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FROM RESEARCH TO INDUSTRY



New methods to estimate the internal pressure of xenon in fission bubbles using SEM-EPMA-SIMS and EBSD in irradiated fuels

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EMAS2015 |

5 MAY 2015

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I. CONTEXT

II. ESTIMATING THE PRESSURE IN BUBBLES

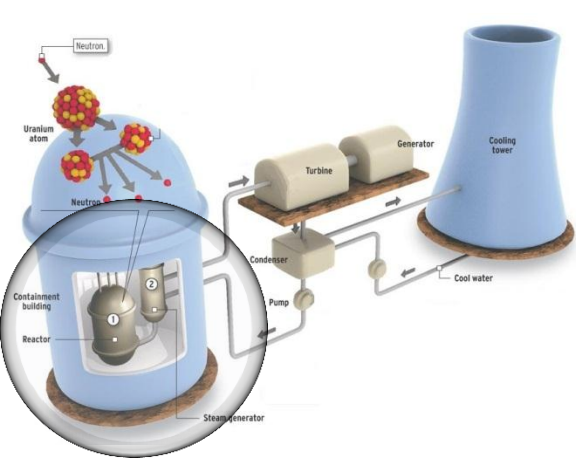
- ❑ Direct method : Measurement by SEM/EPMA/SIMS
- ❑ Indirect method :
 - Strain measurement by EBSD/cross-correlation,
 - Finite element modeling to calculate the pressure

