# Radiation tolerant fiber optic sensors for long-term humidity monitoring in the CMS experiment

G. M. Berruti
(University of Sannio and CERN PH-DT-DI)

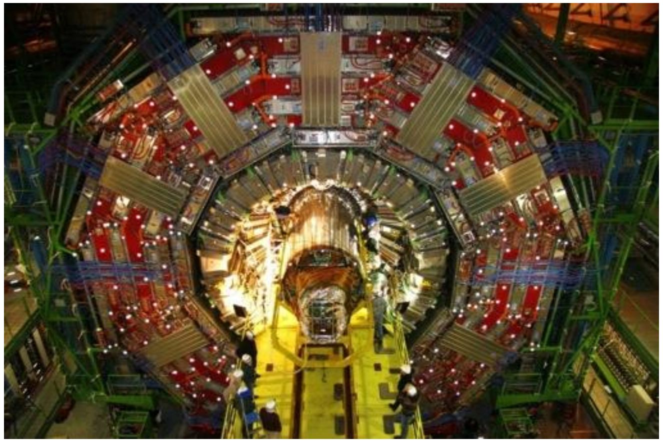
on behalf of FOS4HEP Group

A collaboration of:

# Humidity Sensors Issues in HEP Trackers

**CMS specifications for new generation RH sensors:**

- ✓ Low mass and Small dimensions
- ✓ Insensitivity to magnetic field
- ✓ Environment T down to -10 ˚C and in [0, 100] %RH range
- ✓ Accuracy: better than ±3 %RH
- ✓ Reduced number of wires
- ✓ High long term stability
- ✓ Radiation resistance to dose up to 1 MGy (100 Mrad)



**G. M. Berruti's CERN Doctoral student program (2012) :**

⇨ Funded by :
- CERN PH-DT group
- CMS TC
- CMS TRACKER
- University of Sannio

# Currently at CERN for RH monitoring

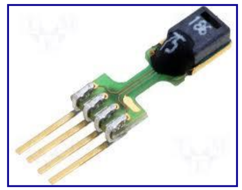
1) Different types of **miniaturized sensors**

(standard capacitive)

**PRECON HS2000**

**HONEYWELL HIH4030**

**SENSIRION SHT75**



**NO-ONE satisfies CERN requirements:**

- Not radiation hard
- “Dead” at absorbed radiation doses ≤ 10 kGy

2) **Remote air sniffers**

Measurements with laboratory instrument on air samples transferred over long distance

**Vaisala DRYCAP Dewpoint Transmitter DMT242**

**Sniffer rack in remote laboratory**

**- No distributed sensing**

**- Only time-averaged measurements provided**

**<u>Our solution: Fiber Optic-based relative humidity sensors</u>**

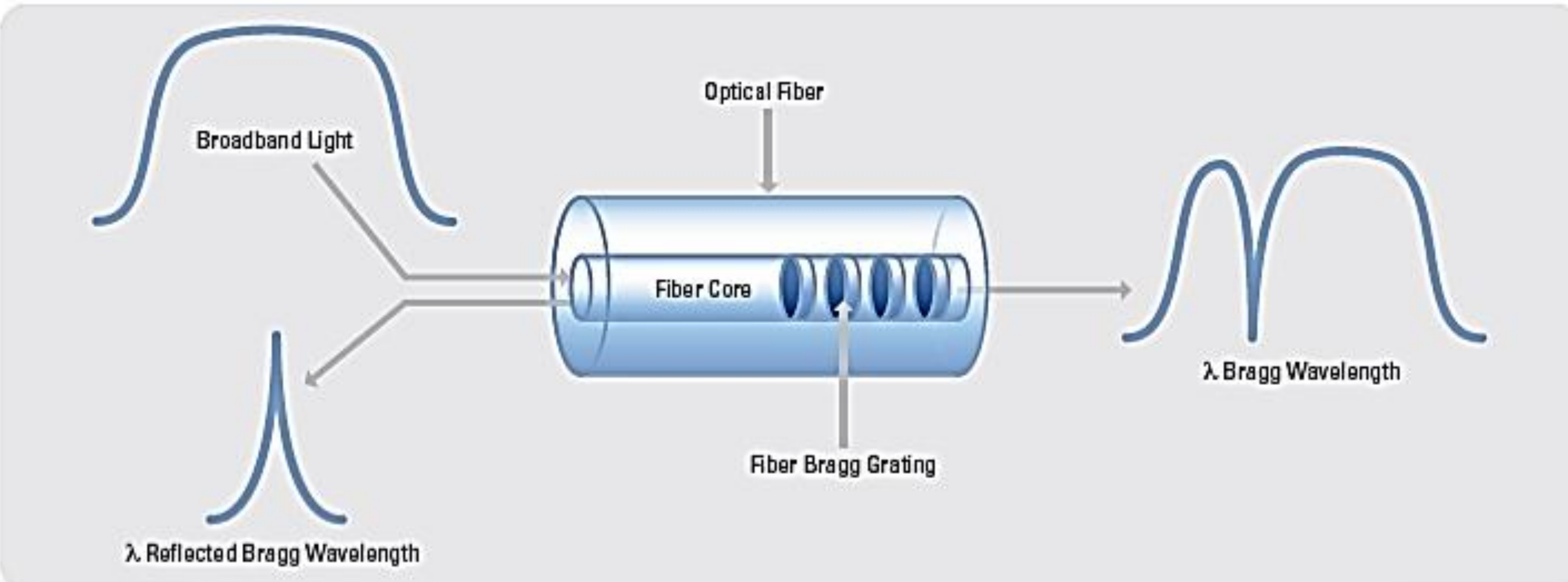
# Fiber Optic Sensors

For a large number of environmental monitoring and industrial applications fiber-optic sensor technology offers several advantages for significant metrological improvement through:

- High sensitivity
- Immunity to electromagnetic interference
- Lightweight
- Possibility to work in harsh environments
- Versatility
- Absence of electronic circuitry in the measurement area

# Fiber Bragg Grating fundamentals

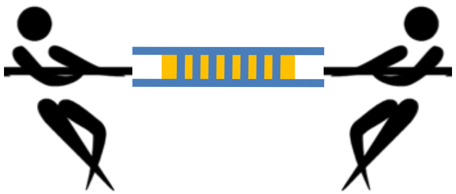
FBG is a permanent periodic modulation of the refraction index in the core of the fiber




$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda$$

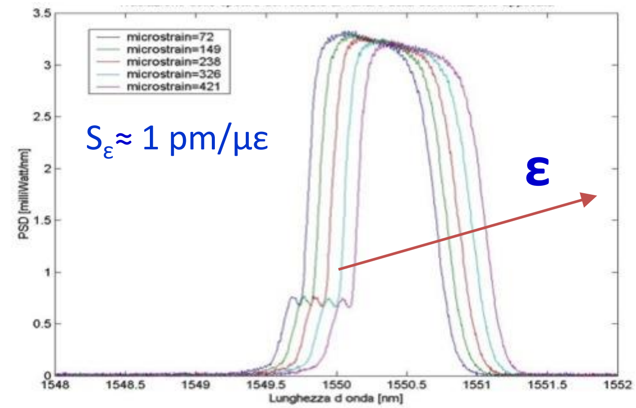
- $n_{eff}$ is the fiber effective refractive index
  ($n_{eff}$ ~ 1.455 in silica)
- $\Lambda$ is the grating pitch
  (typically ~ 500 nm)
- $\lambda_B$ is the reflected Bragg's wavelength

# FBG- based Strain and Temperature Sensors



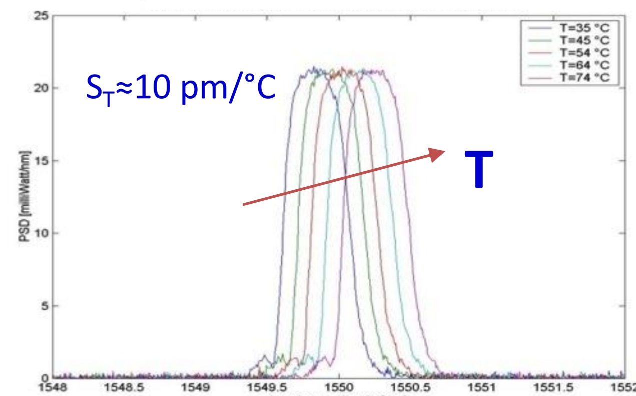
## Strain changes:

- $\Lambda$ via direct deformation
- $n_{eff}$ via elasto-optic effect




## Temperature Changes:

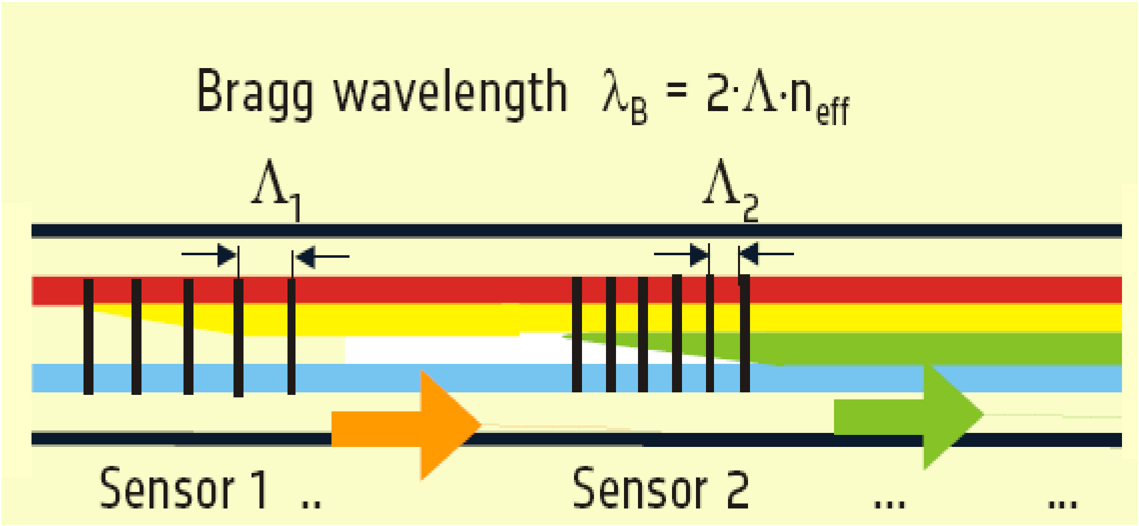
- $\Lambda$ via thermal expansion
- $n_{eff}$ via thermo-optic effect

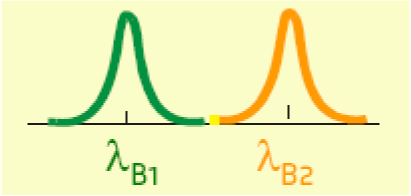



For strain measurements, discrimination between temperature and strain needed:
Strain free reference FBG sensor coupled to another FBG
(**T-Compensation technique**)

- FBG- based Temperature and Strain Sensors already in use in CMS since 2009

# FBG Multiplexing Principle



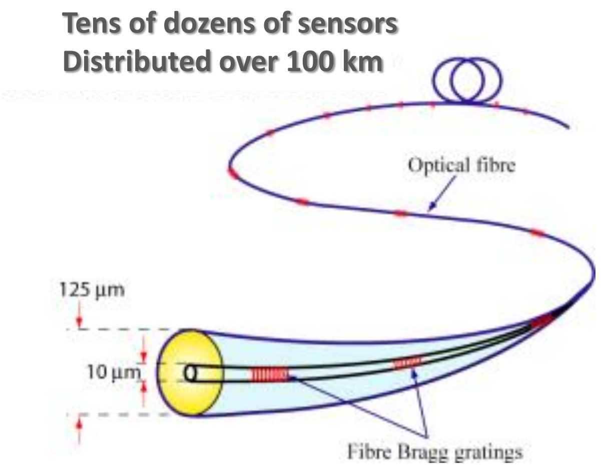

- Up to hundreds of FBG sensors can be realized within a single optical fibers by changing the grating period

$$\Delta\lambda_{B-i}=2n\ \Lambda_i$$

- Maximum number of sensors is ruled by taking into account:
  - spectral range of the light source
  - maximum wavelength shift of each sensor

