LIU Wire Scanner Bake-Out Studies

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Motivation

Proton
Synchrotron

Proton
Synchrotron
Booster

Large Hadron Collider

Environmental Requirements for LHC

UHV of $10^{-10} mbar$

Achieved by:

- **Cryogenic temperatures**
- **NEG coating**
- **Bake-out**

Research Question

→Is the fast wire scanner bakeable?

→Under which conditions is it bakeable?

Proceeding

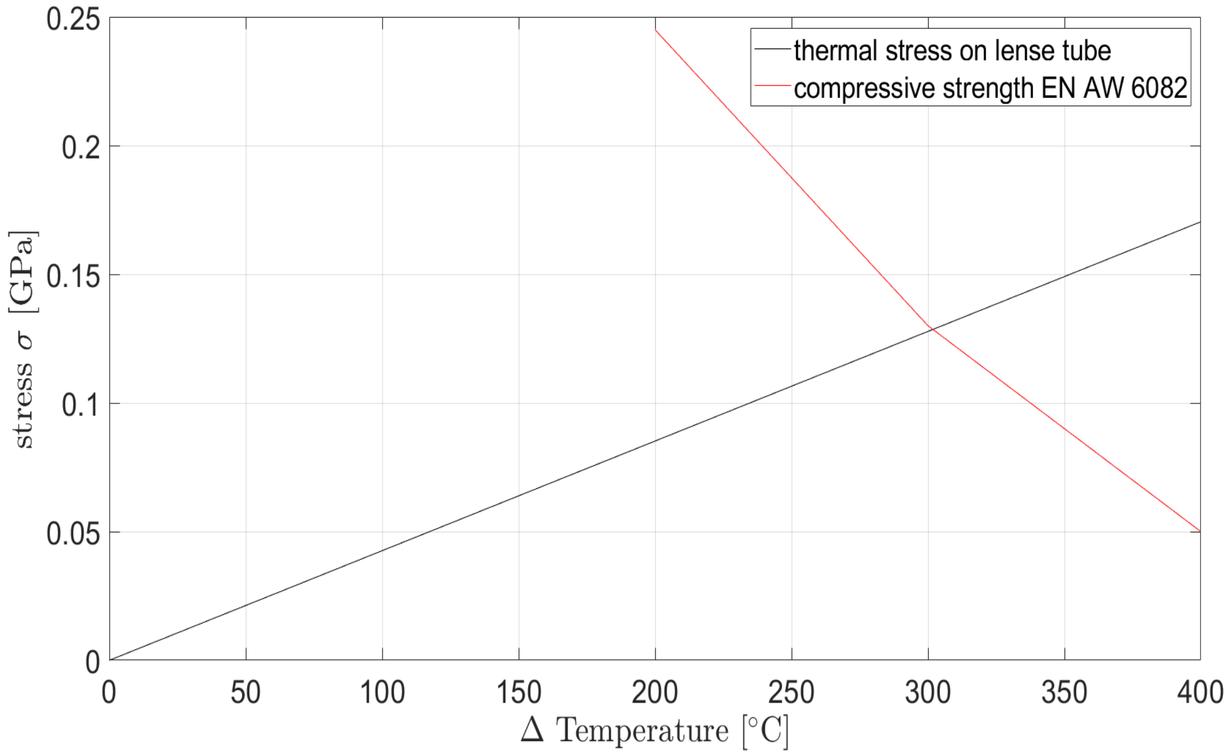
Limitations

Thermal Limits

Maximum Temperature

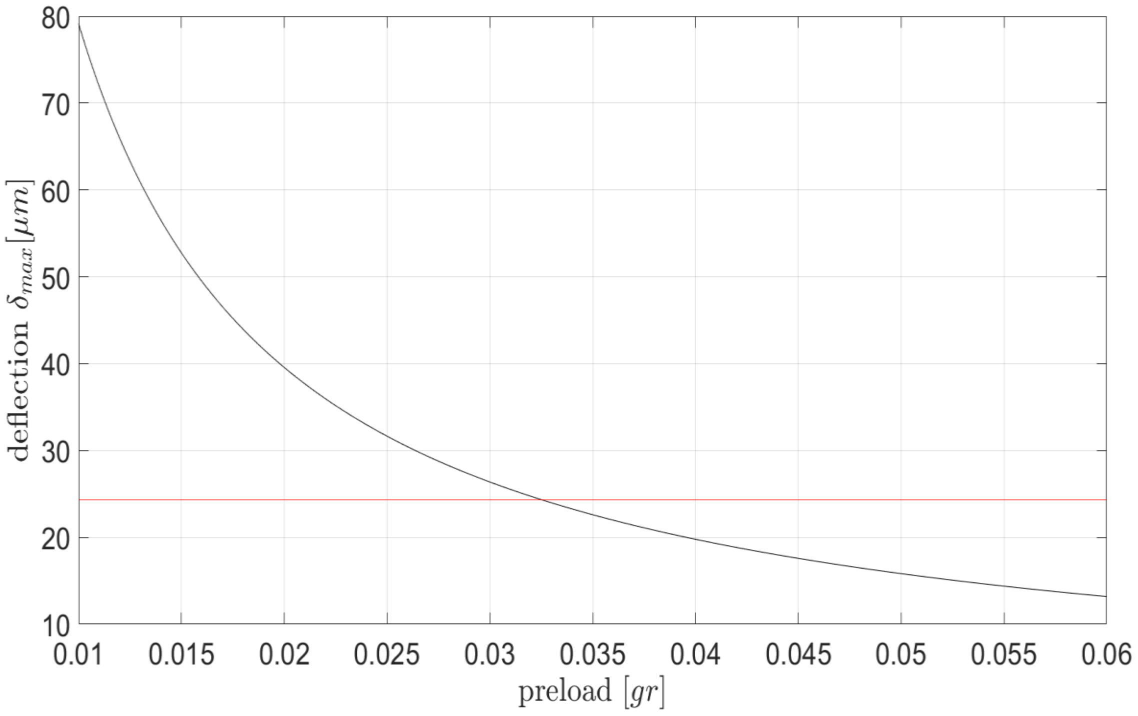
Component	Maximum Temperature [°C]
Connectors and cables	80
Solder spot	180
Stator resin	180
Stator coils	200
Encoder disk	200
Bearings	200
Resolver	200

Thermal Expansion



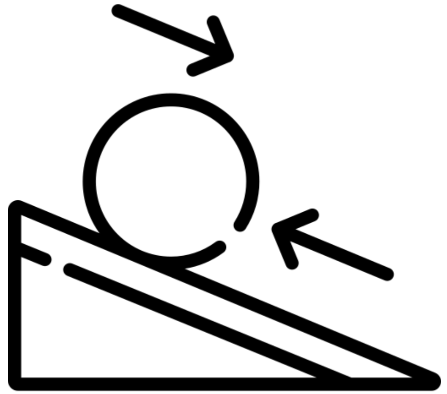
Operational Limits

Minimum required wire tension



Maximum acceptable friction torque

- **For motor:** $T_{fr} = 22.4\ Nm$
- **For brake:** $T_{fr} < 0.5\ Nm$



Proceeding

Limitations → Failure Analysis → → →

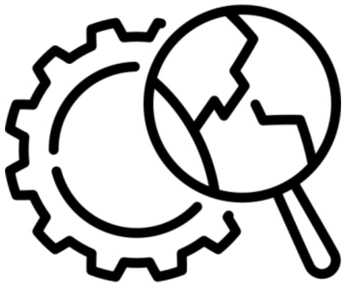
Bake-Out Proposal

Temperature: $250°C$

Duration: $min\ 24h$

Pressure: $10^{-10} mbar$

Failure Analysis

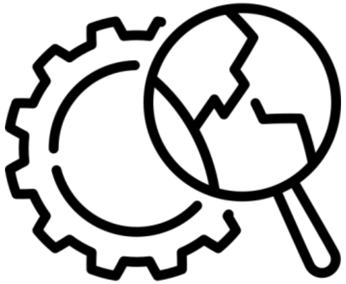


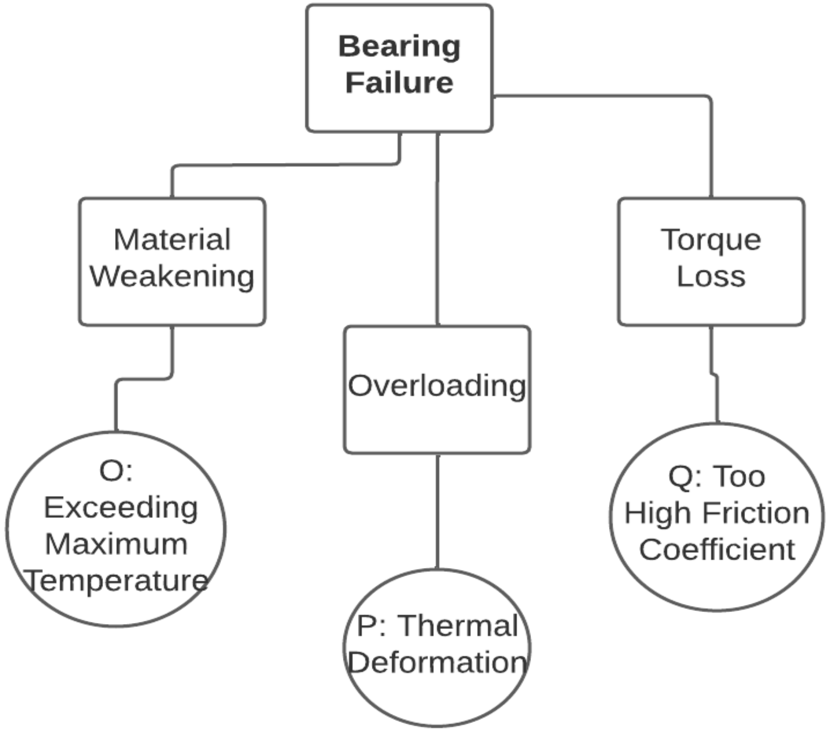
1. **Define subsystems**
2. **Define top level failure cases**

