Passive and active contact pressure measurement systems in SC magnets

TE-MSC-SMT- Felix Wolf

02/09/2021, TE-MSC seminar

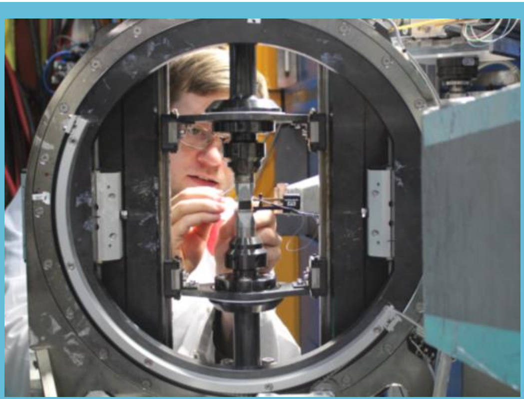
Outline

- Motivation / Introduction
- Review of existing contact pressure measure systems
- Passive measurement systems
- Active measurement systems
- Conclusion / summary and outlook

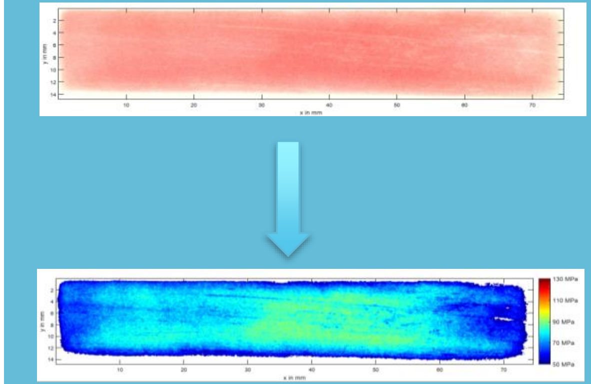
Introduction

- My work at CERN, with the following problems
  - PhD characterization of the Nb_3Sn conductor
  - Conductor limitation due to applied pressure
  - Mechanical measurement on the Rutherford cable stacks
  - Mechanical characterization of the insulation system
  - Characterization of the stress distribution

Mechanical characterization



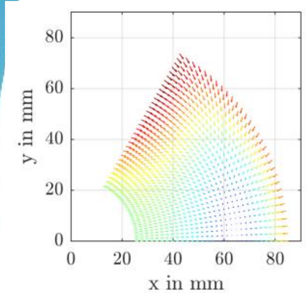
Neutron diffraction measurements



Contact stress analysis

Magnet preload

Required preload



Magnetic force distribution in a sector coil.

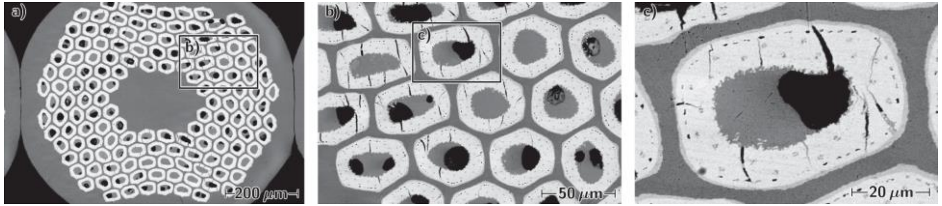
Dipole magnet	Magnetic field	Mid plane stress
LHC [3]	8.3 T	70 MPa - 75 MPa
HL-LHC 11T [4]	11 T	125 MPa - 135 MPa

- Preload to balance magnetic forces
  - Prevent conductor motion induced quenches

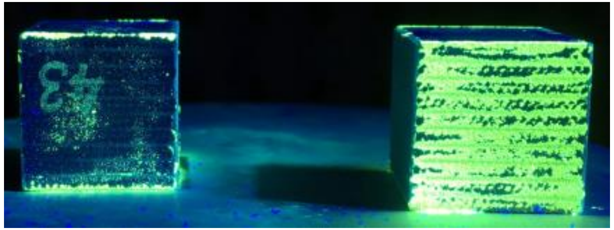
The origin of a quench may be a conductor motion under the influence of Lorentz forces resulting in a heating of the cable by frictional energy. [1]

Too high preload

- Permanent degradation of the conductor
- Cracks in the insulation system



SEM micrographs of transverse metallographic cross section of the 200 MPa loaded area of a Nb_3Sn Rutherford cable. [2]



Comparison of an virgin sample (left) and a sample after loading (right) under UV light prior application of a fluorescent penetrant.

[2] Patrick Ebermann et al 2018 Supercond. Sci. Technol. 31 065009

[1] Meß, K.H., Schmüser, P., Wolff, S.: Superconducting Accelerator Magnets, World Scientific, Singapore, 1996

[3] O. S. Brüning, P. Collier, and P. Lebrun, et al., ”LHC Design Report”, CERN Yellow Reports: Monographs, Geneva, 2004.

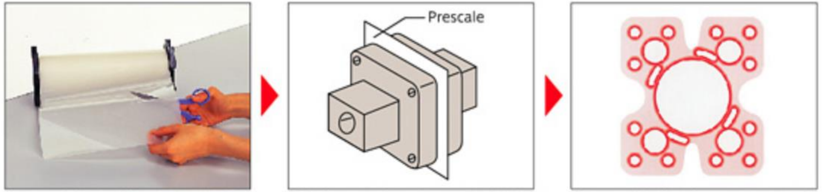
[4] M. Karppinen et al., “Design of 11T twin-aperture dipole demonstrator magnet for LHC upgrades,” IEEE Trans. App. Supercond., vol. 22, no. 3, 2012.

Commercially available systems

Passive systems

Name	Stress range	Analysis tool
Fuji Prescale [5]	**0 MPa to 300 MPa**	**Fuji Analysis**
EZ-Nip paper [7]	0 MPa to 7 MPa	Shoe Press Profile
Mold Align [7]	7 MPa to 41 MPa	Topaq Analysis System
PressureX-Micro Green [7]	0.05 MPa to 12.4 MPa	Point scan
PressureX-Micro [7]	0 MPa to 0.14 MPa	Auto-Nis
Surface Profiler Film [7]	0.1 MPa to 10 MPa	-

All systems are based on pressure sensitive films



①Cut Prescale to desired dimensions

②Insert Prescale in desired location and apply pressure

③Remove Pressure and Prescale and you can now See and check the pressure and it's distribution

[2]

Active systems

Name	Stress range	Method
TekScan [8]	**0 MPa to 200 Mpa**	**Piezo-resistive**
Tactylus [7]	0 MPa to 2.7 MPa	Piezo-resistive
Tactarry [6]	0 MPa to 5 MPa	Capacitive
Sigma-Nip [7]	0.3 MPa to 70 MPa	Thin-film resistor
CERN capacitive gauges	**0 MPa to 160 MPa**	**Capacitive**

[7]

[6]

[7]

[5] FUJIFILM Prescale Instruction Manual

[6] PPS [Online]. https://pressureprofile.com/ [Accessed 2021].

[7] Sensor Products, Inc., [Online]. Available: http://www.sensorprod.com/ [Accessed 2021].

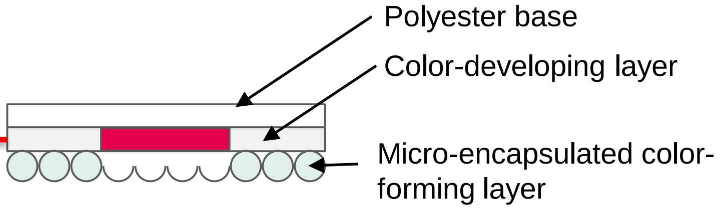
[8] Tekscan, Inc., I-Scan® Product Selection Guide, [Online]. Available: https://www.tekscan.com [Accessed 2021].

Passive system

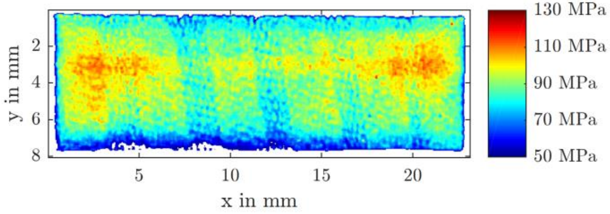
FUJI prescale film

FUJI prescale film – how it works

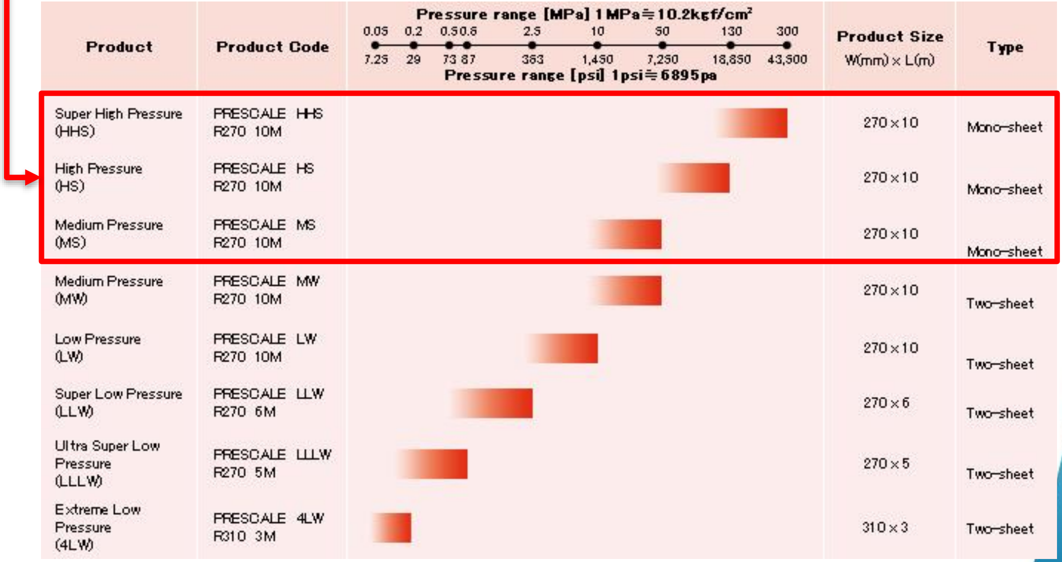
- Mono-sheet
  - MS 10 – 50 MPa
  - HS 50 – 130 MPa
  - HHS 130 – 300 MPa
- Thickness: 100 ± 5 µm
- Spatial resolution: 0.05 mm
- Micro capsules (ø 4 to 15 µm) with different wall thickness per film Type
- Size: 270mm x 10m



Layout of a Mono-sheet Prescale Film. [5]



Analysed Prescale film similar to ANSYS stress plot .



