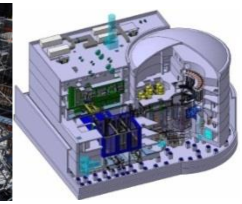
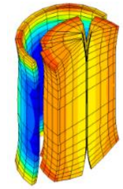
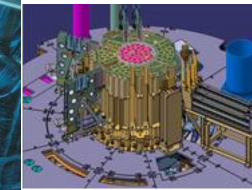
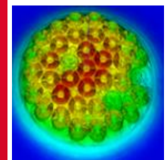
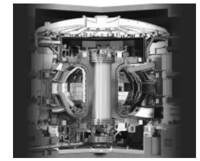
DE LA RECHERCHE À L'INDUSTRIE






Radiation detection and measurement for non-destructive characterization and control in nuclear media.

Abdallah Lyoussi
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Senior Fellow
IEEE Distinguish Lecturer
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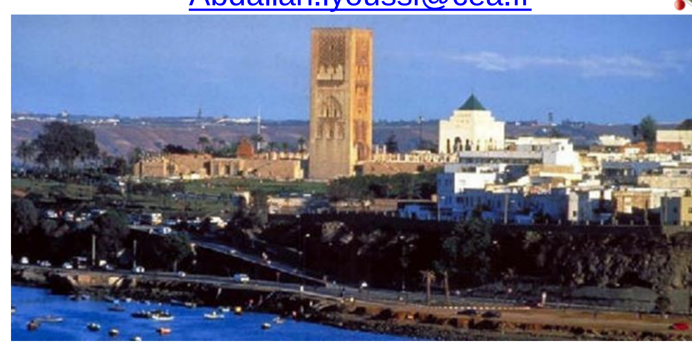
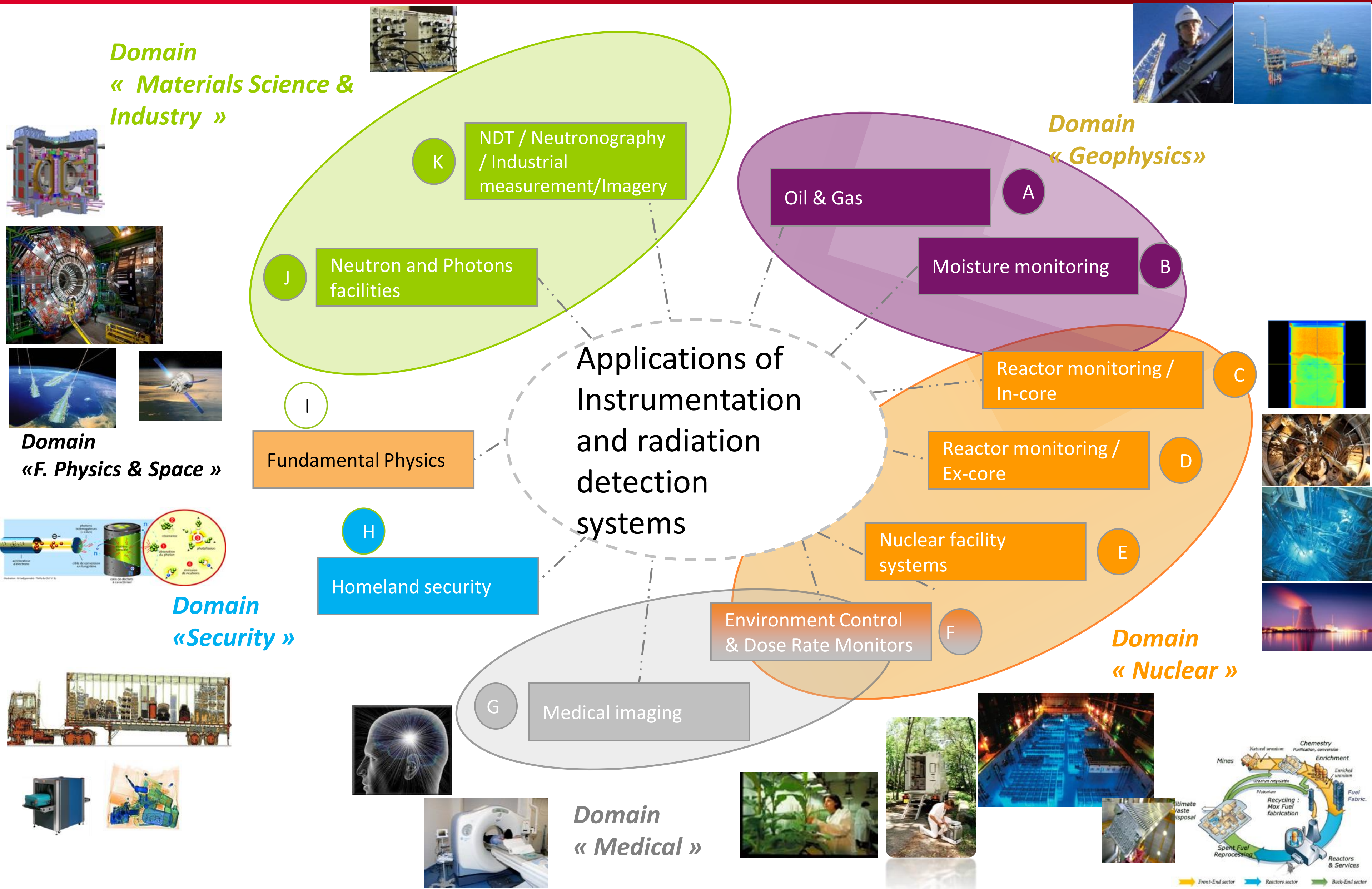


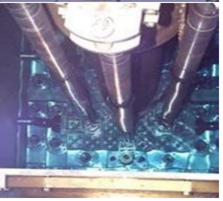
Rabat Educom Instrumentation Summer School; Univ Of Rabat, July 1st-11th 2024

SUMMARY

- INTRODUCTION
- Specific features, constraints and requirements
- Examples of radiation measurements and associated instrumentation for :
  - In Pile Measurements
  - Radioactive waste characterization and control
- Conclusions and prospects

RADIATION DETECTION & MEASUREMENTS: APPLICATION DOMAINS / SUB-DOMAINS





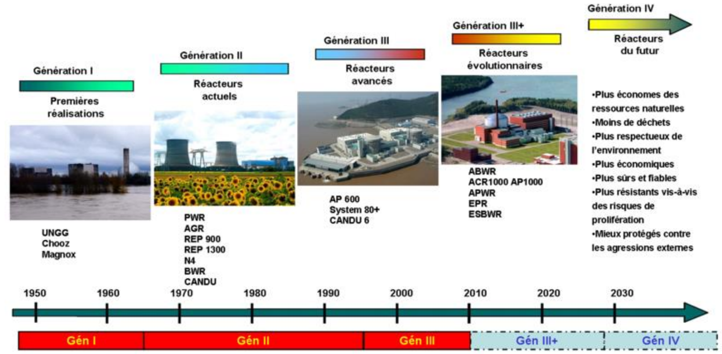
2 Main Families

Experimental and Research Reactors :

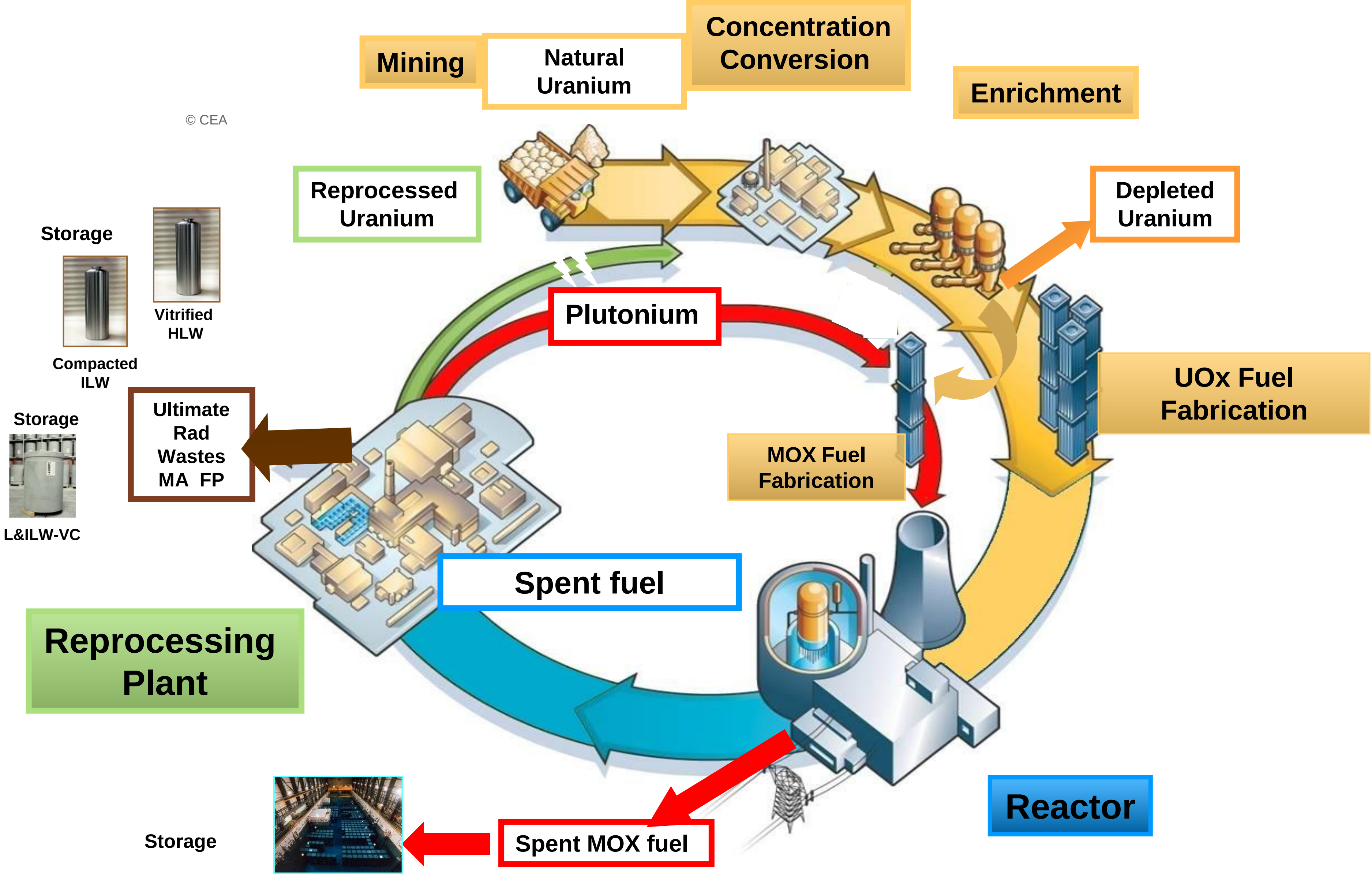
- Zero Power Reactors ZPR (Eole, Minerve, Masurca, LR0…)
- Material Research Reactors MTRs (Osiris, JHR, BR2, Maria, ATR…)
- Research Reactors (ILL, Orphée, TRIGA)
- Safety Study Reactors (Cabri, Treat…)
- Reactors for special applications (RES)
- Research and Education Reactors (Ulysse, Minerve, ISIS, TRIGAs…)

Nuclear Power Reactors NPPs :

- GEN II (REP, REB …)
- GEN III et III+ (AP600, EPR, AP1000 …)
- SMR, AMR
- GEN IV (SFR…)



Nuclear Fuel Cycle

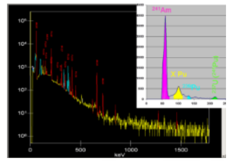


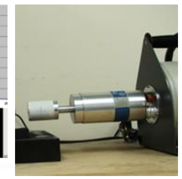
Nuclear Fuel Cycle :

Instrumentation & measurement are key aspects for control & characterization

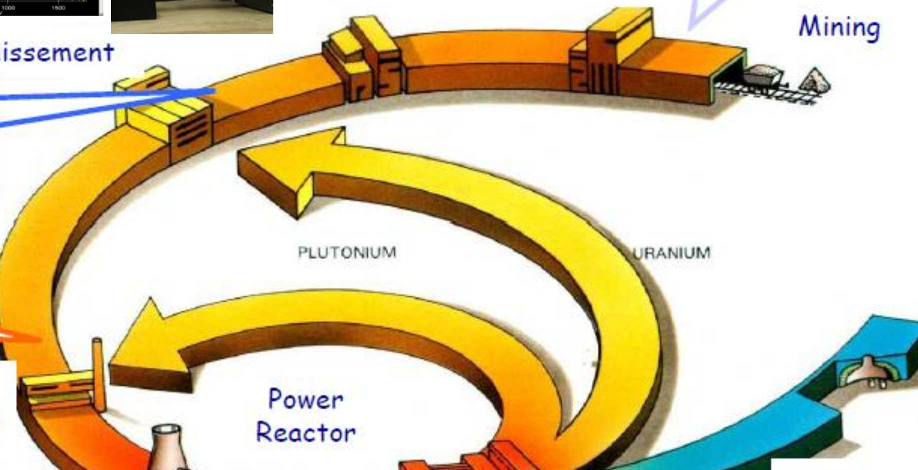
Measurements and Specific Controls are Strongly needed and necessary at each step /sub-step of Nuclear Fuel Cycle.

