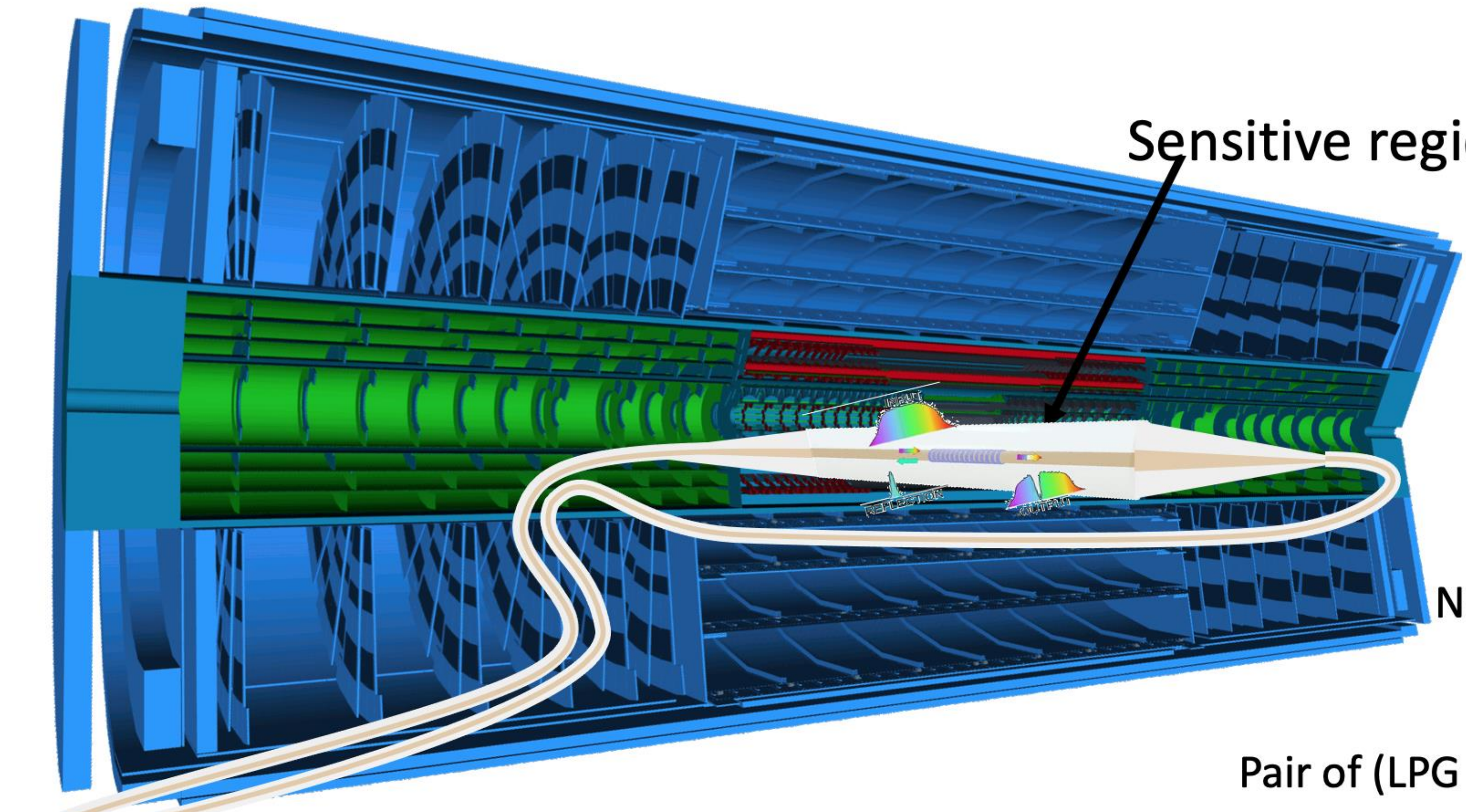
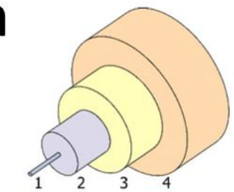
Fibre Optic Sensors in ATLAS … Keep ATLAS Dry !

UNIVERSITY OF JOHANNESBURG





Typical structure of a single mode optical fiber *(not to scale)*
1. Core 8 - 9 μm diameter
2. Cladding 125 μm dia.
3. Buffer 250 μm dia.
4. Jacket 900 μm dia

ATLAS ITK
New radiation hard fibre optic humidity sensors
Pair of (LPG for RH, FBG for T)

Humidity in the ITk: Keep ATLAS ITk dry

UNIVERSITY OF JOHANNESBURG

Novel Fibre Optic Sensor (FOS) system

FOS technology

1. Rad Hard
2. Long Term Stability
3. Sufficiently precise
4. Need Companion conventional sensor for calibration, then they die
5. R&D, Procurement, Manufacture, QA, Ongoing development during Run 3
6. Take charge of feed throughs, cabling
7. Dashboard at PP1 via OPC Server

R&D

1. Develop FOS technology further
2. Bare fibre type selections
3. Grating writing technology
4. Functional Coating Technology
5. Environment Chamber for tests, calibrations
6. Algorithms for readout, compensation, calibration

