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ORIGINALARBEITEN/ORIGINALS

Influence of lubricant particle contamination on discharge events in electrical loaded radial cylindrical roller bearings

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Abstract

The economic efficiency of wind turbines is considerably affected by the occurrence of premature bearing failures in gearboxes. Due to their proximity to the generator, gearbox bearings experience additional electrical stress, leading to voltage buildup across the bearing. When this voltage exceeds a certain threshold (breakdown voltage), it discharges as an arc. It is well established that electrical discharge across a bearing can induce surface- and structural-damage to the bearing material. The effect of particles on the electrical properties of oil, and consequently on potential current conduction, is well documented in other technical fields. The existing design standards for wind turbine gearboxes and bearings only consider the mechanical effects of particles. Therefore, only particles with a diameter $\geq 6\,\mu m$ are considered. This study experimentally investigates the influence of particles $< 6\,\mu m$ on the breakdown voltage and frequency in electrically loaded cylindrical roller bearings. These particles, which are not considered in current design standards for wind turbine gearboxes, constitute the majority of contaminants. The results show that higher particle concentrations lead to a reduction in breakdown voltage. This effect is also evident within the typical particle contamination levels found in wind turbine gearboxes. Additionally, higher particle concentrations correlate with increased breakdown frequency and reduced energy per breakdown, suggesting a possible shift from surface- to structure-induced damage mechanisms.

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Einfluss von Partikeln im Schmierstoff auf das Durchschlagsverhalten in elektrisch belasteten Radialzylinderrollenlager

Zusammenfassung

Die Wirtschaftlichkeit von Windenergieanlagen wird erheblich durch das Auftreten vorzeitiger Lagerausfälle in Getrieben beeinträchtigt. Aufgrund ihrer Nähe zum Generator sind die Getriebelager einer zusätzlichen elektrischen Belastung ausgesetzt, welche einen Spannungsaufbau über das Lager bedingt. Überschreitet diese Spannung eine bestimmte Schwelle (Durchschlagsspannung), entlädt sie sich in Form eines Lichtbogens. Aus dem Stand der Forschung ist bekannt, dass diese elektrischen Entladungen zu oberflächen- sowie strukturinduzierten Schäden der Lagerkomponenten führen können. Die Auswirkung von Partikeln auf die elektrischen Eigenschaften von Schmierstoffen ist in anderen technischen Bereichen gut dokumentiert. Die bestehenden Konstruktionsnormen für Getriebe und Lager von Windenergieanlagen berücksichtigen lediglich die mechanischen Auswirkungen von Partikeln und daher nur Partikel mit einem Durchmesser ≥6 μm. In Getriebeschmierstoffen von Windenergieanlagen weißt der Großteil der Partikel jedoch einen kleineren Durchmesser auf. In diesem Beitrag wird experimentell der Einfluss von Partikeln <6 μm auf die Durchschlagsspannung und -frequenz in einem elektrisch belasteten Zylinderrollenlager untersucht. In den Untersuchungen konnte gezeigt werden, dass höhere Partikelkonzentrationen zu einer Reduktion der Durchschlagsspannung führen. Dieser Effekt ist auch für typische Partikelverunreinigungen von Getriebeölen in Windenergieanlagen zu beobachten. Darüber hinaus korreliert eine höhere Partikelkonzentration mit einer höheren Durchschlagshäufigkeit und einer geringeren Energie pro Durchschlag, was auf eine mögliche Verschiebung von oberflächen- zu strukturinduzierten Schadensmechanismen hindeutet.

1 Introduction

To maintain competitiveness in the renewable energy market, wind turbine developers are focused on reducing the levelized cost of electricity (LCOE). A significant factor contributing to damage-related downtimes, maintenance costs, and thus LCOE, is gearbox failure [1]. Notably, 76% of wind turbine gearbox failures are attributed to damaged bearings [2]. The occurrence of premature bearing failures within the first 10% of their calculated service life indicates that fatigue-based rolling bearing designs (e.g. DIN ISO 281 [3]) may not fully address all critical factors contributing to these failures.

