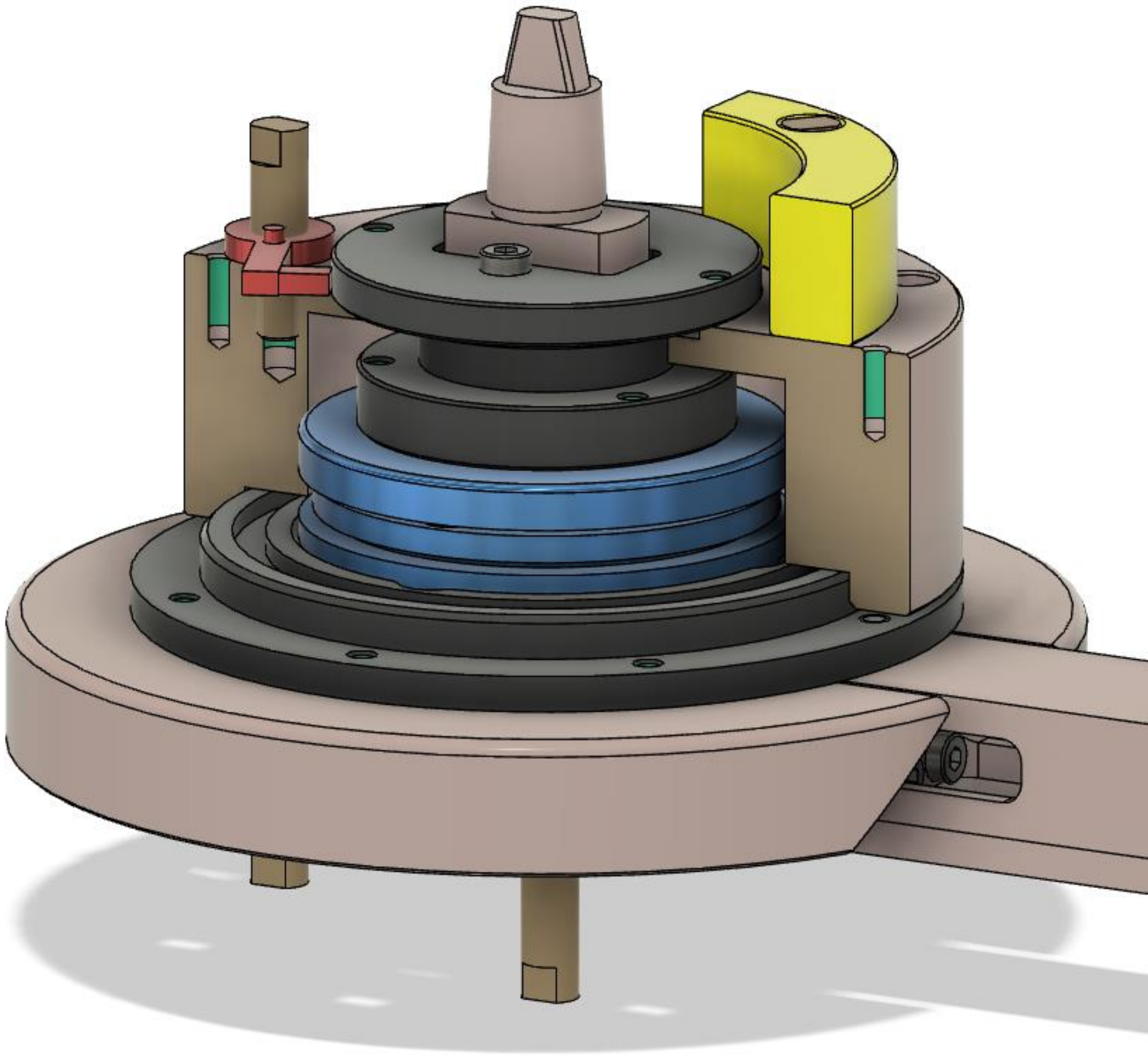
2 Dynamic Electrical Lubricant Tests

- **Dynamic tests: variable electrode gap** (d ≙ h_{min})
- **Electrical characterization** of oils and greases in a controlled tribological contact of a lubricated test bearing
- Measurement of the **bearing impedance at variable frequency** and the **electrical breakdown tendency** as functions of the operating conditions
  - lubricant temperature
  - speed
  - axial load
  - voltage signal
- **NA 062-06-53-B** & **NA 062-06-53-C** standardization
- DIN draft procedure includes impedance spectroscopy at different operating points and breakdown tests



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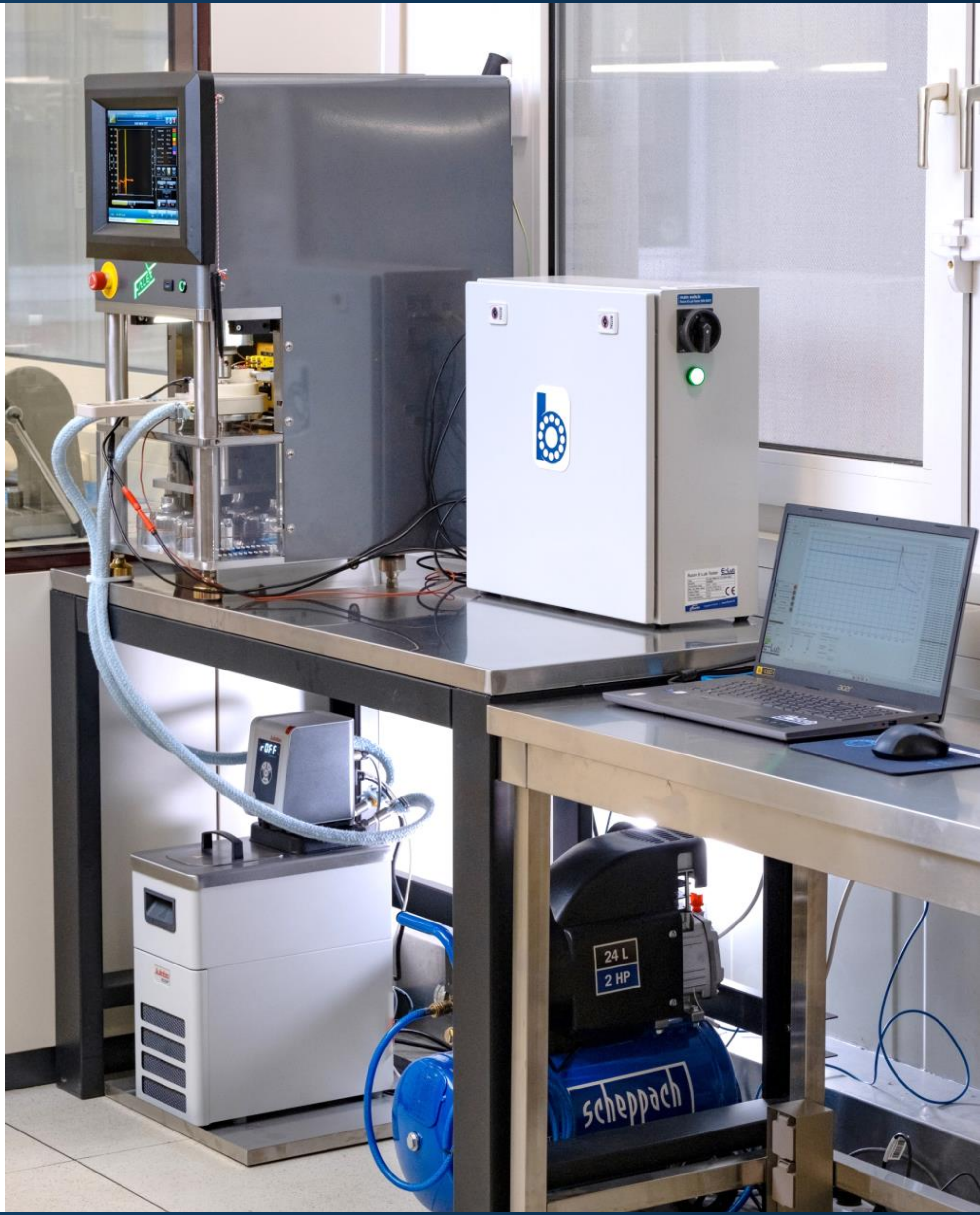
2 Dynamic Electrical Lubricant Tests

- **Electrified tribometer "E-Lub Tester"** with automatic speed and load variation
- **Four-ball tester**-adapted bearing test cell with temperature control
- Uses type 51208 **thrust ball bearing** with 30 ml oil / 5 g grease
- Requires initial 16 hour **run-in** @ {80°C | 1,000 rpm | 2.4 kN}
- Measurement of impedance (100 Hz – 10 MHz) and determination of **ohmic resistance R** & **capacitance C** for any operating point to assess the lubricating condition
- Measurement of the **initial breakdown voltage** U_{crit} for any operating point (non-damaging "Breakdown Finder" method)
- Determination of the **discharge distribution** at one operating point (damaging method)



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Exemplary Tests – Lubricant Selection

Fluid Analysis | Q-Vis VISCOMETER | EPSILON+ DIELECTRICITY METER | E-Lub Tester DIELECTRIC TRIBOMETER

			OM	**GM**	**OP**	**GP**
Substance Type			Mineral Oil	Mineral Grease (Base Oil: OM)	Polyglycol	Polyglycolic Grease (Base Oil: OP)
Rheology	Dynamic Viscosity	**η** [mPa*s] @ 80°C	18.9	18.9 (OM)	**87.1**	87.1 (OP)
		η [mPa*s] @ 80°C; 1 GPa	**10,164,000**	10,164,000 (OM)	1,545,000	1,545,000 (OP)
	Pressure-Viscosity Coefficient	α_p [1/bar] @ 80°C	1.32 E-03	1.32 E-03 (OM)	0.98 E-03	0.98 E-03 (OP)
Dielectricity	Specific Electrical Conductivity	**κ** [nS/m] @ 80°C	1.21	1.68	2.24	**2,238.00**
	Relative Permittivity	ε_r [ ] @ 80°C	2.222	2.727	**4.521**	**5.087**
	Dielectric Dissipation Factor	**tan δ** [ ] @ 80°C	0.196	0.221	0.178	158.164

