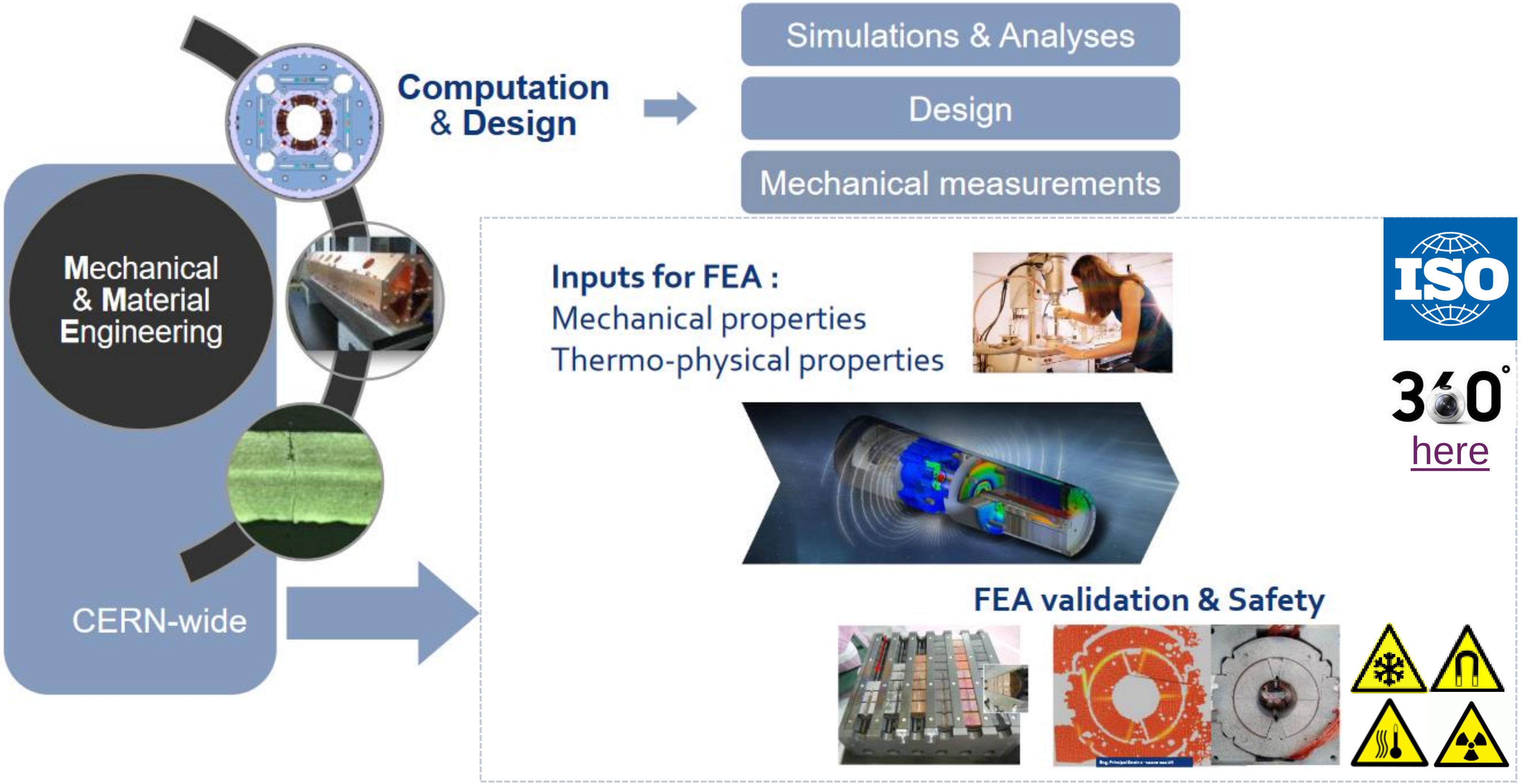
Optical Fibre Sensing CRAB Cryomodule

Michael GUINCHARD on behalf of EN-MME-EDM

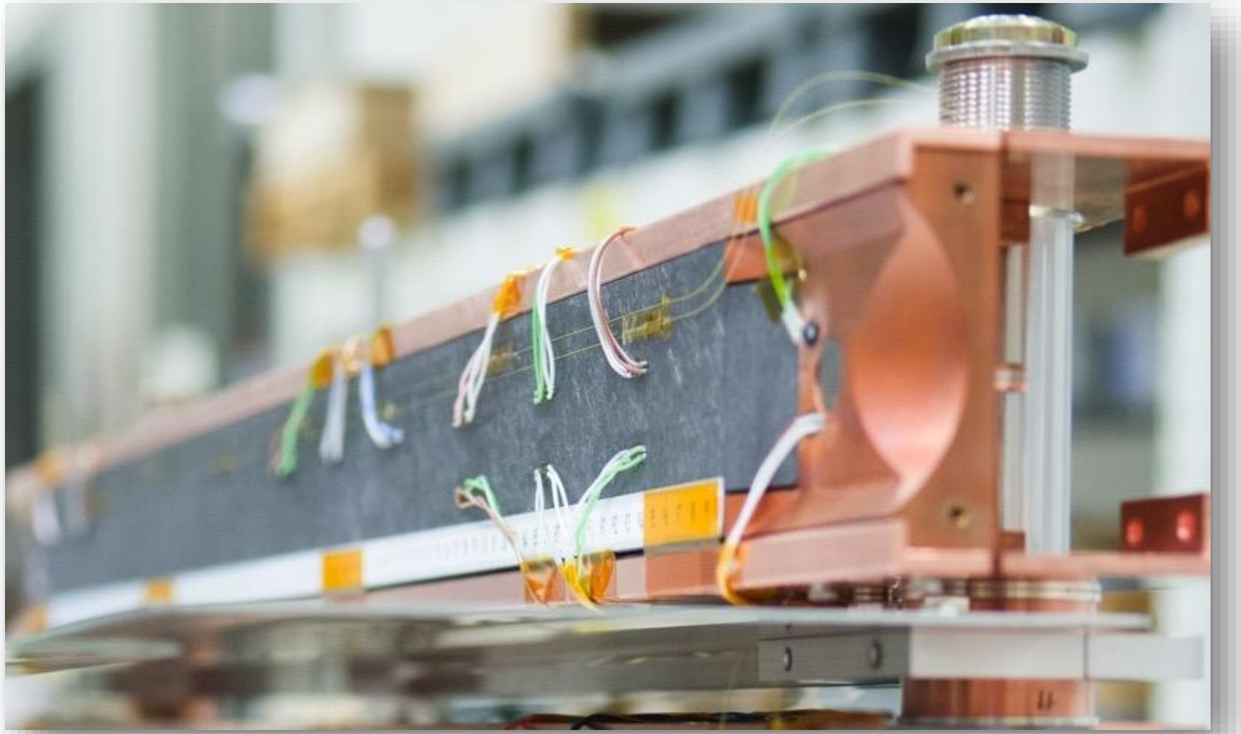
STFC Visit

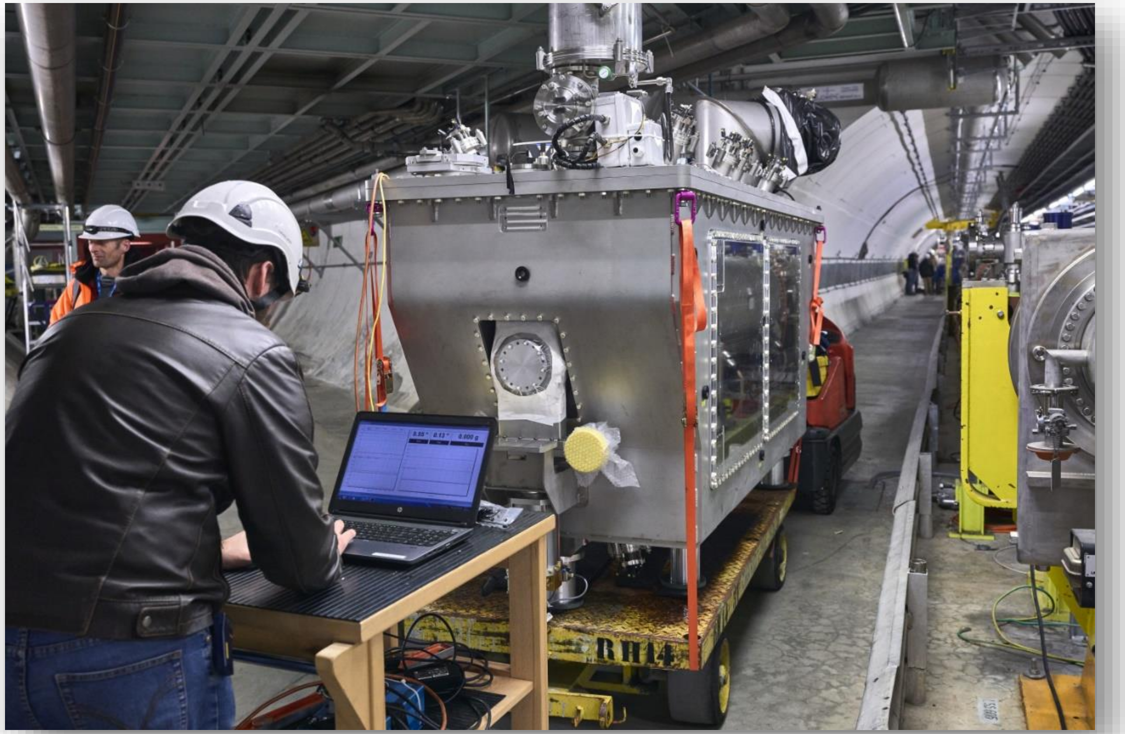
Introduction



Introduction

Mechanical measurements are done on several types of components : superconducting magnets, dumps, RF cavity, detectors in different conditions as electro-magnetic field, vacuum, radiation, cryogenic, water, etc…





Introduction

CERN-wide Support

Experimental stress analysis

Vibration analysis

Seismic measurements

Mechanical testing

Thermo-physical analysis

Sensors development

Stress / strain analysis
Dynamic strain measurements
Residual stress measurements

Experimental modal analysis

Load cell based on strain gauges
Displacement sensors
Optical fibre based sensors

STRAIN MEASUREMENTS IS A KEY TECHNIQUE !

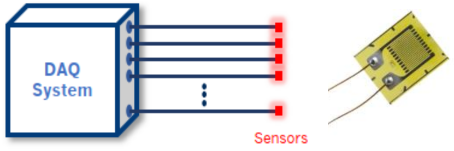
- Strong interest in optical strain measurement systems for harsh environmental conditions ;
- Beginning of the study in 2011 with FBG technology;
- Main requirements:
  - Optical strain measurements
  - 1.9 K up to 400 K
  - DAQ integrated system
- As a measurement lab, we must perform a metrology qualification of new systems before field implementation.

Strain Sensing Techniques at CERN

80's | 2011 | 2021

Electrical Strain Gauge (ESG) / Fiber Bragg Grating (FBG)

Multiple Copper Wires Per Sensor



Discrete

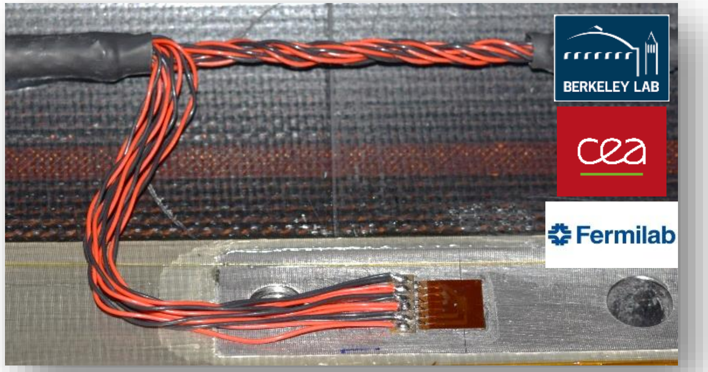
Rayleigh Backscattering (RBS)

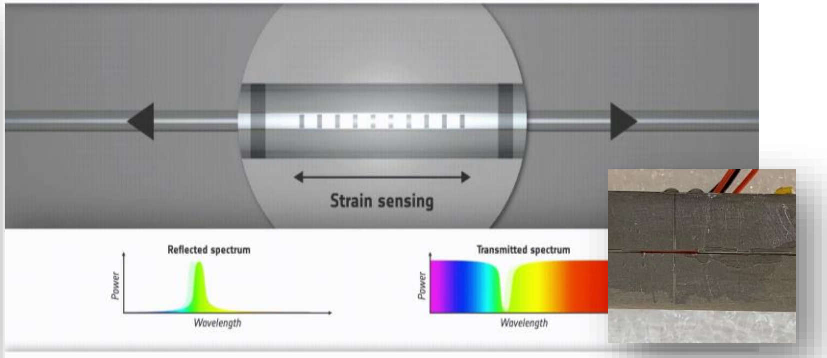
Distributed

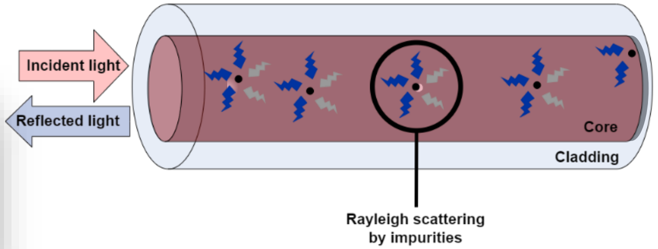
- Robust well proven technology
- Bulky cabling

- Single optical fiber
- Challenging bonding process for cryogenic temperatures

- Single optical fiber
- Sub mm spatial resolution
- Challenging bonding process for cryogenic temperatures

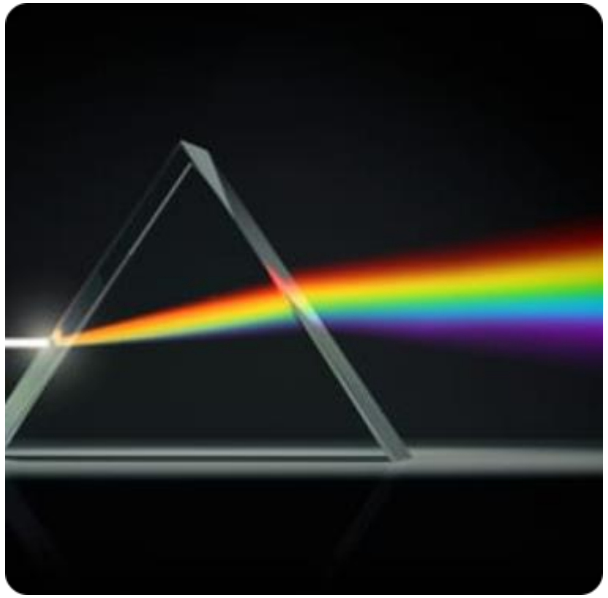






Principles of Optical Fibre Sensing (OFS)

Optical Fibres Sensing refers to the use of optical fibres to measure various physical parameters:
temperature, strain, pressure, chemical composition, vibrations, radiation, rotation, shape, EM field, etc.



The information is encoded in at least one property of the light travelling in the optical fibre:
intensity, phase, polarization, wavelength

Intrinsic sensors

When the OF itself is the sensing element

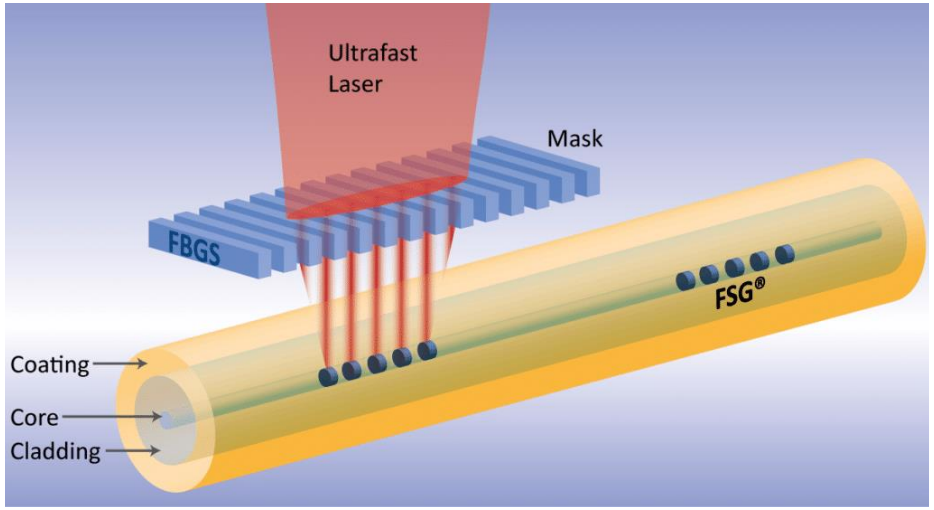
The physical measurand modulates one of the light properties.

Extrinsic sensors

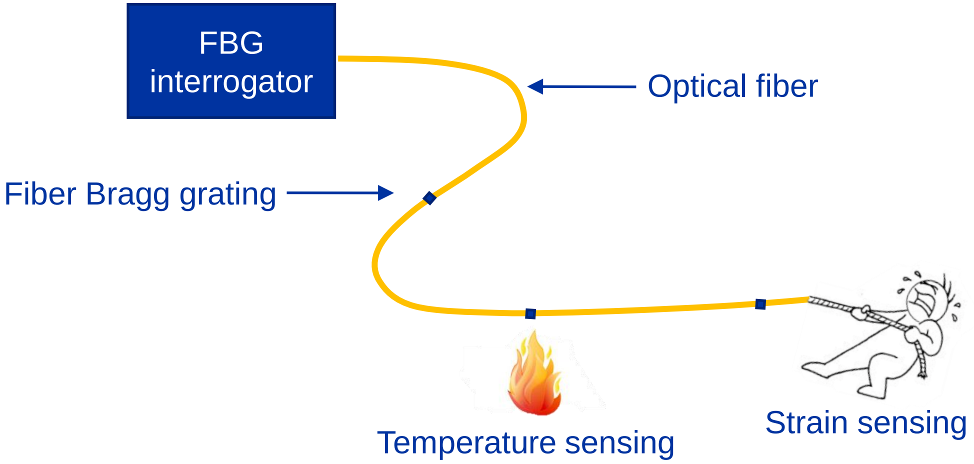
When the OF is only used to transmit the light

The physical measurand modulates the light emission in an object external to the fibre.