Premature failures in bearings of wind turbines are frequently linked to white etching cracks (WEC), which can lead to white structure flaking, micro pitting, and axial cracking [4–8]. Multiple studies have correlated electrical loads on rolling bearings with the occurrence of WEC [9–14]. In the case of wind turbines those loads are primarily induced by the power converter [15]. Depending on the magnitude and characteristics of the electrical load, it can either contribute to premature bearing failures through WEC formation [9] or cause immediate surface damage due to electrical erosion [16, 17]. Operating conditions, including temperature, pressure, moisture, and particle contamination [18, 19], can significantly influence the electrical properties of the lubricating oil, which acts as a dielectric in the rolling contact [17].

In power transformers, particle contamination is known to affect the electrical properties of lubricants and the characteristics of the electrical load during a breakdown. Wang et al. examined how different conductive particle materials, sizes, and concentrations affecting the breakdown voltage in mineral and natural ester oils. The AC breakdown voltage in the test lubricant was measured during continuous stirring (Fig. 1). The results showed a decrease in breakdown voltage with increasing particle concentration [20].

The same behavior was observed by Dan et al. with DC voltage and mineral oil. The alteration in breakdown voltage is attributed to a change in the distribution of the electric field by the particles, with conductive iron particles having a greater impact on this change than non-conductive cellulose particles [21].

Cleanliness in lubrication systems is classified according to ISO 4406, which classifies the cleanliness by counting particles per 100 ml in three size bins: ≥4 μm, ≥6 μm and ≥14 μm. Each size bin is assigned a cleanliness class on a logarithmic scale from 0 to 28, indicating the concentration of particles [22].

In gearboxes of wind turbines, the primary lubrication flow undergoes two stages of filtration typically using 10 and 50 μm filters, primarily targeting particles corresponding to size bin ≥14 μm [23, 24]. The IEC 61400-4 standard calculates wind turbine bearing service life based

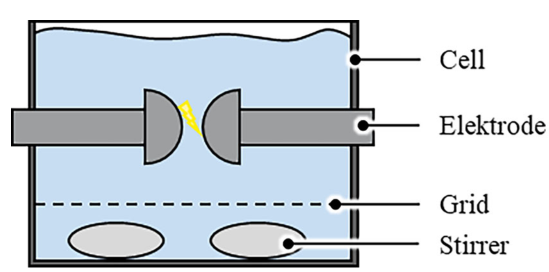


Fig. 1 Breakdown voltage measuring setup [20]

on particles ≥6 µm, as these are assessed for their potential to cause mechanical damage [3, 25]. Particles <6 µm are excluded from consideration in both the IEC standard for wind turbine gearboxes and the equivalent ANSI/AGMA 6006-A03 guideline [26].

Particle contamination in lubricant systems originates from initial oil impurities and the process of system commissioning [23, 27]. During specific load events, the wear of the gears generates additional particles. It is estimated that approximately 75% of these particles are <4 µm in size and are not accounted for by ISO 4406. Of the remaining 25% (which are addressed by ISO 4406), approximately 44% are also <6 µm [23]. Consequently, most particles are neither captured by the filtration system nor considered in cleanliness standards.

The effect of these particles on the electrical properties of the lubricant in wind turbines—and consequently on electrically induced damage mechanisms in real bearing contacts—remains unknown. This paper experimentally investigates the changes in breakdown voltage and frequency due to varying levels of particle contamination in an electrical loaded radial cylindrical roller bearing.