Product	Product Code	Pressure range [MPa] 1 MPa≒10.2kgf/cm² 0.05, 0.2, 0.5, 0.6, 2.5, 10, 50, 130, 300 7.25, 29, 73, 87, 363, 1,450, 7,250, 18,850, 43,500 Pressure range [psi] 1psi≒6895pa	Product Size W(mm) × L(m)	Type
Super High Pressure (HHS)	PRESCALE HHS R270 10M		270×10	Mono-sheet
High Pressure (HS)	PRESCALE HS R270 10M		270×10	Mono-sheet
Medium Pressure (MS)	PRESCALE MS R270 10M		270×10	Mono-sheet
Medium Pressure (MW)	PRESCALE MW R270 10M		270×10	Two-sheet
Low Pressure (LW)	PRESCALE LW R270 10M		270×10	Two-sheet
Super Low Pressure (LLW)	PRESCALE LLW R270 6M		270×6	Two-sheet
Ultra Super Low Pressure (LLLW)	PRESCALE LLLW R270 5M		270×5	Two-sheet
Extreme Low Pressure (4LW)	PRESCALE 4LW R310 3M		310×3	Two-sheet

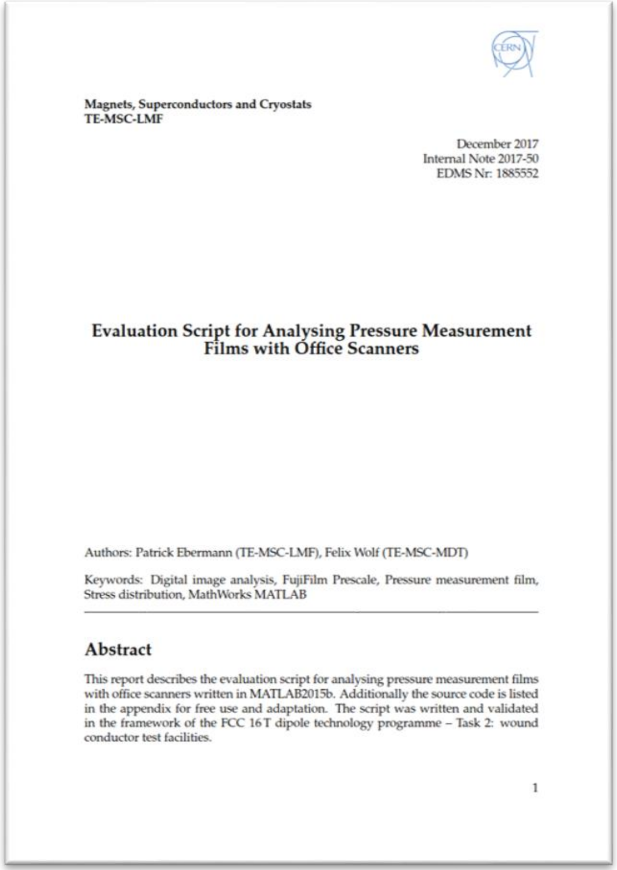
Overview of available Prescale film types. [5]

[5] FUJIFILM Prescale Instruction Manual

FUJI prescale film – analysis EDMS 1885552 /1

- Documentation of the developed code
- Mathematical explanation of the used functions
- Explanation of the generated output parameter
- Validation of the measurements
- Source code

https://edms.cern.ch/document/1885552/1



Magnets, Superconductors and Cryostats
TE-MSC-LMF

December 2017
Internal Note 2017-50
EDMS Nr: 1885552

Evaluation Script for Analysing Pressure Measurement Films with Office Scanners

Authors: Patrick Ebermann (TE-MSC-LMF), Felix Wolf (TE-MSC-MDT)

Keywords: Digital image analysis, FujiFilm Prescale, Pressure measurement film, Stress distribution, MathWorks MATLAB

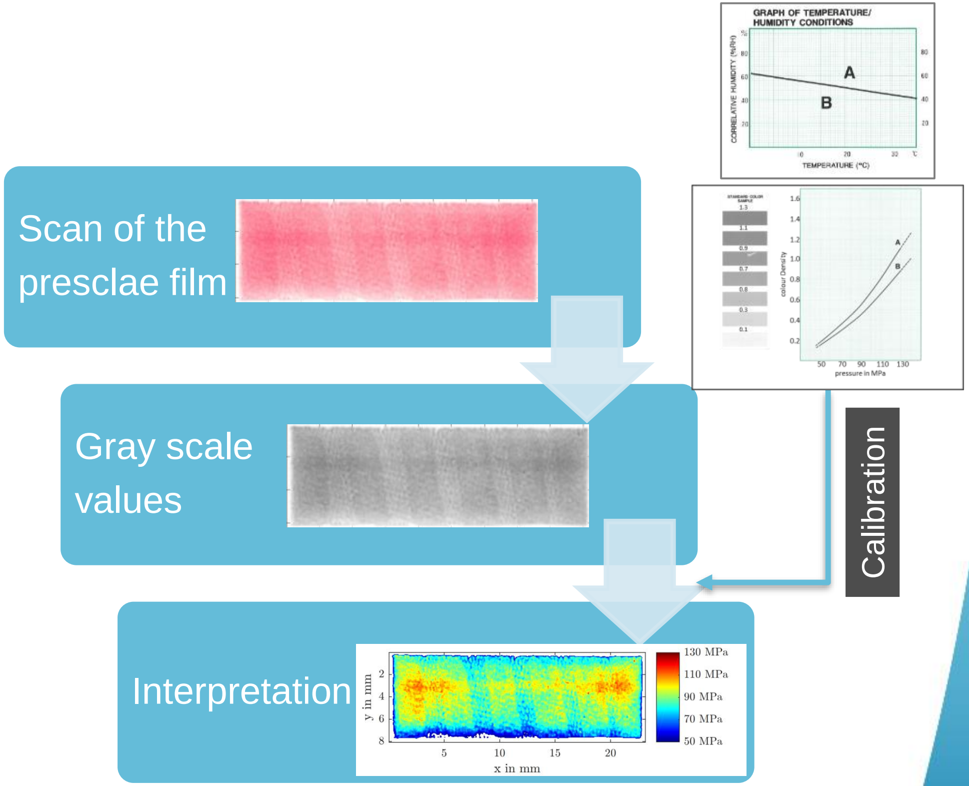
Abstract

This report describes the evaluation script for analysing pressure measurement films with office scanners written in MATLAB2015b. Additionally the source code is listed in the appendix for free use and adaptation. The script was written and validated in the framework of the FCC 16 T dipole technology programme – Task 2: wound conductor test facilities.

1

FUJI prescale film – analysis EDMS 1885552 /2

- Scan and crop the colorized presclae film
- Calibrate the script according to the used scanner
- Select a transfer function according temperature and humidity during the test
- Execute the analysis script
  - Convert color values into gray scale values
  - Transfer the gray scale values into stress values via an implemented transfer function



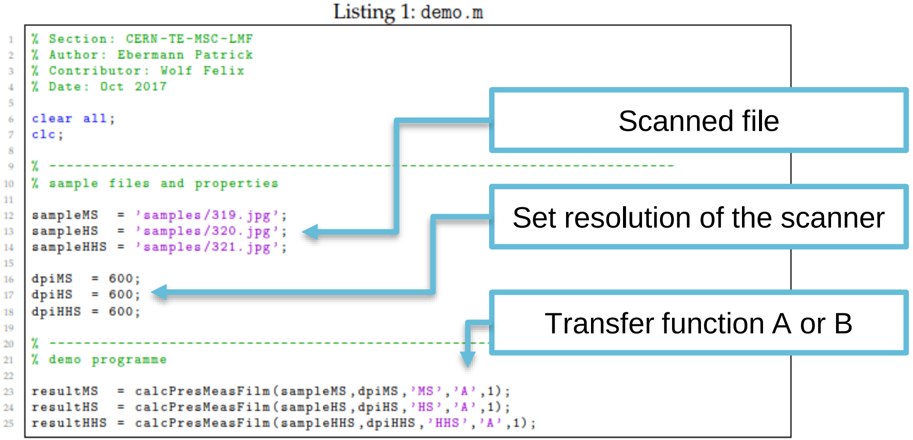
Scan of the presclae film

Gray scale values

Interpretation

Calibration

FUJI prescale film – analysis EDMS 1885552 /3



Listing 1: demo.m

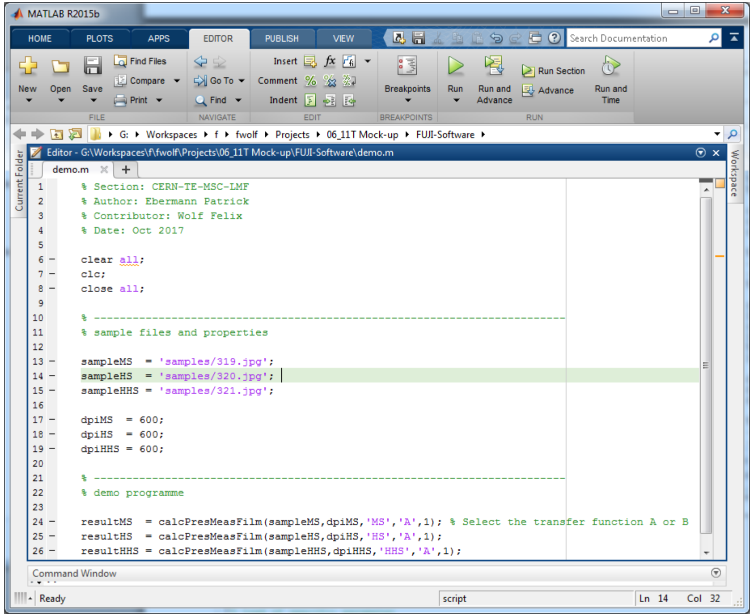
```
% Section: CERN-TE-MSC-LMF
% Author: Ebermann Patrick
% Contributor: Wolf Felix
% Date: Oct 2017

clear all;
clc;

% ---------------------------------------------------------------------
% sample files and properties

sampleMS  = 'samples/319.jpg';
sampleHS  = 'samples/320.jpg';
sampleHHS = 'samples/321.jpg';

dpiMS  = 600;
dpiHS  = 600;
dpiHHS = 600;

% ---------------------------------------------------------------------
% demo programme

resultMS  = calcPresMeasFilm(sampleMS,dpiMS,'MS','A',1);
resultHS  = calcPresMeasFilm(sampleHS,dpiHS,'HS','A',1);
resultHHS = calcPresMeasFilm(sampleHHS,dpiHHS,'HHS','A',1);
```

Scanned file

Set resolution of the scanner

Transfer function A or B

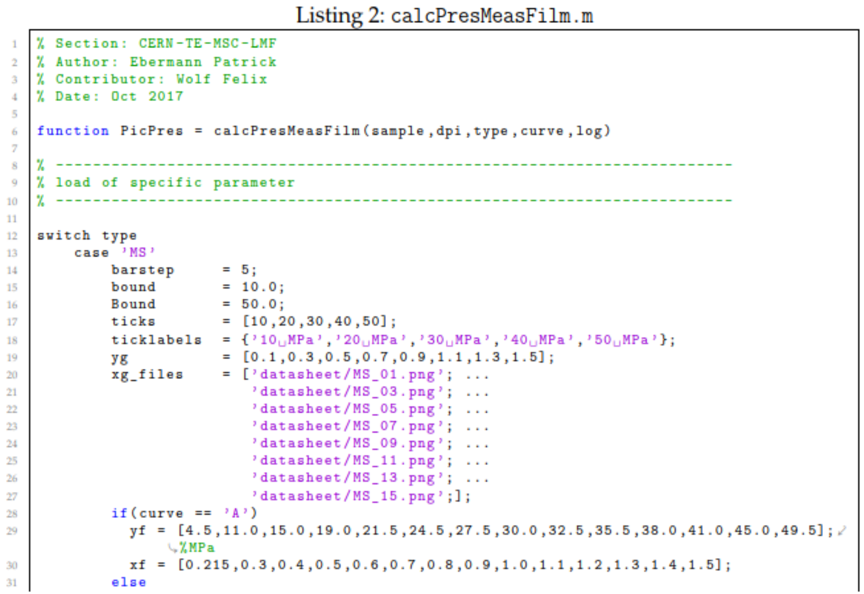
Code for data input as documented in the technical node.



```
% Section: CERN-TE-MSC-LMF
% Author: Ebermann Patrick
% Contributor: Wolf Felix
% Date: Oct 2017

clear all;
clc;
close all;

% ---------------------------------------------------------------------
% sample files and properties

sampleMS  = 'samples/319.jpg';
sampleHS  = 'samples/320.jpg';
sampleHHS = 'samples/321.jpg';

dpiMS  = 600;
dpiHS  = 600;
dpiHHS = 600;

% ---------------------------------------------------------------------
% demo programme

resultMS  = calcPresMeasFilm(sampleMS,dpiMS,'MS','A',1); % Select the transfer function A or B
resultHS  = calcPresMeasFilm(sampleHS,dpiHS,'HS','A',1);
resultHHS = calcPresMeasFilm(sampleHHS,dpiHHS,'HHS','A',1);
```

Code for data input in the MATLAB environment.

