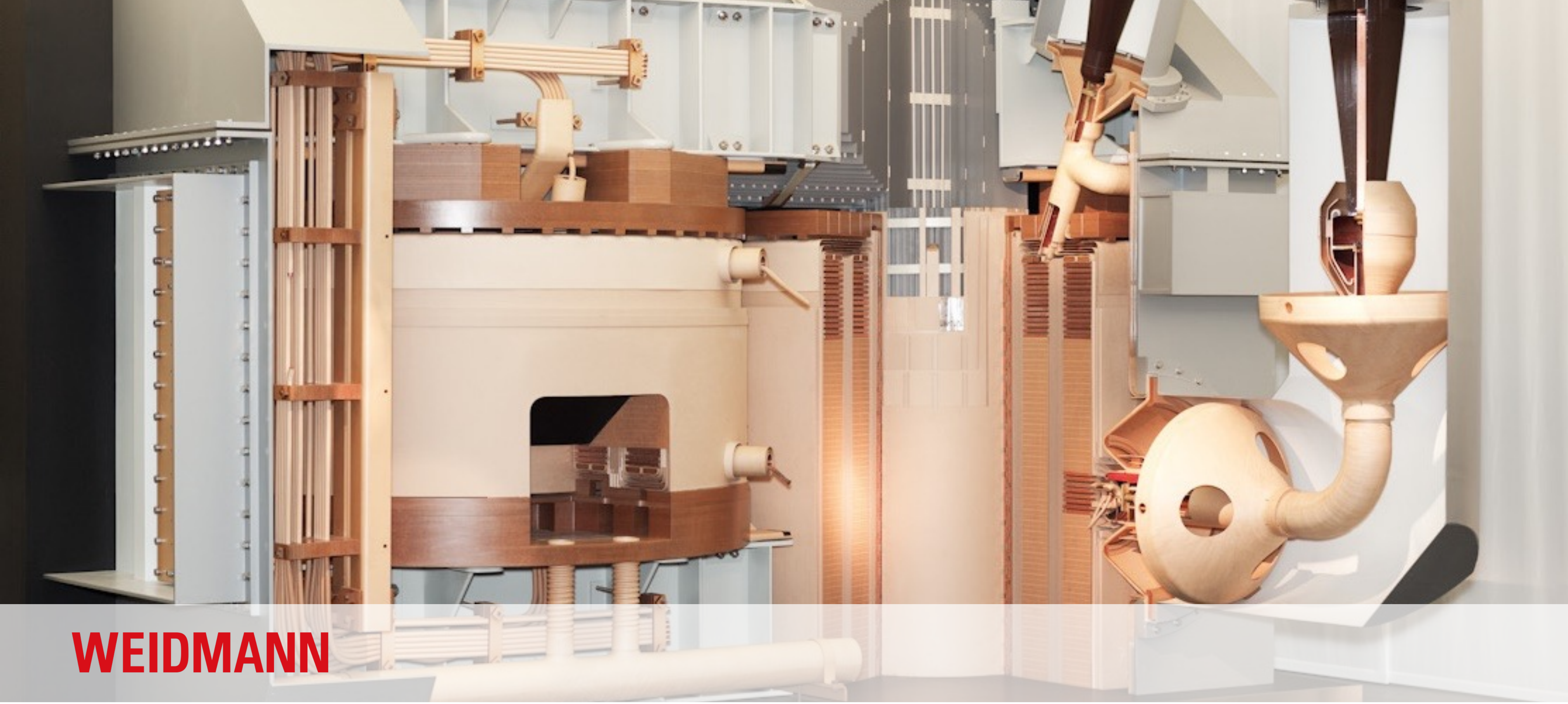

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AVOIDING CATASTROPHIC FAILURES DUE TO SHORT CIRCUIT EVENTS IN POWER TRANSFORMERS

STEFAN JAUFER

DISCLAIMER

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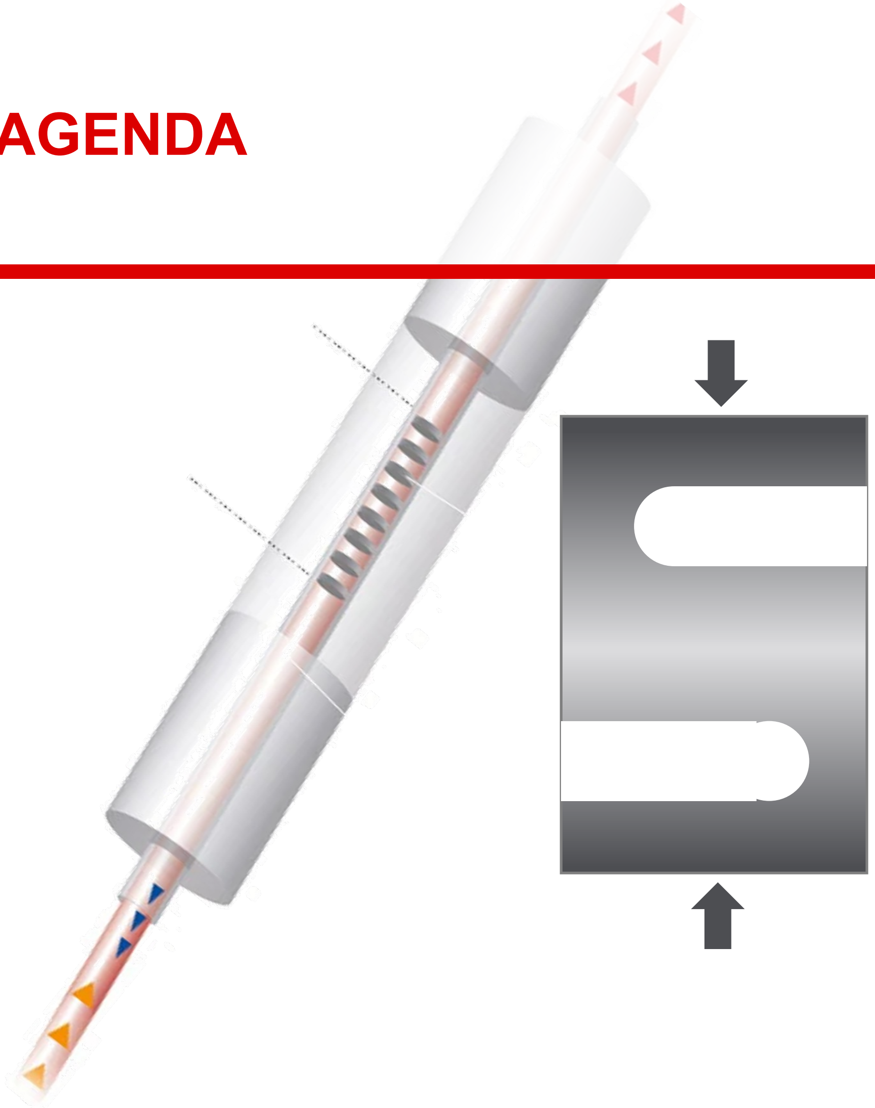
AGENDA



INTRODUCTION

TASKS OF TRANSFORMER IN THE NETWORK

- Change system voltage
  - Reduction of transmission losses by using HV, UHV, EHV
- Galvanic separation of grids
  - Different grounding strategies (solidly earthed, compensated, isolated neutral system,…)
- Reduction of short circuit currents
  - Short circuit impedance
    - Distribution transformers: 4-6 %
    - SMPT: 6-12 %
    - Large power transformers: 9-16 %

→ High currents

- Function of transformer must be guaranteed during short circuit events
- Key component in transmission
- Reliable but expensive component

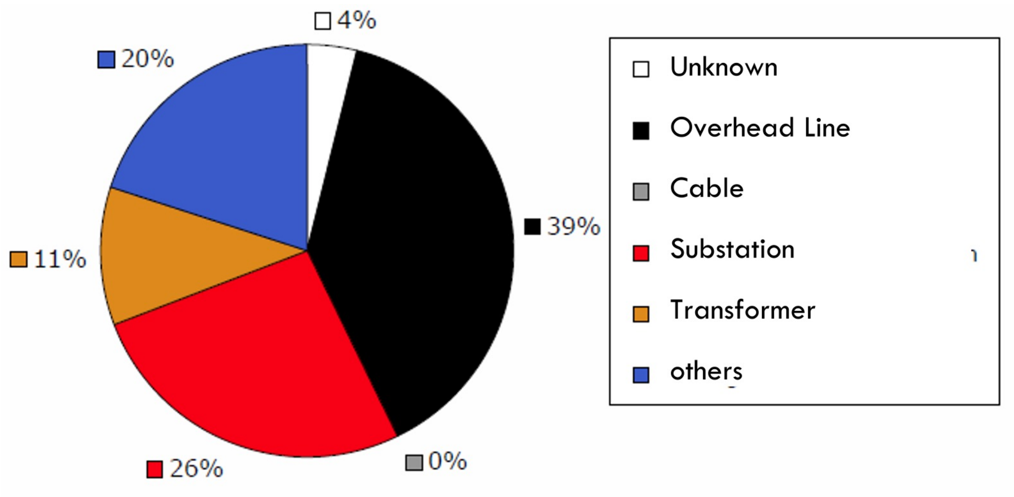


FIGURE 11: PERCENTAGE OF PRIMARY LOCATION OF DISTURBANCE FOR 220 KV AND 380 KV

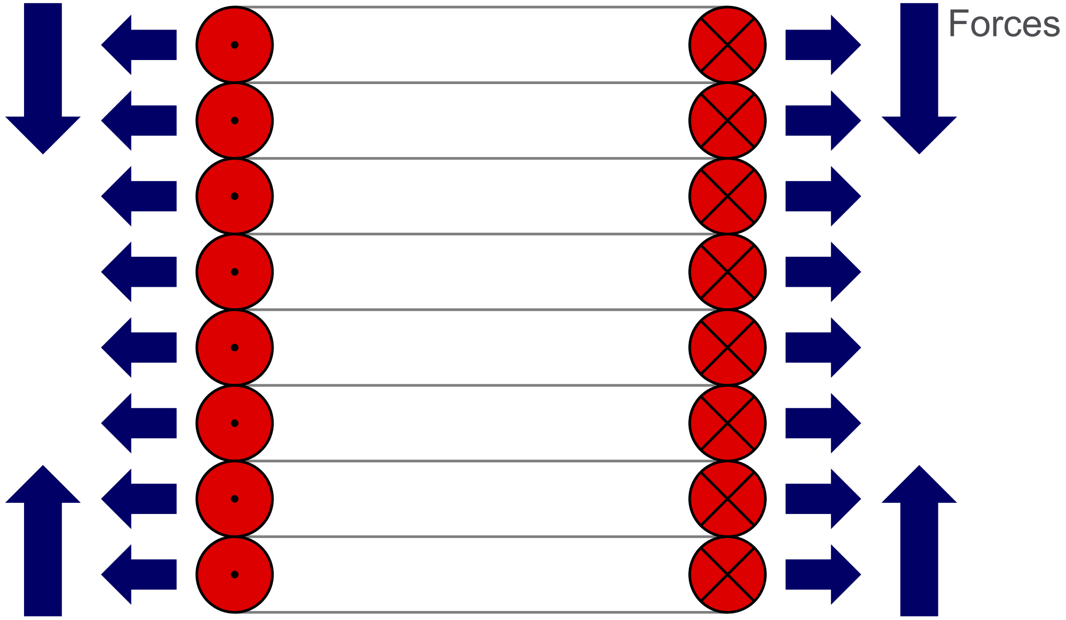
Source: CIGRE TB 642

INTRODUCTION

FORCES INSIDE (SINGLE) WINDING

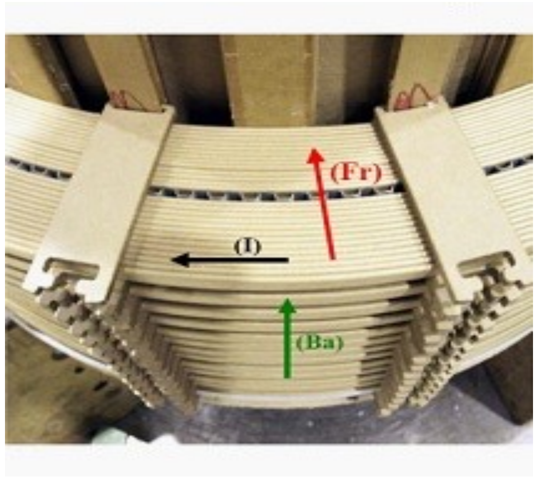
Lorenz Forces:
Current and resulting magnetic field makes:

