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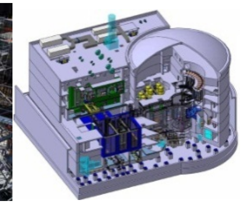
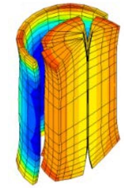
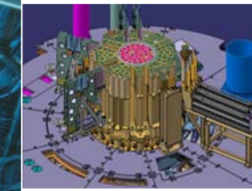
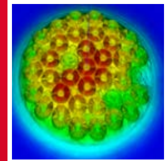
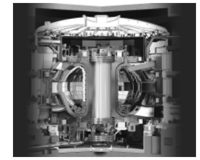
LiMMEX



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



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IEEE Distinguish Lecturer
Cape Town Instrumentation School (Virtual)
August 24th, 2023

IEEE NPSS
NUCLEAR & PLASMA SCIENCES SOCIETY

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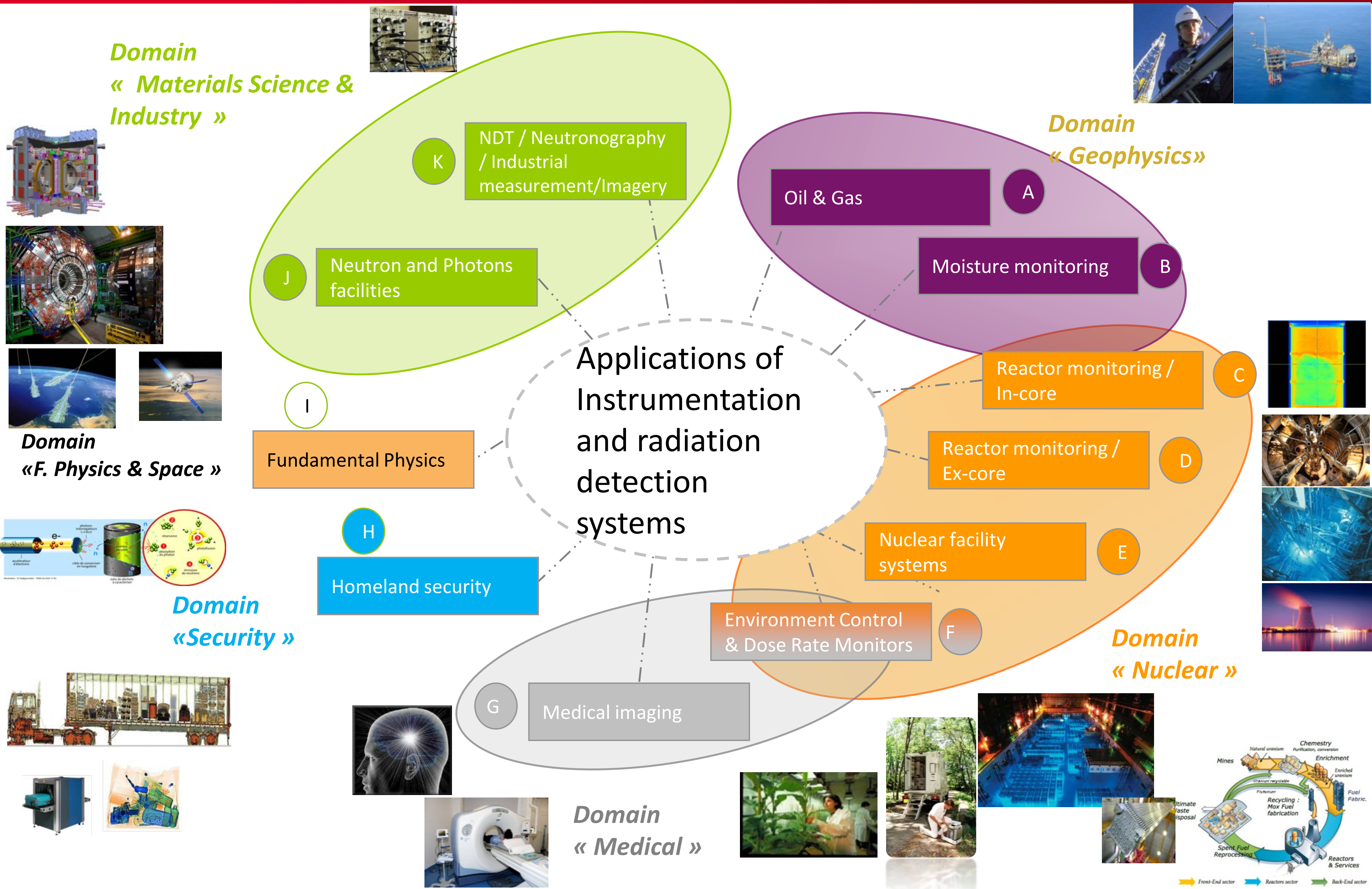
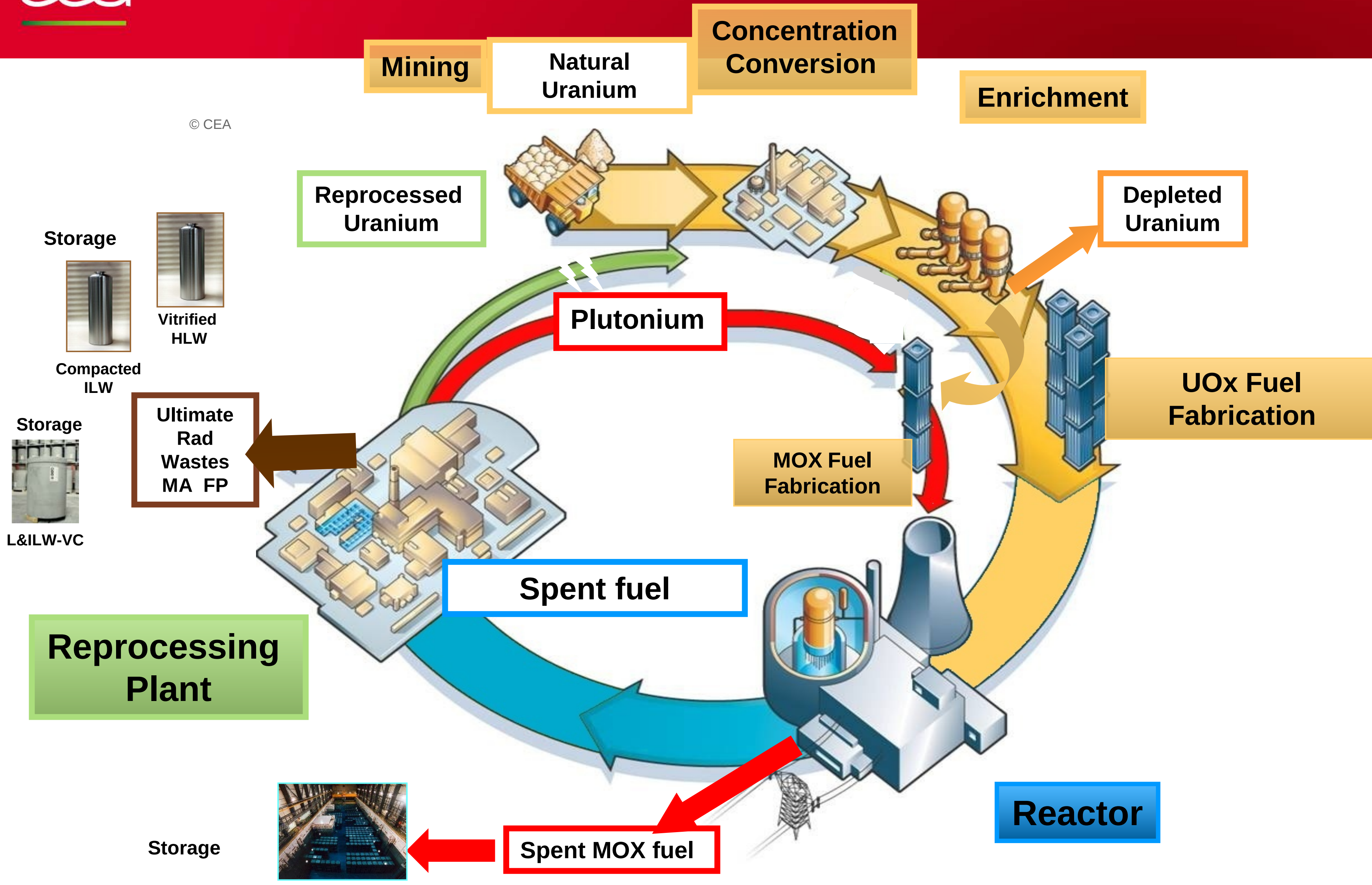
SUMMARY

