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Trib Net

Fundamentals of Tribology in Electric Vehicles

Invited speaker

Dr. Jonny Hansen
Senior Tribologist @
Scania Group

2022-12-16

jonny.hansen@scania.com

Abstract

In this talk, Dr. Jonny Hansen discusses the fundamentals of tribology in electric vehicles (EVs). Special attention is given to the lubrication and electric breakdown mechanisms that may occur in bearings and gears of heavy-duty EVs.

More specifically, it will be shown that when subjected to an electric field, surface-initiated problems are possible even under conditions previously considered safe, i.e., in the full film elasto-hydrodynamic lubrication (EHL) regime. Because of this, and when considering tribological contacts for EV's, it is crucial to be able to estimate the transition between the EHL and mixed lubrication (ML) regimes to a good degree of accuracy.

Traditionally, Tallian's lambda ratio, i.e. the nominal film thickness over the composite surface RMS level ($\Lambda = hm/Sq$), has often been employed for this purpose, and for assessing rolling contact fatigue (RCF) life. However, although some research has proven the model beneficial with regard to the latter, it cannot be used to accurately assess the transition between EHL and ML [1-5]. In fact, and as will be shown, it may falsely suggest contact interference, boundary lubrication (BL), despite a fully developed EHL film has formed – a very risky outcome in the design of tribological contacts for EV's.

The presentation will proceed by revealing the main deficiencies of the Λ-ratio that stems from the nature of surface roughness and micro elasto-hydrodynamics. With this in mind, and inspired by Tallian, a new recently published film parameter [4], Λ^*, is put forward as a more reliable tool to estimate the transition between EHL and ML. Subsequently, it is shown that the new film parameter can be used to assess under which lubrication conditions electrically induced surface damages may occur, and when the lubricant film is sufficiently thick to protect surfaces by electrical insulation.

With knowledge of the fundamental film formation and breakdown mechanisms, the presentation expands to cover the lubrication conditions of EV drivetrains in the context of the proposed film parameter, and is finally concluded by putting forward prospects pertinent to EV lubrication research.

References

A recording of the presentation can be found on the following webpage:
https://network.tribonet.org/webinar/fundamentals-of-tribology-in-electric-vehicles-by-dr-jonny-hansen/

Key references (all Open Access) leading to this work include:

1. Hansen J, Björling M, Larsson R. Mapping of the lubrication regimes in rough surface EHL contacts. Tribol Int 2018;131:637–51. https://doi.org/10.1016/j.triboint.2018.11.015.
2. Hansen J, Björling M, Larsson R. Topography transformations due to running-in of rolling-sliding non-conformal contacts. Tribol Int 2020;144:106126. https://doi.org/10.1016/j.triboint.2019.106126.
3. Hansen J, Björling M, Larsson R. Lubricant film formation in rough surface non-conformal conjunctions subjected to GPa pressures and high slide-to-roll ratios. Sci Rep 2020;10:1–16. https://doi.org/10.1038/s41598-020-77434-y.
4. Hansen J, Björling M, Larsson R. A New Film Parameter for Rough Surface EHL Contacts with Anisotropic and Isotropic Structures. Tribol Lett 2021;69:1–17. https://doi.org/10.1007/s11249-021-01411-3
5. Hansen J. Elasto-hydrodynamic film formation in heavily loaded rolling-sliding contacts (Doctoral dissertation). Luleå University of Technology, 2021.

Agenda

- Part 1 ► Tribology
- Part 2 ► Elasto-hydrodynamic lubrication (EHL)
- Part 3 ► What is e-tribology?
- Part 4 ► Needs for a new film parameter
- Part 5 ► Electric discharge mechanisms
- Part 6 ► Stray (bearing) currents in EV’s
- Part 7 ► Discharge damages in EV’s
- Part 8 ► Mitigation strategies
- Part 9 ► Prospects
- Part 10 ► Conclusions

Part 1 ▸ Tribology

Tribology

Historical Tribology

Dowson, D. (1998)

Space tribology

Geo tribology

iStockphoto

Biomimetic tribology

case.edu

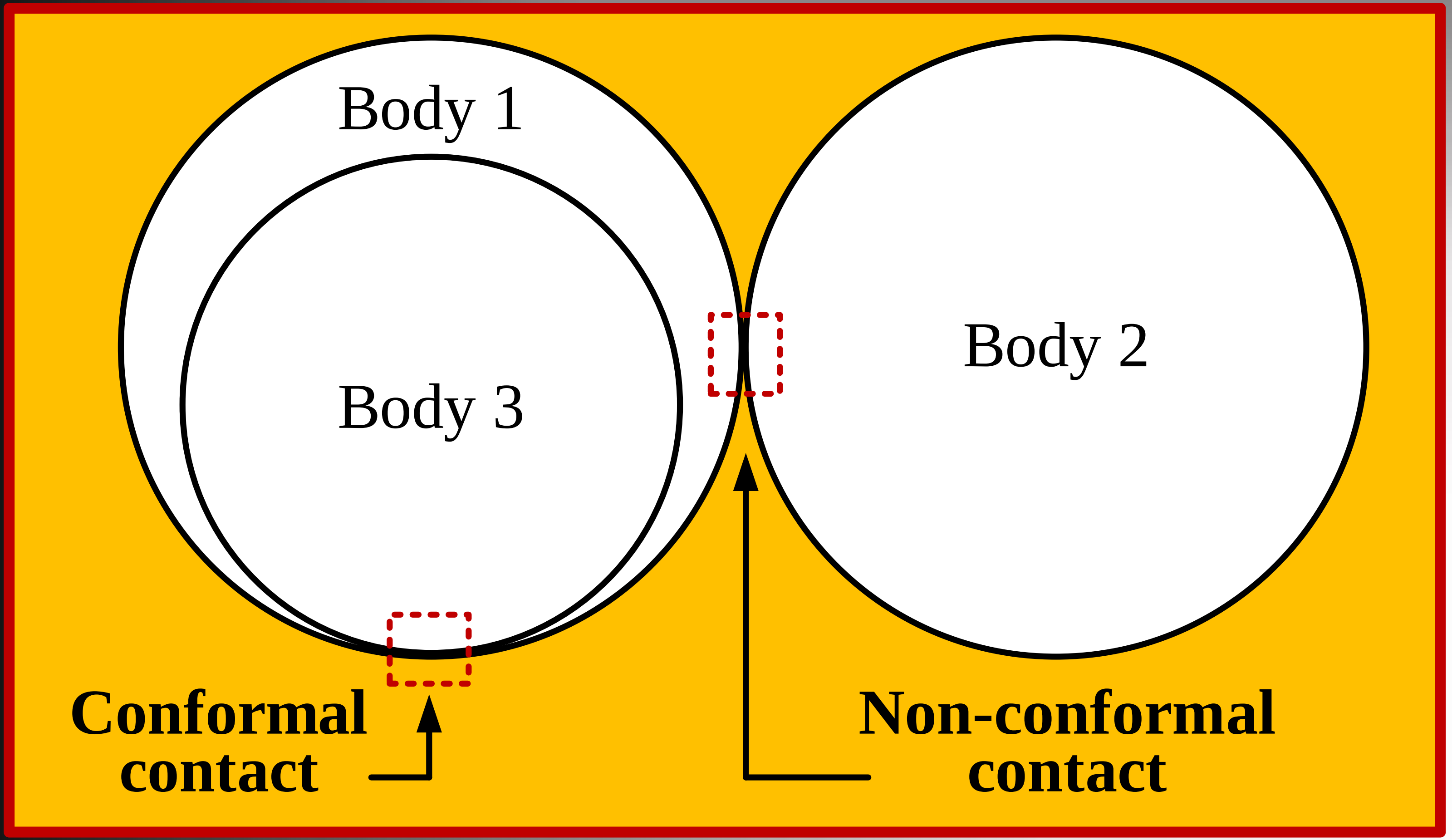
Bio tribology

frontiersin.org/

Classical tribology

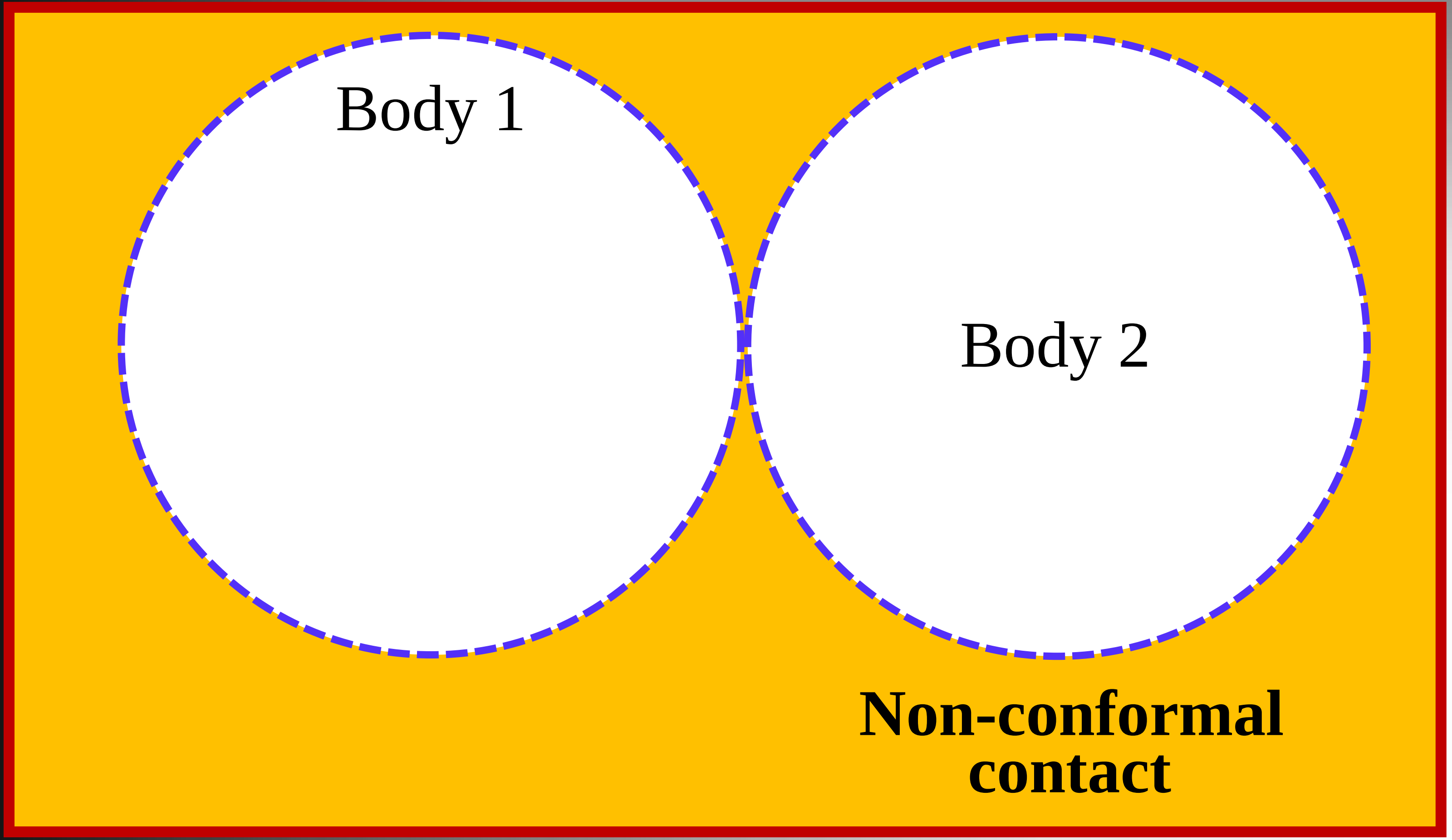
Jonny Hansen, jonny.hansen@scania.com

Contact classifications



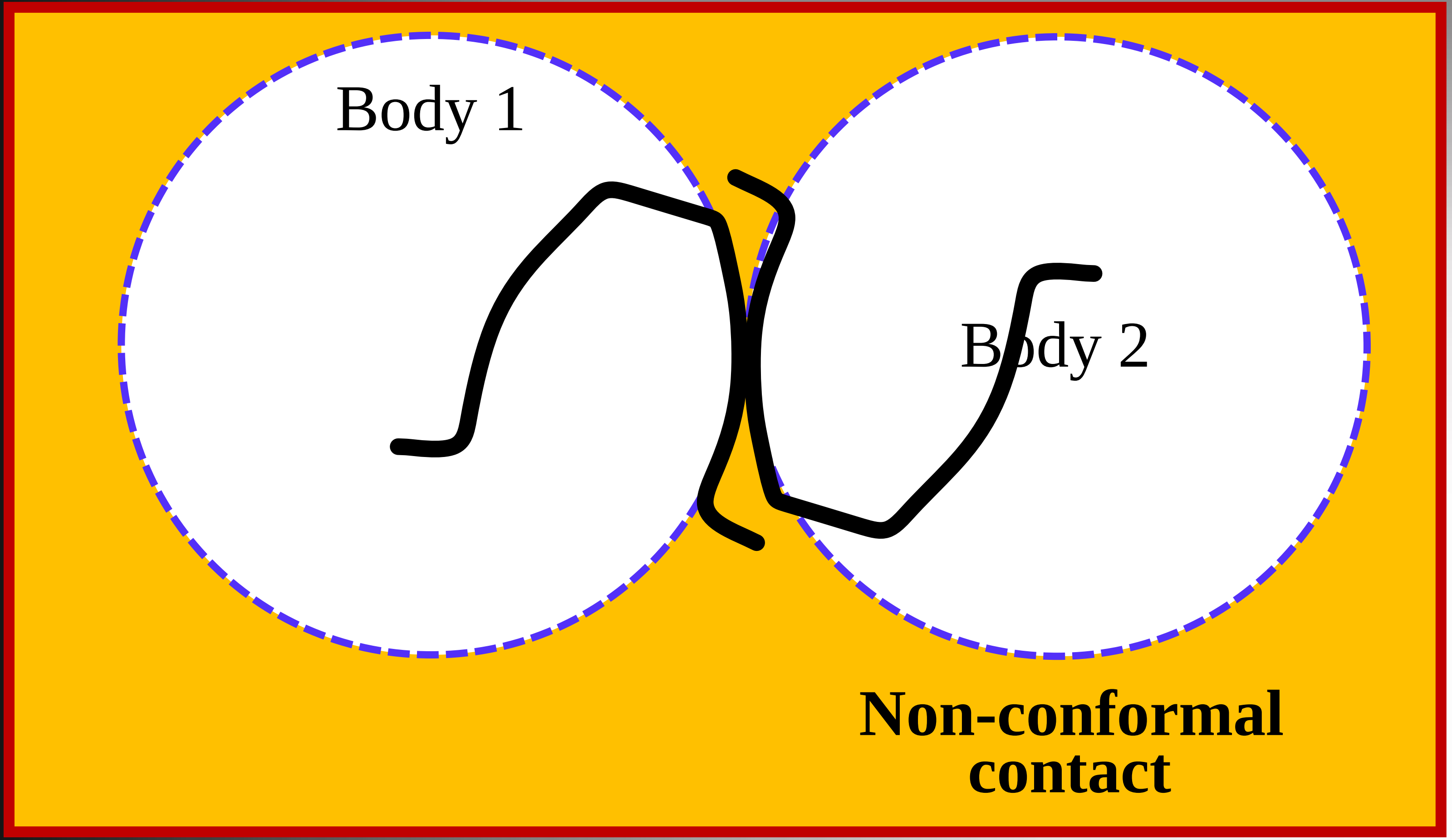
Classical tribology

Contact classifications



Classical tribology

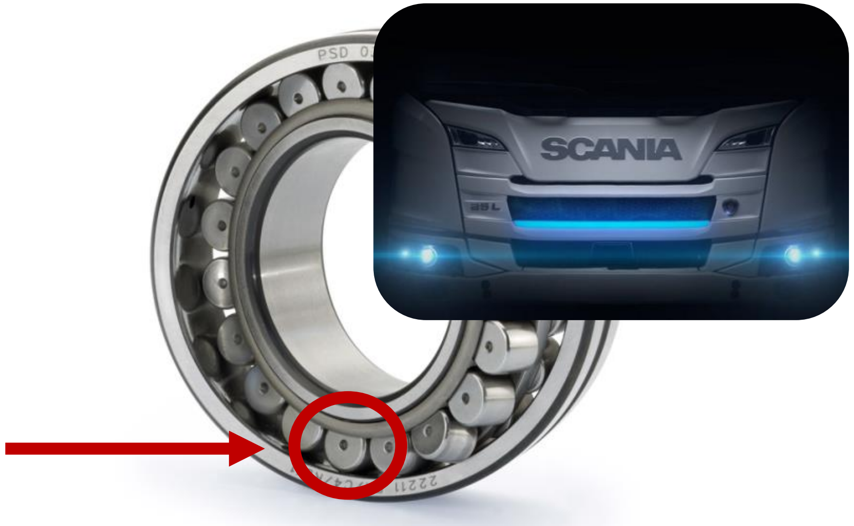
Contact classifications



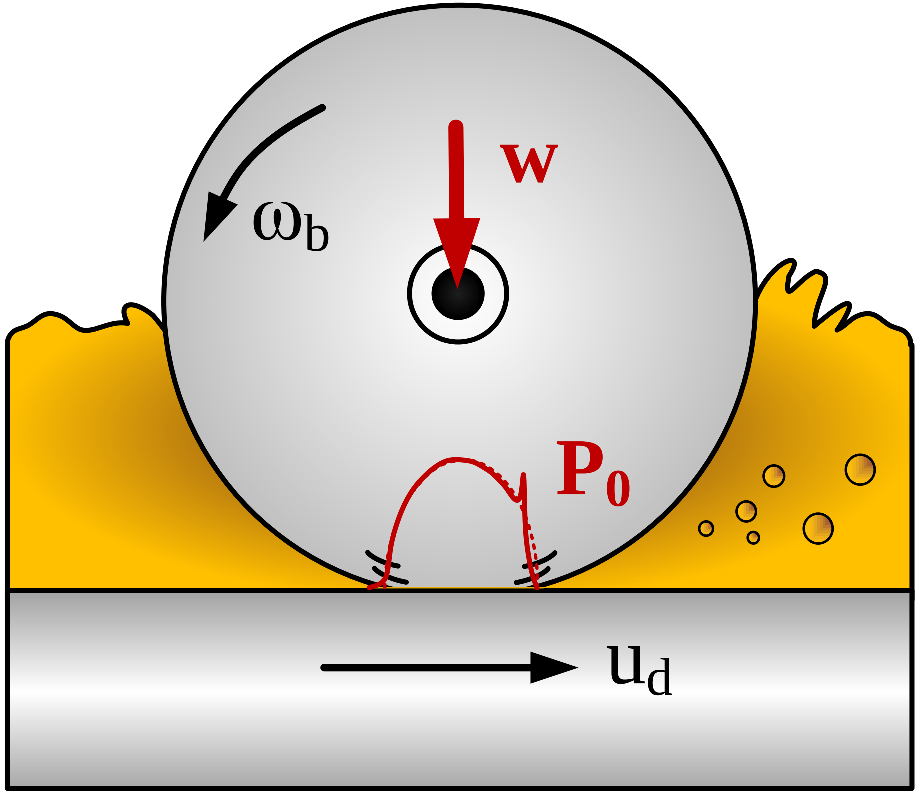
Classical tribology

Part 2 ▸ EHD lubrication mechanisms

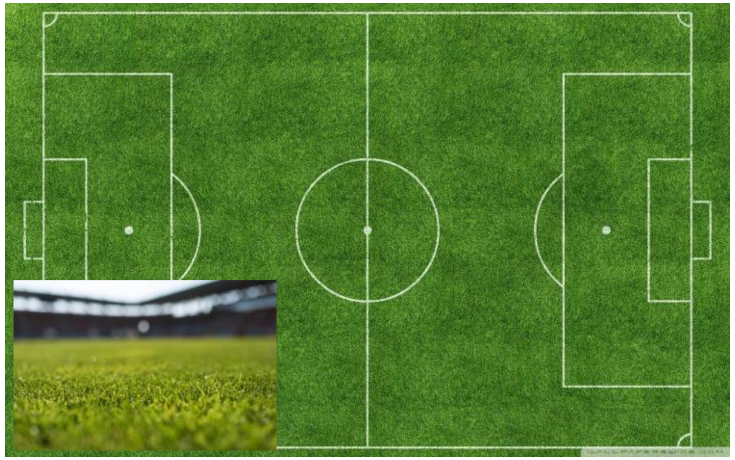
Classical tribology



The mechanism of EHL

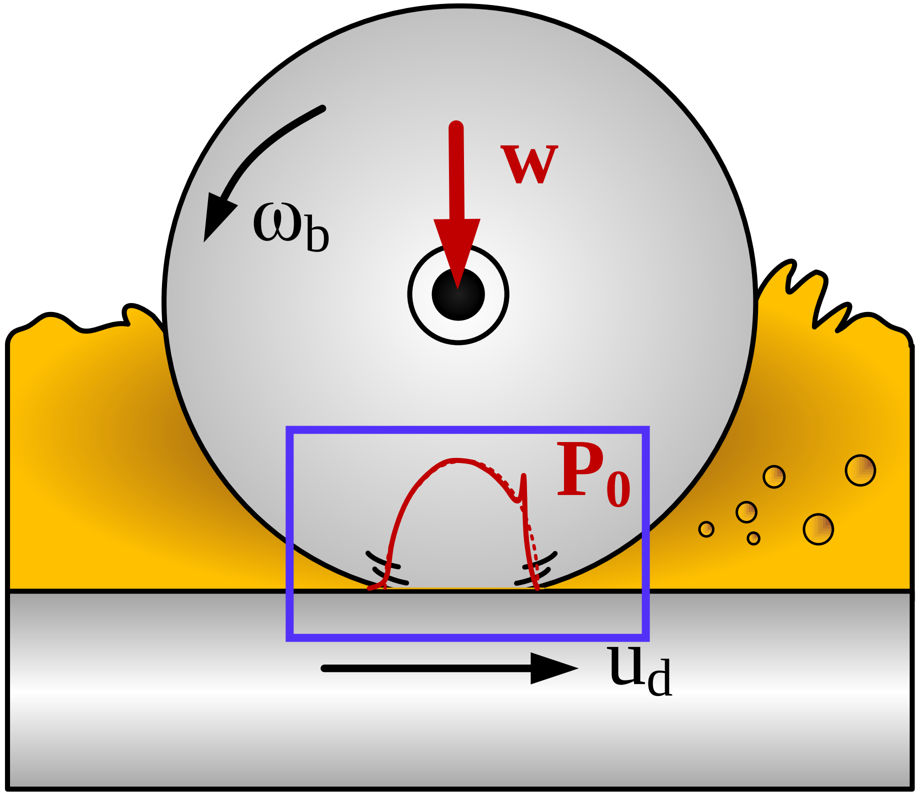


Typical values for a ball bearing
L=1 mm and h=100 nm

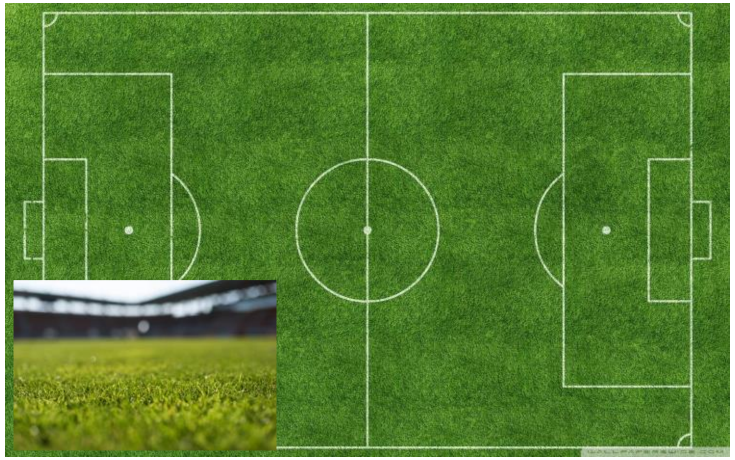


Typical values for a football pitch
L=100 m, h=1 cm

The mechanism of EHL

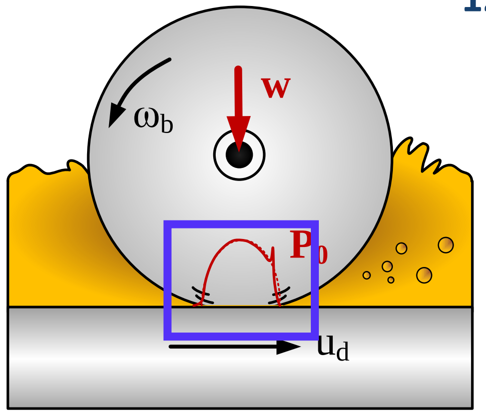


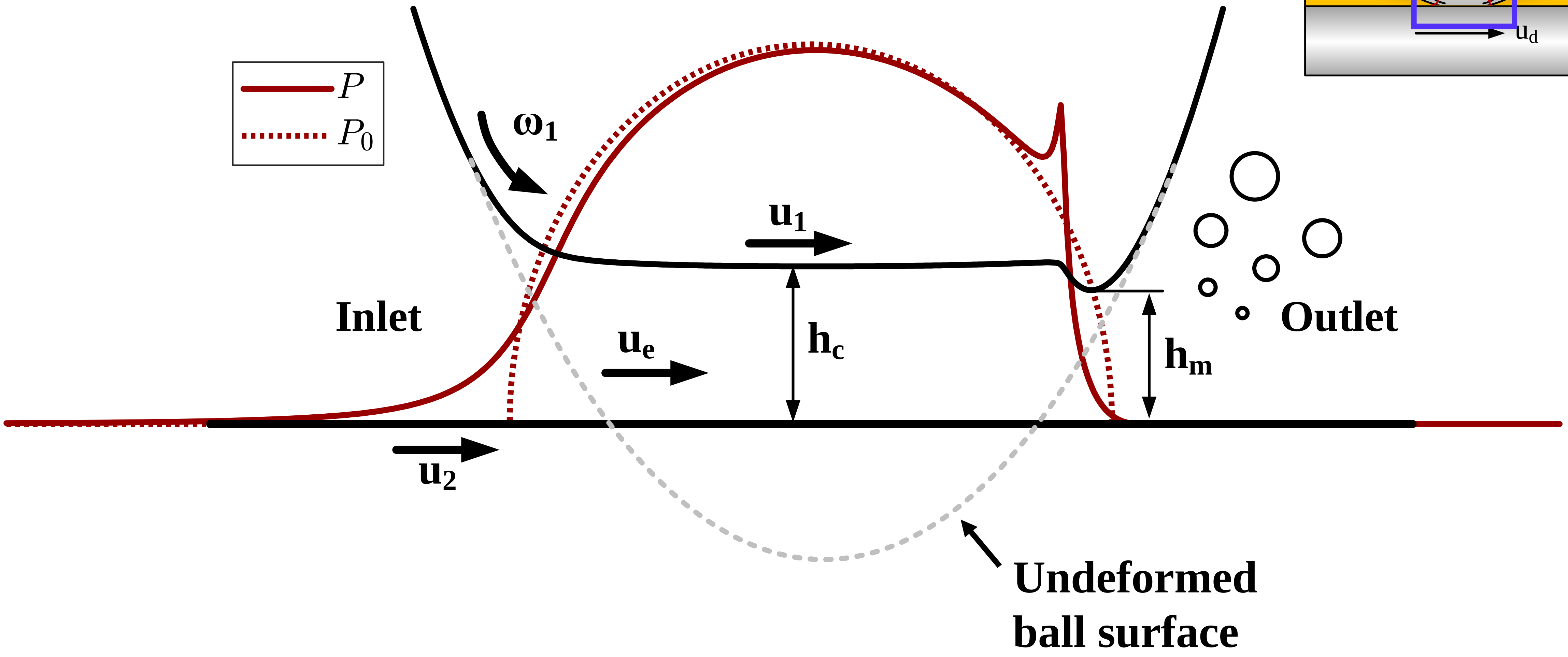
Typical values for a ball bearing
L=1 mm and h=100 nm



Typical values for a football pitch
L=100 m, h=1 cm

The mechanism of EHL





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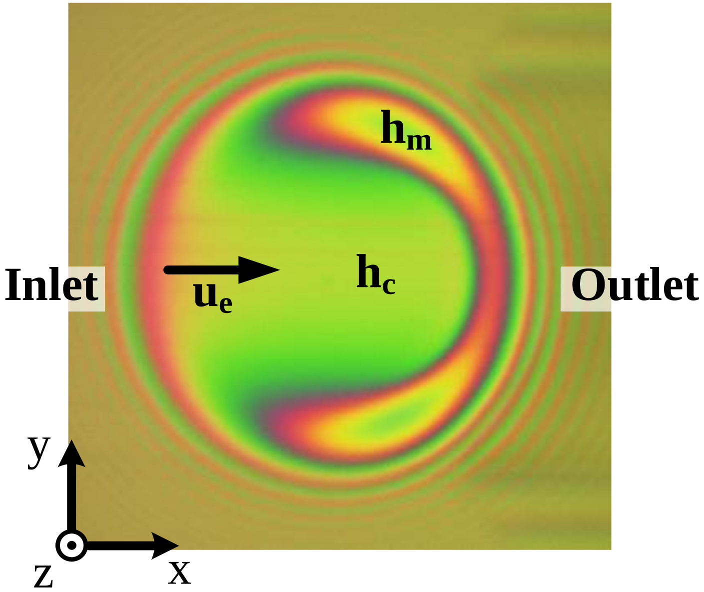
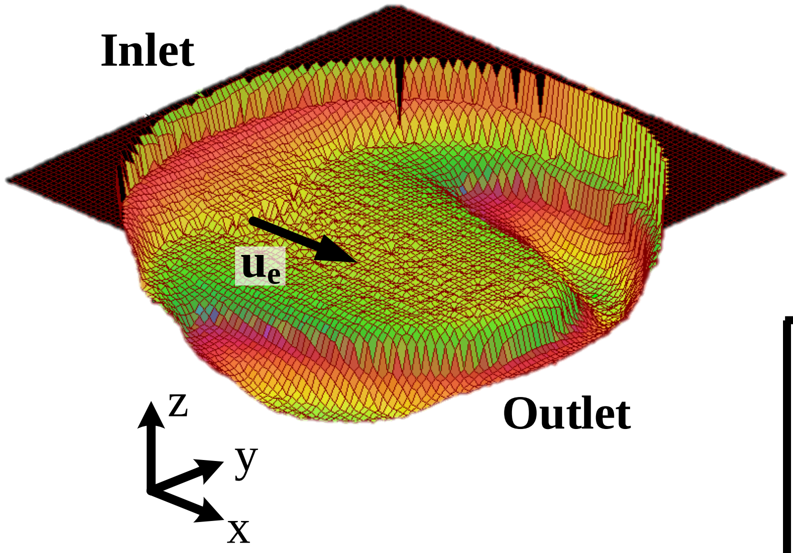
The mechanism of EHL





History at a glance

First ever recorded horseshoe shape

Material hidden for publication rights

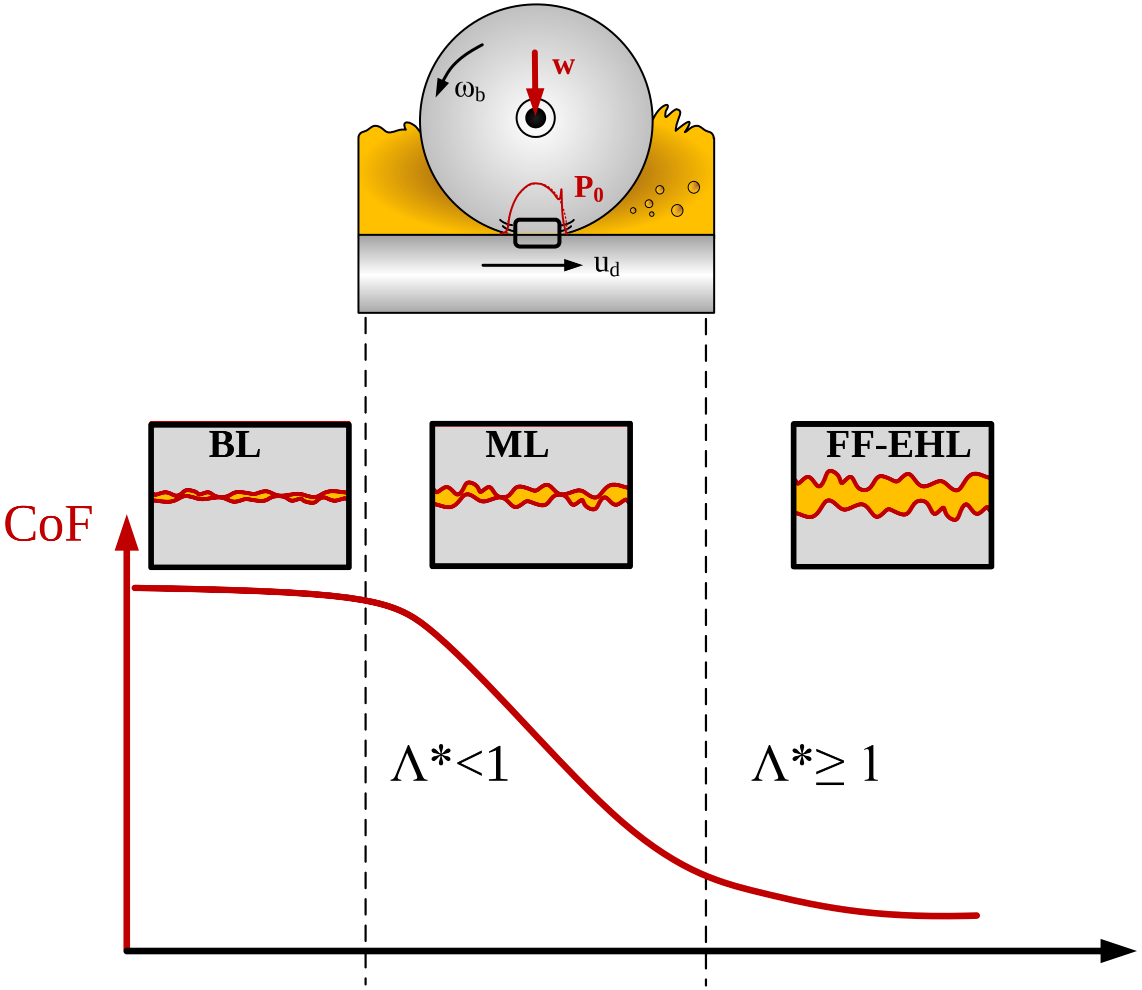
Gohar & Cameron (1963) *Nature*
https://doi.org/10.1038/200458b0

‘Stribeck curve’

Classical Λ-ratio

$$\Lambda = \frac{h_m}{Sq} \geq 3 \quad \text{for EHL}$$

Tallian, T.E.: On competing failure modes in rolling contact. *ASLE Trans*. 10, 418–439 (1967)
ISO: ISO/TS 6336-22:2018(E): Calculation of micropitting load capacity. (2018)



$$\Lambda^* = f\left(\frac{Speed \times Viscosity}{Load \times Surface\ Roughness}\right)$$

History at a glance

Development of the ’Stribeck’ Curve
Hirn GA (1854) – More speed, less friction
Thurston RH (1879) – Had the data!
Martens A (1888) – Established the curve