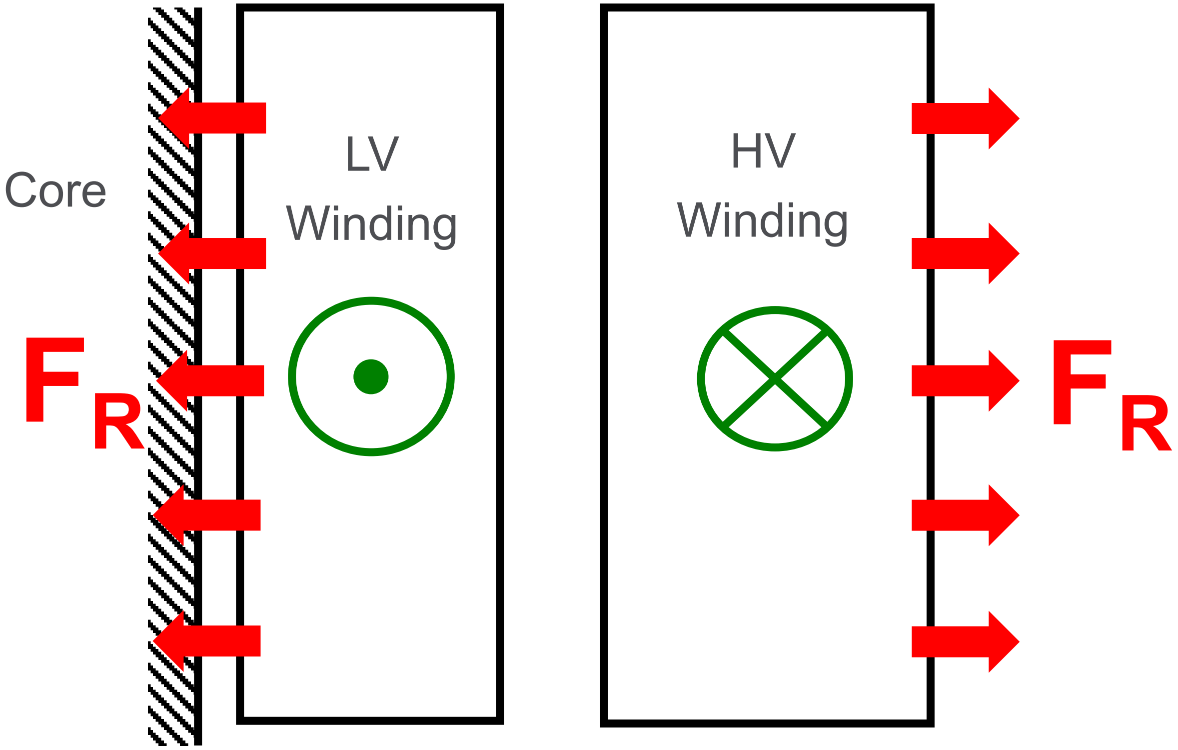
- Compression of the winding in axial direction
- Expansion forces in radial direction