- ❑ 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



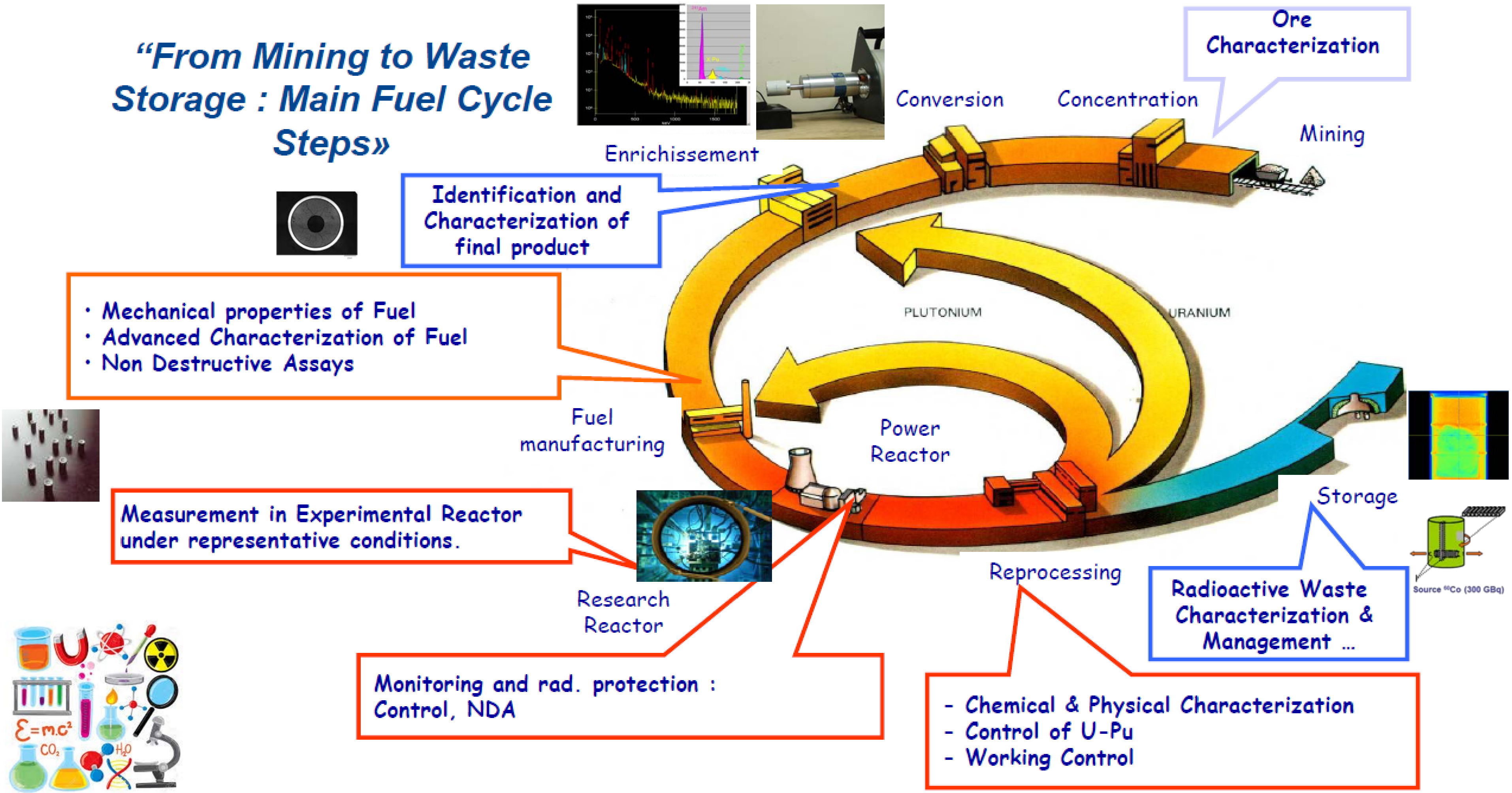
Nuclear Media : Nuclear Fuel Cycle



Nuclear Fuel Cycle :

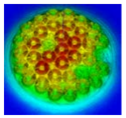
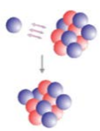
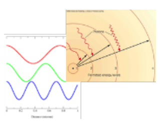
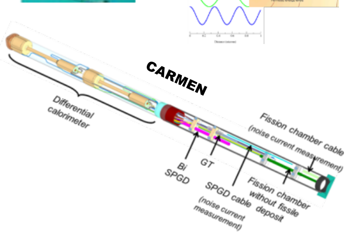
Instrumentation & measurement are key aspects for control & characterization

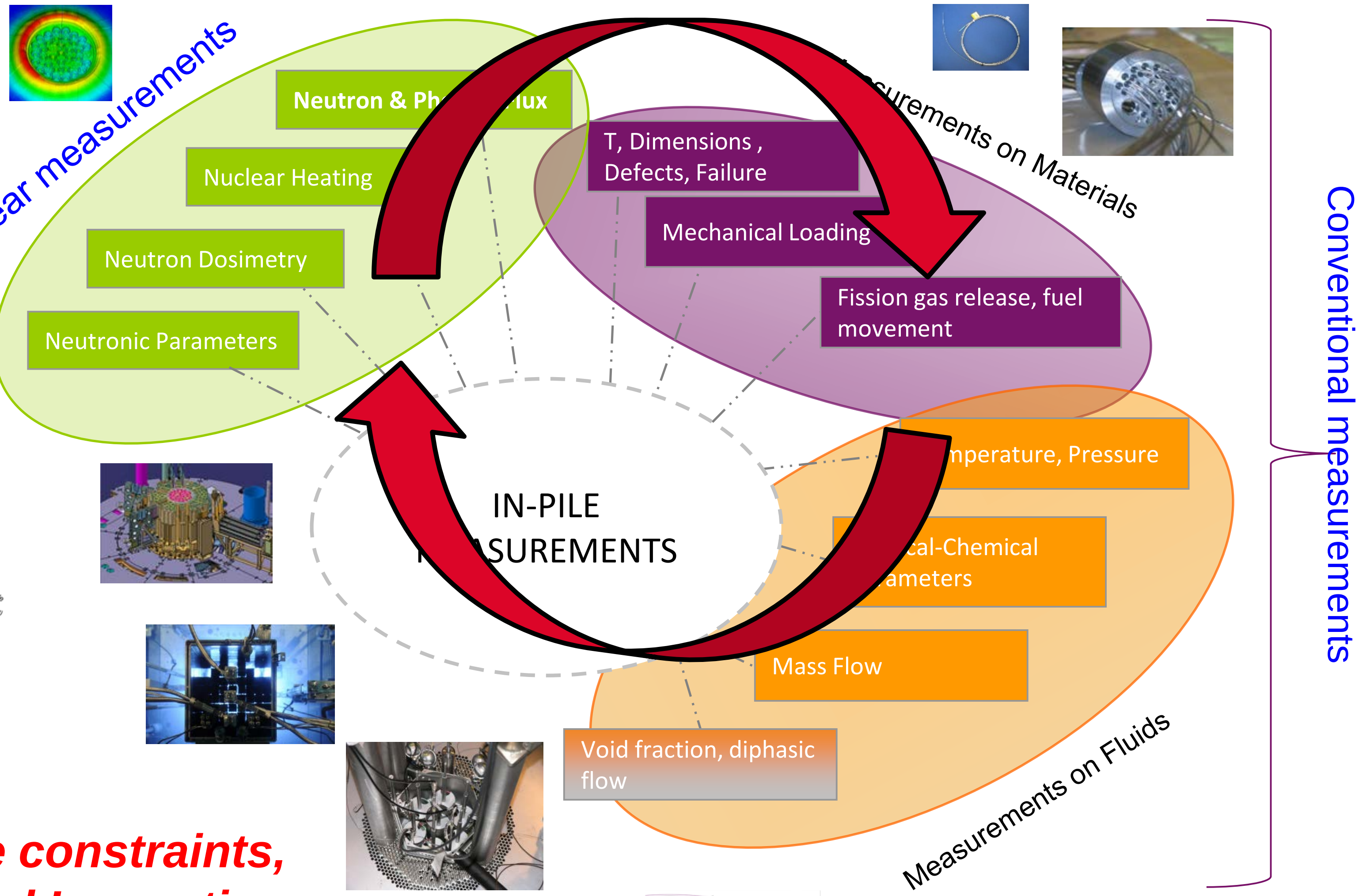
Measurements and Specific Controls are Strongly needed and necessary at each step /sub-step of Nuclear Fuel Cycle.

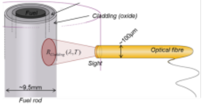


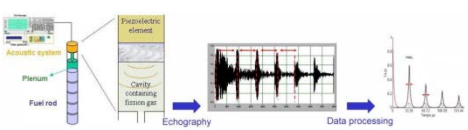
Main in-pile measurements





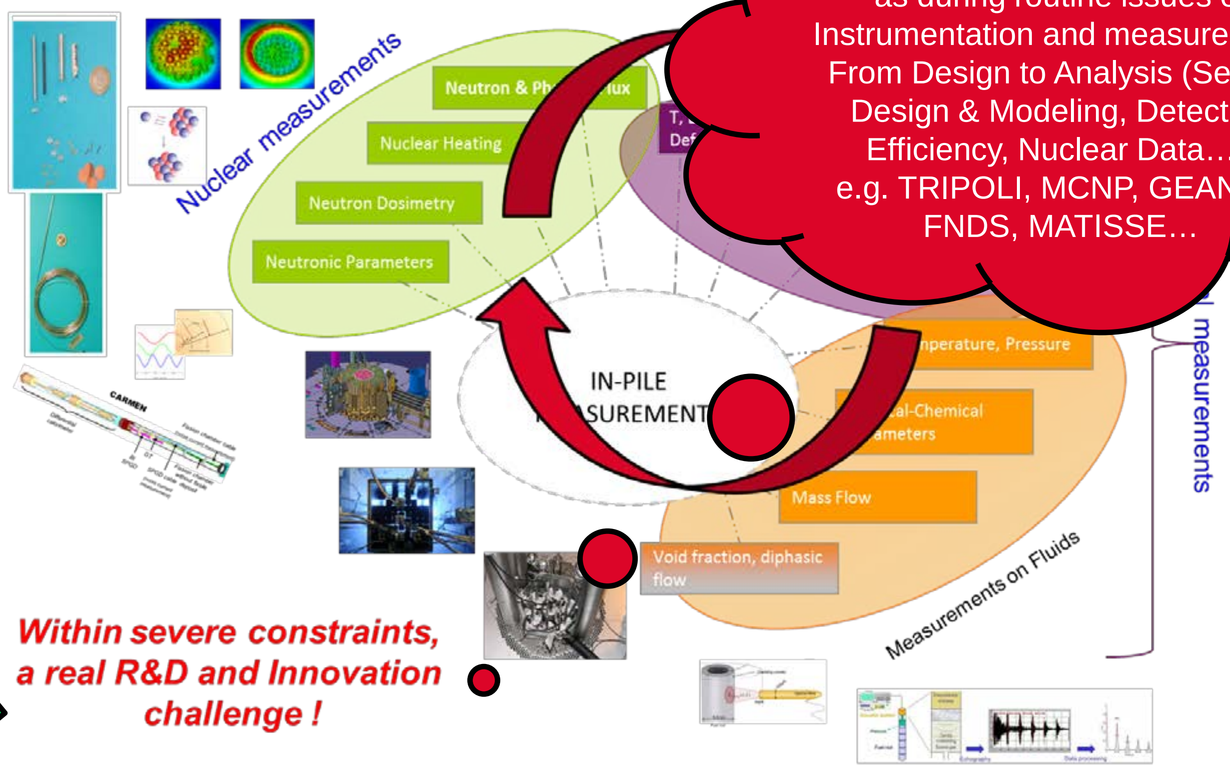




Within severe constraints, a real R&D and Innovation challenge !

