Structural and environmental monitoring of tracker and vertex systems using **Fiber Optic Sensors**

ILWS ECFA Vertex session, Geneva Oct 20th 2010

ECFA Study
Physics and Detectors for a Linear Collider

IFCA

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_Outline

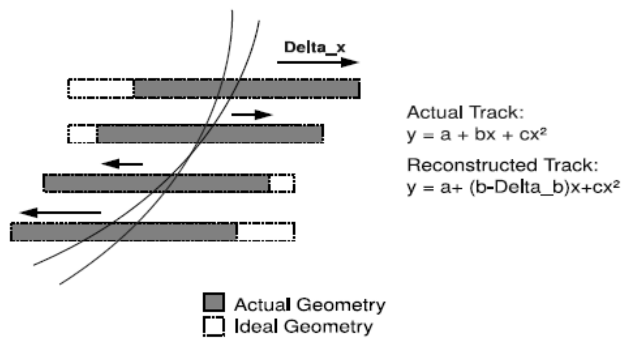
- VTX & TK systems monitoring requirements.
- Introduction to FOS:
  - Working principle & advantages.
- Cases of use:
  - FOS-based displacement sensors.
  - Application to Belle-II vertex detector.
  - Smart structures self-monitoring supports.
- Current R&D lines:
  - Calibration of FBG-FOS
  - Qualification for radiation fields.
  - Glue-free fixation: Embedding in CFRP/micromachined clamps.
- Conclusions and Outlook

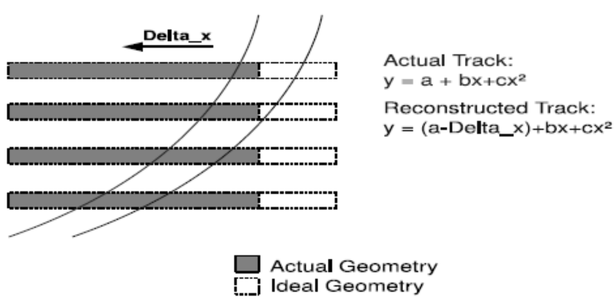
_ Monitoring requirements for Si-Trackers

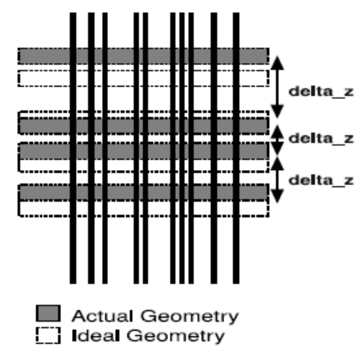
- Current and future silicon systems need for:
  - Real-time monitoring of environment variables: temperature, humidity, CO_2, magnetic field, etc.
  - Real time structural monitoring: deformations, vibrations (push & pull operation), movements.
- Conventional monitoring technologies based on electric relatively bulky transducers with low multiplexing capability, low granularity, and cooper readout and powering lines (conductive EM noise propagation lines).

_Monitoring requirements: Weak Modes

– First lesson from LHC detectors: position and deformation monitors must cover the weak modes of software (track-based) alignment algorithms.





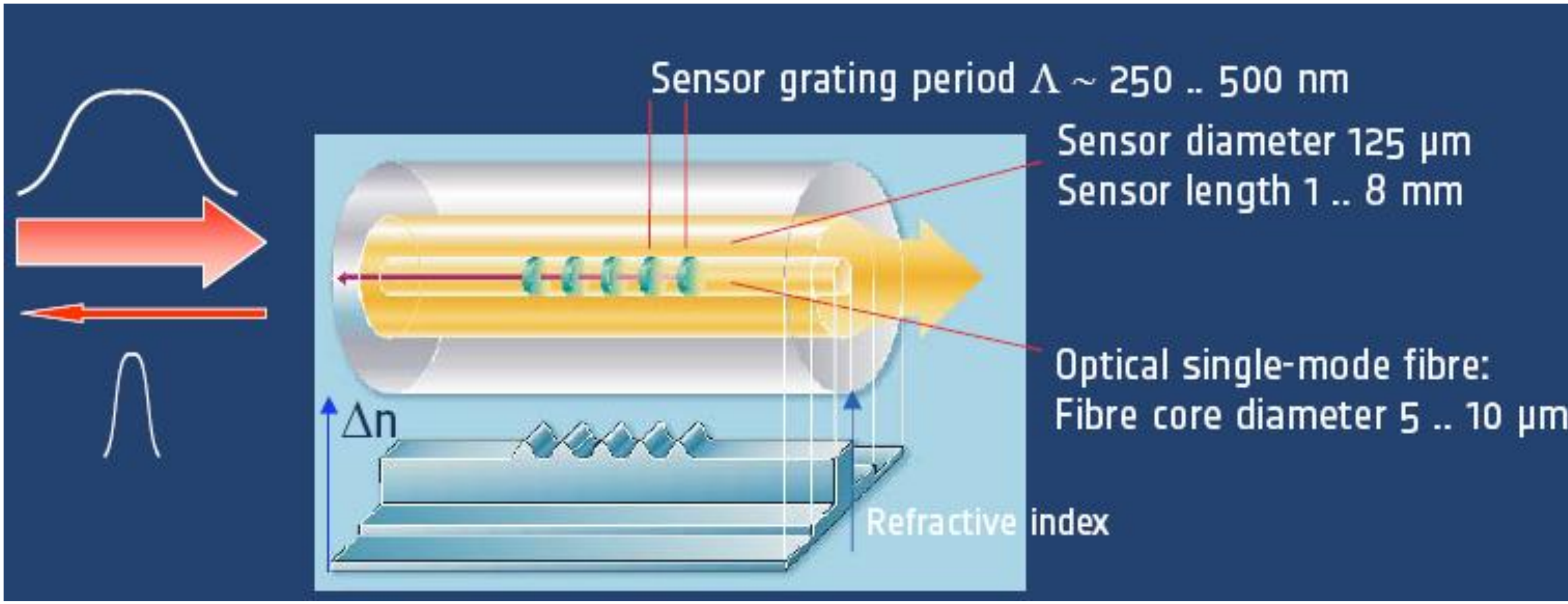


_Introduction to OFS

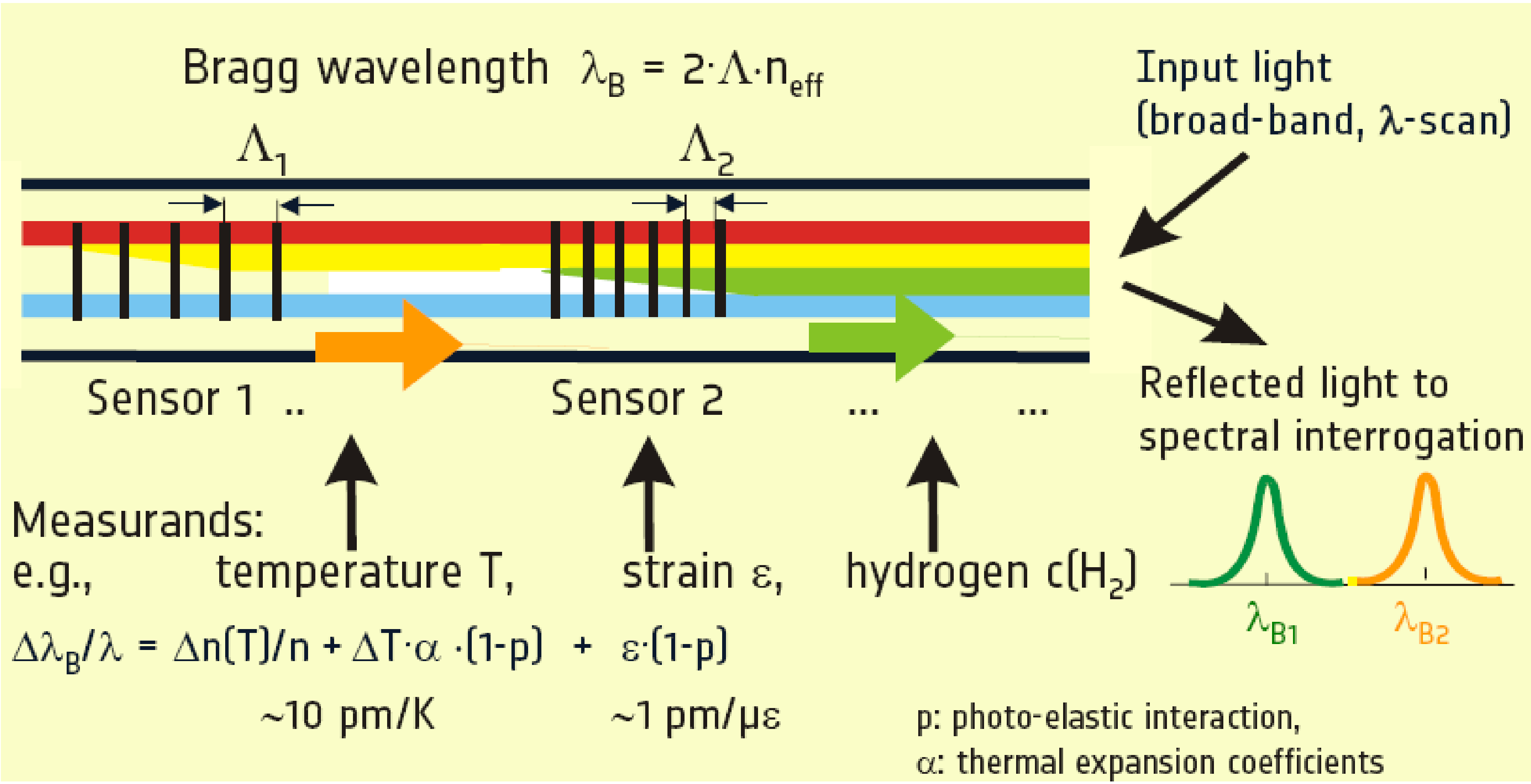
- Well know monitoring technologies in aeronautics and civil works based on optical fiber sensors (OFS)
- Distributed strain & temperature sensors are conventionally used for structure health monitoring : *SMART structures*
- Other OFS: dosimetry, humidity, B field, acceleration, etc.
- In aeronautics (embedded or bonded) on the of the CFRP composite (for instance, plane radar radome)

