Advanced techniques for length detection : Fiber optics

Lecture contents

- **Research reactors**
  - Generalities
  - French material testing reactors

- **Generalities about in-pile instrumentation**
  - Measurement needs
  - Particularities
  - Facing in-pile constraints
  - R&D programs

- **Length detection with fiber optics**
  - Generalities about optical fiber sensors
  - In-pile use of optical fiber sensors

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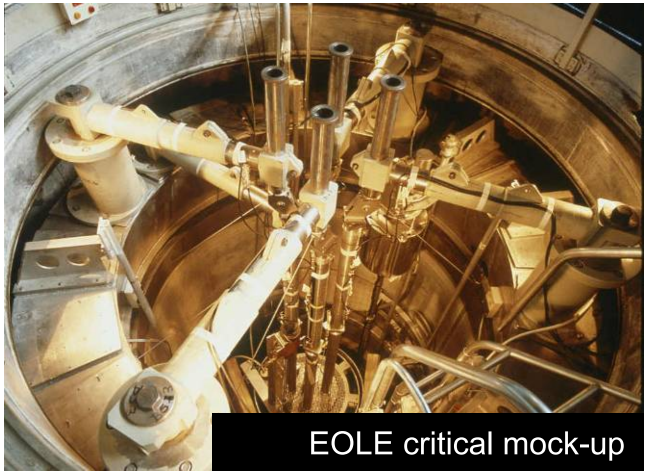
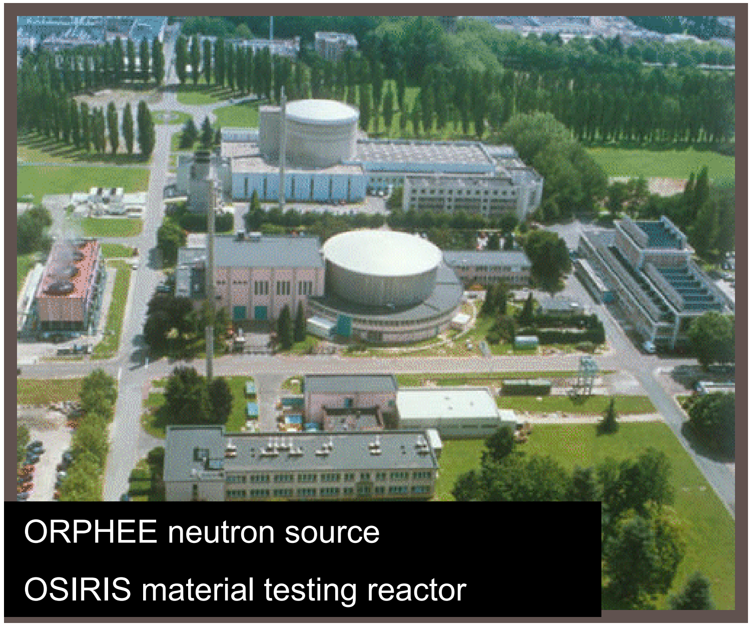
~ 250 research reactors operated in 56 countries (373 in 1975)
2/3 are more than 30 years old

Research reactors in CEA:

- Critical mock-ups (3)
- Prototype reactor (1)
- Teaching reactors (2)
- **Material testing reactors (1 + 1 under conception)**
- Neutron sources (2)
- Safety studies reactors (2)



EOLE critical mock-up



ORPHEE neutron source

OSIRIS material testing reactor

Role of Material Testing Reactors

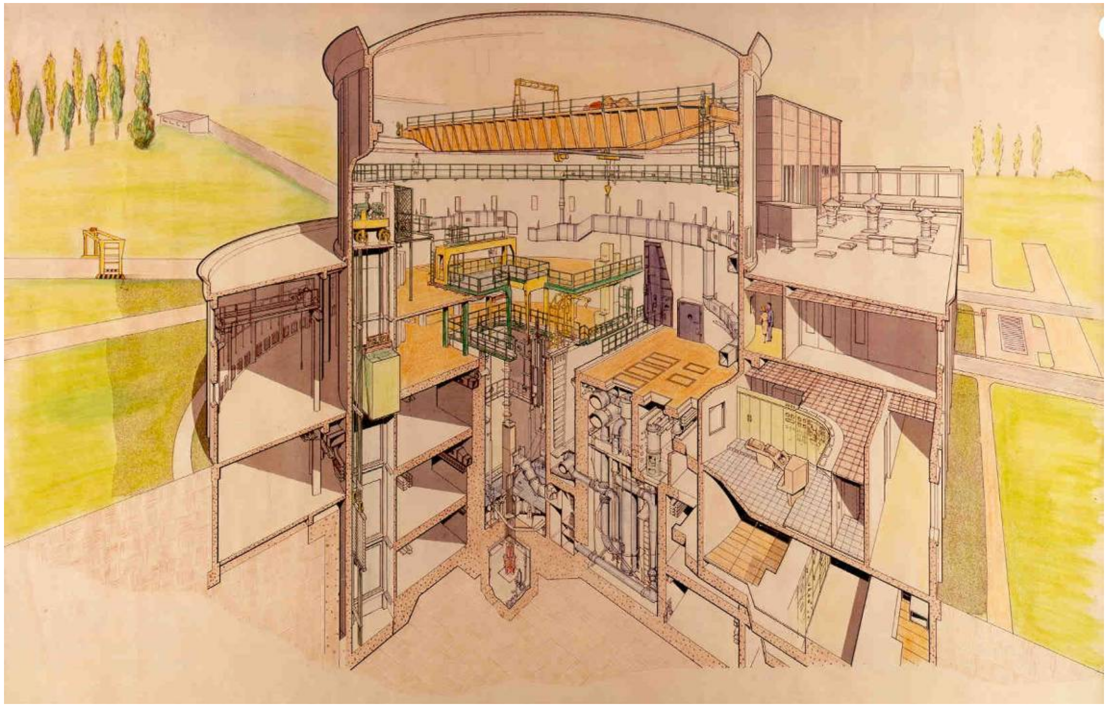
Effective irradiation experiments are required to sustain nuclear energy

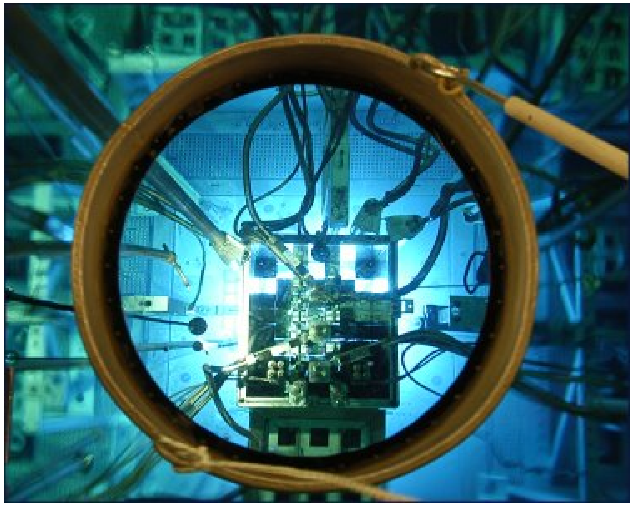
- to **reduce the existing uncertainties** on margins and limits for **safety** and plant **life time** management of nuclear power plants
- **to optimize designs and safety** for improved technologies in power reactors
- **to qualify innovative fuels & materials** for future reactors

Assessment of material and fuel behaviour under radiation :
from "cook and look" irradiations toward highly instrumented experiments

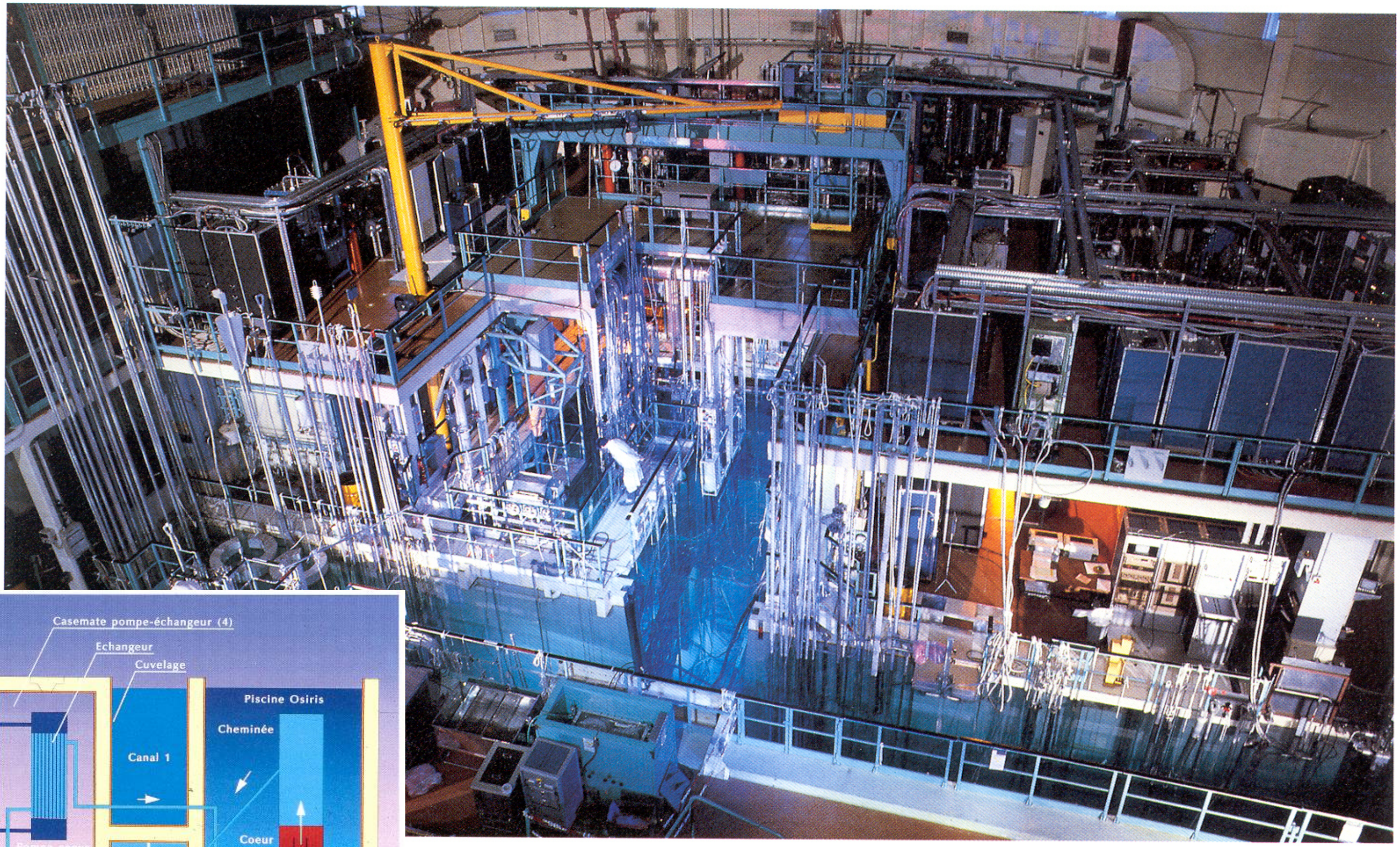
OSIRIS

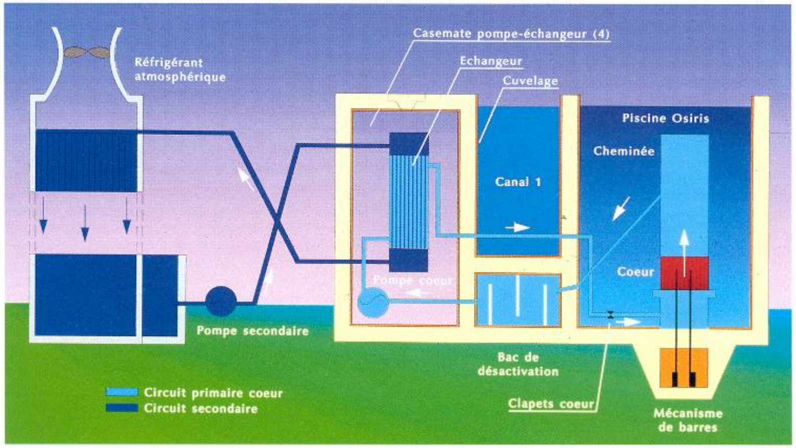
- **Thermal power : 70 MW**
- **Critical achievement : 1966**
- **Fuel : U_3Si_2 (19.75 %)**
- **Neutron flux**
  - **Thermal n. : 3 10^{14} n/cm²/s**
  - **Fast n. (E>0.1 MeV) : 4.5 10^{14} n/cm²/s**



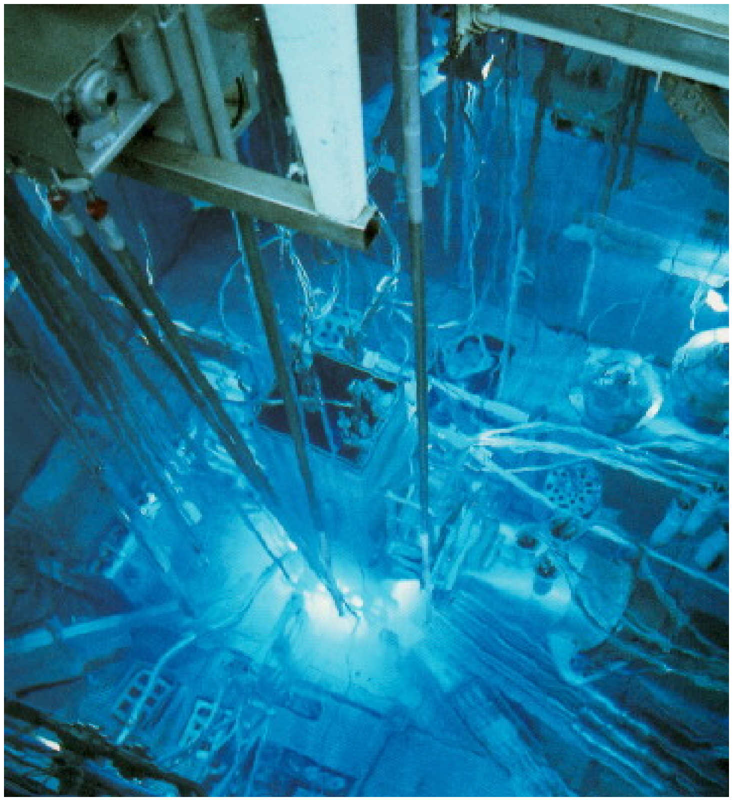


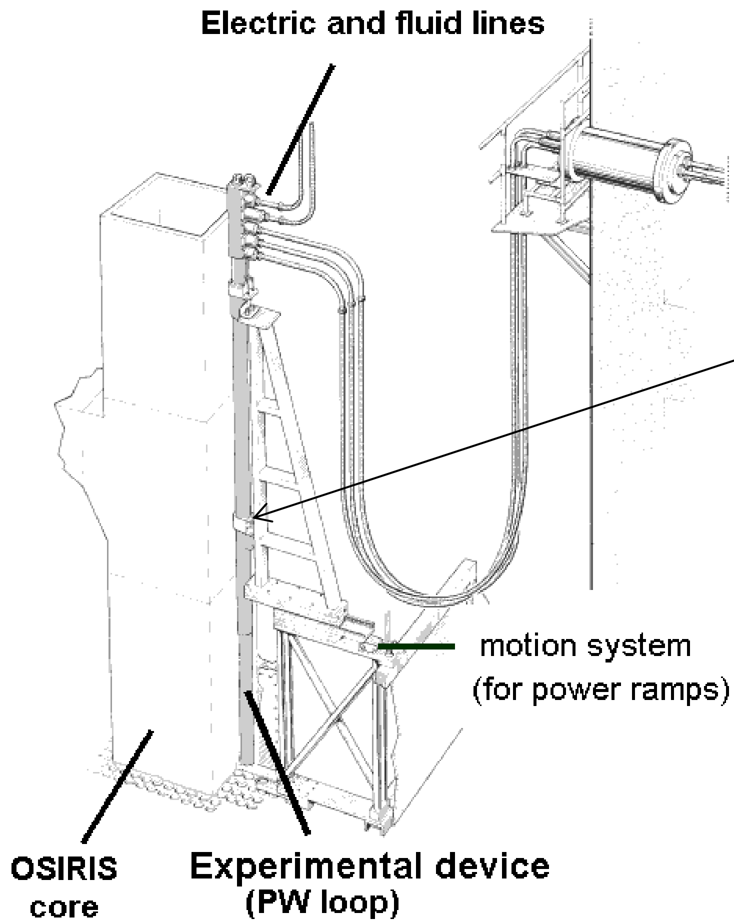
OSIRIS

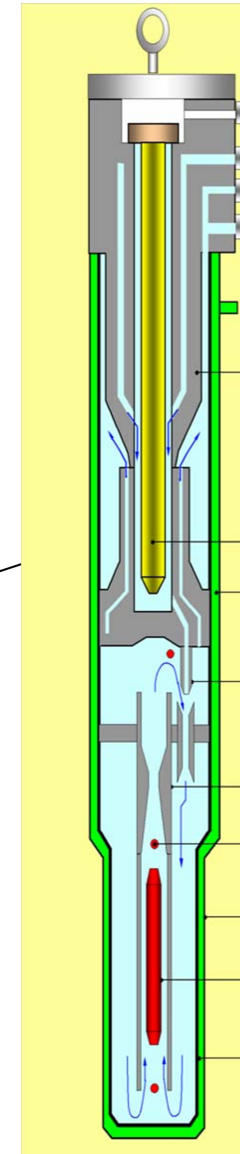



Réfrigérant atmosphérique
Casemate pompe-échangeur (4)
Echangeur
Cuvelage
Piscine Osiris
Cheminée
Canal 1
Coeur
Pompe coeur
Pompe secondaire
Bac de désactivation
Clapets coeur
Mécanisme de barres
Circuit primaire coeur
Circuit secondaire

