Forum on Tracking Detector Mechanics 2017
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Fiber optic-based sensors for relative humidity monitoring in the experiments running at CERN

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CMS environmental monitoring: needs and requirements

CMS needs: a reliable multi-point thermo-hygrometric distributed monitoring of the environmental water vapor content at DP ≤ -30 °C

My last presentation at "Forum on Tracker and Mechanics 2015" – Amsterdam here:
https://indico.cern.ch/event/363327/timetable/#20150617

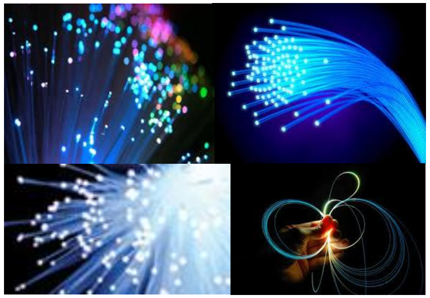
REQUIREMENTS FOR RH SENSORS

- Low mass and Small dimensions
- Insensitivity to magnetic field
- Operation down to -10 ˚C and [0- 100] %RH
- Accuracy: better than ±3 %RH
- Radiation resistance to dose up to 1 MGy

NO miniaturized humidity sensor available on the market well suited for HEP detector applications

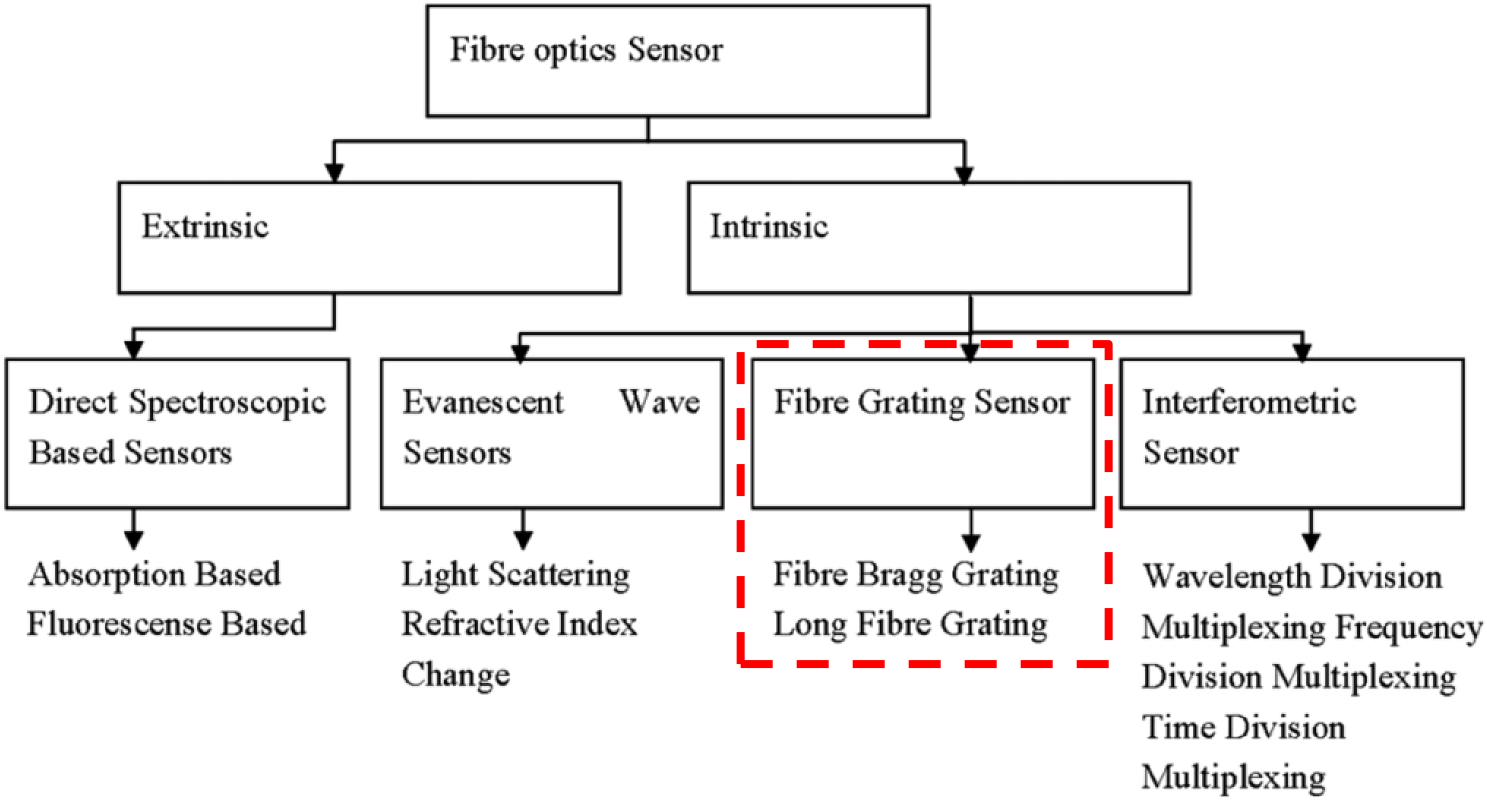
Our solution:
Fiber Optic-based humidity sensors

- ✓ Immunity to electromagnetic interference
- ✓ Possibility to work in harsh environments
- ✓ Radiation tolerance
- ✓ Absence of electronic circuitry in the measurement area

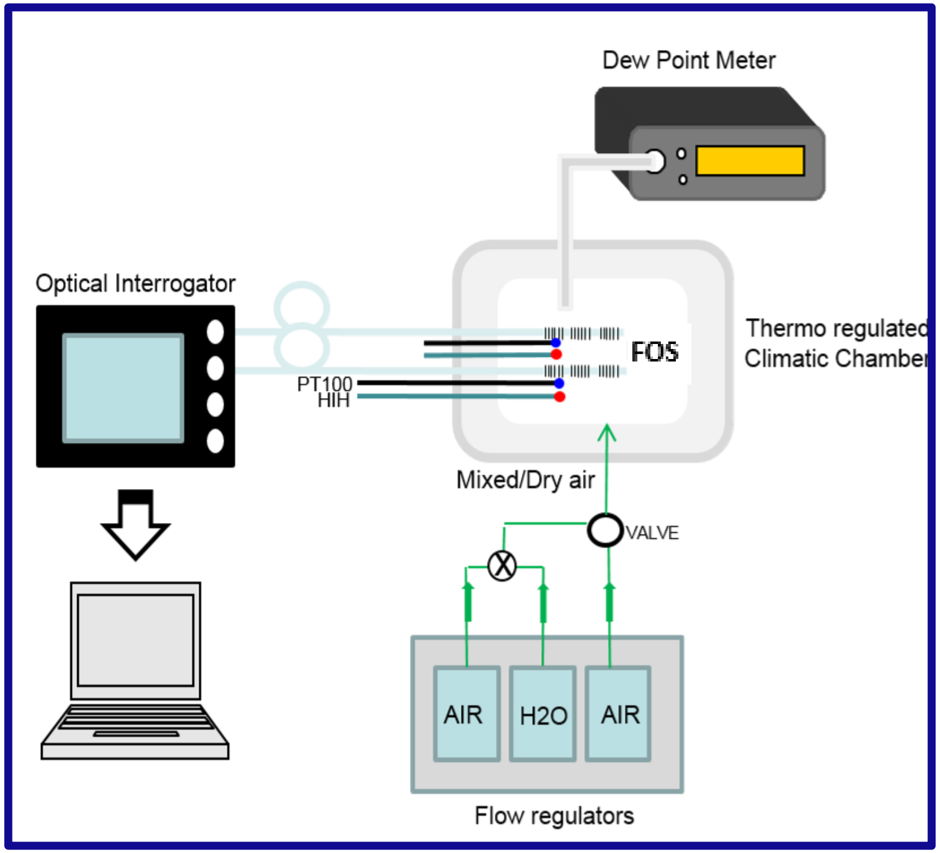


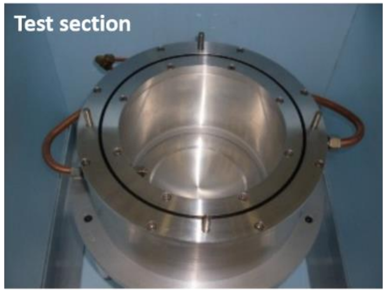
FOS classification

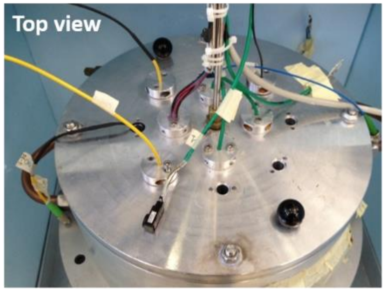
- Increased popularity and market acceptance of fiber optic sensors:
  - <u>Intrinsic sensor</u>: the fiber itself is the sensing element
  - <u>Extrinsic sensor</u>: fiber simply transports light to or from the sensing element

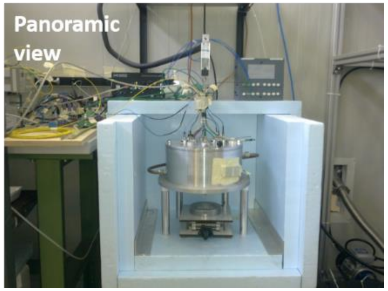


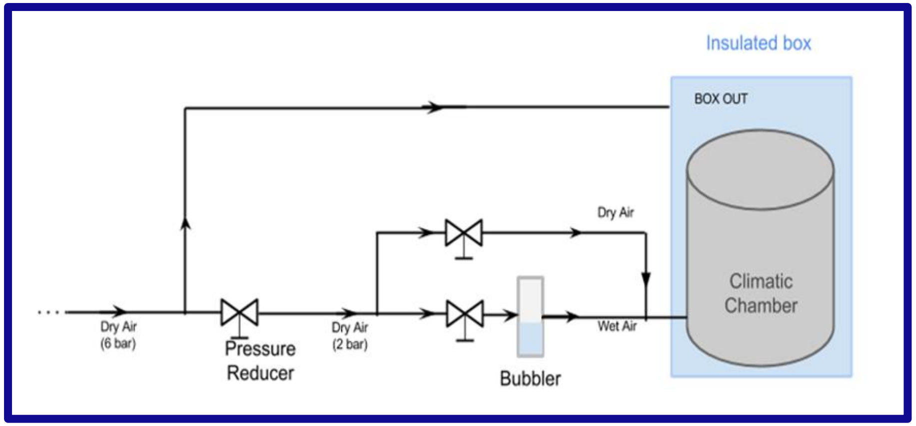
Experimental set-up at CERN





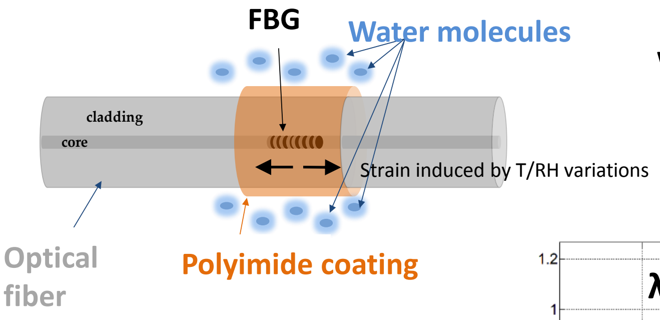






- T range: [-20 , 30]°C
- Stability of T measurements: ± 0.05°C
- RH range: [0, 100]%RH
- Stability of RH measurements: ± 0.1 %RH

First generation: Polyimide-coated FBGs



Water molecules absorbed by the coating

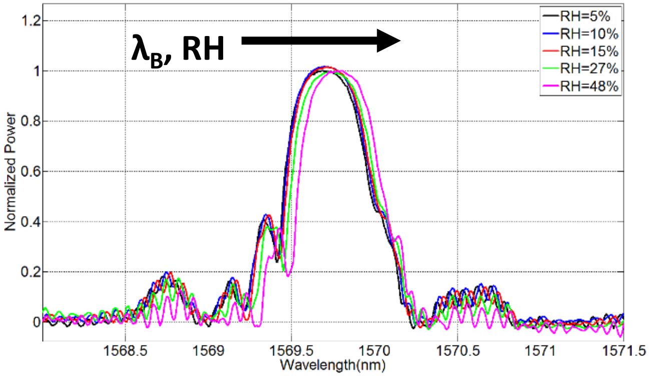
Coating expansion (“Swelling effect”)

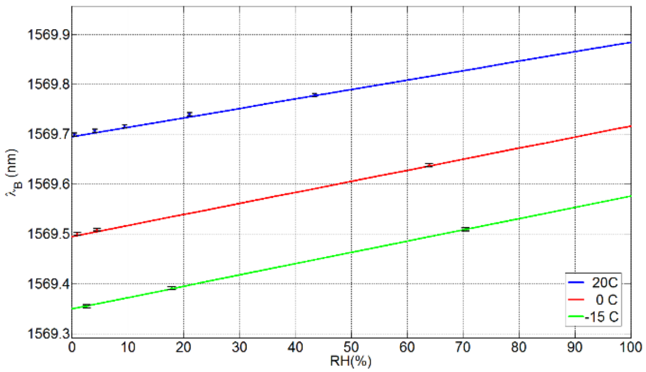
Strain induced on the FBG

Bragg wavelength shift ($\Delta\lambda_B$)

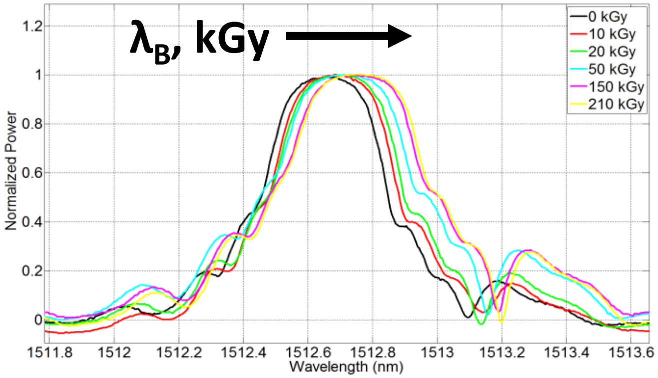
Radiation Hard Humidity Sensors for High Energy Physics Application using Polyimide-coated Fiber Bragg Gratings Sensors