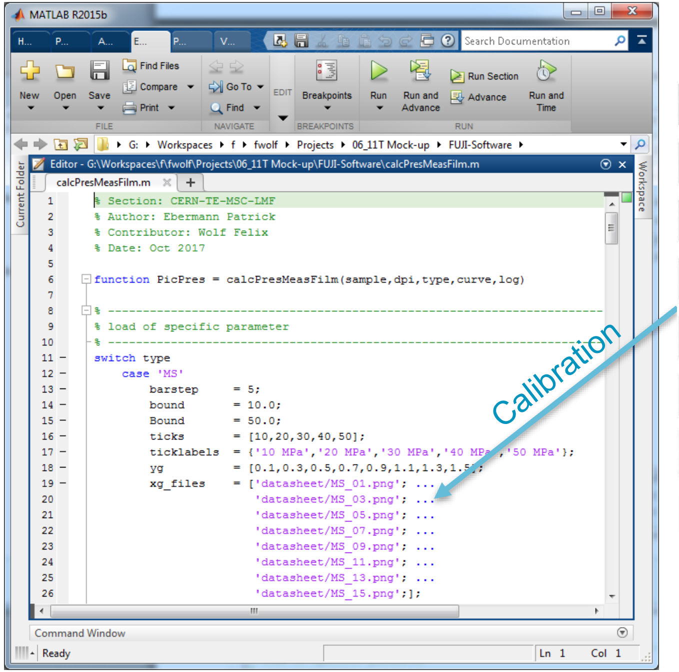
FUJI prescale film – analysis EDMS 1885552 /4



Listing 2: calcPresMeasFilm.m

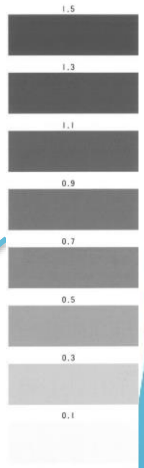
```
% Section: CERN-TE-MSC-LMF
% Author: Ebermann Patrick
% Contributor: Wolf Felix
% Date: Oct 2017

function PicPres = calcPresMeasFilm(sample,dpi,type,curve,log)

% -------------------------------------------------------------------
% load of specific parameter
% -------------------------------------------------------------------

switch type
    case 'MS'
        barstep     = 5;
        bound       = 10.0;
        Bound       = 50.0;
        ticks       = [10,20,30,40,50];
        ticklabels  = {'10␣MPa','20␣MPa','30␣MPa','40␣MPa','50␣MPa'};
        yg          = [0.1,0.3,0.5,0.7,0.9,1.1,1.3,1.5];
        xg_files    = ['datasheet/MS_01.png'; ...
                       'datasheet/MS_03.png'; ...
                       'datasheet/MS_05.png'; ...
                       'datasheet/MS_07.png'; ...
                       'datasheet/MS_09.png'; ...
                       'datasheet/MS_11.png'; ...
                       'datasheet/MS_13.png'; ...
                       'datasheet/MS_15.png';];
        if(curve == 'A')
          yf = [4.5,11.0,15.0,19.0,21.5,24.5,27.5,30.0,32.5,35.5,38.0,41.0,45.0,49.5];
              ↪%MPa
          xf = [0.215,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1.0,1.1,1.2,1.3,1.4,1.5];
        else
```

Code for analysis as documented in the technical node.



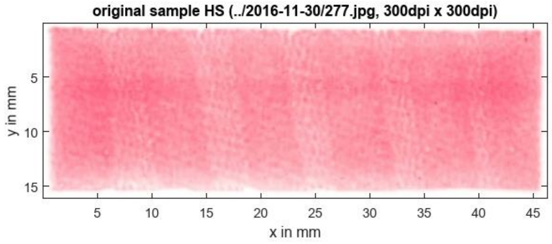
```
% Section: CERN-TE-MSC-LMF
% Author: Ebermann Patrick
% Contributor: Wolf Felix
% Date: Oct 2017

function PicPres = calcPresMeasFilm(sample,dpi,type,curve,log)

% -----------------------------------------------------------------------
% load of specific parameter
% -----------------------------------------------------------------------
switch type
    case 'MS'
        barstep     = 5;
        bound       = 10.0;
        Bound       = 50.0;
        ticks       = [10,20,30,40,50];
        ticklabels  = {'10 MPa','20 MPa','30 MPa','40 MPa','50 MPa'};
        yg          = [0.1,0.3,0.5,0.7,0.9,1.1,1.3,1.5];
        xg_files    = ['datasheet/MS_01.png'; ...
                       'datasheet/MS_03.png'; ...
                       'datasheet/MS_05.png'; ...
                       'datasheet/MS_07.png'; ...
                       'datasheet/MS_09.png'; ...
                       'datasheet/MS_11.png'; ...
                       'datasheet/MS_13.png'; ...
                       'datasheet/MS_15.png';];
```

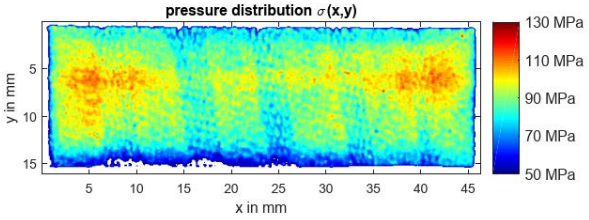
Calibration

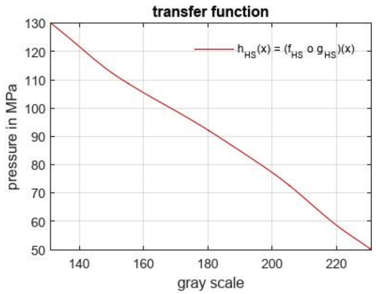


Code for analysis in the MATLAB environment.

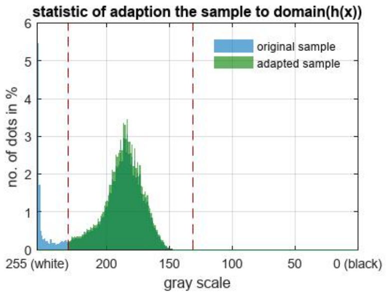
FUJI prescale film – analysis EDMS 1885552 /5





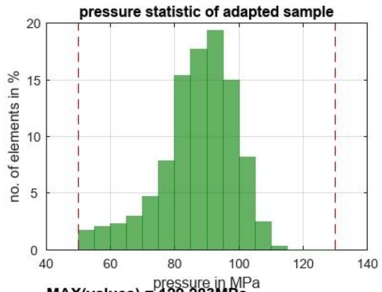


HS Pressure Sensitive Film
CODOMAIN(h_{HS}(x)): [50.00MPa,130.00MPa]
DOMAIN(h_{HS}(x)): [131.23,230.82]



ORIGINAL grayscales: [127,255]
NO. ELEM. = 103740

ADAPTED grayscales: [132,230]
NO. used ELEM. = 91435 (88.14%)
too DARK = 1 (0.00%)
too BRIGHT = 12304 (11.86%)
nearly WHITE = 1232 (1.19%)



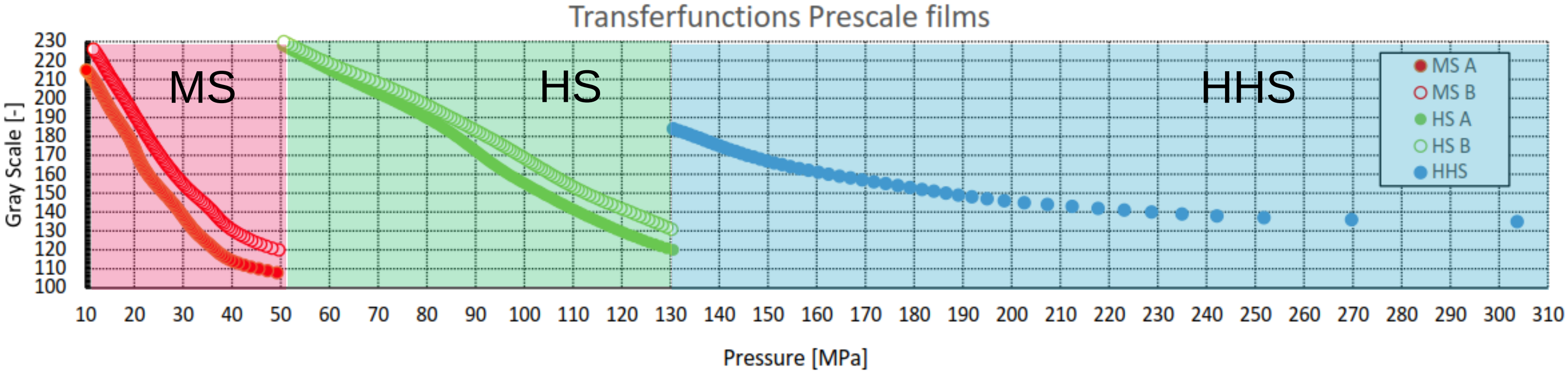
MAX(values) = 129.283MPa
MIN(values) = 50.681MPa
MEAN(values) = 87.104MPa
StdD(values) = 11.621MPa

A_{SCAN} = 743.65443mm^2 … Total scanned area
$A_{RESOLUTION}$ = 0.00717mm^2 … Resolution of the scanner
A_{DOMAIN} = 655.44672mm^2 (88.14%) .. . Area in the pressure domain
A_{DARK} = 0.00717mm^2 … Area above the pressure domain
A_{BRIGHT} = 88.20054mm^2 … Area below the pressure domain
F(A_{DOMAIN}) = 57.09230kN … Total integrated force
$F_{approx.}$(A_{SCAN}-A_{WHITE}) = 58.21206kN

Note:
Stress values below or above the stress domain are interpretated equal 0MPa.

FUJI prescale film – limitation

- Stress resolution depends on the gray scale step size (8-bit)
- Analysed gray scale values between 110-230 (120 Steps)
- Stress range can be extended by stacking different types of prescale film



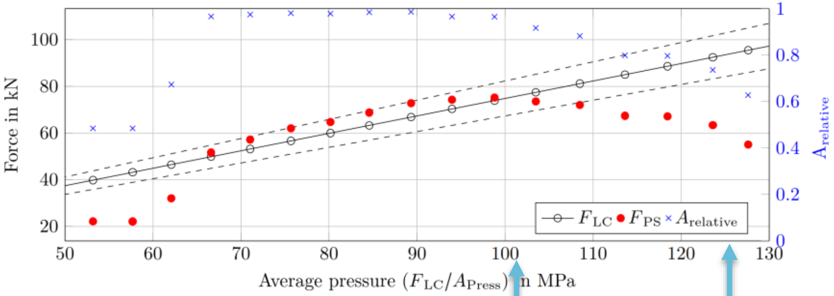
Discrete transfer between gray scale values and stress values.