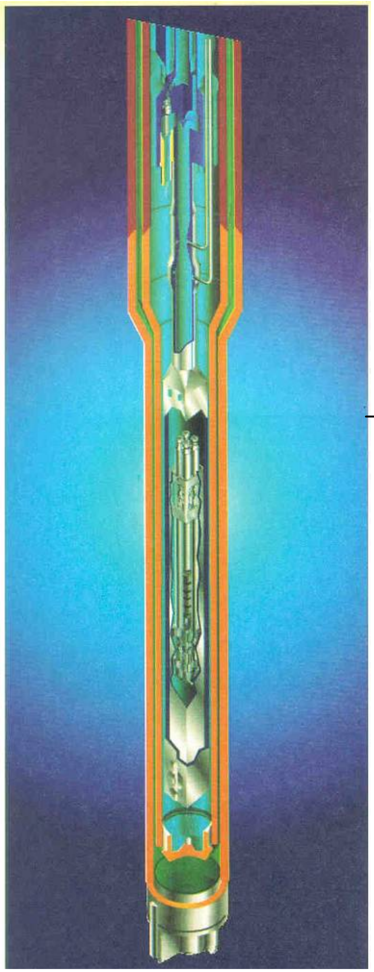
Example of OSIRIS irradiation device:
ISABELLE 1 PWR loop







OSIRIS irradiation programs



Irradiation of materials :

- PWR vessel steels
- PWR fuel rods
- PWR internals
- Zr/Nb alloys (CANDU)

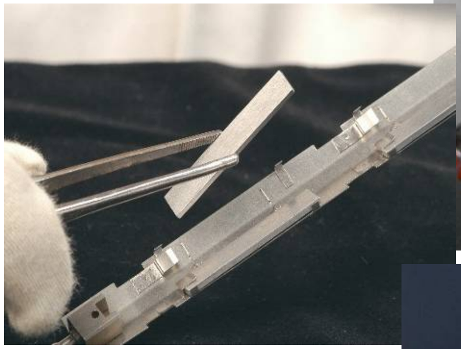
\+ *refractory (Fusion)*

Irradiation of fuels :

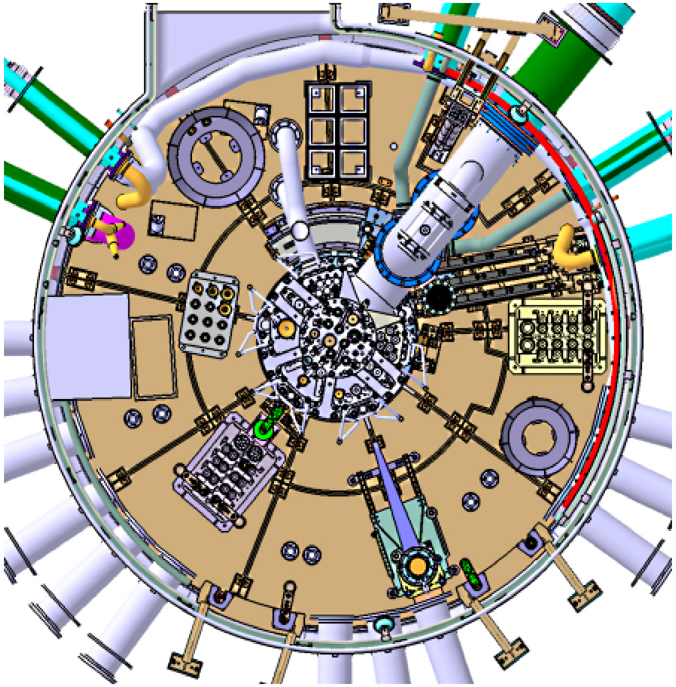
- Power ramps
- Increasing burn-up
- Advanced fuels
- Fuel for research reactors : UMo

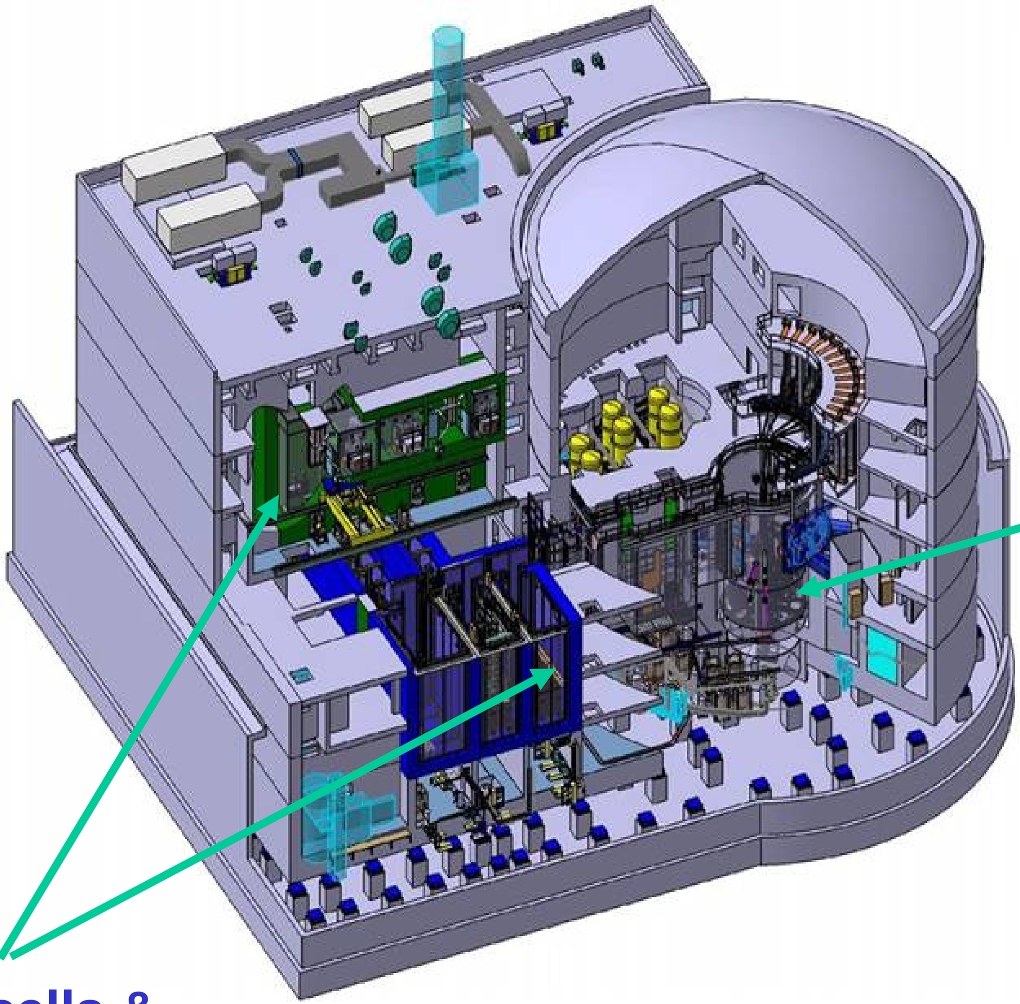
+ Qualification of instrumentation :

SPND, fission chambers, optical fibres, innovative sensors…



JHR, a new Material Testing Reactor under construction in Cadarache





JHR power = 100MW
Start of operation 2014

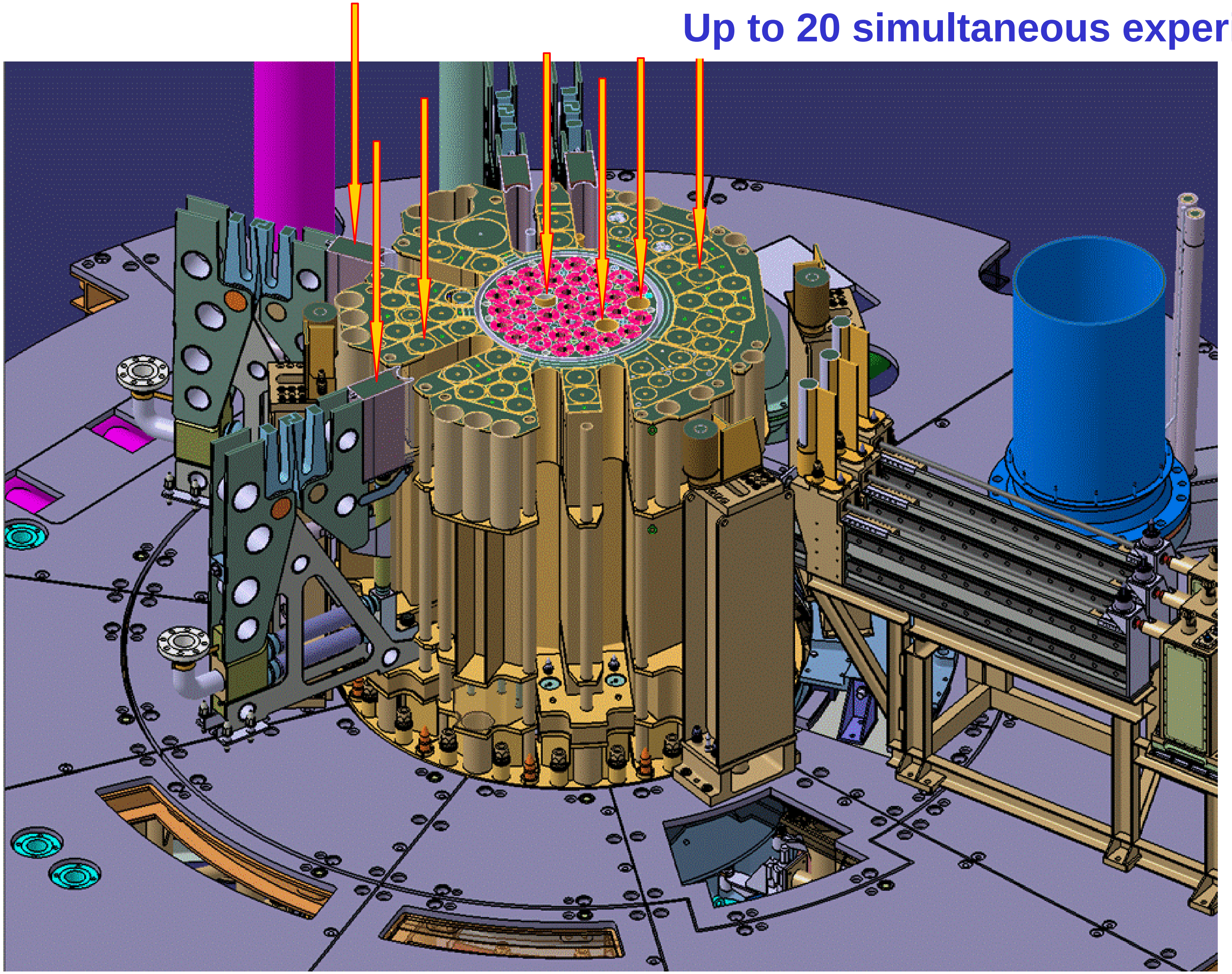
Reactor pool

Hot cells & storage pools

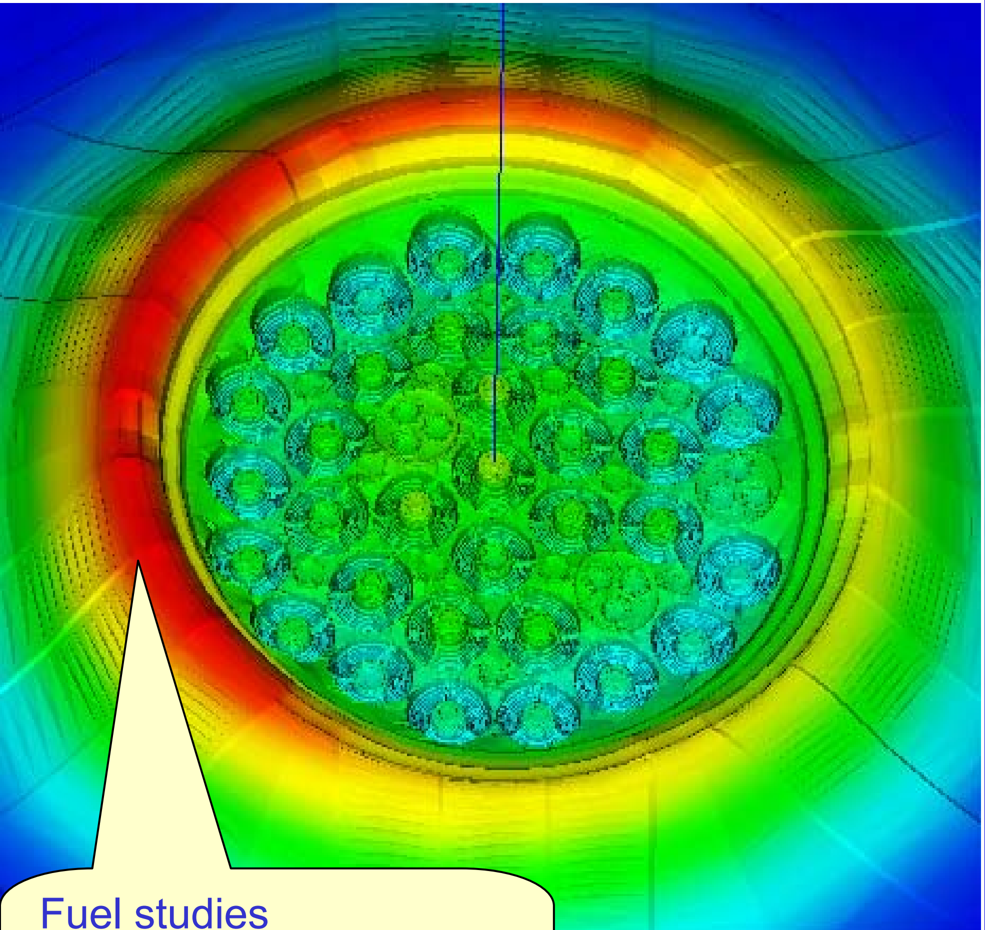
JHR characteristics
51 m x 47 m + Φ 37 m

French material testing reactors : Jules Horowitz Reactor

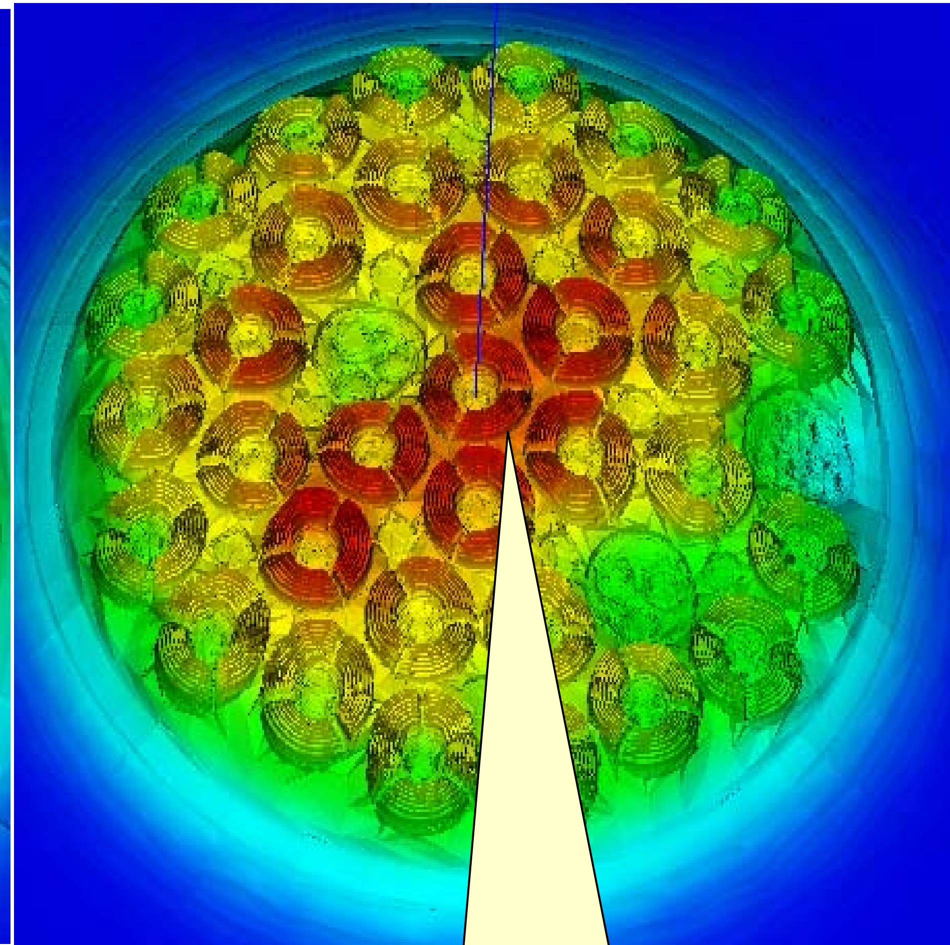
Up to 20 simultaneous experiments



Thermal neutron Flux



Fast neutron Flux



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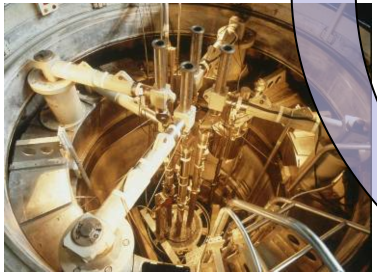
In-pile measurements is required to design and use nuclear systems from basic studies to operation