Wire Failure | **Bearing Failure** | **Motor Failure** | **Control Failure** | **Magnetic Brake Failure**

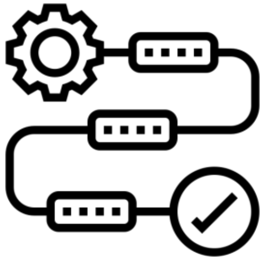
3. **Trace failure tree down to base level failures**

Failure Analysis





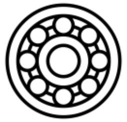
Proceeding

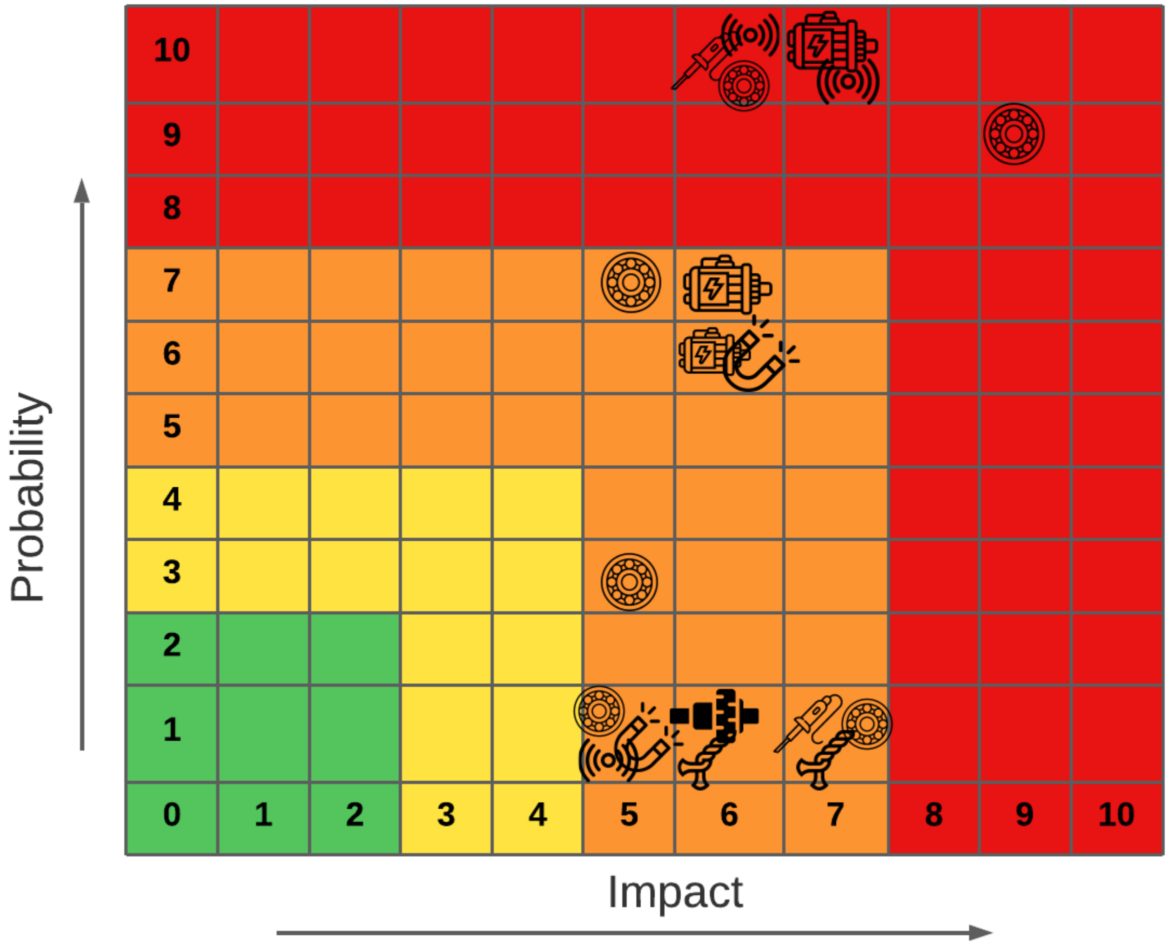


Limitations → Failure Analysis → Risk Analysis → →

Risk Analysis

$$Risk = Probability \ x \ Impact$$

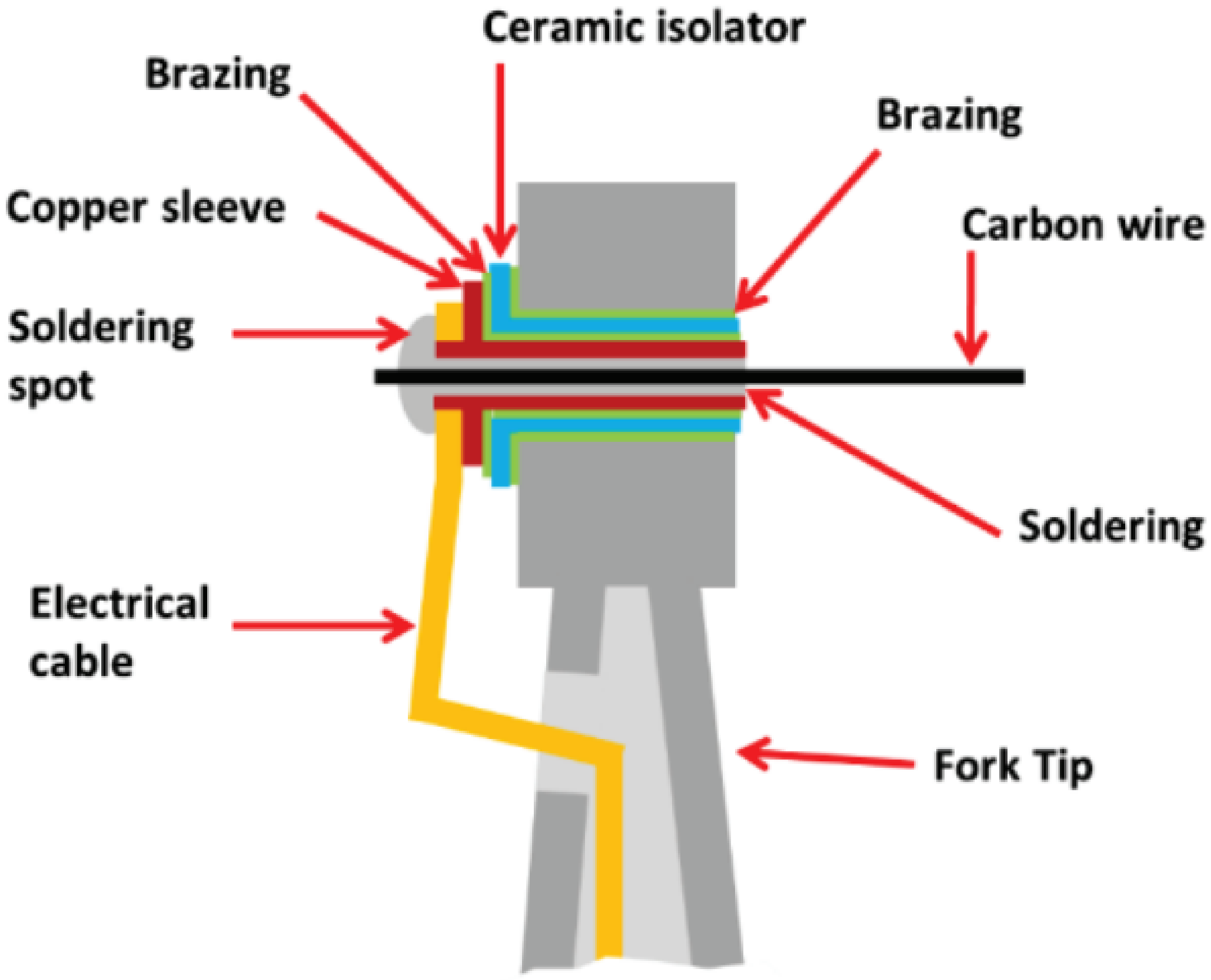
- **Ball Bearings:** 
- **Shaft and Fork:** 
- **Solder:** 
- **Wire:** 
- **Electric Machine:** 
- **Sensors:** 
- **Magnets:** 



Most Critical Components

Wire/ Fork

- **Soldering spot 62Sn/26Pb/2Ag:** $T_{melt} = 180°C$
- **Minimum wire tension**
- **Thermal creep**



Most Critical Components

Bearings

- No lubrication
- Bake-out → bearing friction increases
- Oscillating operation mode

Bake-Out Specifications

Thermal Limitations of Components

Bake-out Requirements

$$T_{bake} = 150°C$$

$$\Delta T = 50\ \frac{°C}{h}$$

$$t_{bake} = 48h$$

Proceeding

Limitations → Failure Analysis → Risk Analysis → Test Design →

Operational Tests

- **No additional sensors required**
- **Read out of control parameters**

Verification Test

- Compliance with requirements

  - Magnetic brake test
  - Constant speed operation
  - Calibration
  - Electrical Insulation Test

