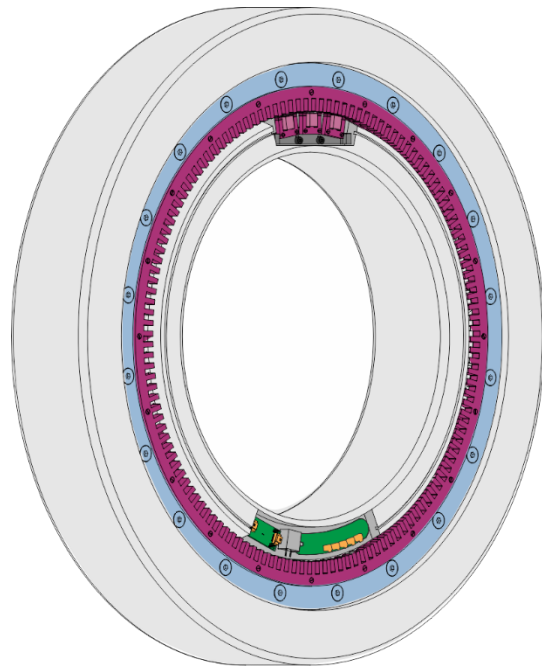


Sensor-integrated roller bearing with inductive energy harvesting for condition-based monitoring

M. Kleinhans, H. Siemßen, T. Steppeler, D. Konopka, F. Pape, B. Wicht, M. Wurz, M. Marian



Outline



- **Motivation**
- **Sensor Manufacturing**
- **Energy Harvesting**
- **Measurement Electronics**
- **Summary and Outlook**

- Global demand for electrical energy is constantly increasing
- Renewable energies play a crucial role
- Wind turbines meet key energy demands (especially at night and during winter)
- Main bearings and azimuth system support the entire weight of the rotor and nacelle
- Bearings must withstand extreme dynamic and mechanical forces

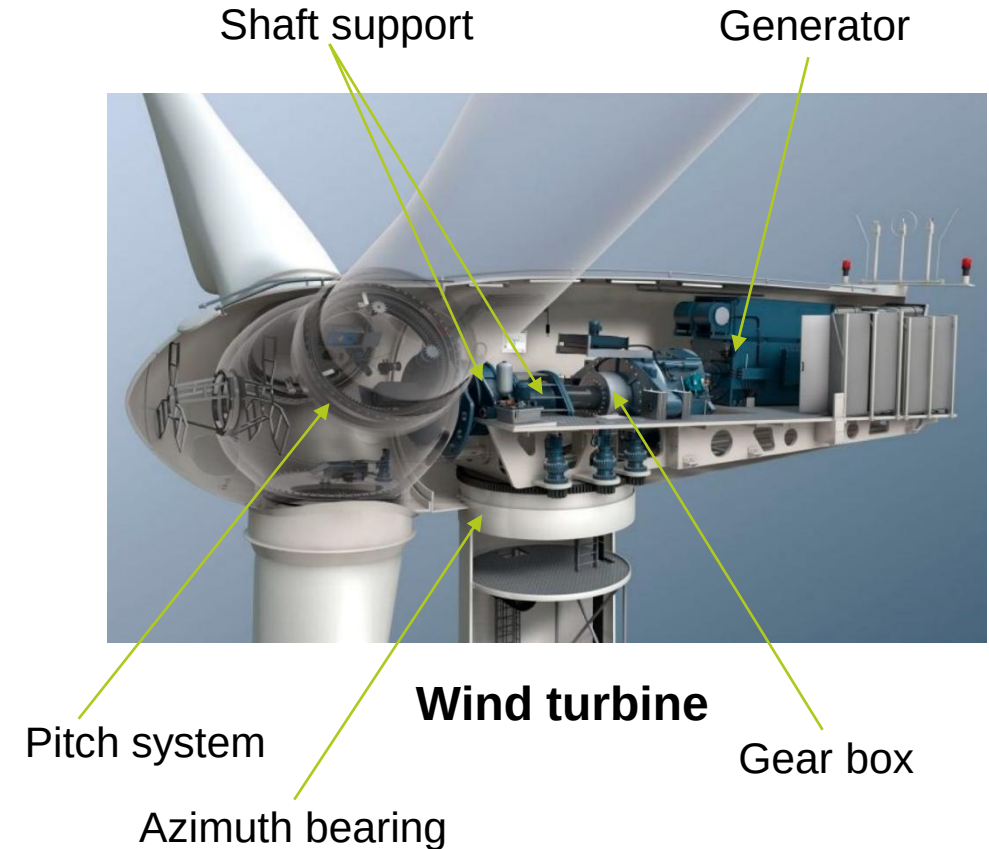


Image Source: ifm.com

Condition Monitoring

- Maintenance efforts increase with turbine size and offshore deployment
 - Effect of ocean waves and salt water
 - Strong wind loads
 - Restricted accessibility
- Specialized machine elements
 - High manufacturing costs
 - Long delivery lead times
- Maximized maintenance intervals for gears and bearings
- Continuous condition monitoring to estimate remaining useful life (RUL) and schedule replacement