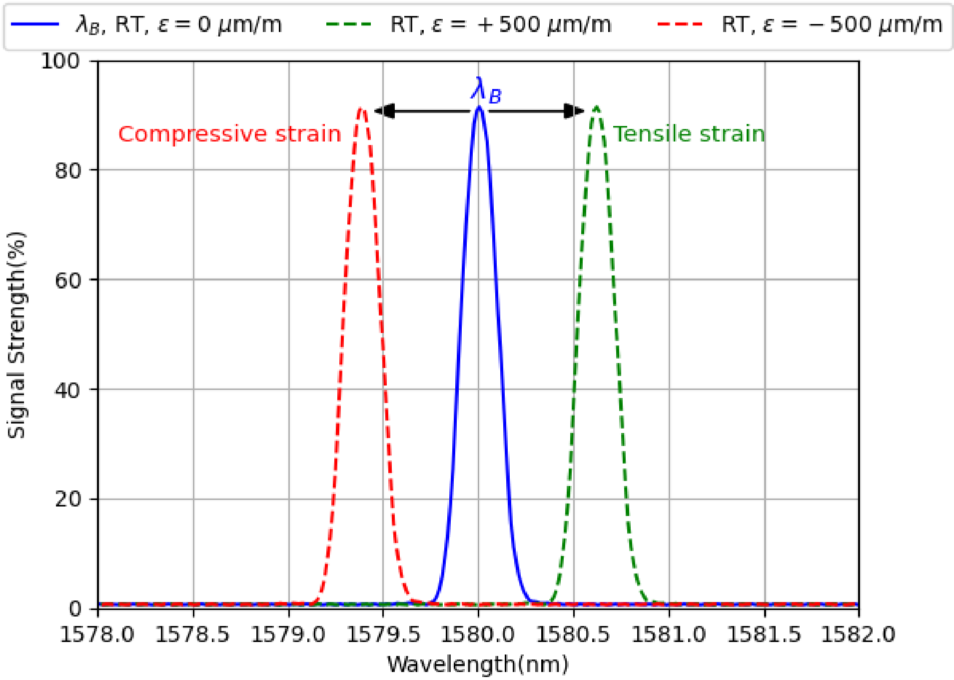
Working principle of the FBG



Through-coating FBG inscription process [4].



- Through the coating inscription technique;
- Fabricated with ultra short femtosecond laser pulses [7].



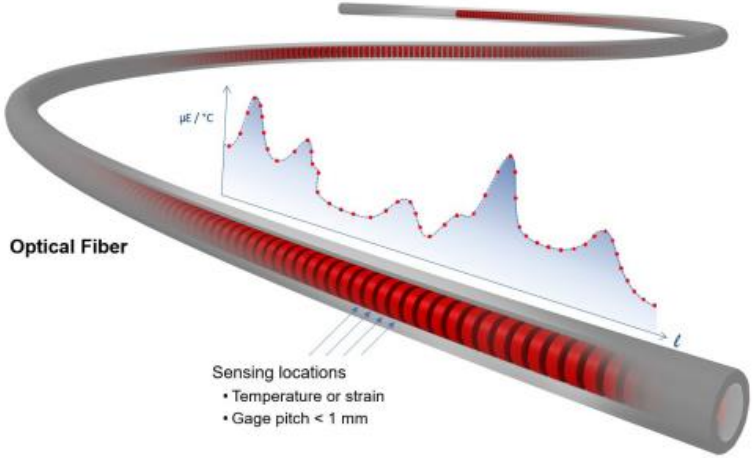
Reflection spectra of an FBG presenting the effect of tensile and compressive strains on the Bragg wavelength.

$$\Delta\lambda_B = \lambda_B[(1 - p_e)\varepsilon + (\alpha + \xi)\Delta T] \quad [8]$$

Working principle of the RBS

Rayleigh scattering [9].

Rayleigh scattering from air molecules [9].



Distributed sensing in optical fiber [10].

- Rayleigh backscattering is caused by the random fluctuations in the index profile along the optical fiber.

- Optical Frequency Domain Reflectometry (OFDR) technology in a single-mode optical fiber was reported in 1981 for the first time (Eickhoff and Ulrich, 1981) as a method to measure the spatial distribution of the Rayleigh scattering and optical losses along the optical fiber (**0.5 m** spatial resolution achieved) [6];
- However, it has recently been investigated and commercialized for numerous monitoring applications (**0.1 mm** spatial resolution achieved) [11].

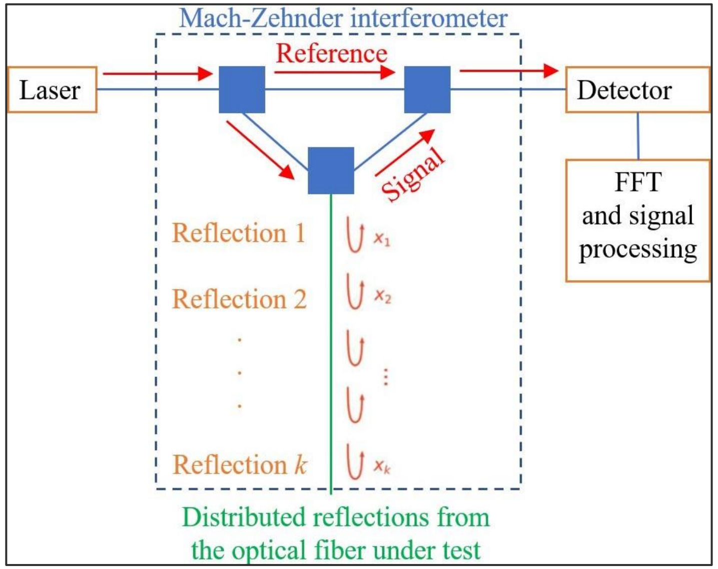


Diagram of the operating principle behind c-OFDR.

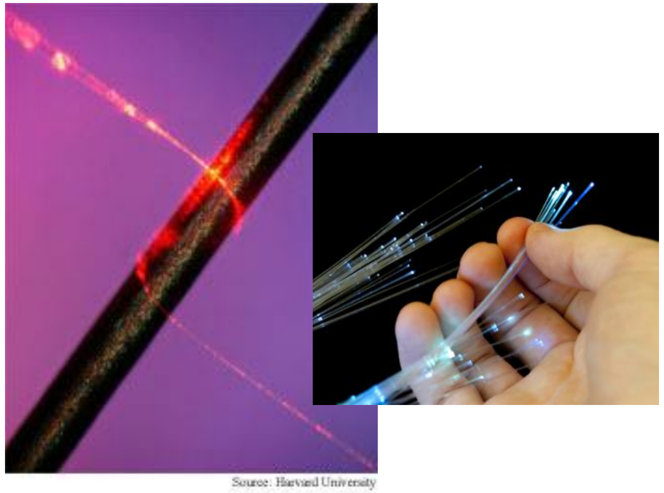
Advantages of the optical fiber strain sensors

Works in harshest environments

Source: CERN

- Immune to electromagnetic interference;
- Chemically inert;
- Different optical fiber types can be used depending on the need (radiation-hard; high-temperature, water-resistant, etc.).

Flexibility



The red strand is a lit, nano-scale optical fiber. The black rod is a human hair.

- Very small;
- From 125 µm down to **40 µm** cladding diameter;
- Less invasive than ESG;
- Lightweight.

Applications at CERN

FBG technique

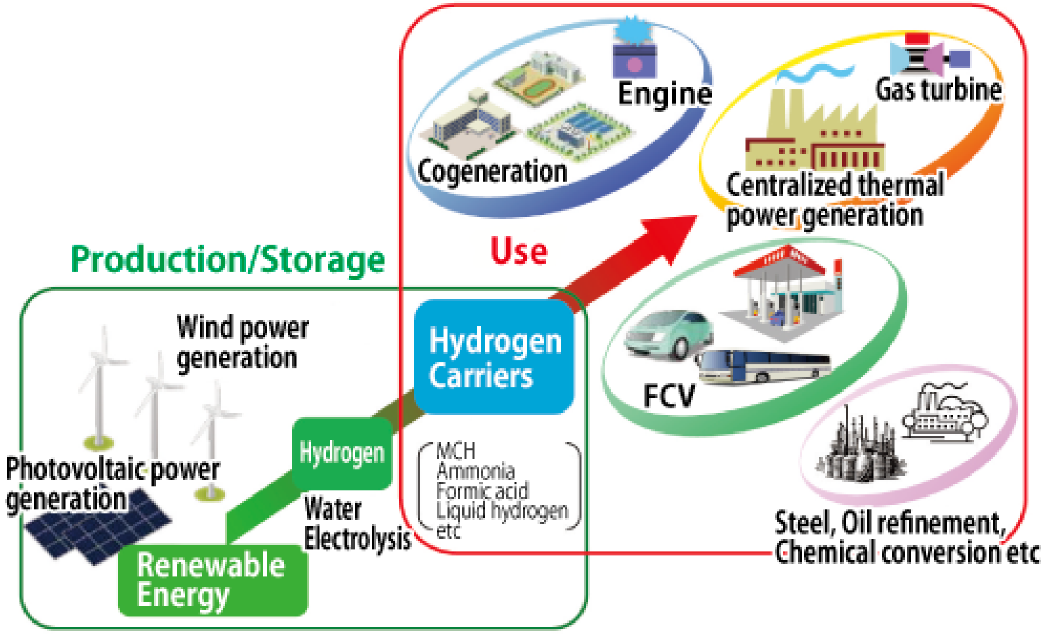
- Real-time sensing up to 40 sensors per single optical fiber (depending on the optical interrogator performance);
- Static and dynamic measurements up to 2000 Hz;
- **Better time resolution.**

RBS technique

- Ultra-high spatial resolution down to 0.65 mm;
- Static and dynamic measurements up to 250 Hz;
- **Better spatial resolution.**

Strain sensing at cryogenic temperatures

- A perhaps surprising property of optical fibers is that they remain flexible at cryogenic temperatures [12];
- Zirconia ferrule has a very low thermal expansion coefficient, which reduces material stresses caused by temperature gradients; and is also very close to that of the fiber.

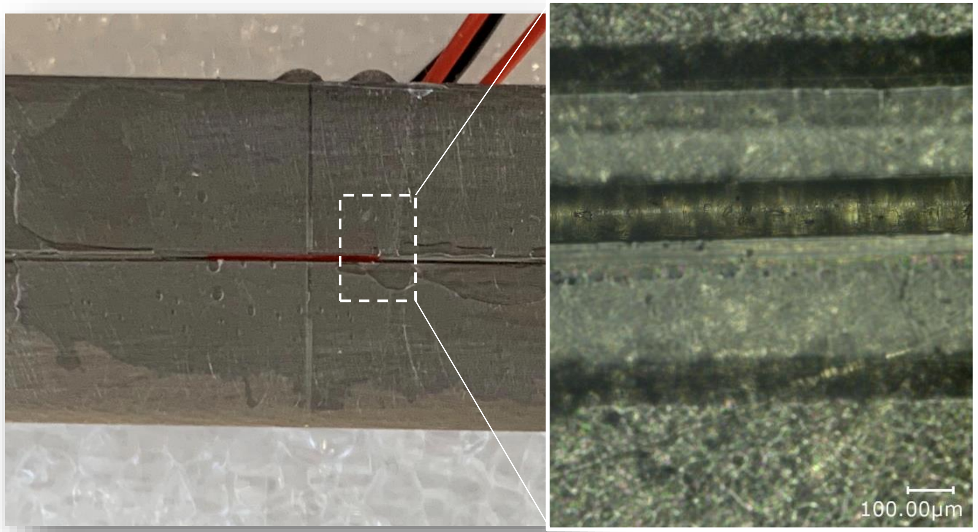


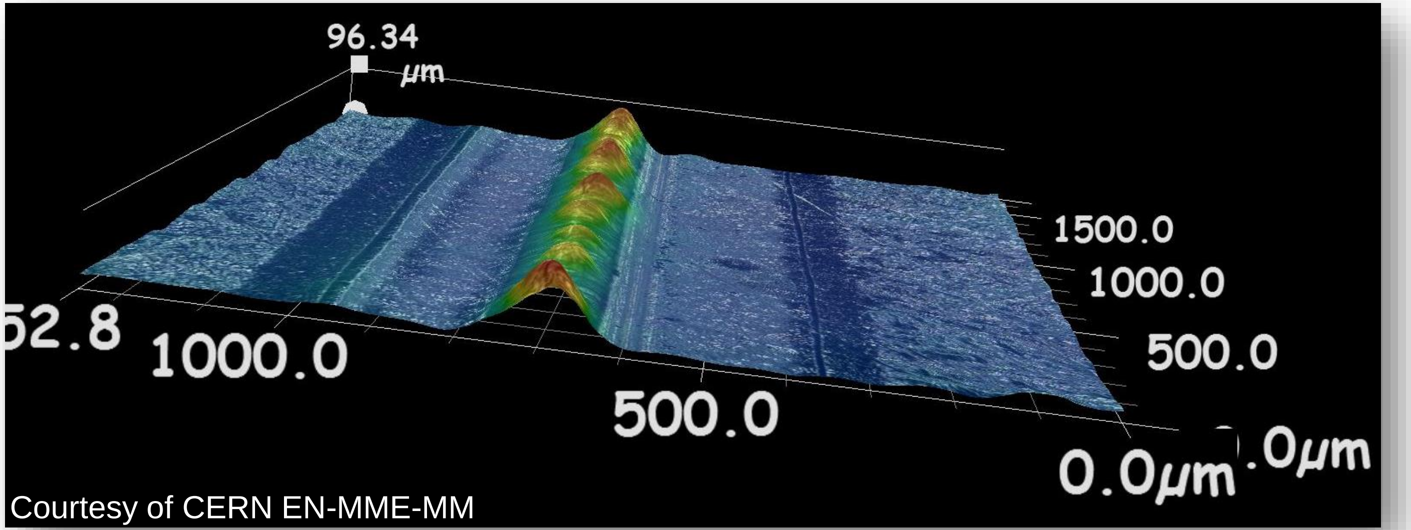
Production and utilization of hydrogen from renewable energy [13].

- Hydrogen liquid is seen as one of the energy vectors of the future;
- H_2 must be cooled to 20.28 K to be in liquid state;
- Future emerging research with strain sensing at cryogenic temperatures.

Technical Challenges

- Adhesion technique is a crucial parameter as the deformations of the studied material need to be perfectly transferred to the sensor and need to be repeatable → Specific procedure
- Adhesion technique developed internally at CERN for strain sensing experience in harsh environments such as cryogenic temperatures.



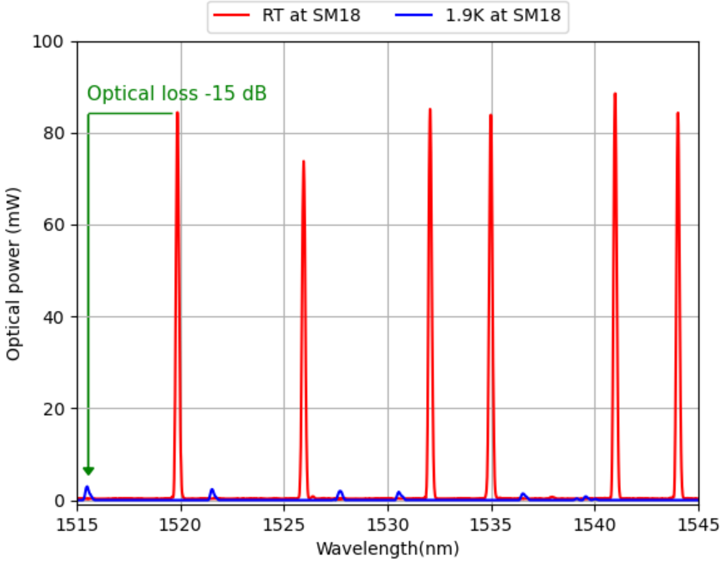


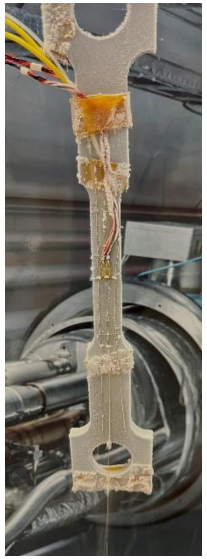
Courtesy of CERN EN-MME-MM

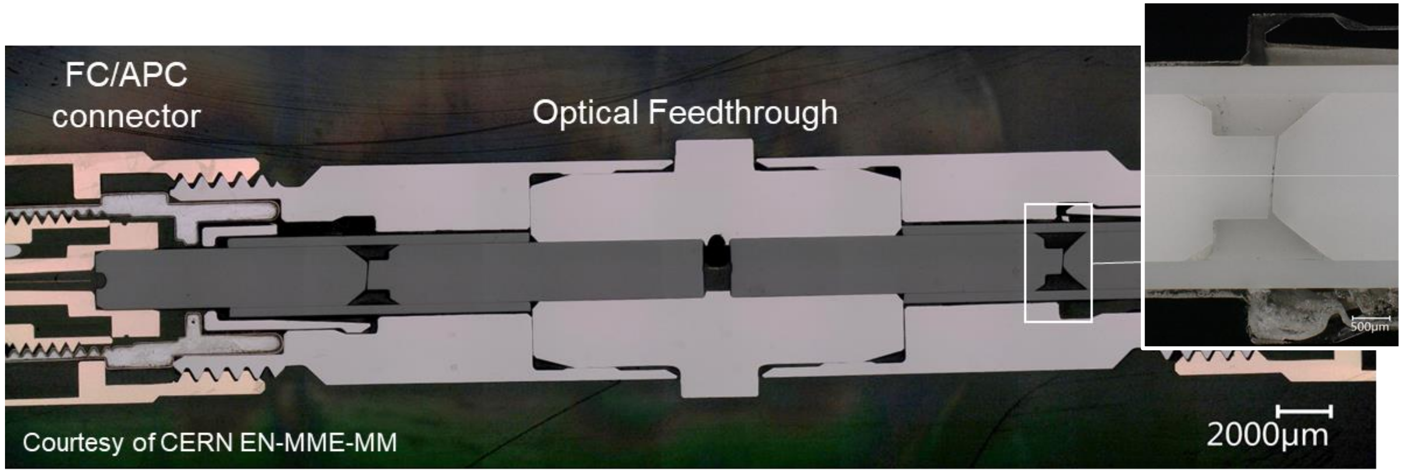
Technical Challenges

Main temperature effects on the optical fibers :

- Strong attenuation of the optical power due to the thermal contraction (- 15 dB) which can disturb the peak tracking (optical budget issue);
- High insertion losses observed at cryogenic temperatures on the optical fiber feedthroughs / connectors.



