WIISHEEP 2021

Materials for Energy – Materials and Irradiation

Prof. Frederico Garrido

Laboratoire de Physique des 2 Infinis Irène Joliot-Curie
Université Paris-Saclay-CNRS, Orsay Campus

Frederico.Garrido@ijclab.in2p3.fr
Frederico.Garrido@universite-paris-saclay.fr

Materials & Irradiation

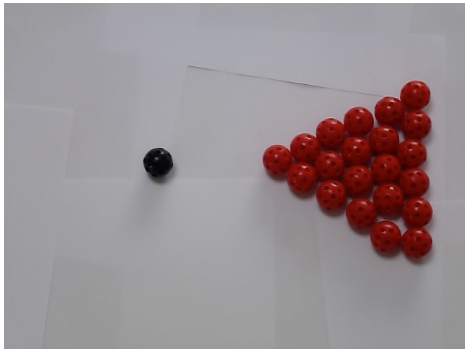
Interaction between a solid and a projectile is important in many fields in science

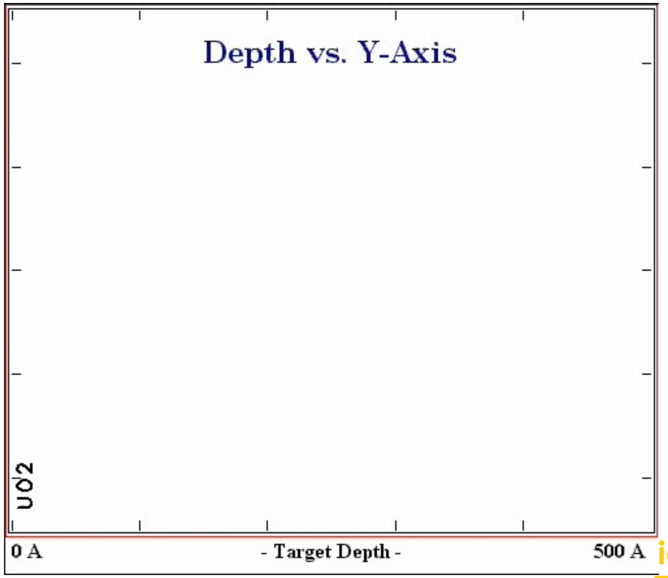
- Basis fundamental science heavily relies on the interaction of a projectile with a target
  - Investigation of the intimate structure of matter
  - Characterization techniques mostly based on the interaction of 'radiations' with matter
- Applied science
  - Ion accelerators (stripping targets)
  - Ion detectors
  - Tools for matter investigation: non destructive characterization techniques (Ion Beam Analysis)
  - Knowledge of radiation damage: nuclear reactors, space vehicle, planets
  - Tailoring new materials: modification of properties in a controlled way (mechanical, electrical, magnetic, microelectronic industry, single ion implantation, radiation tolerant materials)

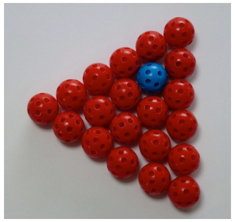
Materials & Irradiation

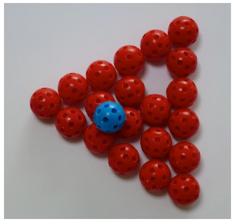
Particle-matter interaction at the atomic scale

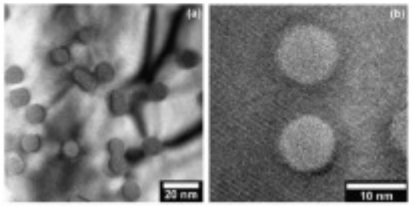
- Processes of the energy deposition of particles in matter
- Processes of displacements of atoms and electrons