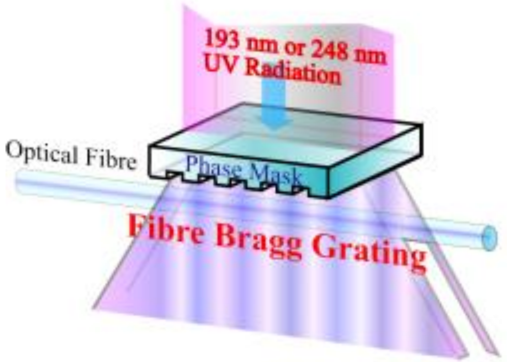
- Typically a dozen of FBGs is a reasonable number

# FBG Sensors: Standardized Technological Platform




## … An attractive sensing solution:

- All the FOS Advantages
- Wavelength encoded
- Linear output
- Multiplexing
- Reduction of cabling complexity
- Multi point Sensing
- Multi parametric sensing

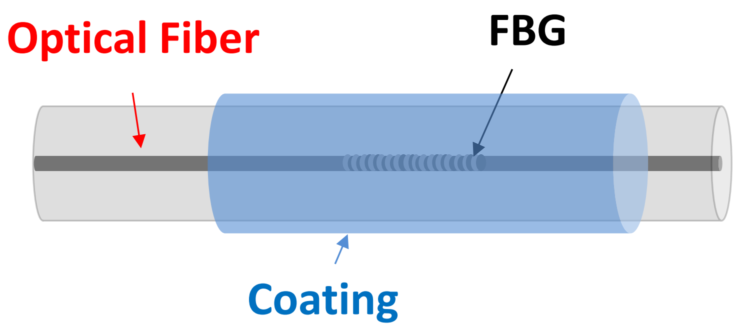


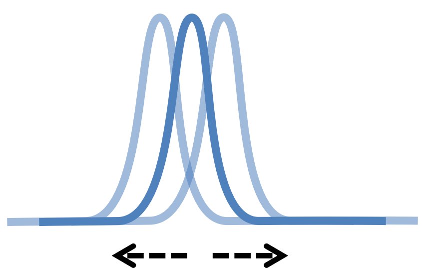
# FBG as multifunctional sensors

**Functionalization**: integration with appropriate materials and suitable packaging to measure physical, chemical and biological parameters

## FBG + COATING:
## <u>Multi-parametric sensing</u>

- Magnetic field
- Humidity
- Cryo temperatures
- Acoustic waves
- Weight
- Chemical and biological analytes
- ....



Bragg wavelength Shift

# FBG-based sensors for CERN

**FOS Community:**

academic and industrial partners

**CERN:**

CMS Experiment
PH-DT Group
LHC
TE-MSC Group

High Luminosity LHC
CERN PH – DT Detector Technologies
Università degli Studi del Sannio
INFN
CMS
MTA atomki Debrecen
optosmart

# FOS4HEP collaboration from 2009:

**R&D on:**

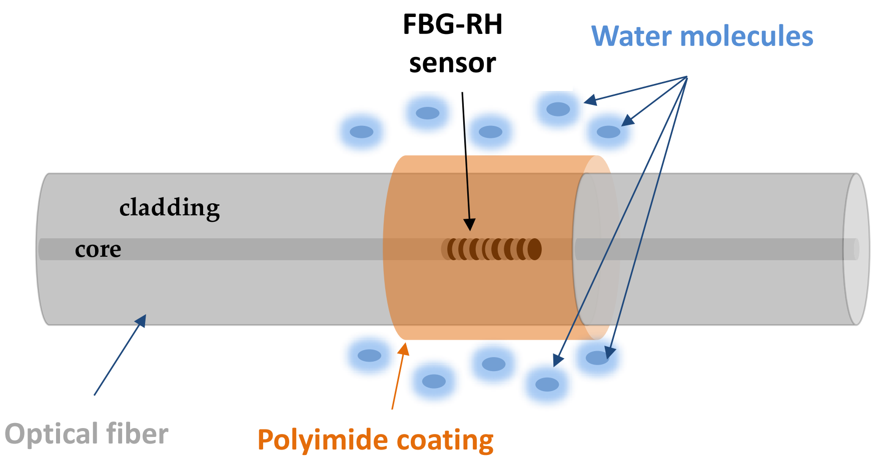
- RH- FOS based sensors
- T and strain FBG-based sensors
- T and strain FBG-based sensors for superconductive magnets
- B-field FBG-based sensors
- Dosimetry

# FBG-based relative humidity sensors

- Bare FBGs are insensitive to humidity
- Use of a sensitive material as coating of the FBG to induce a mechanical effect
- Hygroscopic polymers swell upon adsorption of water molecules

**Development of humidity sensor by coating the FBG with a polyimide film**

Water molecules absorbed by the hygroscopic coating → Coating expansion ("Swelling effect") → Strain induced on the FBG → Bragg wavelength shift ($\Delta\lambda_B$)



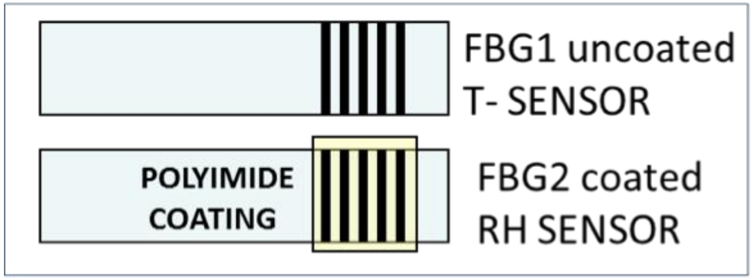
# Temperature compensation

- Polyimide-coated FBGs intrinsically sensitive to temperature:

$$\Delta\lambda_B = f(\Delta T, \Delta RH) = S_T(T, RH)\cdot\Delta T + S_{RH}(T, RH)\cdot\Delta RH$$

- Temperature compensation scheme required to extract RH measurements from the sensor readings

**Final configuration of FBG-based thermo-hygrometers developed for CMS**:
2 FBGS coupled side by side
(1 poly-coated and 1 bare)




# ..Use of FBG as RH sensor not new in literature..

**Relative humidity sensor with optical fiber Bragg gratings**


Pascal Kronenberg and Pramod K. Rastogi

*Institute of Structural Engineering and Mechanics, Swiss Federal Institute of Technology, CH-1015 Lausanne, Switzerland*

Philippe Giaccari and Hans G. Limberger

*Institute of Applied Optics, Swiss Federal Institute of Technology, CH-1015 Lausanne, Switzerland*



Received February 20, 2002

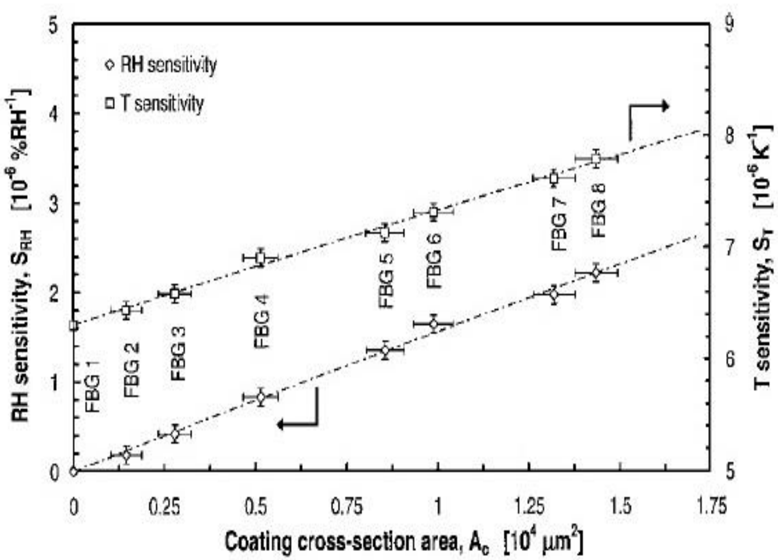

**Characterisation of a polymer-coated fibre Bragg grating sensor for relative humidity sensing**

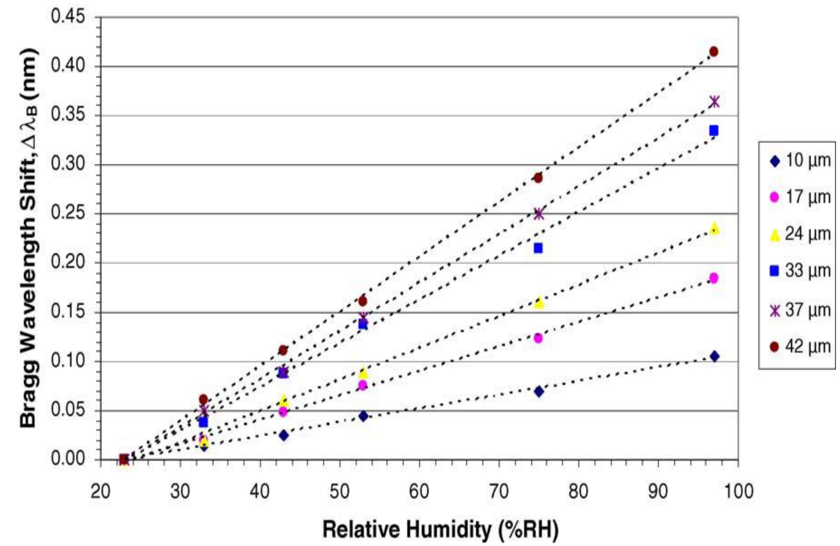

T.L. Yeo [a,*], T. Sun [a], K.T.V. Grattan [a], D. Parry [b], R. Lade [b], B.D. Powell [b]

[a] *School of Engineering and Mathematical Sciences, City University, Northampton Square, London, EC1V 0HB, UK*
[b] *Kidde Plc, Colnbrook, Berkshire, SL30HB, UK*



Received 17 November 2004; accepted 24 January 2005
Available online 19 February 2005


- RH measurements limited to [10, 65] °C and [0-10] %RH ranges
- Completely unexplored the effect of ionizing radiations

# Optoelectronic interrogation system

- Commercial optoelectronic interrogation system
- Same interrogator already in use at CMS for T/strain FBG-based sensors


**FOS interrogation system in PH-DT laboratory**

## Optical Sensing Interrogator | sm125

MICRON OPTICS

| Specifications | sm125-200 | sm125-500 | sm125-700 |
|---|---|---|---|
| **Optical Properties** | | | |
| Number of Optical Channels [1] | 1 (up to 16) | 4 (up to 16) | 4 (up to 16) |
| Scan Frequency | 1 Hz | 2 Hz | 5 Hz |
| Wavelength Range | 1520-1570 nm | 1510-1590 nm | 1510-1590 nm |
| Wavelength Accuracy [2] | 10 pm | 1 pm | 2.5 pm |
| Wavelength Stability [3] | | | |
| Wavelength Repeatability [4] | 1 p | | |
| Dynamic Range [5] | | | |
| Full Spectrum Measurement | | | |
| Internal Peak Detection Mode | | | |
| Optical Connectors | | | |
| **Data Processing Capabilities** | | | |
| Interfaces | | | |
| Protocols | | | |
| Remote Software | | | |
| LabVIEW™ Source Code | | | |
| Enhanced Data Management | | | |
| **Mechanical, Environmental, Electrical Pr** | | | |
| Dimensions; Weight | | | |
| ; Humidity | | | |
| Humidity | | | |
| | | | |
| 12V | | | |

