Italian National Agency for New Technologies,
Energy and Sustainable Economic Development

RADIATION TESTS ON COMPONENTS FOR THE ITER PROJECT AT THE CALLIOPE FACILITY

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OUTLINE

- Radial Neutron Camera (RNC) and Vacuum Vessel (VV) for the ITER reactor
- Gamma radiation tests at ENEA ^{60}Co Calliope facility
- RNC components: scintillators, optical windows, PMTs and single-crystal diamond detectors
- Vacuum Vessel components: sensors, optical fibers and metallic wires
- Conclusions

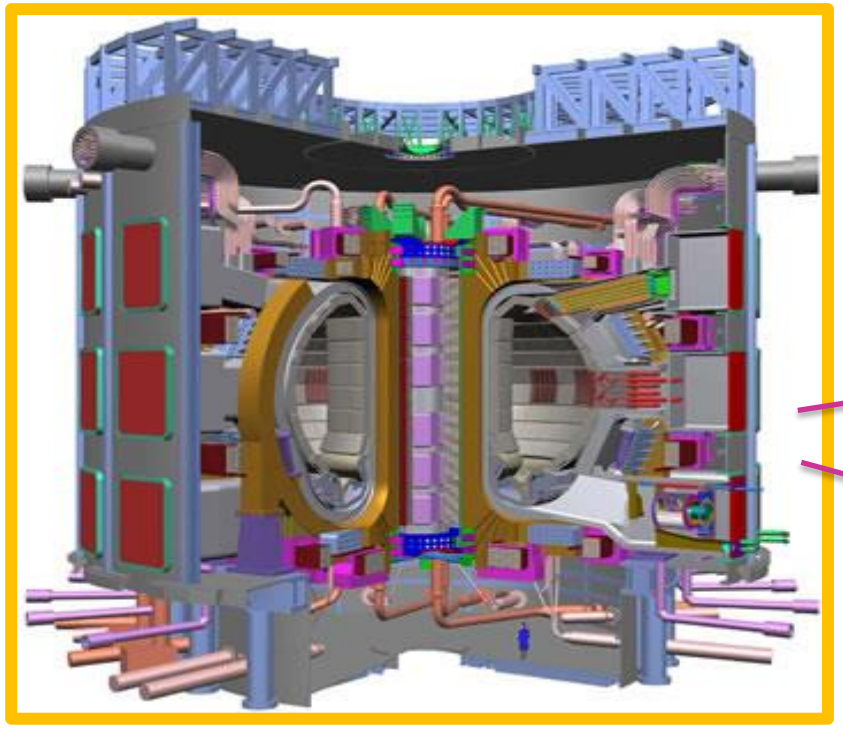
ITER – International Thermonuclear Experimental Reactor Project (1)

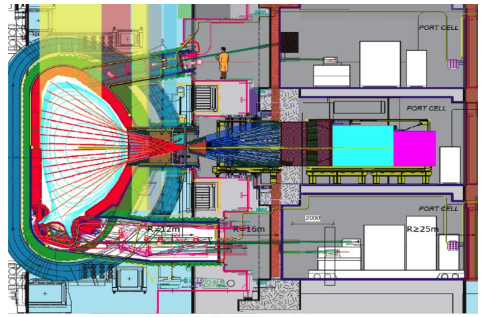
- The most ambitious energy projects in the world to demonstrate scientific and technological feasibility of fusion power
- An international collaboration

During the ITER operation time the plasma will give rise to

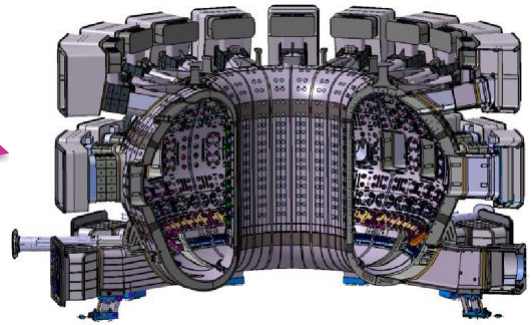
HIGH ENERGY NEUTRON and GAMMA RAYS

Radiation damage and activation on components



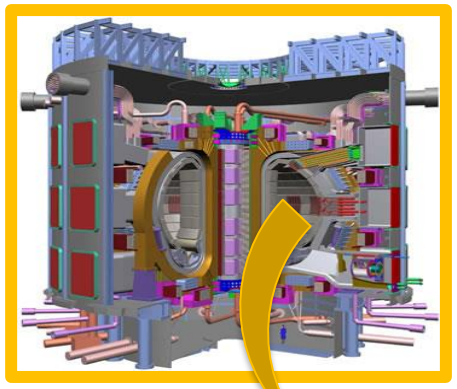


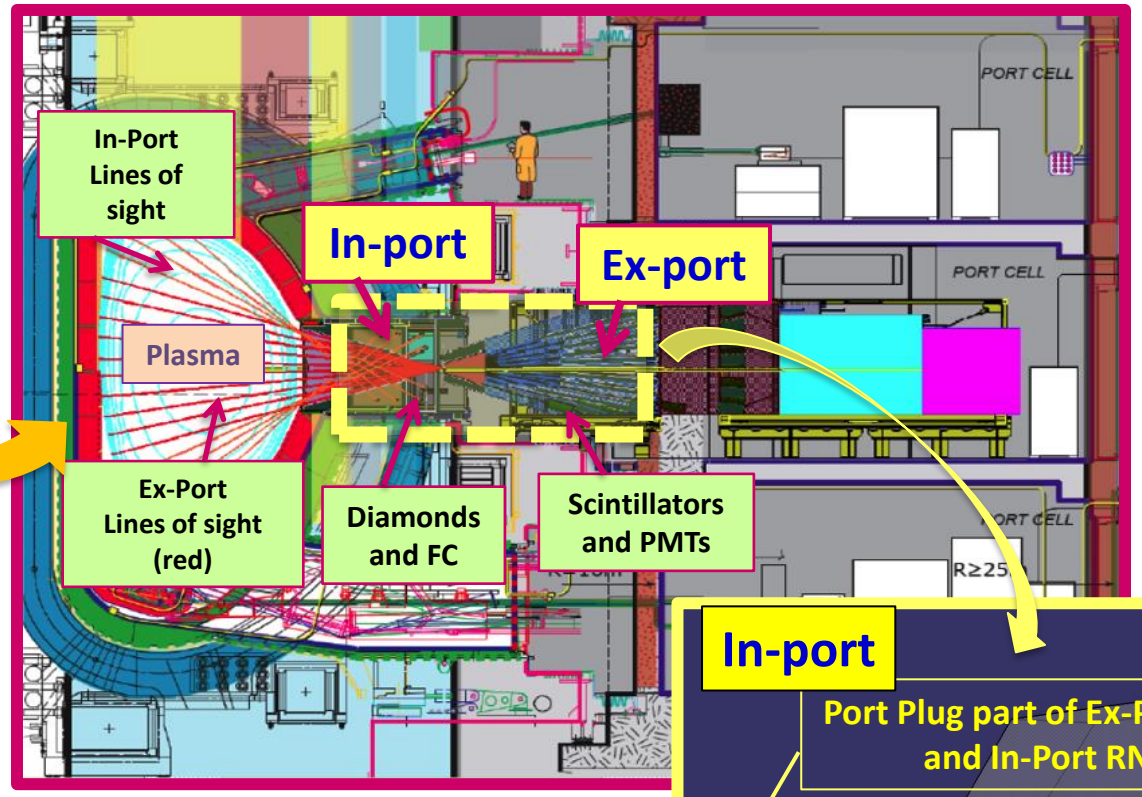
Radial Neutron Camera (RNC)



