Piezo resistive gauge irradiation test results

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VSC seminar on the 13th of June 2023

https://indico.cern.ch/event/1242517/

Agenda

- **About piezo resistive gauges**
- **Their use in the LHC**
- **HL-LHC requirements**
- **Irradiation test results:**
  - External facility
  - Internal facility
- **Conclusions**
- **Future work**

Piezo resistive gauges

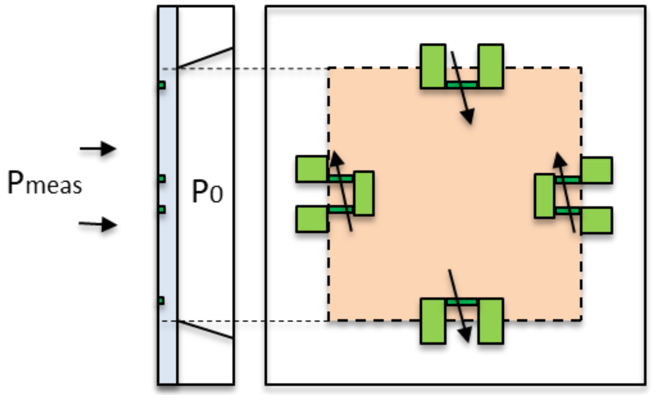
The word piezo derives from ancient Greek “piezein” which means to squeeze or press

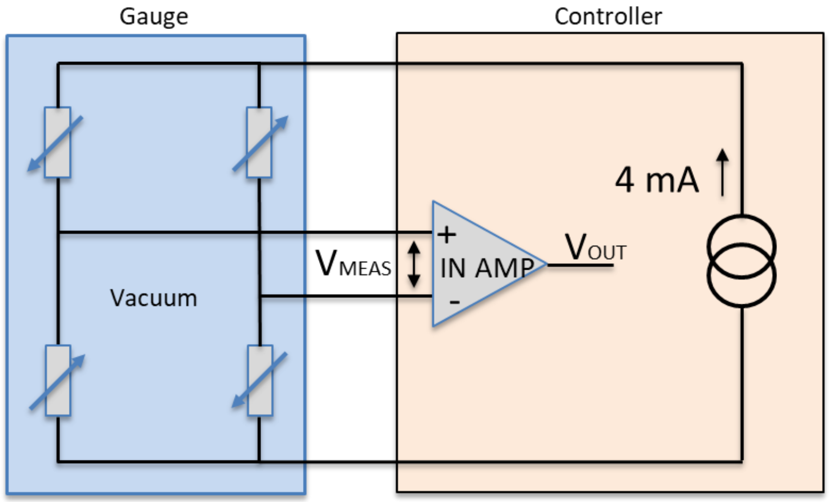
When pressure is applied in a piezoresistive material (silicon):

- Shift in the atomic positions -> affects the electric charge transport -> change in conductivity

Thin silicon crystal layer used as a membrane:

- Membrane deformation -> piezo resistive effect
- Piezo resistive elements form a Wheatstone bridge which can be excited with constant current
- V_{meas} [mV] is a measure of the membrane deformation and therefore the pressure





Piezo gauge variants based on location in LHC

High-radiation areas
Only passive gauges

Low-radiation areas
Active RadTol gauges

LSS | **DS** | **ARC**

Balzers APR017
x65 units

HUBA 680.99413
x168 units

HL-LHC requirements

For HL at P1 and P5 the IV volumes increase and x32 additional piezo gauges are needed:

- QXL (x4)
- Crab cavities (x8)
- D2 (x4)
- Cold powering (x16)

IT-String (x3)

BGC (x2)

The present IV inventory cannot cover the HL needs using APR gauge

- Just few spares in stock for LHC operation

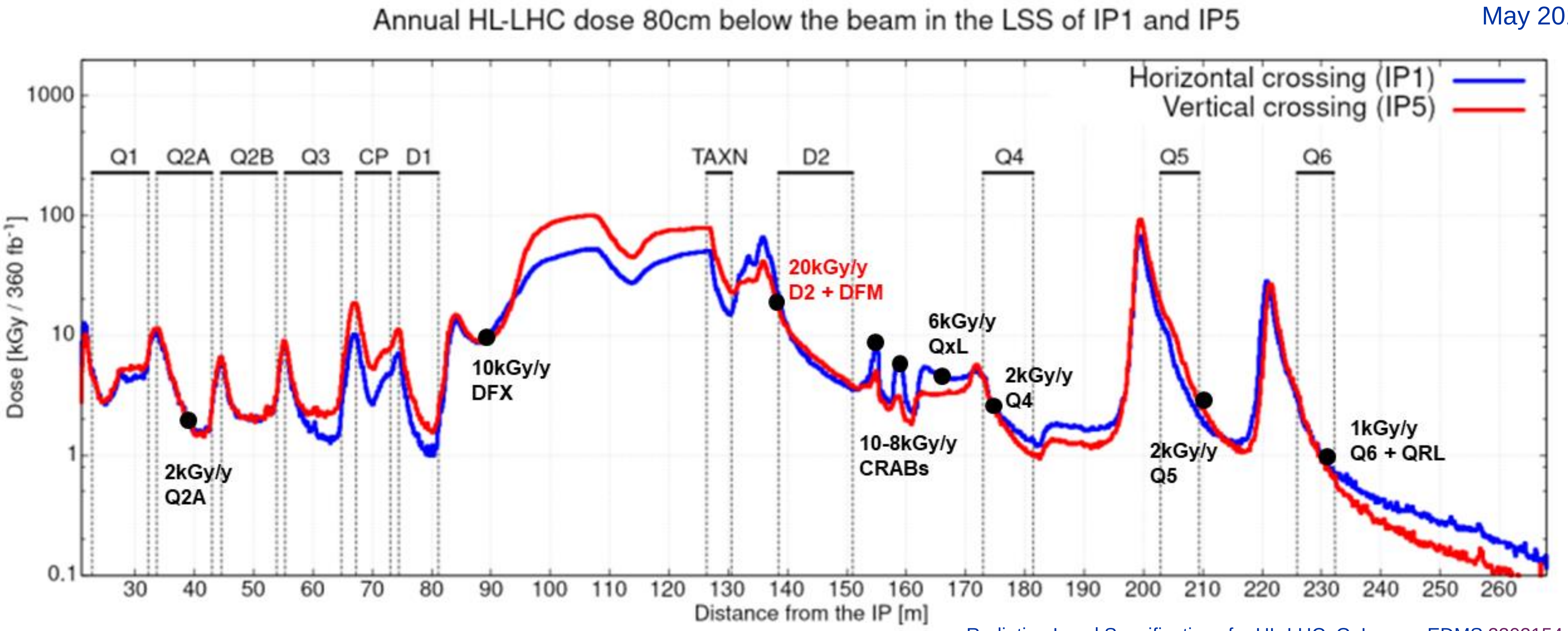
Not manufactured any more

New gauge technical specifications

- **Same range of pressure measurement**
  - 0 – 2000 mbar
  - Sensitivity in the order of 77 uV/(mbar.mA)
- **Same flange (KF16)**
- **Same or similar electrical connection to Burndy 4**
- **Less than ±1% FS accuracy**
- **EPDM seals or preferably fully welded sensor**
- **Compatible with current controller and cabling infrastructure**
  - Bridge excitation in the order of 4mA
  - Differential measurement in the order of 600mV
- **Passive gauge with a tolerance to radiation**
  - 200 kGy

