DSM/IRAMIS

Institut de Physique

Université de Caen Normandie

Overview and prospects of Interdisciplinary researches with GANIL ion beams

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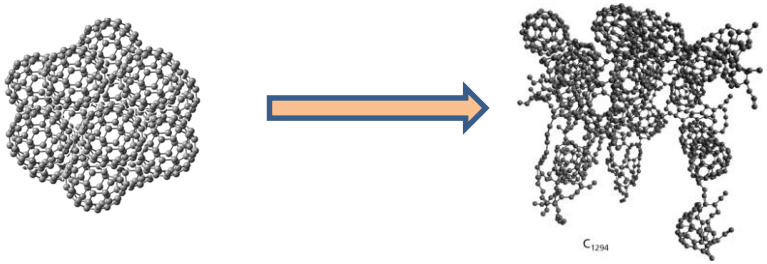
laboratoire commun CEA/DSM spiral2 CNRS/IN2P3

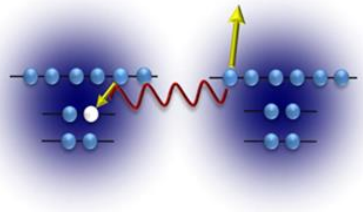
Interdisciplinary research

Dilute matter, molecules, clusters

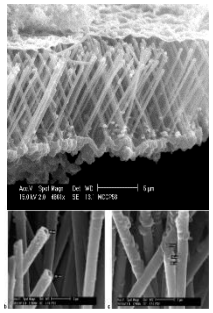


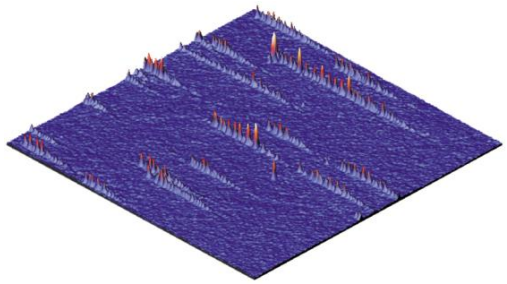
Radiochemistry, Astrophysics/chemistry

Atomic and plasma physics

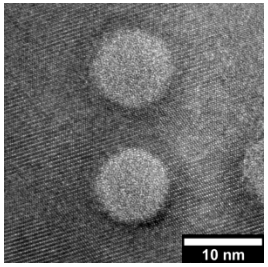


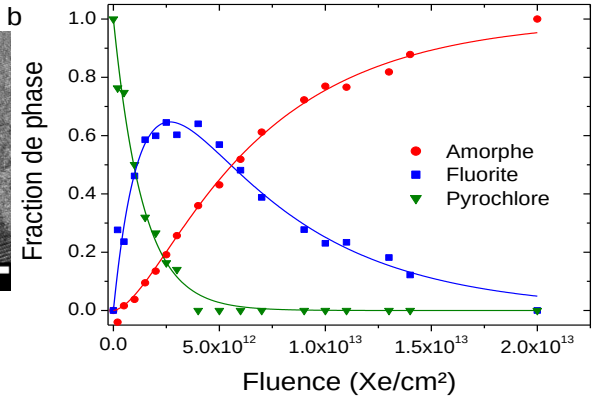
Nano structuration



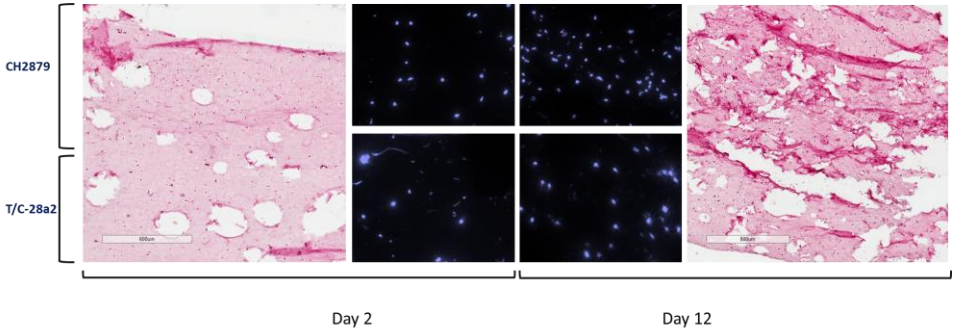


Materials science





Radiobiology



Overview and Prospect of interdisciplinary research

Development of new setups

–> Broaden the ion beam capability

