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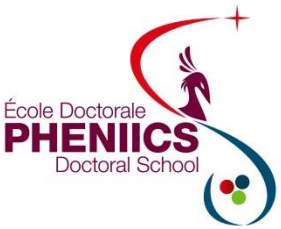
Study of X-ray diagnostics for corium-sodium interaction during severe accident scenario

PHENIICS Fest

Orsay, 31st May, 2017



Shifali SINGH
DEN/DTN/SMTA/LPMA
CEA, Cadarache

Christophe Journeau
Thesis Director

Nathalie Cassiaut-Louis
Supervisor

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Agenda

- Context
- Research Objective
- Research Methodology
- Preliminary Results
- Future Work

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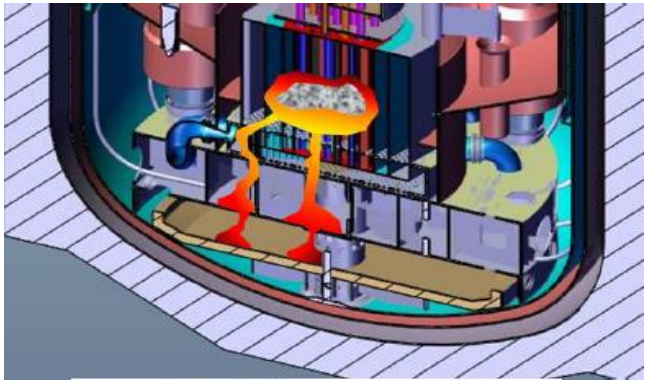
Context

In case of a severe nuclear accident, the fuel can melt forming hot corium !!!

What is corium?

- Hot (~ 3000 K) molten material issuing from degraded core
- Consists of:
  Nuclear fuel, fission products, control rod and structural material



Accidental scenario in a nuclear reactor

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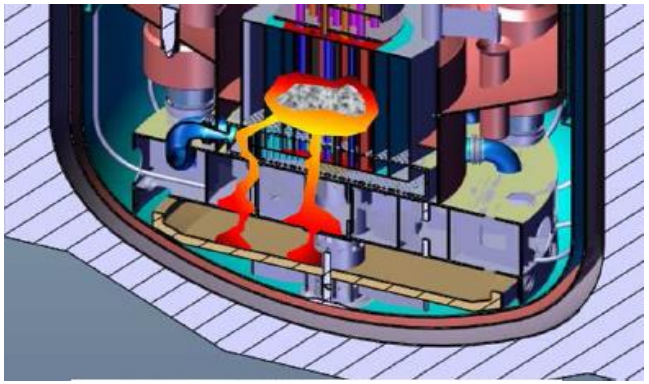

Accidental scenario in a nuclear reactor

Thermal Reactors

Interacting coolant: Water
Corium-water interaction

Fast Reactors

Interacting coolant: Sodium
Corium-sodium interaction

Context

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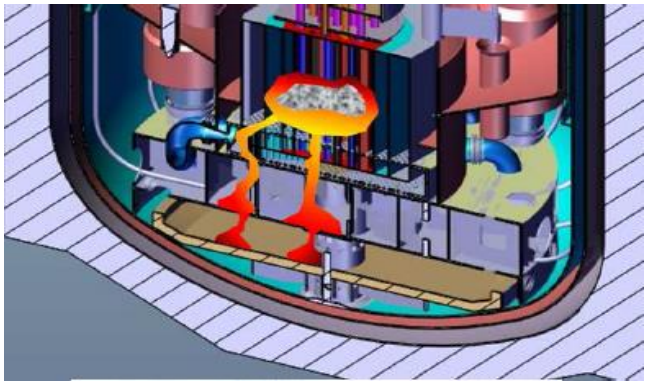

Accidental scenario in a nuclear reactor

Thermal Reactors	Fast Reactors
Interacting coolant: Water Corium-water interaction	**Interacting coolant:** Sodium Corium-sodium interaction

These interaction can lead to **vapor explosions** which can impact the reactor integrity

Study of these interactions are very important !!!

Context

Corium-water interaction studies:

- Stable vapor film formed around fragments
- **Characteristic size of particles: 2-3 mm**
- Test facility at CEA-CAD: **PLINIUS (KROTOS)**
  - Corium-water interaction up to steam explosions
  - Corium mass: 5-8 kg
  - Water temperature: ≈ 60°C

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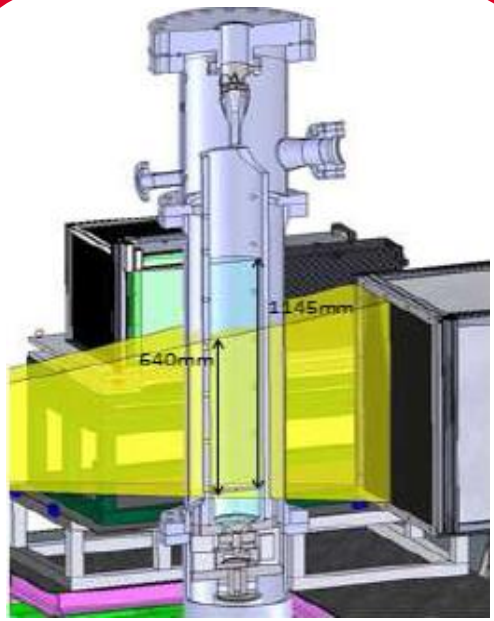

KROTOS facility

- High energy X ray source of Linatron (**9 MeV**).
- Detector: GADOX
- High sensitive CCD camera: **100 fps**.

Context

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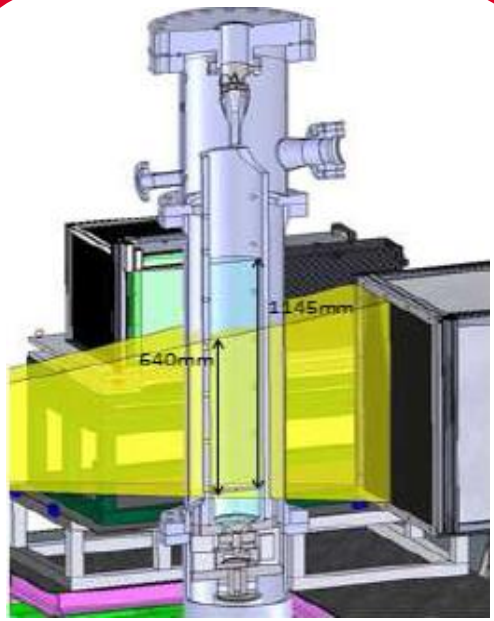

KROTOS facility

- High energy X ray source of Linatron (**9 MeV**).
- Detector: GADOX
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How to visualize/study this interaction ??

- **X-ray radioscopy system:** Qualitative and quantitative analysis of the three phase distribution (Molten corium-Water-Steam)
- **Image Processing algorithm:** KIWI (**K**ROTOS **I**mage analysis for **W**ater Corium **I**nteraction)

Context

Corium-sodium interaction studies:

- Film is difficult to establish in sodium
- **Characteristic size of particles: ~100 µm**
- Test facility at CEA-CAD: **PLINIUS-2 (under construction, expected commissioning-2021)**
  - Corium-sodium interaction up to vapor explosion
  - Corium mass: 50 to 500 kg
  - Sodium temperature: 400 to 850°C

Context

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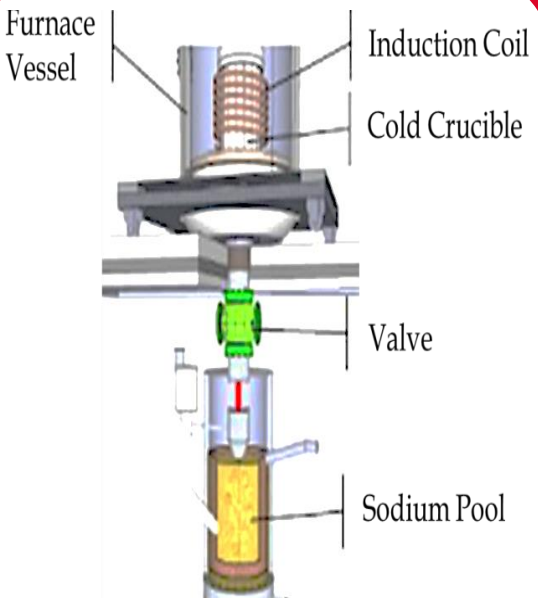


PLINIUS-2
corium-sodium facility

- High energy X ray source of Linatron (**15 MeV**).
- Detector: Gadox
- 4 CMOS camera: **100 fps**.