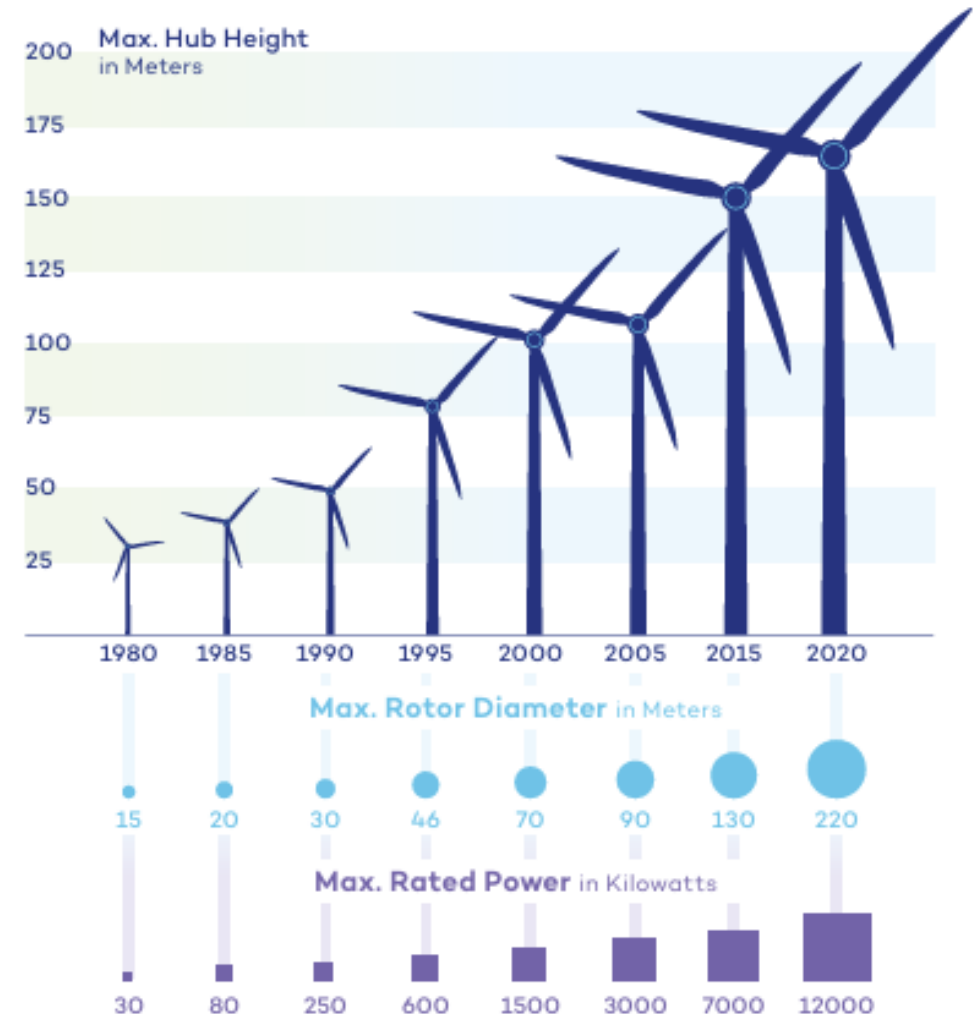


Image Source: cypac.com

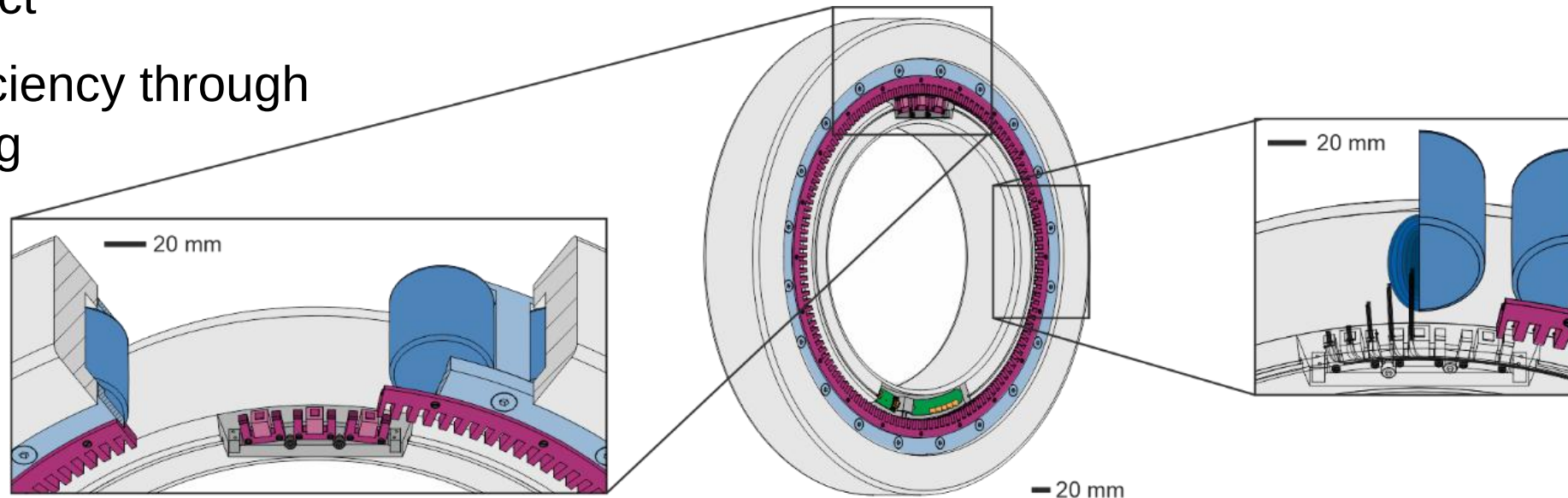
Aim

- **Space-neutral, energy self-sufficient sensor** integration next to the mechanical contact in the roller bearing
- Integration of measurement electronics
- Thin-film sensors directly in the mechanical contact
- Energy Self-Sufficiency through Energy-Harvesting