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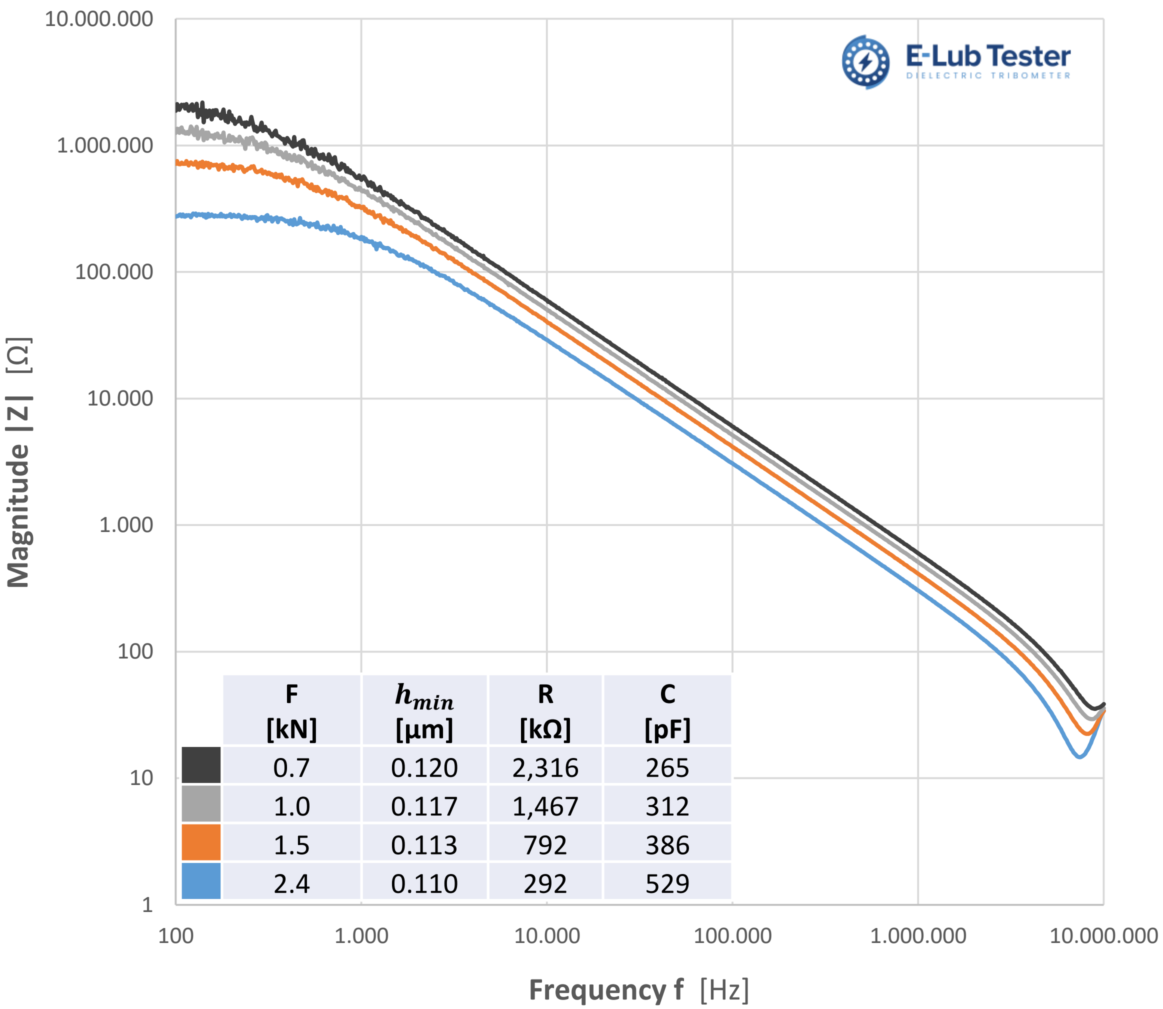
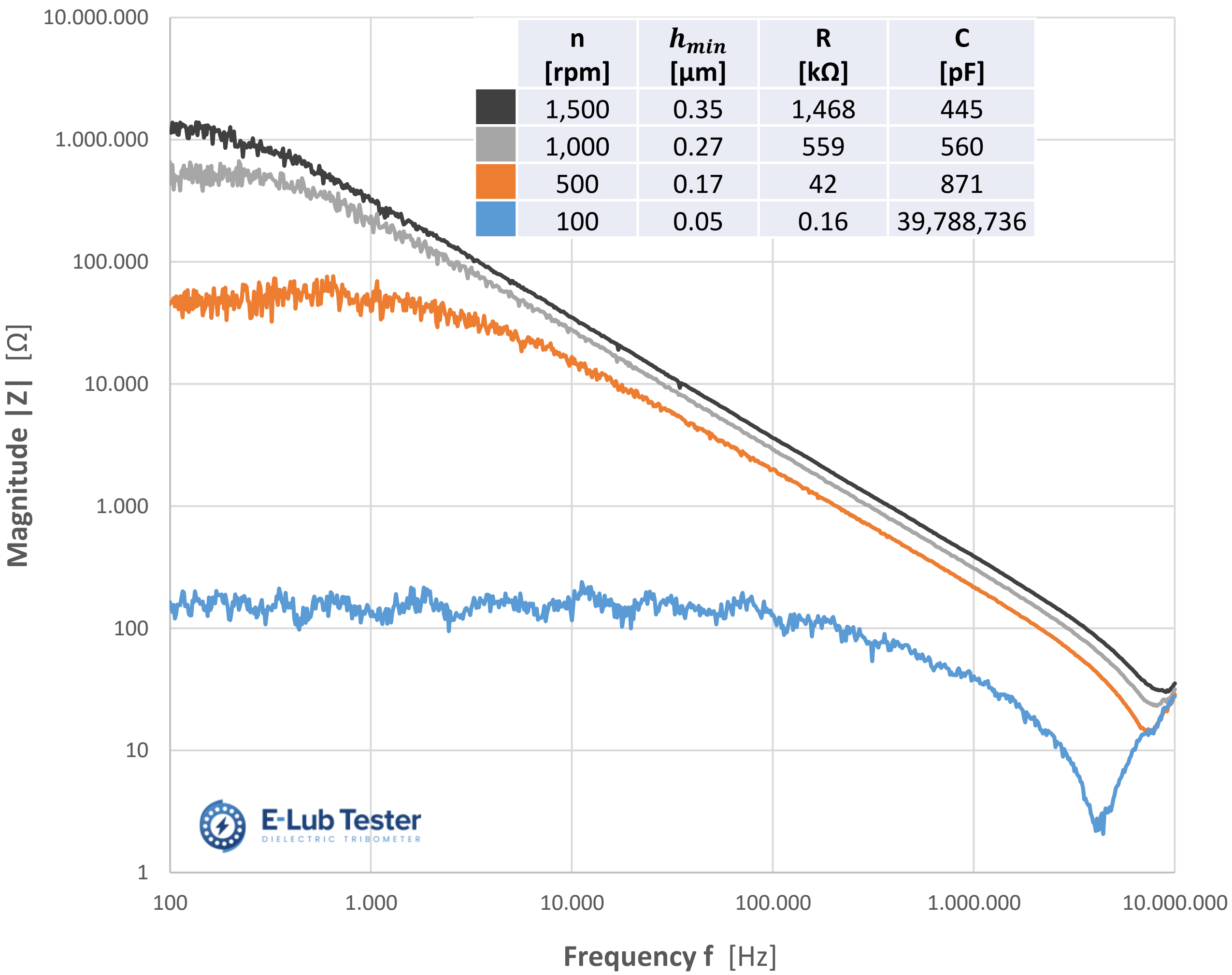
Exemplary Tests – Impedance Spectroscopy

Load variation with OM @ {80°C | 1,000 rpm}



	F [kN]	h_{min} [µm]	R [kΩ]	C [pF]
(dark grey)	0.7	0.120	2,316	265
(light grey)	1.0	0.117	1,467	312
(orange)	1.5	0.113	792	386
(blue)	2.4	0.110	292	529

Speed variation with OP @ {80°C | 2.4 kN}



	n [rpm]	h_{min} [µm]	R [kΩ]	C [pF]
(dark grey)	1,500	0.35	1,468	445
(light grey)	1,000	0.27	559	560
(orange)	500	0.17	42	871
(blue)	100	0.05	0.16	39,788,736

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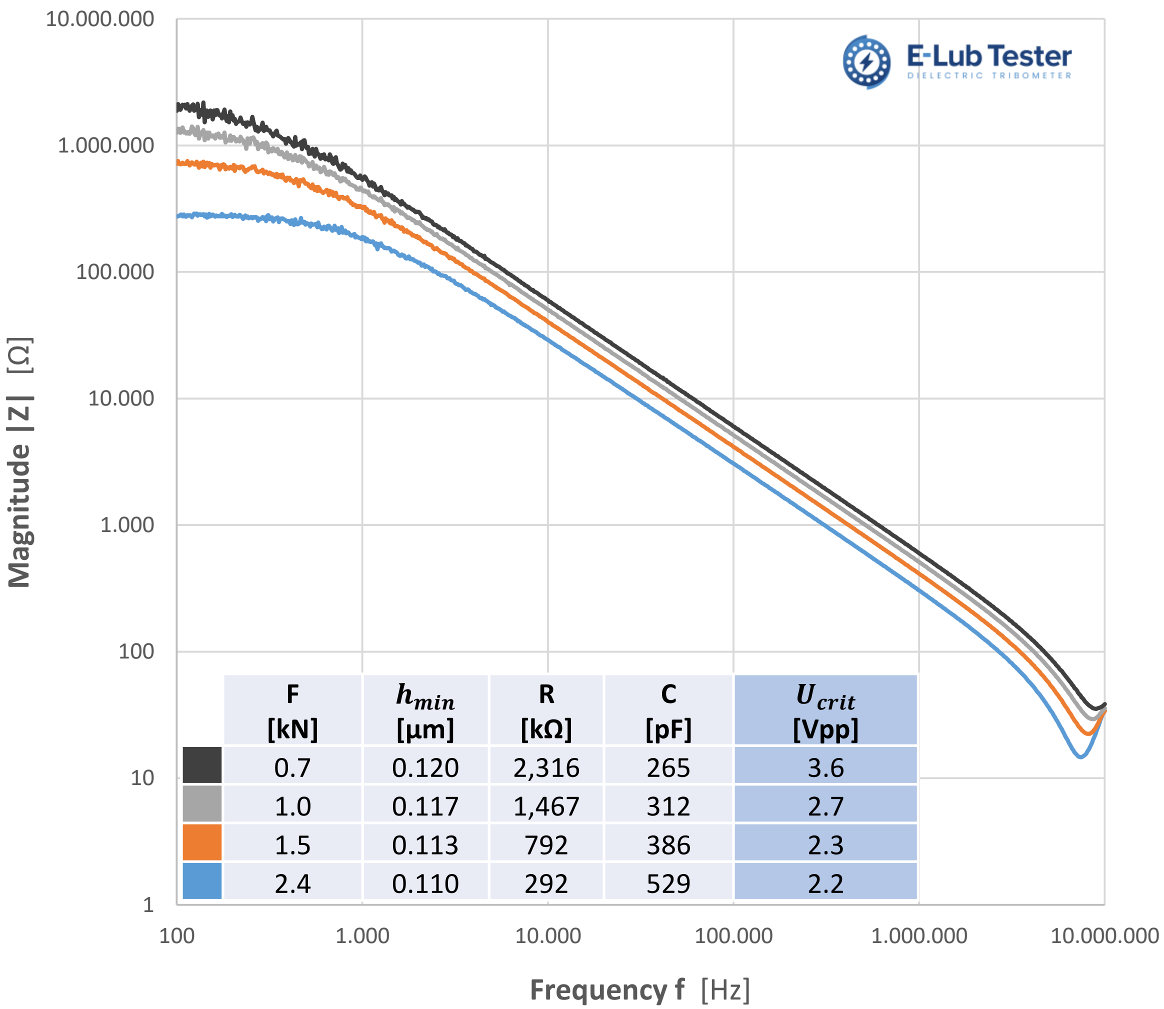
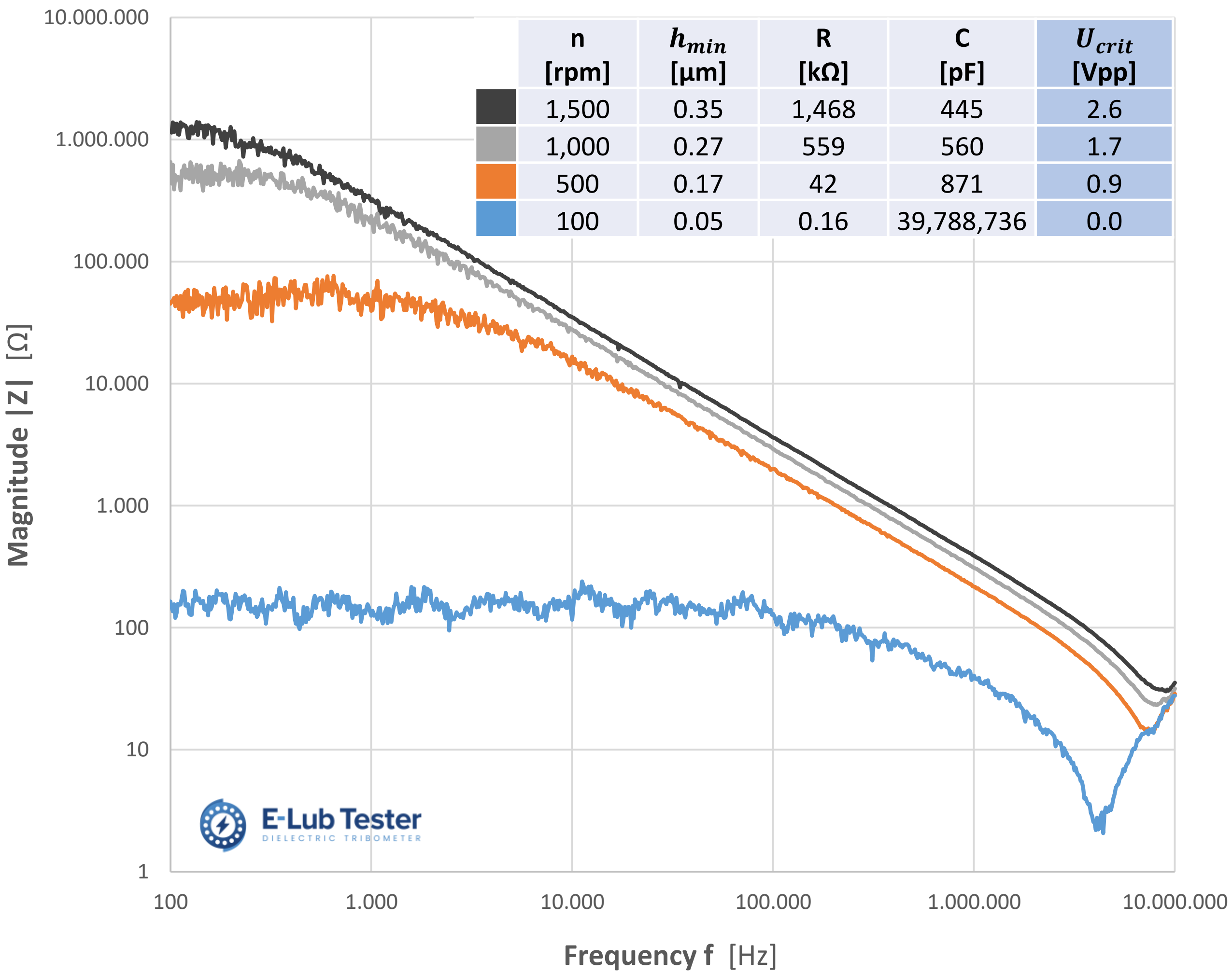
Exemplary Tests – Impedance Spectroscopy & Initial Breakdown Voltages

Load variation with OM @ {80°C | 1,000 rpm}



	F [kN]	h_{min} [µm]	R [kΩ]	C [pF]	U_{crit} [Vpp]
(dark grey)	0.7	0.120	2,316	265	3.6
(light grey)	1.0	0.117	1,467	312	2.7
(orange)	1.5	0.113	792	386	2.3
(blue)	2.4	0.110	292	529	2.2

Speed variation with OP @ {80°C | 2.4 kN}



	n [rpm]	h_{min} [µm]	R [kΩ]	C [pF]	U_{crit} [Vpp]
(dark grey)	1,500	0.35	1,468	445	2.6
(light grey)	1,000	0.27	559	560	1.7
(orange)	500	0.17	42	871	0.9
(blue)	100	0.05	0.16	39,788,736	0.0