–> Improve the understanding of ion/matter interaction

–> Emerging of new topics

HOT topics

–> Astrophysical ices

–> Slow ion- Fast ion

–> Simulation of irradiation

–> New material or new applications / Defect engineering

–> Radiobiology

Overview and Prospect of interdisciplinary research

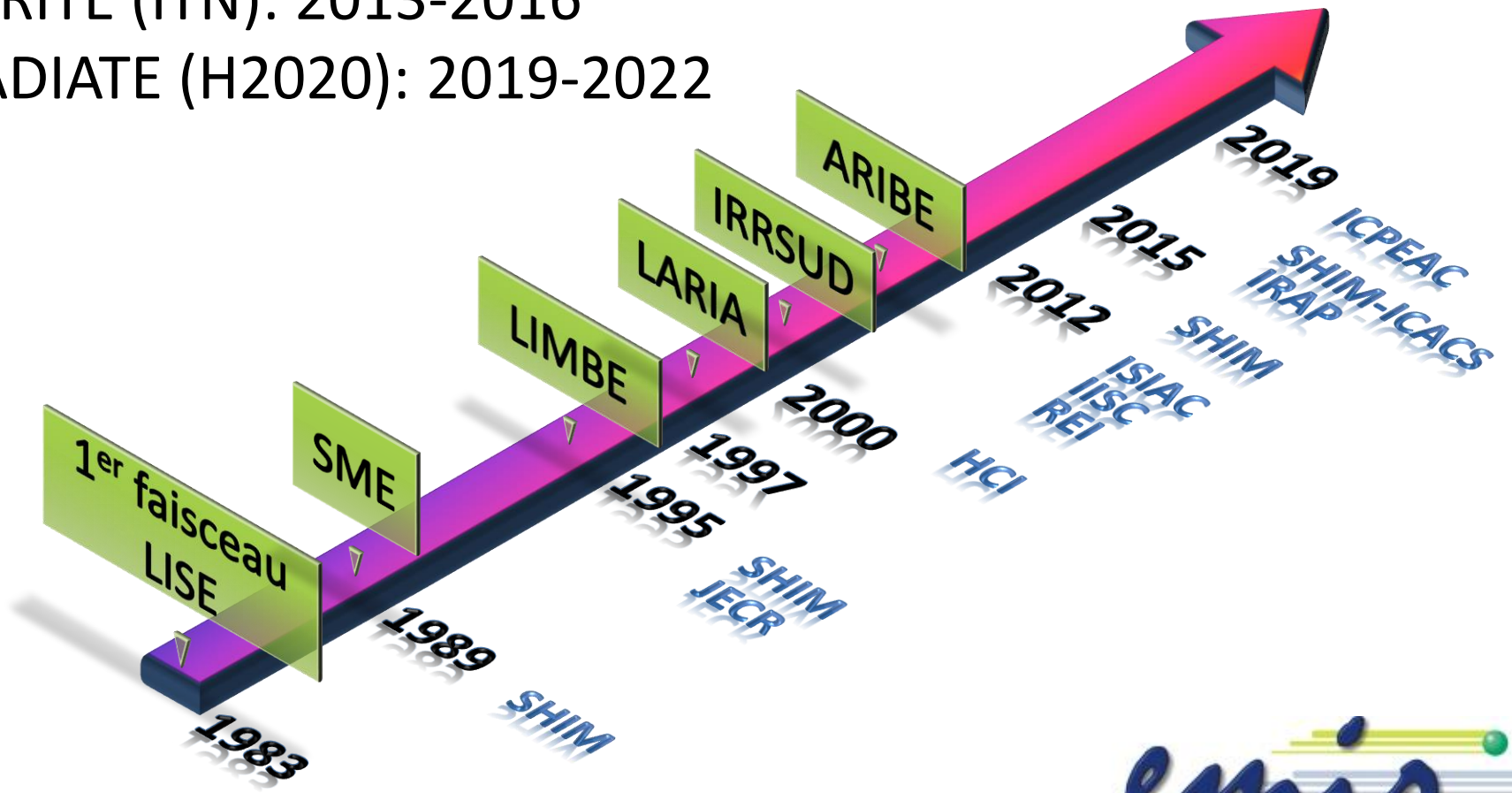
Development of new setups:

–> Broaden the ion beam capability

Interdisciplinary research: historical evolution

ITSLEIF (I^3): 2006-2010
SPIRIT (I^3): 2009-2013
SPRITE (ITN): 2013-2016
RADIATE (H2020): 2019-2022

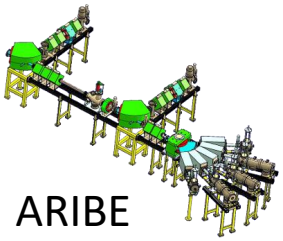
~ 50 experiments per year
~ 200 UT + 50 days ARIBE



GANIL facility beamlines for CIRIL platform

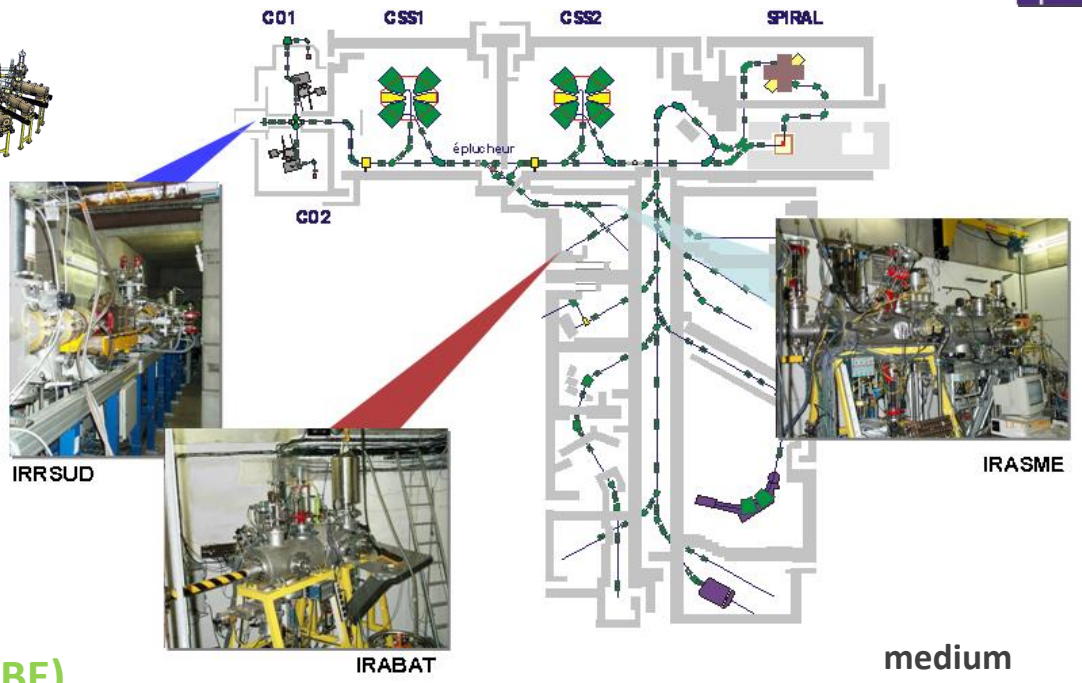
PELIICAEN

ORSAY PHYSICS
TESCAN ORSAY HOLDING



ARIBE

Localized implantation (< µm)
Large ion choice



Irradiation conditions

C (Z=6) to U (Z=92)