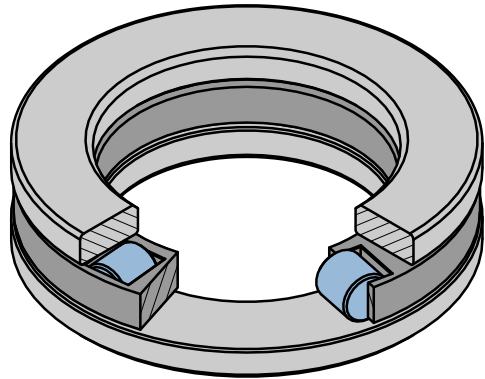
In Situ
Measurement

- Strain / Pressure
- Temperature
- Rotational speed

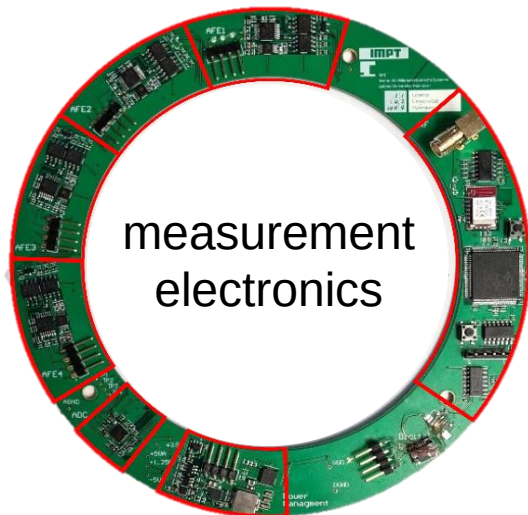


Review on Previous Results

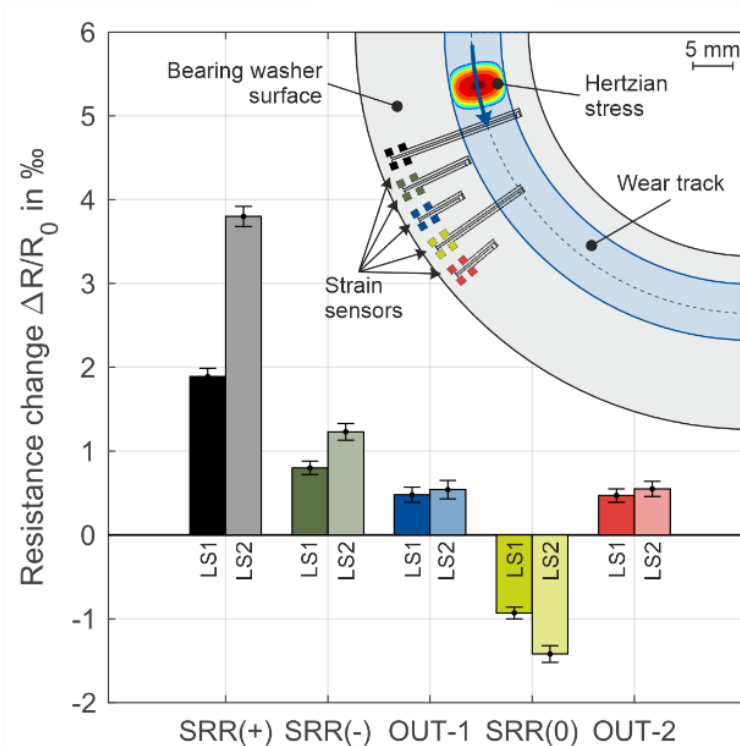
Strain and Temperature Measurements



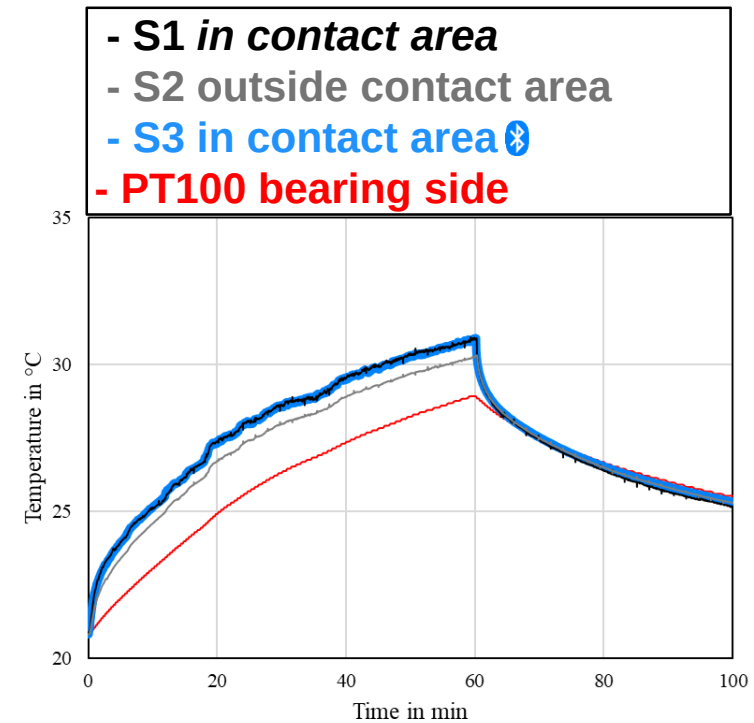
8112 CRTB
Ø 95 mm



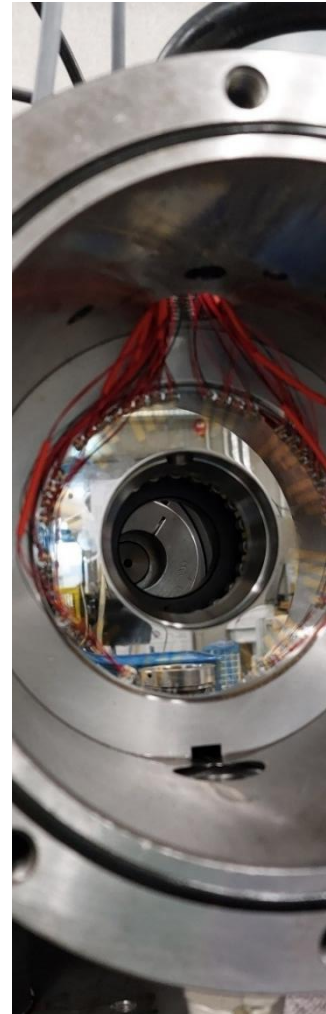
measurement
electronics



Strain Measurements



Temperature Measurements

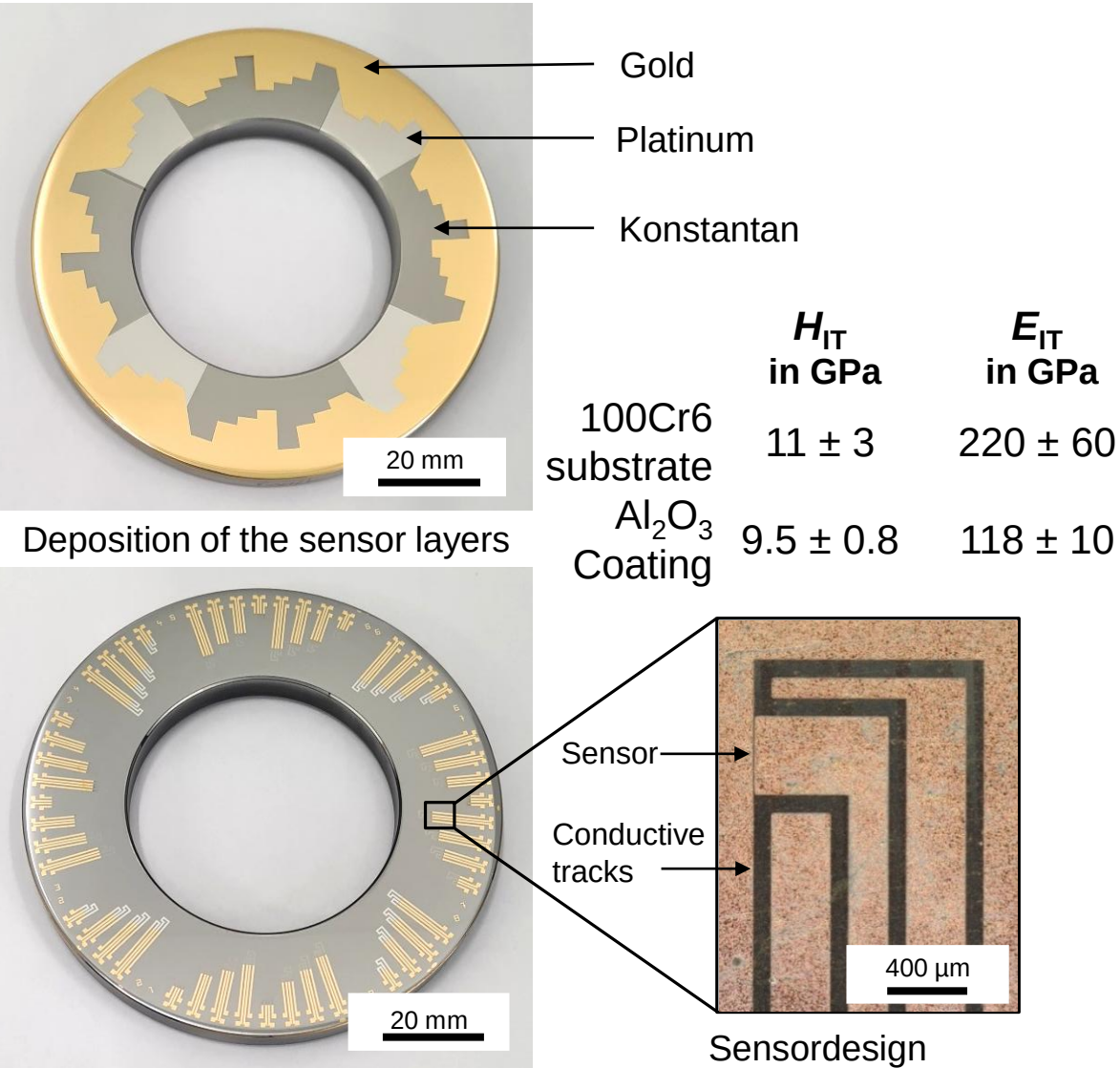


Source: DOI 10.1007/s10010-025-00857-4

Review on Previous Materials and Methods

Sensor Manufacturing

- Physical vapor deposited (**PVD**) **thin film strain & temperature sensors** on cylindrical roller thrust bearings
- Sensor manufacturing process:**
 - Polishing the axial bearing washer
 - Deposition of the insulation and sensor layers
 - Photolithographic structuring of the sensor array
 - Etching of unprotected material
 - Deposition of the wear-resistant protective layer
 - Electrical contact bonding via soldering



Sensor-Integrated bearing washer

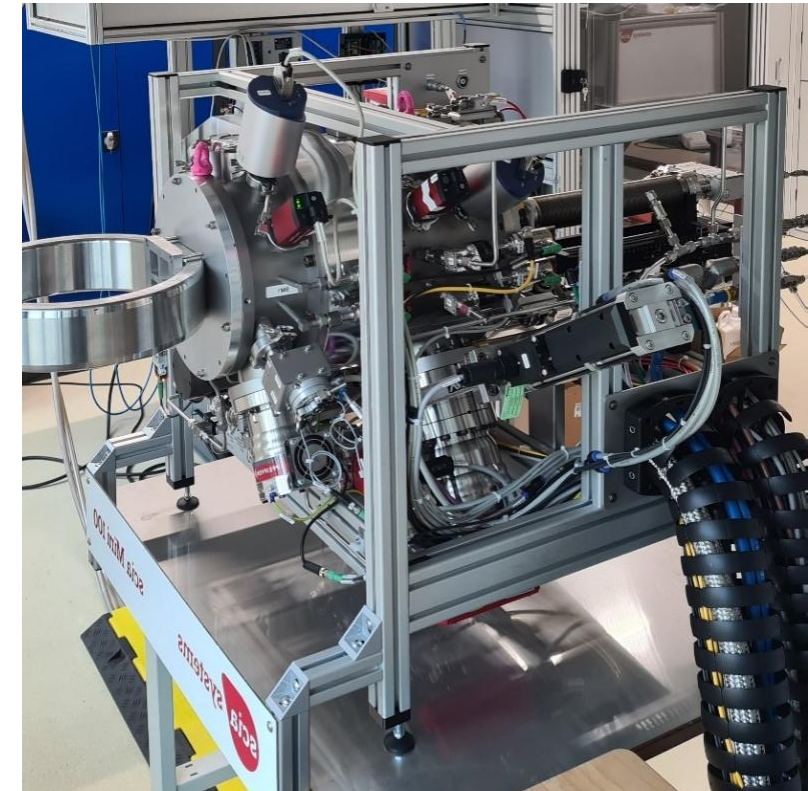
Source: DOI 10.1007/s10010-025-00857-4

Novel Sensor Manufacturing Process

Large Radial Roller Bearing

- Sensor application using a **novel modular deposition unit**
- Fabrication of a custom adapter for vacuum-sealed mounting
- **Sensor manufacturing:**
 - Pre-treatment by etching
 - Deposition of the insulation and sensor layers
 - Sensor structuring via laser ablation
 - Deposition of the wear-resistant protective layer
 - Electrical contact bonding via soldering

Mobile coating system



Etching, laser and sputtering module

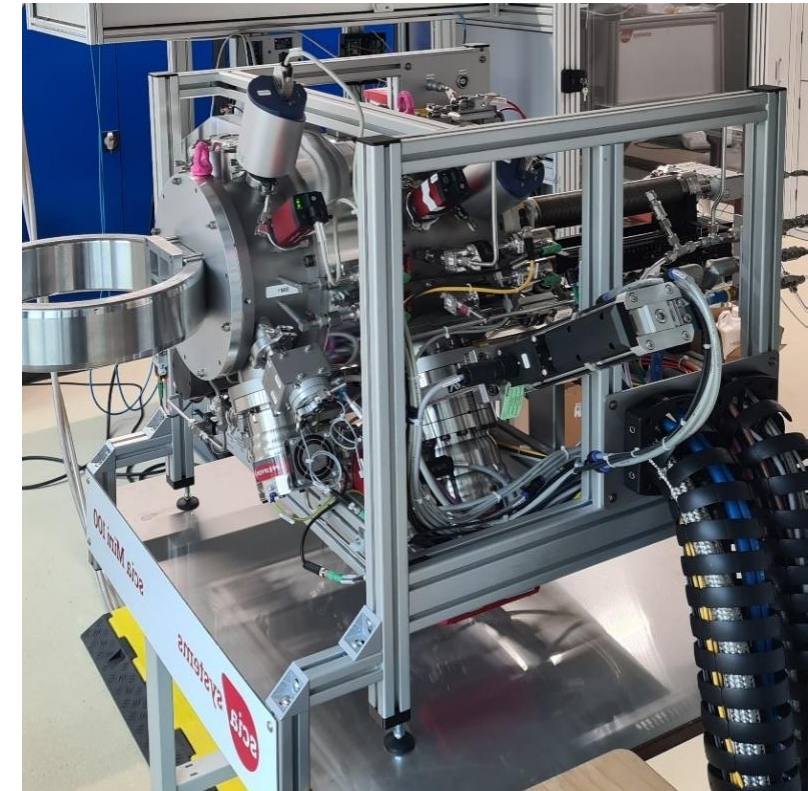


Novel Sensor Manufacturing Process

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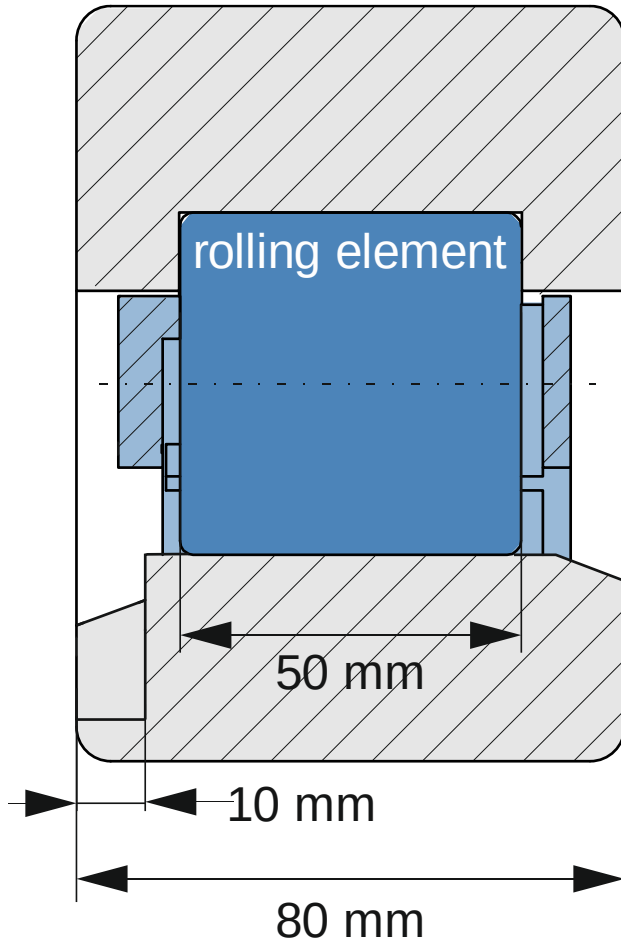
Sputtered layer on roller bearing ring