FUJI prescale film – limitation stress range

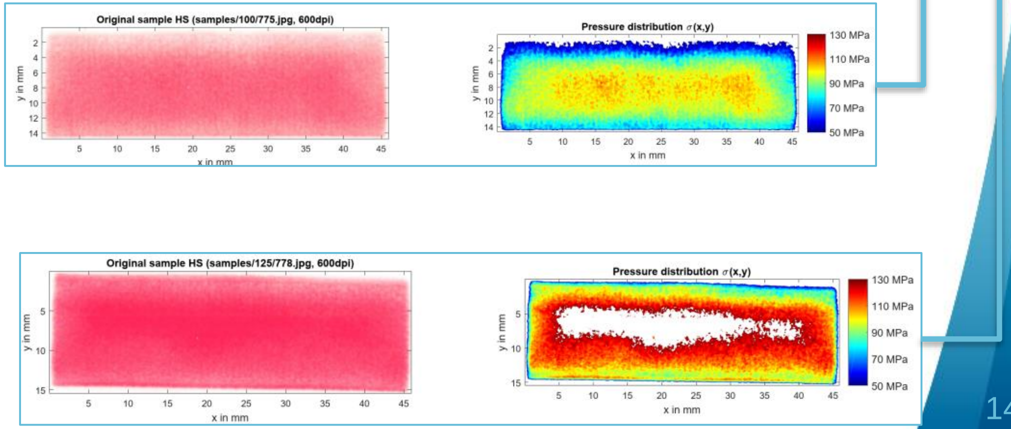
- Good agreement between integrated force and load cell
- Pressed area should be known
- A_{relative} should be close to 1

$$A_{\text{relative}} = \frac{A_{\text{Stress domain}}}{A_{\text{pressed}}}$$

- Saturated values can be also interpreted as σ_{MAX}

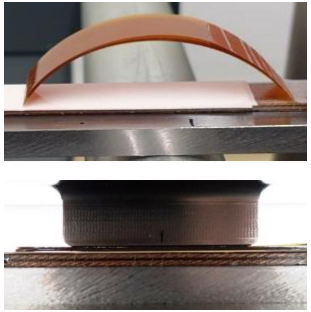


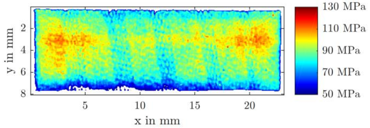
Integrated force to applied average pressure (determined by load cell).



Examples of application

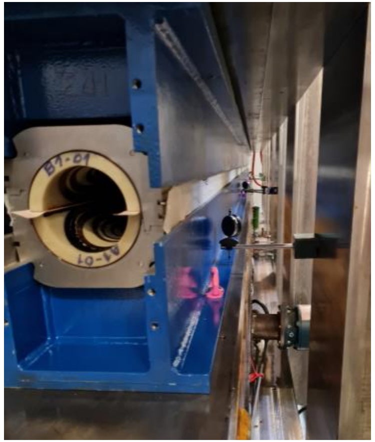
Cable test

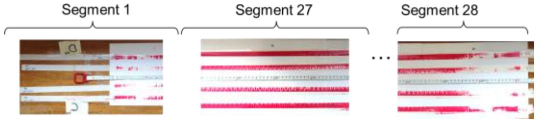


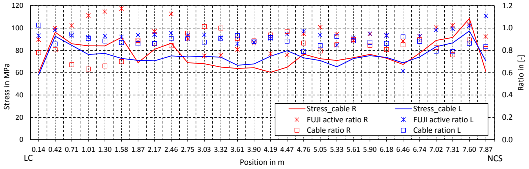


F. Wolf *et al*., "Characterization of the Stress Distribution on Nb3Sn Rutherford Cables Under Transverse Compression," in *IEEE Transactions on Applied Superconductivity*, 2018.

Magnet assembly

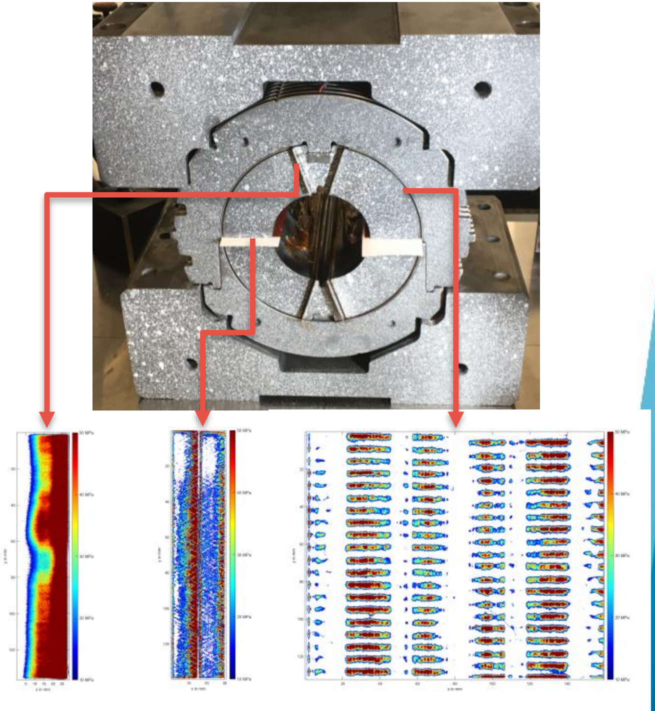






F. Wolf, FUJI Analysis D2 Prototype, CERN, EDMS 2471988

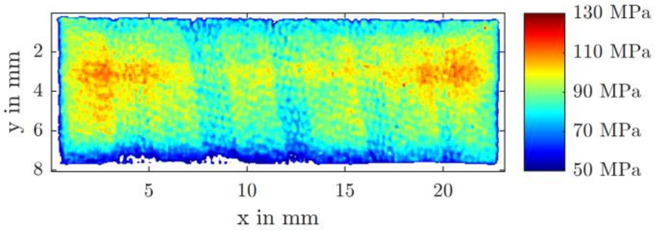
Mockup studies



https://espace.cern.ch/mockuptest2020

FUJI prescale film

- Requires disassembly to access the pressure sensitive film
- Only peak stresses can be determined
- Measurement range can be extended by combination of different types



Active system

Tekscan^{TM} I-Scan system

Tekscan^{TM} I-Scan system

Experience at CERN

- Used by Paolo Fessia in 2000 for the manufacturing control of LHC dipole magnets in the coil ends.
- A special sensor foil was produced for CERN in 2000
- Used in the 11T collaring mockup study in 2018 by Paolo Ferracin

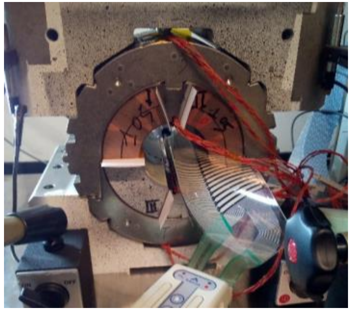
Development:

- High pressure sensor foils with an upper limit about 200 MPa due elastic limits of the foil.
- Low pressure sensor foils to measure the air flow on a surface.
- Only system at the commercial market which allow an online readout of a contact pressure in a range up to 200 MPa.

Company:

- Small company in Boston with 100 employee
- https://www.tekscan.com/

Coil end press and sensor foil with readout system. [9]



Collaring mockup 2018. [10]

[9] Coil ends measuring procedure, CERN, 2002, provided by Paolo Fessia

[10] Collaring kinematics, mechanics, instrumentation, and mock-ups, EDMS 2130333

Tekscan^{TM} I-Scan system

The measurement system:

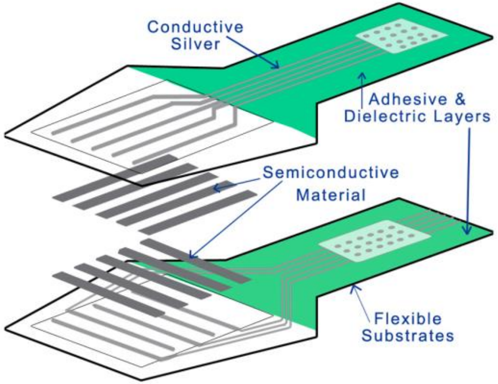
- Matrix based sensor using the piezo-resistive effect
- Minimal spacing between rows od columns: 0.6 mm

- Repeatability: < ± 3.5%
- Hysteresis of the sensor: < ± 4.5%
- Pressure range: up to 207 MPa (limited by the deformation of the foil)

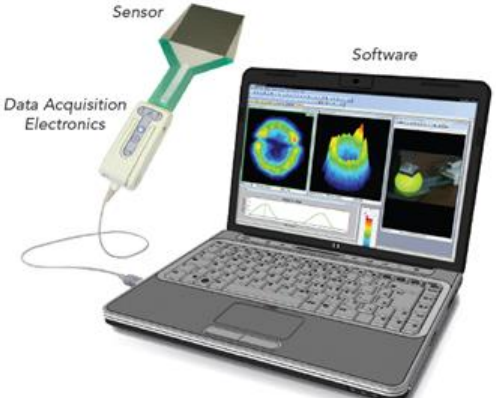
- Maximum number of sensing elements 50*44 = 2200 Thickness: 0.1 mm

- Scanning speed up to 100 Hz
- Digital pressure resolution in 8 bit (0-255)

- All sensor foils must be calibrated with respect to the contact material by the customer



Tekscan sensor design. [8]



Tekscan readout system. [8]

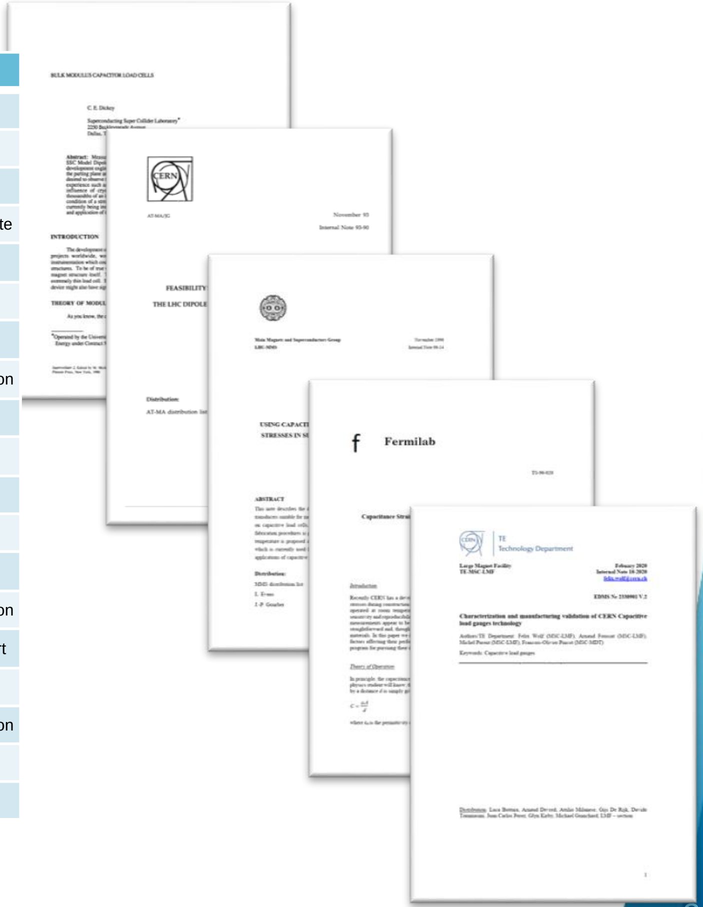
[8] Tekscan, Inc., I-Scan® Product Selection Guide, [Online]. Available: https://www.tekscan.com [Accessed 2021].