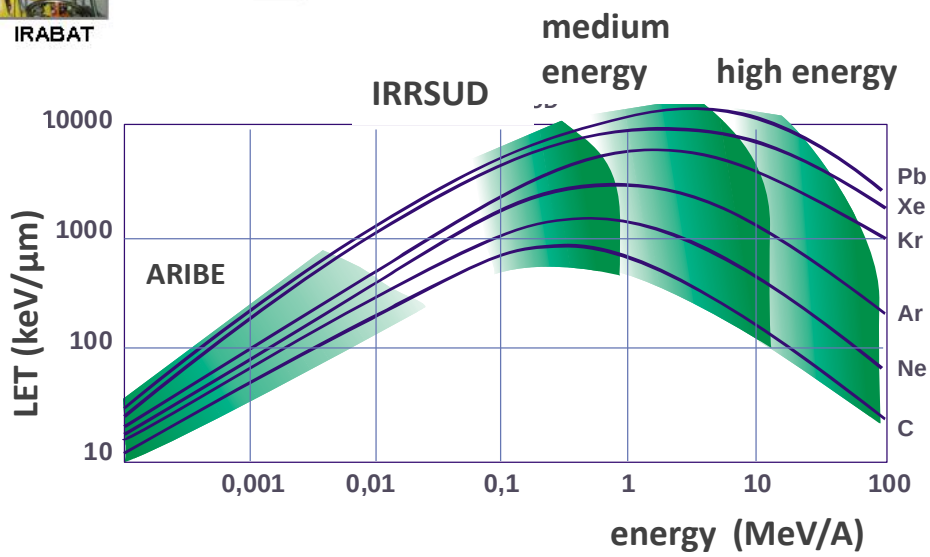
0.3 to 100 MeV/A (qq keV ARIBE)

8 K up to 1500 K

From single ion to flux up to 10^{10} ions.cm^{-2}.s^{-1}

Beam sweeping up to 30cm²

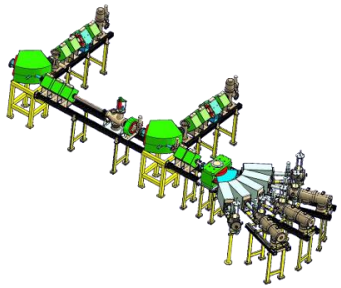
Grazing incidence



GANIL facility beamlines vs energy deposition regime

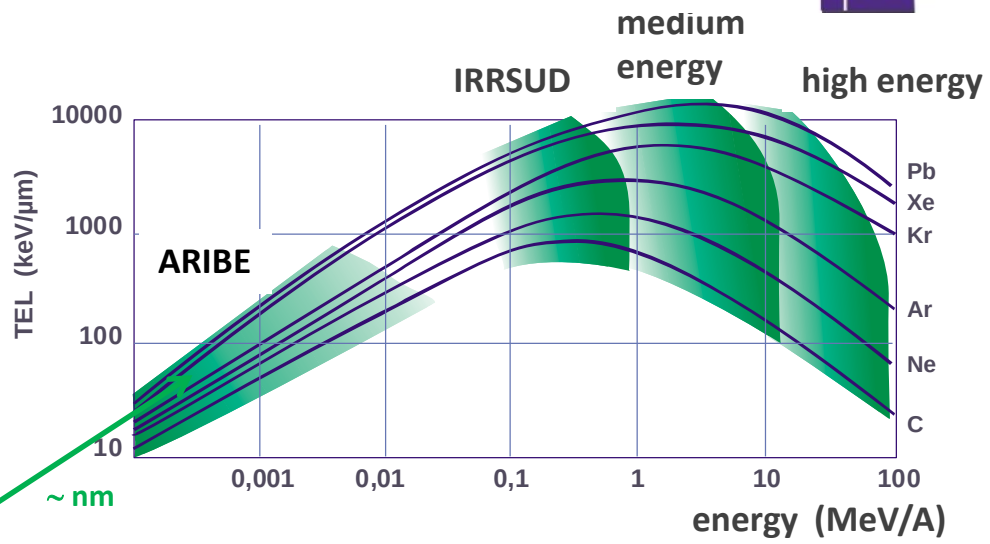
PELIICAEN

ORSAY PHYSICS
TESCAN ORSAY HOLDING



Localized implantation (< µm)
Large ion choice

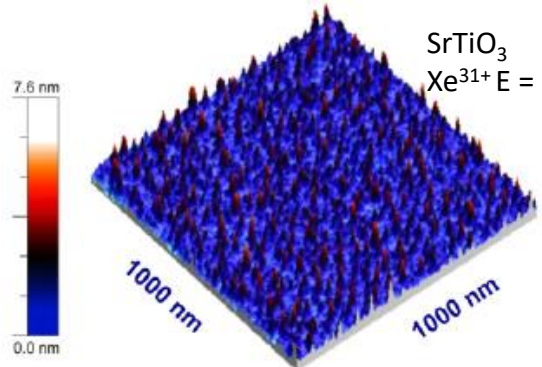
GANIL spiral2



Potential energy deposition

Capture, decay, emission, sputtering

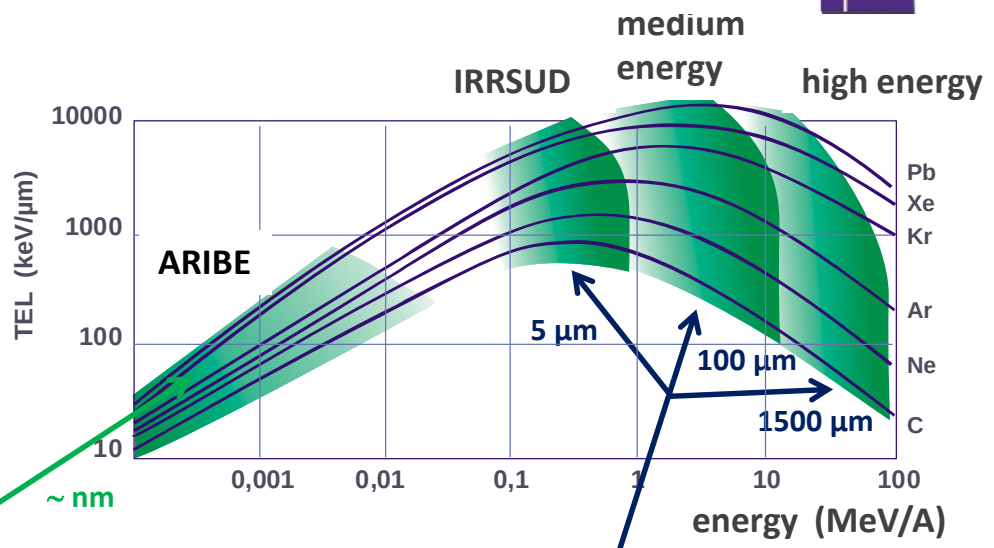
>> Nanostructure formation



$SrTiO_3$
Xe^{31+} E = 110 keV

El Said et al, NIMB 269-1234(2011)
Aumayr et al, JPCPM 23-393001(2011)