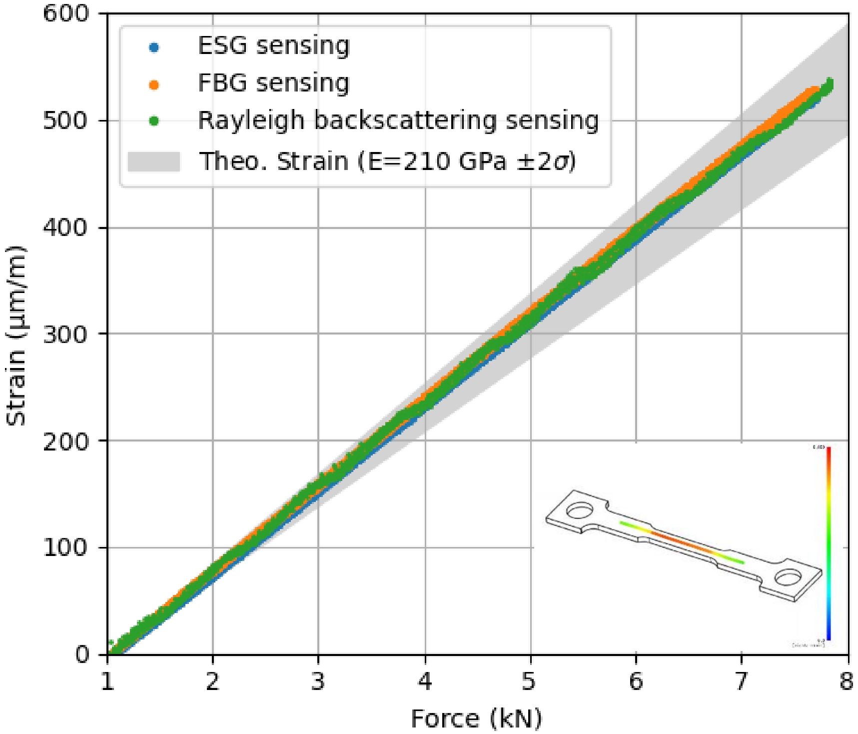




Validation Process

Optical strain gauges validation campaign down to cryogenic temperatures :

- Evaluating the repeatability and reproducibility down to 77 K;
- Evaluating the trueness of the three measuring systems down to 4.2 K according to ISO 5725.

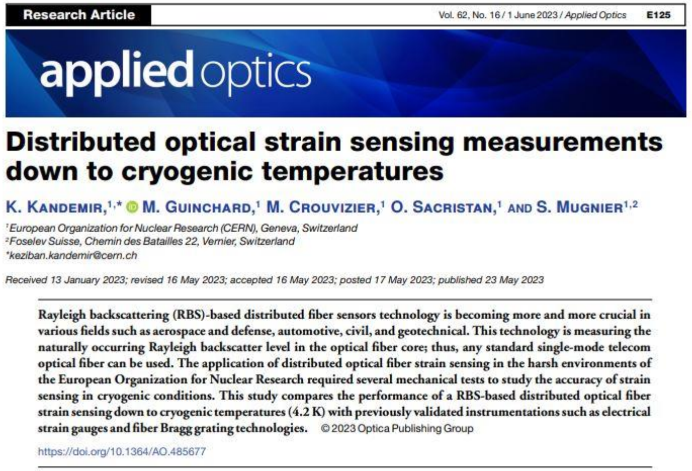


		ESG (1)	FBG (2)	RBS (3)
Apparent strain at 77 K	Mean Value (µm/m) (SS304L)	-3377	-3924	-3954
	Repeatability (µm/m)	9	63	120
	Reproducibility (µm/m)	32	78	122
	Precision (%)	**1.2 %**	**2.5 %**	**4.3 %**
Trueness at 4.2 K (%)		4.3%	3.5 **%**	1.2 **%**
Accuracy at 4.2 K (%)		**4.4 %**	**4.3 %**	**4.5 %**

(1) LC11-3/350 – HBK®
(2) High-reflectivity (>50%) femtosecond FBG in Polyimide coating – FBGS Technologies GmbH
(3) Polyimide coating SM OF – Polytec GmbH

Validation Process

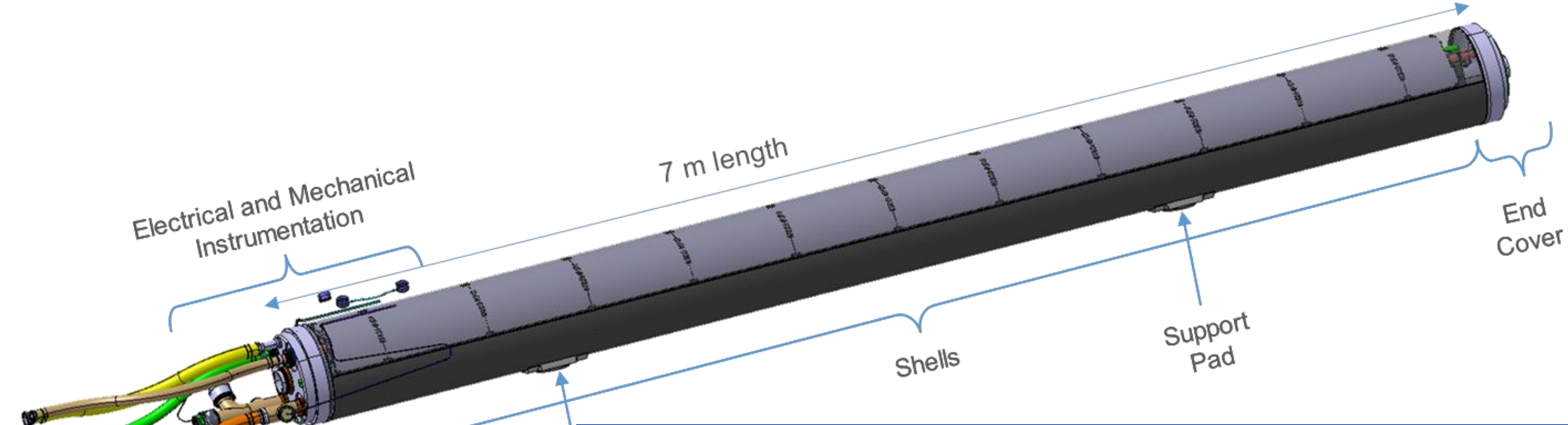
Optical and strain gauges validation campaign down to cryogenic temperatures

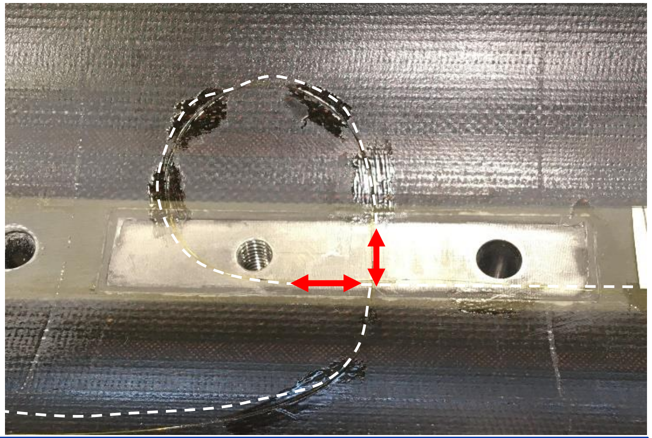


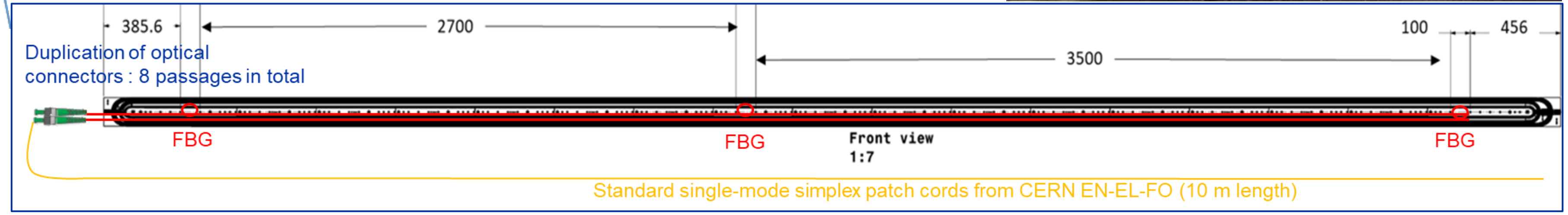
Applications

HL-LHC superconducting quadrupole magnets (MQXF) :

- 7m length coils instrumented with OFS (FBG / discrete measurements) to assess the stress state (key parameter in the magnet performance);
- Stress monitoring performed during the loading, thermal cycles and powering processes.



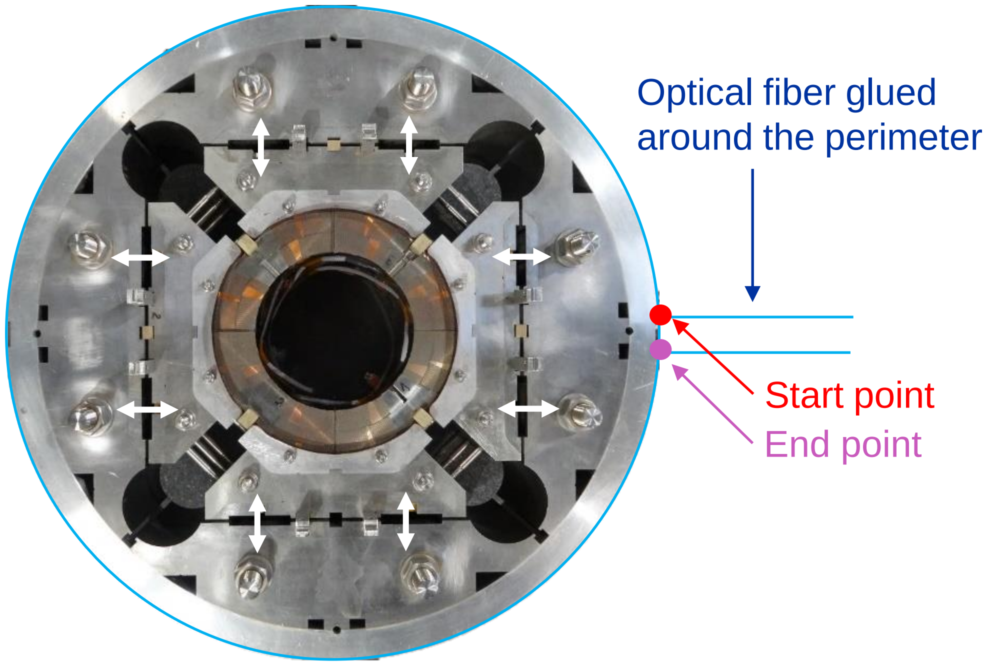


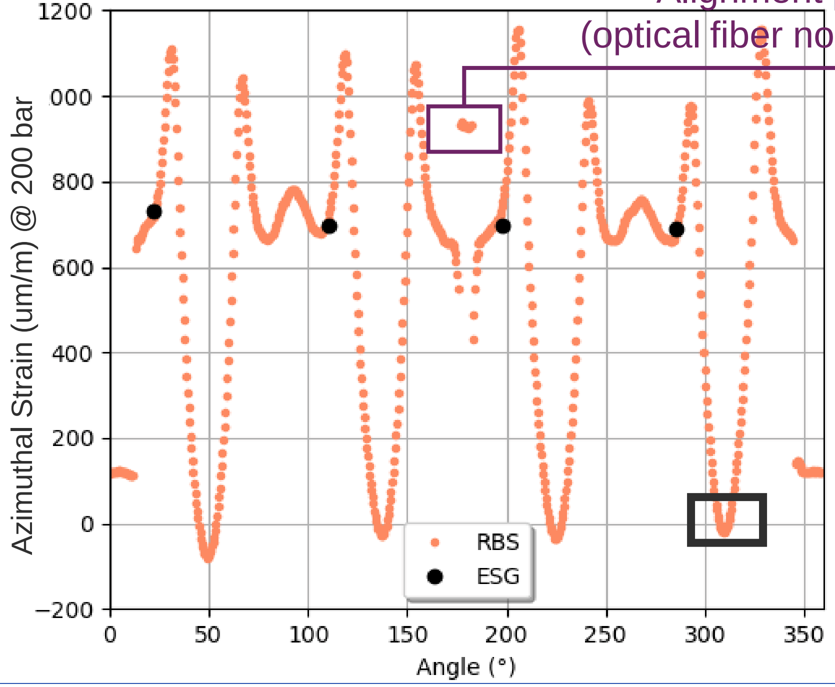


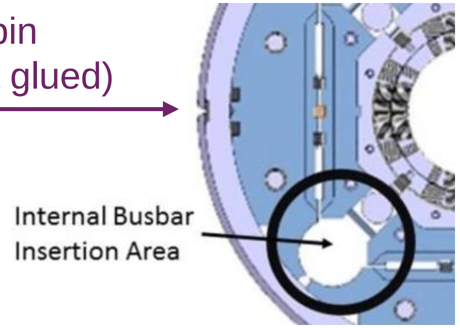
Applications

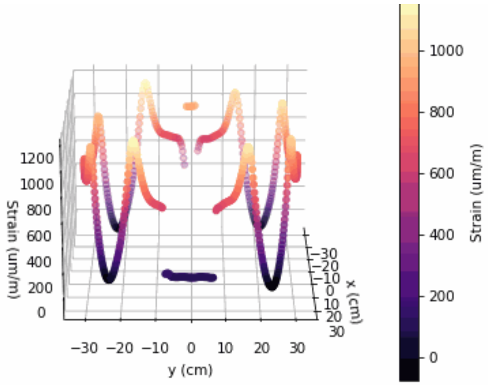
HL-LHC superconducting quadrupole magnets (MQXF) :

- Aluminum outer shell instrumented with OFS (RBS / distributed measurements) to assess the stress state during loading operation;







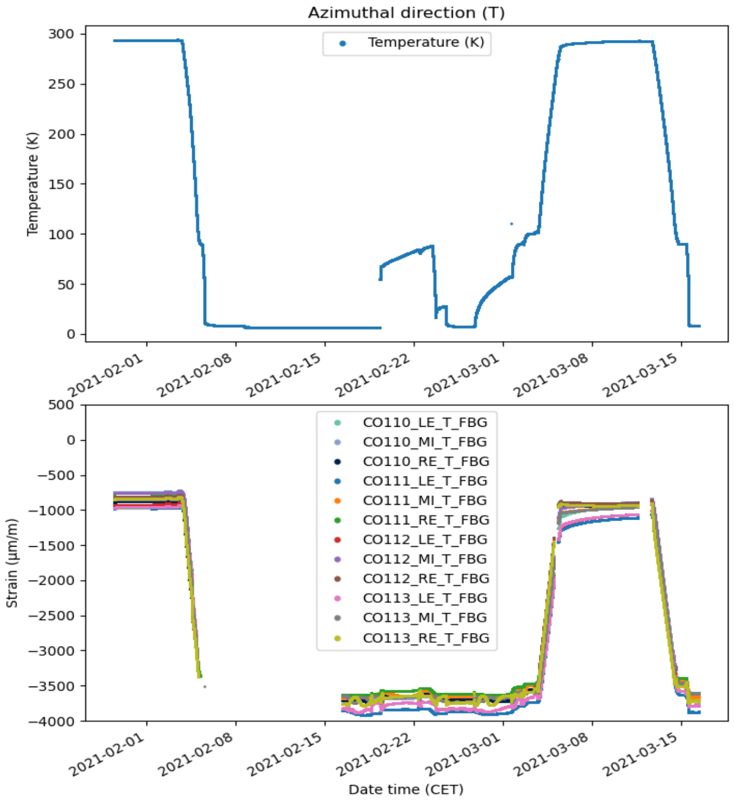


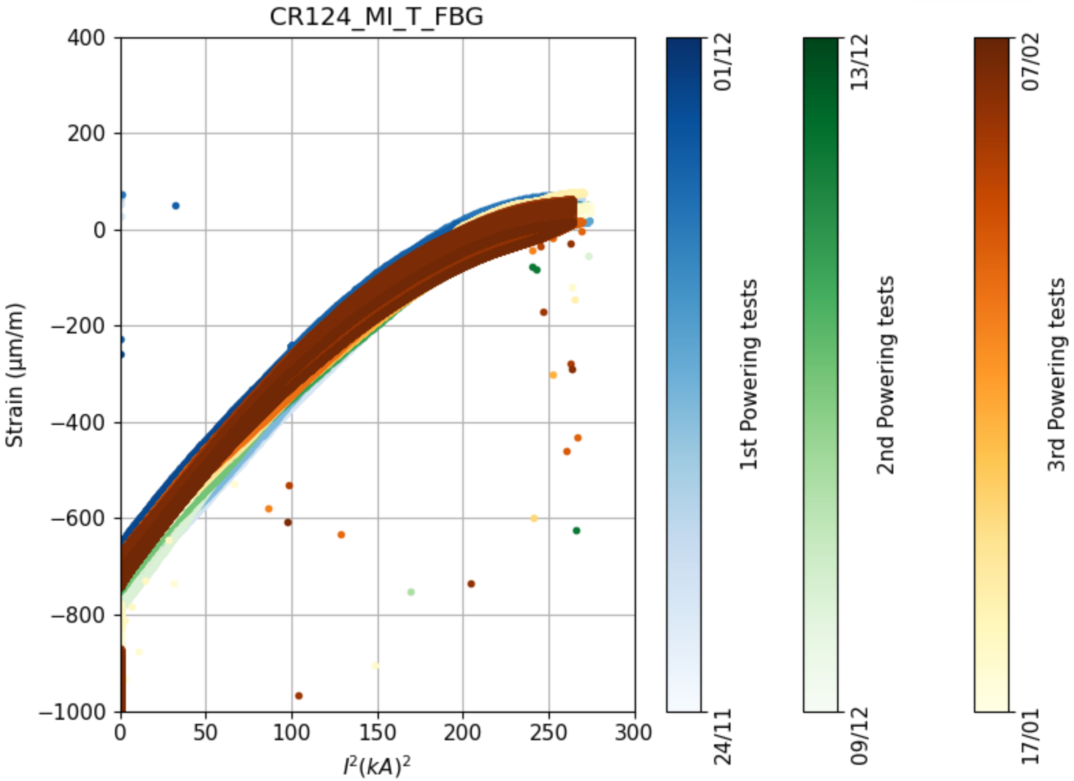
Applications

HL-LHC superconducting quadrupole magnets (MQXF) :