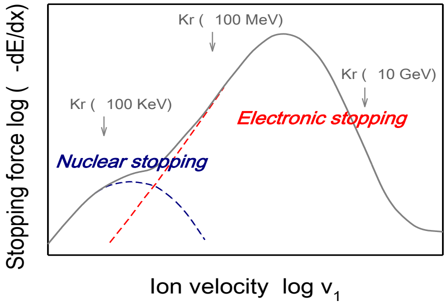








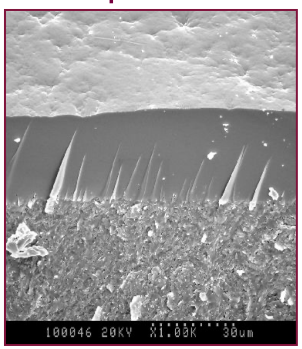
120 MeV U irradiated $Gd_2Ti_2O_7$



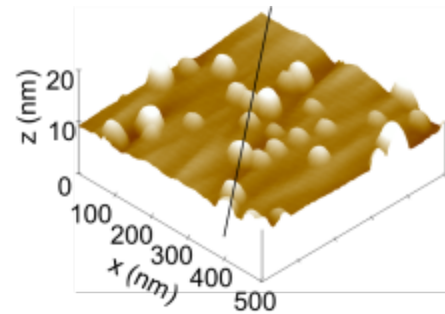
Materials & Irradiation

Designing new materials

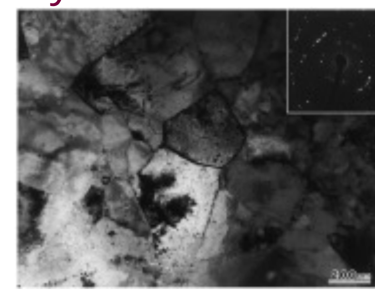
Amorphisation

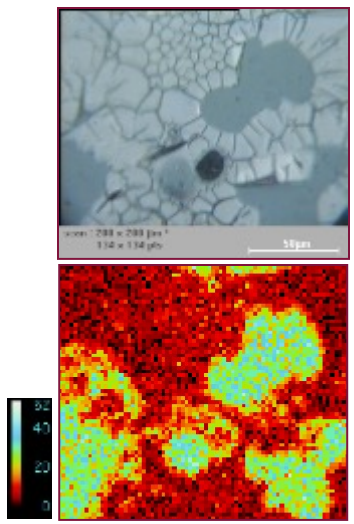


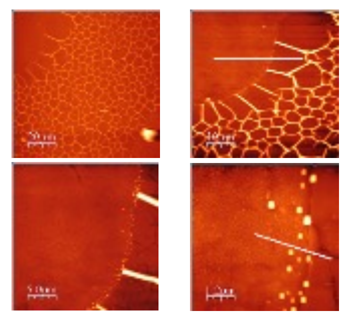
Nanometre-sized hillocks



Crystal subdivision



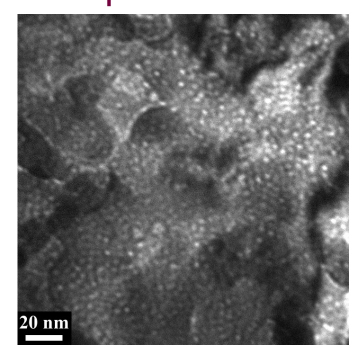




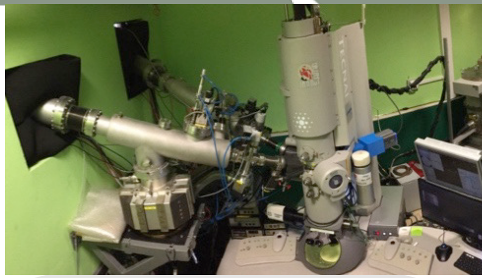
$MgAl_2O_4$ implanted with Cs and annealed at 1120 K