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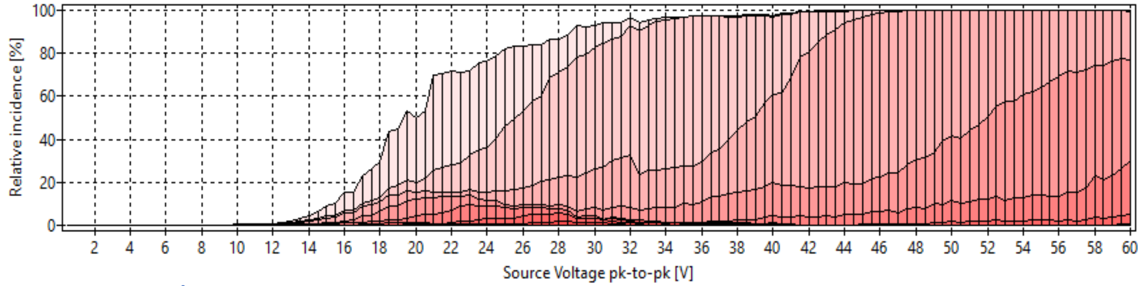
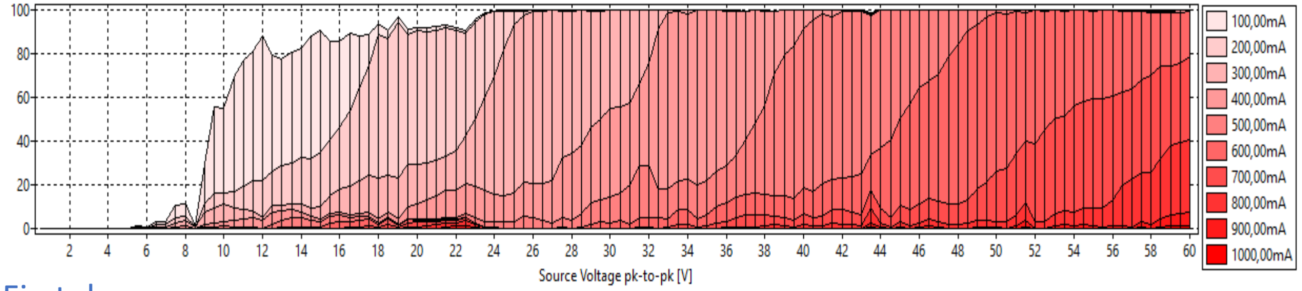
Exemplary Tests – Discharge Distribution Test @ {40°C | 1,000 rpm | 2.4 kN}

E-Lub Tester
DIELECTRIC TRIBOMETER

GM (h_{min} ≈ 0.44 µm) | **GP** (h_{min} ≈ 0.76 µm)

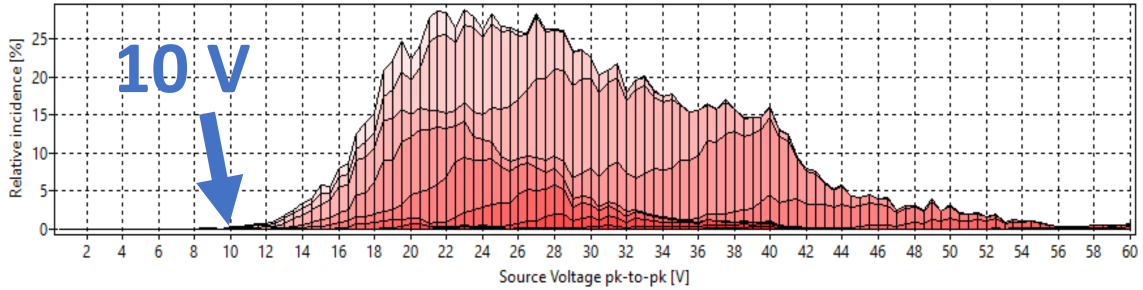
All Currents



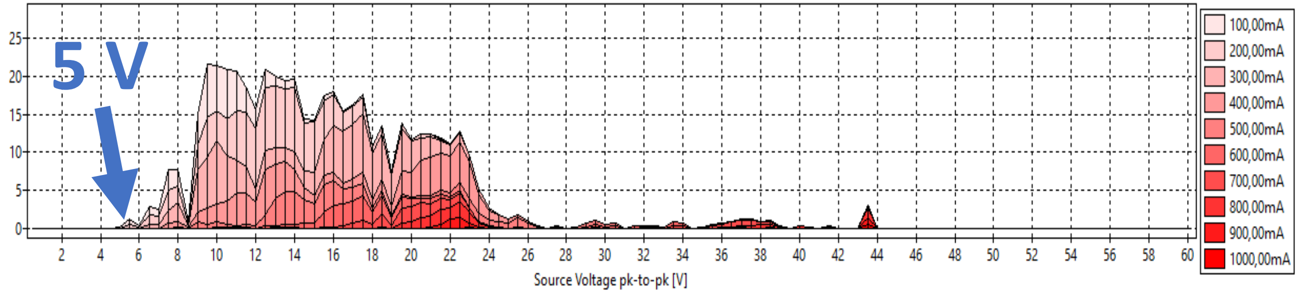


EDM Breakdown

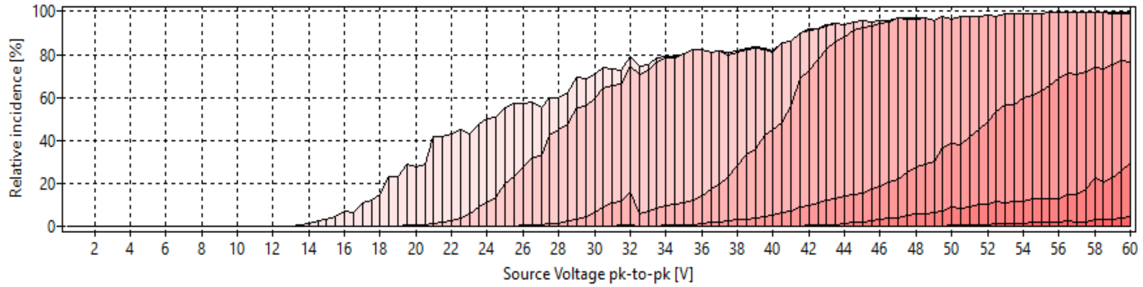
First damage:

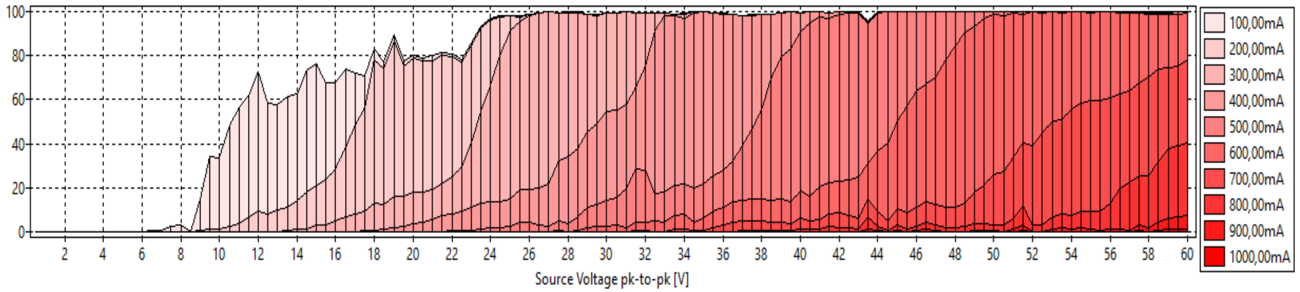


First damage:



Ohmic





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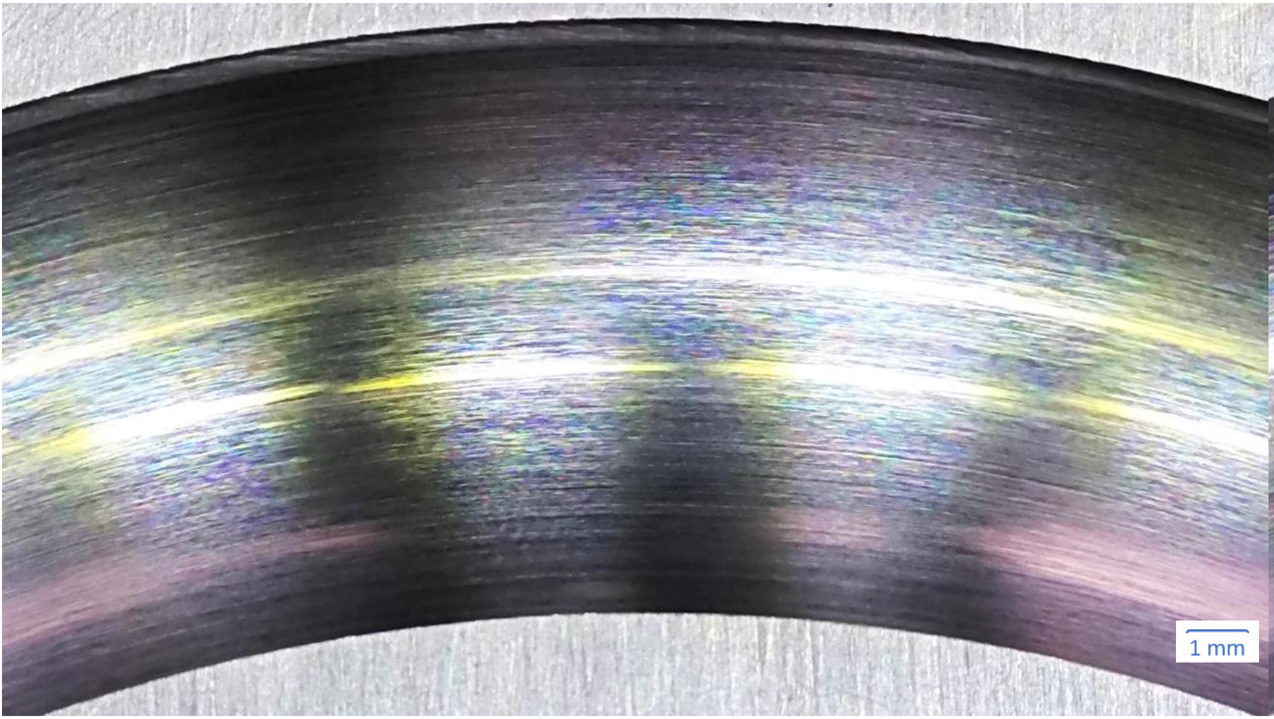
Exemplary Tests – Damage Comparison After 24-Hour Breakdown Test

Raceway of stationary ring after 24-hour test with GP @ {40°C | 1,000 rpm | 2.4 kN}

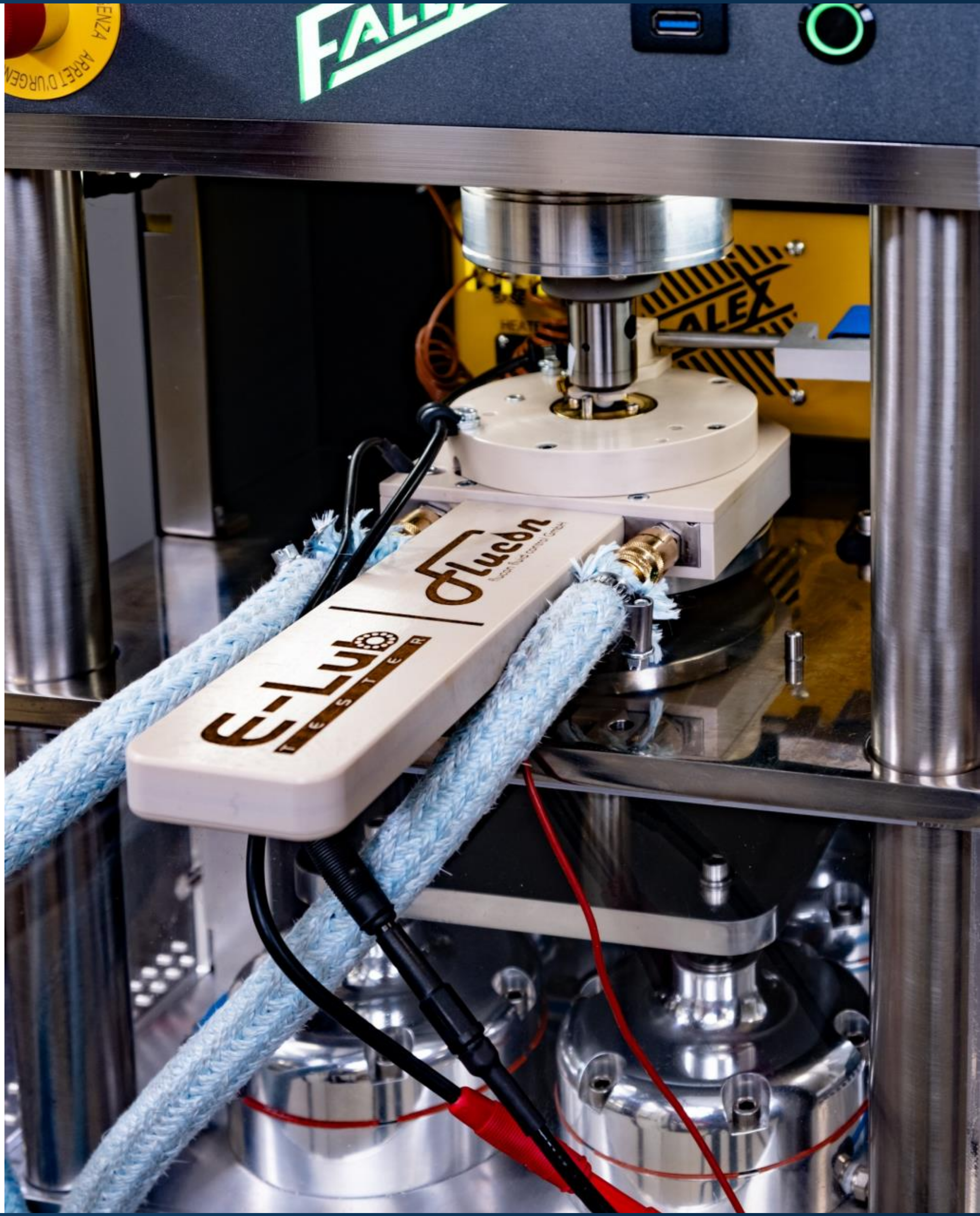


…without replicated shaft voltage

…with **22 Vpp** replicated shaft voltage

Conclusions & Prospect

- **Shaft voltage causes electrical breakdowns** through tribological contacts that damage machine elements and lubricants
- **New test methods are needed** to prevent or minimize electric discharges in the drivetrain
- Impedance (R & C) values can be fully interpreted only when the **electrical lubricant properties** are known
- Oils and greases should be analyzed and **specified in regard to their dielectricity** (e.g. through DIN 51 111 method w/ EPSILON+)
- **Electrified tribometry** w/ E-Lub Tester allows us to replicate operating conditions of electric drivetrains and investigate the lubricant film and its breakdown tendency
- Tomorrow's lubricants can then be developed with an **optimized conductivity and dielectric strength** for the relevant operating conditions