Validation Test

- Perform indented purpose in desired environment

  - Scans

Testing

Calibration → Operational Test

Bake-Out → Operational Test

Calibration

Calibration

Accuracy and Precision Determination

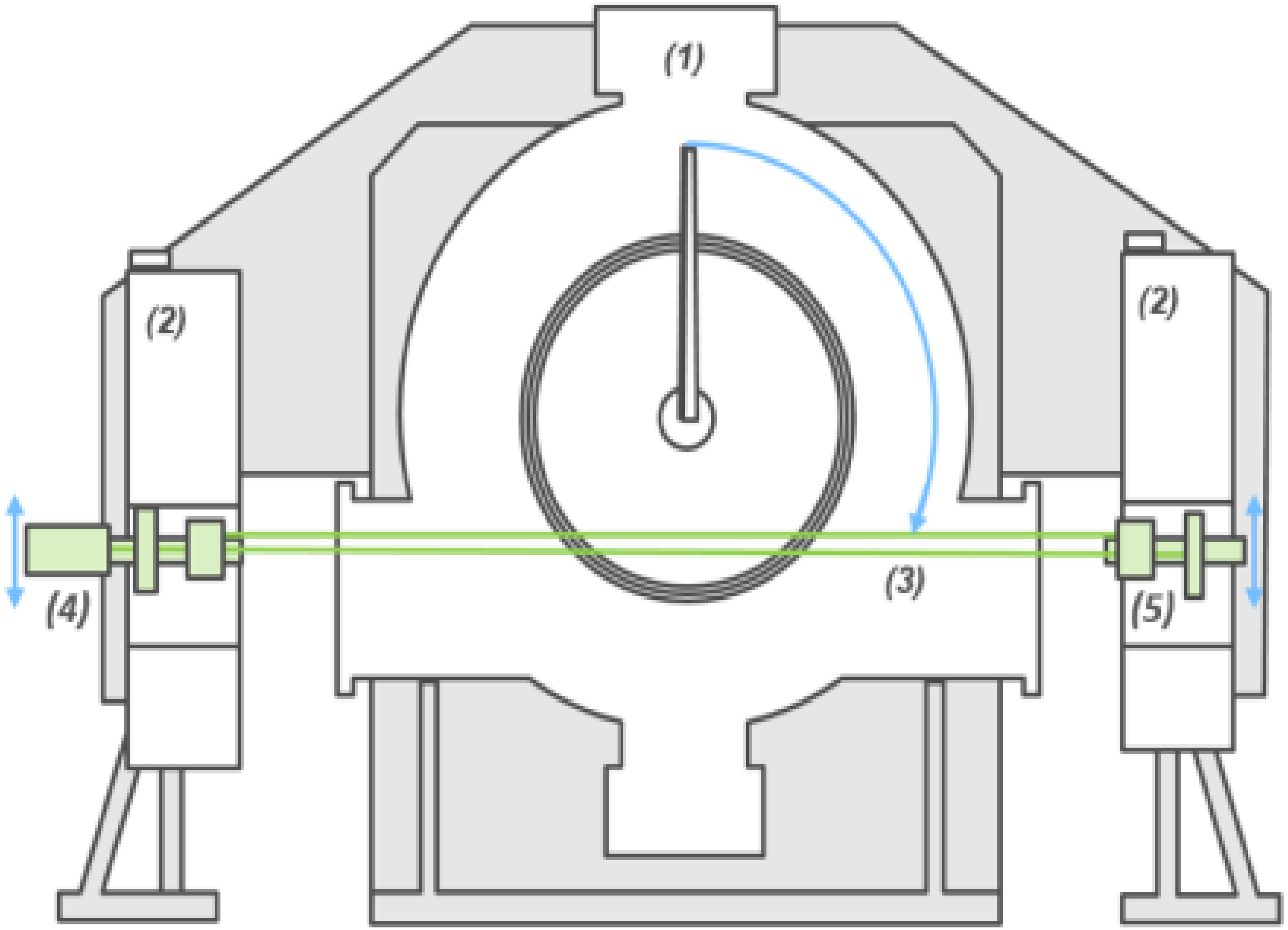
(1) Initial position

(2) Optical system

(3) Intercepting position

(4) Adjustable laser

(5) Adjustable laser diode



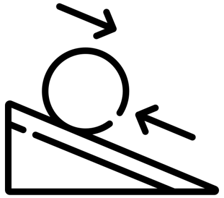
Operational Test

- Install wire scanner in tank
- Attach controller
- Attach vacuum pump
- Install bake-out equipment

Proceeding

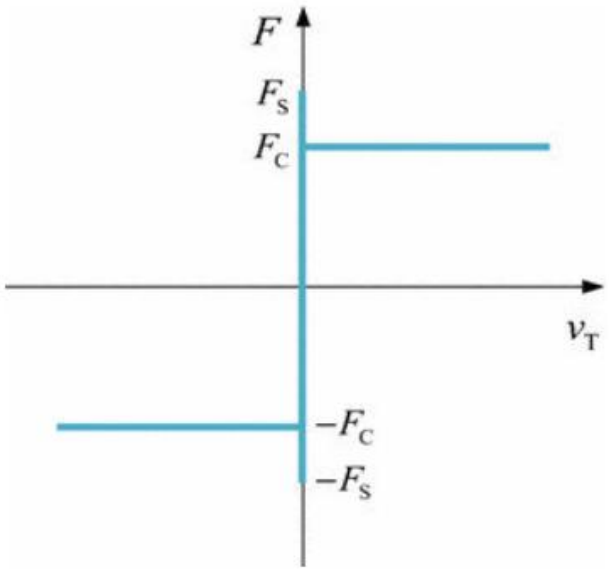
Limitations → Failure Analysis → Risk Analysis → Test Design → Test Execution

Friction Torque Studies



Expectation: Dry Coulomb friction

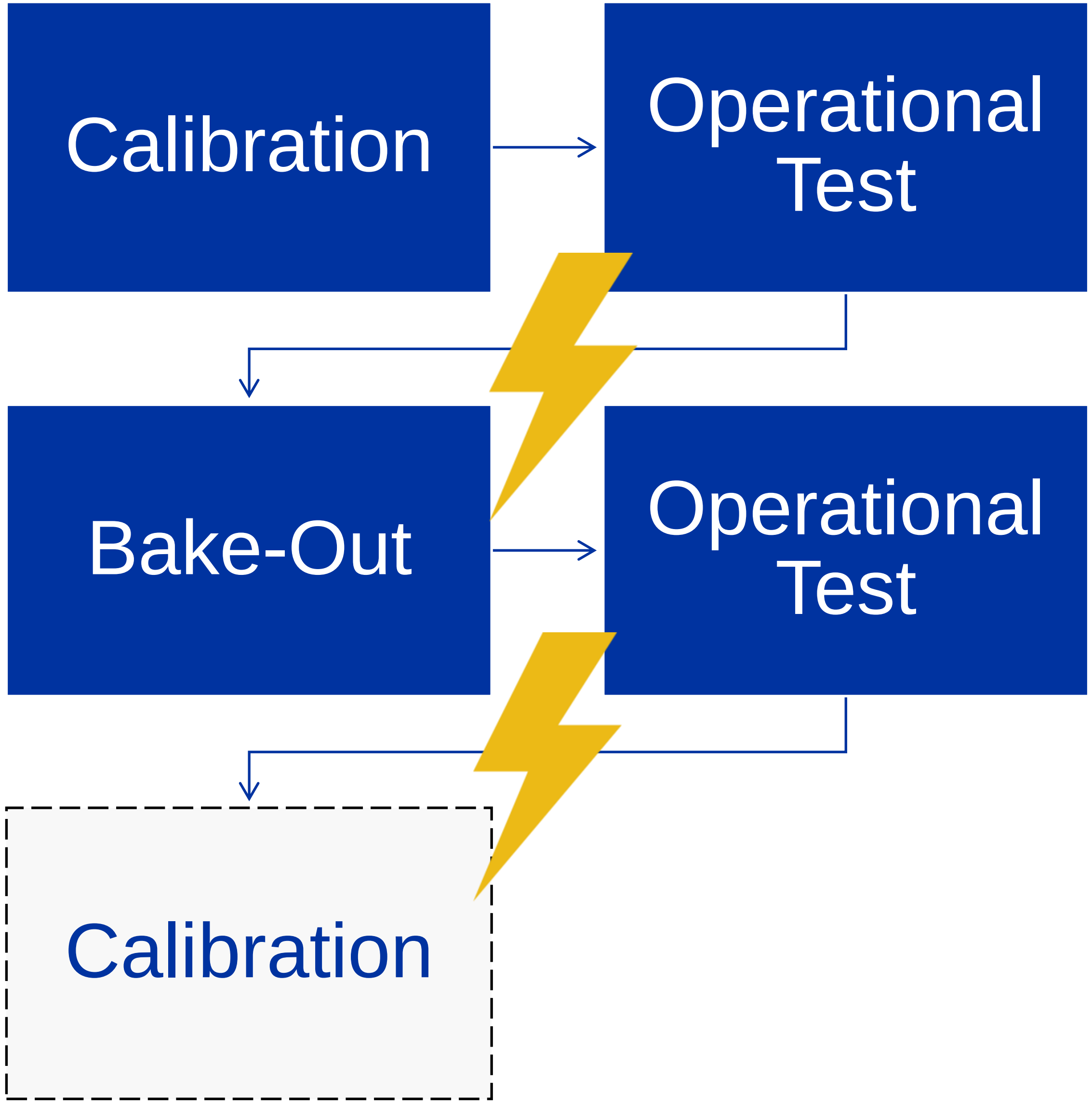
- **Static friction at zero speed**
- **Dynamic friction at non zero speed**