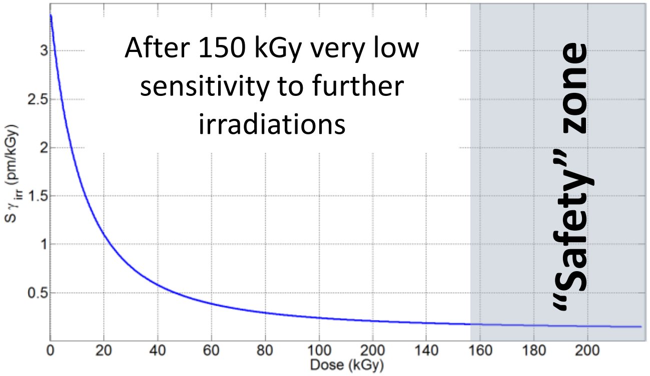
G. Berruti, M. Consales, M. Giordano, L. Sansone, P. Petagna, S. Buontempo, G. Breglio, and A. Cusano (Sensors and Actuators B: Chemical, 2012)





- Irradiation campaigns to investigate their performances in presence of ϒ- ionizing radiations





After 150 kGy very low sensitivity to further irradiations

“Safety” zone

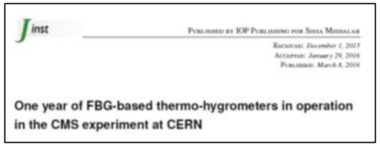
Pre-irradiation of FBGs is suggested to bring them in the “Safety zone” before installation in high radiation environments

Installation in CMS tracker (1)

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

72 FBG- based thermo-hygrometers installed in critical regions of the experiment:

- **limited possibility of RH control**
    - **presence of cold pipes**



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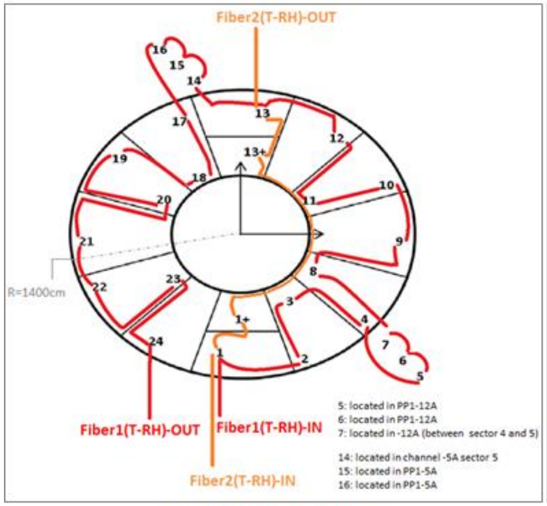
One year of FBG-based thermo-hygrometers in operation in the CMS experiment at CERN

optosmart

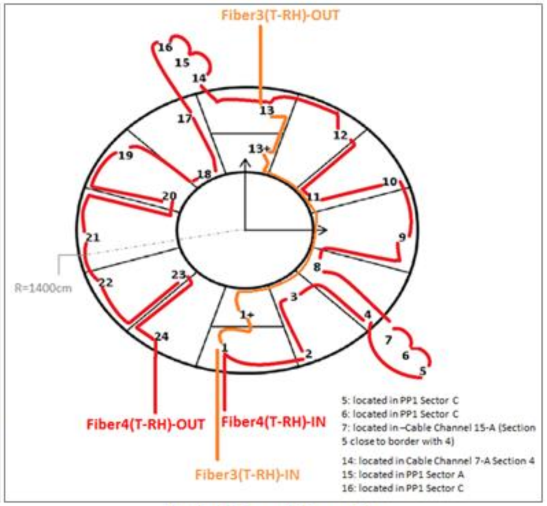
Z- Bulkhead Inside



5: located in PP1-12A
6: located in PP1-12A
7: located in -12A (between sector 4 and 5)

14: located in channel -5A sector 5
15: located in PP1-5A
16: located in PP1-5A

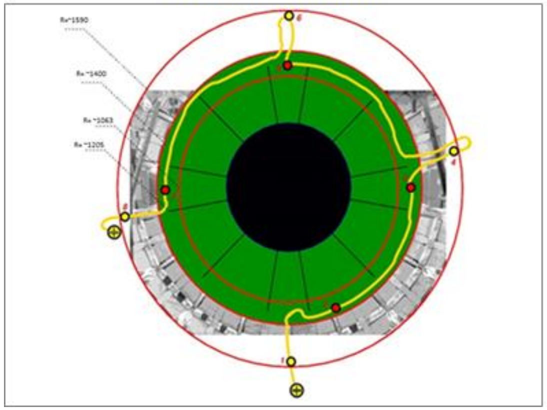
Z+ Bulkhead Inside



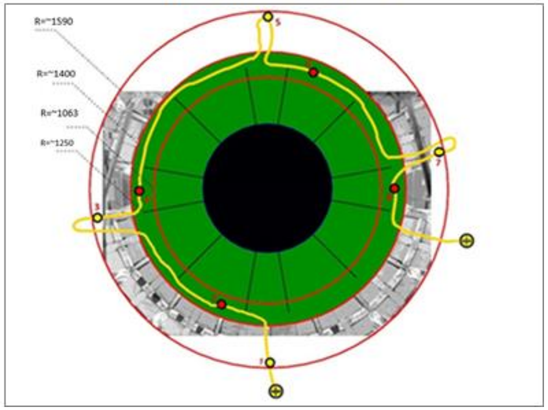
5: located in PP1 Sector C
6: located in PP1 Sector C
7: located in –Cable Channel 15-A (Section 5 close to border with 4)

14: located in Cable Channel 7-A Section 4
15: located in PP1 Sector A
16: located in PP1 Sector C

Z- Bulkhead Outside

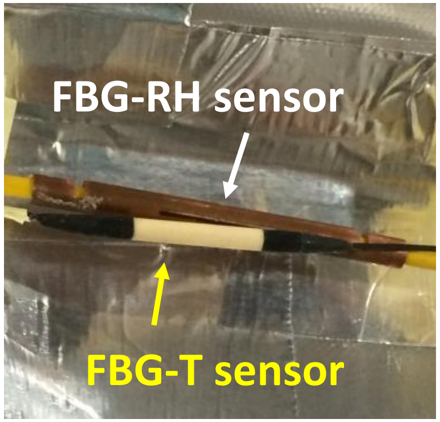


Z+ Bulkhead Outside

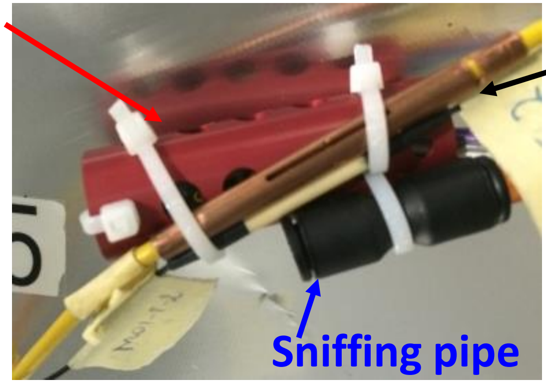


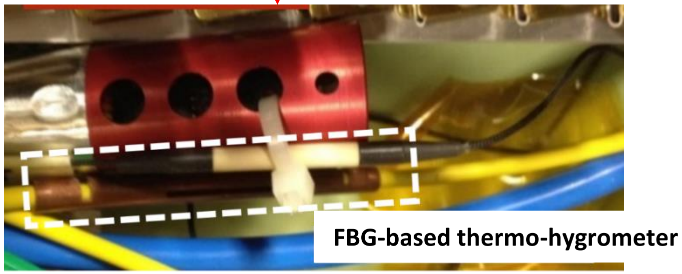
Installation in CMS tracker (2)

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


FBG-based thermo-hygrometer

Capacitive standard sensors


FBG-based thermo-hygrometer



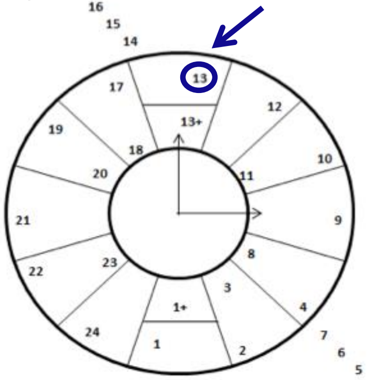
Capacitive standard RH+T sensors: expected to “die” for LHC operations

Remote air SNIFFING: not influenced by LHC collisions but no multi-point sensing provided

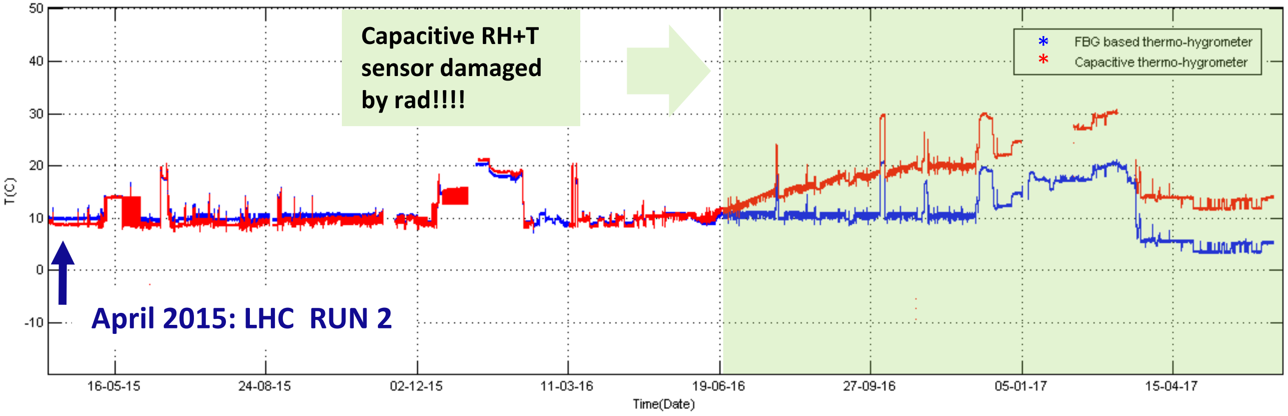
First example of RH-FOS operation in CMS

E.g. 26 months of measurements in CMS (April 2015 - June 2017)

Sensors in this position



Temperature monitoring

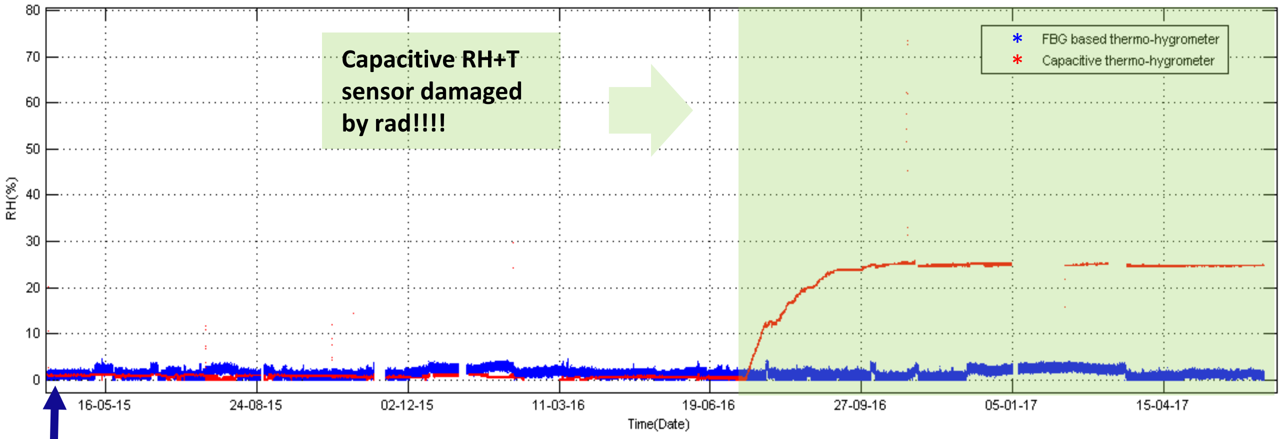


Capacitive RH+T sensor damaged by rad!!!!

April 2015: LHC RUN 2

- The T +RH standard capacitive sensors show drift due to radiation damage from June 2016
  - Expected absorbed dose of 10 kRad (from FLUKA simulations)

Relative humidity monitoring



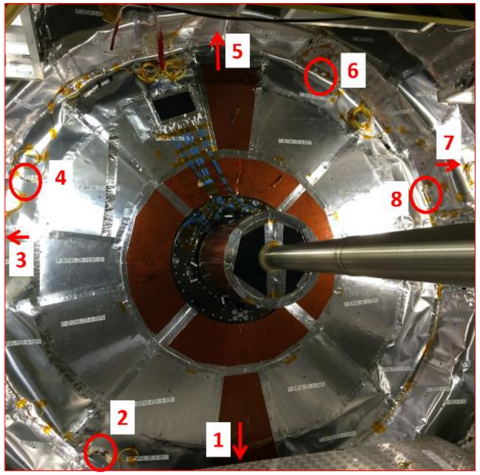
Capacitive RH+T sensor damaged by rad!!!!