“From Mining to Waste Storage : Main Fuel Cycle Steps»



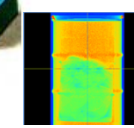


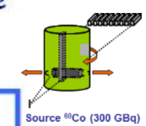
Ore Characterization



Identification and Characterization of final product

- Mechanical properties of Fuel
- Advanced Characterization of Fuel
- Non Destructive Assays





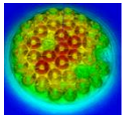
Measurement in Experimental Reactor under representative conditions.

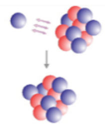
Radioactive Waste Characterization & Management …

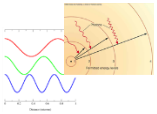
Monitoring and rad. protection : Control, NDA

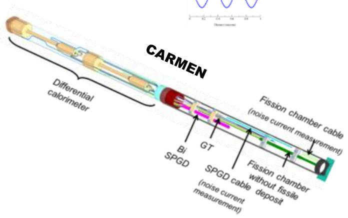
- Chemical & Physical Characterization
- Control of U-Pu
- Working Control

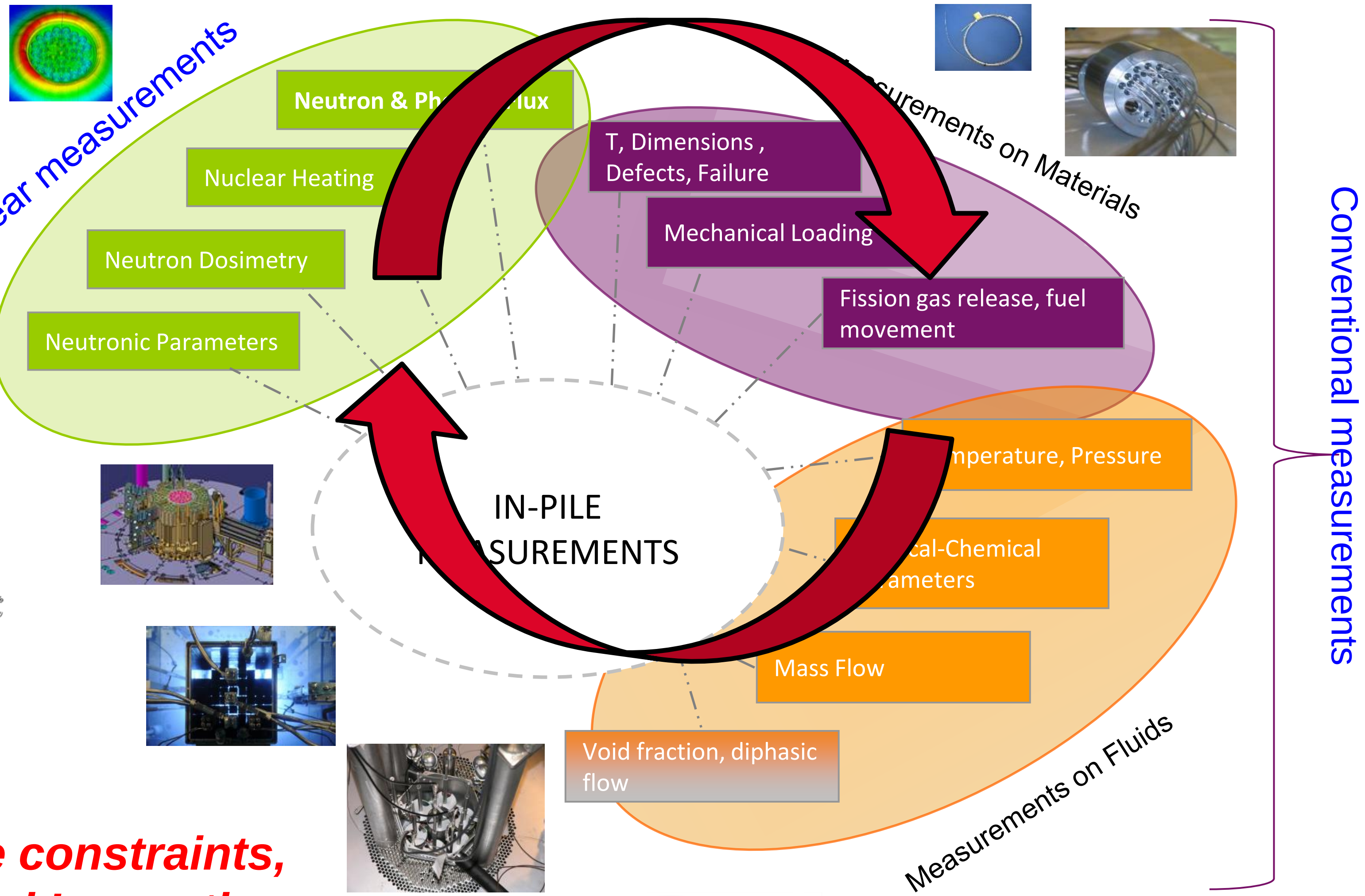
Main in-pile measurements



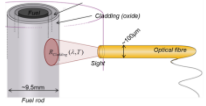


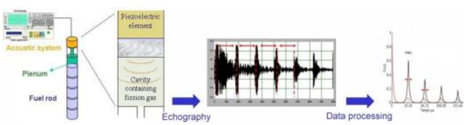






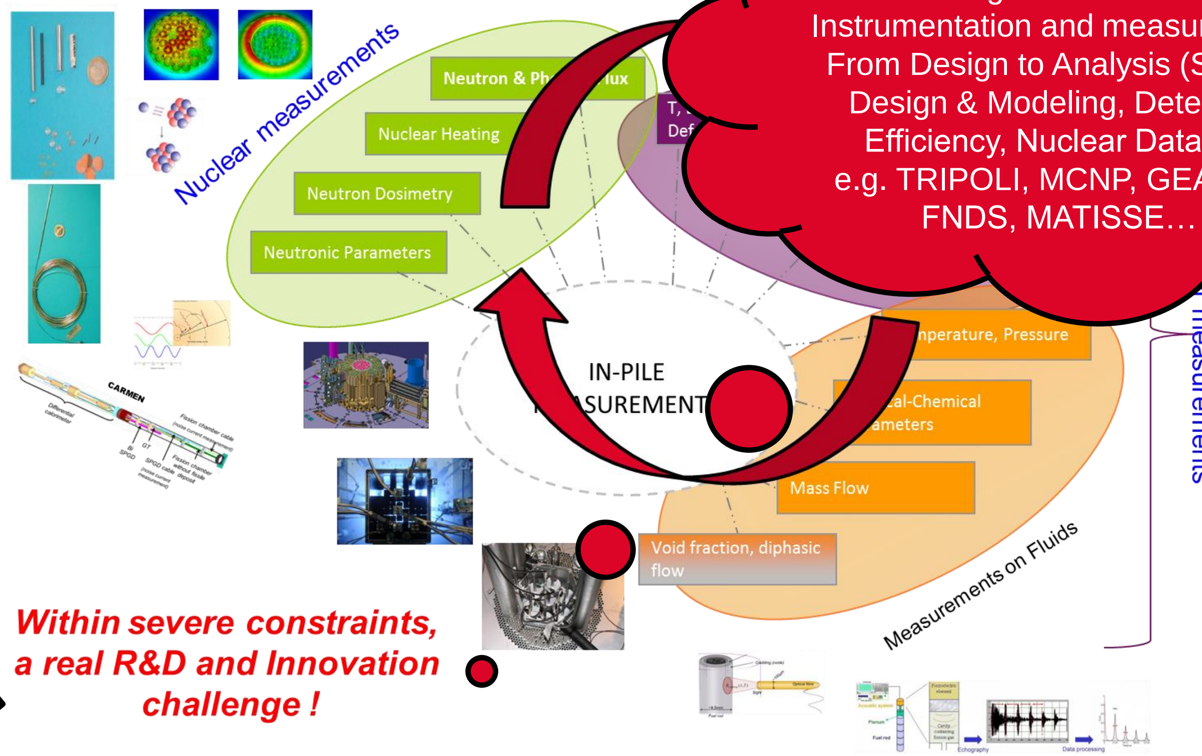
Within severe constraints, a real R&D and Innovation challenge !





INSTRUMENTATION & MEASUREMENTS IN NUCLEAR MEDIA

Modeling / Simulation
is currently used during R&D as well as during routine issues of Instrumentation and measurement: From Design to Analysis (Sensor Design & Modeling, Detection Efficiency, Nuclear Data…).
e.g. TRIPOLI, MCNP, GEANT4, FNDS, MATISSE…



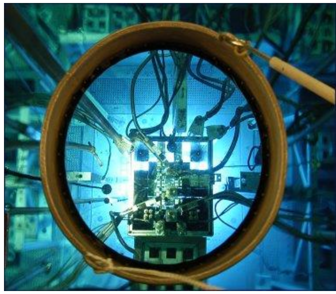
Within severe constraints, a real R&D and Innovation challenge !

Also :
(D/D, RW, NDA, Safeguards)

Dosimetry, Gamma and X-ray spectrometry, Gamma and X Imaging, Neutron Imaging, Alpha radiography, Beta spectrometry, passive & active neutron measurement, PNAA, DNAA, Photon interrogation.

CHALLENGES FOR INSTRUMENTATION & MEASUREMENTS IN *NUCLEAR ENVIRONMENTS*

Sensitivity & Selectivity

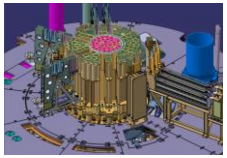


Reliable

impossible or difficult maintenance on irradiated objects

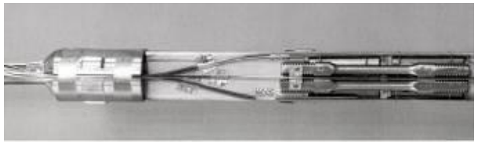
Accurate despite a very severe environment

to follow modelling progress; ex: µm dimensional measurements, ΔT<5°C



Miniature

narrow location to get maximal neutron flux: few mm available

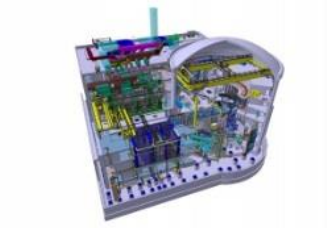


Corrosion resistant

operation in pressurised water, high temperature gas, liquid metals…

High temperature resistant

> 300°C, up to 1600°C



Neutron / γ "resistant"

dose > 15kGy/s and > 10dpa/y

Extremely Conservative

SUMMARY

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  - Radioactive waste characterization and control

- ❑ Conclusions and prospects

Reminder :

Main Aim of Nuclear Reactor Measurements : To reduce uncertainties

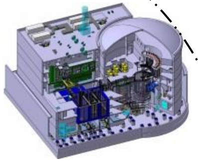
To reduce uncertainties at each step of the process; **from conceptual design to final running of nuclear system(s)**