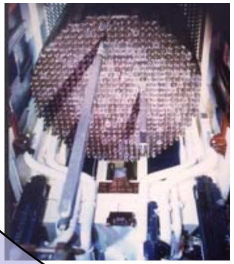
Basic science

Measurements of fundamental **nuclear data**

Online monitoring

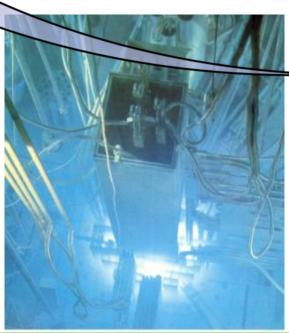
Measurements in **power reactors**





Design studies

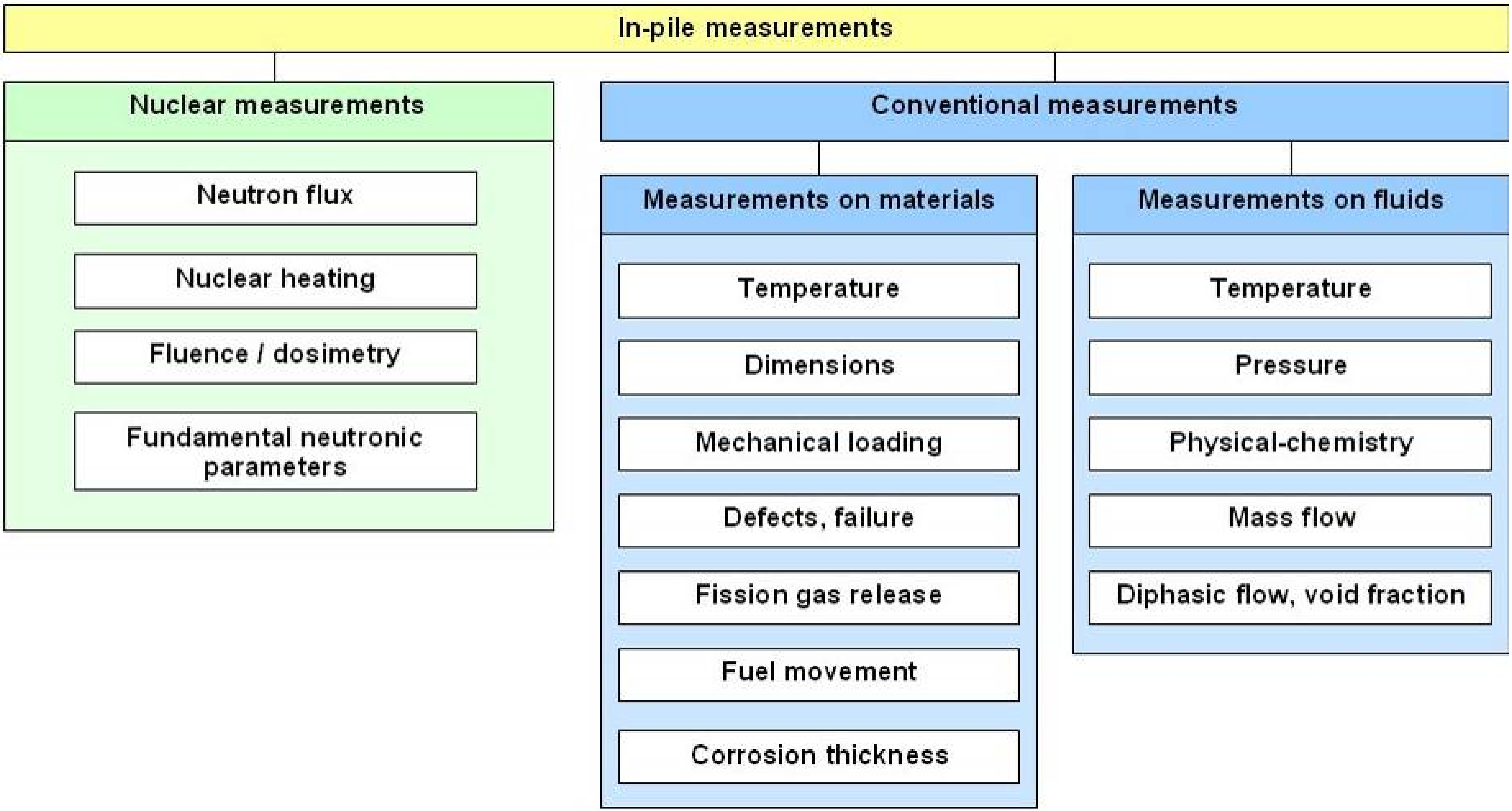
Measurements in **analytic experiments**
→ Prediction / calculation



Verifications

Measurements in **integral experiments**
→ Verification of predictions

Main in-pile measurements needs



Particularities of in-pile instrumentation

In-pile instrumentation has to be :

- **Reliable** (impossible or difficult maintenance on irradiated objects)
- **Accurate** (to meet scientific requirements; ex: µm dimensional measurements)
- **Miniature** (narrow location: few mm available)
- **High temperature resistant** (> 300°C, up to 1600°C)
- **Corrosion resistant** (operation in pressurized water, high temperature gas, liquid metals…)
- **Neutron / γ "resistant"** (dose > 1GGy/d and > 10dpa/y in Material Testing Reactors)

But finally, in-pile instrumentation is above all :

- Extremely **conservative** !

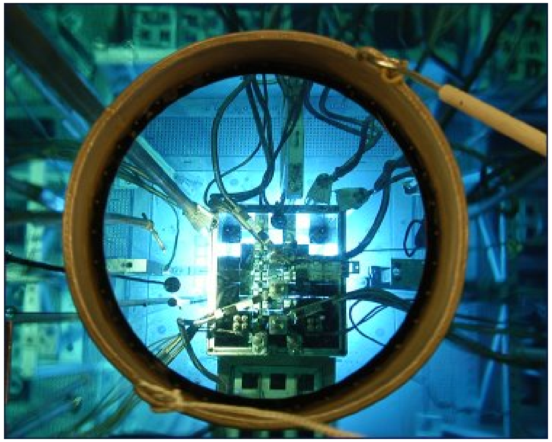
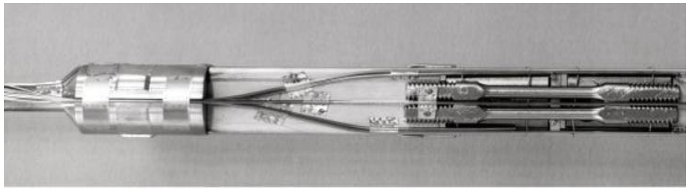
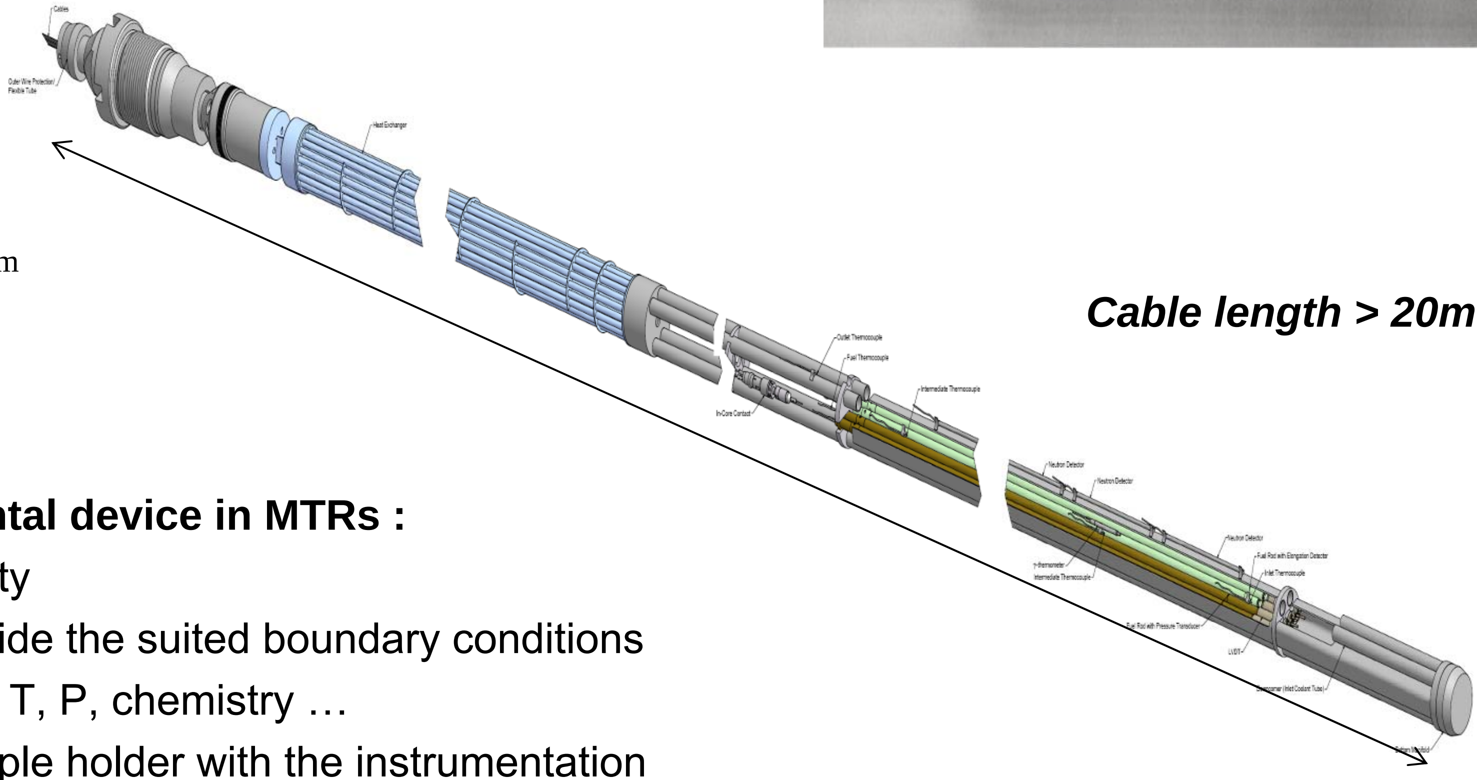


Illustration of in-pile constraints

OSIRIS sample holder
Length: 4 m
Diameter: 24 mm



JHR device
Length: 4.5 m
Diameter: 62 mm



Cable length > 20m

Experimental device in MTRs :

- Safety
- Provide the suited boundary conditions
  - T, P, chemistry …
- Sample holder with the instrumentation
- Connections with an experimental bunker

Main effects of nuclear radiations on sensors

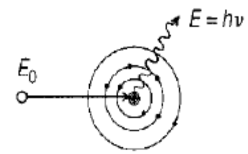
→ **transmutations** : composition changes

→ **damages :**

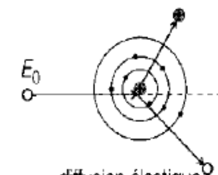
- alteration of electric insulators
- wires breaking
- change in mechanical properties

→ **noise current** (Compton and photoelectric effects)

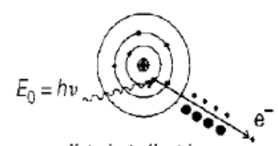
→ **heating**



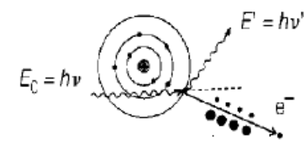
capture radiative
($E_0 < 0{,}8$ MeV)



diffusion élastique
avec déplacement atomique
($E_0 > 0{,}8$ MeV)



effet photoélectrique
(1 eV < E_0 < 5 MeV)

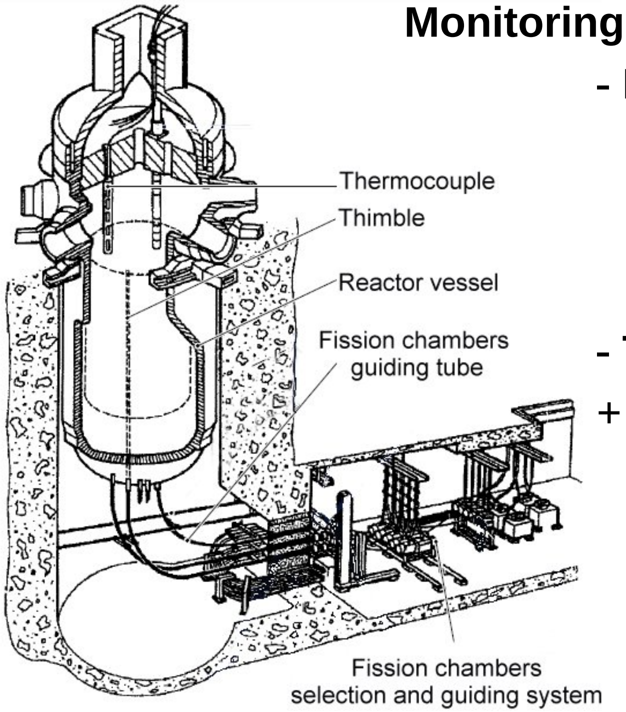


diffusion Compton
(100 keV < E_C < 5 MeV)

→ Precautions :

- **choice of materials**
  - form (metals, oxides, ceramics…)
  - elements → nuclear properties
- **remove sensor from radiation areas when possible**
- **in-situ calibration**
- **comparative measurement methods…**

Power reactors



Monitoring and protection mainly rely on :

- **Neutron flux measurements (in-core or ex-core) :**
  - Fission Chambers (^{235}U deposit)
  - Boron-lined ionization chambers
  - Self-powered neutron detectors (Rh / V / Co)
  - Aeroball Siemens system; γ-thermometers...
- **Temperature measurements** : MIMS type K thermocouples

\+ *fluence dosimetry, void factor, etc.*

Generation IV

Future requirements :

- *Fast neutron flux*
- *High temperatures*
- *Detection in liquid metals*
- *etc.*

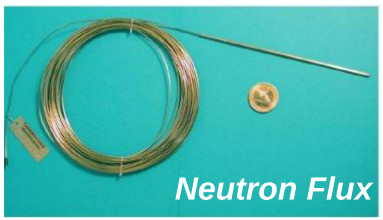
Generation II and III :

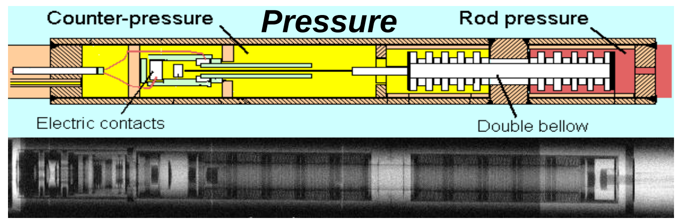
Evolutions but no revolution in short/mid terms…

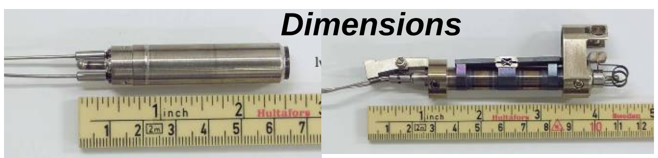
Research reactors

Research reactors push innovation for in-pile measurements to :

- follow scientific experimental requirements
- monitor safety criteria (reduction of margins)
- improve core comprehension







Better performance
New requirements

→ ***Improvements***
→ ***Innovations***

Instrumentation : an open activity suited for collaboration

- Multidisciplinary
- To cross-fertilise technical cultures and experiences
- Limited property issues
- Training

Industrial partnerships

CEA developments

Involved competences & labs

- Reactor and Nuclear Services
- Reactors Studies
- Physical Chemistry
- Systems and Structures Modeling
- Sensor and Signal Processing

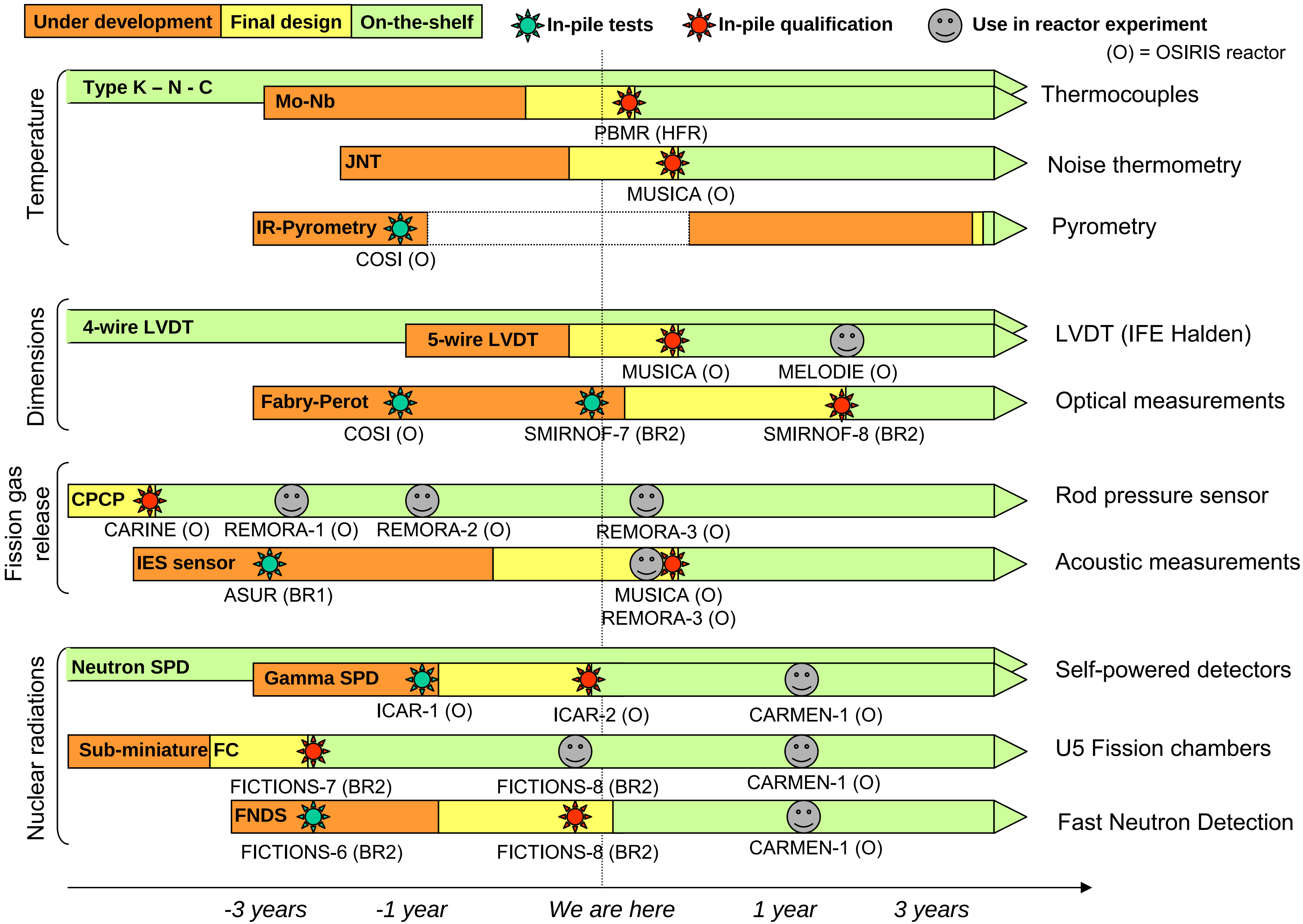
Structural collaborations

SCK•CEN cea Joint Instrumentation Laboratory

FILIERE INSTRUMENTATION UNIVERSITÉ DE PROVENCE

Scientific partnerships

Status of the on-going developments in the framework of the INSNU Project (CEA)



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Dimensions measurements

Objectives :

Measure dimensional changes of materials and fuels under irradiation (µm accuracy – mm changes):

- Diameter and profiles
- Elongation of materiel samples or fuel rod cladding

State-of-the-art :

- Magnetic sensors: **LVDT and Diameter Gauges**

Developments :

- optical dimensional measurements

Optical sensor : **A sensor that measures a physical quantity based on its modulation on the *intensity*, *spectrum*, *phase*, or *polarization* of light traveling through an optical fiber**