April 2015: LHC RUN 2

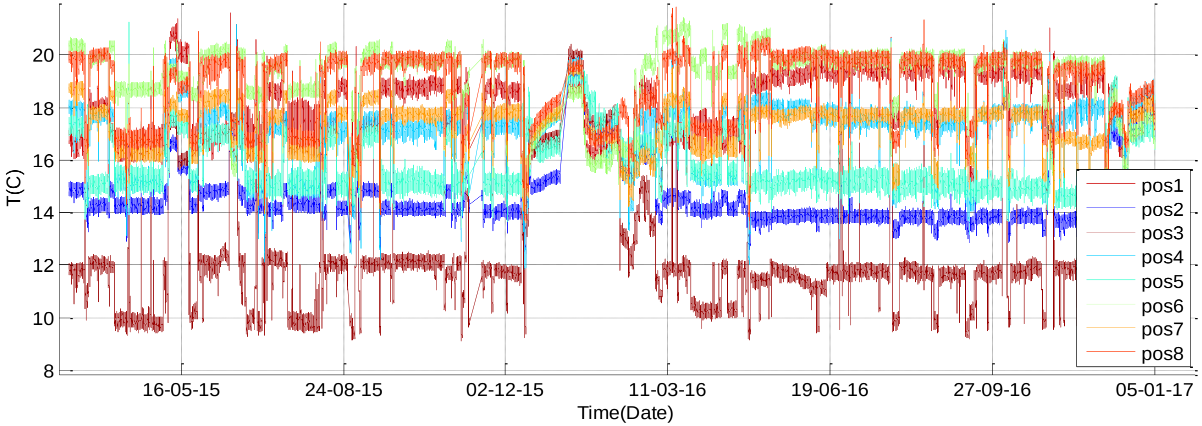
FBG-base thermo-hygrometers:
- radiation resistant
- no drift in time
- providing T and RH reasonable measurements during RUN2

Second example of RH-FOS operation in CMS

E.g. Two years monitoring of temperature and dew point temperature in the Outside Tracker Bulkhead

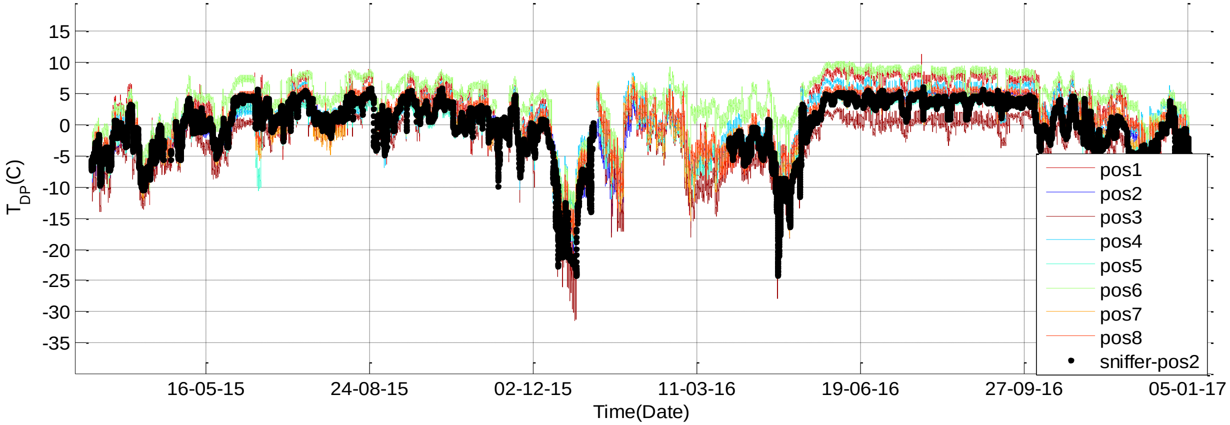


Temperature monitoring



- One sniffing point available on the BH outside in pos. 2

Dew Point temperature monitoring



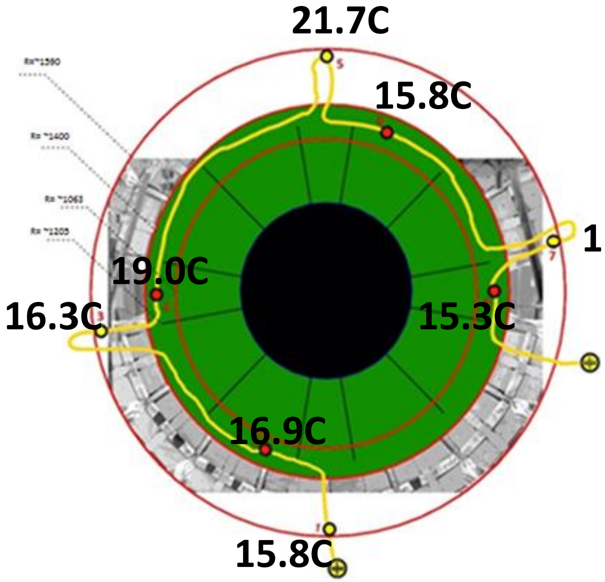
<u>Complete map</u> of Temperature, Relative humidity, Dew point Temperature on the volume <u>provided ONLY by the FBG-based thermo-hygrometers</u>

T, RH and DPT mapping with FOS

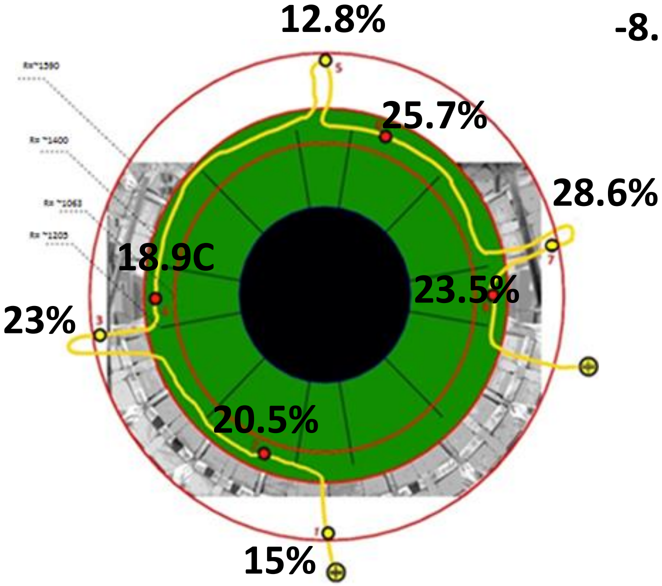
Useful maps that only FBG-based thermo-hygrometers can provide:

- Study of the T, RH and TDP distribution in the volume
- Localization of eventual critical spots

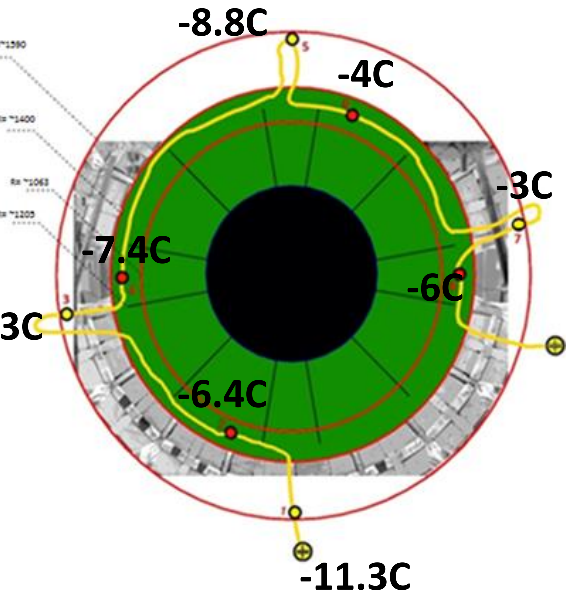
TEMPERATURE



RELATIVE HUMIDITY



DEW POINT TEMPERATURE



* Maps referring to a steady state condition reached during the operation in the CMS Tracker

FBG-based RH sensors: issues to be improved

From experience of FBG-based thermo-hygrometers in operation in CMS experiment:

1. <u>Low RH Sensitivity</u> (S_{RH}~ 1.0 ÷ 2.0 pm/%RH)
<u>High Cross Sensitivity</u> (S_T ~ 10 pm/°C)

⇨ Very precise T compensation needed to decouple the RH and T effects from the sensors measurements

E.g. S_T/S_{RH} =10 %RH/°C means that an T_{error} ≈±1 C corresponds to RH_{error} ≈±10 %RH

2. <u>Low accuracy</u> below RH=+/-5%
..as standard capacitive humidity sensors..

3. <u>Coating adhesion</u> affecting the sensing performances

4. <u>Aging</u> typical of polymers
..not yet observed but..

New generation of RH fiber optic-based sensors for ATLAS

In 2015 ATLAS officially enquired the possibility of installing a small network of FOS-based hygrometers in critical areas during LS2 for water vapor content at DP ≤ -40 °C

1st generation of fiber optic based RH sensors:

- Smooth and reliable performance, as demonstrated with the experience in CMS

BUT

- Limit of applicability considering the performance requested and environmental conditions in ATLAS

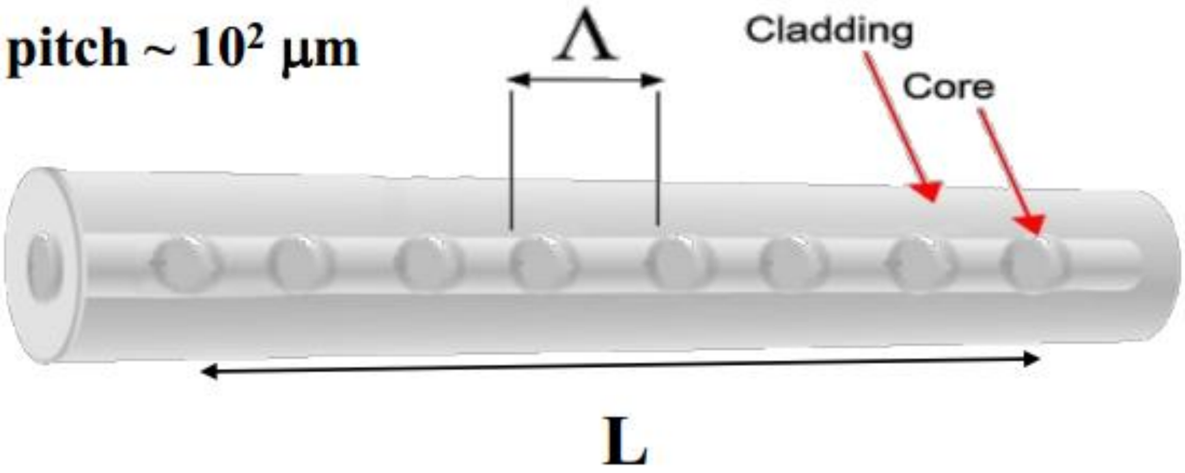
➡ Development of a **second generation of FOS** launched in collaboration with ATLAS and CMS experiments: **Long Period Grating (LPG) based sensors for Relative Humidity monitoring**

Long Period Gratings

Long period gratings (LPGs) are photonic devices obtained by inducing a periodic modulation of the refractive index of the core of a single mode fiber

- “Long” period of the grating (from 100 µm to 1 mm)

Λ = grating pitch ~ 10^2 µm



L= length of the grating ≈ 2-4 cm (against a few mm of FBGs)

LPGs' operation principle

- LPG couples light from the fundamental guided core mode to discrete forward-propagating cladding modes. Each coupling happens at a distinct wavelength:

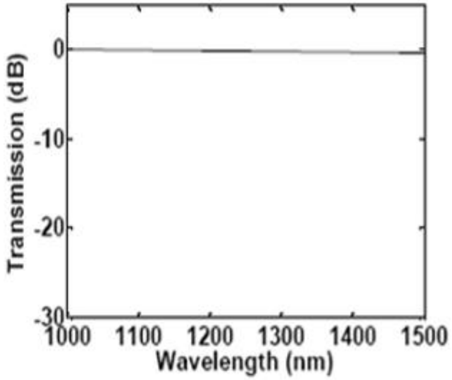
Phase matching condition

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

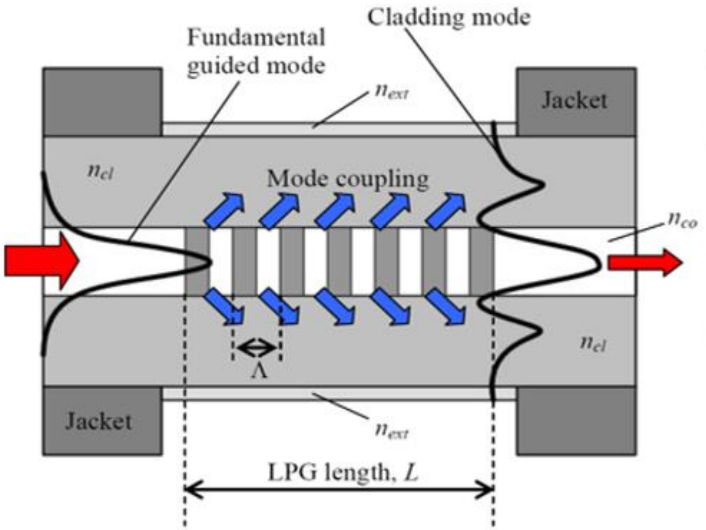
$n_{eff,core}$ = core effective refractive index

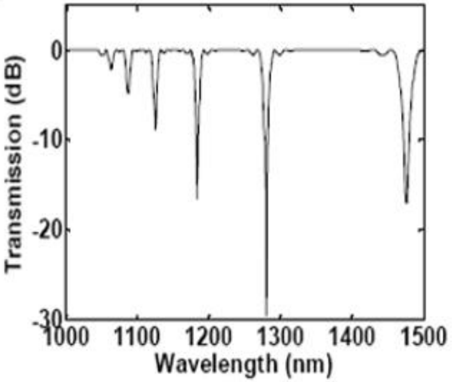
$\lambda_{res,i}$ = resonance wavelength for i_{th} coupled mode

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



Spectrum before the LPG



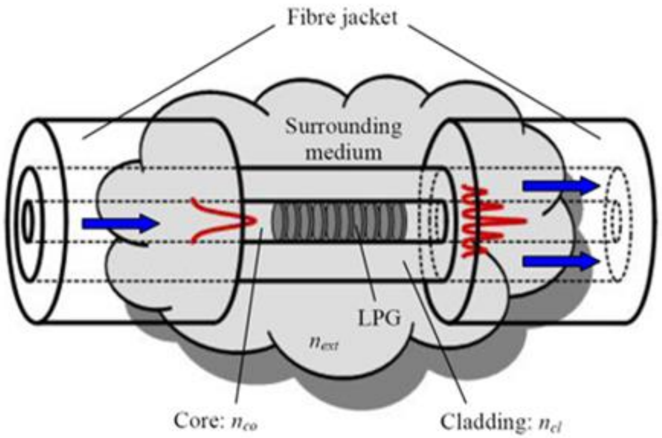


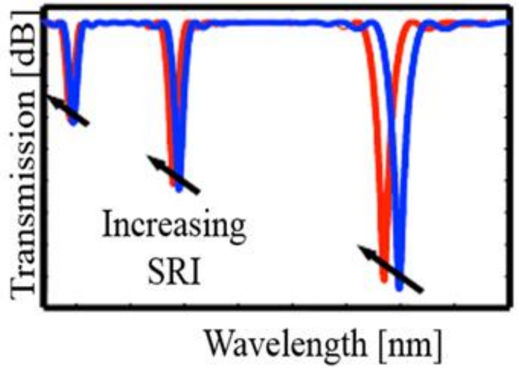
Spectrum after the LPG

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

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



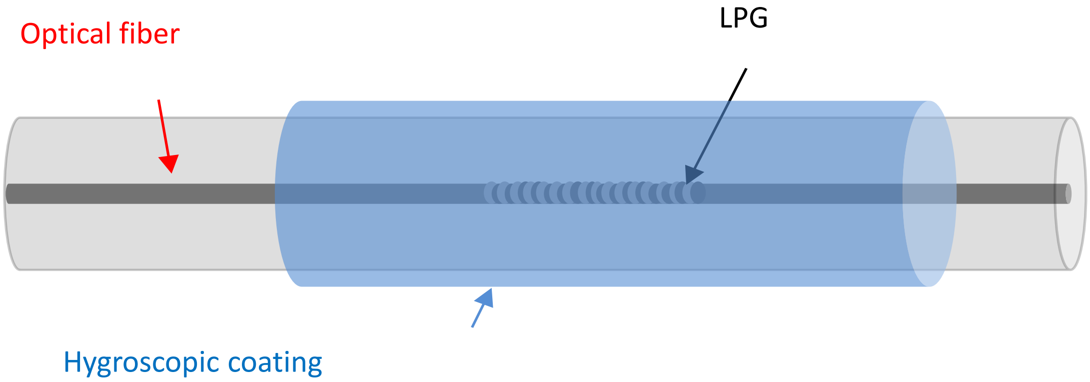


- The SRI change induces a n_{eff} cladding modes variation and, consequently, a different phase matching condition.