III. CONCLUSION AND FUTURE PROSPECTS

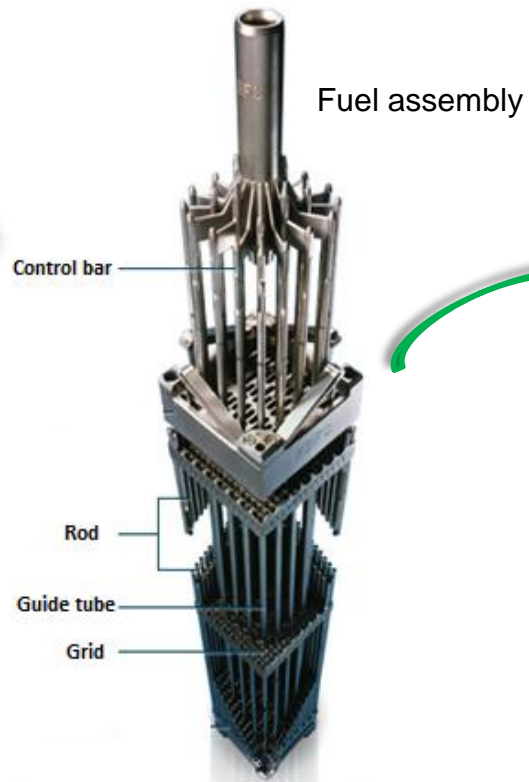
I. CONTEXT

II. ESTIMATING THE PRESSURE IN BUBBLES

II. CONCLUSION AND FUTURE PROSPECTS



PW Reactor



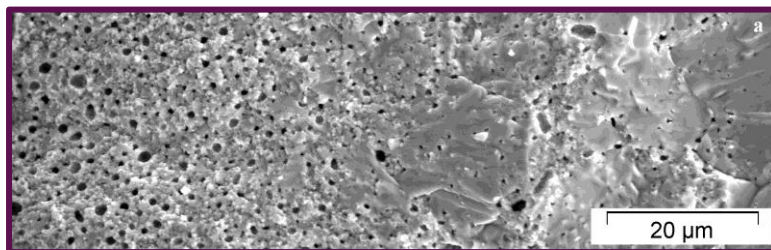
Fuel assembly



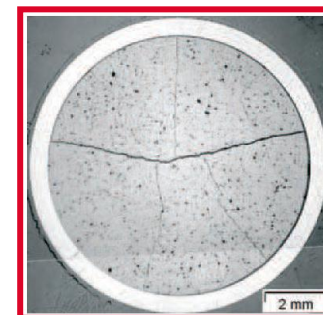
Rods : fuel + cladding



Fuel : UO₂ pellets



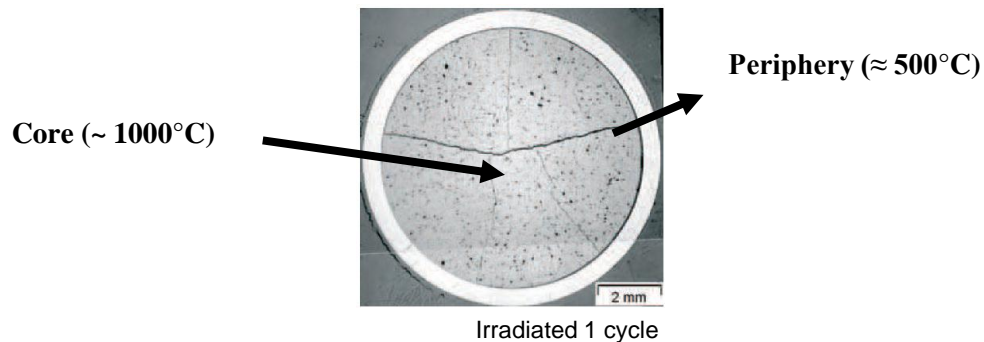
Fuel's microstructure



Radial section of a pellet

- Modeling is an essential tool that is now seeking to translate all phenomena and calculate all physical quantities (temperature, stress, swelling, release of fission gas...) that modify the behavior of PWR fuels.
- Providing new experimental data, such as **fission gas bubbles pressure**, is a way to validate and improve the models' predictions of the fuel behaviour during :