- Real time data acquisition + Cloud data streaming → Grafana Dashboards

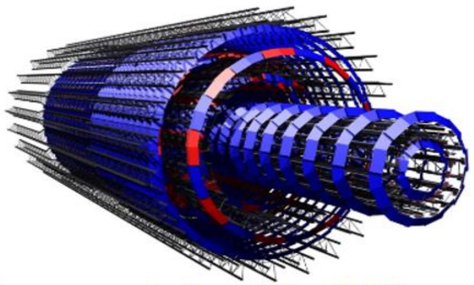
Python



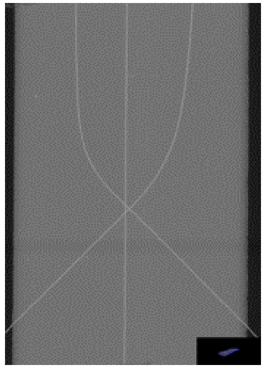


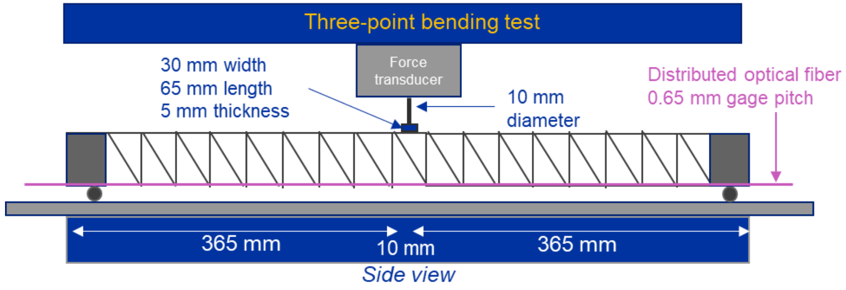
Applications

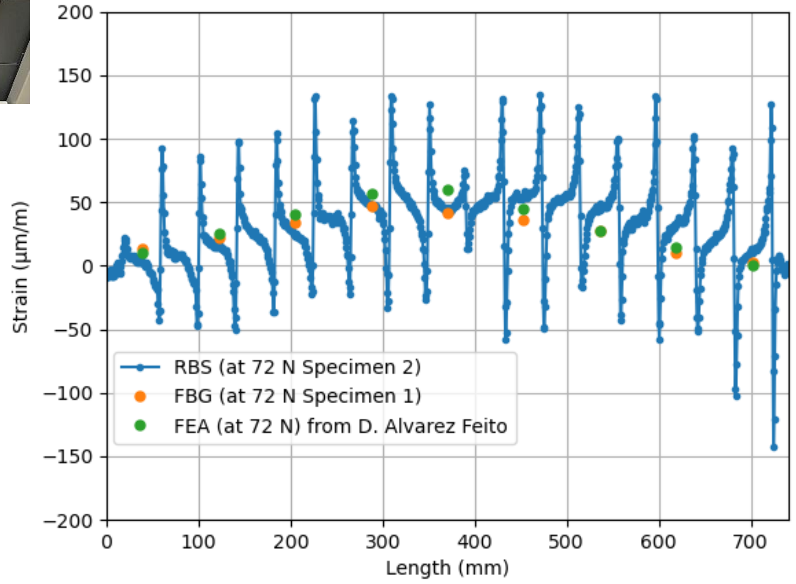
Embedded OFS in carbon fiber structure (EP-DT Collaboration)

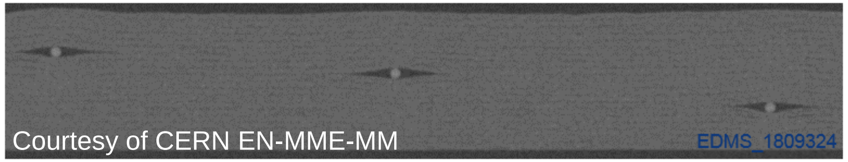


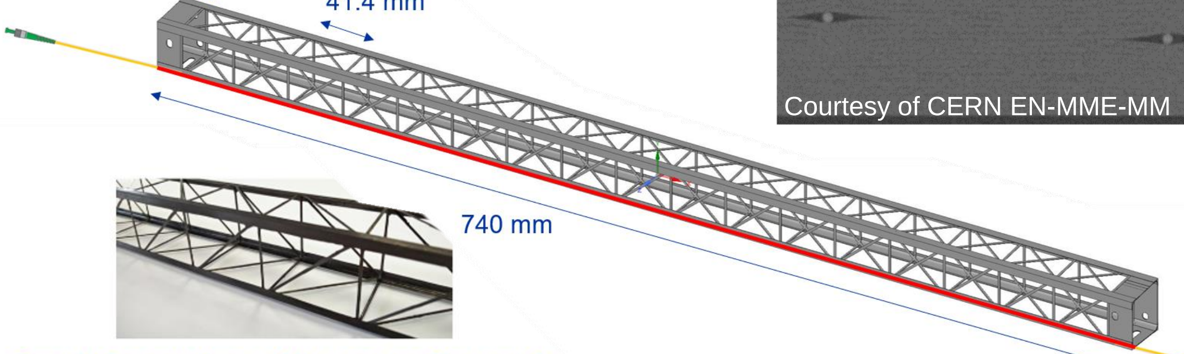
Schematic representation of the SLIM concept for the future ATLAS Pixel detector.









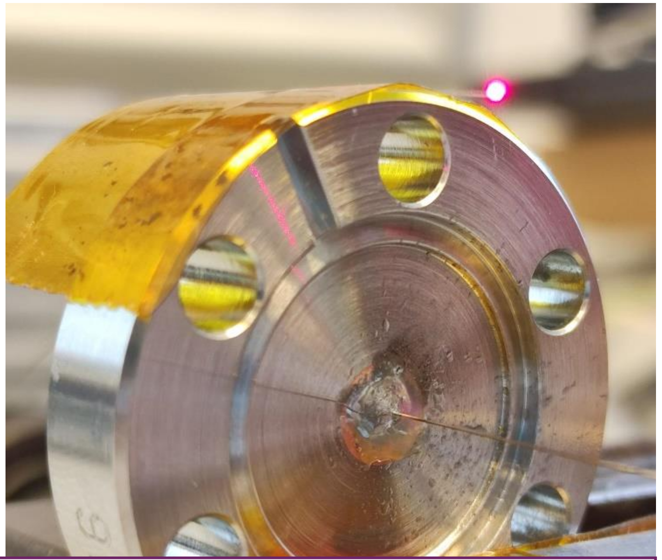


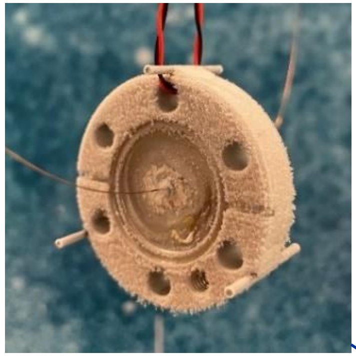
Detail of a prototype of the carbon fibre reinforc... plastic (CFRP) truss to be used as a support stru...

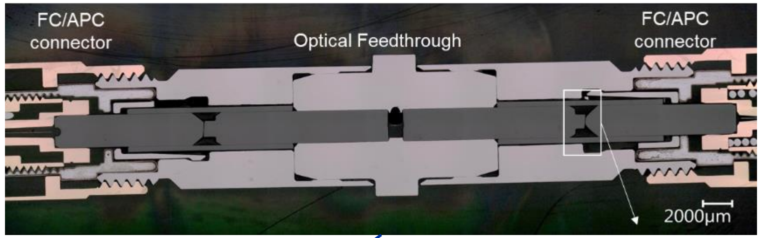
Developments

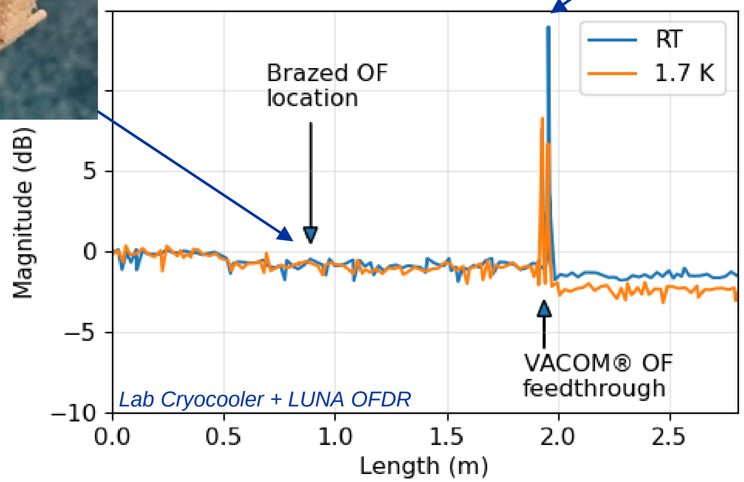
Optical feedthrough development in the EN-MME (Design, FEA, Workshop) :

- Some issues to extract optical fiber signal from 1.9 K bath with commercial connectors ;
- Internal development to produce a brazed solution without connectors to improve the optical losses at cold.







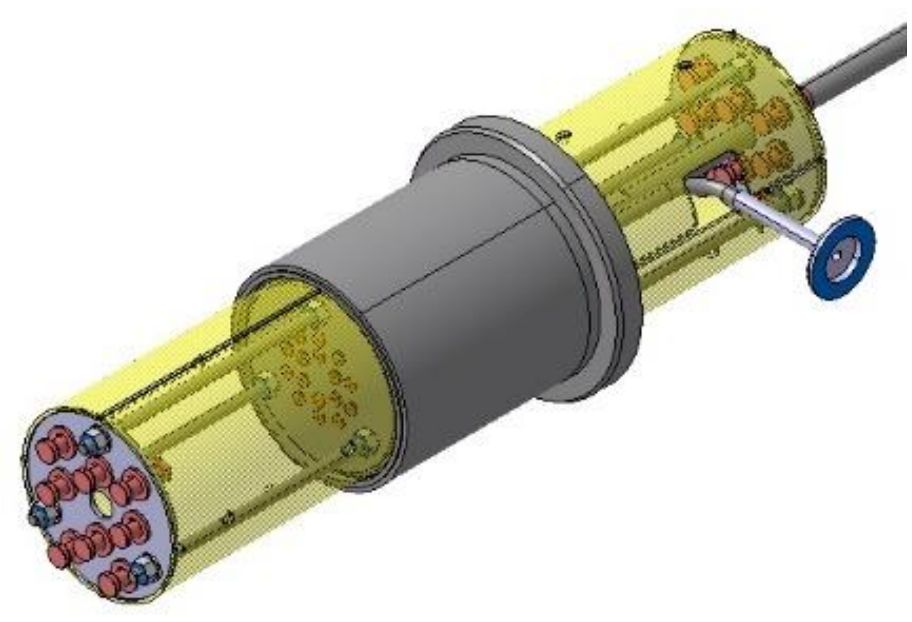


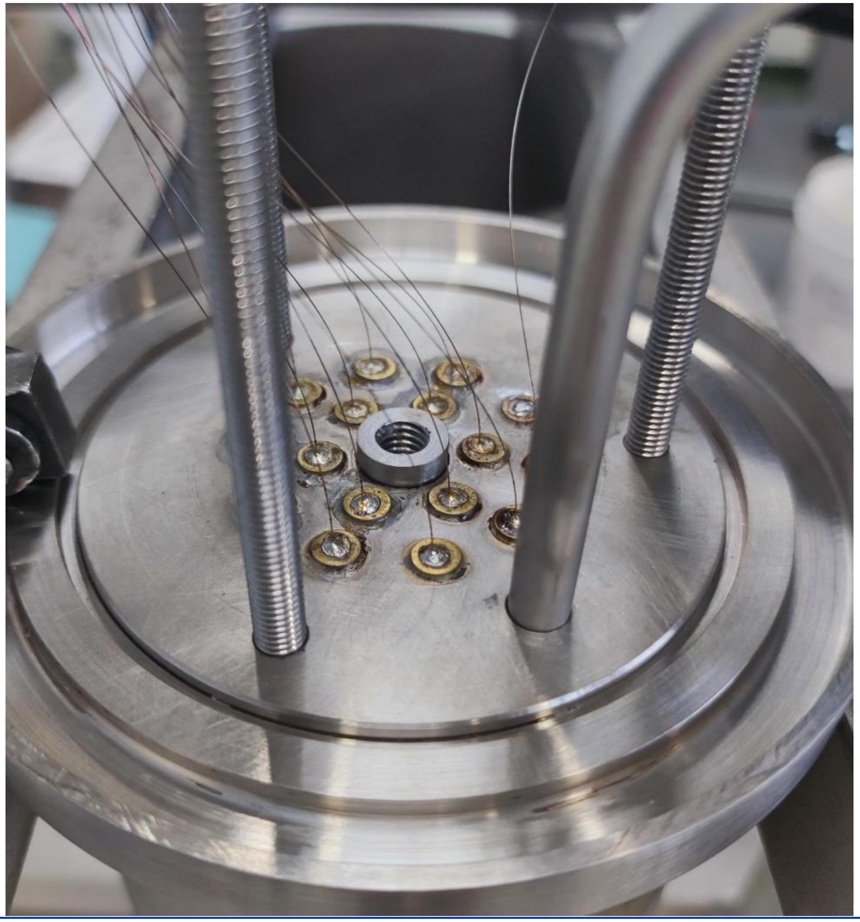
Brazing methodology :

- Single-mode pure-silica core optical fiber with 35 μm ± 5 % Cu-alloy thickness;
- OFE copper inserts also brazed into the center of the AISI 316LN flange

Developments

Optical feedthrough development in the EN-MME group :





Performance after 10 thermal cycles :
- Leak tight at 10-12 mbar.l/s;
- No optical losses visible at 77 K ;
- Next tests will be performed at 1.9 K.

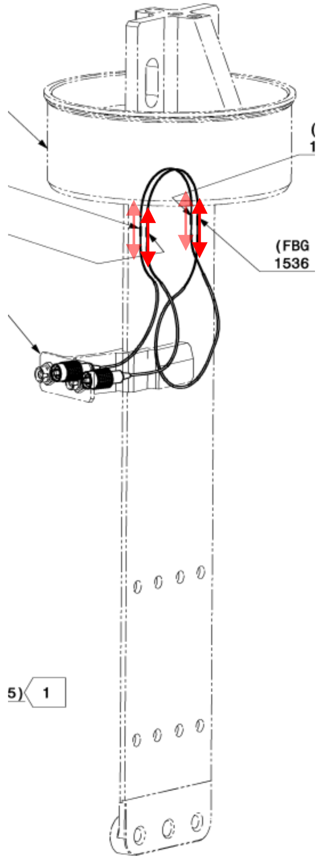
Crab Cavity instrumentation Design

Michael GUINCHARD on behalf of EN-MME-EDM

STFC Visit

Fiber Bragg grating based strain sensor

FSG-A03-AA0	0.609/4/1520-1544/1 FemtoSecond Gratings in Polyimide coated 125µm Bend Insensitive fiber optimized for 1550nm wavelength window Number of FBG's: 4 Lead in: 103mm Lead out: 112mm Total fiber length: 609mm Grating length: ~4mm Spacing between gratings: 83mm, 228mm, 83mm Wavelength configuration: 1520nm, 1528nm, 1536nm, 1544nm PI coated direct FC/APC connector* at lead in and lead out *no kink protection **Individual FBG marking directly at the FBG location over whole FBG length (4mm), Marking Tolerance +/-1mm



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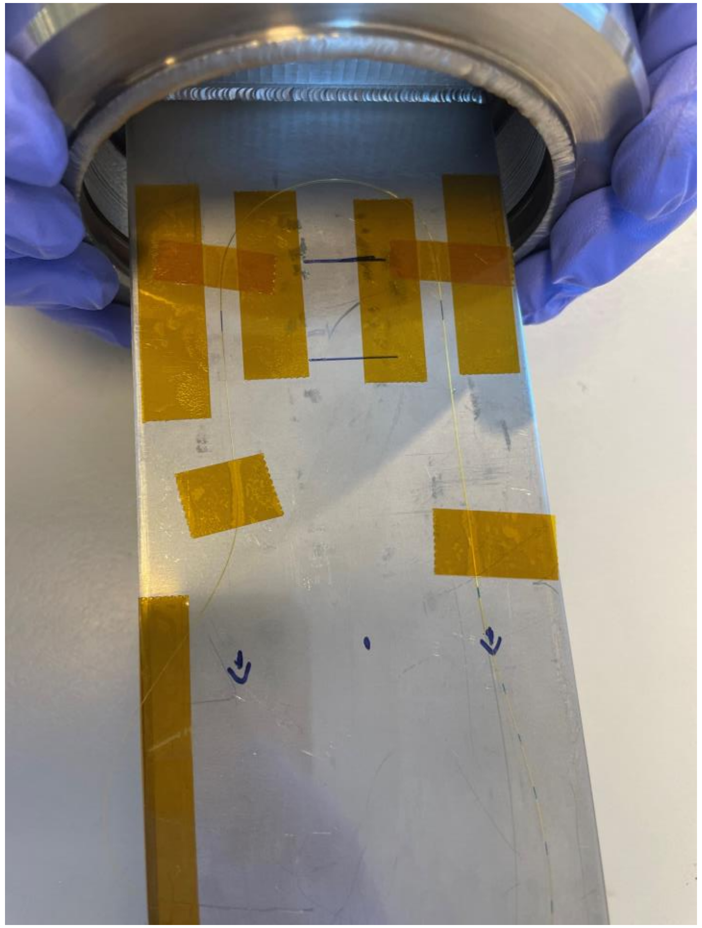
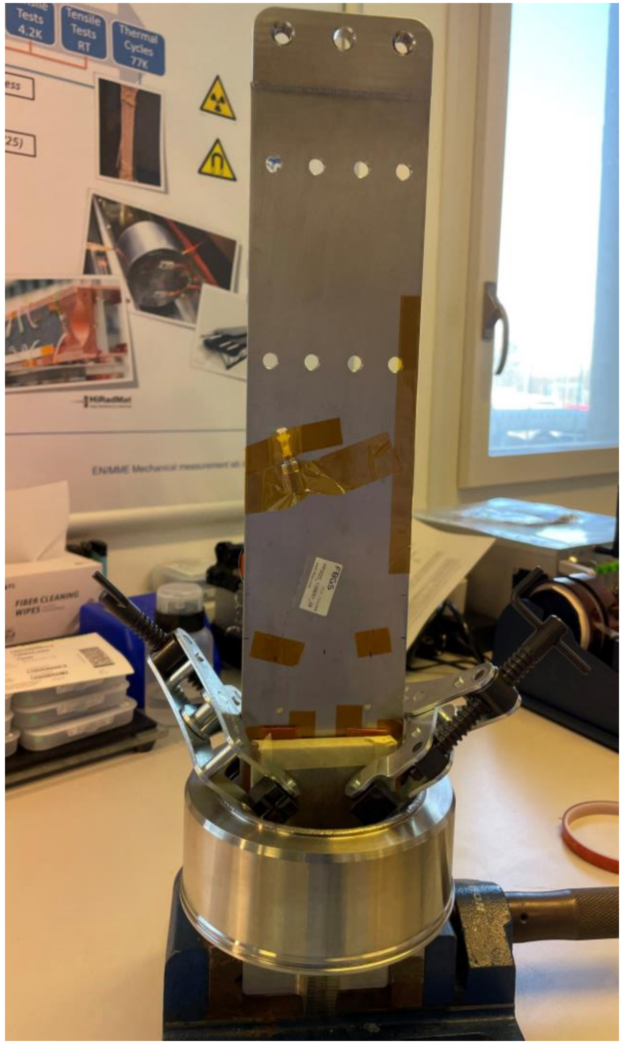
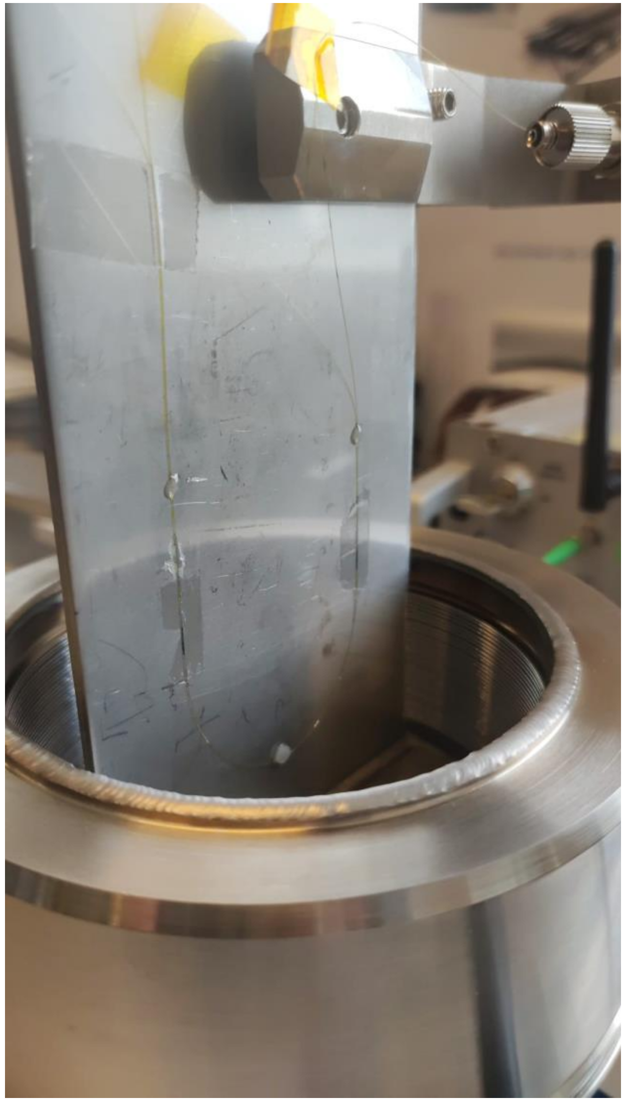
Optical fiber bonding

Optical fiber bonding on the blades.