2 Experimental setup

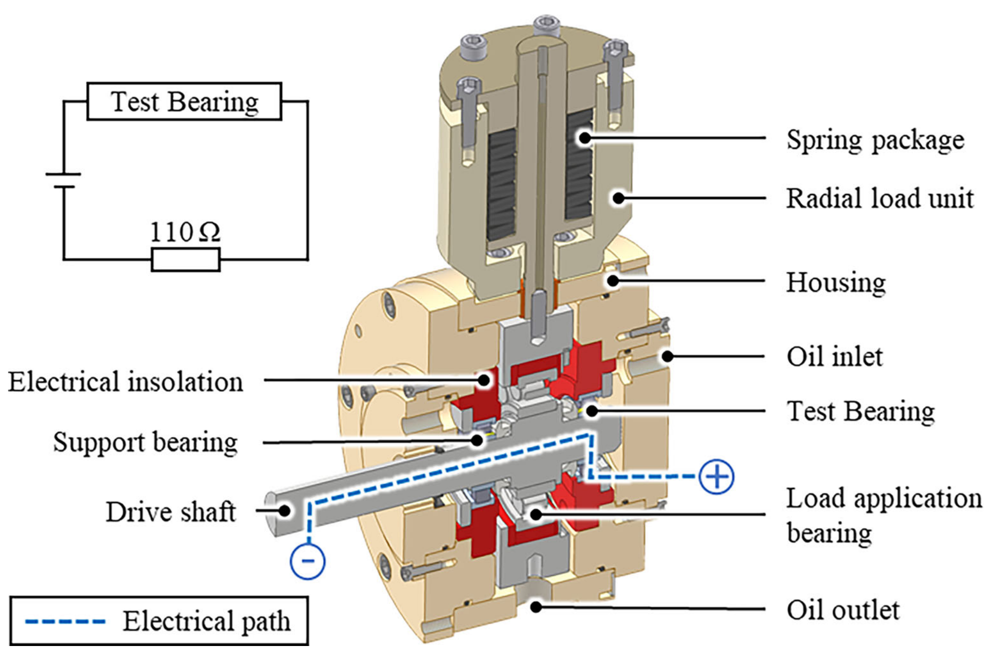
The tests are conducted on a radial bearing test rig (Fig. 2). In the course of the tests, cylindrical roller bearings (N206) are used as test bearings. The bearings are mounted on electrically insulating components. A contact on the outer shell of the test bearing and a carbon brush on the shaft are employed to establish an electrical circuit via the test bearing. Furthermore, a 110 Ω resistor is integrated inline to the test bearing into the circuit in order to delay the rise in voltage subsequent to a breakdown. This allows a better characterisation of the breakdowns in the analysis. A *CPX4000DP* from Thurlby Thandar Instruments Ltd. is utilized as the voltage source, which is computer controlled via the software *Test Bridge V*.

During the experiments, the voltage applied by the voltage source is measured using a voltage probe *TT-SI 9010A* from Testtec Electronic GmbH and an oscilloscope *PicoScope 6824E* from Pico Technology Ltd. Sampling is performed at a rate of 52.1 MS/s. The radial load is applied by disc springs which exert pressure on the load application bearing situated between the support bearing and the test bearing in a central position (Fig. 2). Accordingly, a force of 1.1 kN is applied to each bearing. To ensure full lubrication of the tribological contact, the shaft is driven at a speed of 2500 rpm, resulting in a bearing temperature of 82 °C and a calculated minimum lubrication film height of 0.22 µm.

The bearings are supplied with lubricant via two separate gear pumps, each with a delivery rate of 115 ml/min. The lubricant is fed laterally through the test bearing and the support bearing via the oil inlet opening on each side. The lubricant utilized is a commercial ISO VG320 gearbox oil (poly-alpha-olefin) specifically designed for wind turbines.

The desired particle concentration is introduced into the lubricant tank. An agitator facilitates the continuous circulation of the lubricant within the tank, thereby preventing the particles from settling. An *OPCom SPCO 300–1000* particle monitor from Argo-Hythos Group AG is employed to continuously monitor the particle concentration in the test bearing feed. A pressure-regulated valve on the particle monitor side of the lubricant line enables a pressure build-up, ensuring that air bubbles potentially introduced