- Nominal Irradiation

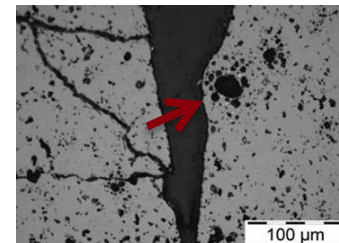


- **Localisation of fission gases**

- In solution inside the fuel
- Intra- and/or intergranular bubbles



Coalescence of bubbles after a ramp

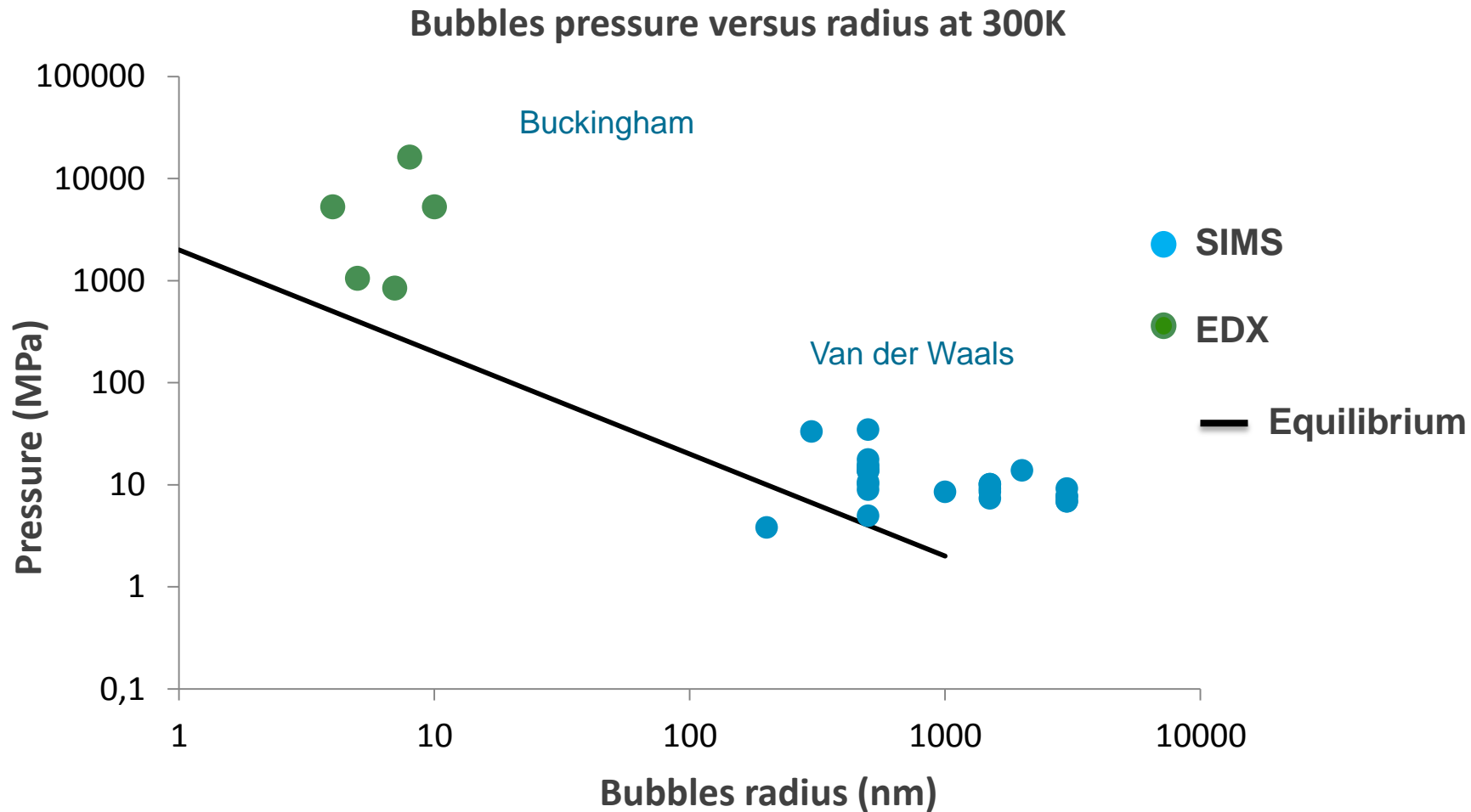


HBS in MOX

- Power ramps

- Accidental situation – RIA (Reactivity Insertion Accident)

■ Experimental data from the literature



I. CONTEXT

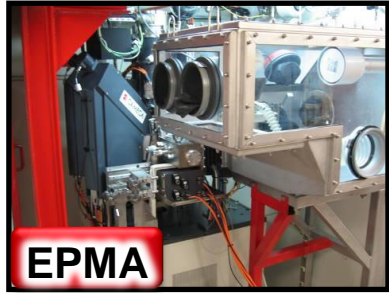
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III- ESTIMATING THE PRESSURE IN BUBBLES – GLOBAL METHODOLOGY