_Bragg grating sensor basics

– Fiber Bragg Grating optical transducer

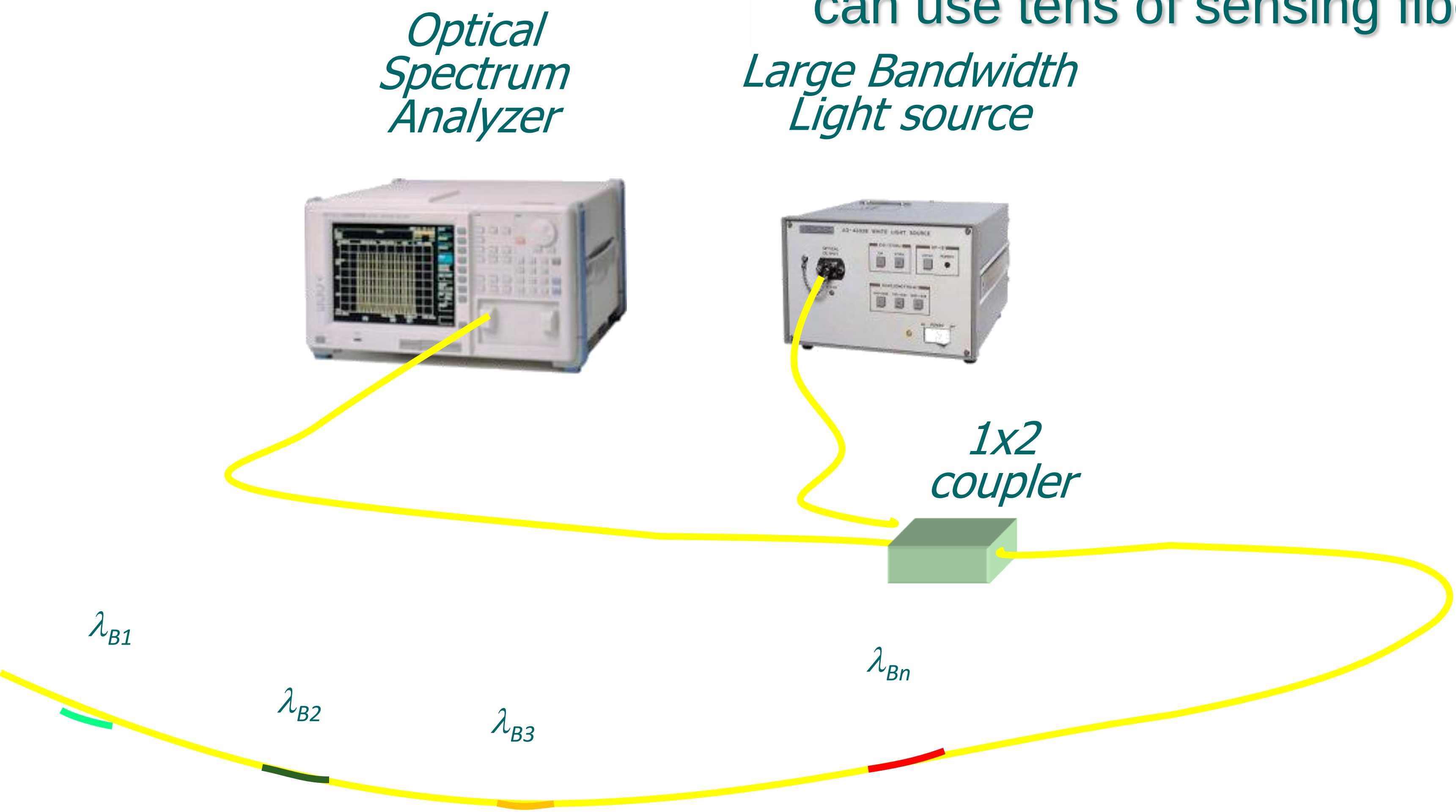


_Bragg grating Multiplexing



_Basic Interrogating Unit

The number of different Braggs is more than 100; moreover by using an optical switching we can use tens of sensing fiber



_OFS & FBG advantages

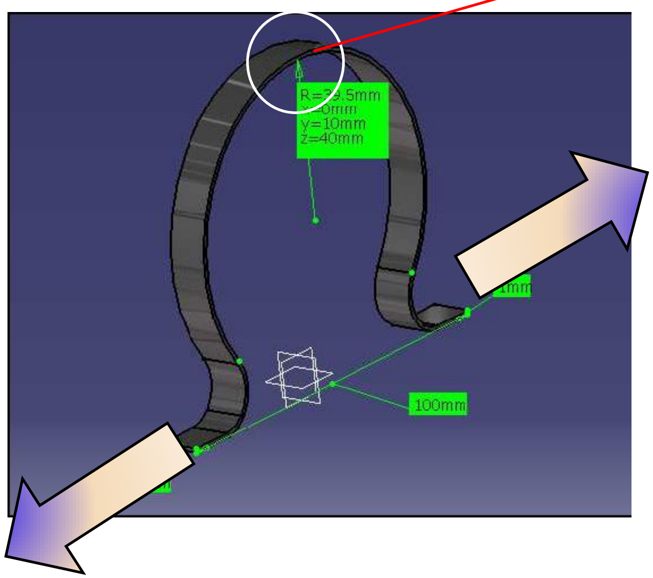
- General attributes of Fiber Optic Sensors:
  - Immunity against:
    - High electromagnetic fields, high voltages.
    - High and low temperatures.
    - Nuclear radiation environments (not in all the cases)
  - Light-weight, miniaturized, flexible, low thermal conductivity.
  - Low-loss, long-range signal transmission(“Remote sensing”)
- Specific FBG attributes:
  - Multiplexing capability (sensor network)
  - Embedding in composite materials.
  - Wavelength encoded (neutral to intensity drifts)
  - Mass producible at reasonable costs.
  - Very high and low temperatures (4 K to 1200 K).

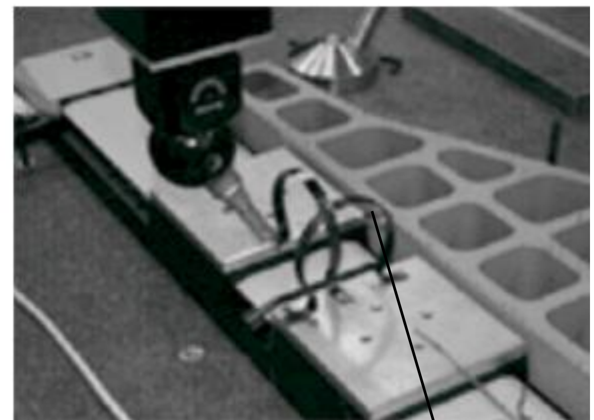
_Case of use: displacement sensors.

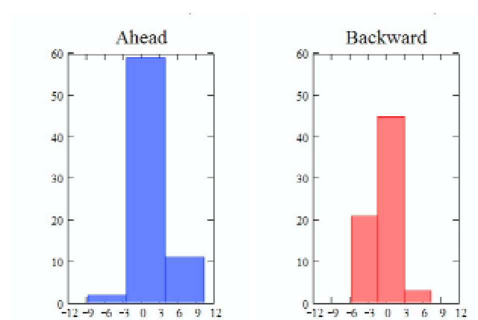
– Original idea from the late BTeV vertex detector: “ The omega-like gauge”

– Mechanical displacement range adapter.