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 !

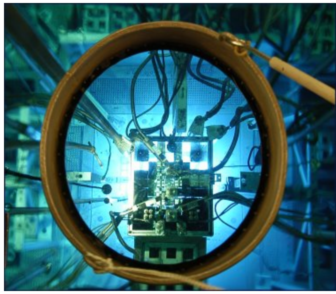
Also : (D/D, RW, NDA, Safeguards)

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

Extremely Conservative



Reliable

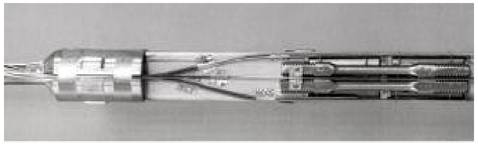
impossible or difficult maintenance on irradiated objects

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

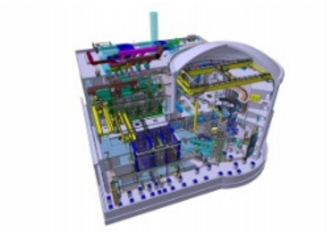


Corrosion **resistant**

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

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Reminder :

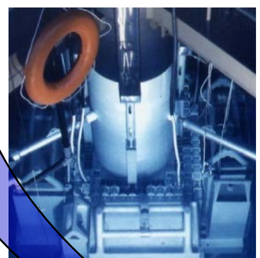
Main Aim of Nuclear Reactor Measurements : To reduce uncertainties

To reduce uncertainties at each step of the process;

from conceptual design to final running of nuclear system(s)

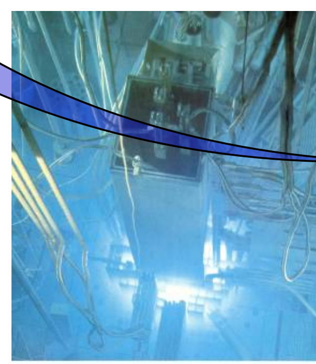
Basic/Fundamental Data

Measurement of Basic Physical Data



Online Monitoring

Monitoring & Control in NPP



Design Tools

Smart/Analytical Experiments

→ Predictive / Calculations

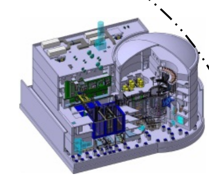
Model Development

Verification

Global/Integral Experiments on ZPR Reactors

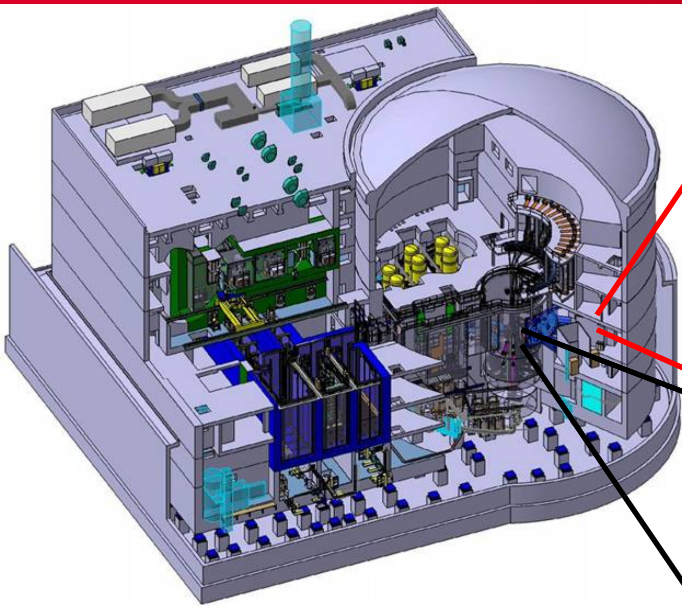
→ Check, verify, predictions

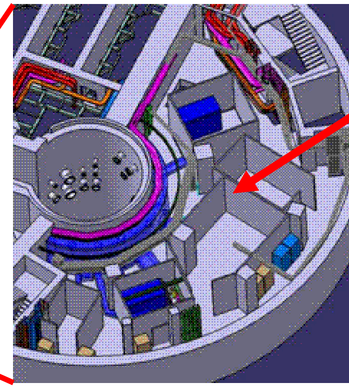
Validation of Models/ Calculation schemes

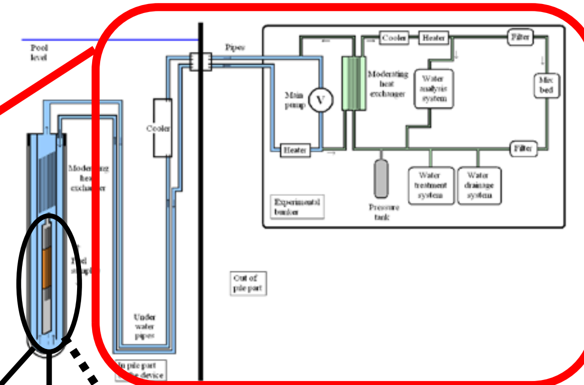


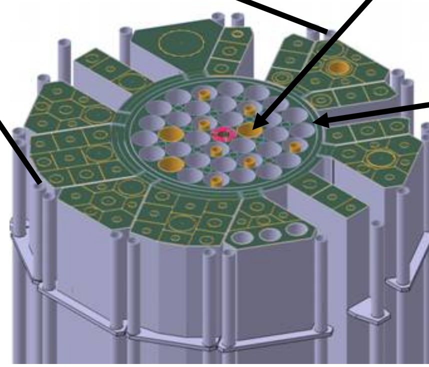
In Pile Measurements, Qualification and Testing in MTRs

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



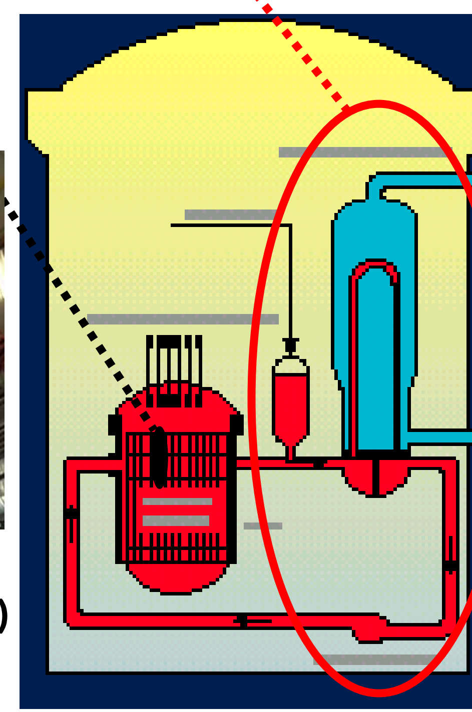






MTR allows to reproduce on a small scale, real power plant conditions and in some cases, more severe conditions for

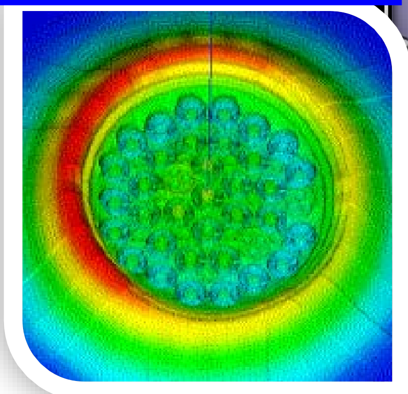
- **Material screening** (comparison of materials tested under representative conditions)
- **Material characterization** (behaviour of one material in a wide range of operating conditions, up to off-normal and severe conditions)
- **Fuel element qualification** (test of one / several fuel rods (clad+fuel))