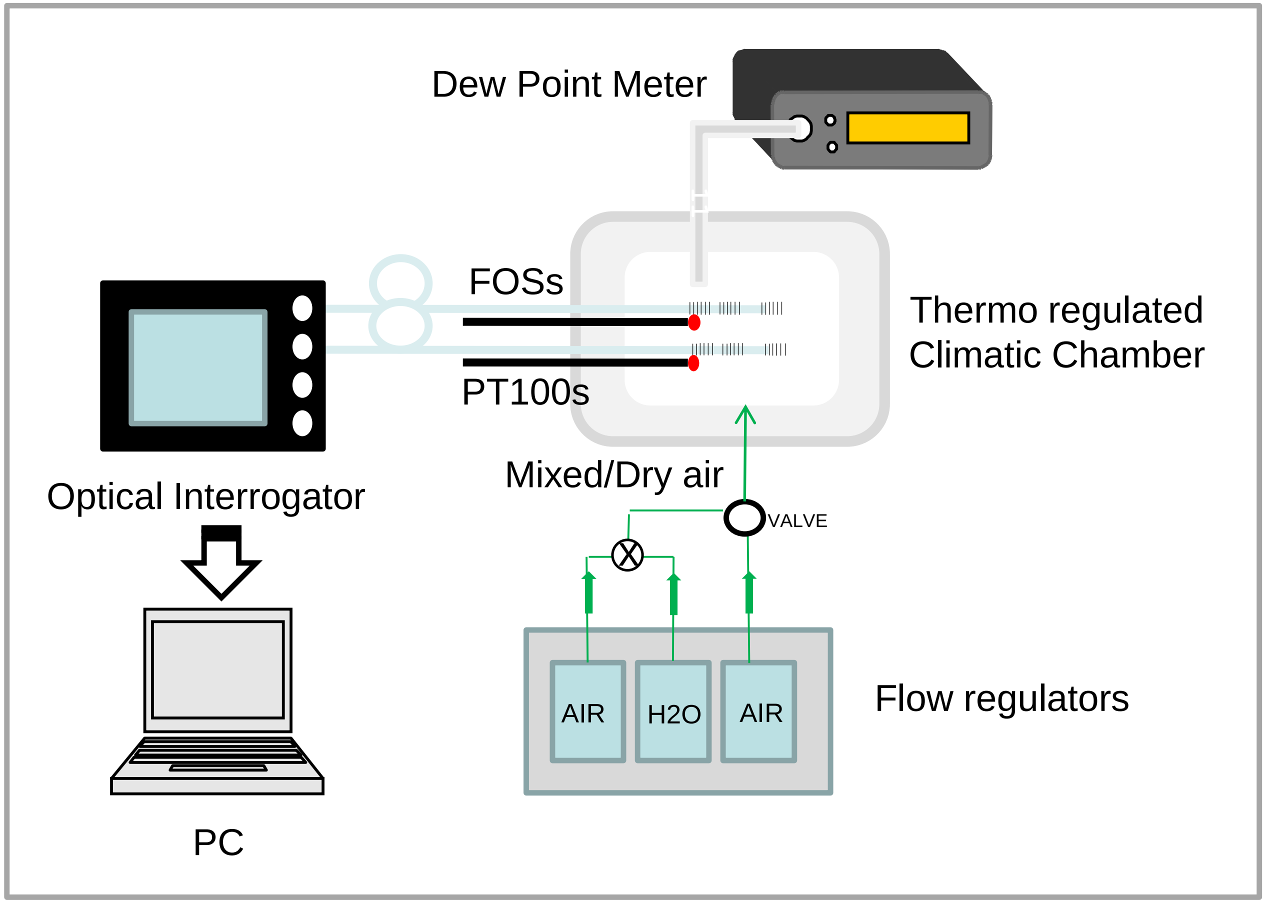
## Optical Sensing Interrogator | sm225

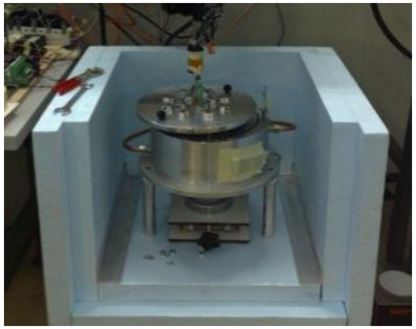
| Specifications [1] | sm225-200 | sm225-500 | sm225-800 |
|---|---|---|---|
| **Optical Properties** | | | |
| Number of Optical Channels | 1 | 4 | 16 |
| Scan Frequency | 1 Hz | 2 Hz | 0.5 Hz |
| Wavelength Range | 1520-1580 nm | 1510-1590 nm | 1510-1590 nm |
| Wavelength Accuracy [2] | 10 pm | 1 pm | 1 pm |
| Wavelength Stability [3] | 5 pm | 1 pm | 1 pm |
| Wavelength Repeatability [4] | 1pm at 1Hz | 0.5pm at 1Hz, 0.2 pm at 0.1Hz | 1pm at 0.5Hz |
| Dynamic Range [5] | 40dB | 50 dB | 40dB |
| Typical FBG Sensor Capacity [6] | 15 | 80 | 320 |
| Full Spectrum Measurement | | Included | |
| Internal Peak Detection Mode | | Included | |
| sm041 Switch Compatible | No | No | Switches internal |
| Optical Connectors | | FC/APC (E2000 available) | |
| **Data Processing Capabilities** | | | |
| Interfaces | | Ethernet - other interfaces available via an optional Internal Sensing Processor | |
| Protocols | | Custom Micron Optics protocol via Ethernet | |
| Remote Software | | Spectral analysis, peak detection, data logger, peak tracking, and instrument control | |
| LabVIEW™ Source Code | | Allows for customization of remote software | |
| Enhanced Data Management | | ENLIGHT Sensing Analysis Software | |
| **Mechanical, Environmental, Electrical Properties** | | | |
| Dimensions; Weight | | 435 mm x 442 mm x 45 mm; 4.1 kg (9 lbs max) | |
| Rack Mount Hardware | | Included | |
| Operating Temperature; Humidity | | 0° to 50°C; 0 to 80%, non-condensing | |
| Storage Temperature; Humidity | | -20° to 70°C; 0 to 95%, non-condensing | |
| Input Voltage | | 7 - 36 VDC (100~240 VAC, 47~63Hz), AC/DC converter included | |
| Power Consumption at 12V | | 20 W typ, 30 max | |


**Rack Mount Module**
-16 channels available
-Hundreds of sensors readable

# PH-DT experimental set-up

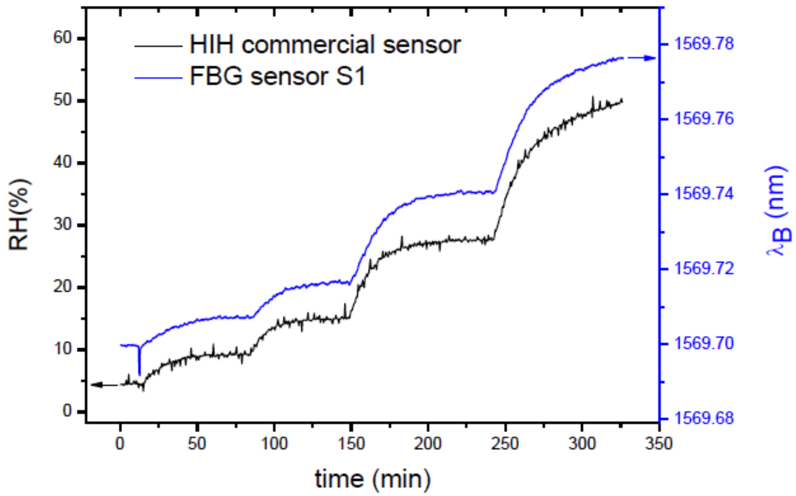
- RH-FOS interrogation setup available in Crystal Palace



# Investigations @ CERN about RH-FBG sensors from 2011

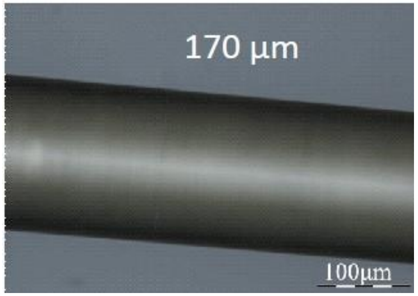
## Response at 20°C




G. Berruti's Master thesis:
- 5 months stage in PH-DT group

**Radiation Hard Humidity Sensors for High Energy Physics Application using Polyimide-coated Fiber Bragg Gratings Sensors**

G. Berruti, M. Consales, M. Giordano, L. Sansone, P. Petagna, S. Buontempo, G. Breglio, and A. Cusano (Sensors and Actuators B: Chemical, 2012)

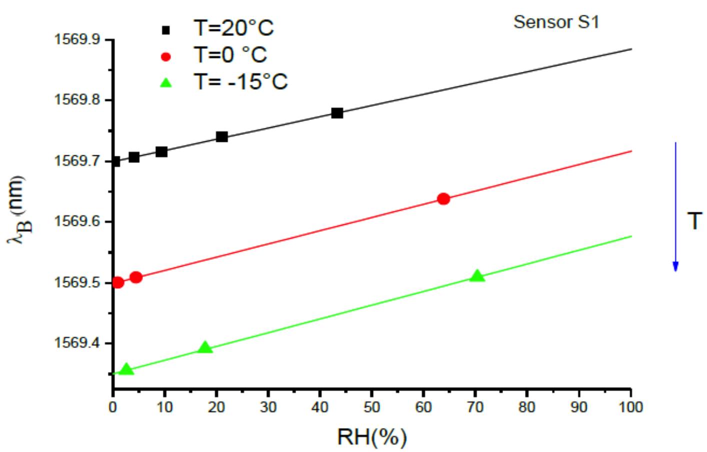



Optical microscope image of sample S1 (~23µm-thick coating)

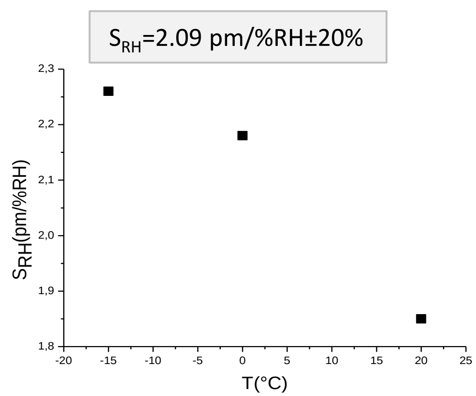
## In-house fabricated sensor:

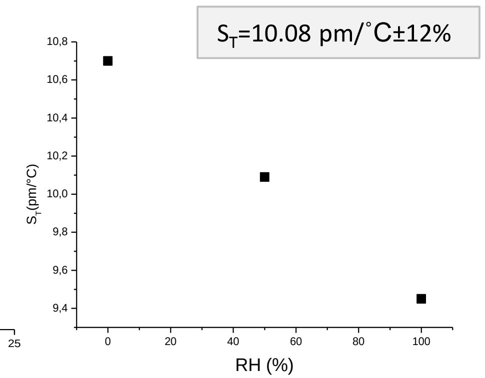
- multiple dip coating
- oven curing cycles
- polyimide: PI2525 HD Microsystem Pyralin 12

## Characteristic curves




## T and RH Sensitivities




Slight dependence of $S_{RH}$ on T and $S_T$ on RH !!

# Issues Related to Radiation Tolerance

2 categories of <u>commercial electronic humidity sensors</u>

→ Sensitive to radiations

→ Not resistant to radiations
(“Die” in presence of radiations)

⇒ NO COMMERCIAL SENSORS AVAILABLE ON THE MARKET SUITABLE FOR HEP APPLICATIONS!!