Measuring the amount of xenon in bubbles

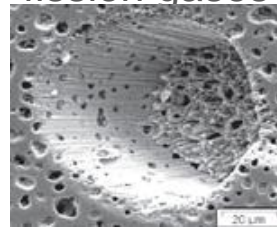


Quantitative analysis

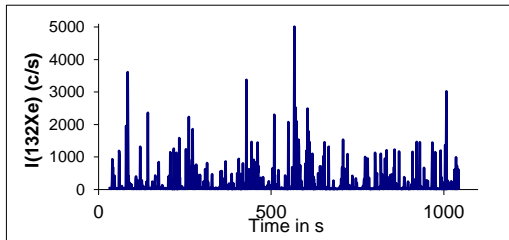
Total inventory of fission gases



SIMS



SIMS crater



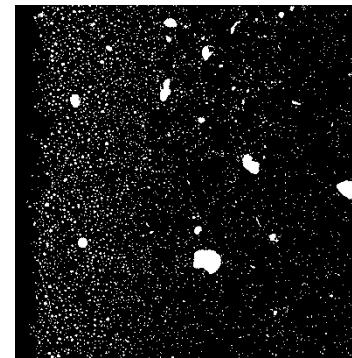
SIMS depth profile

Measuring the volume fraction of bubbles

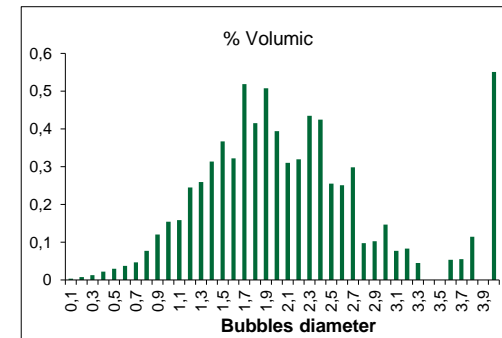


Morphology
Image analysis

SEM



Binary image



■ Quantity of xenon inside the bubbles

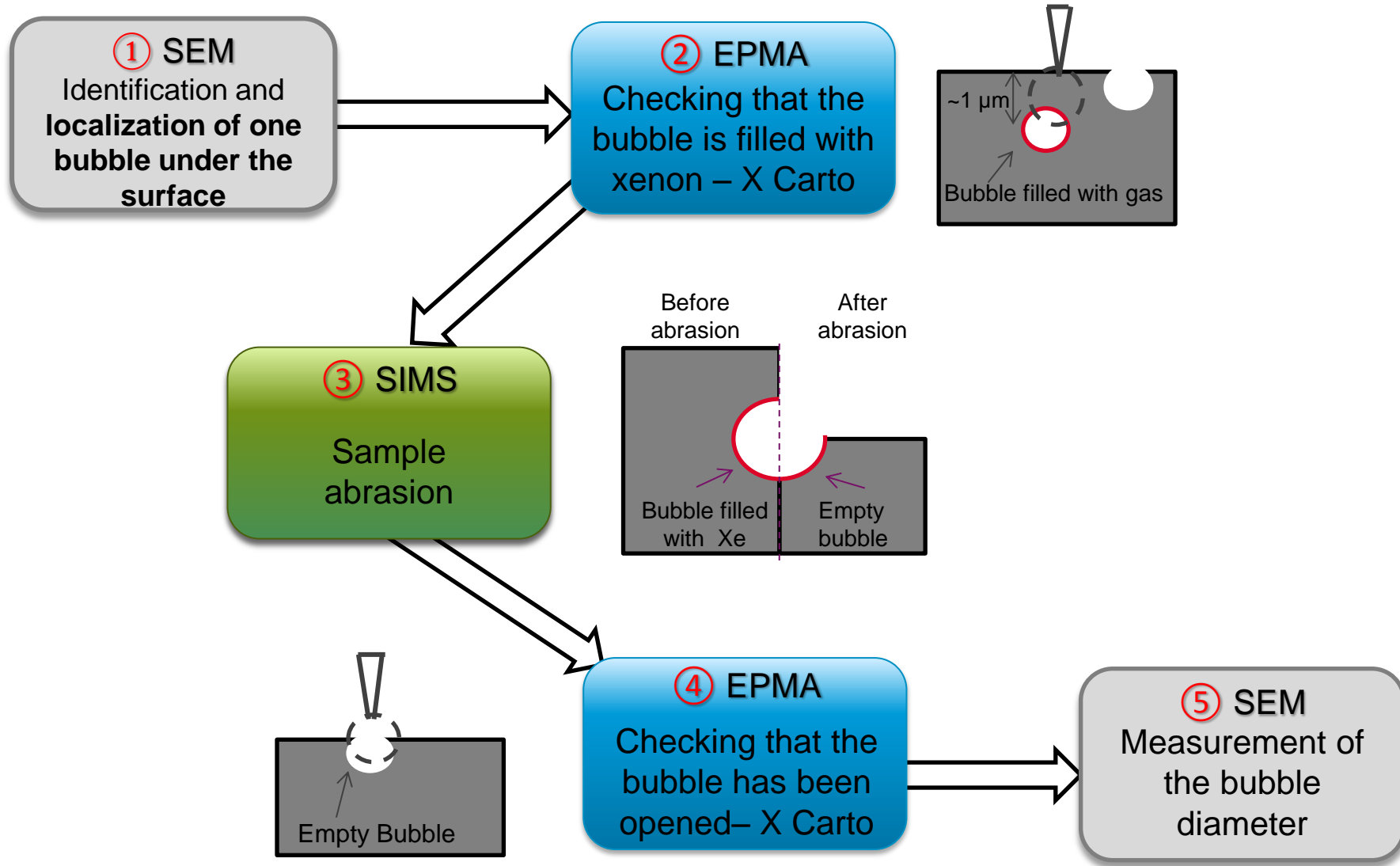