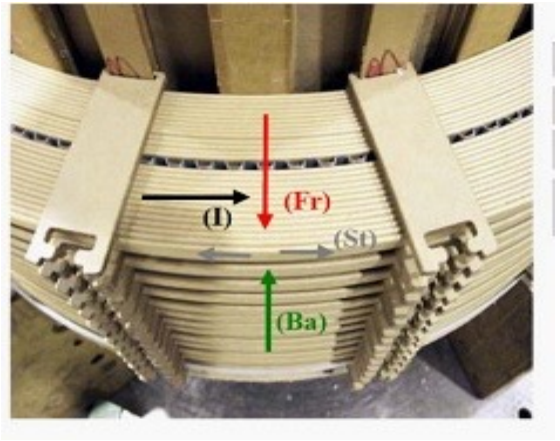


INTRODUCTION

FORCES BETWEEN WINDINGS



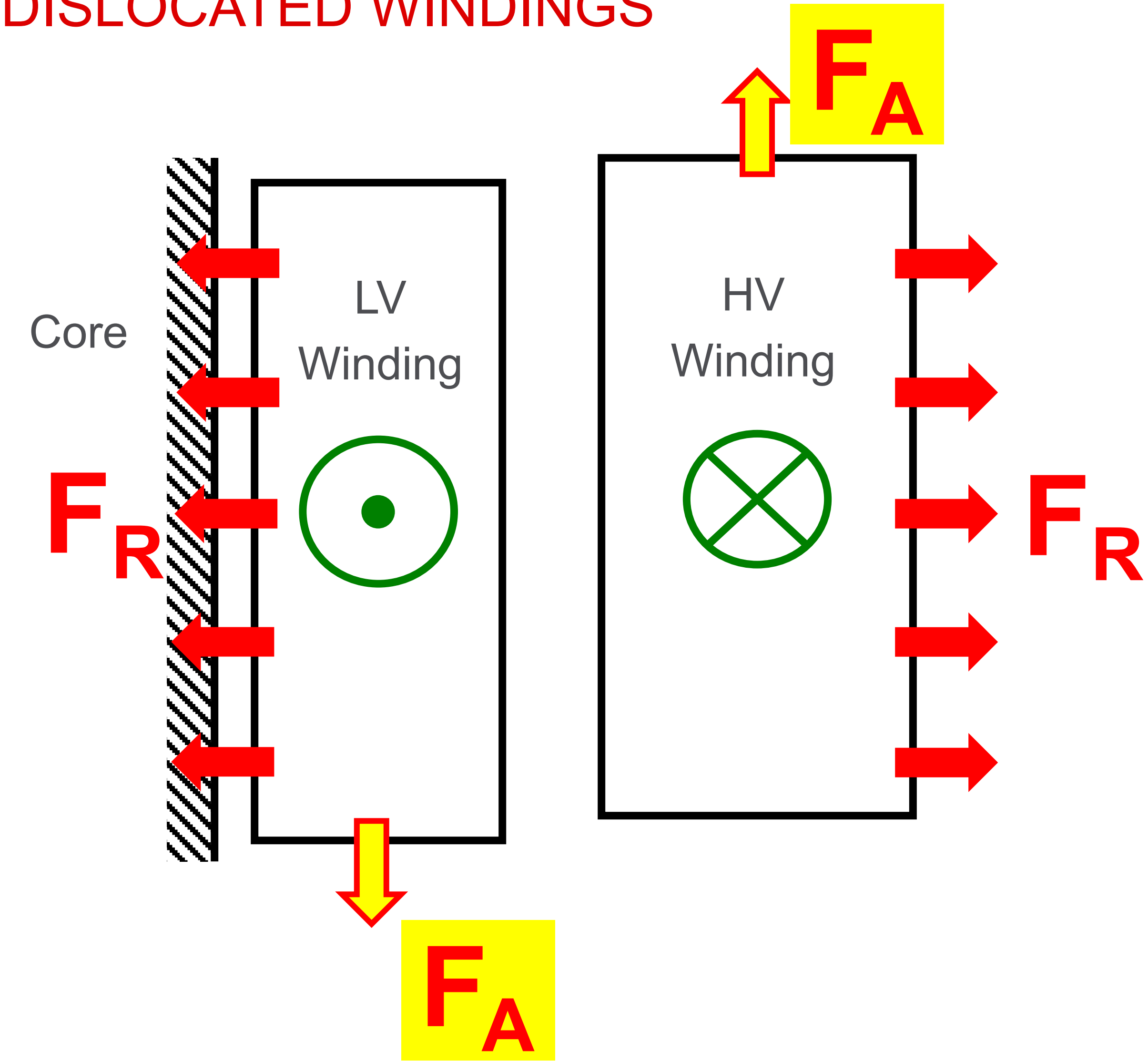




Source: electrical-engineering-portal.com

INTRODUCTION

FORCES BETWEEN DISLOCATED WINDINGS



F_A

Core

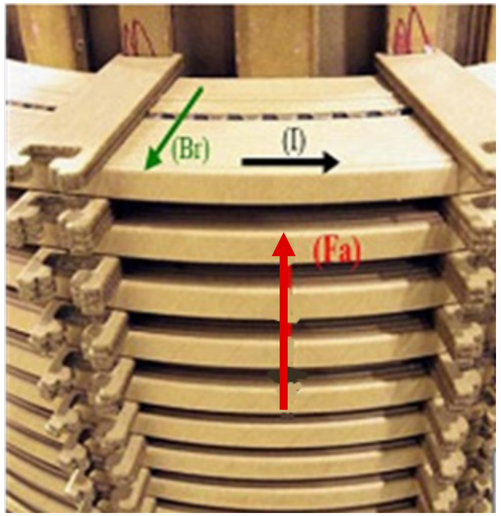
LV Winding

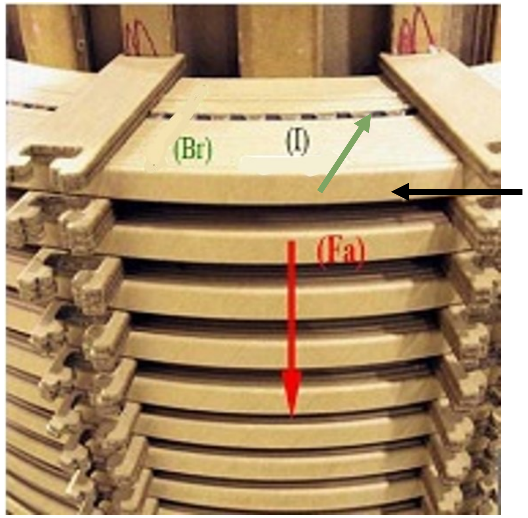
HV Winding

F_R

F_R

F_A

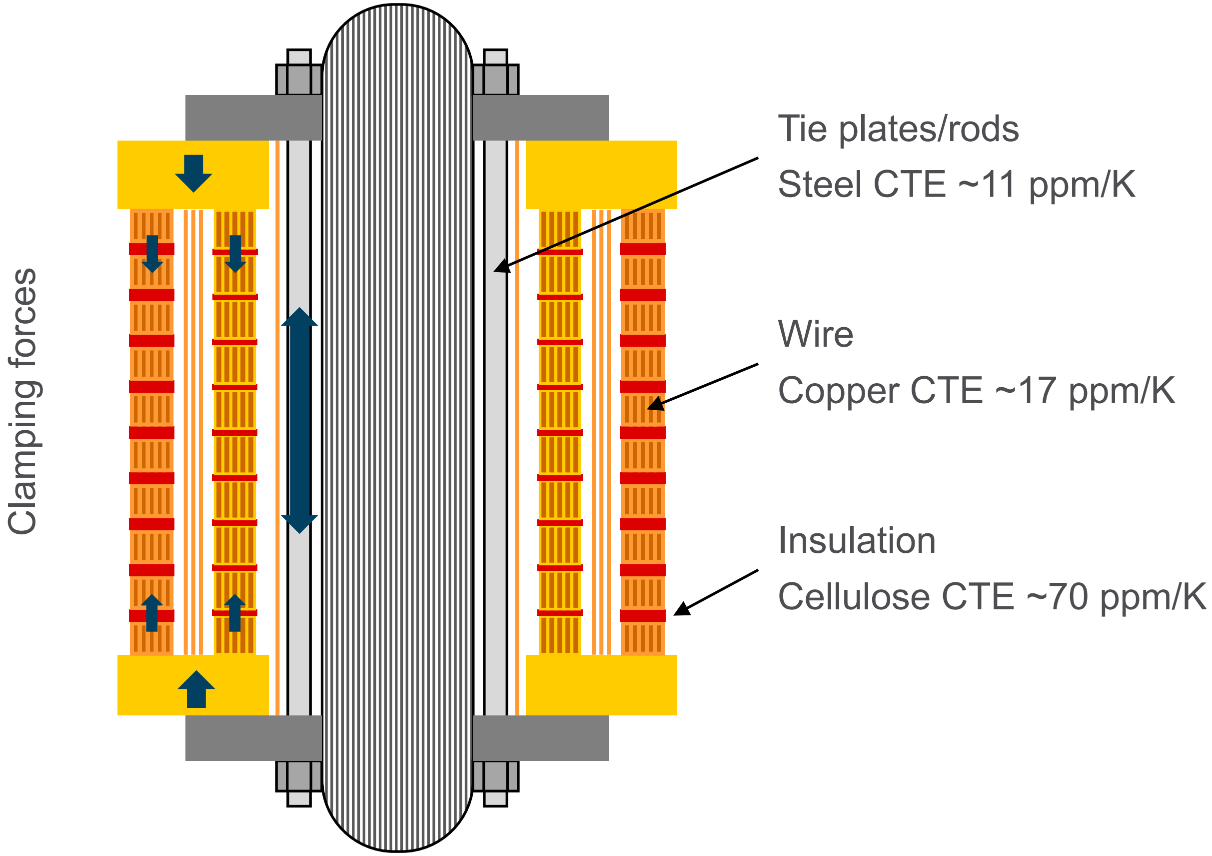




Source: electrical-engineering-portal.com

INTRODUCTION

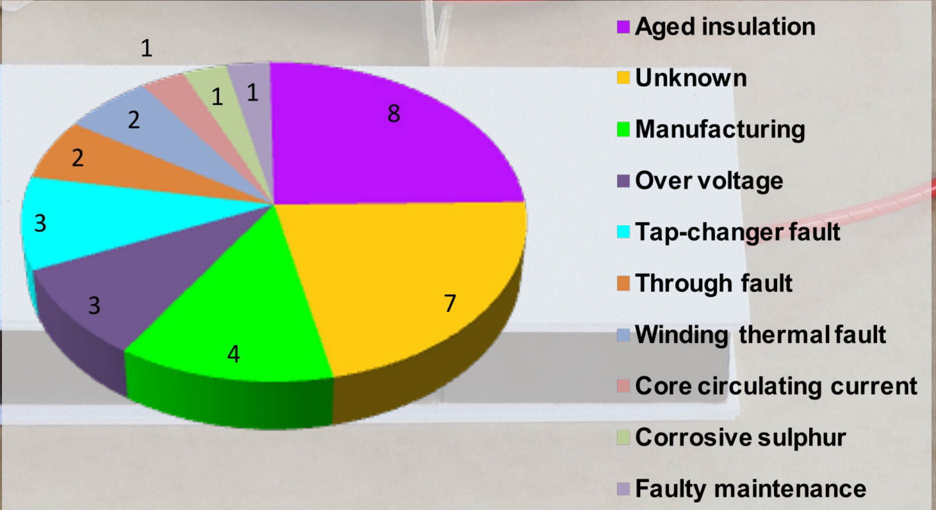
CLAMPING BEHAVIOR



Interactions

- Tie plates
  - Close to the core or outside
  - Stray field
  - Loosen tightening
- Wire
  - Heated by load
  - Tilting of wires
- Insulation
  - Moisture depending swelling/shrinking
  - Viscoelastic and -plastic behavior
  - Aging

FUNDAMENTAL STATEMENTS



Example of failure causes (UK) from Cigre TB642

Tight clamping is required for reliable operation

Keep conductor and windings at designed positions/locations

Clamping forces/pressure designed to transformer type

Deviation due to fabrication reality vs. design

Clamping pressure is dynamic

AGENDA

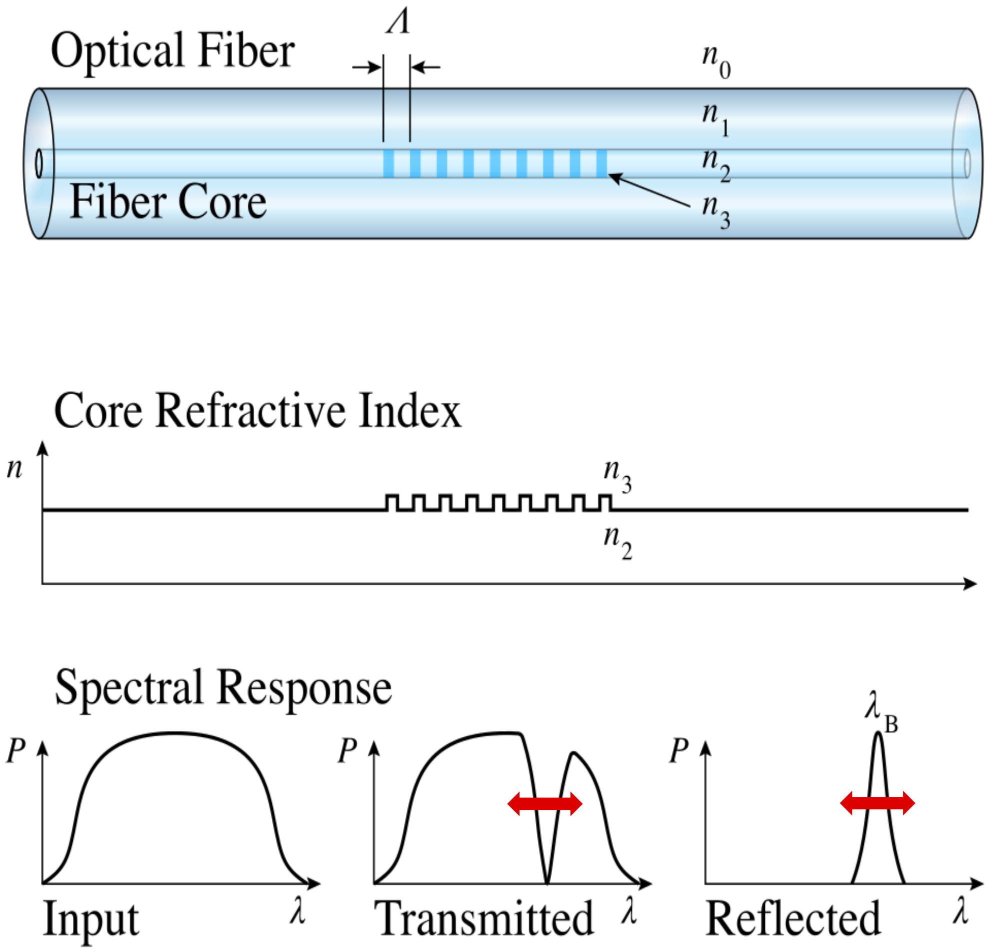
- 1 Introduction
- 2 **Sensor Generation 3**
- 3 Beta Test
- 4 In Service Measurements
- 5 Summary

REQUIREMENTS FOR DESIGN

- Ambient inside transformer and during fabrication
- Immunity to magnetic fields
- Immunity to dielectric stress
- Mechanical strength
- Distant evaluation of signals

CLAMPING FORCE SENSOR

SENSING PRINCIPLE: FIBER BRAGG GRATING



- Single mode fiber
- Periodical changes in core refraction index

→Interference filter

  - Reflected/transmitted signal depending on distance between disturbance
  - Intensity depending on number of disturbance

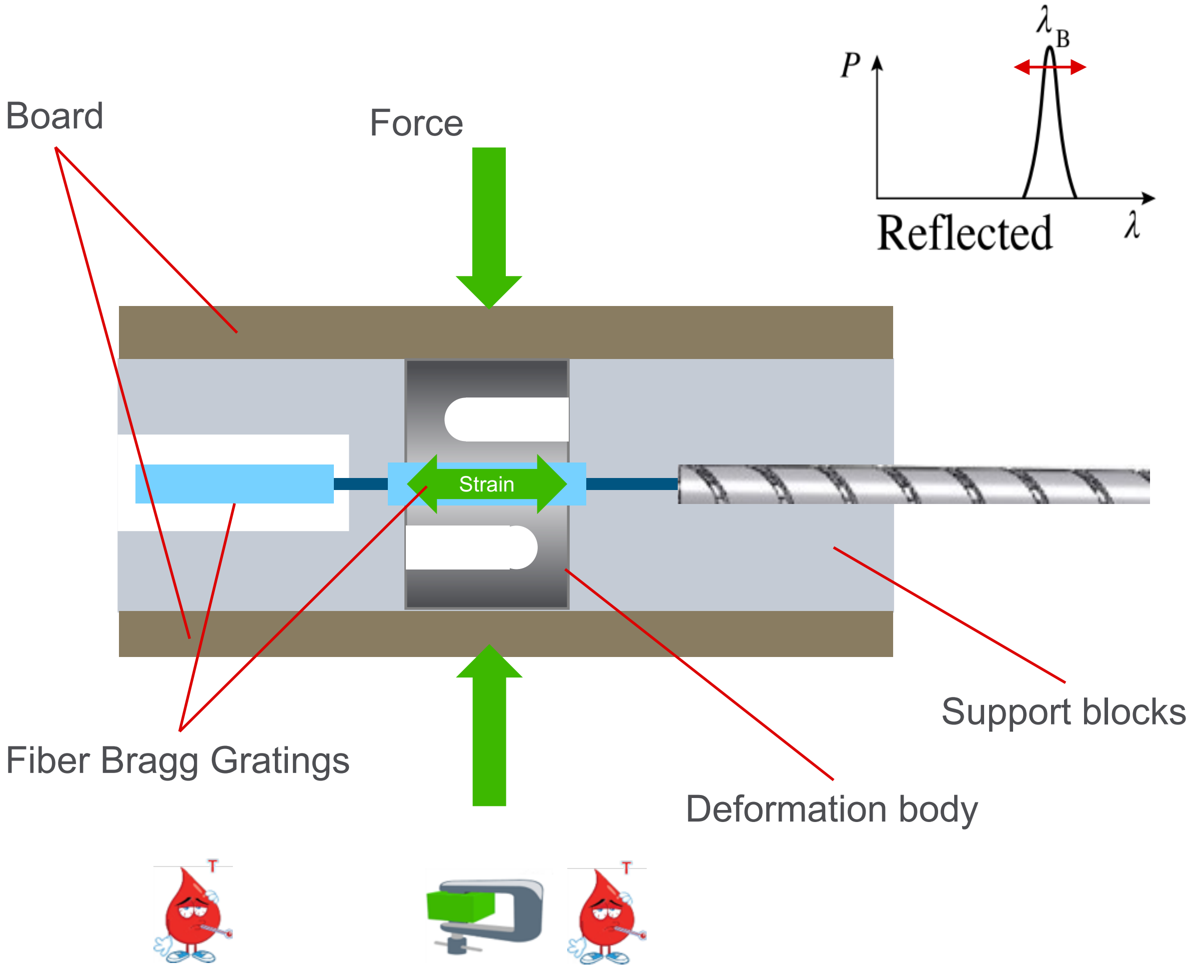
- By changing mechanical tension on fiber
  - Change of length/distance between disturbance