STRAIN FBG SENSOR ON THE TIP







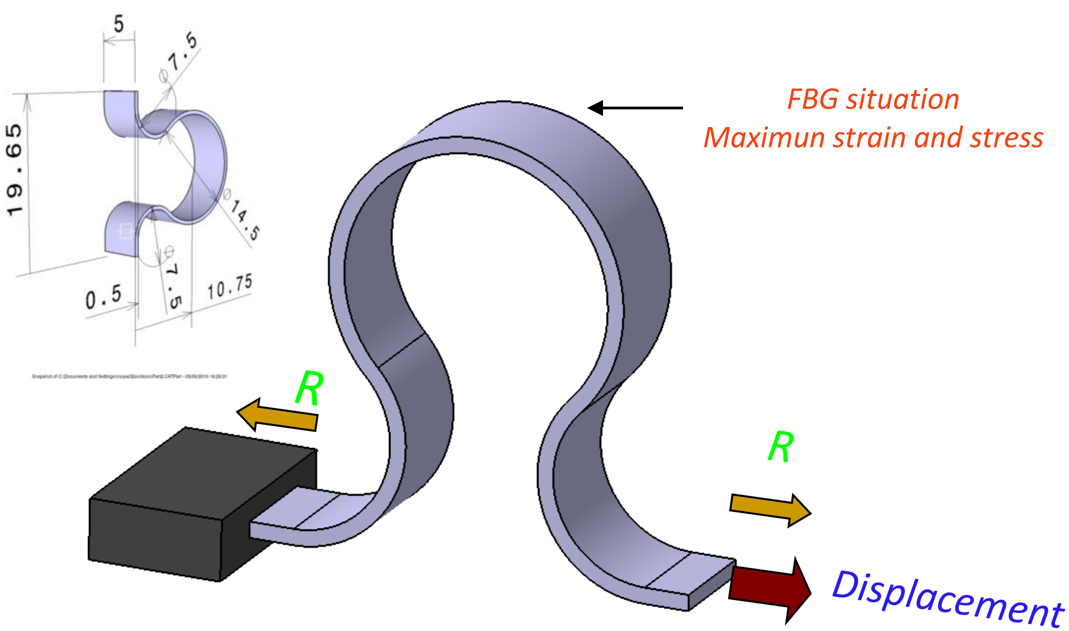
Temperature Compensating “omega”

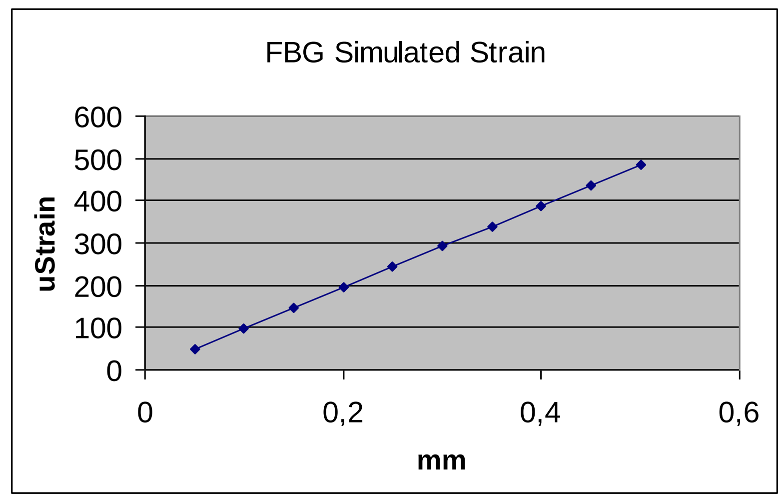
_Displacement-Strain Convertors: FEA Simulation

- *Design criteria:*
  - *Minimal reaction force in both ends*
  - *Maximal strain/displacement ratio (displacement resolution)*
  - *The linearity of the response (μstrain/ displacement)*
  - *An stress bellow the breaking limit of host material*
  - *Strain uniformity along FBG sensor*

Parameters are for a displacement range of ±500um

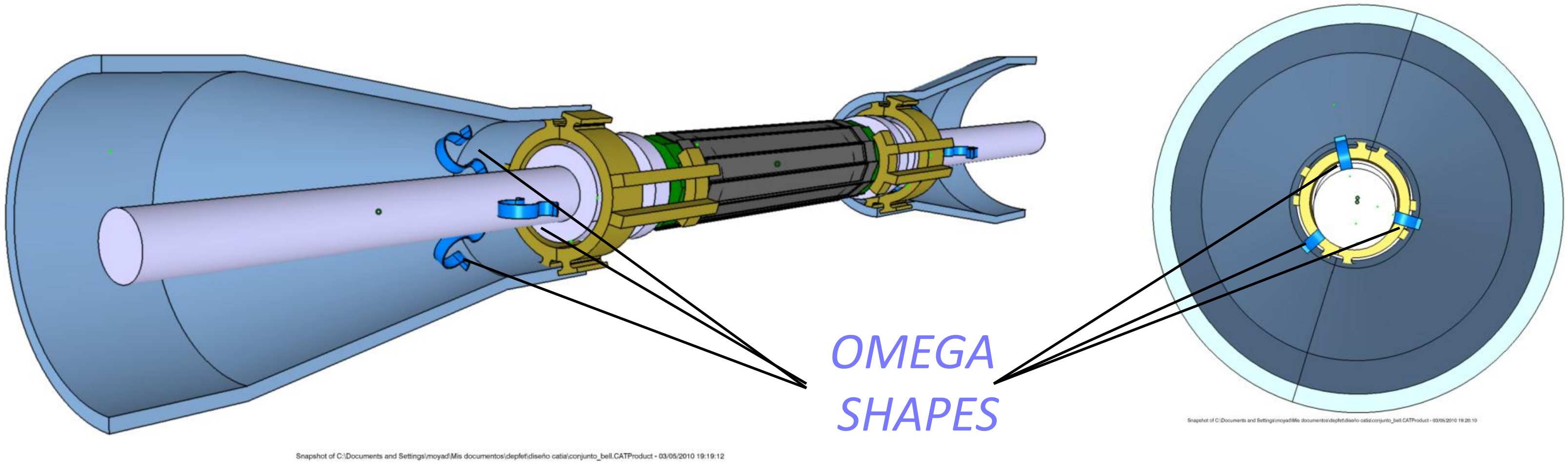
	O-Shape
Strain (με)	503
Max. Stress (N/m^3)	105.309
Reaction (N)	0.255



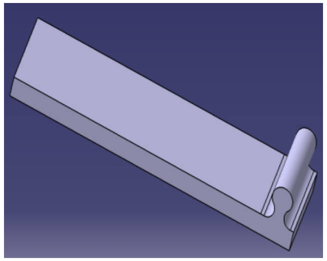


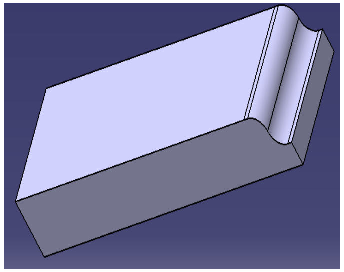
_Case of use: displacement monitoring of Belle-II DEPFET Vertex

SVD is supported by the drift chamber and PXD by the beam pipe



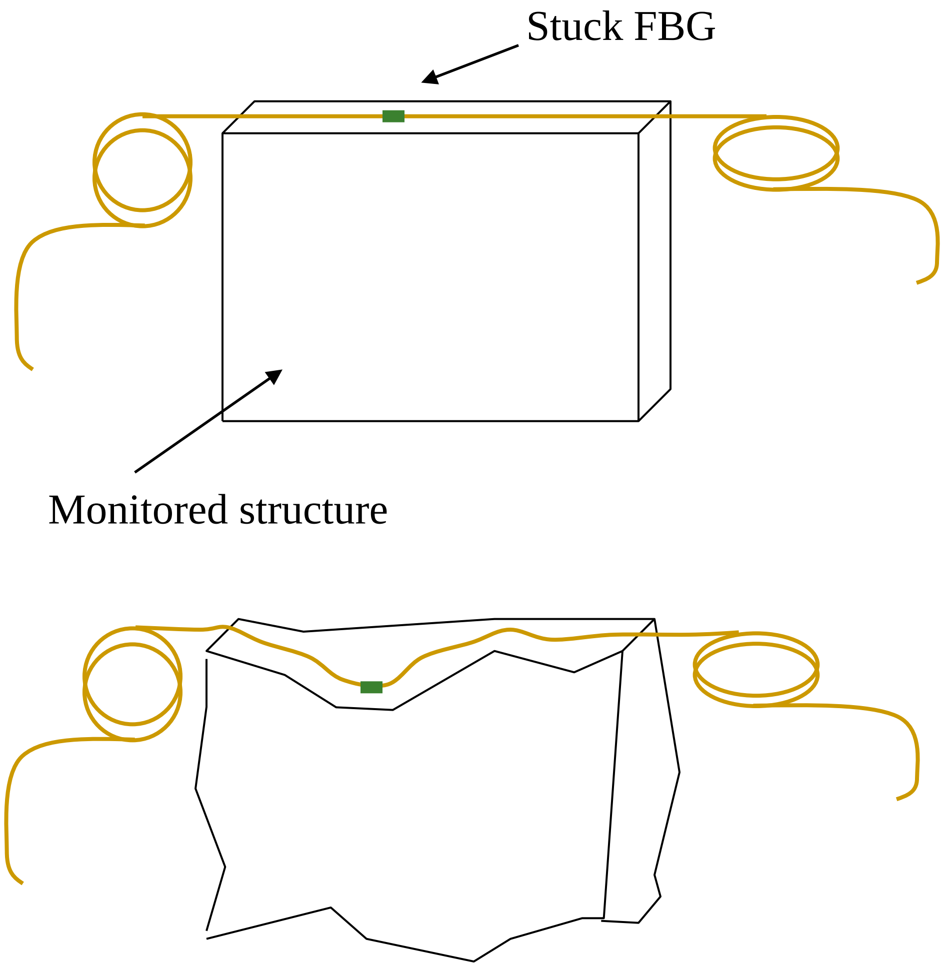
Designs of autoclave molds for fabrication are ready, “omegas” available before the end of the year.