■ 2D -> 3D Volume fraction

Atomic Volume

Mean pressure

Equation of state

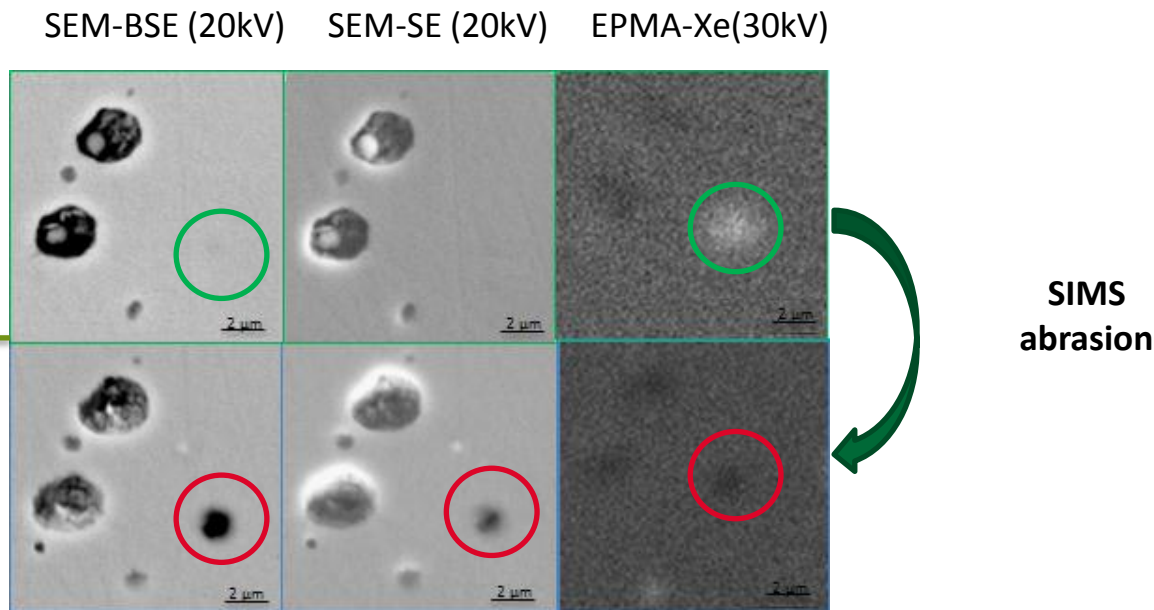
III- ESTIMATING THE PRESSURE IN BUBBLES – SINGLE BUBBLE METHODOLOGY



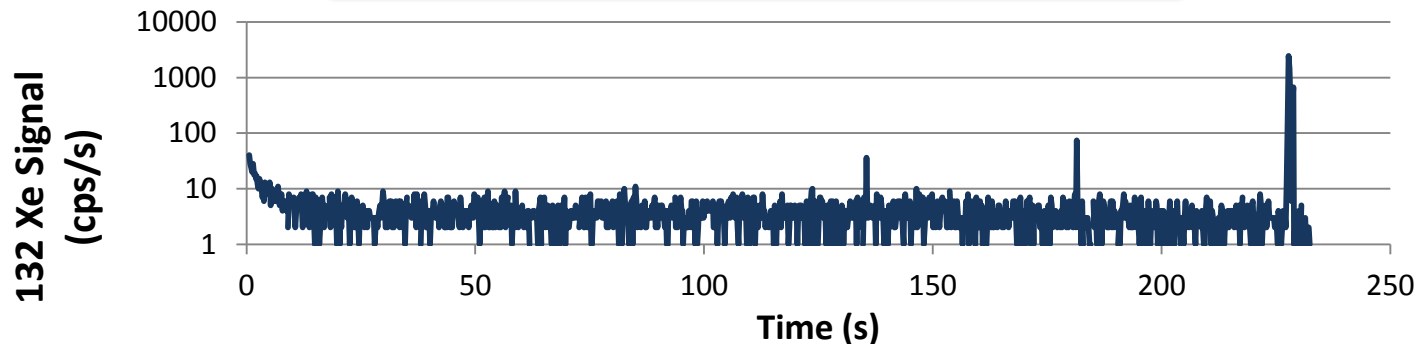
III- ESTIMATING THE PRESSURE IN BUBBLES – SINGLE BUBBLE METHODOLOGY

- An area with isolated bubbles just below the surface is identified by SEM and EPMA.

- Opened bubbles are identified by a second sweep by SEM and EPMA.