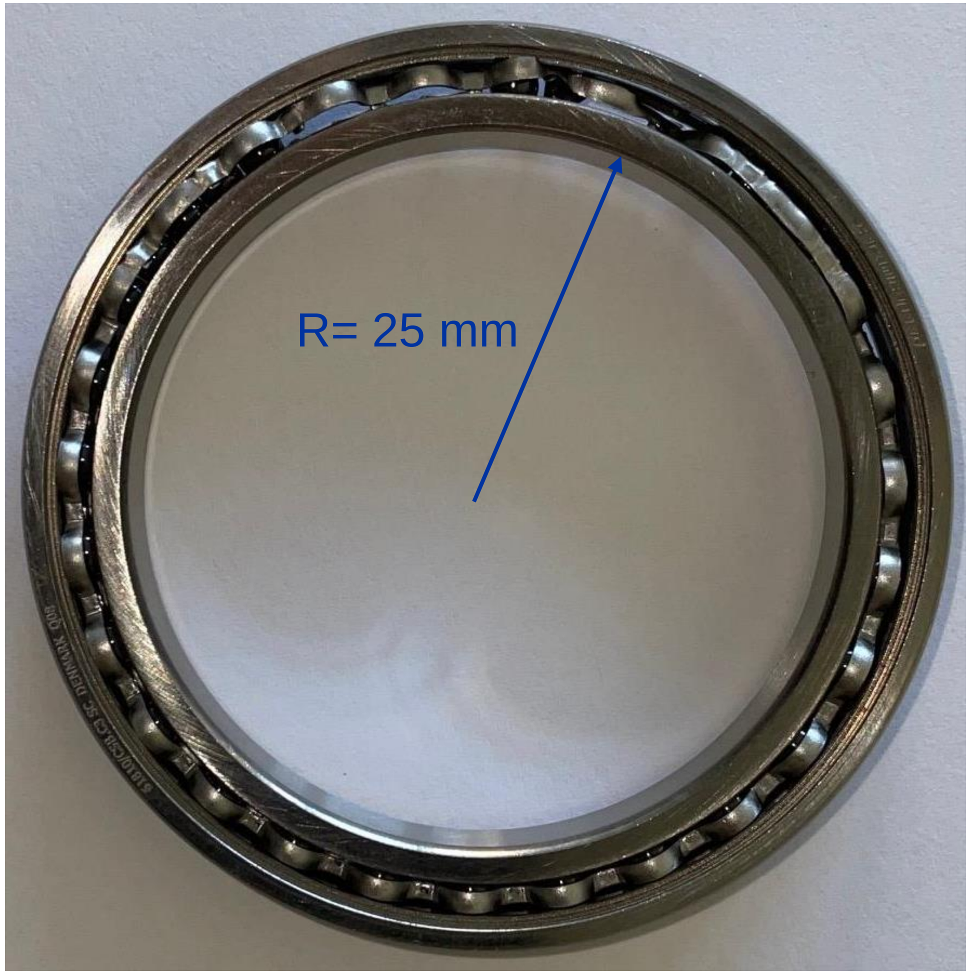
- **No lubrication**
- **Increased friction after bake-out**

Before bake-out	After bake-out
$\mathrm{T}_{\mathrm{fr}_{\mathrm{st}}} = 150.27\ Nmm$	$\mathrm{T}_{\mathrm{fr}_{\mathrm{st}_{\mathrm{bakeout}}}} = 535.05 Nmm$
$\mathrm{T}_{\mathrm{fr}_{\mathrm{dyn}}} = 132.24\ Nmm$	$\mathrm{T}_{\mathrm{fr}_{\mathrm{dyn}_{\mathrm{bakeout}}}} = 540.97\ Nmm$

Tests


Calibration
Operational Test
Bake-Out
Operational Test
Calibration

Bearing Failures



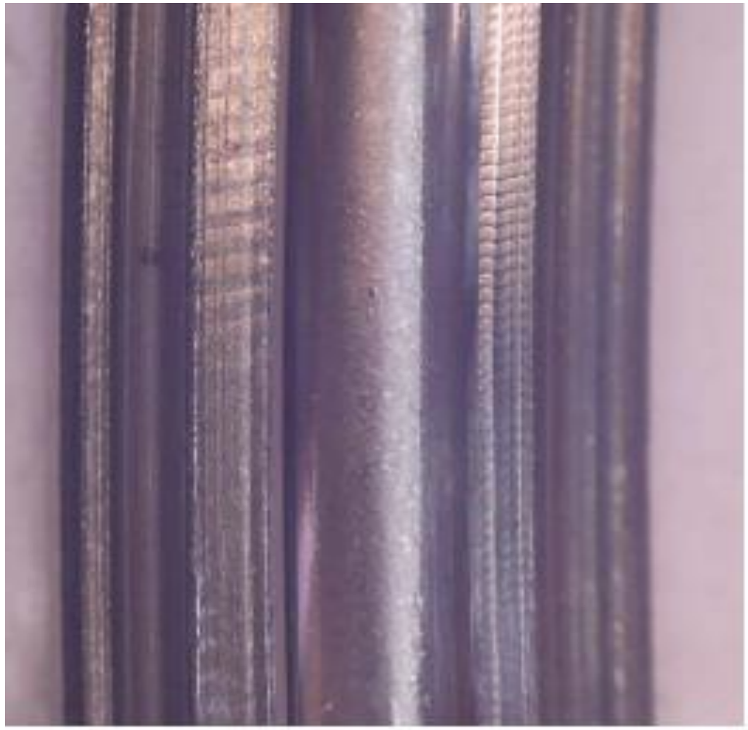
At constant speed operation → cage rupture

Wear Analysis by ceramicspeed

Inner racer:

- **Clear signs of wear**
- **Pitting**

Wear Analysis by ceramic speed



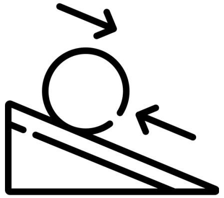
Outer racer:

→ **Wear**

Cage:

- **Visible fracture**
- **Ball pockets undamaged**

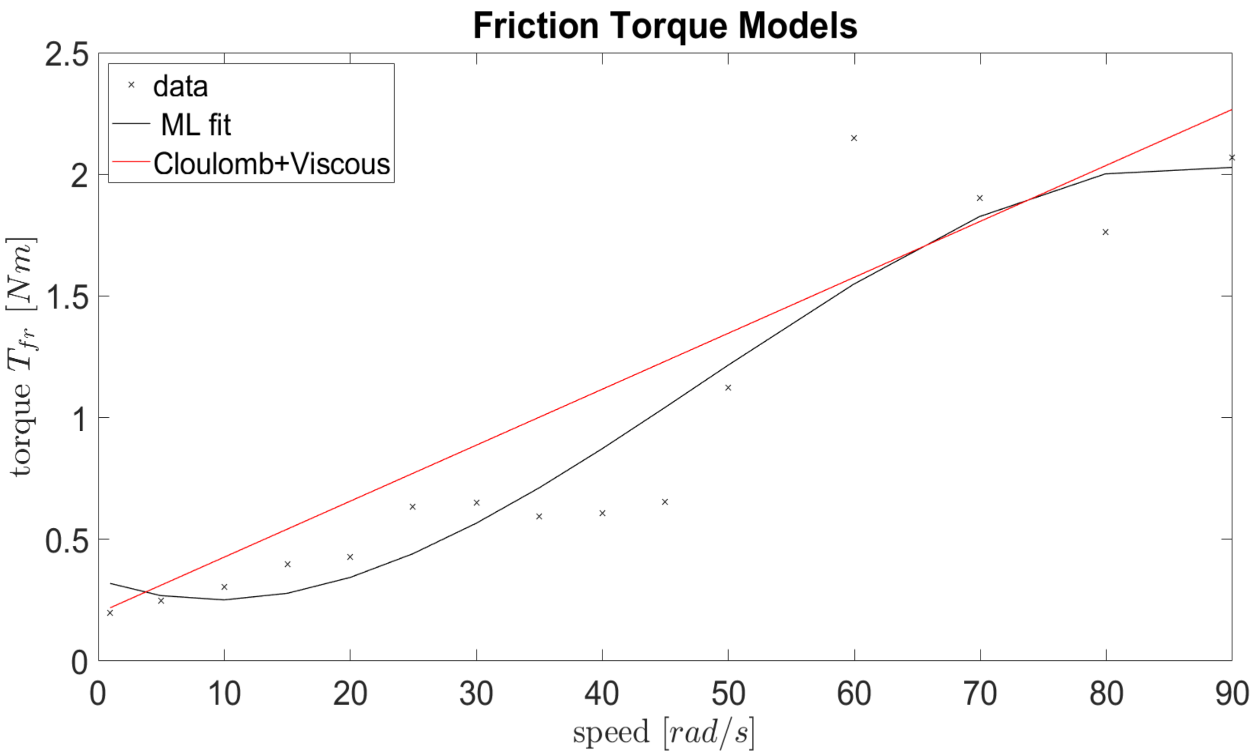
Friction Torque Studies



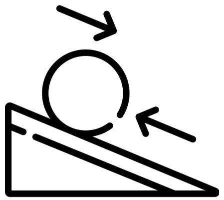
Test Results before Bake-out:

- **Linear regression model**
- **Linear dynamic friction model:**

$$T_{fr} = F_C + \mu_v \cdot \omega = 0.197\ Nm + 0.023 \frac{Nm}{\frac{rad}{s}} \cdot \omega$$