Fig. 2 Cylindrical roller bearing test rig with electrical insulation



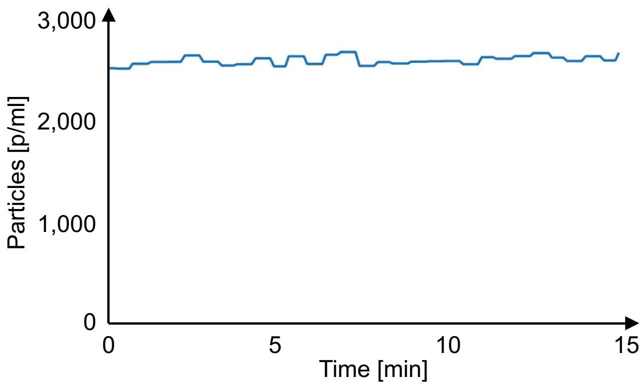


Fig. 3 Particle concentration of Particles ≥4 µm over time on the test rig

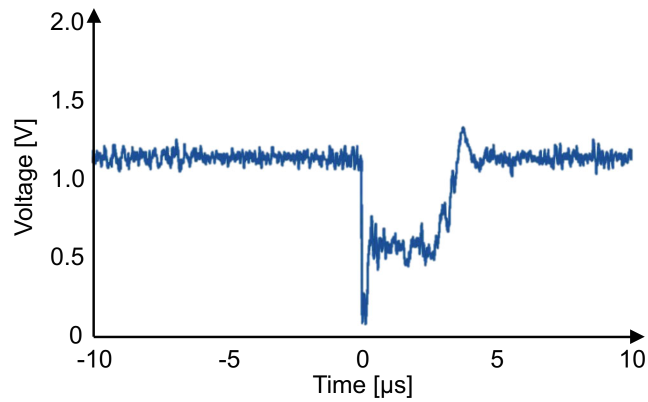


Fig. 4 Voltage profile of a breakdown inside the rolling contact

by the agitator are compressed. This serves to prevent erroneous measurements from being made by the optical particle counter.

In order to simulate different particle contamination levels, the lubricant is mixed with iron test dust. This test-dust contains varying sizes of particles: 50% smaller than 4.2 µm, 90% smaller than 8.14 µm, and 99% smaller than 12.4 µm. The particle size range of 4–6 µm is chosen to adjust the particle concentration within the lubrication system, as it corresponds to the smallest particle size accounted for by ISO 4406 [28]. The resulting particle size distribution reflects real-world conditions, wherein the majority of wear particles in systems such as wind turbines are also smaller than 4 µm [23].

The test series focused on the for fresh oil typical ISO class 19 (lower limit: 2500 p/ml; upper limit: 5000 p/ml) [27], as well as on the ISO class 20 (7500 p/ml), 17 (1000 p/ml), and 14 (100 p/ml), representing a range of contamination levels relevant to wind turbine operation. At the outset of the test, the particles are mixed with the lubricant. Due to the agitator and an adapted oil flow, the set concentration remains constant throughout the individual tests to a high degree of approximation (Fig. 3).

3 Experimental method and results

In order to investigate the influence of particle concentration on the electrical bearing load, the breakdown voltage and the frequency of breakdowns are subjected to analysis.

The occurrence of breakdowns is recorded by means of an interval trigger in the oscilloscope's measurement software. The waveform is saved as soon as a rapid decline in voltage is observed, followed by a subsequent slow build-up to the output voltage. An example of such a breakdown is illustrated in Fig. 4.

3.1 Determination of breakdown voltage

To ascertain the breakdown voltage, a voltage ramp from 0 to 2 V with a gradient of 25 mV/s is applied to the bearing. It is assumed that the voltage at which the first complete breakdown is observed represents the breakdown voltage for the particle concentration in that measurement. To ensure statistical reliability of the results, ten individual measurements were conducted for each particle concentration and the results were averaged.

The data indicate a trend whereby the voltage at which a breakdown occurs decreases with increasing particle concentration. Figure 5 shows the breakdown voltage averaged over ten measurements for each individual particle concentration. The most significant decrease occurs between the two lowest particle concentrations, where adding 900 p/ml (tenfold) reduces the breakdown voltage by 0.381 V (–28%). Adding 2500 p/ml (doubling) within the upper and lower limits of ISO class 19 results only in an 0.1 V (–11.3%) drop in breakdown voltage, despite the absolute change in particles being significantly higher in the first case.