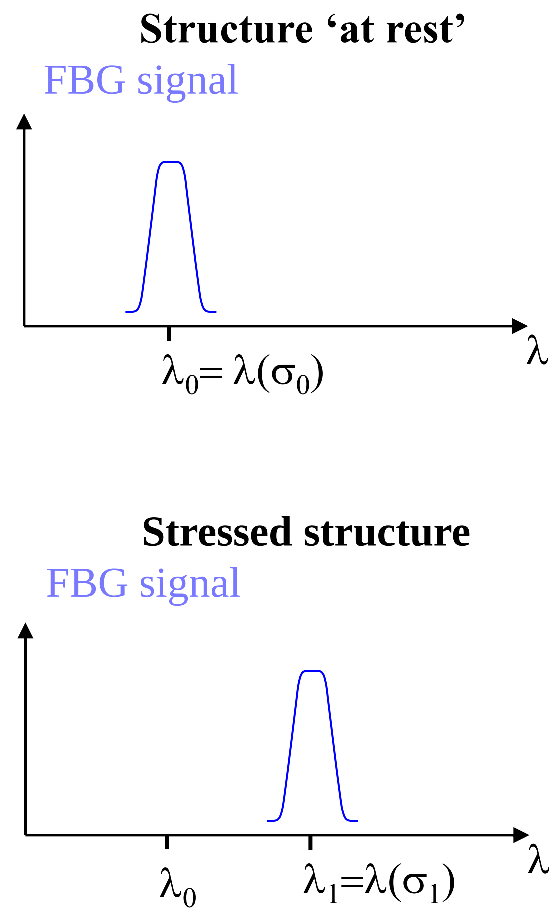




_case of use: deformation monitoring

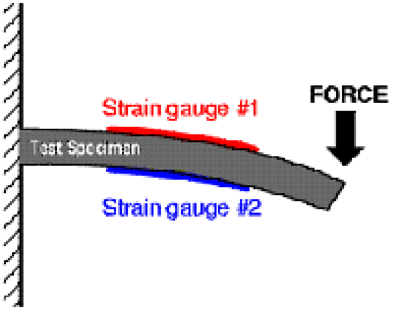
Deformation of a structure can be monitored by embedded FBGs.

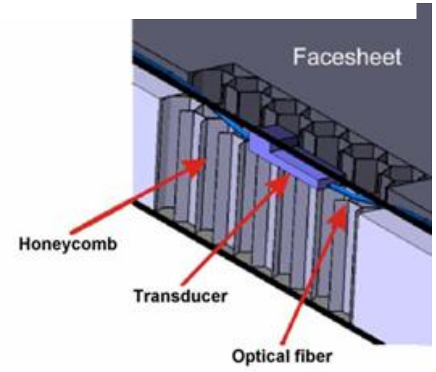


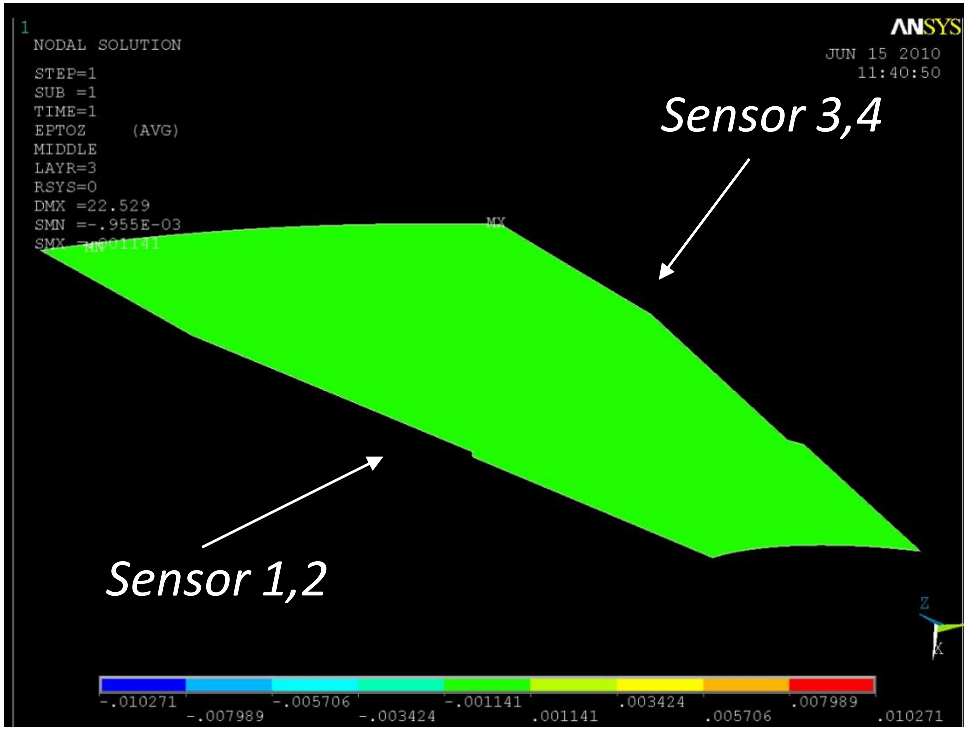


_case of use: deformation monitoring(2)

– A possible application: embedding of FBG sensors in carbon fiber composite to monitor deformations and vibrations.







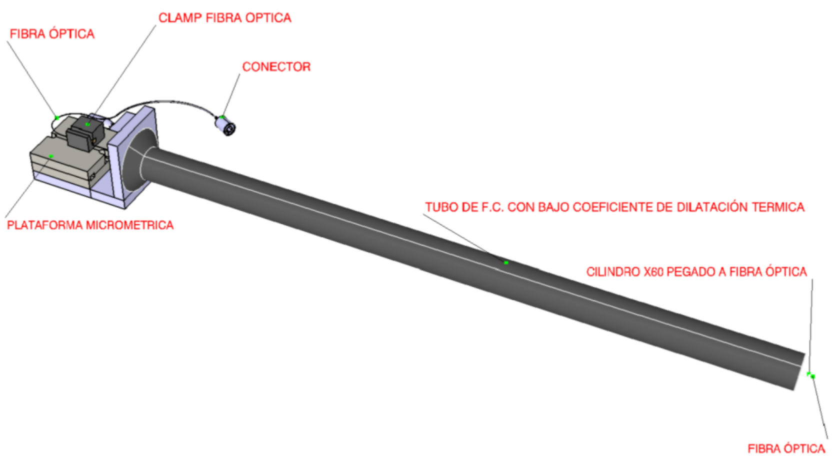
	SENSOR 1 (layer 3)		SENSOR 2 (layer 5)		SENSOR 3 (layer 3)		SENSOR 4 (layer5)	
TORSION	**-0,00367**	**0,00367**	**-0,002264**	**0,002264**	**0,005051**	**-0,005051**	**-0,0017**	**0,0017**

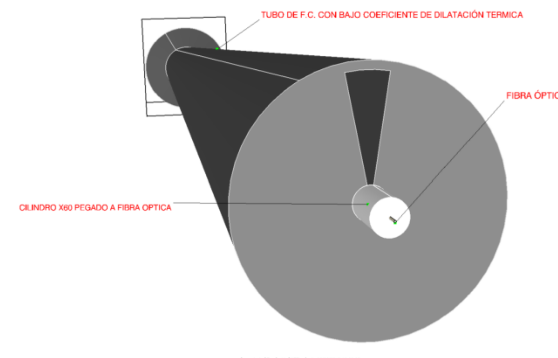
_Current R&D activities

- FBG-FOS Calibration:
  - Reliability and response reproducibility (T,ε).
- FBG-FOS Radiation campaign.
- Glue-free fixation:
  - Embedding of the sensors in CFRP (self-monitoring supports)
  - Micromechanical fixation to silicon wafer.