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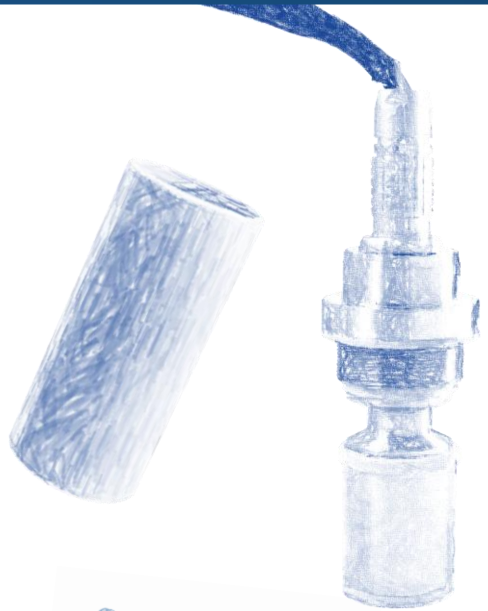
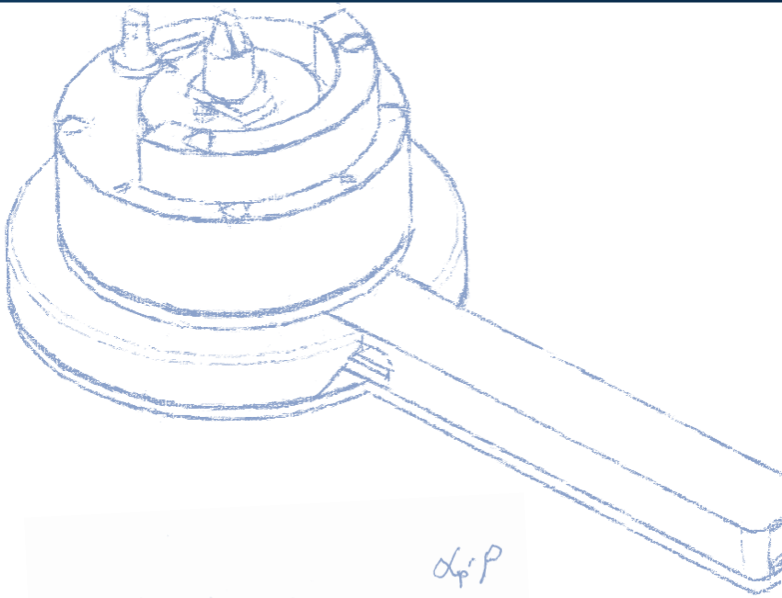


$$\underline{Y} = \frac{1}{\underline{Z}}$$

$$\tan\delta = \frac{Re\{\underline{Y}\}}{Im\{\underline{Y}\}} = \frac{\kappa}{2\pi \times f \times \varepsilon_0 \times \varepsilon_r}$$



Thank you.
Any questions?

$$\varepsilon = \varepsilon_0 \times \varepsilon_r$$

$$\eta(p,T) = \eta_{0,T} * \exp^{\alpha_p \cdot p}$$

$$\rho = \frac{1}{\kappa}$$

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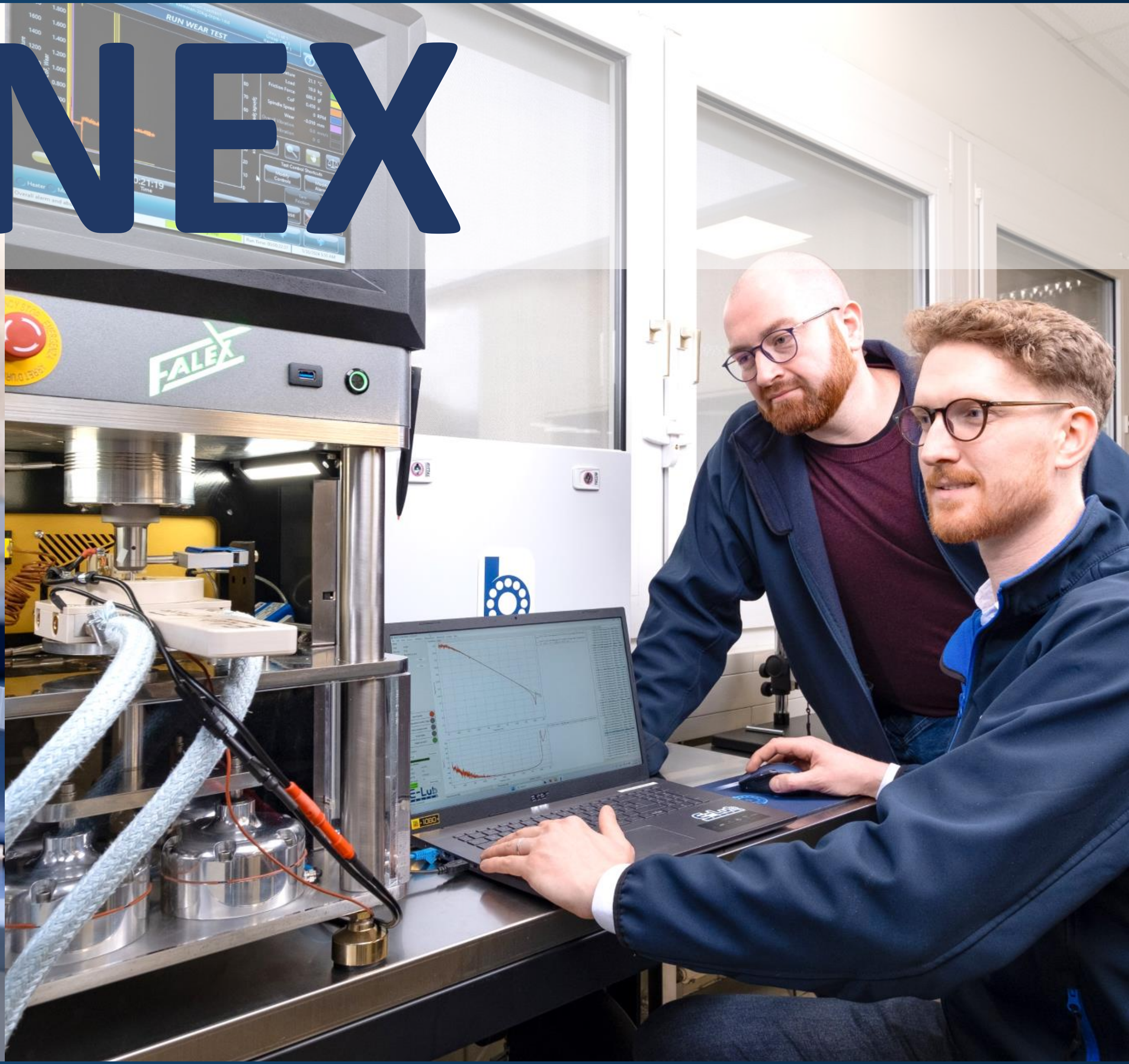
ANNEX



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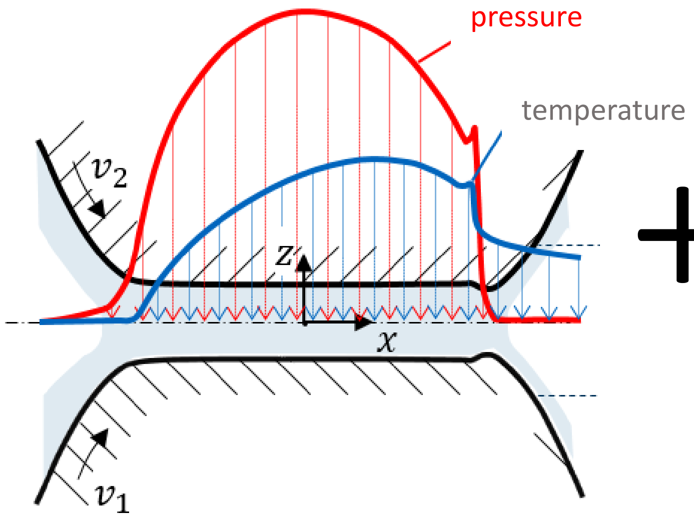
Establishing The Tribo-Electrical Model

Tribological Model



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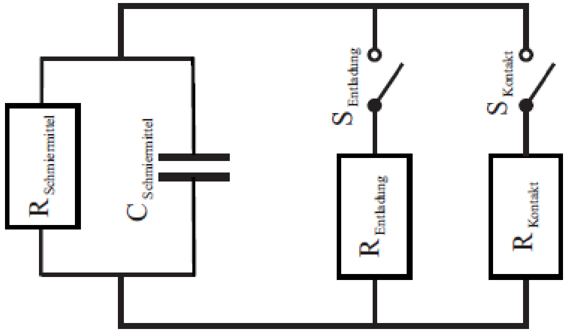
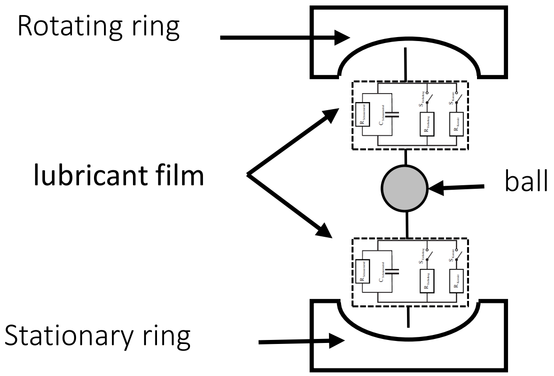
Electrical Model
(circuit diagram)