Basic/Fundamental Data

Measurement of Basic Physical Data

Online Monitoring

Monitoring & Control in NPP



Design Tools

Smart/Analytical Experiments

→ Predictive / Calculations

Model Development

Verification

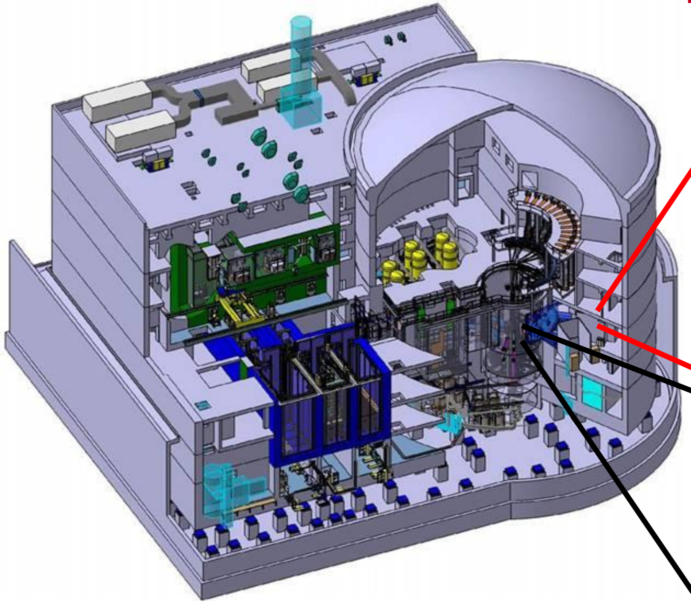
Global/Integral Experiments on ZPR Reactors

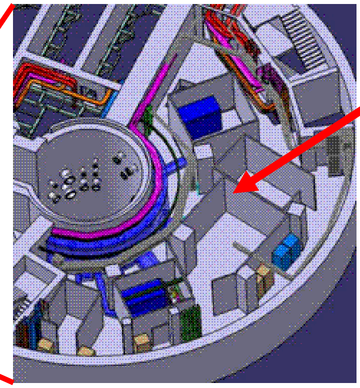
→ Check, verify, predictions

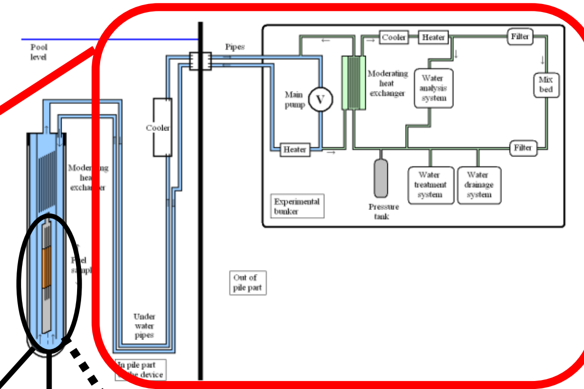
Validation of Models/ Calculation schemes

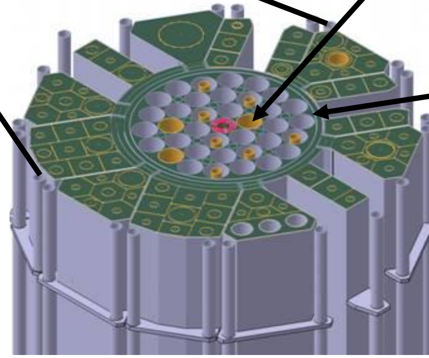
In Pile Measurements, Qualification and Testing in MTRs

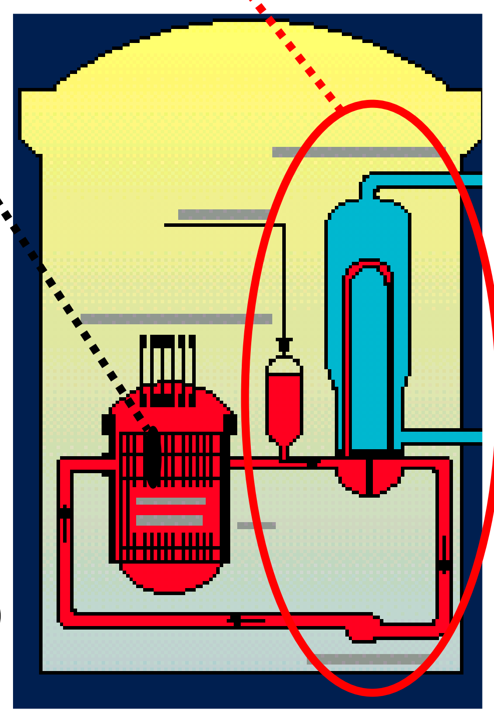
What are the Objectives of a MTR (Material Testing Reactor) ?











MTR allows to reproduce on a **small scale, real power plant** conditions and in some cases, **more severe conditions** for

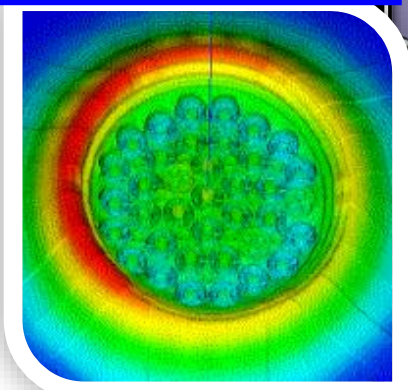
- **Material screening** (comparison of materials tested under representative conditions)

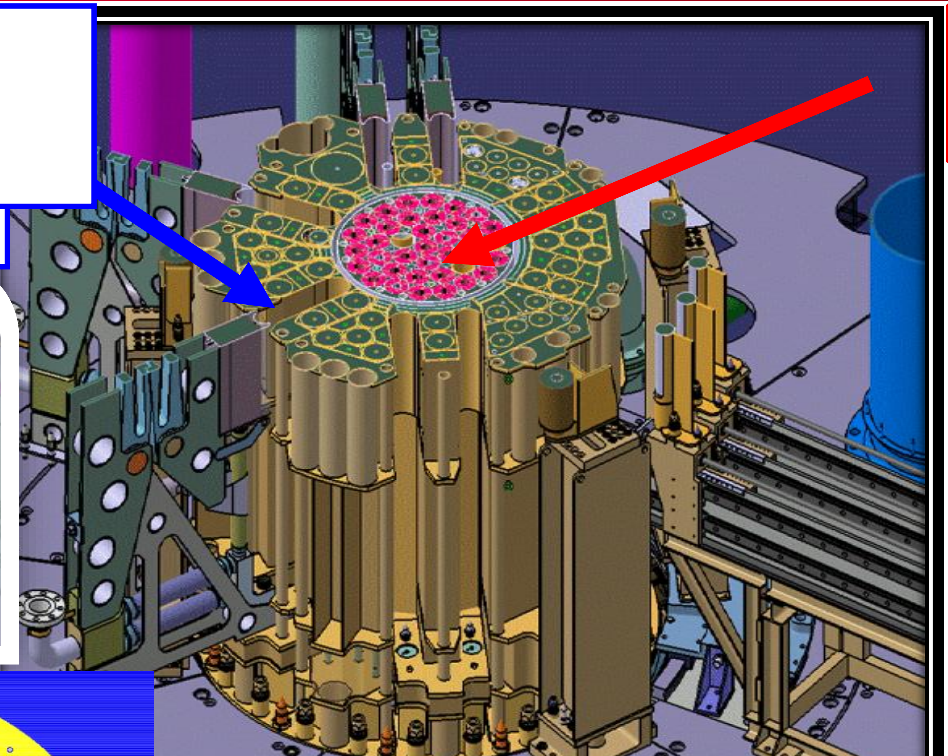
- **Material characterization** (behaviour of one material in a wide range of operating conditions, up to off-normal and severe conditions)
- **Fuel element qualification** (test of one / several fuel rods (clad+fuel))

JULES HOROWITZ (JHR) MTR REACTOR

Reflector
$\Phi \geq 5.5\ 10^{14}$ n/cm².s
20 fixed locations
6 mobile locations

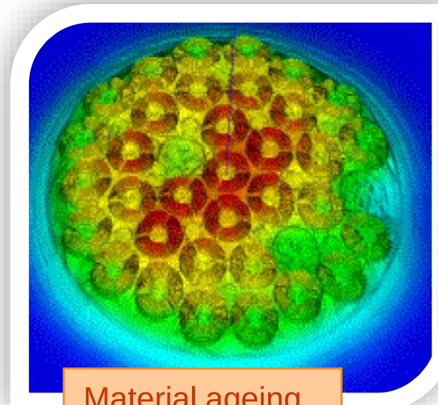
Thermal neutron flux



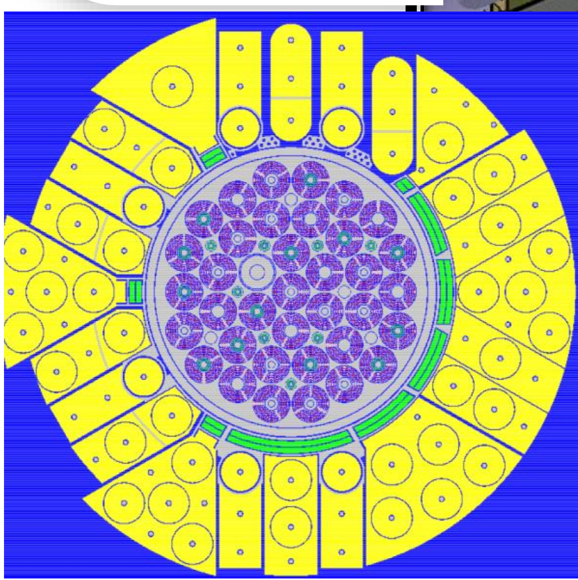


Core
$\Phi \geq 5.5\ 10^{14}$ n/cm².s > 1 MeV
$\Phi \geq 10^{15}$ n/cm².s > 0.1 MeV

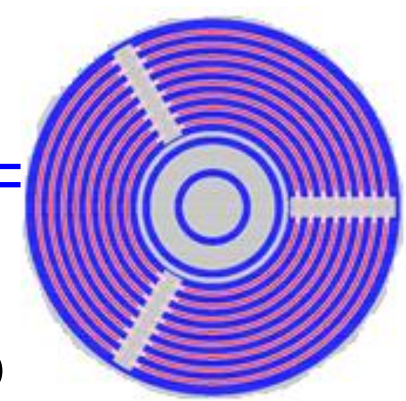
Fast neutron flux



Material ageing
(up to 16 dpa/y)



Applications :
Material and fuel samples irradiation/ageing
Radio-isotopes production for medical use
…



Geometry:
From 34 to 37 cylinder-shaped fuel assemblies
U3Si2-Al fuel enrichment of 19,75% then 27%
Aluminum racks (hosting all the fuel assemblies)
Hafnium control rods (in the center of fuel assemblies)
Beryllium reflector

IN-PILE MEASUREMENTS

Main Stakes

Radiations

Reduction of uncertainties in experimental conditions
- Neutrons / gamma flux
- Neutron spectrum
- Neutron fluence

Better knowledge of nuclear heating
→ design of experimental devices
Major stack for JHR

Physical parameters

Better characterization of thermo-hydraulic conditions
→ temperature field / fluid flows

Highly instrumented experiments
« Cook and look » → Online measurement of experimental parameters

Material behavior
New materials, better representativeness
- Temperature
- Deformations (creep…)

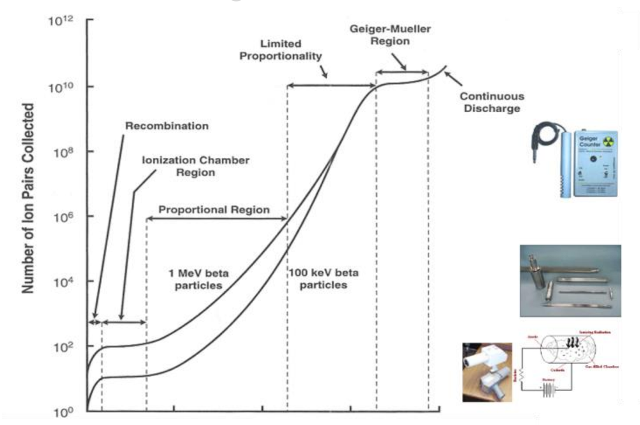
Fuel improvement and qualification
- Fission gas release
- Pellet-cladding interaction
- Accidental conditions (LOCA)

Nuclear Radiation Detectors

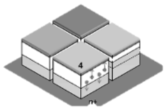
For nuclear reactor neutron detection and measurement

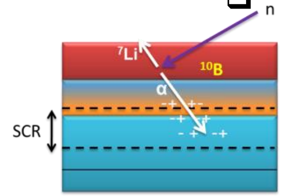
❖ On-line radiation detectors ❖

- ❑ Polarized Gaseous detectors
  - **Ionization chambers (FC, BLD)**
  - **Proportional counters (CPNB, ^{3}He)**
  - Geiger-Müller counters