Calibration of non-irradiated FOS: set-up

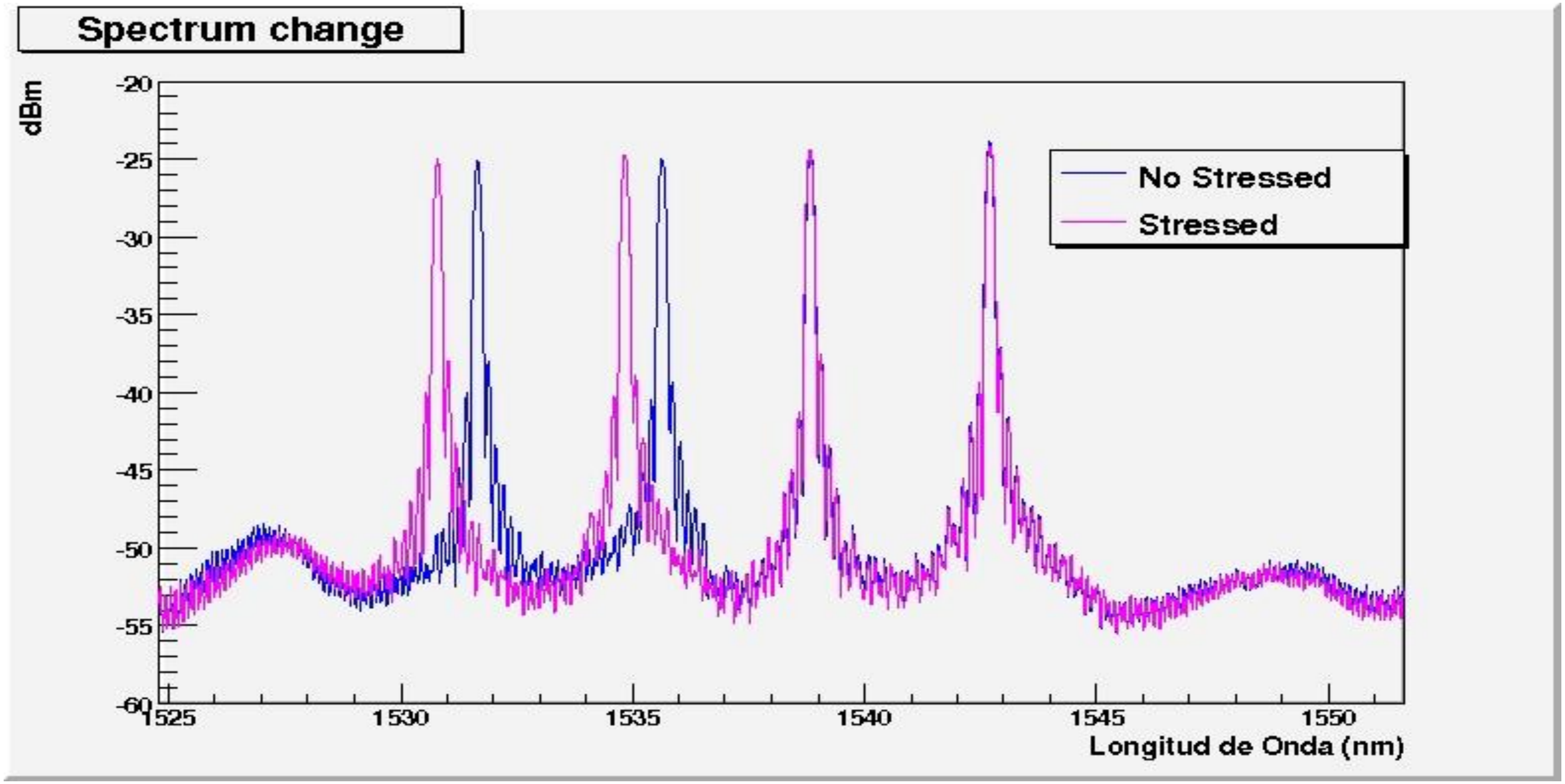
– Optical fiber (with FBG) fixed in one end to a CF bar (635 mm) & and the other end clamped to micrometric stage.



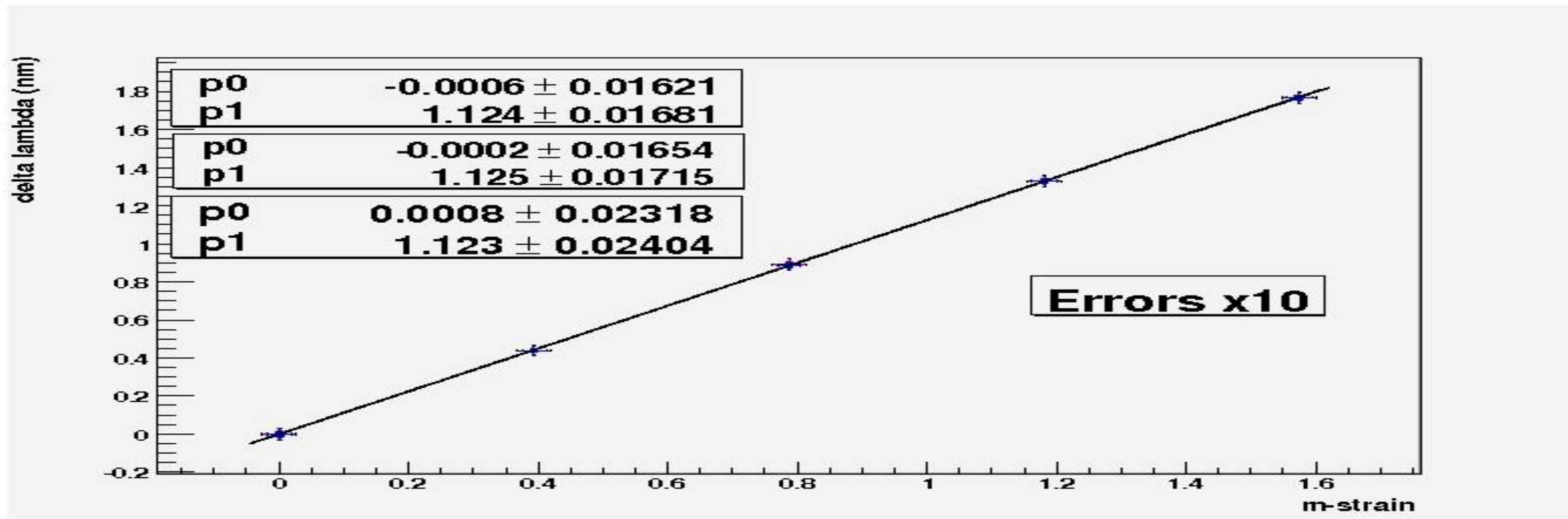


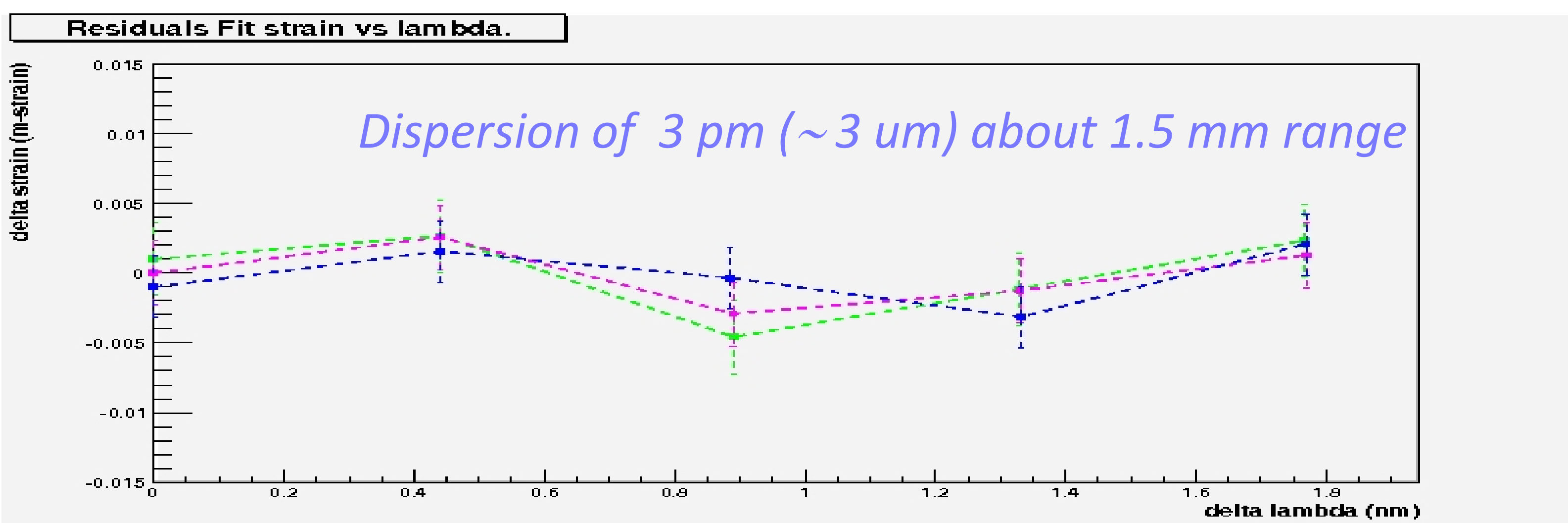
Calibration of non-irradiated FOS: raw spectrum

– The spectrum of the same fiber optic relaxed and with two sensors of the same line stressed.