Active system

CERN capacitive load transducer

History of capacitive gauge in SC magnet comunity

ID	Year	Author	Title	Published	Type
1	1990	C. E. Dick	Bulk modulus capacitor load cells	SSC Lab. Plenum Press	Paper
2	1993	J. Gilquin	Feasibility study of a system for measuring the LHC dipole coil stresses with capacitive probes	Internal Note 93-90	Report
3	1996	I. Vanenkov	Using capacitive force transducer for measuring stresses in superconducting magnet coils for the LHC	Internal Note 96-14	Report
4	1996	J. P. Ozelis	Capacitance strain gauges - an Introduction and Modest Proposal	Fermilab	Internal note
5	1997	N.Siegel, et al.	Design and use of capacitive force transducers for superconducting magnet models for the LHC	lhc-project-report-173	Report
6	2002	A. Foussat, et al.	Mechanical behaviour of the ATLAS B0 Model Coil	IEEE	Paper
7	2009	R.B. Ragland	Capacitive stress gauges in model dipole magnets	Texas A&M University	Thesis
8	2010	M. Guinchard, et al.	Techniques of mechanical measurements for CERN application	EDMS 1064933	Presentation
9	2010	K. Artoos, et al.	New techniques for mechanical measurements in the superconducting magnet models	IPAC 10 Kyoto	Paper
10	2010	C. Benson	Capacitive stress transducers in model dipole magnets	Texas A&M University	Thesis
11	2011	R. Ballester	Failure analysis of a press for testing sensors in the mechanical measurements lab	EDMS 1146460	Report
12	2011	R. Ballester	Analysis for the improvement of the capacitive gauges' performance	EDMS 1154650	Report
13	2012	R. Ballester	Study for the improvement of the capacitive pressure gauges' performance, and design of an automated compressing …	EDMS 1110695	Thesis
14	2012	R. Ballester	Study of the capacitive gauges and the calibration system	EDMS 1110695	Presentation
15	2012	M. Guinchard, et al.	Zwick visit report for capacitive gauge and load cell calibration	EDMS 1214523	Visit Report
16	2012	C. Benson, et al.	Improved capacitive stress transducers for high-field superconducting magnets	AIP Conf. Proceed.	Paper
17	2013	K. Velissaridis	Optimization of the capacitive gauges in terms of testing and manufacturing procedures	EDMS 1341108	Presentation
18	2020	F. Wolf	Characterization and manufacturing validation of CERN Capacitive load gauges technology	EDMS 2330901	Report
19	2020	F. Wolf	TE-MSC-LMF-QA-Manufacturing procedure of CERN Capacitive gauges	EDMS 2361251	Report

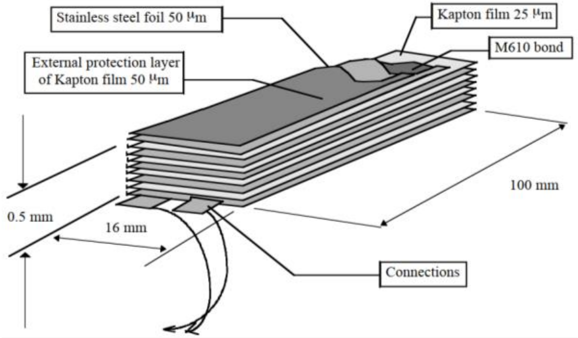


Road map for development of capacitive gauge

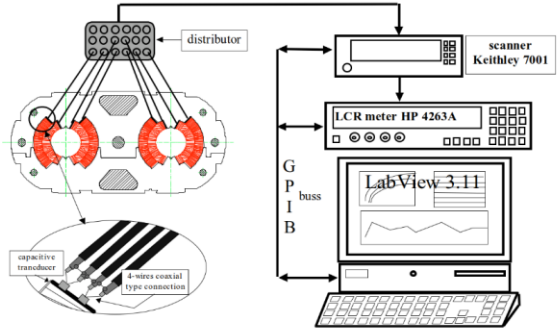
1. Retrieve and collect all available knowledge on capacitive gauges
2. Build first prototype to learn
3. Write manufacturing procedure EDMS: 2361251
4. Validate the sensor performance EDMS: 2330901
5. Study the multi-physic behavior of the sensor
6. Prepare the sensor for implementation and built a small series
7. Prepare enhanced sensor design

Capacitive load gauge development for magnet application

- ✓ Collection of all available documentation about work on capacitive gauges at CERN (until 2000)
- ✓ Knowledge transfer with Michel Parent who was involved in the manufacturing process of capacitive gauges at CERN 20 year’s ago
- ✓ Test and update existing DAQ system (2000) and LabView code for sensor read out



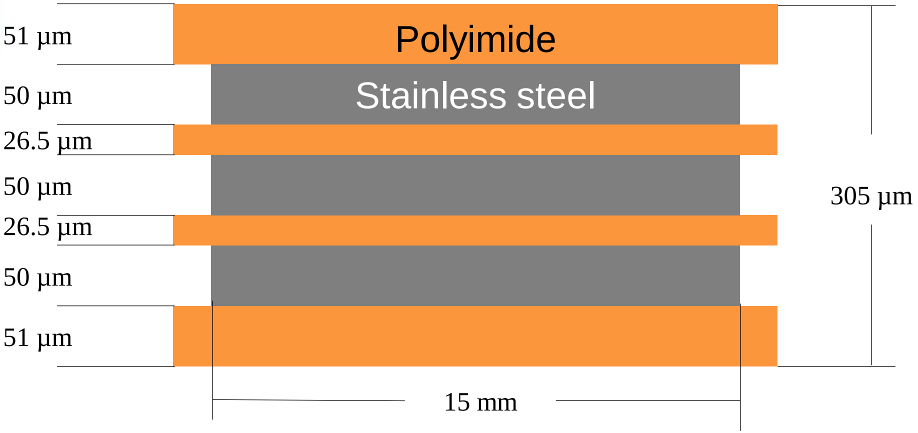
“Sandwich” type capacitive force transducer design. [11]



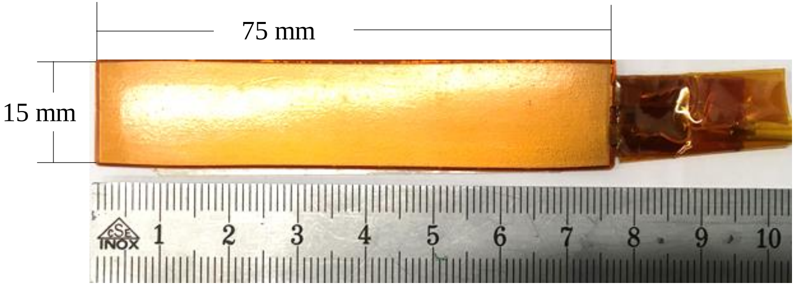
Schematic layout of the data acquisition system. [12]

[11] I. Vanenkov, Internal Note 96-14, 1996
[12] N. Siegel et al. “LHC PROJECT REPORT 173”, 1998

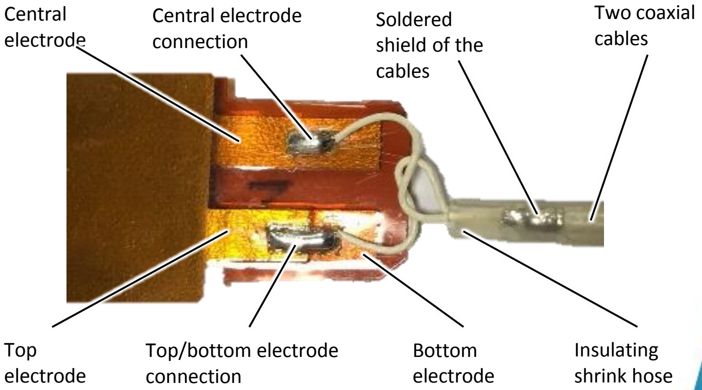
Sensor layout



Schematic cross section of the capacitive gauge.

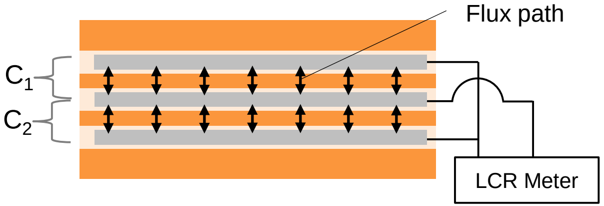


Top view on the a capacitive gauge.



Connections on the capacitive gauge.

Principle of capacitive gauge



🟥 Electrodes (stainless steel foil 50 µm)
⬜ Strain gauge glue (M610 bond)
🟧 Polyimide film 25.4-50.8 µm

Schematic of the capacitive gauge.

Mechanic

- Two springs in series

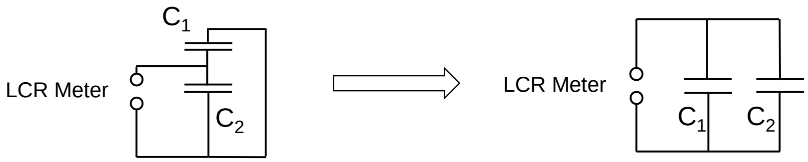
Electric

- Two capacitors in parallel

$$C = C_1 + C_2$$

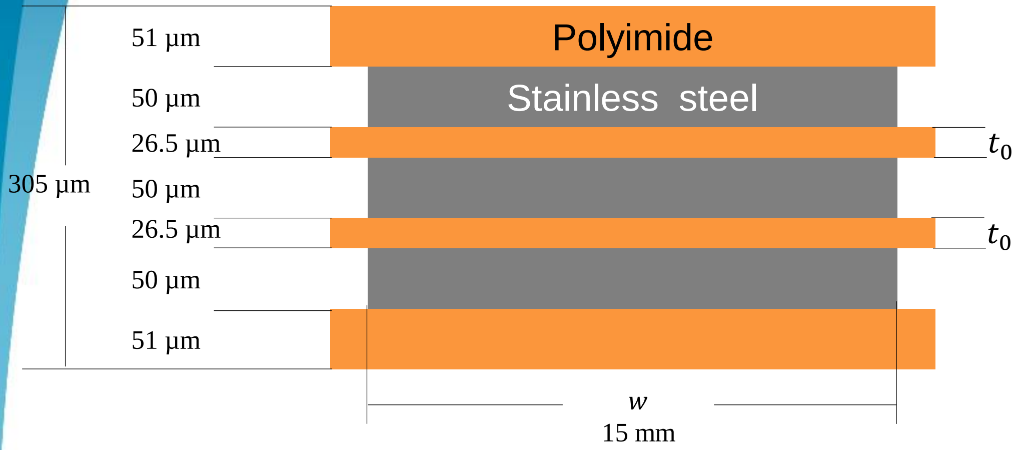
$$C = \varepsilon_r \varepsilon_0 n\, w \frac{l}{t_0}$$

C… capacitance
ε_r... relative permittivity
ε_0… vacuum permittivity (8.85 x 10^{-12} F m^{-1})
n … number of layers
w… width of the gauge
l… length of the gauge
t… thickness of the dielectric material



Circuit diagram of the capacitive gauge.

Layout of the tested capacitive gauge



Sensor properties

Symbol	Property	Value
ε_0	Vacuum permittivity	8.85 x 10^{-12} Fm^{-1}
ε_r	Dielectric permittivity of polyimide film	3.3 [13]
n	Number of parallel capacitors	2
l	Length of the gauge	75 mm
w	Width of the gauge	15 mm
t_0	Thickness of the dielectric layer	25.7µm -28.4µm

$$C = \varepsilon_r \varepsilon_0 n\, w \frac{l}{t_0}$$

$$C(t_0) = 3.3 \cdot 8.85 \cdot 10^{-12}\,\frac{\mathrm{F}}{\mathrm{m}}\; 2 \cdot 0.015\ \mathrm{m} \cdot \frac{75\,000\ \mu\mathrm{m}}{t_0}$$

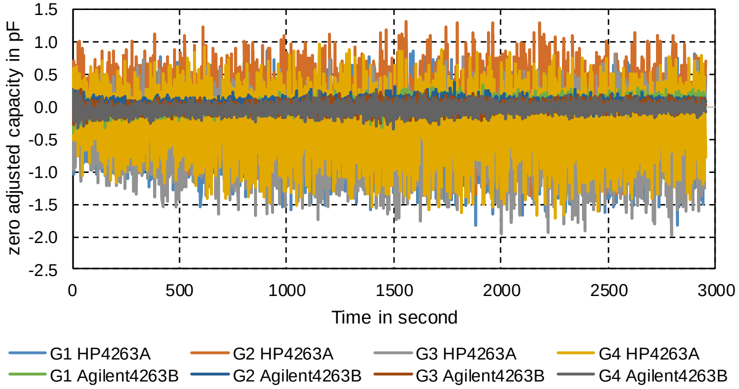
Sensor	Measured sensor thickness in µm	t_0 in µm	Theoretical Capacity C_{th} in nF	Measured Capacity C_m in nF
G1	310	27.9	2.36	2.34
G2	303.3	25.7	2.56	2.41
G3	311.3	28.4	2.31	2.37
G4	308.6	27.5	2.39	2.38

[13] APICAL POLYIMIDE, “Datasheet Apical AV,” [Online]. Available: https://apicalfilm.com/technical-data/. [Accessed 2020].