Context

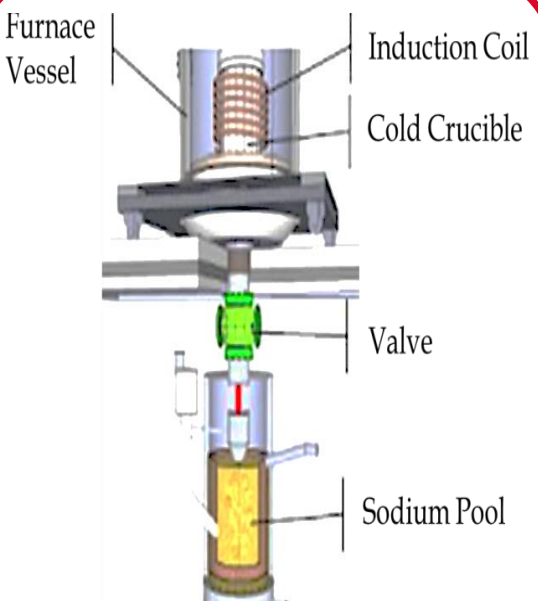
Corium-sodium interaction studies:

- Film is difficult to establish in sodium
- **Characteristic size of particles: ~100 µm**
- Test facility at CEA-CAD: **PLINIUS-2 (under construction, expected commissioning-2021)**
  - Corium-sodium interaction up to vapor explosion
  - Corium mass: 50 to 500 kg
  - Sodium temperature: 400 to 850°C

Lack of knowledge of the corium-sodium interaction phenomenology !!

How to visualize/study this interaction ??

- **X-ray radioscopy system: ??**
- **Image Processing algorithm: ??**



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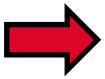
Research Objective

Learn From
Corium-water interaction



Apply to
Corium-sodium interaction

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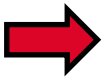
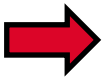
Research Objective

Learn From
Corium-water interaction



Apply to
Corium-sodium interaction

Learn From
Existing X-ray imaging system of KROTOS



Develop
A new X-ray imaging system for PLINIUS-2

Research Objective

Learn From
Corium-water interaction

→

Apply to
Corium-sodium interaction

Learn From
Existing X-ray imaging system of KROTOS

→

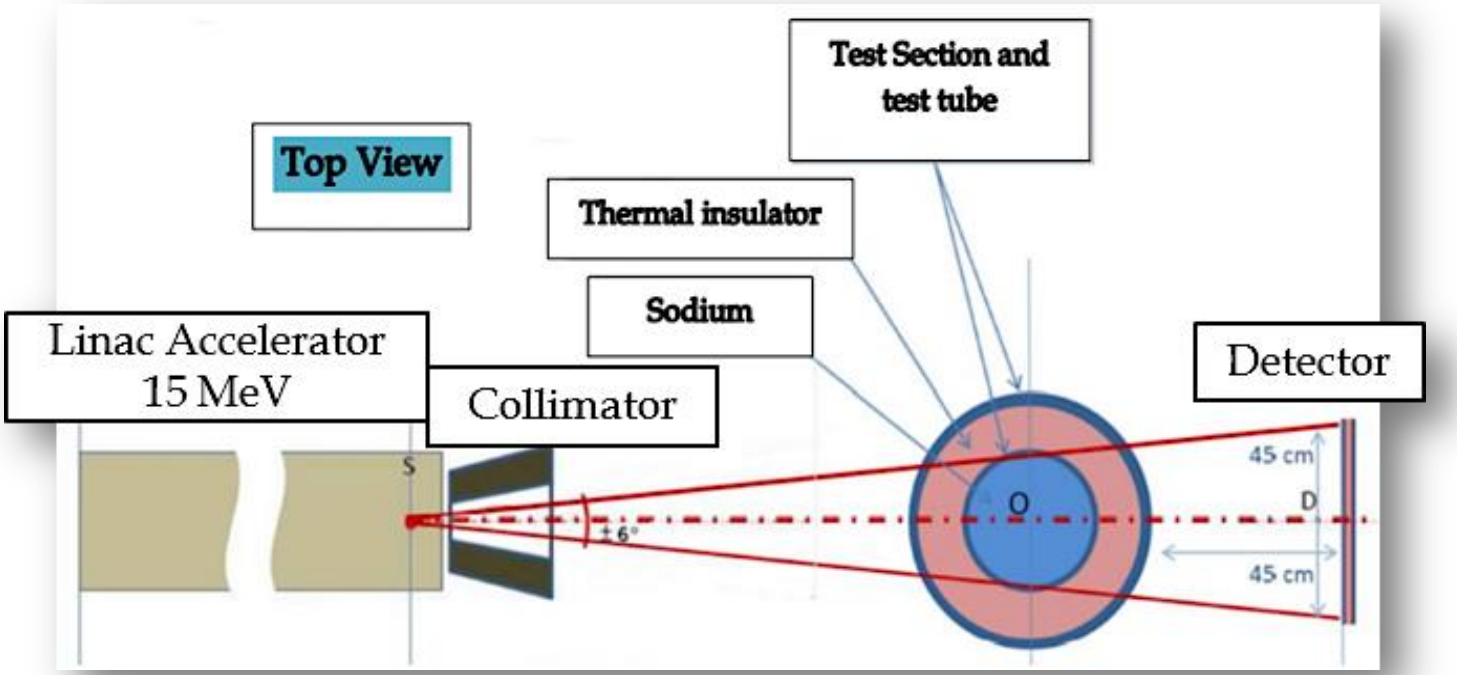
Develop
A new X-ray imaging system for PLINIUS-2