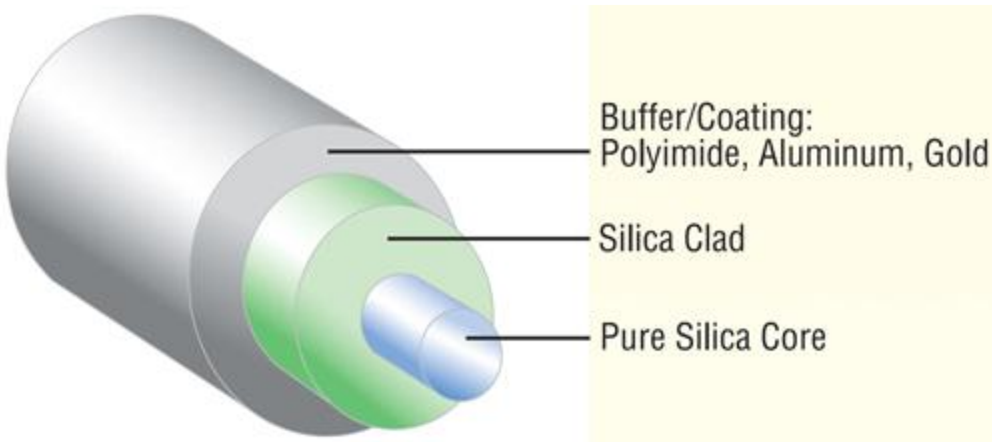
Calibration of non-irradiated FOS: linearity





FBG Radiation resistance: motivation

"Bare" Optical Fibers are quite inhomogeneous



Many coatings available:

Acrylate, polyimide, ormocer, metallic, …

- External agents can induce changes of the mechanical properties of the fiber materials (young, poisson parameter) $\Rightarrow$ grating periodicity (Λ) changes
- Others (radiation) can also induce changes in n

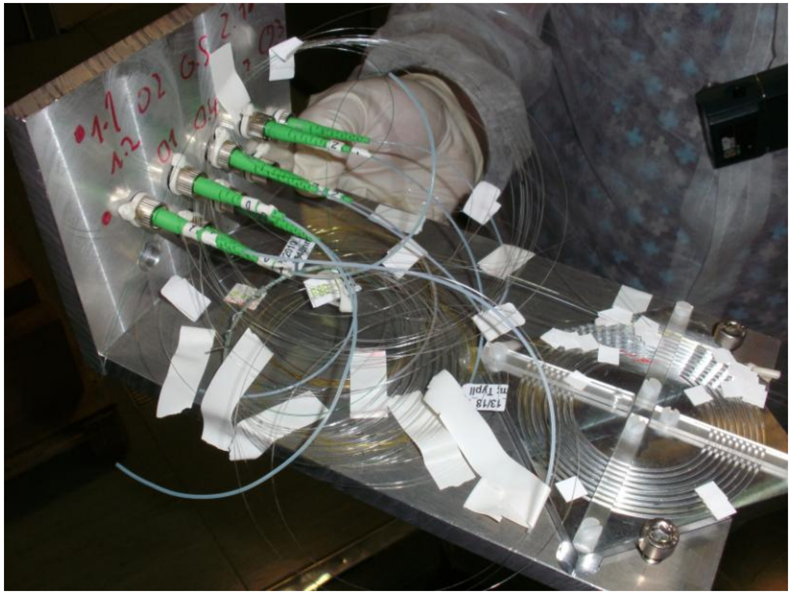
Irradiation campaign: facility

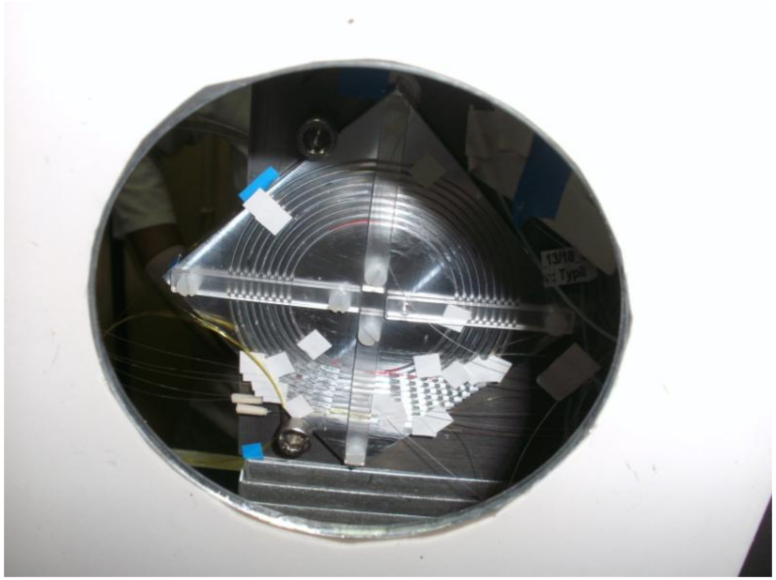
- Irradiation campaign at Centro Nacional de Aceleradores (CSIC) in Seville.
- New Cyclotron facility (max. energy of 18 MeV protons, here 15.5 MeV protons)

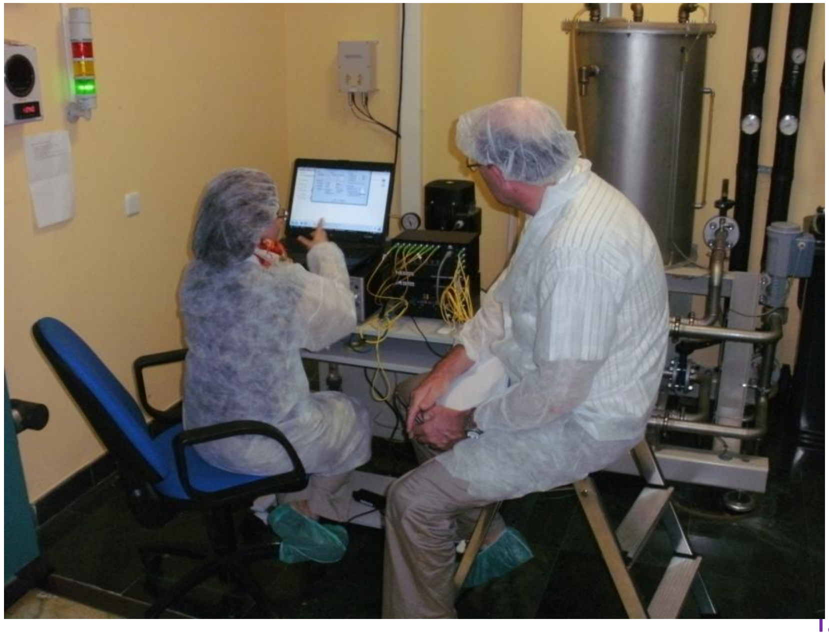
FBG sensors irradiation

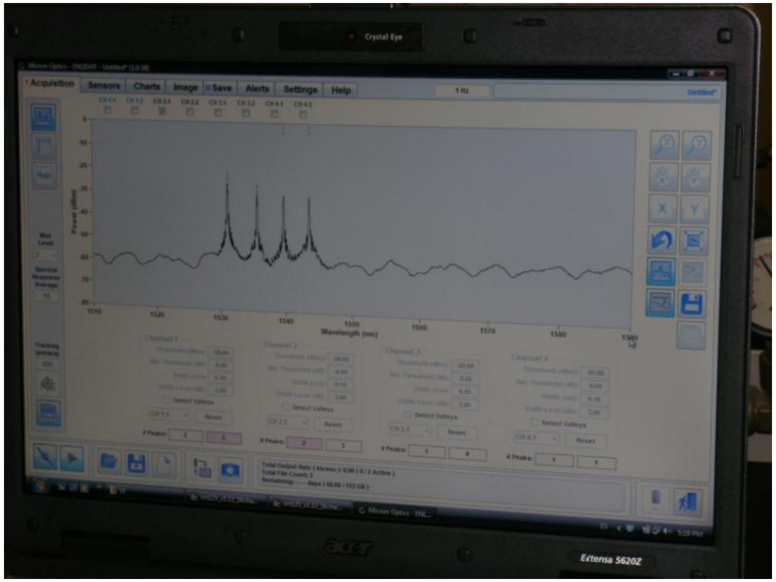
- Active Irradiation of FBG sensors (different coatings and manufacturing technologies).
- Full spectrum periodically stored during irradiation.
- Final fluence of 3.3 10E15 protrons/cm2 (this value comes from SLHC expectation)

FBG sensors irradiation









Irradiation : Preliminary results

– Change of the wavelength before and after irradiation.