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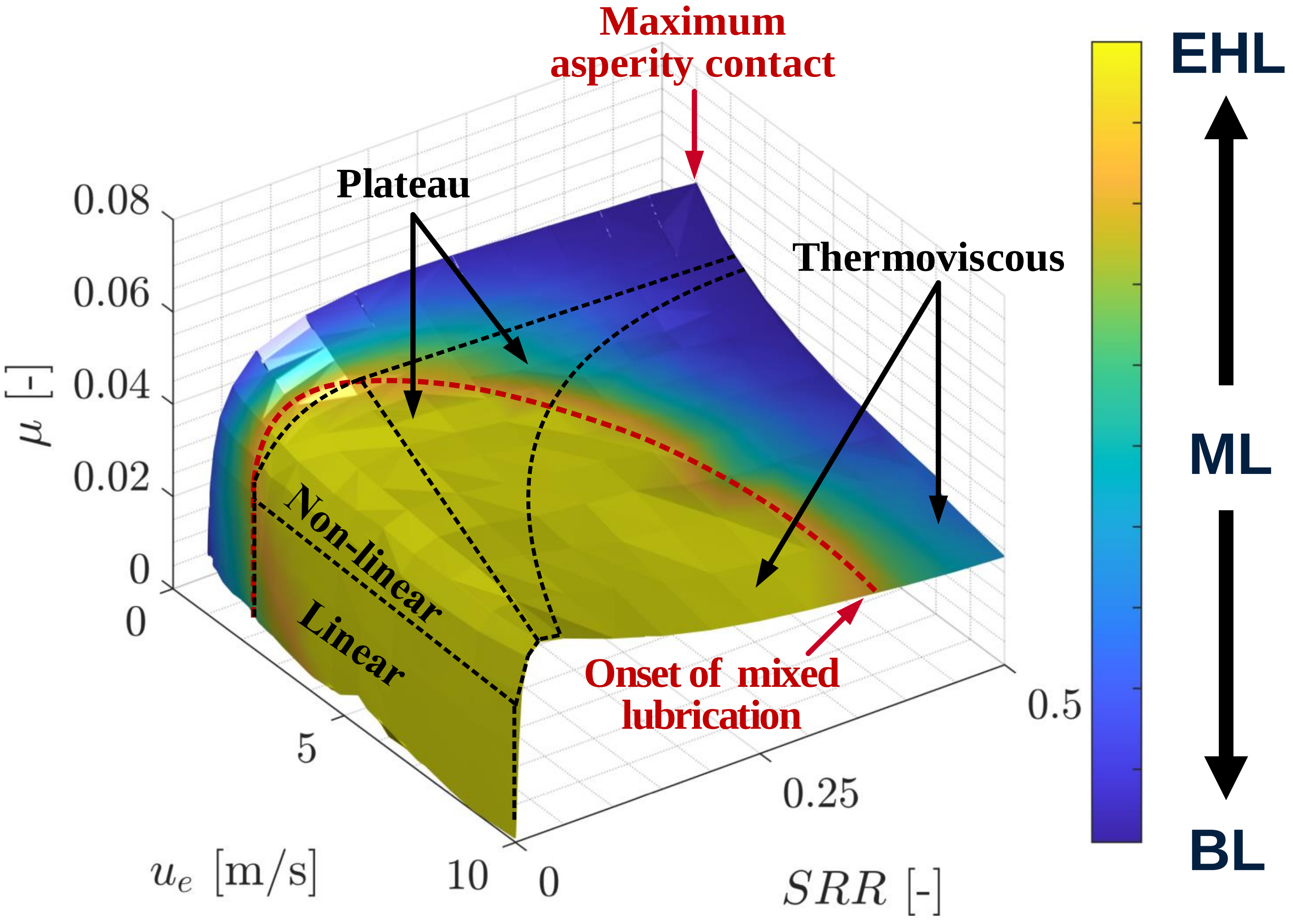
Stribeck R (1901)
Further reading: Wear 2010;268:1542–6

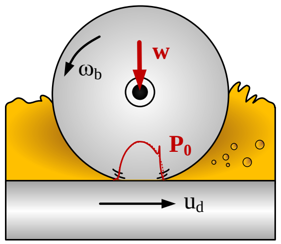
Lambda ratio on the x-axis
Tallian, TE (1967): ASLE Tr. 10, 418–439
Welson & Harris (1969): NASA SP-237.
Hamrock & Dowson (1981). Wiley, London

Updated film parameter, Lambda* ratio
Hansen et al. (2021). Trib. Lett. 69:37

‘Stribeck map’

Hansen, J., Björling, M., Larsson, R.:
Mapping of the lubrication regimes in rough surface EHL contacts.
Tribol. Int. (2018), 131, 637–651





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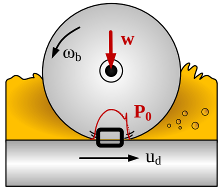
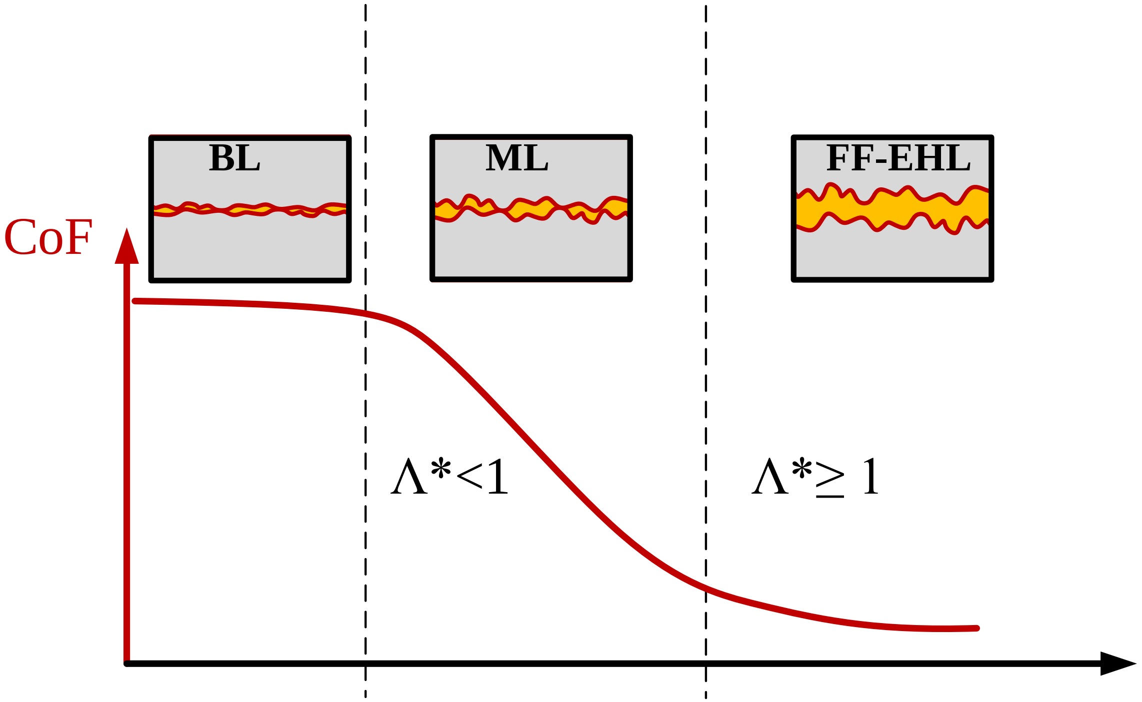
Part 3 ▸ What is e-tribology?

e-Tribology

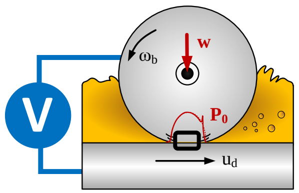


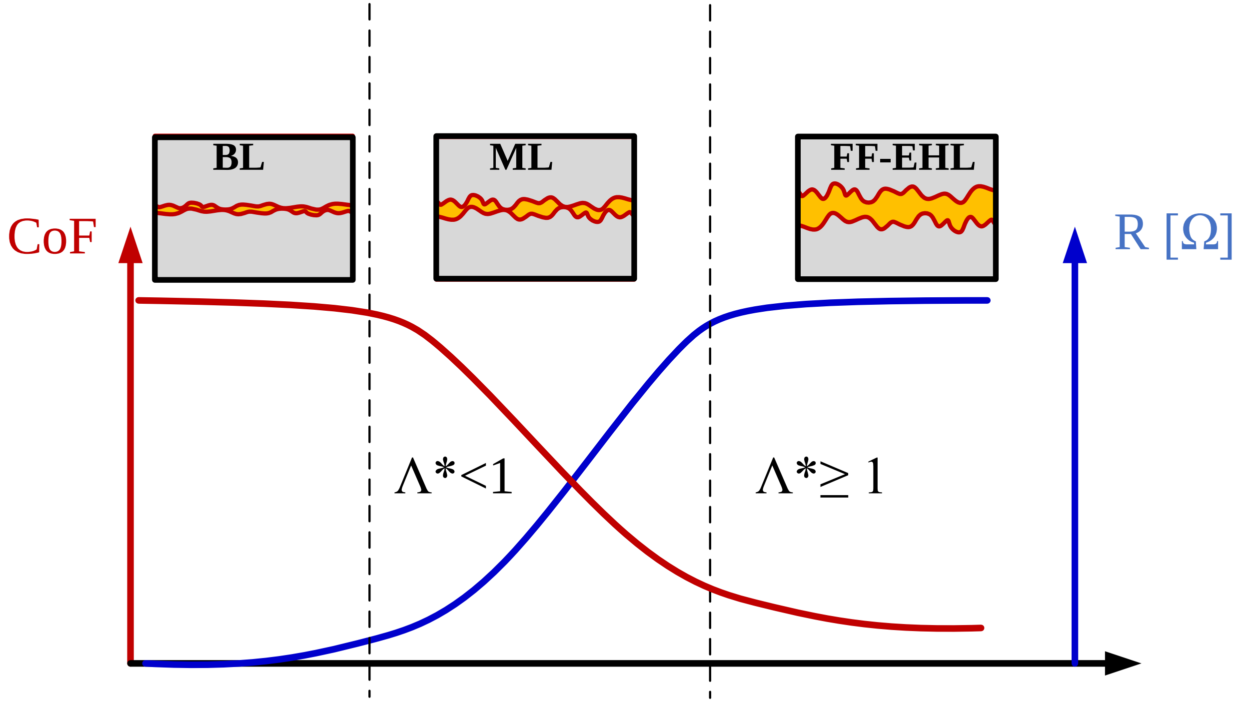


$$\Lambda^* = f\left(\frac{Speed \times Viscosity}{Load \times Surface\ Roughness}\right)$$

Hansen, J. (2021). *Elasto-hydrodynamic film formation in heavily loaded rolling-sliding contacts (Doctoral dissertation)*.

e-Tribology

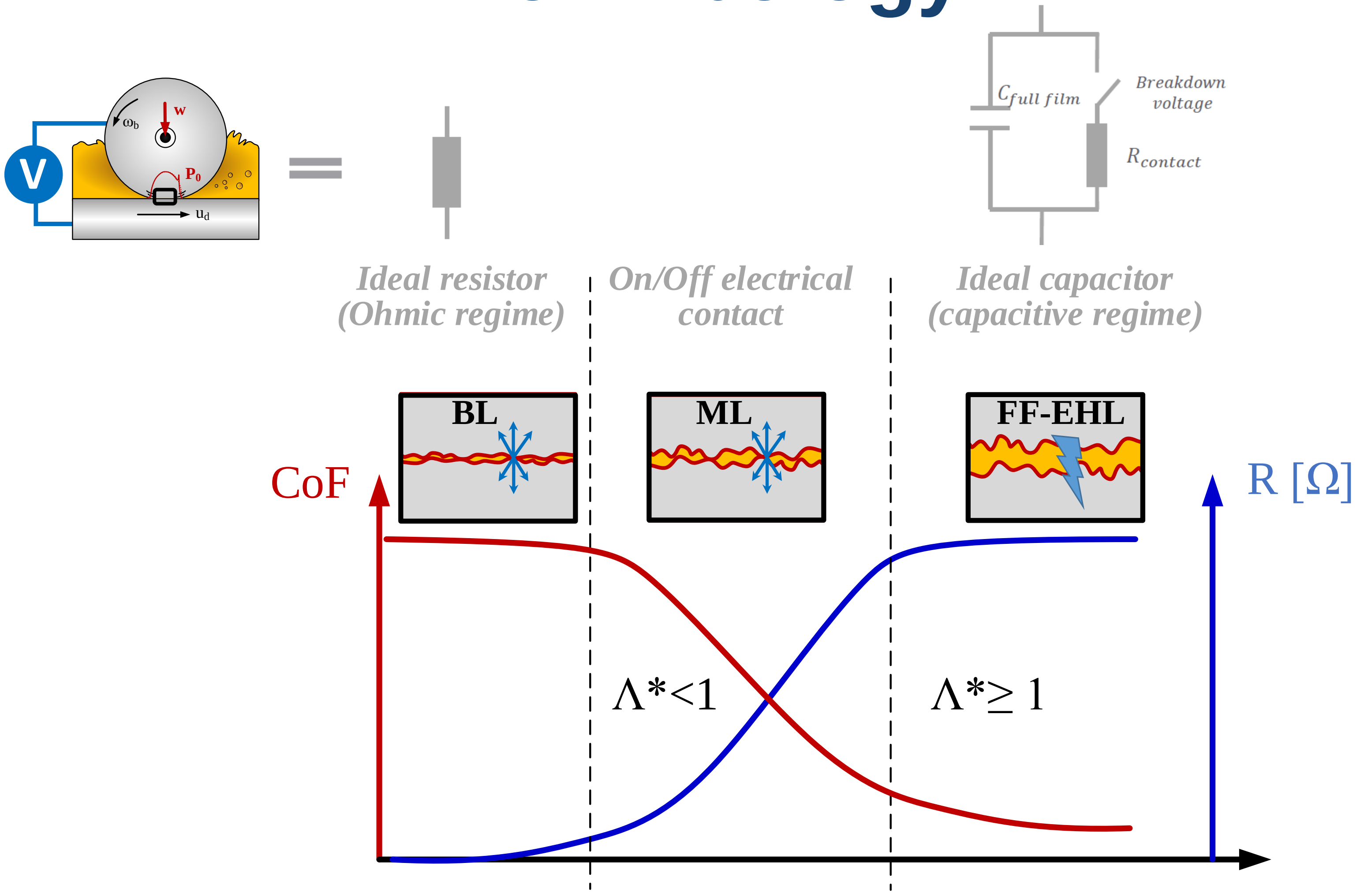




$$\Lambda^* = f\left(\frac{Speed \times Viscosity}{Load \times Surface\ Roughness}\right)$$

Hansen, J. (2021). *Elasto-hydrodynamic film formation in heavily loaded rolling-sliding contacts (Doctoral dissertation)*.

e-Tribology



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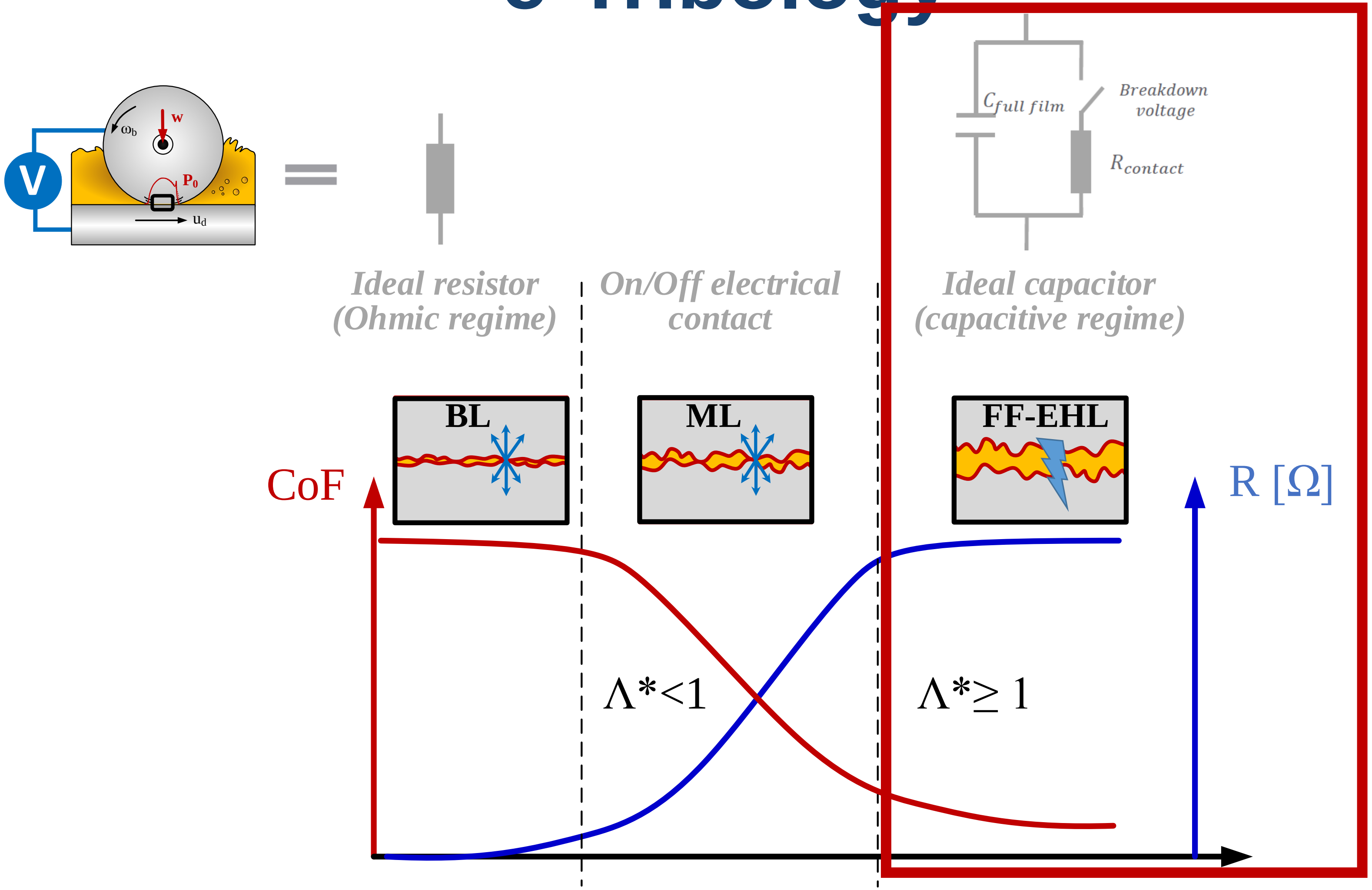

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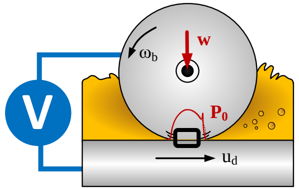
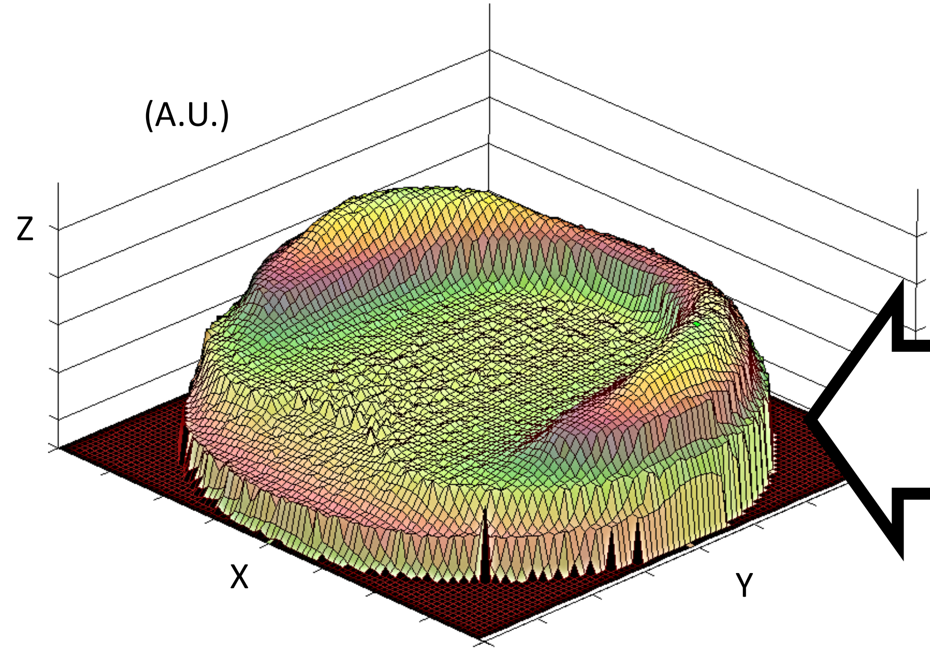
Hansen, J. (2021). *Elasto-hydrodynamic film formation in heavily loaded rolling-sliding contacts (Doctoral dissertation).*

e-Tribology



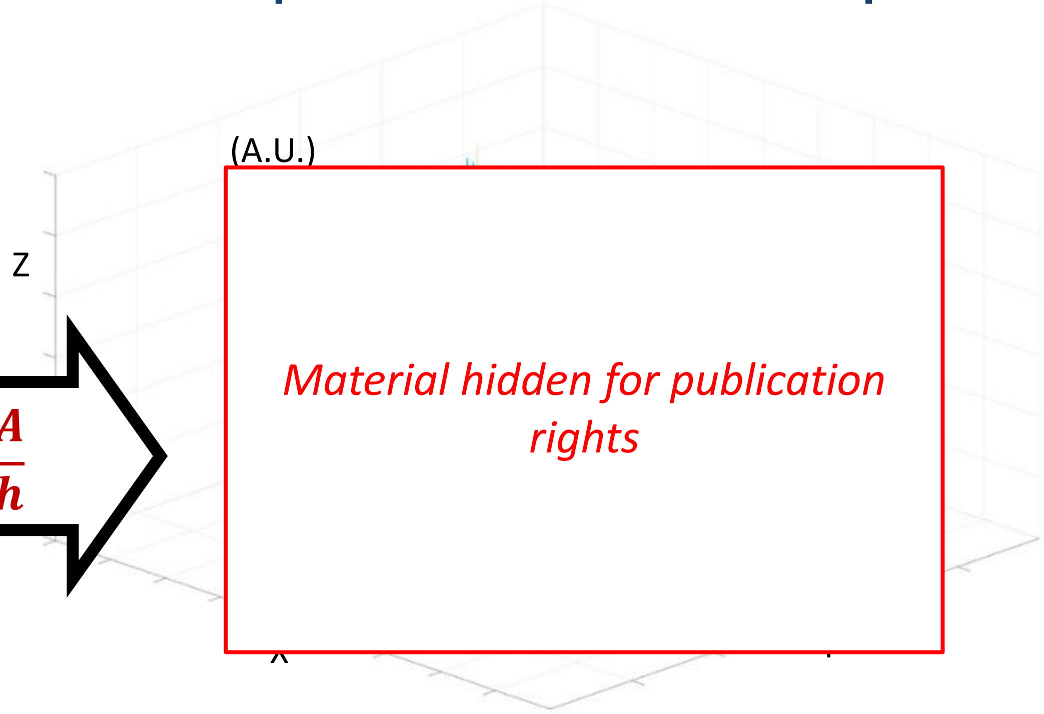
Film thickness horse-shoe shape



Hansen J. (2017)

$$C = \varepsilon \frac{A}{h}$$

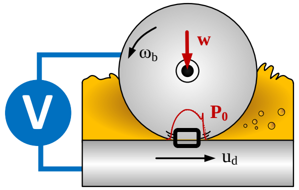
Capacitance horse-shoe shape



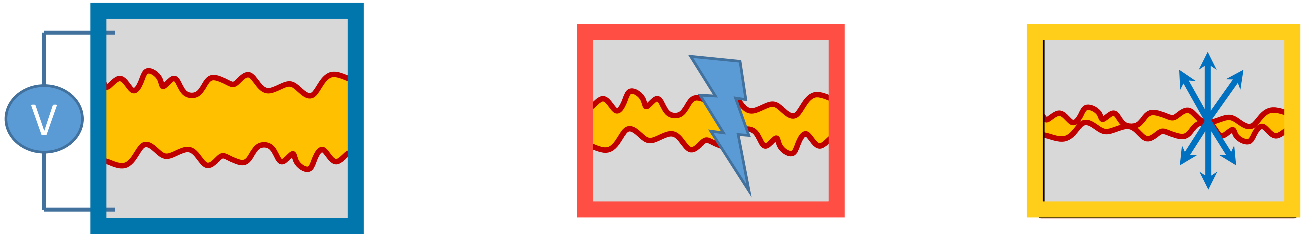
Material hidden for publication rights

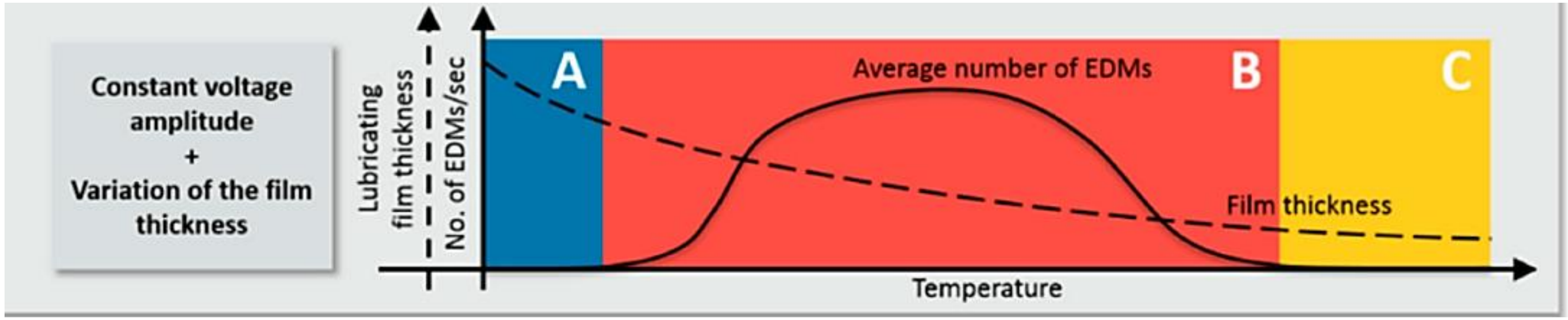
Schneider V, Liu HC, Bader N, Furtmann A, Poll G. Empirical formulae for the influence of real film thickness distribution on the capacitance of an EHL point contact and application to rolling bearings. Tribol Int 2021;154:106714. https://doi.org/10.1016/j.triboint.2020.106714.

e-Tribology



The electrical & lubrication regimes





Surface problems are now present even under lubrication conditions previously considered safe! (close to the transition between EHL & ML)

Mod. fr. Gonda, A., Capan, R., Bechev, D., & Sauer, B. (2019). The Influence of Lubricant Conductivity on Bearing Currents in the Case of Rolling Bearing Greases. Lubricants, 7(12), 108.

Part 4 ▸ Needs for a new film parameter

Needs for a new film parameter

Can full film lubrication be obtained for Λ's much smaller than 3?

www.nature.com/scientificreports

scientific reports

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Lubricant film formation in rough surface non-conformal conjunctions subjected to GPa pressures and high slide-to-roll ratios

Jonny Hansen[1,2]✉, Marcus Björling[1] & Roland Larsson[1]

A ball-on-disc machine was employed in a highly idealised setting to study the interplay between oil film formation and surface irregularities in single-sided rough elasto-hydrodynamic lubricated (EHL) conjunctions. The tests were operated under GPa pressures and high slide-to-roll ratios in a situation where the separating gap was smaller than the combined surface roughness height. Under the initial state of solid contact interference and with the operating conditions held fixed, surfaces were found to gradually conform such that a fully separating oil film of nanometre thickness eventually developed—a thin film lubrication state known as micro-EHL. Additionally, with a previously developed approach for 3D surface re-location analysis, we were able to very precisely specify the pertained nature of surface transformations, even at the asperity scale, by comparing the post-test surfaces to those in the virgin state. The surface roughness Sq was reduced by up to 17% after running-in, while the speed required for full film EHL was reduced by a remarkable 90%. Hence, full film EHL is possible even in cases where the Λ-ratio falsely suggests boundary lubrication. This discrepancy was attributed to the way surfaces are deformed inside the contact, i.e., through the establishment of micro-EHL.

[1]Division of Machine Elements, Luleå University of Technology, 97187 Luleå, Sweden. [2]Transmission Development, Scania CV AB, Södertälje, Sweden. ✉email: jonny.hansen@scania.com

Scientific Reports | (2020) 10:22250 | https://doi.org/10.1038/s41598-020-77434-y nature research 1

Read more:

- https://www.nature.com/articles/s41598-020-77434-y
- Can full film occur when Lambda = 0.6? - About Tribology (tribonet.org)

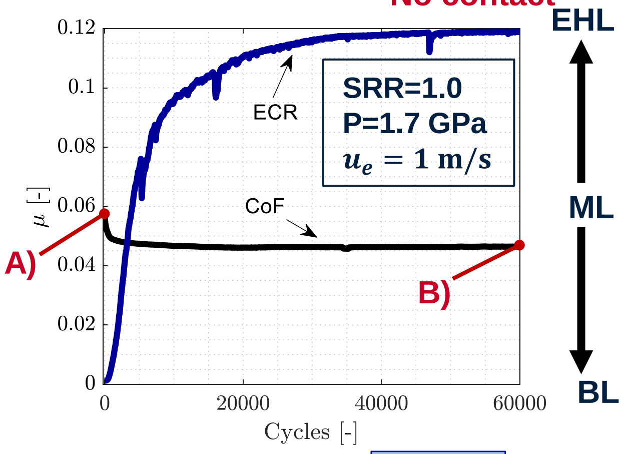
TribNet

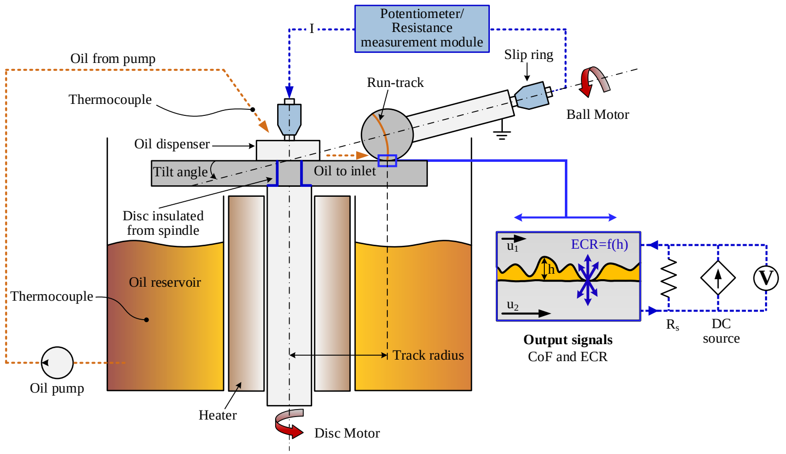
nature research

Needs for a new film parameter

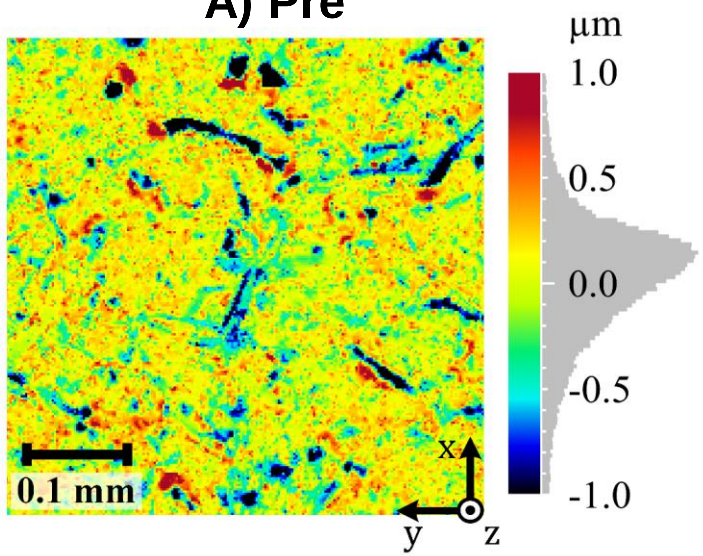
Full film lubrication can be obtained for Λ's much smaller than 3!

EHD lift-off tests



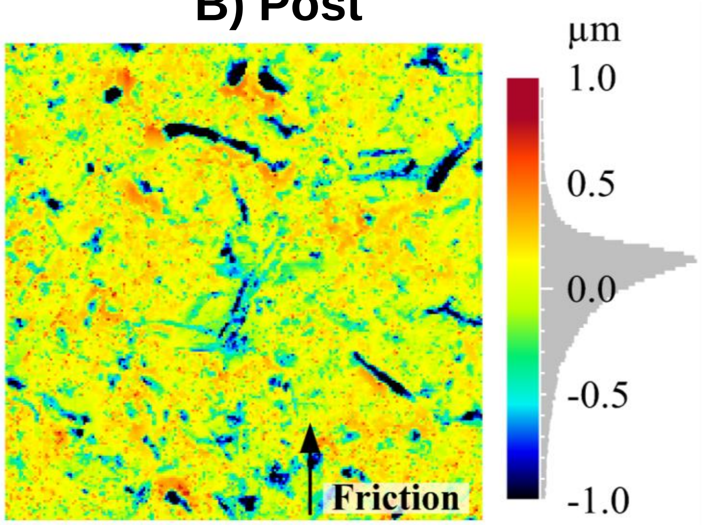


A) Pre



$Sq = 0.35$ μm
$\Lambda = 0.52$
$(h_m = 0.18$ μm$)$

B) Post



$Sq = 0.30$ μm
$\Lambda = 0.61$

Should be ≥ 3!

Hansen, J., Björling, M., & Larsson, R. (2020).
Lubricant film formation in rough surface non-conformal conjunctions subjected to GPa pressures and high slide-to-roll ratios.
Scientific Reports, 10(22250), 1–16. https://www.nature.com/articles/s41598-020-77434-y

Needs for a new film parameter

Full film lubrication can be obtained for Λ's much smaller than 3!

$$\Lambda = \frac{h_m}{Sq} \geq 3$$

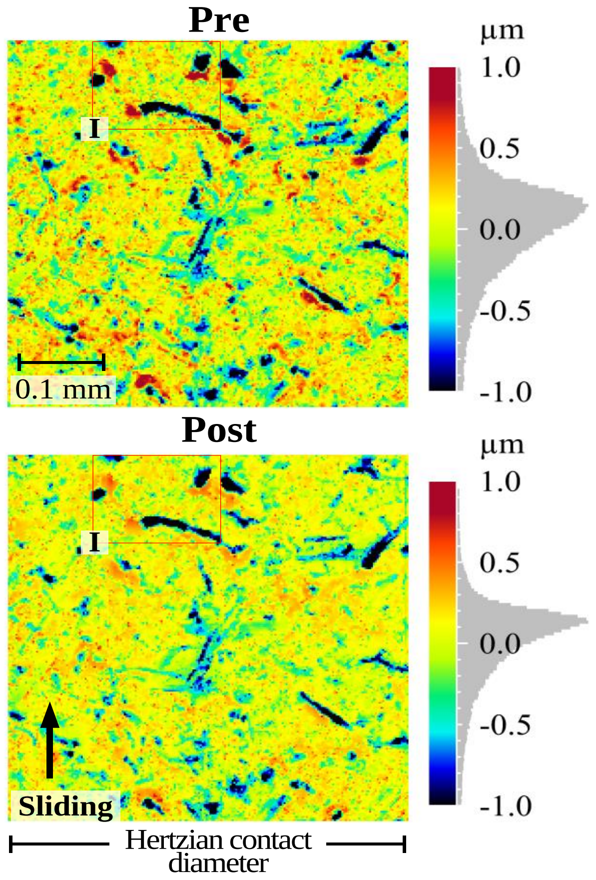
Does not hold for run-inned (non Gaussian) surfaces

Why?