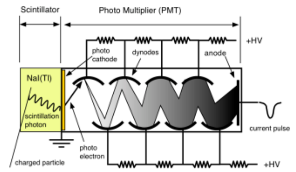


- ❑ Solid state radiation detectors
  - Semiconductor detector (Si, Ge, **SiC**, **CVD**, GaAs, CdTe…)

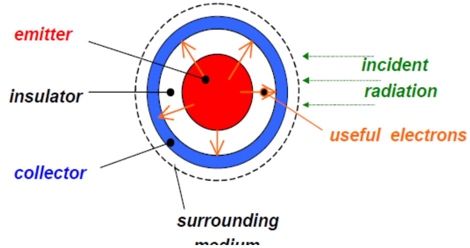




- ❑ Scintillator radiation detectors
  - Cristal scintillator
  - Organic scintillator
  - Gaseous scintillator



- ❑ Non-polarized Gaseous detectors
  - **Self Powered Neutron Detectors (SPND)**



Nuclear Radiation Detectors

On-line radiation detectors

For nuclear reactor neutron detection and measurement

❖ On-line radiation detectors ❖

- ❑ Polarized Gaseous detectors
  - **Ionization chambers**
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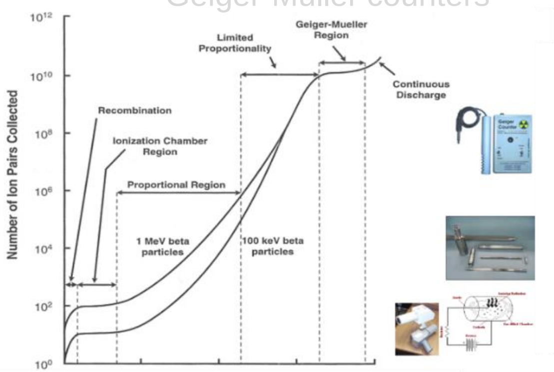
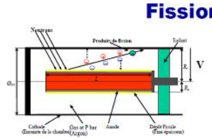


Fission Chamber



$$S = f(\tau_{fiss}, V, P, ...)$$

$$\tau_{fiss} = N\sigma\phi$$

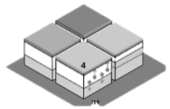
Output Signal depends on :

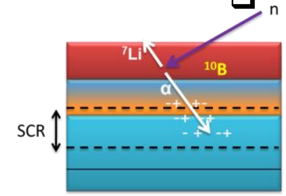
H.V., gas pressure, geometry, converter material, its mass, its thickness, its density, neutron flux…harsh environment.

The main manufacturing steps :

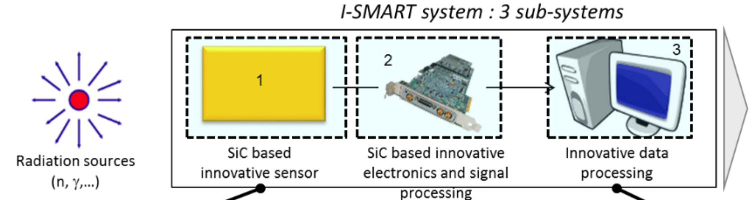
- Process of converter material deposition :
- Chamber assembly
- Filling the chamber with gas (Argon)
- Primary tests of fission chamber

- ❑ Solid state radiation detectors
  - Semiconductor detector (Si, Ge, **SiC**, **CVD**, GaAs, CdTe…)

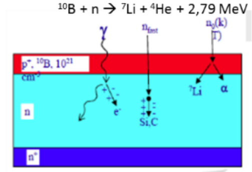




I-SMART system : 3 sub-systems

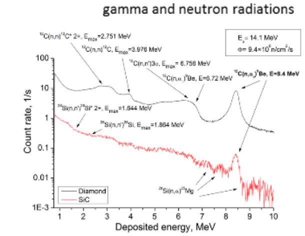


- Silicon Carbide spectroscopic sensor
- Combines detection capacity for thermal and fast neutron as well as γ ray
- Neutron detection based on ^{10}B (3900 barns): $^{10}B + n \rightarrow {}^{7}Li + {}^{4}He + 2{,}79$ MeV



- Silicon Carbide based electronics
- Front end and signal processing
  - Operational amplifier
  - Analog to digital converter
- Designed for High temperature operation
- Proprietary SiC bipolar analog/mixed-signal integrated circuit technology

- Data processing : Tools for signal recognition
- Tools for advanced modeling and signal interpretation of SiC spectroscopic detectors.
- Numerical simulation of radiation interaction with SiC sensor.
- Capability of simultaneous spectroscopic detection of gamma and neutron radiations



Fission chambers

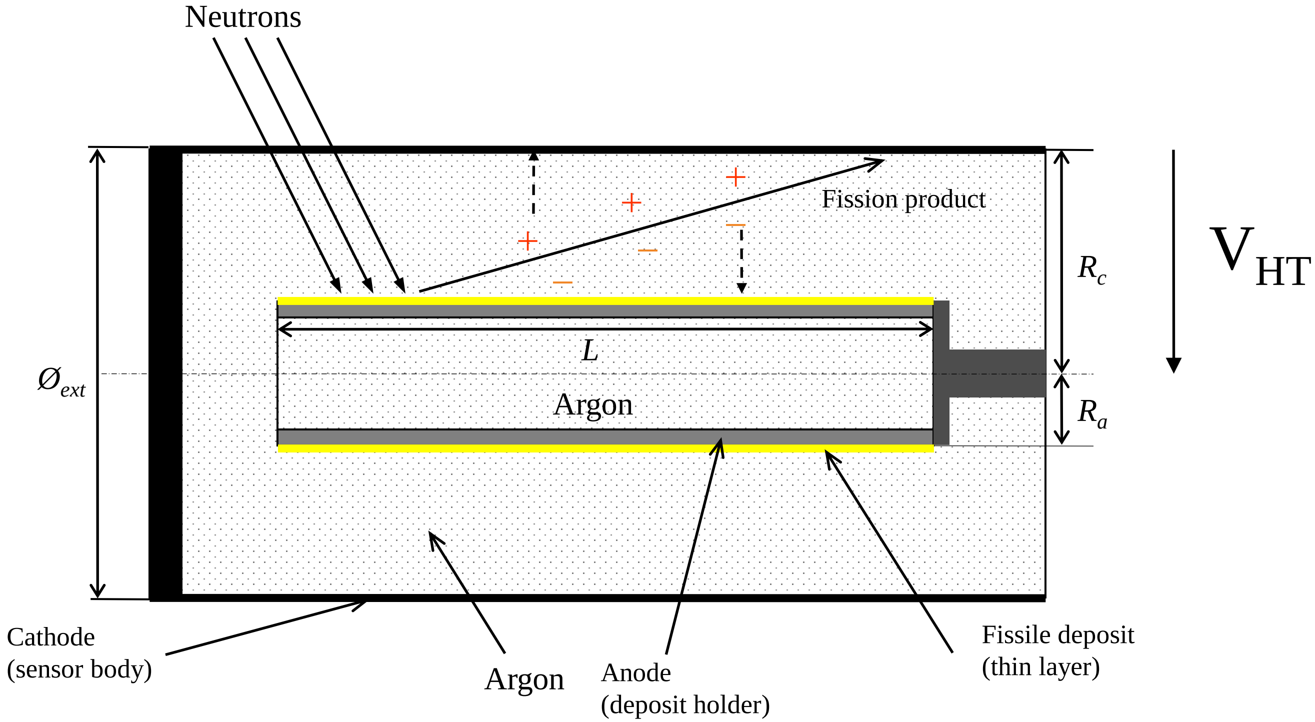
Online and real-time neutron flux measurement :

- ✓ Absolute/relative Measurements
- ✓ Amplitude of 10^6 to 10^{15} $n.cm^{-2}s^{-1}$
- ✓ Absolute or relative measurement (axial flux profile)

Principle: Measurement of the current generated by fission reactions in a fissile material (generally U_{235}) deposited on an electrode

$$s = f(\tau_f, V, P, \ldots)$$

$$\tau_f = N \cdot \sigma \cdot \phi$$

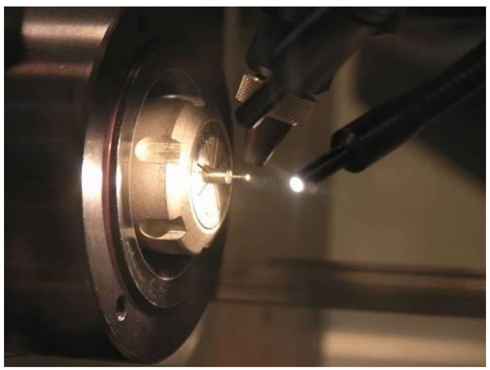


On-line Neutron measurements

CEA – Cadarache Fission Chamber Workshop

PHOTONIS

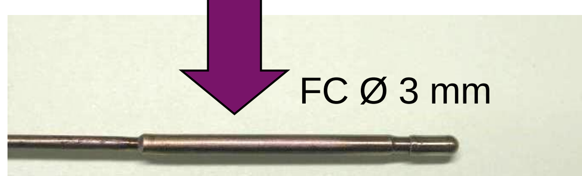
- **Design and Realization of sub-miniature fission chambers**
  - Characterized fissile deposits (mass/composition)
  - Optimized and dedicated Geometries
  - High temperature operation (> 400°C)



Thorium 232
Uranium 233, 234, 235, 238
Neptunium 237
Plutonium 238, 239, 240, 241, 242
Américium 241
Curium 244

FC Ø 1,5mm / 4mm / 8 mm

FC Ø 3 mm

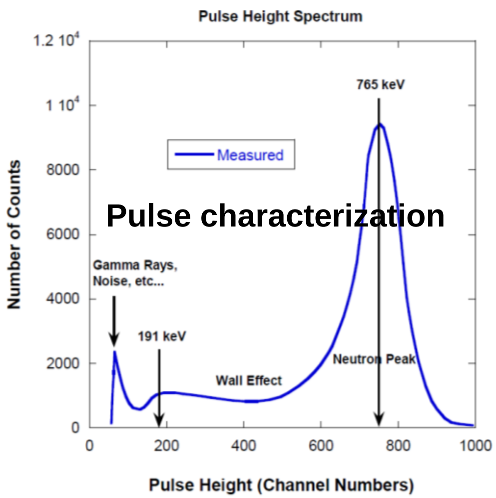


CF Ø 1,5mm

3-Bodies FC

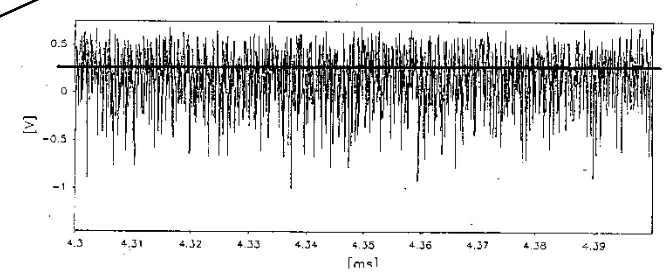
On-line Neutron measurements

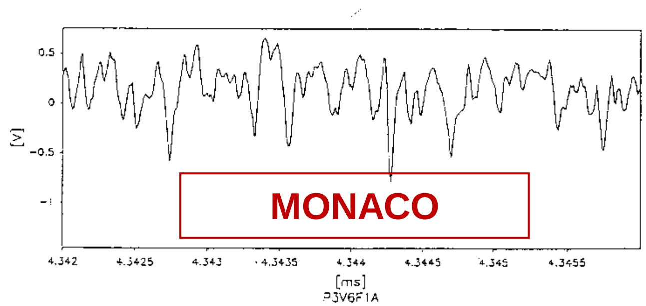
Fission Chamber operating modes

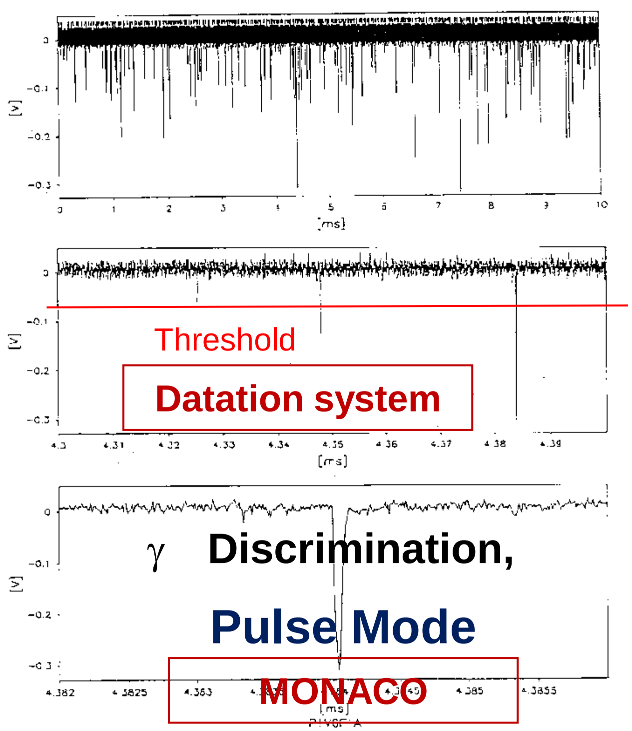


Pulse characterization

Counting Rate







Threshold

Datation system

γ **Discrimination,**

Pulse Mode

MONACO

MONACO

Current Mode

SPECTRON

MONACO

Fluctuation Mode (Campbell)