Associating peaks and bubbles



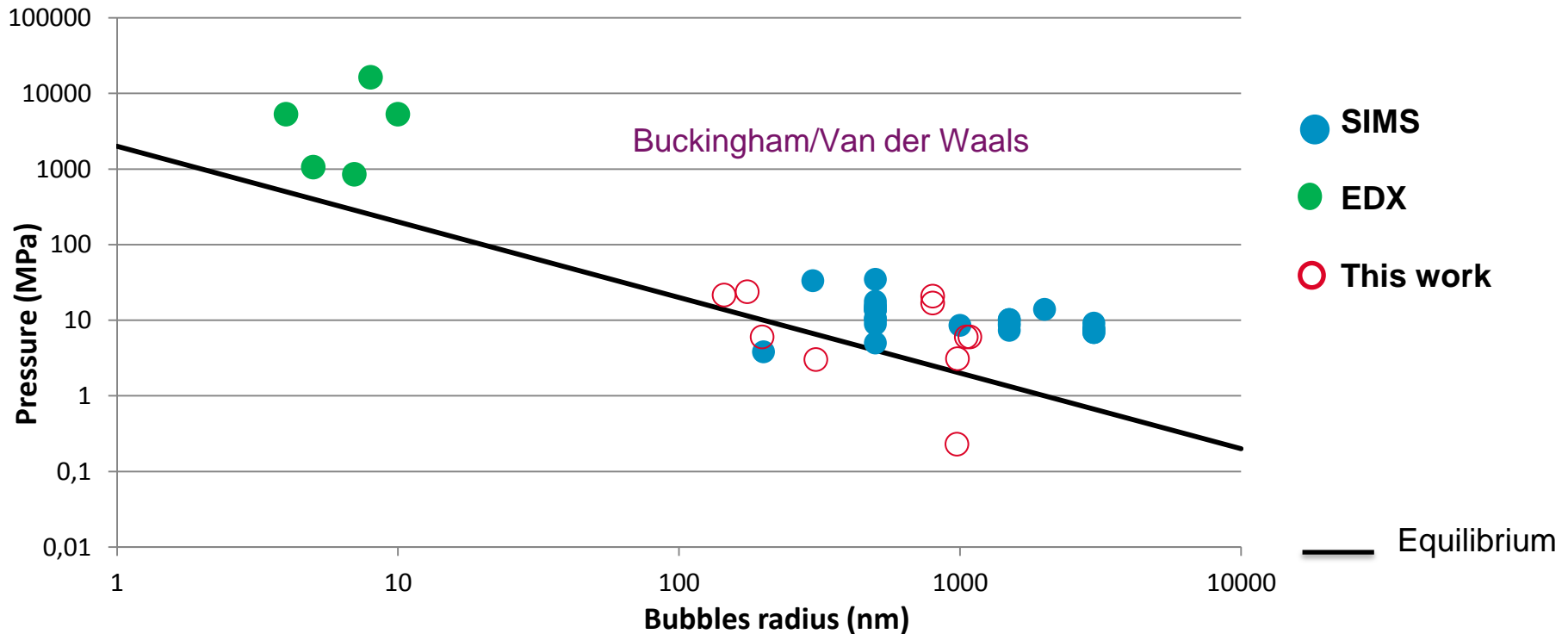
Depth profile by SIMS

III- ESTIMATING THE PRESSURE IN BUBBLES – SINGLE BUBBLE METHODOLOGY

Results

Equation of state : Molar volume $< 90 \text{ m}^{-3} \cdot \text{mol}^{-1}$ Buckingham
 Molar volume $> 90 \text{ m}^{-3} \cdot \text{mol}^{-1}$ Van der Waals

Bubbles pressure versus their radius at 300K



■ At room temperature, the pressure tends to be close to the equilibrium

I. CONTEXT

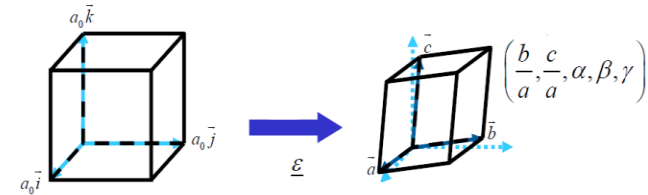
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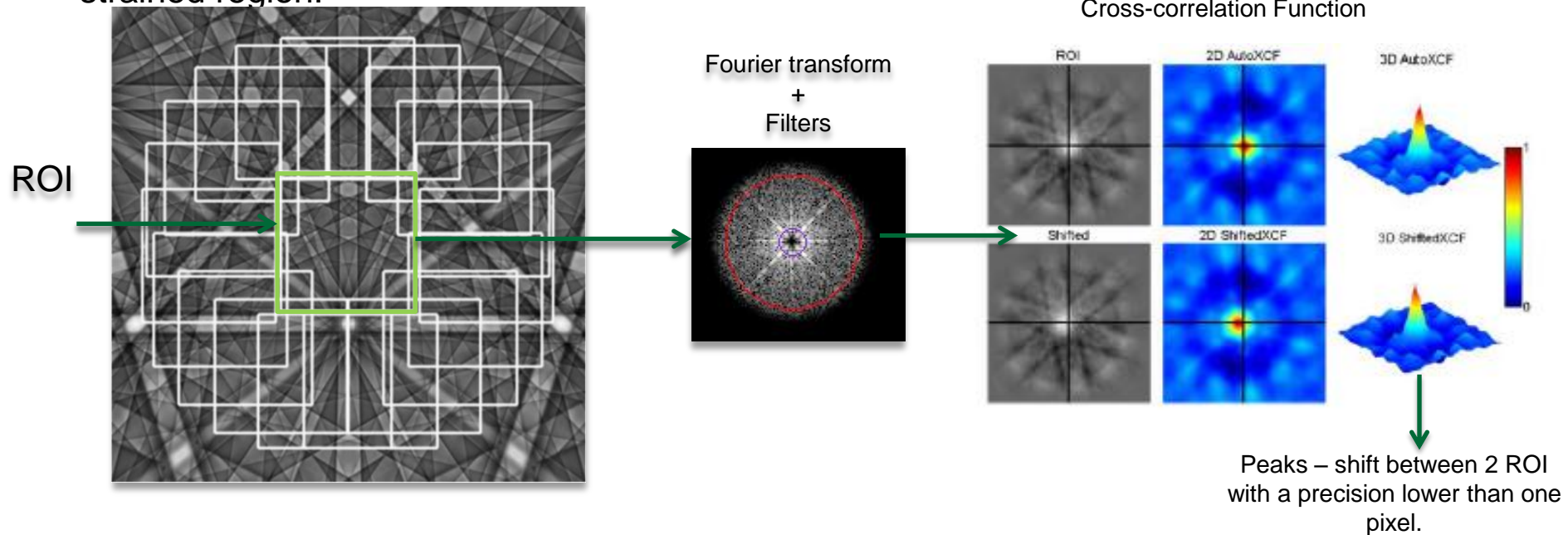
II. CONCLUSION AND FUTURE PROSPECTS

- The stress applied to a material will lead to a **distortion** of its crystal lattice and thus a movement of bands on the EBSD Kikuchi diagram.