Radiation levels in LSS1/5

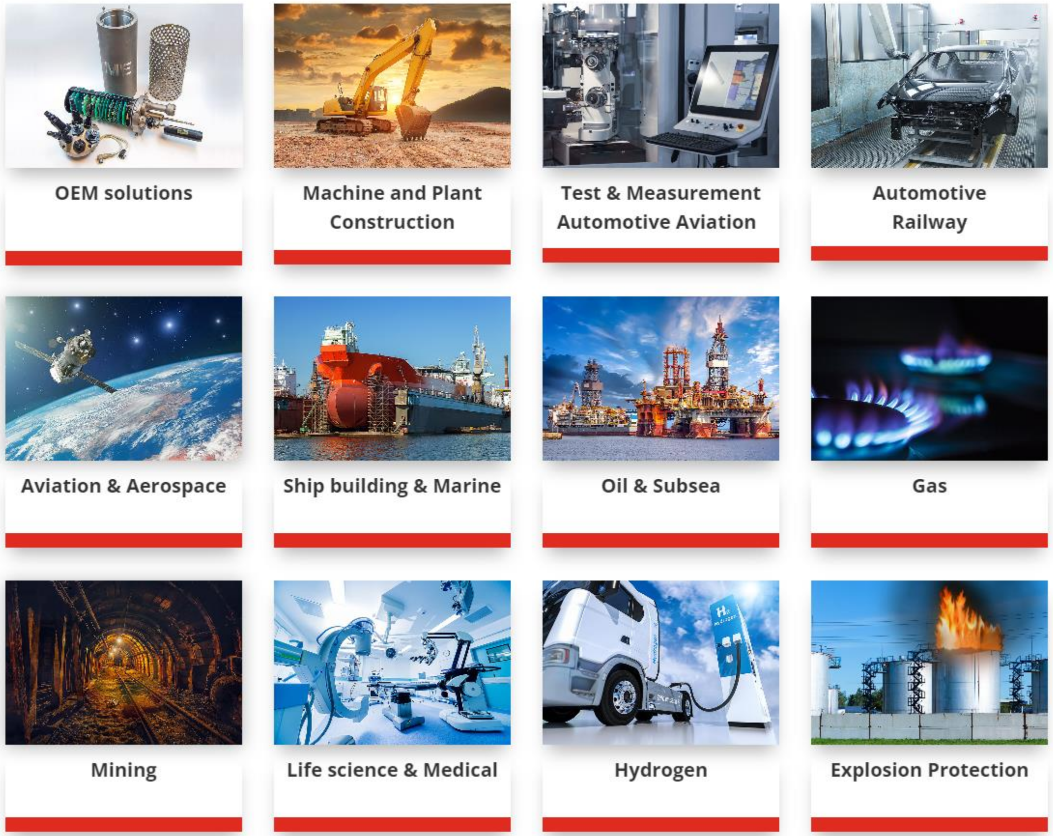
Optics v1.5
May 2019



Radiation Level Specifications for HL-LHC, G. Lerner, EDMS 2302154

The STS company

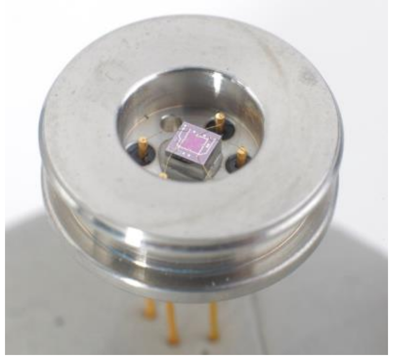
https://www.stssensors.com/

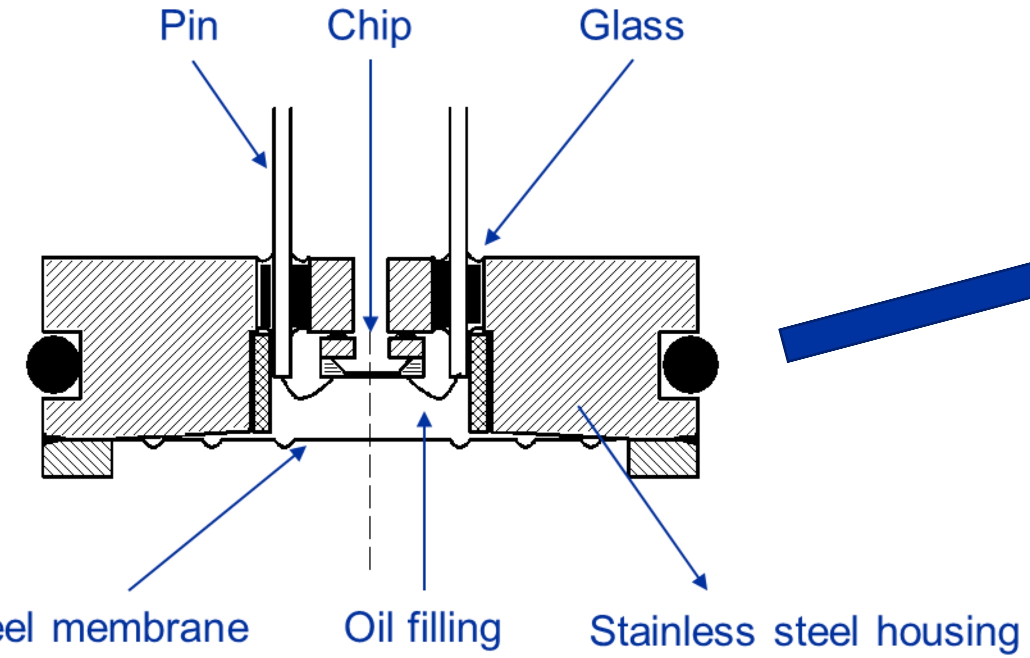


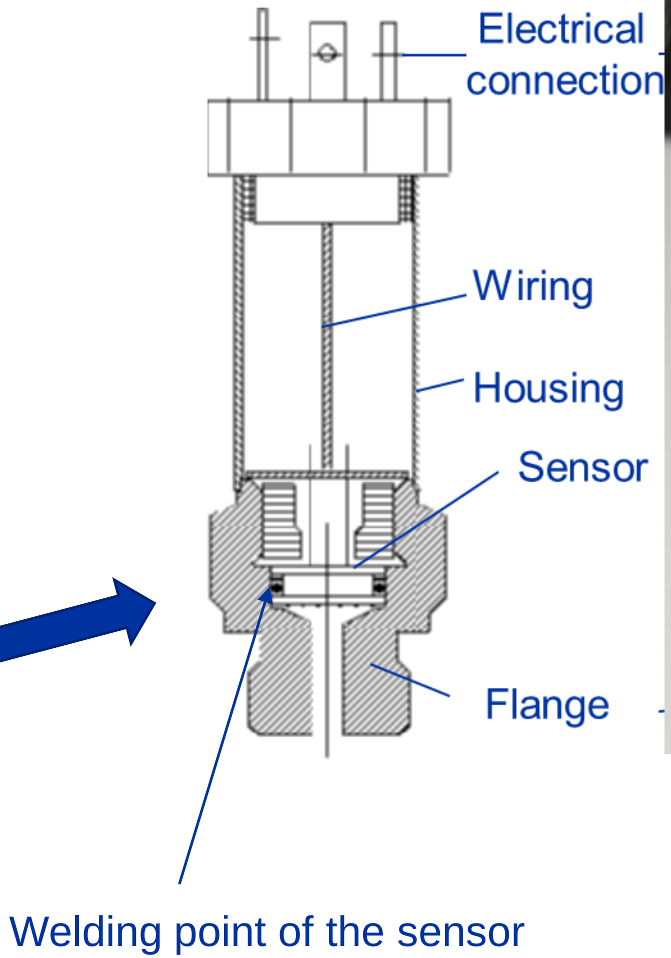
- Swiss company with applications in several industries
- Main products include sensors for:
  - Pressure
  - Level
- Very friendly staff and available for custom solution
  - without a minimum order quantity
- Manage development & productions for other companies
  - HUBA piezo sensor for DS/ARCs manufactured by STS
- Involved with ITER for piezo resistive sensors