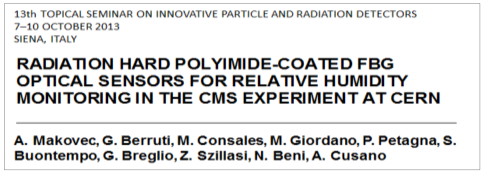
- FBGs are resistant to radiations
- FBGs are not insensitive to radiations

Depending on:
- Writing technique
- Type of fiber
- …

(F. Berghmans et al ,Fiber bragg grating sensors in nuclear environments, in: A. Cusano et al, Fiber Bragg Grating Sensors:Recent Advancements, Industrial Applications and Market Exploitation, Bentham Science Publishers, , Ch. 12 (2011) 218-237 )

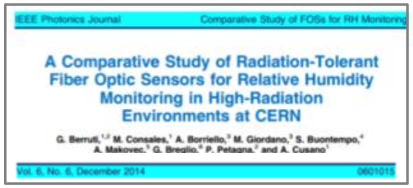
**Are FBG-based thermo-hygrometers suitable for HEP applications?**

# FBG-based thermo-hygrometers under radiation


13th TOPICAL SEMINAR ON INNOVATIVE PARTICLE AND RADIATION DETECTORS
7–10 OCTOBER 2013
SIENA, ITALY

RADIATION HARD POLYIMIDE-COATED FBG OPTICAL SENSORS FOR RELATIVE HUMIDITY MONITORING IN THE CMS EXPERIMENT AT CERN

A. Makovec, G. Berruti, M. Consales, M. Giordano, P. Petagna, S. Buontempo, G. Breglio, Z. Szillasi, N. Beni, A. Cusano


IEEE Photonics Journal    Comparative Study of FOSs for RH Monitoring

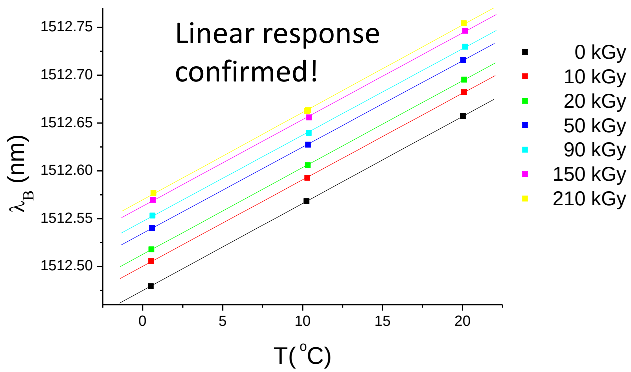
A Comparative Study of Radiation-Tolerant Fiber Optic Sensors for Relative Humidity Monitoring in High-Radiation Environments at CERN

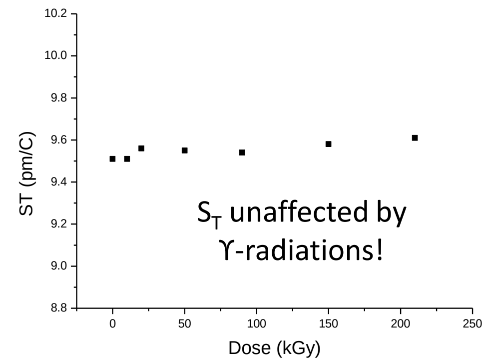
G. Berruti, M. Consales, A. Borriello, M. Giordano, S. Buontempo, A. Makovec, G. Breglio, P. Petagna, and A. Cusano

Vol. 6, No. 6, December 2014    0601015

## Ceramic Packaged FBG T-sensors

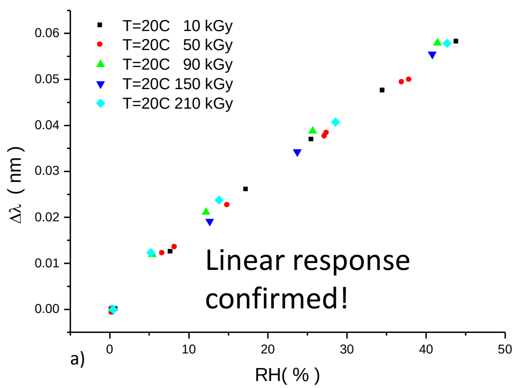
- Commercial Micron Optics (0s4310)
- Irradiated up to 210 kGy
- Negligible variations of $S_T$
- Radiation-induced shift to be taken into account

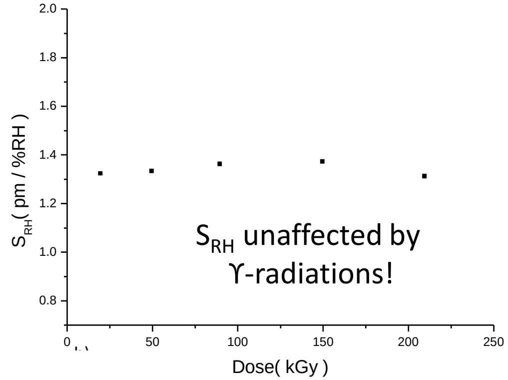


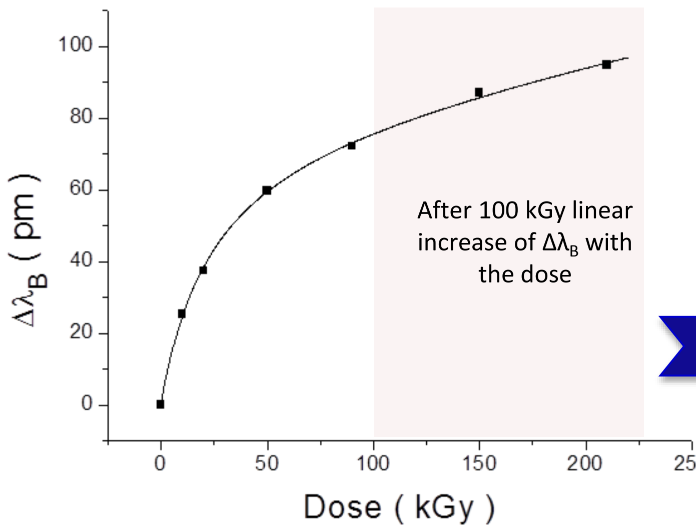

## Poly- Coated FBG RH sensors

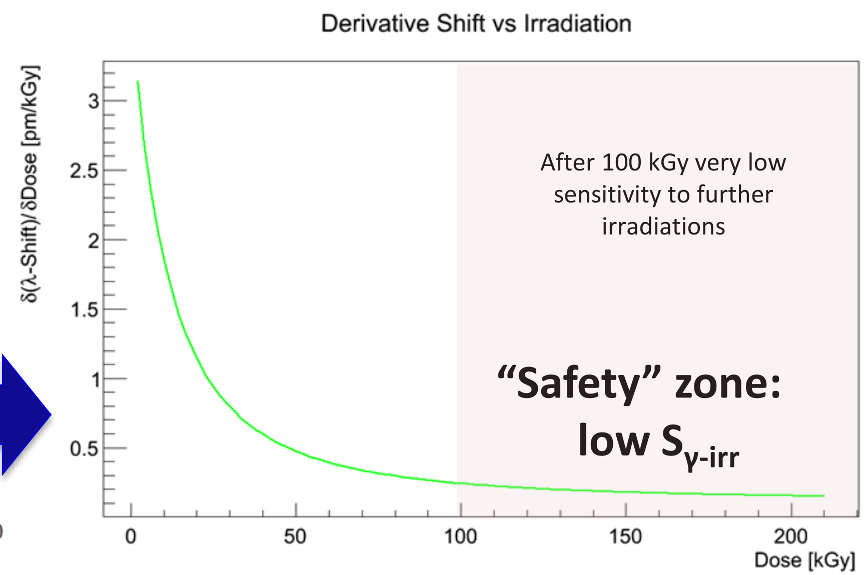
- Commercial sensors (Welltech)
- Coating thickness:10 µm (nominal)
- Irradiated up to 210 kGy
- Sensing performances unchanged
- Radiation-induced shift to be taken into account



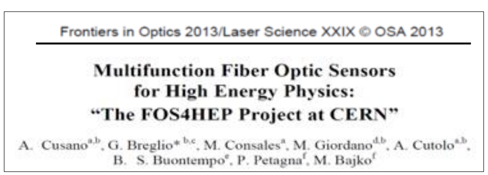



# Engineered FBG sensors for radiation tolerance



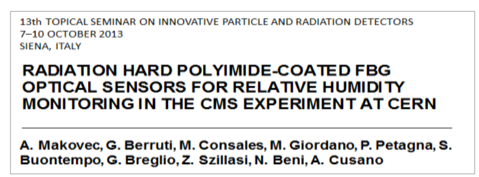




**Pre-irradiation of FBGs is suggested to bring them in the "Low $S_{irr}$ zone" before installation in high radiation environments**


Frontiers in Optics 2013/Laser Science XXIX © OSA 2013

Multifunction Fiber Optic Sensors for High Energy Physics: "The FOS4HEP Project at CERN"

A. Cusano[a,b], G. Breglio[b,c], M. Consales[a], M. Giordano[d,b], A. Cutolo[a,b], B. S. Buontempo[e], P. Petagna[f], M. Bajko[f]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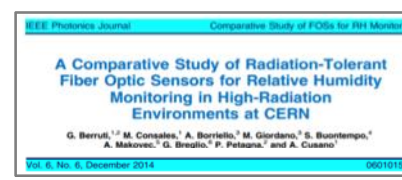
IEEE Photonics Journal — Comparative Study of FOSs for RH Monitoring

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Vol. 6, No. 6, December 2014 — 0601015

- <u>**Commercial capacity RH sensors permanently damaged before the 10 kGy dose**</u>

10 kGy absorbed dose corresponds to 2 years of LHC activity considering ( from Fluka Simulations):
- Luminosity of 100 fb-1
- Sensors 40 cm distant from the beam pipe

# FOS installation in CMS tracker (1)

For the collected very promising results:

CMS Tracker financed in 2012 the purchasing of 80 optical FBG-based thermo-hygrometers for **TEMPERATURE, RELATIVE HUMIDITY and DEW POINT MAPPING** in front of the tracker volume of the experiment

- Design
- Manufacturing
- Quality control

OPTOELECTRONICS group University of Sannio

Consiglio Nazionale delle Ricerche

optosmart

- Calibration and testing Before/After Irradiation
- Installation in the experiment
- Monitoring

CERN PH-DT Detector Technologies

OPTOELECTRONICS group University of Sannio

INFN

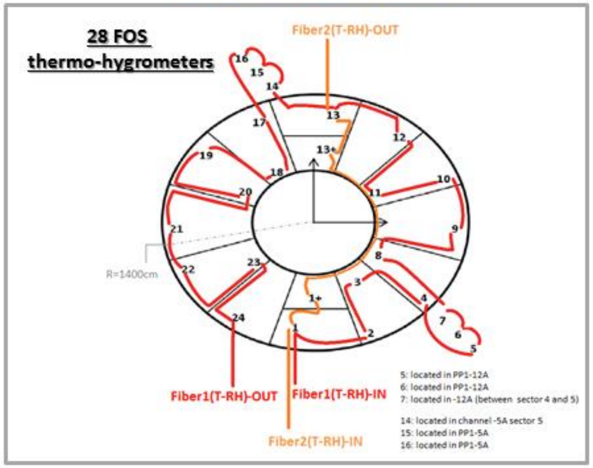
MTA atomki DEBRECEN

Università degli studi di Napoli Federico II

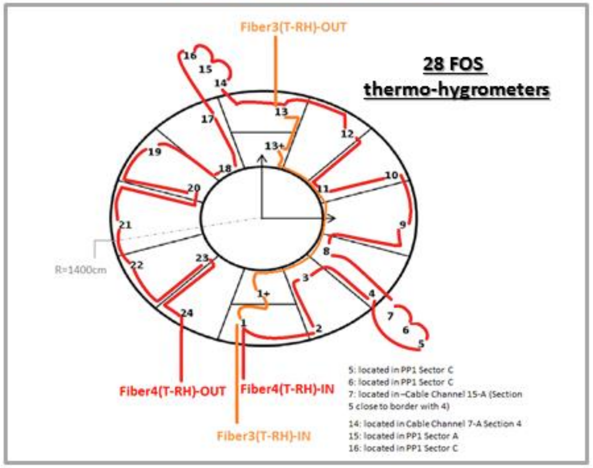
# FOS installation in CMS tracker (2)

**72 FBG- based thermo-hygrometers installed in CMS Tracker, providing a full map of T, RH and DPT in the volume**

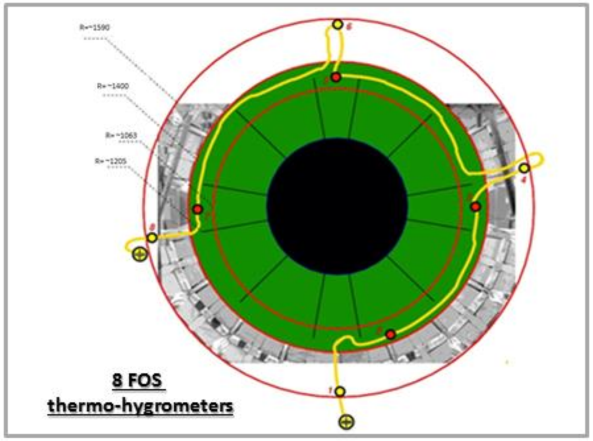
### Z- Bulkhead Inside



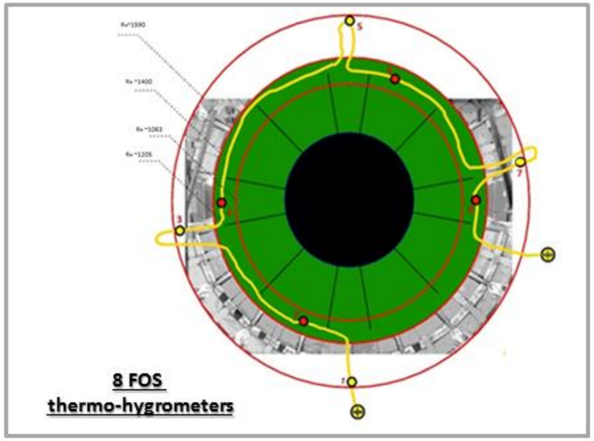

### Z+ Bulkhead Inside




### Z- Bulkhead Outside



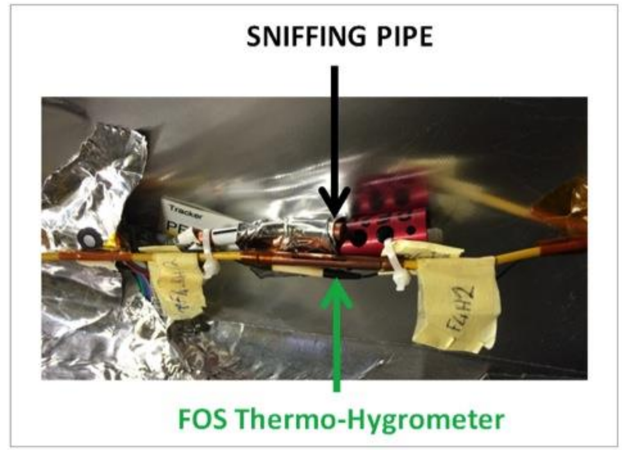

### Z+ Bulkhead Outside




FOS <u>pre-irradiated at **210 kGy**</u> before installation to reduce the cross sensitivity due to irradiation