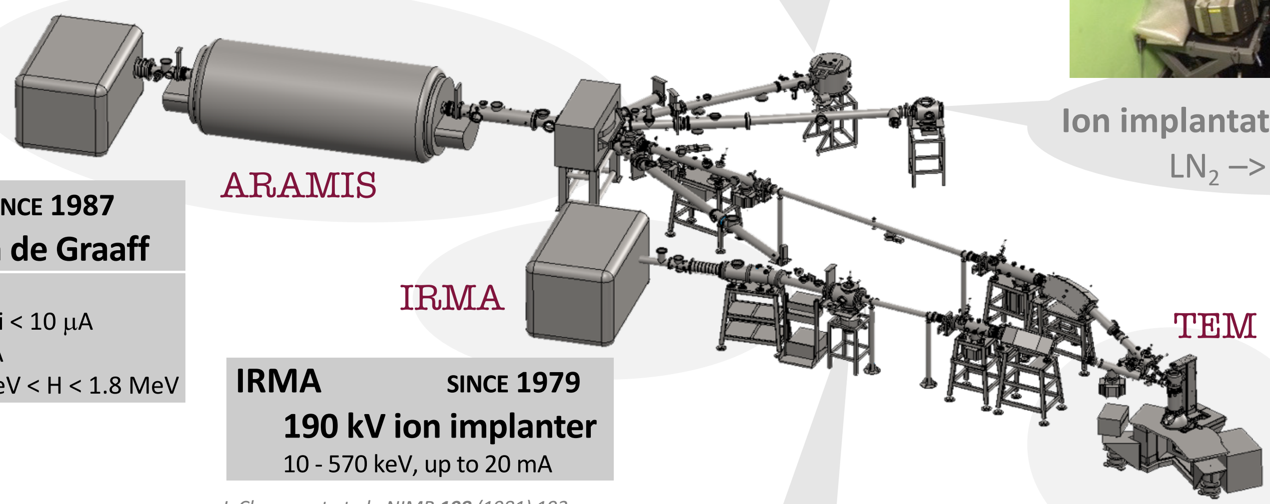
Exfoliation phenomenon

Precipitate formation



Materials & Irradiation
The JANNuS-SCALP facility





ARAMIS SINCE 1987

2 MV Tandem – Van de Graaff

SNICS negative ion source:
500 keV < E < 11 MeV ; 10 nA < i < 10 μA
Penning source @ HV : i < 20 μA
200 keV < He < 3.6 MeV ; 200 keV < H < 1.8 MeV

*E. Cottereau et al., NIMB **45** (1990) 293*
*H. Bernas et al., NIMB **62** (1992) 416*

IRMA SINCE 1979

190 kV ion implanter

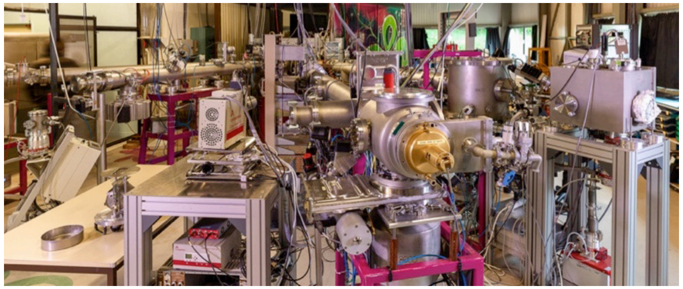
10 - 570 keV, up to 20 mA

*J. Chaumont et al., NIMB **198** (1981) 193*

***In situ* dual ion beam Transmission Electron Microscope**

SINCE 1980 UPDATED IN 1994, 2007

*M.-O. Ruault et al., J. Mater. Res. **20** (2005) 175*
*A. Gentils et al., NIMB **447** (2019) 107*



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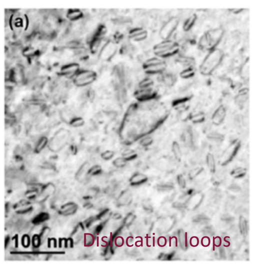
Materials & Irradiation – Ion Beams