STS article

STS gauge construction







Radiation effects on oils and lubricants

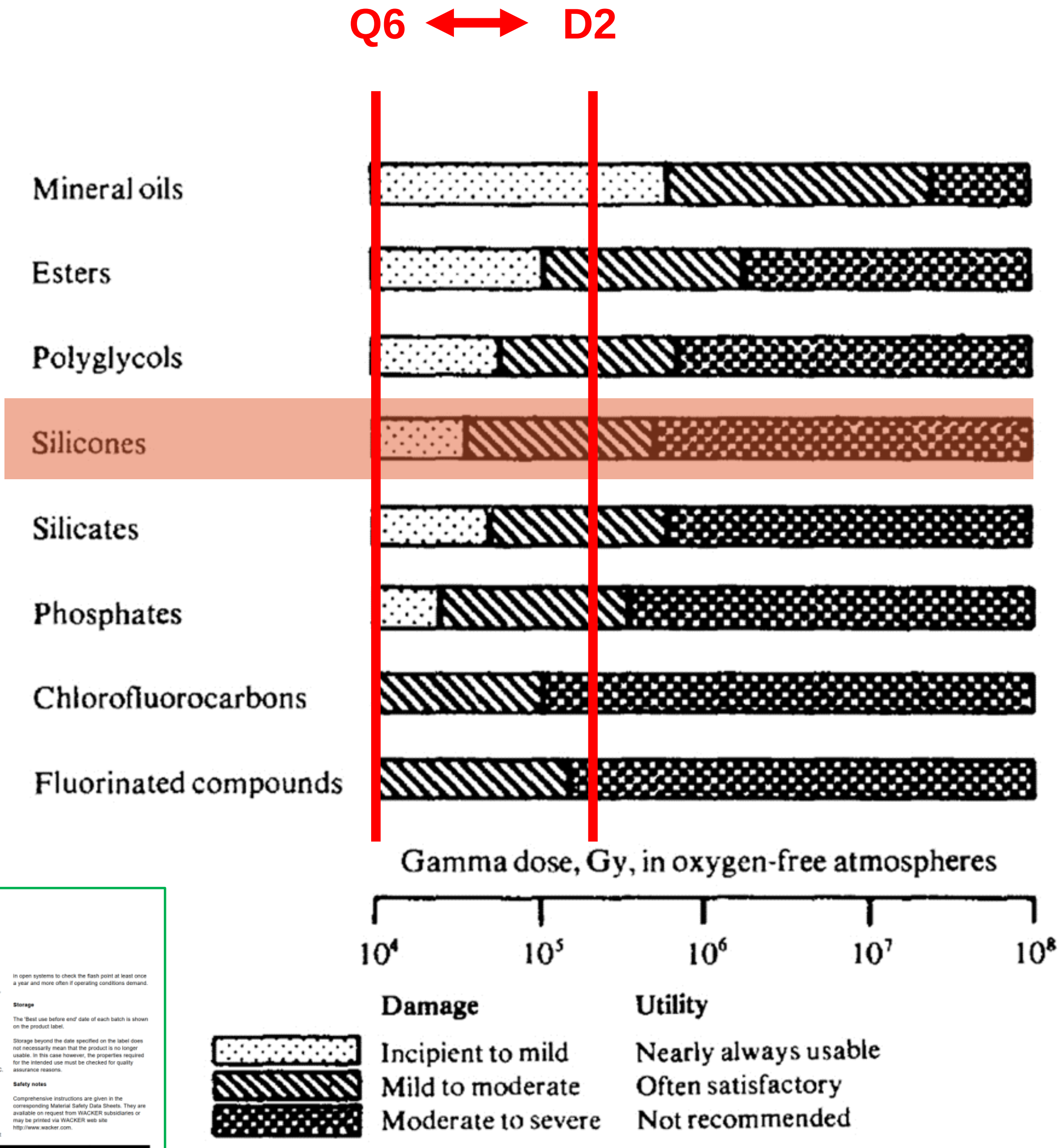
Viscosity change

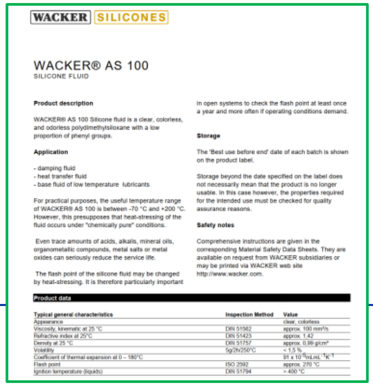
Depends on the exact silicon-based oil chemical composition, the type of radiation, flux and duration

- Chain scission and crosslinking of molecules
- Radiation induced oxidation (caused by production of free radicals)
- many other mechanisms..

Production of gasses

- Radicals recombination into gaseous hydrocarbons (ethane, methane, etc..) depending on temperature and pressure





WACKER SILICONES

WACKER® AS 100
SILICONE FLUID

Product description

WACKER® AS 100 Silicone fluid is a clear, colorless, and odorless polydimethylsiloxane with a low proportion of phenyl groups.

Application

- damping fluid
- heat transfer fluid
- base fluid of low temperature lubricants

For practical purposes, the useful temperature range of WACKER® AS 100 is between -70 °C and +200 °C. However, this presupposes that heat-stressing of the fluid occurs under "chemically pure" conditions.

Even trace amounts of acids, alkalis, mineral oils, organometallic compounds, metal salts or metal oxides can seriously reduce the service life.

The flash point of the silicone fluid may be changed by heat-stressing. It is therefore particularly important in open systems to check the flash point at least once a year and more often if operating conditions demand.

Storage

The 'Best use before end' date of each batch is shown on the product label.

Storage beyond the date specified on the label does not necessarily mean that the product is no longer usable. In this case however, the properties required for the intended use must be checked for quality assurance reasons.

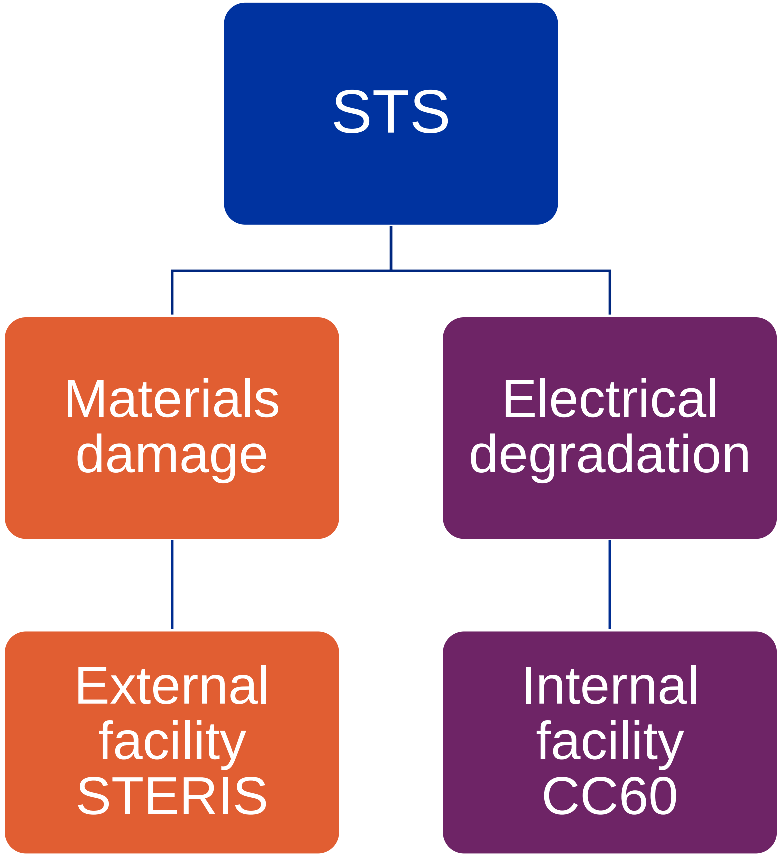
Safety notes

Comprehensive instructions are given in the corresponding Material Safety Data Sheets. They are available on request from WACKER subsidiaries or may be printed via WACKER web site http://www.wacker.com.