Fiber Bragg grating based strain sensor

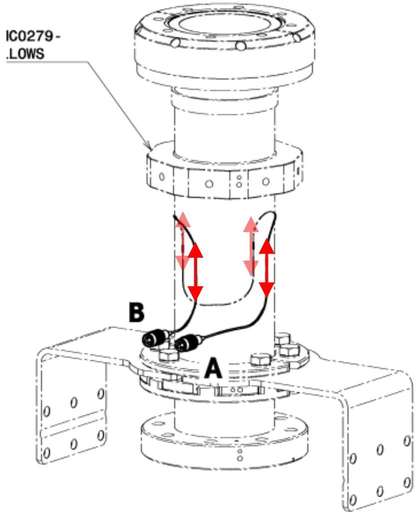
FSG-A03-AA0

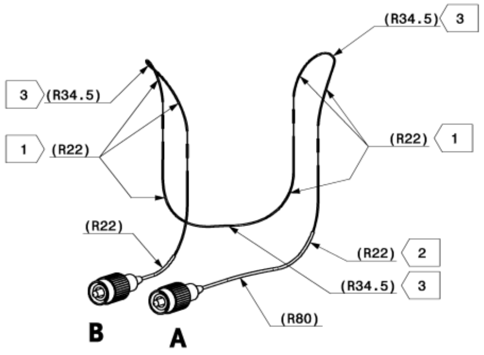
0.462/4/1520-1550/1

FemtoSecond Gratings in Polyimide coated 125µm Bend Insensitive fiber optimized for 1550nm wavelength window

Number of FBG's: 4
Lead in: 99mm
Lead out: 64mm
Total fiber length: 462mm
Grating length: ~4mm
Spacing between gratings: 89mm, 120mm, 90mm
Wavelength configuration: 1520nm, 1530nm, 1540nm, 1550nm
PI coated
direct FC/APC connector at lead in and lead out

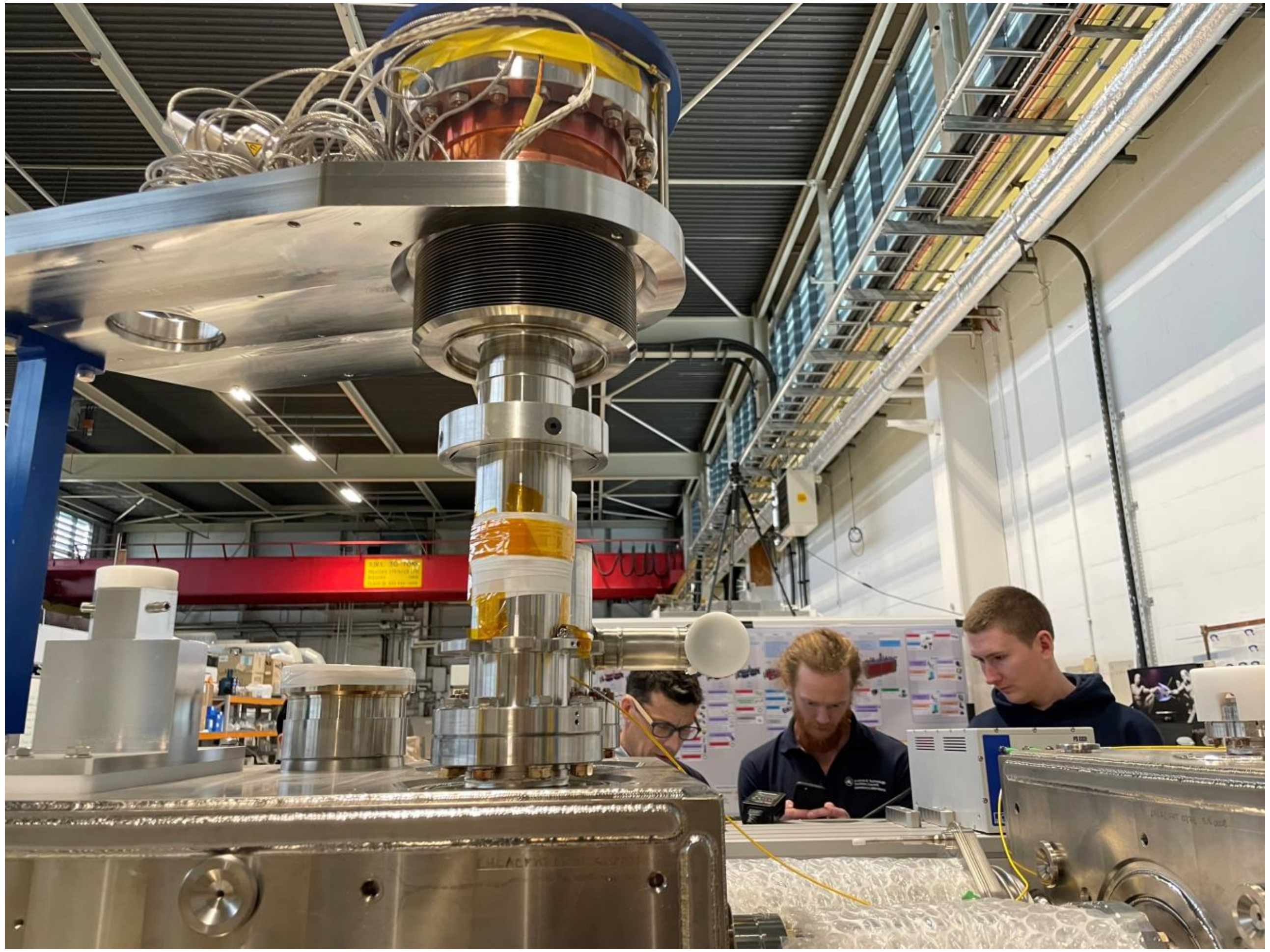
*no kink protection
**Individual FBG marking directly at the FBG location over whole FBG length (4mm), Marking Tolerance +/-1mm





Optical fiber bonding

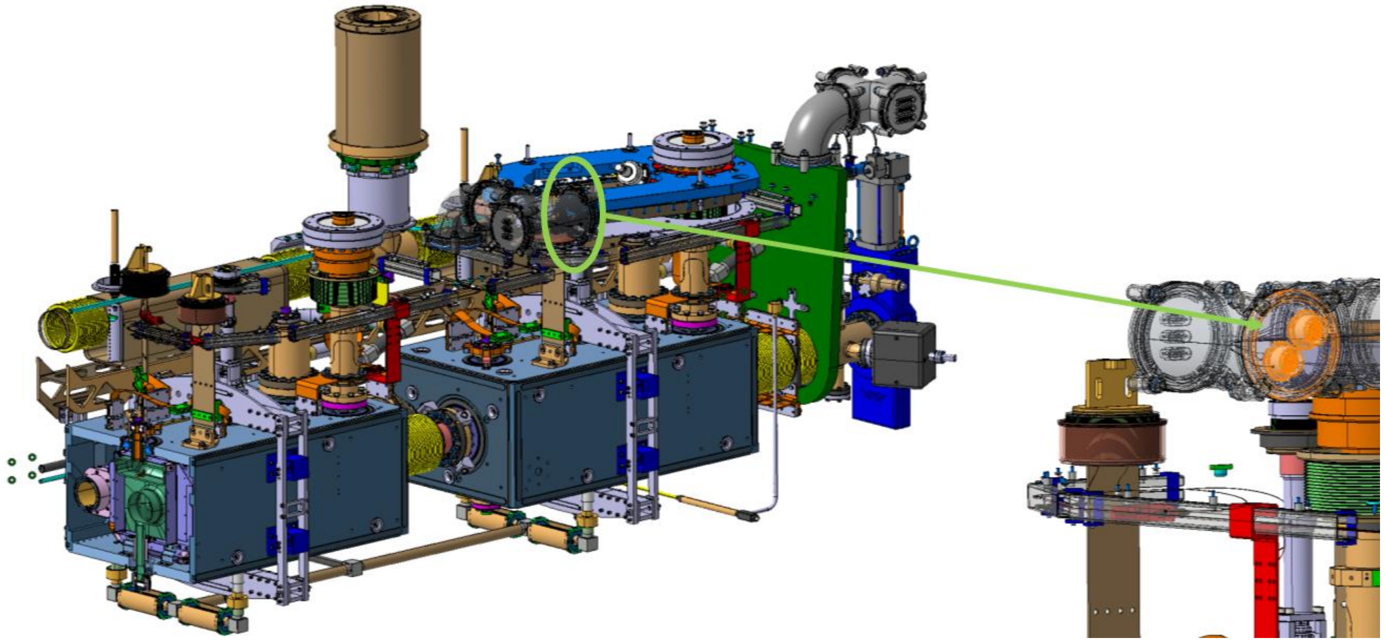
Optical fiber bonding on the FPC tubes.



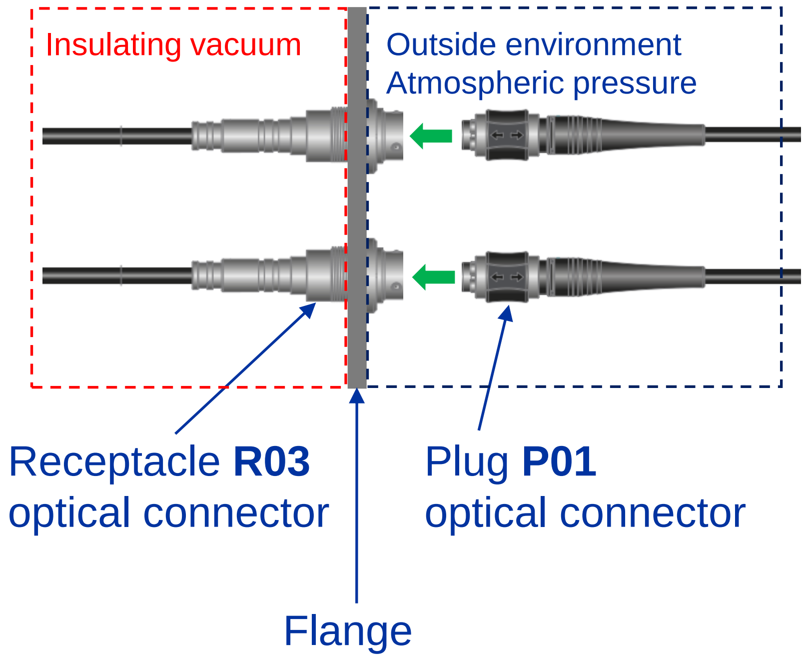
Optical fiber flange configuration

Evaluation of the strain along the blades and FPC:

- Bending strain;
- Traction stress.



Crab cavity design



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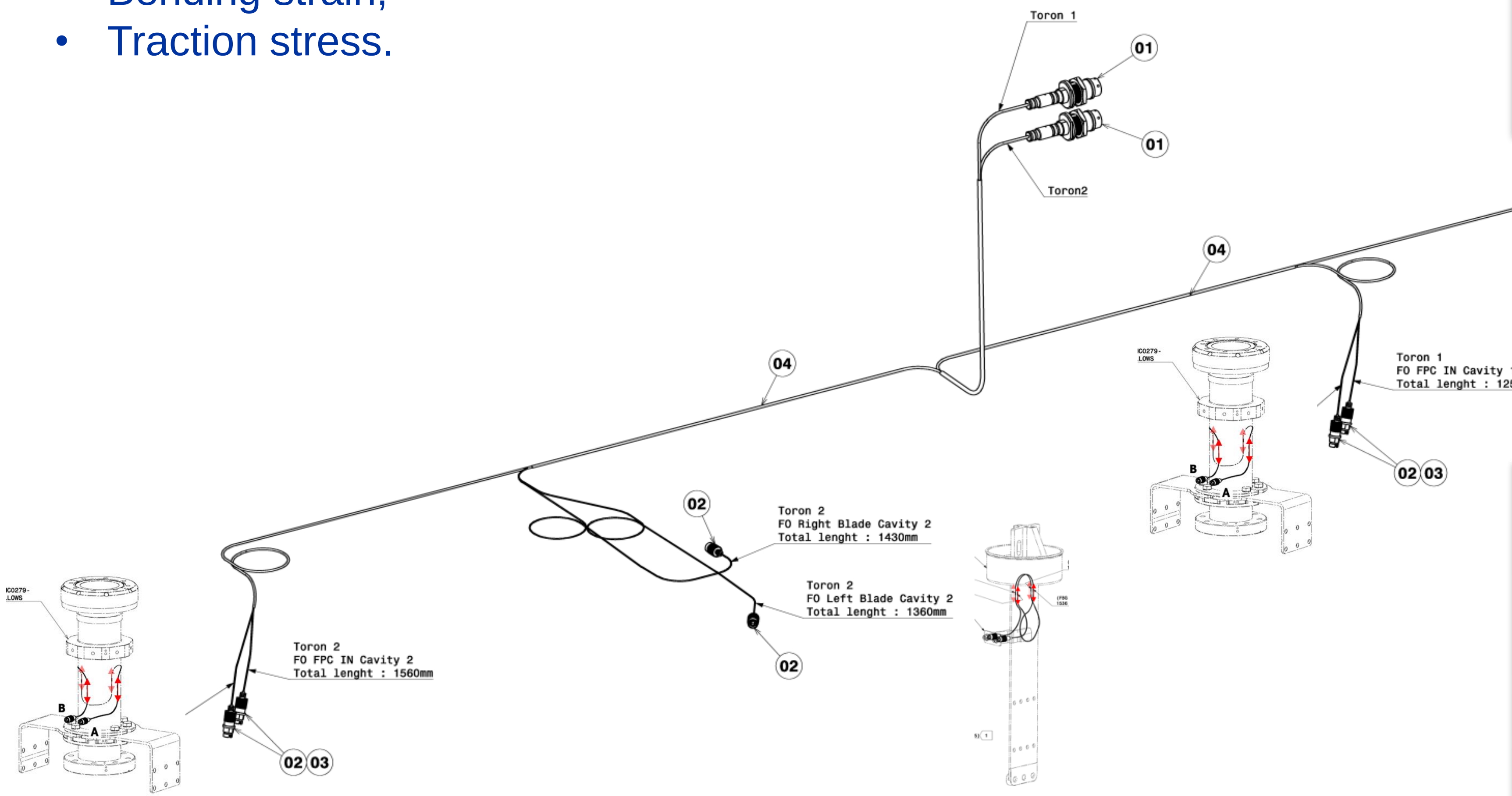
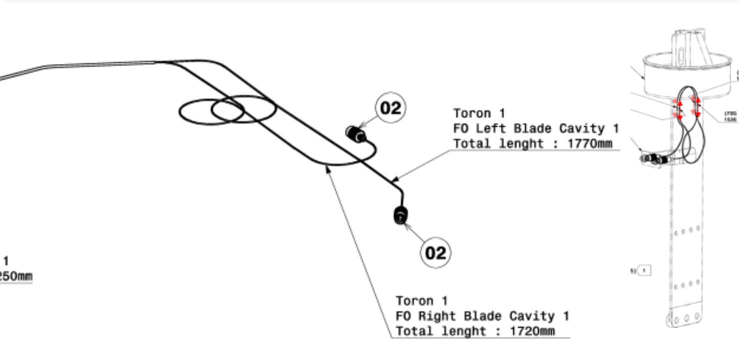
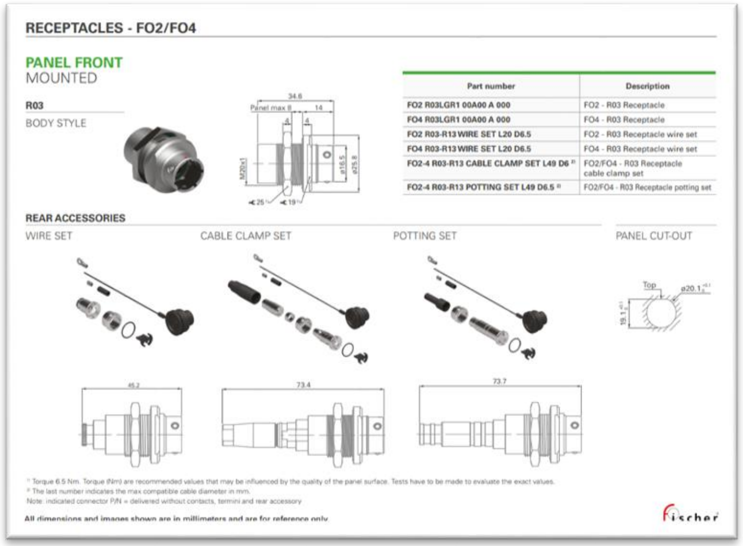





RECEPTACLES - FO2/FO4

PANEL FRONT MOUNTED

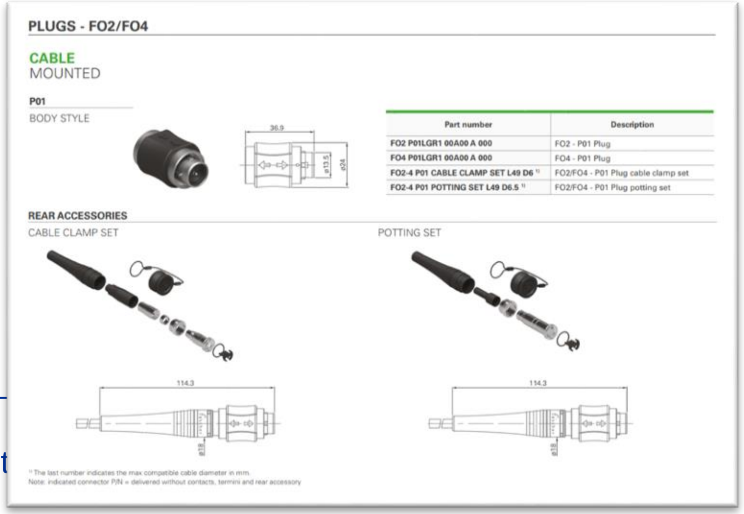
R03 BODY STYLE

Part number	Description
FO2 R03LGR1 00A00 A 000	FO2 - R03 Receptacle
FO4 R03LGR1 00A00 A 000	FO4 - R03 Receptacle
FO2 R03-R13 WIRE SET L20 D6.5	FO2 - R03 Receptacle wire set
FO4 R03-R13 WIRE SET L20 D6.5	FO4 - R03 Receptacle wire set
FO2-4 R03-R13 CABLE CLAMP SET L49 D6 [2]	FO2/FO4 - R03 Receptacle cable clamp set
FO2-4 R03-R13 POTTING SET L49 D6.5 [2]	FO2/FO4 - R03 Receptacle potting set

REAR ACCESSORIES

WIRE SET | CABLE CLAMP SET | POTTING SET | PANEL CUT-OUT

All dimensions and images shown are in millimeters and are for reference only.