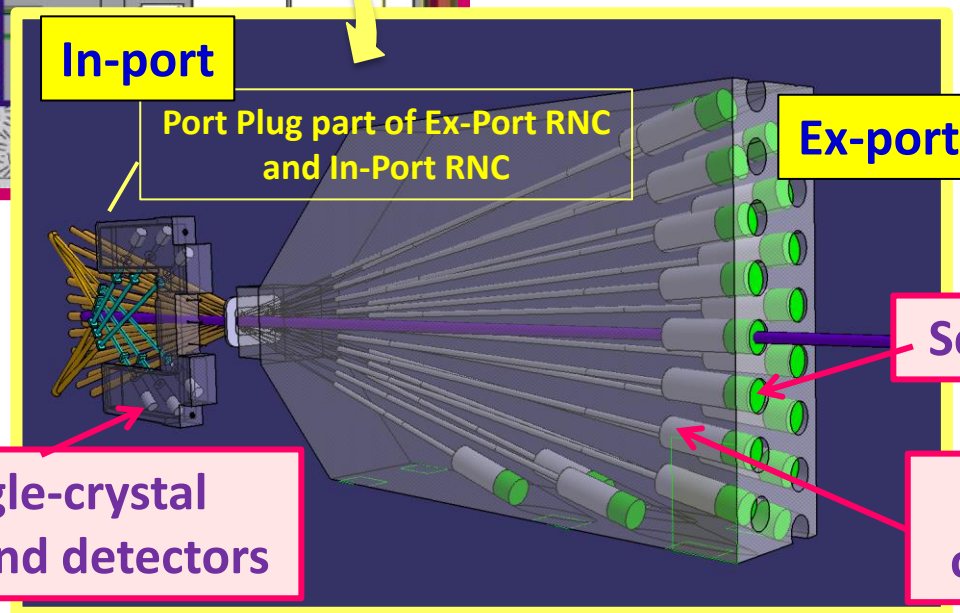
Vacuum Vessel (VV)

ITER – Radial Neutron Camera (2)





Radial Neutron Camera



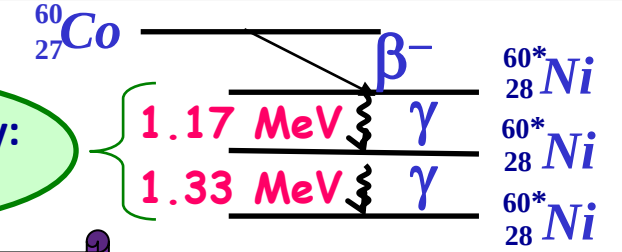
Gamma Total Absorbed Dose during ITER lifetime:

- **Ex-port System: 100 kGy**
- **In-port System: 5 MGy**

Experimental Set-Up:
^{60}Co Calliope γ irradiation facility (1)

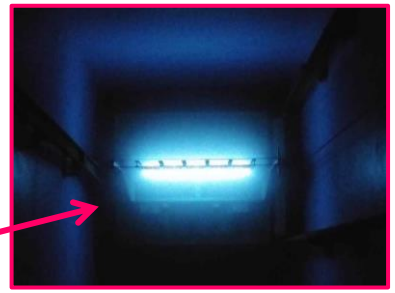
(Picture acquired by remote camera)

Pool-type irradiation facility equipped with a ^{60}Co gamma source in a large volume (7×6×3.9 m^3) shielded cell



Mean energy: 1.25 MeV

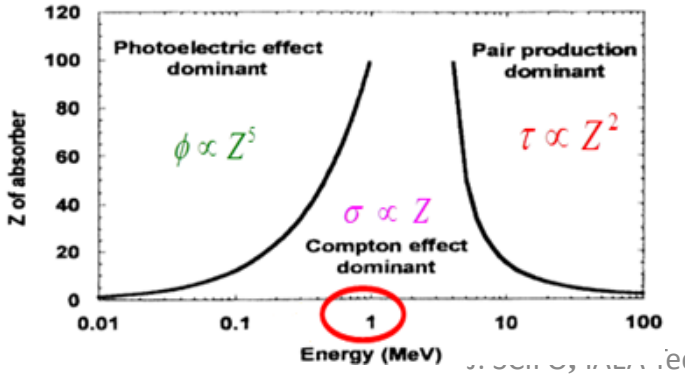
Irradiation and dosimetric certification



Cherenkov effect around the 25 source rods (active area: 41 cm x 75 cm)

<u>Maximum allowed activity</u>: 3.7x10^{15} Bq (100 kCi)

<u>maximum dose rate (May 2022)</u>: 7.4 kGy/h



- **Irradiation tests at different dose rates, atmospheric and temperature conditions and under bias.**
- **Simulation of gamma field by Fluka/MCNP code (irradiation cell and irradiated samples).**
- **Online tests and remote acquisition.**
- **Single camera and touch screen display control integrated system (anomalies and test parameters) monitoring system.**

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Experimental Set-Up:
Calliope dosimetric systems and characterization lab (2)

Dosimetric systems:

Fricke dosimeter (20 - 200 Gy)
Absolute dosimeter

Certification

- Red-Perspex (5-40 kGy), radiochromic (1 kGy-3 MGy) dosim.
- Thermo Luminescent Dosimeter (TLD) (1 mGy-100 Gy)
- Alanine - ESR dosimeter (1Gy-500 kGy)
- Electronic RADFET (0-01 – 1000 Gy) dosimeter

Simulation of Calliope irradiation field with FLUKA & MCNP code

Optical and spectroscopic characterizations →

- UV-VIS spectrophotometer
- FTIR spectrophotometer
- Luminescence measurements
- ESR spectrometer
- Colorimeter

Accelerated ageing test →

- Climatic chamber: -75°C/+180°C (temperature), 10 - 98 % (humidity), UV lamp (220 - 630 nm) accessory
- Furnace (T max = 1200°C)

The Radial Neutron Camera components

Analysis and results on scintillators, optical windows, PMTs and single-crystal diamond detectors