Strain precision estimated at $\sim 2 \cdot 10^{-4}$

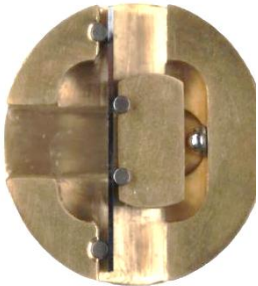


- Two diagrams are taken from a grain, one in a unstrained region (reference) and another in a strained region.

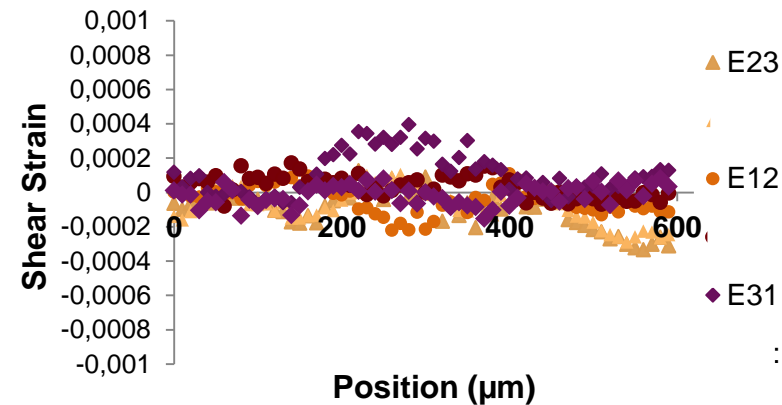
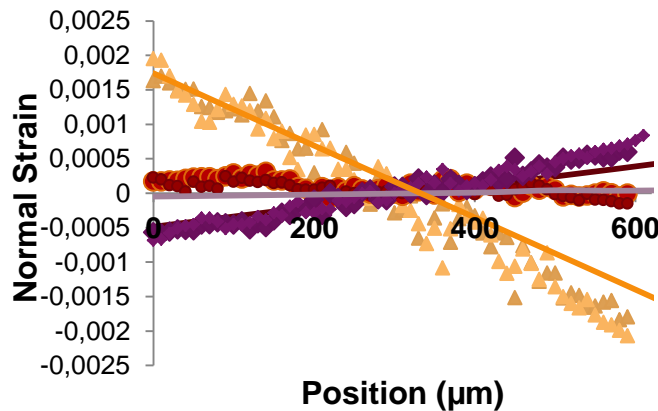
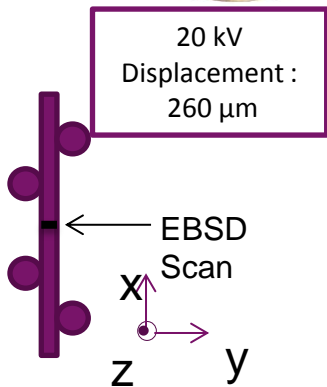


- It is then possible to calculate at any point of the sample **the elastic strain and rotation tensors of the crystal lattice**.