Learn From
Existing Image Processing algorithm: KIWI

→

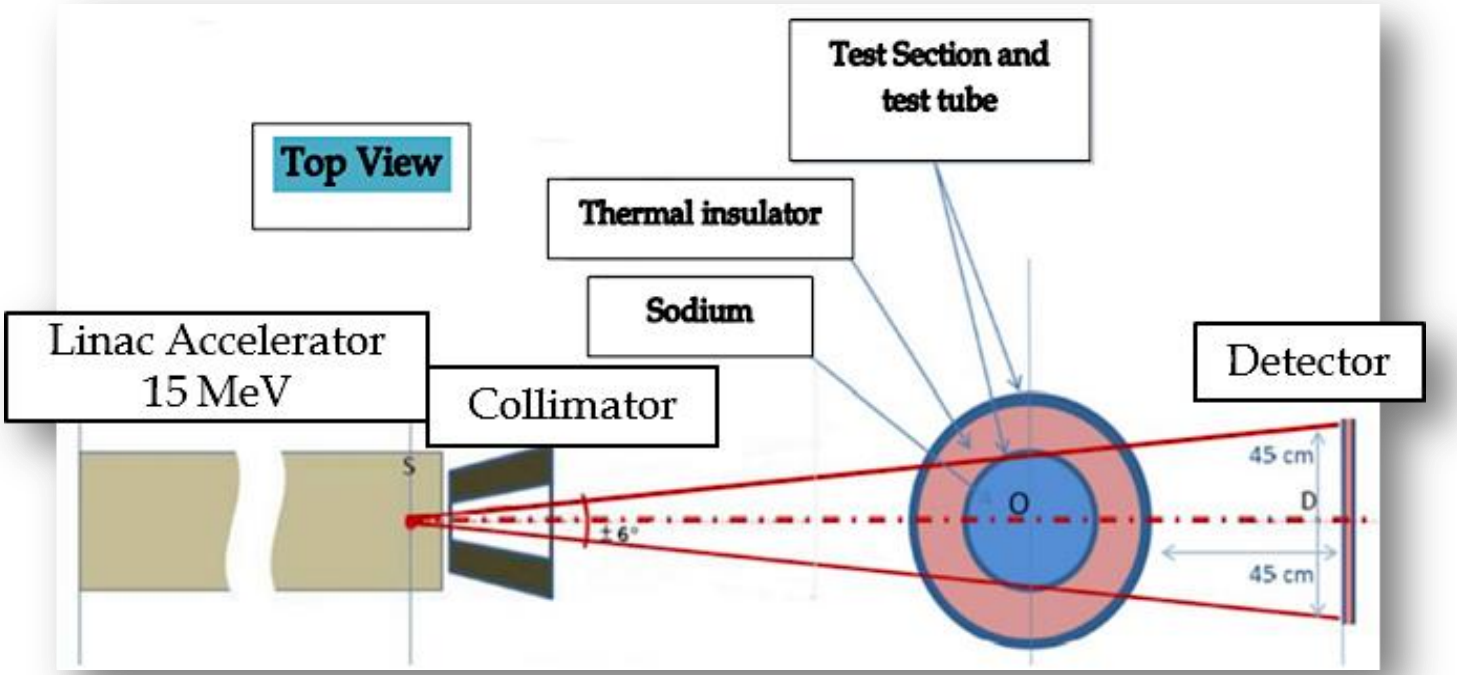
Develop
A new Image Processing software for PLINIUS-2

Research Objective



Foreseen X-ray radiography in PLINIUS-2

Research Objective



Foreseen X-ray radiography in PLINIUS-2

Difficulties

- **Extreme fine fragmentation of corium in sodium**, i.e. ~100 µm
- Resolution of KROTOS X-ray imaging system for water (available) is 3 mm
- High temperature range of sodium

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Research Methodology

- Past Experiments: Particle size distributions in the debris bed
- **Estimate** fragment shape and size to develop phantoms

Bibliography: State of the art

Modelling

- **Simulate** the phantoms with MODHERATO code
- **Design** and manufacture actual phantoms

- **Experiment** with phantoms to obtain images
- **Develop** the image processing and analysis software
- **Validate** the developed software

Software development & validation

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- Past Experiments: Particle size distributions in the debris bed
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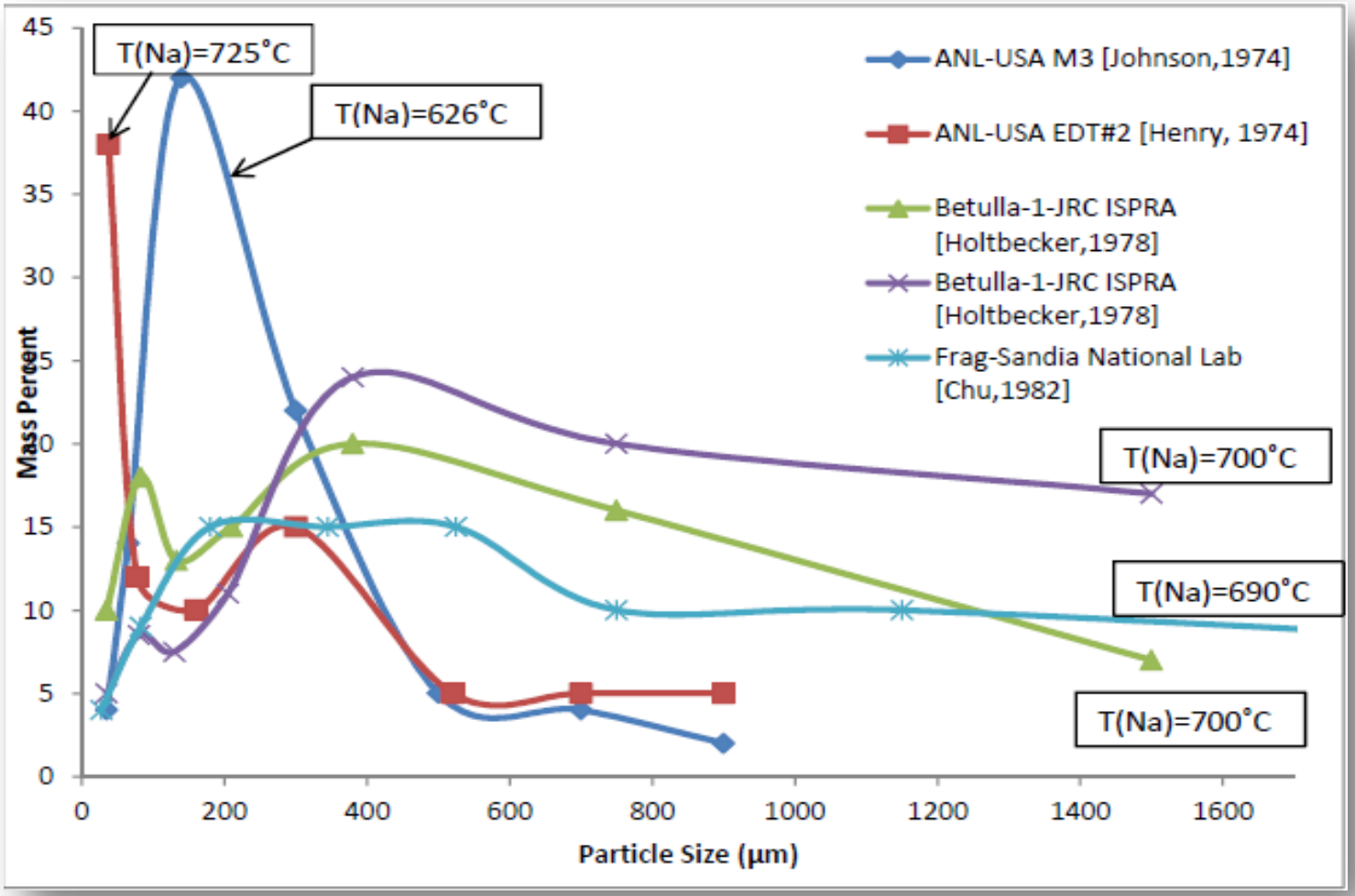
Literature study of the past experiments with sodium-corium:



Statistics of debris particles formed by interaction b/w UO2 and Na

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- **Statistical analysis of the past experiments using R studio:**