Samples and irradiation tests

- ✓ **N.3 SOLID SCINTILLATORS:**
  - crystalline Stilbene (InradOptics) (1” diameter, 1” thick)
  - plastic EJ-299-33A and EJ-299-34 (Eljen Technology) (1” diameter, 1” thick)
- ✓ **N.2 PMT OPTICAL WINDOWS:**
  - synthetic silica WMH6614Q (Hamamatsu) (2” diameter, 1.5 mm thick)
  - borosilicate glass WM-H6614 (Hamamatsu) (2” diameter, 3 mm thick)
- ✓ **N.2 PMTs (with synthetic silica windows):**
  - Electron Tubes 9814QB (ET9814) (2” diameter)
  - Hamamatsu R7494 Mod (1” diameter)
- ✓ **N.2 IDENTICAL SINGLE-DIAMOND DETECTORS:**
  - SC0099, SC0105, SC0109 (MICRON Semiconductor Ltd.) *(4.5x4.5x0.5) mm^3*

Absorbed dose up to 100 KGy

Absorbed dose up to 5 MGy

Experimental measurements

Samples characterization performed before and after irradiation tests (RT, in air, in the dark)

TRANSMITTANCE MEASUREMENTS
on
SCINTILLATORS and **OPTICAL WINDOWS**
Perkin Elmer Lambda 950 UV-VIS Spectrophotometer

QUANTUM EFFICIENCY MEASUREMENTS
on
PMTs

ENERGY SPECTRUM MEASUREMENTS
on
SINGLE-CRYSTAL DIAMOND

- Measure of energy spectrum of 5.5 MeV α particle emitted by ^{241}Am source in a **vacuum chamber**

Gamma radiation damage test: scintillators (1)

Samples	Emission scintillation peaks (nm)	Band-edge (nm)	Producer
EJ-299-33A	420 / 400	416	Eljen Technology
EJ-299-34	420 / 400	415	Eljen Technology
Stilbene crystal	390	378	InradOptics

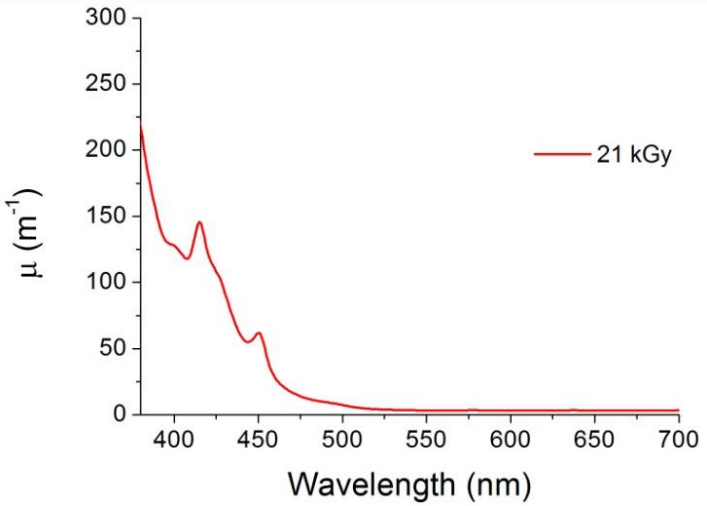
Irradiation up to 108 kGy abs. dose
RT, air, in the dark
(dose rate = 178.24 Gy/h)

Transmittance Measurements

Radiation induced absorption coefficient μ (m^{-1})

$$\mu = \frac{1}{L} \ln\left(\frac{T_0}{T}\right)$$

L (m) = thickness
To = transmittance before irradiation
T= transmittance after irradiation