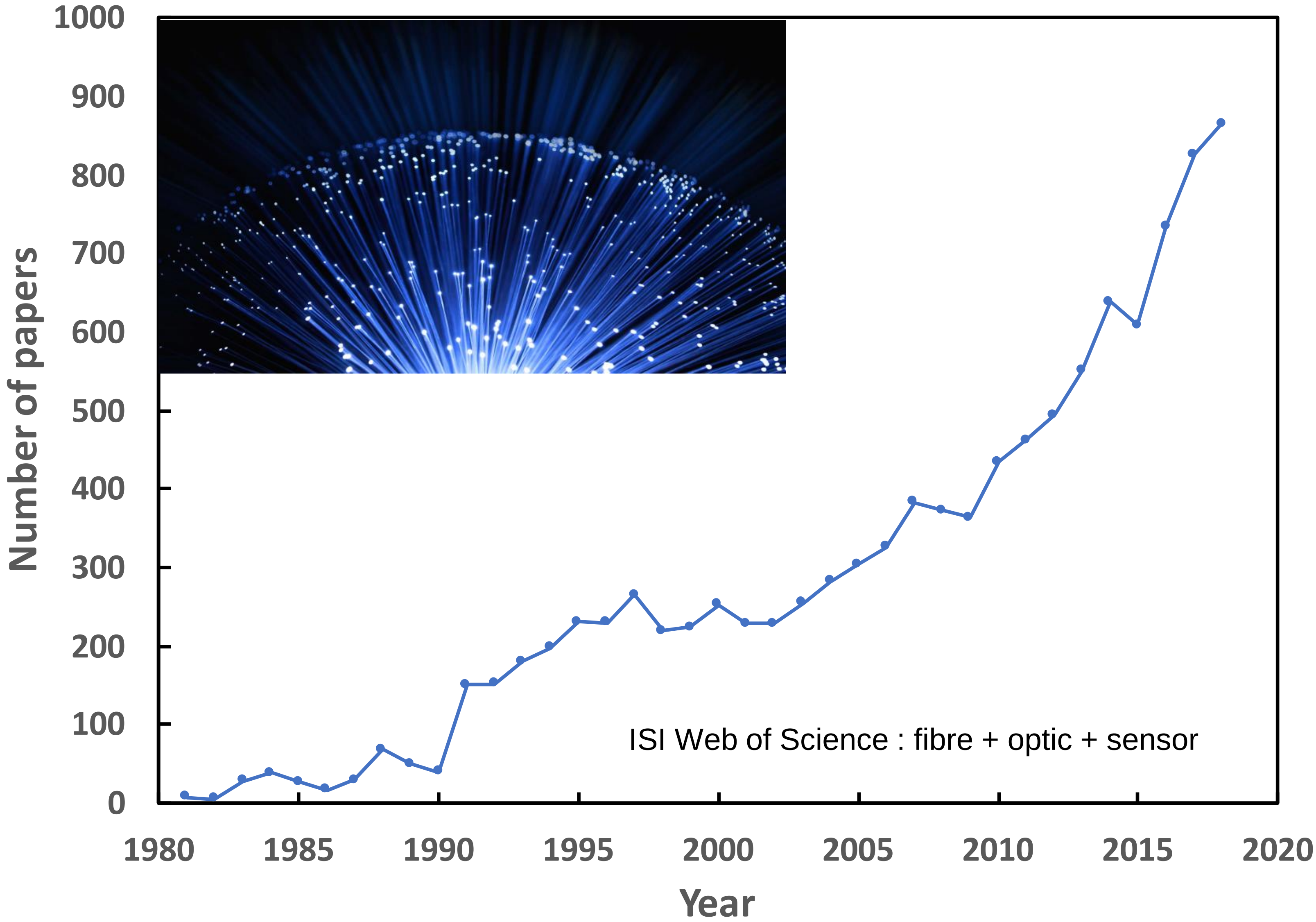
Modelling

1. Continuum Fluid Dynamics (CFD) 3D simulation of fluid flow, thermals, leaks
2. Operational conditions
3. Dry-out, normal, fault, bake-out

Future

1. Manufacture, QA and provide throughout ATLAS ITk : 54 Sensors
2. **More R&D to improve Design, Manufacture, Readout, Performance in long term**

Fibre Optic Sensors : FOS ……. a growth area



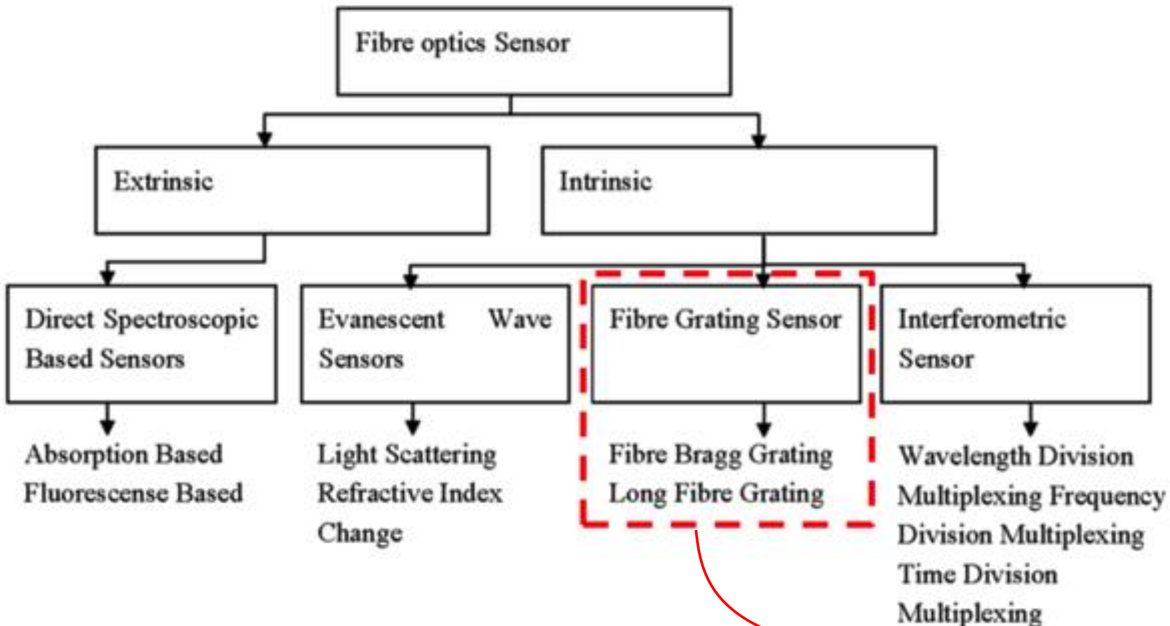
Fibre Optic Sensors : FOS ……. many types

UNIVERSITY OF JOHANNESBURG

(from G Berruti, **Forum on Tracking Detector Mechanics 2017 3 -5- July, CPPM Marseille**)

FOS classification

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



Option : Functional Coating to target sensitivity to specific measurement parameter.

3/07/2017 Forum on Tracking Detector Mechanics 2017 3

Fibre Optic Sensors : FOS ……. advantages

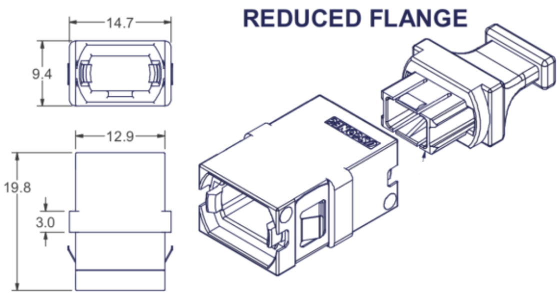
UNIVERSITY OF JOHANNESBURG

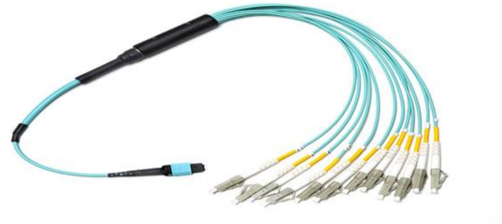
1. **Extreme environments**
   - Dust, moisture, vacuum, temperature (hot / cold), vibration, EM interference, **radiation**, aggressive chemicals

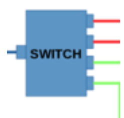
2. **Many Sensing Modes**
   - **Strain, temperature, humidity, vibration** (including 3-D displacements), many specific bio-molecules, **radiation dose**

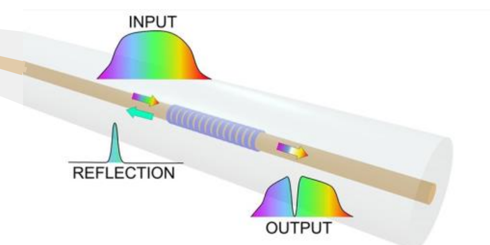
3. **Highly Customisable**
   - **Sensitivity** (enhanced sensitivity to a single environmental parameter and also relative sensitivity between different environmental parameters)
   - Dynamic range
   - **Multiplexing factor**
   - Interrogator (Expensive / cheaper)
   - Type of functional coating (what is sensed)
   - Parameters of the grating (FBG / LPG / no grating)
   - Type and treatment of fibre (modes, physics mechanism)

4. **Smart**
   - Light, near microscopic in size, can be embedded, can be mass-produced, durable, stable, wavelength and time encoded (not reliant on absolute intensity), optical readout, **(very) remote interrogator**, 4IR, IoT, ……





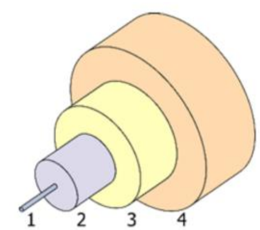




Credit: Maria Konstantaki, Foundation of Research and Technology - Hellas)

Switch

MPT 12 fibre feedthrough



Typical structure of a single mode optical fiber *(not to scale)*

1. Core 8 - 9 μm diameter
2. Cladding 125 μm dia.
3. Buffer 250 μm dia.
4. Jacket 900 μm dia

What does it do?