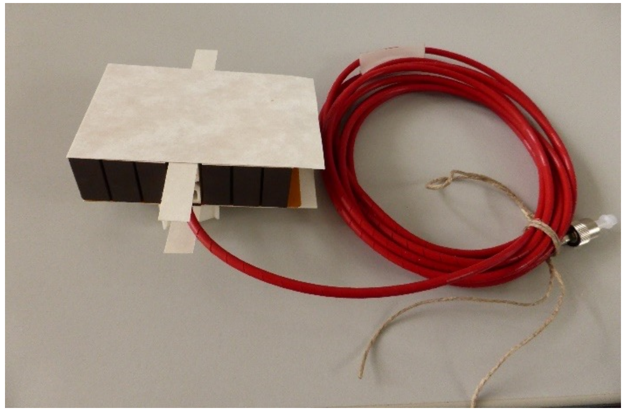
  →Change of optical signal: wavelength

Source: de.wikipedia.org/wiki/Faser-Bragg-Gitter

CLAMPING FORCE SENSOR

WORKING PRINCIPLE



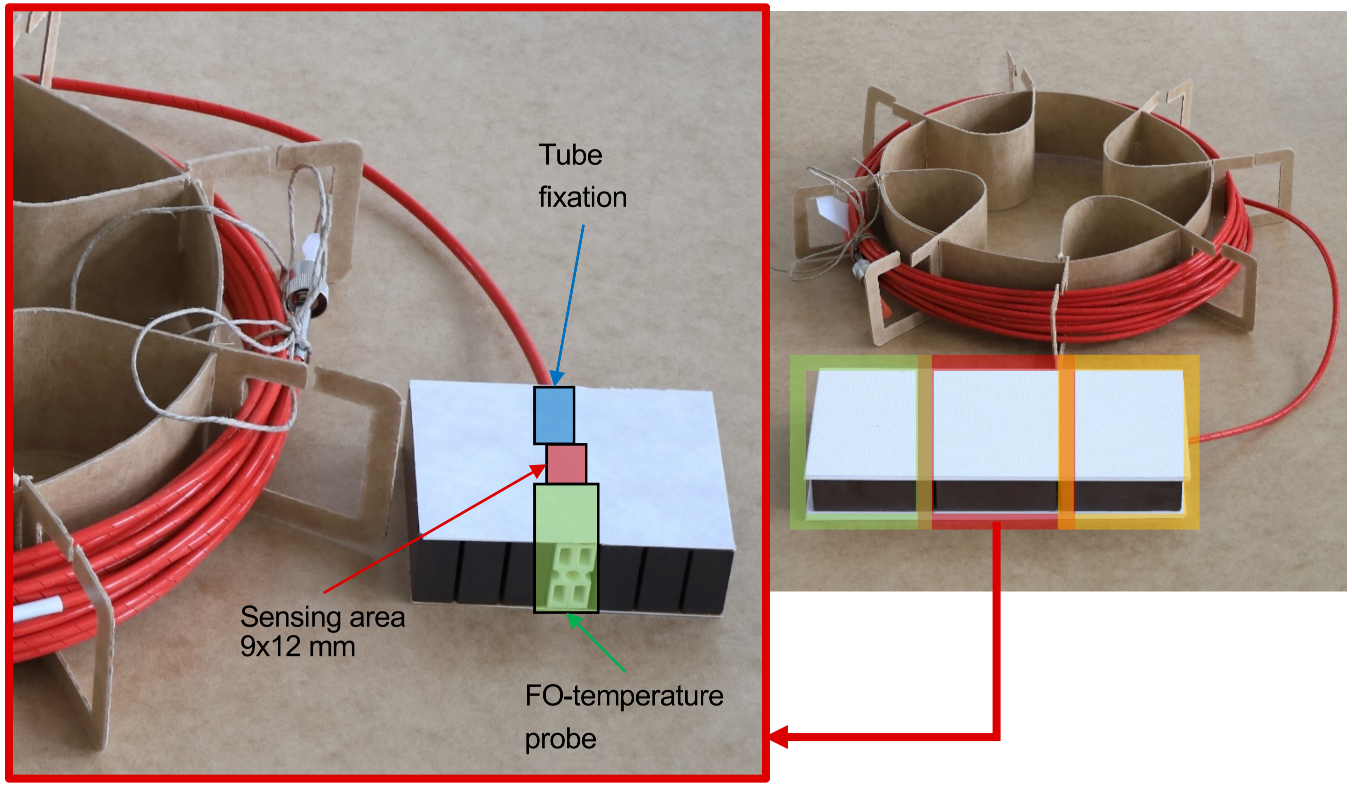


Dielectric Fiber Bragg Load Cell:

- Clamping pressure creates strain at one grating of the fiber
- Wavelength change of reflected light is proportional to the strain
- Temperature change creates thermal expansion and tension on grating
- Second grading is used for temperature measurement and compensation
- Bottom and cover plates are used to adjust the height according to the other spacers

CLAMPING FORCE SENSOR GEN 3

SENSOR FABRICATION

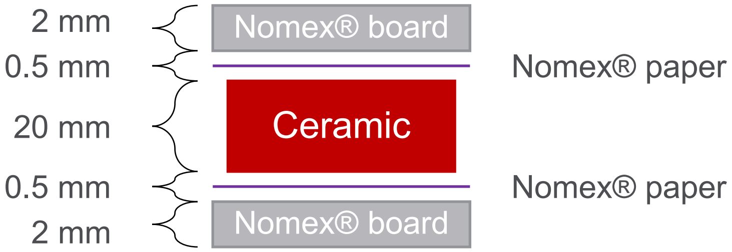


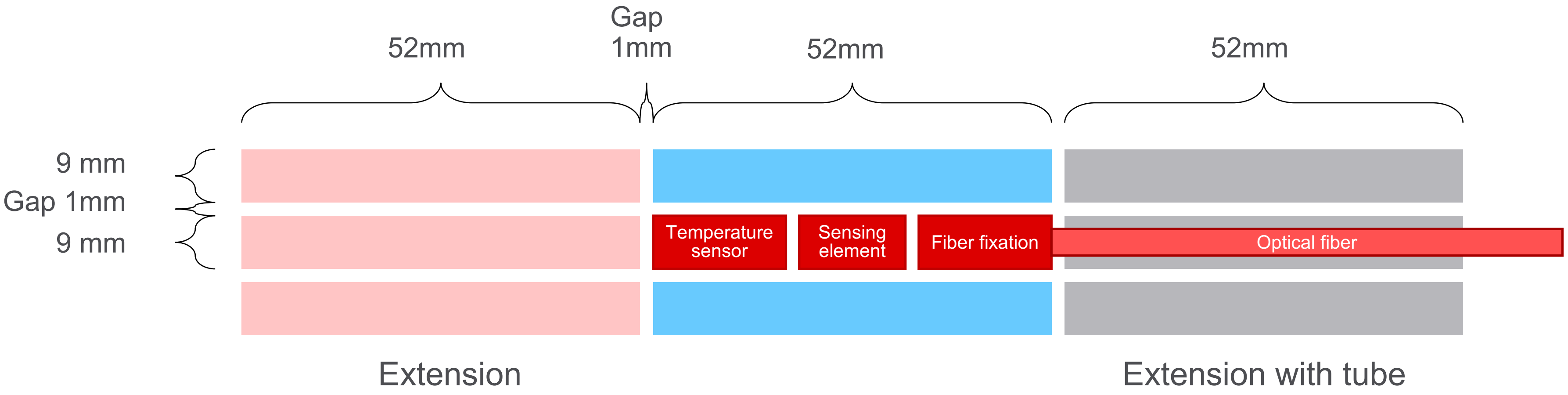
- Sensor size example $165x75\ mm$
- Sensing element in middle of sensor
- Nominal load $\leq 10\ \frac{N}{mm^2}$
- Break load $\geq 35\ \frac{N}{mm^2}$

SENSOR SPECIFICATION

SENSOR SIZE

- Minimum size 52 x 9 mm (Load and temperature sensor, tube fixation)
- Load sensing element 12x9 mm
- Width increments 10 mm (9 mm +1 mm gap)
- Length increments 53 mm (52 mm +1 mm gap)
- Height 21 mm (20 mm + 2 x 0.5 mm) recommended to use 2 x 2 mm Nomex® board as load distributor
- Nominal load $\leq 10 \frac{N}{mm^2}$
- Break load $\geq 35 \frac{N}{mm^2}$





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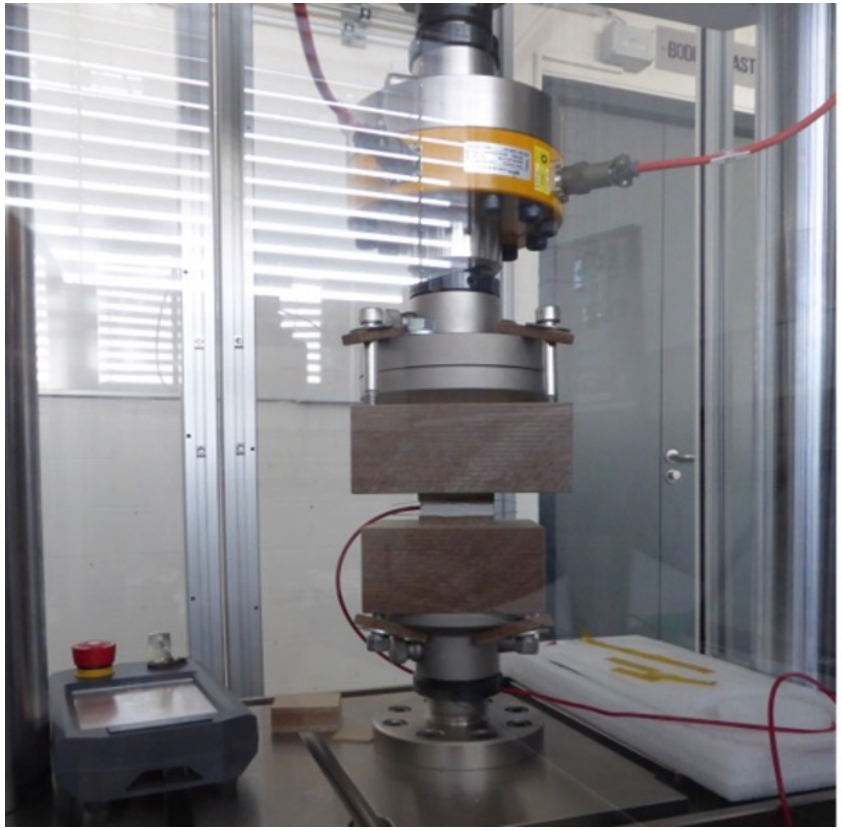
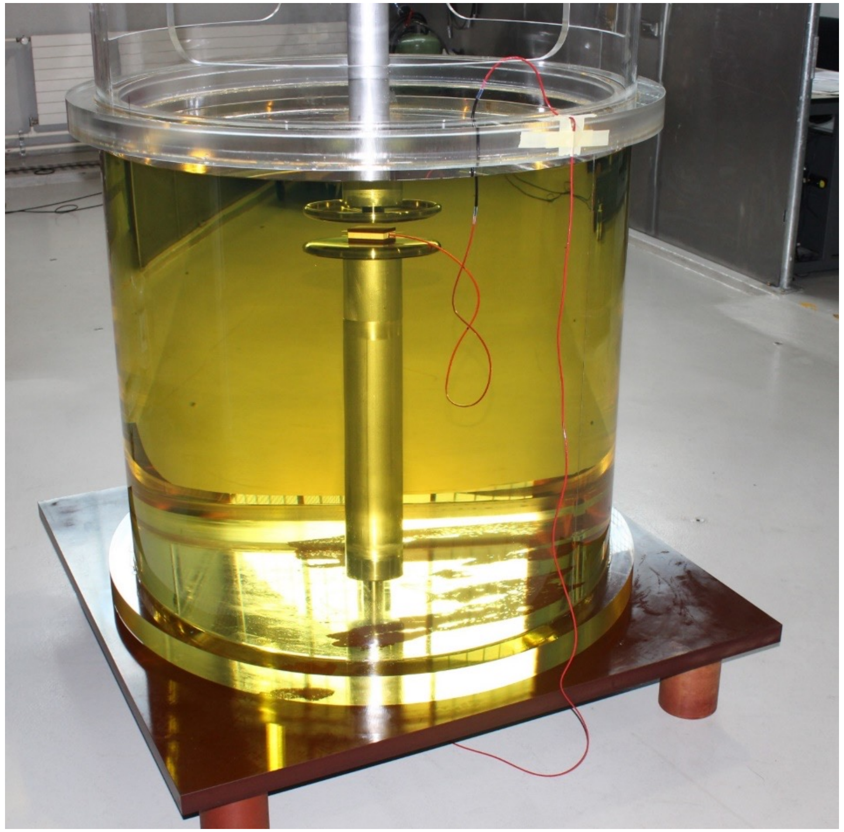
CLAMPING FORCE SENSOR
SPECIFICATION