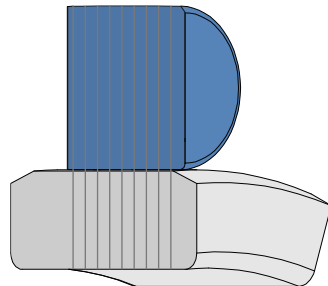
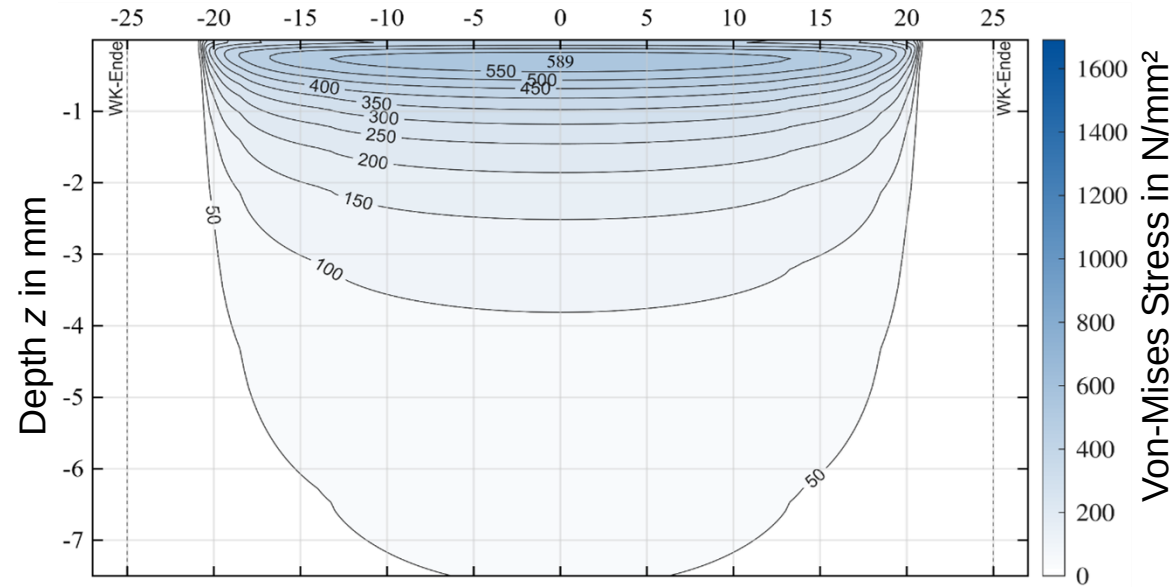
Large Radial Roller Bearing

Inner Ring Modification to Accommodate Electronics

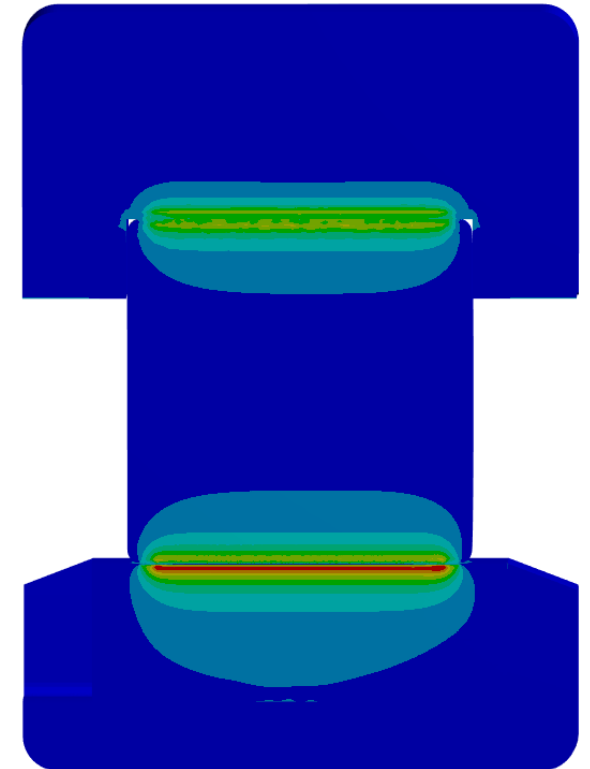
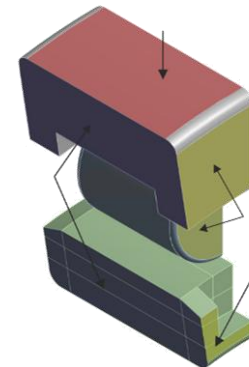
Pockets in Bearing
Inner Ring



Von-Mises Stress at 1 GPa
length y in mm



Semi-numerical
Calculation based on
FEM-Analysis up to 3 GPa



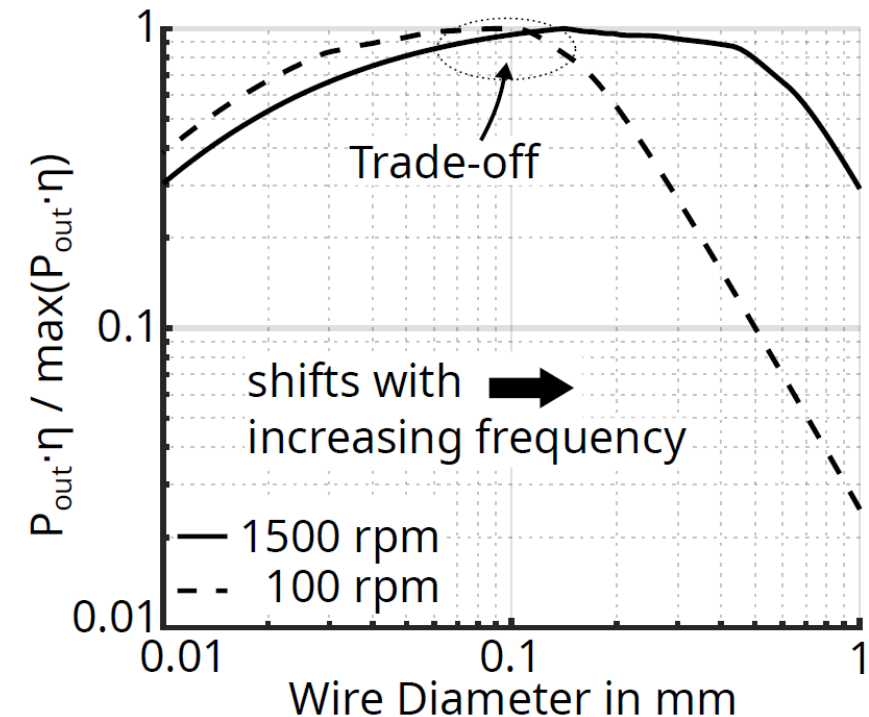
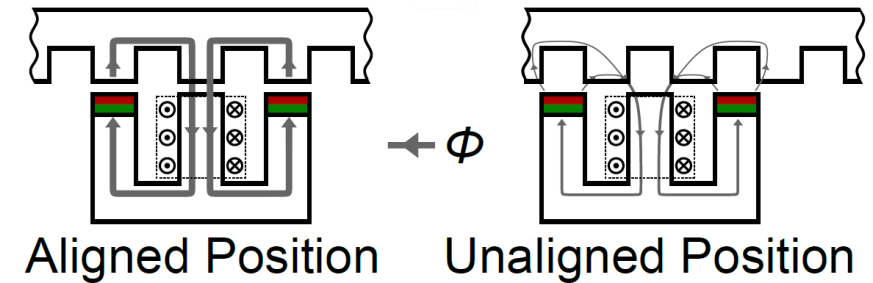
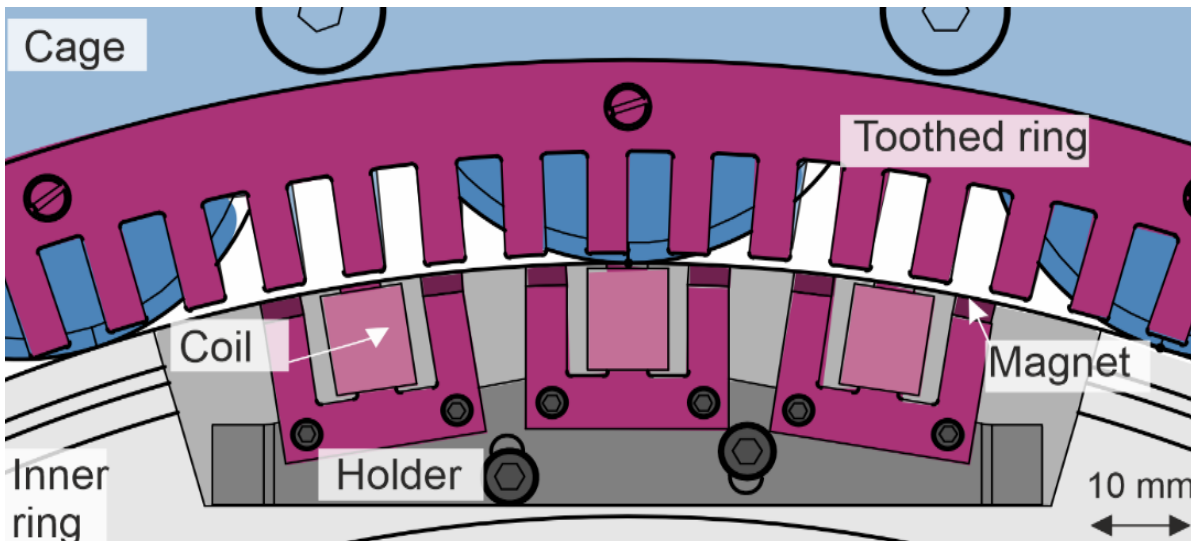
1,68 GPa 0 GPa