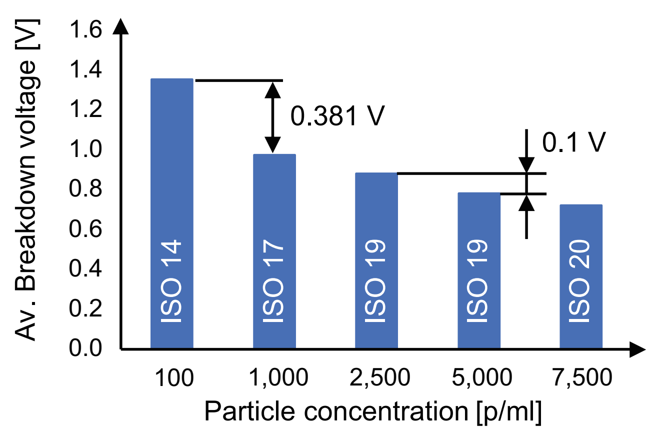


Fig. 5 Average breakdown voltage measured for different particle concentrations

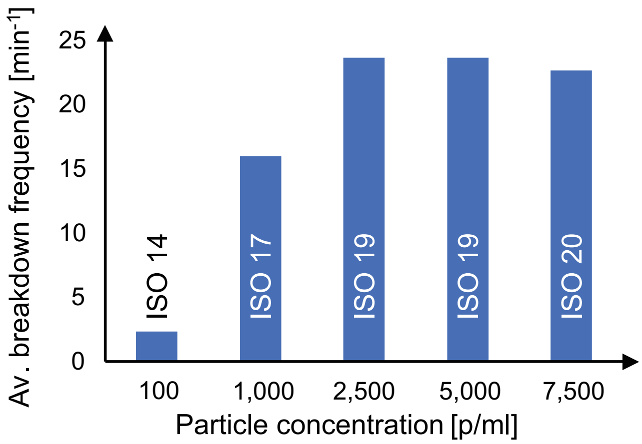


Fig. 6 Average amount of breakdowns per minute for different particle concentrations

3.2 Measurement of breakdown frequency

To investigate the influence of particle concentration on the number of breakdowns, a continuous voltage is applied for a period of one minute. The number of breakdowns is then counted within this time period. It should be noted that the test voltage is set for all particle concentrations to the breakdown voltage of the 1000 p/ml concentration, which equates to 0.968 V. In Fig. 6 the number of breakdowns averaged over three measurements in the respective particle concentrations is plotted.

The data shows that a decreasing particle concentration, at the same applied voltage, is associated with a reduced likelihood of breakdowns. Initially, an increase in particle load results in an elevated number of breakdowns. However, further multiplication of particles does not lead to a proportional increase in the number of breakdowns.

4 Discussion

An electrically loaded rolling contact can simplified be modeled as a capacitor, with the lubricant layer between the rolling element and the raceway serving as the dielectric [16]. The electric capacity (C_C) of the rolling contact is contingent upon the permittivity (ϵ_0), the specific permittivity of the lubricant (ϵ_R), the height of the lubrication gap (h_0) and the Hertzian contact area ($A_{C,Hertz}$) [18]. This correlation can be expressed using the following Eq. 1; [29]:

$$C_C = \epsilon_0 * \epsilon_R * \frac{A_{C,Hertz}}{h_0} \tag{1}$$

The stored electrical energy (E_C) of a rolling contact can be expressed by the electric capacity and the applied voltage (U) as shown in Eq. 2; [16]:

$$E_C = \frac{1}{2} * C_C * U^2 \tag{2}$$

Based on the assumption that the change in bearing capacitance is proportional to the change in the capacitance of one rolling contact, the relative change in breakdown energy in a rolling bearing can be approximated using Eq. 2. While the breakdown voltage decreases according to test results, the capacitance increases with higher particle concentrations, due to a change in the specific permittivity (Eq. 1). Considering the entire range of analyzed concentrations between 100–7500 p/ml, the breakdown voltage decreased by 47%. Dingxin et al. estimate that the influence of particle concentration on the change in specific permittivity is within ±10% of the initial value [30]. In order to provide a rough estimate of the influence on the energy introduced per breakdown (Eq. 2), neglecting the slight change in permittivity of the lubricant due to a change in particle concentration. Furthermore, this estimation does not account for changes in the capacitor surface or the gap between the surfaces. With these assumptions, the energy introduced per breakdown is reduced by 72%.

In the literature, two main approaches are used to describe the damaging effects of electrical discharges in rolling bearings: the apparent bearing current density (J_B) and the discharge energy (E_{EDM}) [16].

The first approach involves assessing the peak bearing current ($\widehat{i_b}$) during a breakdown in relation to the Hertzian contact area of all contacts between the rolling elements and raceways ($A_{B,Hertz}$). The bearing current density (J_B) is then calculated as:

$$J_B = \frac{\widehat{i_b}}{A_{B,Hertz}} \tag{3}$$

The electrical load on rolling bearings can be classified as critical or non-critical based on the apparent bearing current density. The upper limit of the current density for a non-critical operating point is given in the literature as between 0.1 A/mm² and 0.3 A/mm² depending on the source [31, 32]. In contrast to those limits Pohrer was able to show that even far below an apparent bearing current density of 0.1 A/mm² and thus without the occurrence of typical electrical surface erosion, structural changes and crack structures could be identified below the surface [31].