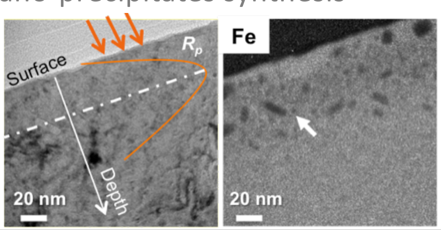
Experimental simulation of irradiation effects by using ion beams

Irradiation effects
- Fission products
- α and recoils
- Slowing-down processes



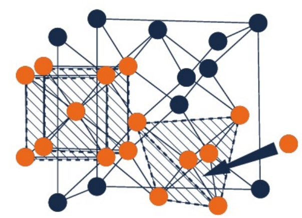
Radionuclides retention
- Actinides
- Fission products, Helium, H

Nano-precipitates synthesis



Irradiation

Low energy ions (100 KeV)
High energy ions (100 MeV)

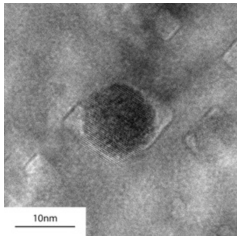


Irradiated solid

Doping

Stables elements
Radioactive elements

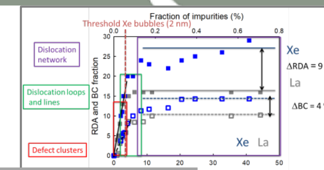
He bubble around a nano-oxide



Materials & Irradiation – Ion Beams

Experimental simulation of irradiation effects

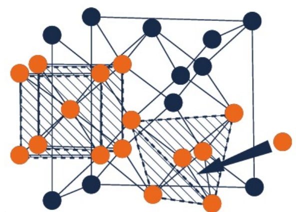
Understanding radiation effects by coupling experiments and modelling



in situ RBS-C

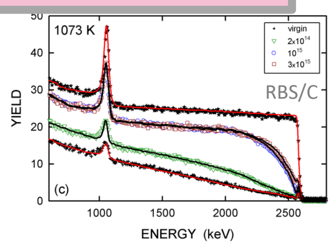
Irradiation

Low energy ions (100 KeV)
High energy ions (100 MeV)



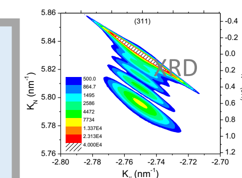
Characterization (*ex* & *in situ*)

- *Ion Beam Analysis (RBS, channelling, ERDA…)*
- *Transmission Electron Microscopy (dual beam)*
- *X-Ray Diffraction*



Irradiated solid

Irradiation-induced defects, atomic diffusion, physical and chemical properties

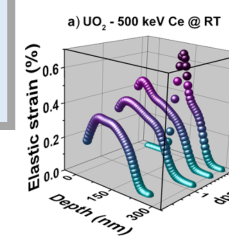


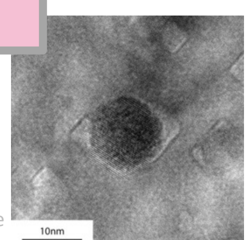
Modelling

Molecular dynamics
Density functional theory
Kinetic Monte Carlo
Simulation of experimental signals