Energy Harvesting

Operating Principle and Design

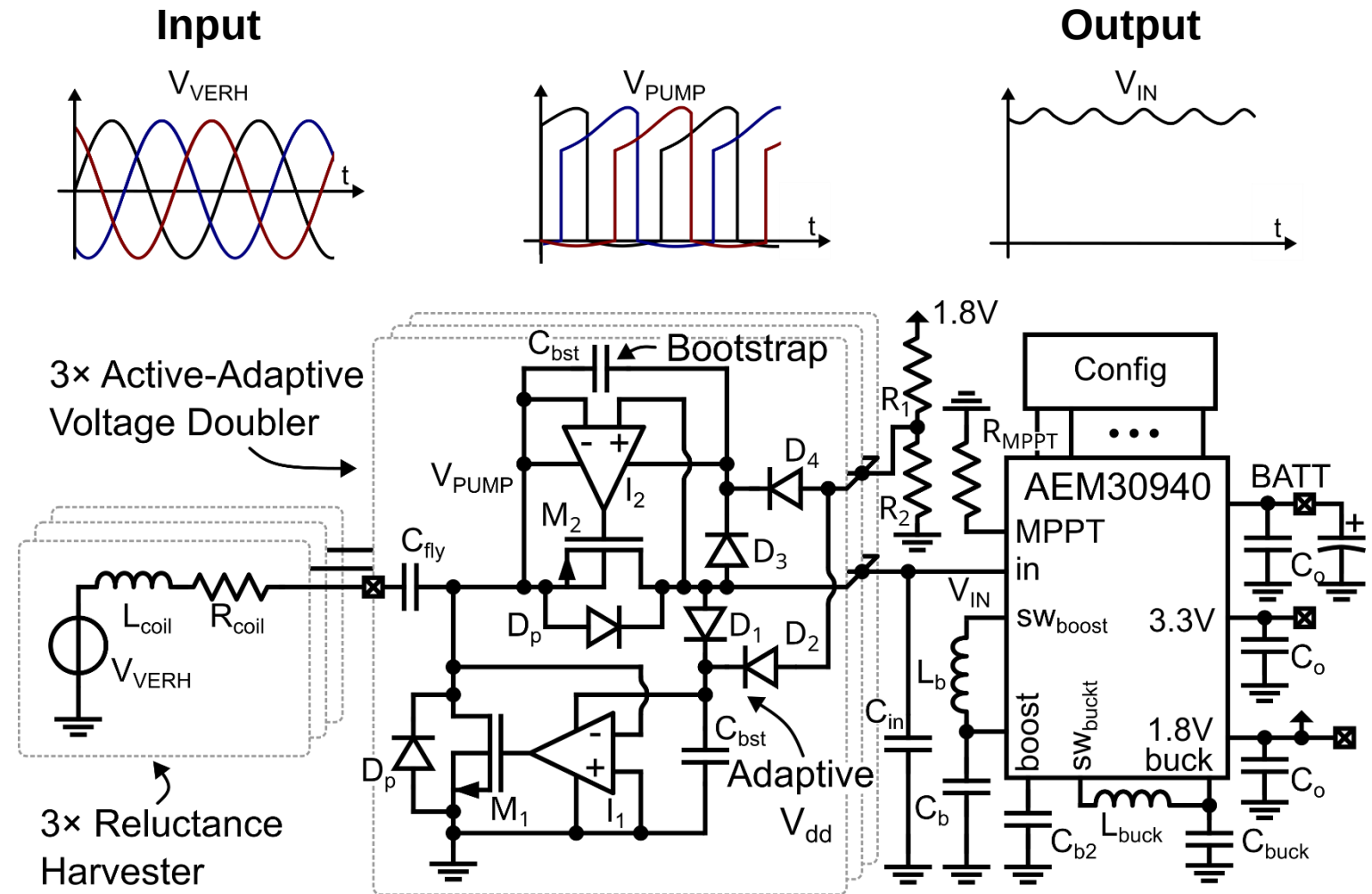
- Variable reluctance harvester
- Design trade-off: number of coil turns vs. Output-Power

➔ Enables high output voltage even at low rotational speeds



Harvesting Electronics

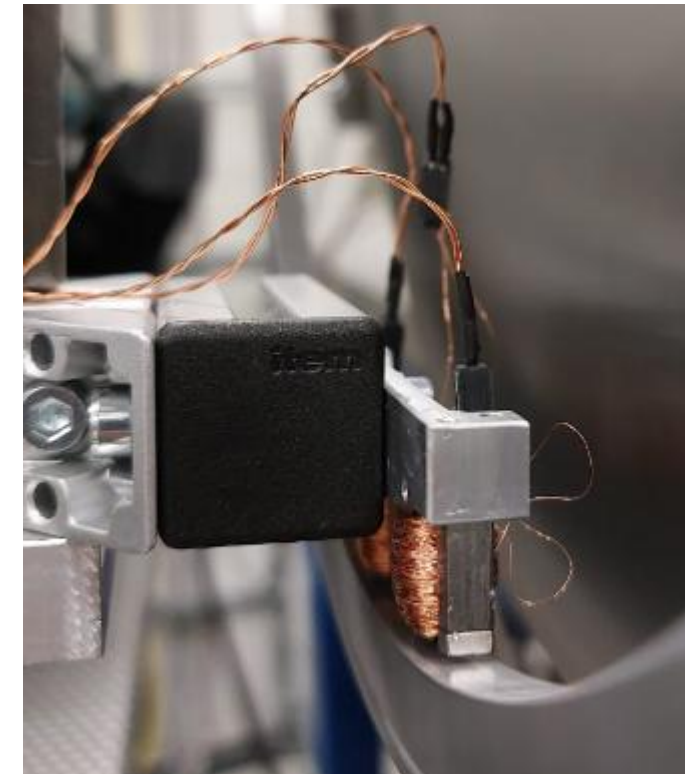
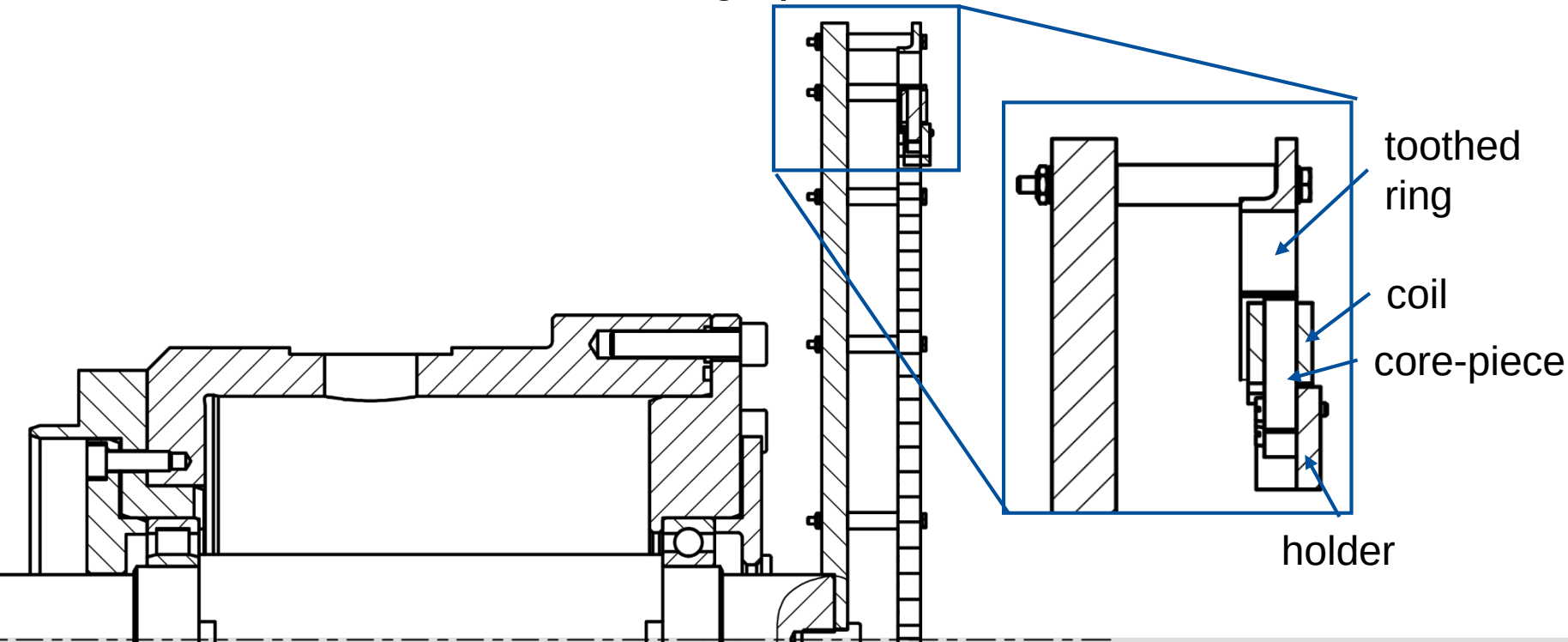
- 3-phase topology increases power and reduces cogging ripple
- Active & adaptive rectification increases harvested energy
- C_{fly} doubles input voltage range and also protects against input voltage limit violations
- 3 μW start-up and cold-start capability