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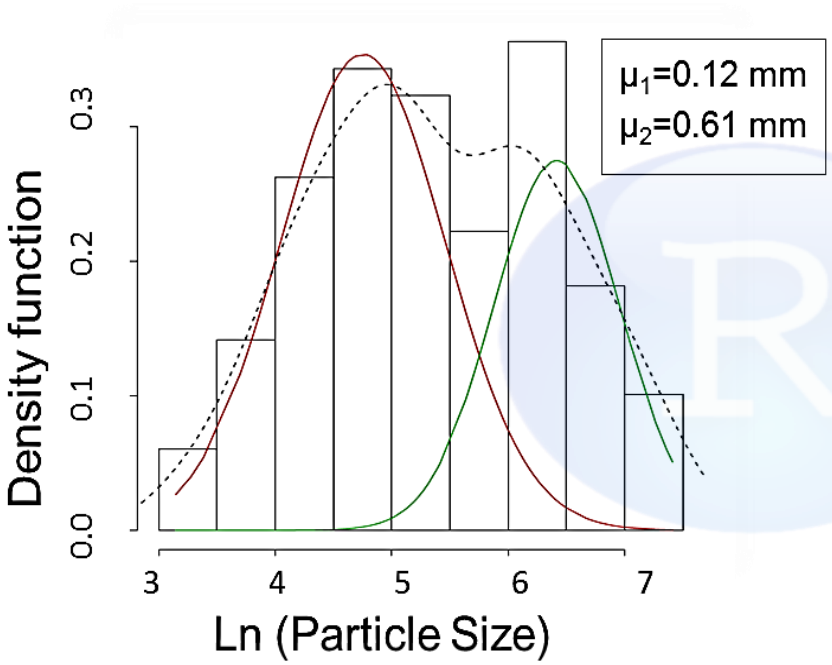

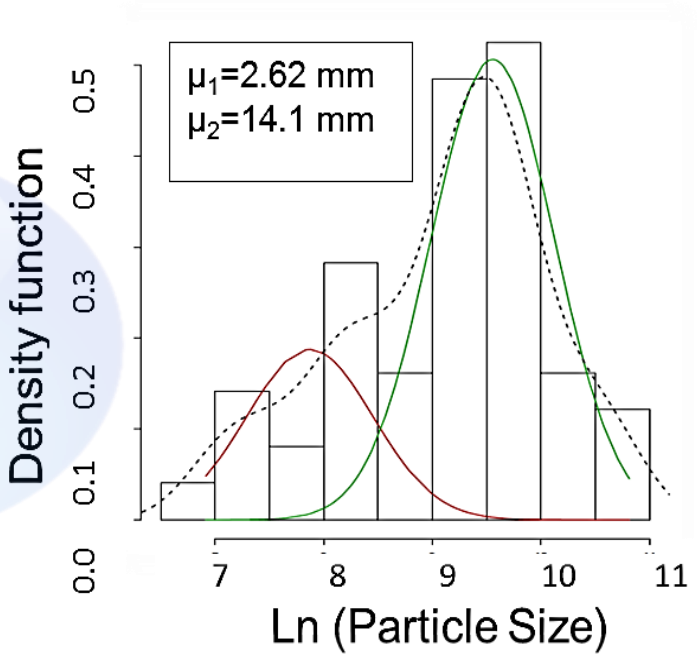

Probability density function of the particle size distribution

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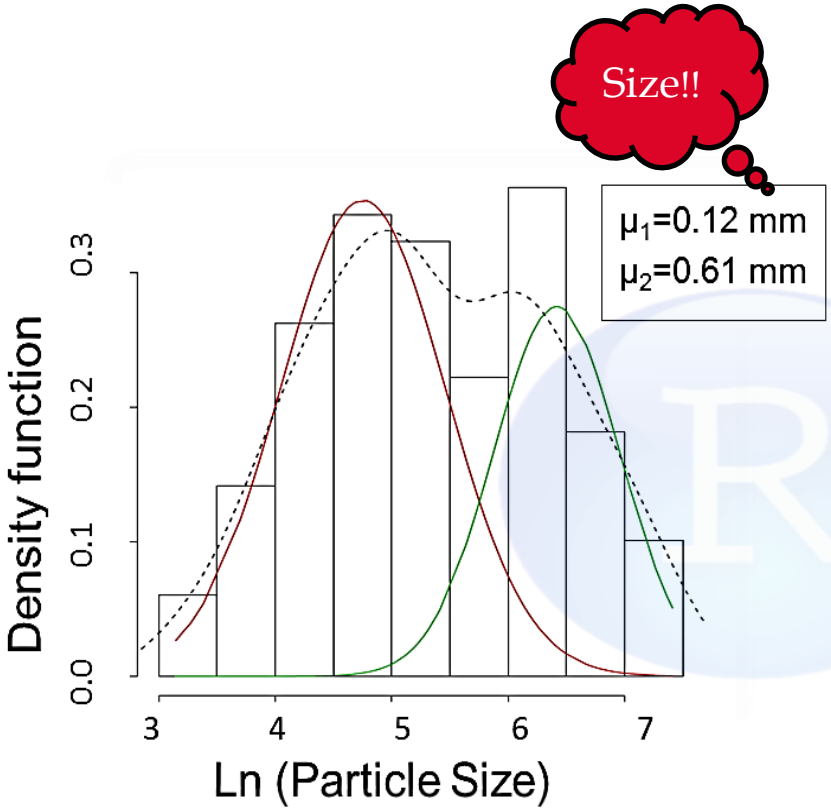

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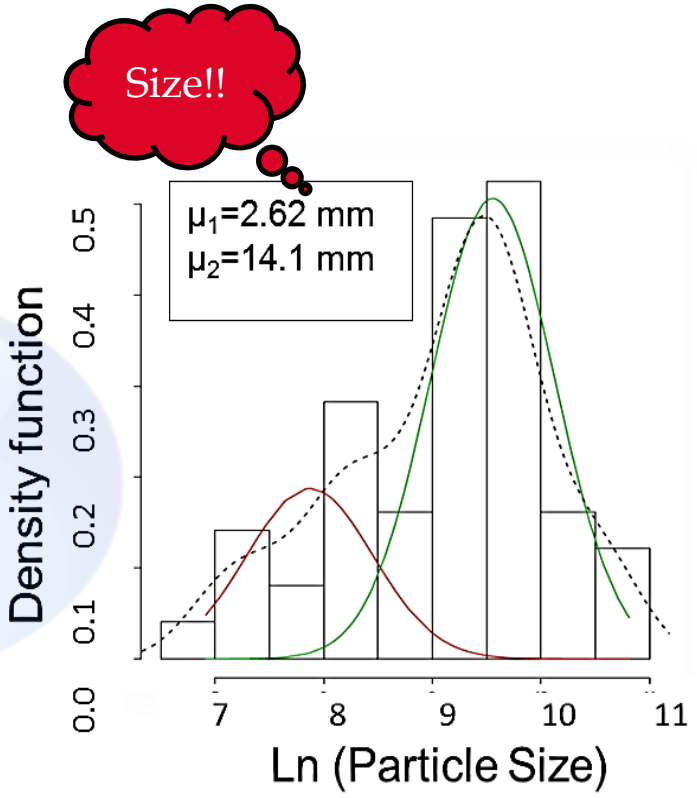