Measuring range: 0…10 N/mm^2
Accuracy: ± 10 %
Operating Temperature: -40…140 °C

Mineral oil compatibility
Compression: <35 MPa / 5000 psi
AC field strength without PD: > 6 kV/mm





AGENDA

BETA TEST DYNALOAD PROJECT

BACKGROUND

Part of the DynaLoad research project

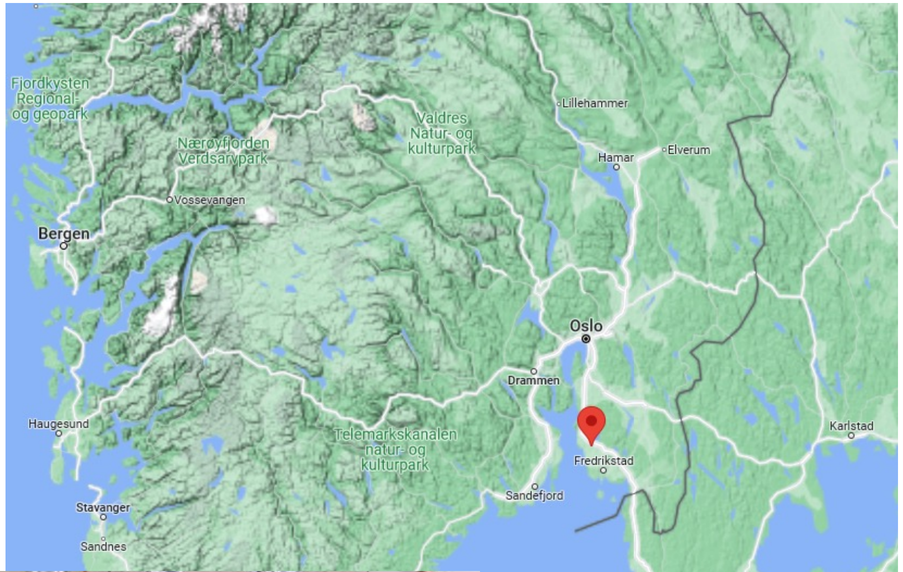
- Partners: SINTEF Energy, ELVIA, Kolektor ETRA, Weidmann, Statnett SF, Statkraft SF, EDF, SP Energy Networks, Siemens Energy

Main goal:

- “To characterize the long-term mechanical endurance of transformer insulation under heavy dynamic loading conditions”

Installation

- Substation Rade, near Oslo (NO)
- Light industry, urban, rural
- Two (2) Transformers 40 MVA (3ph), ONAN 132 kV
- Commissioned in Q4/2020
- Installation of eight (8) x F-sensors at the middle limb of one transformer
- Possibility to switch on/off the xfrm (n-1)