Tribo-Electrical Model



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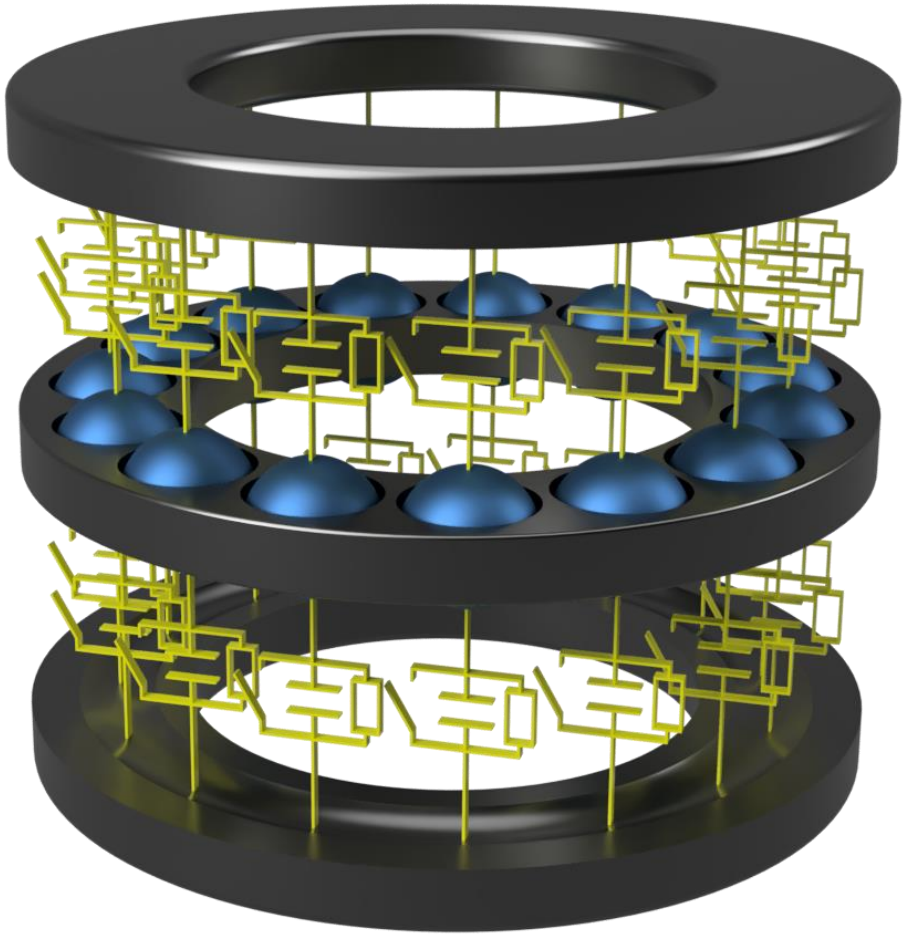
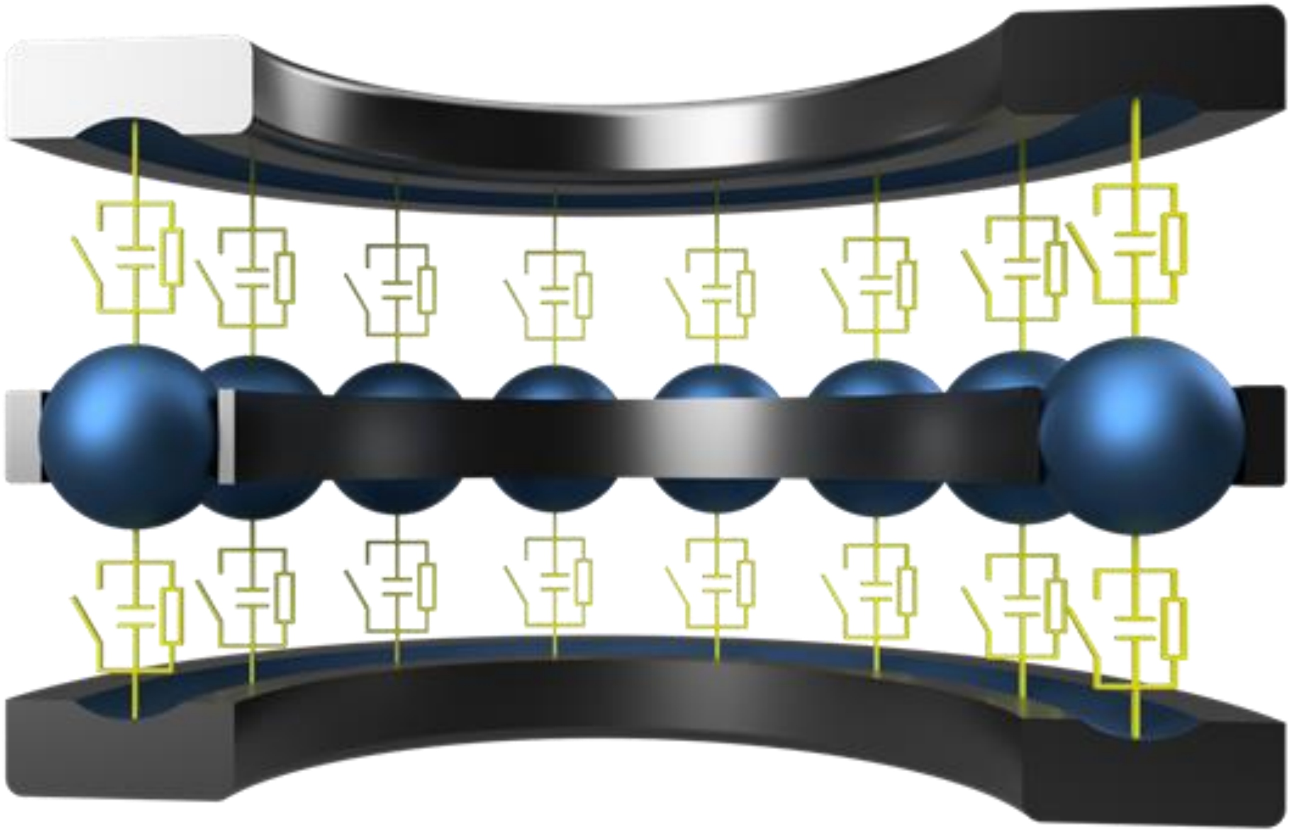
Impedance Measurement w/ Lubricated 51208 Thrust Ball Bearing





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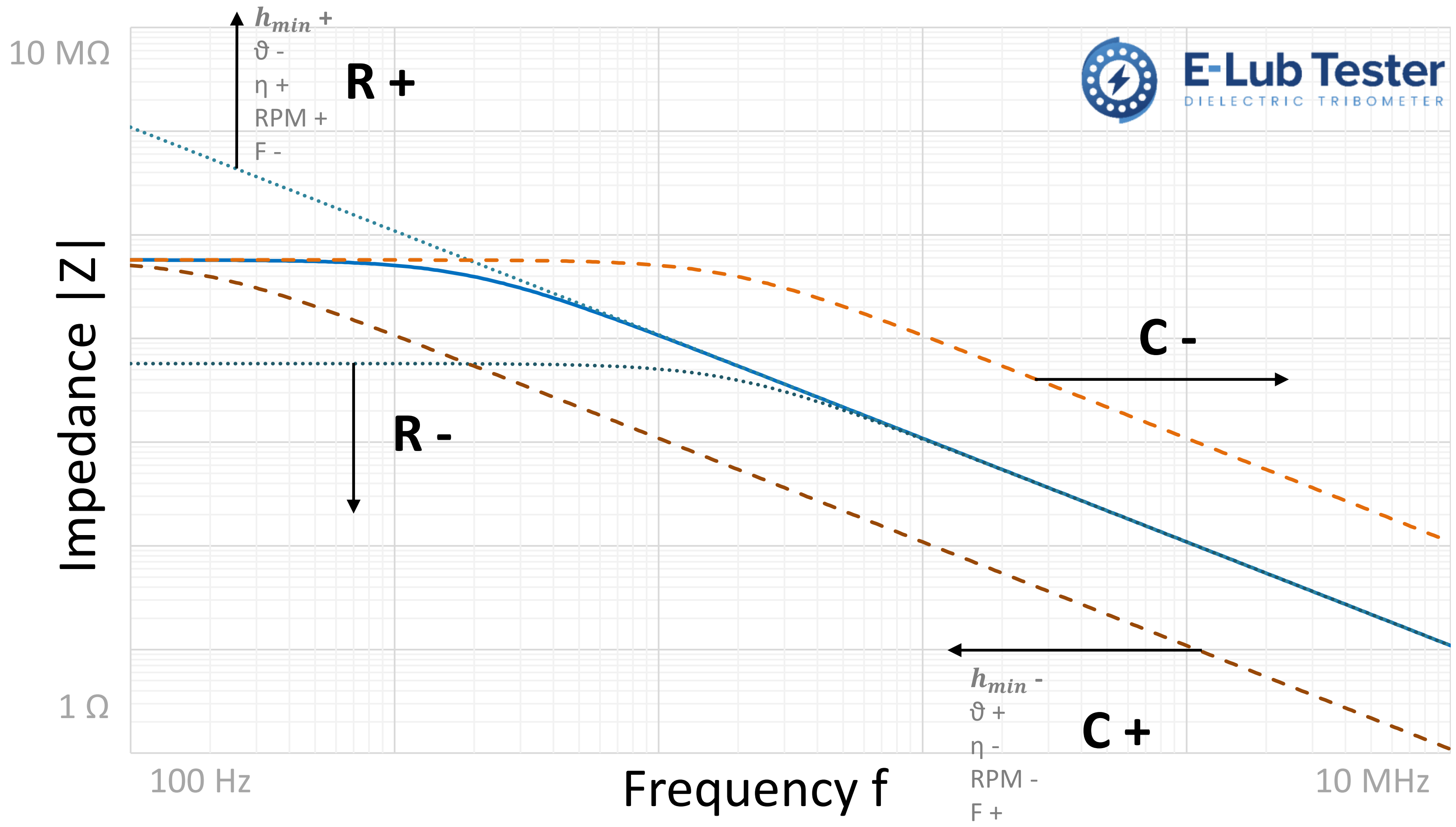
Impedance Spectroscopy With A Lubricated Bearing



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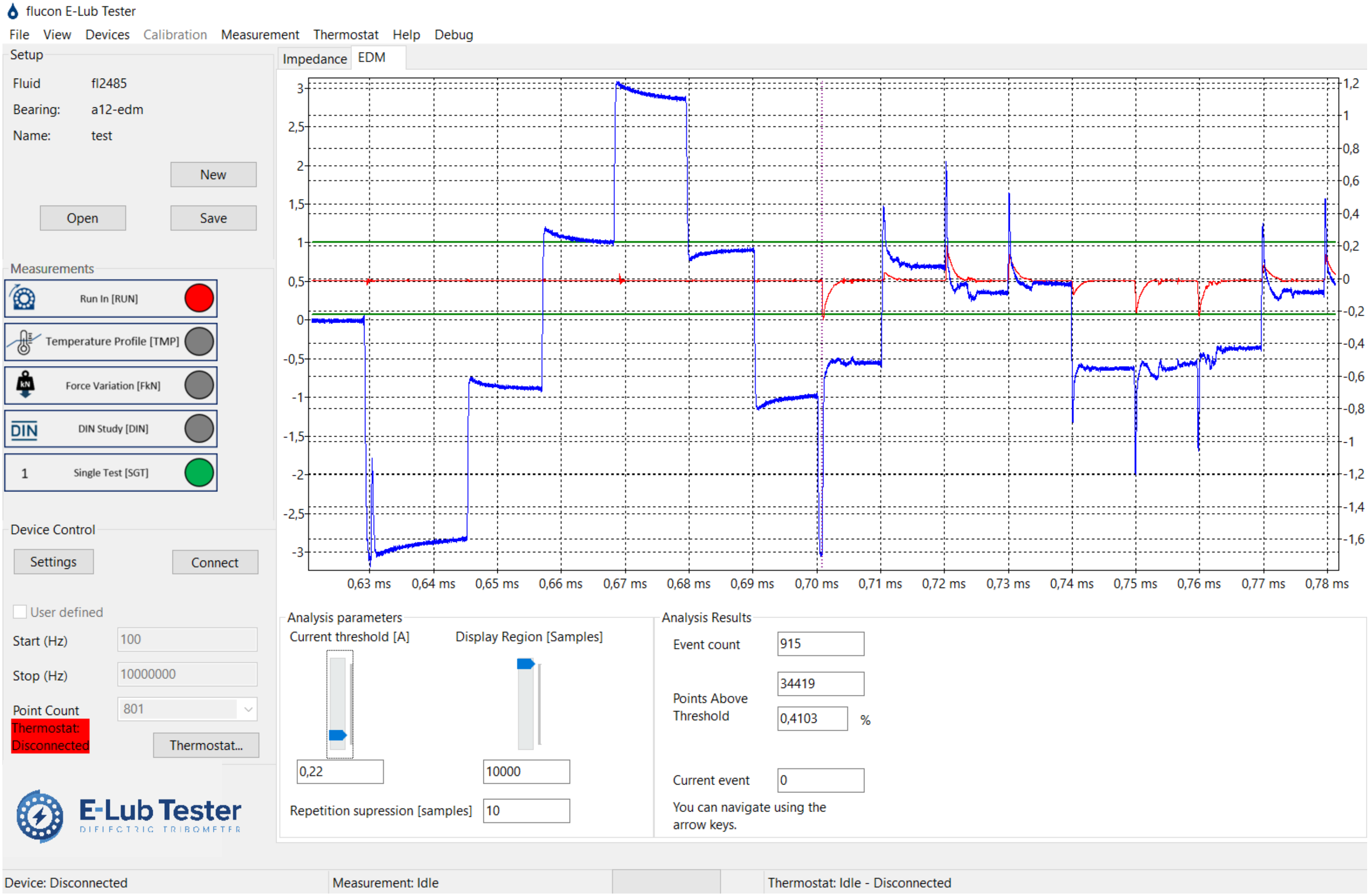
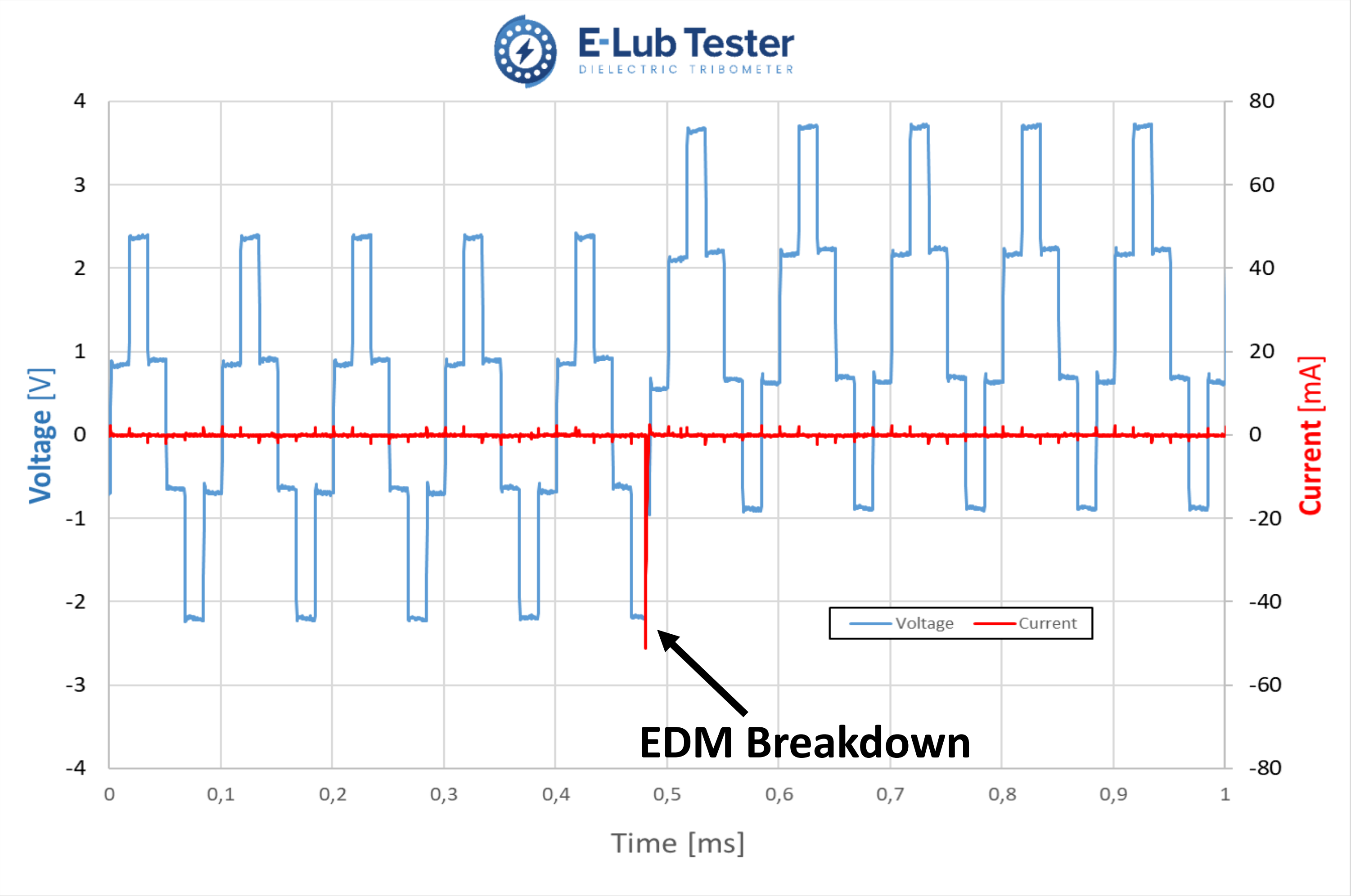
Breakdown Testing With Replicated Common-Mode Voltage & E-Lub Tester Software