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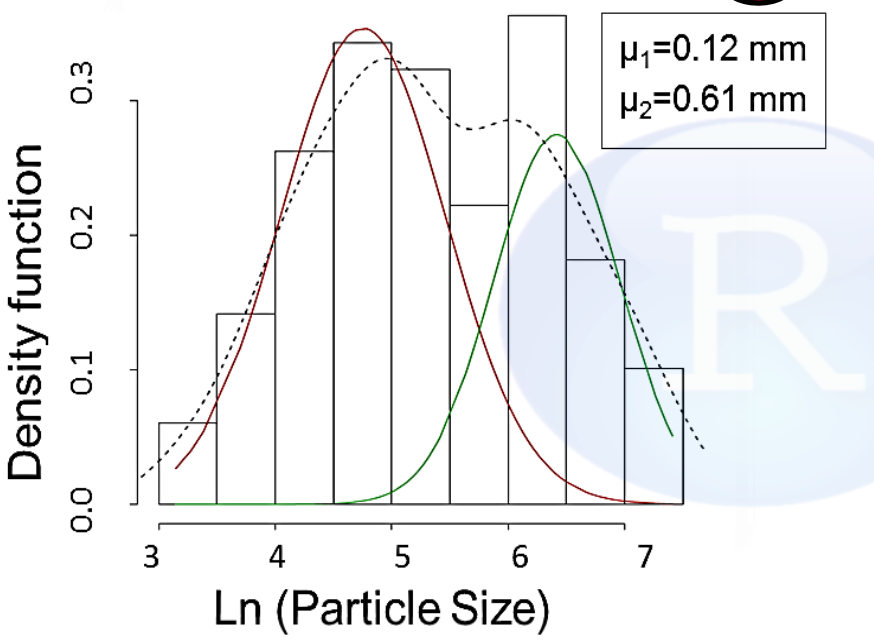
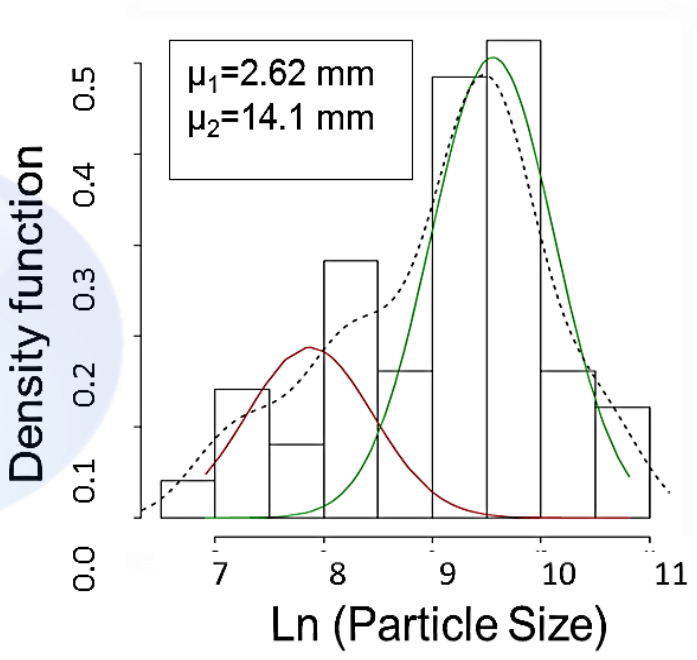
Shape

- Shape: **Angular outline**



Shape

- Shape: **Smooth & spherical**



Probability density function of the particle size distribution

Modelling

Modelling

- **Simulate** the phantoms with MODHERATO code
- **Design** and manufacture actual phantoms

Phantom??

Represents corium fragments with similar attenuation properties.

Sample phantoms

Modelling

Modelling

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  (Cad/LMN tool)

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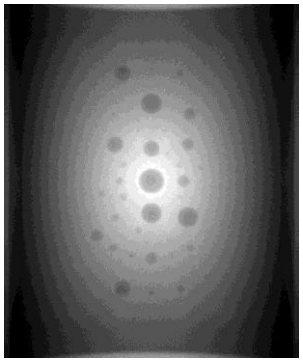

MODHERATO Image

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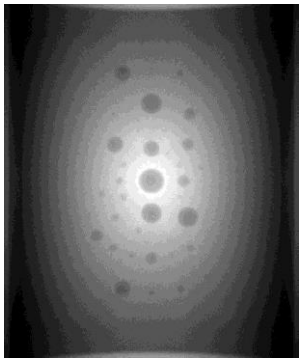

MODHERATO Image

- Study the detection limit of MODHERATO:

Modelling

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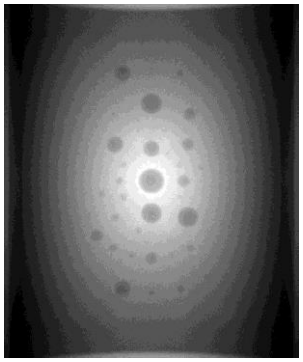

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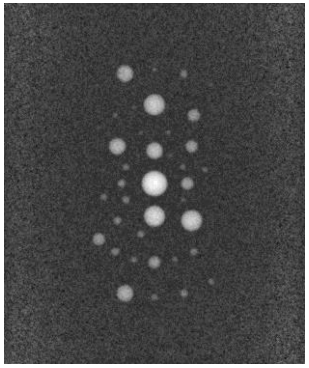

Contrast Image (using IMAGEJ)

Modelling

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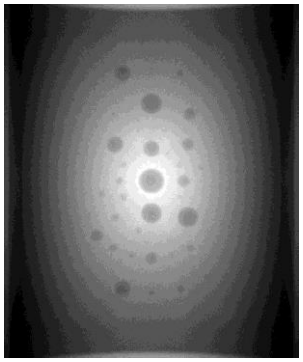

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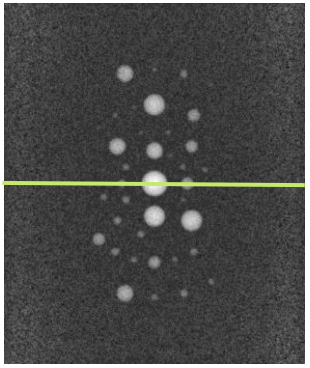

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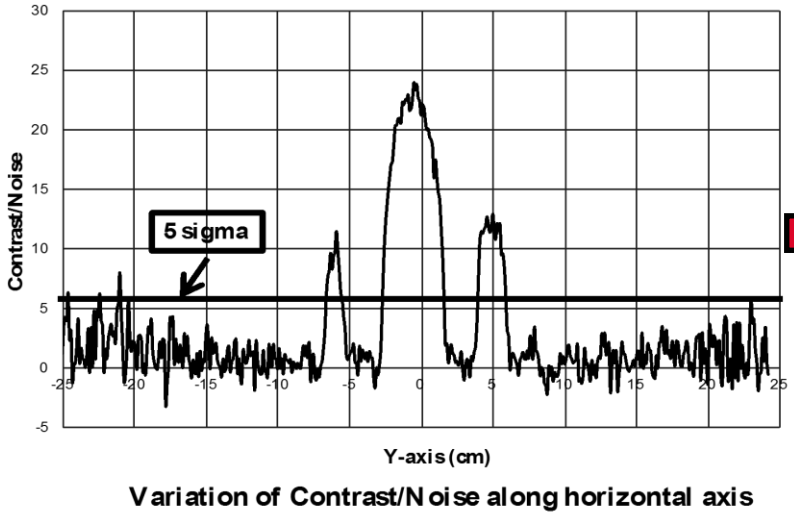
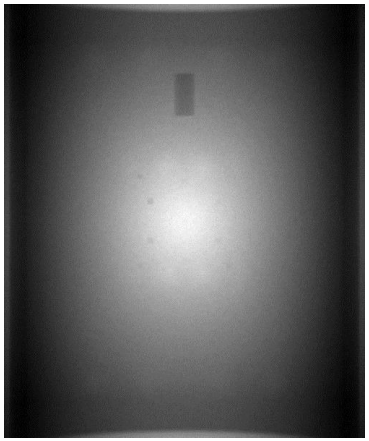


Variation of Contrast/Noise along horizontal axis

- **Contrast/Noise ratio > 5**
- **Detection limit: 5 mm !!**

Modelling

- **Phantoms of size D= 5.5 mm in MODHERATO**



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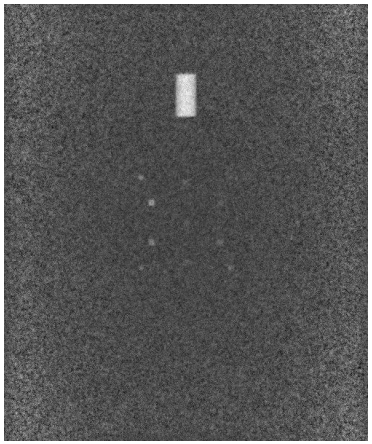