Interrogation sensing unit

Sensing Head

Resistance meter $\varepsilon \propto \frac{\Delta R}{R}$ — Wire — Strain Gage $R = \frac{\rho l}{S}$

Phasemeter $\varepsilon \propto \frac{\Delta \phi}{\phi}$

Wavemeter $\varepsilon \propto \frac{\Delta \lambda}{\lambda}$

Fibre

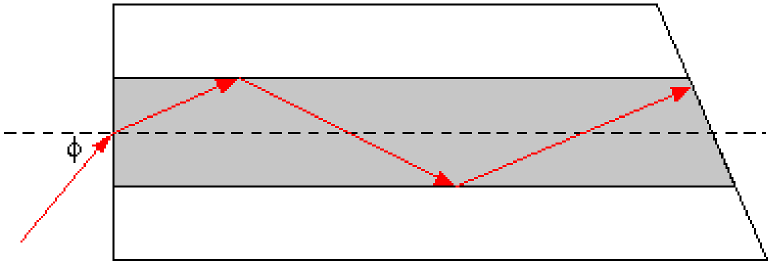
WLI $\phi = \frac{2\pi}{\lambda} nL$

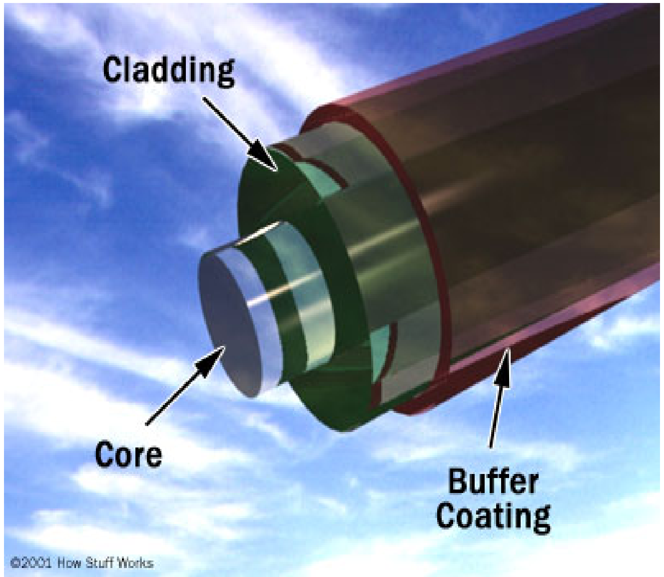
FBG $\lambda = 2n\Lambda$

Fiber optics

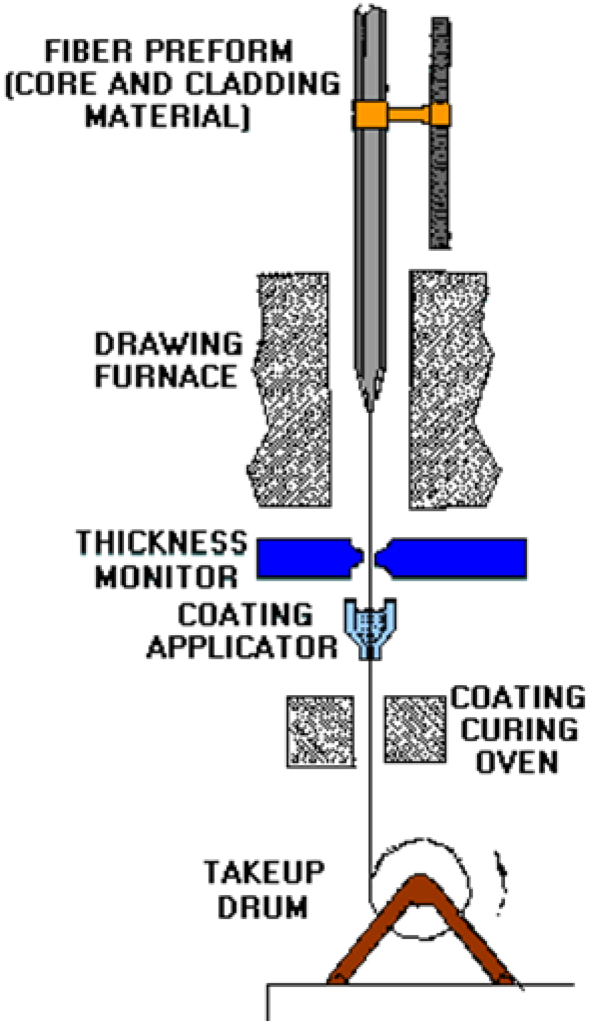
Cylindrical waveguide made of glass

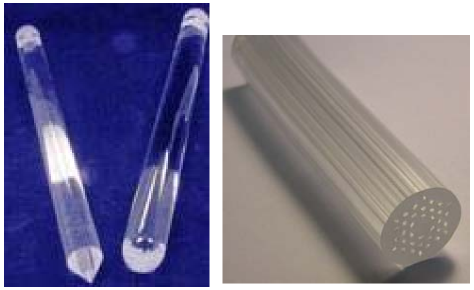
- **Core** – thin glass center of the fiber where light travels.
- **Cladding** – outer optical material surrounding the core
- **Buffer Coating** – protects the fiber.





Drawing process



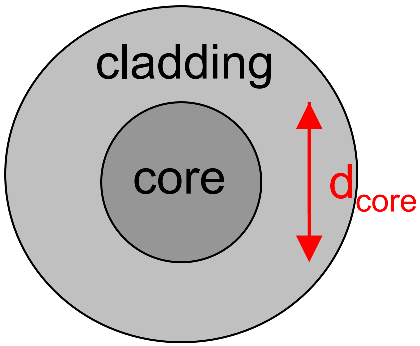


Fiber preforms

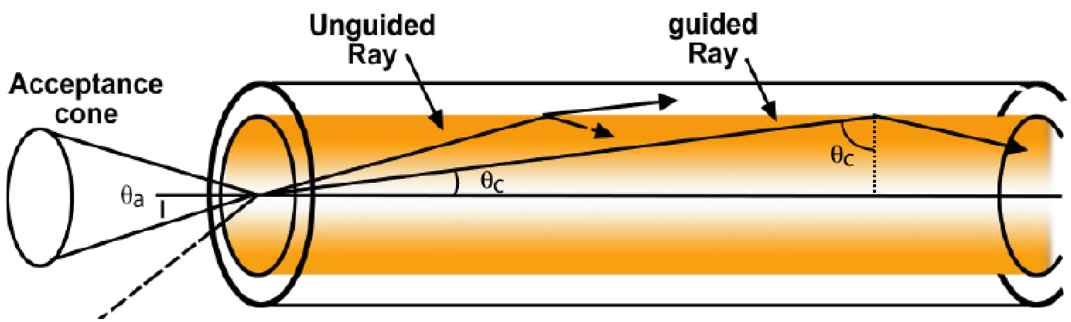
Drawing tower

Fiber spool

Fiber optics



Step-index fiber



$$NA = \sqrt{n_{core}^2 - n_{clad}^2} = \sin \theta_a$$

- $\Delta n = n_{core} - n_{clad} \ll 1$, typical $\Delta n = 0.001 \sim 0.02$
- Common dopants for SiO_2 fiber : Ge, B, Ti

Optical fiber: a cylindrical waveguide made of glass, with very low index contrast and large core size

Types of optical fibers

Optical fibers come in two types:

- **Single-mode fibers** – used to transmit one signal per fiber (used in telephone and cable TV). They have small cores (~ 10 microns in diameter) and transmit infra-red light from laser.
- **Multi-mode fibers** – used to transmit many signals per fiber (used in computer networks). They have larger cores(~ 100 microns in diameter) and transmit infra-red light from LED.

Cut-off Wavelength :

$\lambda \geq \lambda_c$: monomode

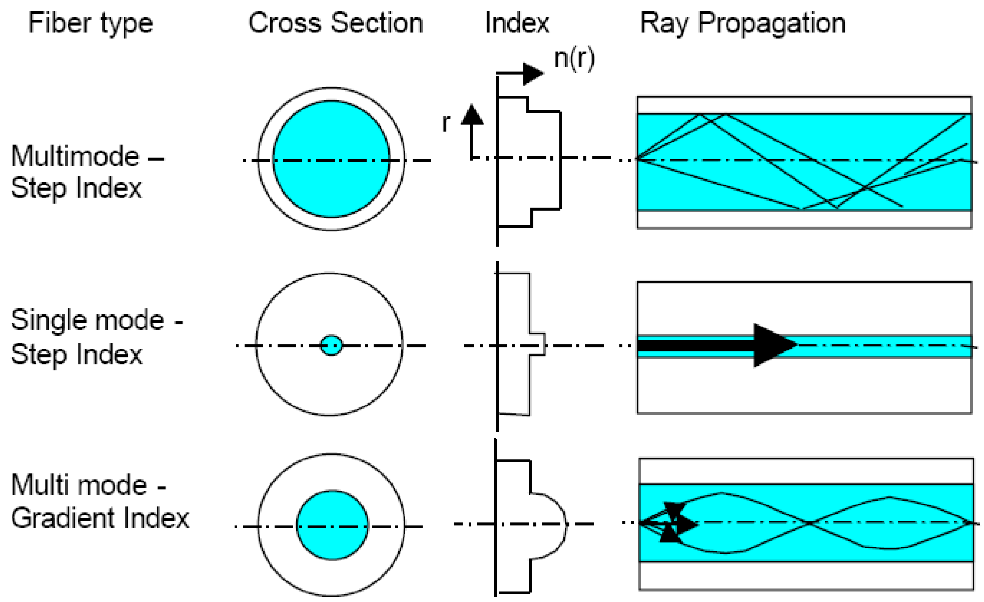
$\lambda < \lambda c$: multi-mode

$$\lambda_c = \frac{2\pi a}{2.405} \times NA$$

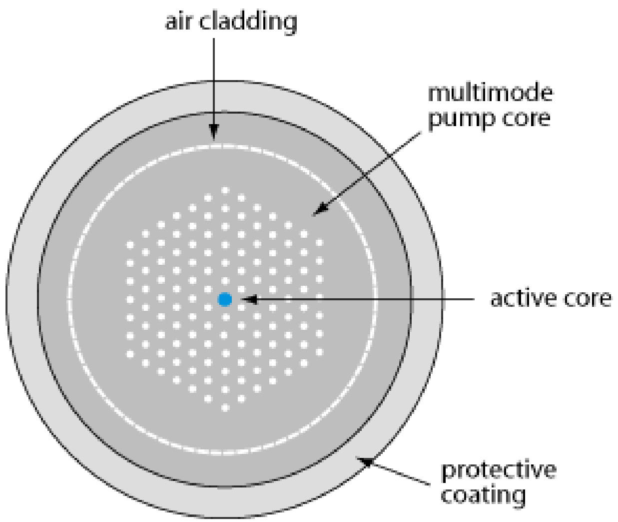
a : core radius

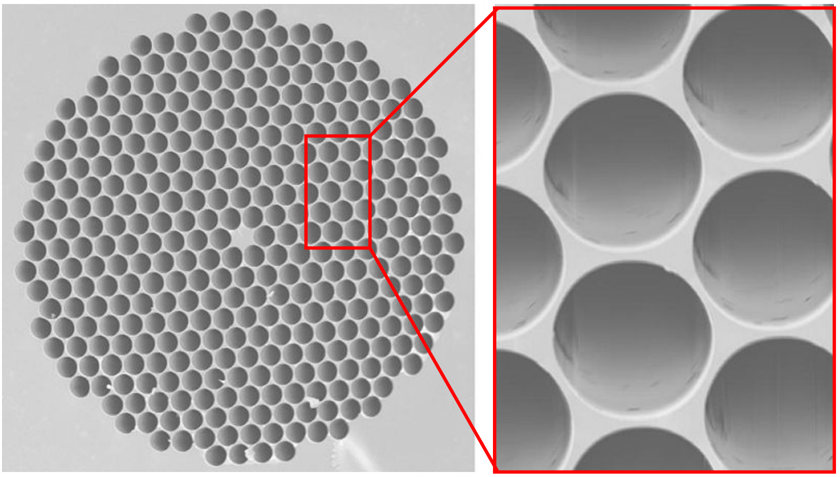
n_c : core optical index

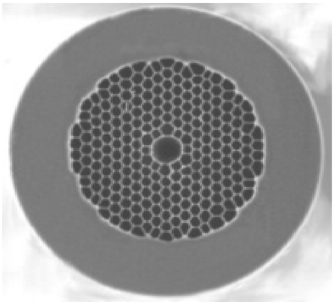
n_g : cladding optical index



Photonic crystal fibers (PCF)
Micro-structured optical fibers (MOF)







- Light is mainly conducted in holes, not in silica
- Single mode over a wide wavelength range

Optical emitters

Definition: a device that converts electrical signal into optical signal

- **Lasers**
  - Fabry-Perot Lasers (FP)
  - Distributed Feedback Lasers (DFB)
  - Vertical Cavity Surface Emitting Lasers (VCSEL)
  - ASE fiber laser

- **Light Emitting Diodes (LED)**
  - Surface-Emitting LED (SLED)
  - Edge-emitting LED (EELED)

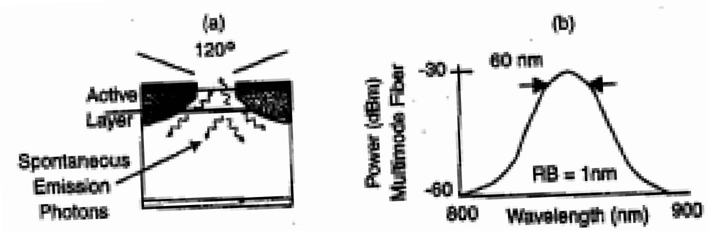
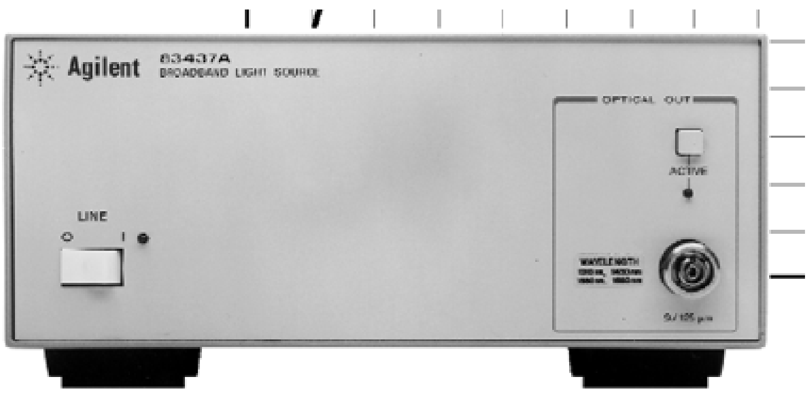


Figure 1.22 (a) Cross-section of a surface-emitting LED (SLED). (b) Power versus wavelength for the SLED as coupled into a 50/125 graded-index multimode fiber. The optical spectrum analyzer bandwidth is 1 nm.



Optical receivers

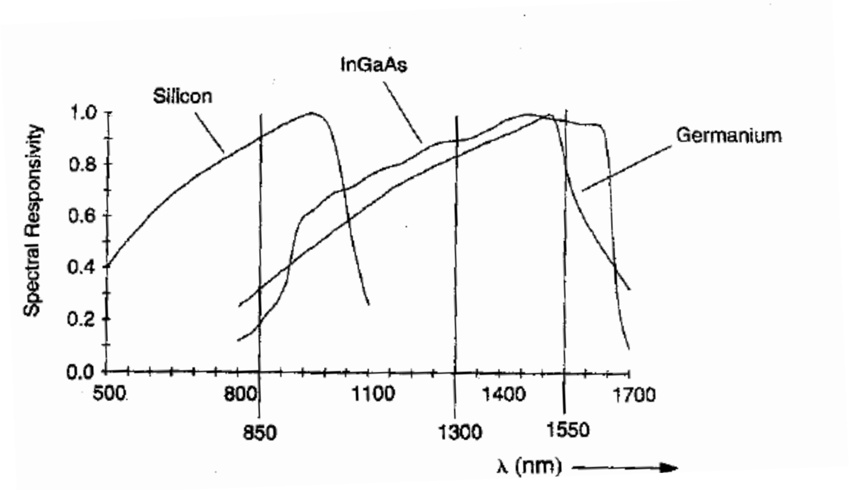
Definition: convert optical signal into electrical signal

Types:

– p-i-n photodetector: photon-electron converter
– Avalanche photodetector (APD): more sensitive for high speed systems

Photodetector parameters:

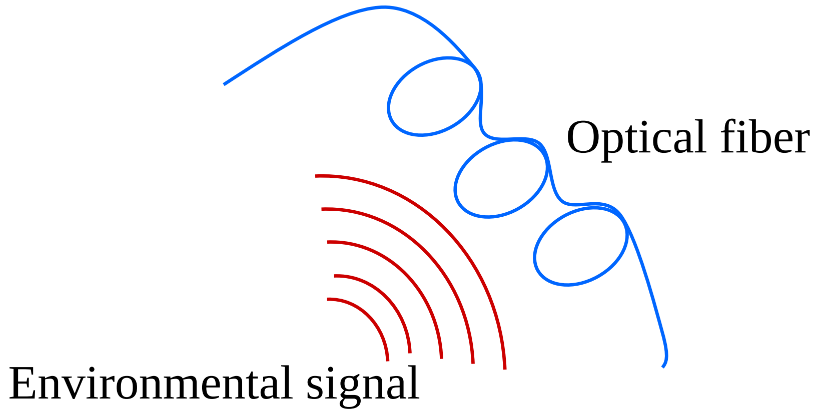
– Responsivity: the amount of current produced per unit of input optical power
– Wavelength bandwidth: the bandwidth the PD is sensitive to.
– Damage threshold: the maximum optical power the PD can take before damage

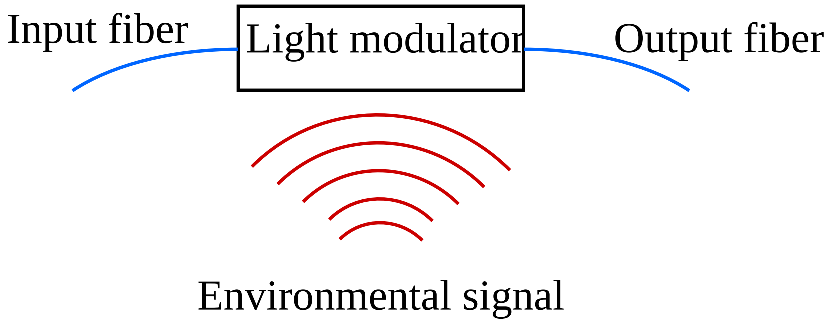


Optical sensors

Intrinsic: the effect of the measurand on the light being transmitted take place in the fiber