# FOS installation in CMS tracker (3)

- FOS coupled to commercial T+RH sensors (read out with ARDUINO microcontrollers) for cross-checks during LS1
- On the volume, a few sniffing points also available for comparisons

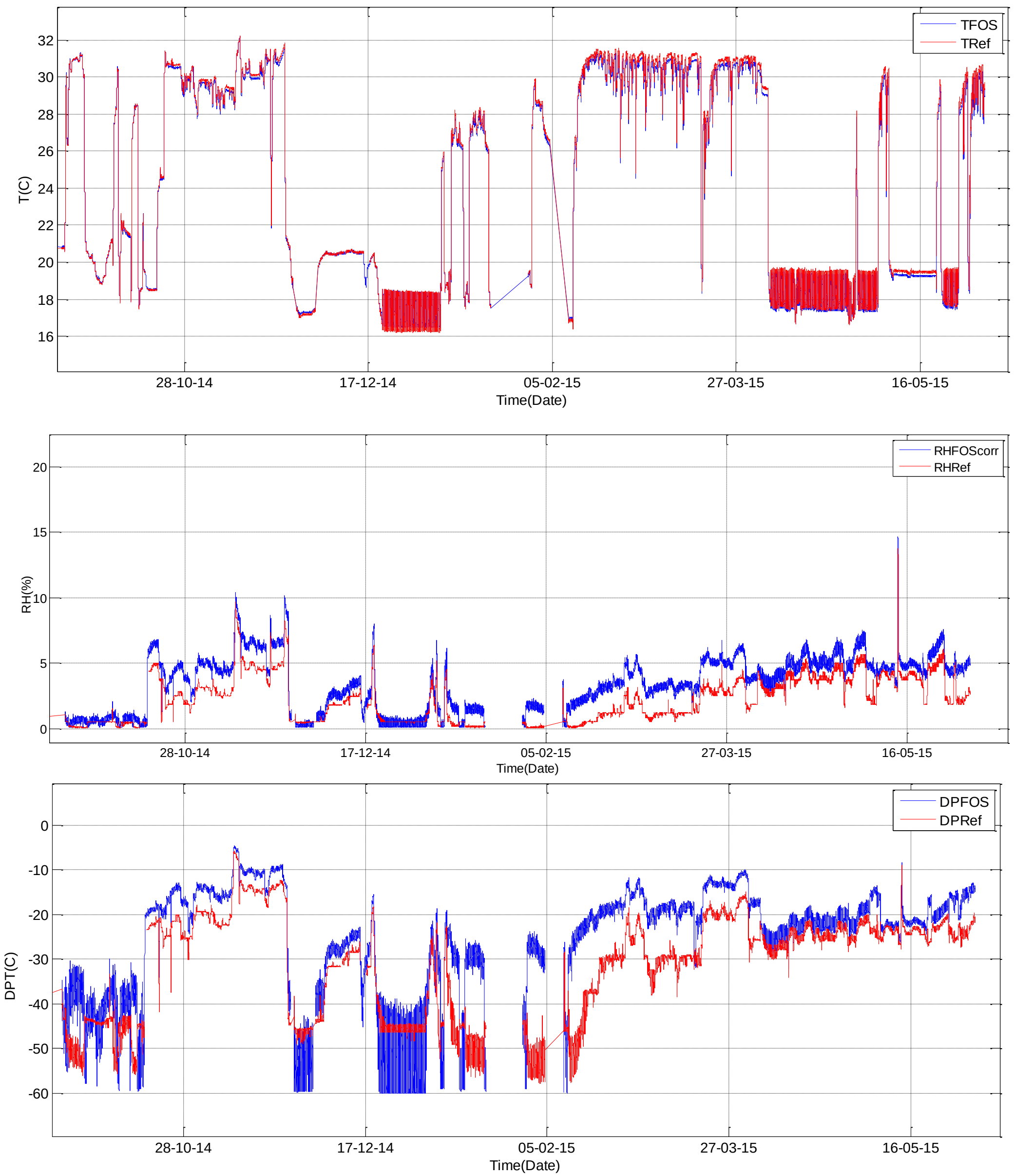



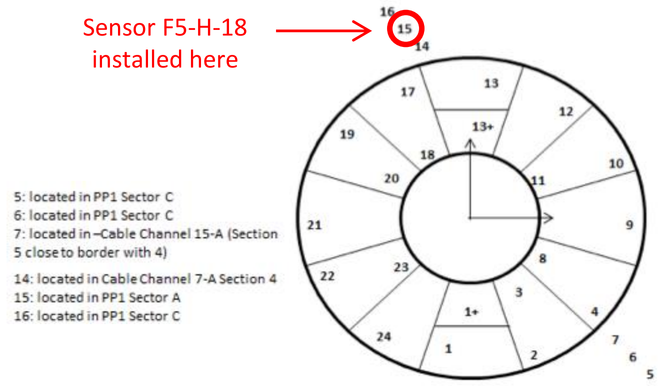

**Commercial RH+T sensors**: expected to "die" for LHC operations, depending on the absorbed dose

**Remote air SNIFFING**: not influenced by LHC collisions but no distributed sensing or T/RH/DTP mapping provided

**FOS-based sensors**: demonstrated to be **TOLERANT TO RADIATIONS**, will provide full mapping of T/RH/TDP in the volume even during LHC operations

# First example of FBG-RH sensors in operation in CMS



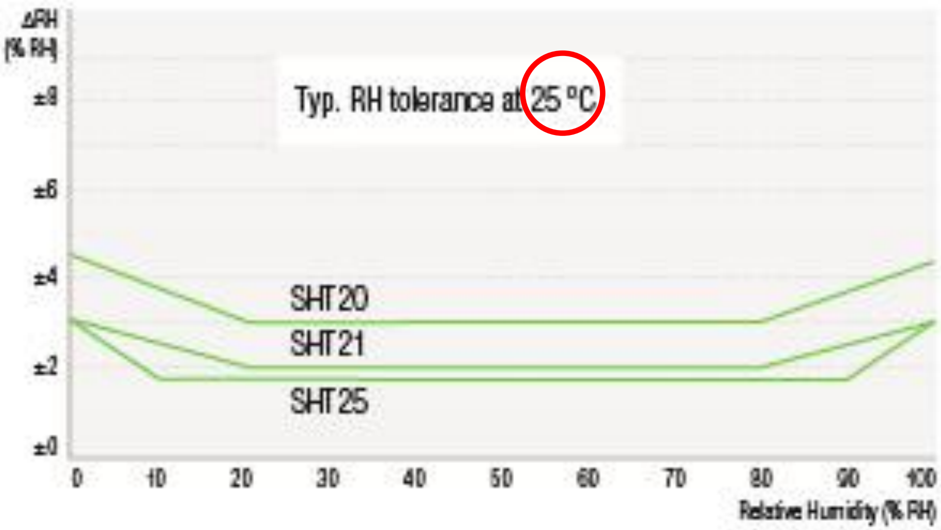

- 9 months of measurements (October 2014 - June 2015)
- Sniffer not available in the installation point
- Commercial based DP sensor coupled to the FOS:
  - expected to die with LHC collisions

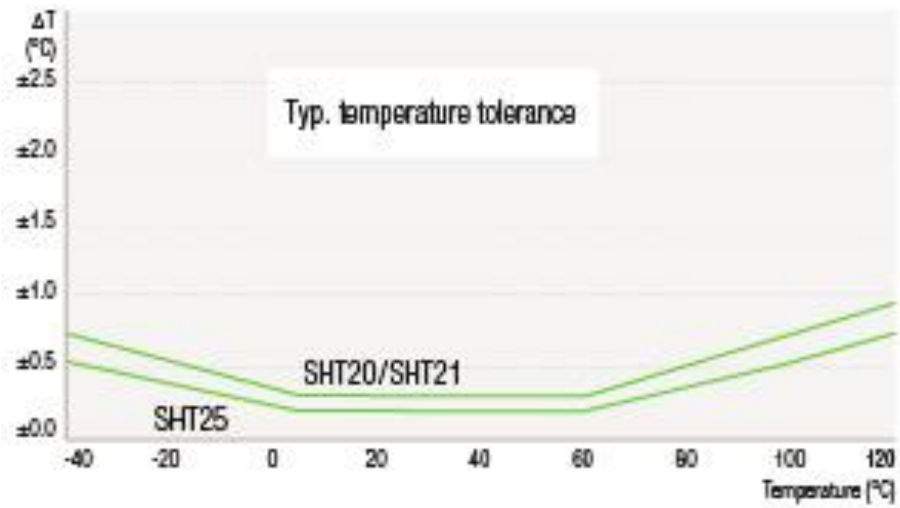
**FBG-based thermo-hygrometer will be the only sensor to provide T, RH and DPT readings during RUN2**

# Benchmark in the RH sensors market

**SHT2X:**
- Developed by Sensirion
- Considered as high-end model of new generation of digital RH+T sensors

## Declared behaviour of Sensirion SHT2X

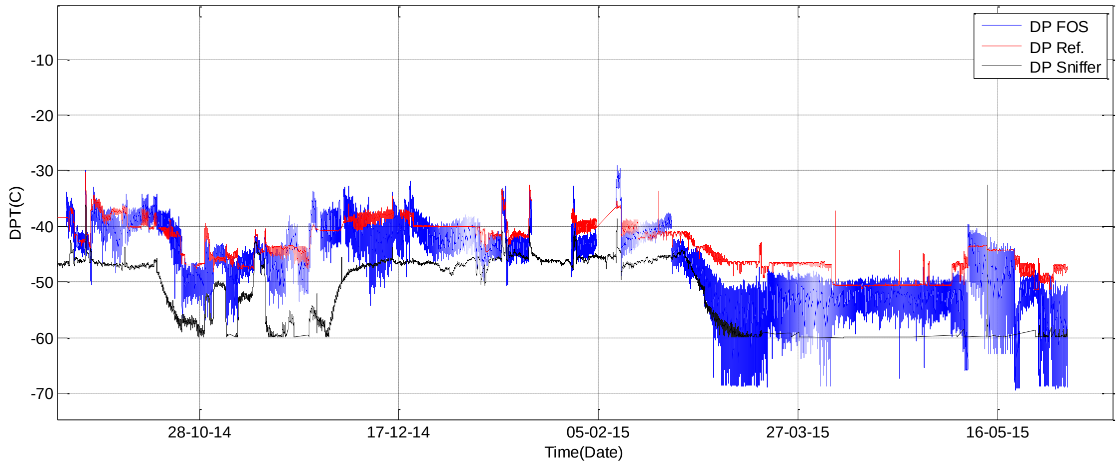


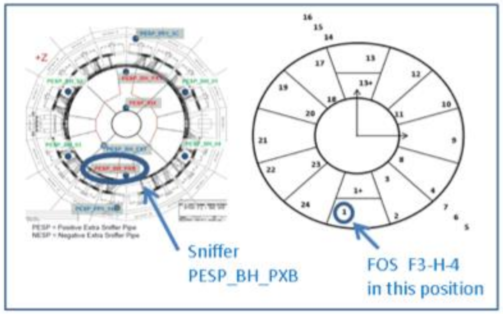




- RH Accuracy values exclude hysteresis (±1 %RH declared in the datasheet)
- HIHs RH sensors installed in CMS and coupled to optical fiber based RH sensors during LS1 show at best comparable performance