GANIL facility beamlines vs energy deposition regime



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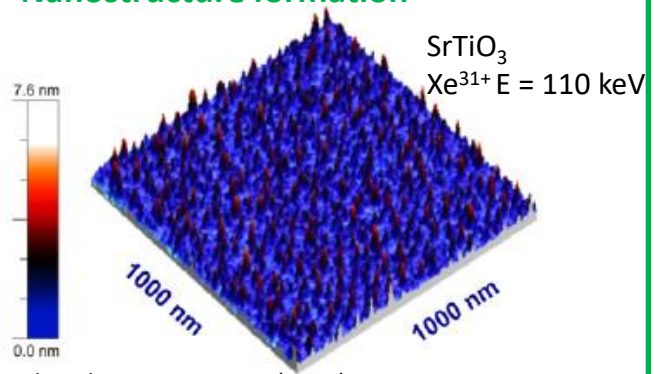

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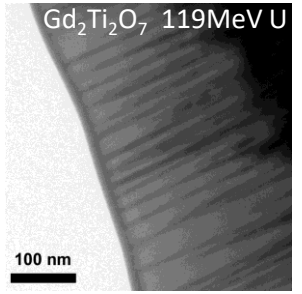
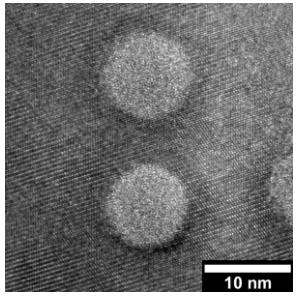
Electronic energy loss

Defect formation by radiolysis

Collective effect: atomic motions by intense electronic excitations -> extended defects

>> Track formation, disorder, phase transitions, surface nanostructures

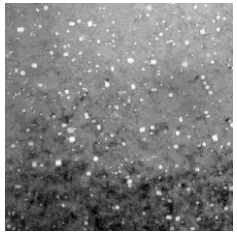


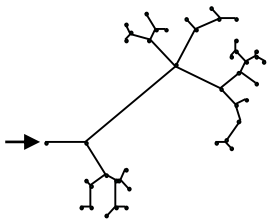


Sattonnay et al, Acta Mat 60-22 (2012)

GANIL facility beamlines vs energy deposition regime

Nuclear energy loss

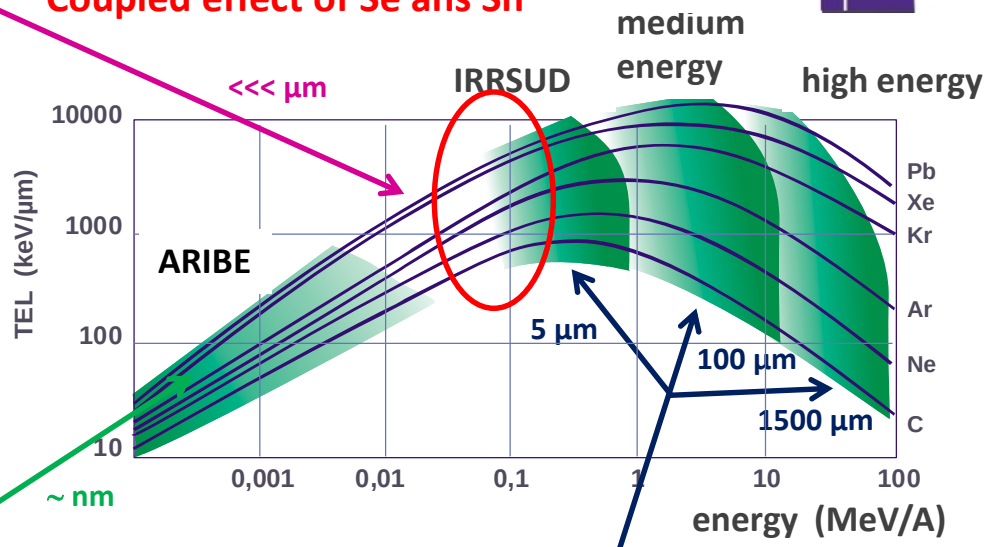




Frenkel pairs, Displacement cascades

>> Cavities, bubbles, dislocation loops, segregation, precipitation, amorphization, phase transitions

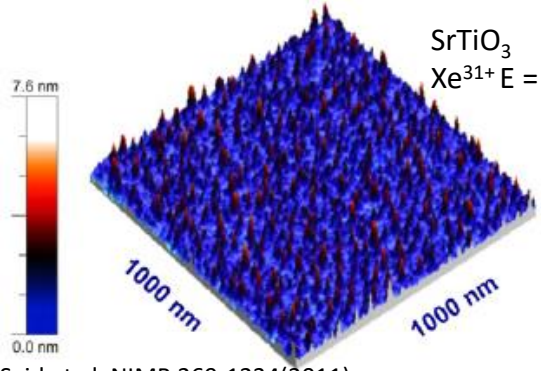
Coupled effect of Se ans Sn



Potential energy deposition

Capture, decay, emission, sputtering

>> Nanostructure formation



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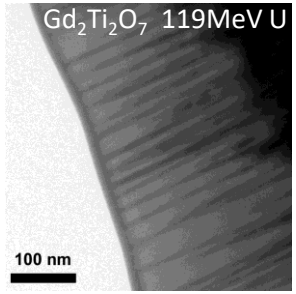
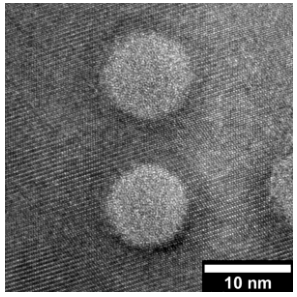




Sattonnay et al, Acta Mat 60-22 (2012)