Product data

Typical general characteristics	Inspection Method	Value
Appearance		clear, colorless
Viscosity, kinematic at 25 °C	DIN 51562	approx. 100 mm²/s
Refractive index at 25°C	DIN 51423	approx. 1,42
Density at 25 °C	DIN 51757	approx. 0,99 g/cm³
Volatility	5g/2h/250°C	< 1,5 %
Coefficient of thermal expansion at 0 – 180°C		91×10^{-5} mLmL^{-1}K^{-1}
Flash point	ISO 2592	approx. 270 °C
Ignition temperature (liquids)	DIN 51794	> 400 °C

Irradiation test workflow



Irradiation at external facility - STERIS

Test procedure

Passive Gamma irradiation at atmospheric pressure

- Pre-irradiation leak test (AL4030)
- 8 samples sent in total:
  - 2 samples at 50kGy
  - 2 samples at 100kGy
  - 2 samples at 500kGy
  - 2 samples at 1MGy
- Post-irradiation leak test (AL4030)

Leak detection pre- and post-irradiation

Sample	Pre-irradiation [mbar.l/s]	Post-irradiation [mbar.l/s]
A1 – 50kGy	4.10^{-8}	$1,8.10^{-8}$
A2 – 50kGy	$2,2.10^{-8}$	$1,6.10^{-8}$
B1 – 100kGy	$2,5.10^{-8}$	$5,7.10^{-8}$
B2 – 100kGy	$4,8.10^{-8}$	4.10^{-8}
C1 – 500kGy	$2,4.10^{-8}$	$2,8.10^{-8}$
C2 – 500kGy	$5,4.10^{-8}$	$6,8.10^{-8}$
D1 – 1MGy	$2,4.10^{-8}$	$3,6.10^{-8}$
D2 – 1MGy	$2,6.10^{-8}$	4.10^{-8}