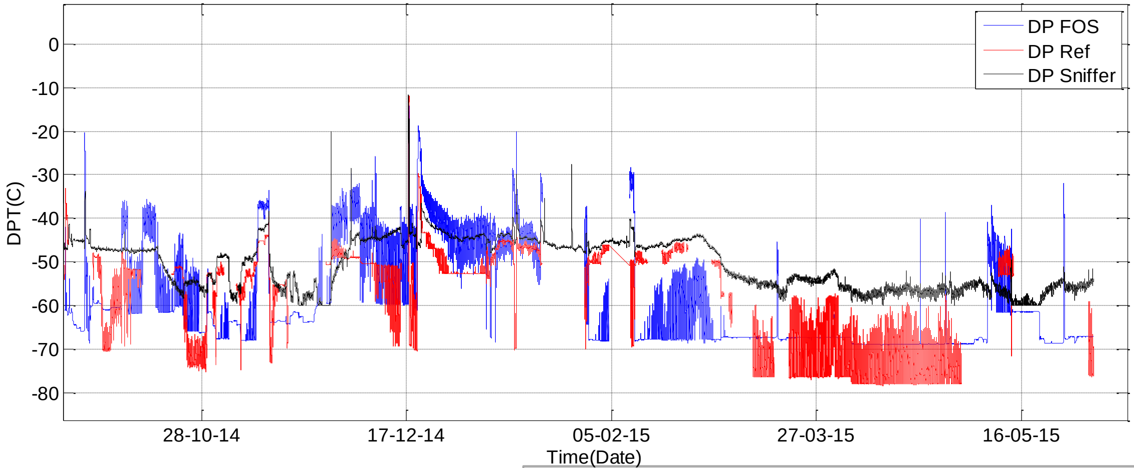
# Second example of FBG-RH sensors in operation in CMS

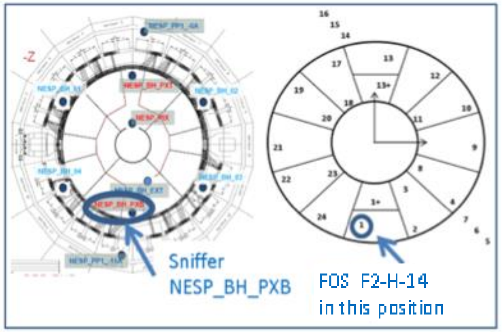
## FOS, Reference and Sniffer readings in comparison on Positive Side




## FOS, Reference and Sniffer readings in comparison on Negative Side

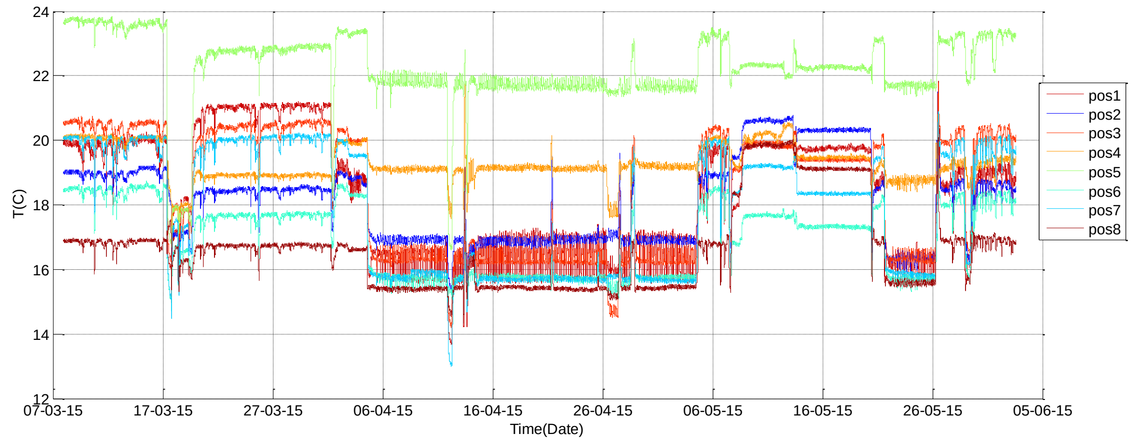


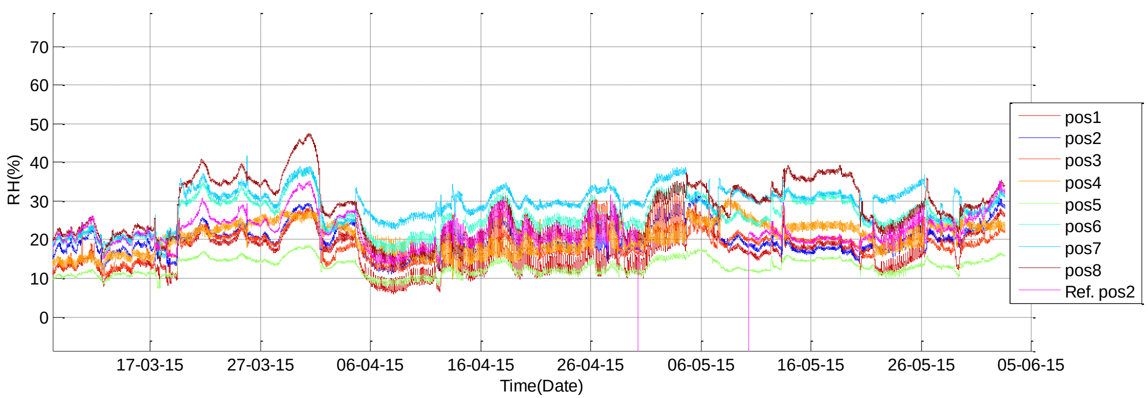

- 9 months of measurements (October 2014 – June 2015)

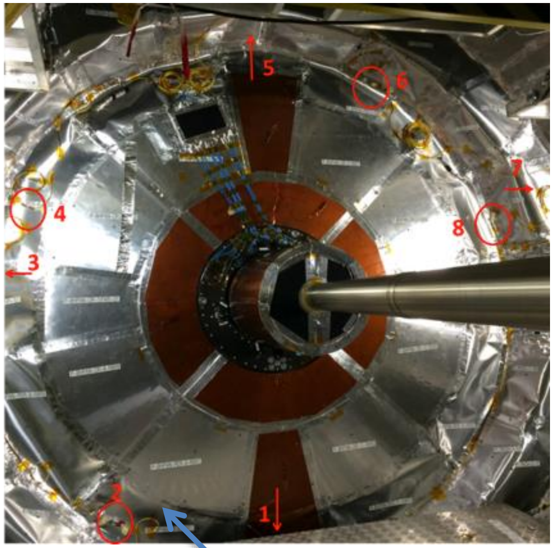
**Very good FOS DP reconstructions** in comparison to reference commercial sensors (which will “die” with LHC radiation) and the sniffer readings (average measurement, as available in only a few sniffing points in the volume)

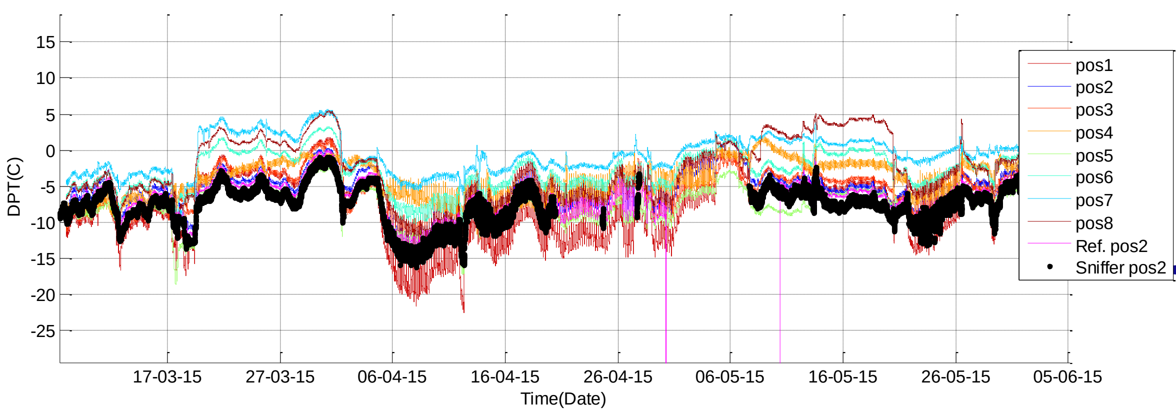
# Third example of FBG-RH sensors in operation in CMS




- BH outside, Positive Side
- ~3 months of measurements (March – June 2015)
- **Complete map of Temperature, Relative humidity, Dew point on the volume provided ONLY by FOS**



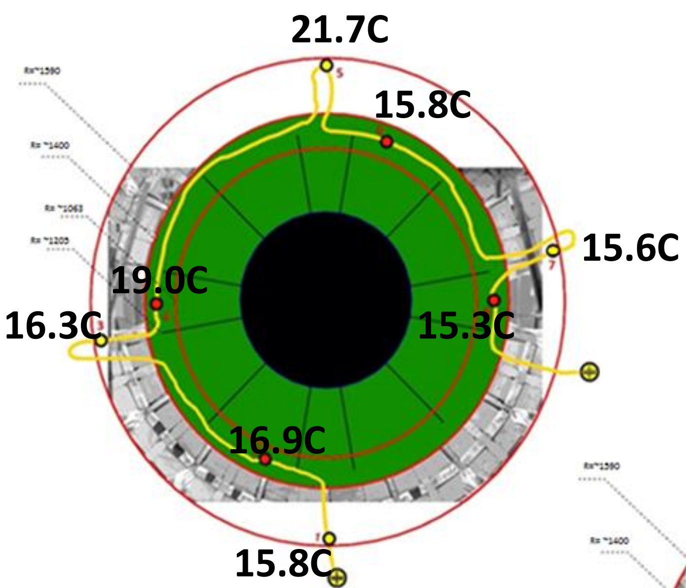




- Only one sniffing point present on the BH outside (pos. 2)
- Commercial RH+T sensor present in pos. 2 will "die" with LHC radiation

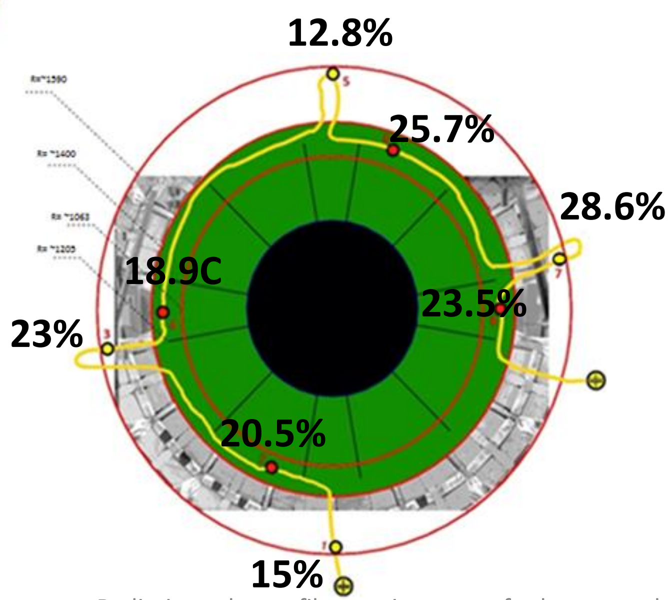
# Example of T, RH and DPT mapping with FOS

- Referring to a steady state condition (referring here to 12[nd] April 2015)
- FOS installed on BH outside-Positive Side