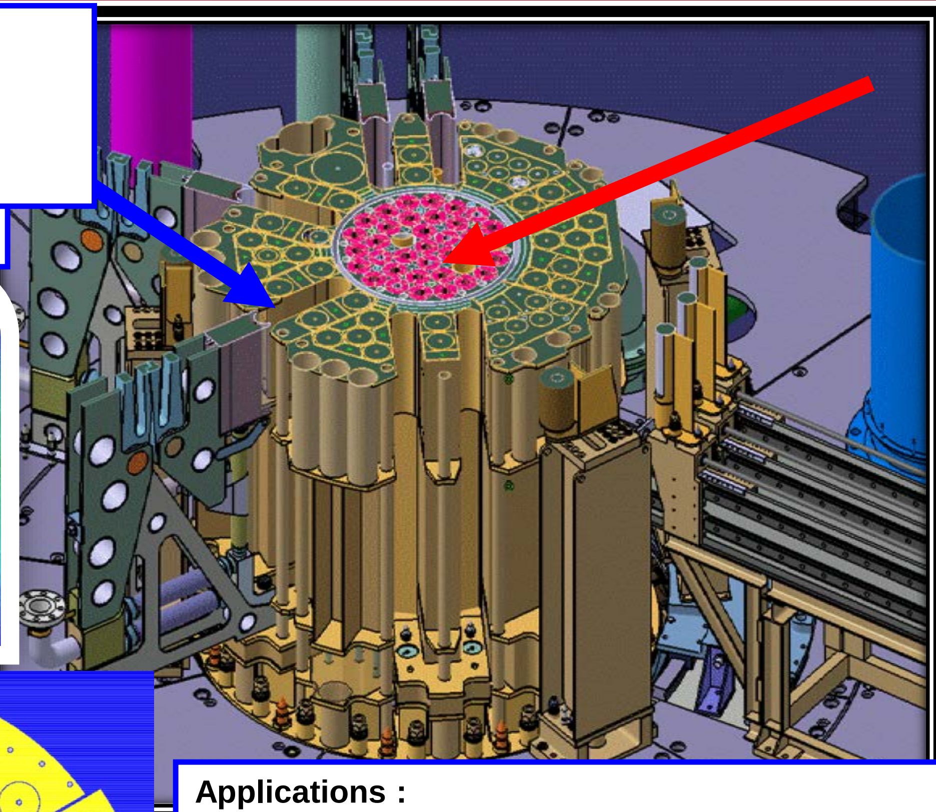


JULES HOROWITZ (JHR) MTR REACTOR

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

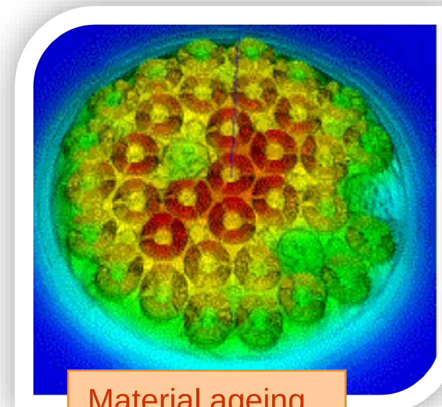
Thermal neutron flux



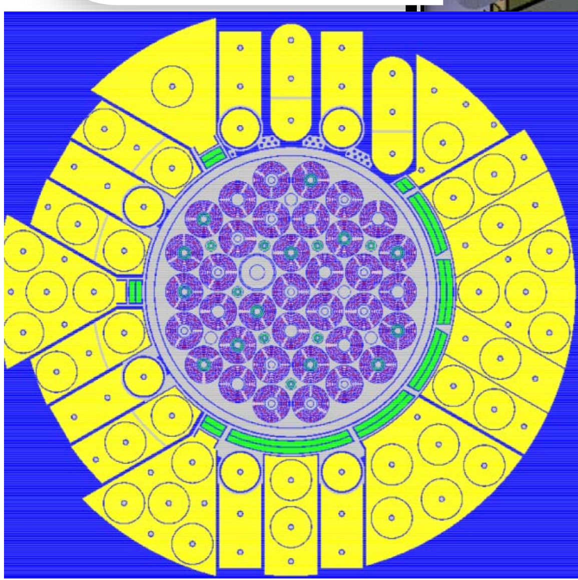


Core
$\Phi \geq 5.5\ 10^{14}$ n/cm².s > 1 MeV
$\Phi \geq 10^{15}$ n/cm².s > 0.1 MeV

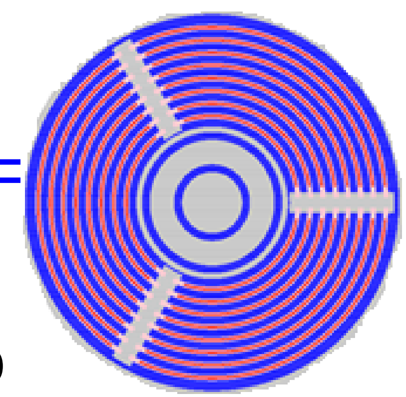
Fast neutron flux



Material ageing
(up to 16 dpa/y)



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



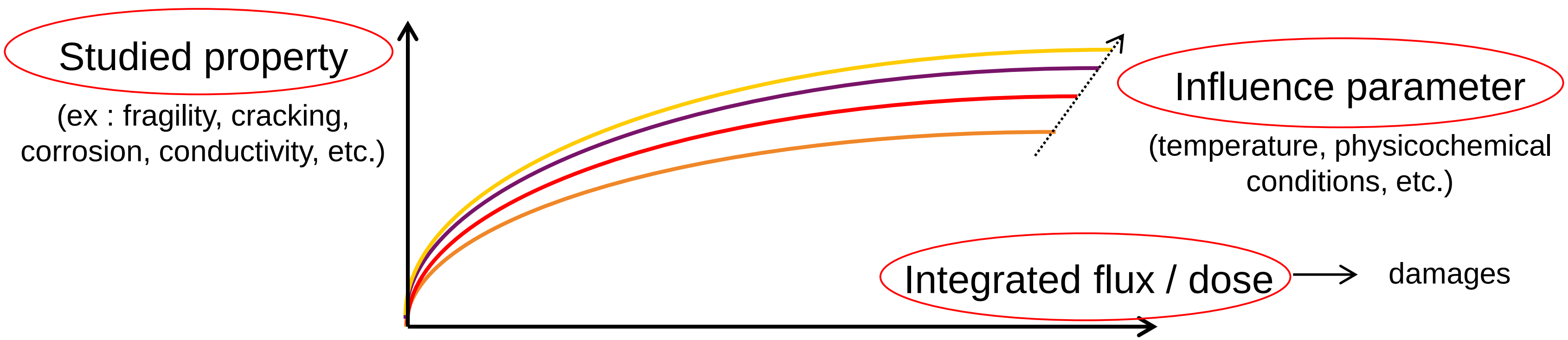
Geometry:
From 34 to 37 cylinder-shaped fuel assemblies
U_3Si_2-Al fuel enrichment of 19,75% then 27%
Aluminum racks (hosting all the fuel assemblies)
Hafnium control rods (in the center of fuel assemblies)
Beryllium reflector

Objectives and Requirements

In-pile measurements are essential to:

- Monitor the experiments

Objectives of irradiation tests :
Assess / verify / increase the precision of behavior laws under irradiation



→ All these parameters must be accurately measured !

- Check safety parameters

= check that some specified parameters stay in their acceptable range
(e.g. : temperature, pressure, etc.)

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

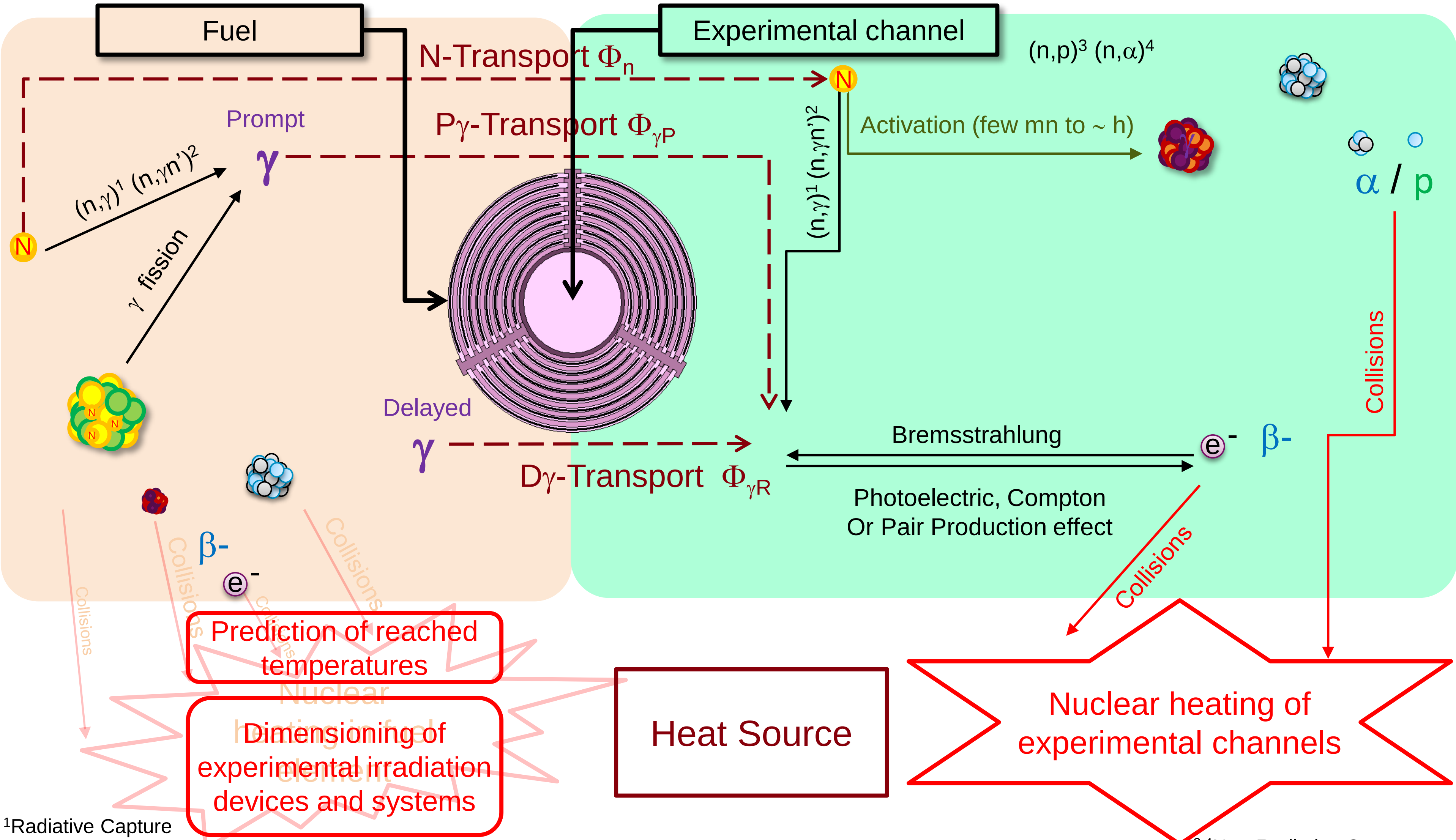
Better characterization of thermo-hydraulic conditions
→ temperature field / fluid flows

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)

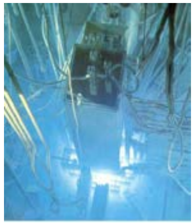
Origin and Basics of Nuclear Heating

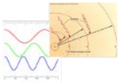


[1]Radiative Capture
[2]Inelastic Scattering
[3] [4]Non-Radiative Capture

C. Devita et al. (2016) : « *Étude et Optimisation de Calorimètres en Milieu Inactif Dédiés à la Mesure de l'Échauffement Nucléaire dans le Réacteur Jules Horowitz : Des Phénomènes Physiques à l'Étalonnage* »; *AMU Thesis defended in 2016.*

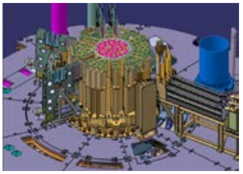
NUCLEAR HEATING IN JHR

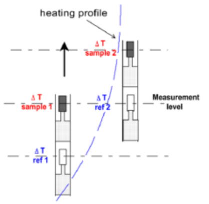




Photon heating is the main contributor to total heating in non-fissile materials and leads to temperature increases.

Heated materials must therefore be accordingly cooled down so as to eliminate risks of local boiling ,e.g. around hafnium rods, and of creep deformations, e.g. of the aluminum rack. A good knowledge of the profiles of photon heating in irradiation devices is also necessary for the design of irradiation experiments. Temperature of irradiated samples is one of the key parameters to establish the representativeness of JHR irradiation with regards to irradiation in other light-water reactors, e.g. Pressurized-Water Reactors(PWR).