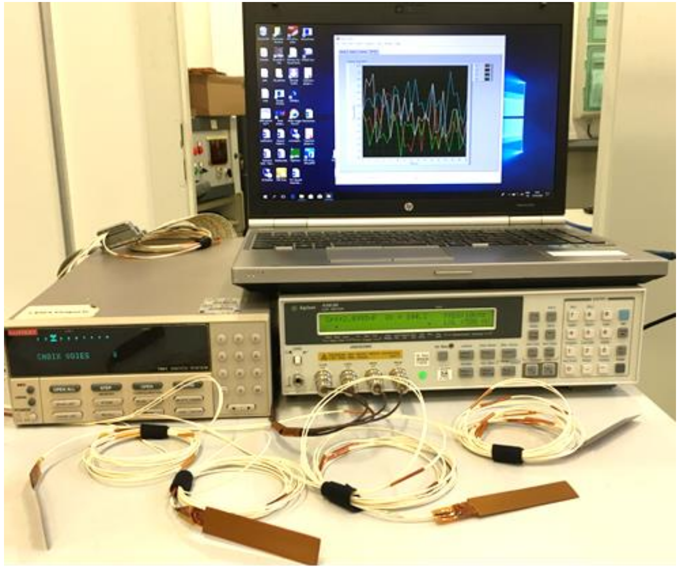
State of the art LCR meter

- LCR meter (Agilent 4263B)
- Switch system (Keithley 7001)
- LabView

Sensor	HP4263A		Agilent 4263B	
	Capacitance in nF	STDEV in pF	Capacitance in nF	STDEV in pF
G1	2.33773	0.4734	2.33745	0.0924
G2	2.41452	0.4759	2.41463	0.0714
G3	2.37228	0.4827	2.37295	0.0712
G4	2.38197	0.4795	2.38184	0.0726



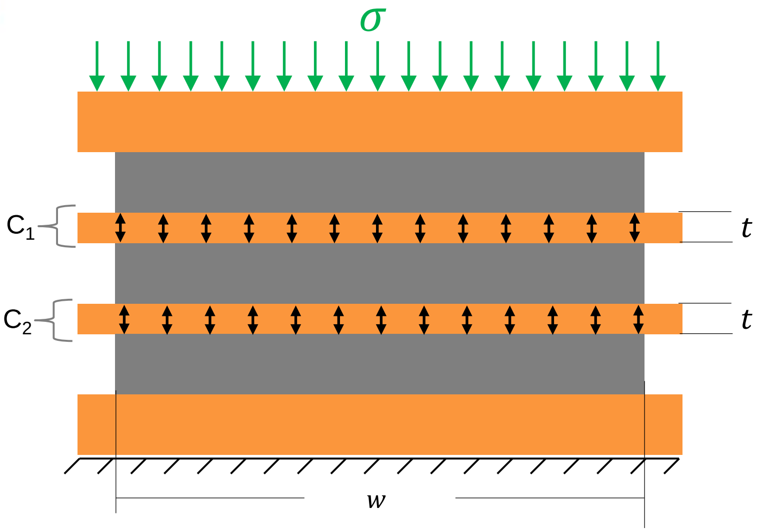
Comparison of the capacitance signal measured by the old (2000) and the new LCR meter.



DAQ for the capacitive gauges.

- Improved precision by factor of 5

Sensor principle under mechnical load



Schematic of the capacitive gauge.

$$\Delta t = t_0 - t_1$$

$$\Delta C = \varepsilon_r \varepsilon_0 n\, wl \left(\frac{1}{t_1} - \frac{1}{t_0} \right)$$

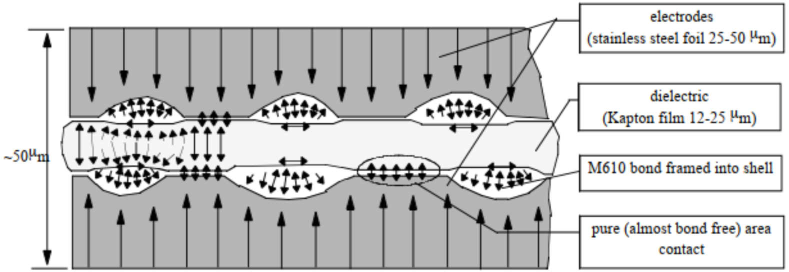
$$\Delta C \sim k\, \sigma$$

$C\ldots$ capacitance
ε_r... relative permittivity
$\varepsilon_0\ldots$ vacuum permittivity (8.85 x 10^{-12} F m^{-1})
$n\ldots$ number of layers
$w\ldots$ width of the gauge
$l\ldots$ length of the gauge
$t\ldots$ thickness of the dielectric material
$\sigma\ldots$ applied compressive stress

Basic model for capacitance variation

C.E. Dickey, 1990
I. Vanenkov, 1996

- Dielectric material is put under hydrostatic stress



Hydrostatic” type design of capacitor load cell. [6]

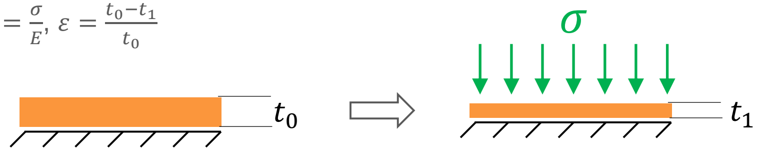
R.M. Ballester 2012

- Uniaxial load in the dielectric layer

$$\Delta C = C_1 - C_0 = \varepsilon_r \varepsilon_0 n\, wl \left(\frac{1}{t_1} - \frac{1}{t_0}\right) = \varepsilon_r \varepsilon_0 n\, wl \frac{1}{t_0} \left(\frac{-\varepsilon_{y_{\mathrm{diel}}}}{\varepsilon_{y_{\mathrm{diel}}} + 1}\right)$$

$$\Delta C = \varepsilon_r \varepsilon_0 n\, wl \frac{1}{t_0} \left(\frac{-\sigma}{\sigma + E_{\mathrm{diel}}}\right)$$

$$\varepsilon = \frac{\sigma}{E}, \ \varepsilon = \frac{t_0 - t_1}{t_0}$$



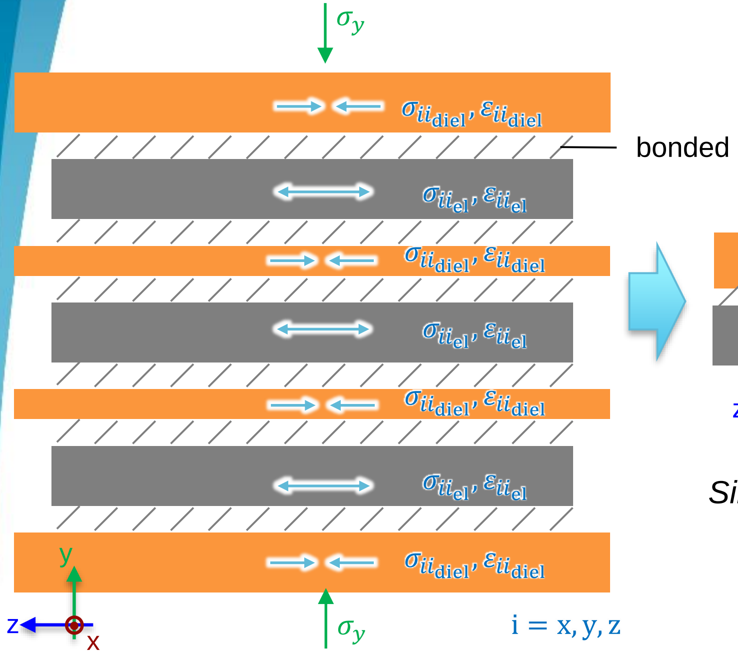
Uniaxial stress-strain state of the dielectric layer.

- Both models needed to introduce a calibration factor k, based on measurements

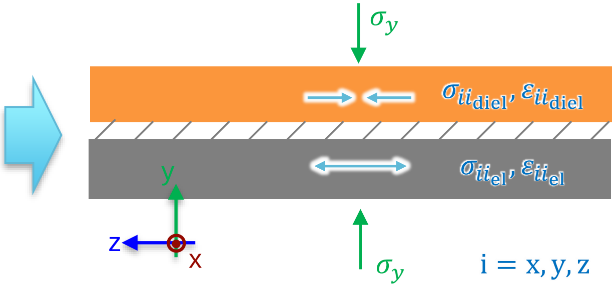
$$\Delta C \sim k\, \sigma$$

[11] I. Vanenkov, Internal Note 96-14, 1996
[14] C. E. Dick “Bulk modulus capacitor load cells”, 1990

Stress - strain calculation of the capacitive gauge



Schematic of the capacitive gauge with stress components.



Simplified schematic for analytic model.

Stress – strain state in the dielectric layer

$$\varepsilon_{\mathrm{xx_{diel}}} = \frac{1}{E_{\mathrm{diel}}}\left(\sigma_{\mathrm{xx_{diel}}} - \nu_{\mathrm{diel}}\left(\sigma_{\mathrm{yy_{diel}}} + \sigma_{\mathrm{zz_{diel}}}\right)\right)$$

$$\varepsilon_{\mathrm{yy_{diel}}} = \frac{1}{E_{\mathrm{diel}}}\left(\sigma_{\mathrm{yy_{diel}}} - \nu_{\mathrm{diel}}\left(\sigma_{\mathrm{xx_{diel}}} + \sigma_{\mathrm{zz_{diel}}}\right)\right)$$

$$\varepsilon_{\mathrm{zz_{diel}}} = \frac{1}{E_{\mathrm{diel}}}\left(\sigma_{\mathrm{zz_{diel}}} - \nu_{\mathrm{diel}}\left(\sigma_{\mathrm{xx_{diel}}} + \sigma_{\mathrm{yy_{diel}}}\right)\right)$$

Stress – strain state in the electrode

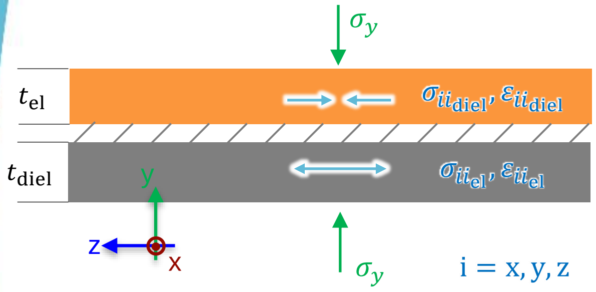
$$\varepsilon_{\mathrm{xx_{el}}} = \frac{1}{E_{\mathrm{el}}}\left(\sigma_{\mathrm{xx_{el}}} - \nu_{\mathrm{el}}\left(\sigma_{yy_{\mathrm{el}}} + \sigma_{zz_{\mathrm{el}}}\right)\right)$$

$$\varepsilon_{\mathrm{yy_{el}}} = \frac{1}{E_{\mathrm{el}}}\left(\sigma_{\mathrm{yy_{el}}} - \nu_{\mathrm{el}}\left(\sigma_{\mathrm{xx_{el}}} + \sigma_{\mathrm{zz_{el}}}\right)\right)$$

$$\varepsilon_{\mathrm{zz_{el}}} = \frac{1}{E_{\mathrm{el}}}\left(\sigma_{\mathrm{zz_{el}}} - \nu_{\mathrm{el}}\left(\sigma_{\mathrm{xx_{el}}} + \sigma_{\mathrm{yy_{el}}}\right)\right)$$

Stress - strain calculation of the capacitive gauge

$$t_{\mathrm{el}} = \sum t_{\mathrm{el}_i} \qquad t_{\mathrm{diel}} = \sum t_{\mathrm{diel}_i}$$



Simplified schematic for analytic model.