Source: ARWtr 2022

BETA TEST DYNALOAD PROJECT

INSTALLATION AT THE MIDDLE LIMB OF THE TRANSFORMER

Courtesy: Kolektor ETRA

BETA TEST DYNALOAD PROJECT

MONITORING OF THE CLAMPING FORCES DURING THE HEAT RUN TEST

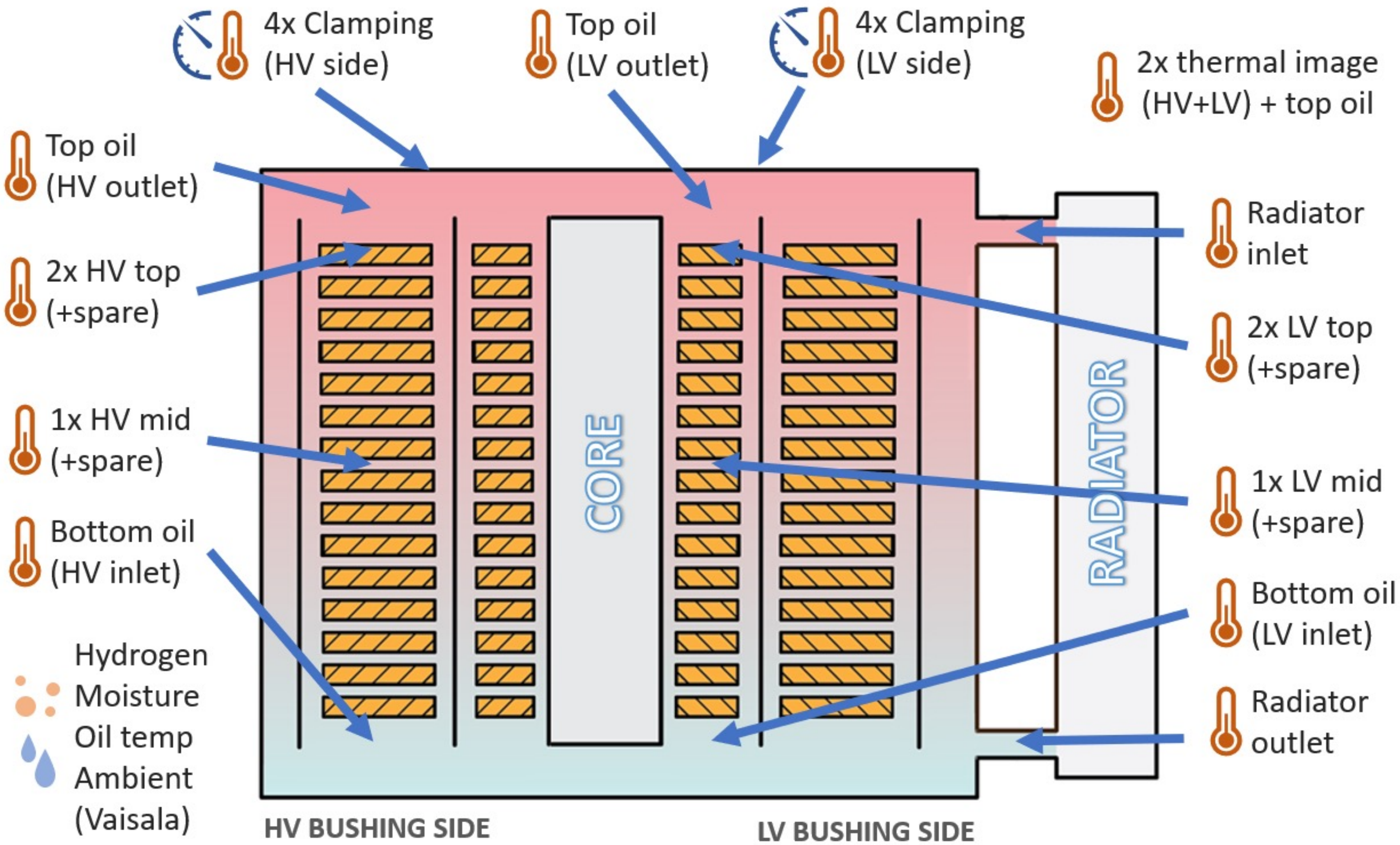
Transformer during Heat Run Test

Courtesy: Kolektor ETRA

WIA – The **W**inding **I**ntegrity **A**nalyzer

IN FIELD INSTALLATION

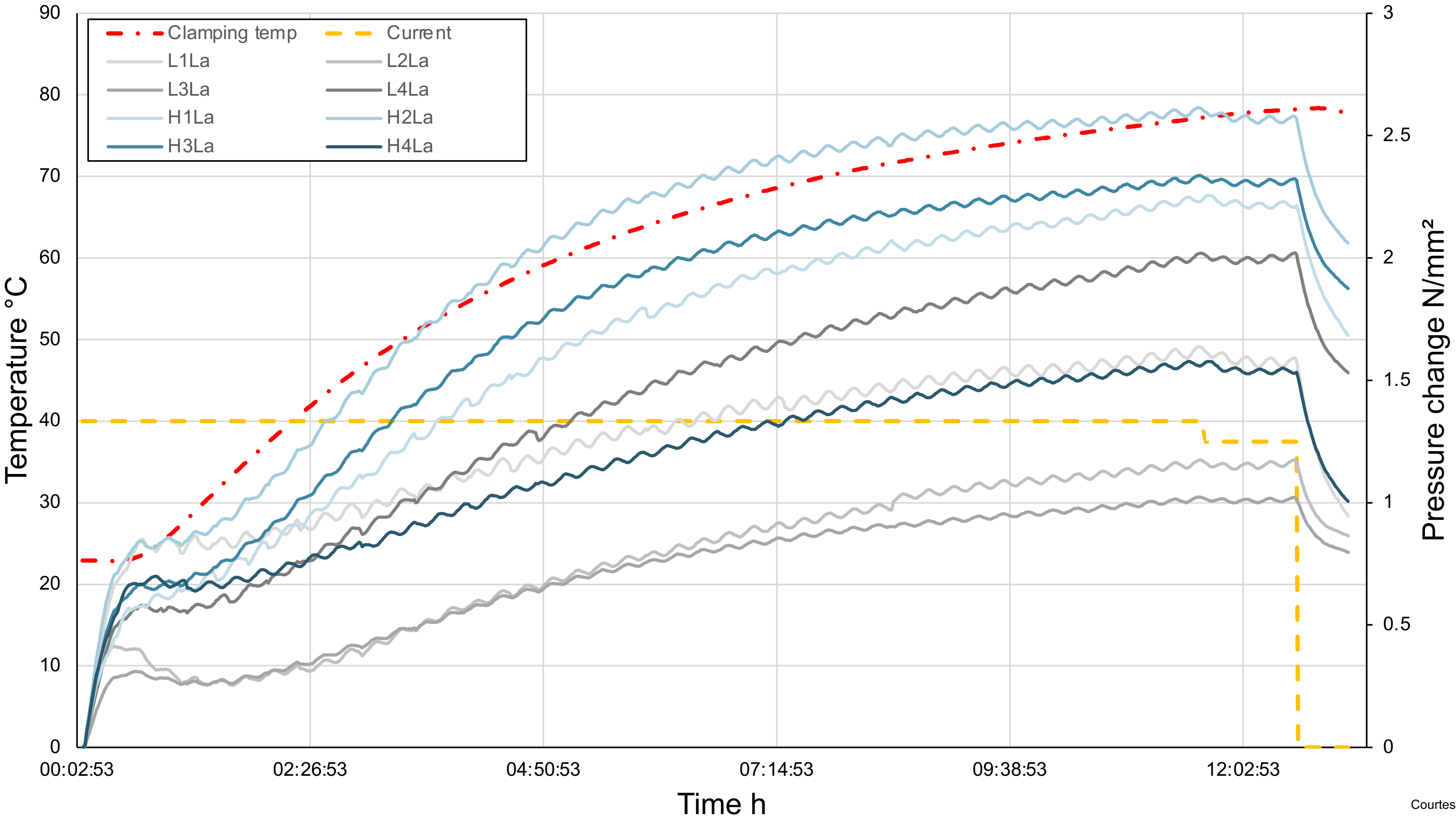
SENSORS ON TRANSFORMER



Source: ARWtr 2022

HEAT RUN TEST

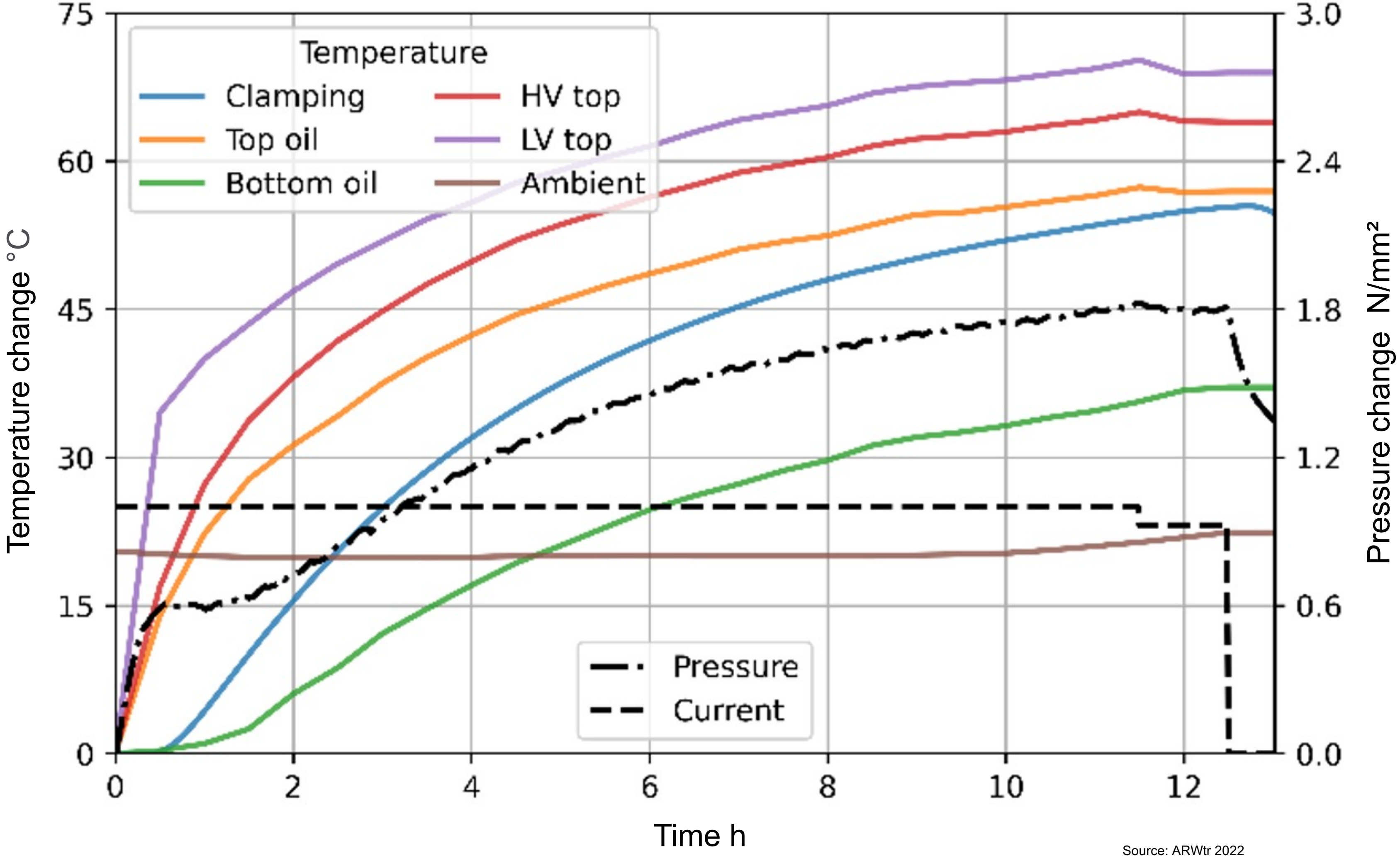
CHANGE OF CLAMPING PRESSURE DURING THE TEST



Courtesy: DynaLoad project

HEAT RUN TEST

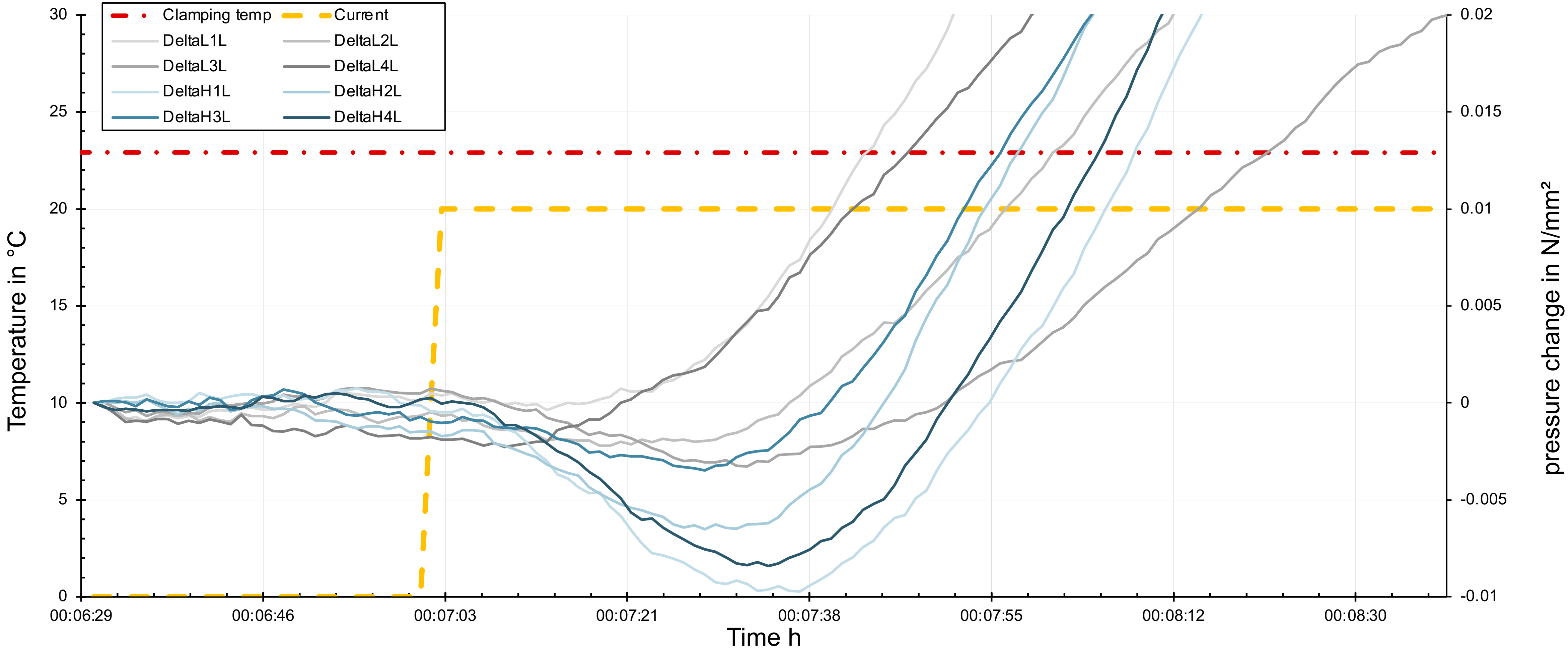
CHANGE OF CLAMPING PRESSURE DURING THE TEST - CONTINUING



Source: ARWtr 2022

HEAT RUN TEST

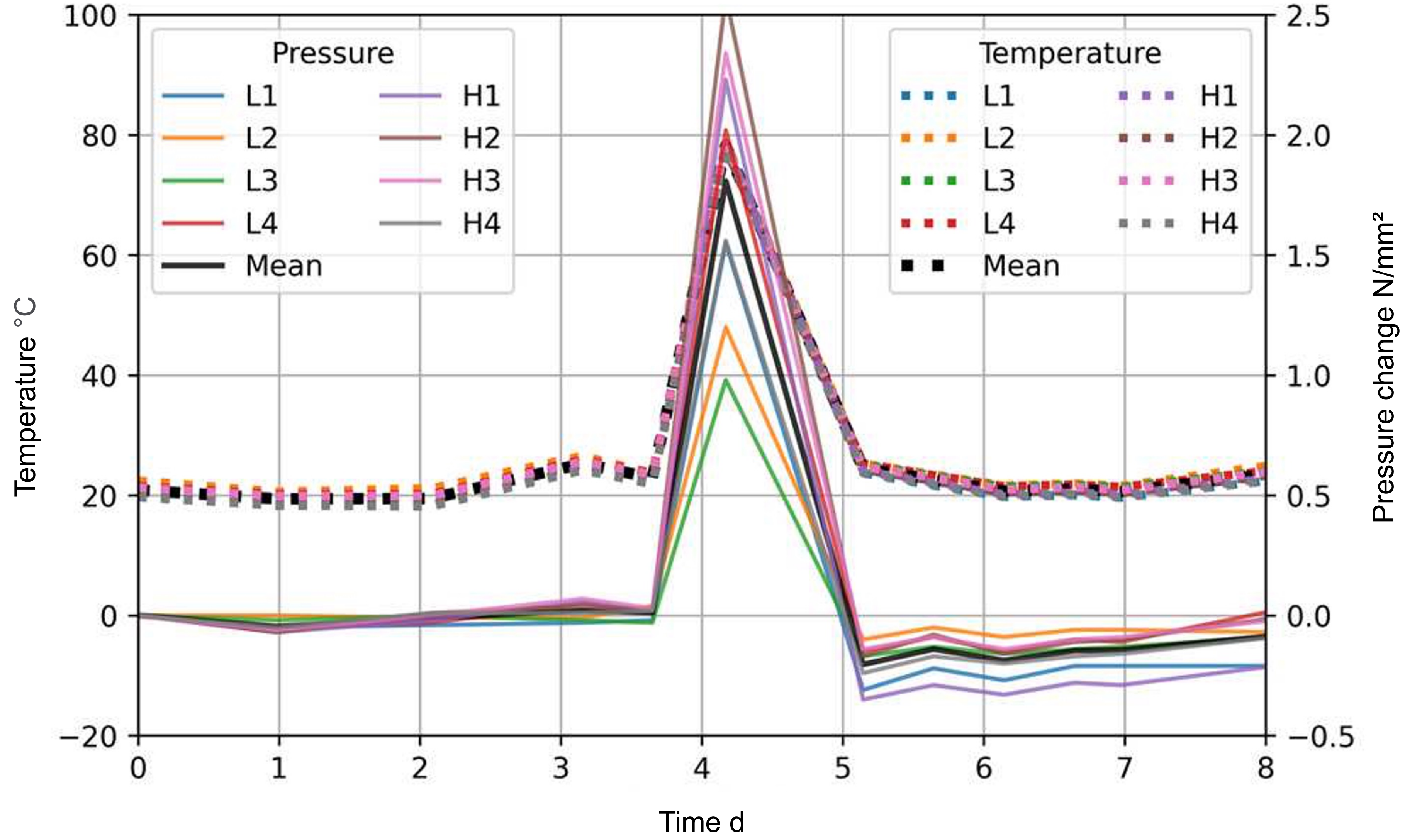
CHANGE OF CLAMPING PRESSURE, FIRST TWO (2) MIN