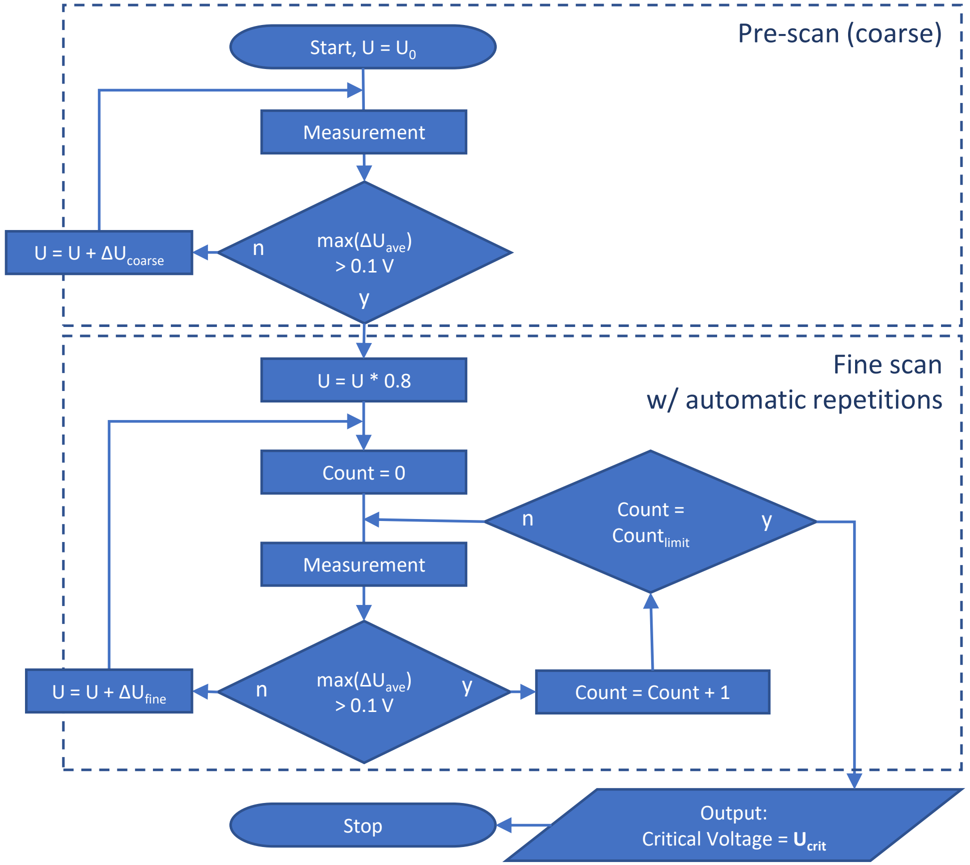


- Arbitrary waveform generator
- Standard: 10 kHz Common-Mode Voltage
- stair-shaped 3-step signal
- up to 60 V pk-to-pk
- Configurable current threshold
- U/I measurement with 125 MS/sec rate

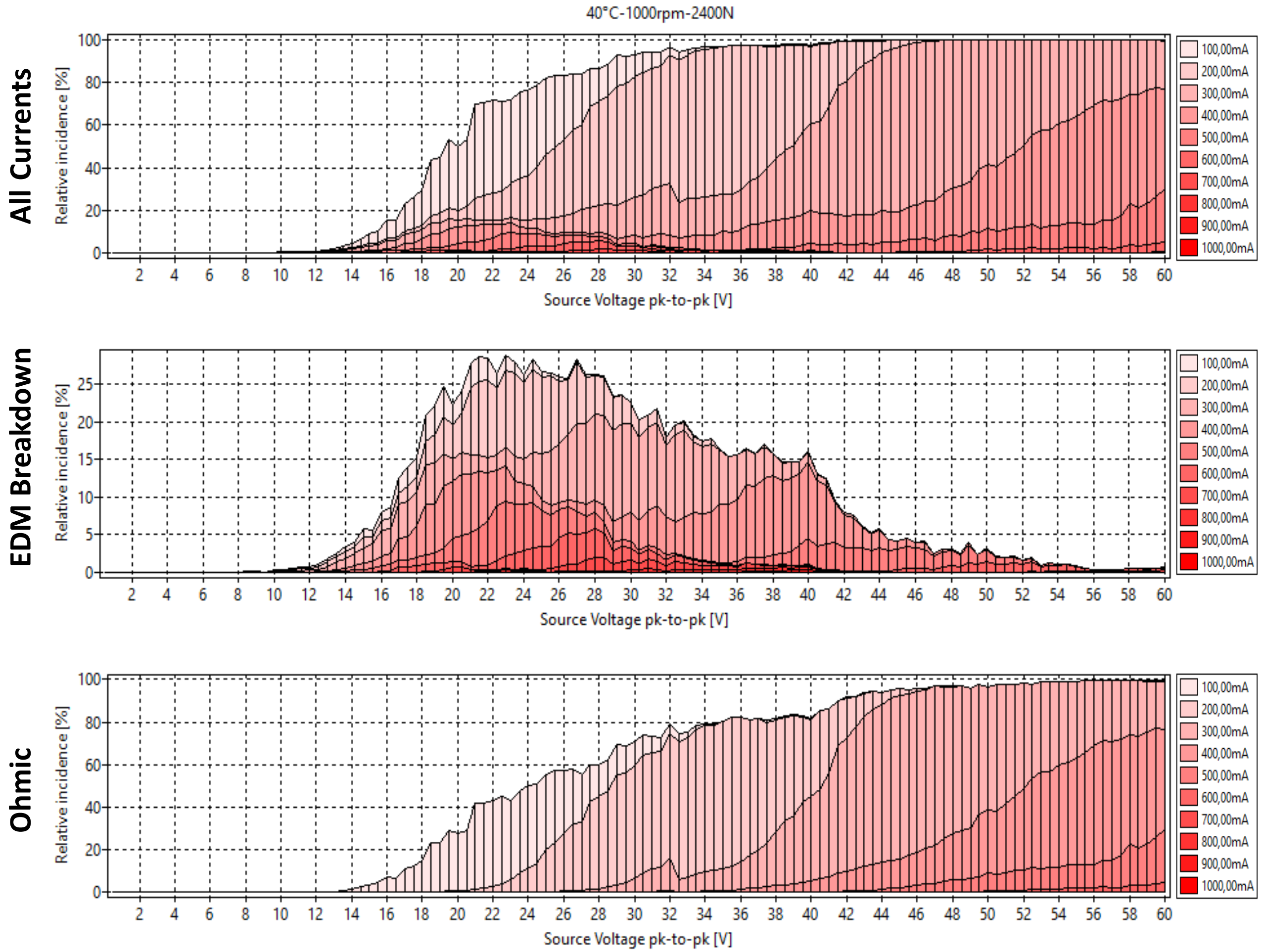
Initial Breakdown Test (Reversible Method At Multiple Operating Points)



“Breakdown Finder” algorithm:



Discharge Distribution Test (Damaging Method At One Operating Point)



- Accurate **differentiation** between **EDM breakdown currents** (spark-erosive damage) and **ohmic currents** (e.g. with asperity contact or after breakdown)
- Assessment of **harmfulness** by amperage, power and incidence
- Graphical and numeric **result report**

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DIN Method Draft

| Round-robin test procedure: NA 062-06-53-B, NA 062-06-53-C

1) Run-In

16 h

- axial load: 2.4 kN
- speed: 1,000 min-1
- total duration 16 h:
  4 h to steady state temperature
  12 h @ T_{soll} = 80°C
- hourly impedance measurement

2) 1st Isotherm

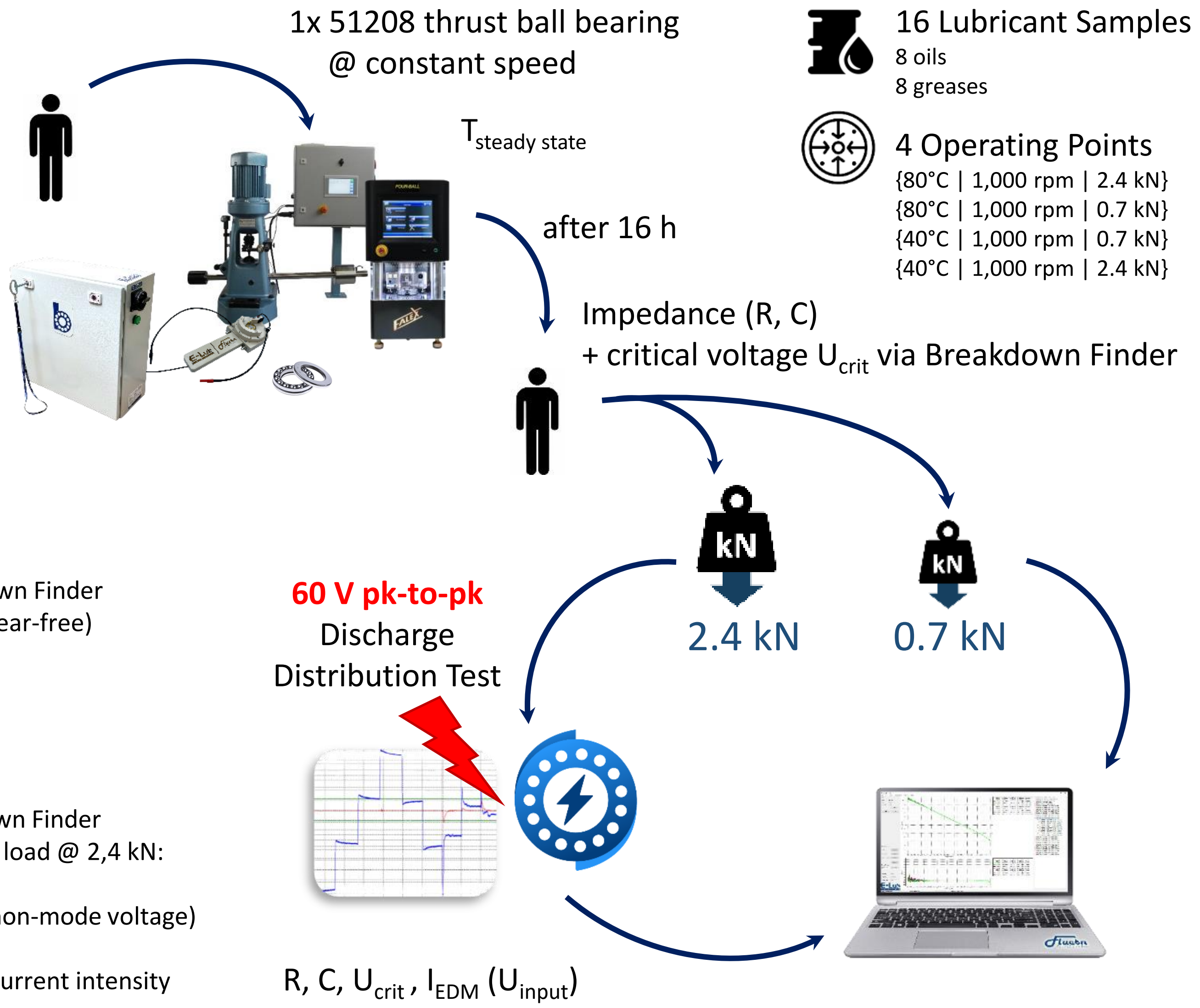
80°C

- axial loads: 2.4 kN; 0.7 kN
- speed: 1,000 min-1
- temperature: 80°C
- impedance measurement & Breakdown Finder (test stops after initial discharge -> wear-free)
- parameters: R, C, U_{crit}