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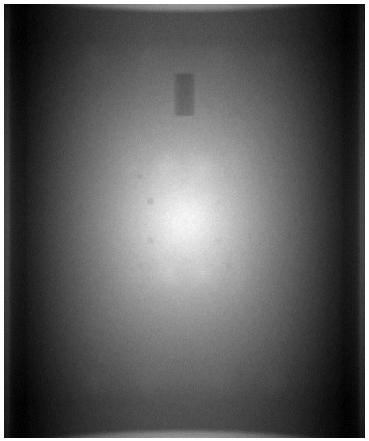

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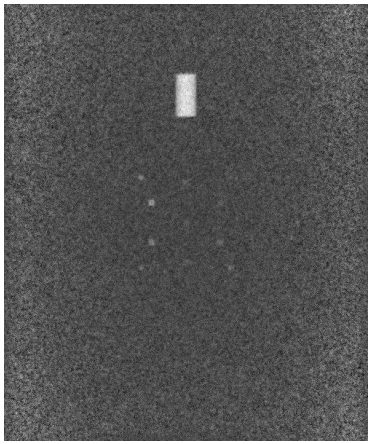
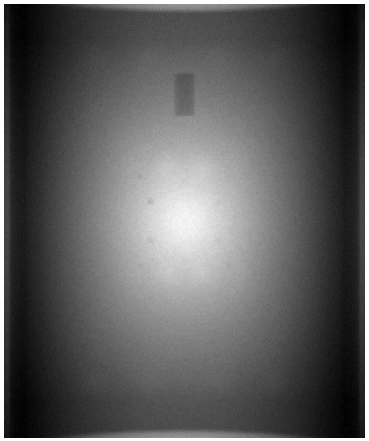


Contrast Image

Atomic fraction of Corium in corium-sodium mixture	50%	60%	70%	80%	90%	100%
Density of the mixture (g/cm3)	2.51	3.16	4.03	5.23	7.03	10.0
Contrast / Noise ratio	3.9	4.5	4.9	5.6	6.75	9.8

Modelling

- **Phantoms of size D= 5.5 mm in MODHERATO**



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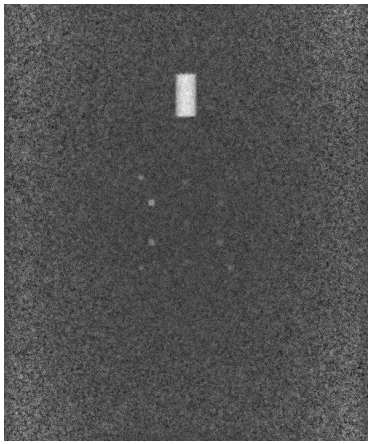

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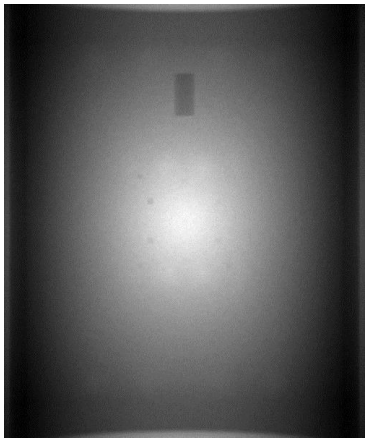
Contrast / Noise ratio	3.9	4.5	4.9	5.6	6.75	9.8

Contrast/Noise ratio > 5

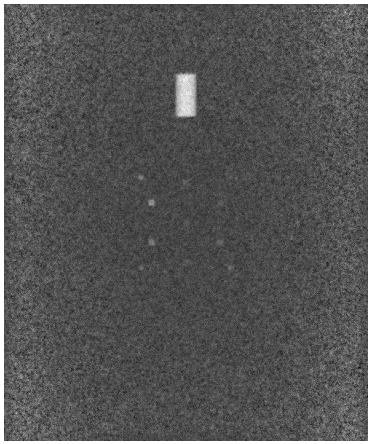
Clearly distinguishable !

Modelling

Phantoms of size D= 5.5 mm in MODHERATO



MODHERATO Image



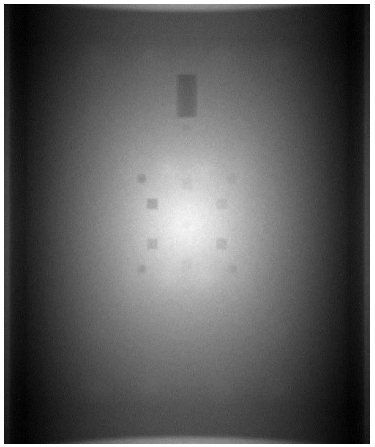
Contrast Image

Atomic fraction of Corium in corium-sodium mixture	50%	60%	70%	80%	90%	100%
Density of the mixture (g/cm3)	2.51	3.16	4.03	5.23	7.03	10.0
Contrast / Noise ratio	3.9	4.5	4.9	5.6	6.75	9.8

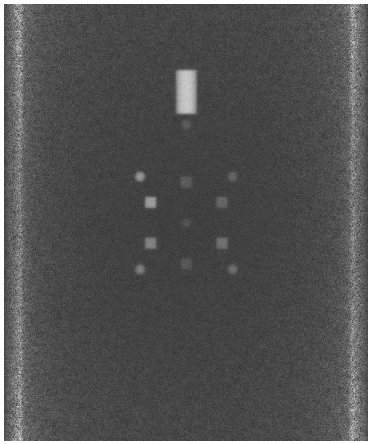
Contrast/Noise ratio > 5

Clearly distinguishable !

Phantoms of size D= 10 mm in MODHERATO



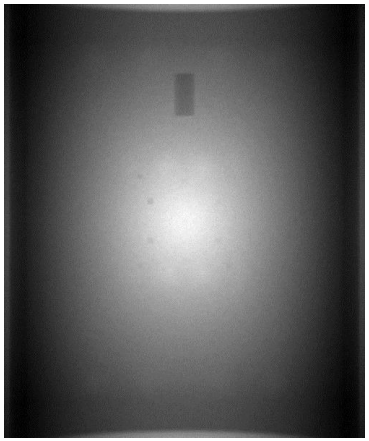
MODHERATO Image



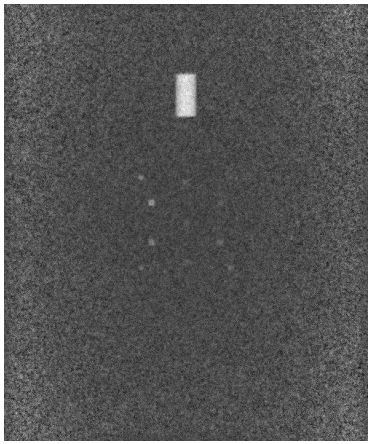
Contrast Image

Modelling

Phantoms of size D= 5.5 mm in MODHERATO



MODHERATO Image



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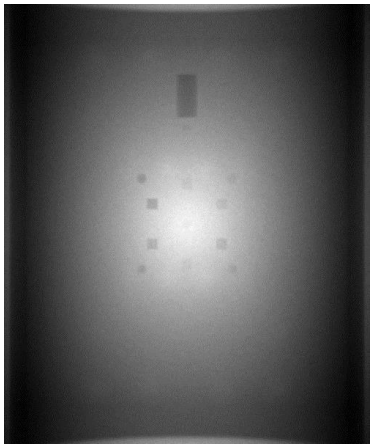
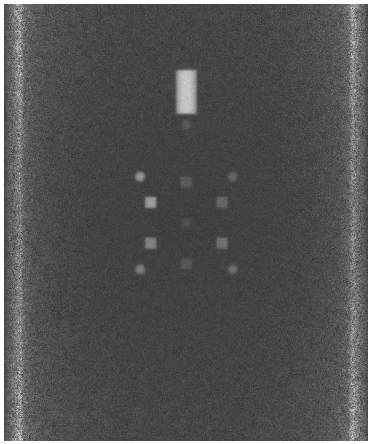
Contrast/Noise ratio > 5

Clearly distinguishable !