Courtesy: DynaLoad project

HEAT RUN TEST

CHANGE OF CLAMPING PRESSURE BEFORE, DURING AND AFTER THE TEST



Source: ARWtr 2022

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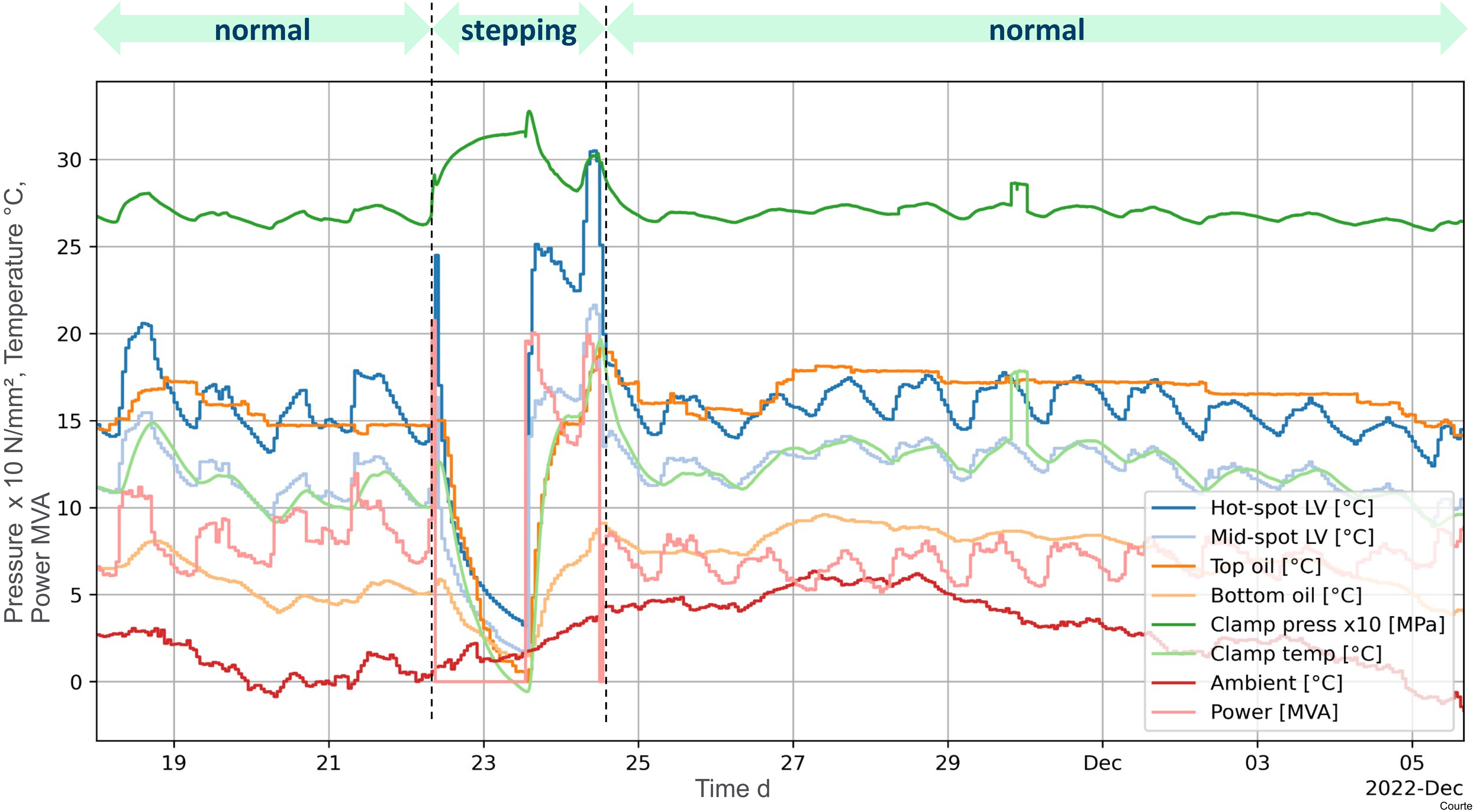
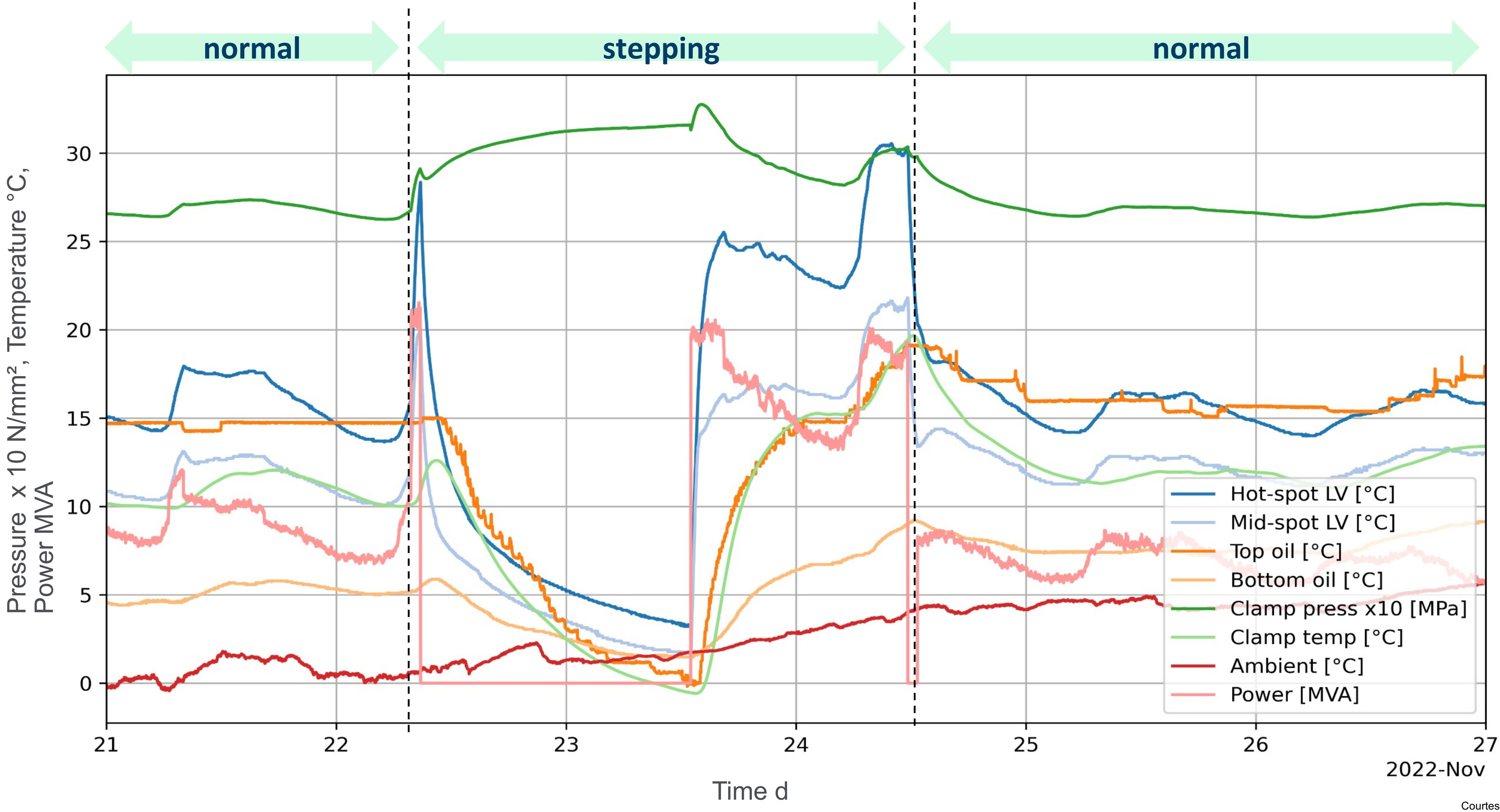
STEP TEST – OVERVIEW