PLUGS - FO2/FO4

CABLE MOUNTED

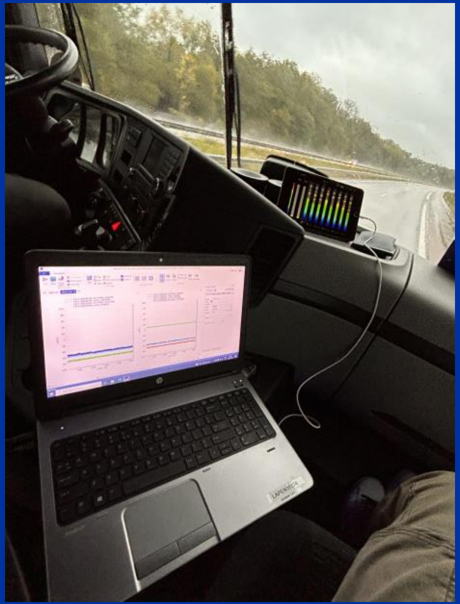
P01 BODY STYLE

Part number	Description
FO2 P01LGR1 00A00 A 000	FO2 - P01 Plug
FO4 P01LGR1 00A00 A 000	FO4 - P01 Plug
FO2-4 P01 CABLE CLAMP SET L49 D6 [1]	FO2/FO4 - P01 Plug cable clamp set
FO2-4 P01 POTTING SET L49 D6.5 [1]	FO2/FO4 - P01 Plug potting set

REAR ACCESSORIES

CABLE CLAMP SET | POTTING SET

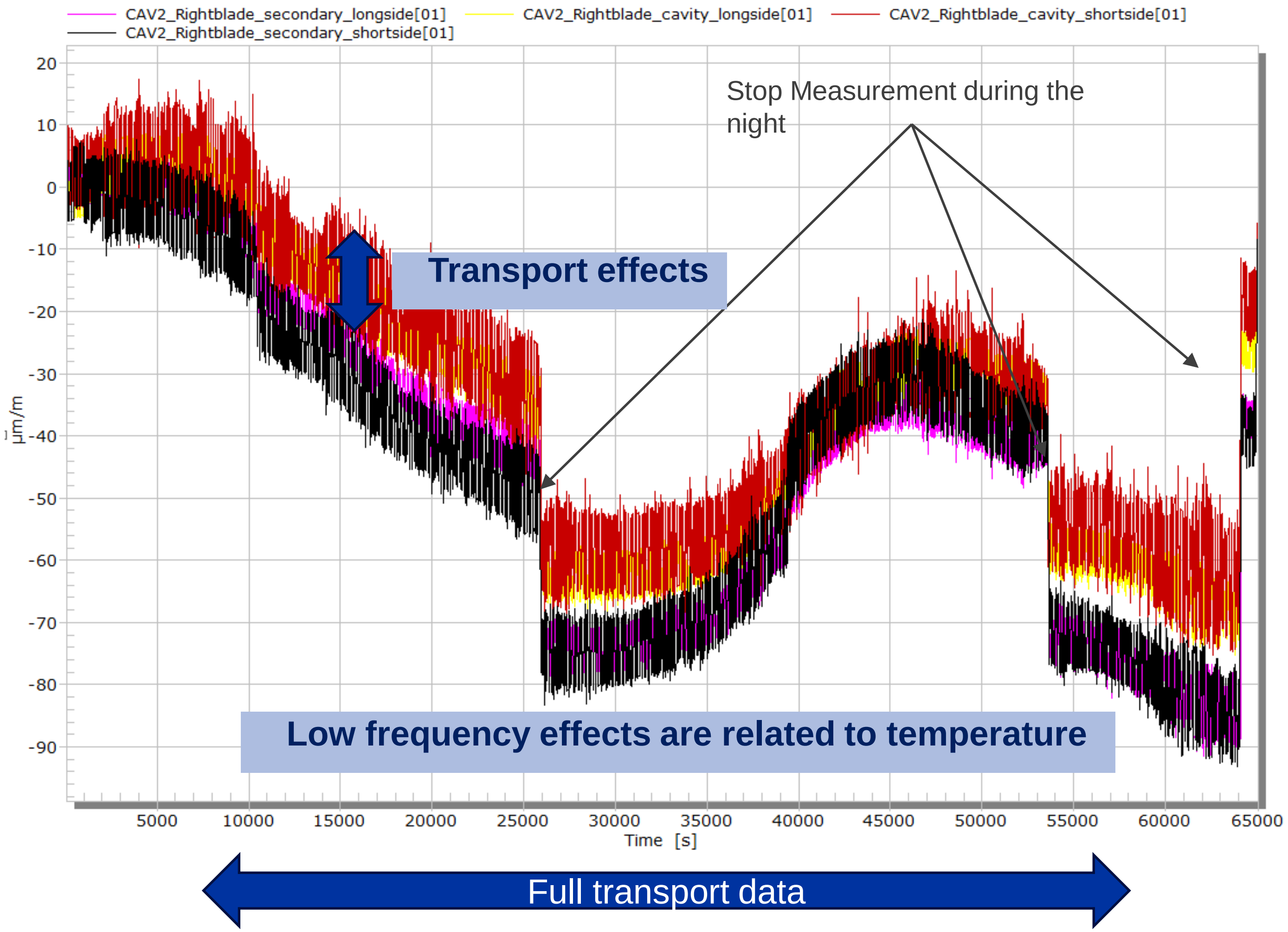
Crab Cavity instrumentation Results

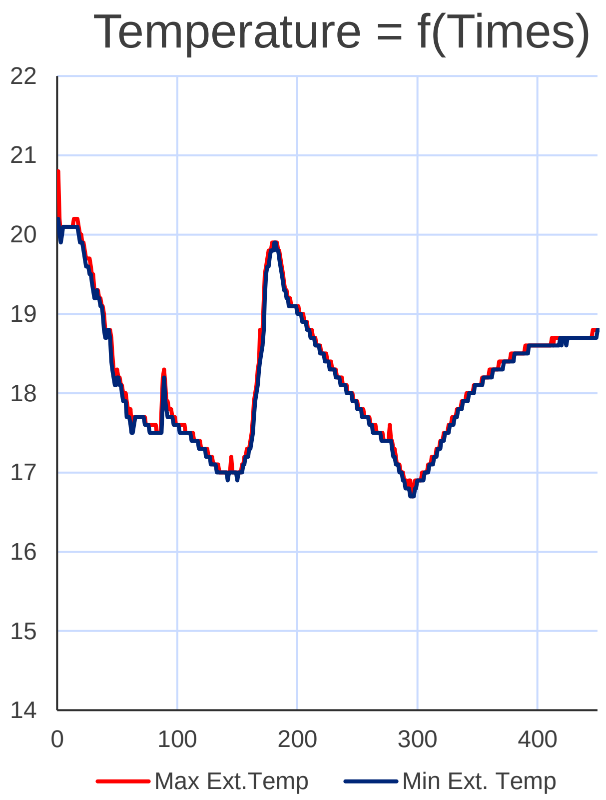


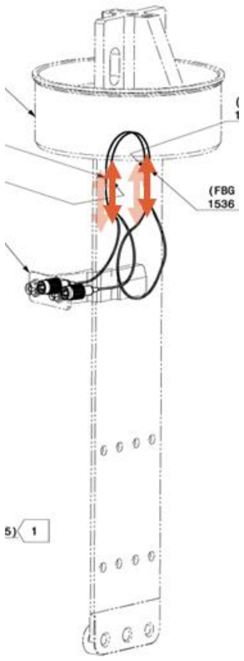
Michael GUINCHARD on behalf of EN-MME-EDM

STFC Visit

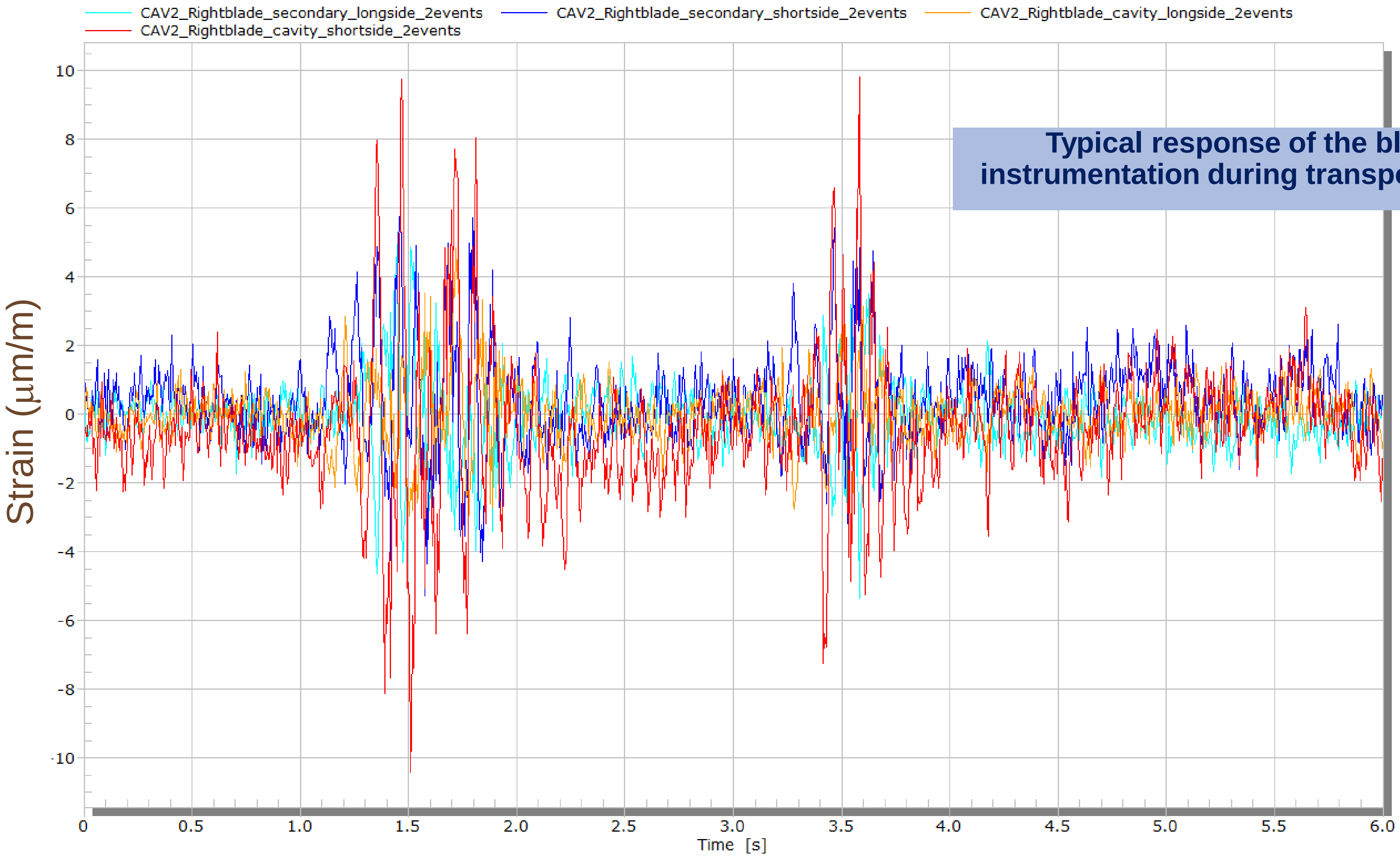
Transport results – Optical measurement system



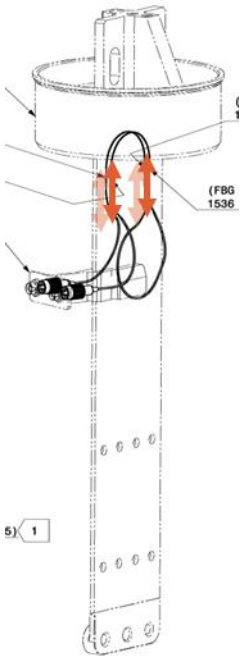




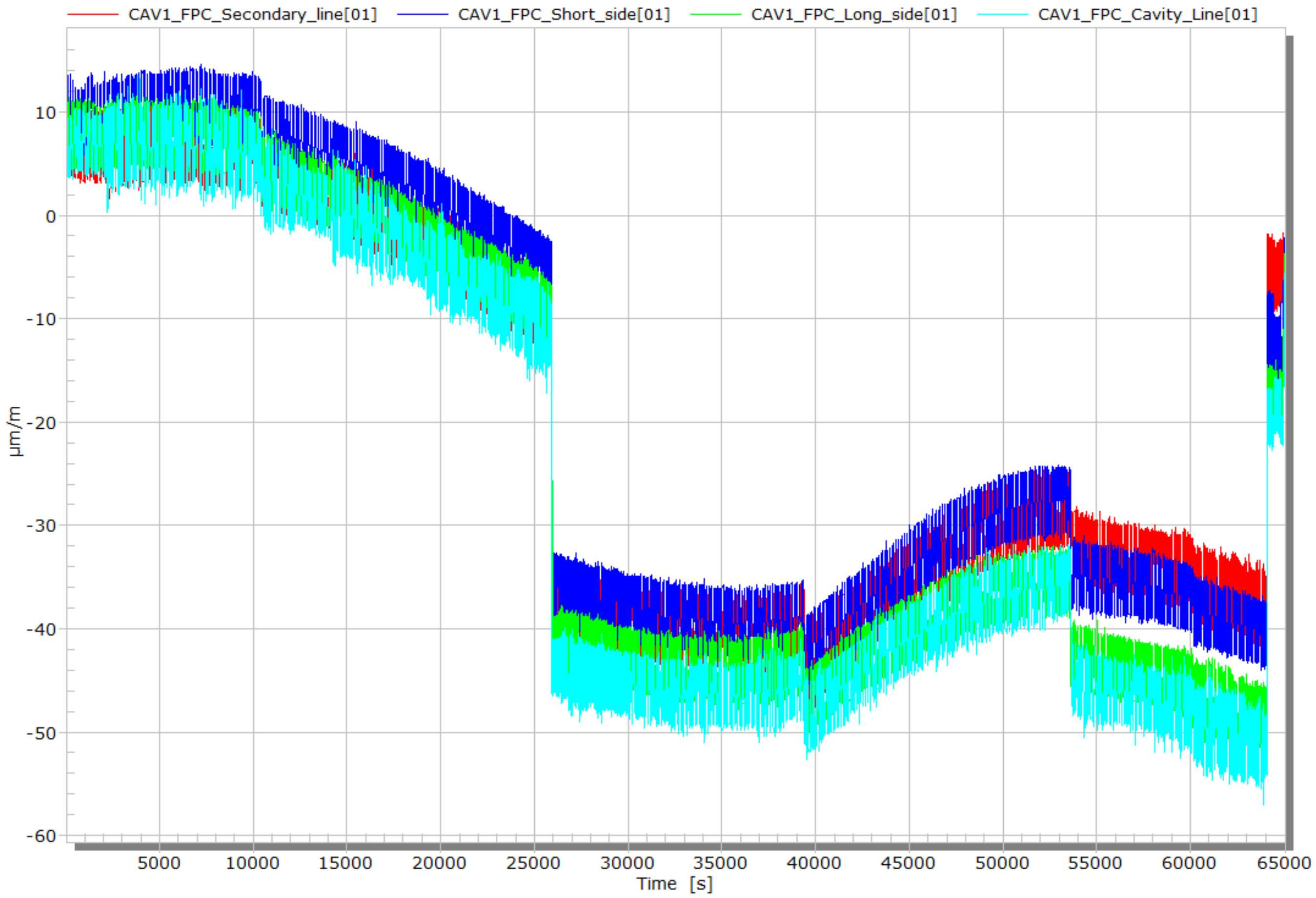
Transport results – Optical measurement system

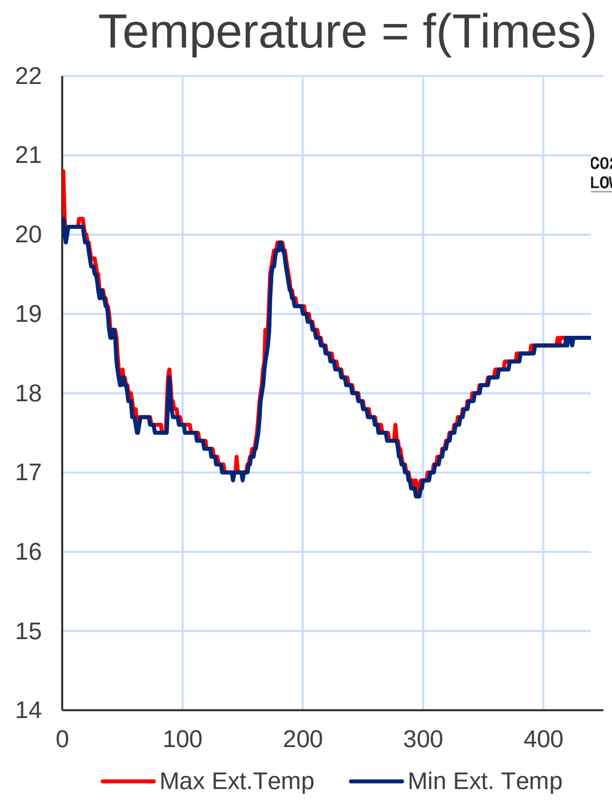


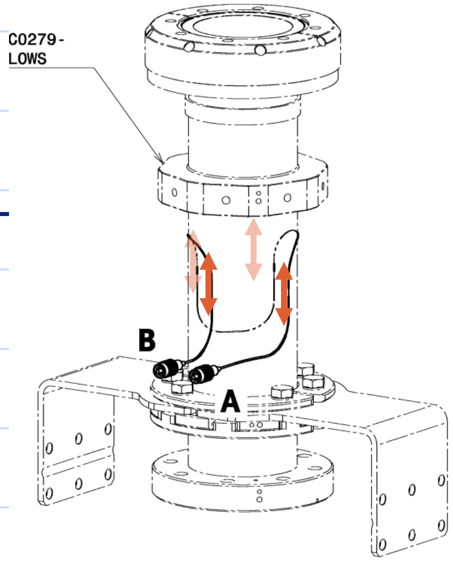
Typical response of the blade instrumentation during transport event