No significant differences between pre- and post-irradiation

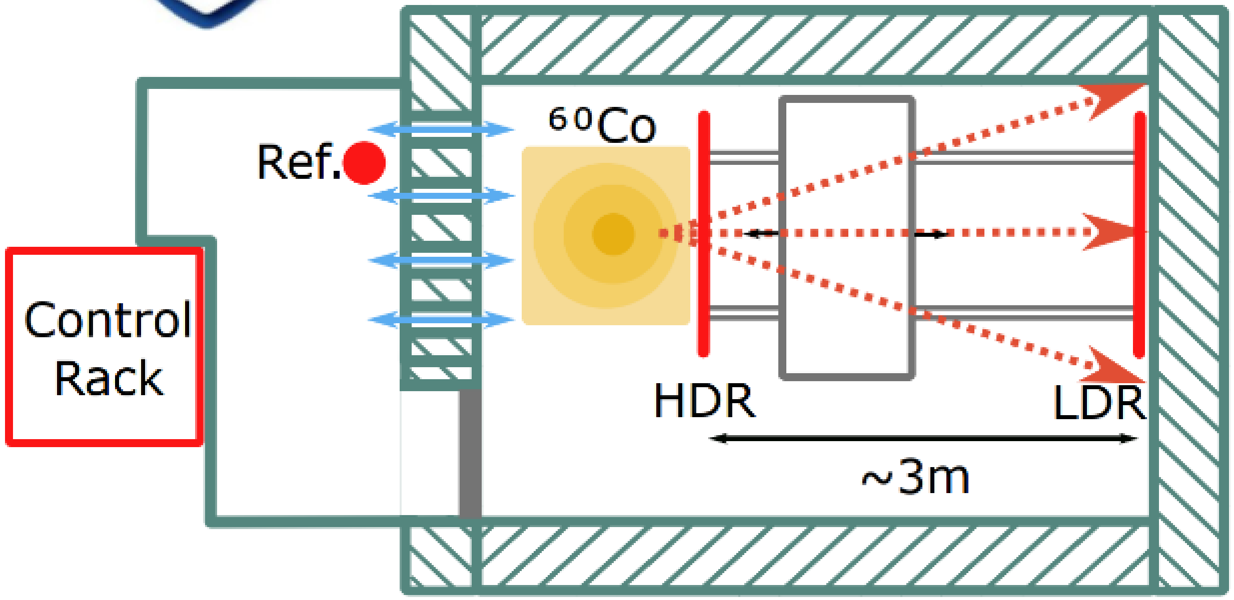
Irradiation at internal facility – CC60

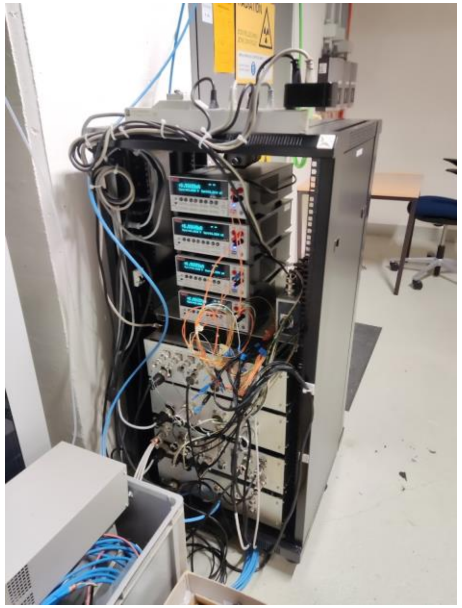
Internal facility CC60

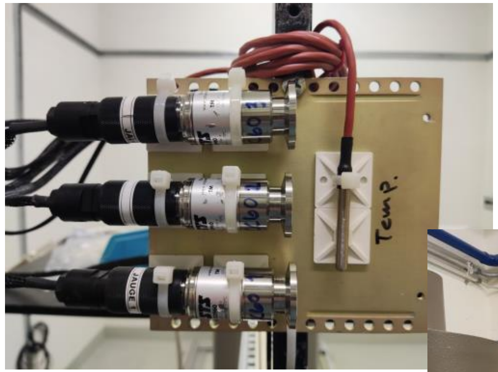
Located in 772 at Prevessin site

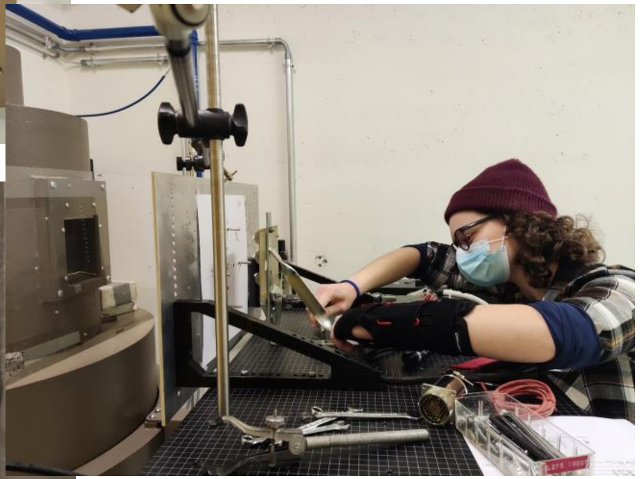
Equipped with a 110TBq gamma source

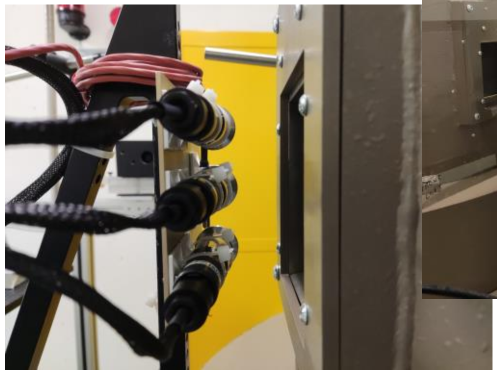
Dose rates from 436 Gy/h to 0.36 Gy/h







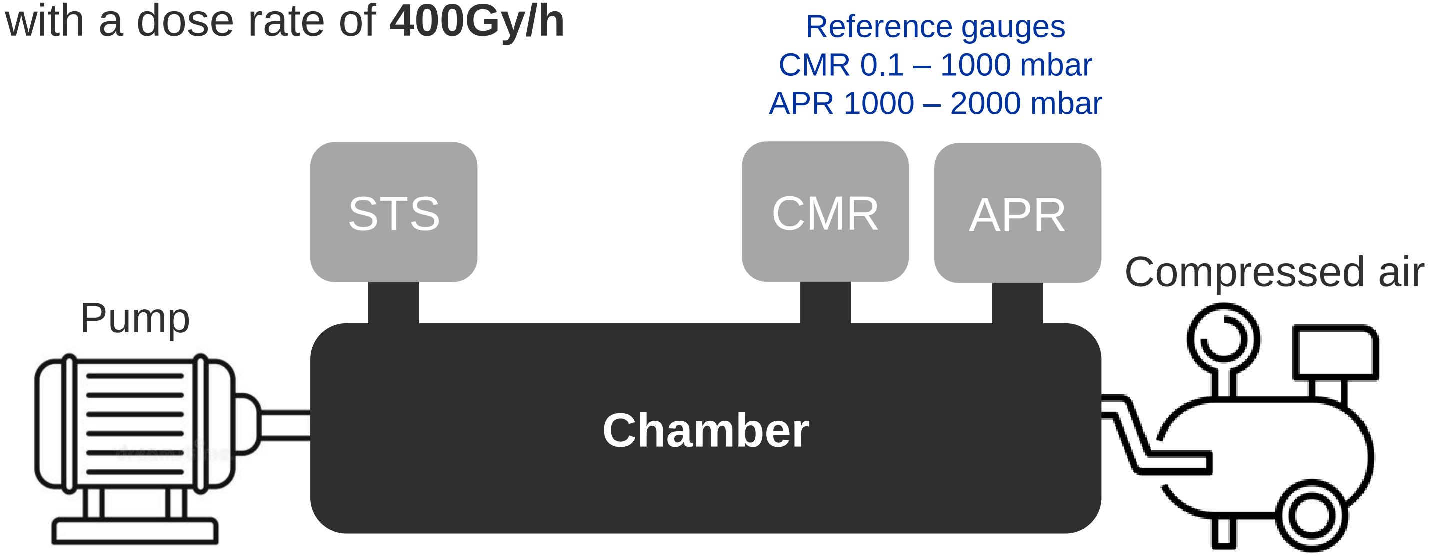




Test procedure

Active Gamma irradiation at atmospheric pressure

- Pre-irradiation leak test (AL4030)
- Pre-irradiation characterization (lab)
- 3 samples and 1 reference with online monitoring every 1s:
  - 1 campaign in **2022** up to **60kGy** with a dose rate of **65Gy/h**
  - 1 campaign in **2023** from 60kGy to **180kGy** with a dose rate of **400Gy/h**
- Post-irradiation leak test (AL4030)
- Post-irradiation characterization (lab)