LPG + COATING: Multi-parametric sensing

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

$$\boxed{\Delta\lambda_{\mathrm{res},0i} = f(\Delta RH) = g\left(\Delta n^{0i}_{eff,cl}\right)}$$

with $\Delta n^{0i}_{eff,cl}$ function of:

- $\Delta \mathrm{RI}_{\mathrm{coating}}$
- $\Delta \mathrm{Thickness}_{\mathrm{coating}}$

Selection of the sensitive coating material

- Different coatings explored in literature for the development of LPG-based relative humidity sensors:

  - polymers, hydrogels, gelatin..

- No indication in literature concerning LPG-based RH sensors in terms of:

  - behavior below 20 %RH and below 15 °C

  - effect of radiations

- For our application:

  - we decided to avoid polymeric coatings

  - we concentrated our attention on metal oxides

Well known in traditional humidity sensing application

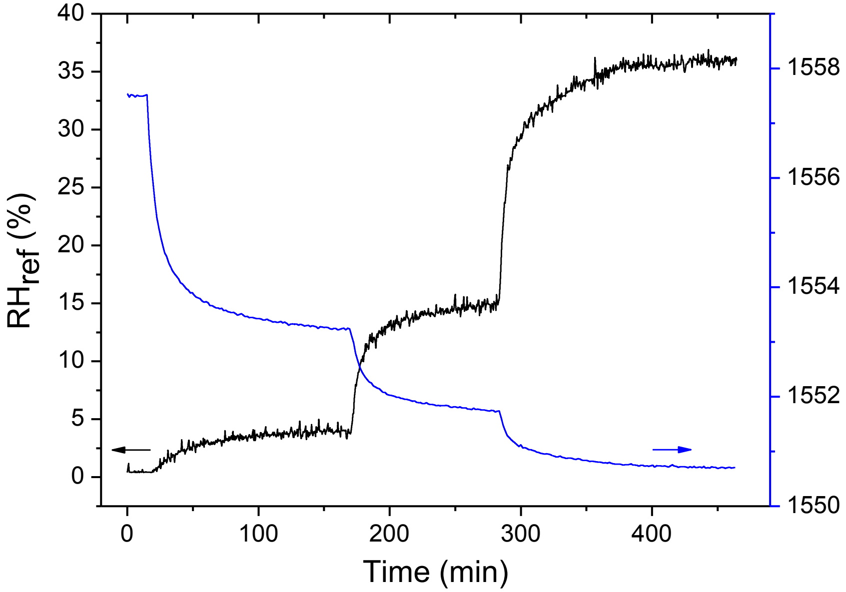
More stable

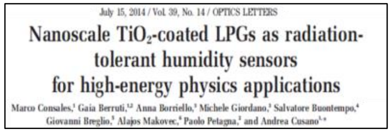
Expected to be rad. resistant

TiO_2 selected as coating material for our application

Characterization of TiO_2 coated LPG RH sensors

Typical response at 25 °C

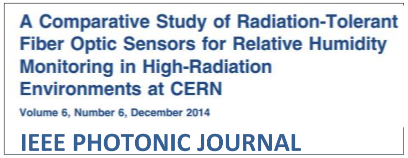




July 15, 2014 / Vol. 39, No. 14 / OPTICS LETTERS

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

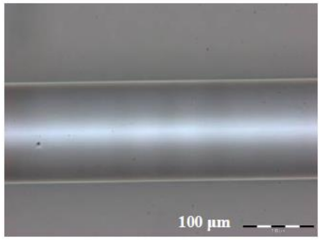
Marco Consales,[1] Gaia Berruti,[1,2] Anna Borriello,[3] Michele Giordano,[3] Salvatore Buontempo,[4] Giovanni Breglio,[5] Alajos Makovec,[6] Paolo Petagna,[2] and Andrea Cusano[1,*]



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

Volume 6, Number 6, December 2014

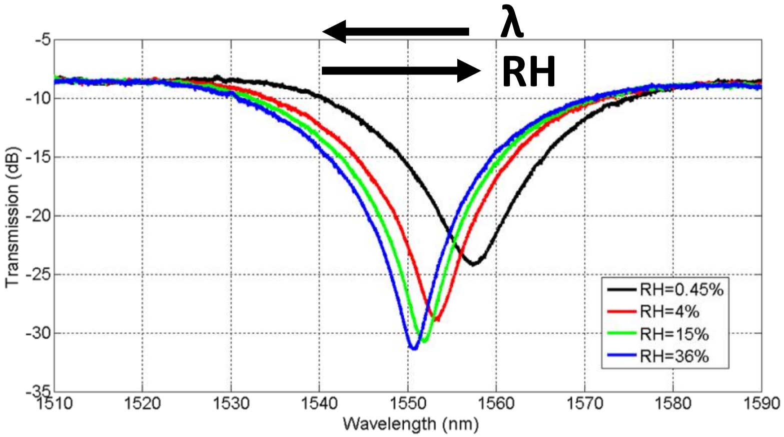
IEEE PHOTONIC JOURNAL



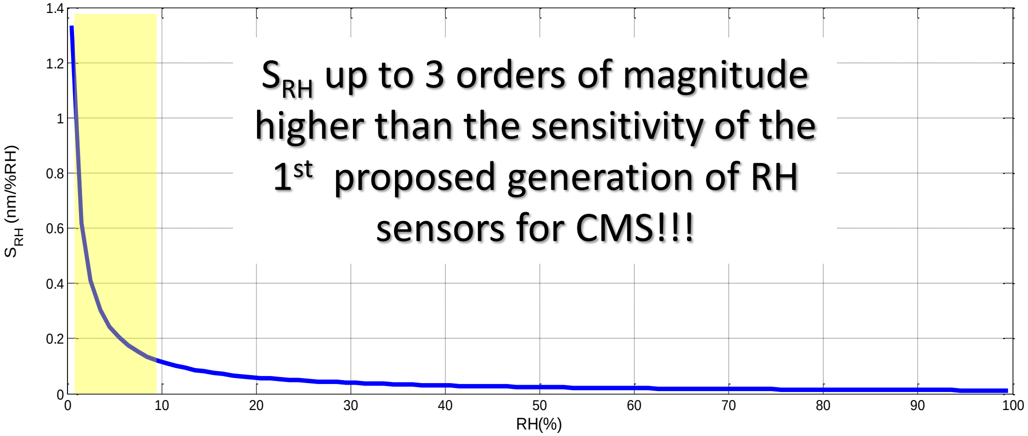
20x microscope image of a TiO_2-coated LPG probe

In-house fabricated sensor:

- Sol- gel dip coating for TiO_2 deposition
- Multiple depositions needed to get the desired thickness
- <u>~100 nm estimated TiO_2thickness</u>



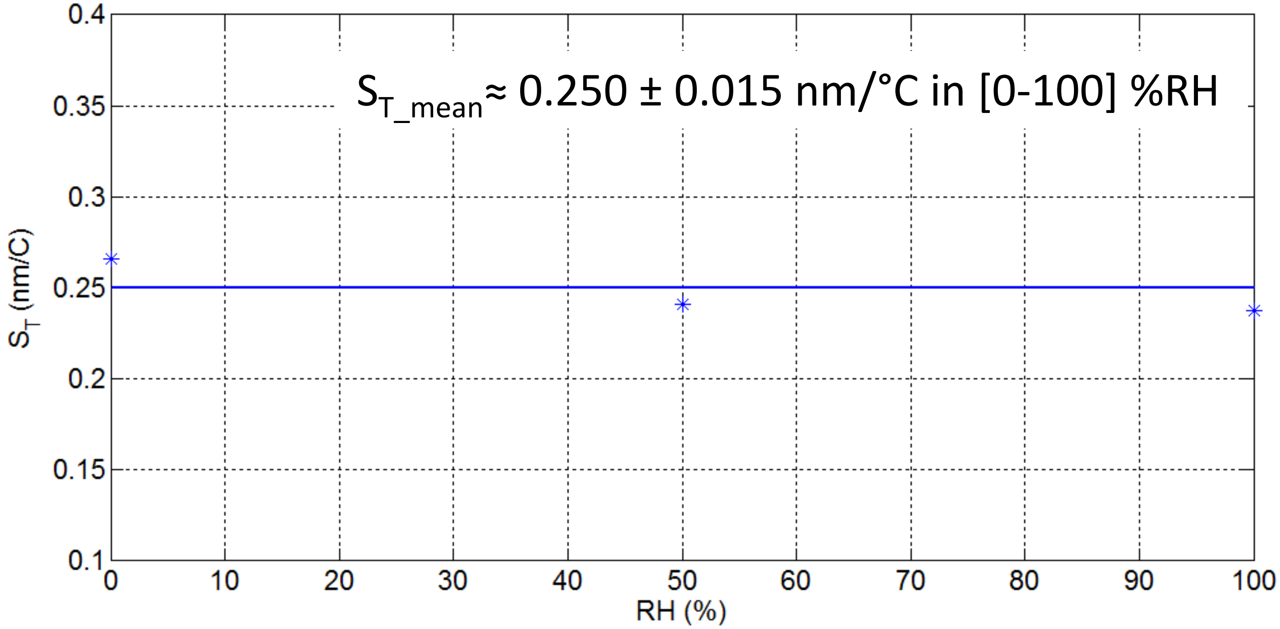
RH sensitivity Curve



S_{RH} up to 3 orders of magnitude higher than the sensitivity of the 1st proposed generation of RH sensors for CMS!!!

- <u>High sensitivity </u>in the range of low humidity
- Appealing for <u>high precision measurements</u>

T Sensitivity of TiO_2 coated sensors



- 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***

Typical declared behaviour for commercial RH sensors (ONLY AT 25 °C):

- RH Accuracy=± 2÷3 %RH in the range [10-80]%
- RH Accuracy=± 3÷5 %RH in the range [0-10]%
- Hysteresis not included (typ. ±1 %RH)

Resistance to ϒ-radiation of LPG based sensors

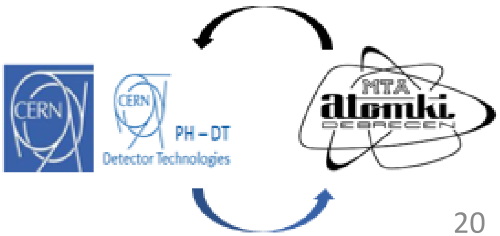
WHY?

- Damage expected to be higher in case of ionizing radiations
- Investigations about the **effect of radiation on the sensing performance of LPGs**
- Study of the **saturation properties of the LPG radiation induced wavelength shift** - as observed for the first generation developed for CMS

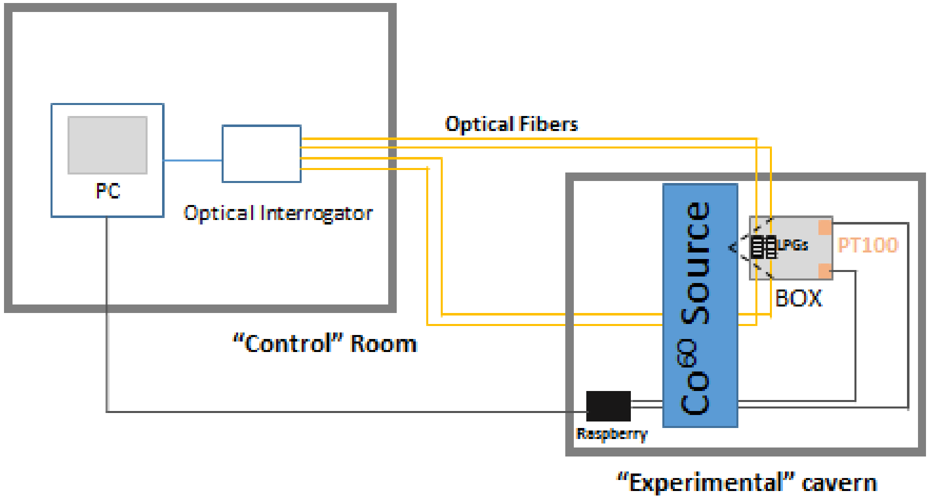
- On going collaboration with ATOMKI (Hungarian Academy of Sciences - Institute for Nuclear Research) in Debrecen
- LPG sensors travelling from CERN to ATOMKI and vice versa for irradiation campaigns
- Currently investigating the behaviour of uncoated LPGs under irradiation

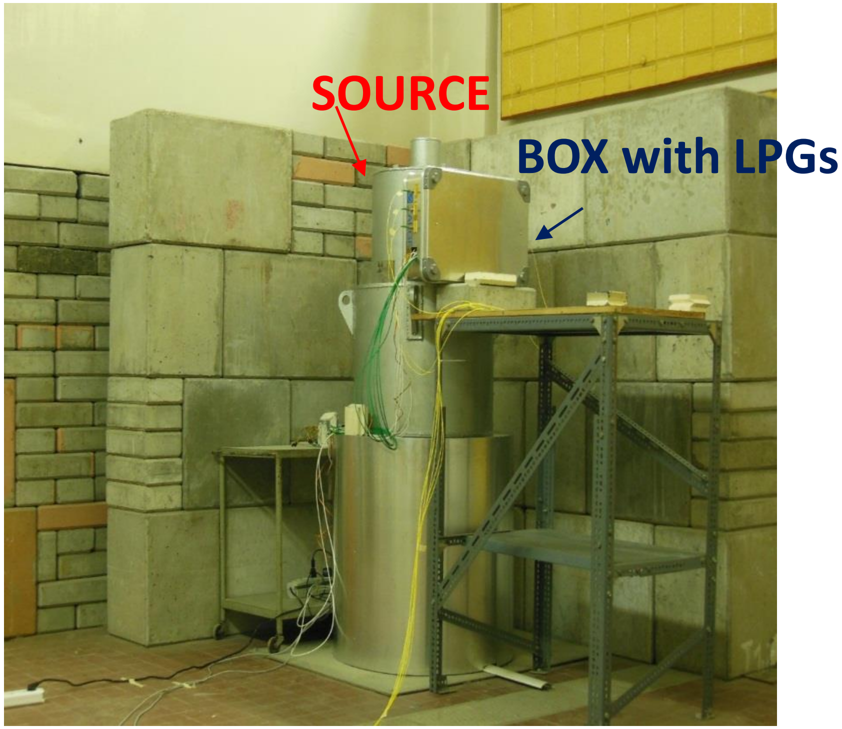
  - for a better understanding of the effect of the radiation on the grating
- Incremental irradiation campaigns with TiO_2 coated LPGs scheduled for the next months