Transport results – Optical measurement system



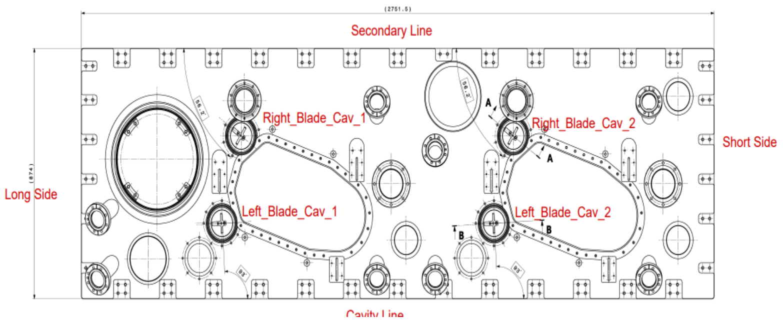


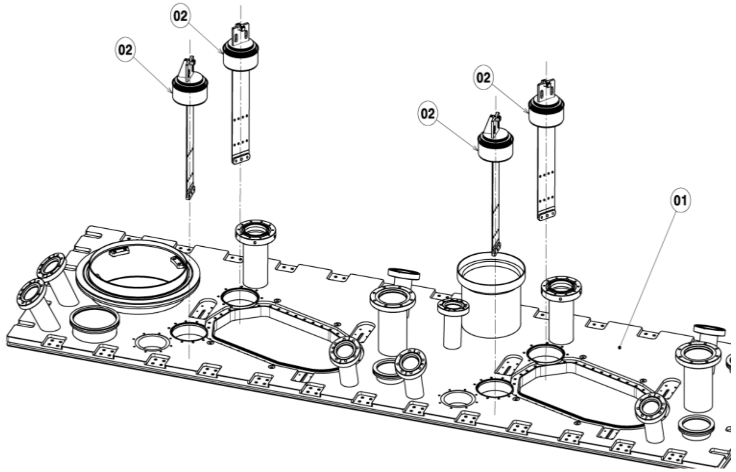


Full transport data

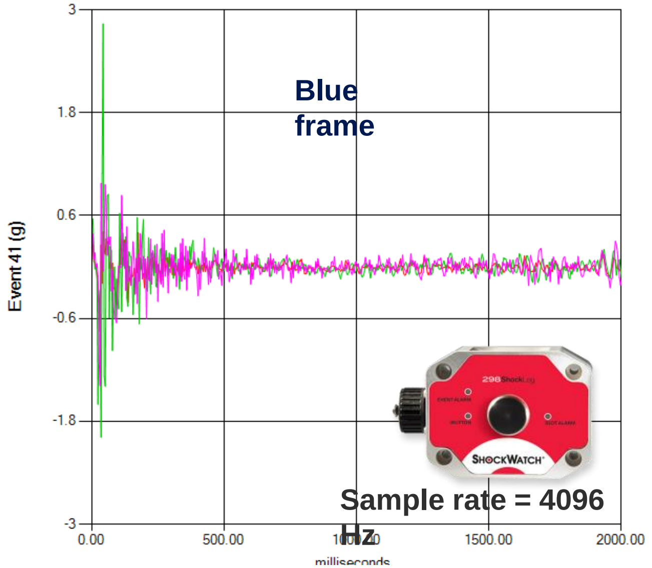
Transport results – Optical measurement system

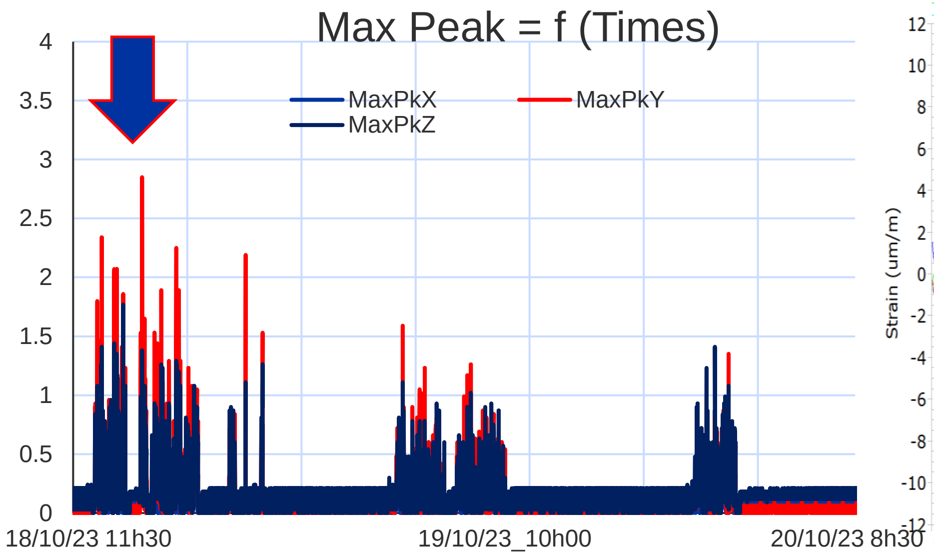
	18th August 2023	17th October 2023	23th October 2023	**variation due to transport**
	Strain (µm/m)	Strain (µm/m)	Strain (µm/m)	**Strain (µm/m)**
CAV1_FPC_Secondary_Line	29.12	-13.4	-23.8	**-10.4**
CAV1_FPC_Short_Side	-29.91	-43.41	-59.47	**-16.06**
CAV1_FPC_Long_Side	17.97	-76.33	-99.1	**-22.77**
CAV1_FPC_Cavity_Line	104.7	-24.16	-46.58	**-22.42**
CAV1_RightBlade_Cavity_Long Side	299.1	281.62	262.4	**-19.22**
CAV1_RightBlade_Secondary_Long Side	22.24	-43.96	-52.49	**-8.53**
CAV1_RightBlade_Secondary_Short Side	-268.3	-418.47	-447.9	**-29.43**
CAV1_RightBlade_Cavity_Short Side	-388.7	-489.43	-519.1	**-29.67**
CAV1_LeftBlade_Secondary_Long Side	90.7	59.36	26.7	**-32.66**
CAV1_LeftBlade_Cavity_Long Side	6.579	-47.39	-41.57	**5.82**
CAV1_LeftBlade_Cavity_Short Side	-147.3	-242.3	-267.74	**-25.44**
CAV1_LeftBlade_Secondary_Short Side	-103.3	-146.14	-161.43	**-15.29**
CAV2_FPC_Secondary_Line	-73.02	-129.23	-141.69	**-12.46**
CAV2_FPC_Short_Side	41.06	-19.99	-29.3	**-9.31**
CAV2_FPC_Long_Side	168.6	64.92	53.54	**-11.38**
CAV2_FPC_Cavity_Line	48.74	-44.96	-58.38	**-13.42**
CAV2_LeftBlade_Secondary_Long Side	-182.9	-139.04	-170.8	**-31.76**
CAV2_LeftBlade_Cavity_Long Side	-34.94	-153.79	-169.67	**-15.88**
CAV2_LeftBlade_Cavity_Short Side	-360.1	-411.13	-387.81	**23.32**
CAV2_LefttBlade_Secondary_Short Side	48.44	-23.51	-42.46	**-18.95**
CAV2_RightBlade_Cavity_Short Side	-44.86	-97.98	-118.8	**-20.82**
CAV2_RightBlade_Secondary_Short Side	-184.1	-321.01	-354.98	**-33.97**
CAV2_RigthBlade_Secondary_Long Side	150.6	98.07	64.25	**-33.82**
CAV2_RightBlade_Cavity_Long Side	26.02	-5.79	-31.13	**-25.34**