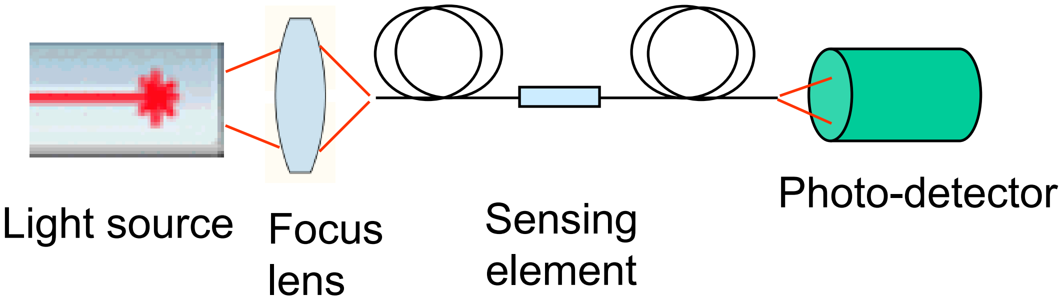
Extrinsic: the fiber carries the light from the source and to the detector, but the modulation occurs outside the fiber



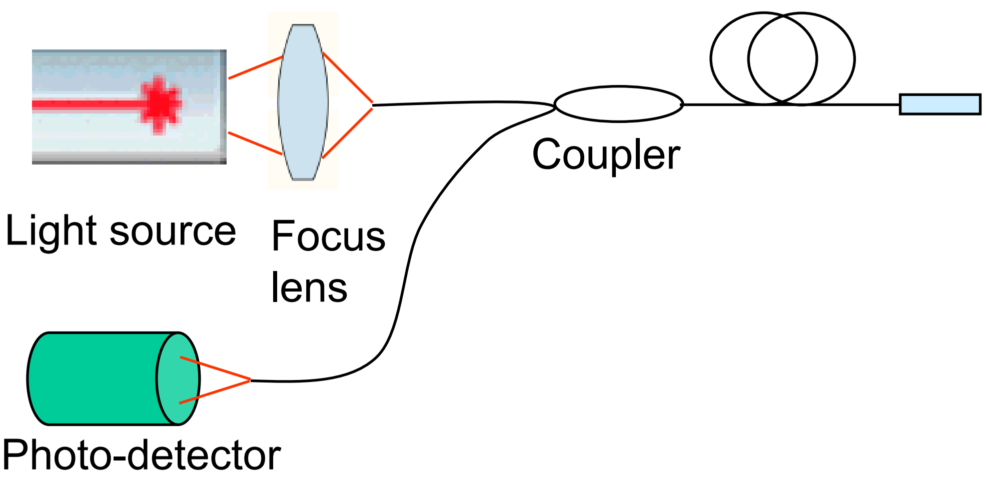


Typical optical sensors mechanisms

Transmission Measurement

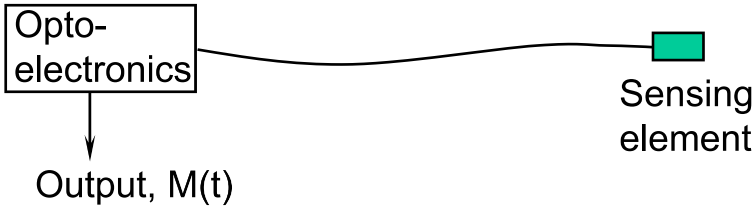


Reflection Measurement

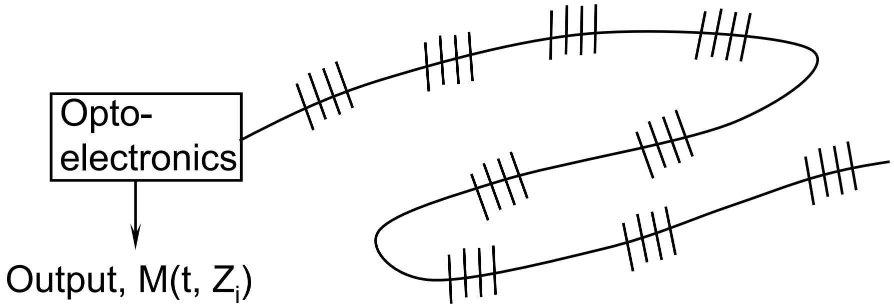


Typical optical sensors types

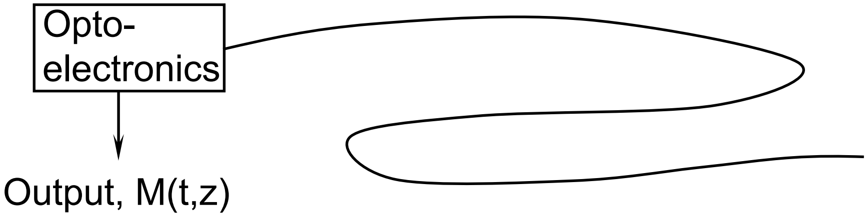
Point sensor: detects measurand variation only in the vicinity of the sensor



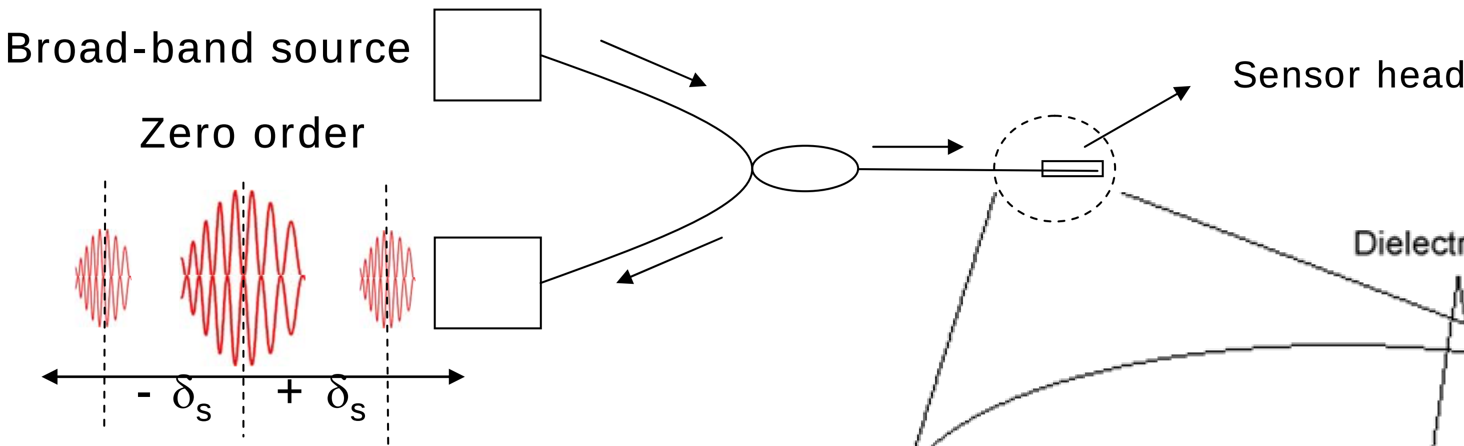
Multiplexed sensor:
Multiple localized sensors are placed at intervals along the fiber length.



Distributed sensor:
Sensing is distributed along the length of the fiber

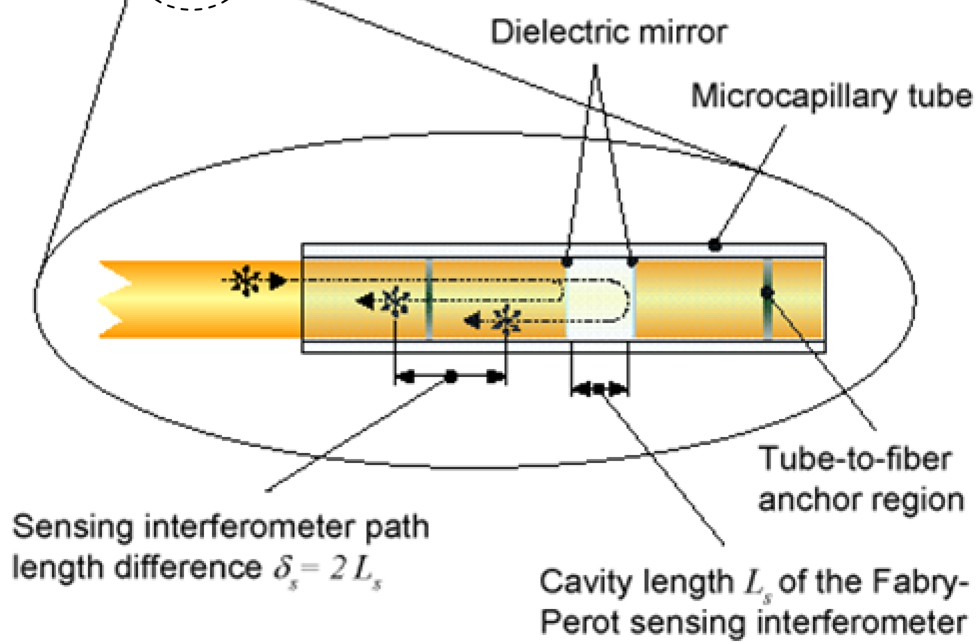


White-light interferometry
allows to measure absolute Fabry-Perot cavity length



Scanning Interferometer

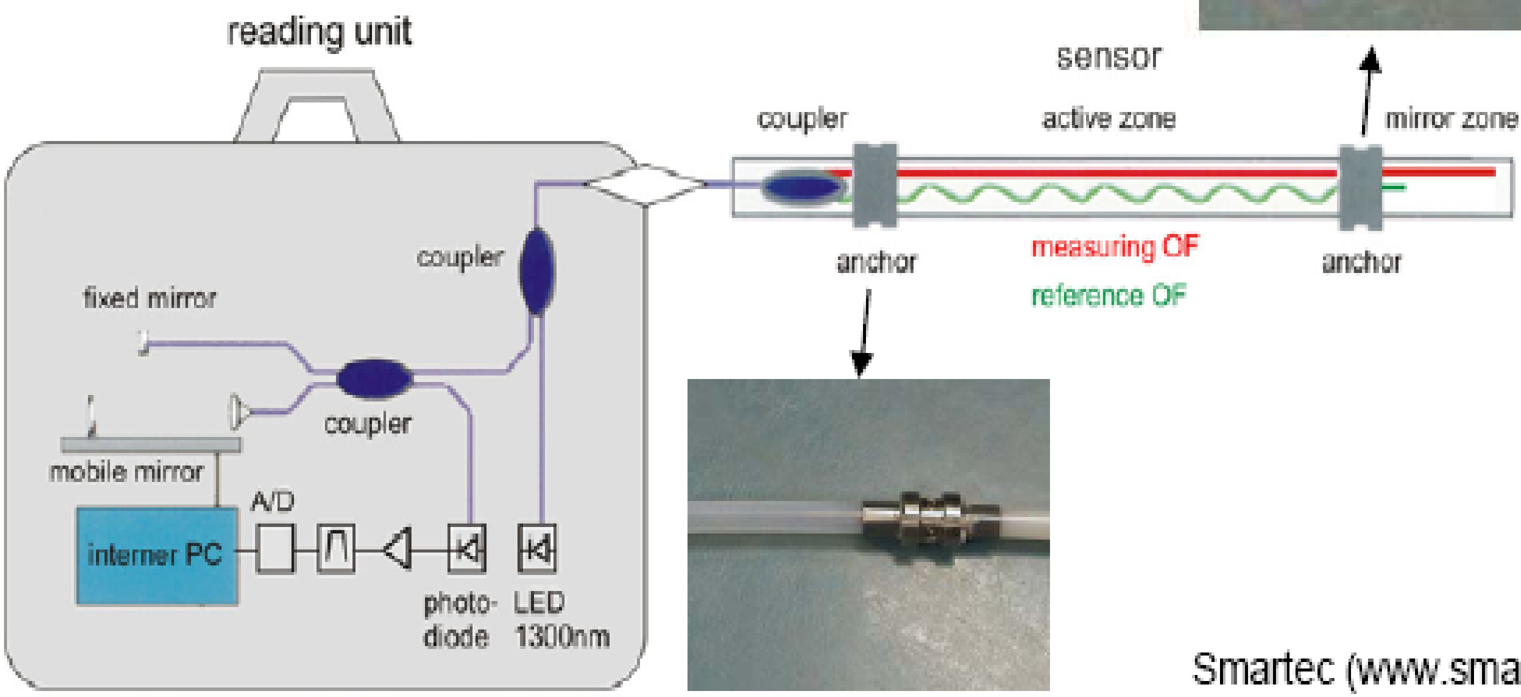
Demodulates the signal to recover the ***absolute*** cavity length



- compact
- cheap technology
- typical Range: 1000 -10000 μ ε
- resolution: < 0.003 %
- precision: 0.01 %
- bandwidth: 10 Hz

IR Low-coherence interferometry
based on Michelson Interferometer

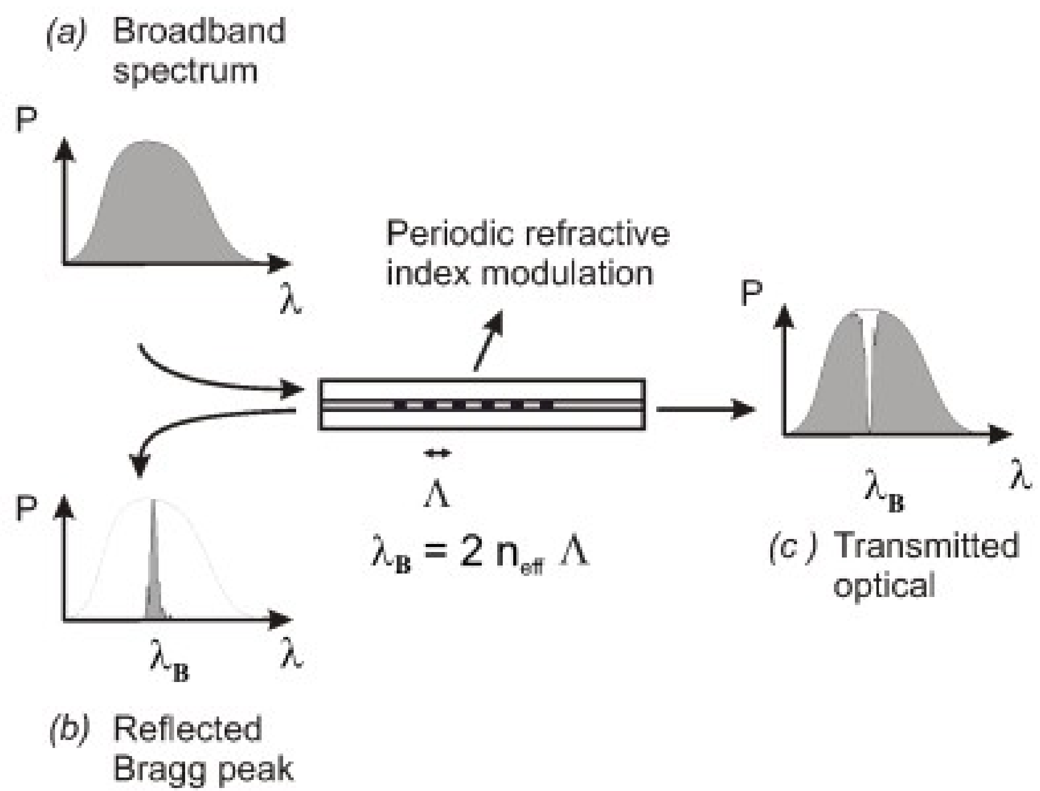
- typical Range: -5000 -10000 μ ε
- resolution: 2 μm
- bandwidth: up to 10 kHz



Smartec (www.smartec.ch)

Fiber Bragg Gratings

- Sensitivity: 1.1 pm/με
- Typical range: +-2000 με
- Resolution: < 1 μ ε
- accuracy: ~ 1 μ ε
- Bandwidth: 250 Hz
- Temperature: up to 600°C

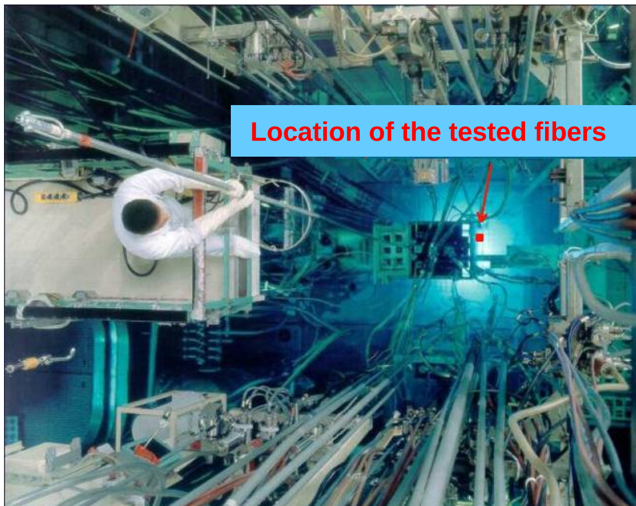


Main advantages of optical fiber sensors

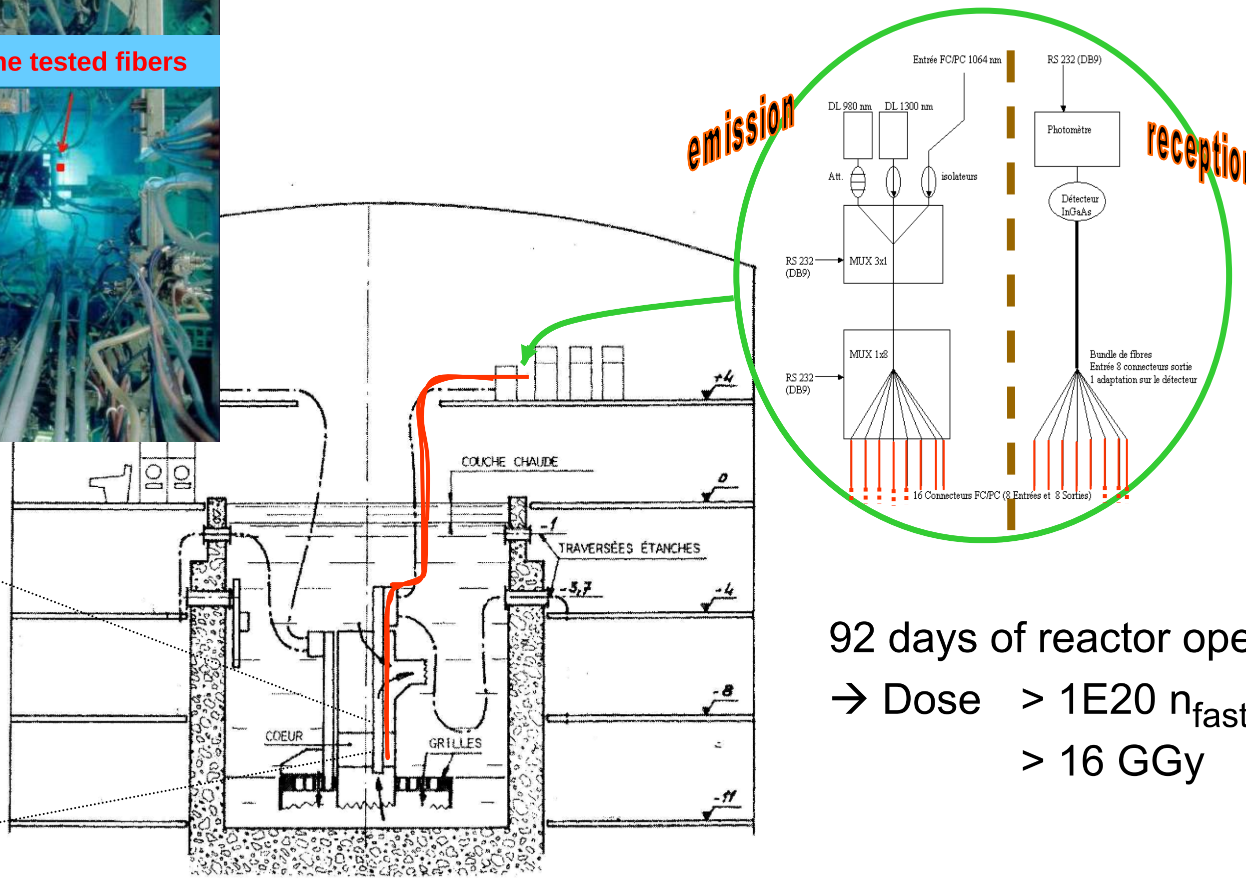
- Compact size
- Multi-functional
- Remote accessible
- Multiplexing
- Resistant to harsh environment
- Immunity to electro-magnetic interference