  - no relevant difference expected as TiO_2 should be insensitive to ϒ – rays
- Investigations to be extended to protons in near future



Measuring irradiation set-up in ATOMKI





- Co^{60} source
- Cone shaped window in the cylindrical lead shielding
- Sensors installed in the box placed in front of the source

SIDE VIEW OF THE SOURCE

FOR OUR APPLICATION :

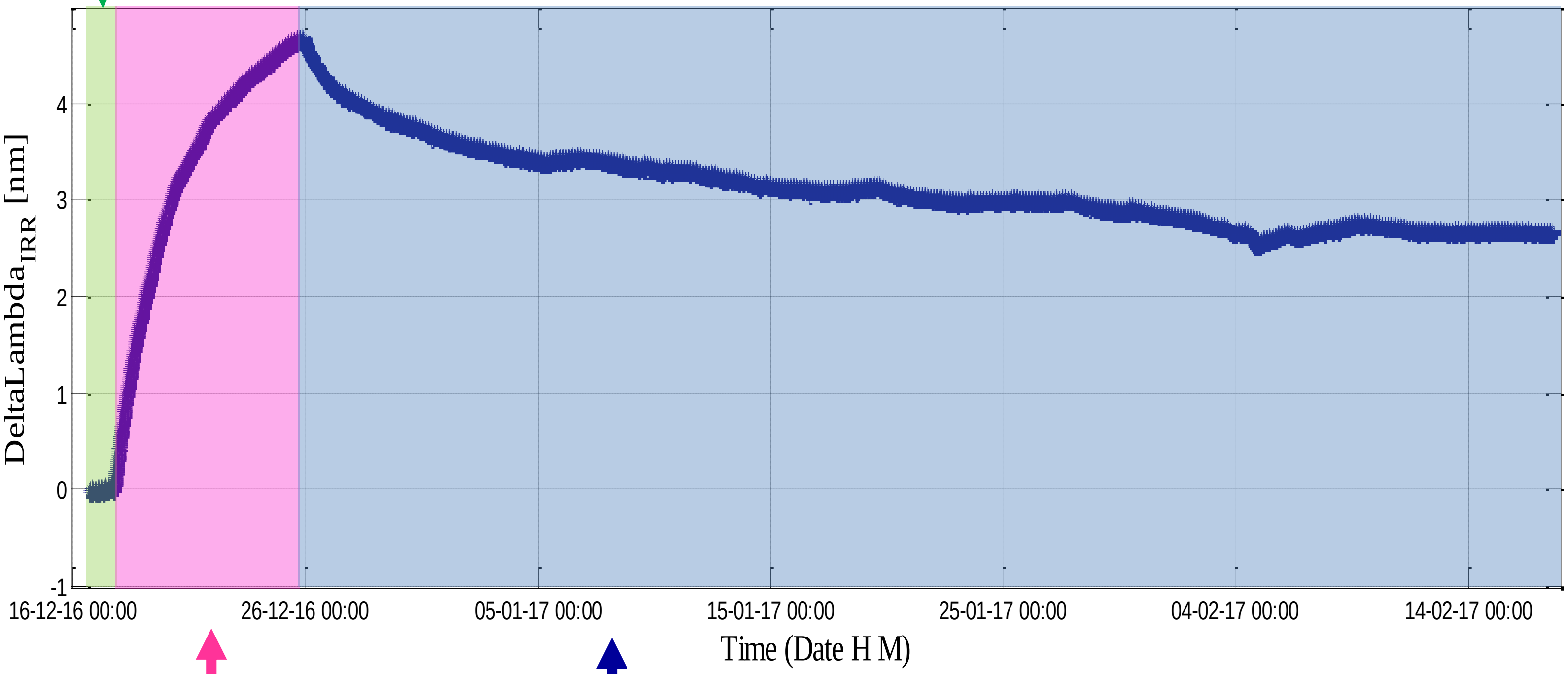
- @ 26.7 cm far from the middle of the source (LPGs installation point) a dose rate of 0.108 kGy/h* is expected
- To get 10 kGy, 92.4 hours (exposure time) are needed

*** 0.11 KGy/h is the same irradiation dose rate of an oject exposed to 10 MGy in 10 years**

On-line monitoring during irradiation campaign

- **ON LINE acquisition :**
  1. Thermalization phase
  2. Source ON phase
  3. Relaxation phase
- E.g.: Response of LPG sensor during a ϒ-ionizing irradiation exposure at 20 kGy

1. THERMALIZATION



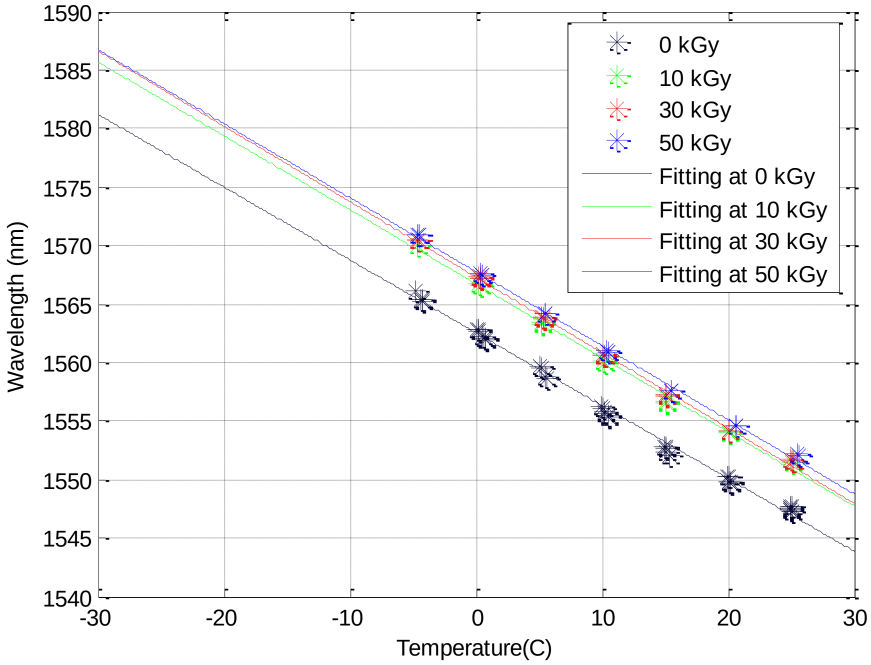
2. SOURCE ON

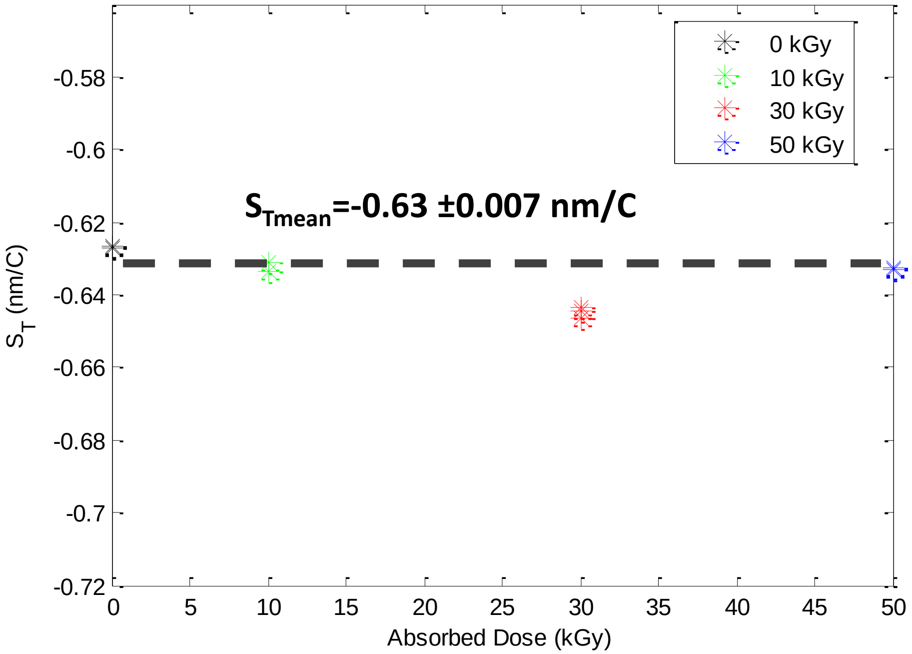
3. RELAXATION PHASE

Off line re-characterization @ CERN

Sensors re-characterized in EP-DT climatic chamber after each campaign

- Initial radiation induced shift, as observed for the first generation of RH sensors for CMS
- Sensor performance not significantly affected by radiation





S_{Tmean}=-0.63 ±0.007 nm/C

Next steps concerning irradiation

- ϒ-ionizing irradiation campaigns at higher doses
  - more investigations about the saturation properties of the radiation induced shift needed
  - more statistics to collect
  - study of the radiation damage on optical fibers, relaxation time, effect of the dose rate in collaboration with ATOMKI

- From next months, extend ϒ-irradiation studies to Ti0_2 coated LPG samples
  - same testing protocol as described before
  - statistics to collect

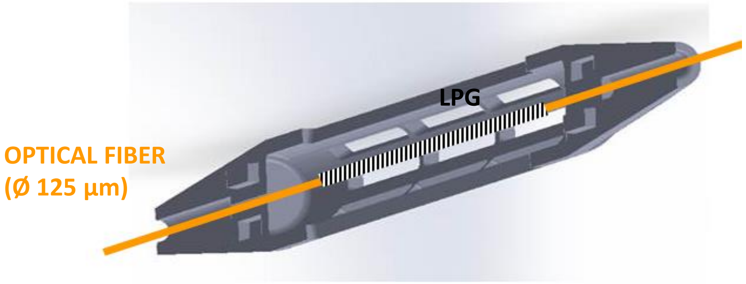
- Neutron and mixed beam irradiation on coated and uncoated LPG sensors
  - in contact with irradiation facilities at CERN
  - possible start at IRRAD (with Federico Ravotti) in summer 2017

Other tasks under investigation..

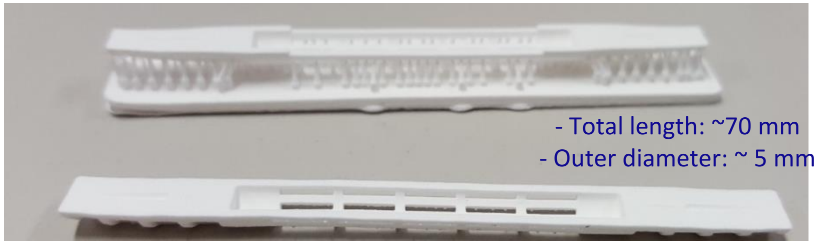
Development of final package for application in real environment

Specifications for a LPG-based sensor package:
- Strain free
- Small dimension
- Not intrusive

- First protoype of 3D-printed sensor packaging in ceramic (SiO_2)



3-D Model for the proposed packaging design



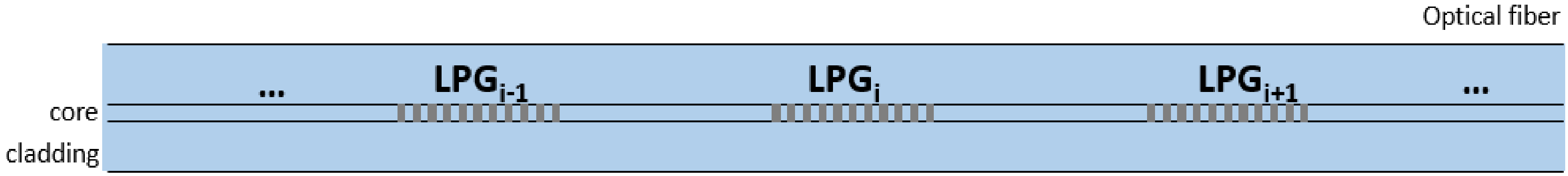
First prototype developed at CSEM

- Slight modifications of the first design under development

Other tasks under investigation..