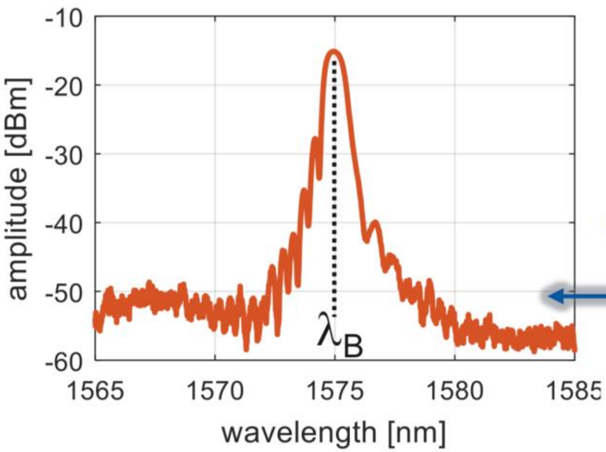
Bernardo Castaldo, Marta Bajko, Hugues Bajas, Antonella Chiuchiolo, Sara Benitez Berrocal, Michele Giordano[1], Luca Palmieri[2], Jeroen Van Nugteren

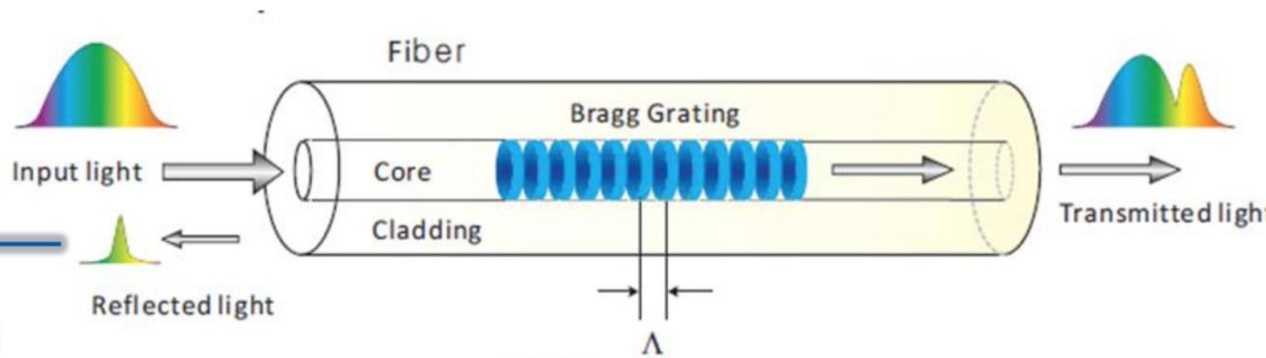
[1] IPCB-CNR, Napoli, Italy

[2] University of Padova, Padova, Italy

From https://indico.cern.ch/event/837593/

Acts as a band-stop **filter** passing all wavelengths that are not in resonance with the grating and reflecting wavelengths that satisfies the Bragg condition



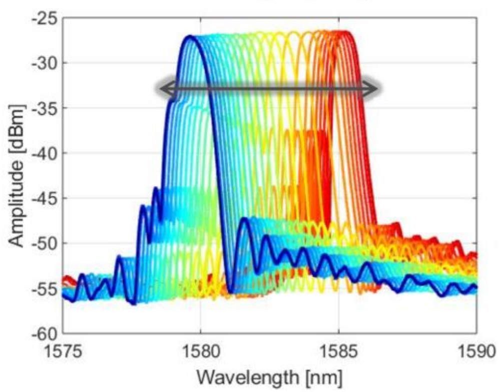


$$\lambda_B = 2\, n_{eff}\, \Lambda$$

Temperature and strain dependent

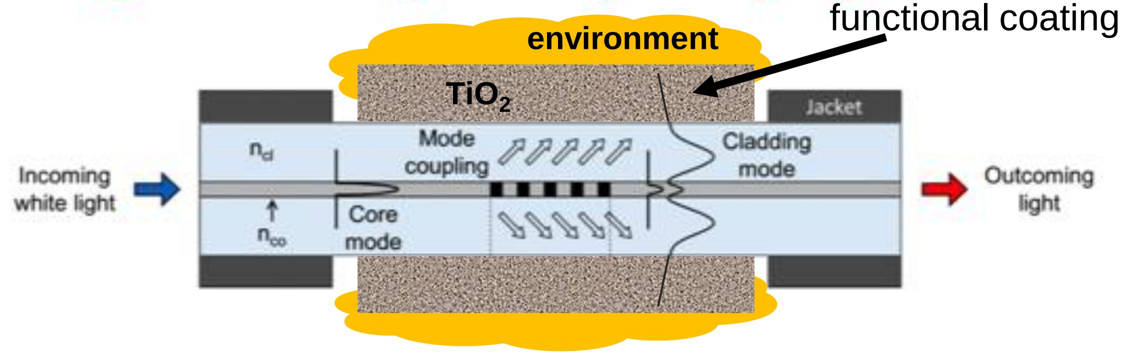
- n_{eff} = effective refractive index of the core
- Λ [nm] = grating period

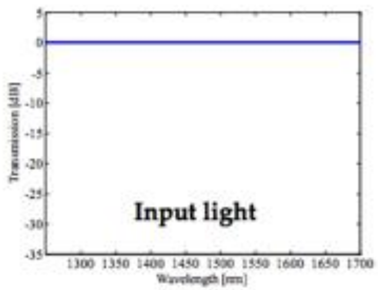
$$\Delta\lambda_B = \frac{\partial\lambda}{\partial T}\Delta T + \frac{\partial\lambda}{\partial\varepsilon}\Delta\varepsilon$$



Long Period Fiber Gratings (LPG) principle of operation

Long Period Fiber Gratings (LPGs) are in fiber photonic devices realized by creating a periodic refractive index modulation of the core of a single-mode optical fiber along a small portion of its length