3) 2nd Isotherm

40°C

- axial loads: 0.7 kN; 2.4 kN
- speed: 1,000 min-1
- temperature : 40°C
- impedance measurement & Breakdown Finder
- Discharge Distribution Test: electrical load @ 2,4 kN: 0,0 V up to 60.0 V pk-to-pk (500 mV increments w/ 10 kHz common-mode voltage)
- parameters: R, C, U_{crit}, distribution I_{EDM} (U_{input}) by current intensity



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DIN 51 111:2024-02

“Electrical properties of fresh and used oils from electric drives in vehicles –Measurement of the specific electrical conductivity, the relative permittivity (εr) and the dielectric dissipation factor (tan δ)”

DIN 51 111

Isotherm	50°C	• specific electrical conductivity • relative permittivity/dielectric constant εr • dielectric loss factor tan δ
Isotherm	80°C	• specific electrical conductivity • relative permittivity/dielectric constant εr • dielectric loss factor tan δ
Isotherm	100°C	• specific electrical conductivity • relative permittivity/dielectric constant εr • dielectric loss factor tan δ
Isotherm	150°C	• specific electrical conductivity • relative permittivity/dielectric constant εr • dielectric loss factor tan δ

| tbd: **greases**

| **oils only**

DIN

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Measuring the Electrical and Dielectric Properties in Tribometry

Standard	Quantities of Interest
ASTM D149	Dielectric Strength
ASTM D257	DC Resistance or Conductance
ASTM D877	Method for Dielectric Breakdown Voltage of Insulating Liquids using Disk Electrodes
ASTM D924	Dissipation Factor (or Power Factor) and Relative Permittivity (Dielectric Constant) of Electrical Insulating Liquids
ASTM D1169	Specific Resistance (Resistivity) of Electrical Insulating Liquids
ASTM D1816	Dielectric Breakdown Voltage of Insulating Liquids
ASTM D2624	Electrical Conductivity of Aviation and Distillate Fuels
ASTM D3300	Method for Dielectric Breakdown Voltage of Insulating Liquids under Impulse Conditions
ASTM D4308	Electrical Conductivity of Liquid Hydrocarbons
DIN 51 111	Electrical Properties of Fresh and Used Oils from Electric Drives in Vehicles - Spec. El. Conductivity, Relative Permittivity & Dielectric Dissipation Factor
DIN 53483-3	Determination of Dielectric Properties - Measuring Cells for Liquids for Frequencies up to 100 MHz [WITHDRAWN]
IEC 60156 (alt. DIN EN)	Dielectric Breakdown Voltage of Insulating Liquids (at Power Frequency)
IEC 60247 (alt. DIN EN)	Relative Permittivity, Dielectric Dissipation Factor and DC Resistivity of Liquids
IEC 61620 (alt. DIN EN)	Insulating Liquids - Determination of the Dielectric Dissipation Factor by Measurement of the Conductance and Capacitance - Test Method
TBA (DIN 51 111 extension)	Spec. El. Conductivity, Relative Permittivity & Dielectric Dissipation Factor **for Greases**
TBA (NA 062-06-53 project)	Impedance & Breakdown Measurement of Lubricants used in a **Tribological Contact under Variable Operating Conditions**
TBD	Aging of Lubricants in Electrical Fields

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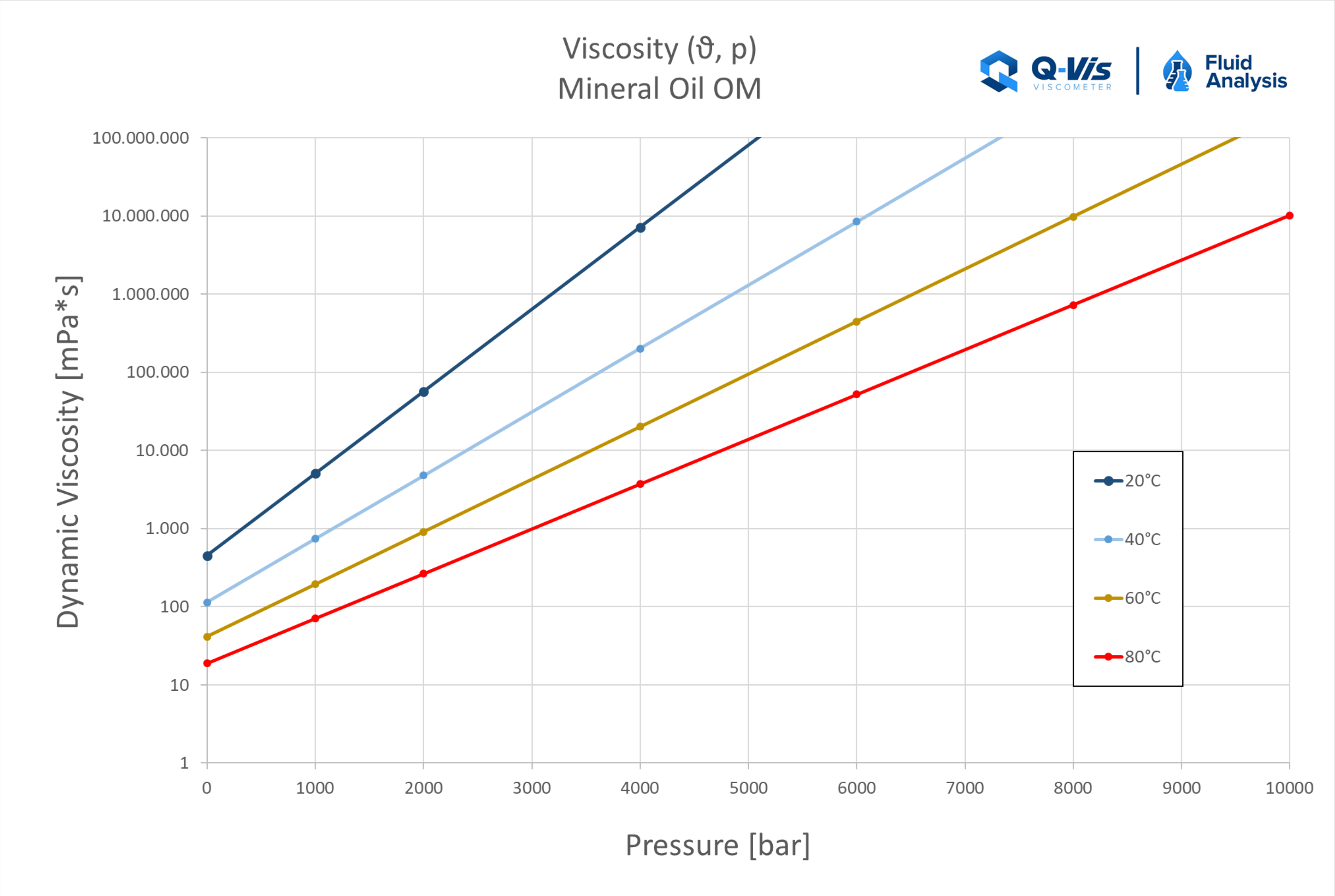
Lab Results



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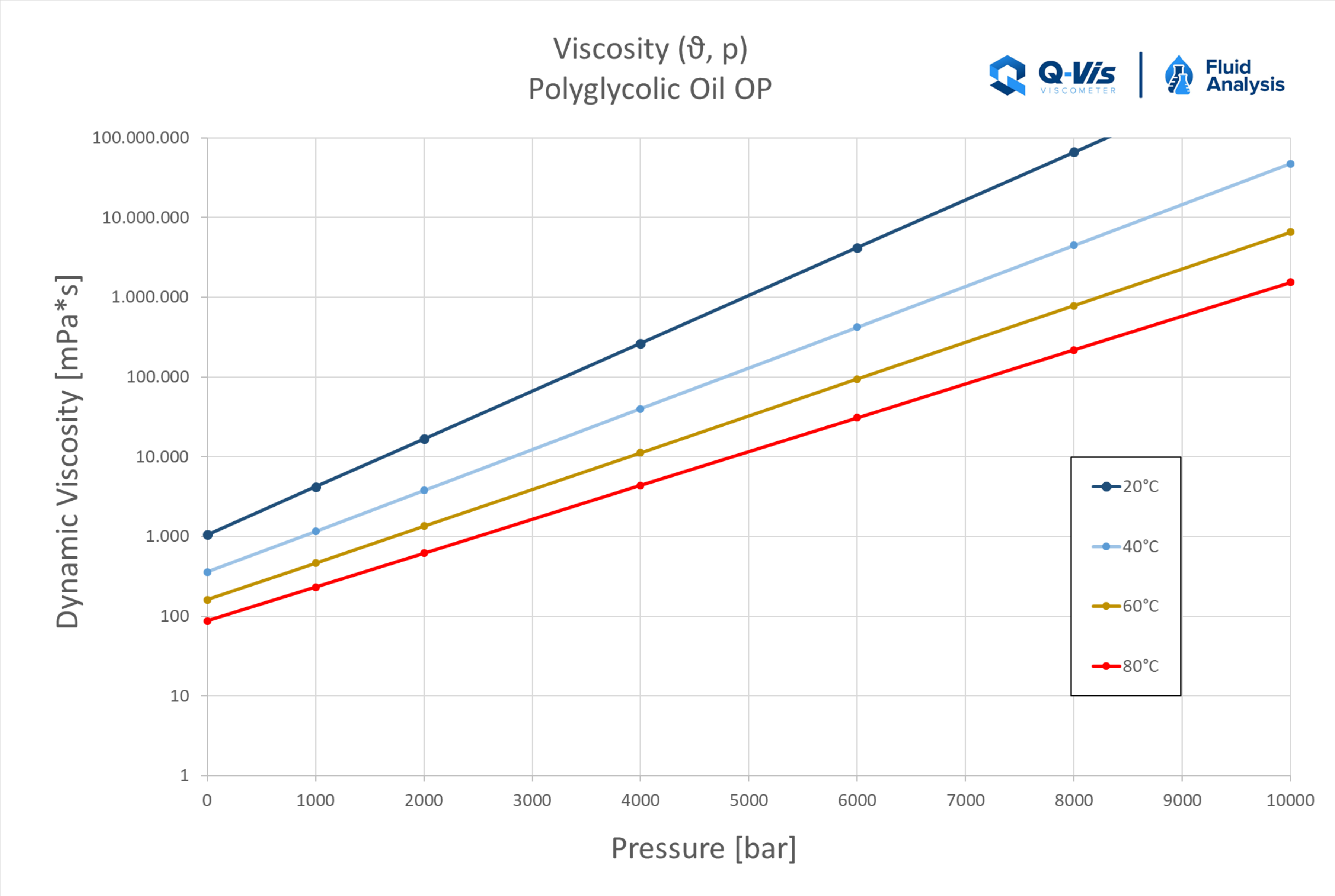
Lab Results



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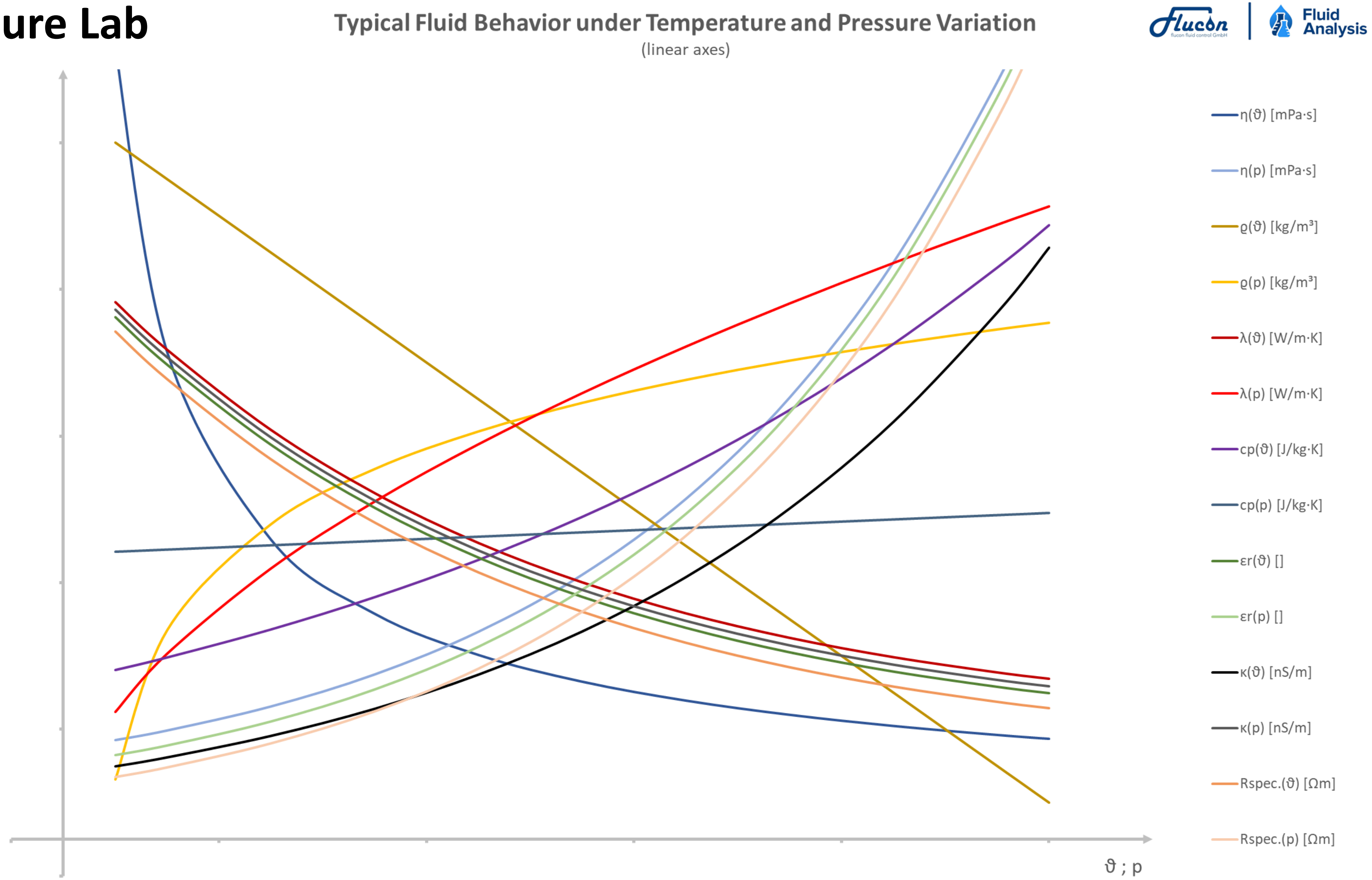
High-Pressure Lab