Study of multiplexing solutions

- Possibility to write several LPG-based sensors within the same optical fibers:



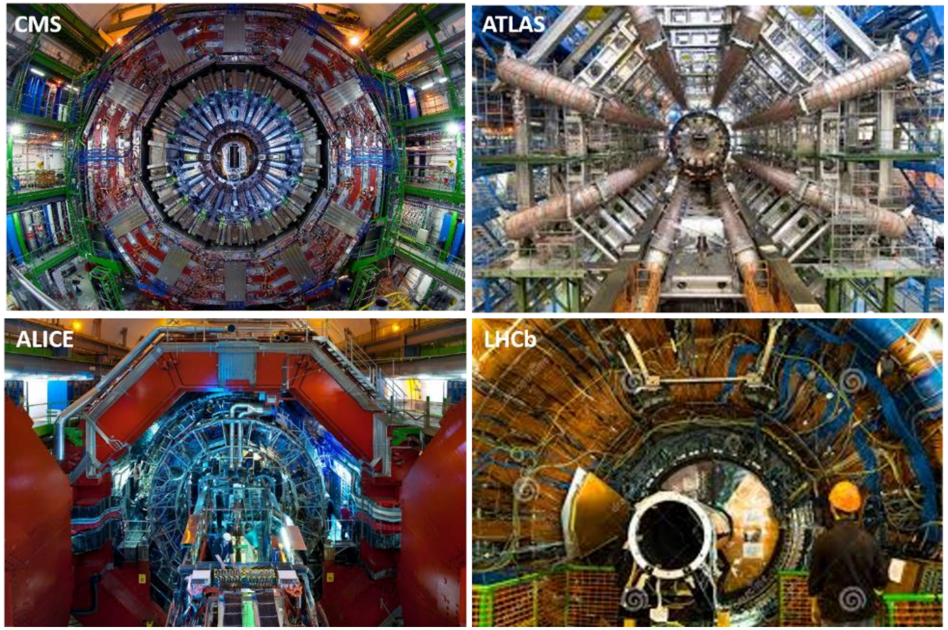
- Maximum number of sensors is ruled by taking into account:
  - spectral range of the light source
  - maximum wavelength shift of each sensor

Reasonable number for our application could be 4-5 in the range [0-50] %RH

RH high sensitivity applications for future HEP detectors

High
Luminosity
LHC

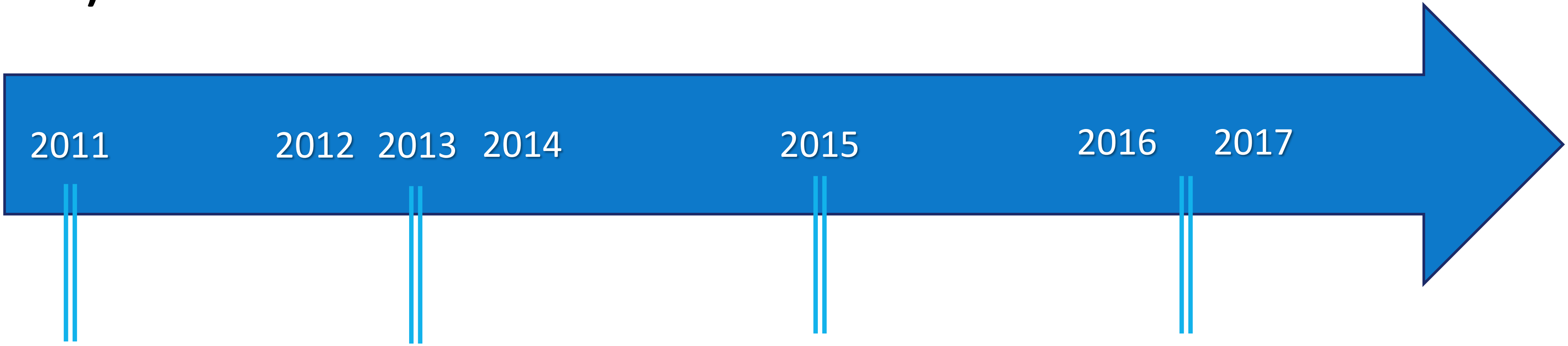
- New generation of particles detectors
- More challenging low operation temperatures
- Humidity monitoring extremely important
- Better accuracy of RH sensors at low humidity requested by experiments



THE ENHANCED SENSITIVITY OF LPG-BASED RH SENSORS (from 1000 to 100 times higher than the sensitivity of the first proposed generation) GUARANTEES HIGH PRECISION MEASUREMENTS AT LOW HUMIDITY!!!

Conclusions

1) FBG-based RH sensors



R&D PROGRAM DEFINITION

Development and testing of the first prototype of FBG-based thermo-hygrometer

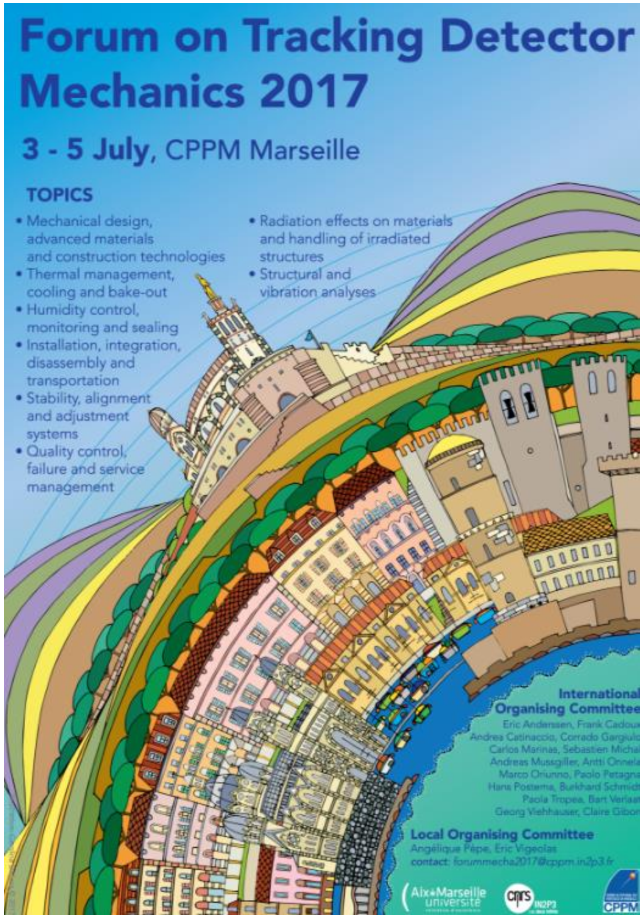
Installation of FBG thermo-hygrometers in CMS detector
(72 measurement points)

FBGs in operation in CMS: data taking and monitoring

Conclusions

2) LPG-based RH sensors

2013	2014 2015	2016	2017-2018	2019
R&D PROGRAM DEFINITION	**Preliminary investigations and assessment of the technology**	**My Research Fellowship Program in EP-DT Group** (ATLAS+CMS)	**Engineering**	**Target installation in ATLAS**



Forum on Tracking Detector Mechanics 2017

3 - 5 July, CPPM Marseille

TOPICS

- Mechanical design, advanced materials and construction technologies
- Thermal management, cooling and bake-out
- Humidity control, monitoring and sealing
- Installation, integration, disassembly and transportation
- Stability, alignment and adjustment systems
- Quality control, failure and service management
- Radiation effects on materials and handling of irradiated structures
- Structural and vibration analyses

International Organising Committee
Eric Anderssen, Frank Cadou
Andrea Catinaccio, Corrado Gargiul
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Hans Postema, Burkhard Schmid
Paola Tropea, Bart Verlaa
Georg Viehhauser, Claire Gibon

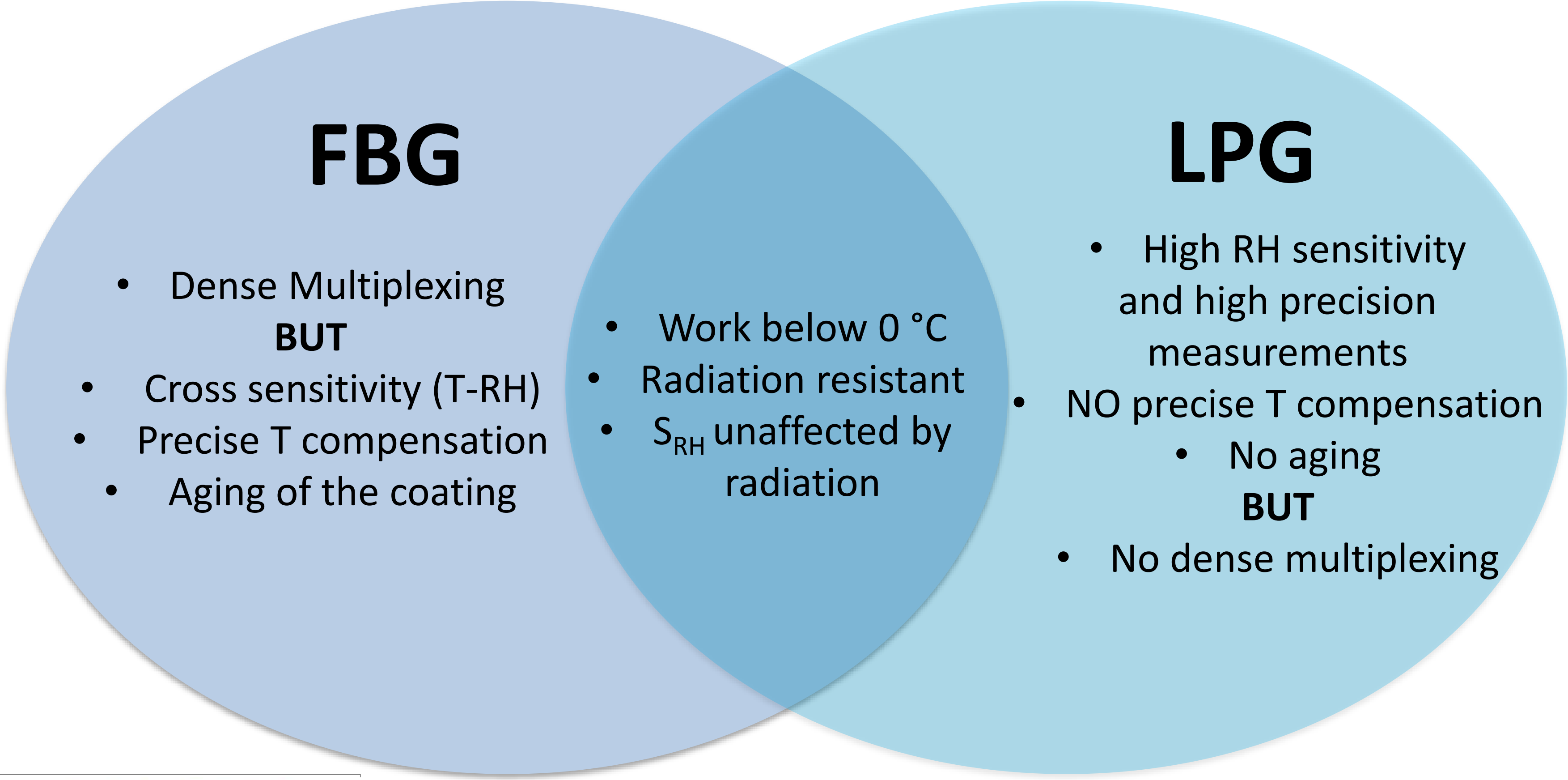
Local Organising Committee
Angélique Pépe, Eric Vigeolas
contact: forummecha2017@cppm.in2p3.fr

Merci pour votre attention!

gberruti@cern.ch

Back-up slides

FBGs or LPGs for RH monitoring in HEP environments?



FBG

- Dense Multiplexing

BUT

- Cross sensitivity (T-RH)
- Precise T compensation
- Aging of the coating

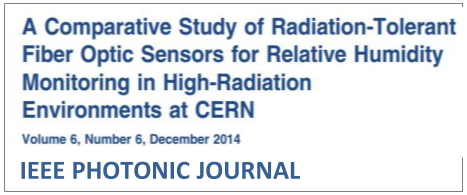
- Work below 0 °C
- Radiation resistant
- S_{RH} unaffected by radiation

LPG

- High RH sensitivity and high precision measurements
- NO precise T compensation
- No aging

BUT

- No dense multiplexing



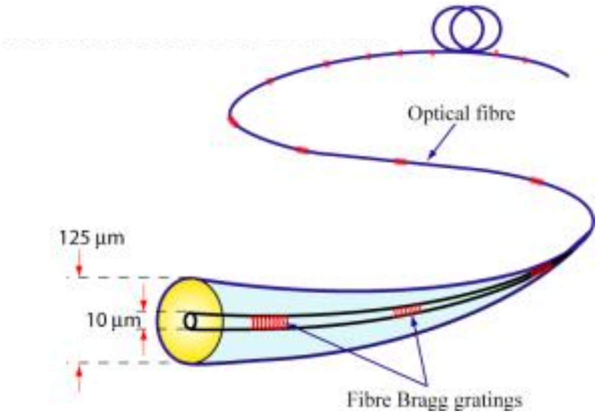
A Comparative Study of Radiation-Tolerant Fiber Optic Sensors for Relative Humidity Monitoring in High-Radiation Environments at CERN

Volume 6, Number 6, December 2014

IEEE PHOTONIC JOURNAL

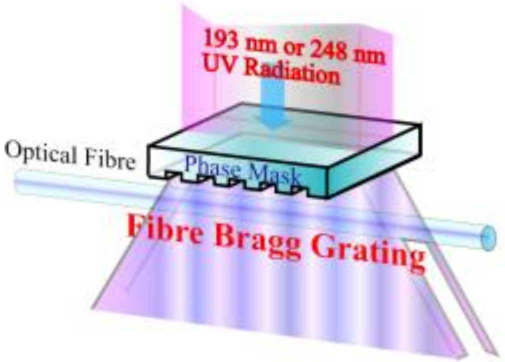
.. Why -based sensors?

FBG as a standardized technological platform



… and an attractive sensing solution:

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



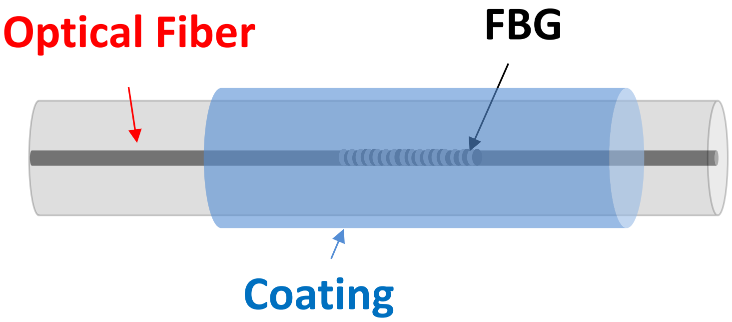
FBG as multifunctional sensors

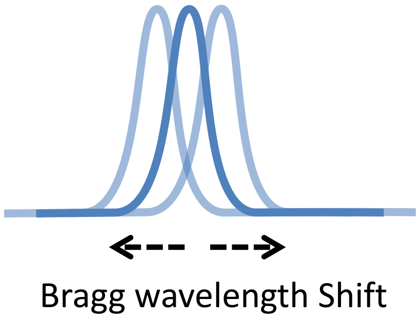
Functionalization: integration with appropriate materials and suitable packaging to measure physical, chemical and biological parameters

FBG + COATING:

Multi-parametric sensing

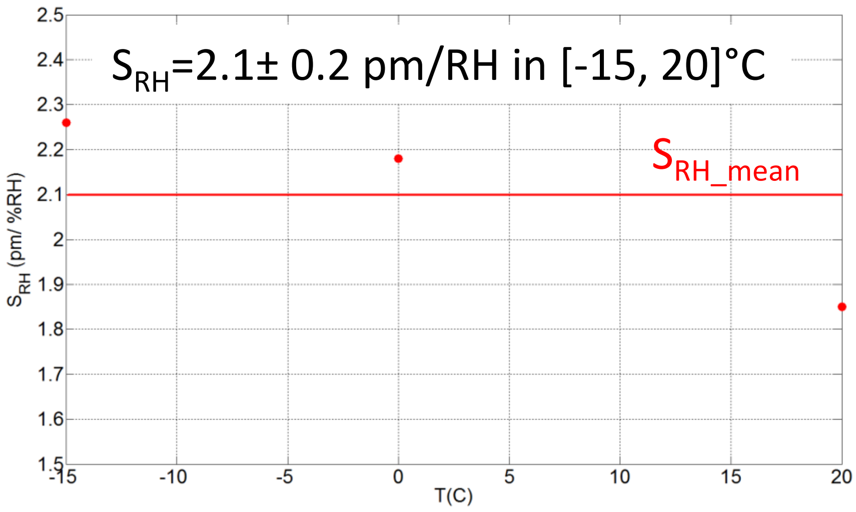
- Magnetic field
- Humidity
- Cryo temperatures
- Acoustic waves
- Weight
- Chemical and biological analytes
- ....