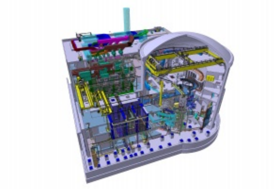




Depending on expected values of heating, irradiation devices must appropriately be designed with systems to monitor and control sample temperature. It was estimated* that an <u>uncertainty of 5% </u>(at one standard deviation) on calculated photon heating, associated with the nuclear data used in the photon calculations, is required to meet these challenges.

(*) M. Lemaire et al. (2015). *Experimental validation on photon heating calculation for the JHR.* NIM-A, 780, p. 68-80

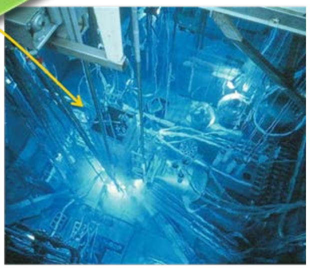
Nuclear heating and nuclear radiation measurement and mapping

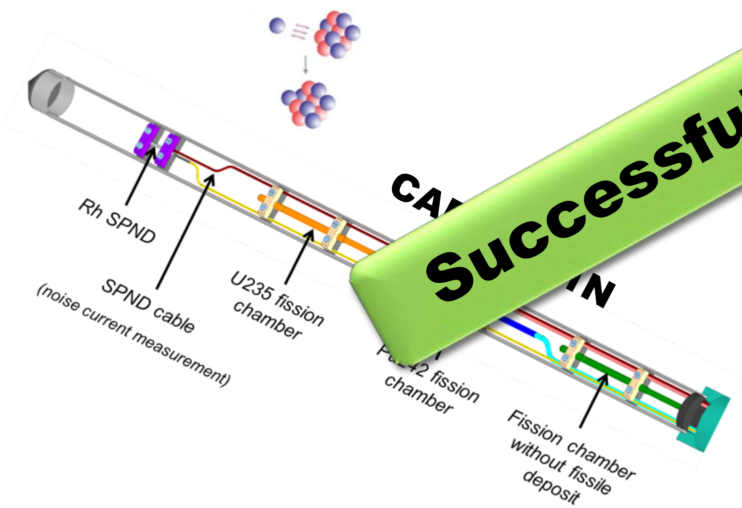


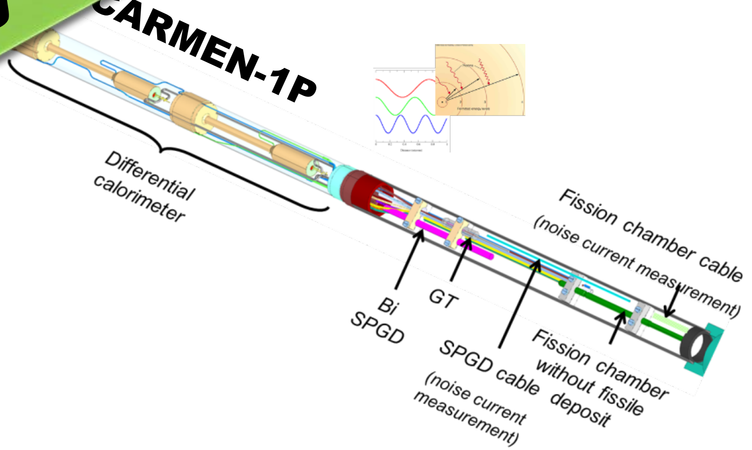
Combined measurement devices CARMEN-1 N & P

- Improve measurement quality
- Reduce uncertainty budget
- Combined Analysis
- Enhance Knowledge and predictive capacity
- Cross-qualify measurements and analysis methodologies

- 4 exp. locatio[...] in 3 radial positions
- Measurem[...] an Plan



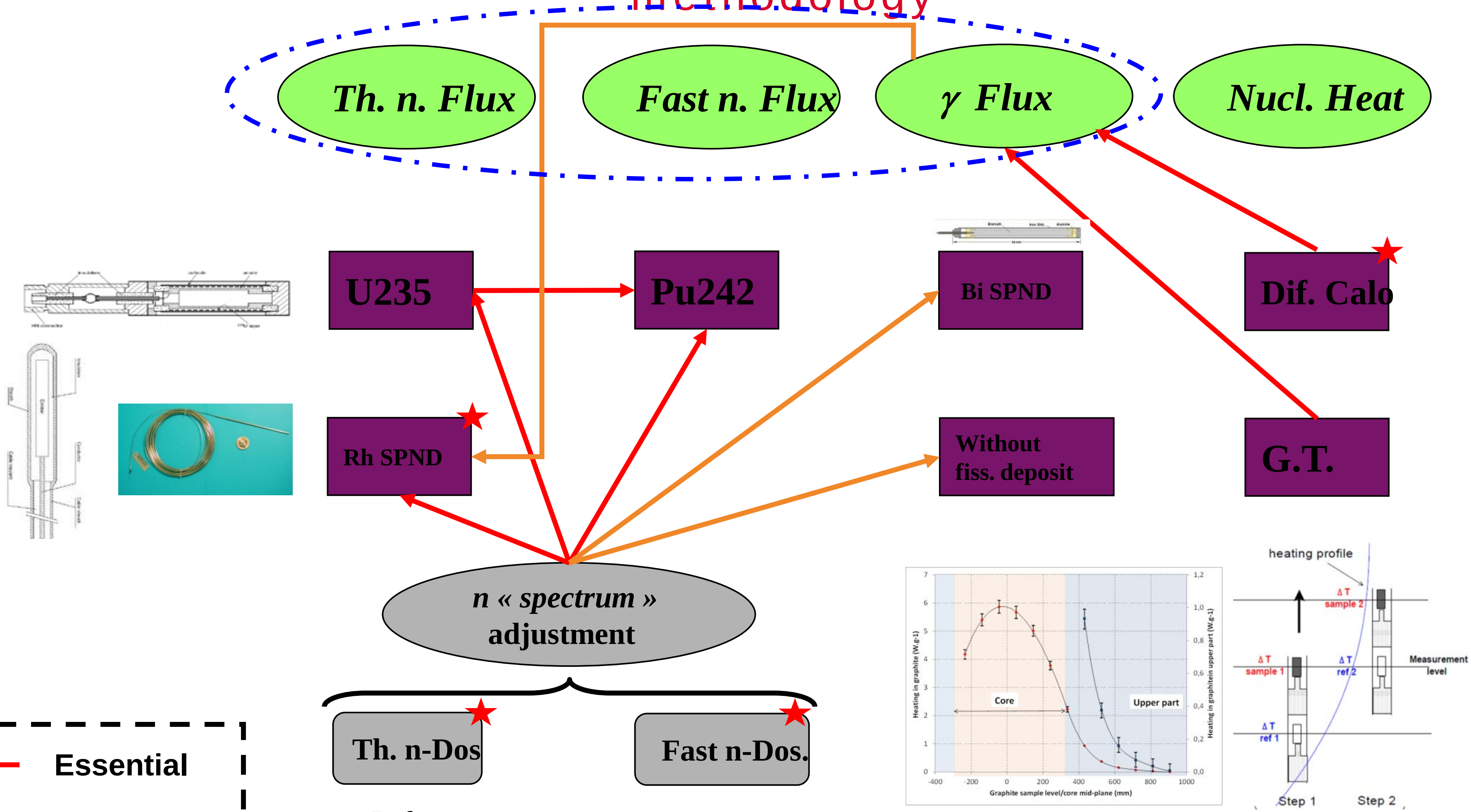




Successfully tested & performed

Combined measurement device CARMEN

Basics of Combined measurements methodology



Essential

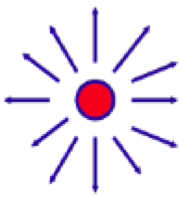
Secondary

★ Reference measurements

A. Lyoussi (Invited Talk) et al.: "Research Advanced methodology and instrumentation for accurate on line measurements of neutron, photon and nuclear heating parameters inside Jules Horowitz MTR Reactor" Reactor Fuel Material Management & International Group on Research Reactor (RRFM – IGORR 2012), Prague, Czech republic , 18 - 22 Mars 2012

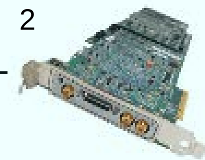
I-SMART : European Project aimed to develop and test advanced solide state sensors & measurement system for selective n-γ detection in Severe Media

I-SMART system : 3 sub-systems

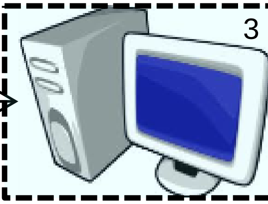


Radiation sources
(n, γ,…)

SiC based
innovative sensor



SiC based innovative
electronics and signal
processing

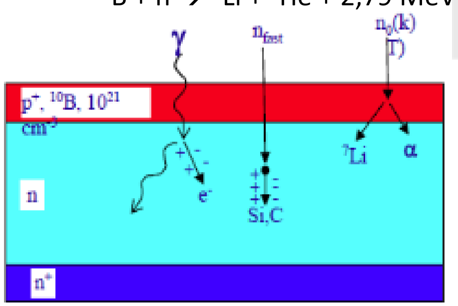


Innovative data
processing

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 ?