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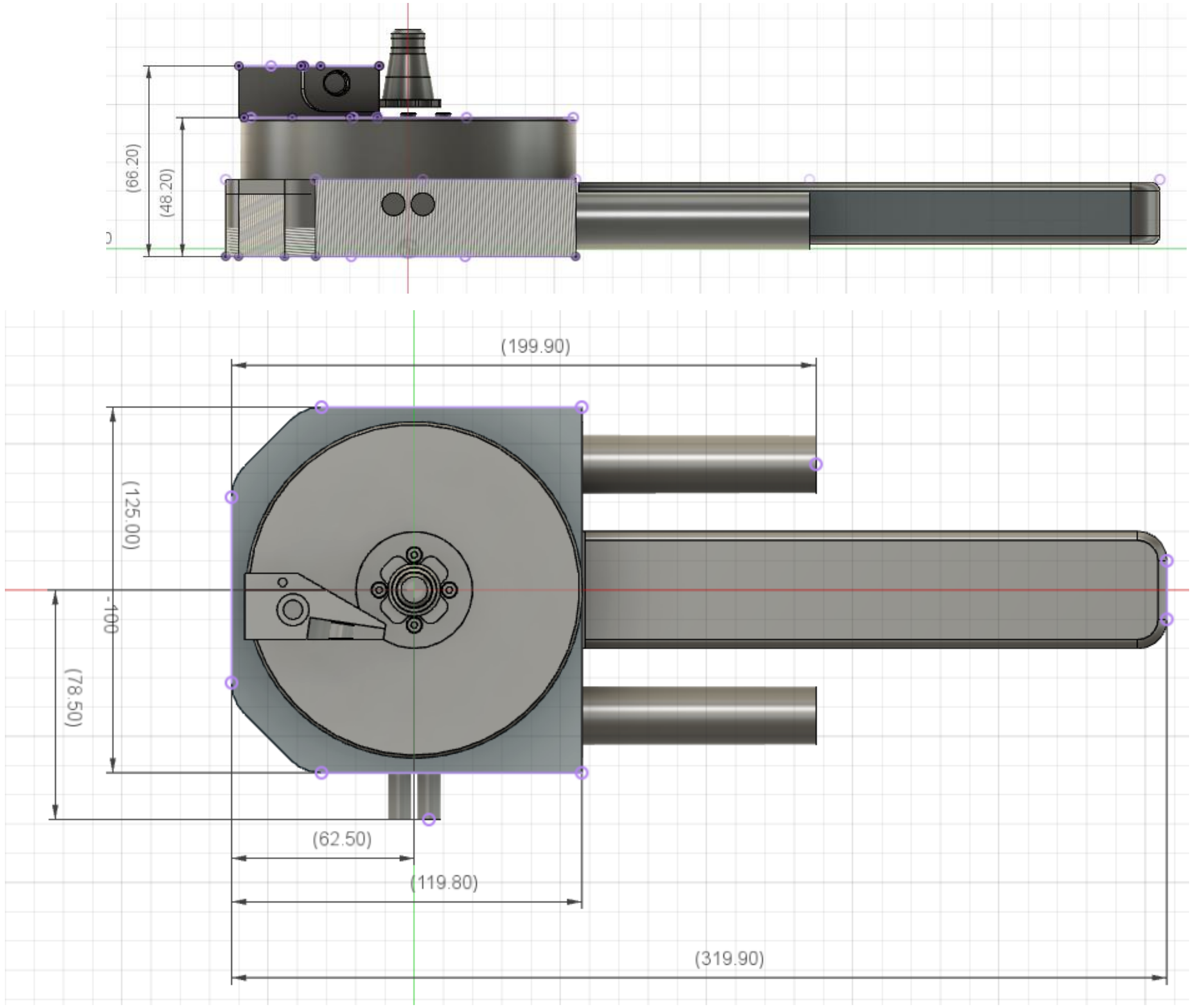
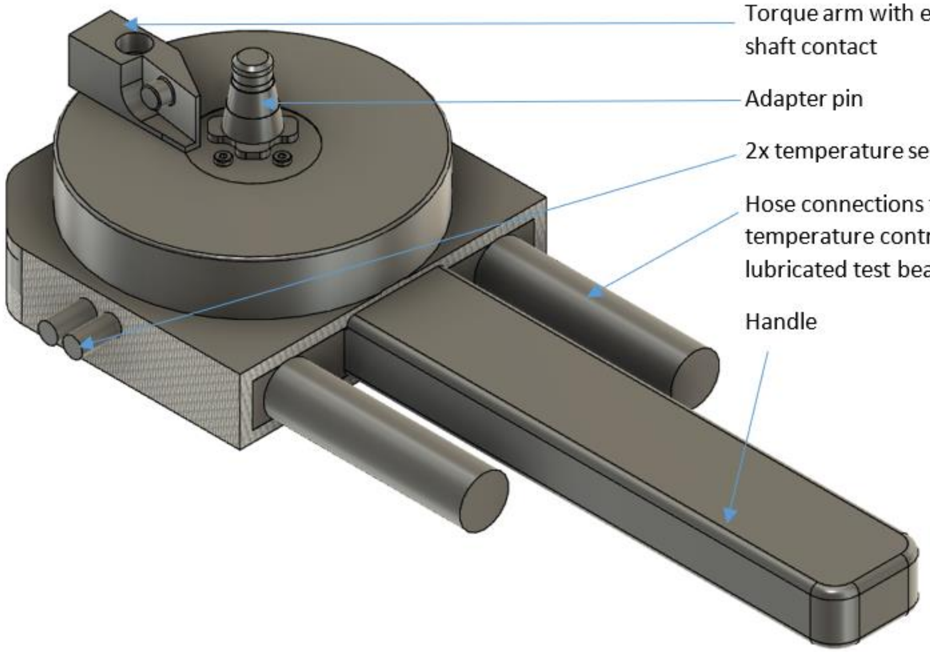
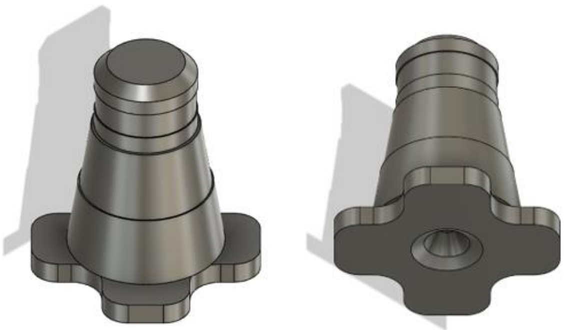
"E-Lub Tester" Four-Ball Bearing Test Cell







Adapter pin (upper restraint)

Material: PEEK

Centering via 6 mm ceramic ball placed in centering hole

Torque transmission by form fit

Conical dimensions corresponding to those of the ball chuck

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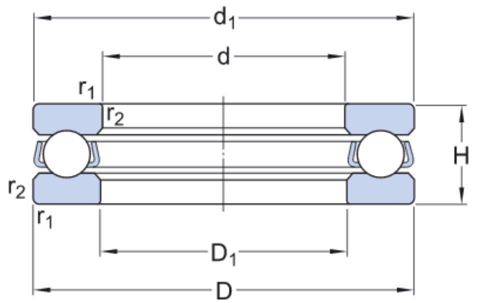
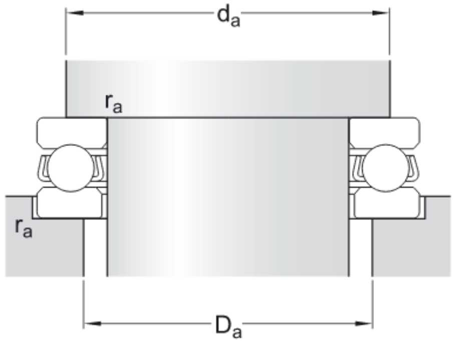
"E-Lub Tester" Test Object: Lubricated 51208 Thrust Ball Bearing



Abmessungen

d	40 mm	Bohrungsdurchmesser
D	68 mm	Außendurchmesser
H	19 mm	Höhe
d_1	≈ 68 mm	Außendurchmesser Wellenscheibe
D_1	≈ 42 mm	Innendurchmesser Gehäusescheibe
$r_{1,2}$	min. 1 mm	Kantenabstand Scheibe



Anschlussmaße

d_a	min. 57 mm	Durchmesser der Wellenanlauffläche
D_a	max. 51 mm	Durchmesser der Anlauffläche im Gehäuse
r_a	max. 1 mm	Rundungsradius

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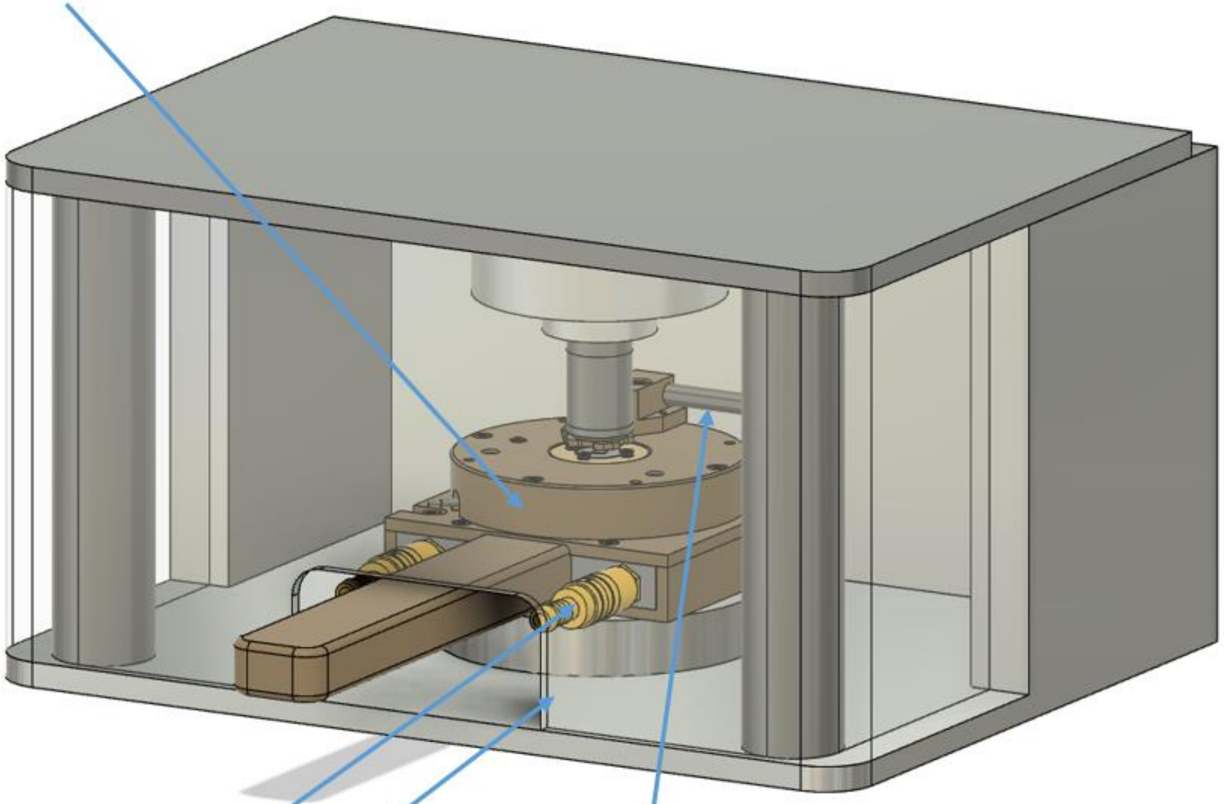
"E-Lub Tester" Four-Ball Adaption



Technical specifications - E-Lub Tester

Compatible FBT models	Falex Four-Ball, Hansa VKA-110
Determined data	ohmic resistance, capacitance, breakdown frequency (number & amplitude of EDM currents)
Compatible substances	Greases and oils
Bearing types	51208 (optionally: 6008)
Material - Test cell (FBT adapter)	stainless steel with PEEK housing and assembly handle
Temperature measurement	Pt100 by bearing
Temperature range	20°C to 120°C
Load	2.400 N max.
Speed	6.000 rpm max.
Frequency range	100 Hz to 10 MHz
Common-Mode Voltage	60 V max. (peak-to-peak)
Connectivity	USB, ethernet
Power supply	110-240 V AC, 50/60 Hz

The test cell is galvanically, capacitively and thermally insulated from the (Four-Ball Tester) drive unit.
It contains the test bearing, which is electrically contacted and on which the bearing impedances are measured.