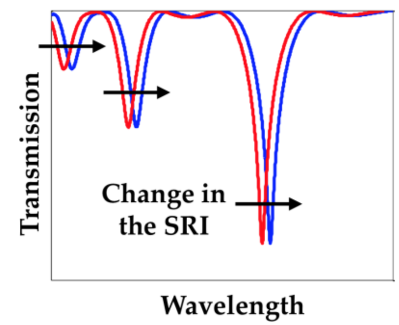


Λ = grating period ~ hundreds of μm

$n_{eff,core}$ = effective refractive index (RI) of the fiber core

$n^{i}_{eff,clad}$ = effective RI of the i^{th} cladding mode

$\lambda_{res,i}$ = resonance wavelength of the i^{th} cladding mode



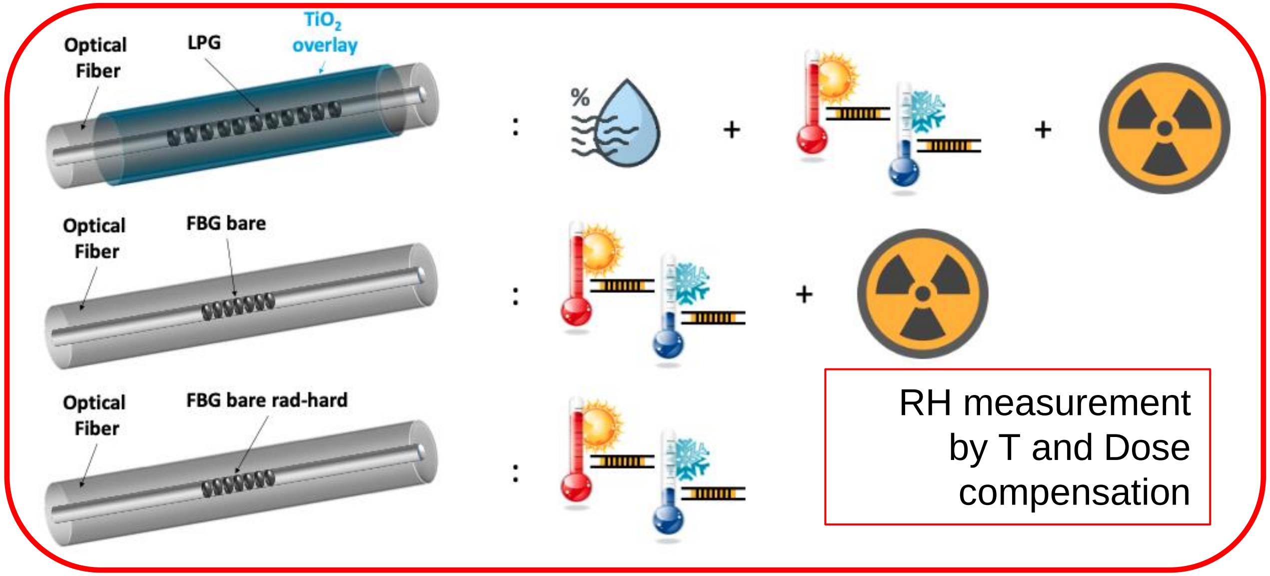
*LPGs act coupling the fundamental guided core mode to discrete forward propagating cladding modes, and to each of them at a distinct wavelength where the so-called **phase matching condition** is satisfied:*

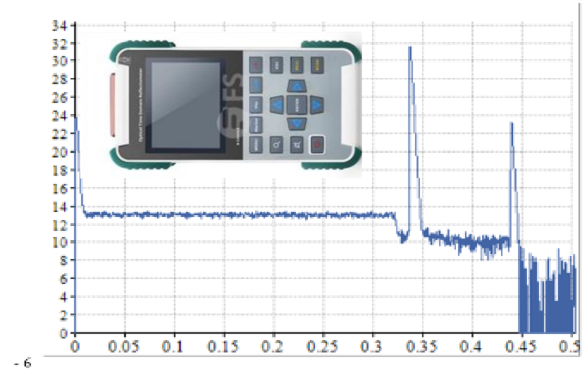
$$\lambda_{res,i} = (n_{eff,co} - n^{i}_{eff,cl}) \times \Lambda$$

from G. Berruti and A. Cusano

functional coating : nano-crystalline layer of TiO_2 - absorbs H_2O reversibly
Leads to both change in Λ and also $n^{i}_{eff,cl}$

UNIVERSITY OF JOHANNESBURG

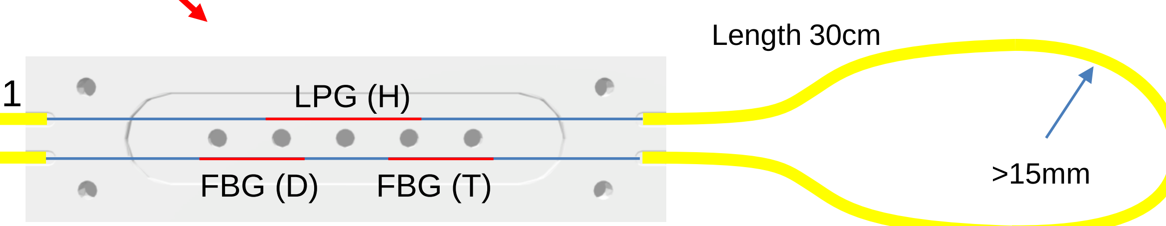




QA during integration by OTDR

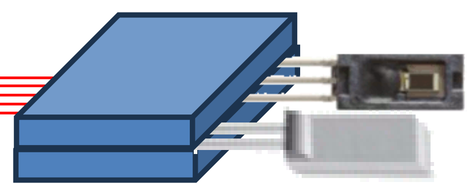
FOS Package (54)

Free end as flylead (6m)
Will later splice to flylead from PP1



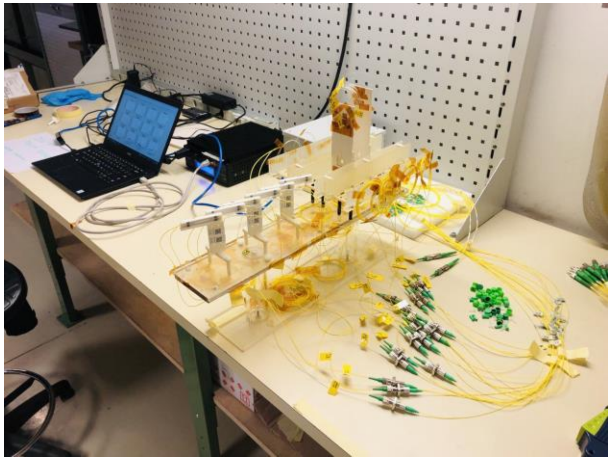
5 wire Sacrificial Sensors (58)

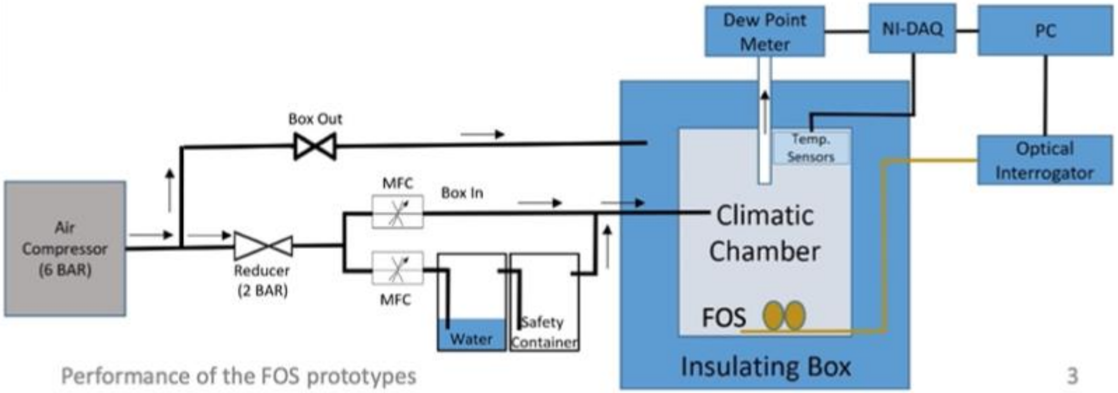
Mount very close to FOS package holes



HIH4000
Pt10k

The EP-DT characterization setup





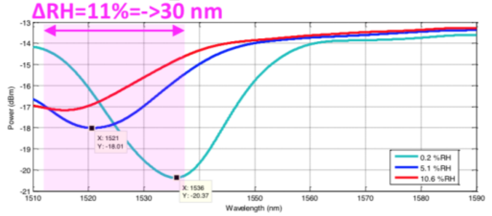
UNIVERSITY OF JOHANNESBURG

Optimization of the LPG- humidity sensor fabrication (2)