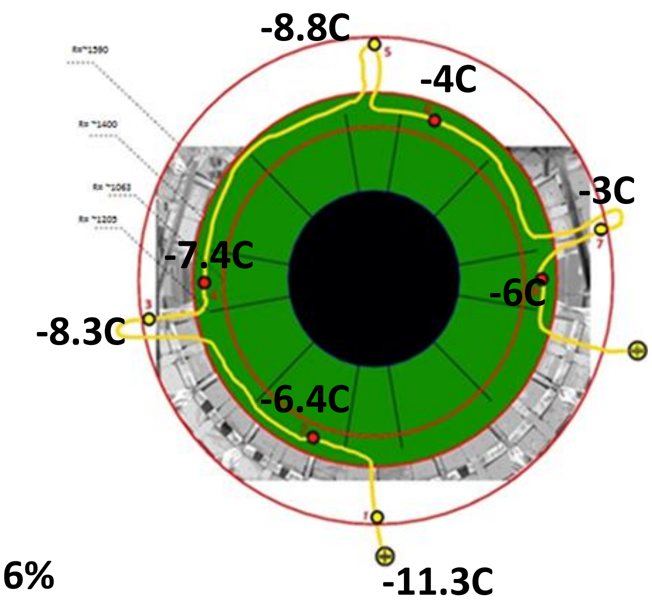
**TEMPERATURE**




**RELATIVE HUMIDITY**




**DEW POINT TEMPERATURE**

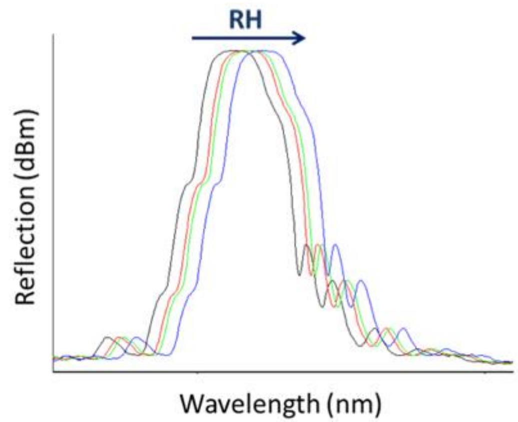



**Complete map of Temperature, Relative humidity, Dew point on the volume provided ONLY by FOS**

# Summarizing..

**FIBER BRAGG GRATING-BASED RELATIVE HUMIDITY SENSORS:**

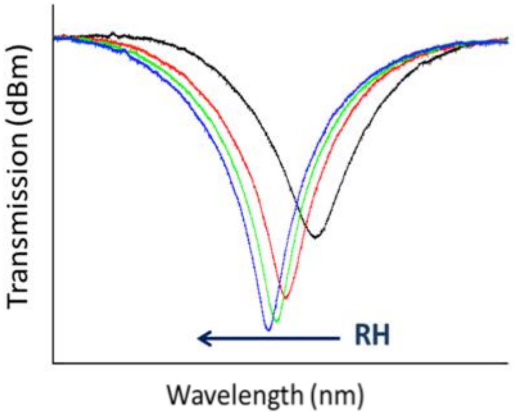
- R&D program completed
- Consolidated technology
- 3 years of work experience accumulated




- The installation of the FBG-based thermo-hygrometers in CMS tracker represents **the very first real application of this technology in real environment**
- All the requests from CMS experiment fully satisfied:
  - Reliable system
  - Multi-point map in terms of T, RH, DP conditions in the tracker volume
  - Sensors surviving to radiation exposure

For higher accuracy at low dew point,
development of a second generation of FOS launched:
**LONG PERIOD GRATING-BASED RELATIVE HUMIDITY SENSORS**

-R&D in PH-DT from 2013



# LPGs' operation principle

- "Long" grating (from 100 µm to 1 mm )
- LPG couples light from the fundamental guided core mode to discrete forward-propagating cladding modes
- Each coupling happens at a distinct wavelength:

**Phase matching condition**

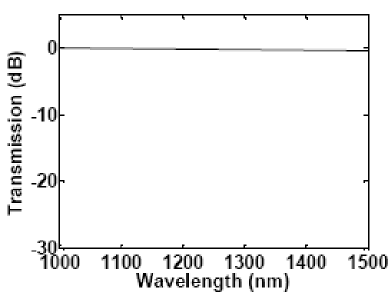
$$\lambda_{res,i} = \left(n_{eff,core} - n^{i}_{eff,clad}\right) \cdot \Lambda$$

$n_{eff,core}$ = core effective refractive index

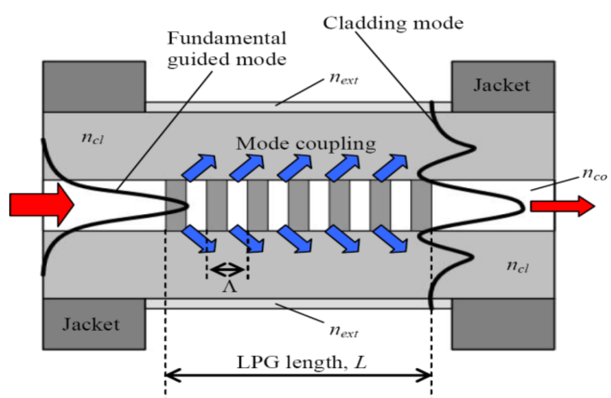
$\lambda_{res,i}$ = resonance wavelength for $i_{th}$ coupled mode

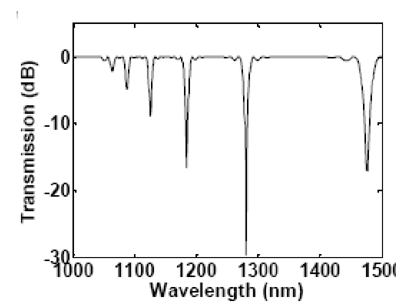
$n^{i}_{eff,clad}$ = cladding effective refractive index for $i_{th}$ coupled mode

- As a result of this process, the LPG transmission spectrum shows several attenuation bands




Spectrum before the LPG

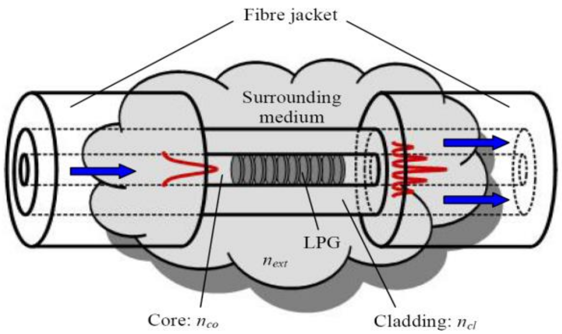


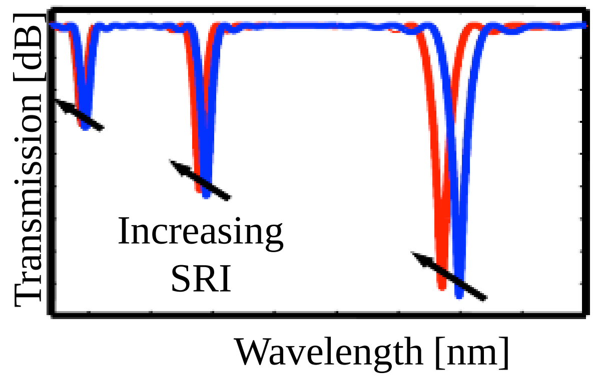




Spectrum after the LPG

# Multi-parametric sensing with LPGs

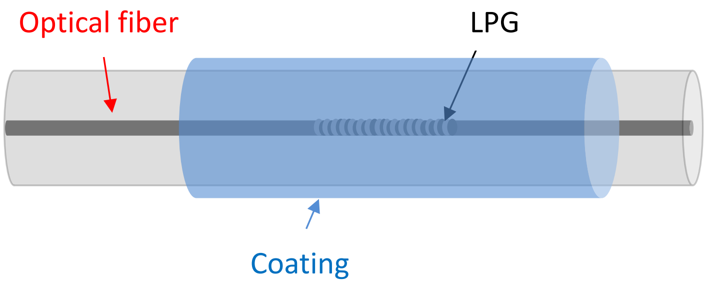
- LPGs are sensitive to different environmental parameters (T, strain, bending…)
- Particularly interesting is their sensitivity to surrounding medium refractive index



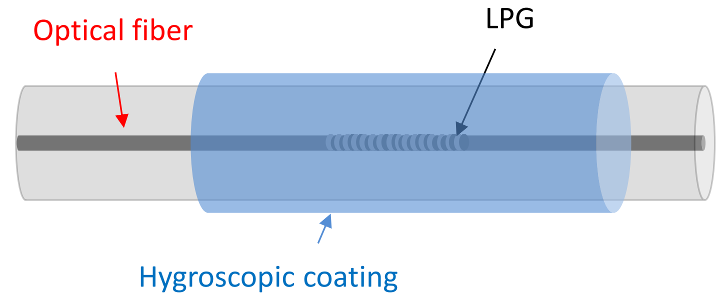

- The SRI change induces a $n_{eff}$ cladding modes variation and, consequently, a different phase matching condition.

**LPG + COATING:**
**<u>Multi-parametric sensing</u>**



# LPG as RH sensor

**Development of LPG-based RH sensors by coating the grating with material able to respond to physical stimuli**




Moisture absorbtion/desorption by the coating → Modification of coating RI → Spectral variation of attenuation bands

- Different coatings explored in literature:
  - polymers, hydrogels, gelatin..
- Completely unexplored in literature:
  - behavior below 20 %RH and below 15 °C
  - effect of radiations
- Idea: to use oxides as coatings:
  - stable
  - expected to be radiation resistant

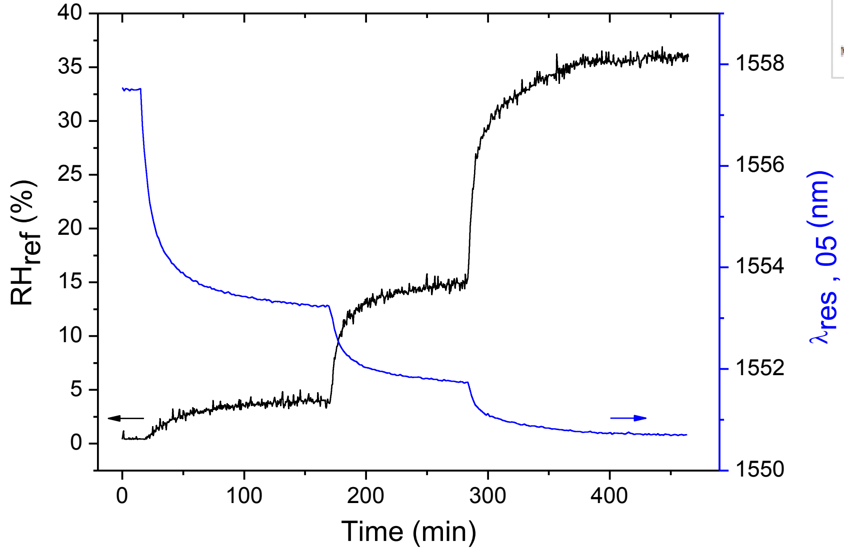
Three different metal oxides tested ( $SnO_2$, $TiO_2$ and $Al_2O_3$)

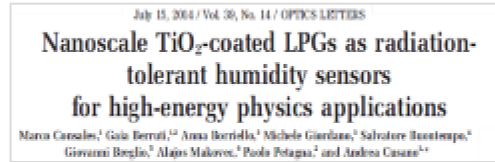
**$TiO_2$ selected:**

- high refractive index (n = 1.96)
- hygro-sensitive characteristics
- very stable (no aging)

# Characterization of LPG

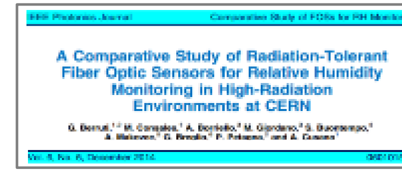
## Response at 25 °C

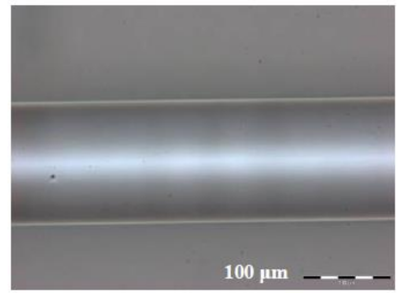




July 15, 2014 / Vol. 39, No. 14 / OPTICS LETTERS

Nanoscale $TiO_2$-coated LPGs as radiation-tolerant humidity sensors for high-energy physics applications

Marco Consales, Gaia Berruti, Anna Borriello, Michele Giordano, Salvatore Buontempo, Giovanni Breglio, Alajos Makovec, Paolo Petagna, and Andrea Cusano