In plane stress and strain isotropy

$\varepsilon_{\mathrm{xx}_k} = \varepsilon_{\mathrm{zz}_k} = \varepsilon_{\mathrm{l}_k}$

$\sigma_{\mathrm{xx}_k} = \sigma_{\mathrm{zz}_k} = \sigma_{\mathrm{l}_k}$

$$\varepsilon_{\mathrm{l_{diel}}} = \frac{1}{E_{\mathrm{diel}}}\left(\sigma_{\mathrm{l_{diel}}} - \nu_{\mathrm{diel}}\left(\sigma_{\mathrm{y}} + \sigma_{\mathrm{l_{diel}}}\right)\right) \qquad \varepsilon_{\mathrm{l_{el}}} = \frac{1}{E_{\mathrm{el}}}\left(\sigma_{\mathrm{l_{el}}} - \nu_{\mathrm{el}}\left(\sigma_{\mathrm{y}} + \sigma_{\mathrm{l_{el}}}\right)\right)$$

Equilibrium of lateral strain between the layers

$\varepsilon_{\mathrm{l_{diel}}} = \varepsilon_{\mathrm{l_{el}}}$

Equilibrium of lateral forces

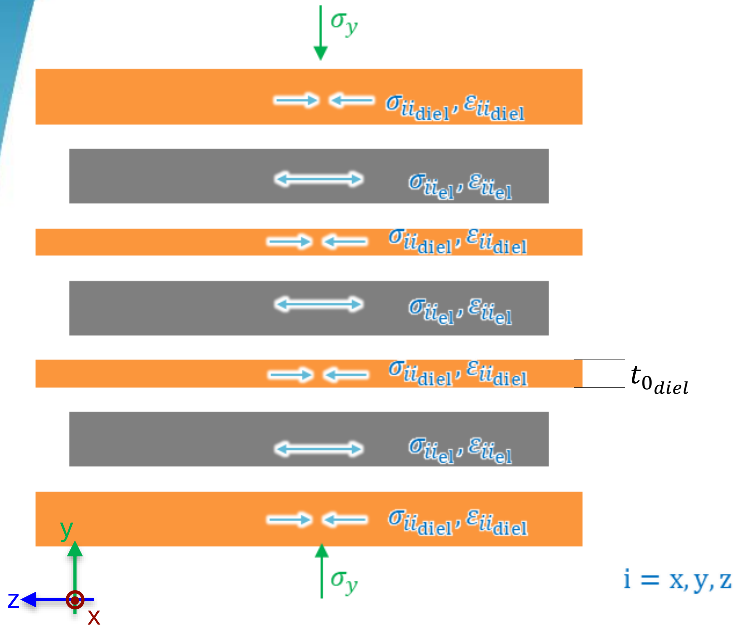
$F_{\mathrm{l_{diel}}} = -F_{\mathrm{l_{el}}}$

$t_{\mathrm{diel}}\, w\, \sigma_{\mathrm{l_{diel}}} = -t_{\mathrm{el}}\, w\, \sigma_{\mathrm{l_{el}}}$

Lateral stress calculation

$$\sigma_{\mathrm{l_{diel}}} = \frac{\dfrac{\nu_{\mathrm{diel}}}{E_{\mathrm{diel}}} - \dfrac{\nu_{\mathrm{el}}}{E_{\mathrm{el}}}}{\dfrac{1-\nu_{\mathrm{diel}}}{E_{\mathrm{diel}}} + \left(\dfrac{1-\nu_{\mathrm{el}}}{E_{\mathrm{el}}}\right)\dfrac{t_{\mathrm{diel}}}{t_{\mathrm{el}}}}\sigma_{\mathrm{y}} \qquad \sigma_{\mathrm{l_{el}}} = \frac{\dfrac{\nu_{\mathrm{diel}}}{E_{\mathrm{diel}}} - \dfrac{\nu_{\mathrm{el}}}{E_{\mathrm{el}}}}{-\left(\dfrac{1-\nu_{\mathrm{diel}}}{E_{\mathrm{diel}}}\right)\dfrac{t_{\mathrm{el}}}{t_{\mathrm{diel}}} - \dfrac{1-\nu_{\mathrm{el}}}{E_{\mathrm{el}}}}\sigma_{\mathrm{y}}$$

Stress - strain state in the capacitive gauge



Schematic of the capacitive gauge with stress components.

Lateral stress calculation

$$\sigma_{\rm l_{diel}} = \frac{\frac{\nu_{\rm diel}}{E_{\rm diel}} - \frac{\nu_{\rm el}}{E_{\rm el}}}{\frac{1-\nu_{\rm diel}}{E_{\rm diel}} + \left(\frac{1-\nu_{\rm el}}{E_{\rm el}}\right)\frac{t_{\rm diel}}{t_{\rm el}}}\,\sigma_{\rm y}$$

Strain dielectric layer

$$\varepsilon_{\rm yy_{diel}} = \frac{1}{E_{\rm diel}}\left(\sigma_{\rm yy_{diel}} - \nu_{\rm diel}\left(\sigma_{\rm xx_{diel}} + \sigma_{\rm zz_{diel}}\right)\right)$$

$$\varepsilon_{\rm y_{diel}} = \frac{1}{E_{\rm diel}}\left(1 - 2\,\nu_{\rm diel}\frac{\frac{\nu_{\rm diel}}{E_{\rm diel}} - \frac{\nu_{\rm el}}{E_{\rm el}}}{\frac{1-\nu_{\rm diel}}{E_{\rm diel}} + \left(\frac{1-\nu_{\rm el}}{E_{\rm el}}\right)\frac{t_{\rm diel}}{t_{\rm el}}}\right)\sigma_{\rm y}$$

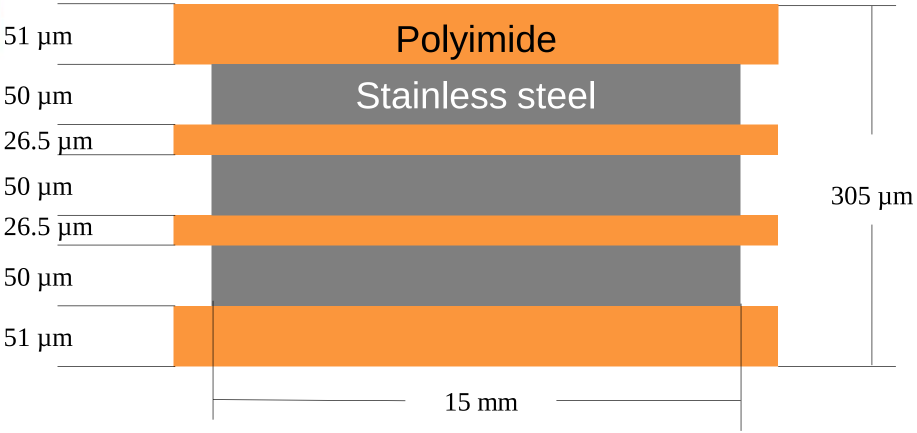
Capacitance variation of the gauge under applied load

$$\Delta C = \varepsilon_r\varepsilon_0 n\,wl\left(\frac{1}{t_1} - \frac{1}{t_0}\right) \text{ and } t_1 = t_0\,\varepsilon_{y_{\rm diel}} + t_0$$

$$t_{\rm el} = \sum t_{{\rm el}_i}$$
$$t_{\rm diel} = \sum t_{{\rm diel}_i}$$

$$\Delta C = \frac{\varepsilon_r\varepsilon_0 n\,wl}{t_{0_{\rm diel}}}\left(\frac{1}{\frac{1}{E_{\rm diel}}\left(1-2\,\nu_{\rm diel}\frac{\frac{\nu_{\rm diel}}{E_{\rm diel}} - \frac{\nu_{\rm el}}{E_{\rm el}}}{\frac{1-\nu_{\rm diel}}{E_{\rm diel}} + \left(\frac{1-\nu_{\rm el}}{E_{\rm el}}\right)\frac{t_{\rm diel}}{t_{\rm el}}}\right)\sigma_{\rm yy} + 1.} - 1\right)$$

Material properties of the components



Schematic cross section of the capacitive gauge.

Polyimide APICAL AV100 [13]

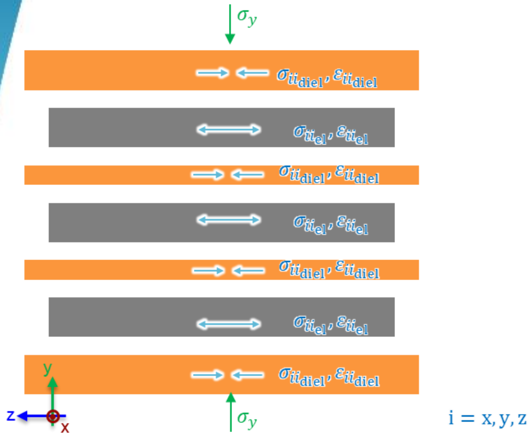
Symbol	Property	Value
E	Elastic modulus	3.1 GPa
ν	Poisson ratio	0.34
σ_y	Yield strength	69 MPa

Stainless steel 316L [15]

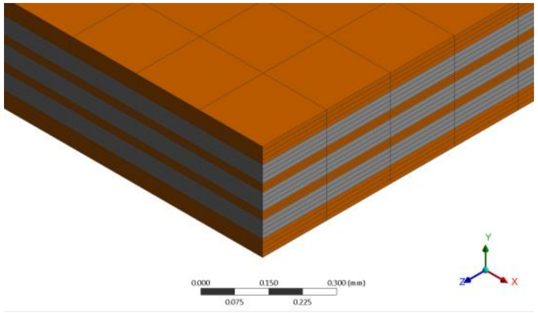
Symbol	Property	Value
E	Elastic modulus	191 GPa
ν	Poisson ratio	0.3 [16]
σ_y	Yield strength	320 MPa

[13] APICAL POLYIMIDE, “Datasheet Apical AV,” [Online]. Available: https://apicalfilm.com/technical-data/. [Accessed 2020].
[15] C. Scheuerlein, et al., “Mechanical Properties of the HL-LHC 11 T Nb3Sn Magnet Constituent Materials,” IEEE Transactions on Applied Superconductivity, 2017.
[16] P. Shankar, et al. , “Nitrogen redistribution, microstructure, and elastic constant evaluation using ultrasonics in aged 316LN stainless steels,” Metall and Mat Trans A 32, 2001.

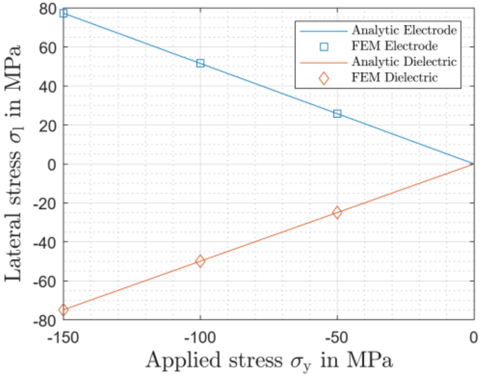
Stress state in the capacitive gauge



Advanced analytical model of the gauge.



Numerical model of the gauge.



Comparison of analytical and numerical lateral stress components.