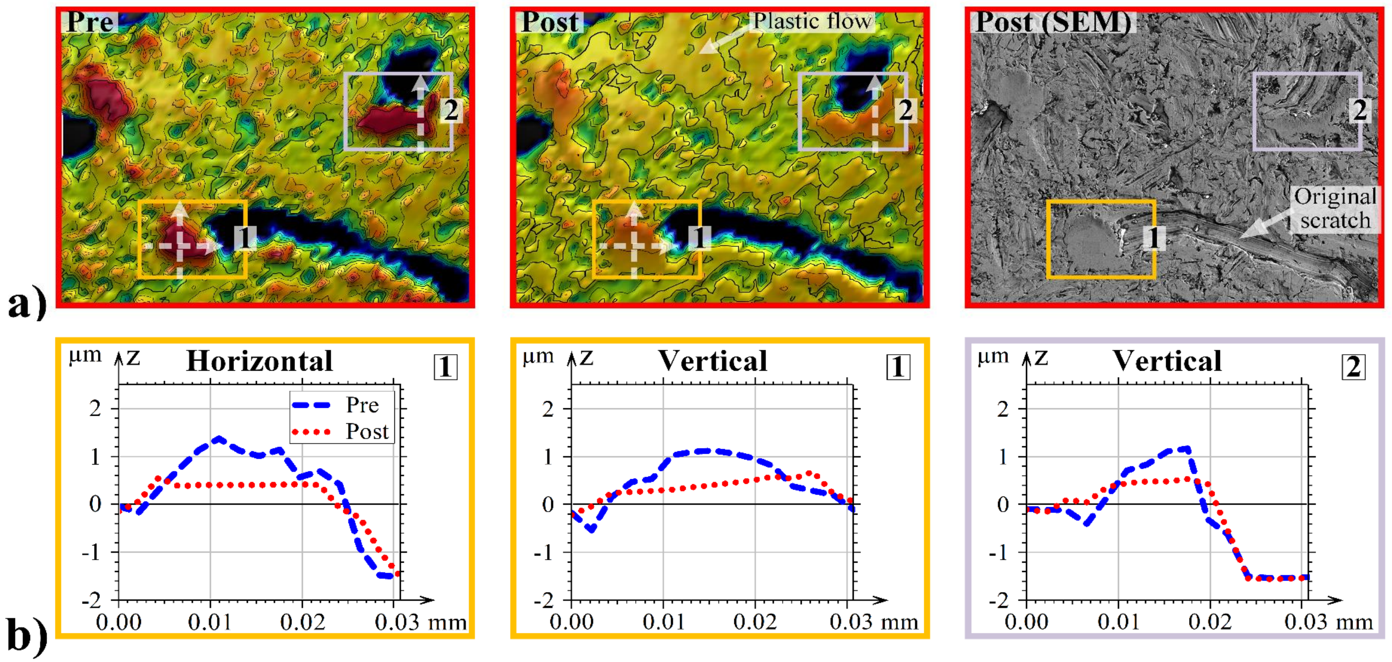
Needs for a new film parameter

- Asperity peaks are moderately flattened during running-in
- Deep valleys are hardly affected at all

} **Reflects poorly on Sq (RMS)**



Asperity deformations



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Lubricant film formation in rough surface non-conformal conjunctions subjected to GPa pressures and high slide-to-roll ratios.
Scientific Reports, 10(22250), 1–16. https://www.nature.com/articles/s41598-020-77434-y

Needs for a new film parameter

- Asperity peaks are moderately flattened during running-in
- Deep valleys are hardly affected at all
- Asperity summit radii becomes much larger

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Reflects poorly on Sq (RMS)

Hansen, J., Björling, M., & Larsson, R. (2022). A new film parameter with micro-elasto-hydrodynamics. In *7th world tribology congress, WTC*.

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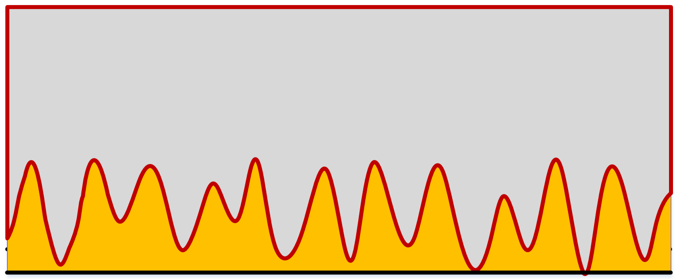

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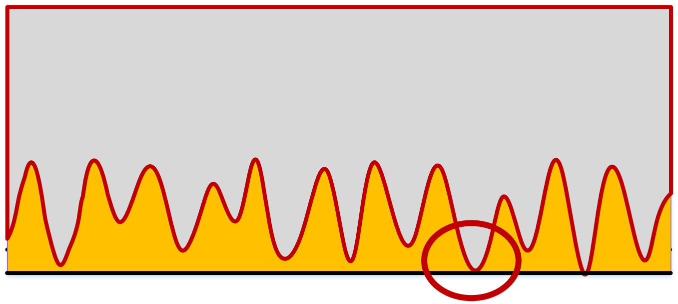

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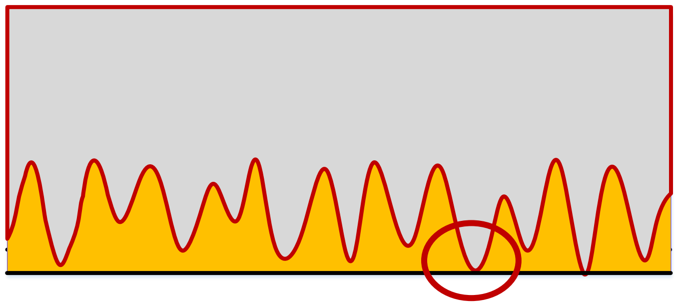

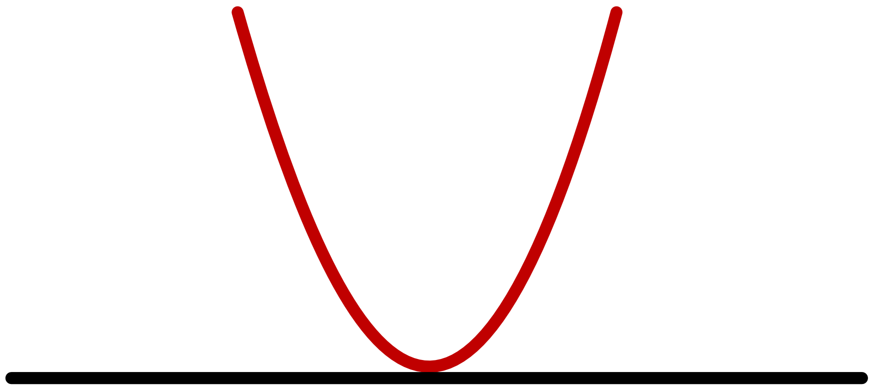

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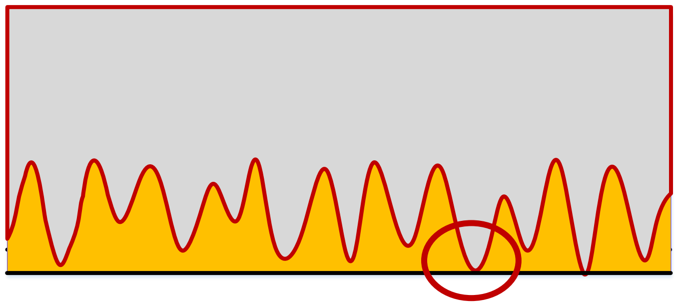

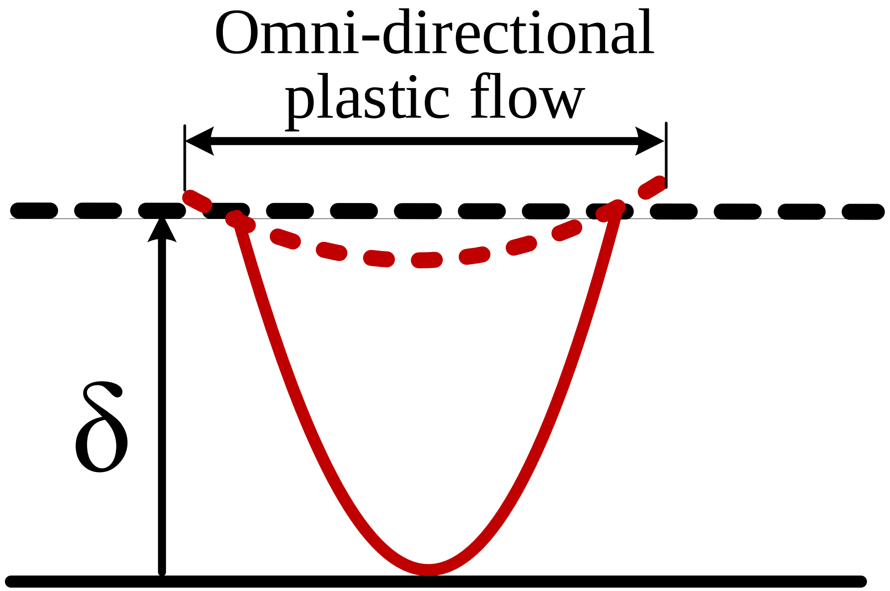

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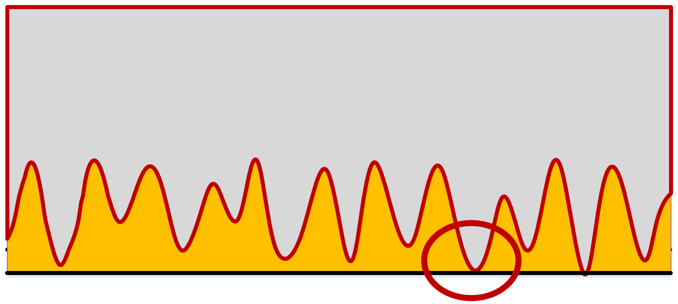
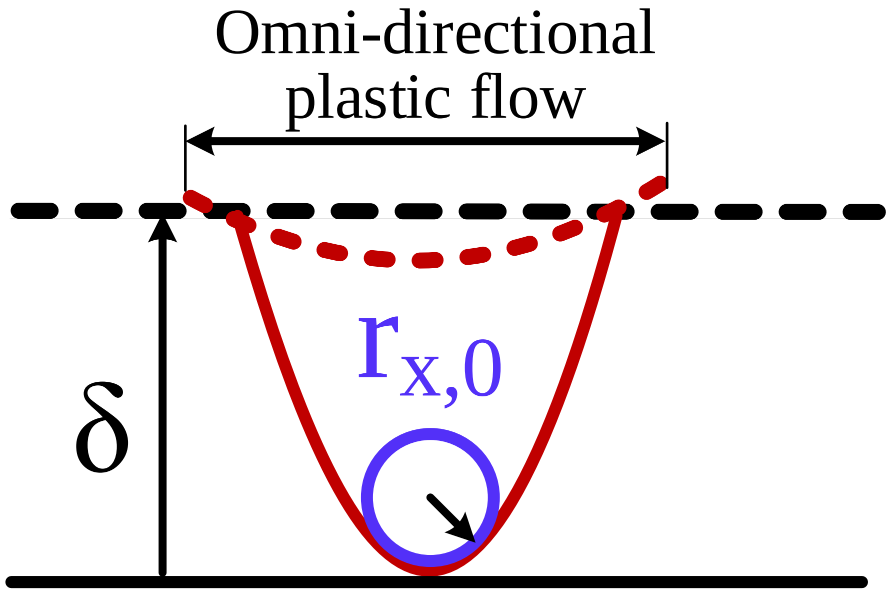
Reflects poorly on Sq (RMS)



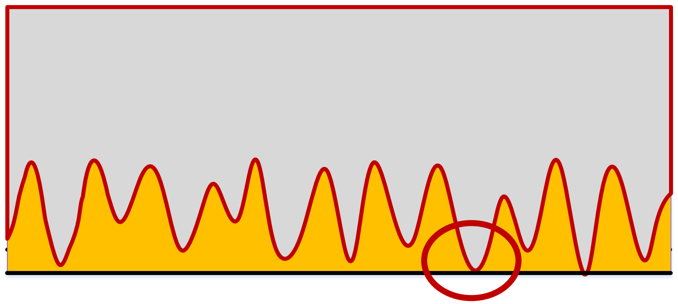


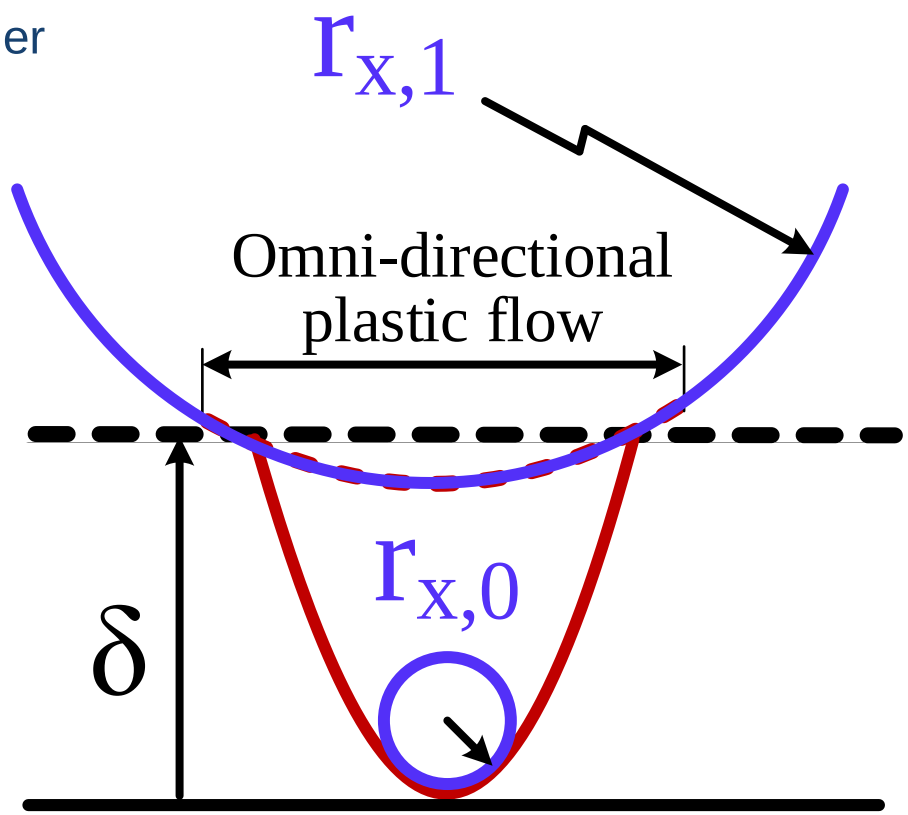
Hansen, J., Björling, M., & Larsson, R. (2022). A new film parameter with micro-elasto-hydrodynamics. In *7th world tribology congress, WTC*.

Needs for a new film parameter

- Asperity peaks are moderately flattened during running-in
- Deep valleys are hardly affected at all
- Asperity summit radii becomes much larger

Reflects poorly on Sq (RMS)





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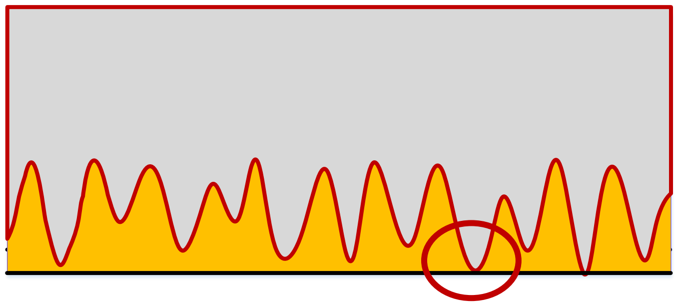
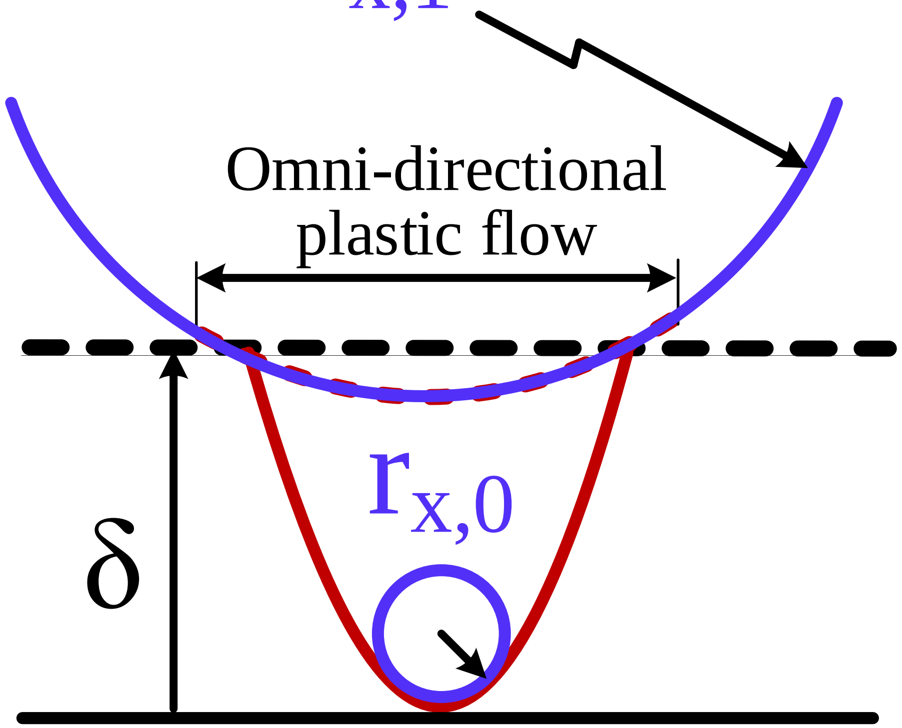
Needs for a new film parameter

- Asperity peaks are moderately flattened during running-in
- Deep valleys are hardly affected at all
- Asperity summit radii becomes much larger

} **Reflects poorly on Sq (RMS)**

$r_{x,1}$ — **Affects micro-EHL**



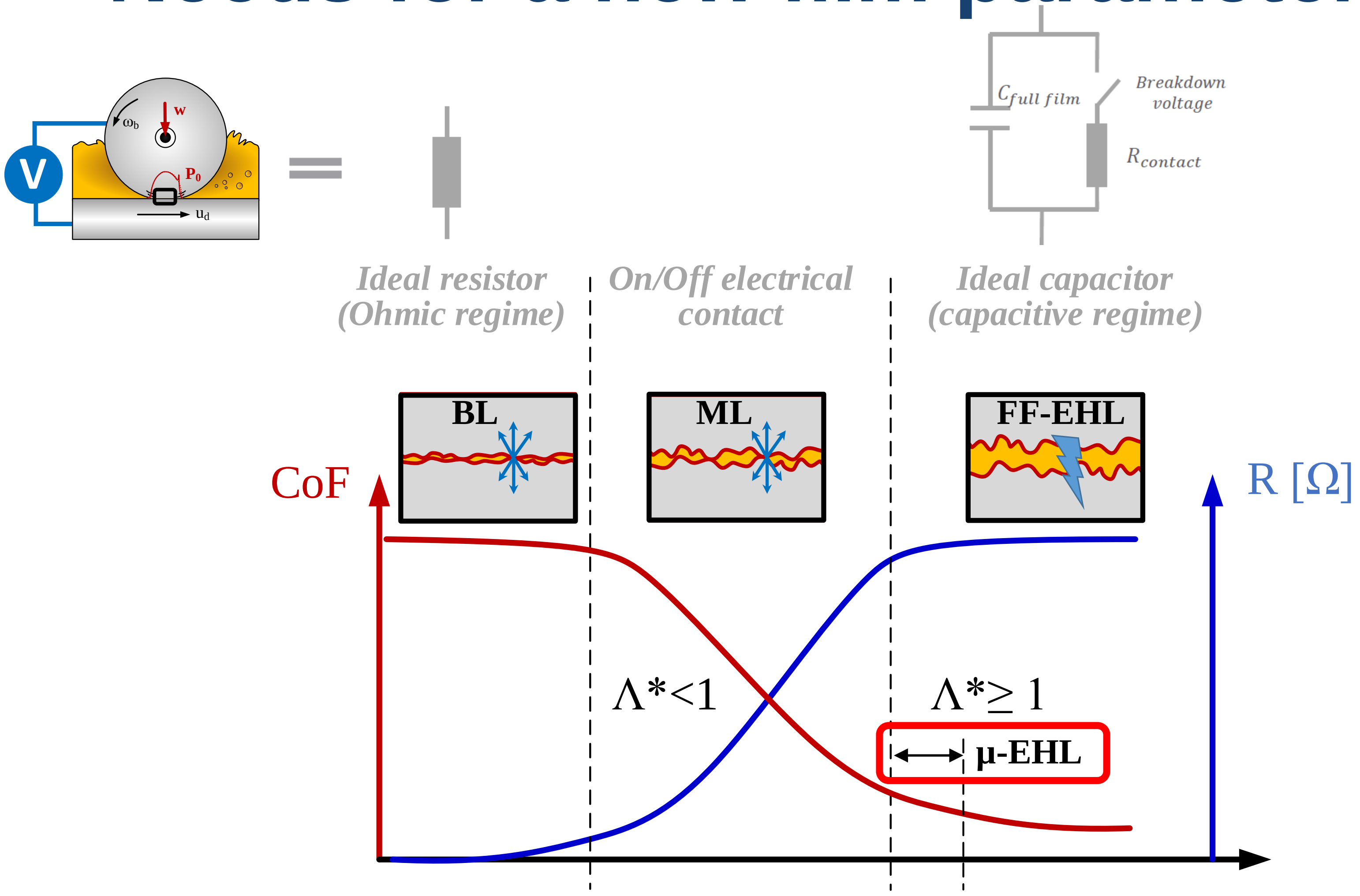


$$h_a = h_c \times \left(\frac{r_x}{R_x}\right)^{0.464}$$

Choo JW, Glovnea RP, Olver A V., Spikes H. A. (2003). Journal of Tribology 2003;125:533.

Hansen, J., Björling, M., & Larsson, R. (2022). A new film parameter with micro-elasto-hydrodynamics. In *7th world tribology congress, WTC*.

Needs for a new film parameter



$$\Lambda^* = f\left(\frac{EHD\ film\ thickness}{(Surface\ Roughness - Roughness\ Deformation)}\right)$$

Hansen, J. (2021). *Elasto-hydrodynamic film formation in heavily loaded rolling-sliding contacts (Doctoral dissertation).*

Needs for a new film parameter

Micro-Elastohydrodynamic Lubrication

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u_e

SRR = -100%

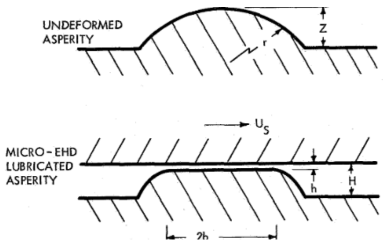
Micro-horseshoe film thickness shapes (..& capacitance constrictions)

$$h_{asp} = h_c \times \left(\frac{r_x}{R_x}\right)^{0.464}$$

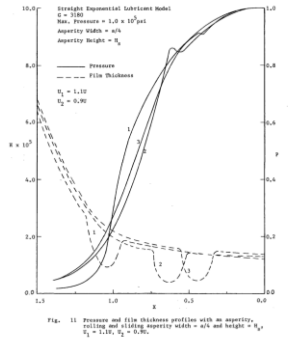
Choo JW, Glovnea RP, Olver A V., Spikes H. A. (2003). Journal of Tribology 2003;125:533.

History at a glance

Early theoretical postulates
Fein, R.S., Kreuz, K.L. (1967).
NASA SP-181



Early (first?) simulation attempt
Lee K, Cheng H.S. (1973).
NASA CR-2195



First experimental attempt
Jackson A & Cameron A. (1976).
ASLE Transactions 1976;19:1

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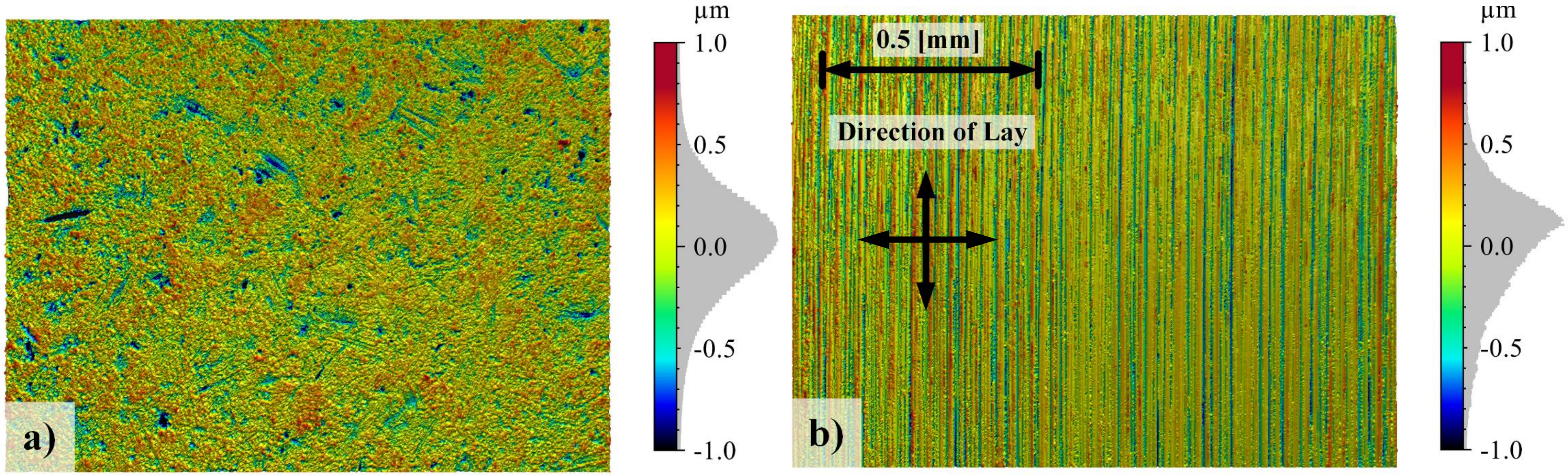
Needs for a new film parameter

Engineering roughness is 3D in nature and deformable and this affects micro-EHL (and side leakage)



Isotropic
RMS Sq=0.282 µm

Transversal/Longitudinal
RMS Sq=0.284 µm

Hansen, J. (2021). *Elasto-hydrodynamic film formation in heavily loaded rolling-sliding contacts (Doctoral dissertation)*.

$$\Lambda = \frac{h_m}{Sq} \geq 3$$

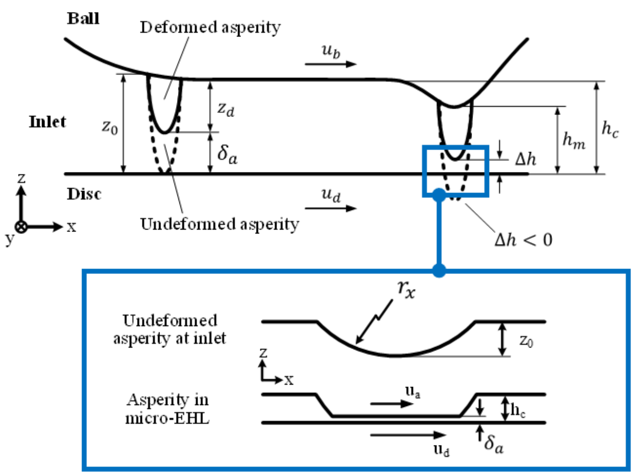
Key takeaways

- ✓ Sq is not a sufficient representation of the roughness height
- ✓ Asperity radii increase with running-in promotes micro-EHL
- ✓ 3D nature of roughness affect micro-EHD film formation

→ **Must be accounted for to get a good estimate of the EHL-ML transition!**

Needs for a new film parameter

An Updated Film Parameter with Micro-Elastohydrodynamics can be used to assess the electrical & lubrication regimes to a good degree of accuracy



$$\Lambda^* = \frac{h_m}{z_0 - \delta_a} = \frac{h_m}{S_{pk} - [f_q(r_x) \times h_c]}$$

$\Lambda^* \geq 1$: Full film lubrication

$\Lambda^* < 1$: Mixed lubrication

Hansen, J., Björling, M., & Larsson, R.,
”**A New Film Parameter for Rough Surface EHL Contacts with Anisotropic and Isotropic Structures**”,
Tribology Letters (2021) 69:37

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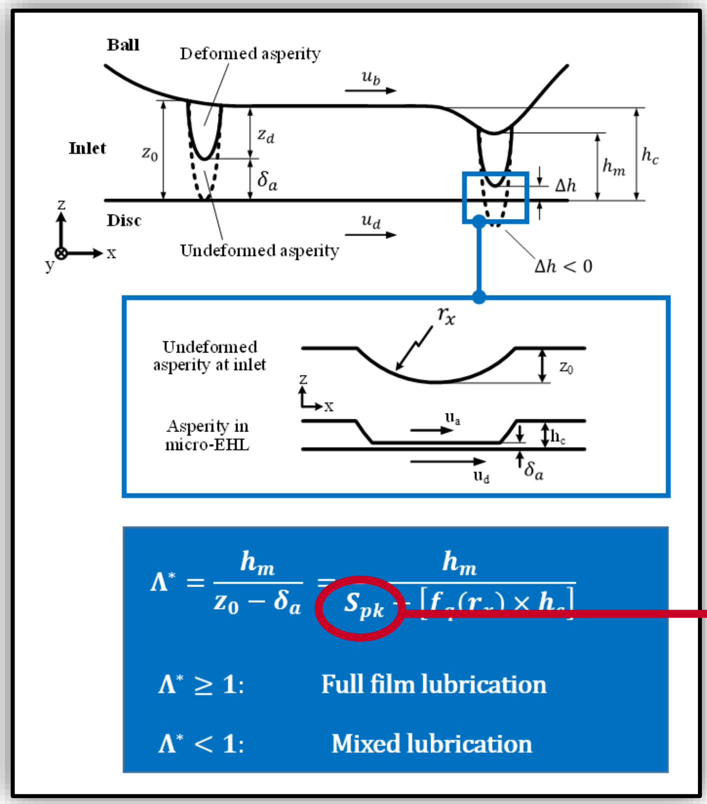
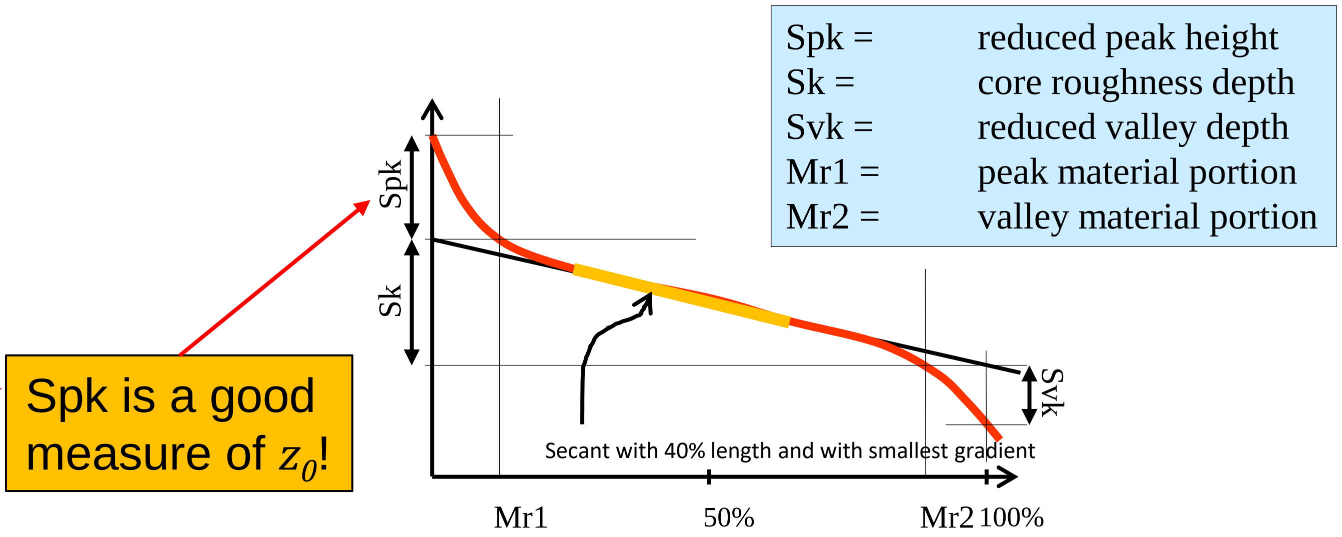


The bearing ratio curve

and parameters defined from it



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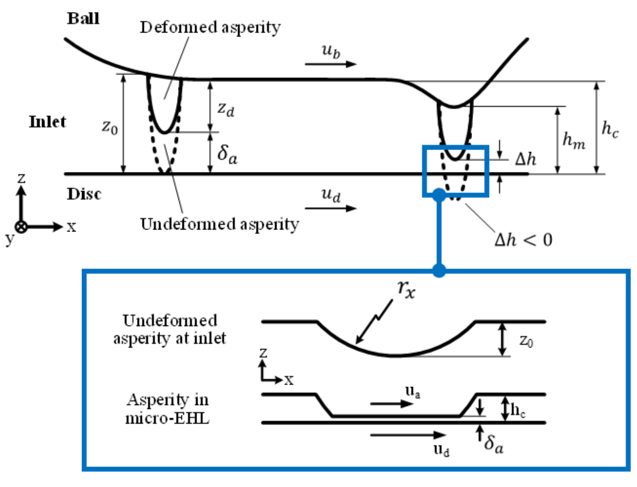

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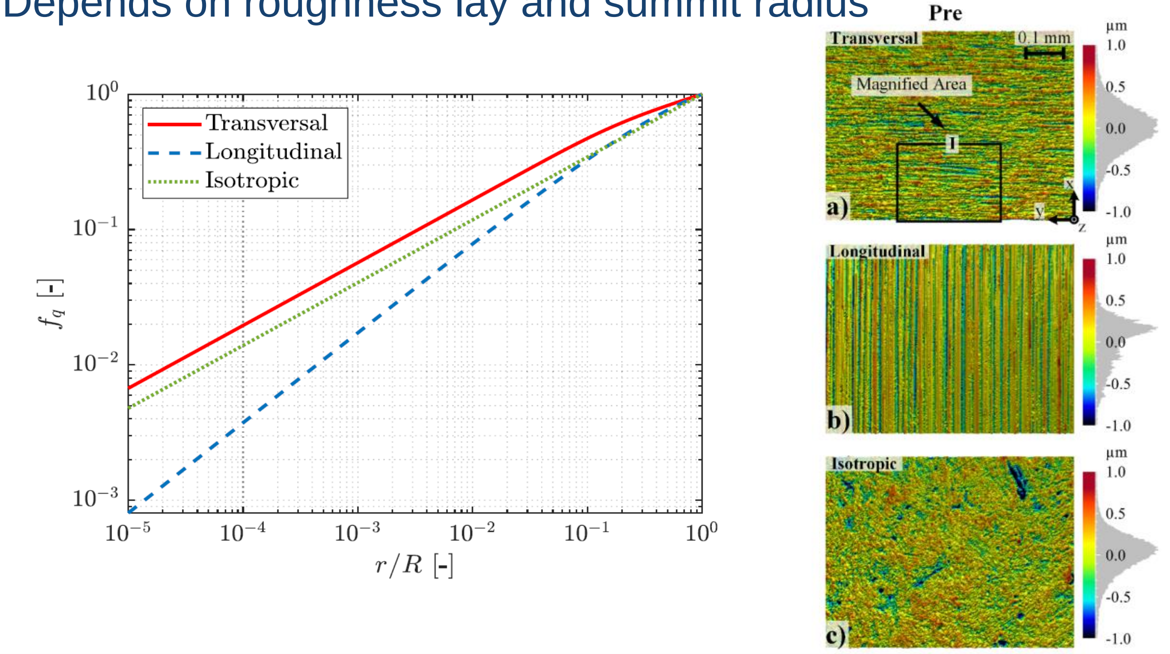
$\Lambda^* \geq 1$: Full film lubrication