Energy Harvesting

Prototype Testing

- Modified FE-8 test rig
 - Adjustable clearance between core and toothed ring
 - Rotational speeds: 30 – 500 min⁻¹
- 60 – 1000 min⁻¹ bearing speed



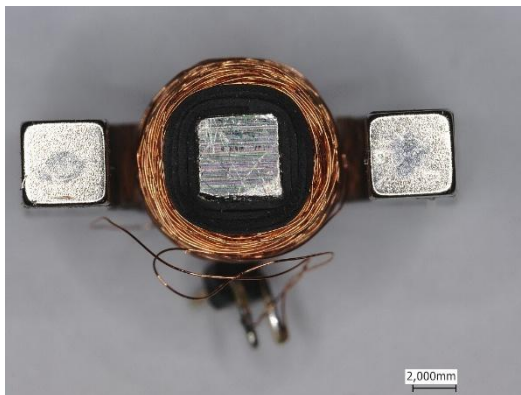
Energy Harvesting

Harvester Cores

Generation 1



- m-shaped core pieces
- Winding around center



Generation 2



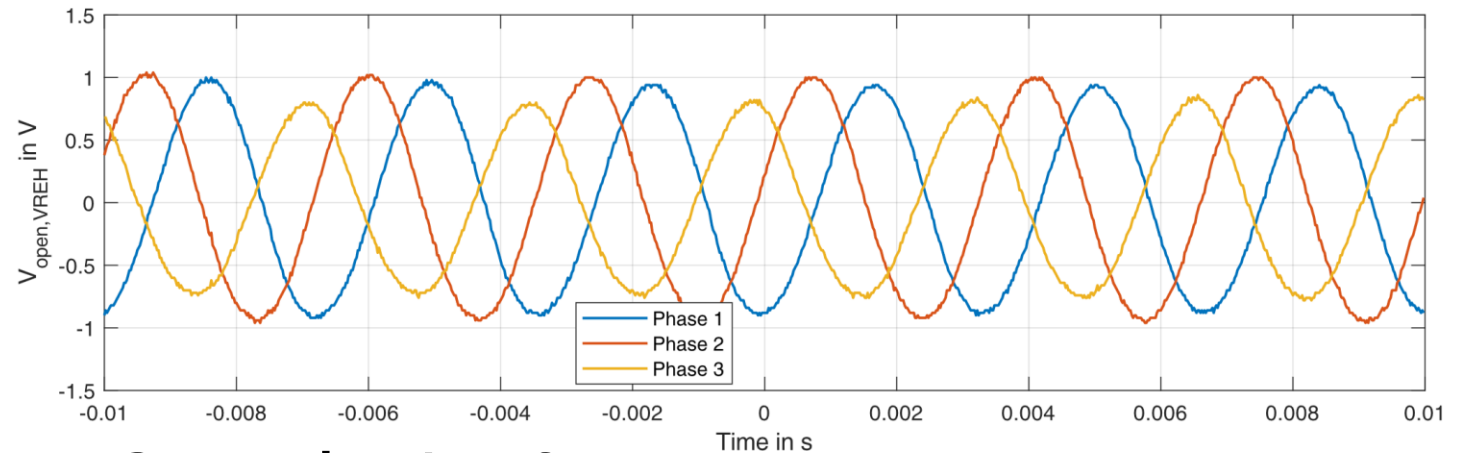
- Modular core pieces
- Winding around round component
- Press fitting of coil and u-piece



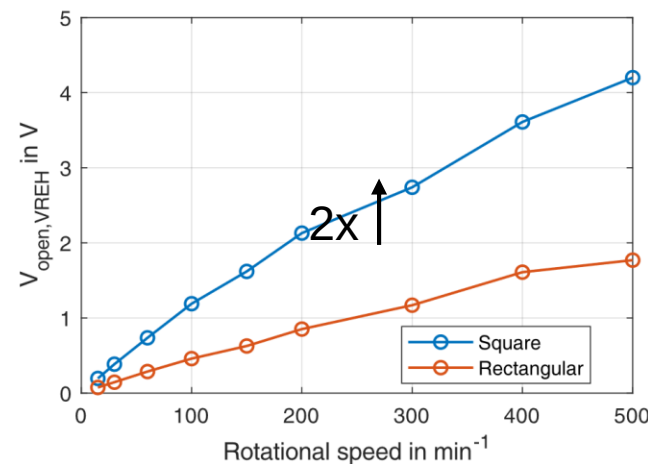
Initial Measurement Results

- Function: 3-phase VREH implemented
- Impact of different coil turn numbers
- More than 2x improvement with square pole piece
- C_{fly} important for low-rpm output power