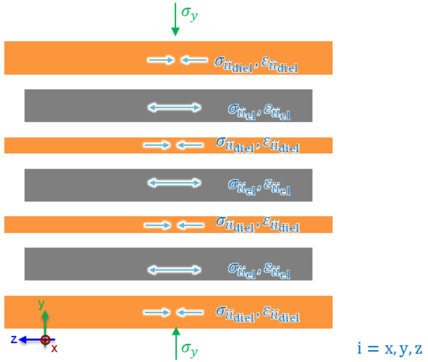
- Good agreement between numerical and analytical model
- Stress state in the polyimide is **not** hydrostatic as assumed in the past [Dickey 1990, Vanenkow 1996]
- Load state in the polyimide is **not** uniaxial as assumed in the past [R.M. Ballester 2012]

Validation of the analytical model

Simple analytical model

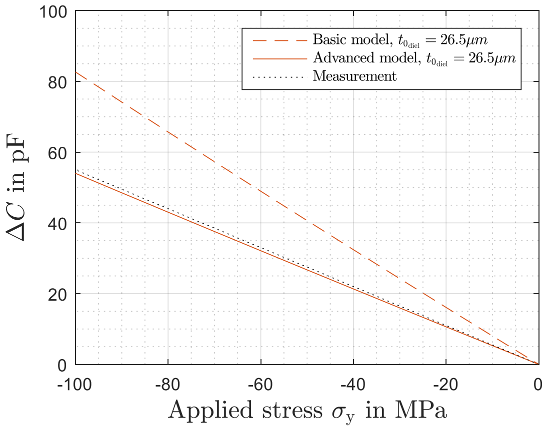
$$\Delta C = \varepsilon_r\, \varepsilon_0 n\, wl \frac{1}{t_0}\left(\frac{-\sigma_y}{\sigma_y + E_{\mathrm{diel}}}\right)$$

Advanced analytical model



$$\Delta C = \frac{\varepsilon_r \varepsilon_0 n\, wl}{t_{0\,\mathrm{diel}}} \left(\frac{1}{\frac{1}{E_{\mathrm{diel}}}\left(1-2\,\nu_{\mathrm{diel}} \frac{\frac{\nu_{\mathrm{diel}}}{E_{\mathrm{diel}}} - \frac{\nu_{\mathrm{el}}}{E_{\mathrm{el}}}}{\frac{1-\nu_{\mathrm{diel}}}{E_{\mathrm{diel}}} + \left(\frac{1-\nu_{\mathrm{el}}}{E_{\mathrm{el}}}\right)\frac{t_{\mathrm{diel}}}{t_{\mathrm{el}}}}\right)\sigma_{\mathrm{yy}} + 1.} - 1 \right)$$

Comparison of model and measurements



Comparison between model and measurement of the capacitance variation under applied load.

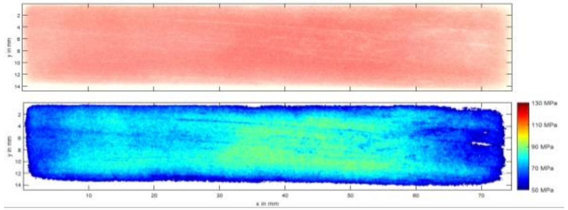
- Requires the introduction of a calibration factor.
- Allows a direct determination of the applied stress.
- Advanced model agrees well with the measurement.

Conclusion: The advanced model allows a direct calculation of the capacitance change without a calibration factor.

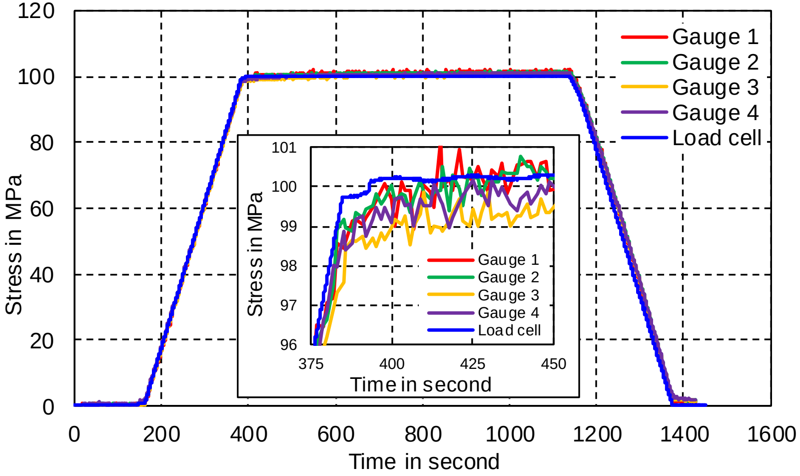
Sensor validation up to 100MPa

Four gauges stacked on top of each other in one load line

- Good agreement of load cell and capacitive gauge measurement
    - Deviation to load cell 1%
    - Resolution ± 2 MPa (at 100MPa)



Stress distribution applied on the capacitive gauge.

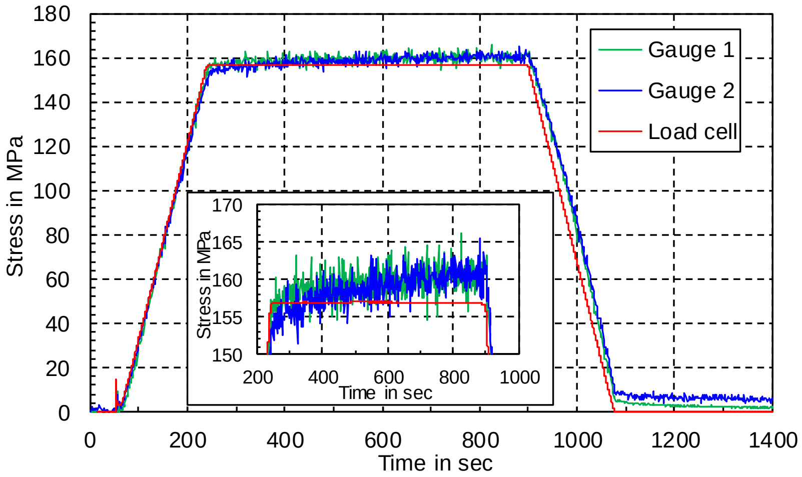


Comparison of the average stress determined by a load cell and capacitive gauge.

Sensor validation above 100MPa

Two gauges stacked on top of each other in one load line

- Deviation to load cell decreases at high load
  - (2 % at 160 MPa compared to load cell)
- Time dependent capacity increase at constant load



Comparison of the average stress determined by a load cell and capacitive gauge.

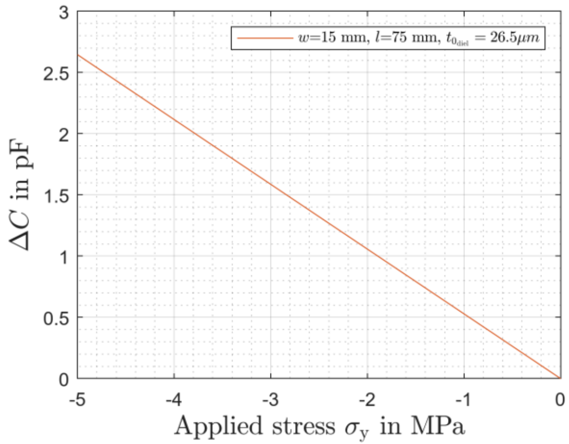
Requirements for test equipment

Requirements for an LCR meter

- A stress resolution of 1 MPa requires a capacitance resolution of 0.5 pF
- The stress resolution can be improved by reducing the thickness of the dielectric layer
- Alternative sensor design can be rapidly studied

Presented gauge design

$$\Delta C = \frac{\varepsilon_r \varepsilon_0 n\, wl}{t_{0_{\mathrm{diel}}}} \left(\frac{1}{\frac{1}{E_{\mathrm{diel}}} \left(1 - 2\, \nu_{\mathrm{diel}} \frac{\frac{\nu_{\mathrm{diel}}}{E_{\mathrm{diel}}} - \frac{\nu_{\mathrm{el}}}{E_{\mathrm{el}}}}{\frac{1-\nu_{\mathrm{diel}}}{E_{\mathrm{diel}}} + \left(\frac{1-\nu_{\mathrm{el}}}{E_{\mathrm{el}}}\right) \frac{t_{\mathrm{diel}}}{t_{\mathrm{el}}}} \right) \sigma_{\mathrm{yy}} + 1.} - 1 \right)$$



Capacitance variation under applied load a sensor.

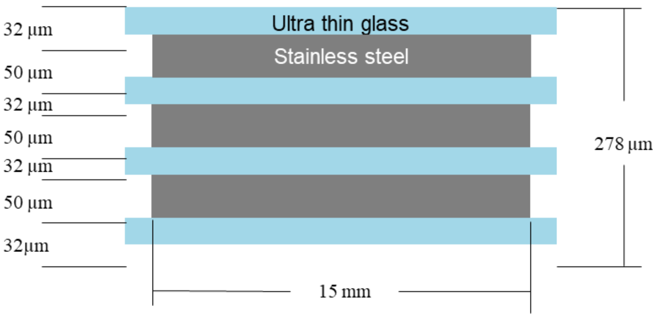
Proposal for capacitive gauge design

Ultra thin glass [17]

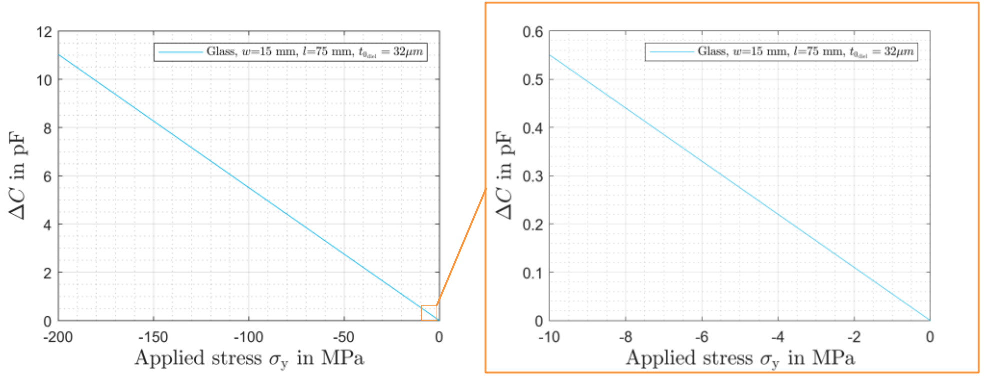
Symbol	Property	Value
E	Elastic modulus	72.9 GPa
ν	Poisson ratio	0.208
ε_r	Dielectric permittivity	6.7
t_0	Dielectric thickness	32 µm

Stainless steel 316L [17]

Symbol	Property	Value
E	Elastic modulus	191 GPa
ν	Poisson ratio	0.3 [16]
σ_y	Yield strength	320 MPa



Schematic cross section of the capacitive gauge.



Capacitance variation under applied load a sensor with a dielectric layer made from glass.

- Ultra thin glass seems a good candidate as dielectric layer for high stress applications
- The in the capacity can be determined with a presented system with a resolution of 10 MPa
- Ultra thin glass does not creep under high load
- Feasibility study ongoing to machine and process the glass

[17] Präzisions Glas & Optik GmbH, D 263 T Dünnes und ultradünnes Borosilikatglas, [Online]. Available: https://www.pgo-online.com/de/D263.html. [Accessed 2020].

Summary

FUJI Prescale film

- Powerful and cost-effective tool to determine a compressive stress distribution
- Good agreement with calibrated load cells
- Stress determination up to 300 MPa

TekScan

- Only commercially available system to measure up to 200 MPa compressive stress
- No further developments were done to increase the stress range
- Locally too high stresses can damage the sensor

Capacitive gauges

- The sensor has been tested in ideal uniaxial load in laboratory conditions
- A time dependent behavior was observed at high loads (above 100 MPa)
- The gauge allows only to determine an integrated average stress
  - Stress unbalances can bot be determined
  - Shear stresses can damage the sensor
- Analytical modelling approach was validated by numerical calculations and measurements
- Potential improvements are shown by substituting used dielectric material
- The application of the sensor at cryogenic temperature need to be tested