Overview and Prospect of interdisciplinary research

Development of new setups:

–> Broaden the ion beam capability

- **IRRSUD, LARIA, ARIBE,…..**
- **PELIICAEN**

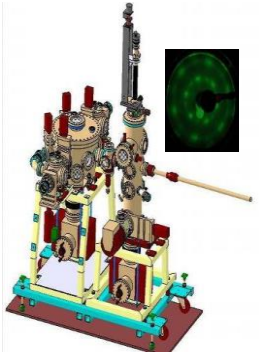
–> Improve the understanding of ion/matter interaction

Improve the understanding of interaction and material modifications

Nuclear processes

Electronic processes

Neutrals (atoms, molecules, clusters…)



Backscattered particles

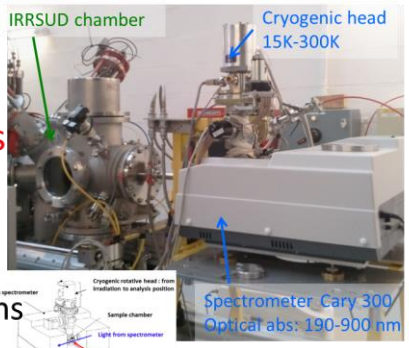
Recoils Ions

Ion beam

X-rays

Electrons

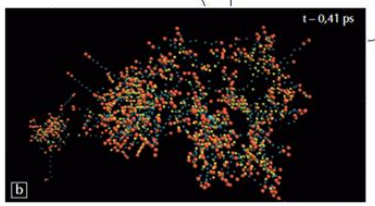
Photons



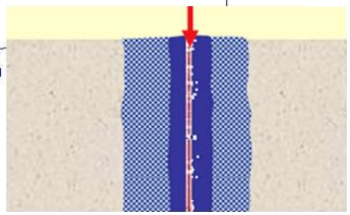
Surface effects

Nuclear energy loss

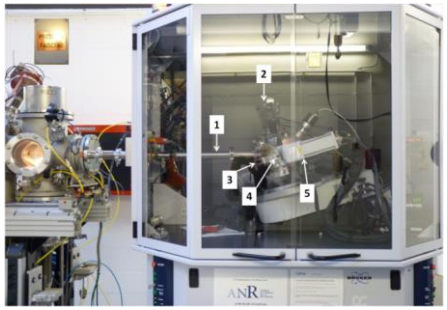
Electronic energy loss



400



Bulk effects



New setups for in-situ characterizations (absorption or emission spectroscopy, FTIR, gaz release, mass spectroscopy, X-Y TOF SIMS, XRD, Auger or Raman spectroscopy, STM ….)

Overview and Prospect of interdisciplinary research

Development of new setups:

–> Broaden the ion beam capability

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–> Improve the understanding of ion/matter interaction

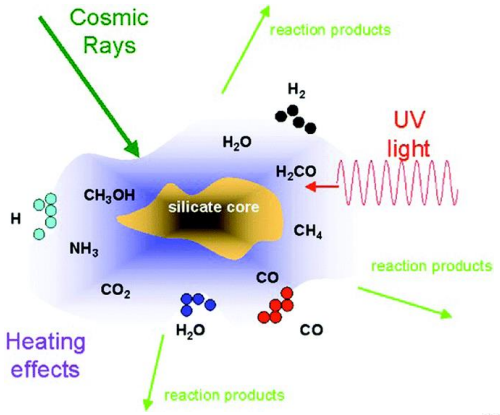
–> Emerging of new topics

IGLIAS : astrophysical ices (huge increase of demand)

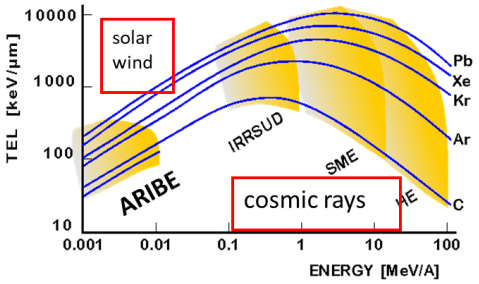
IMAGERI: Measure of the energy of the electrons emitted during the interaction

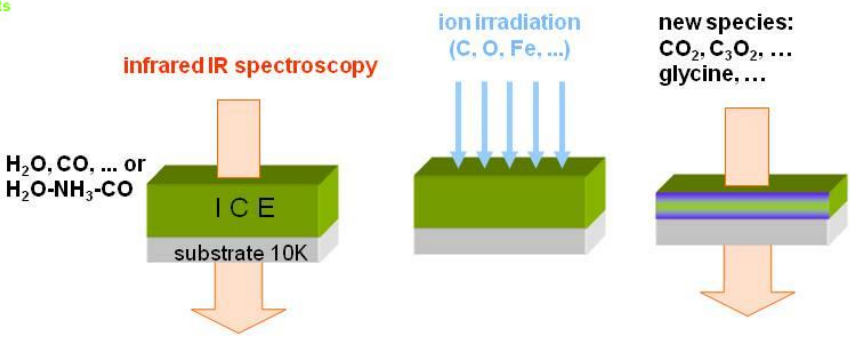
New setup: IGLIAS

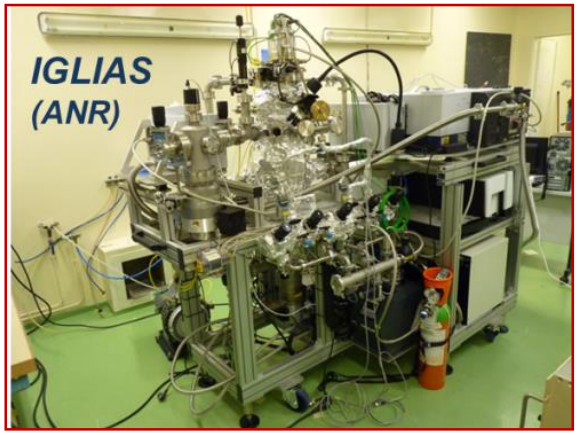
Interstellar ices exposed to cosmic rays, stellar wind, UV, electrons:



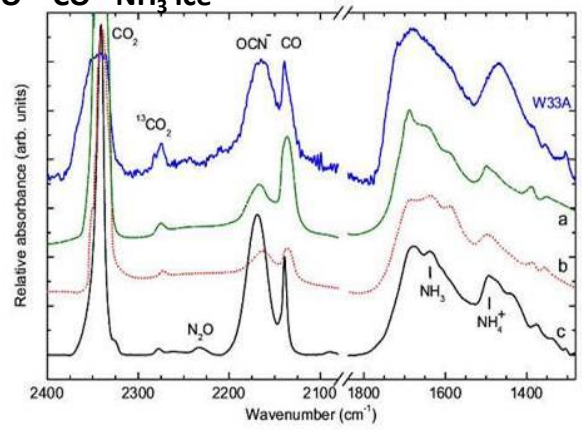
fragmentation/destruction
formation of molecules
Desorption / Sputtering /implantation
Compactation / Amorphization







H_2O – CO - NH_3 ice



Space observation:

ISO Infrared Space Observatory, protostellar source W33a

Laboratory simulation:

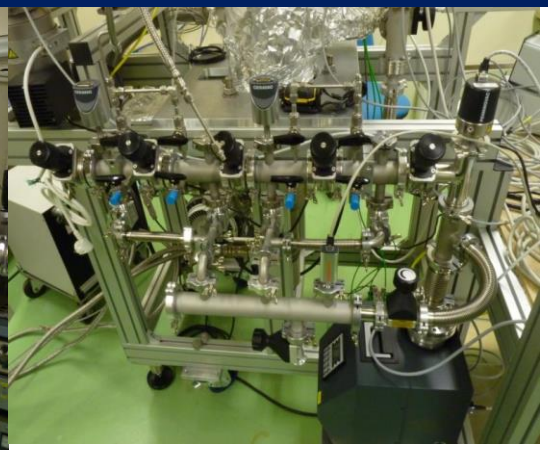
UV photons

protons

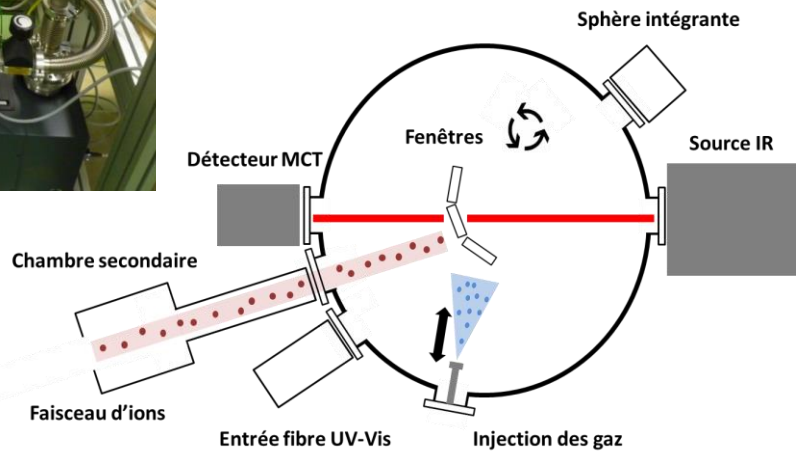
heavy ions

S. Pilling et al. Astronomy & Astrophysics 509 (2010) A87

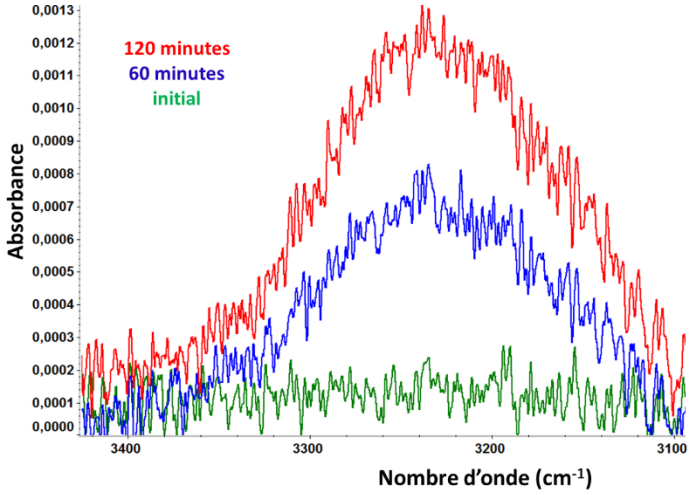
New setup: IGLIAS

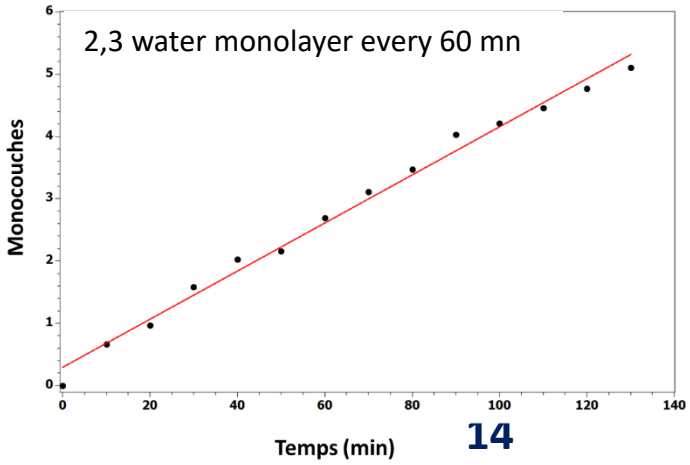


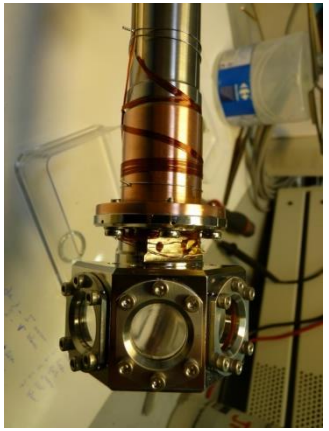
$1.5\ 10^{-10}$ mbar
10-300K



In-situ gas deposition
3 spectrometers (UV-visible, FTIR, QMS)