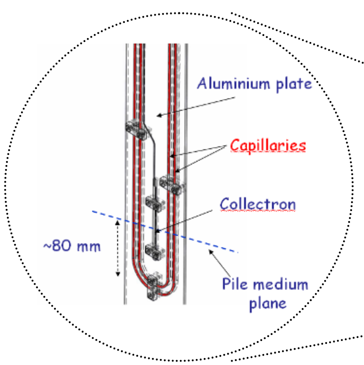
Recent results : new fibers can survive in reactors

Example : **COSI experiment (OSIRIS reactor, France – 2006)**



Irradiation of 12 recently developed optical fibers





92 days of reactor operation

→ Dose > 1E20 n_{fast}/cm^{-2}

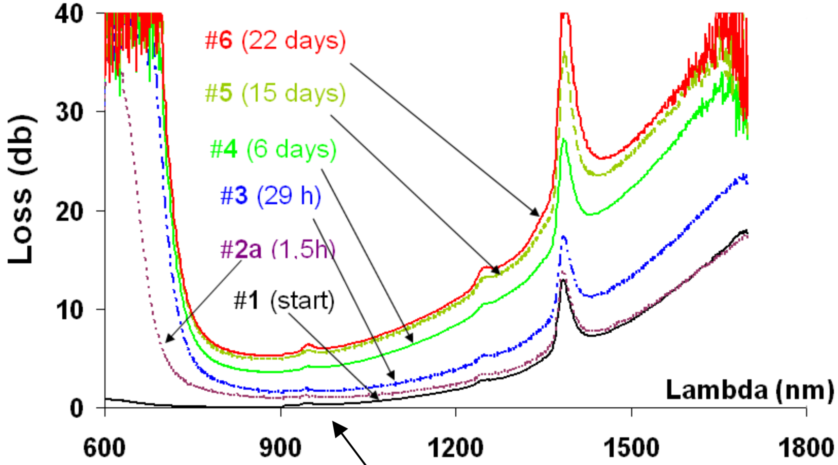
> 16 GGy

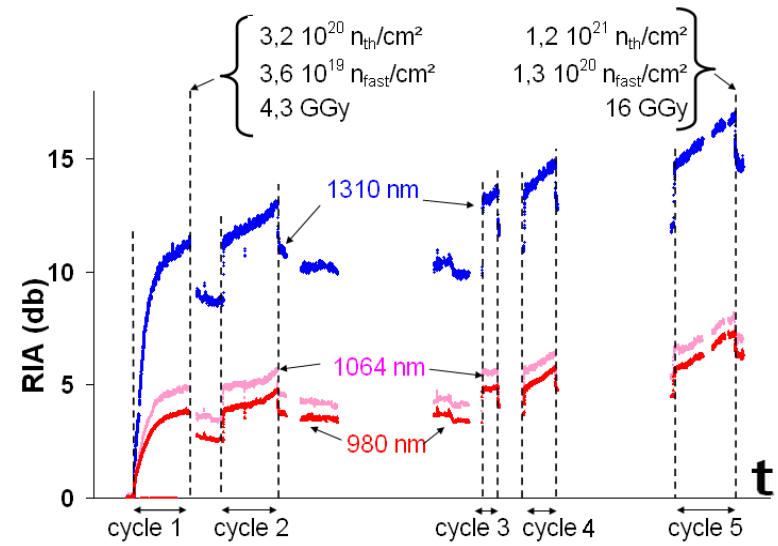
Tested fibers

Fibers	Manufacturer	Manufacturer reference / type (SM or MM)	Core/cladding diameter	coating
Forc1 Forc2 Forc3	FORC	- / SM	~10µm/150µm	acrylate
Bl1 Bl3	Blaze Photonics (Cristal Fibre)	HC 1060-02 /SM	9.7µm (hole) /125µm	acrylate
STU1 STU2	Polymicro	FIP100.110.125STU / MM	100µm / 110µm	polyimide
FIL1 FIL2	Polymicro	FIL100.110.150 / MM	100µm / 150µm	aluminium
FVL1 FVL2	Polymicro	FVP100.110.150 / MM	100µm / 150µm	aluminium

General results from COSI experiment:

Radiation induced absorption



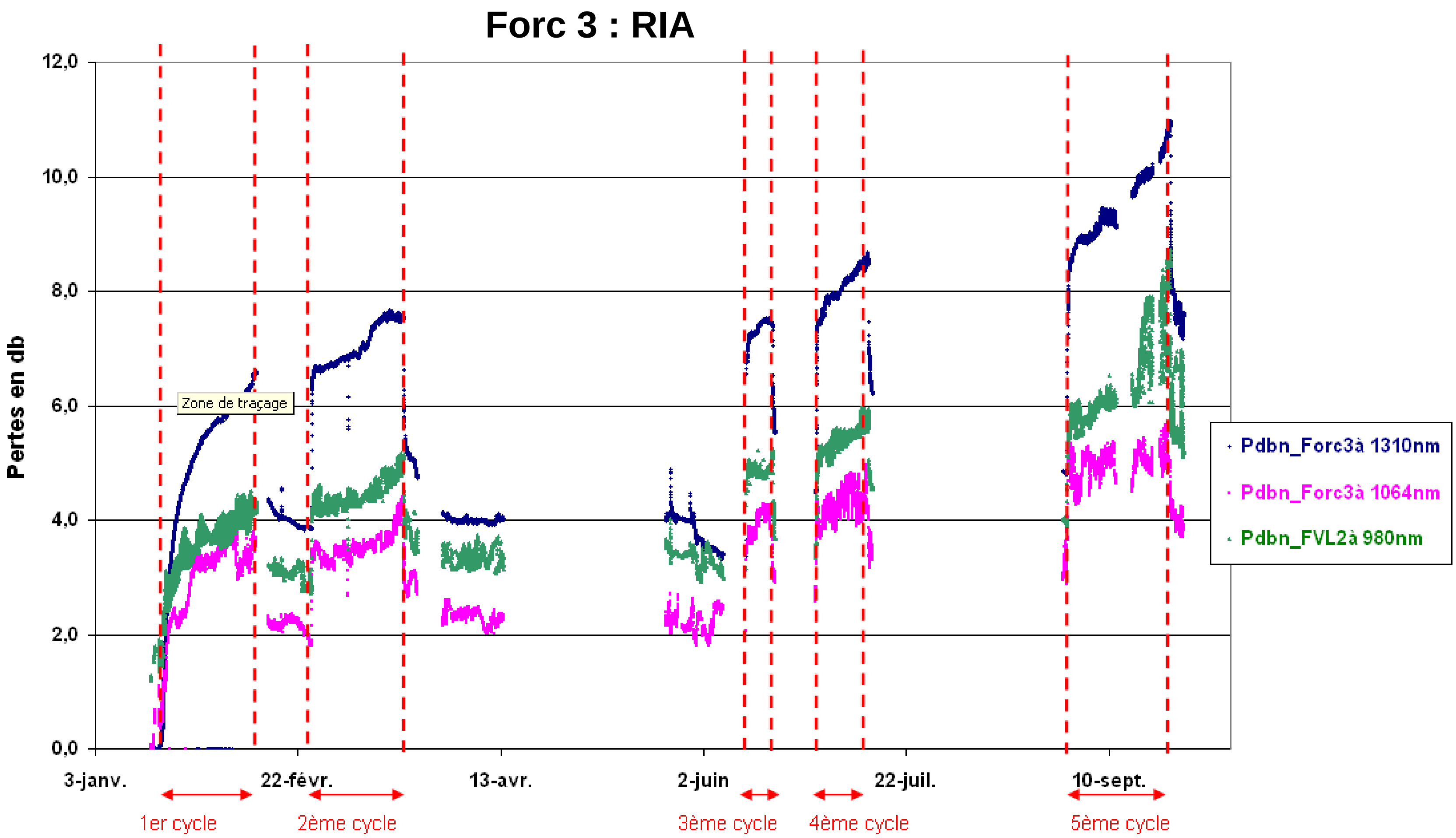


- **Favorable spectral region in the 800-1200 nm range**
- **RIA measured losses < 10 dB → suitable multimode and single mode fibers exist for in-pile applications**

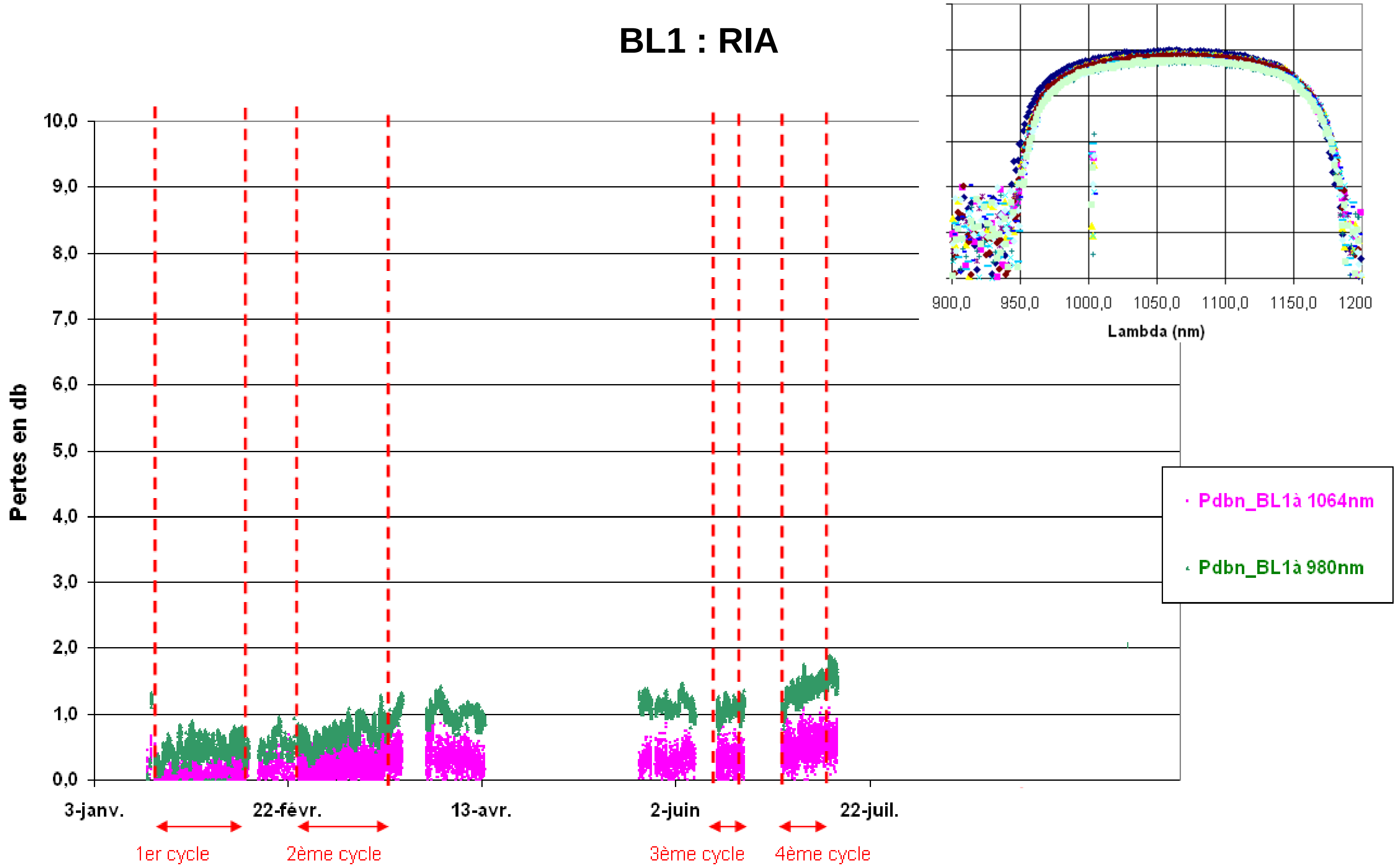
However in-pile optical measurement systems have to be independent of light intensity