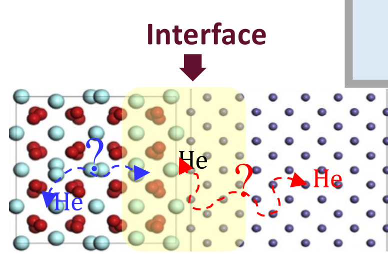
Doping

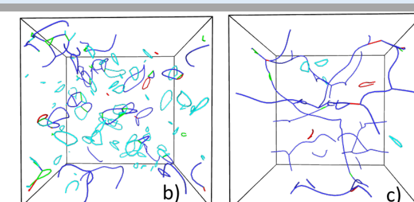
Stables elements
Radioactive elements





He bubble around a nano-oxide





Atomistic simulations

Synthesis of ODS steel by ion implantation

Structural and chemical characterization at nanoscale

ODS steels (Oxide Dispersion Strengthened) Alloys

- Metal matrix with small oxide aggregates embedded within it
  - Properties strongly depends on the size of clusters
- Application in many fields due to enhanced mechanical resistance: nuclear energy, aeronautics, space crafts
  - Incoherency between of the particles within the matrix, preventing creep
  - Mainly prepared par mixing of ball-milling an oxide (YTi_2O_3) with pre-alloyed metal powder
- Ion beam synthesis to investigate the mechanisms of cluster formation
  - Sequential implantation of various selected elements (Y, Ti, O) to initiate the formation of nanoparticles
  - Nice possibility to investigate the role of the various parameters in the nuclear and growth

Synthesis of ODS steel by ion implantation

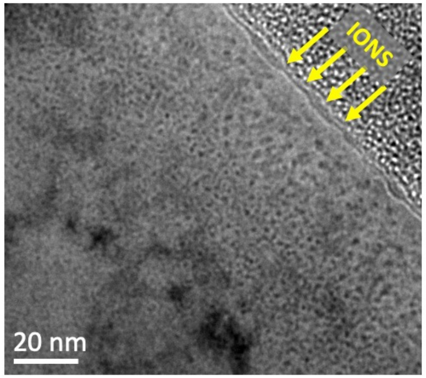
Structural and chemical characterization at nanoscale

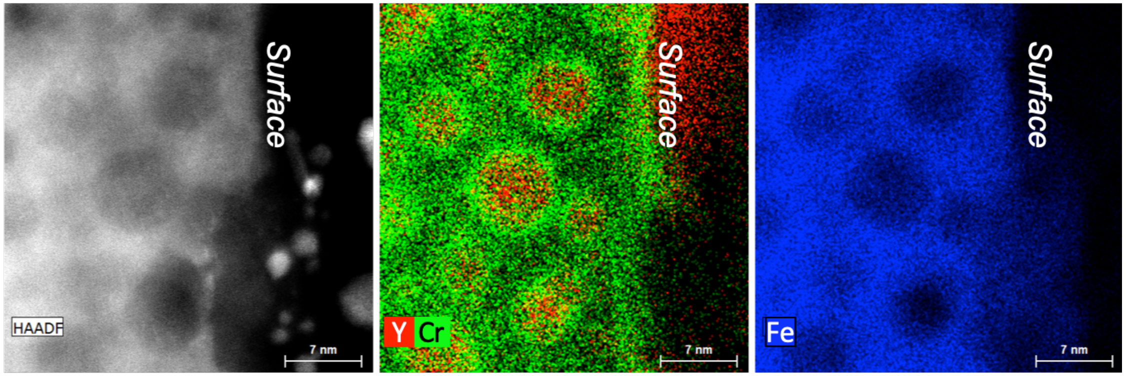
Ion beam synthesis – Y+Ti+O implantations in FeCr

Y+Ti+O ions in FeCr, ann. 1100° C @ JANNuS-SCALP   Y+O ions in FeCr, annealing 1100° C @ JANNuS-SCALP ; HAADF, STEM-EDX 4X detectors @ PANAM, C2N