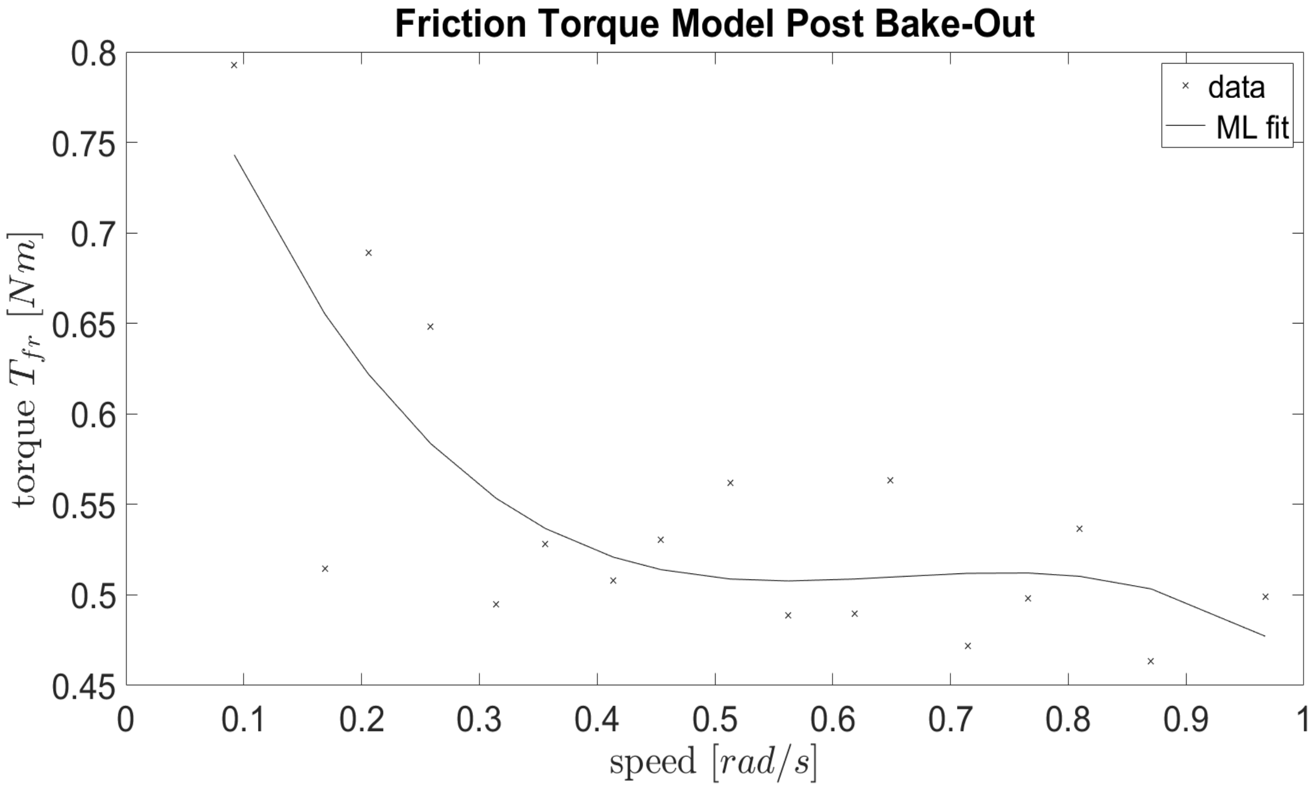
Friction Torque Studies



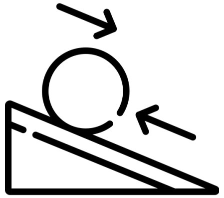
Test Results after Bake-out:

- **Static and dynamic friction:**

$$T_{fr} = \begin{cases} 0.79\ Nm & for\ \omega < 0.3\dfrac{rad}{s} \\ 0.49\ Nm & for\ \omega > 0.3\dfrac{rad}{s} \end{cases}$$



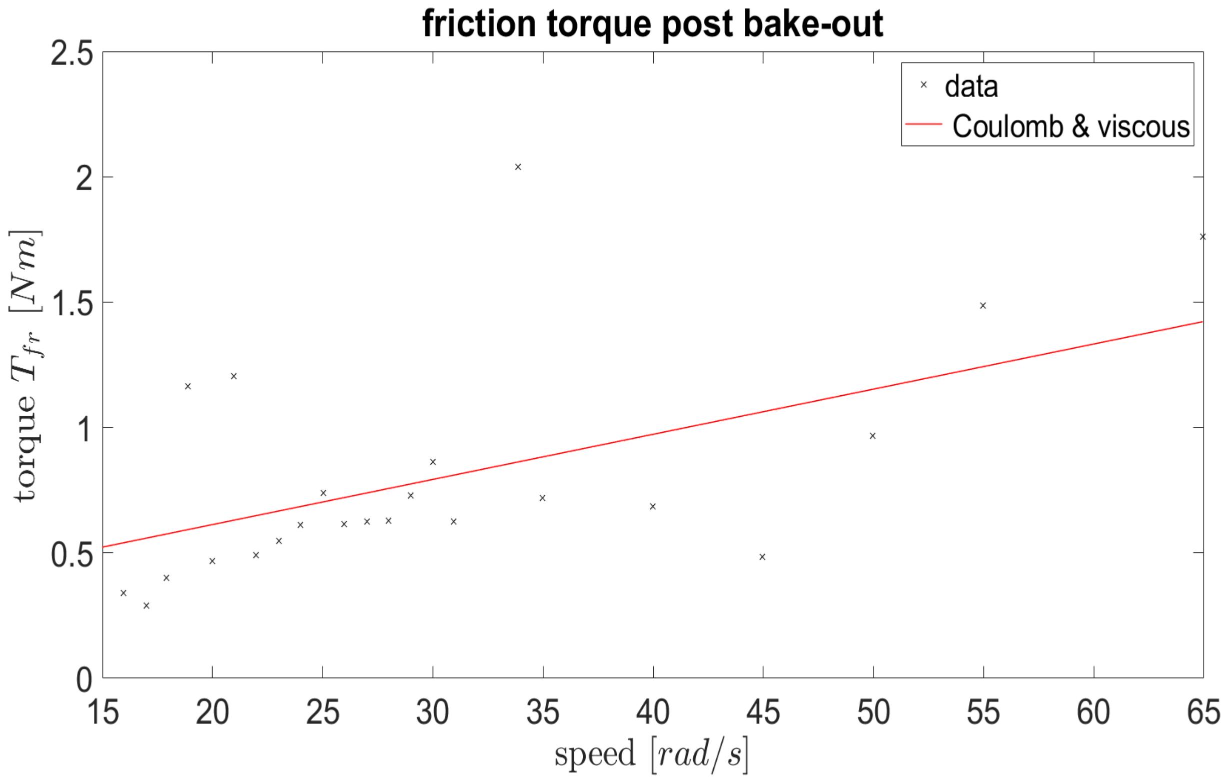
Friction Torque Studies



Test Results after Bake-out:

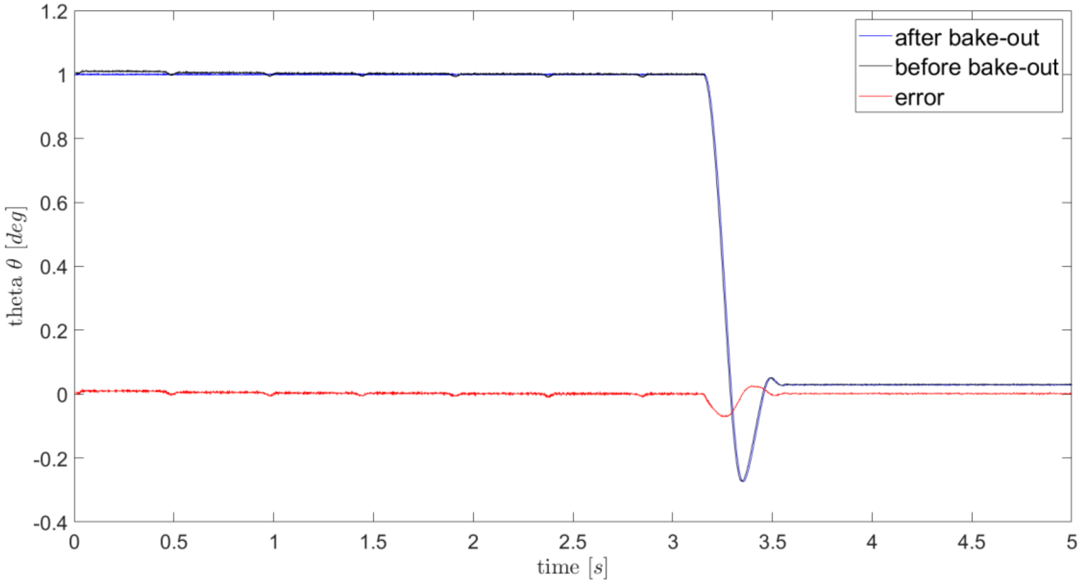
- **Speed dependent dynamic friction linear model**