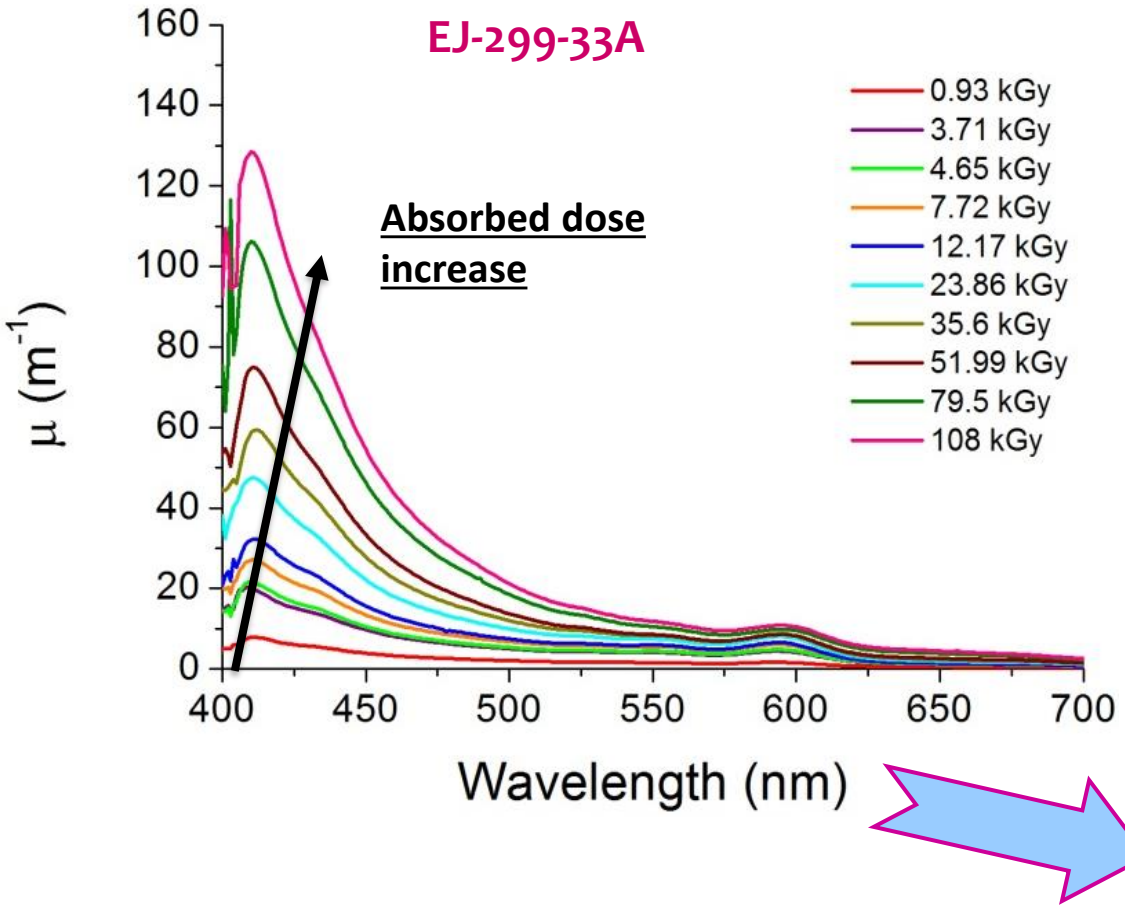


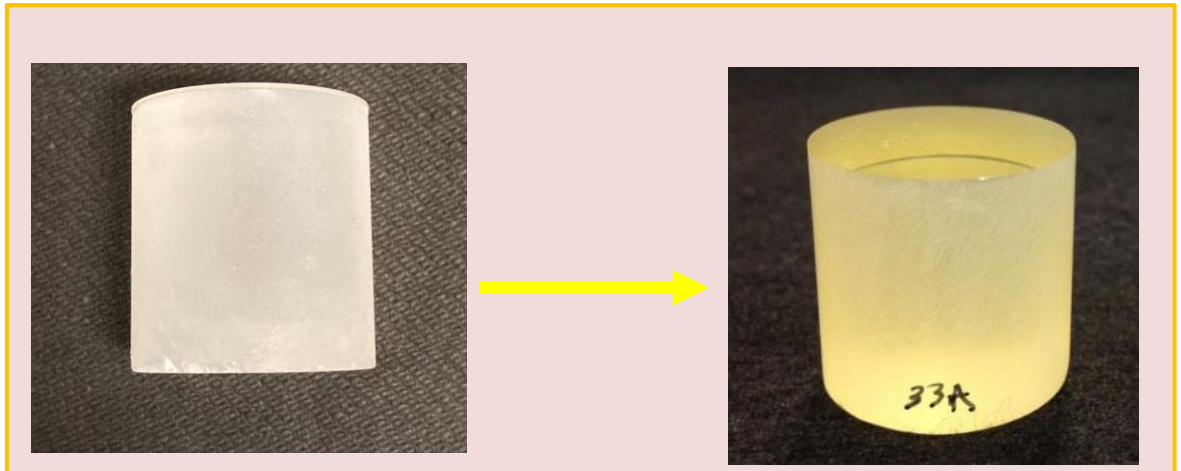
Stilbene crystal:

✓ **heavy damaged also at low doses (21 kGy)**

Not suitable for ITER environment

Gamma radiation damage test: scintillators (2)





EJ-299-33A before irradiation

EJ-299-33A sample irradiated @ 24 kGy

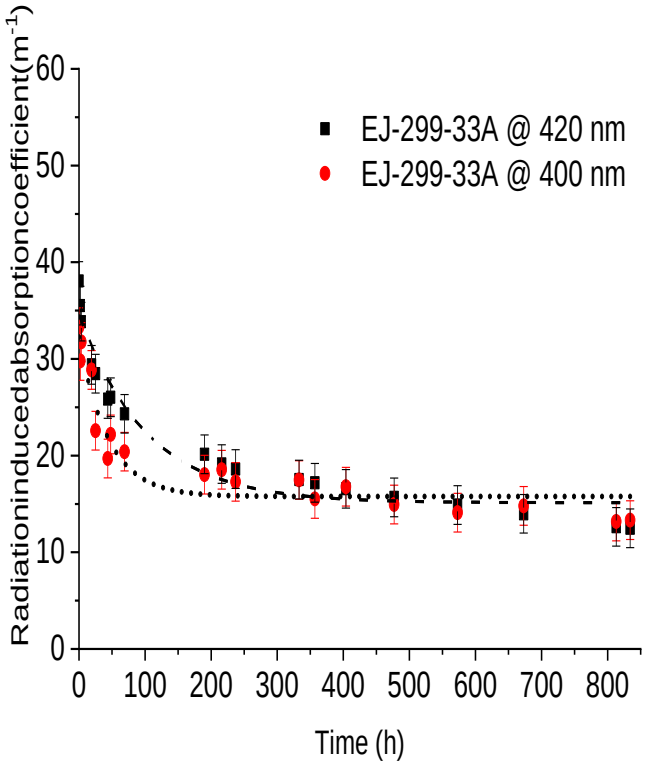
EJ-299-33A and EJ-299-34:

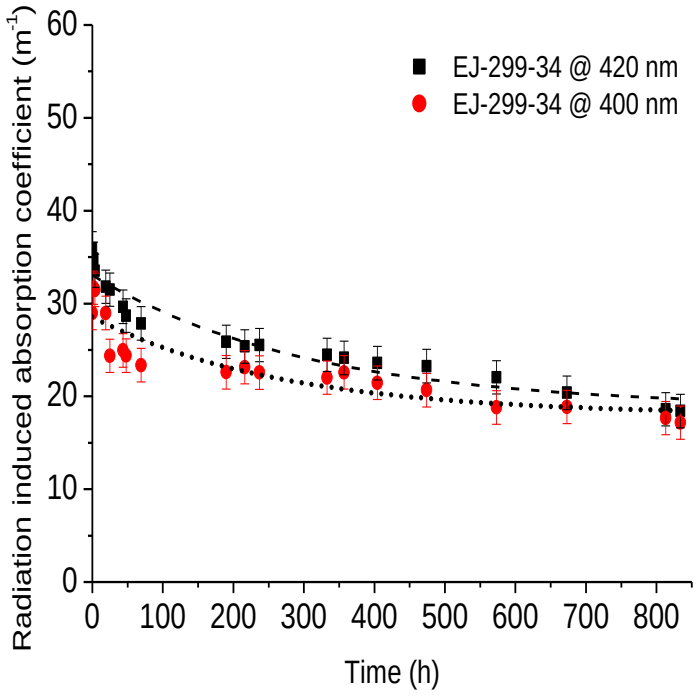
- ✓ radiation damage @ 420nm (emission wavelength peak) linearly increases with the absorbed dose
- ✓ no saturation is reached

Gamma Radiation Damage Test: scintillators (3)

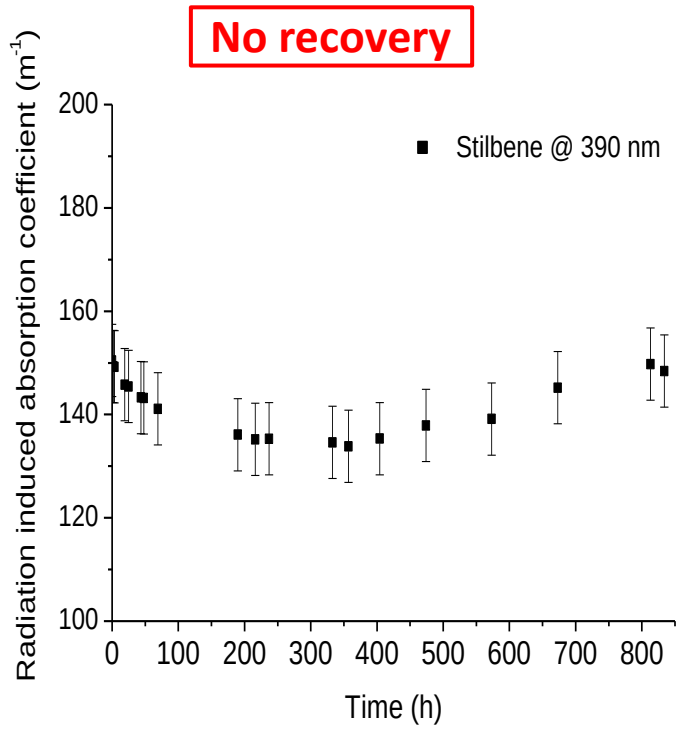
Radiation induced damage recovery after 24 kGy absorbed dose