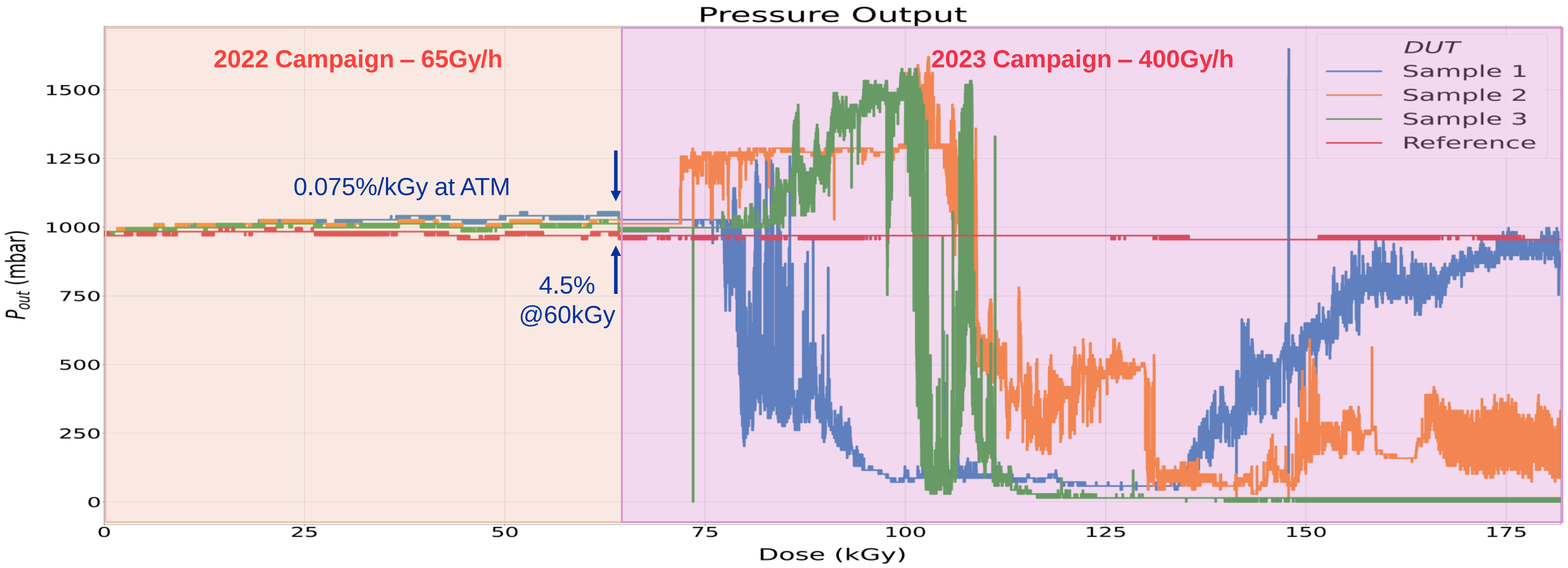


Leak detection pre- and post-irradiation

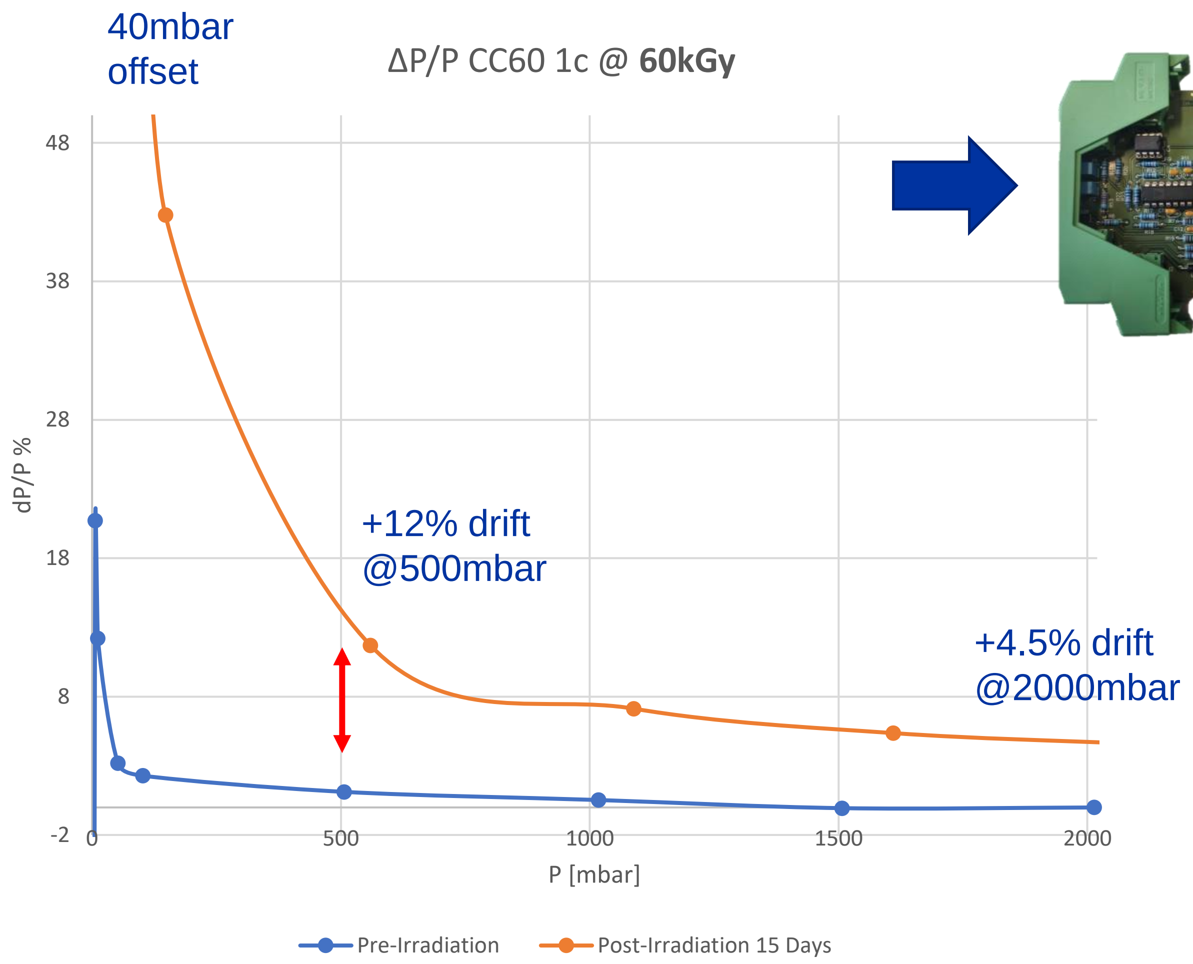
		2022 campaign	2023 campaign
Gauges	**Pre-irradiation** [mbar.l/s]	**Post-irradiation @ 60kGy** [mbar.l/s]	**Post-irradiation @ 180kGy** [mbar.l/s]
Reference	$1{,}3.10^{-7}$	$1{,}3.10^{-7}$	1.10^{-8}
DUT1	$9{,}2.10^{-8}$	$1{,}5.10^{-7}$	$2{,}3.10^{-8}$
DUT2	$9{,}4.10^{-8}$	$7{,}3.10^{-8}$	$7{,}6.10^{-8}$
DUT3	$1{,}2.10^{-7}$	1.10^{-7}	$1{,}7.10^{-8}$

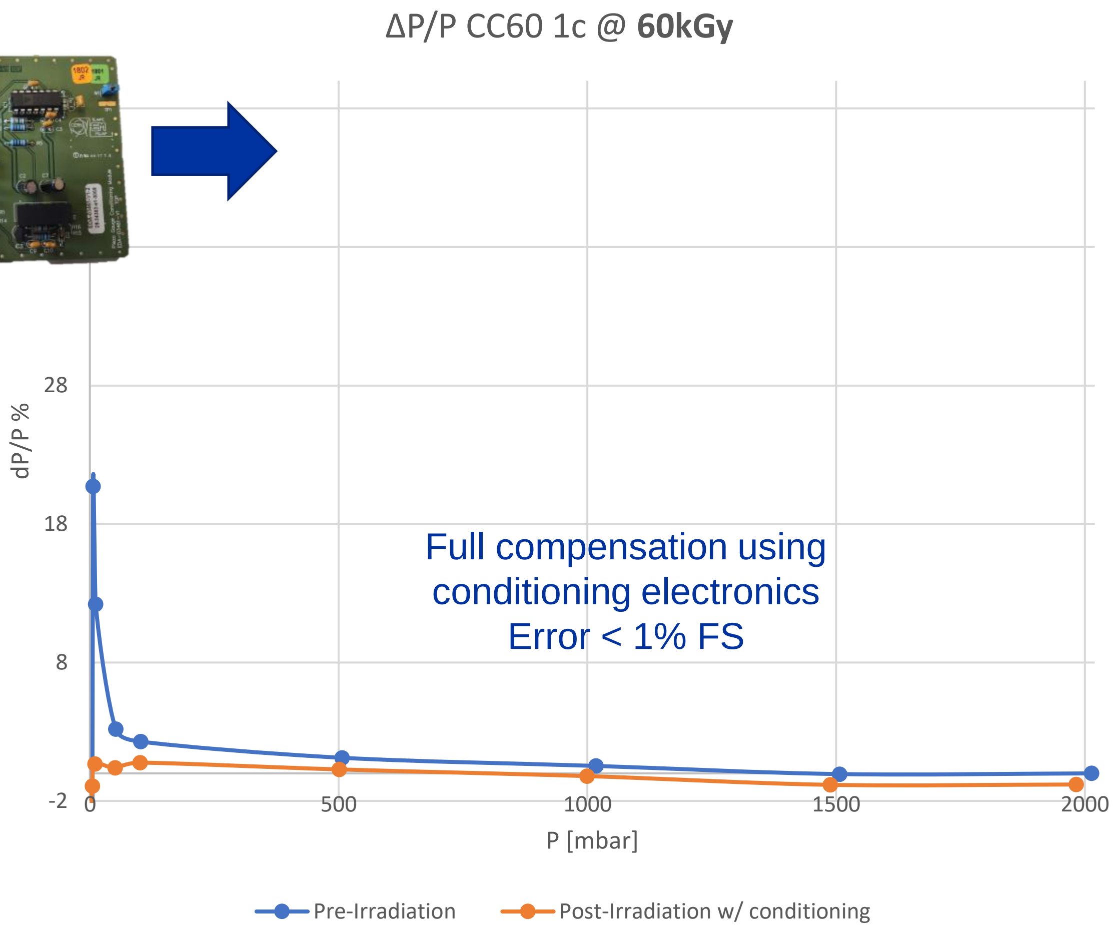
Not increased leak rate due to radiation

Measurement error from the online monitoring



Measurement error from 2022 campaign





Description of issues from 2023 campaign

The gauges start failing during the 2nd campaign at around 70 – 75 kGy

Apart from the very high dose rate (400Gy/h), no other apparent reason for these failures