$V^2 = KNQ^2$

V^2 : variance

Q : Average charge per element ($Q\gamma < Qn$)

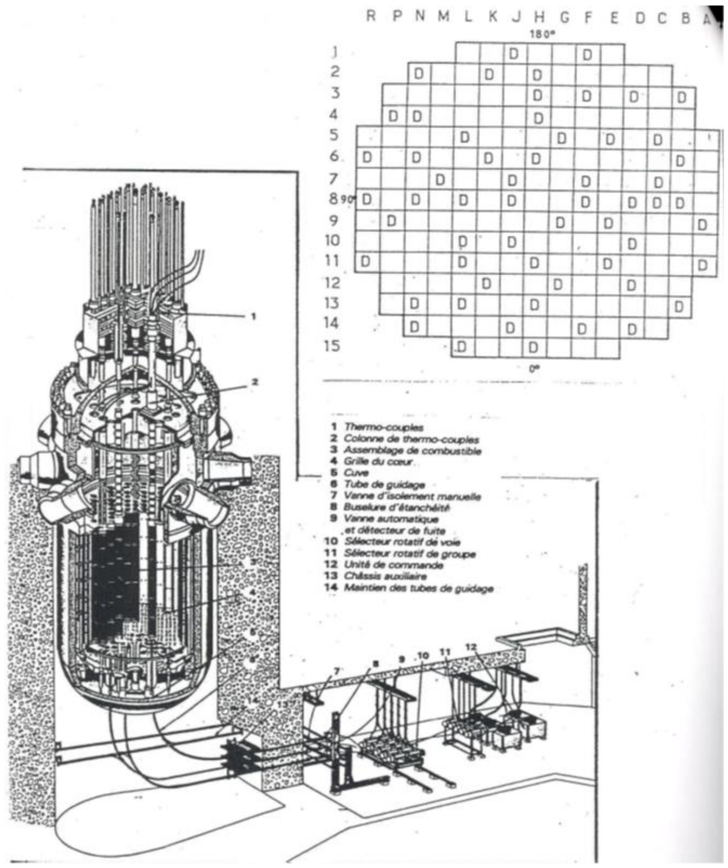
N : Average counting rate

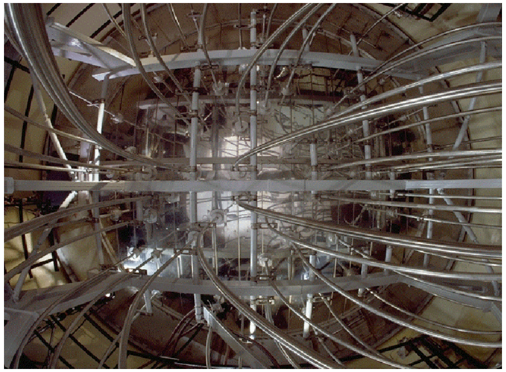
→ **γ rejection**

Mesure Incore

Pour les REP: Chambre à fission mobile (CFUF43) associée à une mesure du courant moyen via un câble minéral

Pour le réacteur RES (propulsion nucléaire): Chambre à fission (CFUR64) associée à une mesure grande dynamique (modes impulsion, fluctuation et courant et via un câble minéral





Fond de cuve d'un réacteur de 1300 MWe

235U Fission Chamber : Predominant response to n_{th}

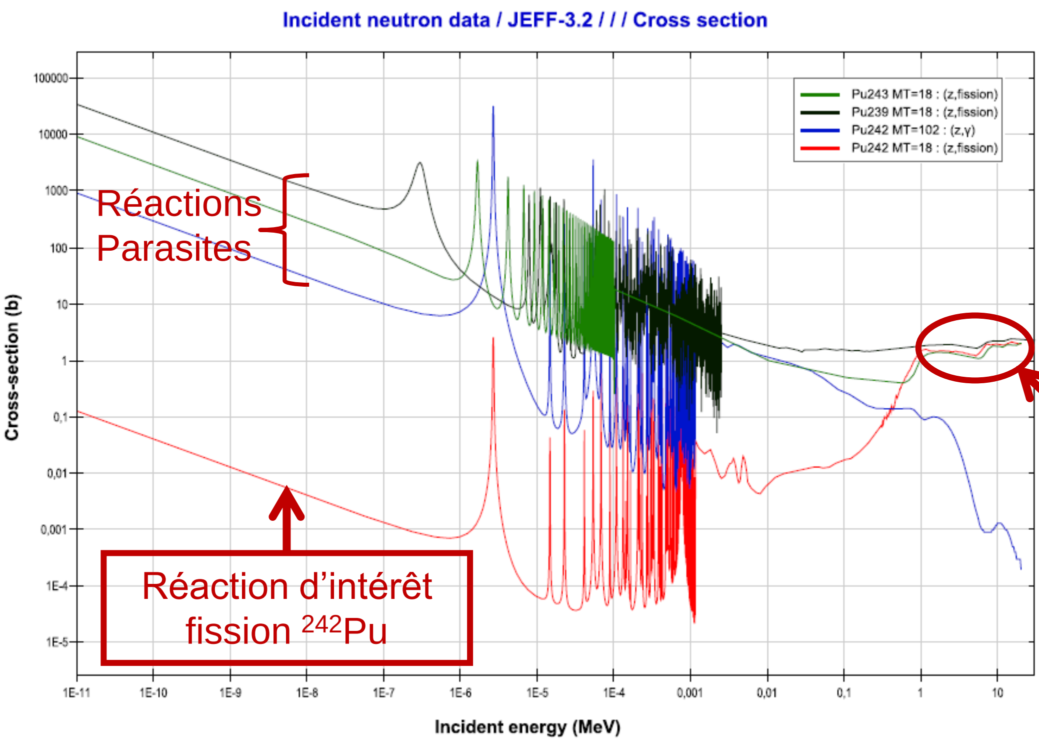
Fission Chamber for Fast Neutrons

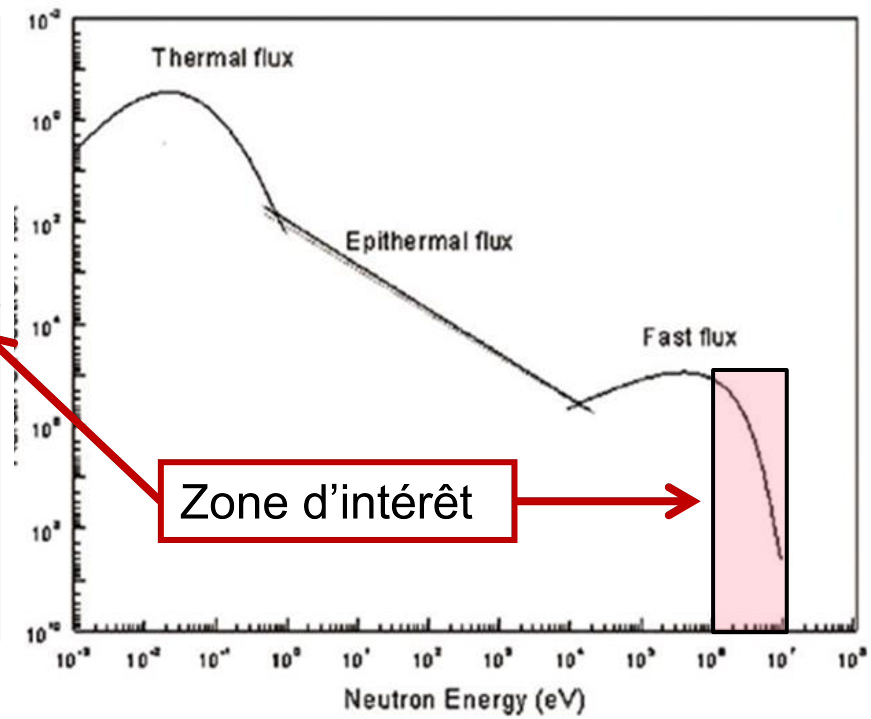
Fast Neutron Detector System - FNDS

SCK•CEN cea
Laboratoire Commun d'Instrumentation

Problématique

→ Measurement of neutron flux >1MeV is an indicator of Material Damage (dpa)





Chambre à fission pour neutrons rapides

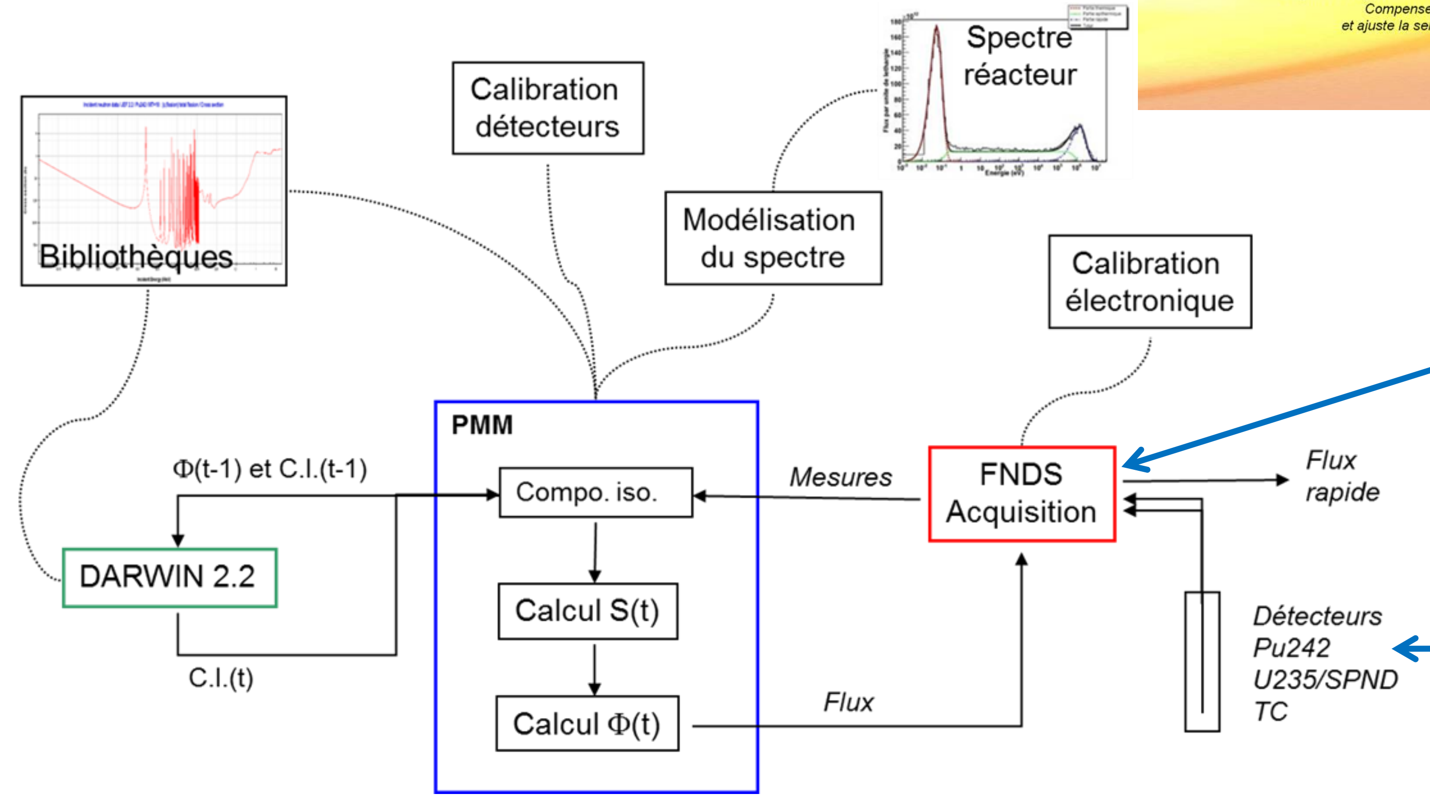
Fast Neutron Detector System - FNDS

SCK•CEN cea Laboratoire Commun d'Instrumentation

→ On-line fast n-flux measurement (E>1 MeV, σ <10%)