Phantoms of size D= 10 mm in MODHERATO



MODHERATO Image



Contrast Image

Atomic fraction of Corium in corium-sodium mixture	50%	60%	70%	80%	90%	100%
Density of the mixture (g/cm3)	2.51	3.16	4.03	5.23	7.03	10.0
Contrast / Noise ratio	4.5	5	6.75	8.75	11.6	15.4

Clearly distinguishable !

Modelling

- **Simulate** the phantoms with MODHERATO code
- **Design** and manufacture actual phantoms

Designing and manufacturing of phantoms

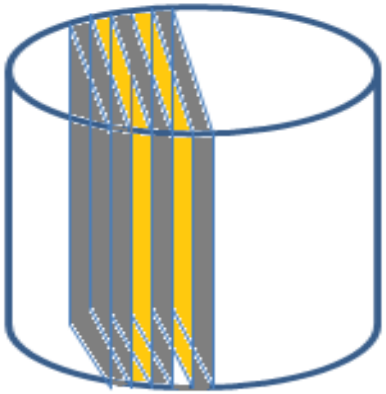
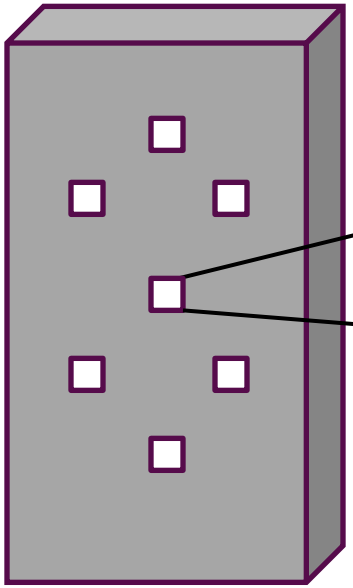


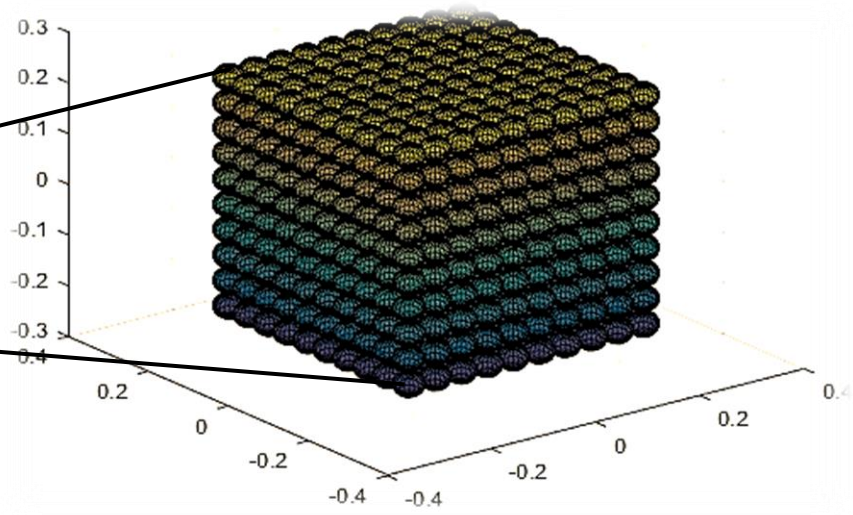
Plate of SS in polyethylene

Plate of void in polyethylene

SS : corium
void : sodium vapor
polyethylene : sodium liquid



Cloud of small particles

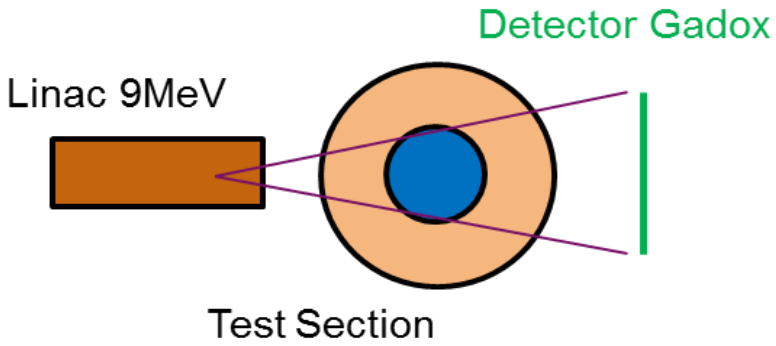


Software development and Validation

- **Experiment** with phantoms to obtain images
- **Develop** the image processing and analysis software
- **Validate** the developed software

Software development & validation

Experiment with phantoms to obtain radiographic images



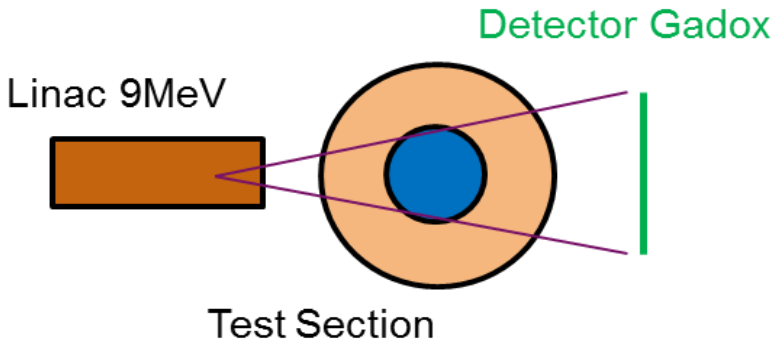
Experimental configuration for physical simulation

Software development and Validation

- **Experiment** with phantoms to obtain images
- **Develop** the image processing and analysis software
- **Validate** the developed software

Software development & validation

Experiment with phantoms to obtain radiographic images



Experimental configuration for physical simulation

- **Available LINAC** at present: **9 MeV** (from KROTOS facility)
- **Available detector and high sensitive CCD camera** (from KROTOS facility)
- Available test section: **KROTOS**
- Manufactured phantoms can be placed in the KROTOS test section to study the static and dynamic phenomenon with the phantoms.