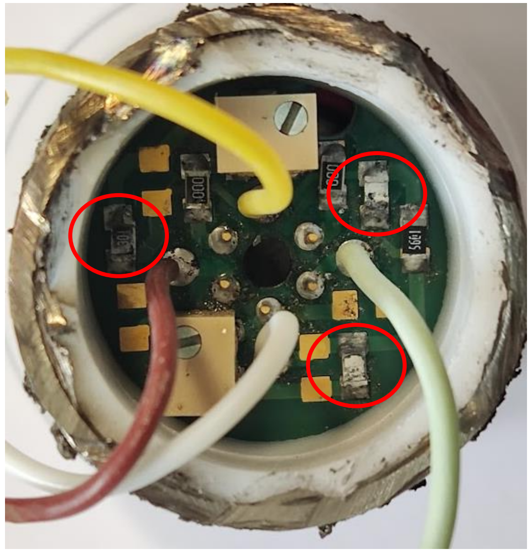
- Control system and cabling cross-checked and OK
- No failure of the reference gauge
- No indication of sudden temperature rise
- Similar behavior to a load changing its resistance

2 DUT sent to STS company for debugging & 1 DUT remained at CERN

Visual inspection

CERN analysis

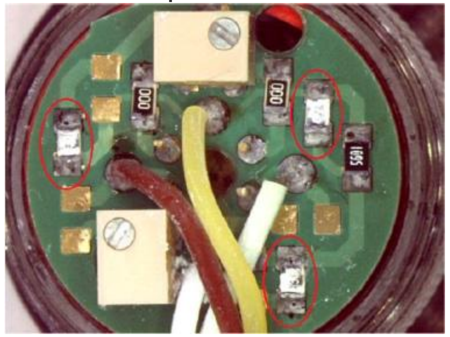
Sample CC60 1C



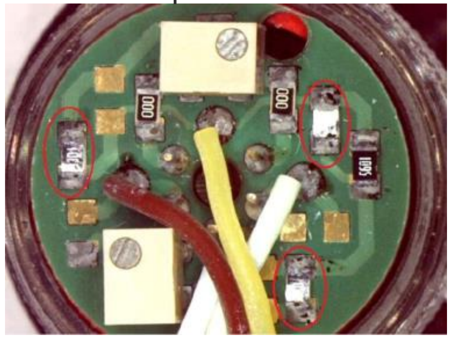
STS analysis

Samples CC60 2C & 3C

Sample CC60 2C



Sample CC60 3C



CERN and STS have seen the same issue for all 3 samples: **resistors!**

CERN analysis

Reverse engineered the PCB

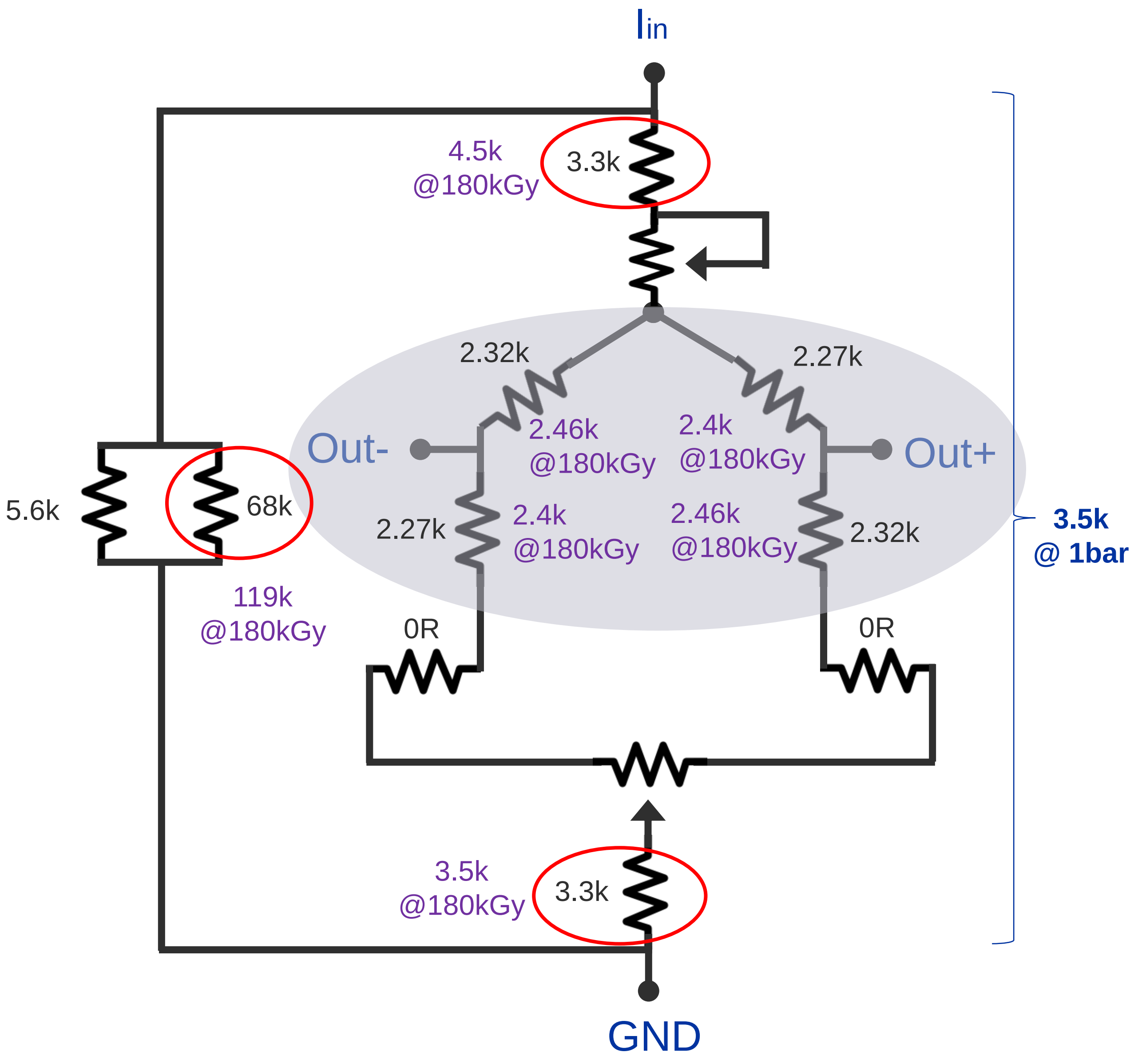
- 3.3k resistors seems to be part of the calibration for gain and offset
- 68k resistor seems to be balancing the bridge (possibly temperature compensation – TBC by STS)

Each individual resistor was measured

- 68k increased to 119k
- 3.3k increased to 4.5k and 3.5k

Measured the measuring cell

- Fully operational with a small resistance deviation
- R ratio from 0Gy to 180kGy deviated by 0.01kOhm