Chemical composition identification

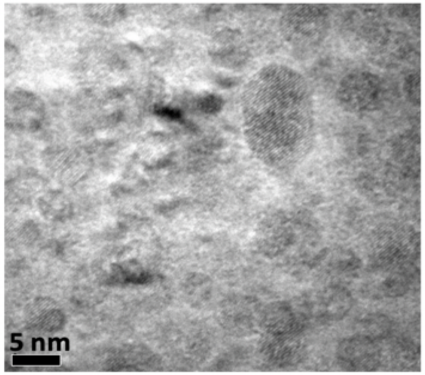
Conventional TEM @ JANNuS-SCALP

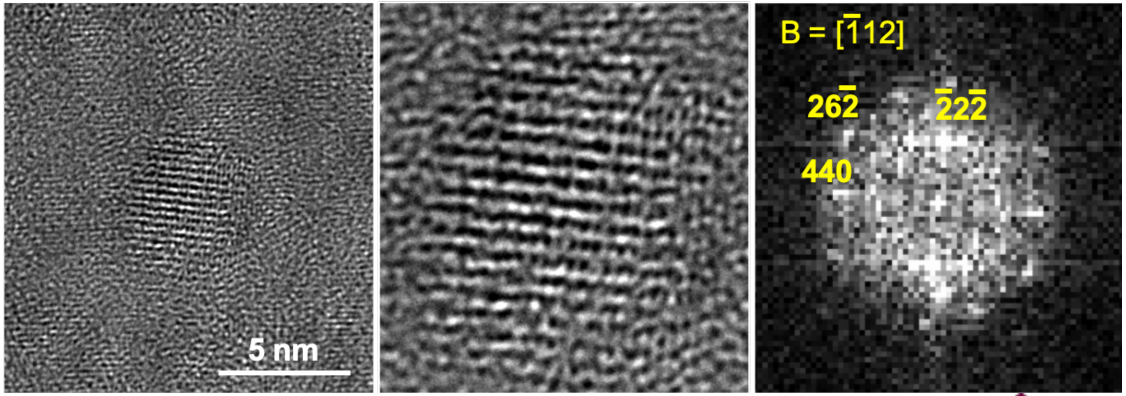




Crystallographic structure

HRTEM low magnification @ JANNuS-SCALP





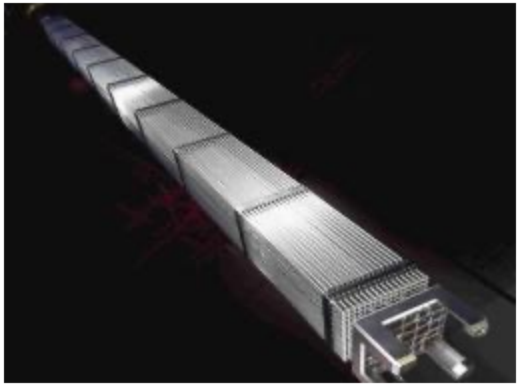
High Resolution TEM @ PANAM, C2N

PhD thesis Martin Owusu-Mensah, 2019

Simulation of in-reactor irradiation effects – High Burn-up Structure formation (HBS)

UO_2 is today's nuclear fuel

- Ceramic-type material stable at (very) high T and extremely stable towards irradiation
- Fuel pellets are stacked into a zirconium alloy cladding
- Microstructural evolution at the surface of fuel pellets due to Pu enrichment (epithermal neutrons are captured by ^{238}U)
- Crystal subdivision and mosaic structure formation limited to the boundary zone (~ 200 μm)



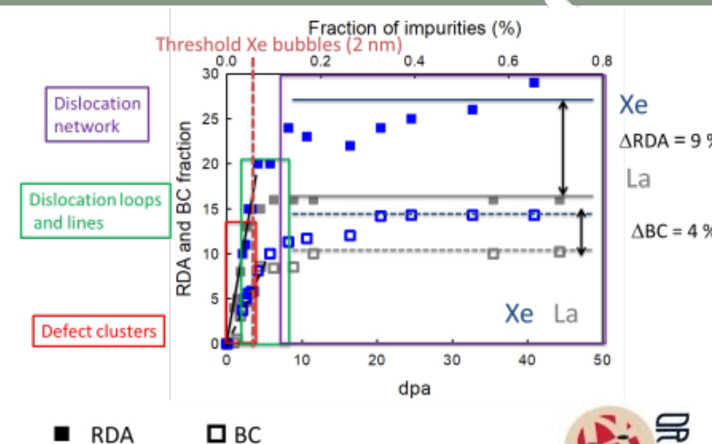
Simulation of in-reactor irradiation effects – High Burn-up Structure formation (HBS)