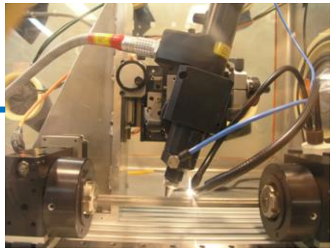
→ Flux max 10^{14} n/cm²/s - Fluence max 10^{20} n/cm²

2 Patents



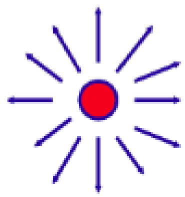
MONACO

Atelier CF



I-SMART : European Project aimed to develop and test advanced solide state sensors & measurement system for selective n-γ detection in Severe Media

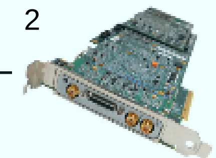
I-SMART system : 3 sub-systems



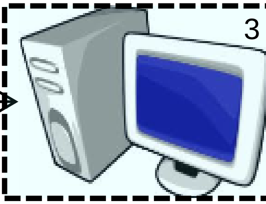
Radiation sources
(n, γ,…)

1

SiC based
innovative sensor



SiC based innovative electronics and signal processing

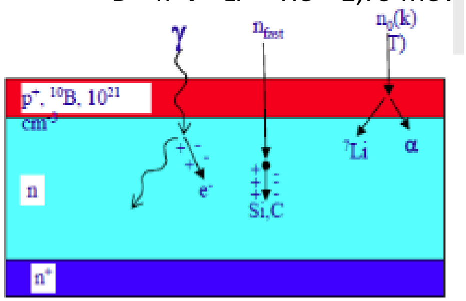


Innovative data processing

System designed and validated by :
- Simulation & Calculation (interpretation, conceptual design, feasibility studies)
- Radiation testing and calibration in experimental facilities

- Silicon Carbide spectroscopic sensor
- Combines detection capacity for thermal and fast neutron as well as γ ray
- Neutron detection based on ^{10}B (3900 barns):

$^{10}B + n \rightarrow {}^{7}Li + {}^{4}He + 2{,}79$ MeV



- Silicon Carbide based electronics
- Front end and signal processing
  - Operational amplifier
  - Analog to digital converter
- Designed for High temperature operation
- Proprietary SiC bipolar analog/mixed-signal integrated circuit technology

- Data processing : Tools for signal recognition
- Tools for advanced modeling and signal interpretation of SiC spectroscopic detectors.
- Numerical simulation of radiation interaction with SiC sensor.
- Capability of simultaneous spectroscopic detection of gamma and neutron radiations

Why SiC and Diamond for Nuclear Detection ?

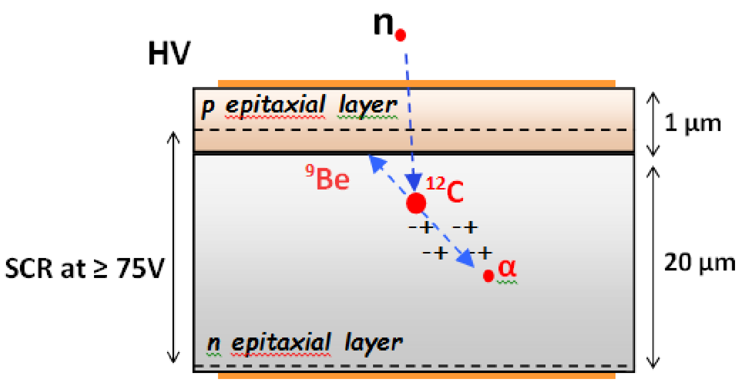
Property	Si	GaN	Diamond	4H-SiC
Bandgap (eV)	1.12	3.45	5.5	3.27
Break down field (MV cm^{-1})	0.3	2	10	3
e-hole creation energy (eV)	3.6	8.9	13	7.78
Threshold displacement energy (eV)	13-20	10-20	40-50	22-35
Thermal conductivity (W/cm·K)	1.5	1.3	22	4.9

The main advantages of SiC and Diamond :

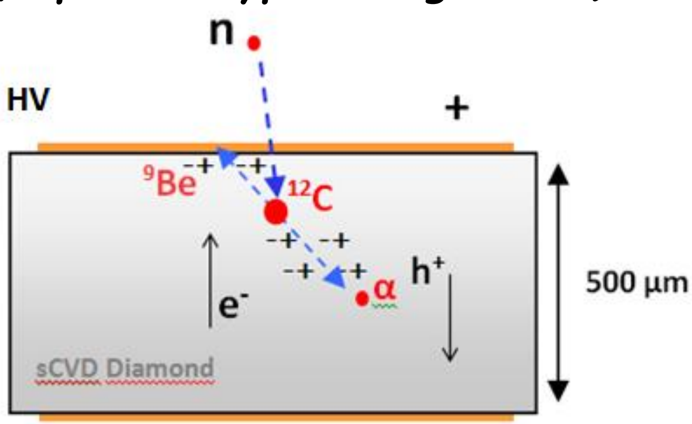
- **Wide band gap : low leakage current**
- **High breakdown field : fast response (ns)**
- **High Energy threshold of defect formation : stability versus radiations**
- **High thermal conductivity : no cooling system required**
- **Carbon : good neutron/gamma discrimination**
- **Epitaxial Growth control (for SiC) : low defect concentration**

Fast Neutron Detection with solid detector

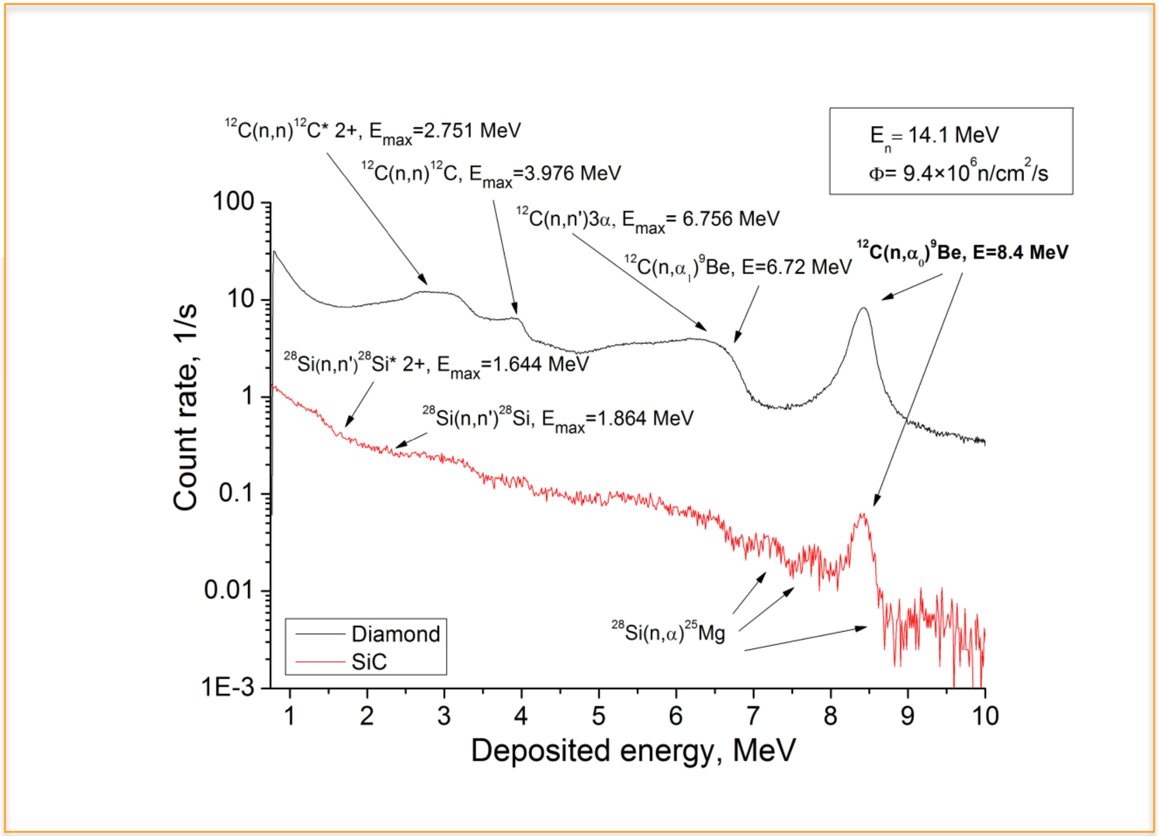
SiC detector (I_SMART project)



Diamond detector (Capacitor type configuration)



- D-T neutron generator
- E_n=14.1 MeV (90°)
- $\Phi = 9.4 \times 10^{6}$ $cm^{-2}s^{-1}$



SiC : lower intensity (thinner SCR), Si-related peaks

Thermal Neutron Detection / Tested @ Minerve ZPR reactor

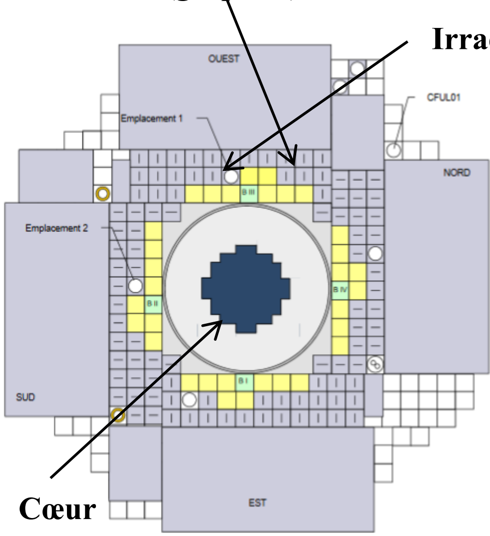
GOALS

- CVD and SiC sensor response to thermal neutron flux in a mixed n/g field
- CVD and SiC stablility and performance comparison

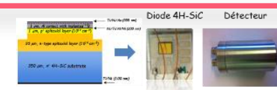
MINERVE

- ZPR – Nominal Power 100 W

Reflector (graphite)

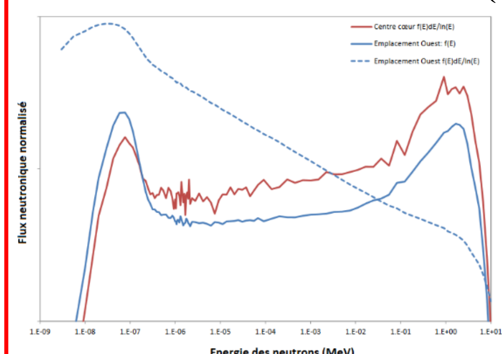


Cœur



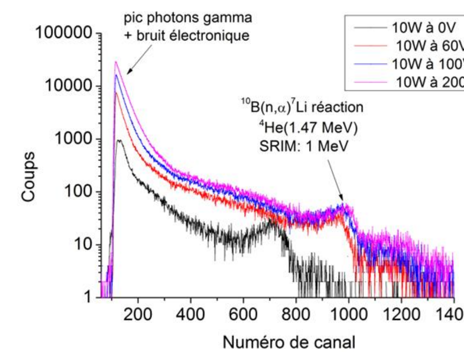
Irradiation Location $\Phi_{total} = 9.41\times10^{8}$ n/(cm²s¹) à 80W

Calculated neutron flux (MCNP5 JEFF3.1.1)



Energie de neutrons	
E_n<0.5eV	**30.6%**
0.5 eV <E_n <100 keV	26.9%
100 keV <E_n <1MeV	26.5%
1MeV <E_n <5MeV	14.8%
5 MeV <E_n <10MeV	1.2%

Also tested in BR1 @ 7.10⁸ n. cm⁻² . s⁻¹ (thermal flux).



Décalage du pic → Changement de la CCE

CCE incomplète à 0V
piégeage des porteurs de charge, recombinaison ?