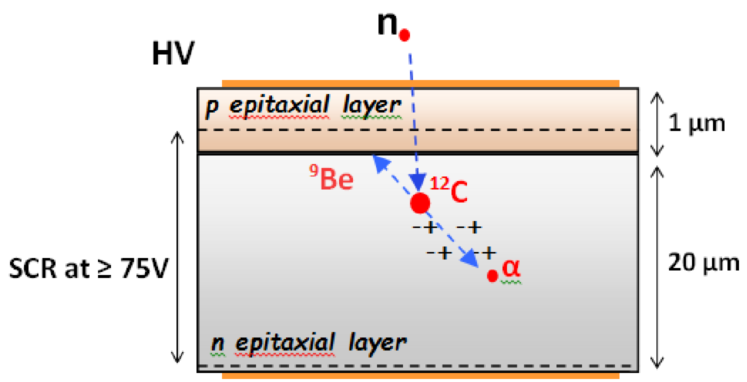
Property	Si	GaN	Diamond	4H-SiC
Bandgap (eV)	1.12	3.45	5.5	3.27
Break down field (MV cm^{-1})	0.3	2	10	3
e-hole creation energy (eV)	3.6	8.9	13	7.78
Threshold displacement energy (eV)	13-20	10-20	40-50	22-35
Thermal conductivity (W/cm·K)	1.5	1.3	22	4.9

The main advantages of SiC and Diamond :

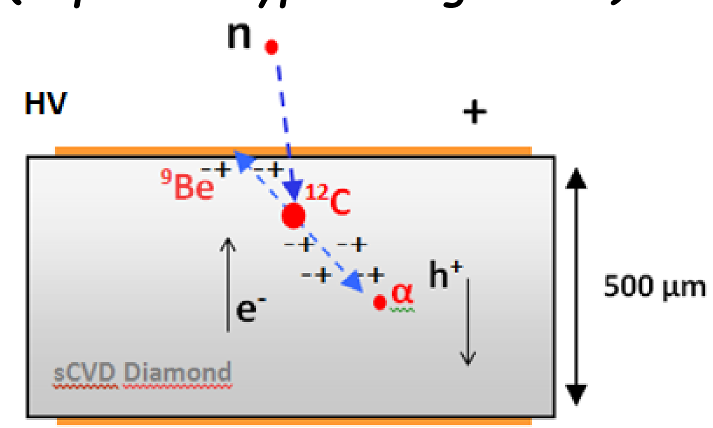
- **Wide band gap : low leakage current**
- **High breakdown field : fast response (ns)**
- **High Energy threshold of defect formation : stability versus radiations**
- **High thermal conductivity : no cooling system required**
- **Carbon : good neutron/gamma discrimination**
- **Epitaxial Growth control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

Fast Neutron Detection with solid detector

SiC detector (I_SMART project)

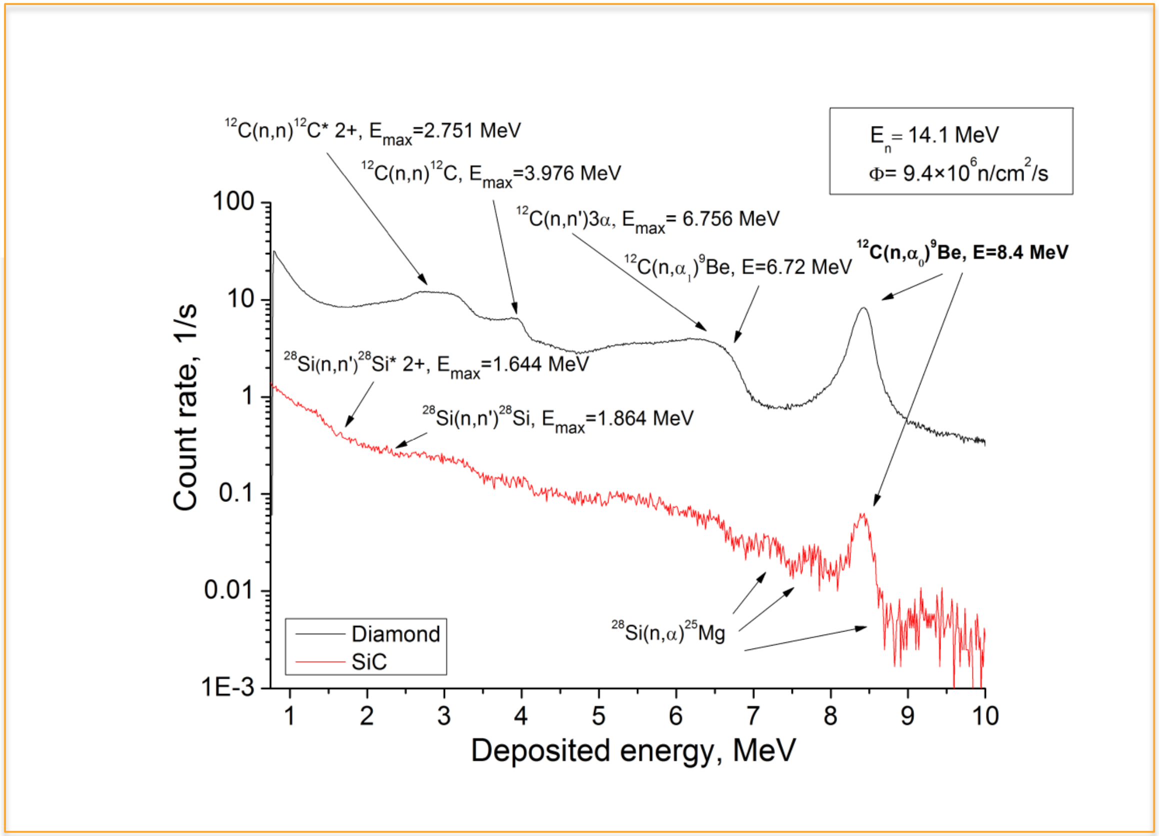


Diamond detector (Capacitor type configuration)



- D-T neutron generator
- E_n=14.1 MeV (90°)
- $\Phi = 9.4\times10^{6}\ cm^{-2}s^{-1}$

Karlsruhe Institute of Technology



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

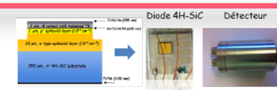
Thermal Neutron Detection / Tested @ Minerve ZPR reactor

GOALS

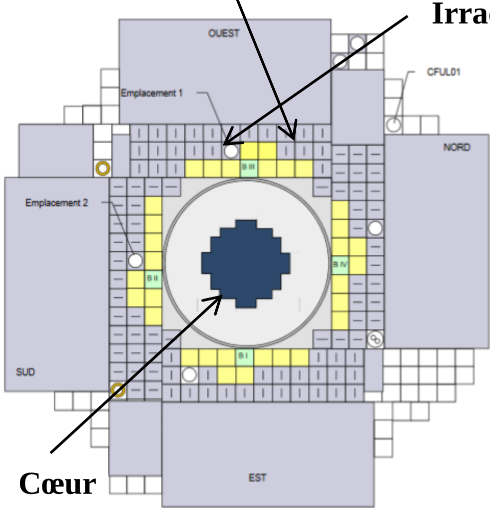
- CVD and SiC sensor response to thermal neutron flux in a mixed n/g field
- CVD and SiC stablility and performance comparison

MINERVE

- ZPR – Nominal Power 100 W



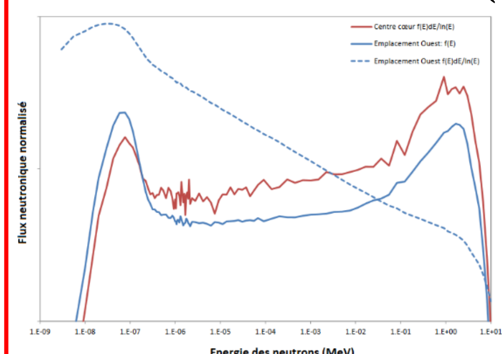
Reflector (graphite)



Cœur

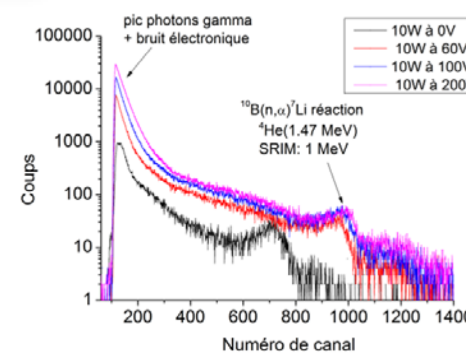
Irradiation Location $\Phi_{total} = 9.41\times10^{8}$ n/(cm²s¹) à 80W

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

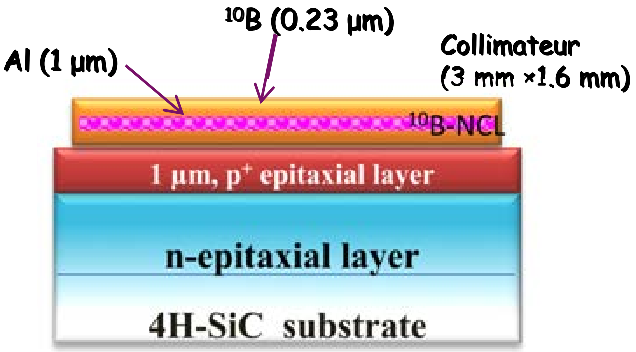
$0\ V:\ W(ZCE) = 4.02\ \mu m$

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

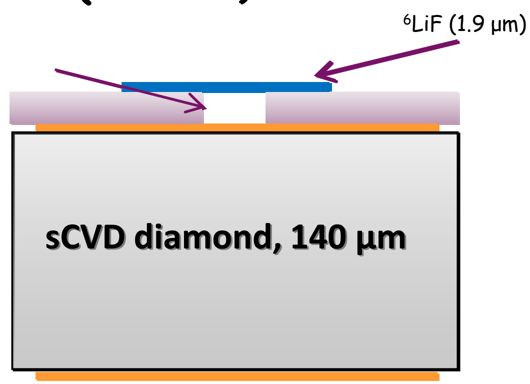
Augmentation de la ZCE

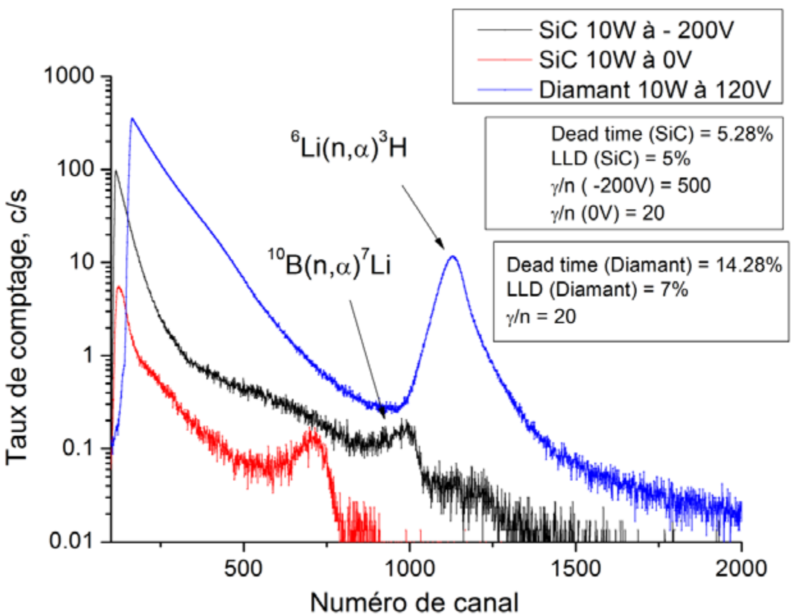
Thermal Neutron Detection / Tested @ Minerve ZPR reactor