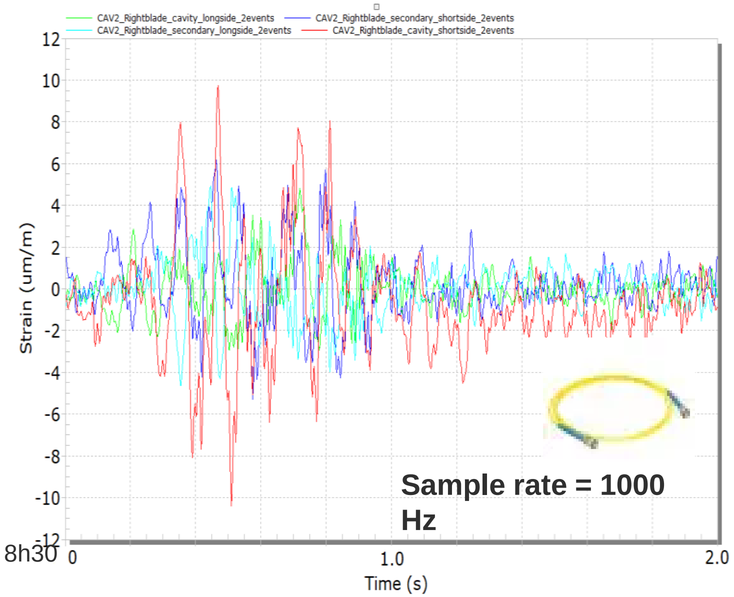


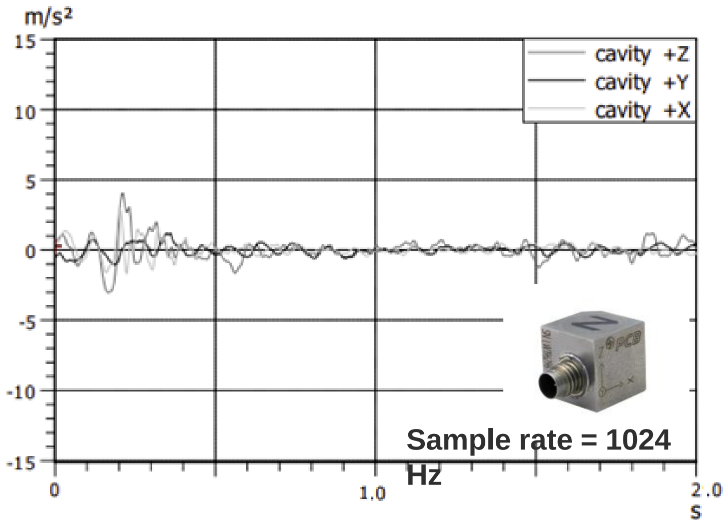


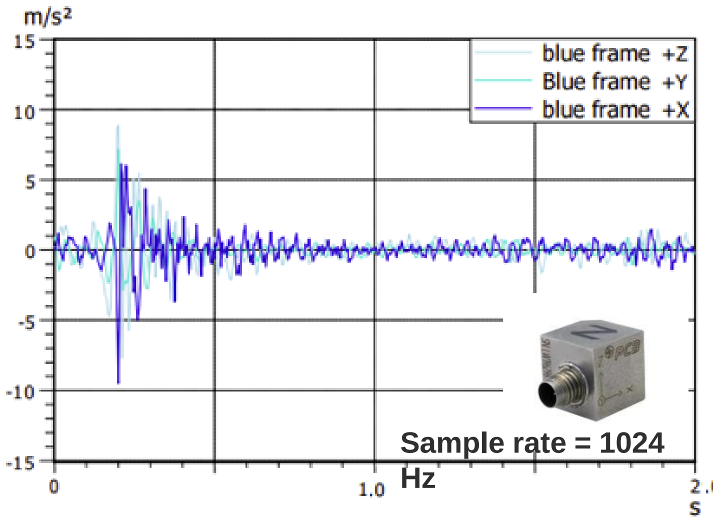
Transport Results – Worst case event

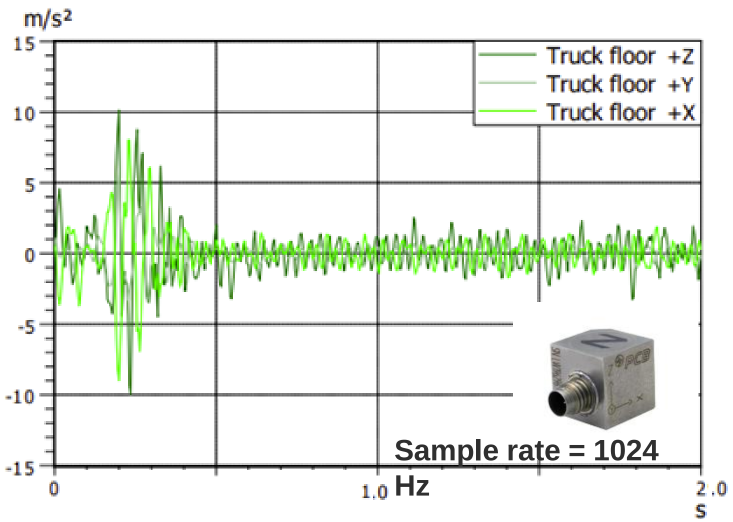




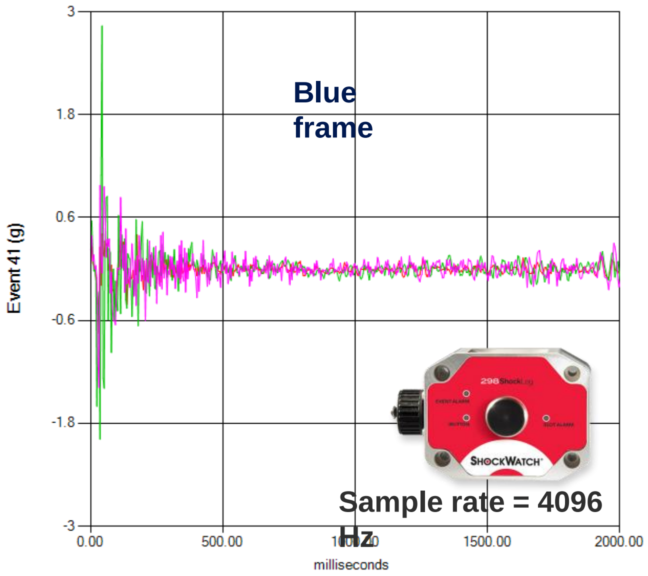


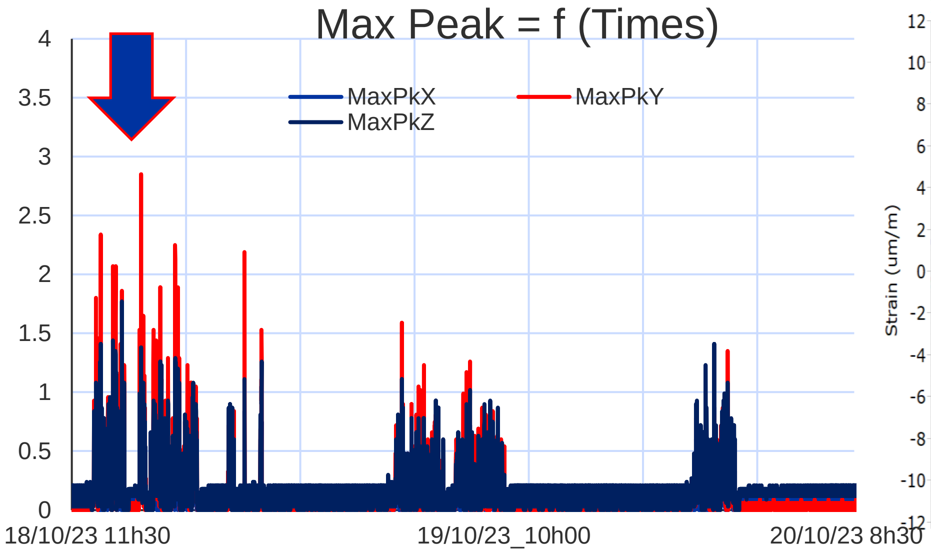


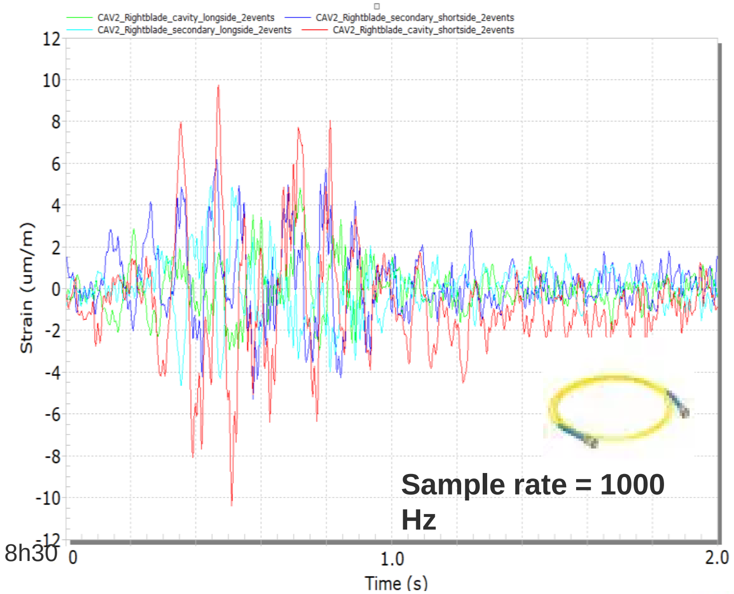


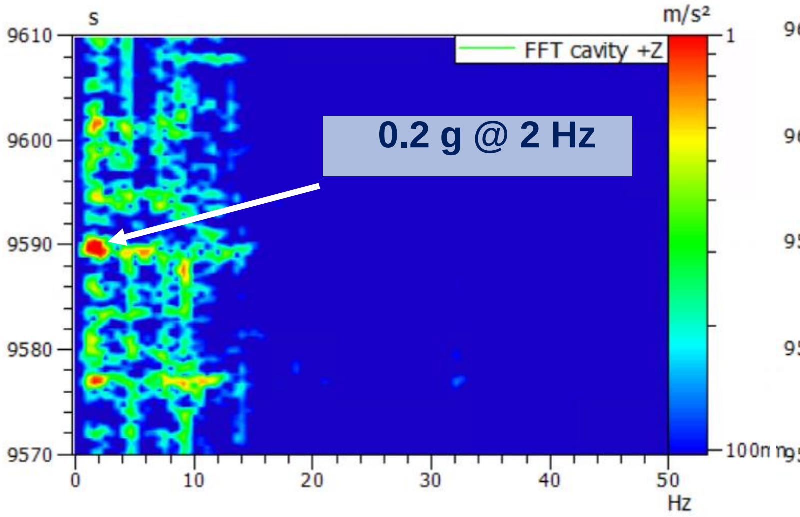


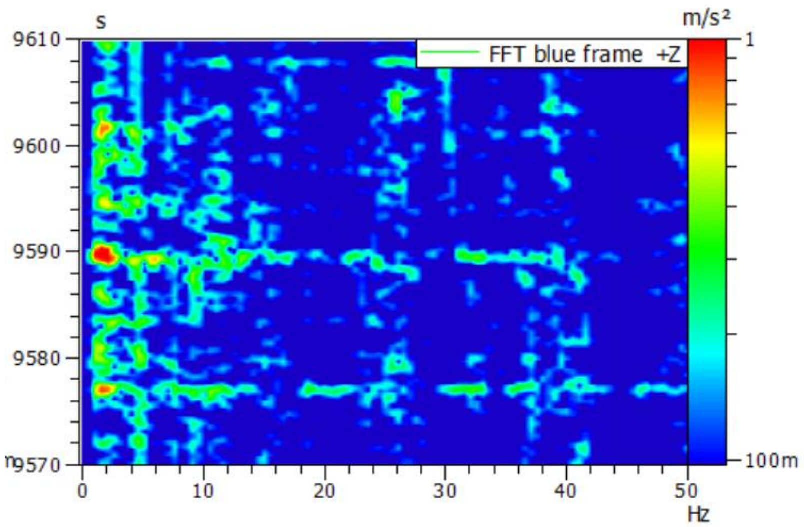
Transport Results – Worst case event

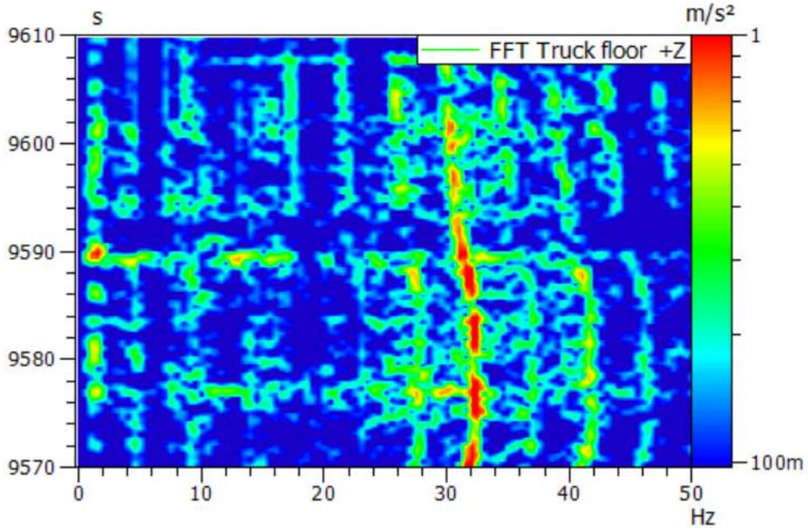




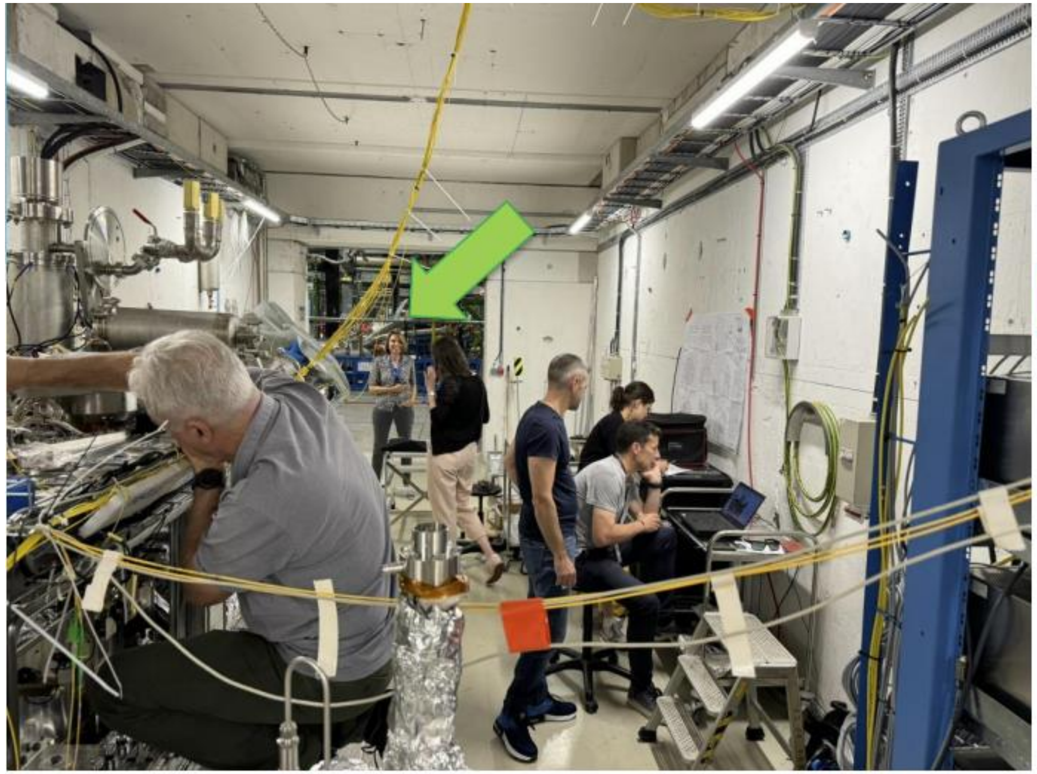


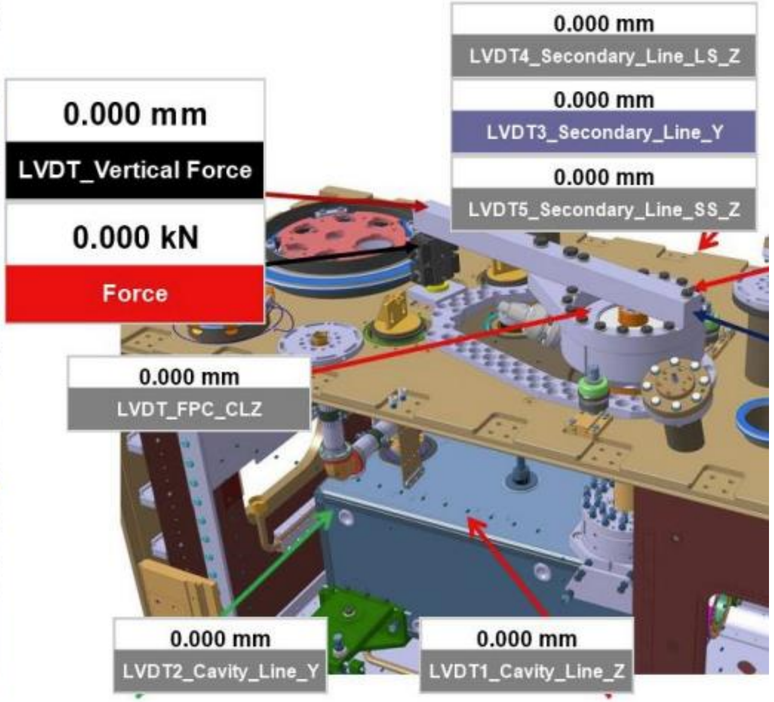




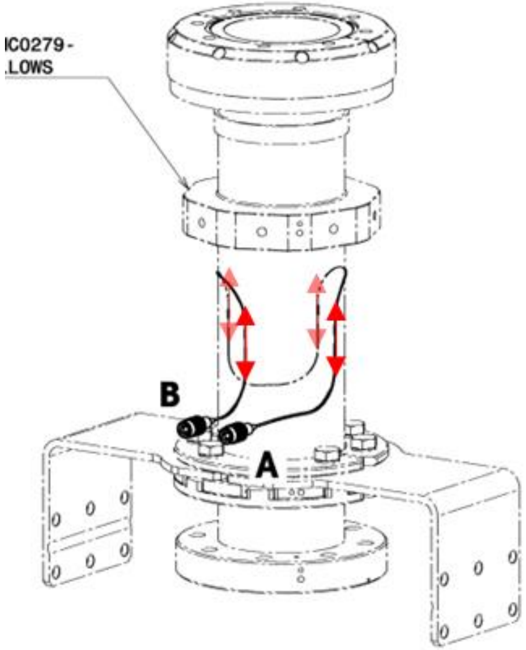


Repair of Cavity #1 FPC (Straightening)



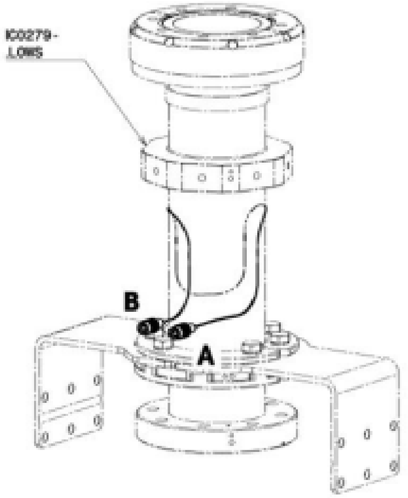


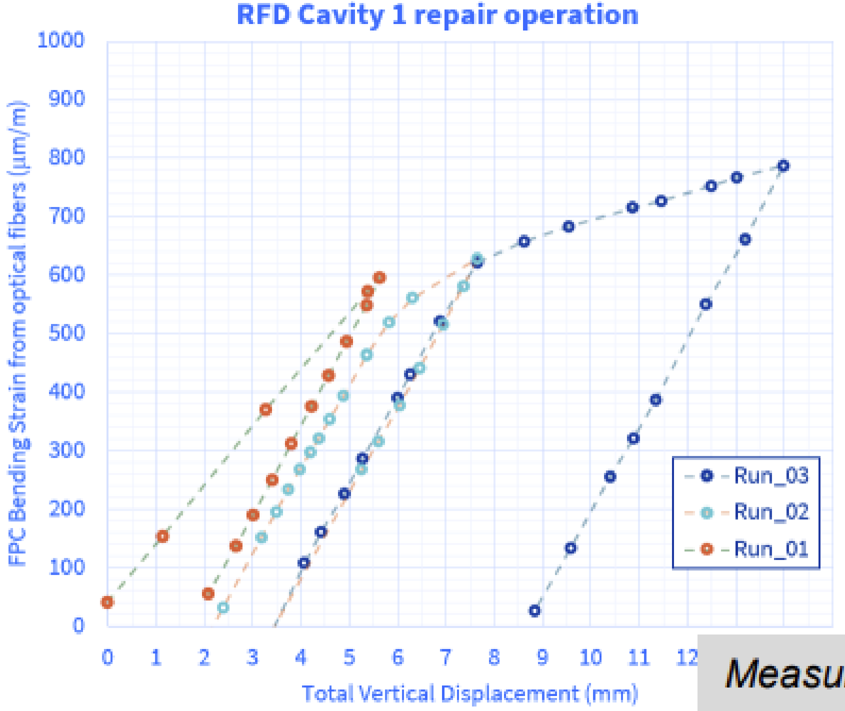
LVDT set up

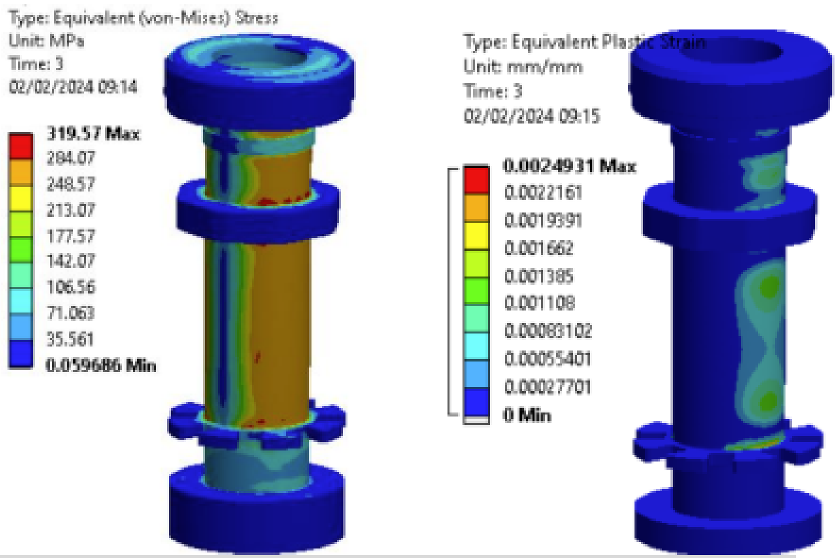


Repair of Cavity #1 FPC (Straightening)

Presence of strain gauges - very useful!







*Measurements done by **Michael Guinchard & David Thuliez***

Crab Cavity instrumentation
What's next ?

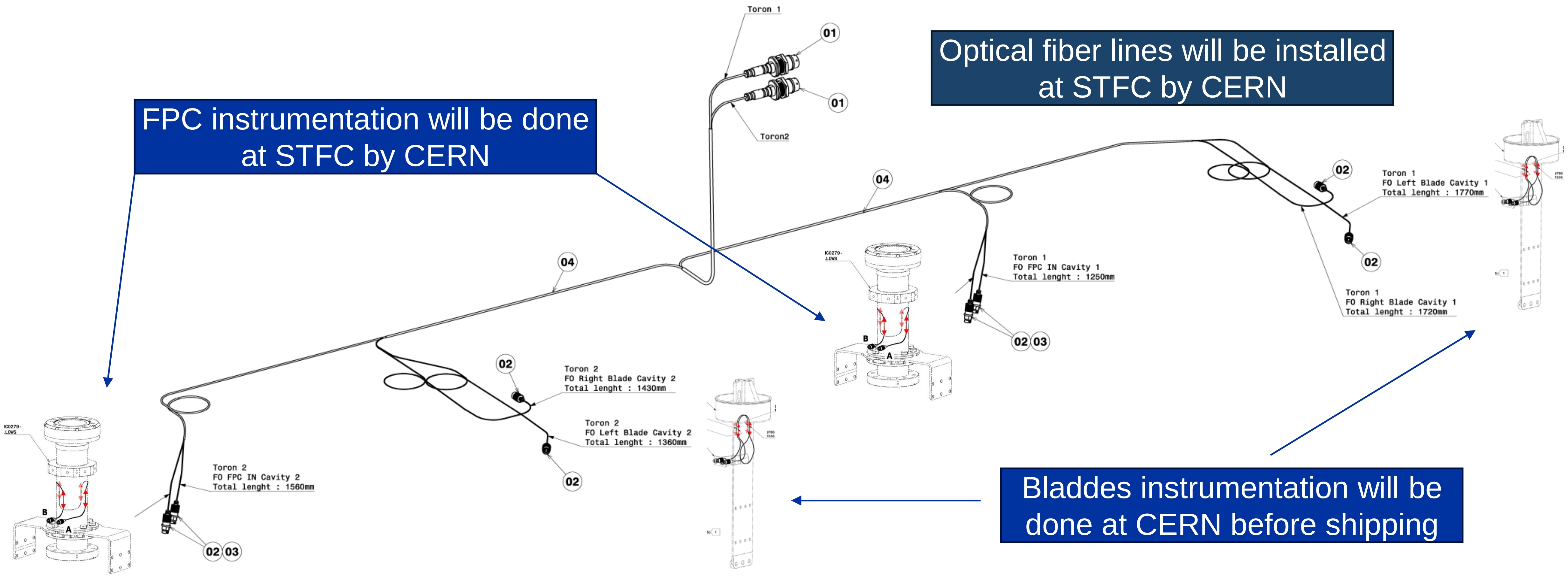
Michael GUINCHARD on behalf of EN-MME-EDM

STFC Visit

Expected instrumentation

FPC instrumentation will be done at STFC by CERN

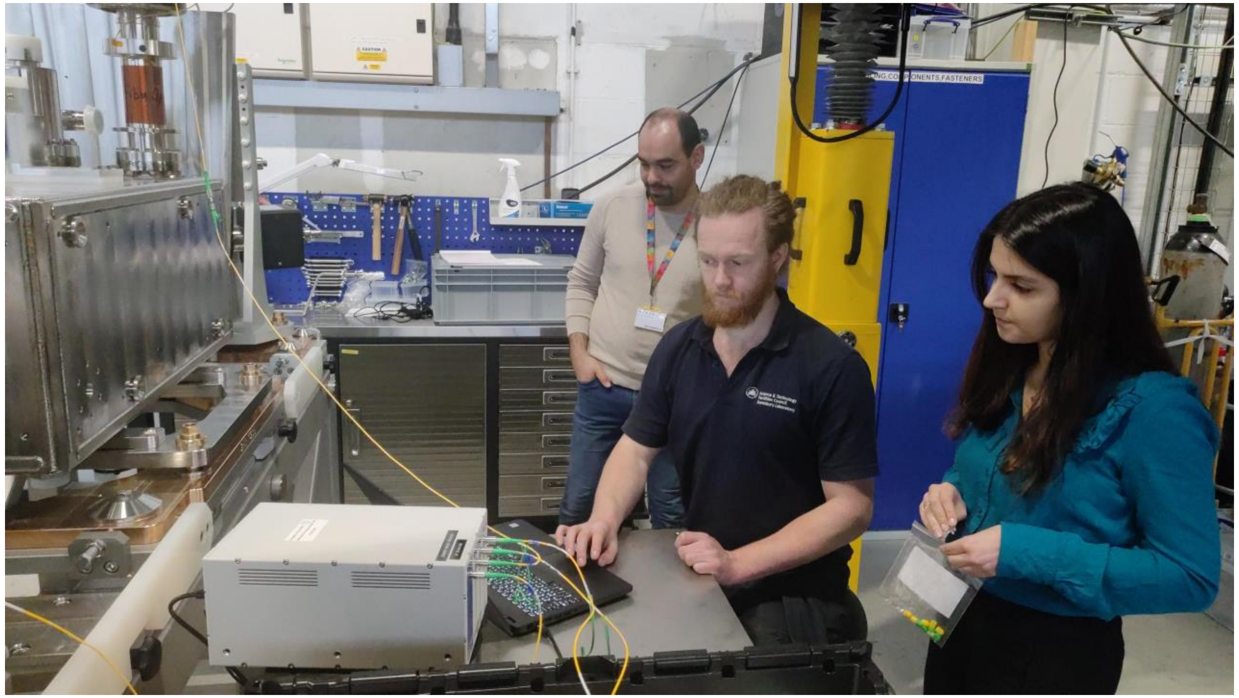
Optical fiber lines will be installed at STFC by CERN



Bladdes instrumentation will be done at CERN before shipping

What do we expect from STFC team ?

- Local experts must be identified and/or trained to support our activities remotely.
- Internal instrumentation based on optical fibers is useful also during assembly operations → Optical instrumentation must be connected most of the time !



Discussions and Lab Visit