$$T_{fr} = 0.253Nm + 0.018\frac{Nm}{\frac{rad}{s}} \cdot \omega$$

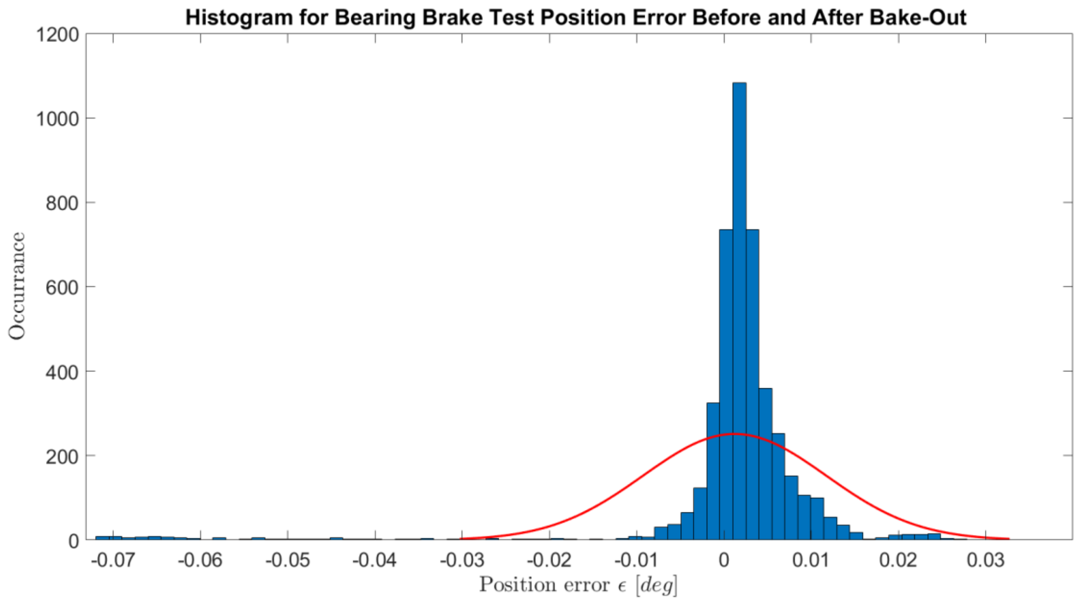


Results Nominal Bearings

Magnetic Brake Restoring Test Position

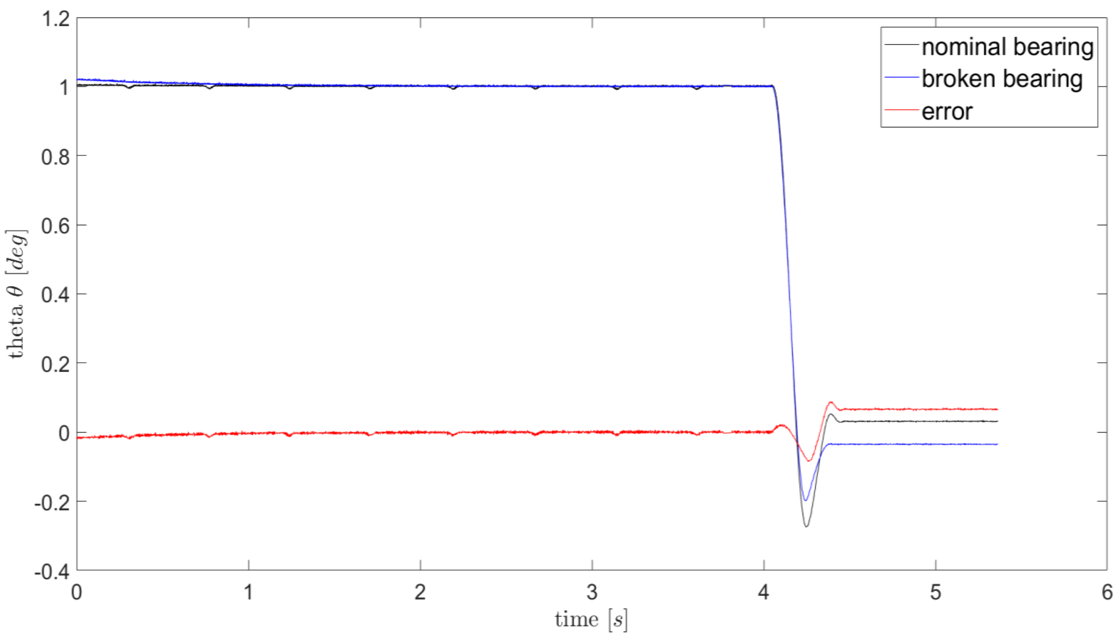


Error Histogram

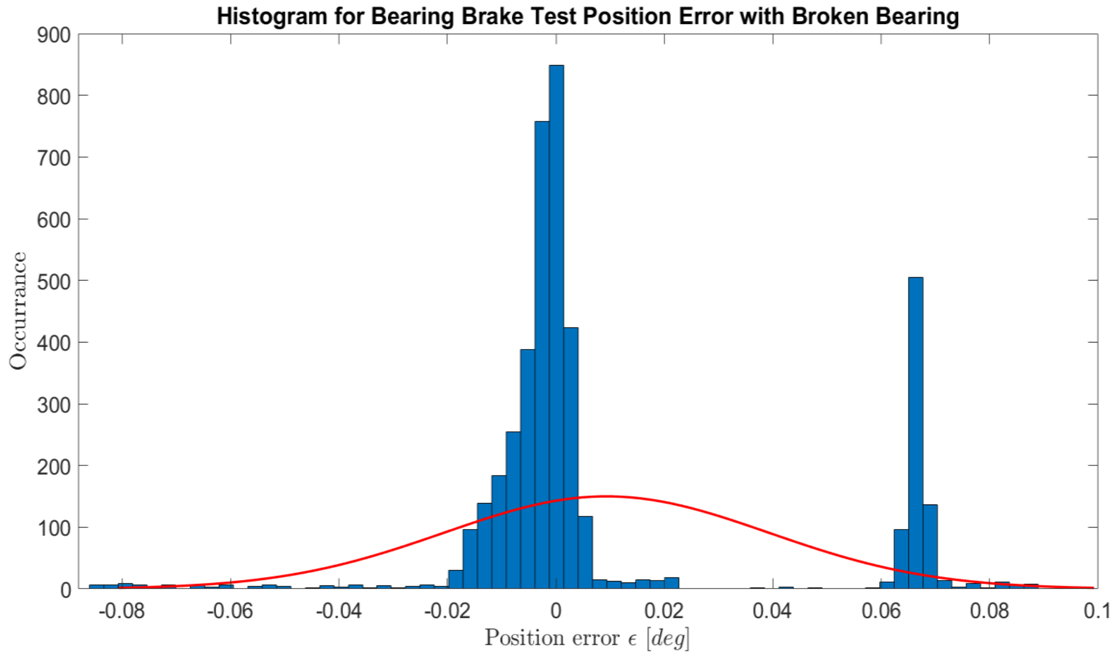


Results Broken Bearings

Magnetic Brake Restoring Test Position



Error Histogram



Conclusion

- **Wire scanner is operational after bake-out**
- **Successfully conducted tests:**
  - Insulation resistance
  - Calibration
  - Magnetic brake restoring mechanism
  - Scan operation
  - Friction torque measurements
- **Wire scanner can operate with constant speed**
- **Ball bearing cages are source of failure**
- **Friction torque in current system is speed dependent**

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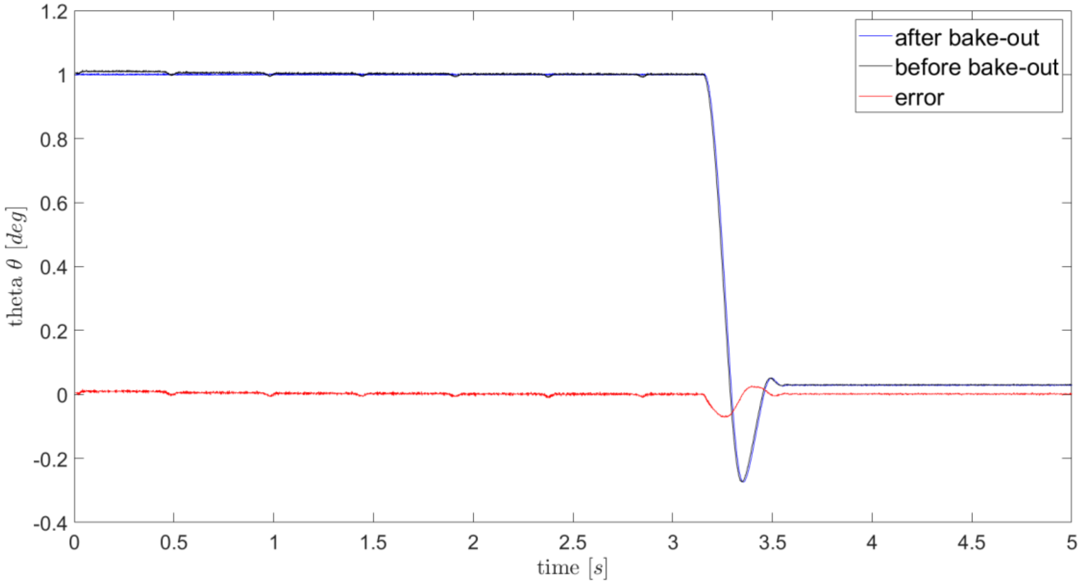
LHC Beam

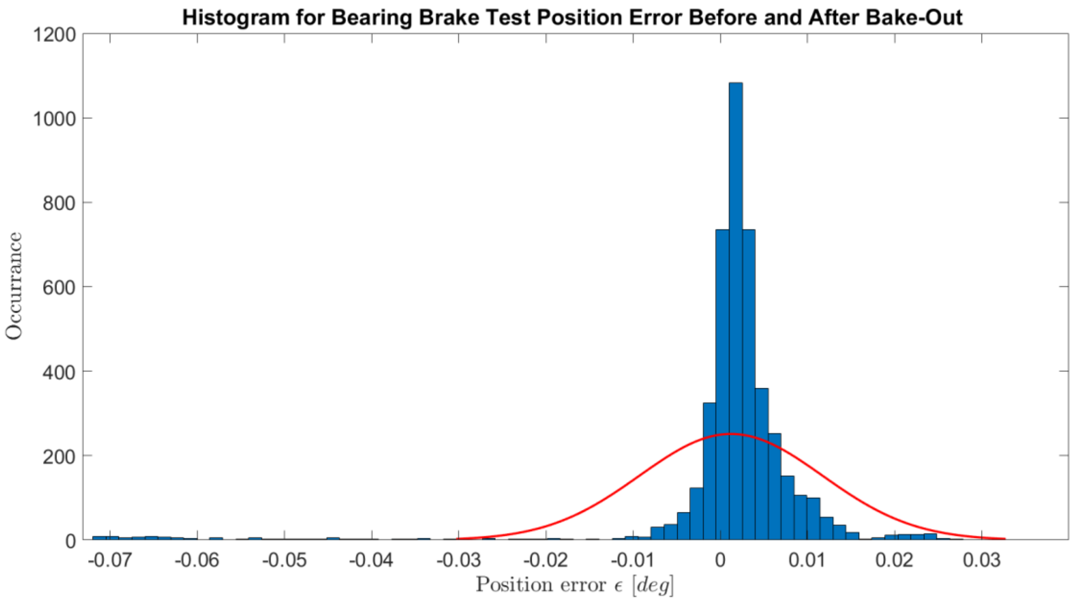
Characteristic	Values
Top Energy	$E = 13\, TeV$
Injection Energy	$E = 0.45\, TeV$
Injection Profile	$\sigma_x = 0.53\, mm$
	$\sigma_y = 0.8\, mm$
Required Position Accuracy	$\epsilon_y = 20\, \mu m$