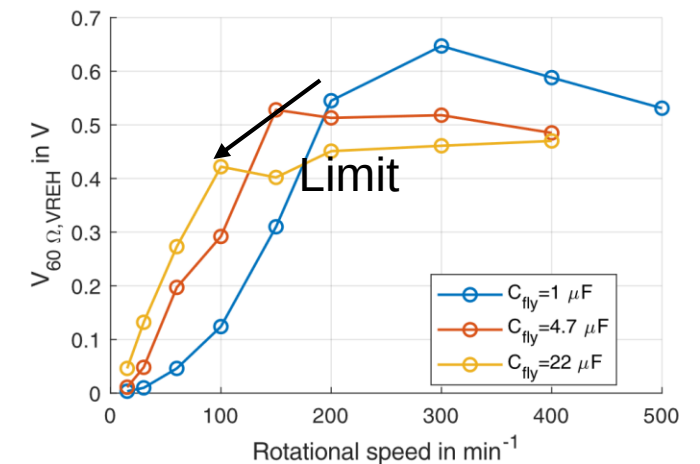
3-phase VREH output voltage



Generation 1 vs 2



Impact of C_{fly}



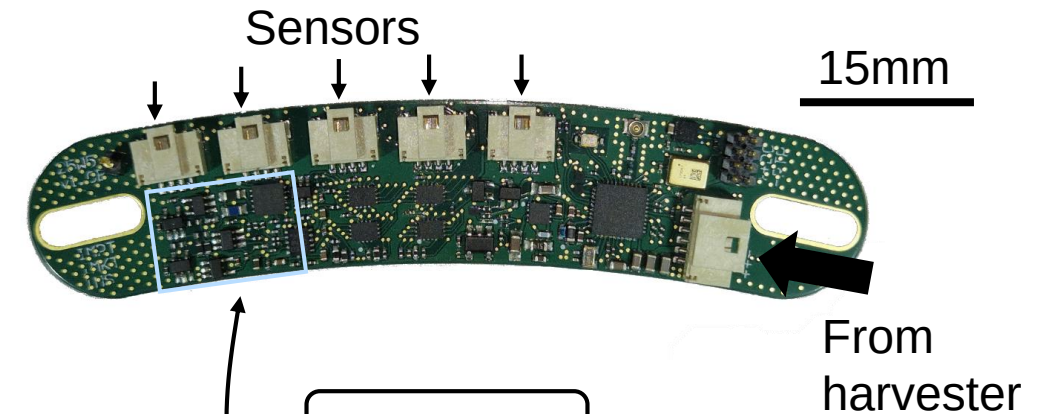
Measurement Electronics

Overall Implementation

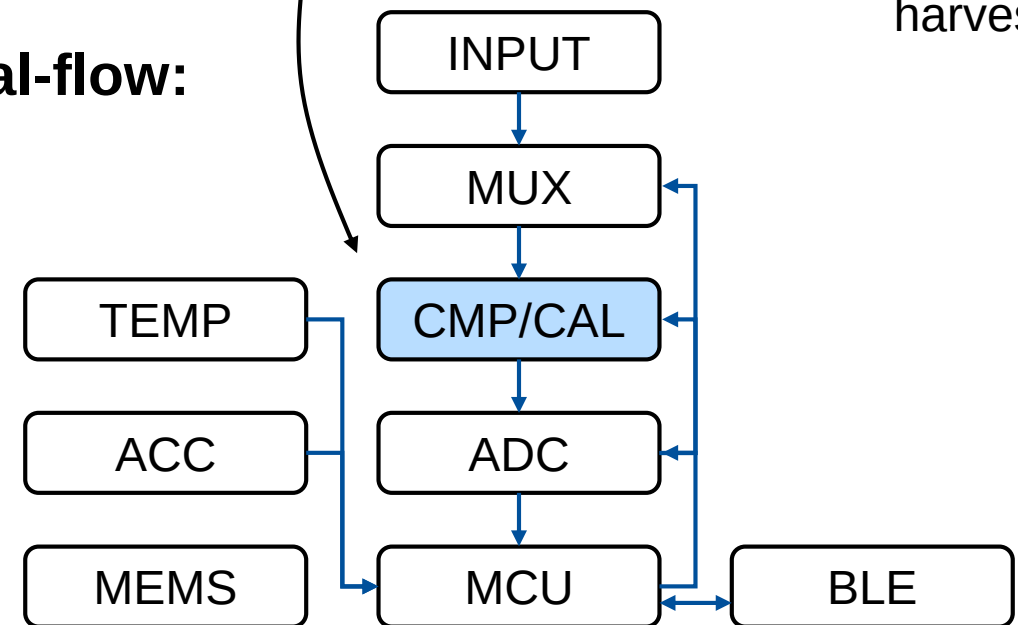
- Strain gauge measurement with leadwire compensation on five channels
 - 4× strain, 1× temperature
- Due to sensor placement, additional channels possible:
 - PCB temperature
 - Accelerometer
 - MEMS microphone
- Initial power consumption:
 - Active: 27 mW
 - Passive: 7.7 μ W

➔ **Less than expected input power**

PCB:



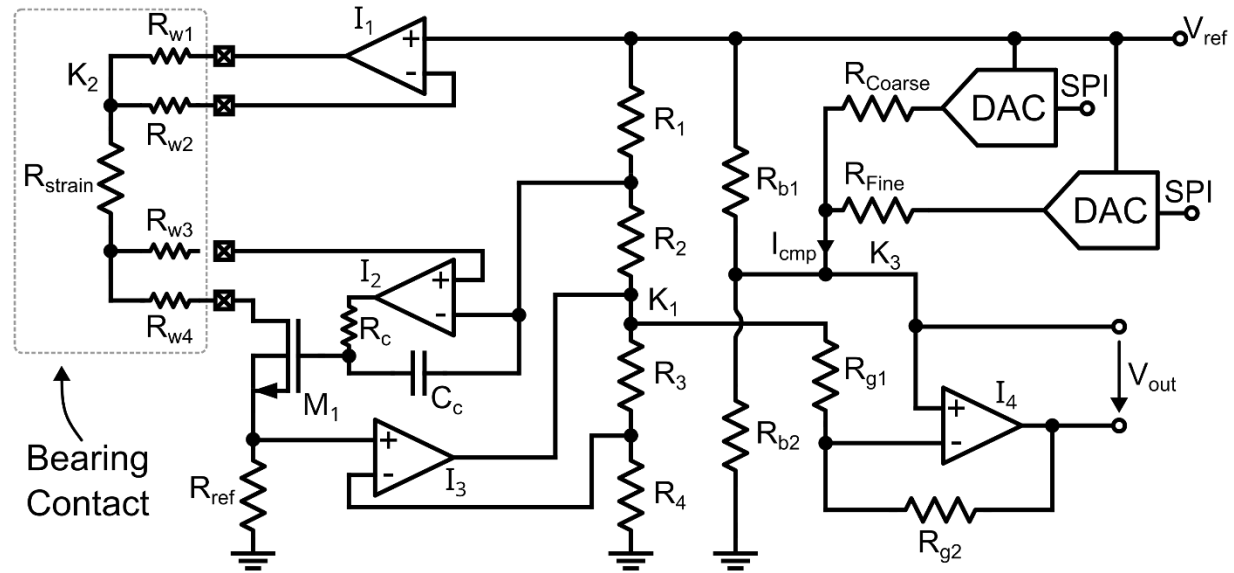
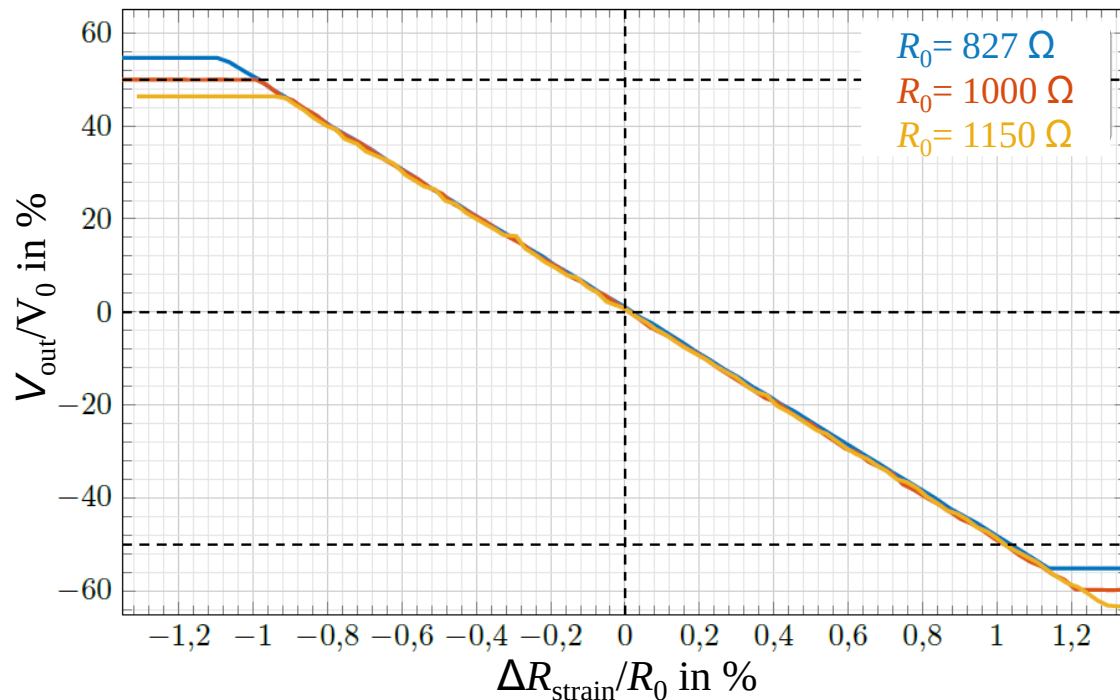
Signal-flow:



Leadwire compensation

- Compensation via I1-3 and M1
- Four amplifiers needed
- Coarse/fine calibration