Treatment description
35 days in the dark, at RT





No recovery



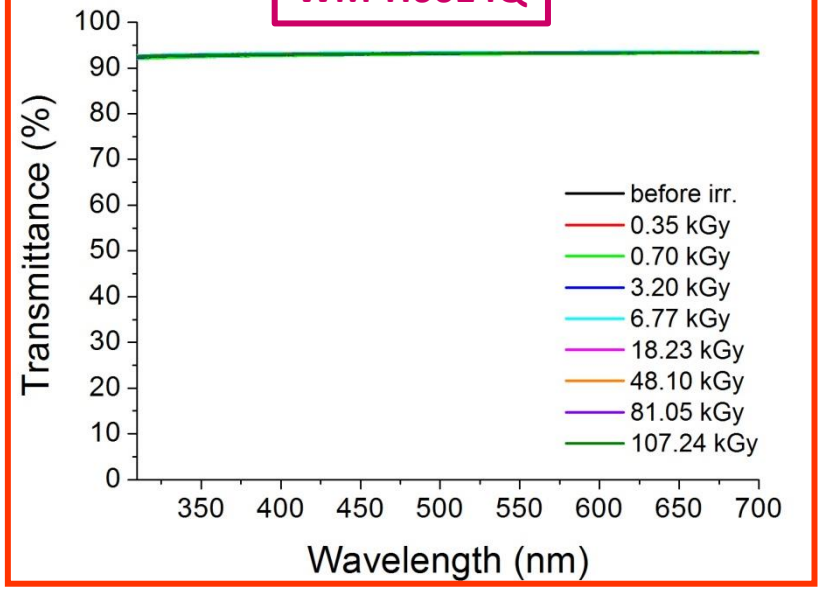
Gamma radiation damage test: Optical Windows (1)

Samples	Diameter (“)	Thickness (“)	Composition	Producer
WM-H6614Q	2	1.63	Synthetic silica	Hamamatsu
WM-H6614	2	3.27	Borosilicate glass	Hamamatsu

Irradiation up to 107 kGy abs. dose
RT, air, in the dark
(dose rate ~ 160 Gy/h)

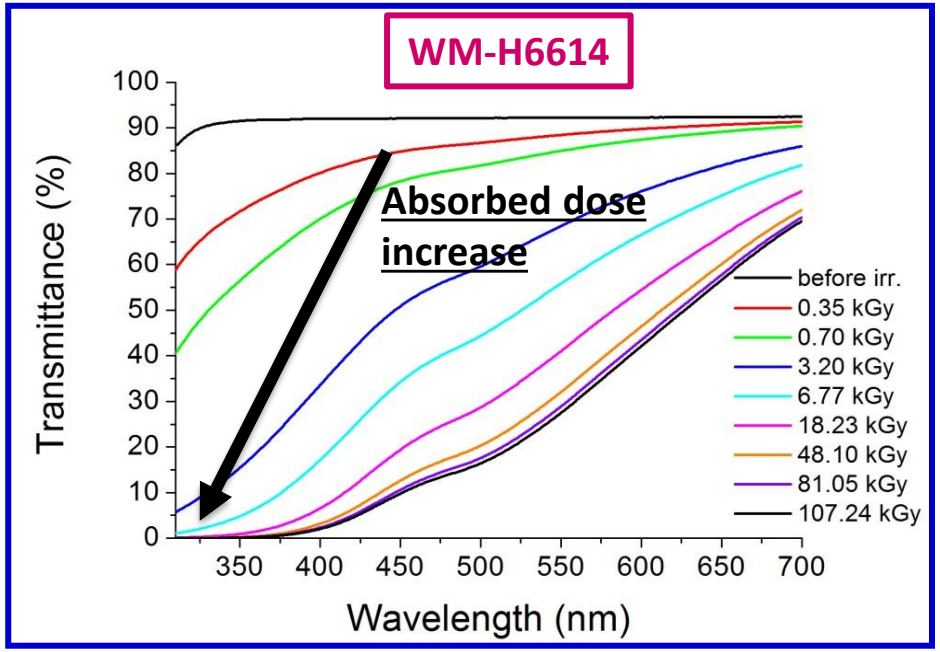
Synthetic silica: no modification up to 107 kGy!