Results Nominal Bearings

Magnetic Brake Restoring Test Position

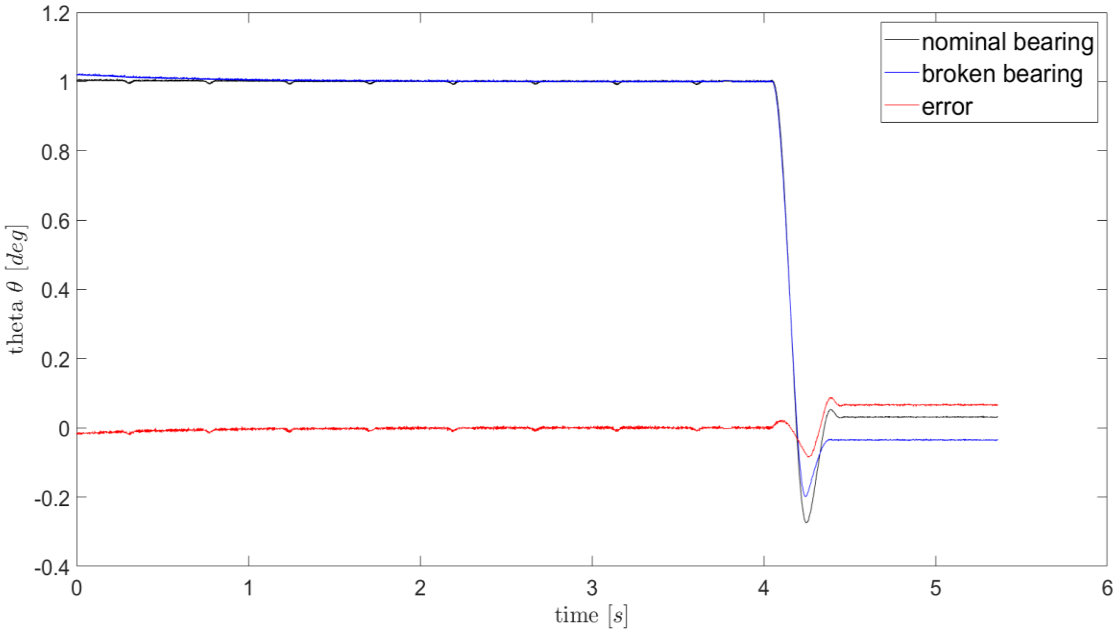


Error Histogram

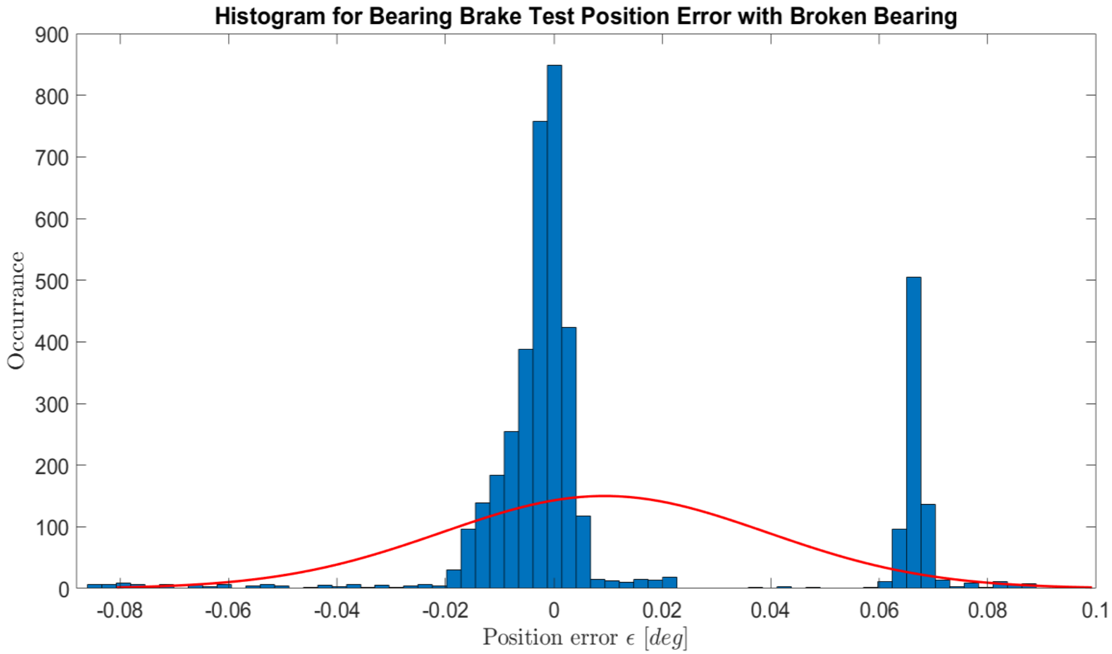


Results Broken Bearings

Magnetic Brake Restoring Test Position

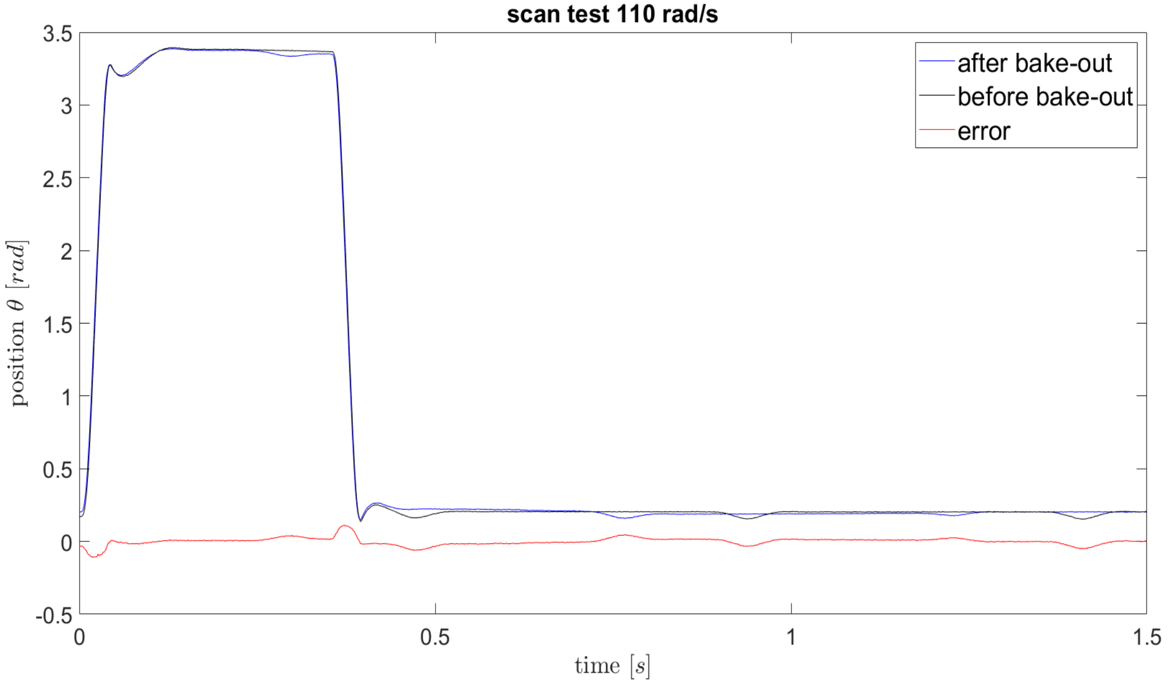


Error Histogram

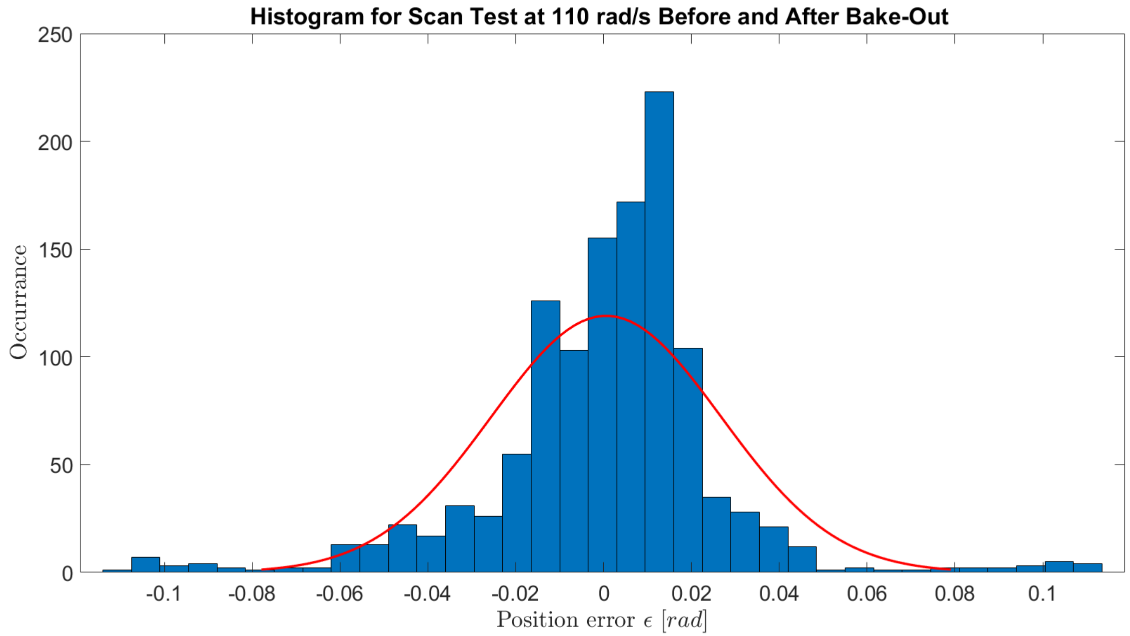


Scans

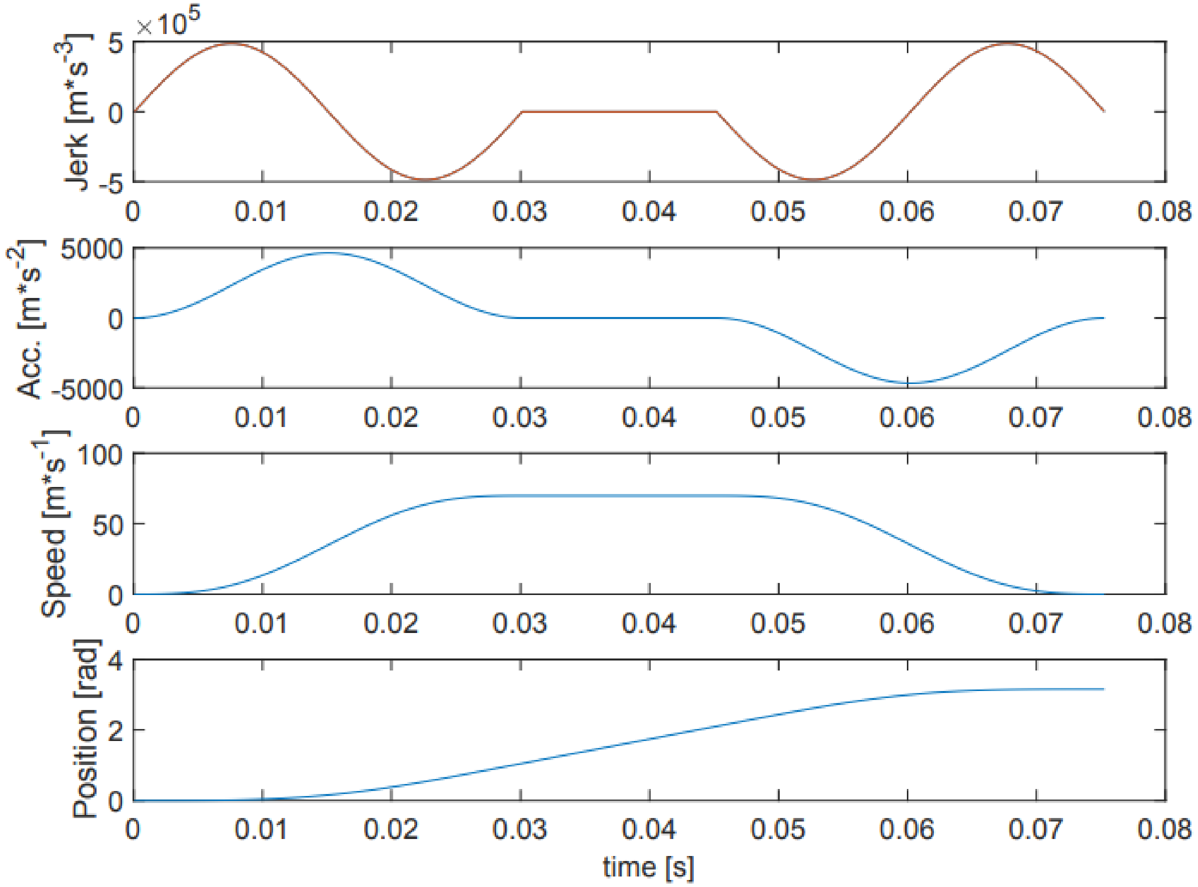
Scan Test at $110\,\frac{rad}{s}$



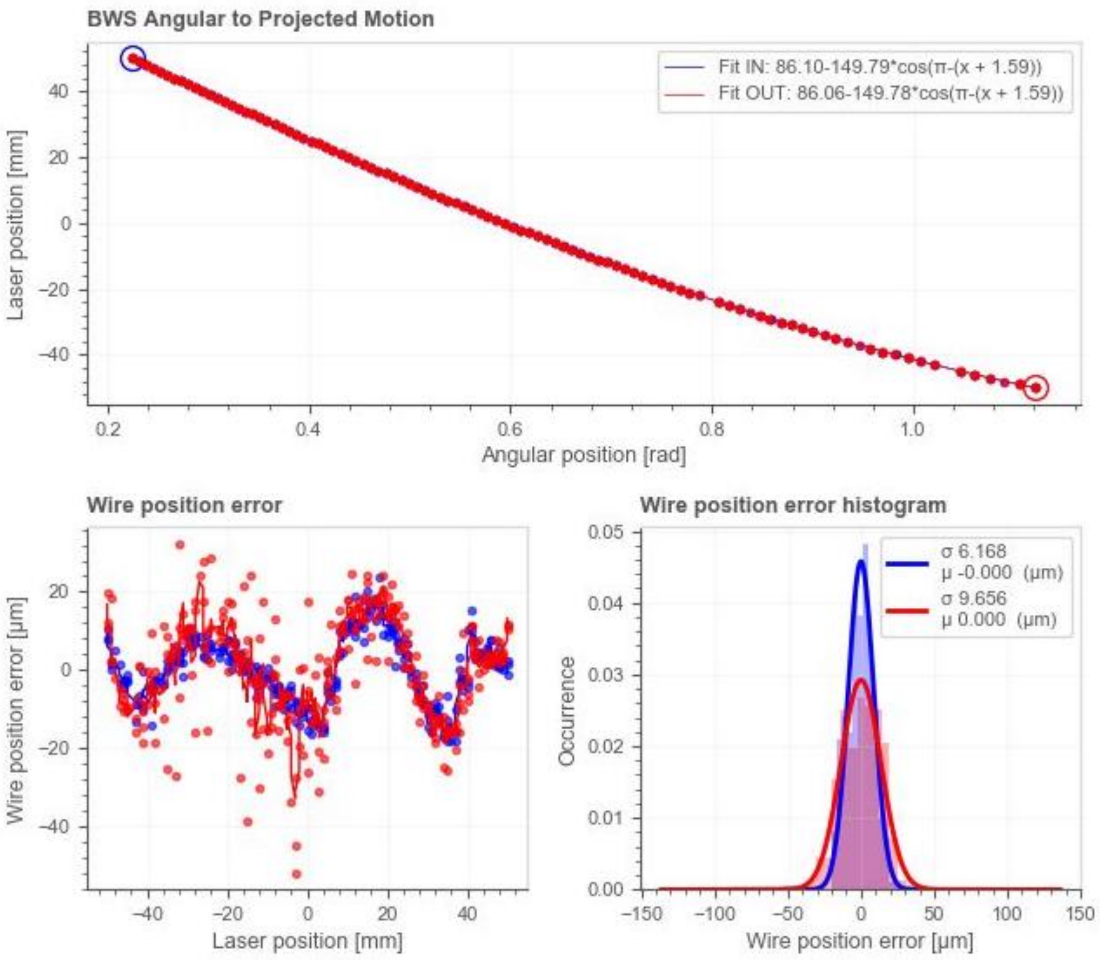
Error Histogram



Motion Profile



Calibration Results



- **Scan at** $55\frac{rad}{s}$
- **Expected wire position error:**
  - **IN-OUT offset:** $31.9\ \mu m$
- **Measured wire position error:**
  - **IN-OUT offset:** $26\ \mu m$

Ball Bearing Updates

- No clearance issues according to manufacturer
- Inspection for wear in the racers
- Possibility to add solid lubricant compatible with UHV

Solid Lubricants

Requirements:

- **UHV compability $(10^{-10} mbar)$**
- **High temperature resistance**
- **Radiation resistance**
- **Durability**
- **Chemical cleaning approved**

Solid Lubricants

- **Soft metal coatings: lead, gold, silver**
- **Lamellar solids: molybdenum disulfide (MoS2) and tungsten disulfide (WS2)**
- **Polymers: PTFE and PEEK**

Molybdenum-Disulfide

- ✓ Vacuum acceptance test for ELENA
- ✓ Bake-out at 250°C
- ✓ Low friction coefficient: $\mu < 0.01$
- ✓ Good radiation stability
- ✓ Low electrical conductance
- Poor performance under atmospheric conditions
- Oxidation due to storage
- Corrosion

Tungsten-Disulfide

- ✓ **Better oxidation resistance**
- ✓ **Worse sliding endurance in vacuum than MoS2**
- ✓ **Friction coefficient:** $\boldsymbol{\mu = 0.03\ to\ 0.09}$
- ✓ **Thermal stability:** $\boldsymbol{-188°C\ to\ 1316°C}$
- ✓ **Chemical cleaning with acid ☹**