Software development and Validation

- **Experiment** with phantoms to obtain images
- **Develop** the image processing and analysis software
- **Validate** the developed software

Software development & validation

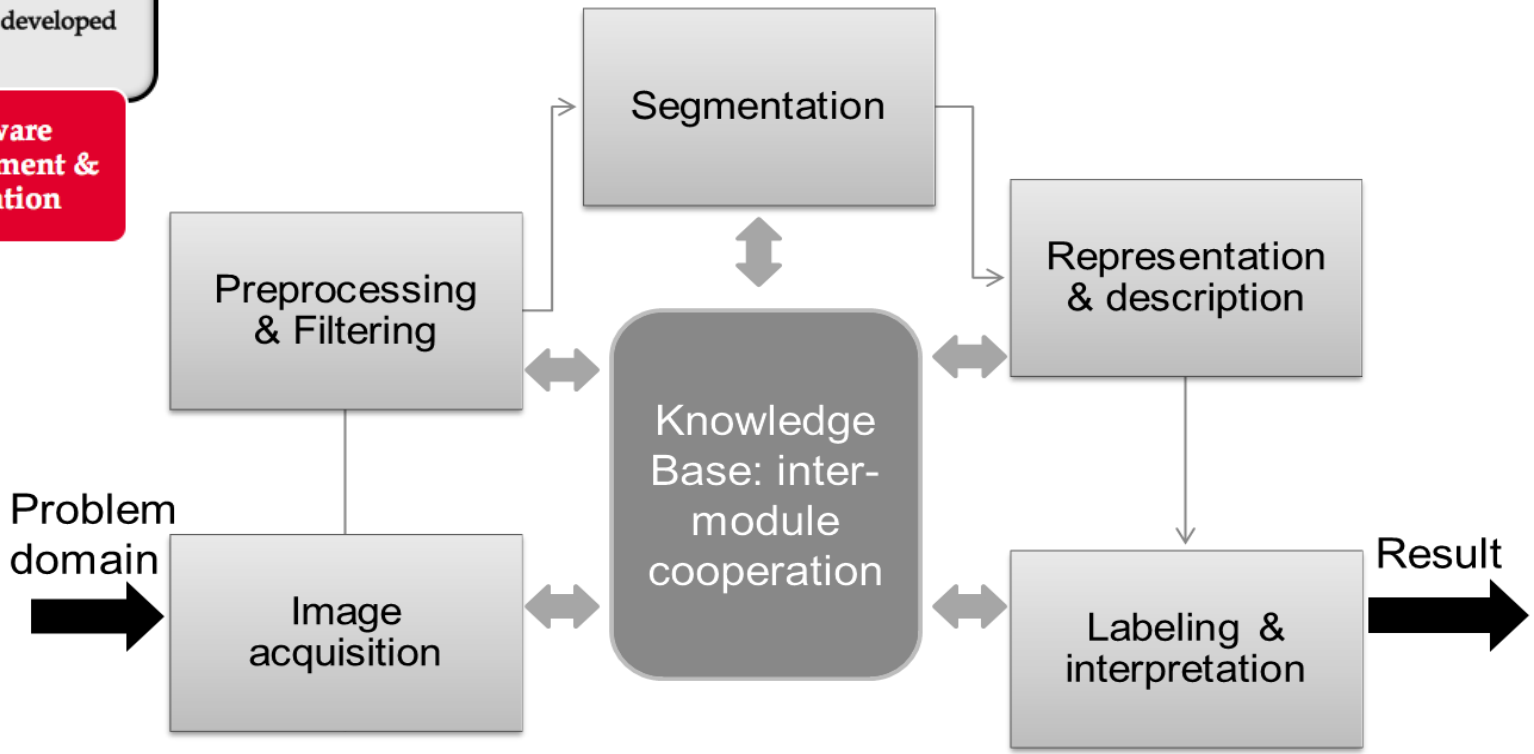
- **Software Development:** **KIWI's equivalent for sodium-corium interaction (in MATLAB)**

Software development and Validation

- **Experiment** with phantoms to obtain images
- **Develop** the image processing and analysis software
- **Validate** the developed software

Software development & validation

- **Software Development:** **KIWI's equivalent for sodium-corium interaction (in MATLAB)**



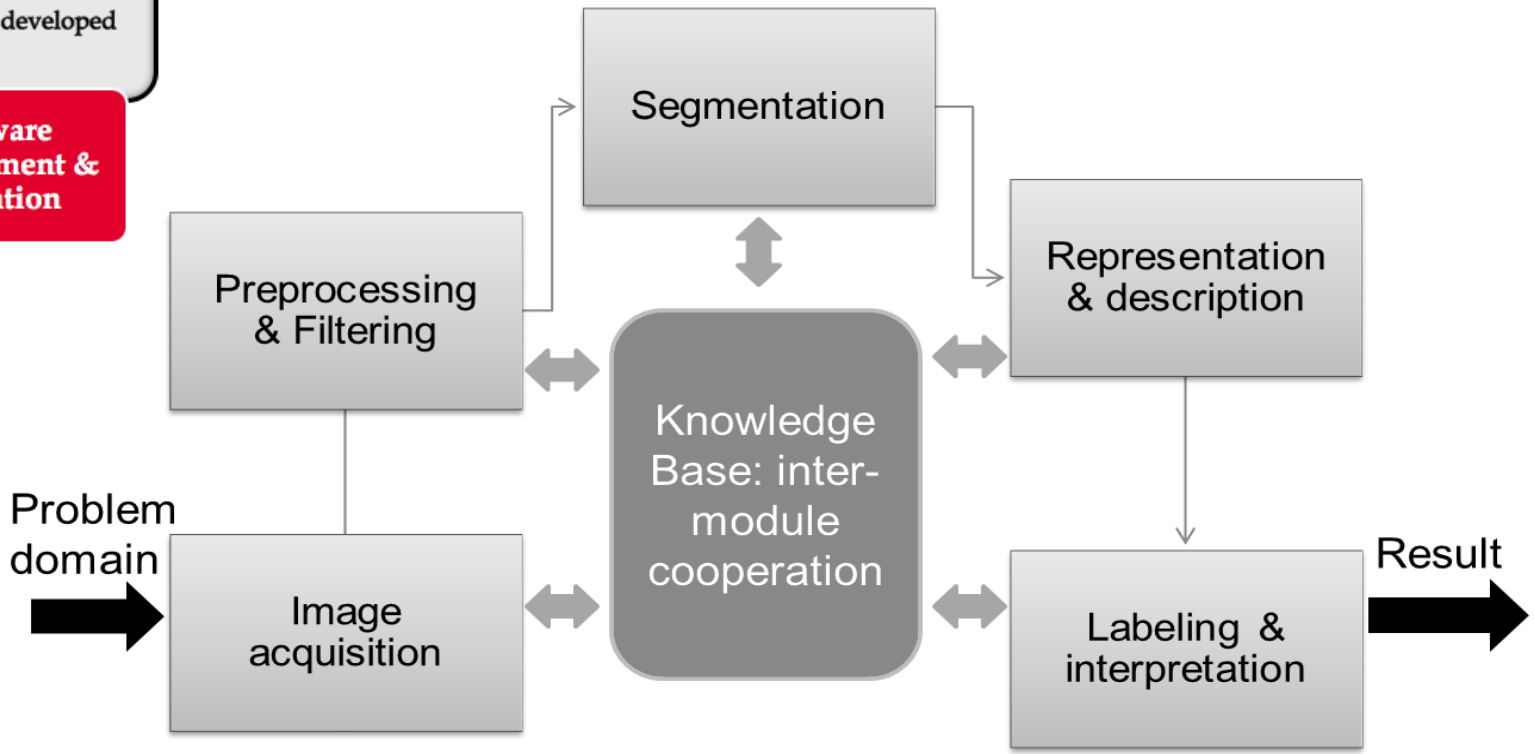
Block Diagram showing the code structure

Software development and Validation

- **Experiment** with phantoms to obtain images
- **Develop** the image processing and analysis software
- **Validate** the developed software

Software development & validation

- **Software Development: KIWI's equivalent for sodium-corium interaction (in MATLAB)**



Block Diagram showing the code structure

The developed software will then be validated on the images obtained from the experiment with the phantoms.

Work Timeline

THESIS

First Year

- Bibliography
- Modelling phantoms with MODHERATO

Second Year

- Designing & manufacturing phantoms
- Image processing & analysis software

Third Year

- Experiment
- Software validation

1 2 3

Years

Thank you for your attention

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Service Mesures et Modélisation des Transferts et des Accidents graves
Laboratoire de Physique et de modélisation des Accidents