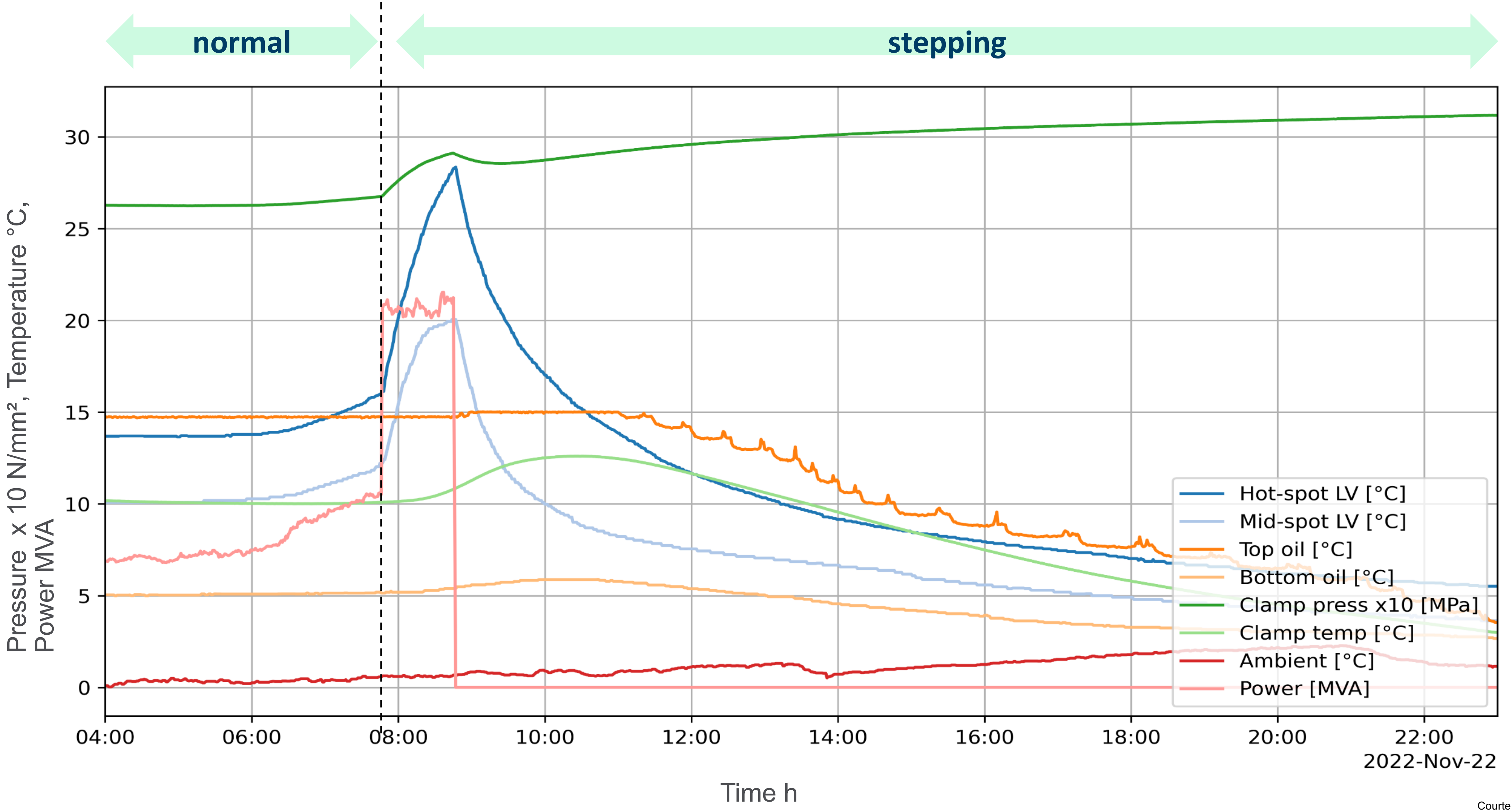
Courtesy: Dynaload 2022/23

STEP TEST – CLOSER VIEW



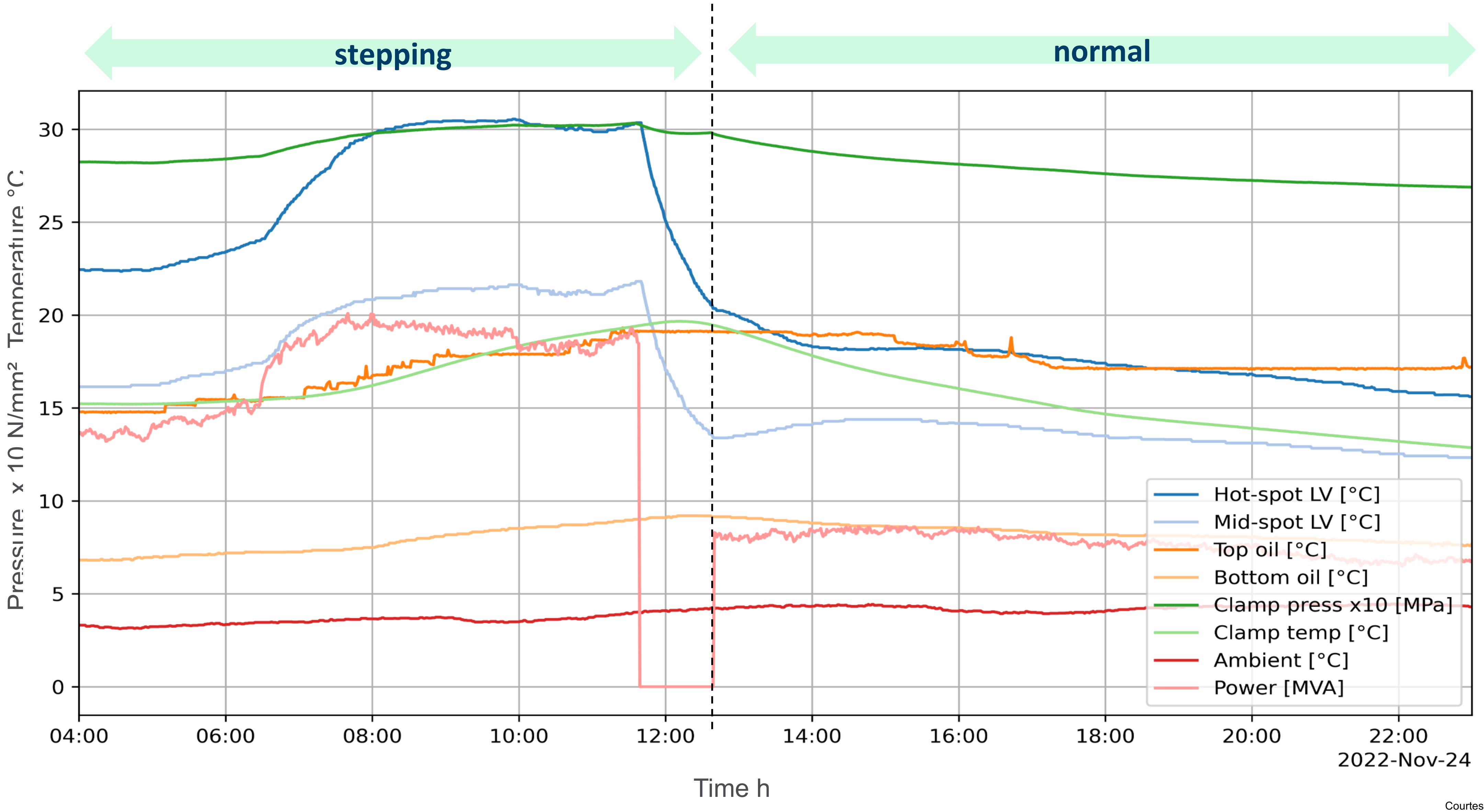
Courtesy: Dynaload 2022/23

STEP TEST – STEP UP/STEP DOWN (FIRST PERIOD)



Courtesy: Dynaload 2022/23

STEP TEST – BACK TO NORMAL OPERATION



Courtesy: Dynaload 2022/23

AGENDA

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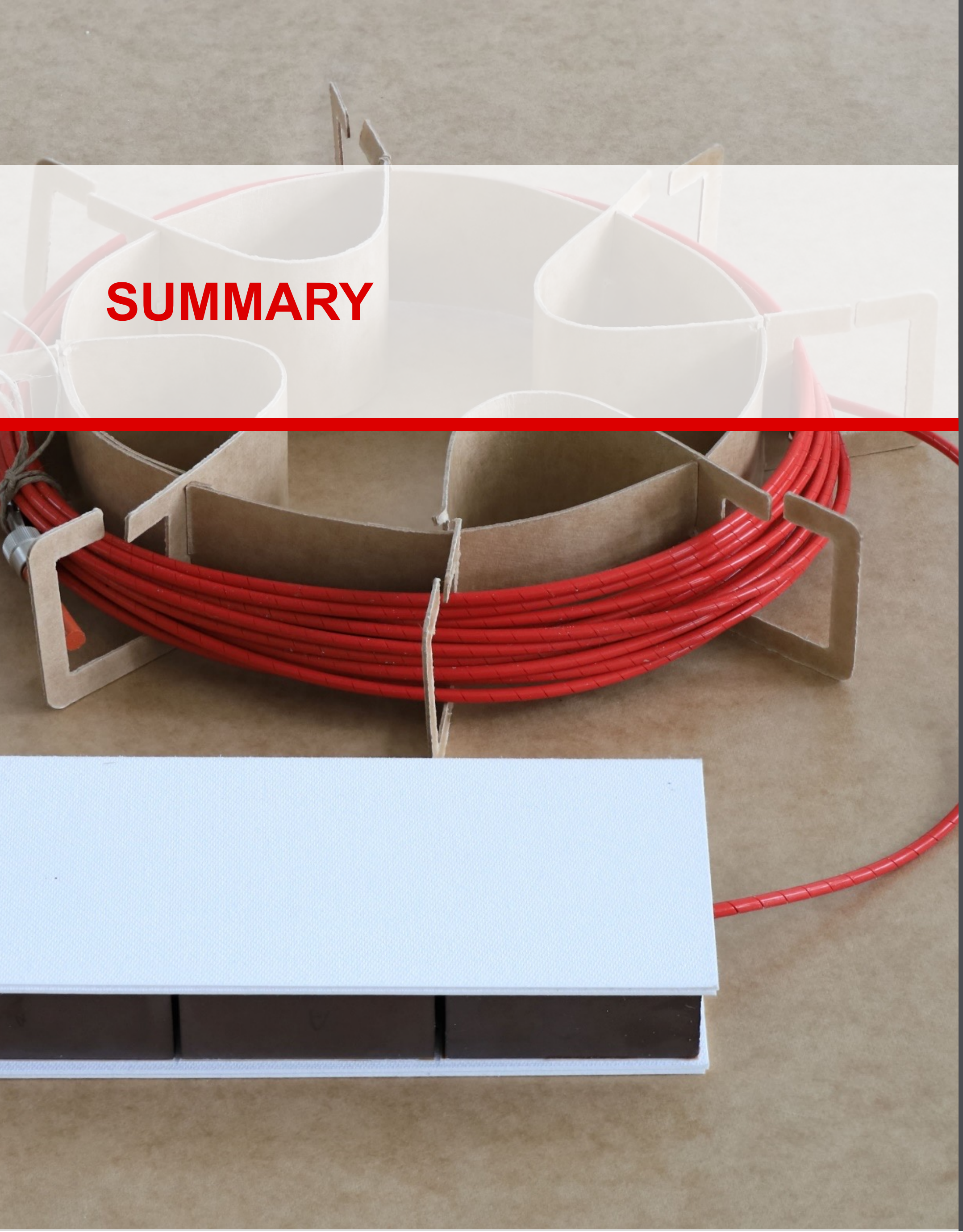


SUMMARY

Tight clamping is required for reliable operation

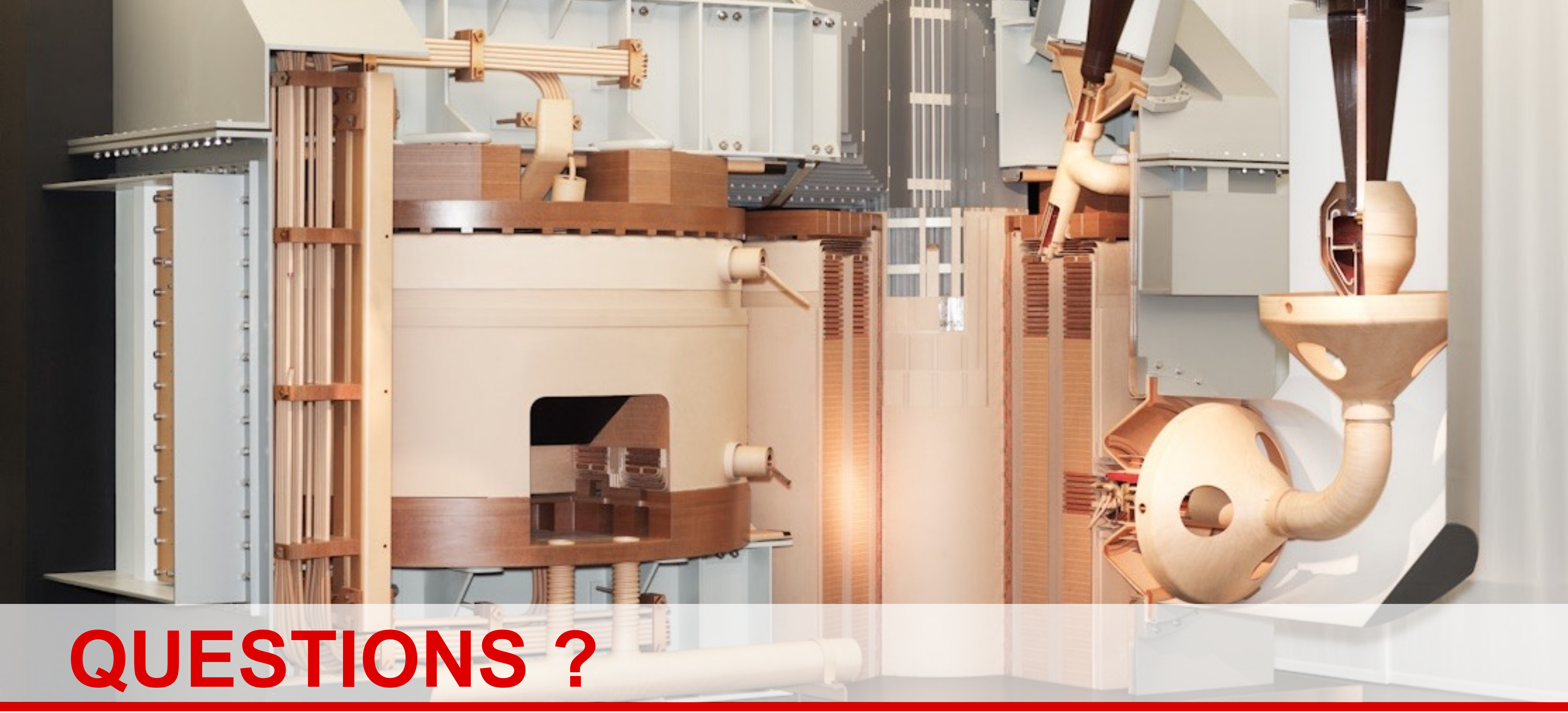
Clamping is temperature related and will change over time

Sensors for clamping measurement available

Small changes are detectable

Interpretation of the clamping force records requires expertise and experience

Monitoring of clamping force to improve transformer reliability



QUESTIONS ?

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ADDITIONAL SOURCES

- DynaLoad:
  - https://www.sintef.no/en/projects/2021/dynaload-dynamic-loading-of-transformer-insulation/
  - https://prosjektbanken.forskningsradet.no/project/FORISS/319289
- Cigre TB642
  - “Transformer reliability survey”, 2015, WG A2.37, https://e-cigre.org/publication/642-transformer-reliability-survey
- ARWtr 2022
  - Inge MADSHAVEN et al.: “On-line Direct Clamping Pressure Monitoring of Power Transformer Windings”, 7th International Advanced Research Workshop on transformers, 24-26th Oct. 2022, Baiona Spain, Paper 2.10
  - https://ieeexplore.ieee.org/document/9959909