Augmentation du comptage avec V dans le 1er pic

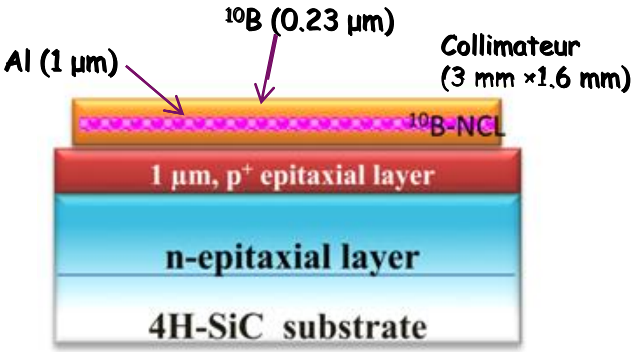
$0\ V: W(ZCE) = 4.02\ \mu m$

$-200\ V: W(ZCE) = W_n = 20\ \mu m$

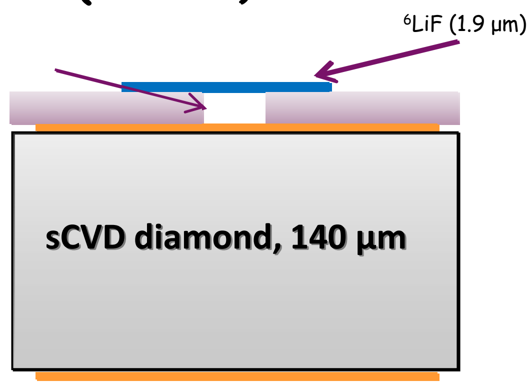
Augmentation de la ZCE

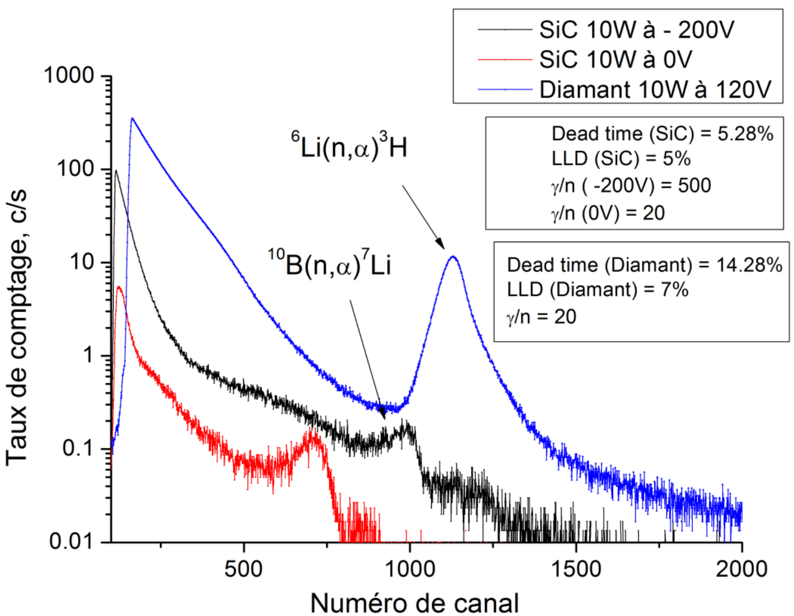
Thermal Neutron Detection / Tested @ Minerve ZPR reactor

SiC detector (I_SMART project)

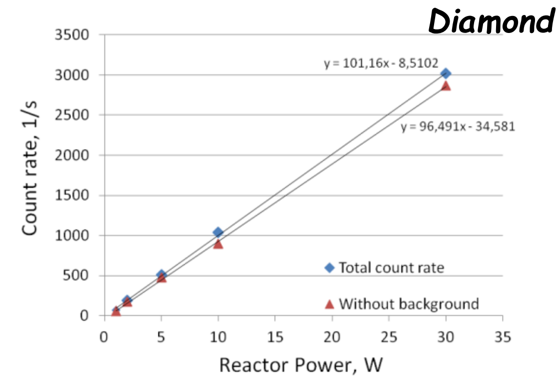


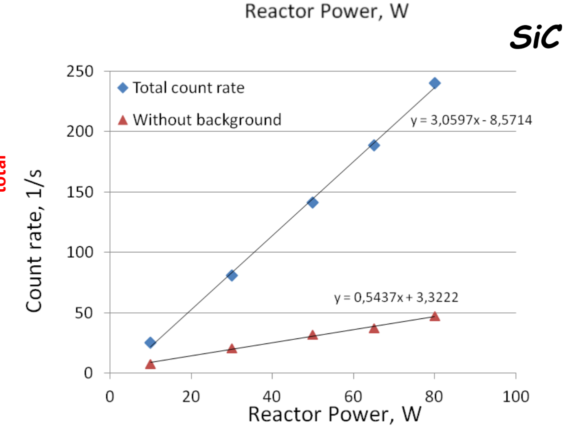
sCVD Diamond detector (CIVIDEC)





$\Phi_{total} = 9.41 \times 10^8$ n/cm^{2}s^{-1}





SiC Detector :

- ➢ *Better gamma/neutron discrimination at <u>0V (Full Detection)</u>*

Diamond Detector :

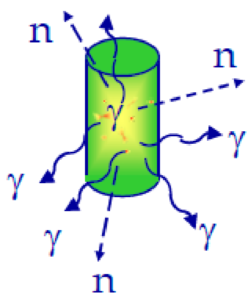
- ➢ *Higher count rate (higher C density)*

SUMMARY

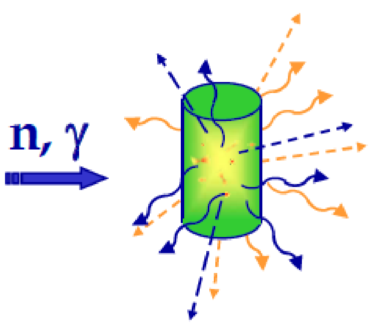
- ❑ INTRODUCTION
- ❑ Specific features, constraints and requirements
- ❑ Examples of radiation measurements and associated instrumentation for :
  - In Pile Measurements
  - **Radioactive waste characterization and control**
- ❑ Conclusions and prospects

Radioactive Wastes Characterization & Management

Non Destructive Measurements (NDM)

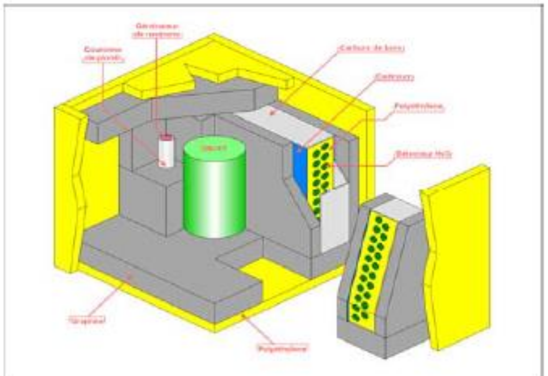


- **Passive Measurements**
  - photons : Dose rate, gamma spectrometry, gamma tomography
  - neutrons : Global counting, neutron coincidences counting and neutron multiplicities counting.

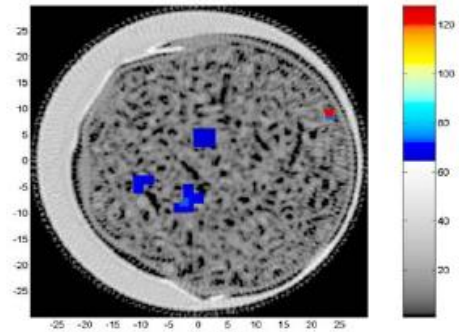


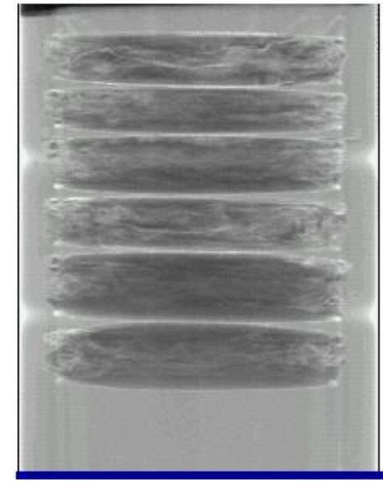
- **Actives measurement**
  - Photon/Neutron Transmission Imagery/Radiography
  - Neutron Interrogation ⇨ fission prompts and delayed neutrons, Gamma rays emission from (n,n'γ), (n,γ) and following neutron activation reactions (n,p), (n,α)…
  - Photon interrogation ⇨ delayed neutrons and gamma from photofission, Gamma rays from photon activation

MEASUREMENT & INSTRUMENTATION FOR NDA



Interrogation (n,f)