$\Lambda^* < 1$: Mixed lubrication

The micro-EHD film parameter f_q

Depends on roughness lay and summit radius



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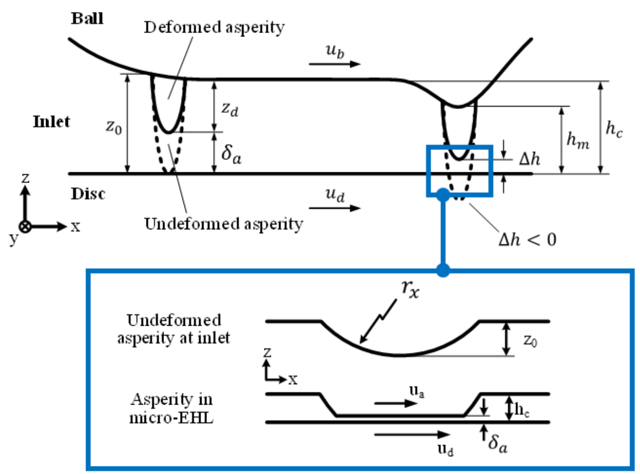

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$\Lambda^* \geq 1$: Full film lubrication

$\Lambda^* < 1$: Mixed lubrication

Minimum film thickness

The Hamrock-Dowson equation:

$$h_m = 3.63 R_x^{0.47} \bar{u}^{0.68} \eta_0^{0.68} E'^{-0.12} \alpha^{0.49} w^{-0.073} \left(1 - e^{-0.68k}\right)$$

$$k \approx \left(R_y / R_x\right)^{2/\pi}$$

$\bar{u}$	Average surface velocity (entrainment speed) [m/s]
w	Load per unit width [N/m]
η_0	Viscosity at atmospheric pressure [Pa·s]
α	Pressure-viscosity coefficient [Pa^{-1}]
E'	Effective elastic modulus [N/m^2]
R_x	Effective radius in rolling direction [m]

Hamrock, B. J. *Fundamentals of Fluid Film Lubrication.* NASA RP-1255 (1991)

Hansen, J., Björling, M., & Larsson, R.,
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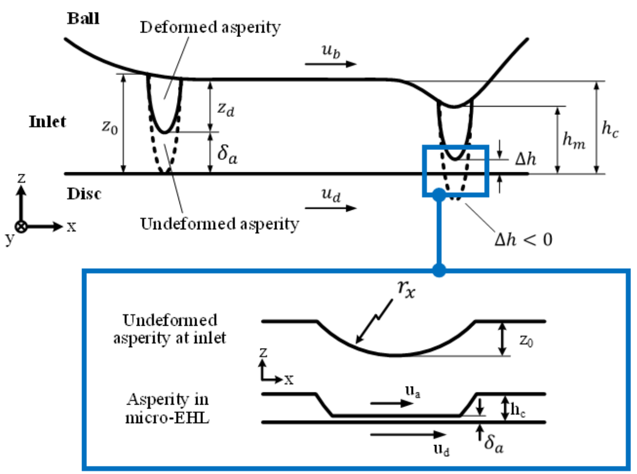

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$\Lambda^* \geq 1$: Full film lubrication

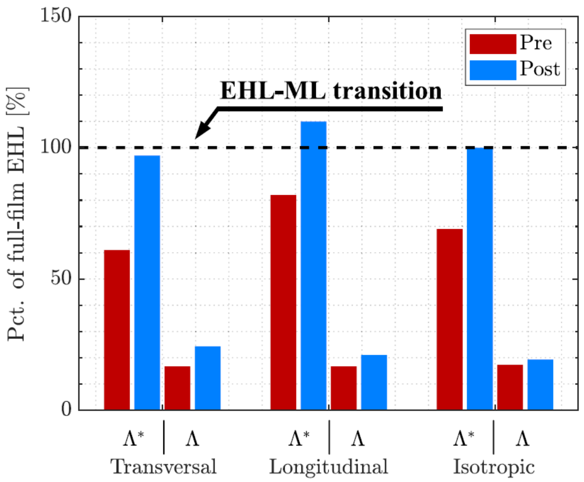
$\Lambda^* < 1$: Mixed lubrication

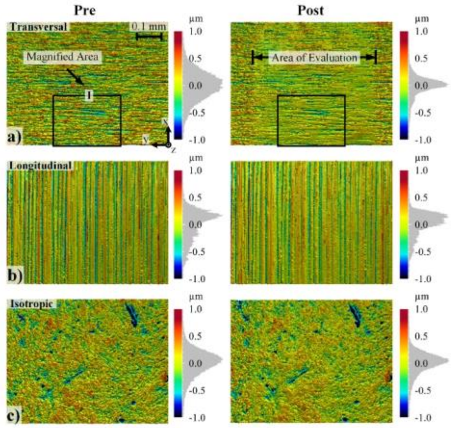
Experimental validation

100% full film if:

$\Lambda \geq 3$

$\Lambda^* \geq 1$





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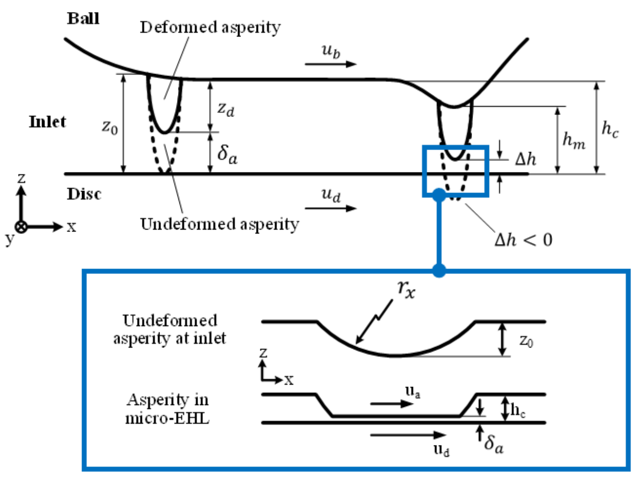

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$\Lambda^* \geq 1$: Full film lubrication

$\Lambda^* < 1$: Mixed lubrication

Calculation example

Solving Λ^* for constant operating conditions

- Load
- Speed
- Lubricant properties
- Oil temp

…and as a function of Spk and r_x, assuming transversal roughness lay (f_q), we get…

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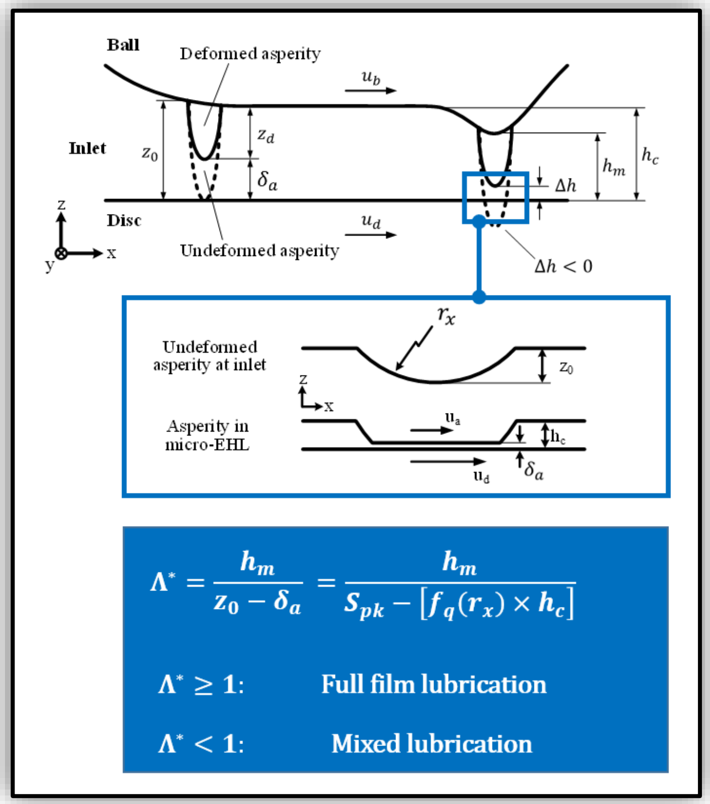

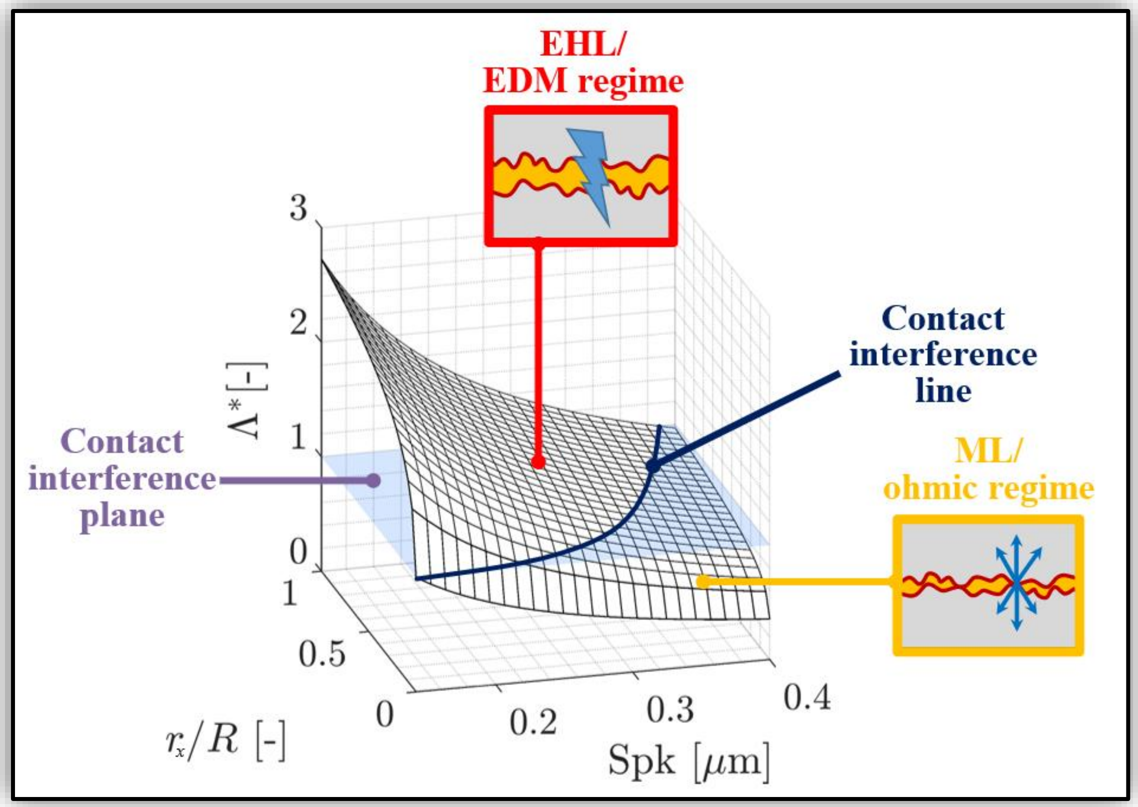

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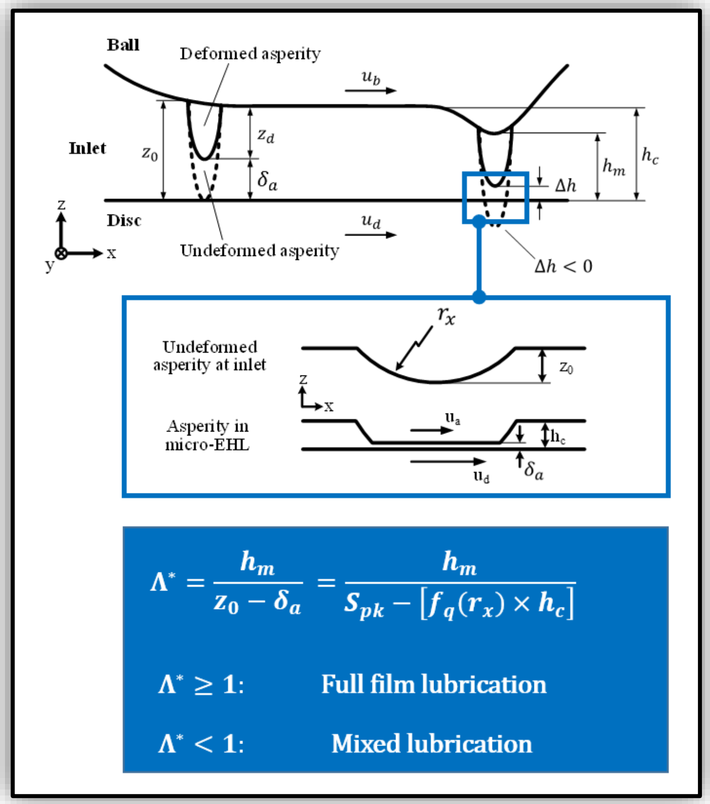

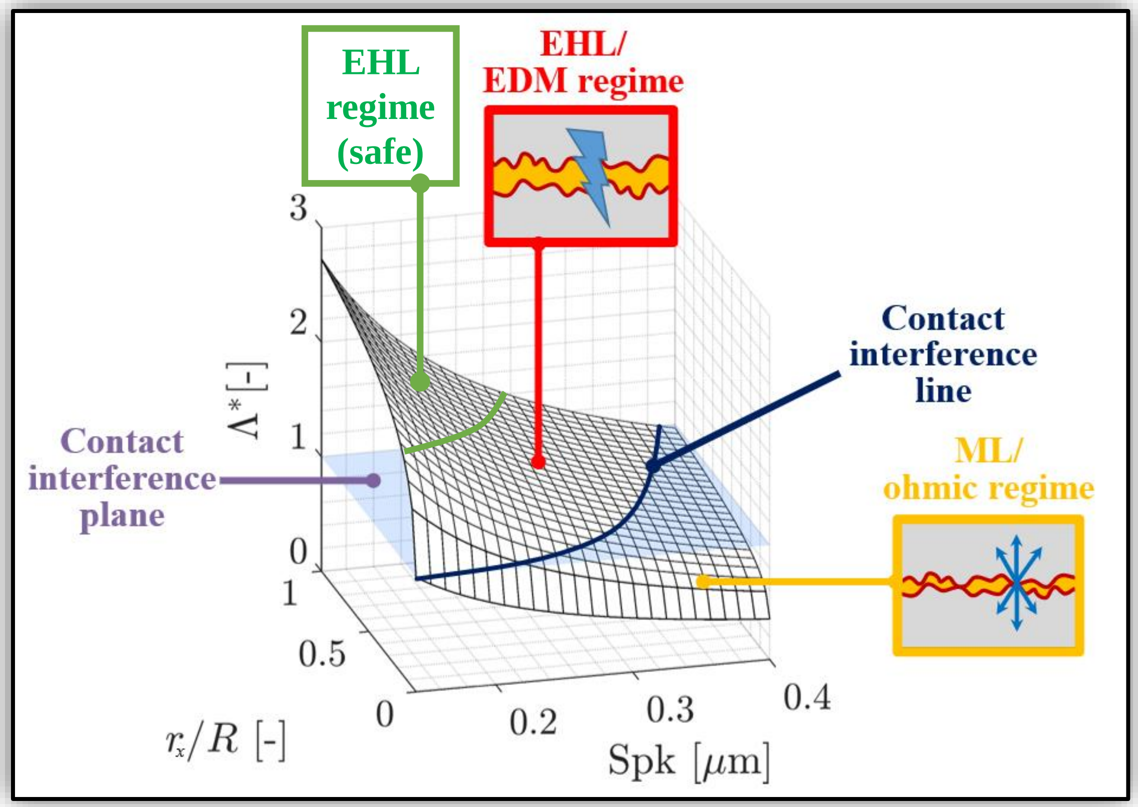

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Jonny Hansen, jonny.hansen@scania.com

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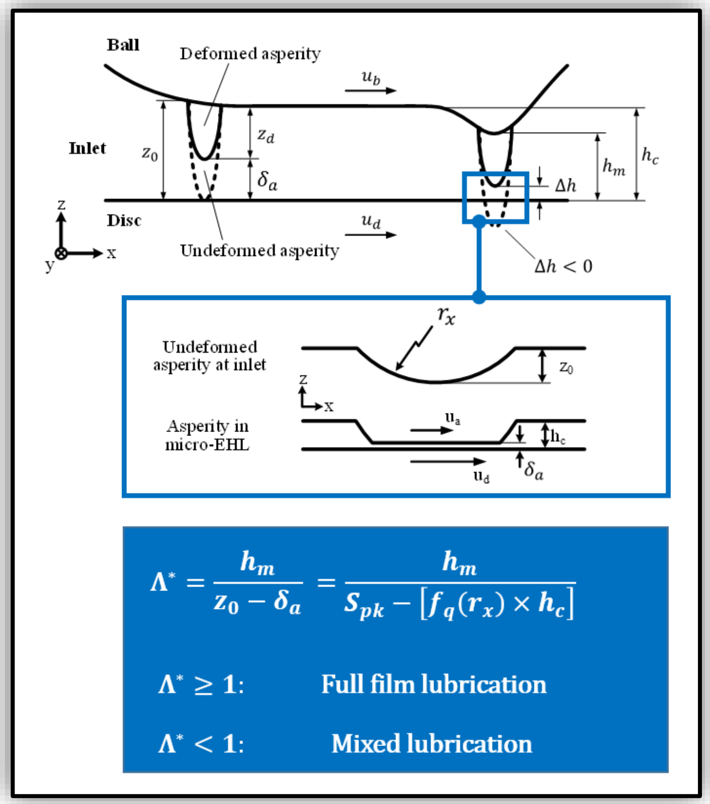

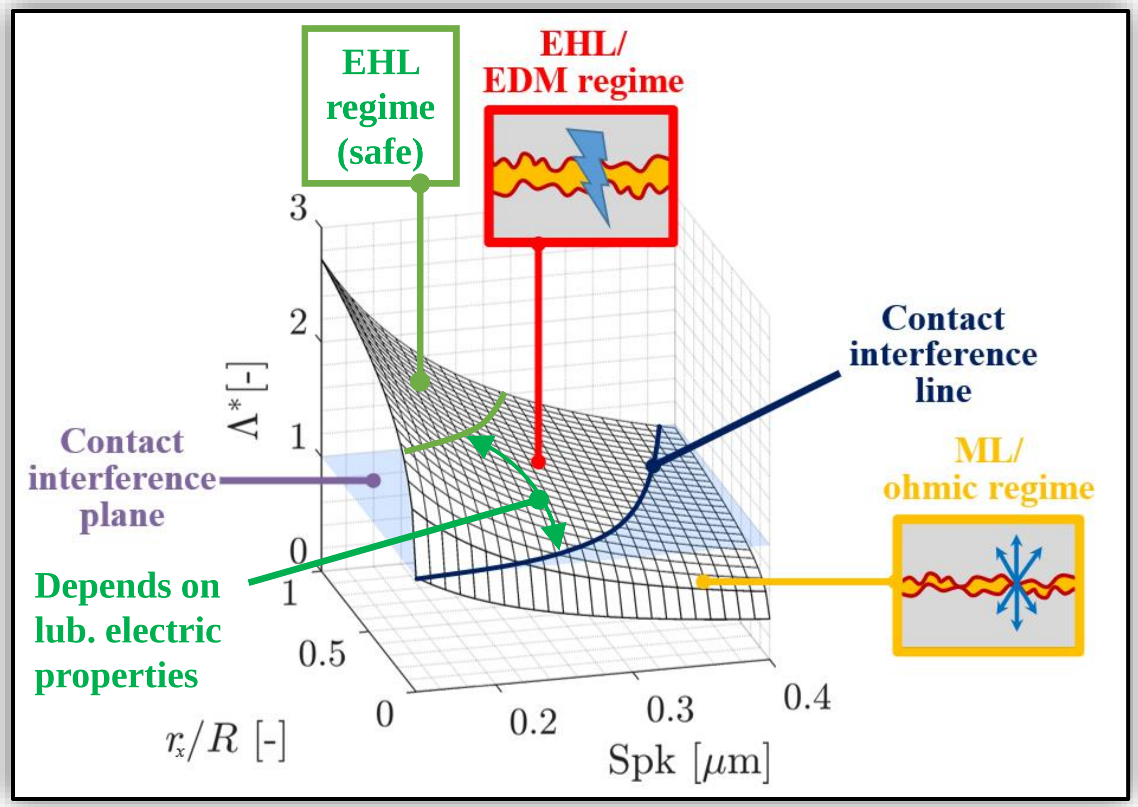

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Tribology Letters (2021) 69:37
https://doi.org/10.1007/s11249-021-01411-3

ORIGINAL PAPER

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A New Film Parameter for Rough Surface EHL Contacts with Anisotropic and Isotropic Structures

Jonny Hansen[1,2] · Marcus Björling[2] · Roland Larsson[2]

Received: 25 October 2020 / Accepted: 7 February 2021

Abstract
Numerous tribological contacts worldwide rely on adequate lubrication quality for proper functionality. Despite this, there is no existing approach to accurately predict the state of lubrication. The default model since introduced in the 1960s—the Λ-ratio, defined as the oil film thickness over the surface roughness height—is unpredictable and may yield erroneous results. Here, we put forward a framework for a new updated film parameter, Λ*, which accounts for the elasto-hydrodynamic lubrication (EHL) effects induced by surface irregularities on the microscopic scale (micro-EHL). This new film parameter was validated in ball-on-disc tribological tests with engineering surfaces comprising isotropic and anisotropic structures. As expected, the new model was found to accurately predict the experimentally measured true mixed and full-film EHL regimes. The ability to accurately predict the mode of lubrication represents a major advance in designing tribological interfaces for optimal efficiency and durability.

Keywords Micro-EHL · Mixed lubrication · Surface roughness · Lambda ratio

1 Introduction

When two non-conformal surfaces under relative motion are brought together under a steady supply of oil, a thin elasto-hydrodynamic lubrication (EHL) film will form [1–5]. The thickness of the film is typically no more than a few hundred nanometres. Despite this modest thickness, its materialization is crucial for the functionality of rotating machinery such as gears, rolling-element bearings and cam followers. Ideally, the developed oil film is thicker than the composite surface roughness height, thus mitigating contact distress by preventing wear of surface irregularities. However, due to economical restrictions typically imposed in the design stage of manufacturing, this situation is seldom the case. In contrast, rough surface EHL contacts are more often forced to operate under various degrees of contact interference. The outcome is precarious since it risks impairing operation through increased friction and reduced service life [6–8]. Furthermore, this situation is of substantial environmental concern given that ~23% of the total annual energy consumption worldwide originates from friction- and wear-related causes [9]. The need for improved tribological technologies is undoubtedly vast.

At present, well-established theories exist for predicting the EHL film thickness for nominally smooth surfaces [10–12]. However, surprisingly little is known about the film-forming mechanisms when surfaces are microscopically rough, and existing design tools are insufficient by means of practical use. This claim is rooted in the fact that the default model in lubrication science and engineering still involves the use of the relatively simple and often critically debated [13–23] Λ-parameter, i.e., the ratio of the nominal minimum lubricant film thickness and the composite root-mean-square (RMS) surface roughness height, $\Lambda = h_m/Sq_c$. With this ratio, the regimes of lubrication are typically classified into boundary lubrication (BL) when $\Lambda \leq 1$, mixed lubrication (ML) when $1 < \Lambda < 3$, and EHL when $\Lambda \geq 3$ [2]. While the ratio appears to represent the lubrication quality fairly well when surfaces are mostly Gaussian, particularly with respect to the friction coefficient over the film thickness [20, 24–26], it often falls short when following a running-in process—a process causing a gradual change in lubrication quality due

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Presented at

Tribodays 2021
23 November

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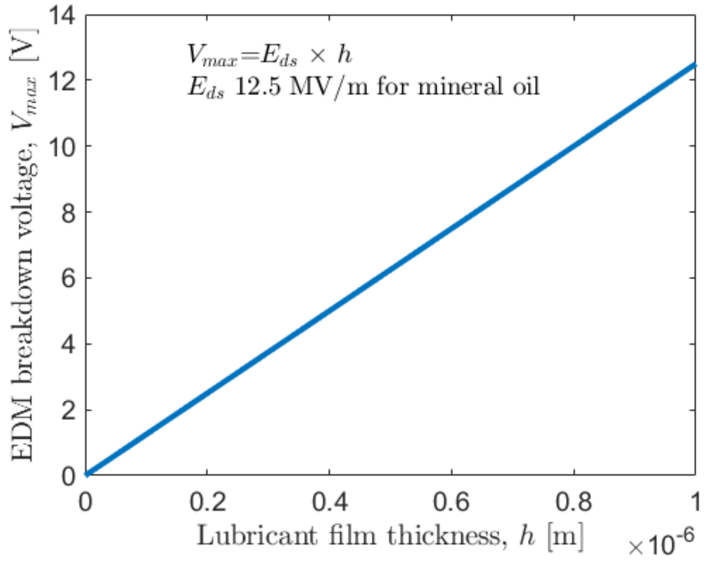
KLÜBER LUBRICATION

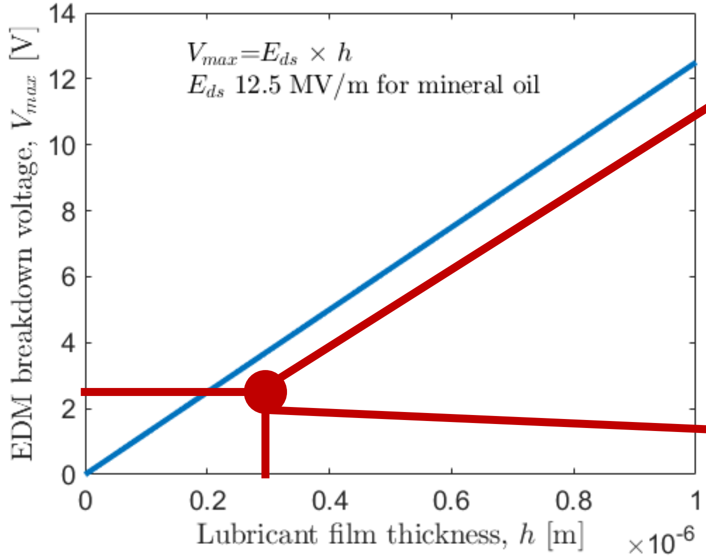
Part 5 ▸ Electric discharge mechanisms

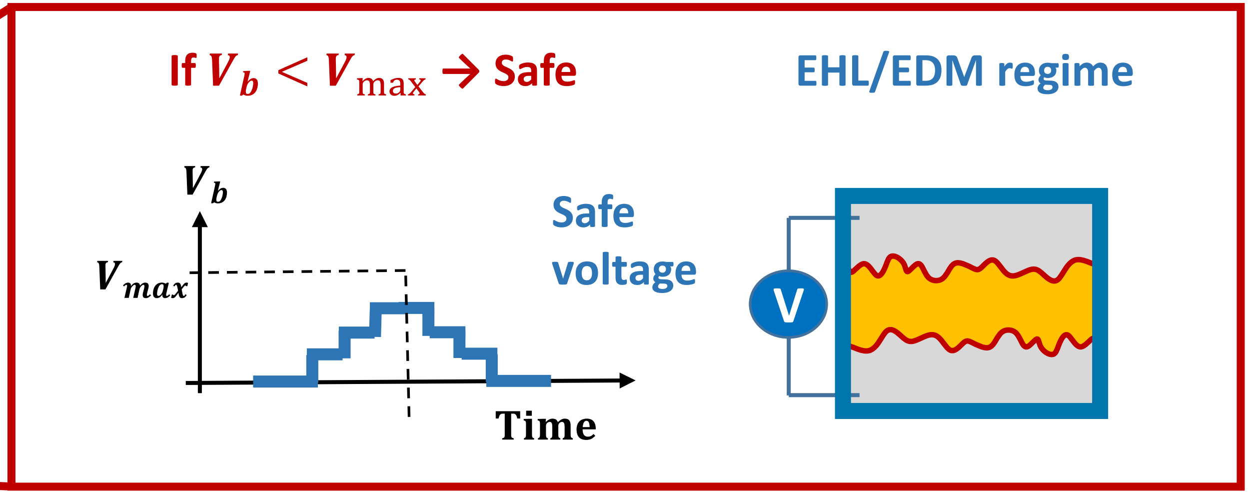
Discharge mechanisms



Discharge mechanisms

V_b and h determines when arcing occurs





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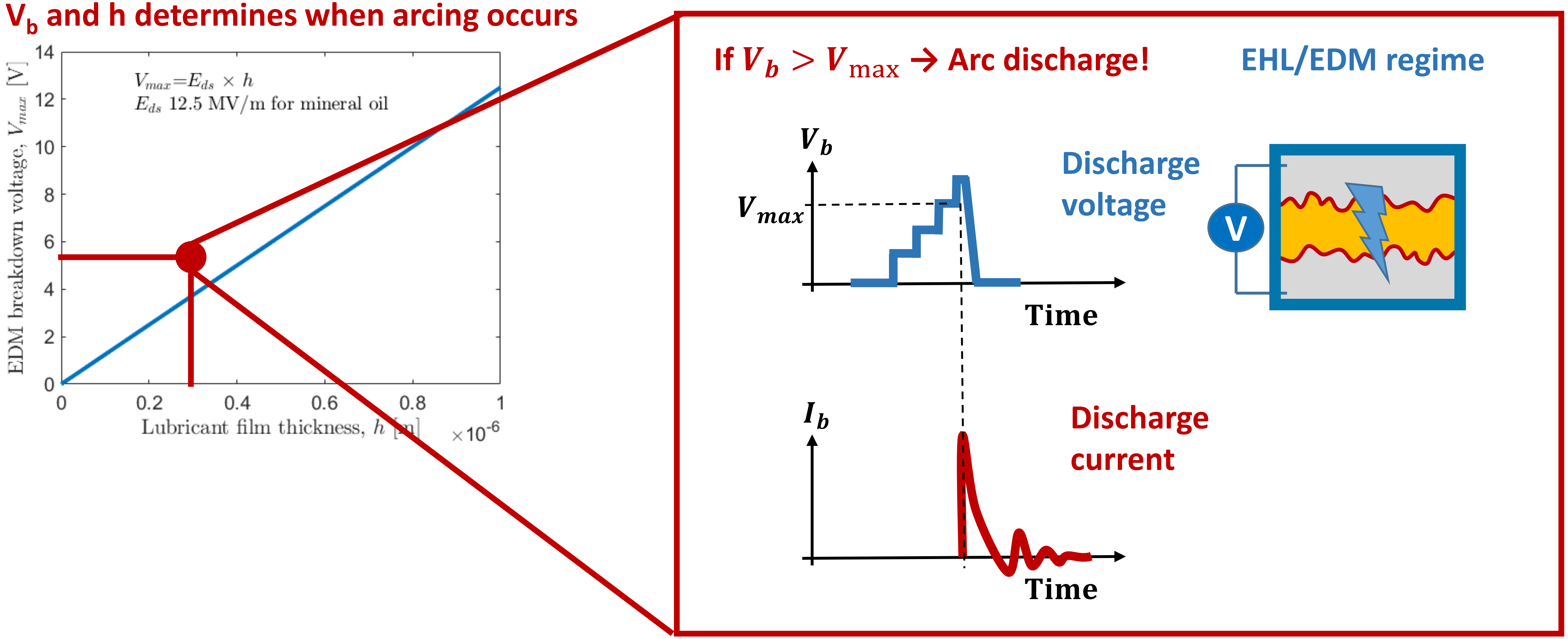

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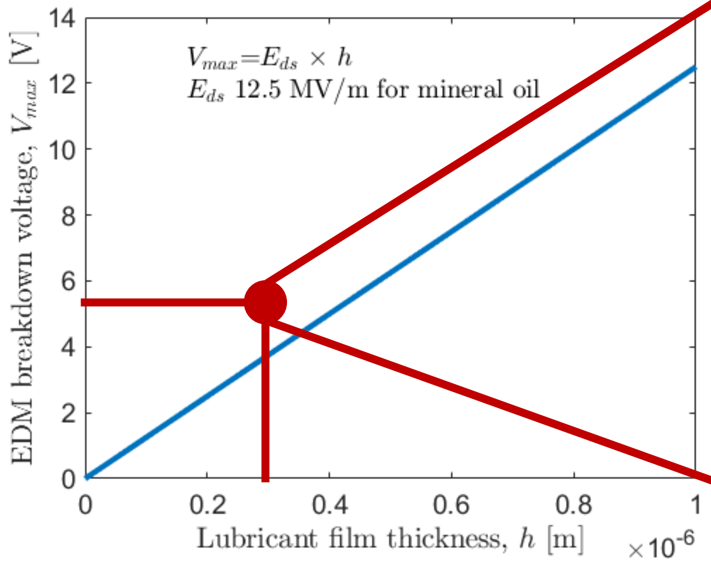
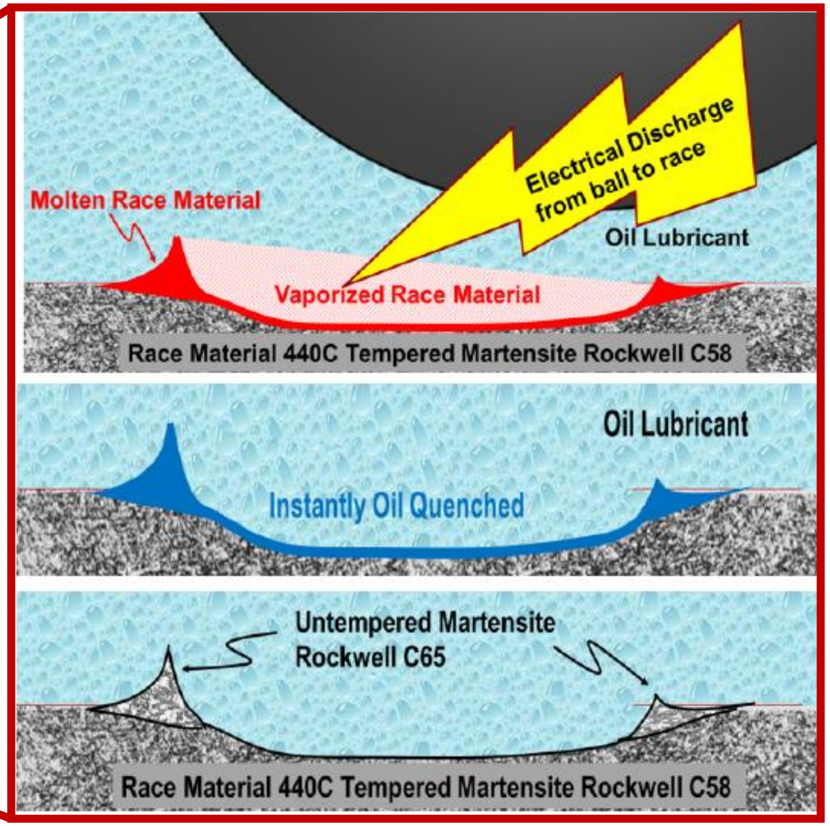




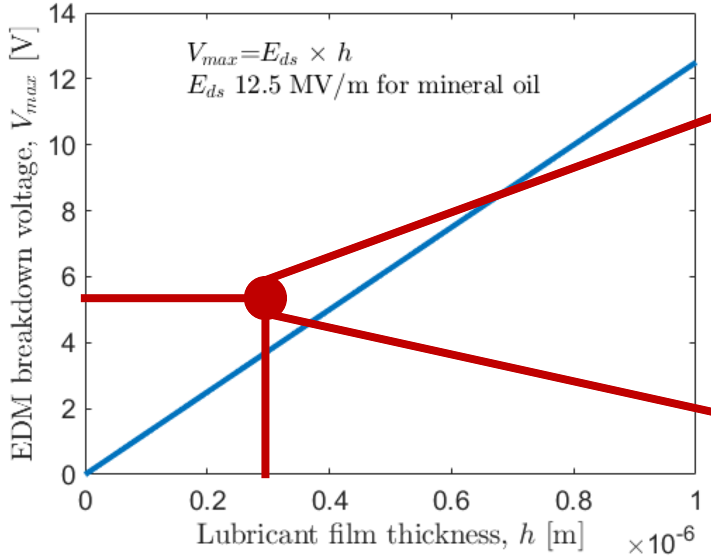
Increased hardness of EDM pits may be a precursor to RCF

$$EDM\ Energy\ (W) = C\frac{V_b^2}{2},where\ C = \varepsilon\frac{A}{h}$$

Bialke, W., & Hansell, E. (2017). A Newly Discovered Branch of the Fault Tree Explaining Systemic Reaction Wheel Failures and Anomalies. *Proceedings of the 17th European Space Mechanisms & Tribology Symposium*, *September*, 20–22. http://esmats.eu/esmatspapers/pastpapers/pdfs/2017/bialke.pdf

Discharge mechanisms

V_b and h determines when arcing occurs



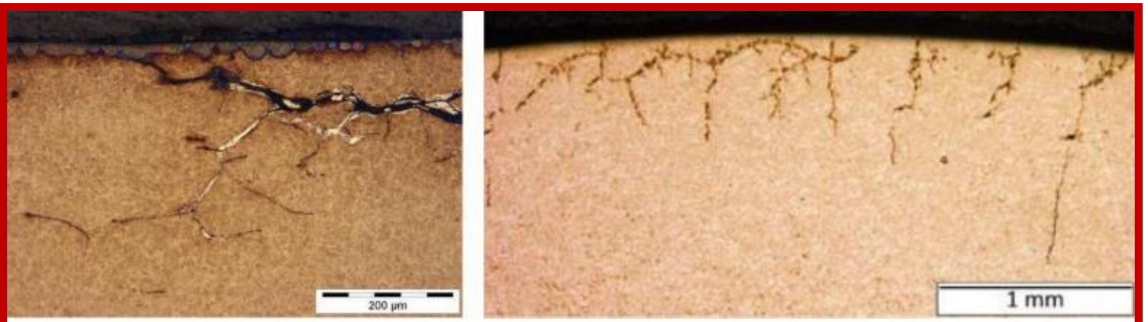


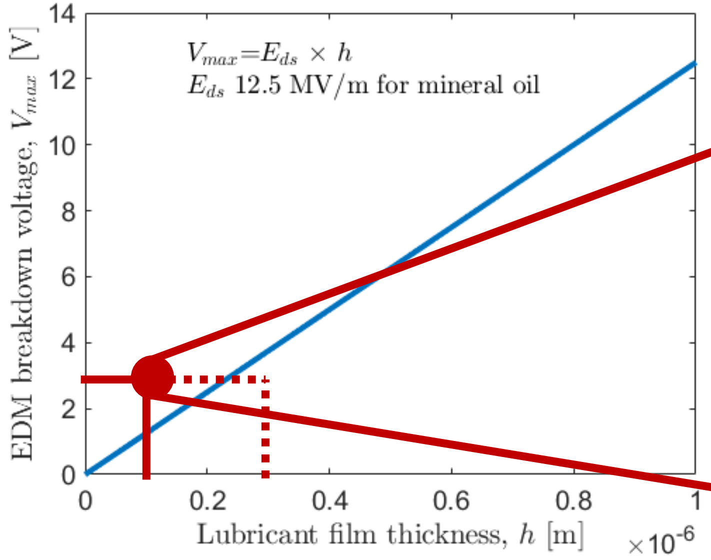
Fig. 1. (left) White etching cracks (WEC) failure due to suspected bearing currents from [21]; (right) light optical micrograph revealing typical discrete WEC networks from a circumferential cross section on an angular contact ball bearing inner ring from an NTN-SNR RCF test rig [32].