This observation leads towards the hypothesis that there is a transition from surface to structural introduced damage patterns with lower currents during the breakdown. KRIESE ET AL. posit that the capacity stored in the bearing—and thus the energy during a discharge—is the critical factor to characterize potential bearing damage [33]. Therefore the second approach for damage assessment calculates the electrical energy release during a discharge in the form of a breakdown (Eq. 2), taking the total bearing capacity into account and correlates this energy to surface material damage [16]. If the energy of a breakdown is too low, it is insufficient to cause damage to the surface. The total energy available for structural changes depends on the breakdown frequency and the energy per breakdown.

With a constant voltage applied to the bearing, there is a marked decrease in the number of breakdowns as the number of particles is reduced (Fig. 6). As the number of particles is increased, the breakdown frequency initially increases. However, with a further doubling and tripling of the number of particles, the breakdown frequency appears to stagnate. One potential explanation is that the set voltage is significantly higher than the breakdown voltage of the respective concentration. In this scenario, the system reaches its maximum number of statistical breakdown events and any further increase in concentration yields no additional effect.

At this time, it is not feasible to calculate the change in energy introduced into the surfaces over time. To obtain a concrete estimate of the energy introduced per breakdown, it is necessary to model the capacitance of the bearing, particularly focusing on the surfaces involved in the formation of the capacitance and their distance from each other. Additionally, it is essential to measure the specific permittivity for the individual particle concentrations. By taking the breakdown frequency into account, the energy introduced into the raceway surface can then be determined. However, due to the rising breakdown frequency, the total energy input into the bearing over time declines less sharply than the energy released per breakdown.

5 Conclusion

This paper experimentally investigates the influence of lubricant particle contamination on the breakdown voltage and frequency in an electrically loaded radial cylindrical roller bearing.

Within the framework of the investigations the particle concentrations in the lubricant were all within the tolerable cleanliness range for wind turbine gearboxes. Due to the exclusion of particles $<6\,\mu m$ from design standards, they remain unfiltered in the lubricant, impacting its electrical properties.

The analysis shows a nonlinear decrease in breakdown voltage with increasing lubricant particle concentration as well as a rise in breakdown frequency. It was observed that relatively small contaminations already led to a significant drop in breakdown voltage, while further increases in contamination resulted in a markedly reduced effect. The analysis of the breakdown frequency shows that, with a constant voltage applied, an elevated number of breakdowns occur with an increased concentration of particles. In cases where the voltage was significantly above the breakdown voltage of the lubricant at the given particle concentration, no additional effect from further increases in frequency was observed. The maximum frequency of breakdowns appears to be a system-specific parameter.

In consideration of the established electric models for roller bearings, it can be anticipated that a reduction in energy input per breakdown will occur as a result of the particle load, due to the observed decrease in breakdown voltage. As an increased particle concentration causes both an increase in the frequency of breakdowns and a reduction in the energy input per discharge, the total energy input into the bearing over time declines less sharply than the energy released per breakdown.

The findings of the conducted experiments demonstrate that the evaluation of particle loading in lubricants must extend beyond the assessment of energy input per breakdown in order to comprehensively account for the intricate relationships between particle concentration, breakdown voltage, frequency and the resulting damage mechanisms in roller bearings.

6 Outlook

Based on the results from this paper, further research is required to investigate the impact of elevated particle concentrations on electrical loads. The hypothesis has been proposed that the particle-induced reduction in energy input per breakdown, coupled with the increased breakdown frequency, alters the damage mechanism. This suggests a shift from surface- to structure-induced damage. However, this assumption must be confirmed in further test series on the test bench. Additionally, it must also be determined whether the potential change in the damage mechanism is also reflected in the time to failure and whether a critical applied energy input over time can be determined in this regard.

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Conflict of interest J.C. Harling, P. Rößler, G. Jacobs and B. Lehmann declare that they have no competing interests.

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