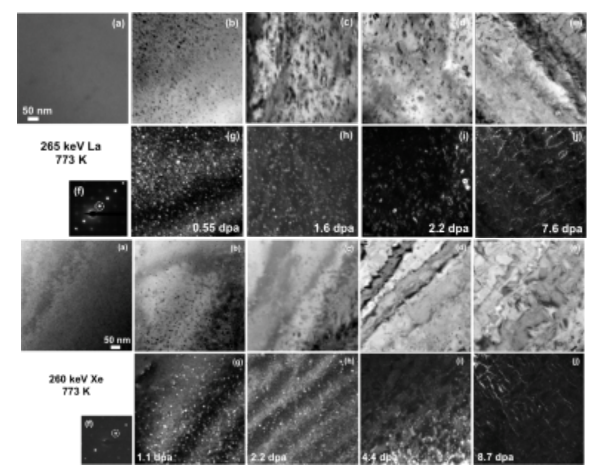
Experiments and modelling to understand this phenomenon – experimental and atomistic simulations (JANNuS@IJCLab and GANIL)

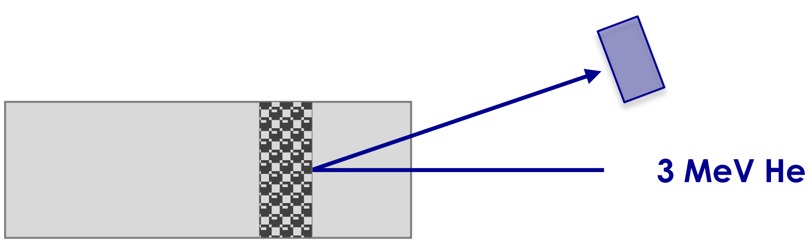
- Temperature relatively low at the rim
  - Recombination of radiation-induced defects not so effective
- Role played by the fission fragments: electronic and nuclear stoppings
  - Extreme electronic stopping induced a single crystal to polycrystal microstructural transformation
- Role played by fission products: chemical nature of incorporated elements
  - Comparison between soluble and insoluble elements

Simulation of in-reactor irradiation effects – High Burn-up Structure formation (HBS)

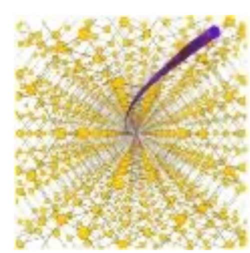
- Formation mechanisms of the HBS at the fuel periphery (high porosity, small grain size; local increase of the Pu content)
- Parametric approach : burnup, T, chemistry of impurities, radiation defects and damage
- UO_2 single crystal as model system
- *In situ* irradiation/RBS-C or TEM at 773 K
  - First step is ballistic (radiation damage): same dpa for Xe and La, same evolution (clusters, dislocations, network)
    Second step : dramatic role of FP solubility – polygonization induced by nanometer-sized gas bubbles







Implanted UO_2 single crystal



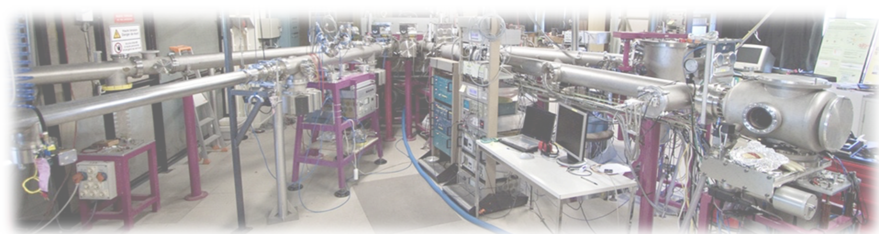
Materials for Energy – Materials & Irradiation

Beams provided by accelerators are unvaluable tools in material science

- Design of materials with selected properties
- Experimental simulation of irradiation-induced effects
- (In situ) characterization (IBA, TEM)

JANNuS facility at IJCLab is opened to various themes

- Energy and nuclear energy
- Microelectronics
- Nuclear astrophysics
- Space technology



PhD students are most welcome !