WM-H6614Q



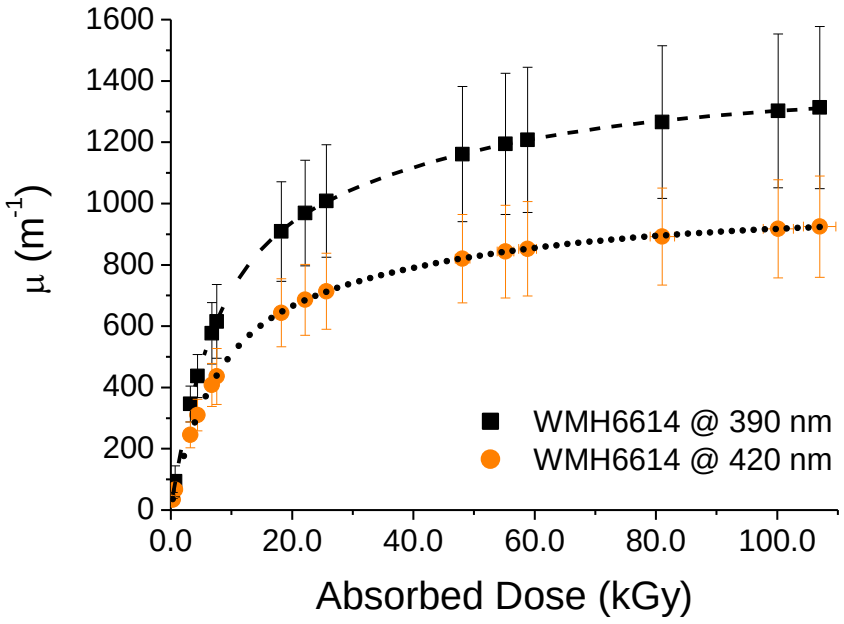
Borosilicate glass: seriously damaged

WM-H6614

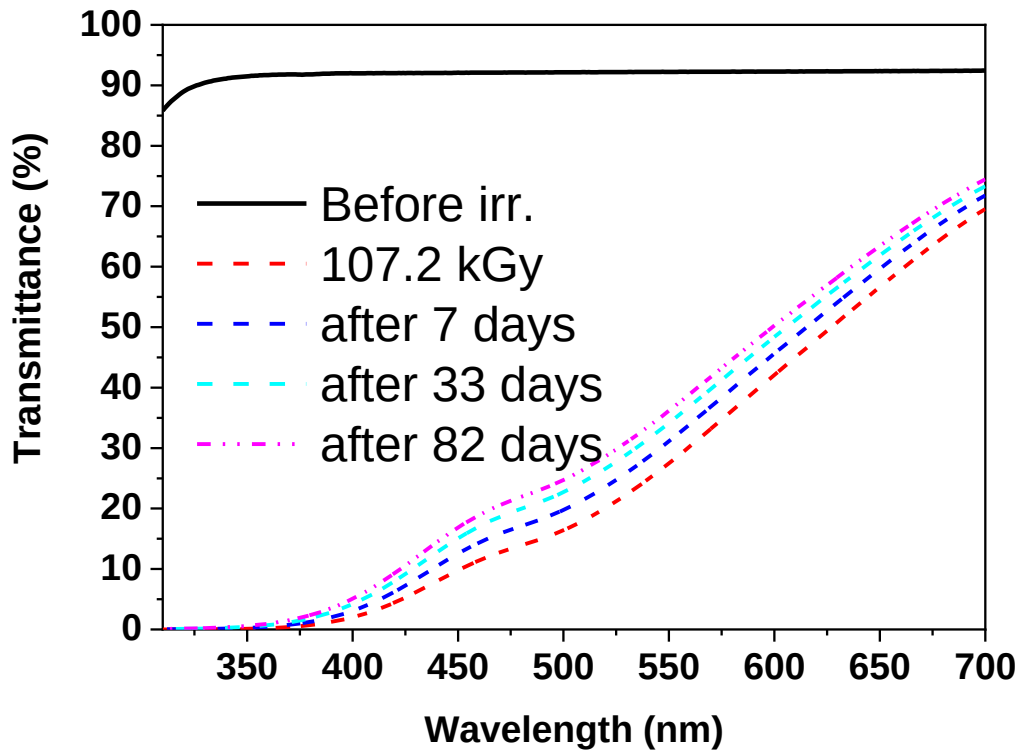


Gamma radiation damage test: Optical Windows (2)

Radiation induced absorption coefficient μ vs absorbed dose at scintillators emission wavelength



- ✓ *Saturation above 50 kGy*
- ✓ *heavier damage at 390 nm (Stilbene emission peak wavelength)*

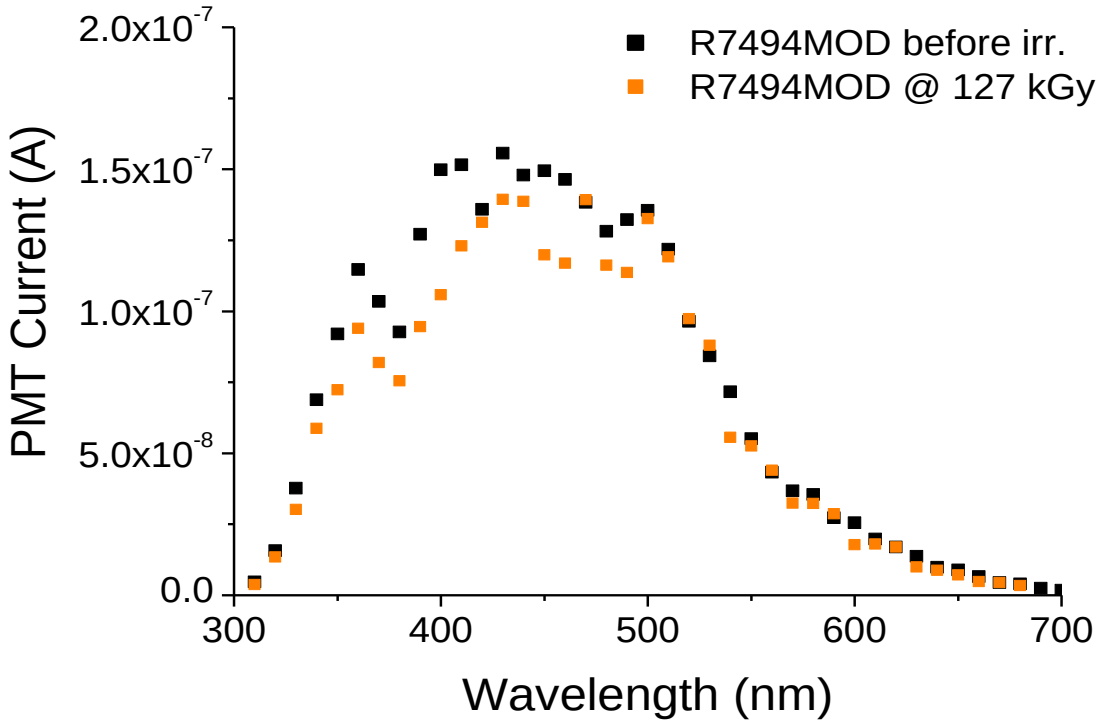


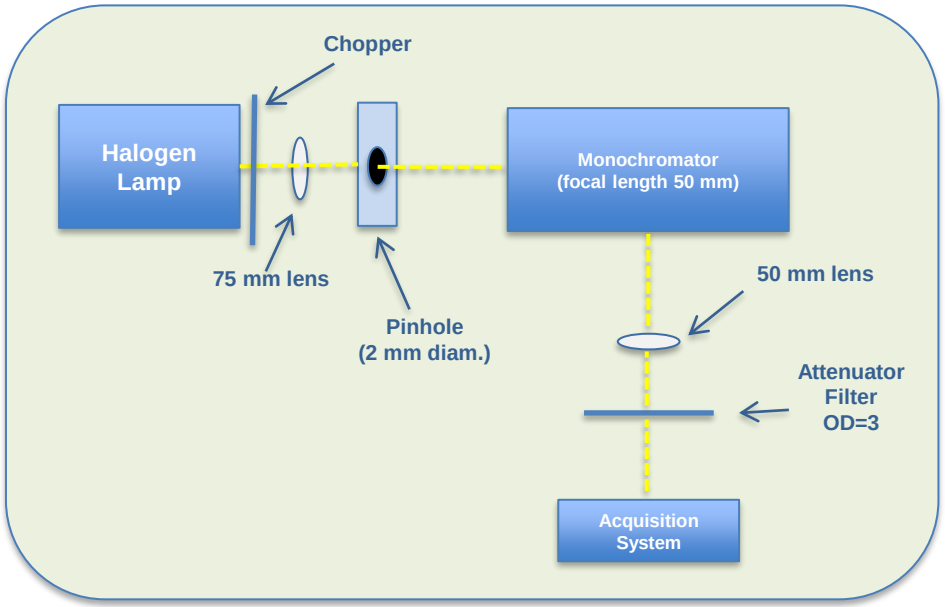
Recovery study (RT, in air, in the dark)

- ✓ *No significant improvement in the range of interest after 3 months*

Gamma radiation damage test: PMTs (3)

Quantum Efficiency evaluation (by PMT anodic current measurement)
Light source: halogen lamp QTH (100 W)



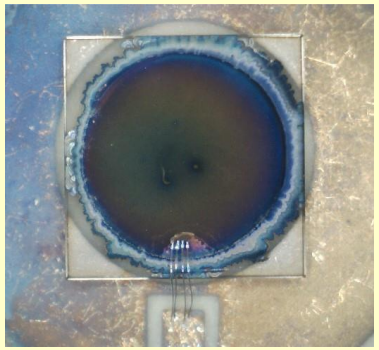


- ✓ **Slight PMT current decrease up to 127 kGy absorbed dose (same results for all PMTs)**
- ✓ **Hamamatsu PMT current around 10 times higher than ET PMTs**

Gamma radiation damage test: Single-crystal diamond detectors (1)