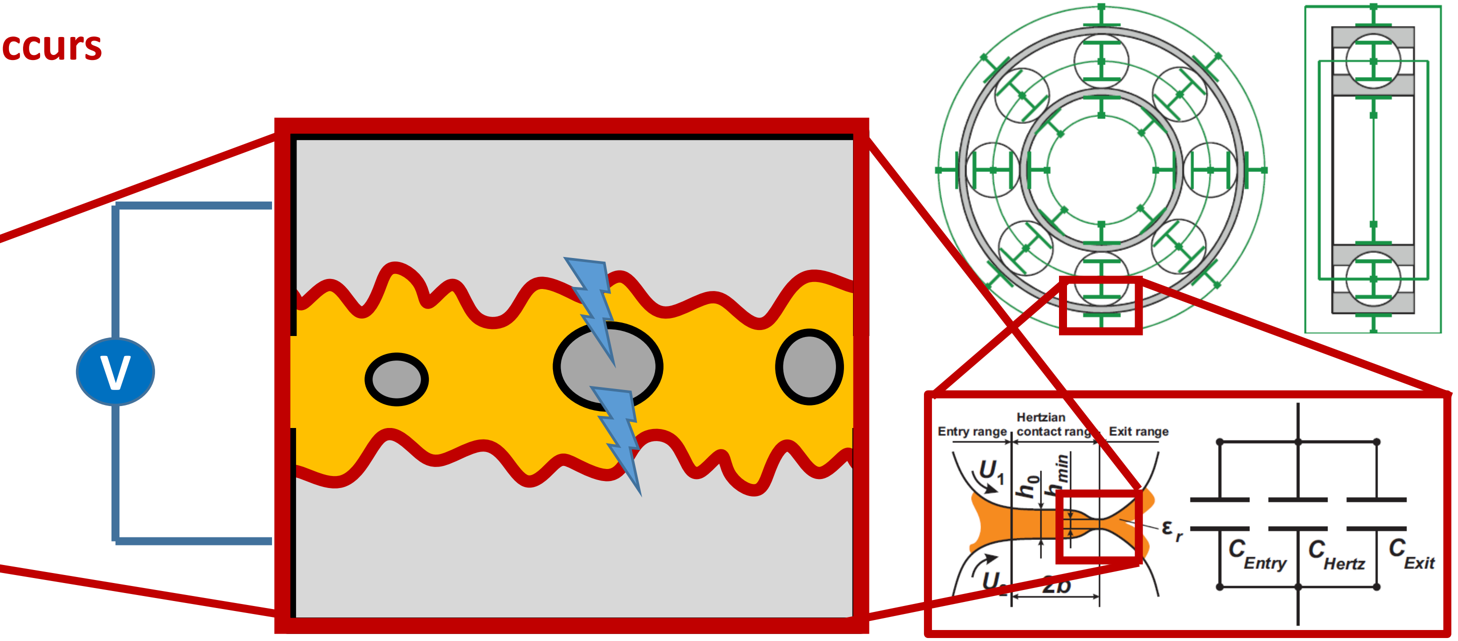
Plazenet T, Boileau T. Overview of Bearing White Etching Cracks due to Electrical Currents. 2021 IEEE 13th Int Symp Diagnostics Electr Mach Power Electron Drives, SDEMPED 2021 2021:440–6. https://doi.org/10.1109/SDEMPED51010.2021.9605561.

Discharge mechanisms

$$EDM\ Energy\ (W) = C\frac{V_b^2}{2},\ where\ C = \varepsilon\frac{A}{h}$$

V_b and h determines when arcing occurs

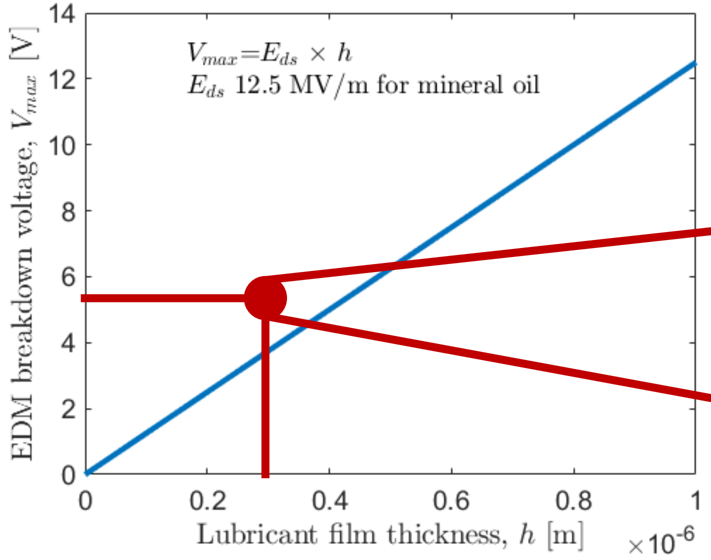




Particles may affect contact voltage and cause discharge
-> Cleanliness may be even more important in electrified drivetrains

Discharge mechanisms

V_b and h determines when arcing occurs

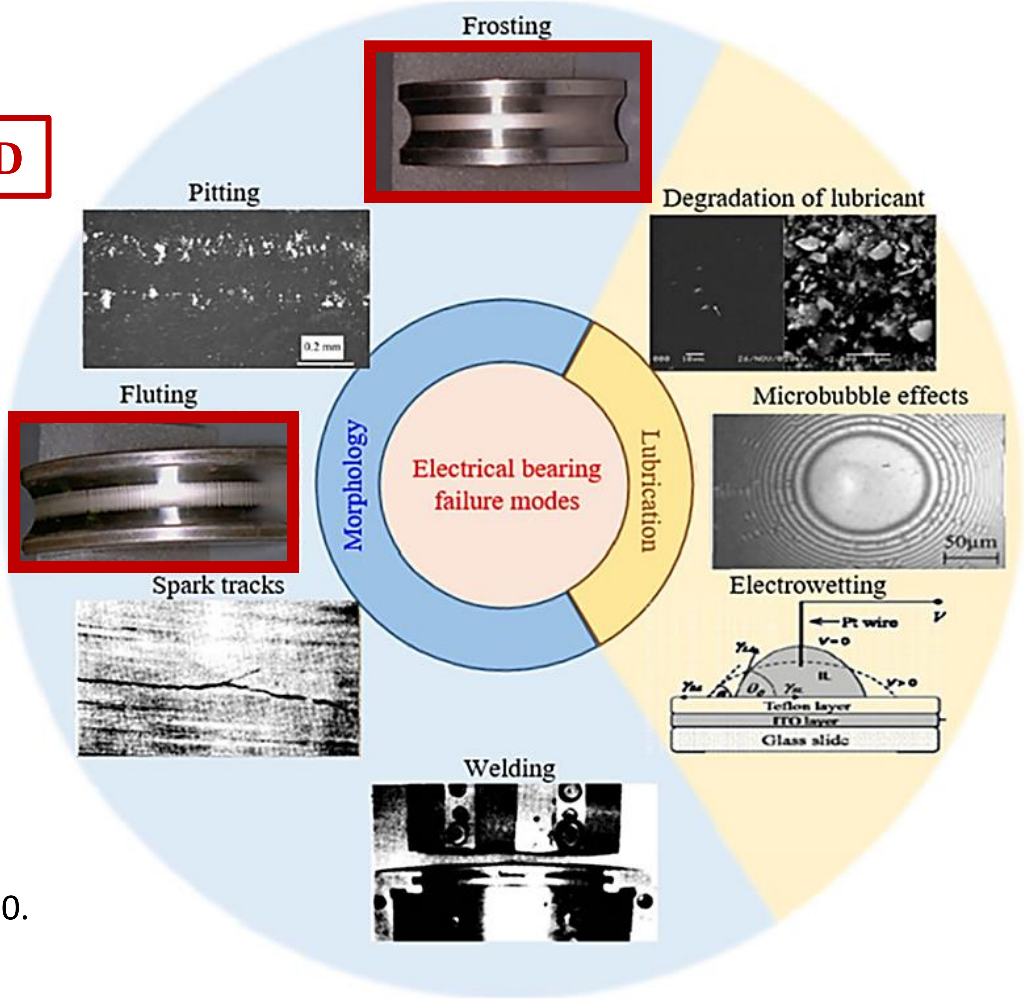


- **Small voltages (>1 V) may cause EDM**
- **Small currents (>1 A) may cause EDM (due to high current densities $J_b = i_b/A_{Hz}$ or A_{asp} locally)**

Jonny Hansen, jonny.hansen@scania.com

Damage classifications of electrical bearing failures

EDM/EDD



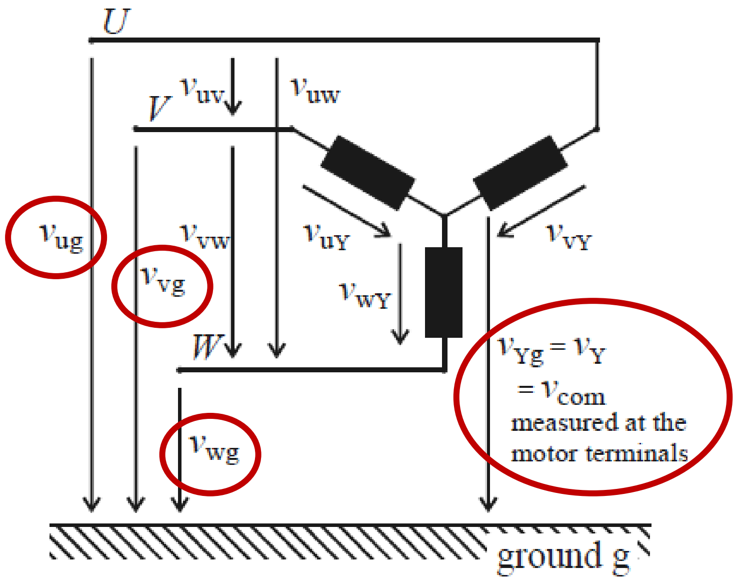
The appearance and classification of the typical electrical bearing failures.

F. He, G. Xie, and J. Luo, "Electrical bearing failures in electric vehicles," Friction, vol. 8, no. 1, pp. 4–28, 2020.

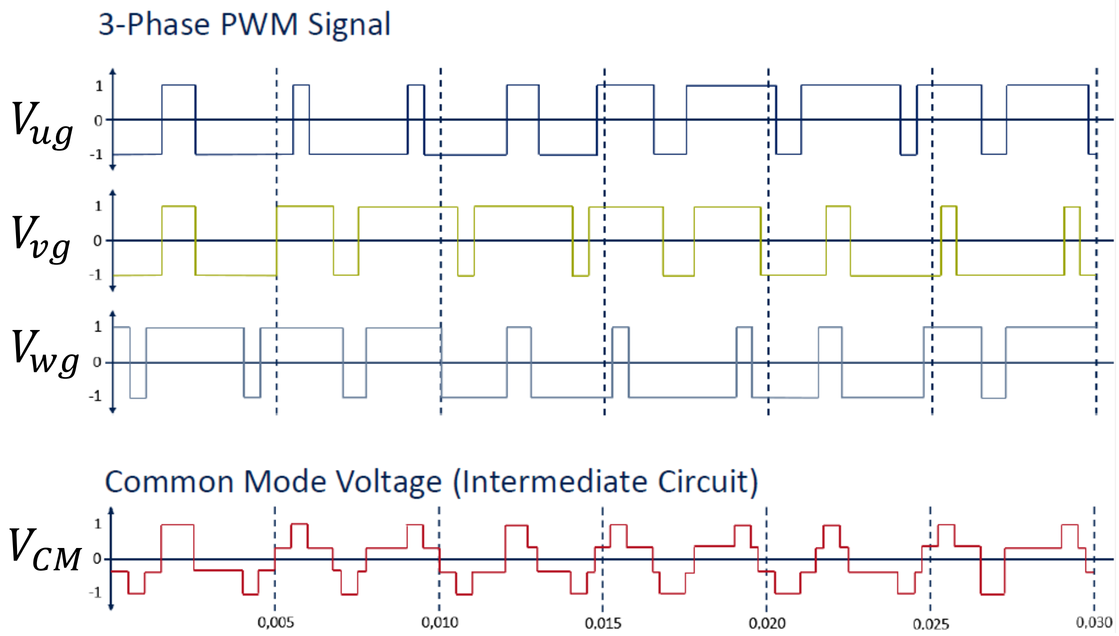
Part 6 ► Bearing currents in EV's

The origin of bearing currents in PWM VFD EM

Voltages of a three phase drive system



Muetze, A. (2003)



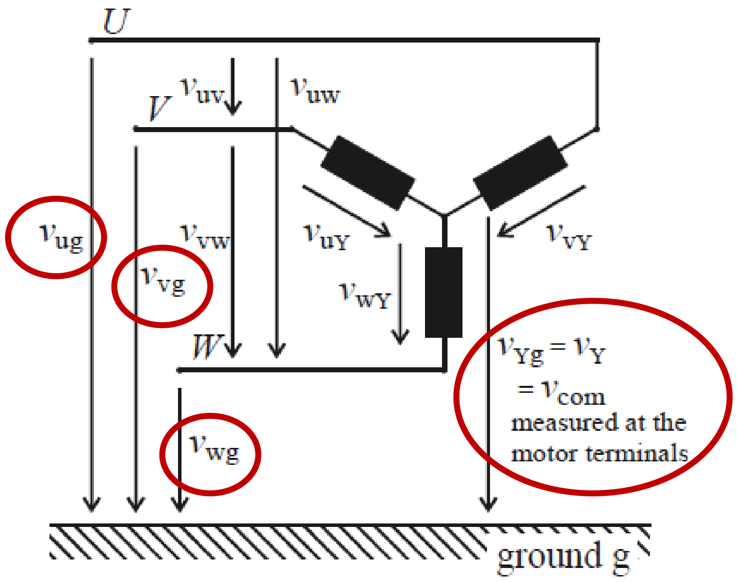
Markus Weber (Shunk 2021)

The mean of the three potentials, i.e. the common mode voltage, is ≠ 0

$$V_{CM} = V_Y = \frac{V_{ug} + V_{vg} + V_{wg}}{3}$$

The origin of bearing currents in PWM VFD EM

Voltages of a three phase drive system



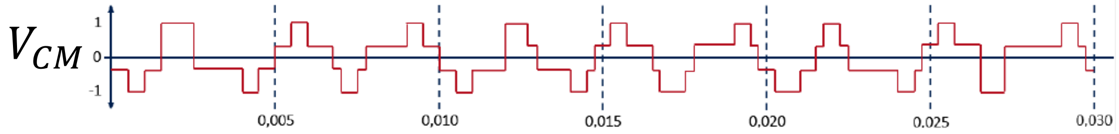
Muetze, A. (2003)

3-Phase PWM Signal

High:
- **Rise time, du/dt (increased risk of discharge)**
- **Switch frequency (no. of available discharges)**

→ Good for EM efficiency (inverter)
→ Dangerous for EDD in bearings and gears

Common Mode Voltage (Intermediate Circuit)



Markus Weber (Shunk 2021)

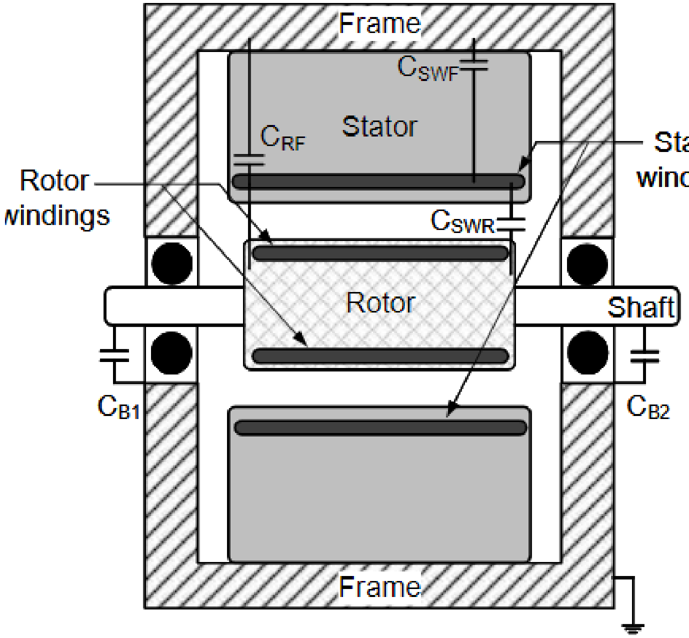
The mean of the three potentials, i.e. the common mode voltage, is ≠ 0

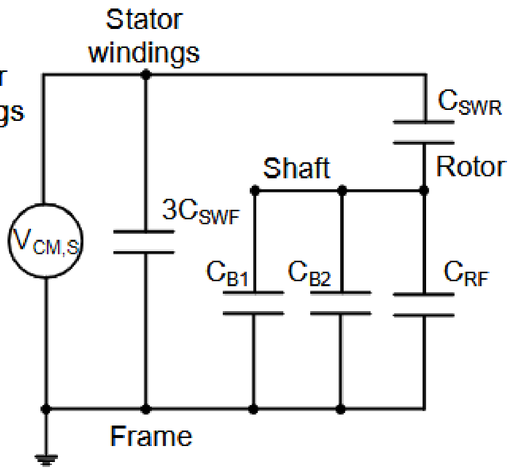
$$V_{CM} = V_Y = \frac{V_{ug} + V_{vg} + V_{wg}}{3}$$

Bearing voltage within the EM

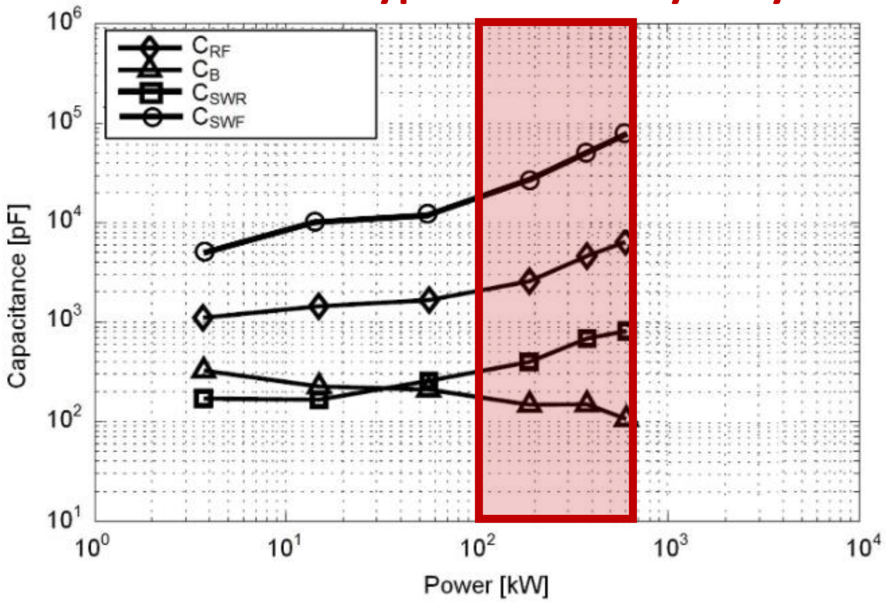
In FF-lubrication, the bearing voltage V_b mirrors the common mode voltage V_{CM} at the stator terminals via the capacitive voltage divider, BVR (bearing voltage ratio):

$$V_b \approx V_{CM} \frac{C_{SWR}}{C_{SWR} + C_{RF} + 2C_b}$$





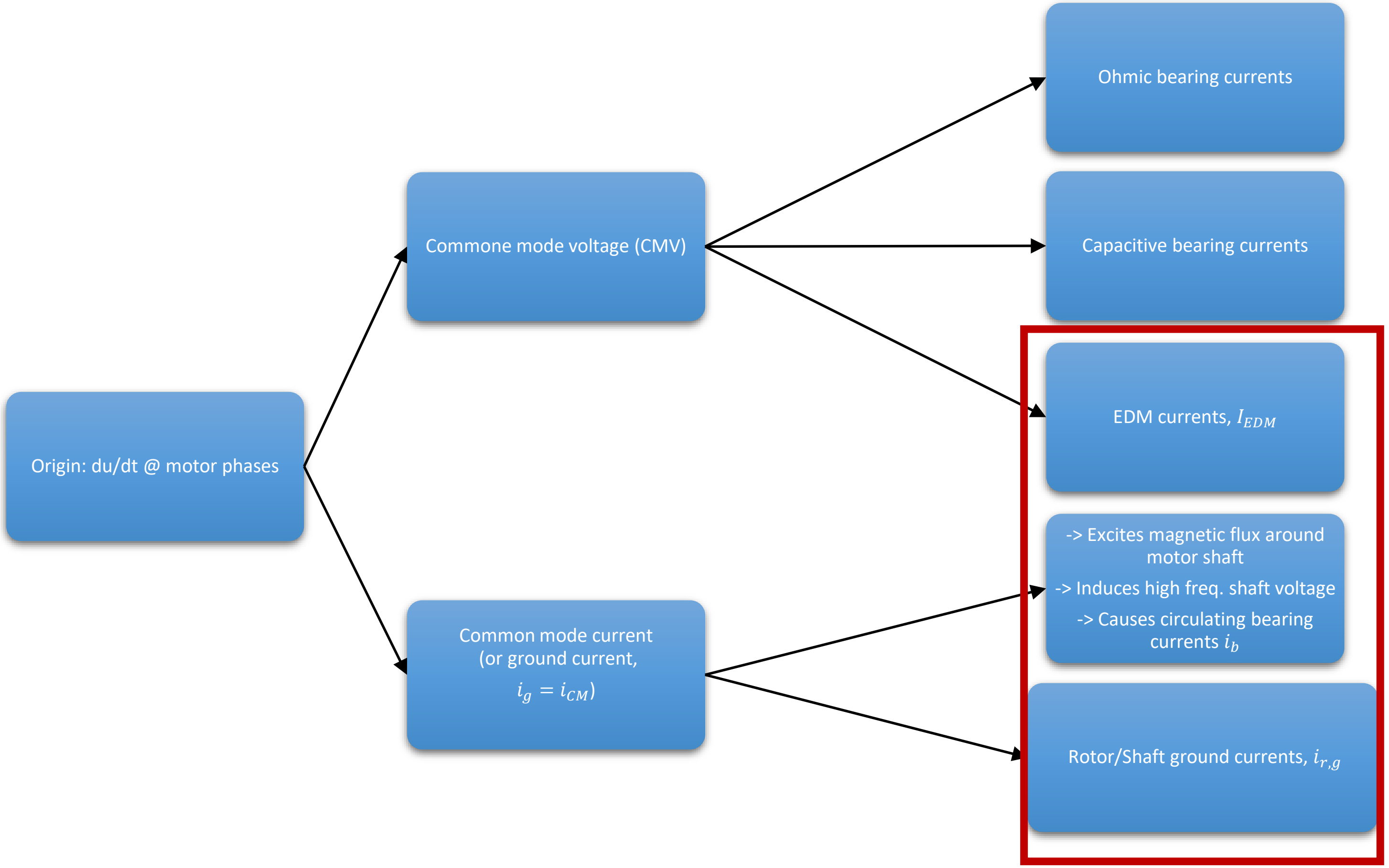
Typical for heavy duty EV's



Muetze, A. (2003). Bearing Currents in Inverter-Fed AC Motors *(PhD Thesis)*

Joshi, A. (2019). Electrical Characterisations of Bearings *(PhD Thesis)*

Types of bearing currents



$$i_b = v_b/R_b$$

$$i_b = C_b \frac{dv_b}{dt}$$

$if\ v_b > V_{breakdown}$ -> i_{EDM}

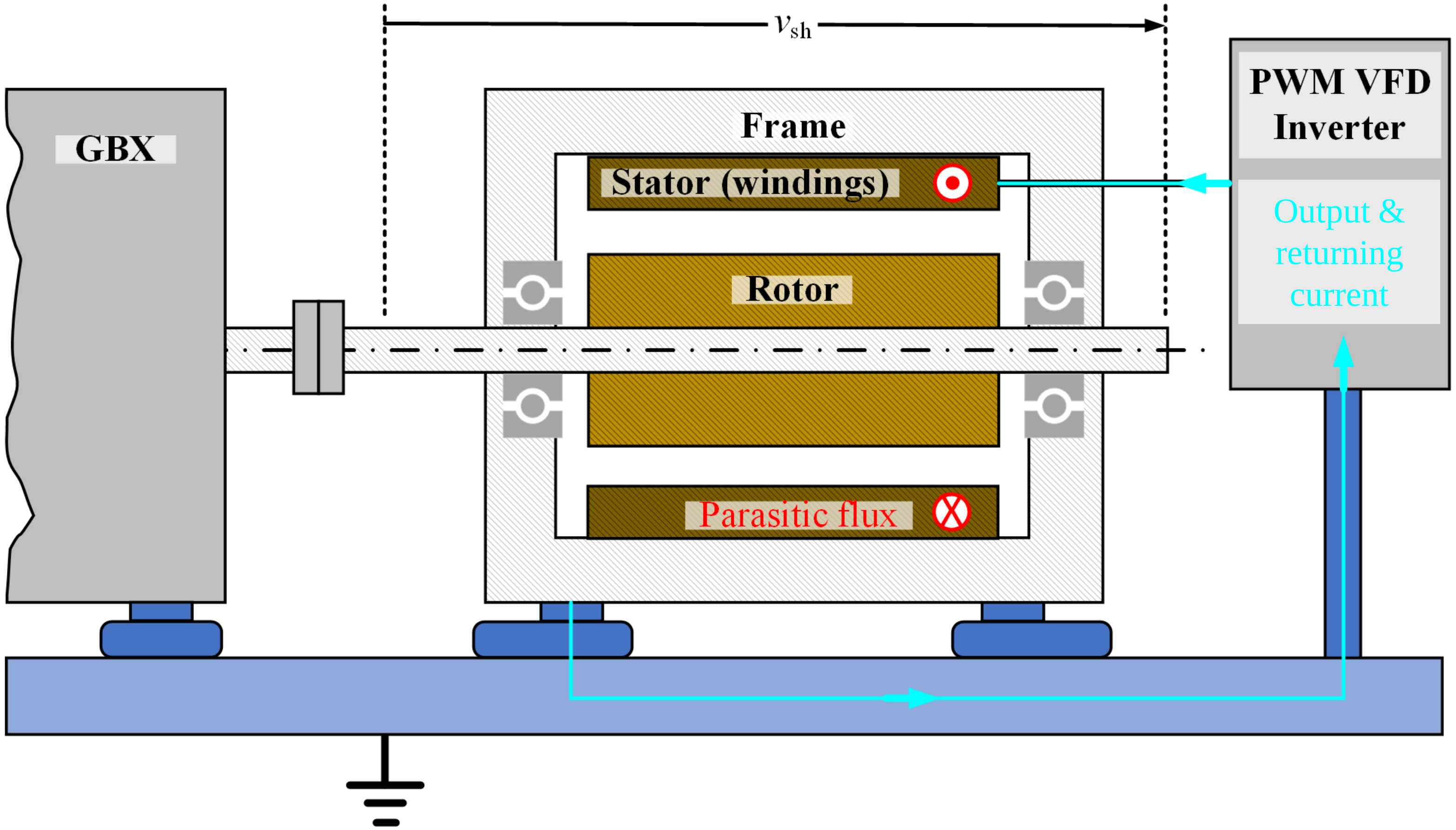
i_{CM} creates v_{sh} which is harmful in full film lubrication if $v_b > V_{breakdown}$ -> i_b (= i_{EDM})

Part of i_b ($i_{r,g}$) may pass the DE bearing, the gearbox bearings and back to the frame via the inverter PE

The high energy bearing current types that may cause bearing damages

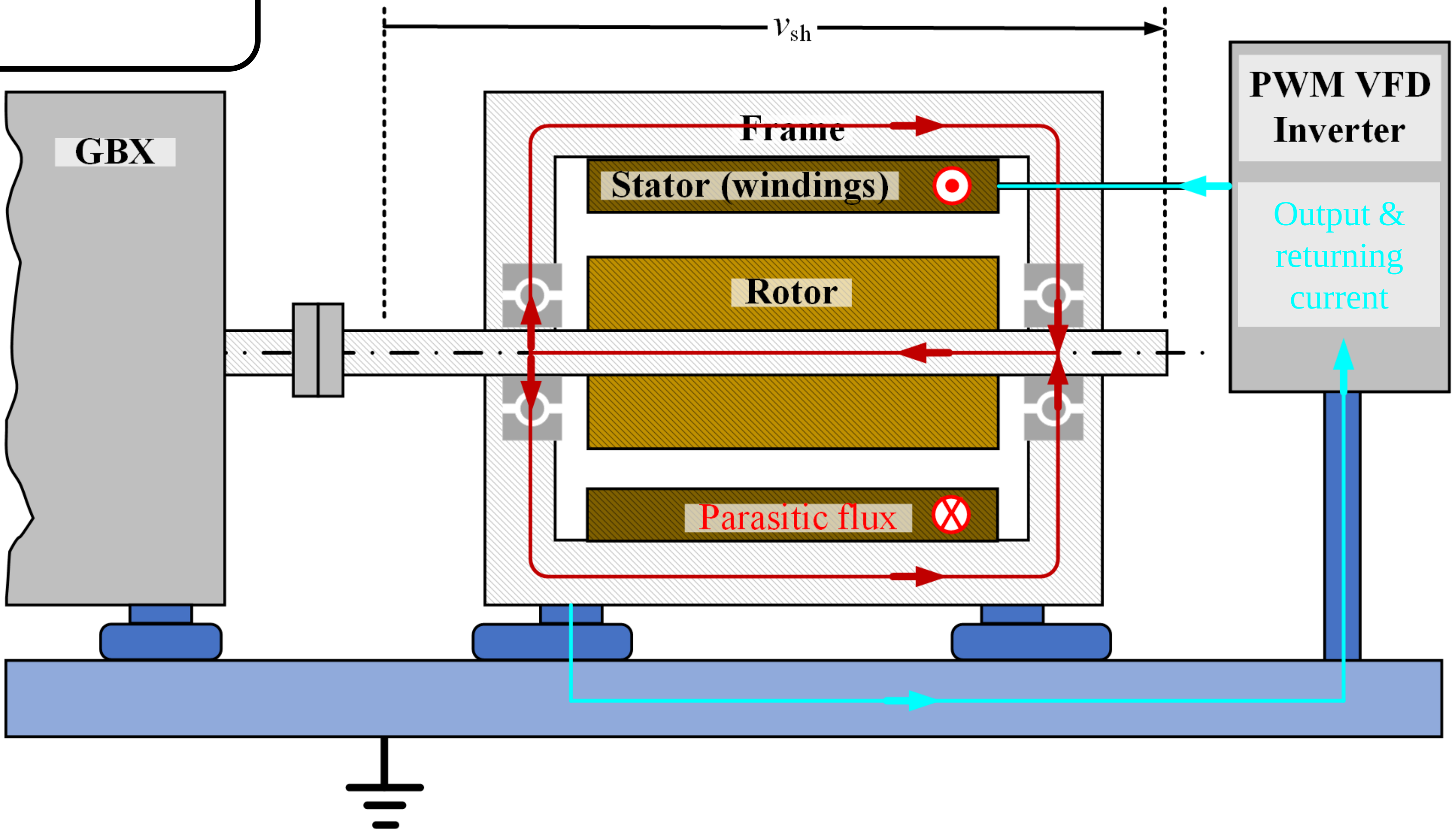
Muetze, A. (2003). Bearing Currents in Inverter-Fed AC Motors *(PhD Thesis)*
Joshi, A. (2019). Electrical Characterisations of Bearings *(PhD Thesis)*