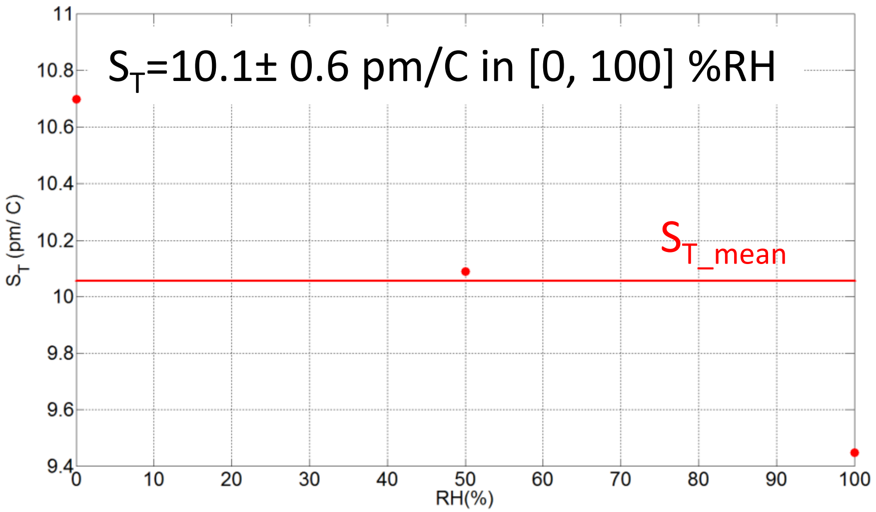


Performance of RH-FBG sensors

Relative Humidity Sensitivity

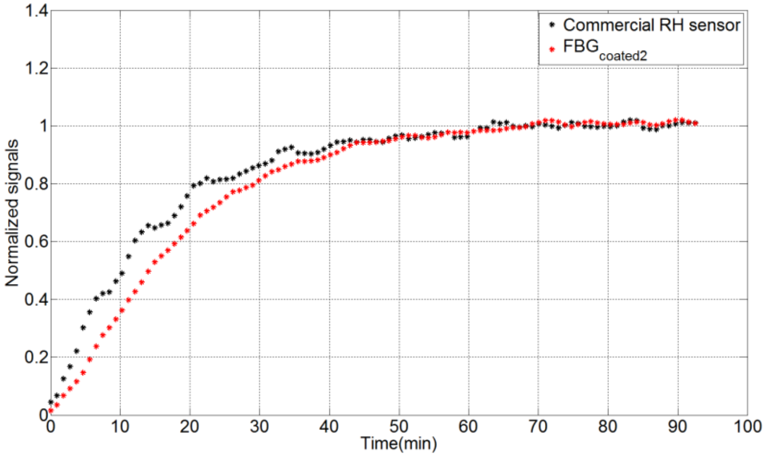

S_{RH}=2.1± 0.2 pm/RH in [-15, 20]°C

Temperature Sensitivity


S_T=10.1± 0.6 pm/C in [0, 100] %RH

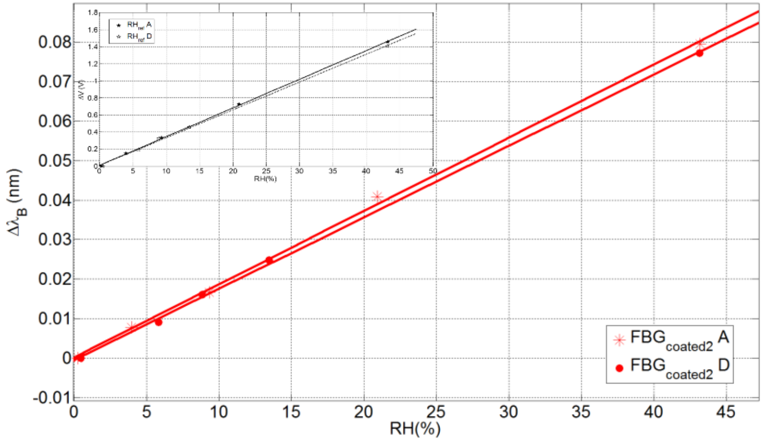
Response Time

$t_{response}$ of a few seconds, comparable to the ref. sensor



Hysteresis

~ 1.6 %RH, comparable to the ref. sensor (INSET)



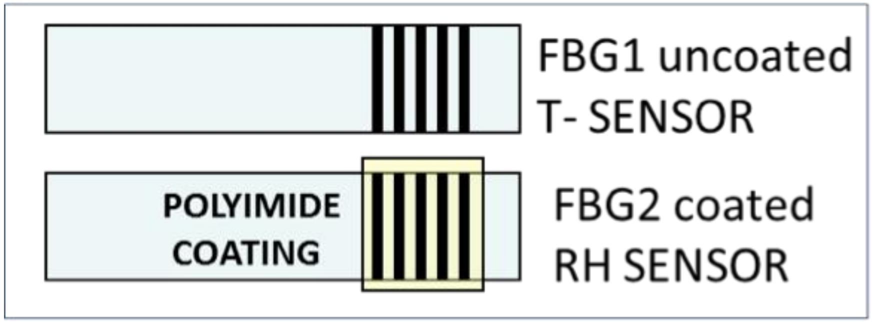
Temperature compensation

- Polyimide-coated FBGs intrinsically sensitive to temperature:

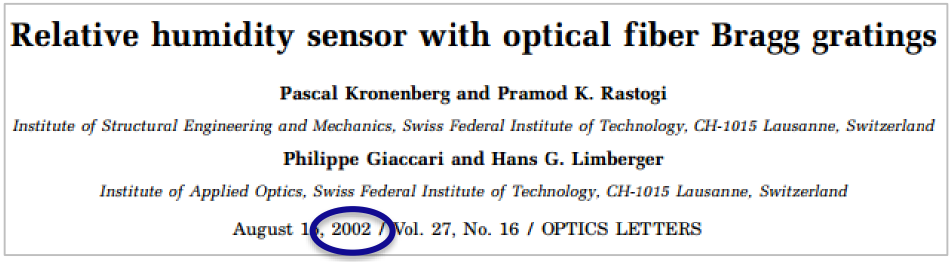
$$\boxed{\Delta\lambda_B = f(\Delta T, \Delta RH) = S_T(T, RH)\cdot\Delta T + S_{RH}(T, RH)\cdot\Delta RH}$$

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

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



.. RH FBG sensor not new in literature..



Relative humidity sensor with optical fiber Bragg gratings

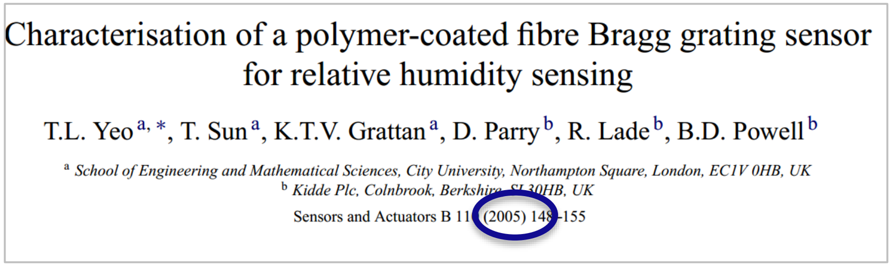
Pascal Kronenberg and Pramod K. Rastogi

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

August 16, 2002 / Vol. 27, No. 16 / OPTICS LETTERS

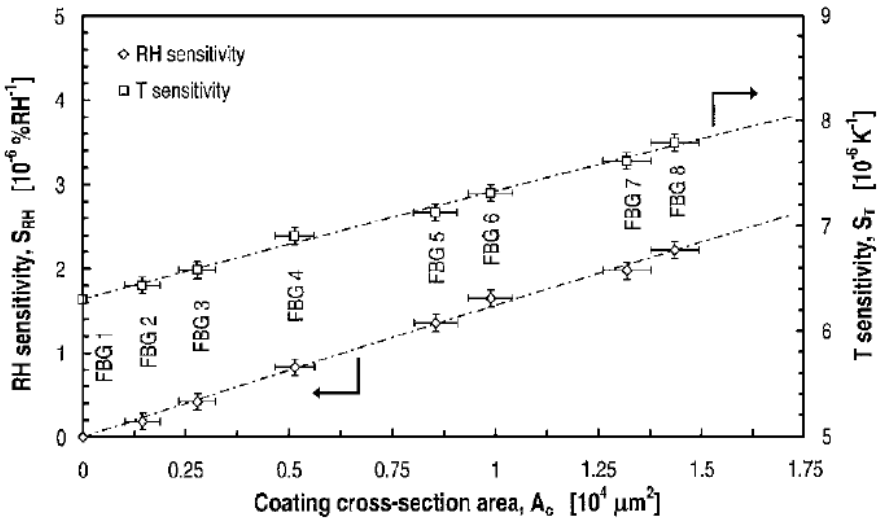


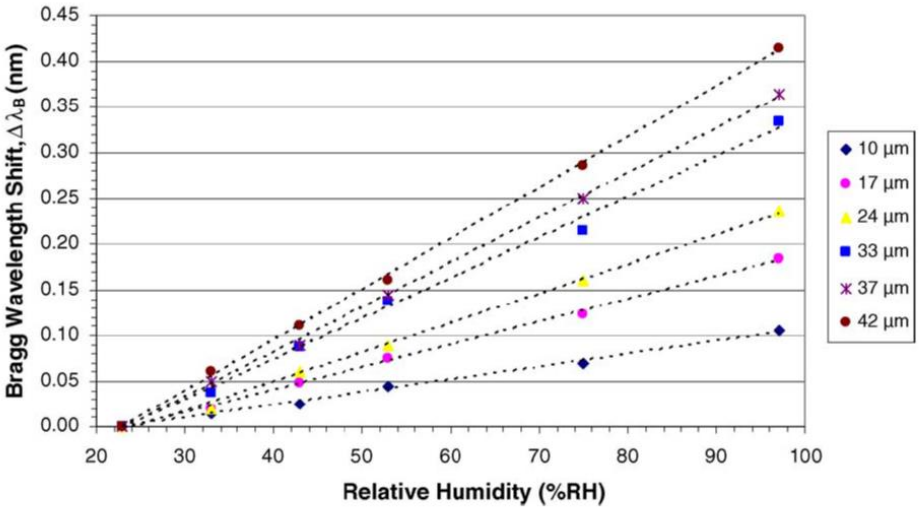
Characterisation of a polymer-coated fibre Bragg grating sensor for relative humidity sensing

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, SL3 0HB, UK*

Sensors and Actuators B 110 (2005) 148-155





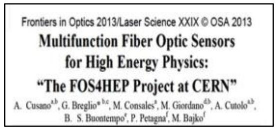
- RH measurements limited to [10, 65] °C and [20-100] %RH ranges
- Completely unexplored the effect of ionizing radiations

FBG-based thermo-hygrometers under radiation

Poly- Coated FBG RH sensors

PI-coated FBG produced by WELLTECH

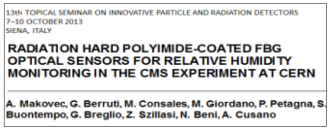
- Designed by Unisannio and CERN
- PI-coated FBGs mounted in free-strain package
- Coating thickness:10 µm (nominal)
- Irradiation campaigns up to 210 kGy
- Same results as FBG-T sensors



Frontiers in Optics 2013/Laser Science XXIX © OSA 2013

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

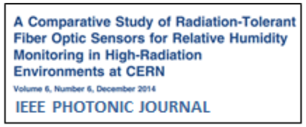
A. Cusano[a,b], G. Breglio*[b,c], M. Consales[a], M. Giordano[d,b], A. Cutolo[a,b], B. S. Buontempo[e], P. Petagna[f], M. Bajko[f]



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



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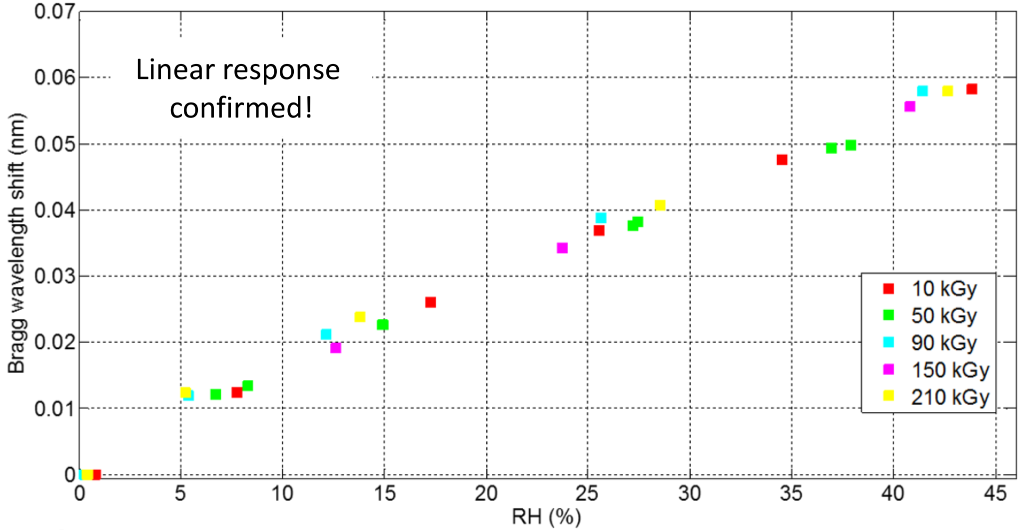
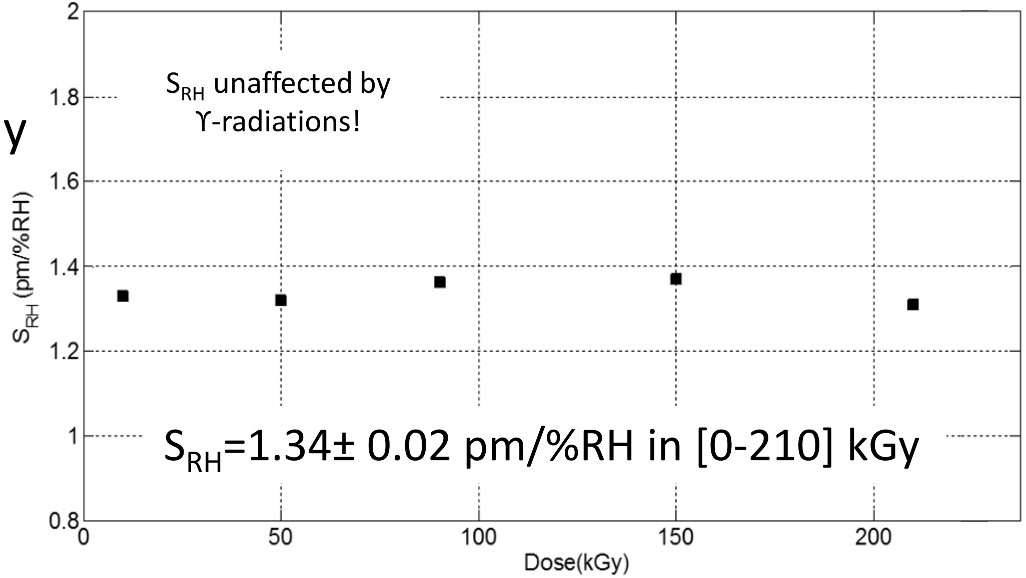


Linear response confirmed!