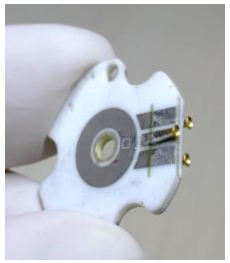
Samples	Irradiation parameters	Composition	Producer
SC0099	1 MGy; dose rate: 300 Gy/h	Single-crystal diamond Contact: TiC/Ag (50nm)	Micron semiconductor Ltd
SC0105	4.66 MGy; dose rate: 1.4 kGy/h	Single-crystal diamond Contact: TiC/Ag (50nm)	Micron semiconductor Ltd

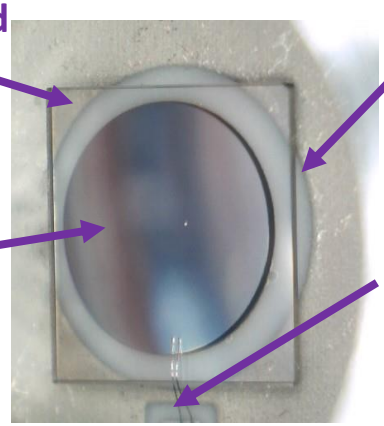
Optical inspection:



SC0099
(1.00 MGy)

SC0105
(4.65 MGy)



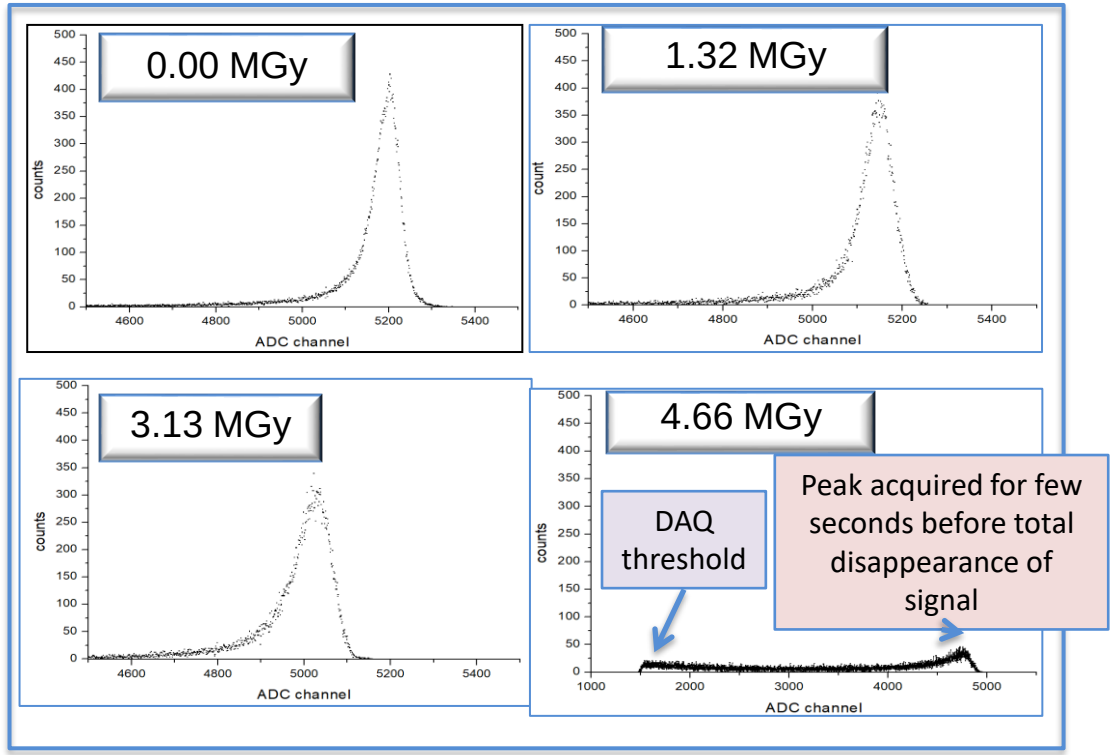


Silver layer seriously peeled and detached at the highest absorbed dose and almost intact up to 1 MGy

Gamma radiation damage test: Single-crystal diamond detectors (2)

Energy spectra with 5.5 MeV α particles
(^{241}Am source, activity = 2.1 kBq)

Absorbed dose [MGy]	peak [ch]	FWHM [ch]	Energy Resolution %	CCE* %
0.00	5197	69	1.3	100
1.32	5147	79	1.5	99
3.13	5025	93	1.7	97
4.66	n/a	n/a	n/a	0



- **Single-crystal diamond detectors have an acceptable behaviour up to 3.13 MGy but with a partial damaging induced by gamma radiation.**

- **At 4.66 MGy detectors were broken.**

Vacuum Vessel components

Analysis and results on sensors, optical fibers and metallic wires

Samples and irradiation tests

Test has been conducted irradiating displacement sensors to monitor deformation in ITER magnets and Vacuum Vessel