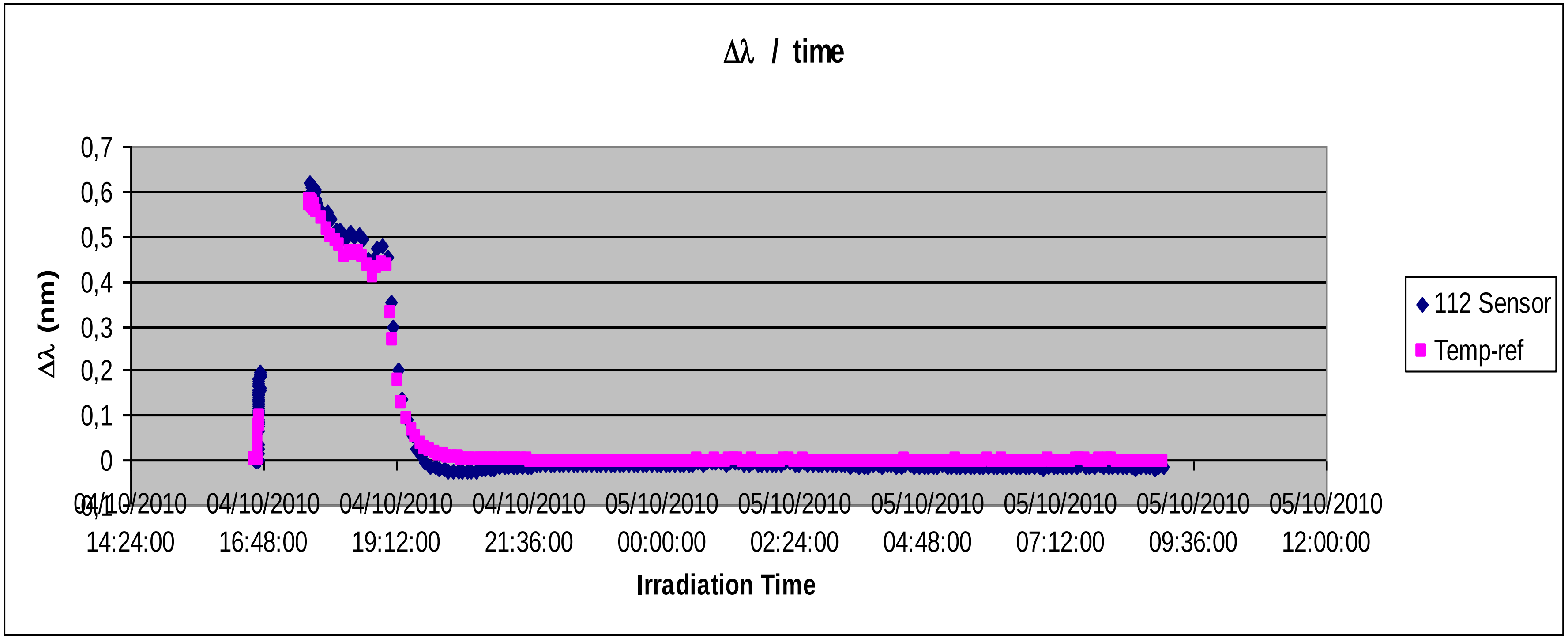
SENSOR	111	112	TEMP	021	022	023	024
λ before	1543,09147	1556,70164	1579,97002	1530,36627	1540,23824	1550,35274	1560,23057
λ After	1543,08417	1556,68547	1579,96555	1530,67244	1540,61578	1550,68497	1560,27519
$\Delta\lambda$(nm)	0,0073	0,01617	0,00447	-0,30617	-0,37754	-0,33223	-0,04462

SENSOR	211	212	213	214	221	222	223
λ before	1530,78032	1534,79001	1538,78534	1542,65345	1546,67373	1550,56059	1554,44931
λ After	1530,78833	1534,9268	1538,9554	1542,82597	1546,83117	1550,73343	1554,6216
$\Delta\lambda$ (nm)	-0,00801	-0,13679	-0,17006	-0,17252	-0,15744	-0,17284	-0,17229

SENSOR	03	011	012	013	014	05	04
λ before	1530,23316	1530,34985	1540,25489	1550,3163	1560,22263	1549,92204	1540,06483
λ After	1530,43829	1530,37196	1540,26169	1550,3279	1560,22446	1550,27877	1540,36961
$\Delta\lambda$ (nm)	-0,20513	-0,02211	-0,0068	-0,0116	-0,00183	-0,35673	-0,30478

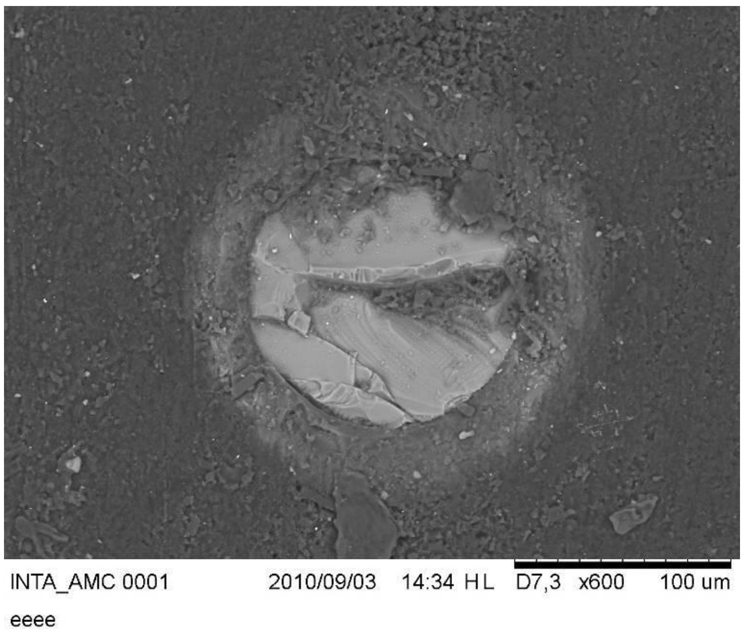
Irradiation : Δλ 112 / FOS reference

– The change of wavelength during irradiation time of sensor 112 and Temperature reference.



Glue-free fixation: FBG Embedding in CFRF

– Optimal mechanical connection between the hosting material and the FGB sensor



Embedding in CFRF: radiation hardness

- When embedding the FBG sensor in material (CF laminate) new issues arise because of the different effect of external agents (like radiation) in thermal expansion coefficient of the host material and the optical fiber.
- Temperature variations can be expressed in terms of equivalent strain (ε_T)

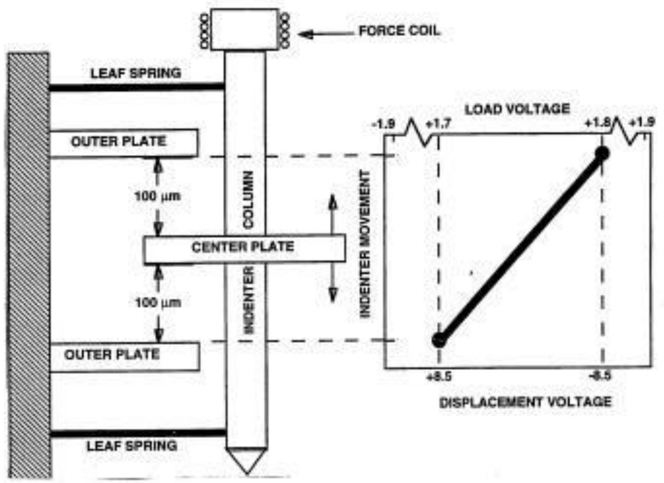
$$\varepsilon_T = (\alpha_H - \alpha_F)\Delta T$$

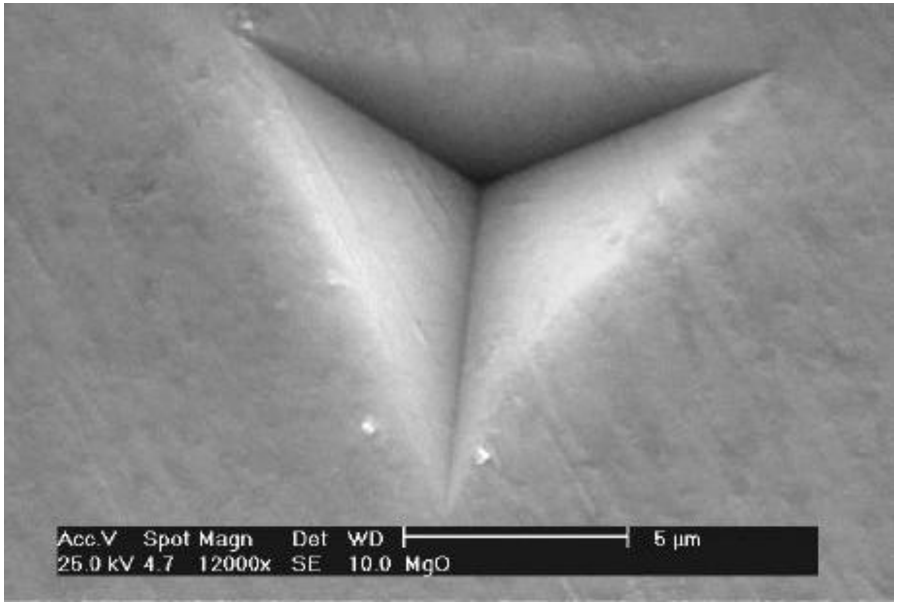
α_H : Host material temperature expansion coefficient
α_F : Fiber material temperature expansion coefficient

- FBG Sensor radiation resistance does not guaranty the "resistance" of the embedded sensor

Embedding in CFRF: radiation hardness (2)

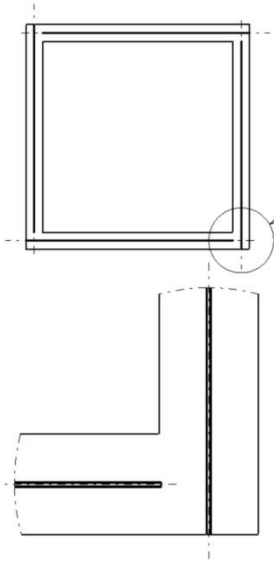
- Irradiation of optical fiber in CFRP composites.
- The change in mechanical properties in the coatings and CF matrix will be measured by nanoindentation.