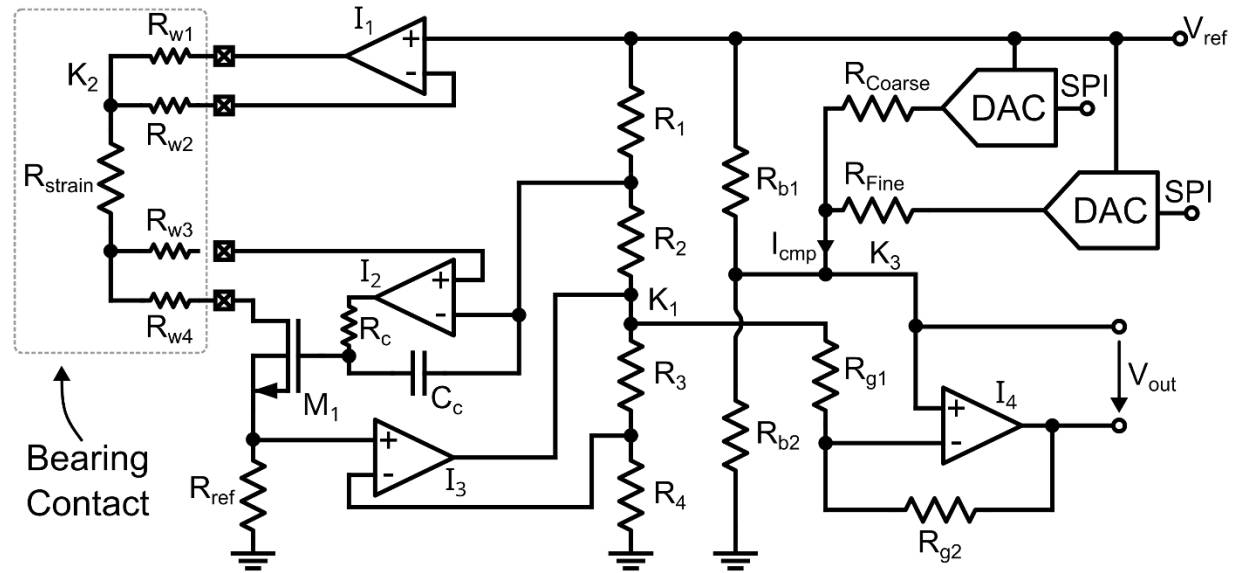
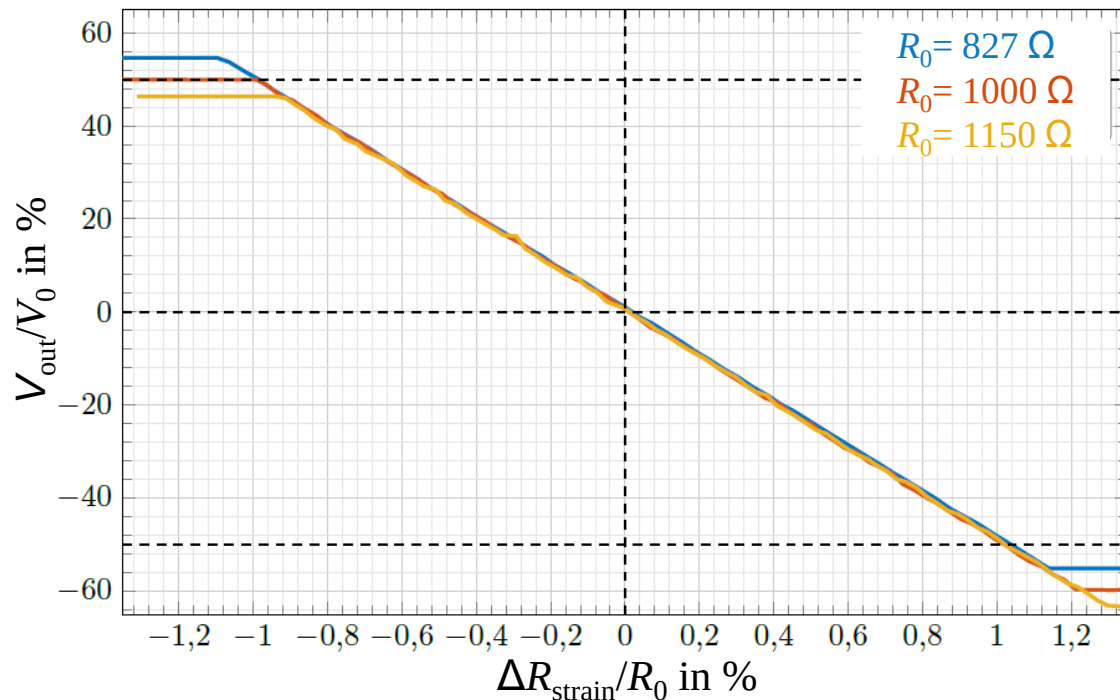
Measured strain sensitivity



Leadwire compensation

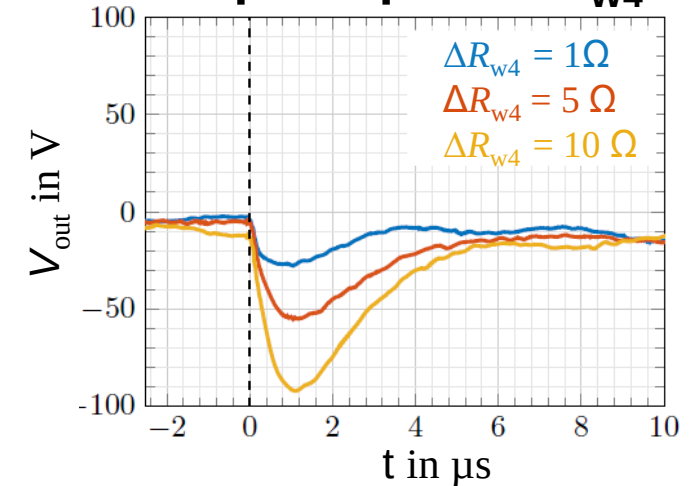
- Compensation via I1-2 and M1
- Four amplifiers needed
- Coarse/fine calibration

Measured strain sensitivity



- Shows fast and accurate suppression
- Sensitivity $R_{strain} = 750 \mu V/\Omega$
- R_w suppressed by more than 40 dB

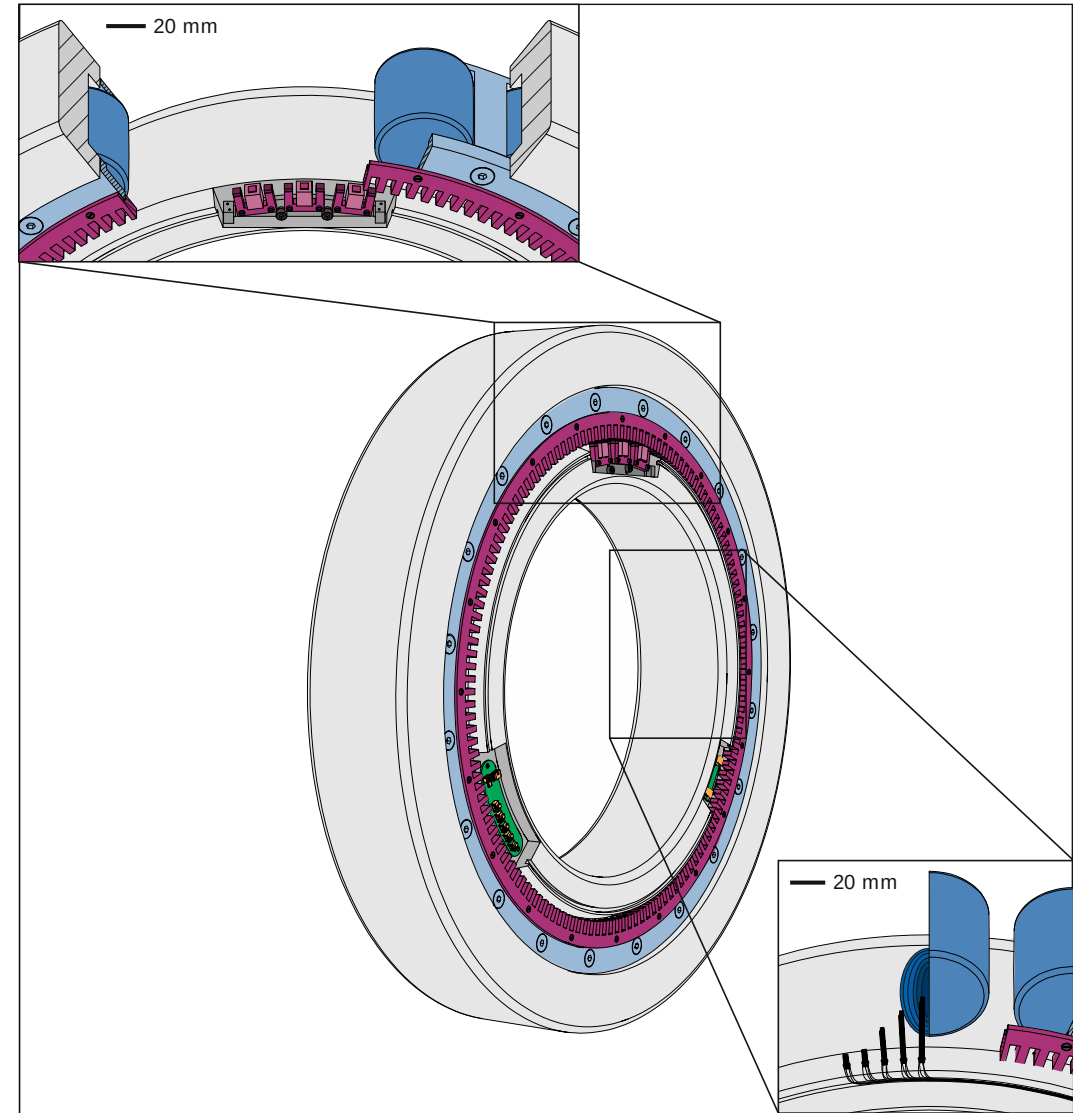
Step Response R_{w4}



Energy Harvesting for sensor-integrated bearings

Summary and Outlook

- Successful functional testing and evaluation of the energy harvester for a large radial roller bearing
- Development of custom measurement electronics
 - Sensors: 4× strain, 1× temperature
 - Wireless data transmission via BLE
 - Power consumption < expected input power
- Integration on large bearings
- Long-term tests and evaluation of reproducibility



Thank you! Any questions?



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