- ✓ **SENSORS**
- ✓ **50 m long OPTICAL FIBER SPOOLS**
- ✓ **NiCr METALLIC WIRE**

Absorbed dose ~ 6 MGy

Dose rate ~ 3.5 kGy_{Si}/h

- **Samples irradiation tests were performed at RT and in air**

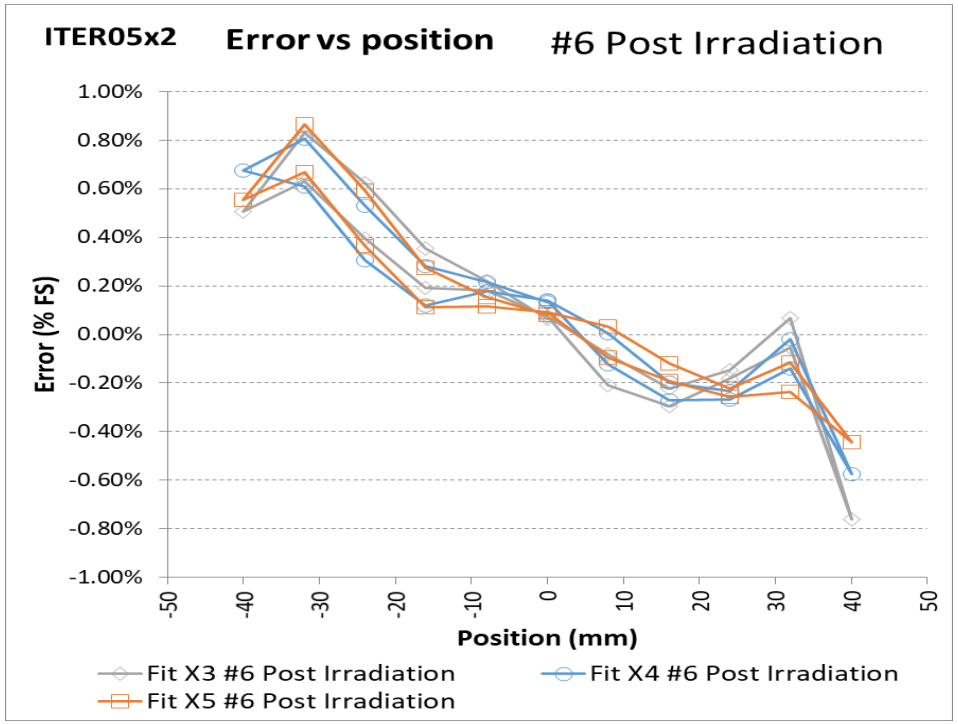
SMARTEC

Sensors and NiCr metallic wire

Gamma radiation damage test: sensors

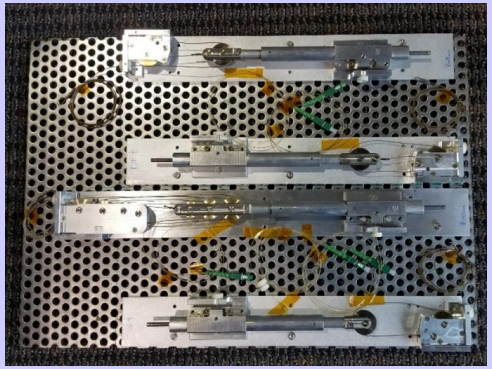
ACCEPTANCE CRITERIA:

- **No significant damage or degradation detected by visual inspection**
- **Sensors work after irradiation test**
- **Sensor signal** (% modulation) **shall be over 6%**



Calibration curve variation after irradiation

- **No significant damage or degradation have been detected**.
- **Some darkening appeared on the metallic surfaces, but** the sensors have **passed the accuracy verification.**
- **Maximum** deviation **lower than 1%** of the Full Scale (FS)
- **Minimum modulation value of 8.7% higher than 6%**



Before Irradiation

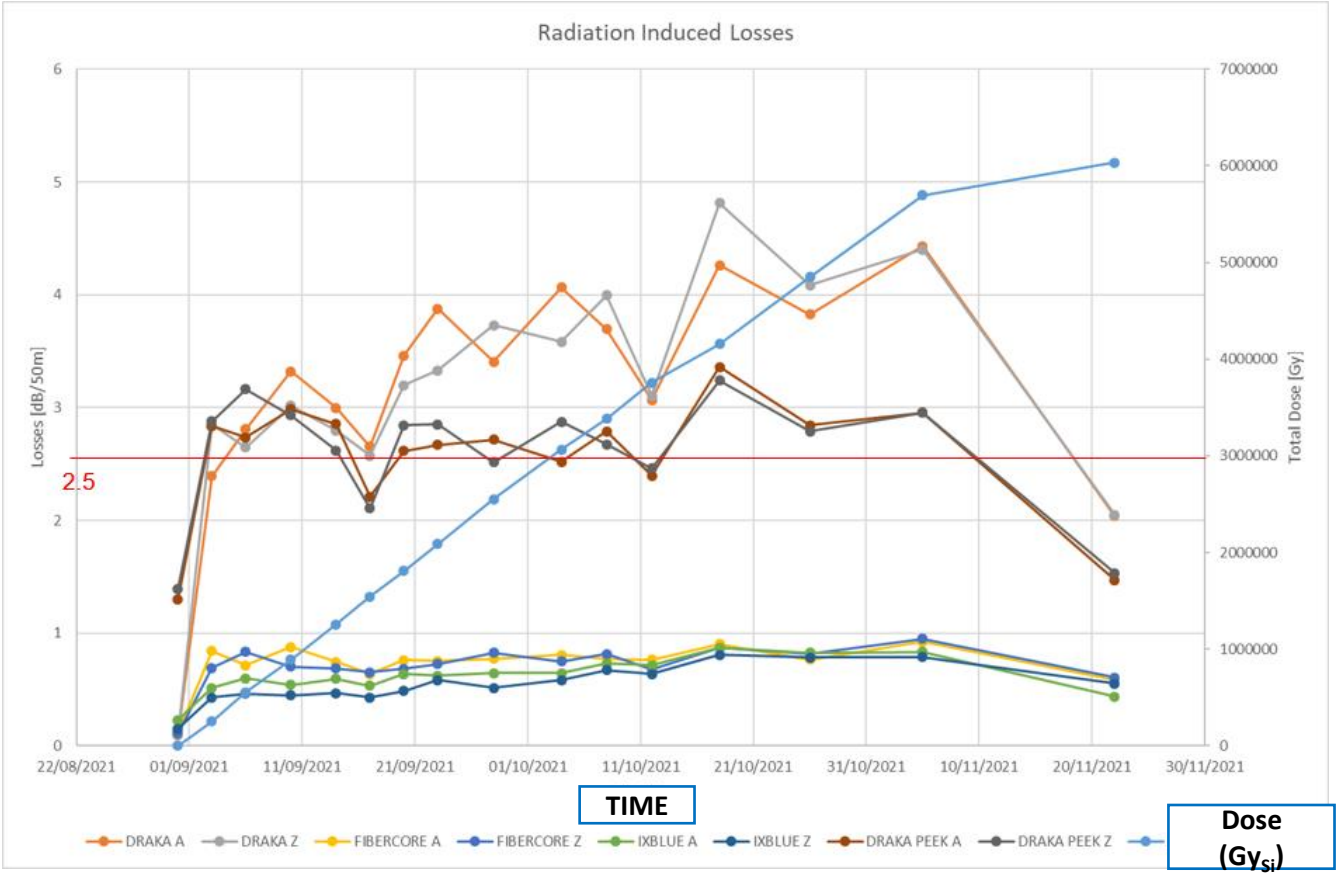
After Irradiation

Gamma radiation damage test: optical fibers

ACCEPTANCE CRITERIA:

- **No significant damage or degradation detected by visual inspection**
- **Measured insertion loss lower than 0.05dB/m**

- To measure the fibre performances, an Optical Time Domain Reflectometer has been used.
- The performances of tested **optical fibre spools** have been measured at regular intervals during irradiation and at the end of the irradiation test
- **No significant damage or degradation have been detected. The insertion losses are below the fixed limit.**



CONCLUSIONS

- **Neutron detector candidates for the ITER Radial Neutron Camera were investigated at the ^{60}Co ENEA Calliope facility:**
  - **scintillators:** for all samples consistent degradation after γ irradiation; Stilbene is heavy damaged also at low doses.
  - **Optical windows:** no modification on synthetic silica; serious damage on borosilicate glass.
  - **PMTs:** R7494 → insensitive to γ rays; ET9107→consistent degradation with the absorbed dose increasing.
  - **Single-crystal diamond:** partial efficiency decrease at 4.7 MGy; silver layer peeled and detached at 4.7 MGy and almost intact at 1 MGy.
- **The Vacuum Vessel components were investigated at the ^{60}Co ENEA Calliope facility**
  - **Sensors, optical fibers and NiCr Metallic wires:** no significant damage or degradation have been detected.
- **Despite the irradiation parameters employed for the ITER project, they can be considered like those expected in the fission nuclear environments, extremely damaging as ITER.**

Thank you for your attention!

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