SiC detector (I_SMART project)



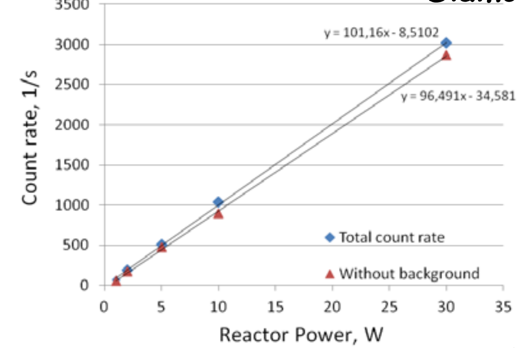
sCVD Diamond detector (CIVIDEC)



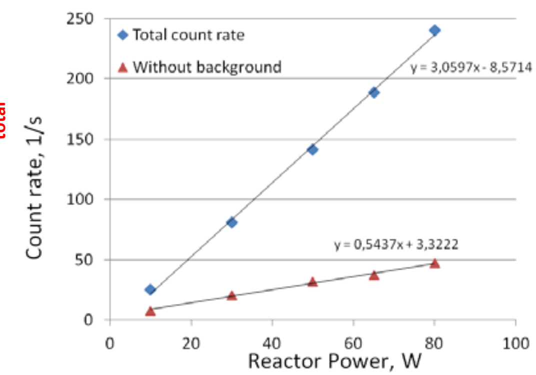


$\Phi_{total} = 9.41\times10^8$ n/cm²s⁻¹

Diamond



SiC



SiC Detector :

- *Better gamma/neutron discrimination at 0V (Full Detection)*

Diamond Detector :

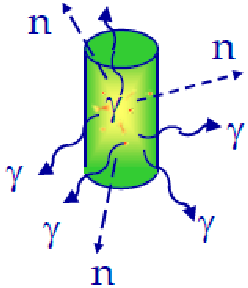
- *Higher count rate (higher C density)*

SUMMARY

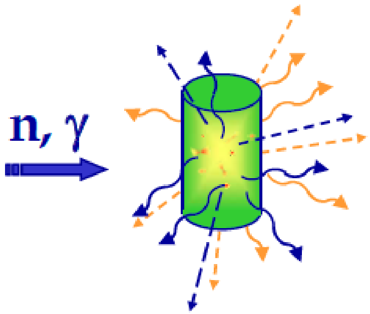
- ❑ INTRODUCTION
- ❑ Specific features, constraints and requirements
- ❑ Examples of radiation measurements and associated instrumentation for :
  - In Pile Measurements
  - **Radioactive waste characterization and control**
- ❑ Conclusions and prospects

Radioactive Wastes Characterization & Management

Non Destructive Measurements (NDM)

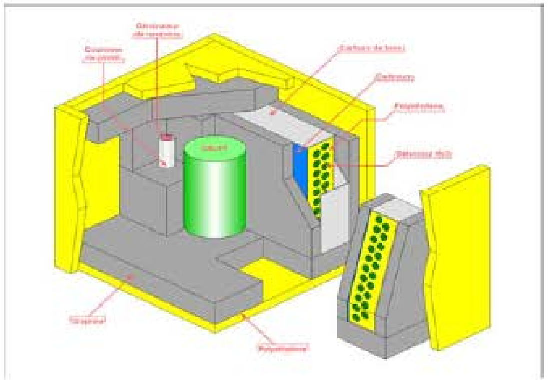


- **Passive Measurements**
  - photons : Dose rate, gamma spectrometry, gamma tomography
  - neutrons : Global counting, neutron coincidences counting and neutron multiplicities counting.

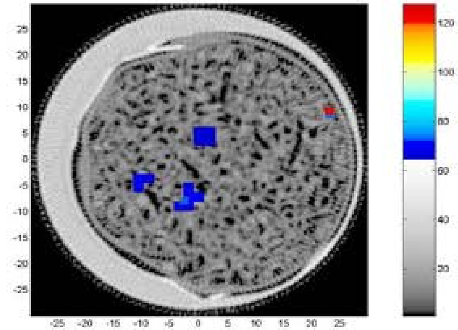


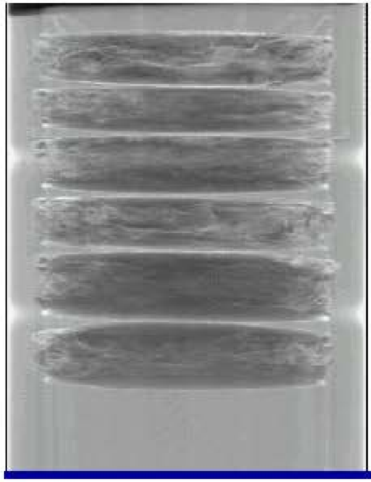
- **Actives measurement**
  - Photon/Neutron Transmission Imagery/Radiography
  - Neutron Interrogation ⇨ fission prompts and delayed neutrons, Gamma rays emission from (n,n'γ), (n,γ) and following neutron activation reactions (n,p), (n,α)…
  - Photon interrogation ⇨ delayed neutrons and gamma from photofission,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

MEASUREMENT & INSTRUMENTATION FOR NDA



Interrogation (n,f)