Please note the RH sensitivity of the first generation of RH FOS (FBG) was ~0.001 nm/RH

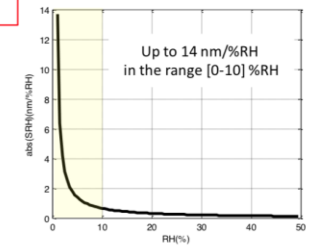
- **12 layers of TiO_2 deposited onto the grating**

ΔRH=11%=->30 nm



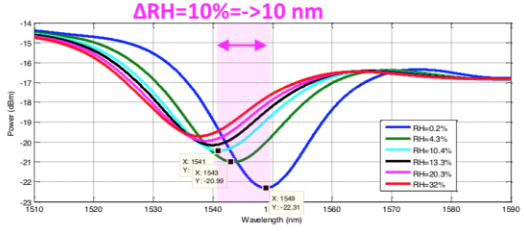
- **Extremely high RH sensitivity**
  Step from 0.2 %RH to 5.1 %RH ⟶ Δλ =~ 15 nm
- **With 3 RH steps in the range [0, 11]% RH, we use 30 nm of bandwidth of the optical interrogator**

⇨



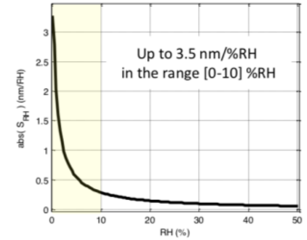
- **11 layers of TiO_2 deposited onto the grating**

ΔRH=10%=->10 nm



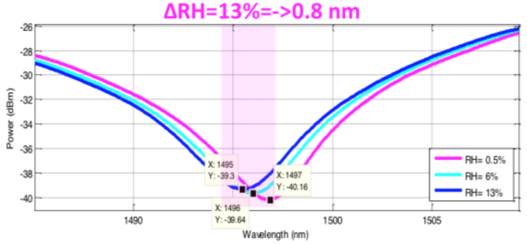
- **Still highly RH sensitive**
  Step from 0.2 %RH to 4.2 %RH ⟶ Δλ=~ 6 nm
- **With 3 RH steps in the range [0, 10]% RH, we use 10 nm of bandwidth of the optical interrogator**

⇨



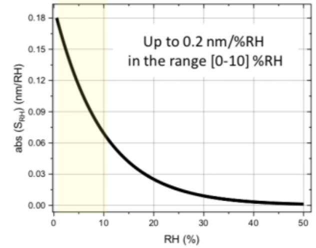
- **8 layers of TiO_2 deposited onto the grating**

ΔRH=13%=->0.8 nm



- **Still highly RH sensitive**
  Step from 0.5 %RH to 5.5 %RH ⟶ Δλ=~ 0.8 nm
- **With 3 RH steps in the range [0, 13]% RH, we use 1.3 nm of bandwidth of the optical interrogator**

⇨

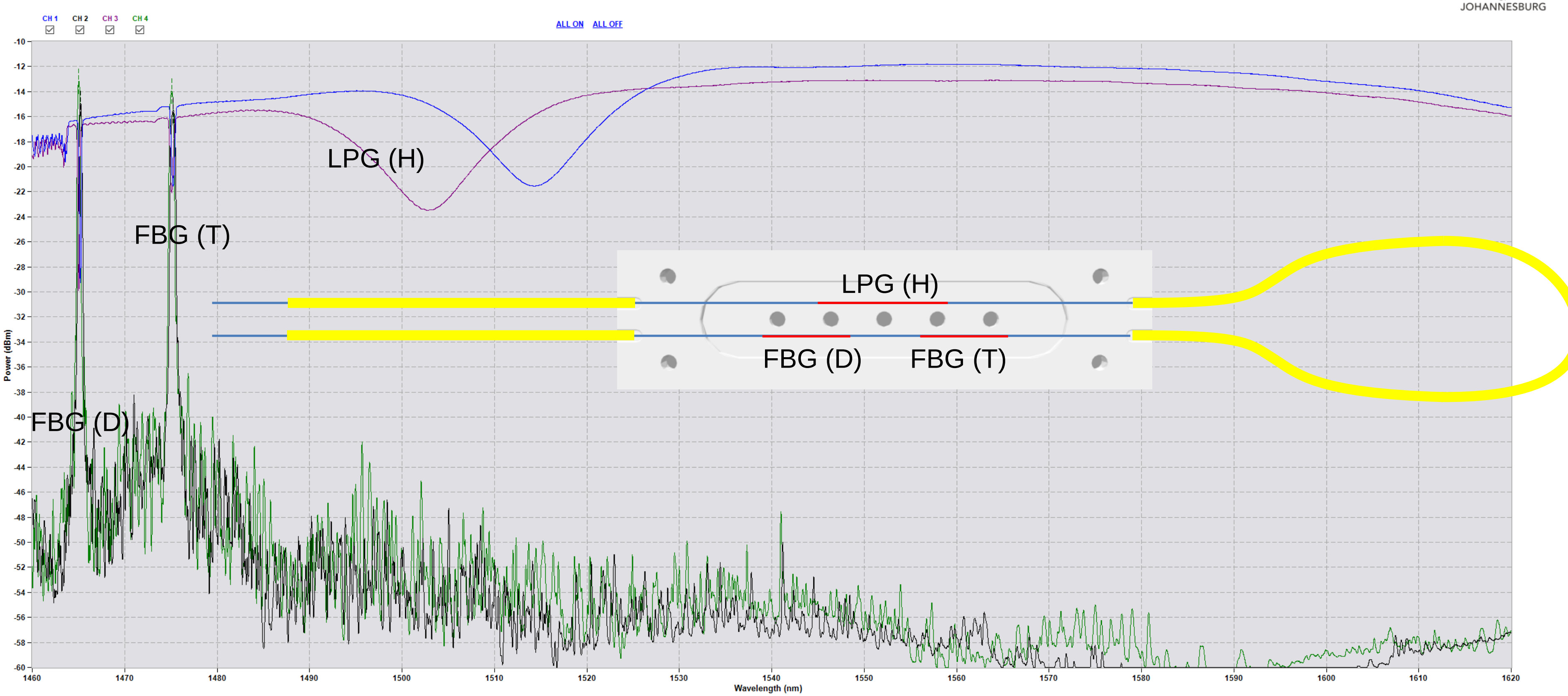


➡ **Trade-off** between sensing performance and wavelength range available for the sensors readings

The choice of the number of layers should be fixed considering the operational RH range of the sensor and the max bandwidth variation assigned to the sensor itself