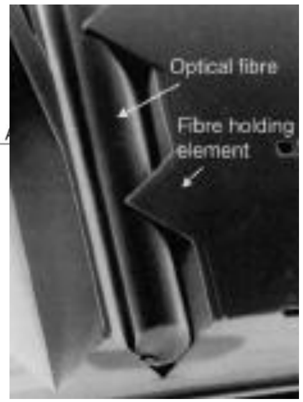


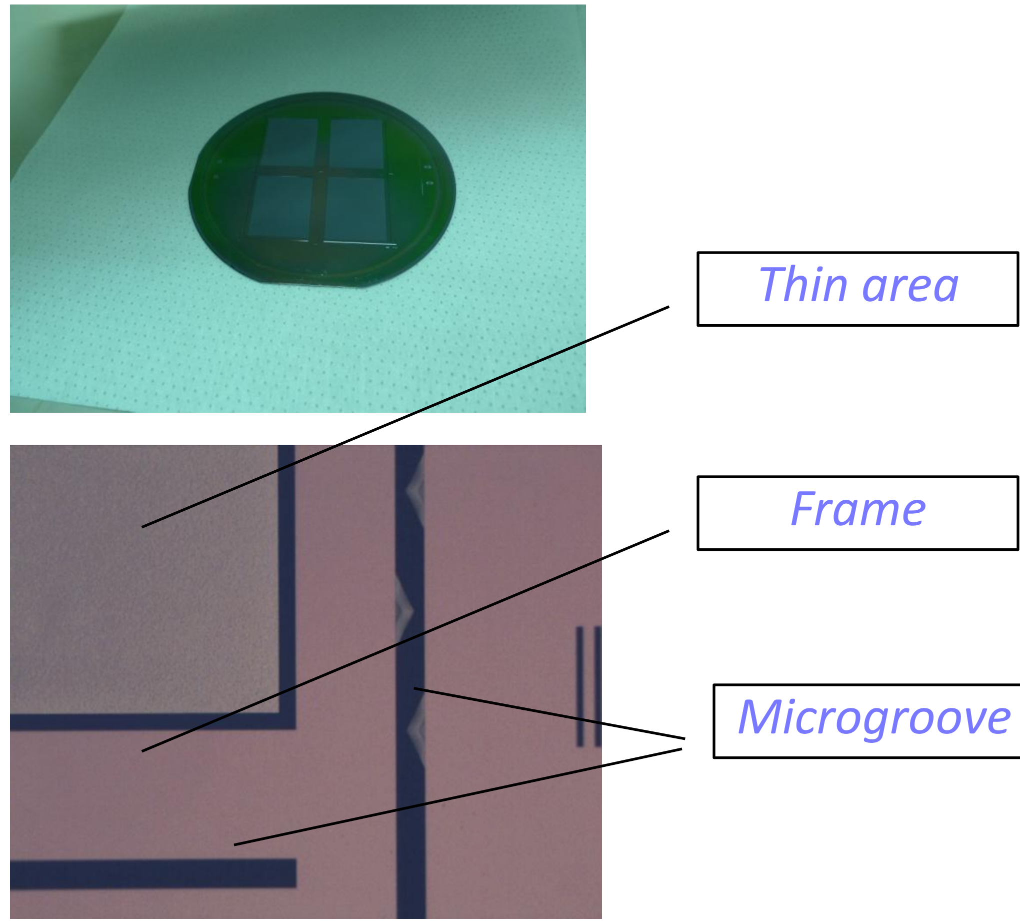


Glue-free fixation: microclamps

– Attaching the fiber directly to the sensors remains parallel R&D line







All components ready work is in progress

Outlook

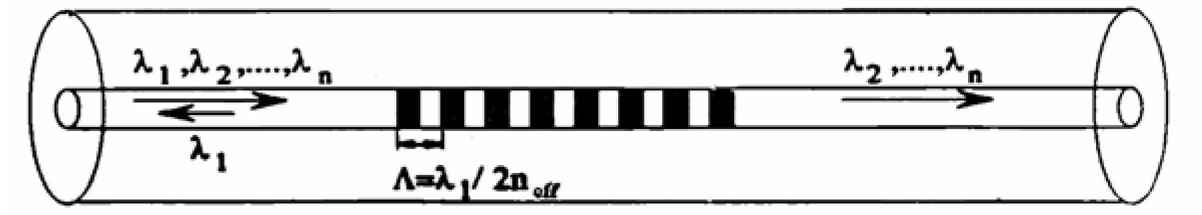
- Optical Fiber Sensors are a priori an attractive technology to be used in particle physics experiments.
- Initial studies focus on reliability and precision within particle physics hostile environments.
- First results show the extreme radiation hardness of some FBG sensors as precision displacement gauges.
- Joint project with Spanish Aerospace Agency (INTA) and National Center of Microelectronics (CNM) to carry out the feasibility of a FOS monitor for future vertex and tracker detectors.

THANK YOU

Sensor reliability: external agents

Stability of the FBG FOS response write in a bare fiber (same response under same conditions T, ε)

Bragg Grating



Selective narrow band mirror

TEMPERATURE CHANGE

Thermal expansion for Λ
Termo-optic effect for $\mathbf{n}_{\mathbf{eff}}$

STRESS

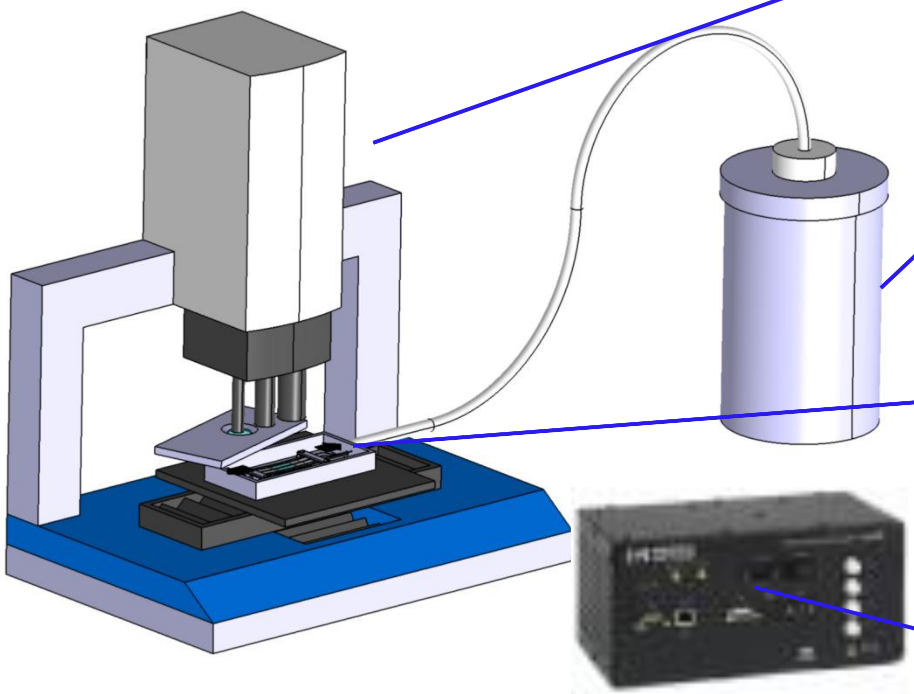
Elasto-optic effect for $\mathbf{n}_{\mathbf{eff}}$
Direct Strain for Λ

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

Depends on refraction Index and geometry stability

Test stand for OFS calibration(2)

Calibration of bare fibers with different coattings (acrylate, polyimide, ormocer) and without coattings.



Confocal profile meter
15nm resolution with
3mm range
Ready (Dec '09)

Cooling/Heating system
Ready (April '10)

Temperature controlled tensile stage
-196 to 350 +-0.2 deg
Ready (April '10)

OFS Interrogating unit(s)
Static (Ready July '10)
Dynamic (Sep '10)

Rad-Hard Qualification of FOS

– Samples about 60 of optical fibers embedded in CF laminates currently in preparation (INTA).
– Each CF laminate with three different fiber coatings.
– Additionally, 21 bare fiber optic sensors will be irradiated (fabricated with different technological processes)
– Planning for an active irradiation
– First irradiation with protons.
– Pre-irradiated and irradiated

Mechanical characterized by

Nano-indentation