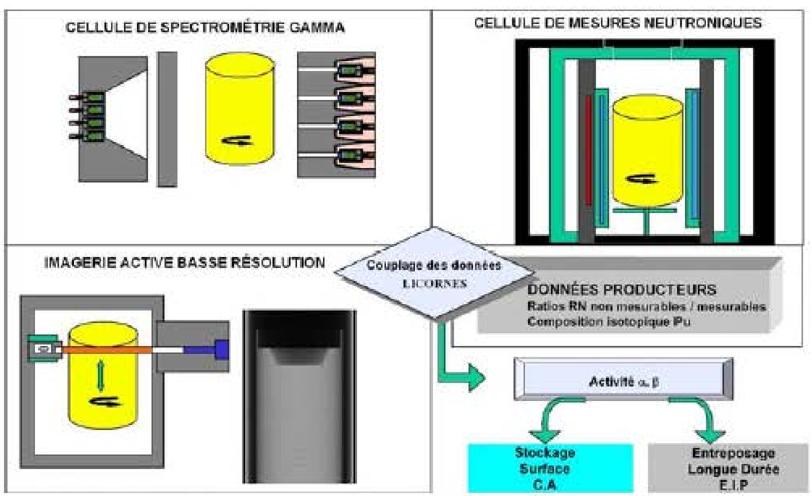


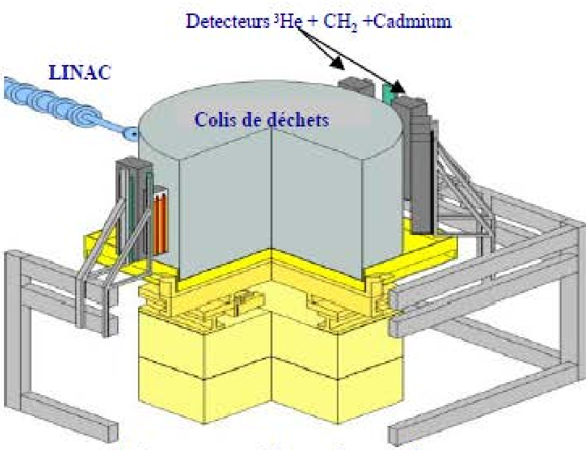


Photon Imagery and tomography

Combination

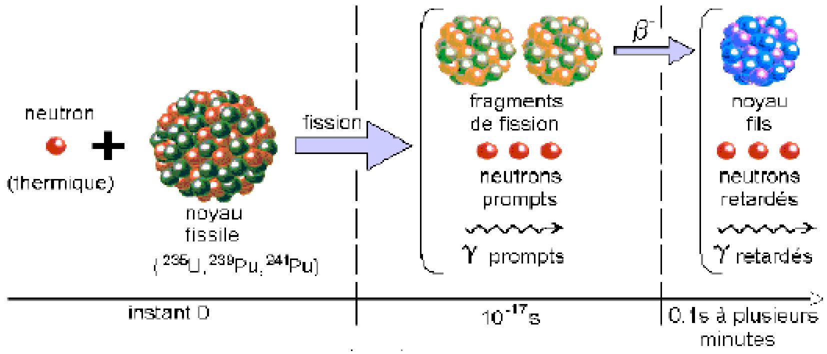
Unité de Tri de Marcoule

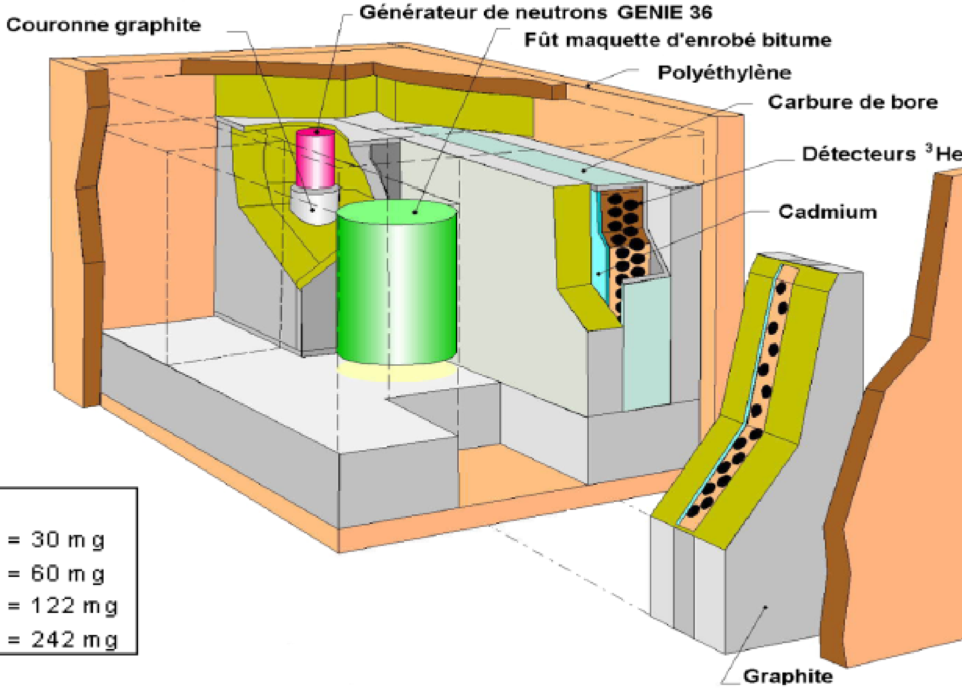


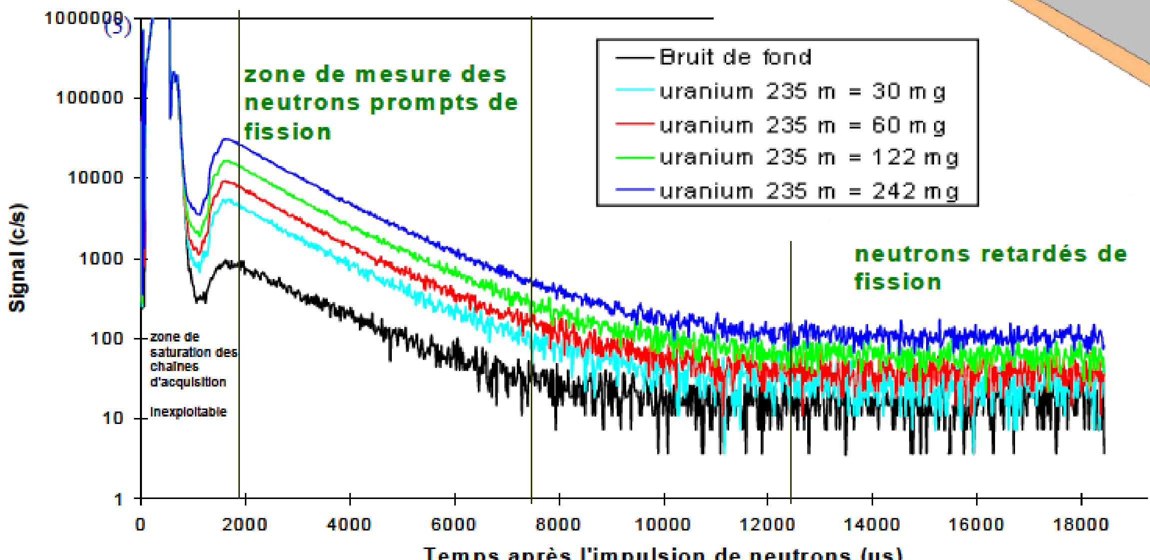


Interrogation (γ,n-f)

Active neutron measurement







- **Neutron prompt signal**

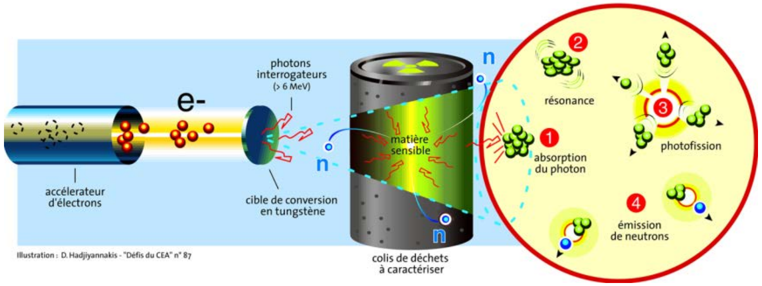
SP = a × m(^{239}Pu) + b × m(^{235}U)

- **Delayed neutron signal**

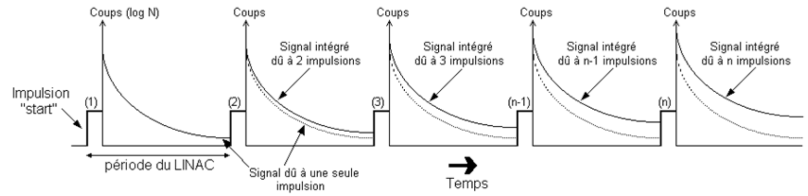
•SR = c × m(^{239}Pu) + d × m(^{235}U)
+ e × m(^{17}O) + f × m(^{238}U)
+ f × m(^{232}Th)

MEASUREMENT & INSTRUMENTATION FOR NDA

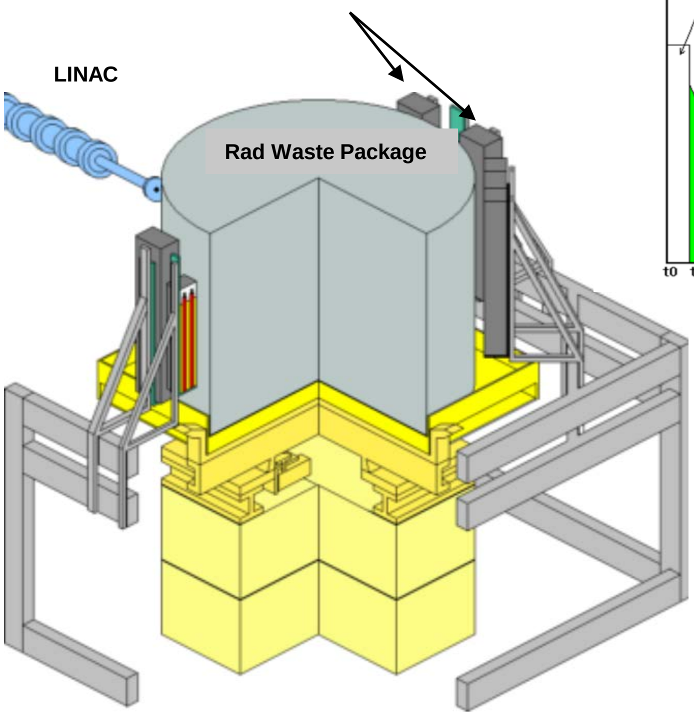
Active Photon Interrogation

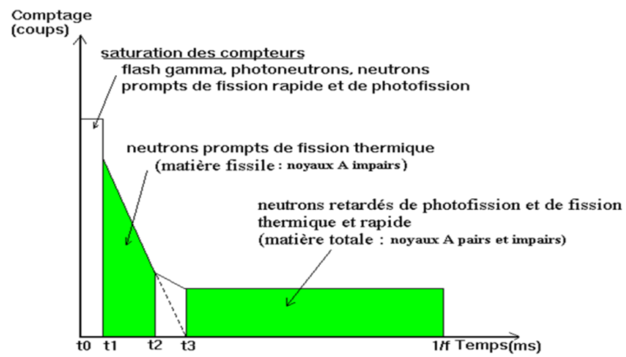


SPHINCS counting technique

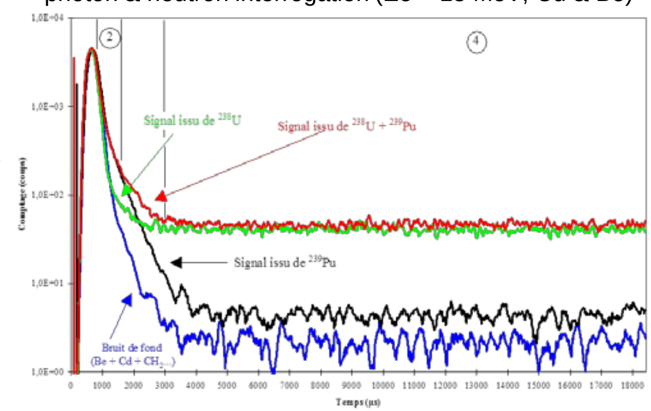


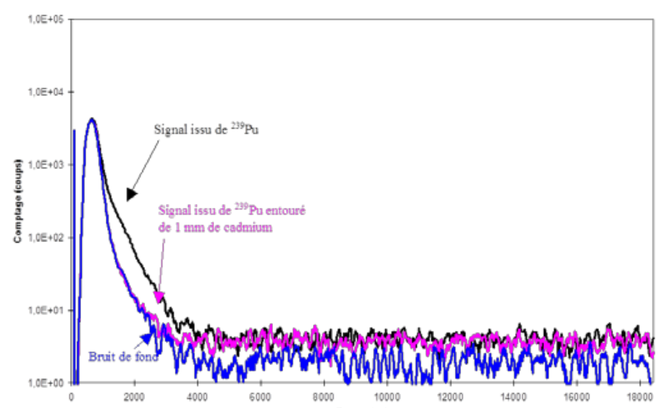
^{3}He Detectors + CH_2 +Cadmium





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 (CABRI, 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 100 dpa !) and temperatures
  - **Measuring and Interpretation Processes** (online / combined measurements)

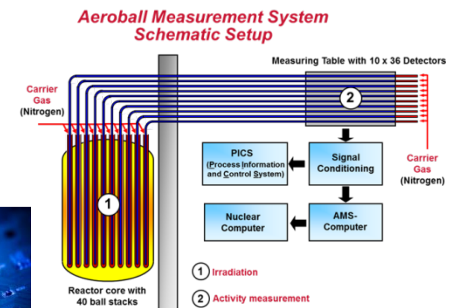
- Due to the closing of several **irradiation facilities** and the disappearance of the associated teams, **collaborations** are a favoured way for instrumentation developments to be enhanced

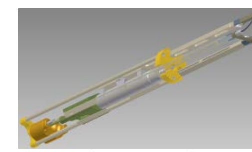
- An attention should paid for **Nuclear Data** which are often not enough developed for instrumentation needs (e. g. charged particles)

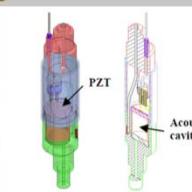
FINALLY…

Maintain and increase 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 analysis**
- ❑ **Uncertainties treatment, analysis and their reduction**
- ❑ **Data mining, Artificial Intelligence, Algorithmic, Machine learning**
- ❑ ….







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)