The final design of LPG RH sensor that we propose consists of a LPG coated with 8 layers of TiO_2

Fibre Optic Sensors : Raw Data



Fibre Optic Sensors : Placements

UNIVERSITY OF JOHANNESBURG

Recap – Original Number of Sensors … see below …

now 4 Additional FOS + partner Sacrificial + 4 Additional Sacrificial

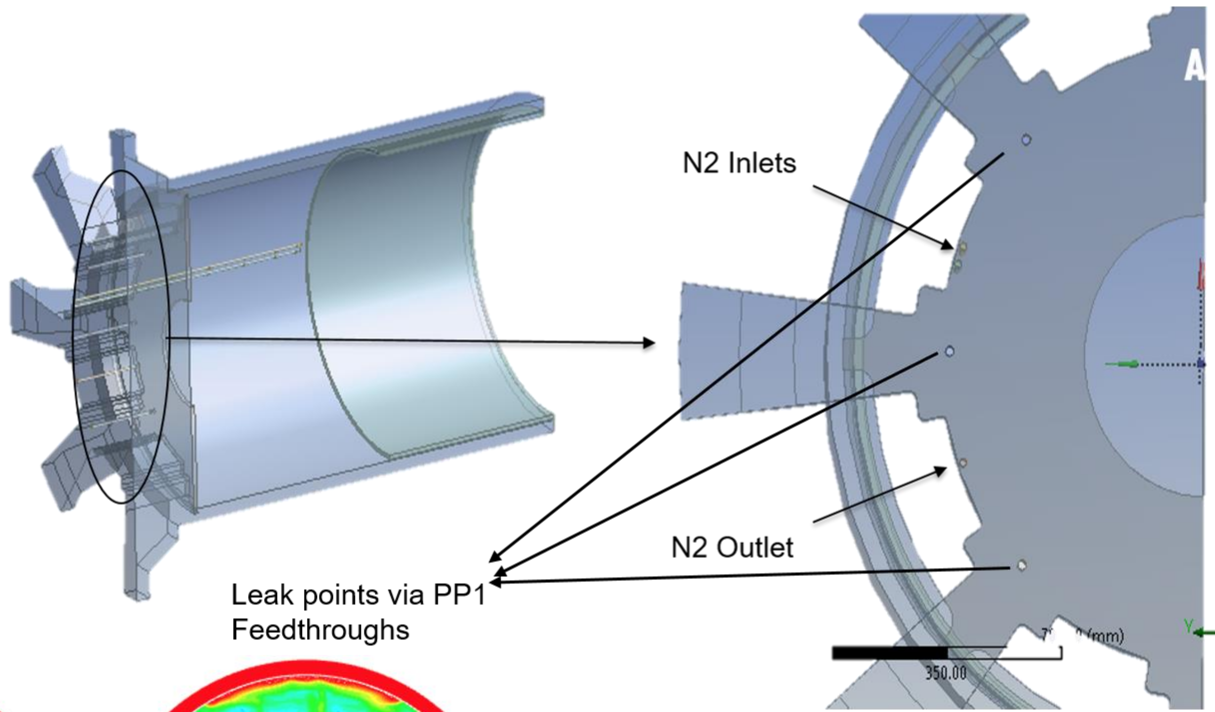
volume		number of			
§		Humidity sensors (LPG+2FBG) package	fibre loops	readout Ch	Connectors and connections
Strip Barrel	3 loops with a single (LPG + 2FBG) sensor package for each end of the barrel (A and C)	6 Barrel + 4 z=0 additional = 10	6+4 2 x (3 loops + 2 loops from z-0) per MTP-12	12	6 Barrel + 4 z=0 sensors 3+2 loops per side 2 x (6+4) = 20 connections. 2 MTP-12 connectors 5 loops each on its own MTP-12 in a BSM per side
Strip EC	3 loops with a single (LPG + 2FBG) sensor package for each EC (A and C)	6	6 3 loops per MTP-12	12	12 connections. 2 MTP-12 connectors 3 loops on its own MTP-12 in a EC penetration MTP occupancy is 6
inner pixel	4 loops with a single (LPG + 2FBG) sensor package each within A and C side for End Caps	8	8 4 loops per MTP-12	16	16 connections. 2 MTP-12 connectors 4 loops on its own MTP-12 in a EC penetration per side MTP occupancy is 8
outer pixel	3 loops with a single (LPG + 2FBG) sensor package each within one half shell for A and C side for End Caps	12	12 6 loops per MTP-12	24	24 connections. 2 MTP-12 connectors 6 loops, 3 from each half shell on its own MTP-12 MTP occupancy is 12
OSV	5 sensors in the OSV per side 4 sensors in the Opto panels This is duplicated for each side	10 8	10 8	20 16	20 16 4 MTP-12 connectors 9 loops or 18 fibres per side MTP occupancy is 10 and 8 per side
Additional	Strips at z = 0 L = 0,1,2,3 … but integrated into Strips Barrel above Additional 4 Sacrificial sensors in the Strips EC to Monitor Drying (Sec 5.2)				See Strips Barrel above
in total		54	54	108	13 MTP-12 connectors 108 connections

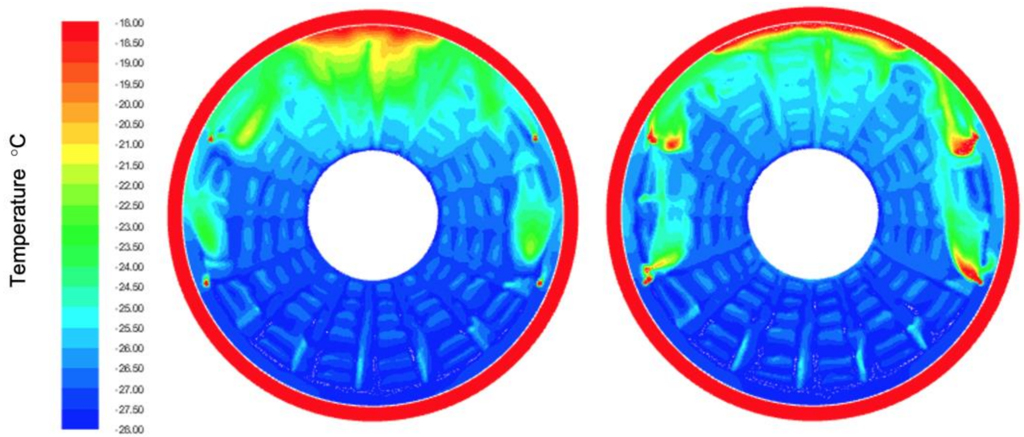
UNIVERSITY OF JOHANNESBURG

Showing buoyancy driven internal flow

Flush gas is warm and rises

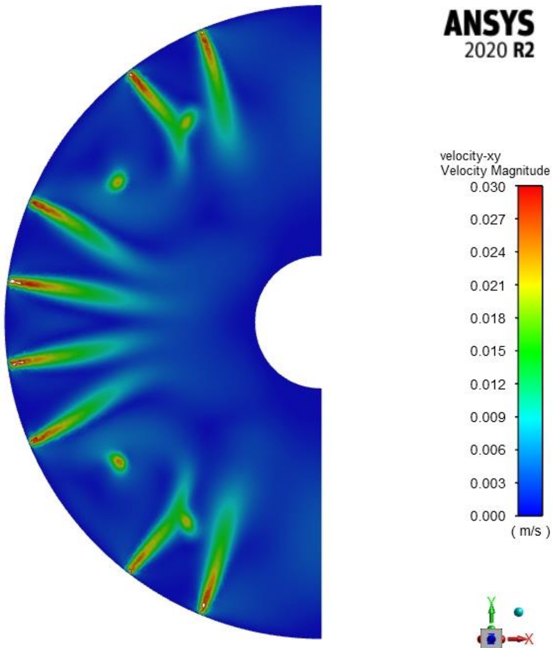
Fluid temperature visualized on a disk 5 mm away from petals