→ *interferometry (Fabry-Perot, Bragg gratings…)*

Some results from COSI experiment

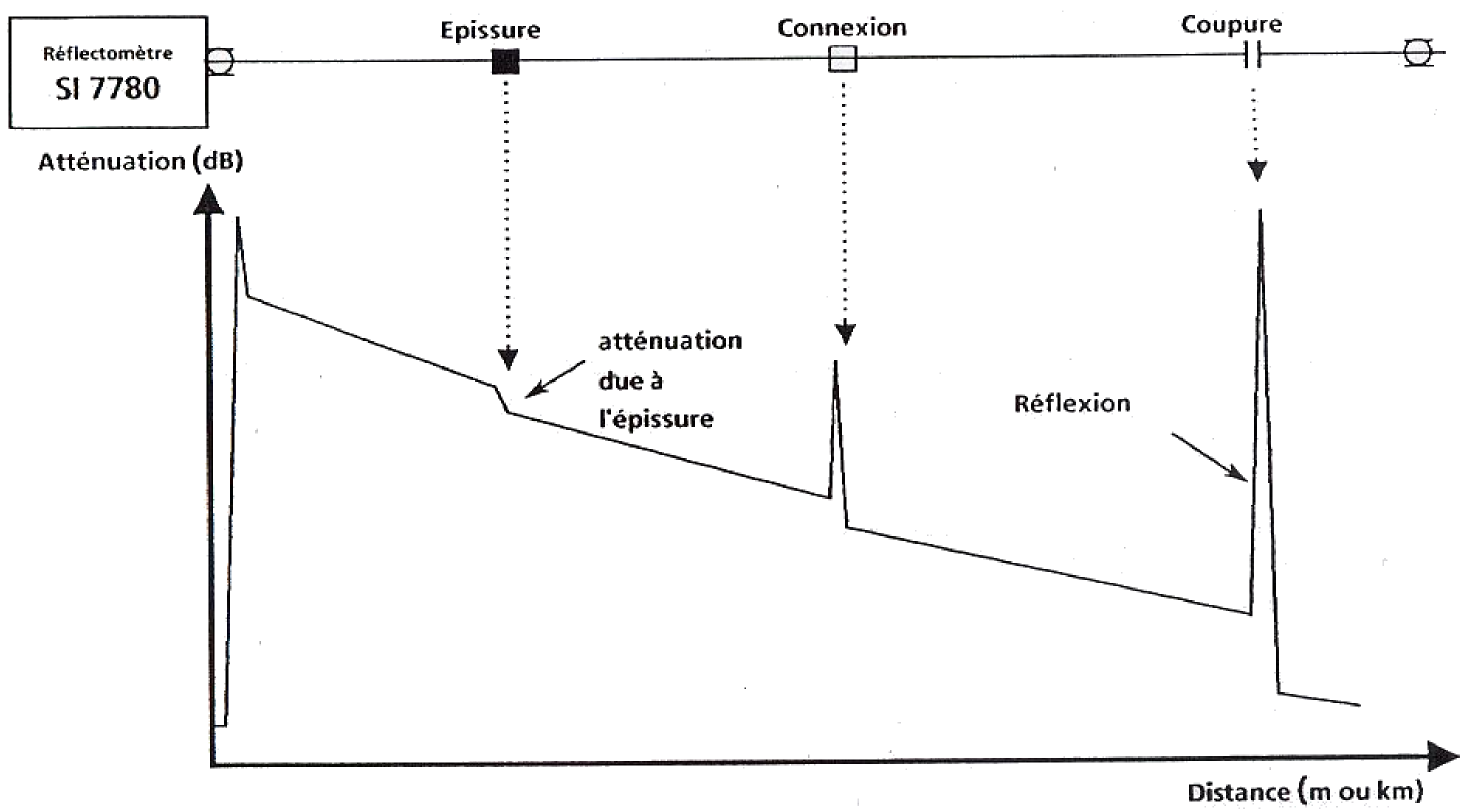


Some results from COSI experiment



Some results from COSI experiment

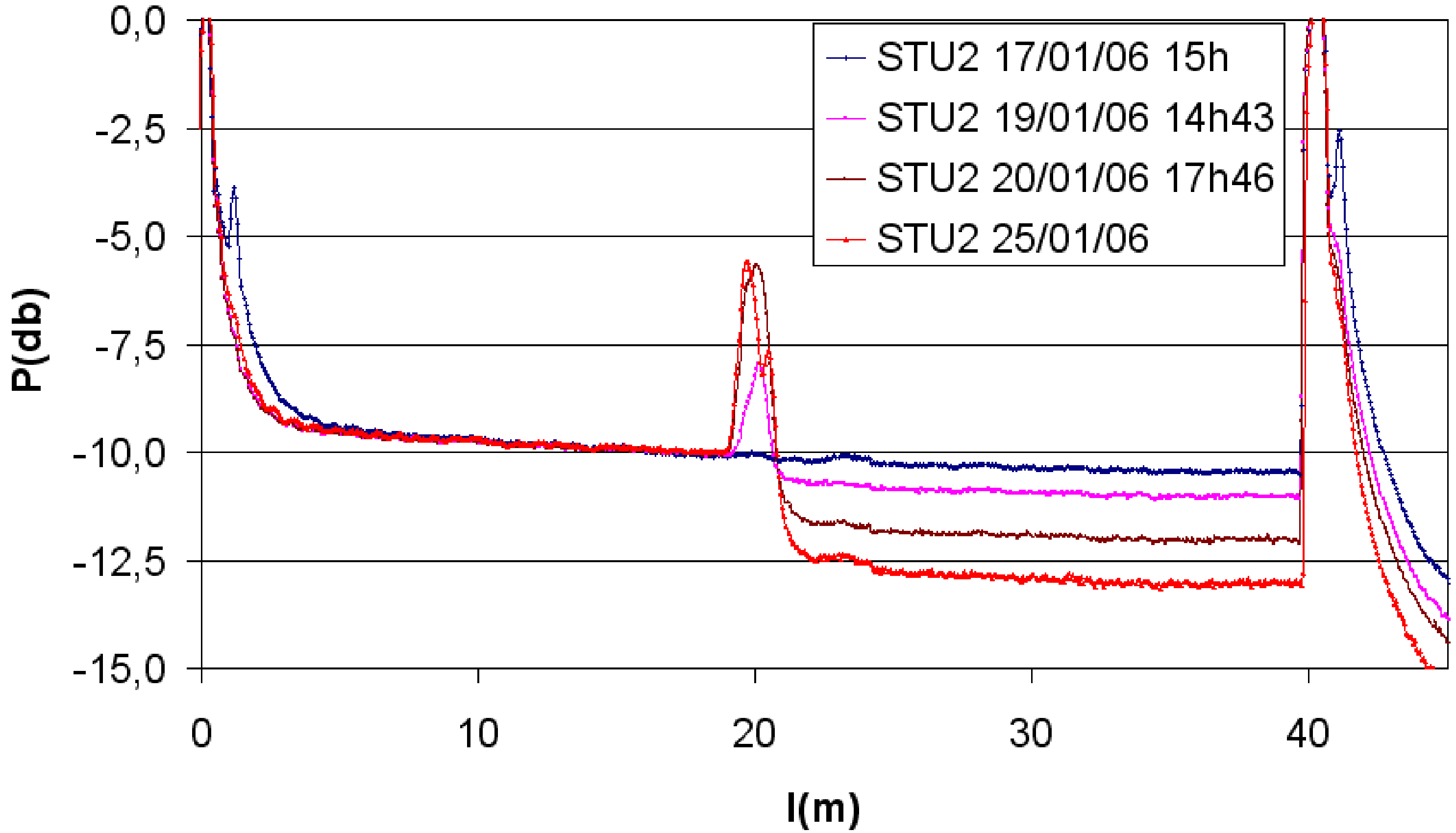
Principle of reflectometry measurement



Typical retro diffused signal

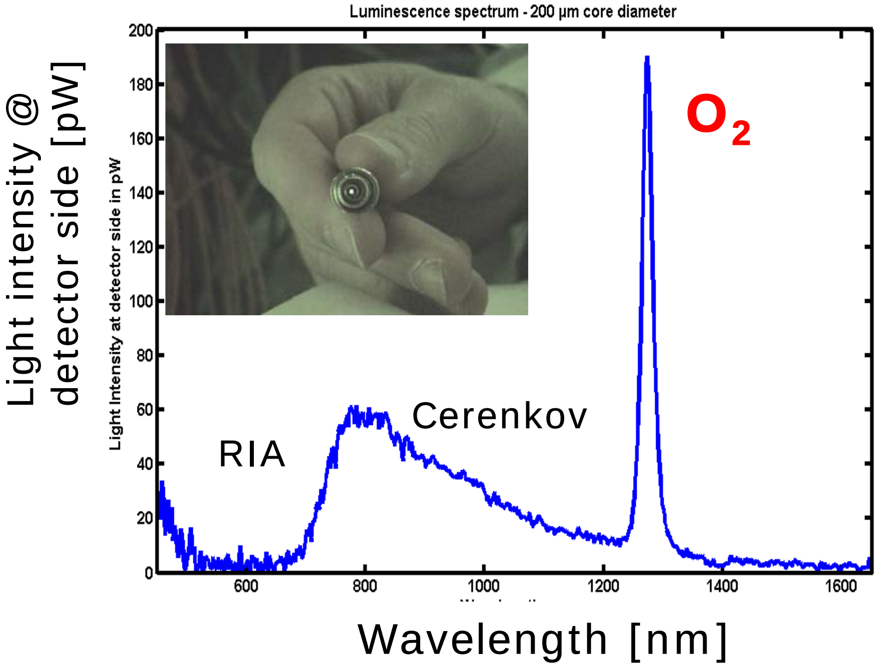
Some results from COSI experiment

Results of reflectometry measurements

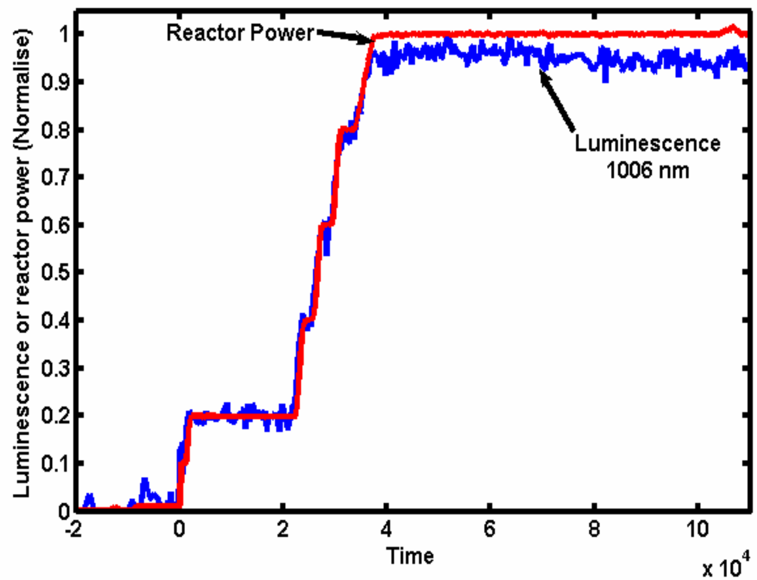


Radiation induces Luminescence

Luminescence spectrum in
200 µm core fiber

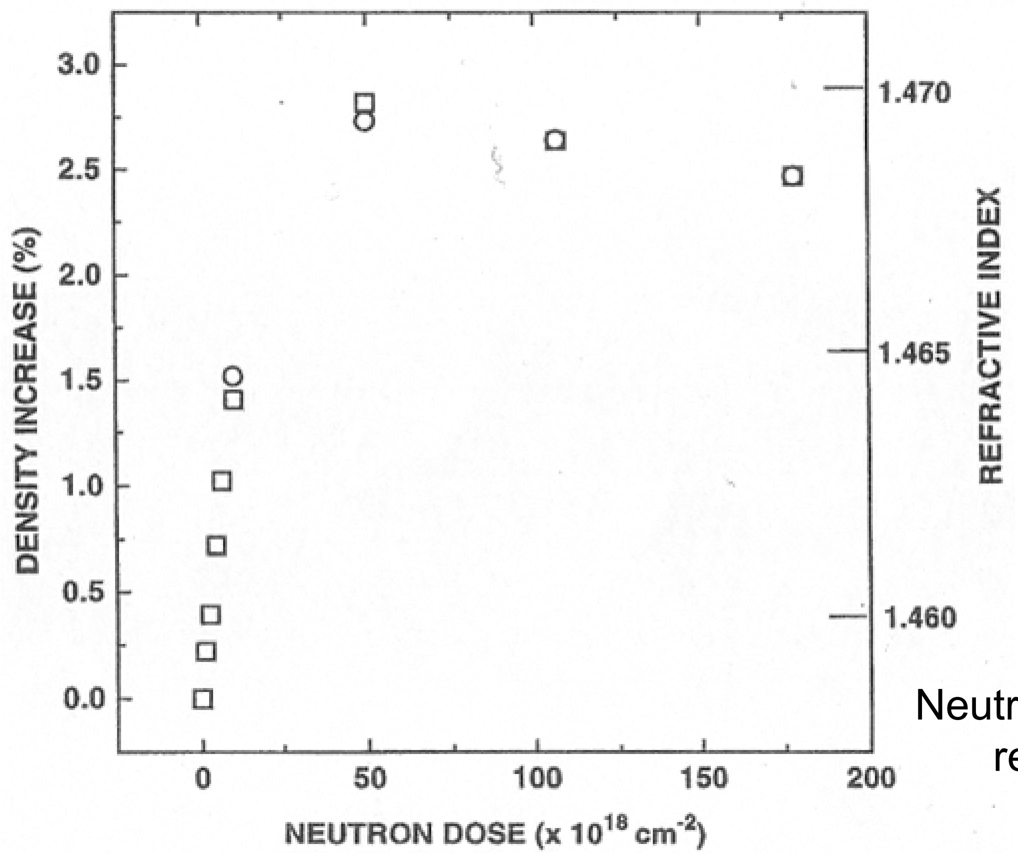


Function of the reactor power



Luminescence is not a problem in IR and SM fibres. However, still need to pay attention to 1275 nm emission line especially at the end of fibre lifetime

Radiation changes refractive index and fiber dimensions



Primak, *Phys.Rev.B, 110, 6, 1240, 1958*

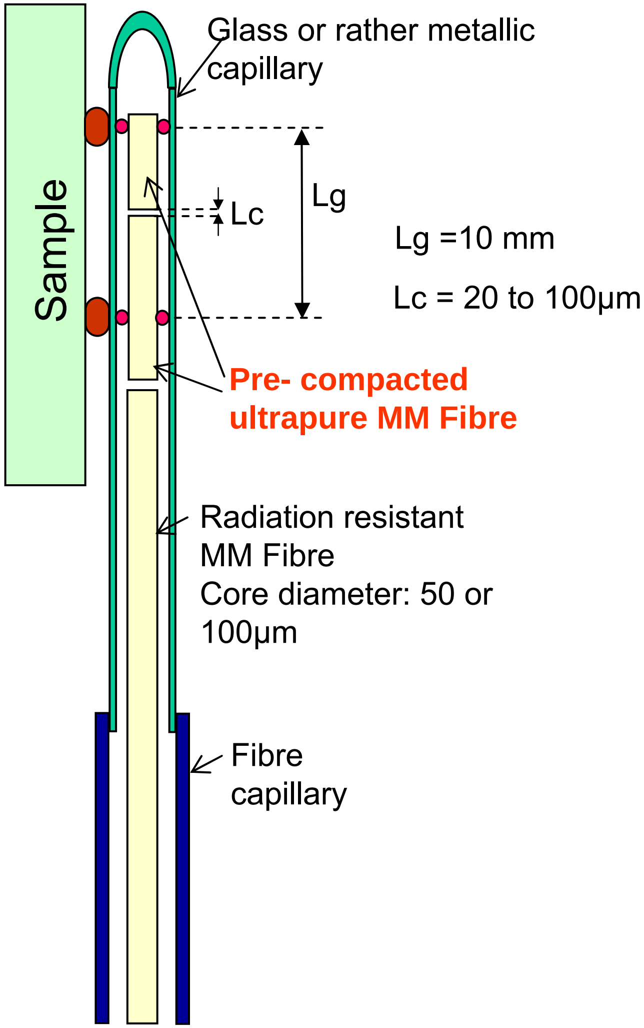
$$\phi = \frac{2\pi}{\lambda}\, n\, L$$

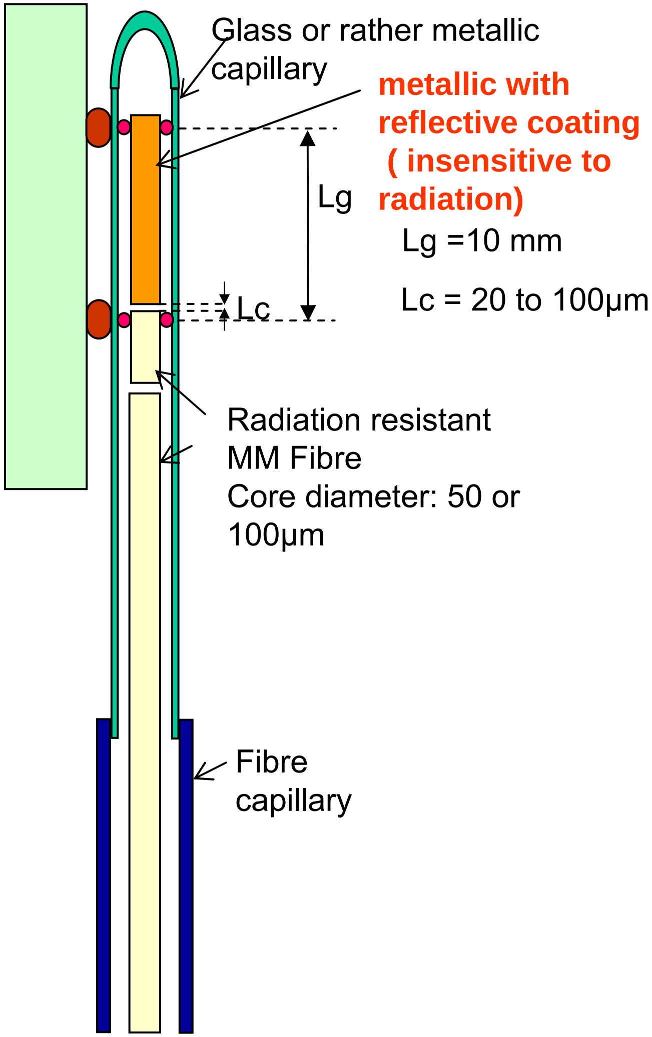
Neutron-induced compaction and associated refractive index change in bulk glass

Conclusion :
some good news but still a lot of issues…

- **Radiation-induced absorption (RIA)**
  - OK if moderate absorption (900-1300 nm)
  - Interferometer little affected by moderate absorption
  - What happens in the very long term (multiple cycles)?
- **Radiation-induced Luminescence (RIL)**
  - negligible but to pay attention at the end of fiber lifetime
- **Radiation-Induced Refractive Index Change**
  - Still questionable for FBGs
  - How to deal with ?
- **How to fix the sensors ?**

Optimized elongation sensor

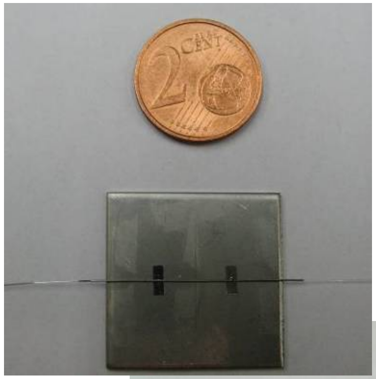


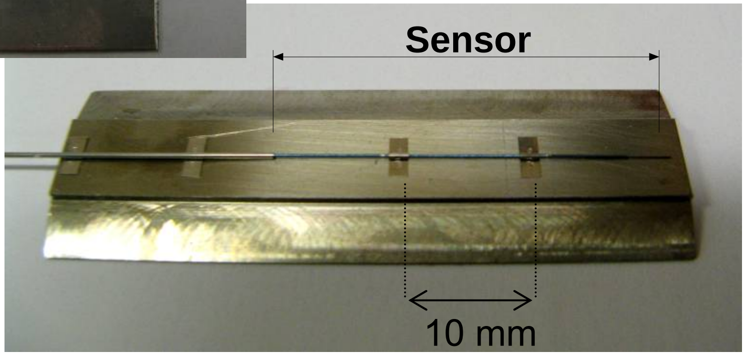


Optimized elongation sensor

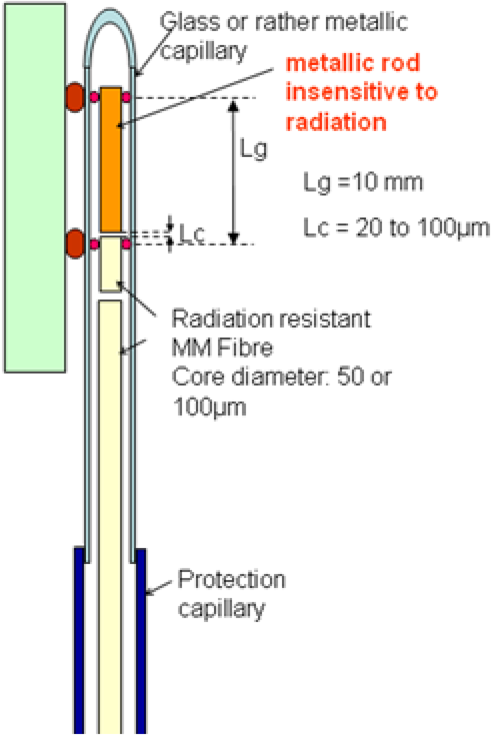
Fiber-based extensometer developed by CEA/SCK·CEN Joint Lab. to measure the elongation of material samples

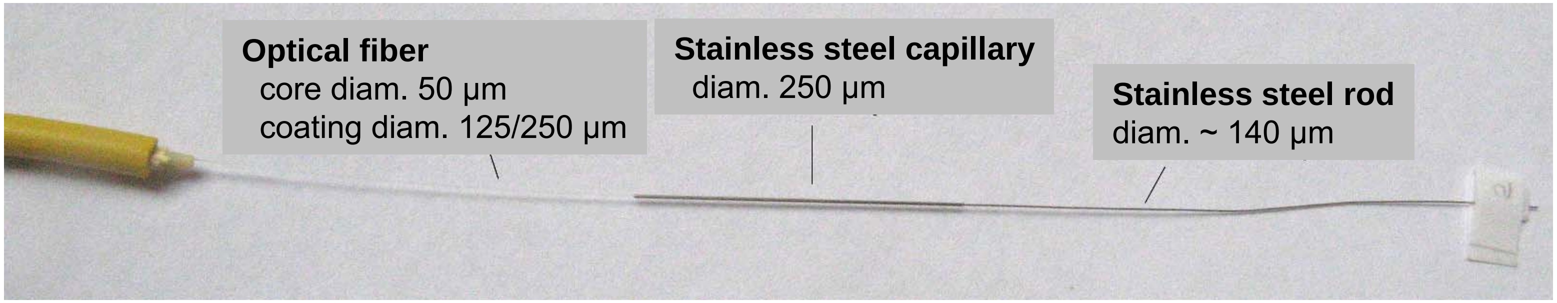
Status : in-pile qualification in BR2 reactor (Belgium) performed at the end of 2009