A Comparative Study of Radiation-Tolerant Fiber Optic Sensors for Relative Humidity Monitoring in High-Radiation Environments at CERN

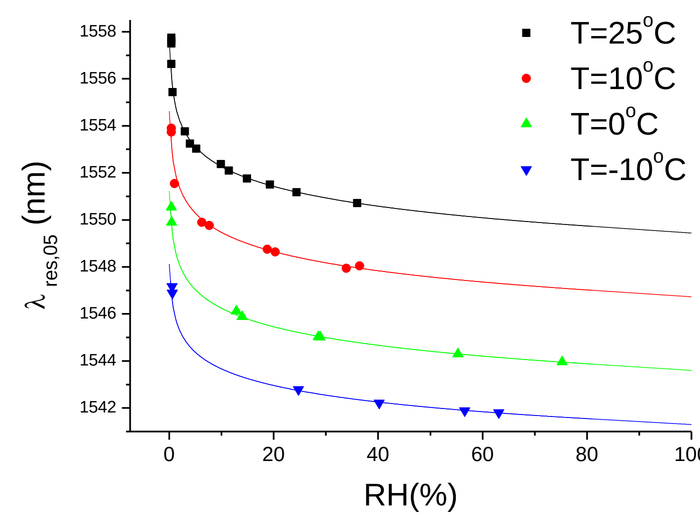



20x microscope image of a $TiO_2$-coated LPGprobe

**In-house fabricated sensor:**

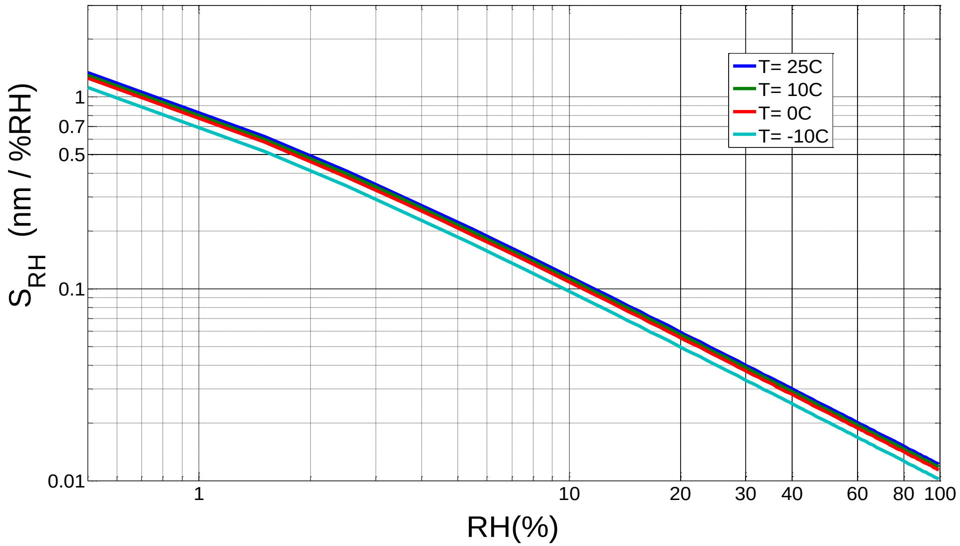
- Sol- gel dip coating for $TiO_2$ deposition
- Multiple depositions needed to get the desired thickness
- ~100nm estimated $TiO_2$thickness

## Characteristic curves




- $\lambda_{res,05}$ blue shift induced by $TiO_2$ water molecules absorption
- Similar results at 10, 0 and -10 °C
- Non linear characteristic curves

# Sensitivities of LPG




## RH Sensitivity

- At 25 °C, $S_{RH}$ is 1.4 ÷ 0.11 nm/%RH in the range [0-10] %RH

$S_{RH}$ **from one to three orders of magnitude higher** than the one of polyimide-coated FBG's*

*** For a coated FBG, $S_{RH}$≈ 1 pm/%RH**

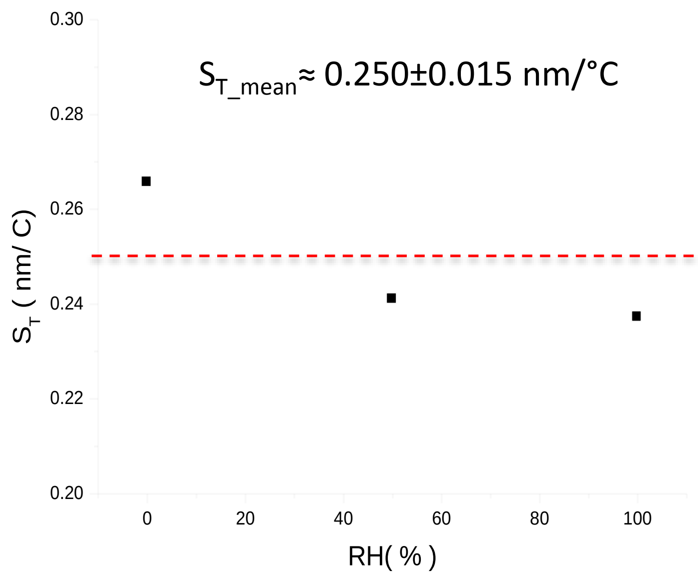
## T Sensitivity

- Precise T - compensation required only if very precise RH measurement is needed

If no compensation is applied, a T reading error of ± 1 °C corresponds to:

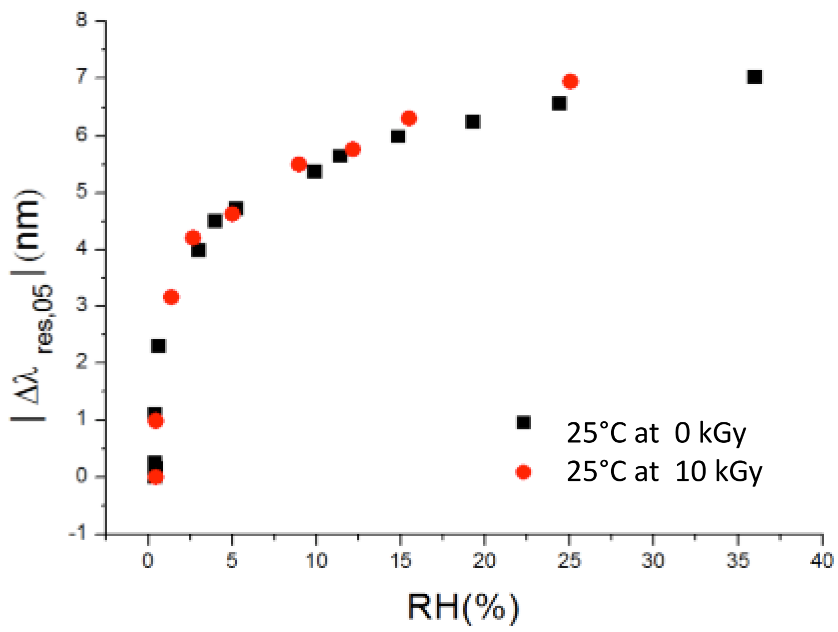
- **7-10 %RH error** for *coated FBG based RH sensors*
- **0.5÷1 %RH error** for *coated LPG based RH sensors*

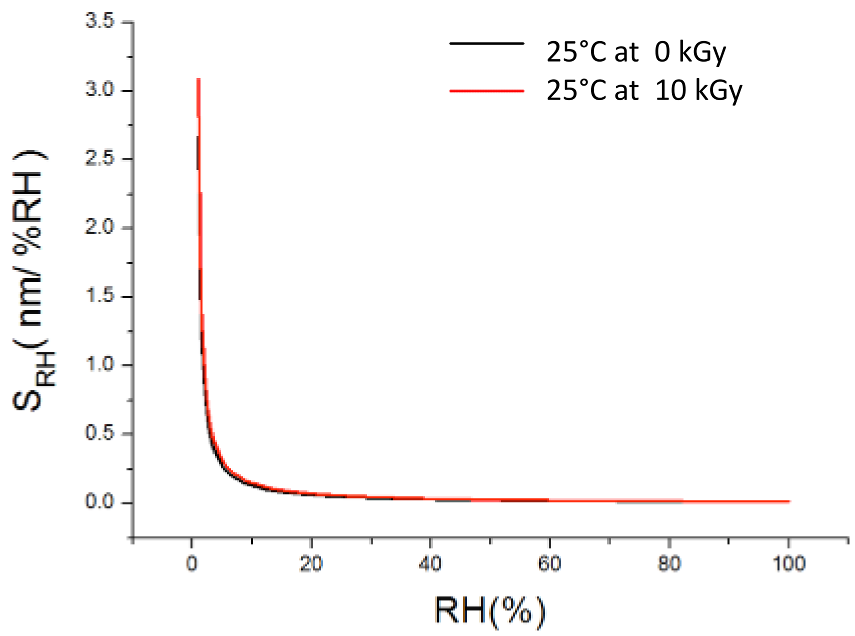
*** ± 1%RH is the typical RH error declared for commercial RH sensors**



# LPG's Radiation Tolerance investigations

- Investigations about the sensing characteristics of LPGs after ϒ radiations dose exposure




- Irradiation campaigns at higher doses to be performed

# Conclusions (1)

- The **FOS4HEP project** started at CERN in 2009 for developing novel and high performance multifunctional fiber optic sensors to be used in CERN experiments and accelerators
- Different **R&D projects launched** over the years launched:

  - FOS for strain and T measurements in CMS (raisers, Ipipe, YE4, T-UXC, PLT, BRM, RPC)
  - FOS for humidity measurements in CMS (tracker)
  - FOS for B fields measurements (prototypes)
  - FOS for cryogenics in LHC (T and strain in SC magnets and cryo Power-lines)
  - FOS for dosimetry (prototypes)
- CMS and PH-DT group fully involved in the development of a new generation of relative humidity fiber optic sensors for high radiation environments in collaboration with academic and industrial partners

# Conclusions (2)

FOS for humidity measurements at CERN:

## 1) **FBG-based RH sensors**

- R&D started in 2011
- 4 years of work experience accumulated
- **72 FBG-based thermo-hygrometers installed** in CMS Tracker:

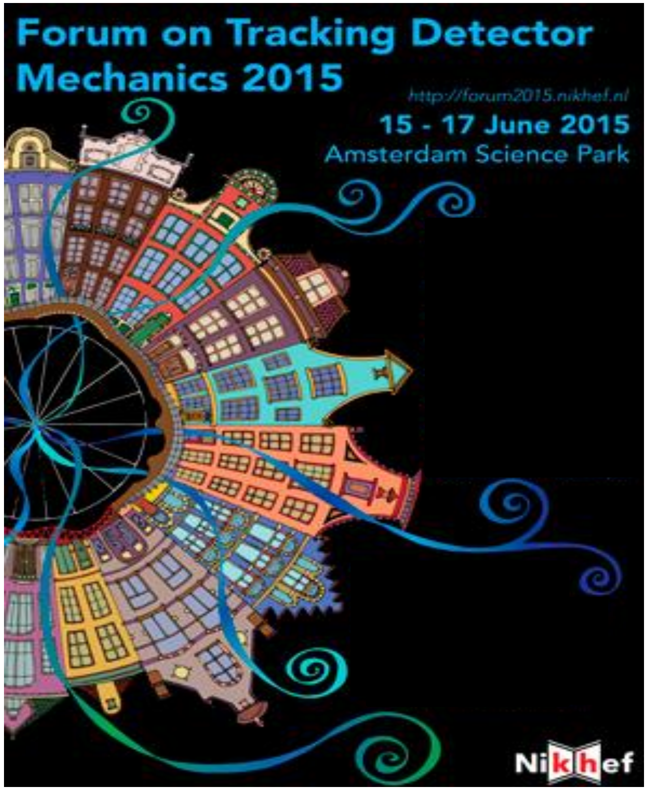
  - Reliable system in acquisition H24

  - Providing for the first time a full punctual **map of T, RH, DPT**

  - Tolerant to radiations, will be the only reference during RUN2 with sniffers for the hygrometric control of the air
    - Conventional sensors will "die" with LHC radiation
    - NO multi-point sensing with sniffers (only a few points available)

## 2) **LPG-based RH sensors**

- R&D started in 2013
- Very promising first results (in terms of performance, radiation tolerance…)




# Thanks for your attention!
# Bedankt voor uw aandacht!

Gaia.Maria.Berruti@cern.ch