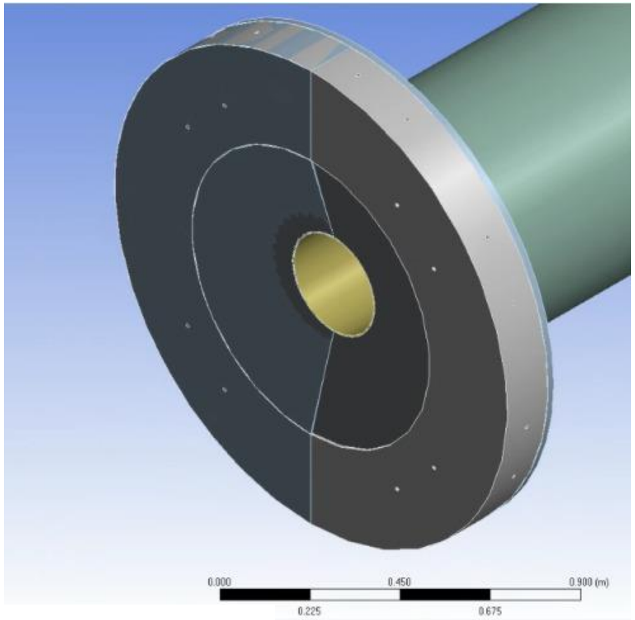


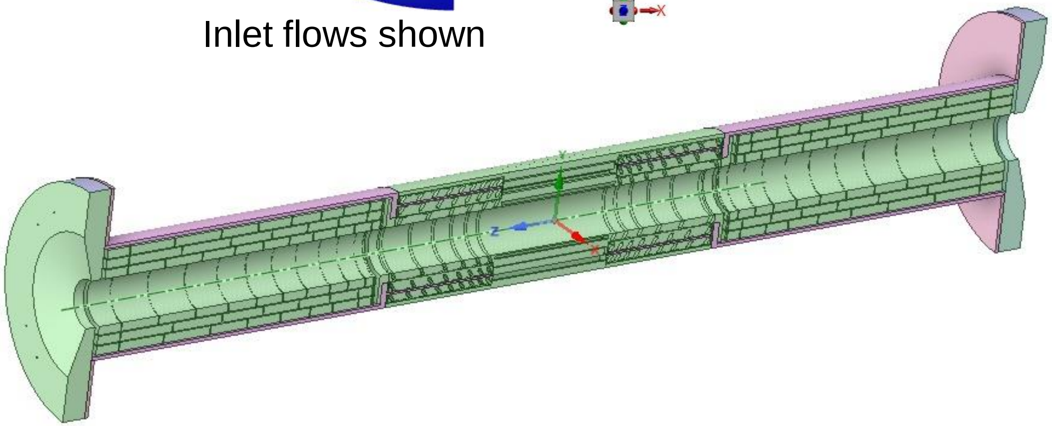
Detector-four **Detector-five**

Similar plot for outer pixels

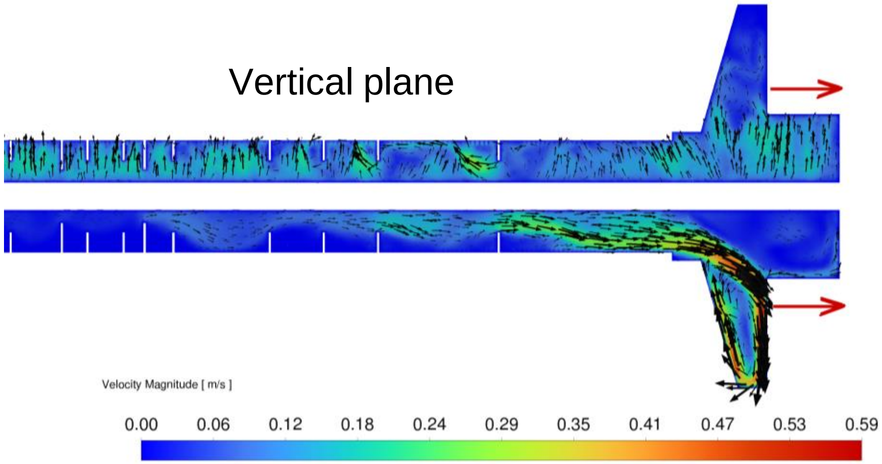


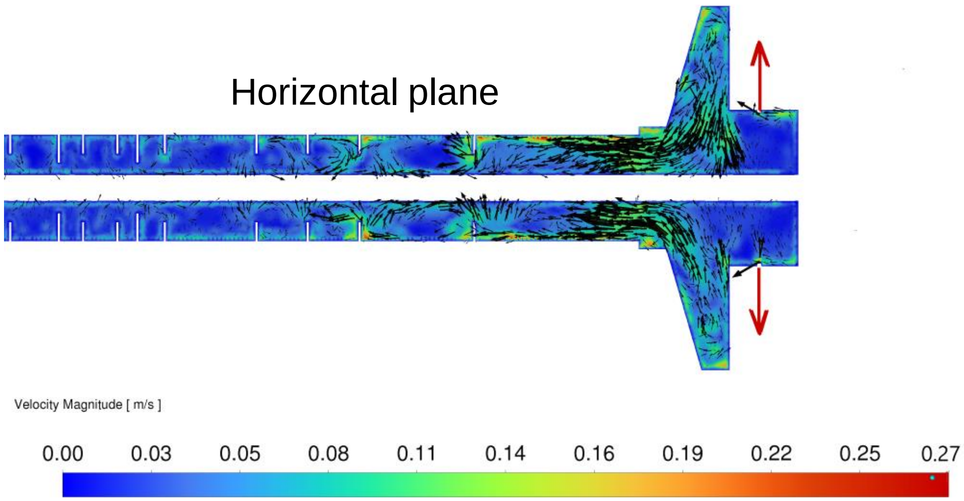
Inlet flows shown





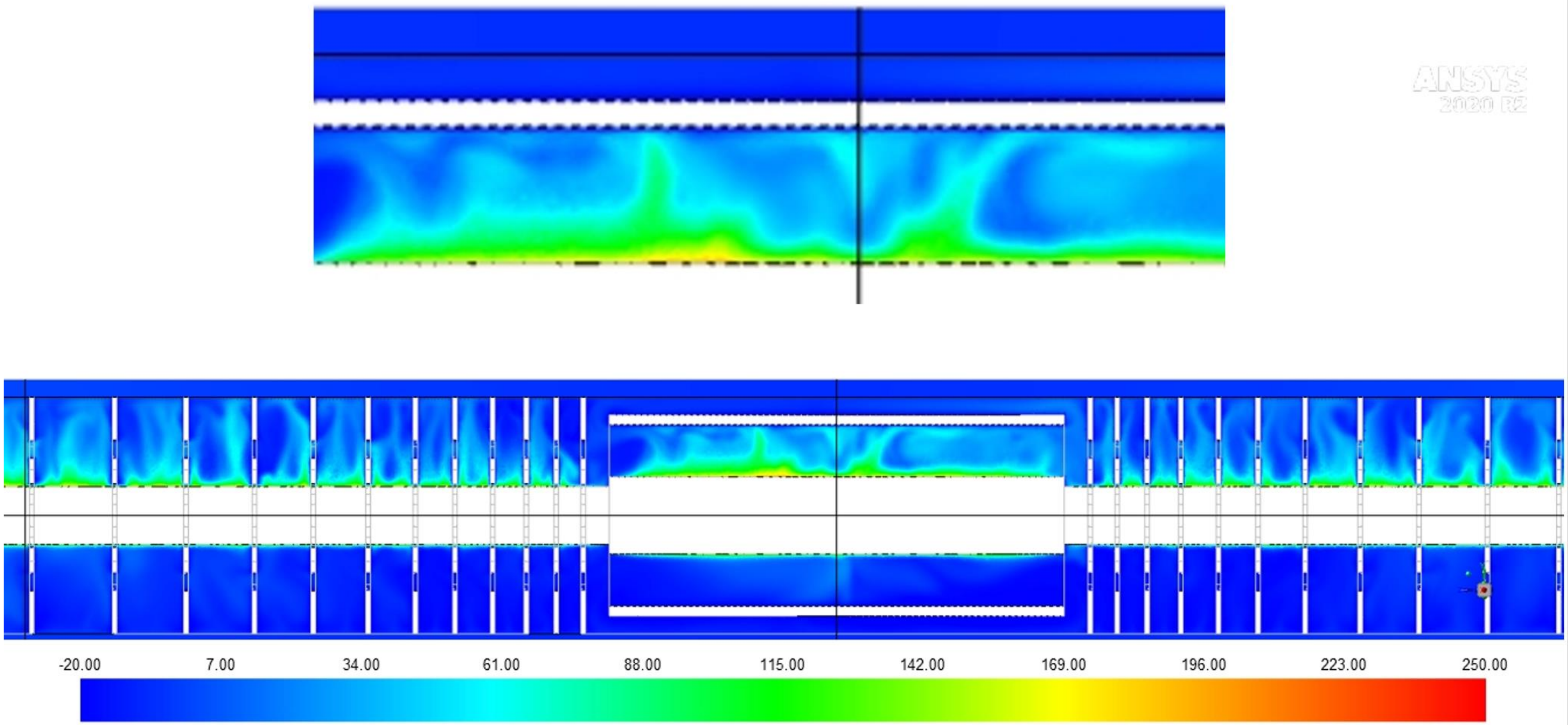
Similar flow pattern in inner pixels





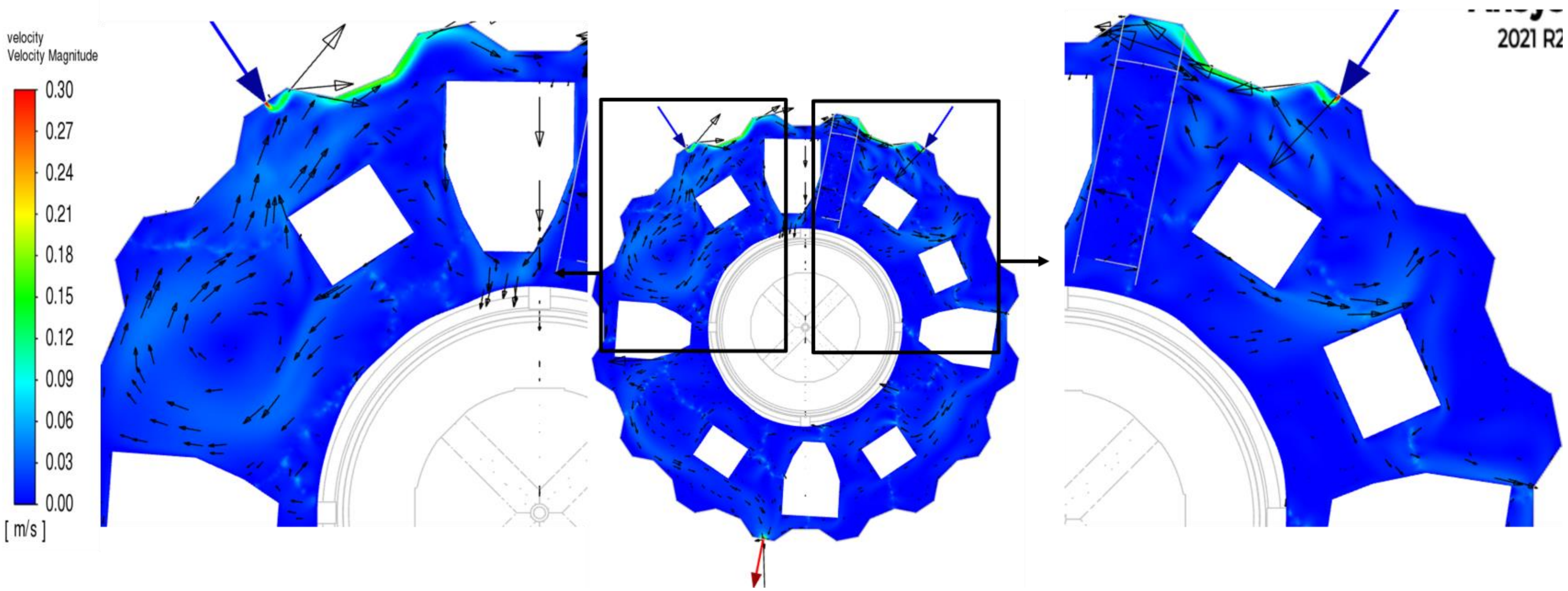
Continuum Fluid Dynamics → CFD : model the fluid system

Simulate fluid flow, drying out, vapour leaks, thermal conditions, sensor placement, performance
Example from ITk Inner Pixels volume …… In this example … bake-out conditions.



Temperature

Flushing ports in OSV still need optimization in order to get circulation throughout.



ITk Humidity : CFD : OSV

UNIVERSITY OF JOHANNESBURG

More R&D to improve Design, Manufacture, Readout, Performance in long term

R&D

1. **Transition the LPG Fibre to a Rad Hard Fibre**
    1. Currently no site of technology that can write in a grating for LPG in a Rad Hard Fibre
        1. It needs to be tensioned and also azimuthally rotated during write.
        2. Requires Femto-second laser, stepper rotation and translation motors
    2. Produce Functional Coating – nano-TiO_2 layer – hygroscopic, reversible, in own lab
2. **Develop further the various compensations**
    1. Requires further radiation resting,
    2. Calibration work in the Environment Chamber
3. **Maintain Integrity and Monitoring of Humidity in ATLAS**
    1. Longer term committmemnt
4. **Spin out the technology**
    1. To SA
    2. Nuclear Industry
        1. First of a Kind, in-core, real-time, on-line, monitoring in Nuclear Power Reactors
        2. Temperature, strain, water level, TID Dose, NIEL Dose
    3. Space
    4. Other