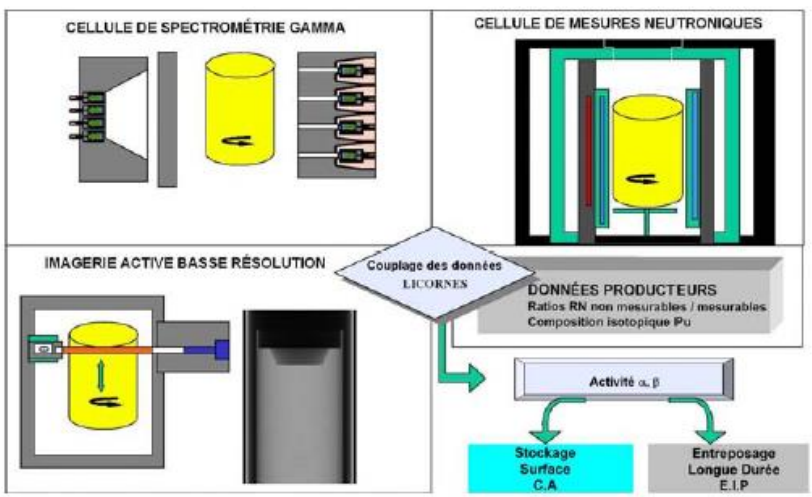


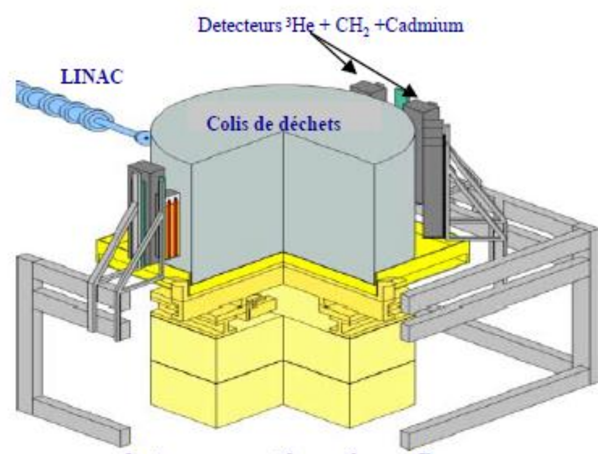


Photon Imagery and tomography

Combination

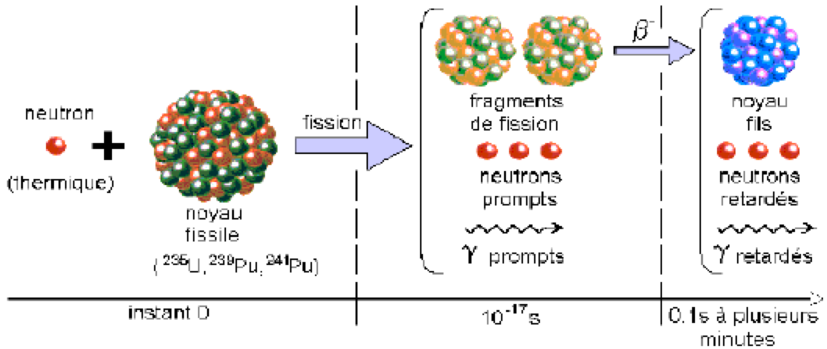
Unité de Tri de Marcoule

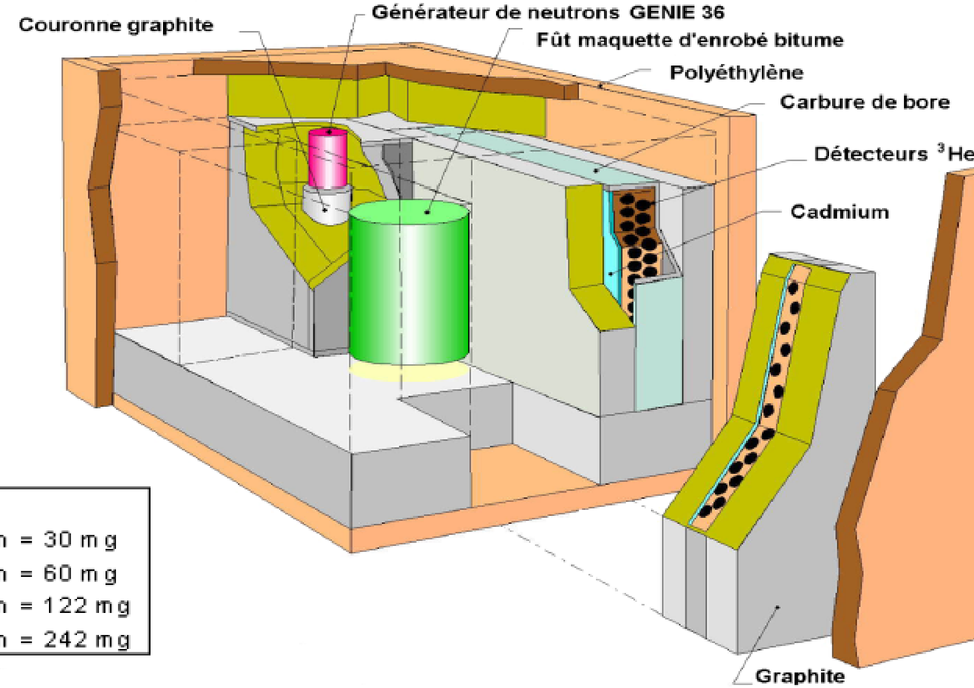


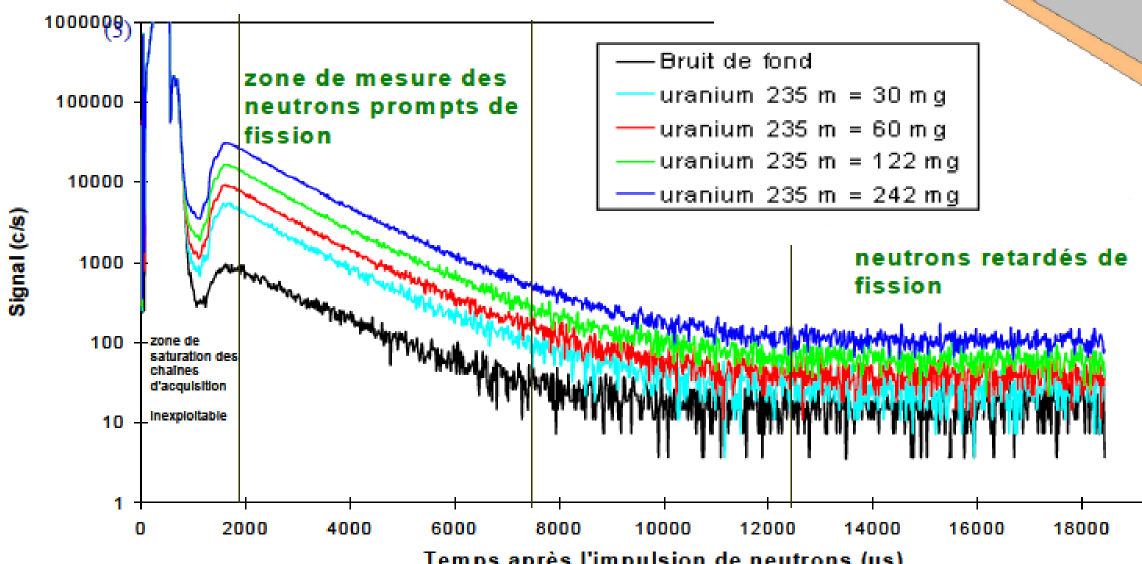


Interrogation (γ,n-f)

Active neutron measurement







- Neutron prompt signal

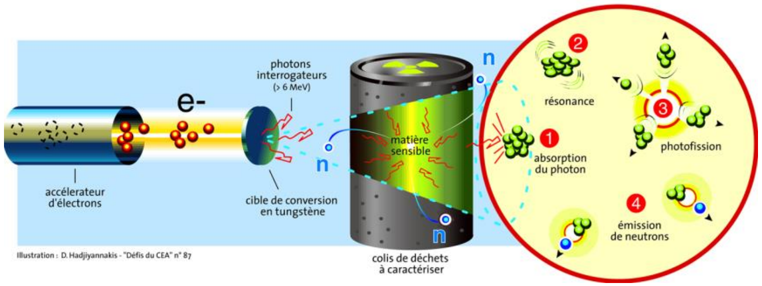
$SP = a \times m(^{239}Pu) + b \times m(^{235}U)$

- Delayed neutron signal

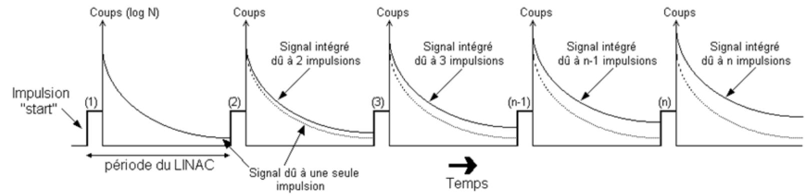
$SR = c \times m(^{239}Pu) + d \times m(^{235}U) + e \times m(^{17}O) + f \times m(^{238}U) + f \times m(^{232}Th)$

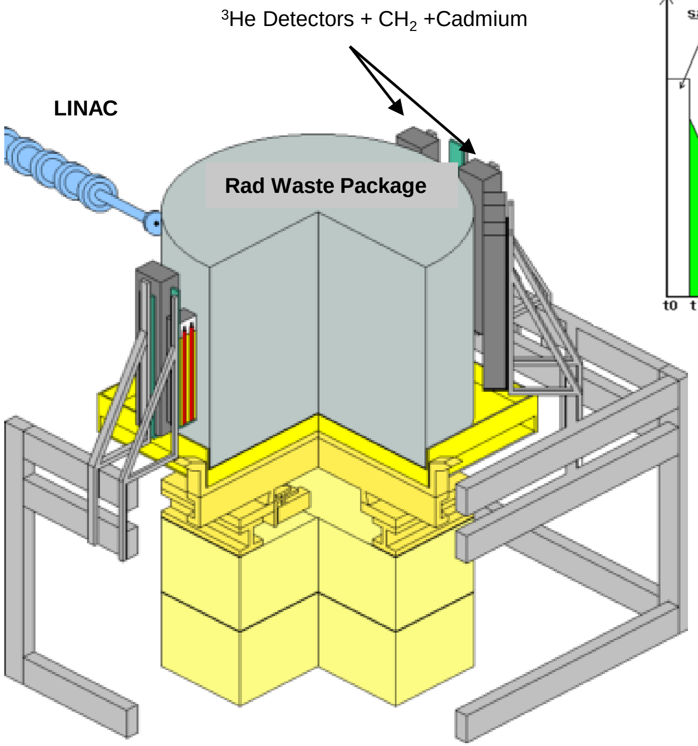
MEASUREMENT & INSTRUMENTATION FOR NDA

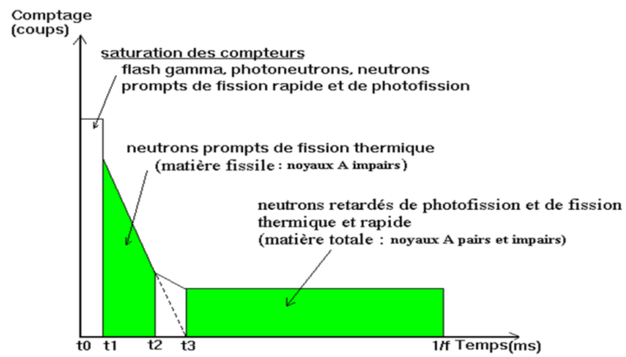
Active Photon Interrogation



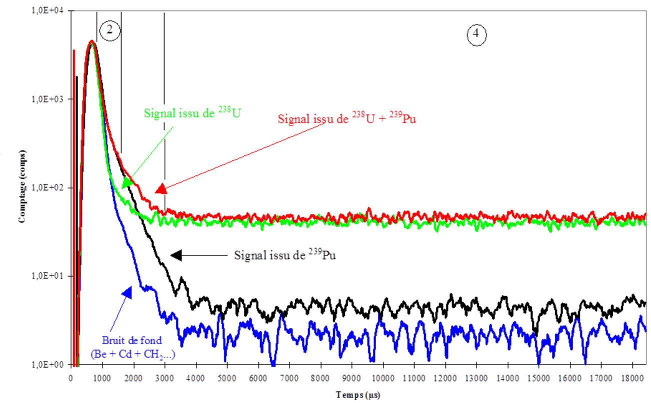
SPHINCS counting technique

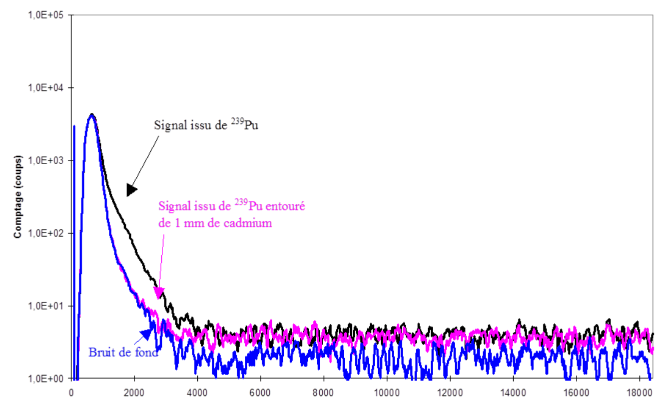






Time distribution of neutron signal for simultaneous photon & neutron interrogation (Ee = 15 MeV, Cu & Be)





Prompt neutron signal comes from thermal neutron interrogation and delayed neutron signal is mainly due to photofission interrogation (~95 %)

CONCLUSIONS

- **Important R&D efforts** are maintained on instrumentation an measurement dedicated to existing and future Research Reactors (JHR,…)

- As codes and nuclear data get more and more accurate, **nuclear instrumentation** should be **continuously improved** in terms of:
  - **Uncertainties** and **Precision** → Absolut measurements
  - **Reliability** to support high fluence (up to 100dpa !) and temperatures
  - **Measuring and Interpretation Processes** (online / combined measurements)

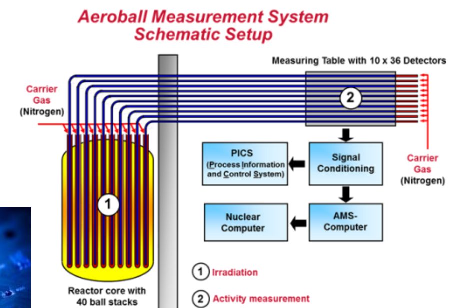
- Due to the closing of several **irradiation facilities** and the disappearance of the associated teams, **collaborations** are a favoured way for instrumentation developments to be enhanced

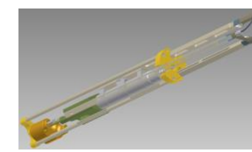
- An attention should paid for **Nuclear Data** which are often not enough developed for instrumentation needs (e. g. charged particles)

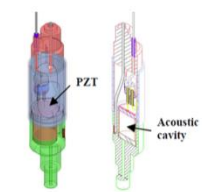
FINALLY…

Maintain and enhance efforts on Research and Innovation in :

- ❑ High temperature measurements (500°C up to 1000°C).
- ❑ High radiation level measurements
- ❑ High count rate measurements
- ❑ Selective radiation measurements n, γ
- ❑ Neutron spectrum measurements
- ❑ Material and electronics hardening
- ❑ Integrated electronics
- ❑ Multiplexing
- ❑ Integration probes
- ❑ Accurate modeling/calculation tools (nuclear data library "corrections")
- ❑ Real time data acquisition
- ❑ **Combined measurements and cross interpretation and analy**
- ❑ Uncertainties treatment, analysis and reduction
- ❑ Data mining,Algorithmic, Machine learning, Artificial Intelligence
- ❑ Numerical Twins
- ❑ ….







ANIMMA

9th International Conference on Nuclear Instrumentation and Measurement

DE LA RECHERCHE À L'INDUSTRIE

THANK YOU

"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are, if doesn't agree with experiment, it is wrong."
Richard Feynman (1918-1988)