Types of bearing currents



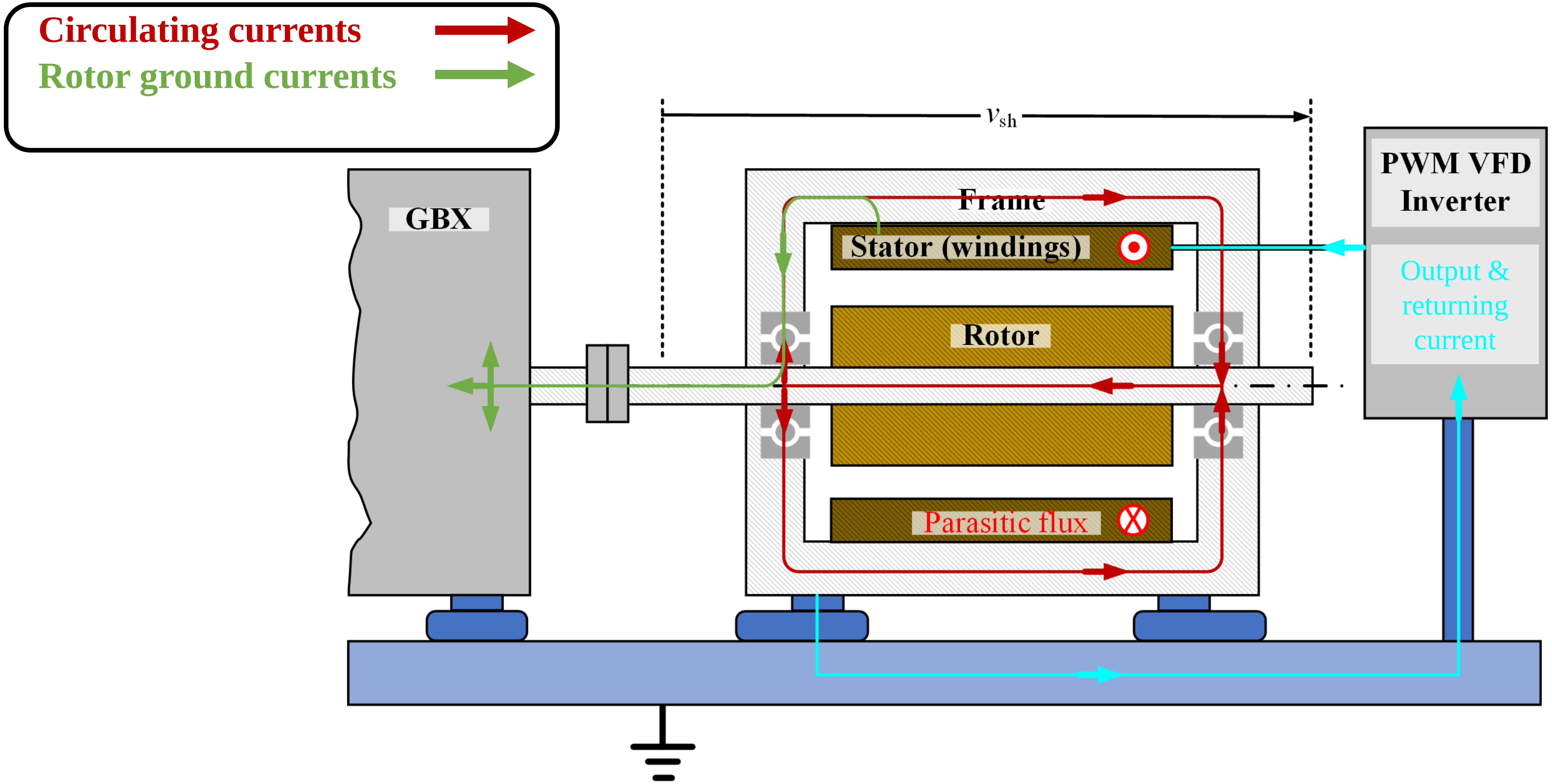
Types of bearing currents

Circulating currents

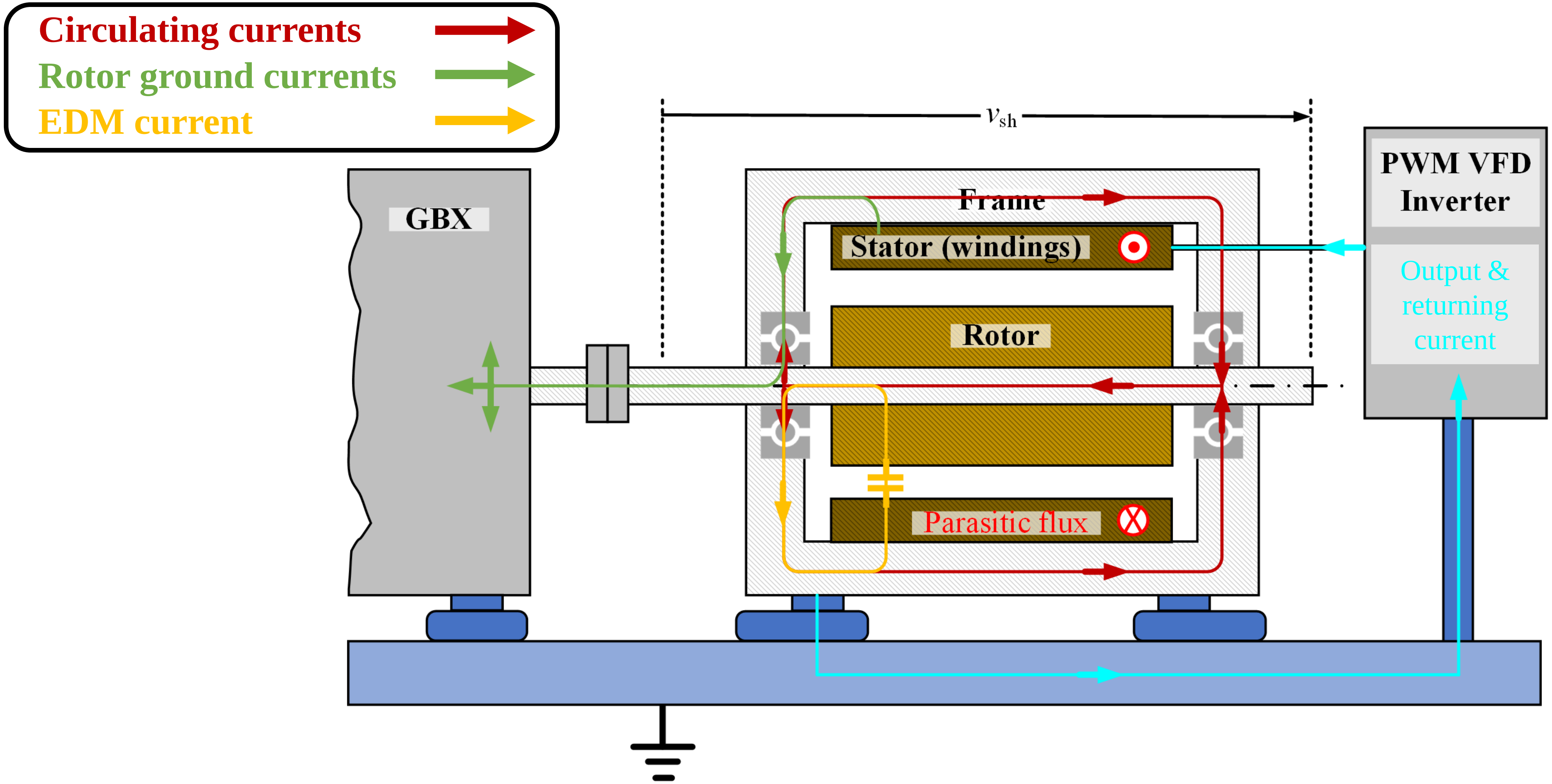


Jonny Hansen, jonny.hansen@scania.com

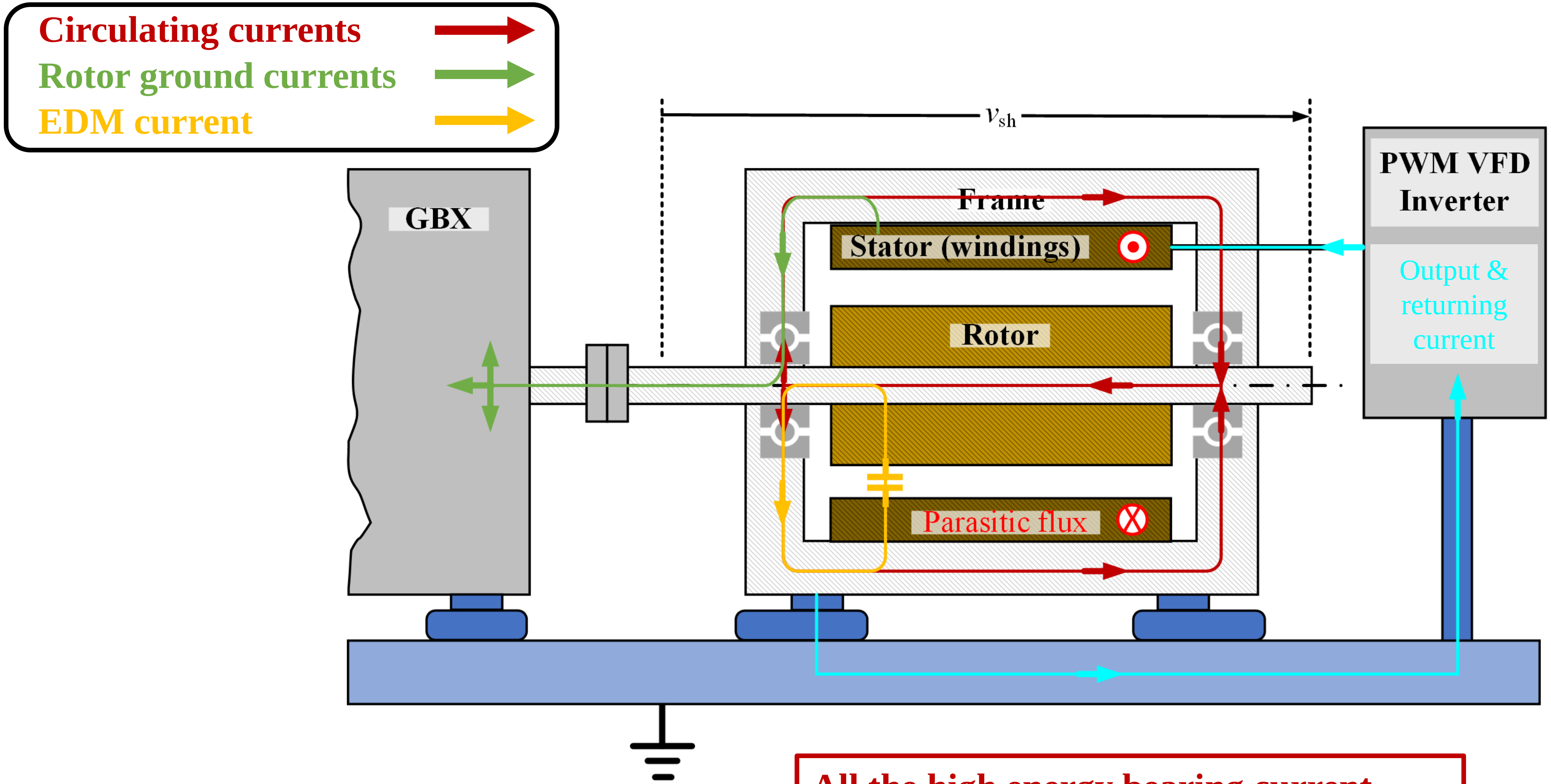
Types of bearing currents



Types of bearing currents



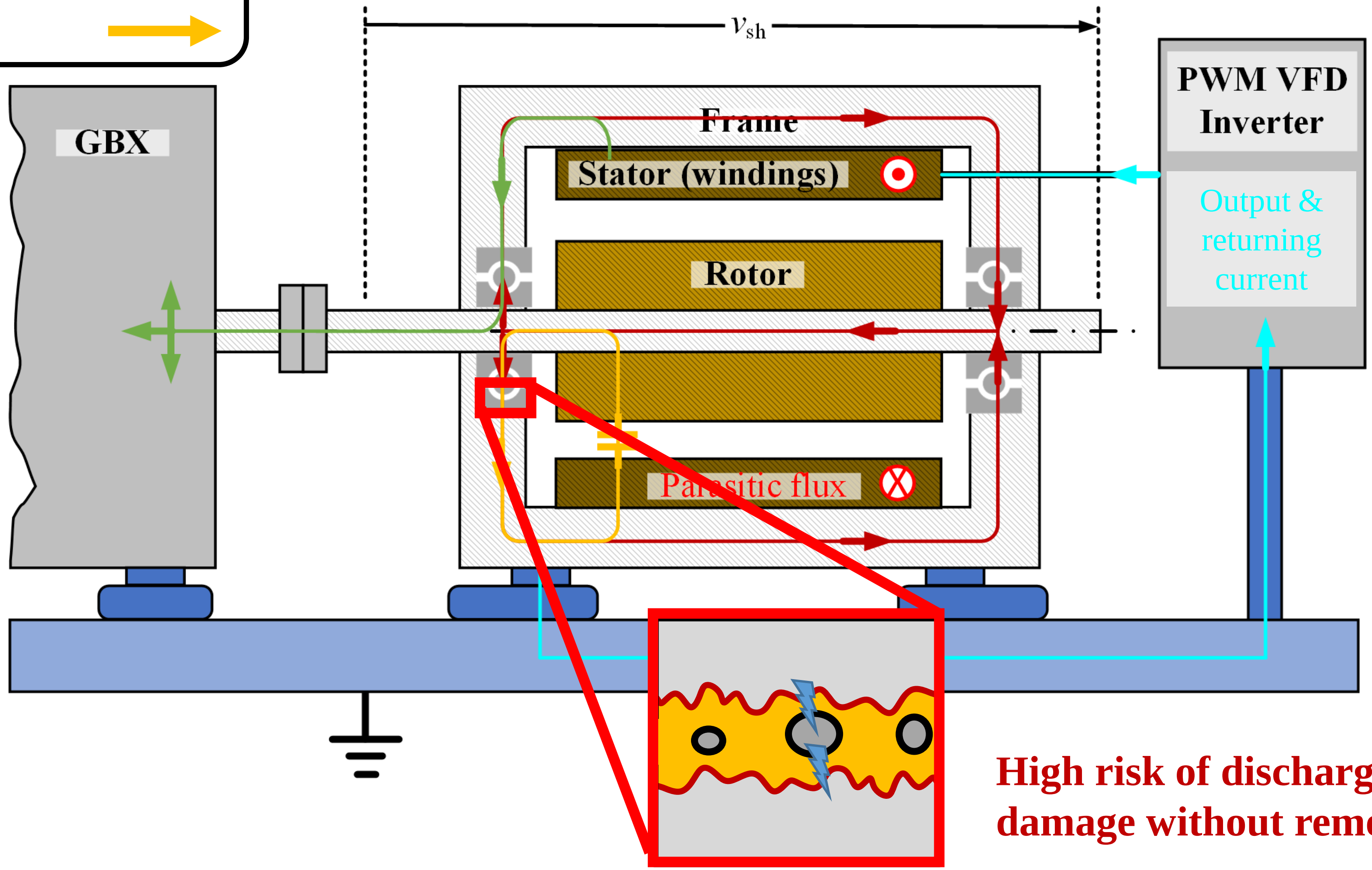
Types of bearing currents



All the high energy bearing current types that may cause bearing damages

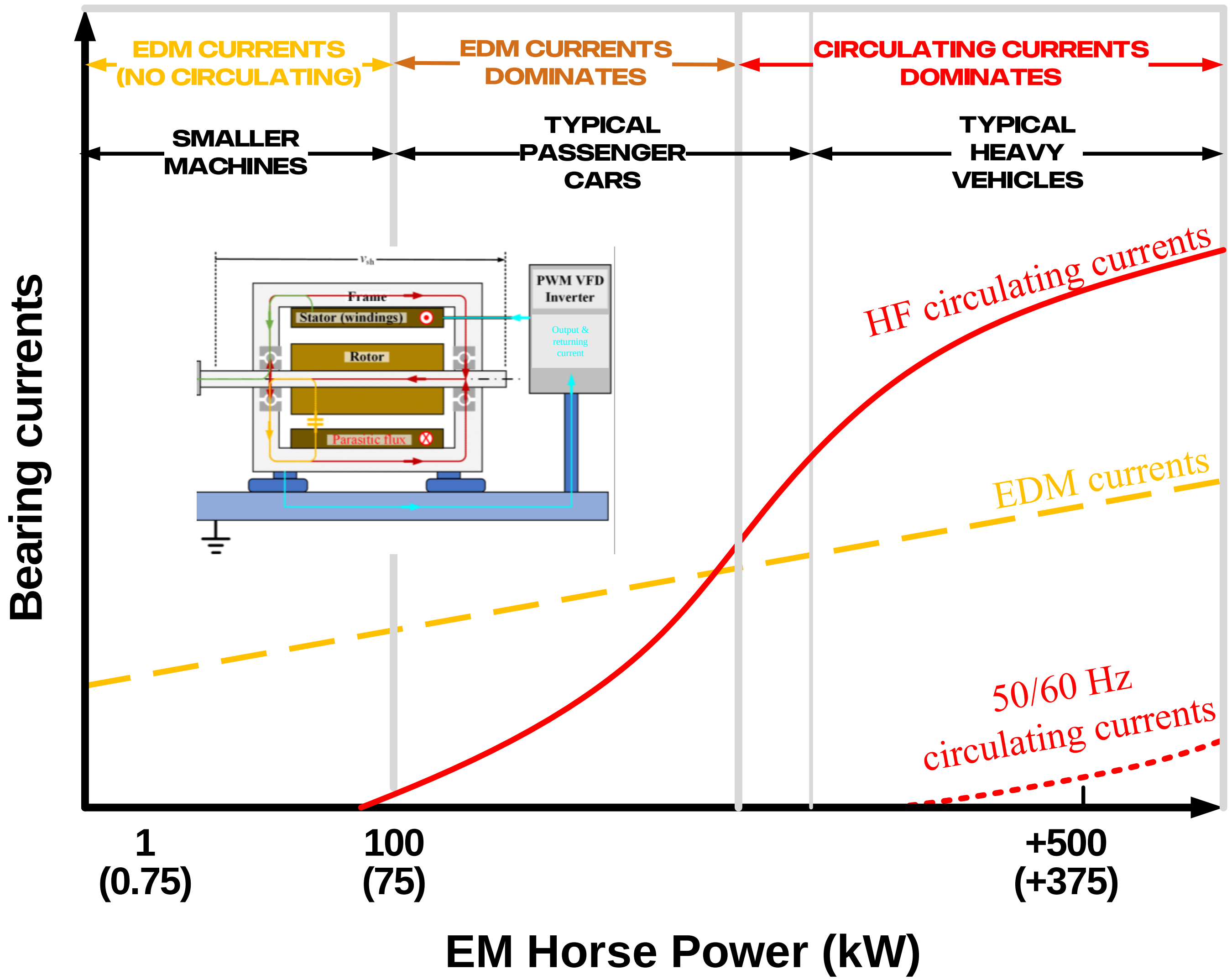
Types of bearing currents

Circulating currents
Rotor ground currents
EDM current



High risk of discharge damage without remedies!

Types of bearing currents

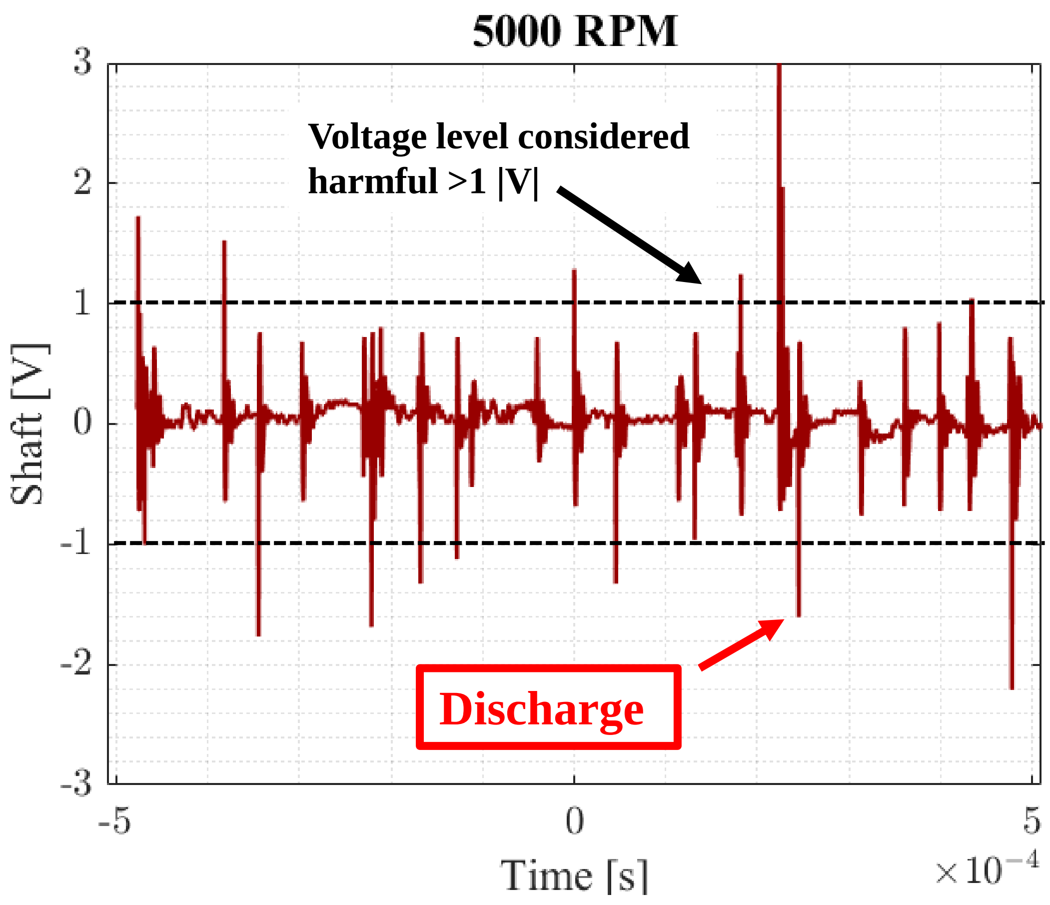


Mod. from AEGIS Bearing protection handbook (Nov. 2022)

Part 7 ► Discharge damages in EV's

Discharge damages in EV's

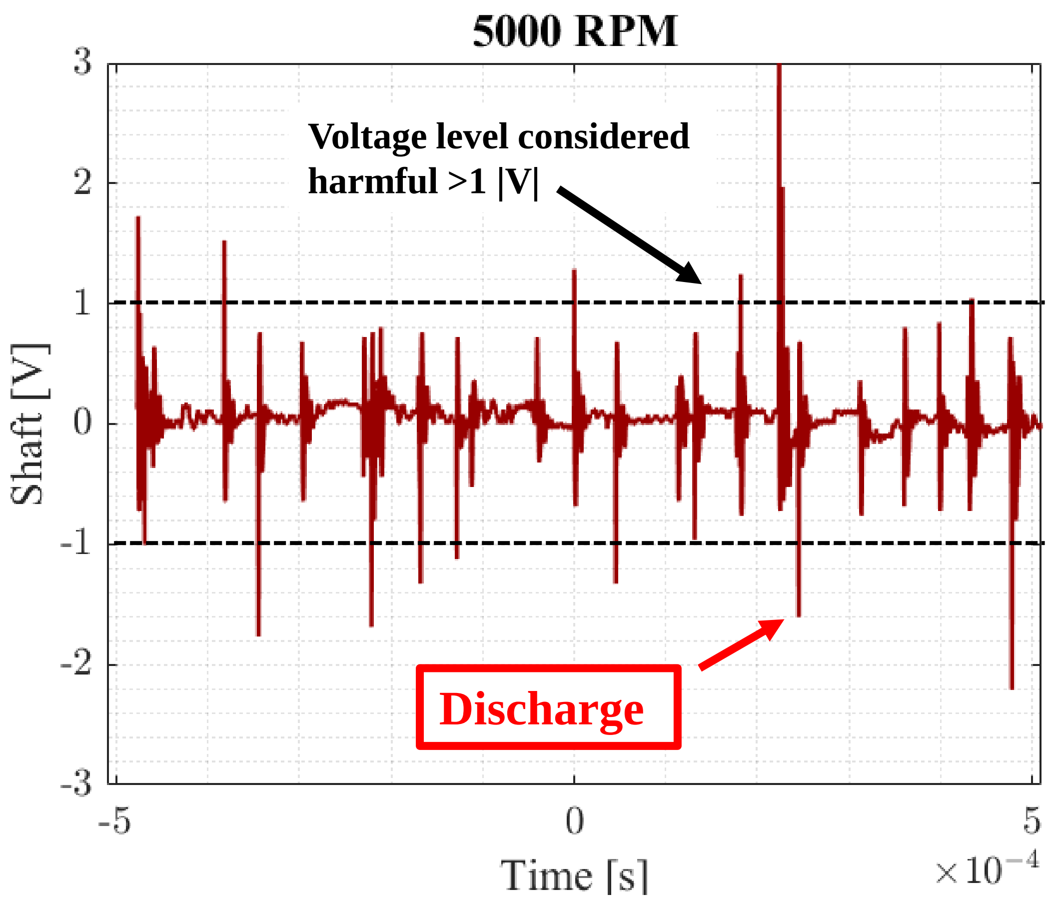
A typical measurement



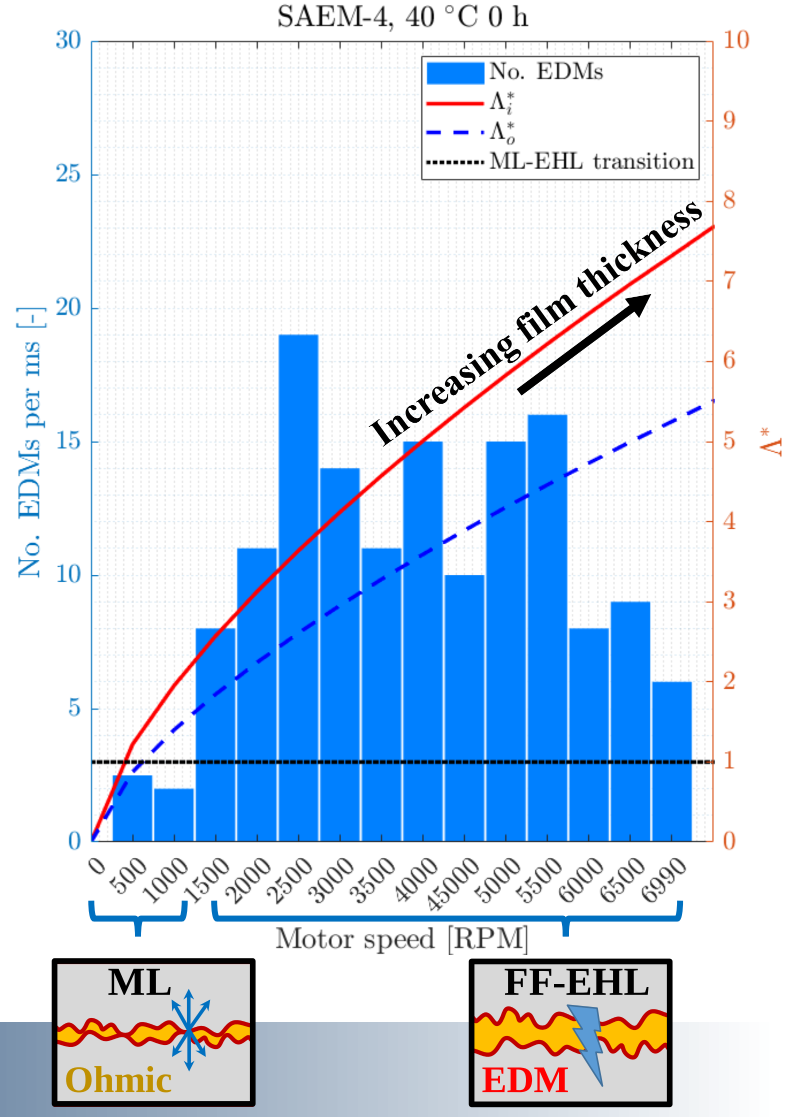
Jonny Hansen, jonny.hansen@scania.com

Discharge damages in EV's

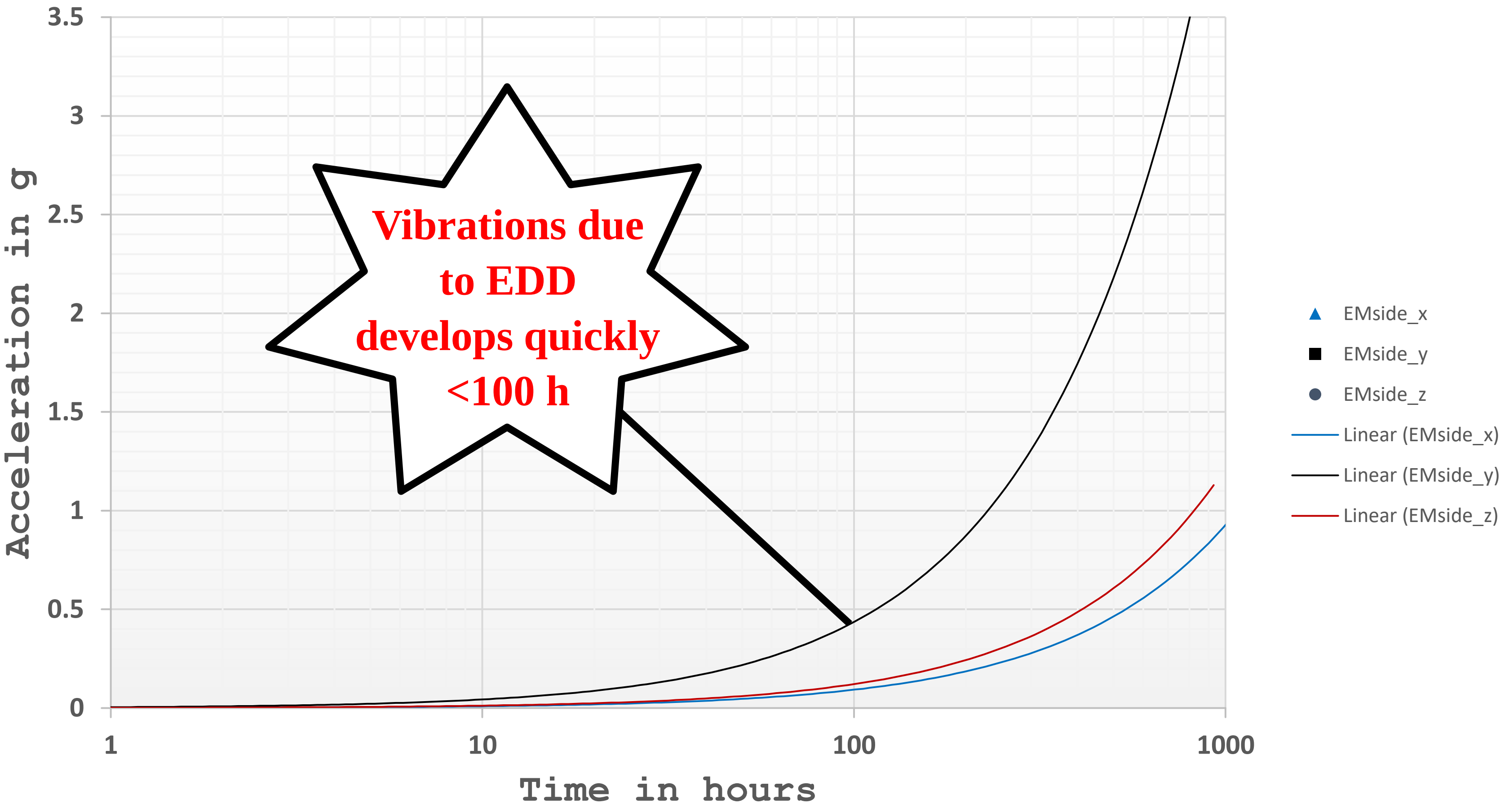
A typical measurement



'EDM' peak counting



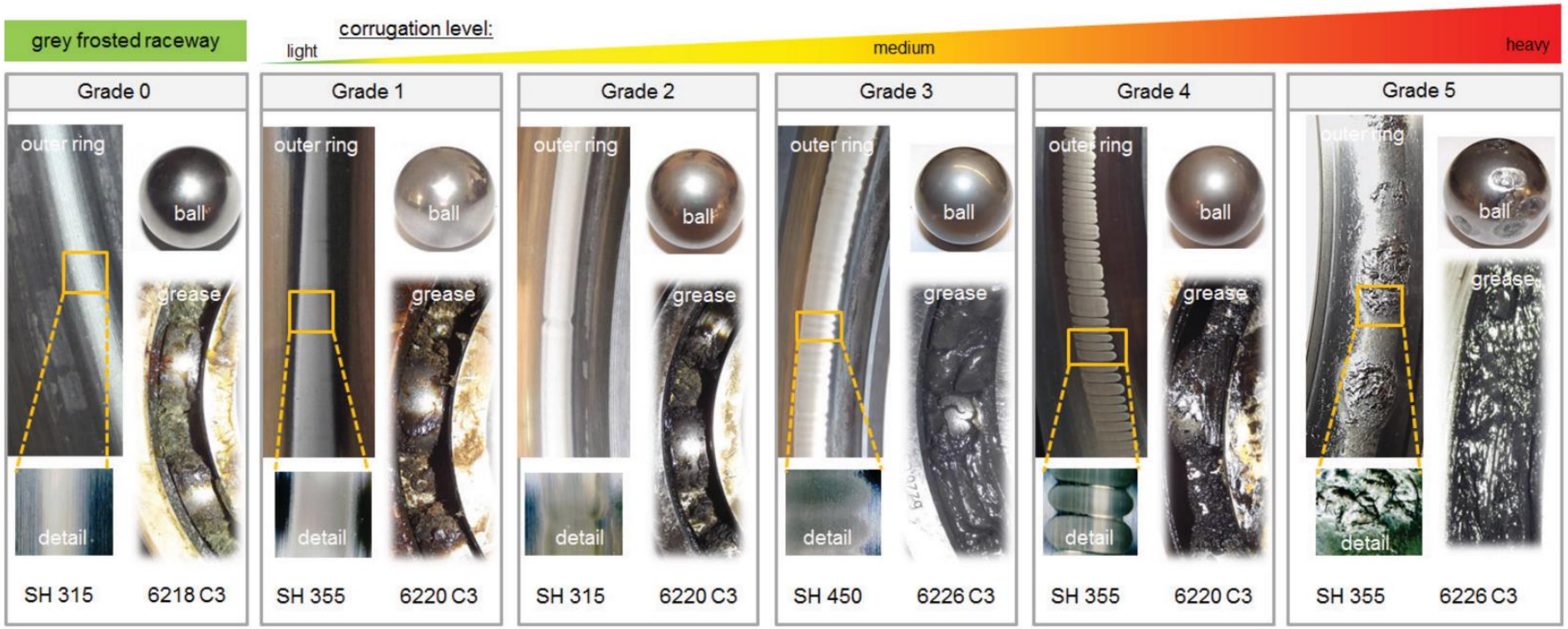
Discharge damages in EV's



Preliminary results

Discharge damages in EV's

Grades of EDM damages

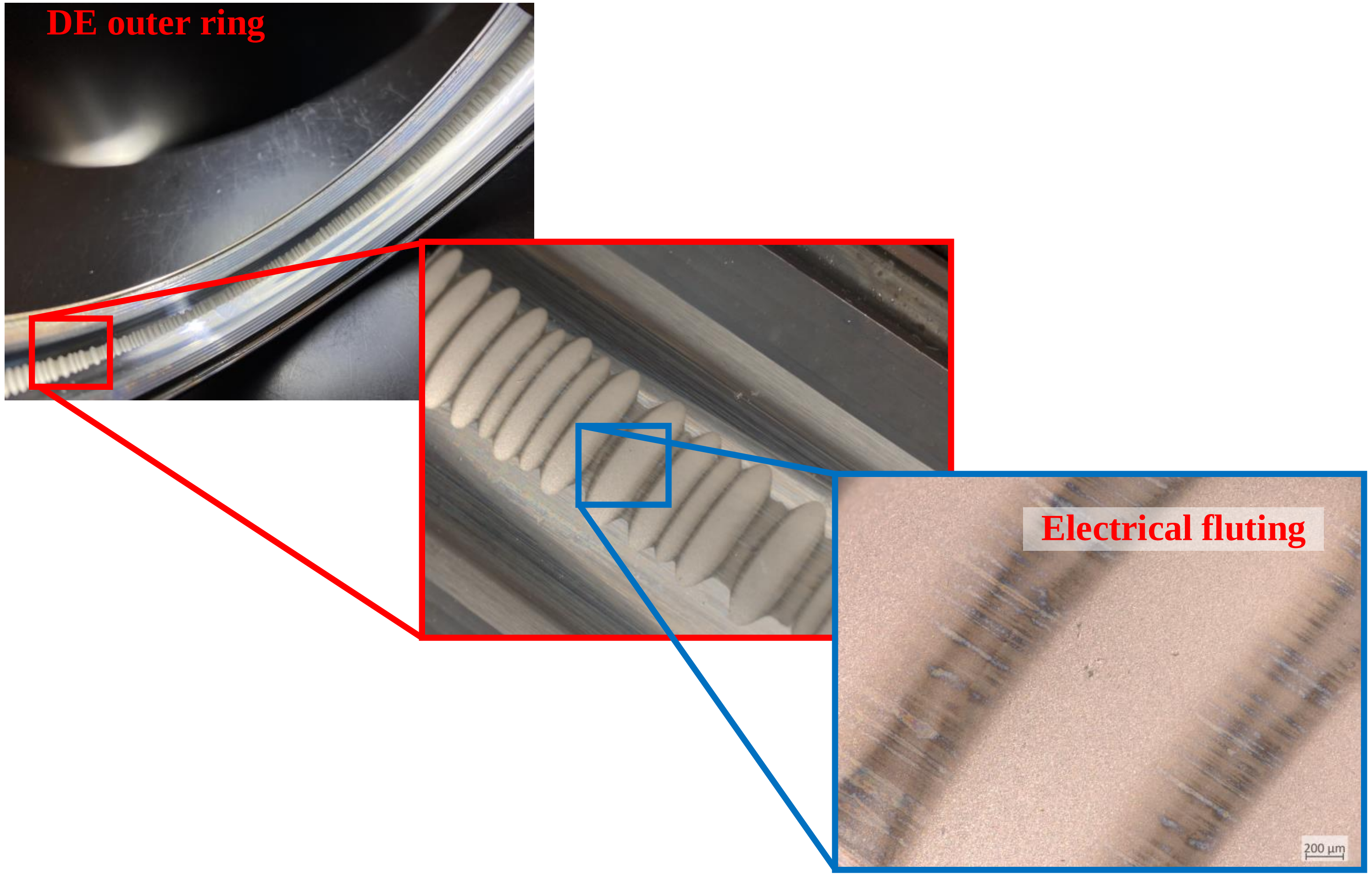


- **Grade 0** → Grey frosted racesways that has insignicant influence on bearing life
- **Grade 1** → Multitude of small melted crates. An emerging crosswise ripple formation are visible. The lubricant already shows typical black discolorations
- **Grade 2-4** → an increasing crosswise ripple formation (fluting) becomes visible. The black coloration of the grease clearly indicates the influence of an electrical bearing load.
- **Grade 5** → fatigue failures in the raceways and at the balls in addition to the corrugation (fluting marks)