S_{RH} unaffected by ϒ-radiations!

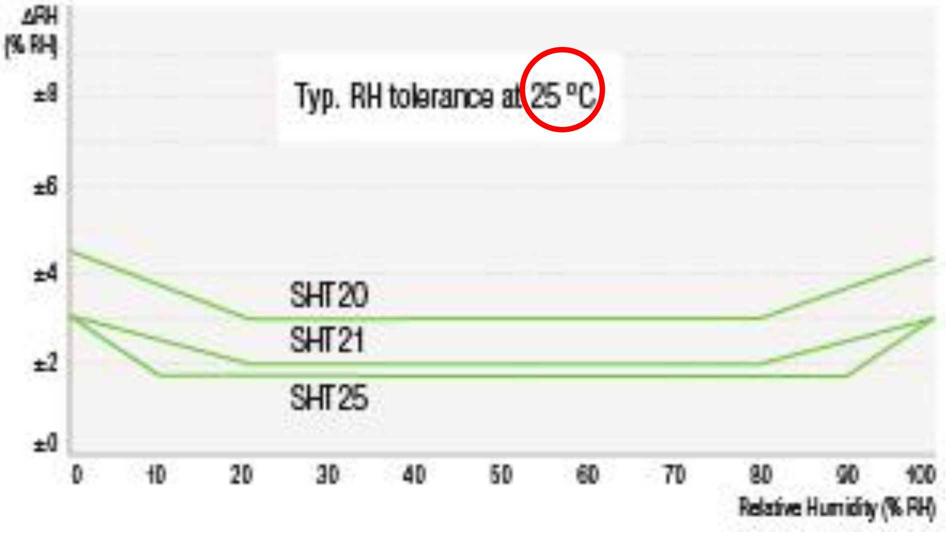
S_{RH}=1.34± 0.02 pm/%RH in [0-210] kGy

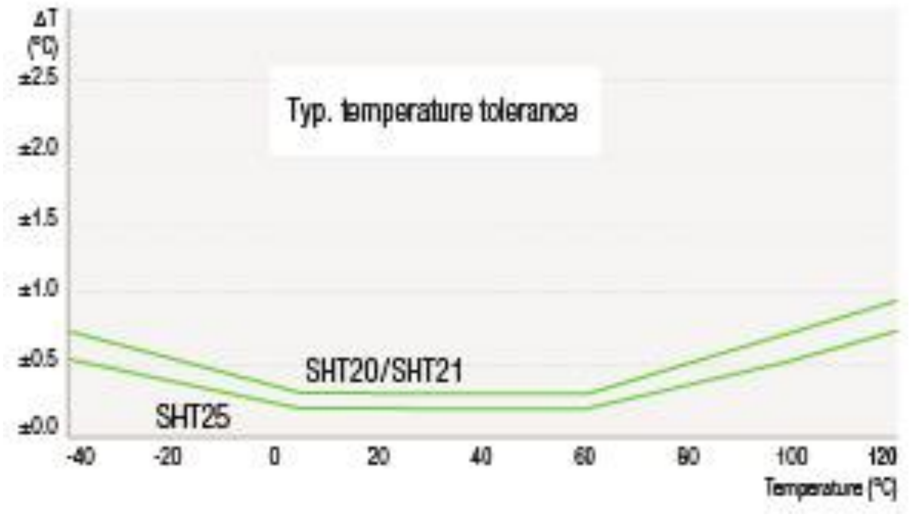
Benchmark in the RH sensors market

SHT2X:

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

Declared behaviour of Sensirion SHT2X



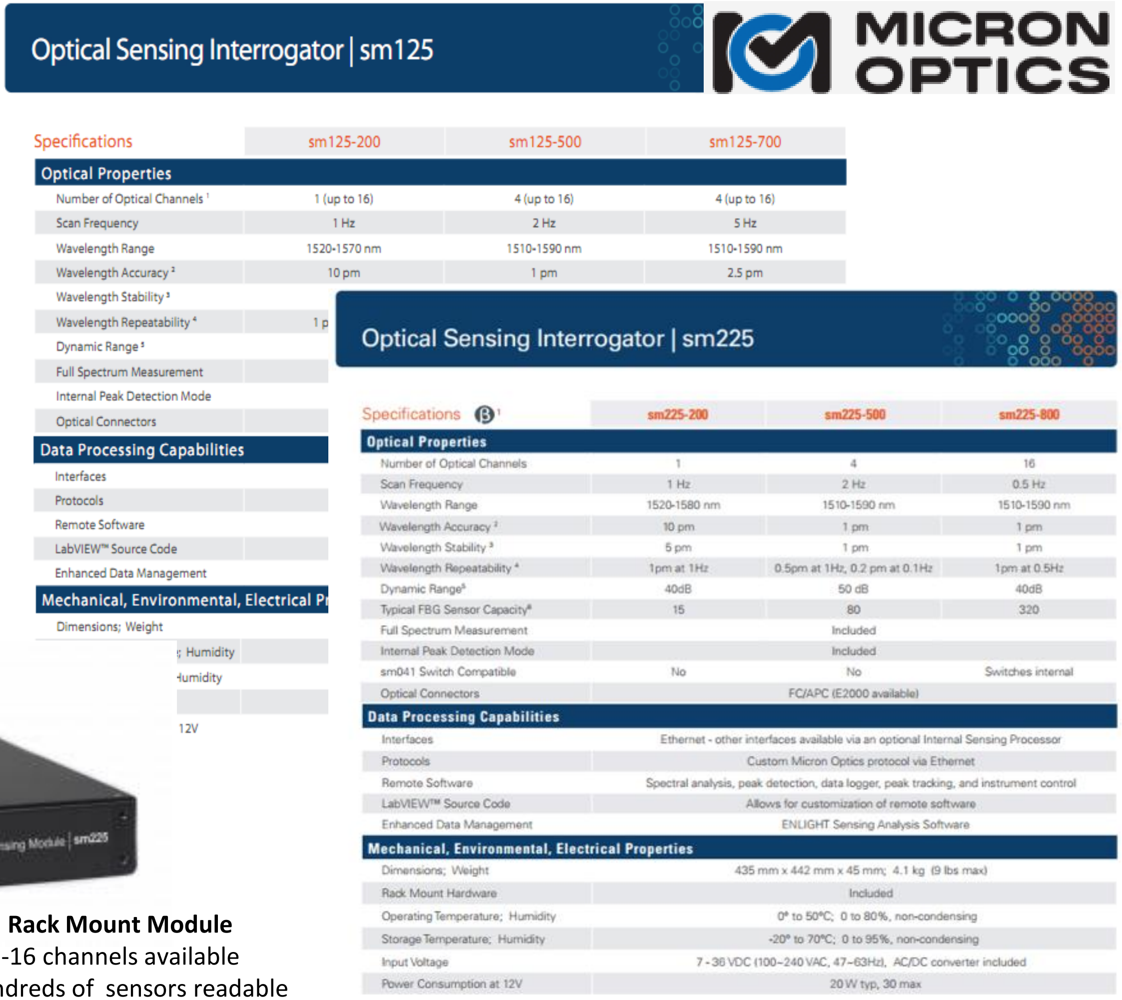


- RH Accuracy values exclude hysteresis (±1 %RH declared in the datasheet)
- HIHs RH sensors installed in CMS and coupled to optical fiber based RH sensors during LS1 show at best comparable performance

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			
umidity			
12V			

Optical Sensing Interrogator | sm225

Specifications ß[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	

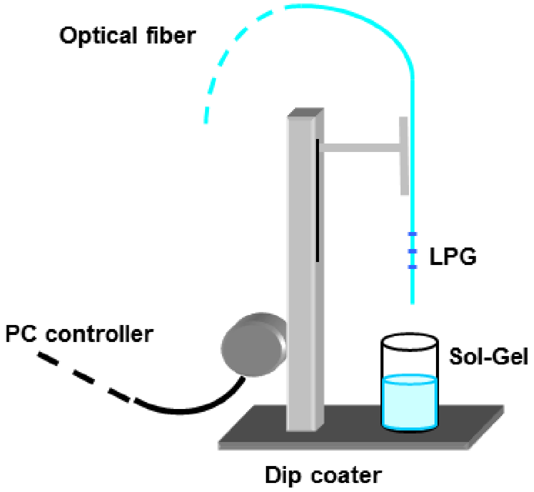
Rack Mount Module

-16 channels available

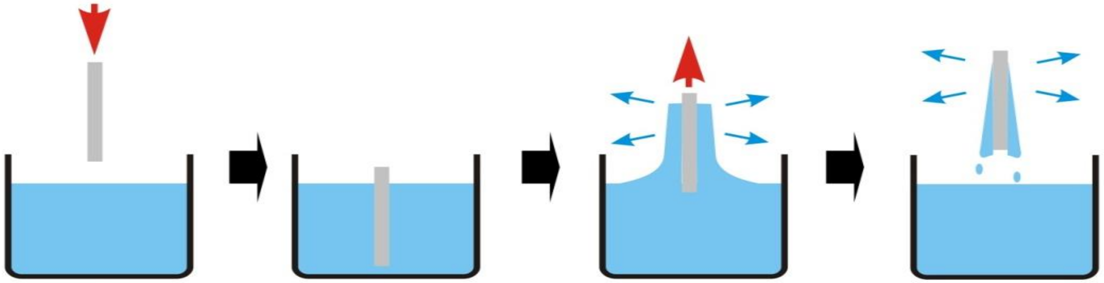
-Hundreds of sensors readable

Coated-LPG: Fabrication process (1)

- Sol- gel dip coating method for TiO_2 layers integration onto LPG surface
  - good optical quality
  - ring shaped simmetry
  - longitudinal uniformity over the grating length...



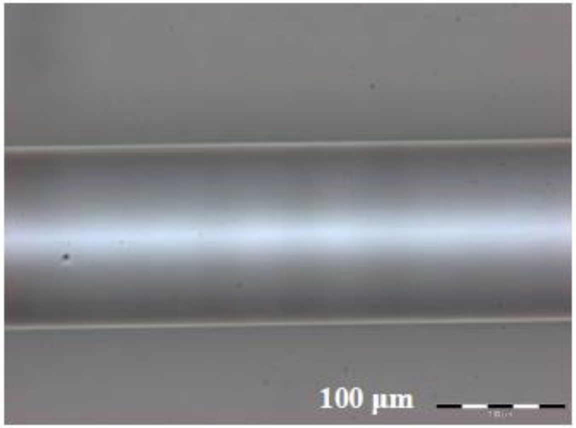
- 4 steps in the fabrication process:



Dipping **Immersion** **Wet layer formation** **Solvent evaporation**

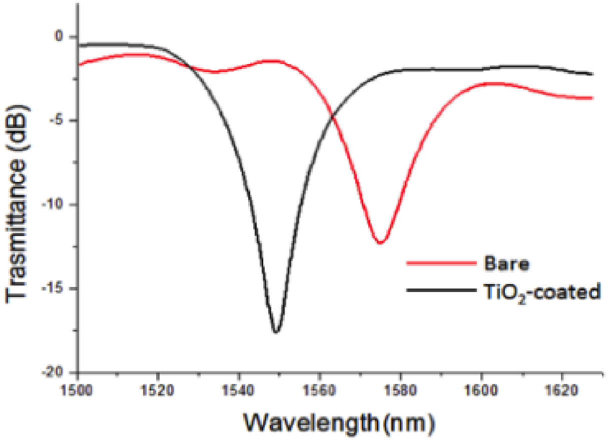
Coated-LPG: Fabrication process (2)

- Multiple depositions needed to get the desired layer thickness (~100nm)



20x microscope image of a TiO_2-coated LPG1 probe

Smooth and homogeneus TiO_2 layer deposited onto the fiber



Trasmittance spectra before and after the TiO_2 deposition

1. Attenuation band of the bare device (5th cladding mode) at $\lambda_{res,05}$=1579.0 nm
2. TiO_2 deposition causes a ~ 24.1 nm resonance blue shift and ~ 5 dB increase in its depth

EFFICIENT ON-LINE THICKNESS CONTROL DURING THE DEPOSITION, THROUGHT THE MONITORING OF THE WAVELENGTH SHIFT

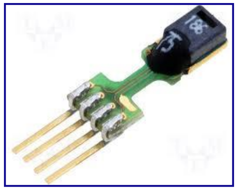
at CMS for RH monitoring

1) Different types of **miniaturized sensors** (standard capacitive)

PRECON
HS2000

HONEYWELL
HIH4030

SENSIRION
SHT75



NO-ONE satisfies CERN requirements:

- Not radiation hard
- No easy cabling

2) **Remote air sniffers**

Measurements 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