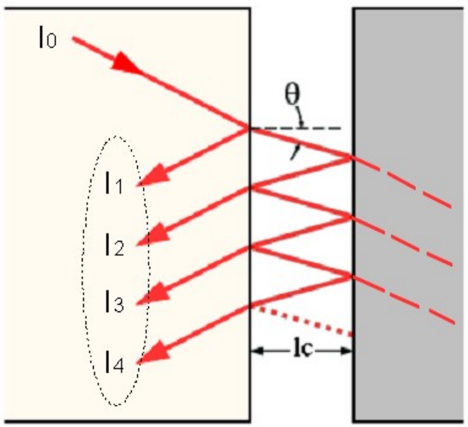


Major interests :
- **Very compact sensor**
- **Low instrusivity**
- **High accuracy (< µm)**





Measuring the cavity length



Plane wave interference model gives the global shape of the fringe pattern

with R1=R2 (same reflexion coefficient on both faces):

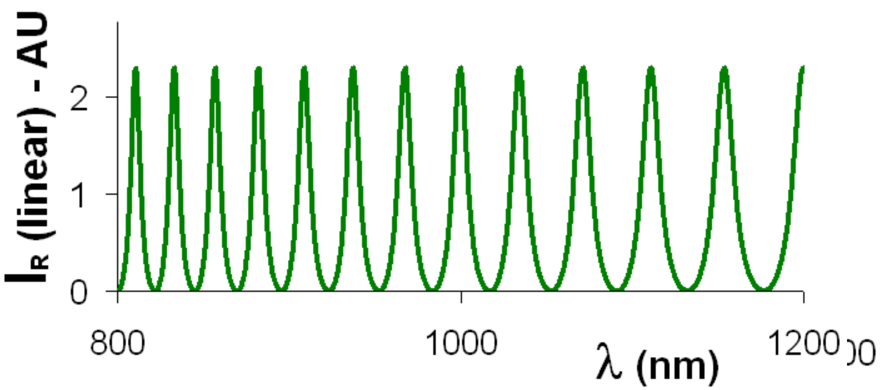
$$I_R = I_0 \left[\frac{(2 - 2\cos\varphi) \times R}{1 + R^2 - 2R\cos\varphi)} \right]$$

with $\varphi = 4.\pi.l_c.\cos\theta/\lambda$

With cosθ ~ 1

The number of fringes Δk over Δλ gives l_c :

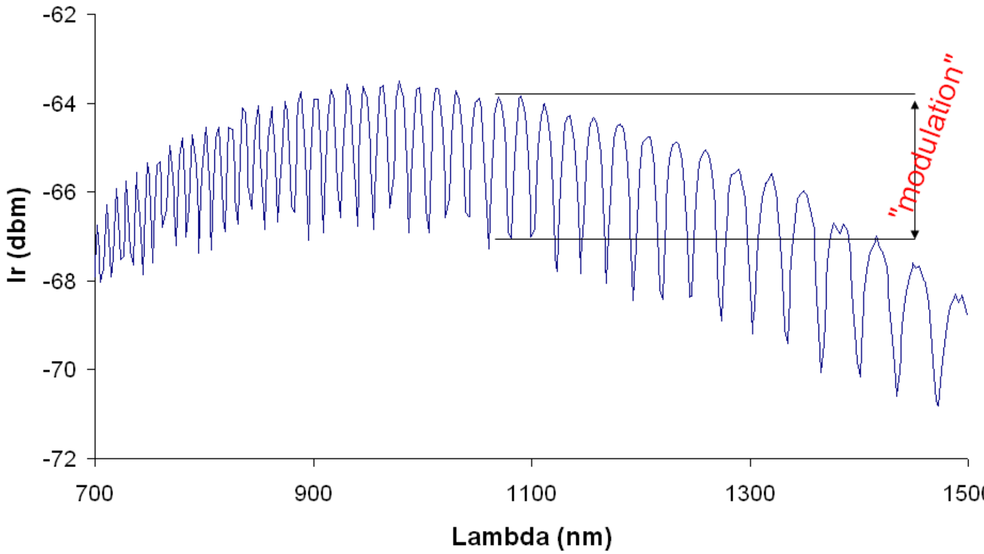
$$\Delta k = 2\, l_c\, \Delta(1/\lambda)$$



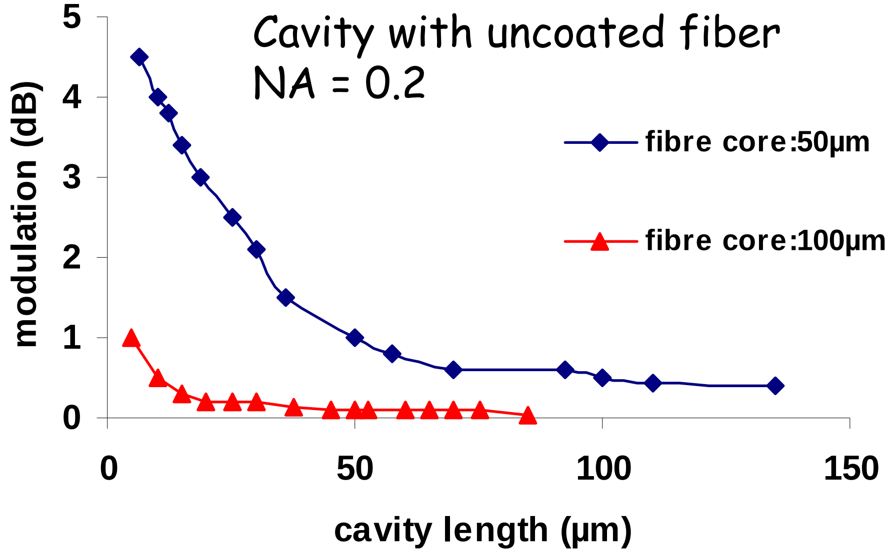
Precise calculation by plotting I_R versus 1/λ and through FFT algorithm.

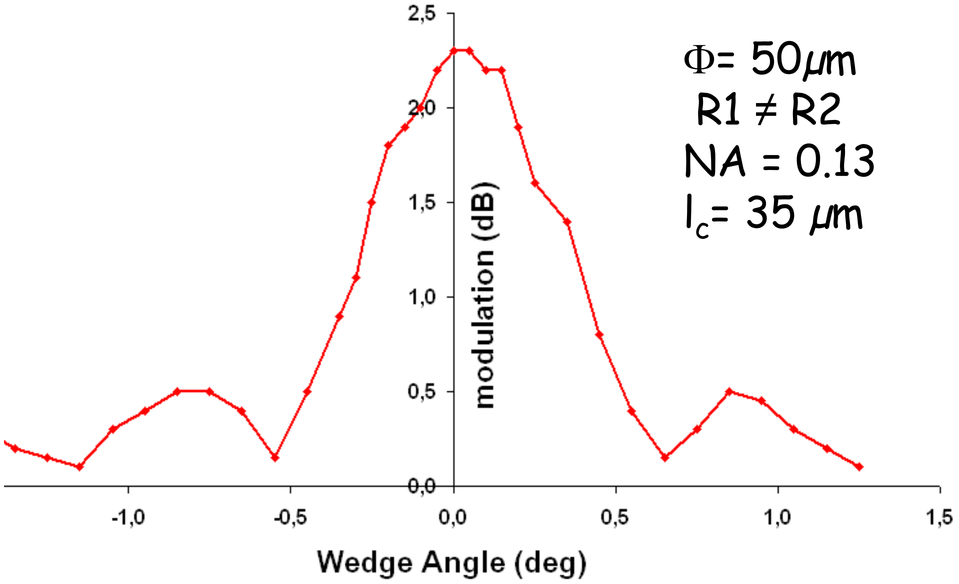
Measuring the cavity length

Modulation depends on:
- fiber core diameter
- NA
- cavity length
- angle/misalignment



Modulation changes with lc, F, angle





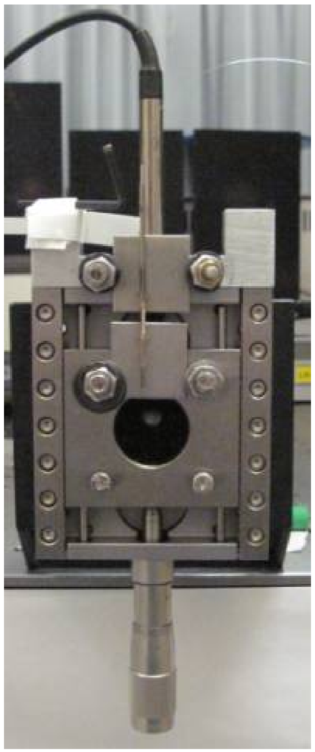
-> larger cavities more difficult to measure

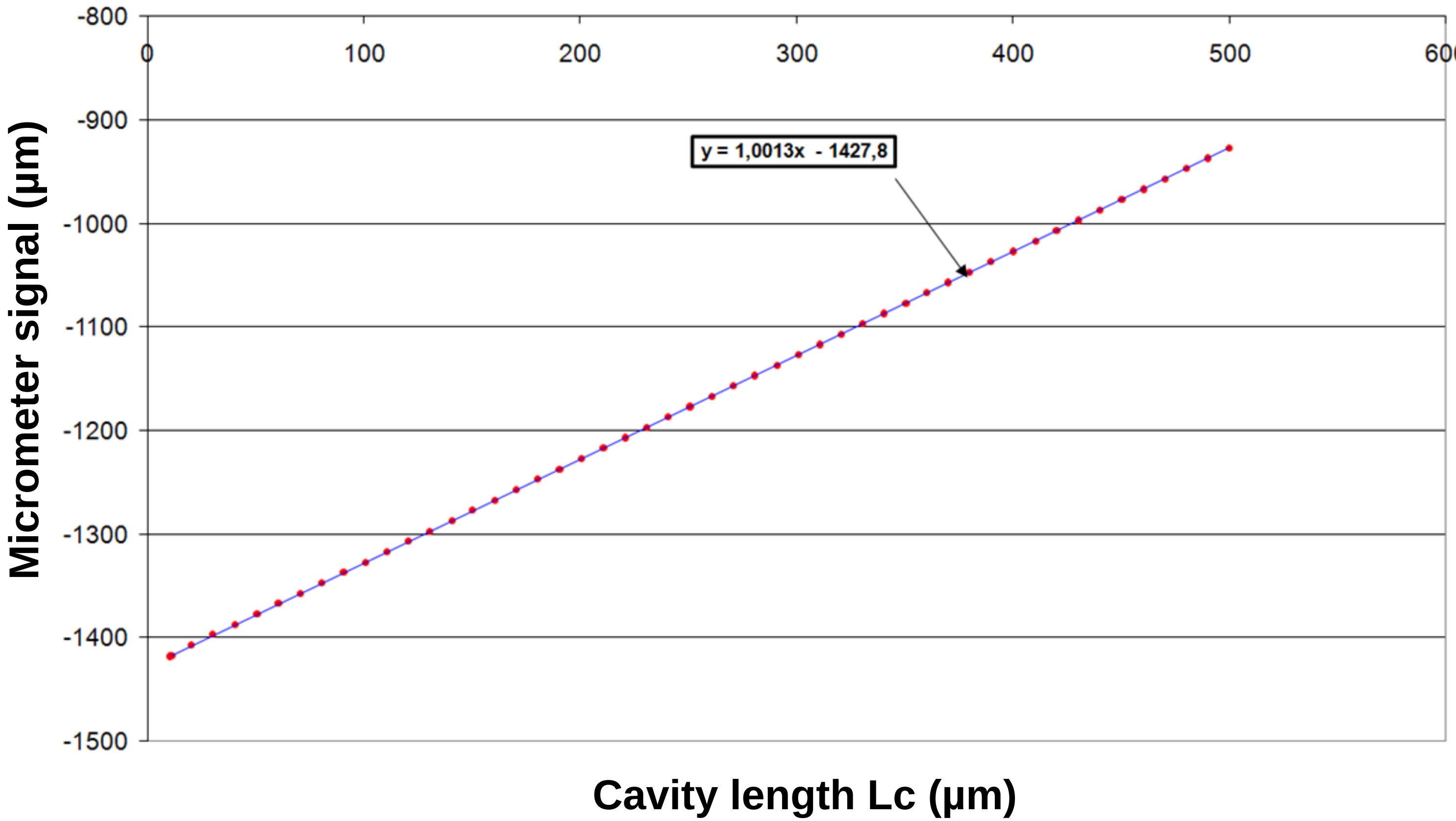
-> smaller diameter to be preferred

-> angle tolerance ~ +/- 0,3° (~ 5mrad).

-> (low NA preferable).

Experimental results for length detection





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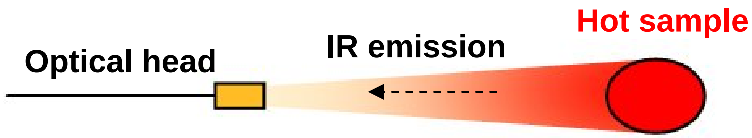
Other potential in-pile applications of optical measurements

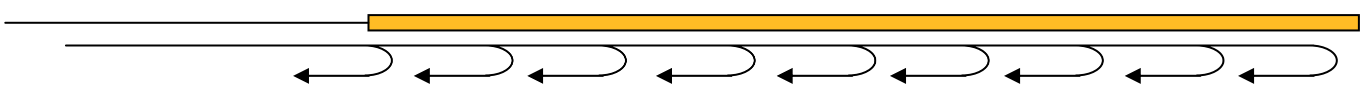
• **High-temperature pyrometry**

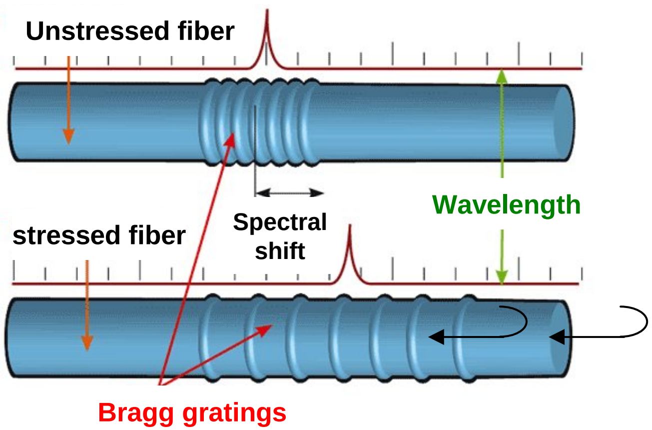
Suitable for surface temperature measurements > 1000°C



• **Measurement along fibers using stimulated scattering**

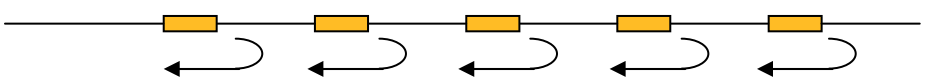
- Raman → temperature distribution (ex : monitoring primary coolant circuit)
- Brillouin → temperature / deformation





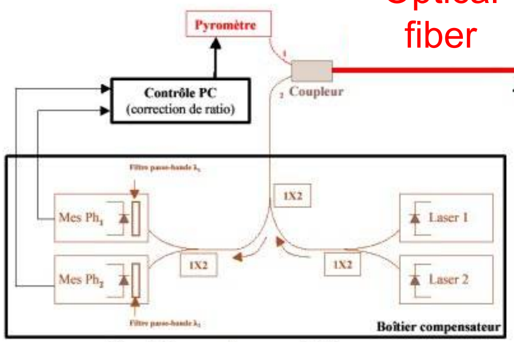
• **Distributed measurements**

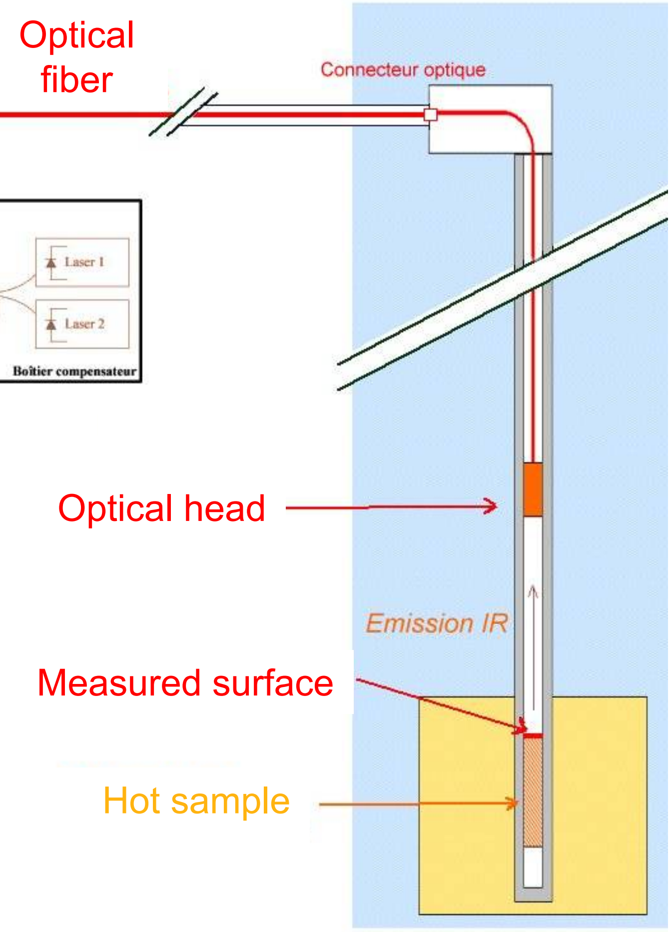
Bragg gratings → temperature, deformation, pressure, etc..



Infrared pyrometry

Signal acquisition and processing system





Principle :

Remote high-temperature measurement, with auto-compensation of RIA

+ low intrusivity
+ no interface problem (no contact with sample)
- surface temperature measurement
- requires good optical transmission between probe and sample