H. Tischmacher, "Bearing Wear Condition Identification on Converter-fed Motors," SPEEDAM 2018 - Proc. Int. Symp. Power Electron. Electr. Drives, Autom. Motion, pp. 19–25, 2018

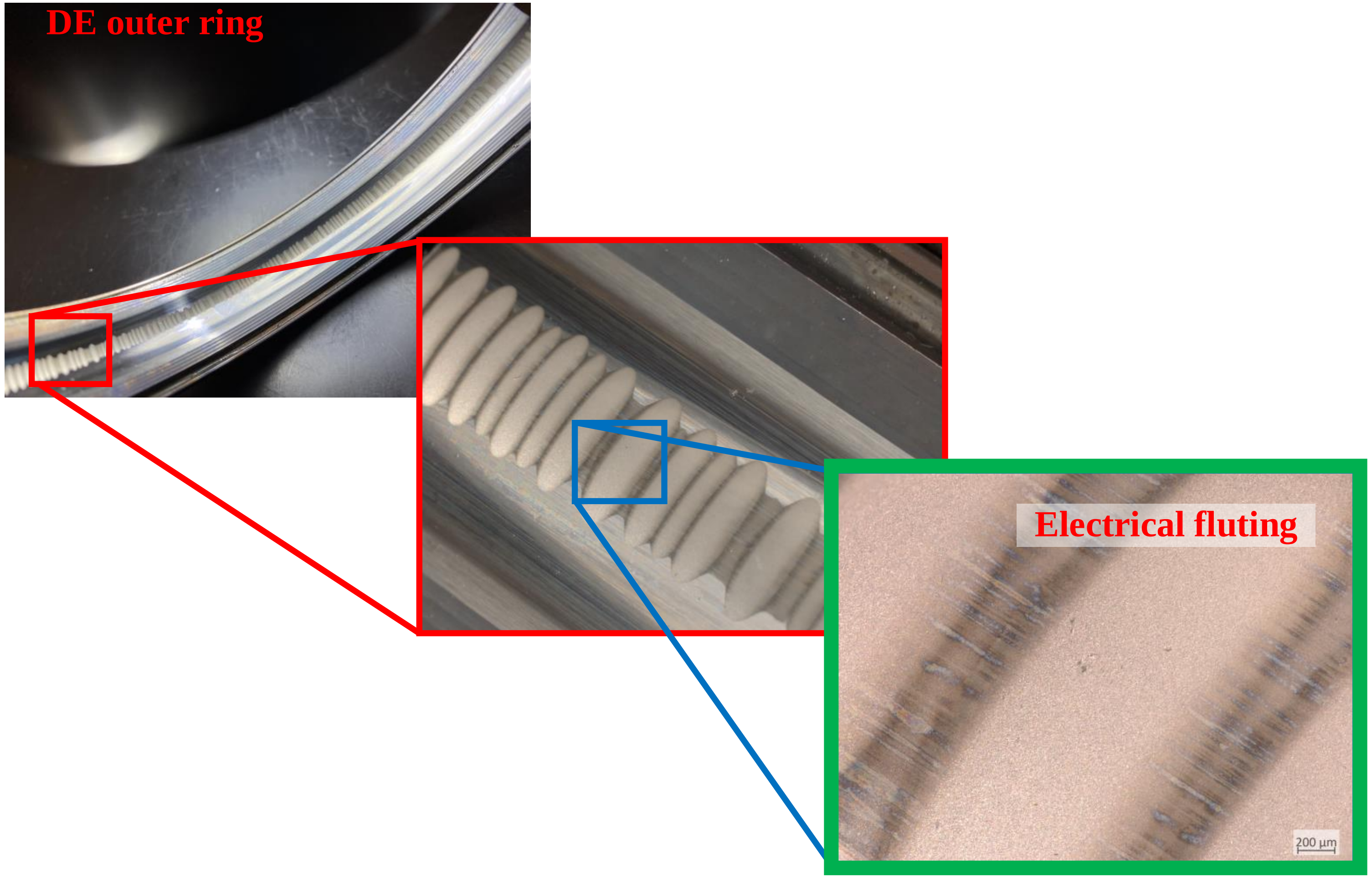
Discharge damages in EV's

Example of fluting due to electrical discharge



Discharge damages in EV's

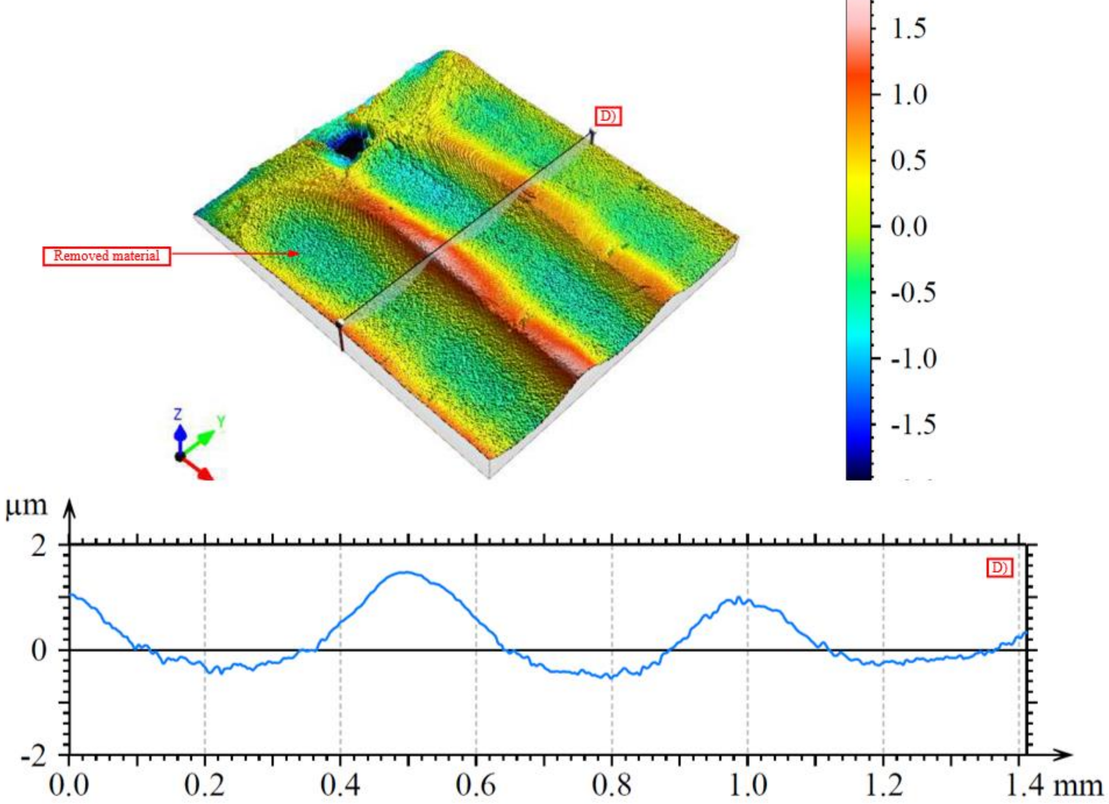
Example of fluting due to electrical discharge



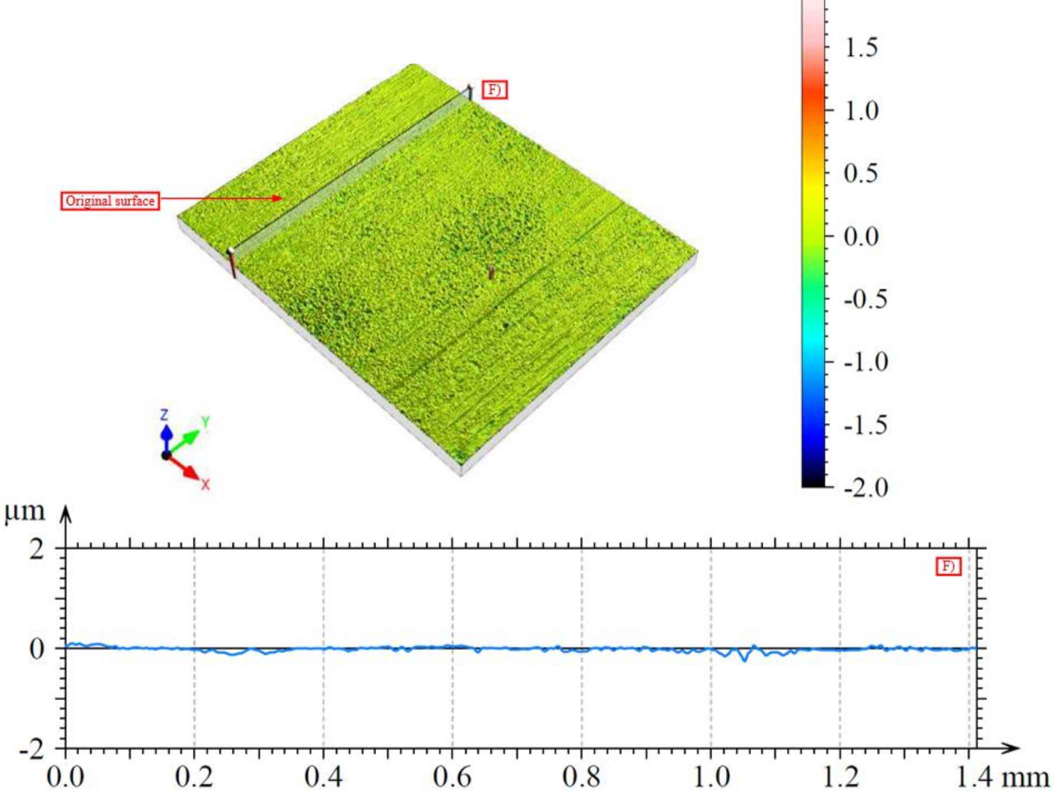
Discharge damages in EV’s

Example of fluting due to electrical discharge

Fluted surface topography

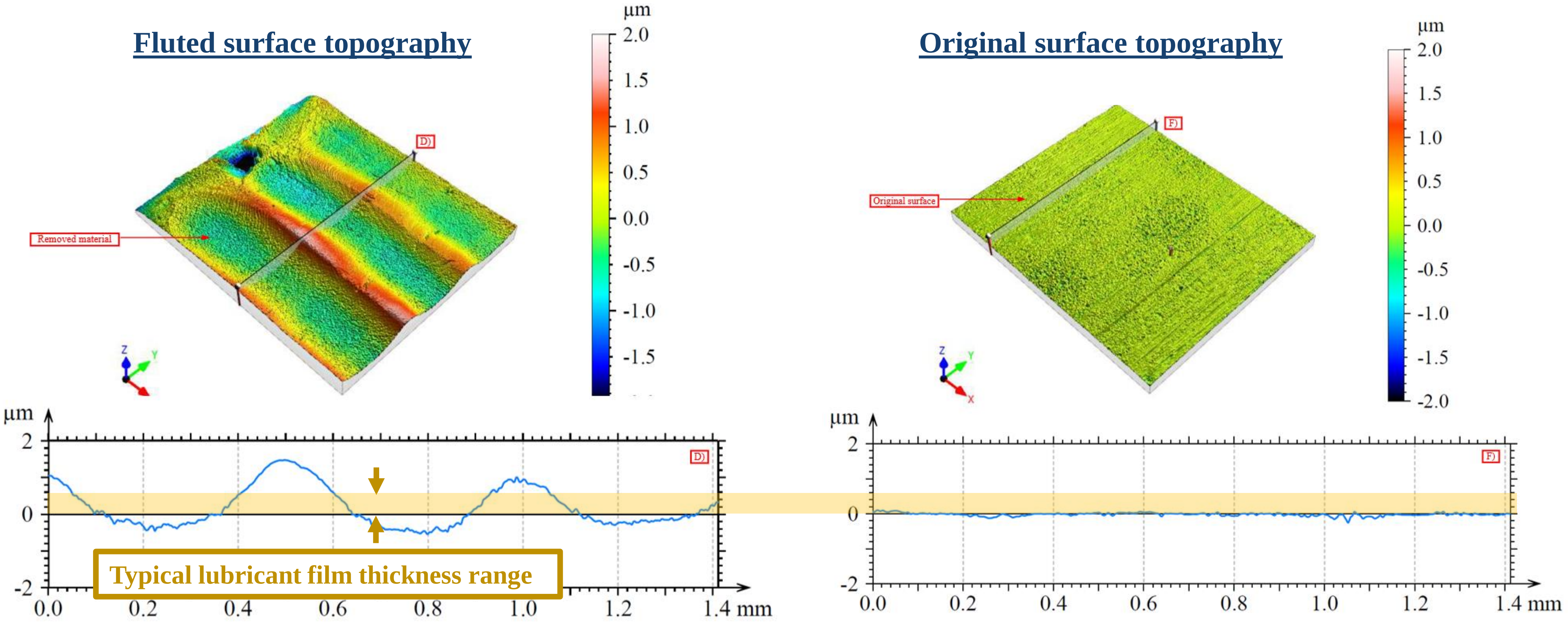


Original surface topography



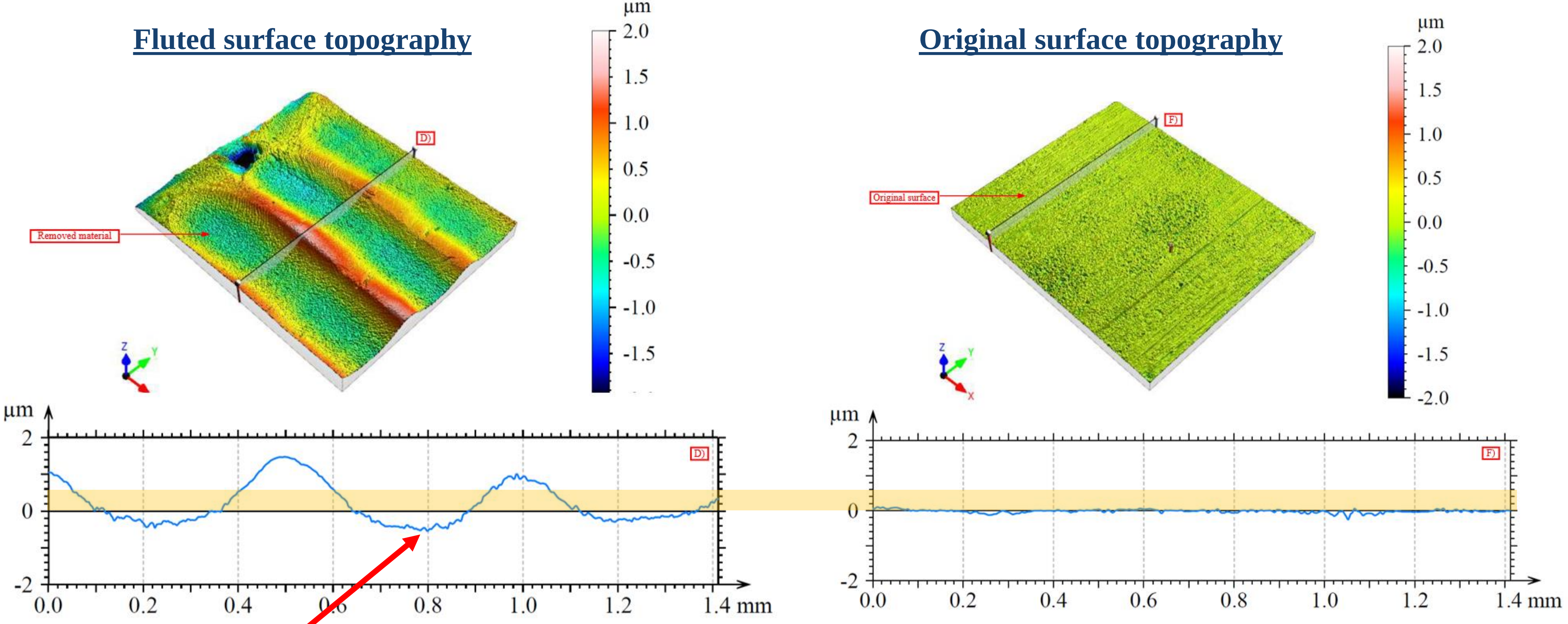
Discharge damages in EV’s

Example of fluting due to electrical discharge



Discharge damages in EV’s

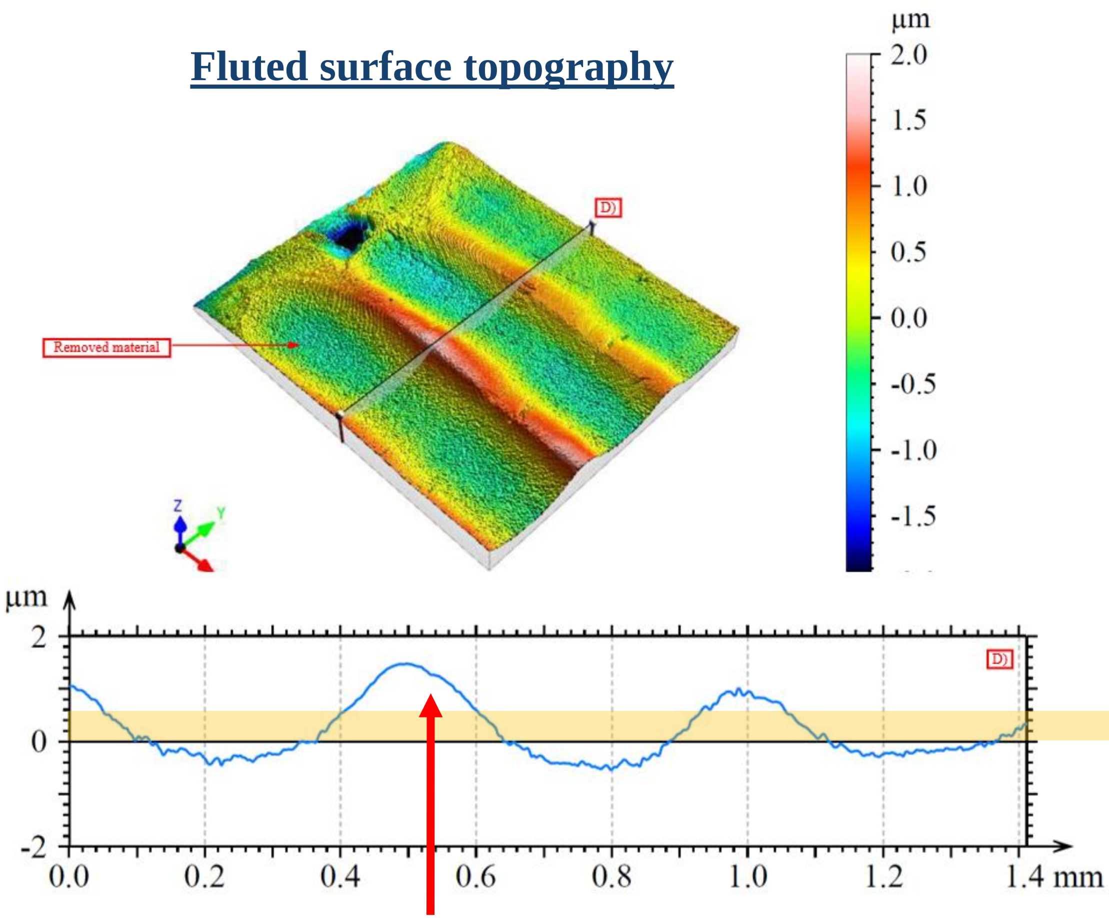
Example of fluting due to electrical discharge

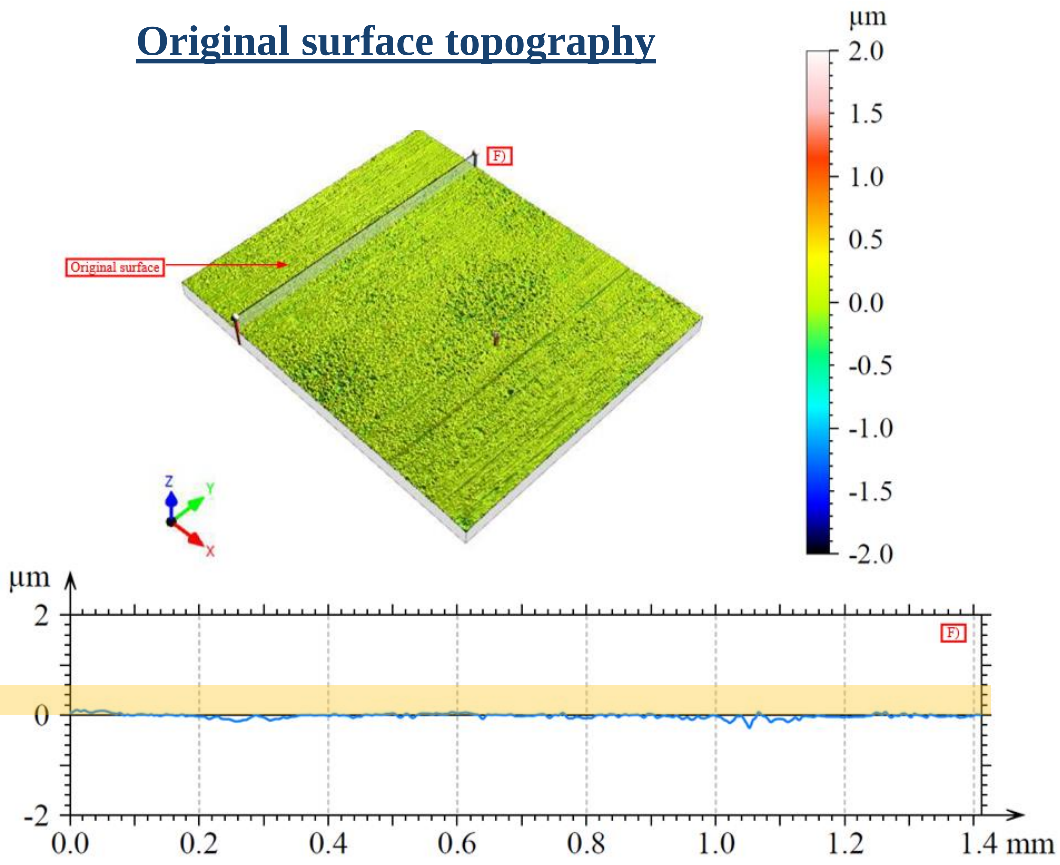


Valley zones – loss of lubrication
→ Fluid film breakdown

Discharge damages in EV's

Example of fluting due to electrical discharge



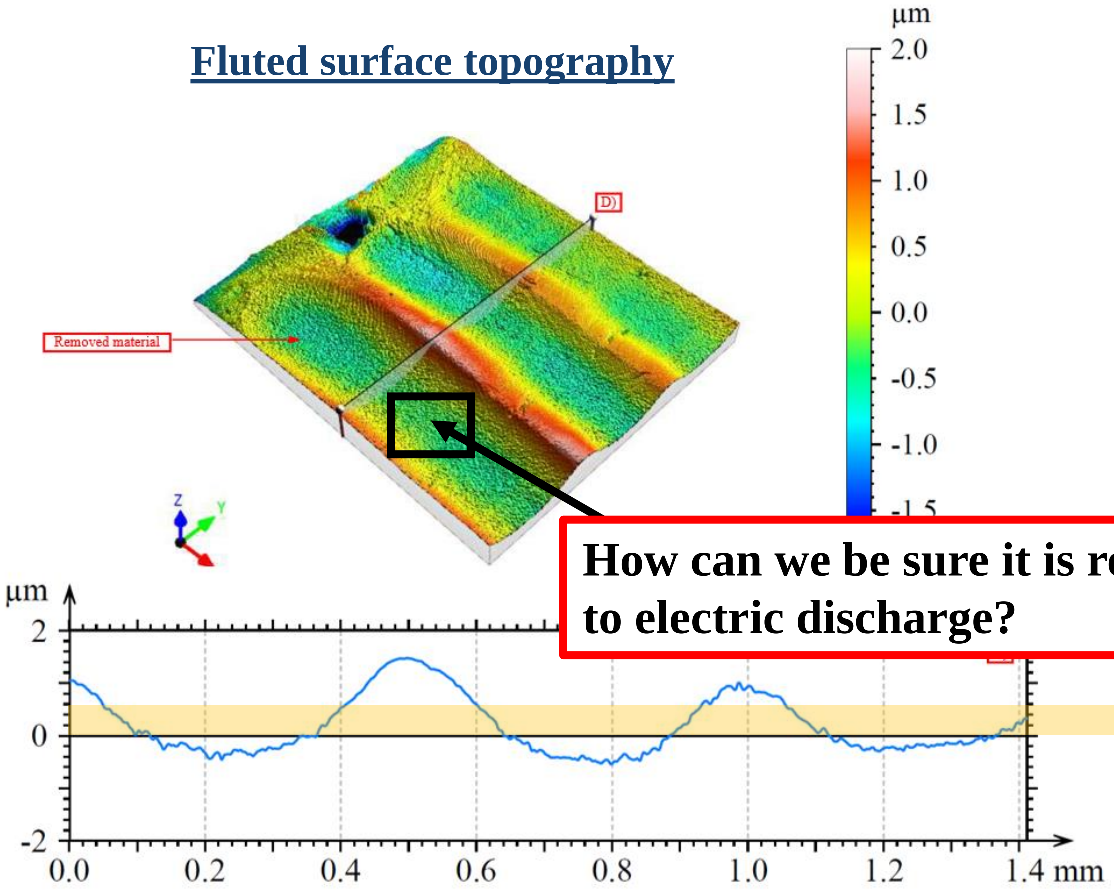


Peaks zones – stress concentrations
→ Precursor to reduced RCF-life

Discharge damages in EV's

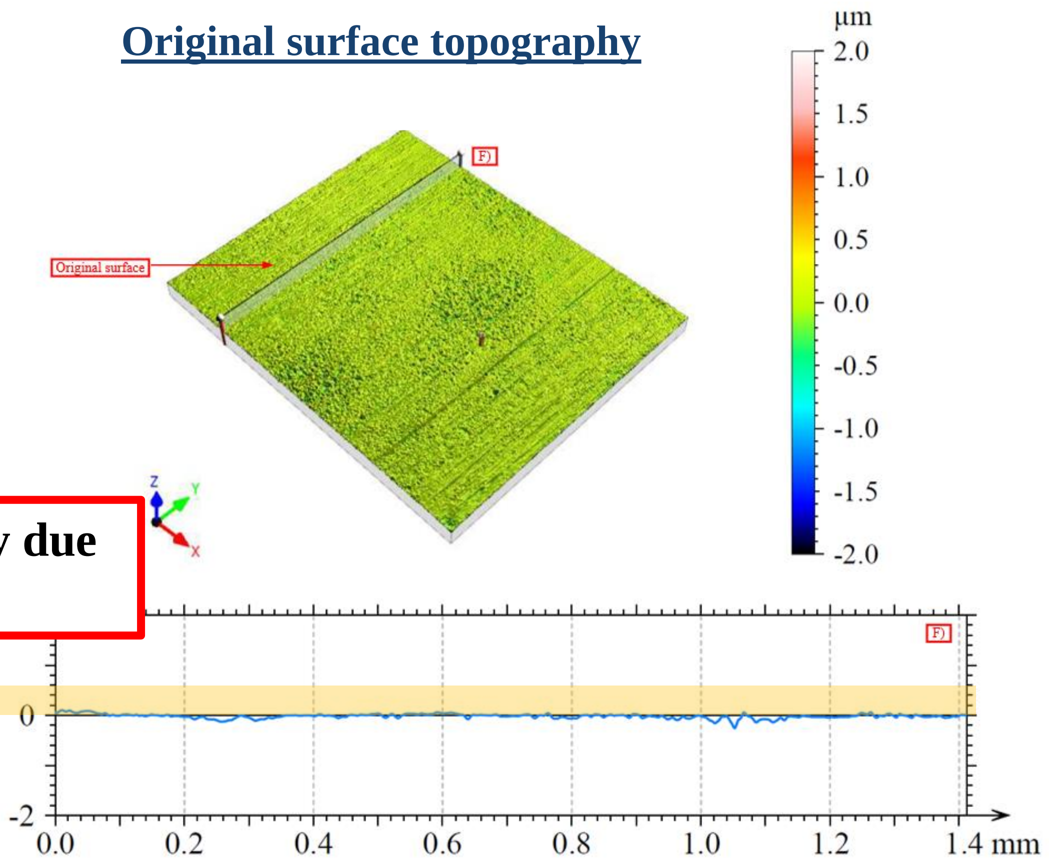
Example of fluting due to electrical discharge

Fluted surface topography



How can we be sure it is really due to electric discharge?