CERN analysis

Understand if the measuring cell is functional

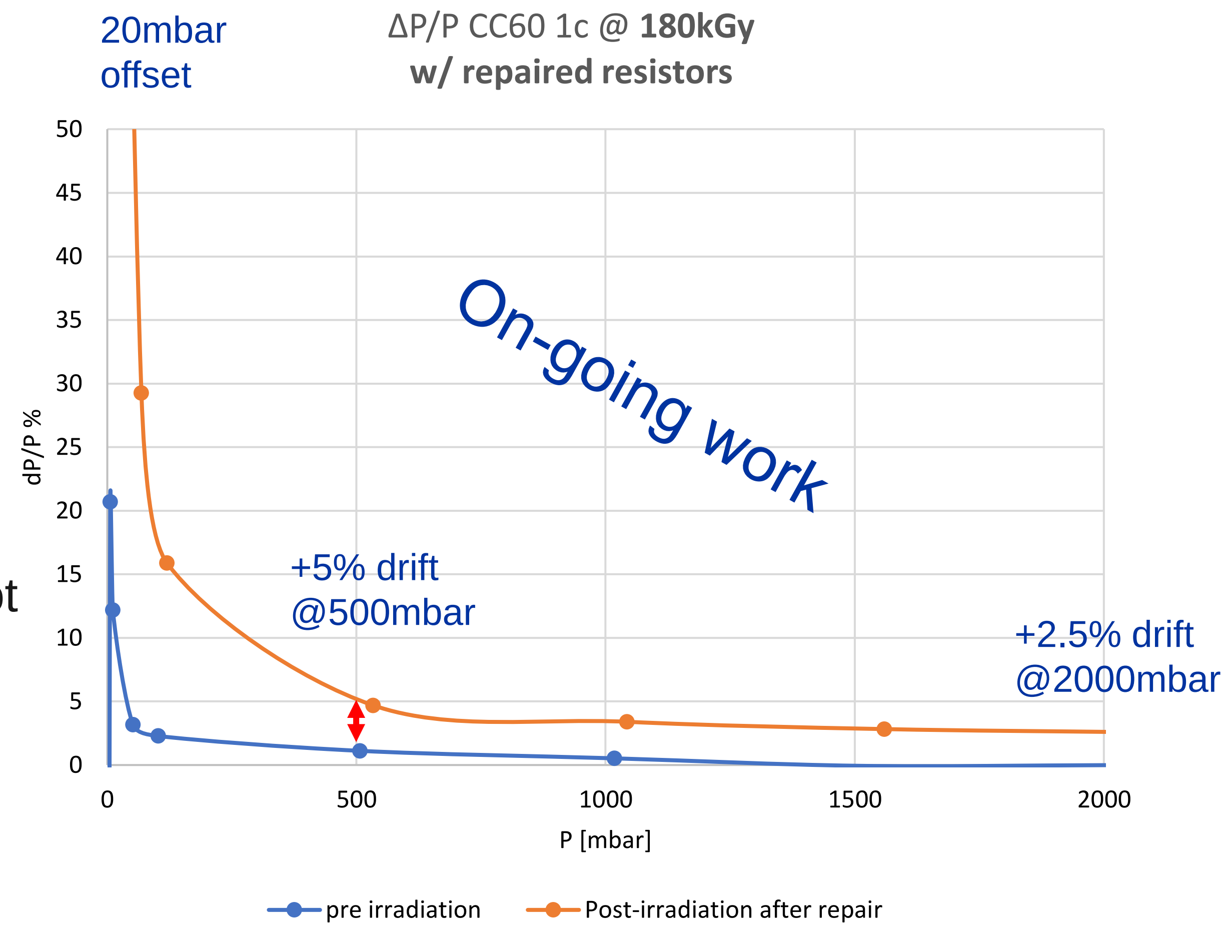
- Replaced all the resistors of the PCB
- Not possible to replace the potentiometers
- Mounted the gauge back to the chamber

The set of cell and potentiometers are degraded but functional

- offset of about 20mbar
- 5% drift at 500mbar
- 2.5% at 2000mbar
- The offset and FS error is less comparing to 60kGy plot

Error can be compensated with the conditioning electronics

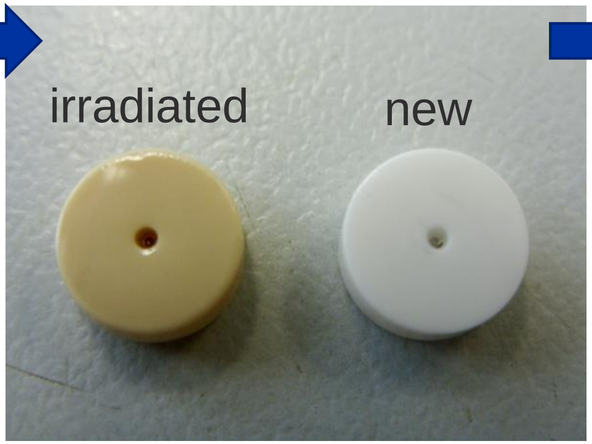
- Compensation works at 60kGy (slide 20)
- To be tested in the lab



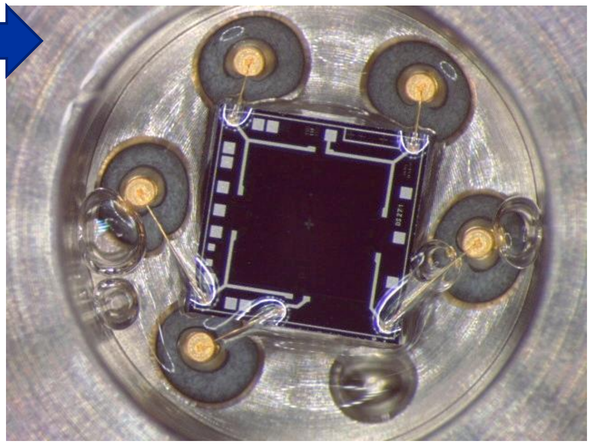
STS analysis

Stainless steel membrane in normal condition

Membrane removed
Discoloration of sintered ceramic



Comparison of sintered ceramic



Chip no abnormality
Viscosity of oil seems unchanged

Degradation of the measuring cell

- Increased bridge resistance from 3.256 to 3.439 kΩ @ 2bar
- Increased errors
- Unable to comment about the contribution of the oil on these results

On-going work

Remarks and conclusions

- **STS makes compatible gauges to the APR which fit well within the control's architecture**
- **The STS gauge show no differences pre- and post-irradiation on leak tightness**
- **The use of oil in the measuring cell is not ideal but can be safely used**
  - Oil can burst only to the outside
  - Burst pressure >200 bar
- **Reasonable errors up to 60kGy**
  - At the beginning of LS offsets may be observed during venting
  - During each LS calibration shall take place (standard procedure)
  - Replacement of gauges when TID of 60-70kGy is reached
    - Small cost impact (gauge < 350CHF)

HL-LHC Location	Annual Dose [kGy/y]	TID [kGy] Run 4	TID [kGy] Run 5
Q2A	2	7	14
DFX	10	35	**70 (replacement)**
D2 & DFM	20	**70 (replacement)**	**70 (replacement)**
CRAB 1	10	35	**70 (replacement)**
CRAB 2	8	28	56 (replacement)
QXL	6	21	42
Q4	2	7	14
Q5	2	7	14
Q6	1	3.5	7
QRL	1	3.5	7

Future work

- **The R2E community at CERN has no explanation so far for the resistor issues**
  - Effort to understand if the high dose rate of the second run had an impact on the resistor failure
  - Several tests are being prepared at CC60 to validate this hypothesis
    - Gauges in HDR and LDR either in active or passive gamma test
    - Test PCBs with a variety of resistors technologies, sizes that can be tested in HDR or LDR
- **Continue the collaboration with STS**
  - Aim to decouple the radiation effects on the chip, on the oil and on the PCB
  - Create a custom product that could replace APR017 and survive the radiation environment of HL-LHC
- **Evaluate other solutions in collaboration with TE-CRG**
  - Baumer strain gauge 0 - 4bar
    - Tested up to 1kGy by TE-CRG
    - Very small sensitivity (1.75 uV/(mbar.mA) vs 25 uV/(mbar.mA) -> has an impact on our electronics)
    - Can be bought in multiples of 100 units (1.3kCHF per gauge)
  - ABB (similar technology with STS; oil filling)
  - Radiation hard gauges from SIGMANETIC and EFE
    - Thin film metal membrane without oil. Very small sensitivity. High price

Thank you!
Any questions?

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