■ First step : calibration



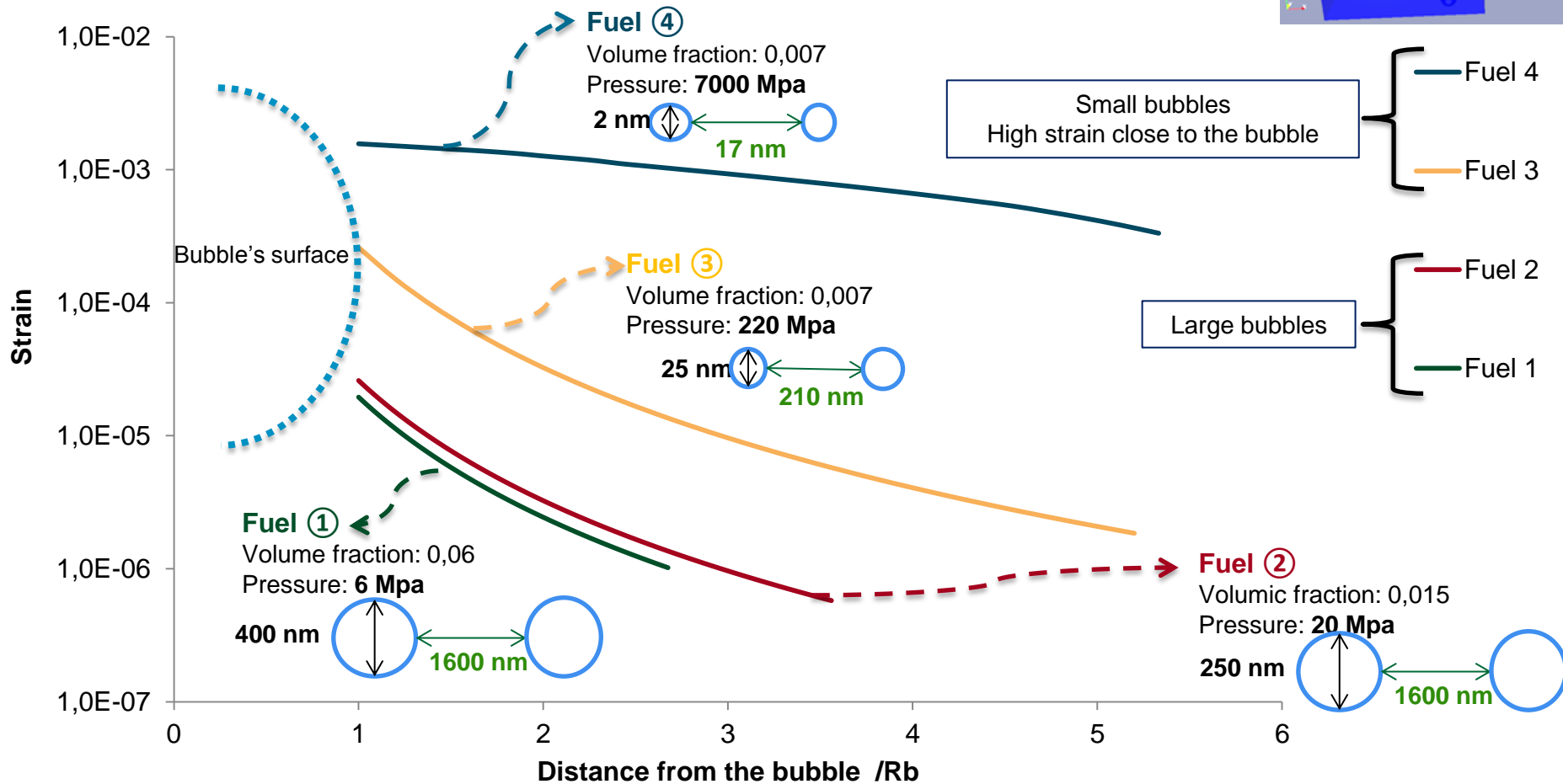
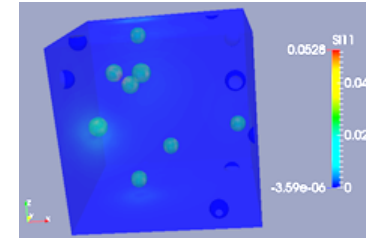
Four point bending test on a silicon single crystal



- Center point of the line = unstrained reference. EBSD patterns are compared to this reference.
- In order to validate the results, the four-point bending experiment was simulated by a FE model assuming anisotropic elasticity of cubic materials ($C_{11} = 396$ Gpa, $C_{12} = 121$ Gpa, $C_{44} = 64$ Gpa).
- According to the calculations, the shear strain should be null over the area. It appears that some points are over $2 \cdot 10^{-4}$. Special care is required to avoid any projection parameters variations, with a flat and parallel sample surface to the stage surface.

From calibration to irradiated fuels

With a finite element model it is possible to estimate the strain reached around the bubbles in irradiated fuels for different microstructures



I. CONTEXT

II. ESTIMATING THE PRESSURE IN BUBBLES

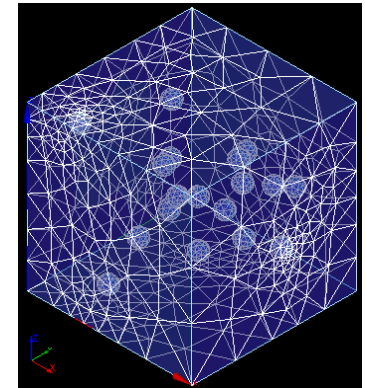
III. CONCLUSION AND FUTURE PROSPECTS

■ SEM/EPMA/SIMS method

- This study will be continued with the aim of adjusting acquisition conditions and adapting the SIMS beam to detect a smaller number of bubbles.
- Work is performed to improve the precision and accuracy of the results by working on the measurement of the bubble diameter (FIB-SEM), peak intensity and the equation of state.
- The results will be compared to a more global method.

■ EBSD and Cross-Correlation method

- Application of the method on material models such as ceramics implanted in xenon.
- Application on irradiated fuels thanks to a FIB-SEM in a hot lab.
- A finite-element model is developed to determine strain caused by bubbles in the irradiated fuel and therefore fission gas pressure.



Finite-element model

Thank you for your attention

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