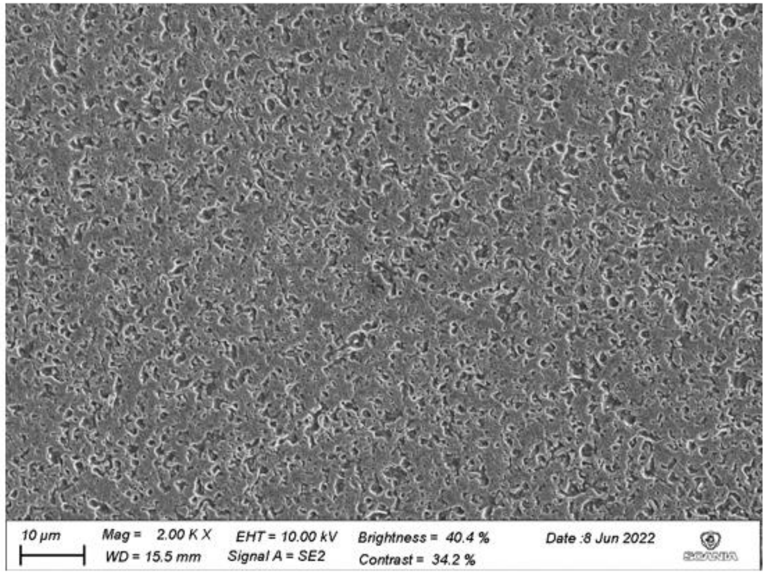
Original surface topography



Discharge damages in EV's

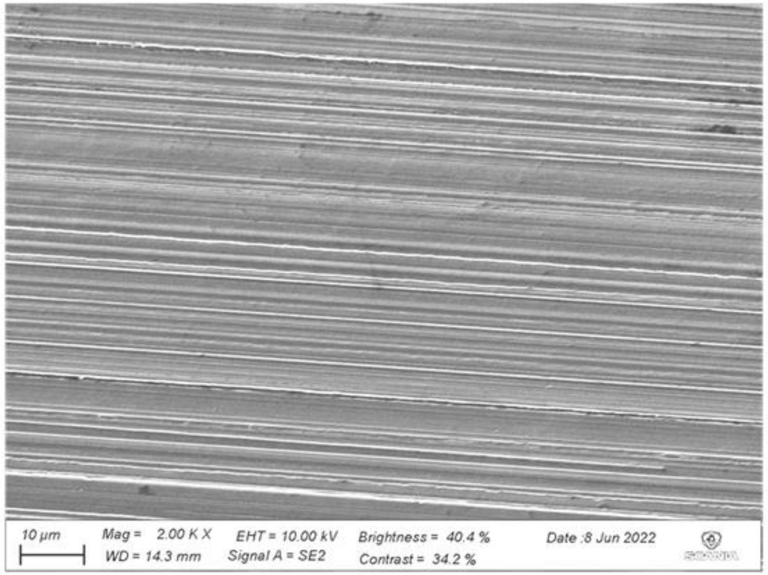
Surface appearance with and without an applied electric field

Steel raceway (steel balls)



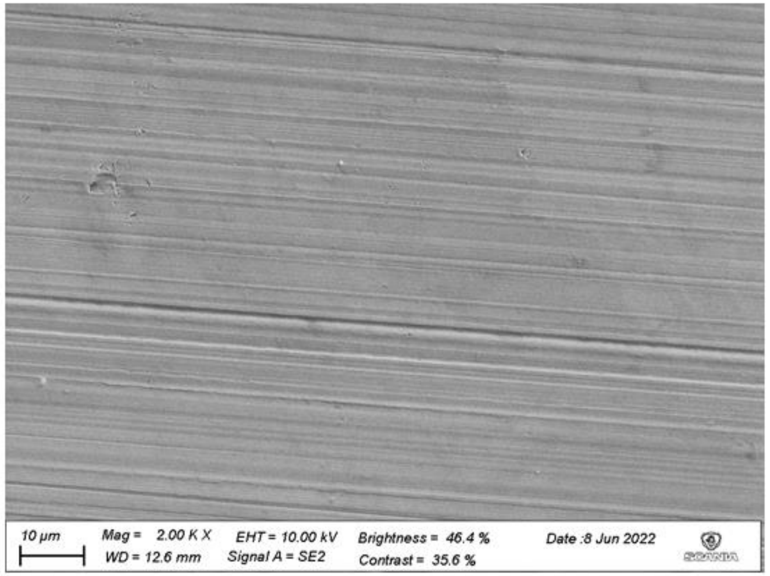
Pits caused by discharges

New raceway surface



(for comparison)

Steel raceway (ceramic balls)

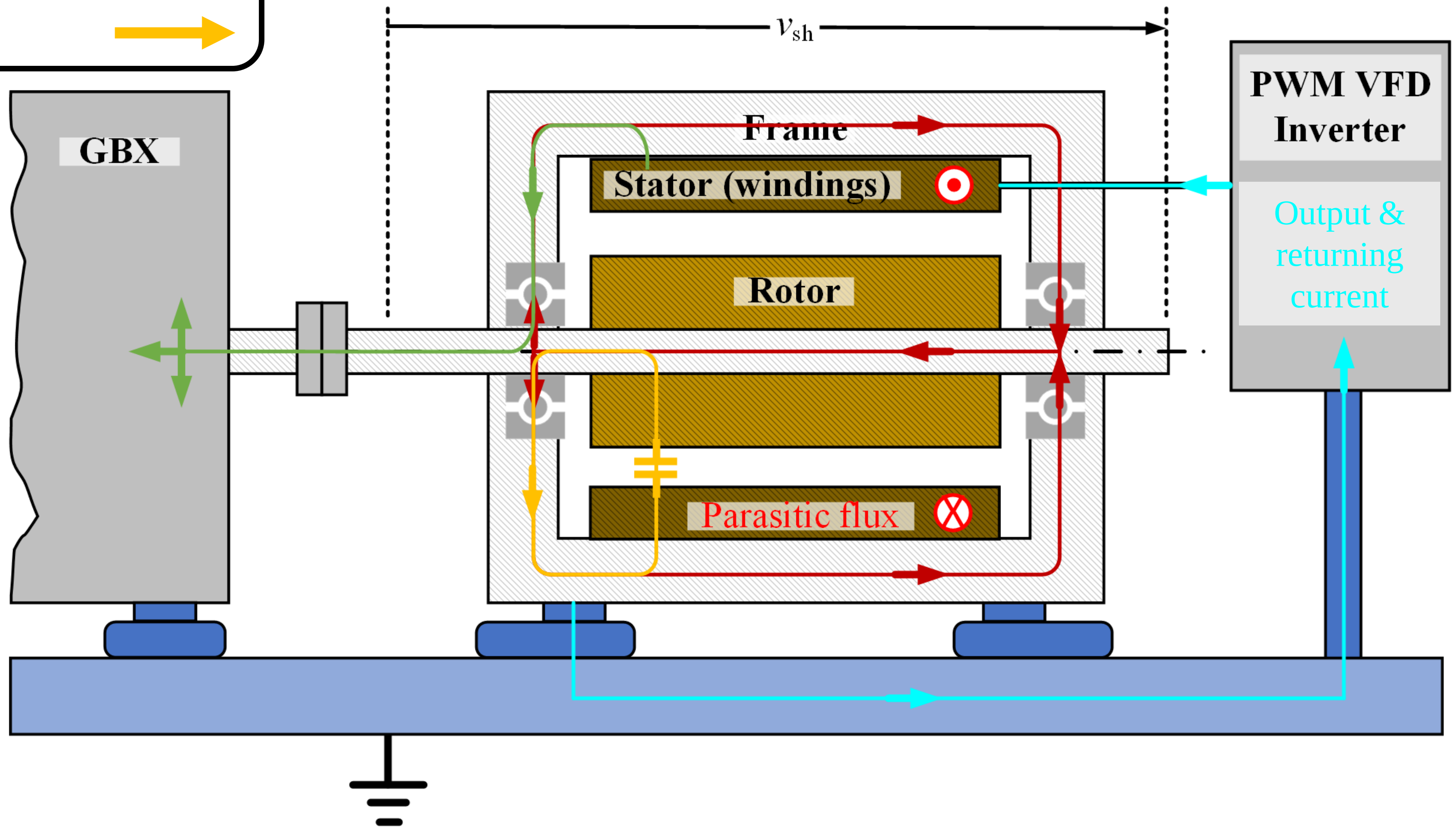


Plastic deformations & mild/ indistinguishable wear (no discharges)

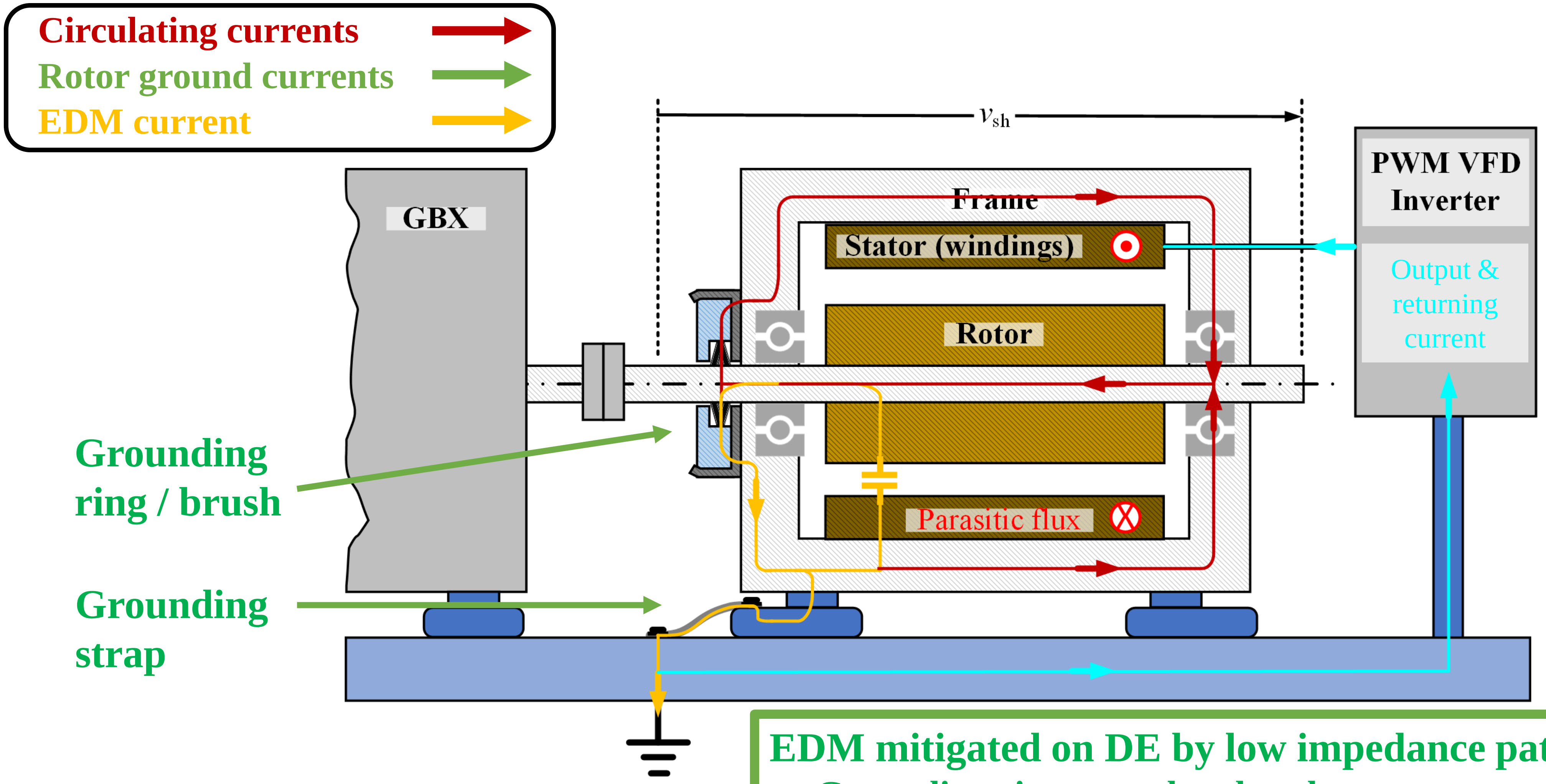
Part 8 ▸ What can be done to mitigate bearing currents?

Types of bearing currents

Circulating currents
Rotor ground currents
EDM current



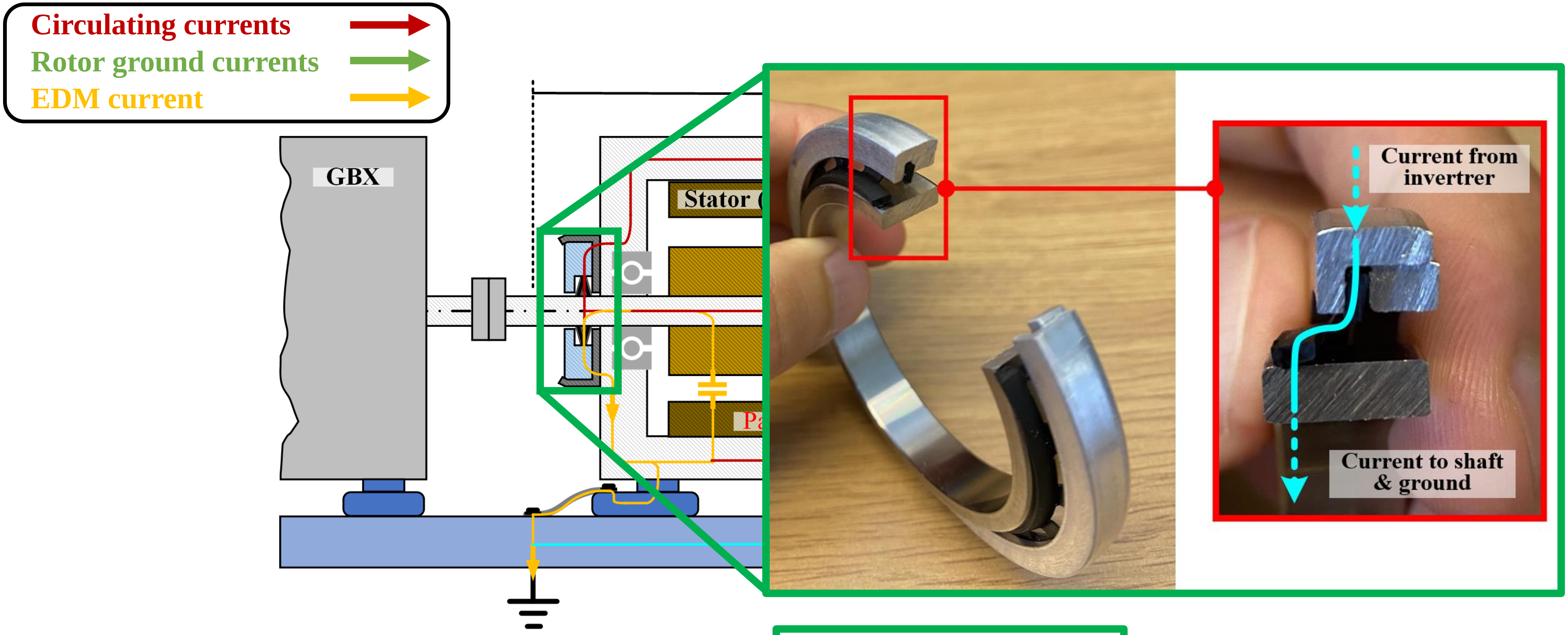
Mitigation for EDM and RG currents



EDM mitigated on DE by low impedance path

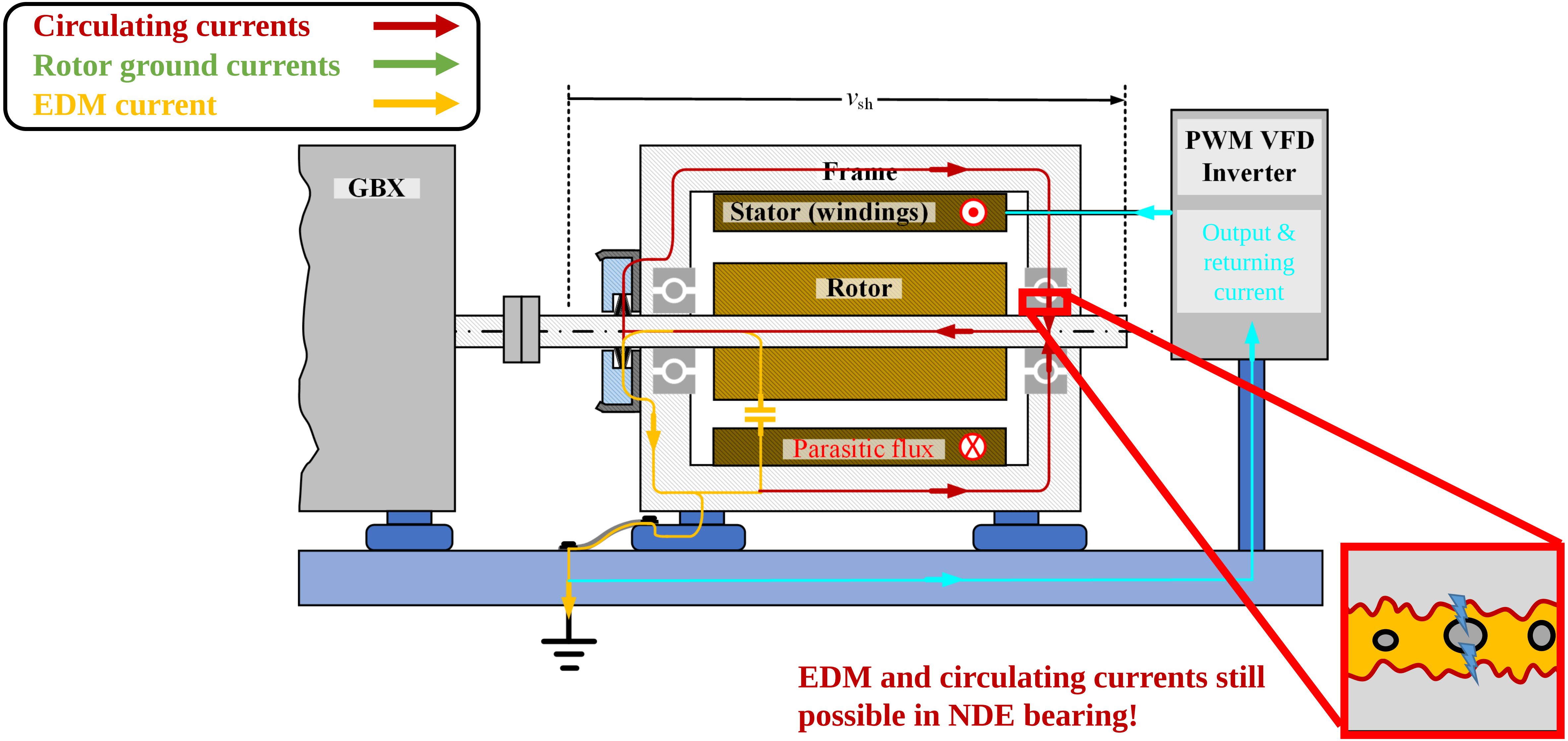
- Grounding ring or carbon brush
- Conductive lubricants (lower voltage over bearing)
- Grounding strap to ensure proper grounding

Mitigation for EDM and RG currents



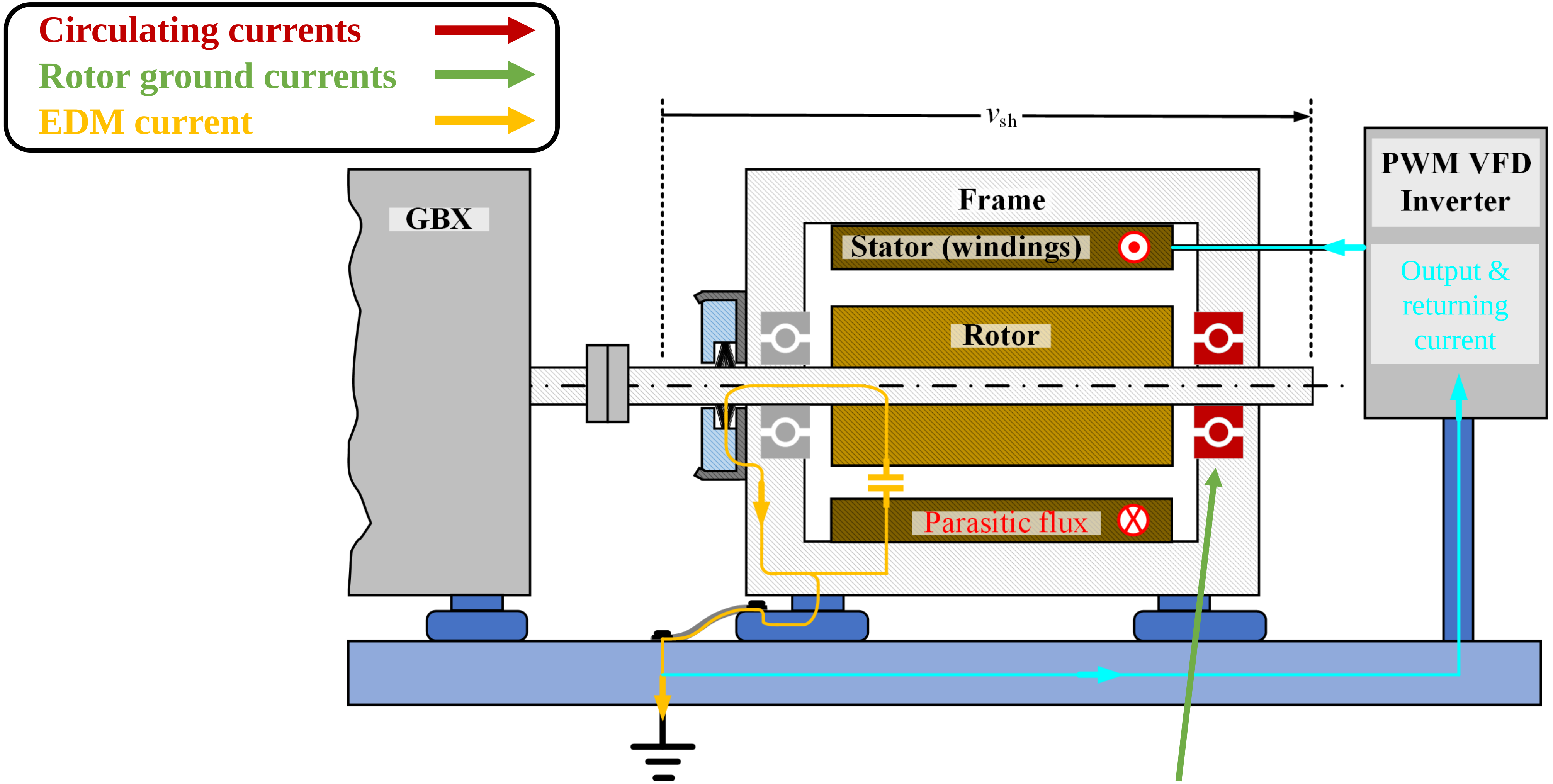
Example grounding ring

Mitigation for EDM and RG currents



EDM and circulating currents still possible in NDE bearing!

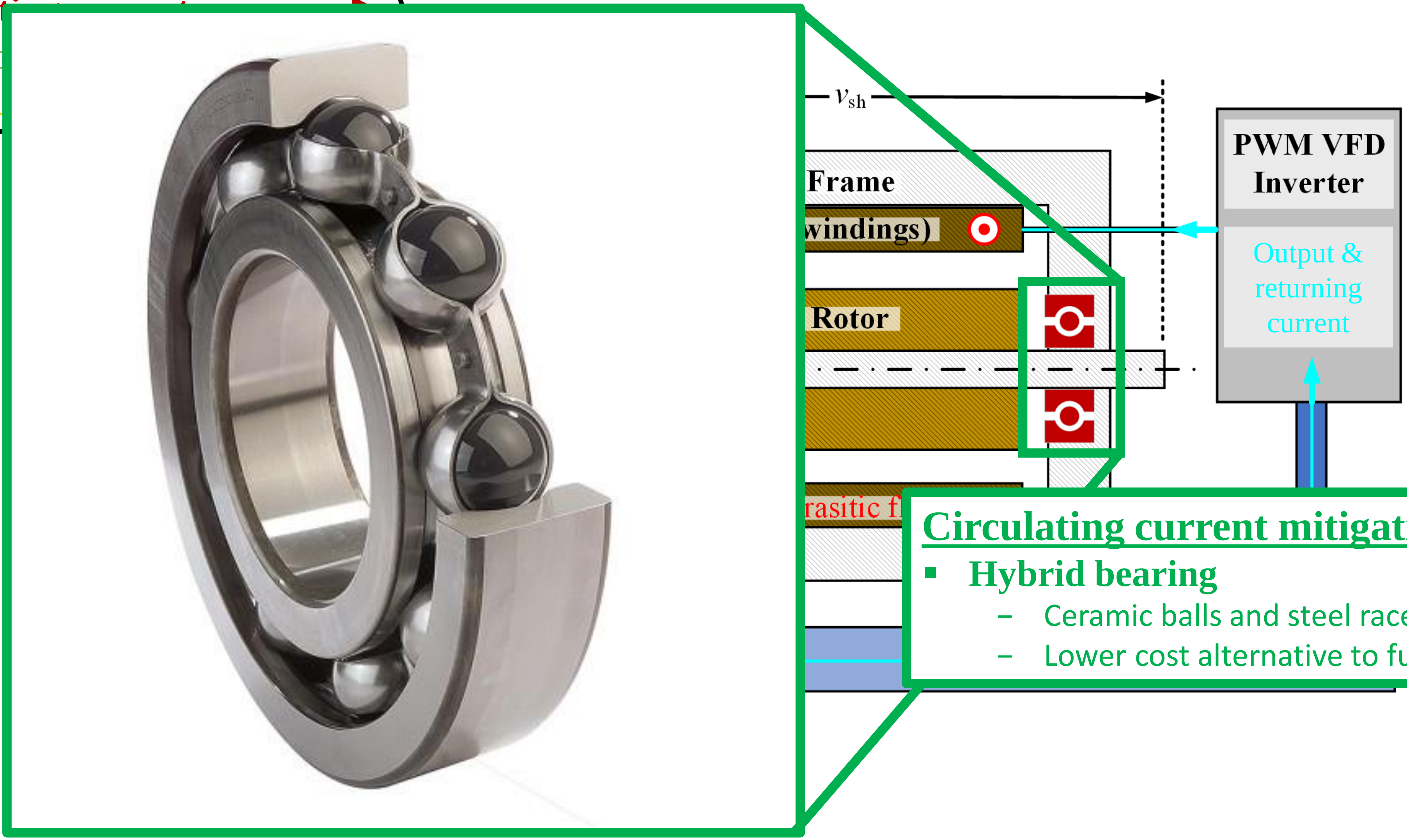
Mitigation for circulating currents



Hybrid bearing on NDE interrupts circulating currents

Mitigation for circulating currents

Circulati
Rotor g
EDM cu

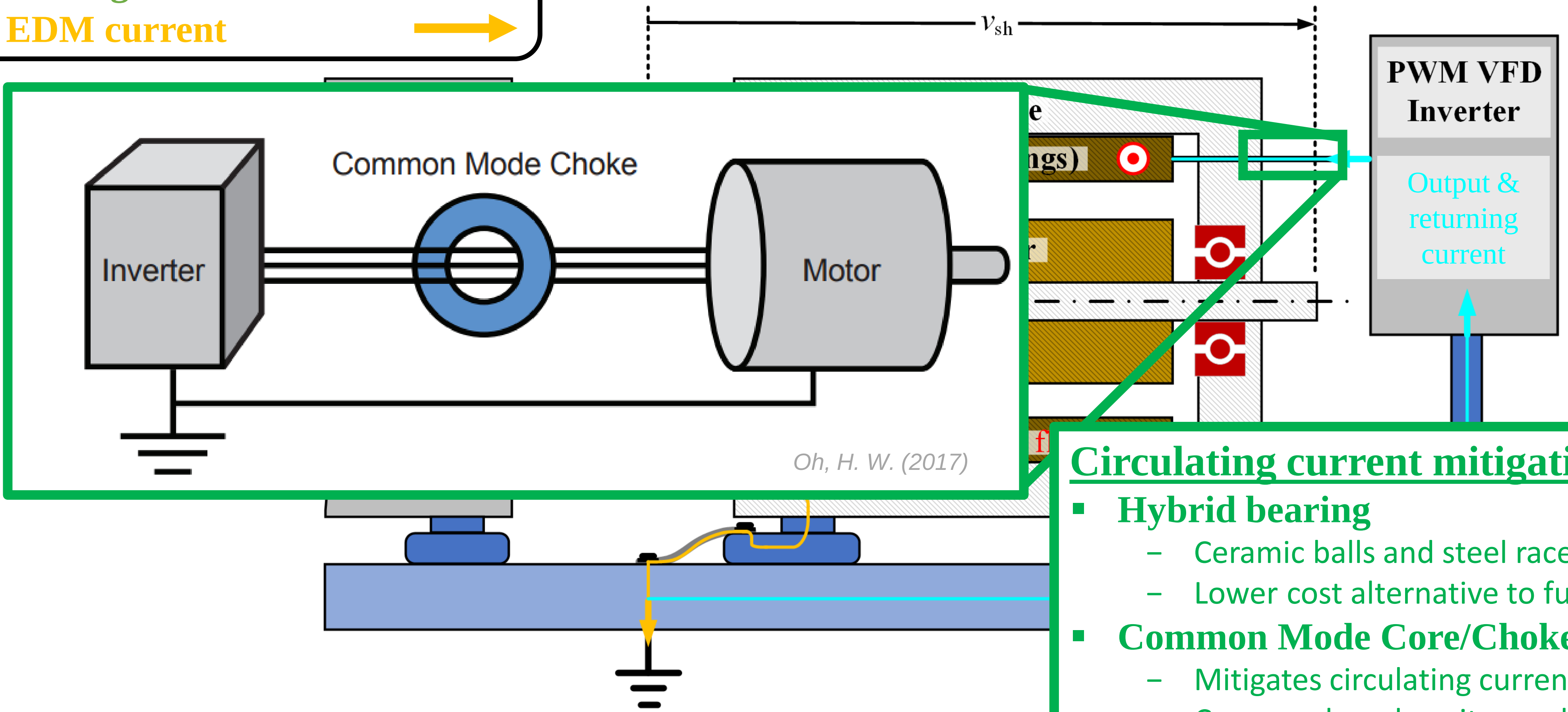


Circulating current mitigation by

- **Hybrid bearing**
  - Ceramic balls and steel raceway
  - Lower cost alternative to fully ceramic bearings

Mitigation for circulating currents

Circulating currents
Rotor ground currents
EDM current

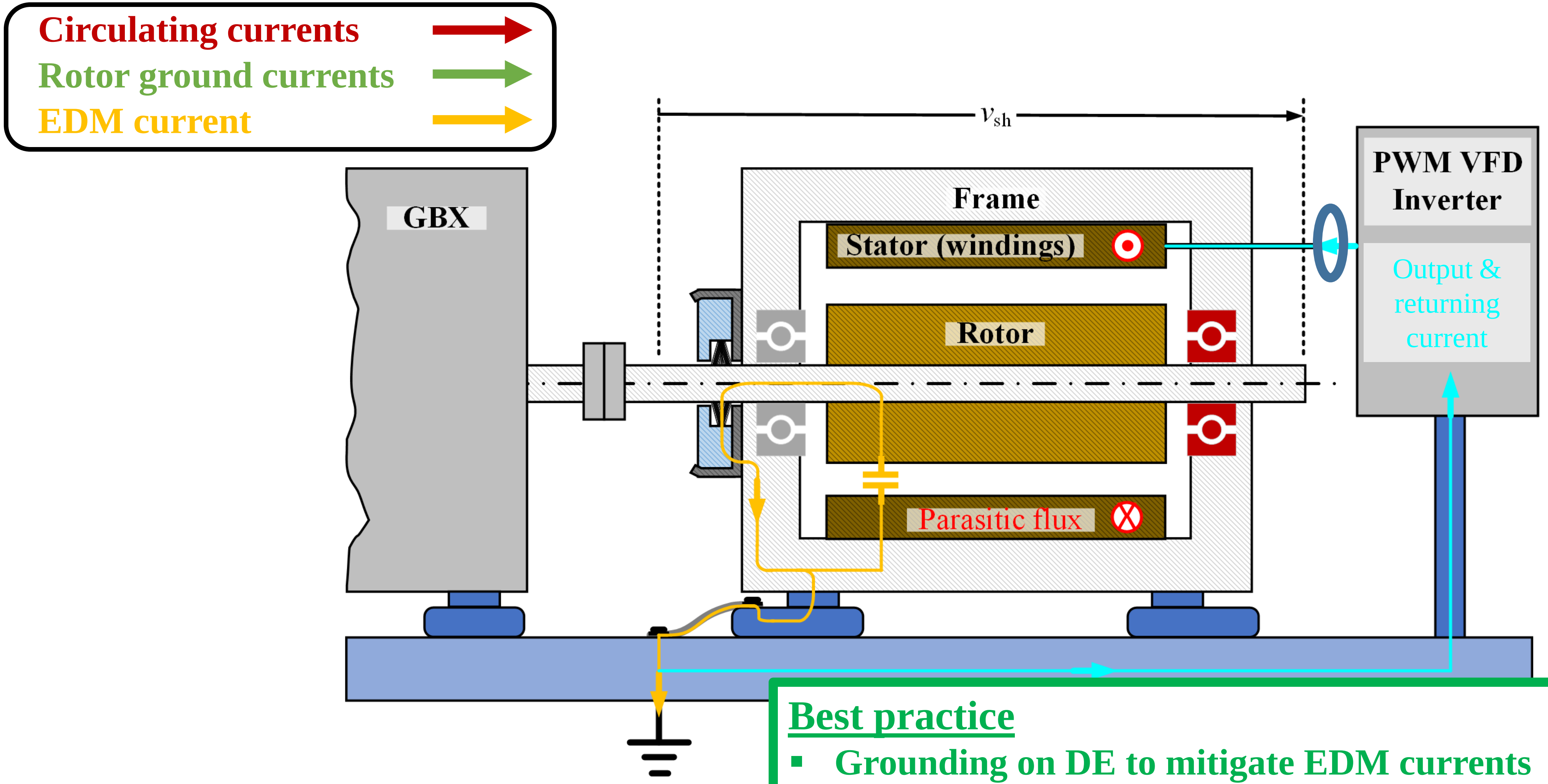


Circulating current mitigation by

- **Hybrid bearing**
  - Ceramic balls and steel raceway
  - Lower cost alternative to fully ceramic bearings
- **Common Mode Core/Choke (CMC)[1]**
  - Mitigates circulating currents by attenuating I_{CM}
  - Can merely reduce its amplitudes and ripples, i.e., the HF components (but not cancel out completely)
  - Has no effect on EDM type of bearing currents

1. Oh, H. W. (2017). Common mode chokes or cores (CMCs) cannot prevent bearing failure in all motors. In *Motor and Drive Systems Conference*.

Mitigation strategies (best practice)



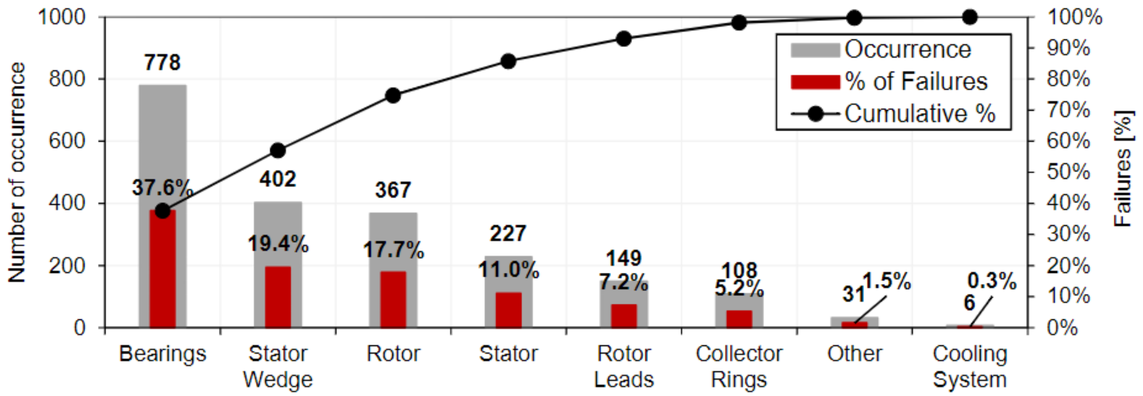
Best practice

- Grounding on DE to mitigate EDM currents
- Electrically insulate the NDE to interrupt circulating currents
- CMC to attenuate circulating currents

Part 9 ► Prospects

Prospects & possibilities

- Mitigation techniques have been known for at least 20-30 years [1-2], problem is still ever present…



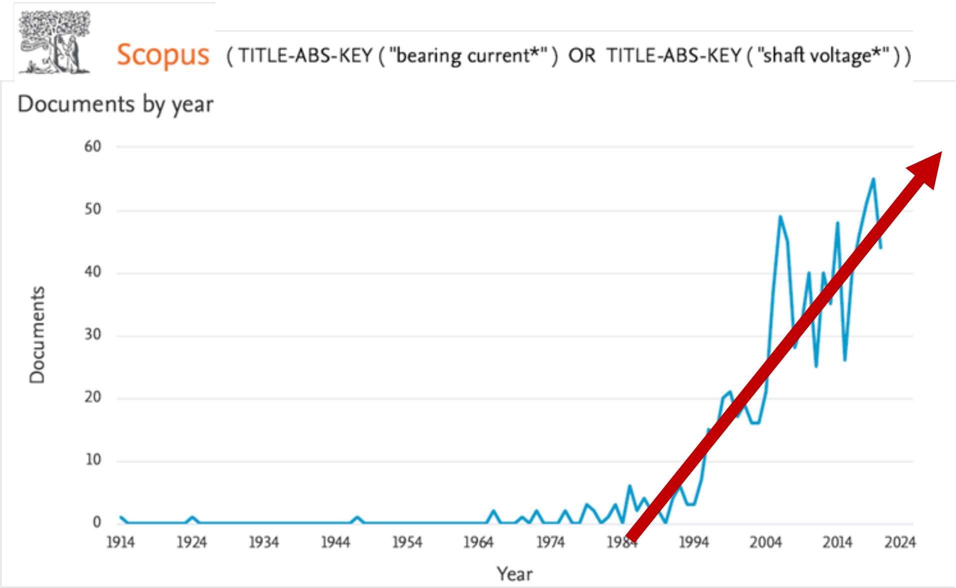
1) Muetze, A. (2003). Bearing Currents in Inverter-Fed AC Motors *(PhD Thesis)*
2) Joshi, A. (2019). Electrical Characterisations of Bearings *(PhD Thesis)*

Premature failures statistics of 2068 wind turbine generators
- Bearing failure leading cause
- Attributed to transient shaft currents and improper maintenance, e.g., worn slip rings / brushes.

Prospects & possibilities

- Mitigation techniques have been known for at least 20-30 years [1-2], problem is still ever present…
- No commercially available grounding contact (ring/brush) confirmed for heavy EV
- No commercially available electrically conducive lubricant solution exists on the marked today
- The mechanisms of EDD and how it affects RCF is only vaguely understood
- The influence of electric fields on lubricant additives & tribofilms is poorly understood
- Shift from IGBT to SiC based VFD is expected to make bearing currents worse
- Skyrocketing trend in bearing current research – a major heads-up for a future trajectory

Prospects & possibilities



Scopus reference search
Indicating rising trend in bearing current research

- Skyrocketing trend in bearing current research – a major heads-up for a future trajectory

Prospects & possibilities

Scopus reference search
Indicating rising trend in bearing current research

- Skyrocketing trend in bearing current research – a major heads-up for a future trajectory

Part 10 ▸ Conclusions

Conclusions

EV Tribology

- Electricity adds further challenges to an already challenging discipline
  - Damages are now possible in the EHL regime (which previously was considered safe)
  - A new micro-EHD film parameter can be used to assess the transition between EHL & ML to a good degree of accuracy

Stray currents in heavy EV's

- Three main types: EDM, circulating and rotor shaft ground currents
- May cause surface damages
  - Frosting and fluting most prominent
  - Leads to reduced energy efficiency, service life and increased noise
- Major influencing factors
  - Lubricant film thickness and electric properties
  - Voltage gradients du/dt (rise time) & switch frequency (no. of available discharges)
  - EM system capacitance (BVR)
  - Mitigation strategy

Prospects

- Many challenges and research opportunities remains
- Trend is towards intensified research on EV tribology

Thank you for listening! :-)

Q&A