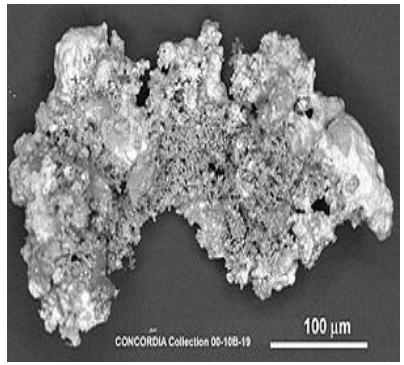


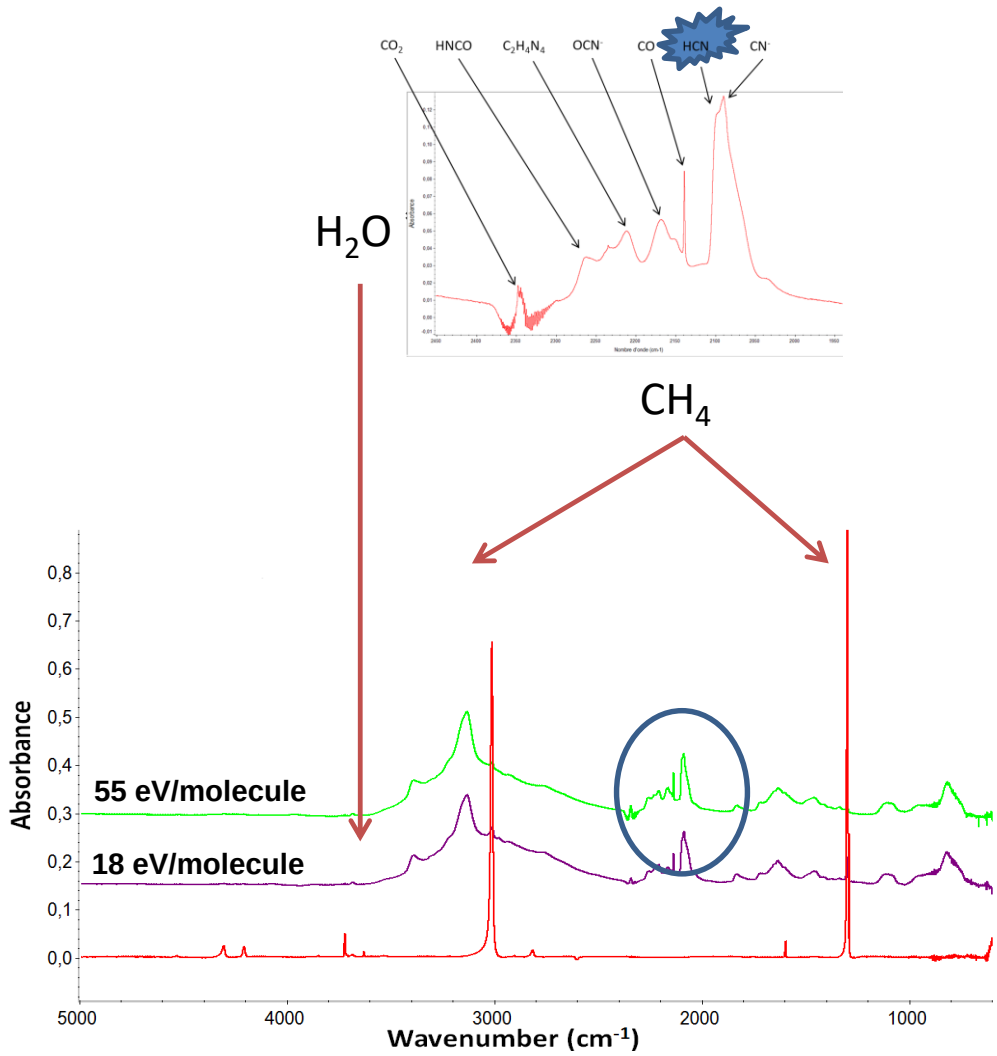


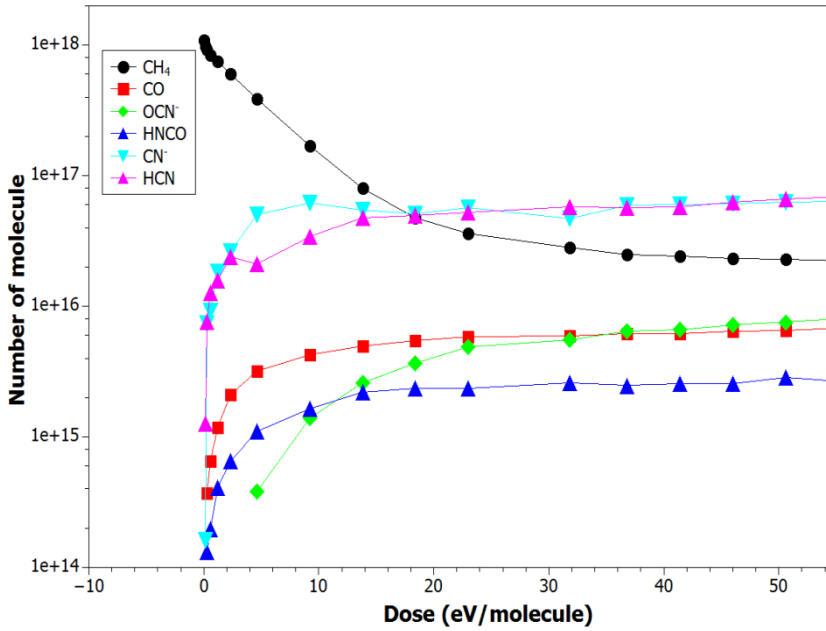


Formation of UCAMM

N_2:CH_4 (90:10)
IRRSUD Ni 44MeV



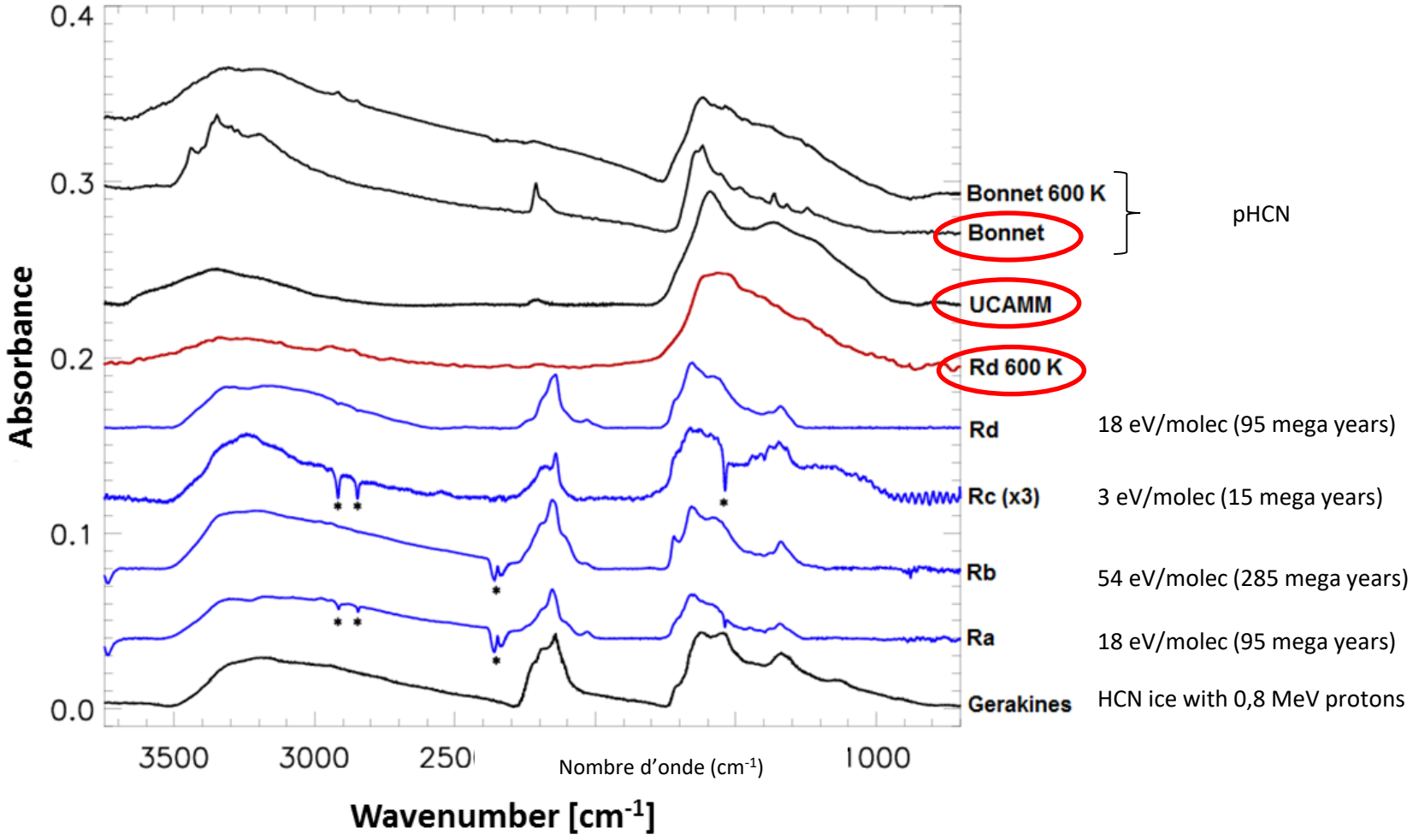




B. Augé et al. *A&A* **592** (2016) A99

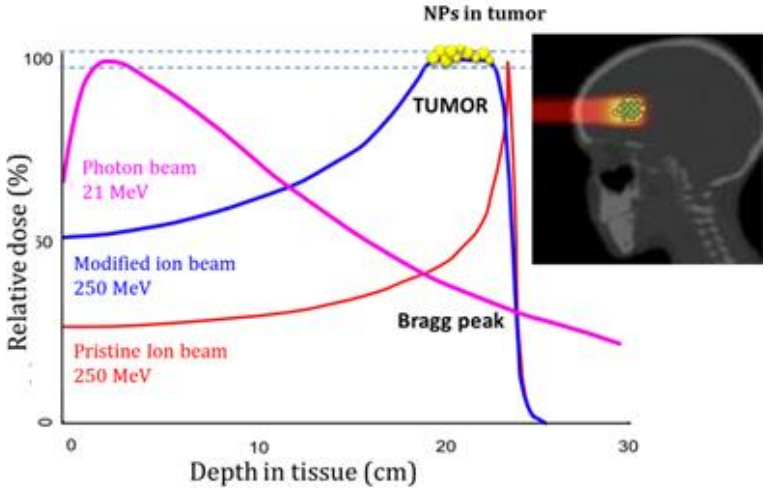
Formation of UCAMM

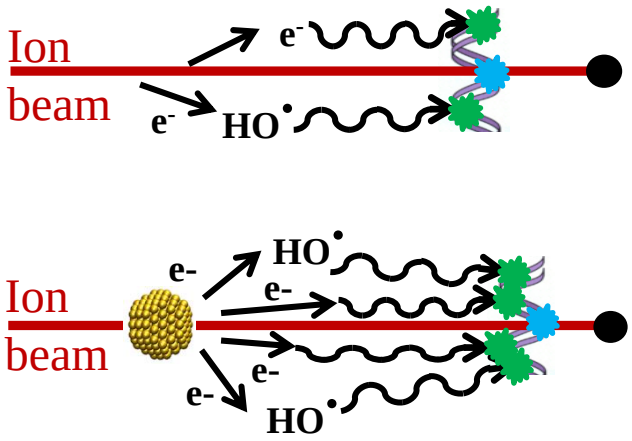
Residues analysis : different proportions, different doses, different T



IMAGERI: Measure of electron emission

Radiosensitizers in ion beam therapy: Measure of absolute cross section for electron emission from metallic nanoparticles upon ion collision





Coupling metallic nanoparticles (NPs) with ion beam therapy

Local dose enhancement due to electron emission

Lack of information on electron emission :

- absolute cross section : energy / angular dependence - $d\sigma/dE$, $d\sigma/d\theta$, $d^2\sigma/dEd\theta$
- physical processus : localized excitation or plasmon resonance

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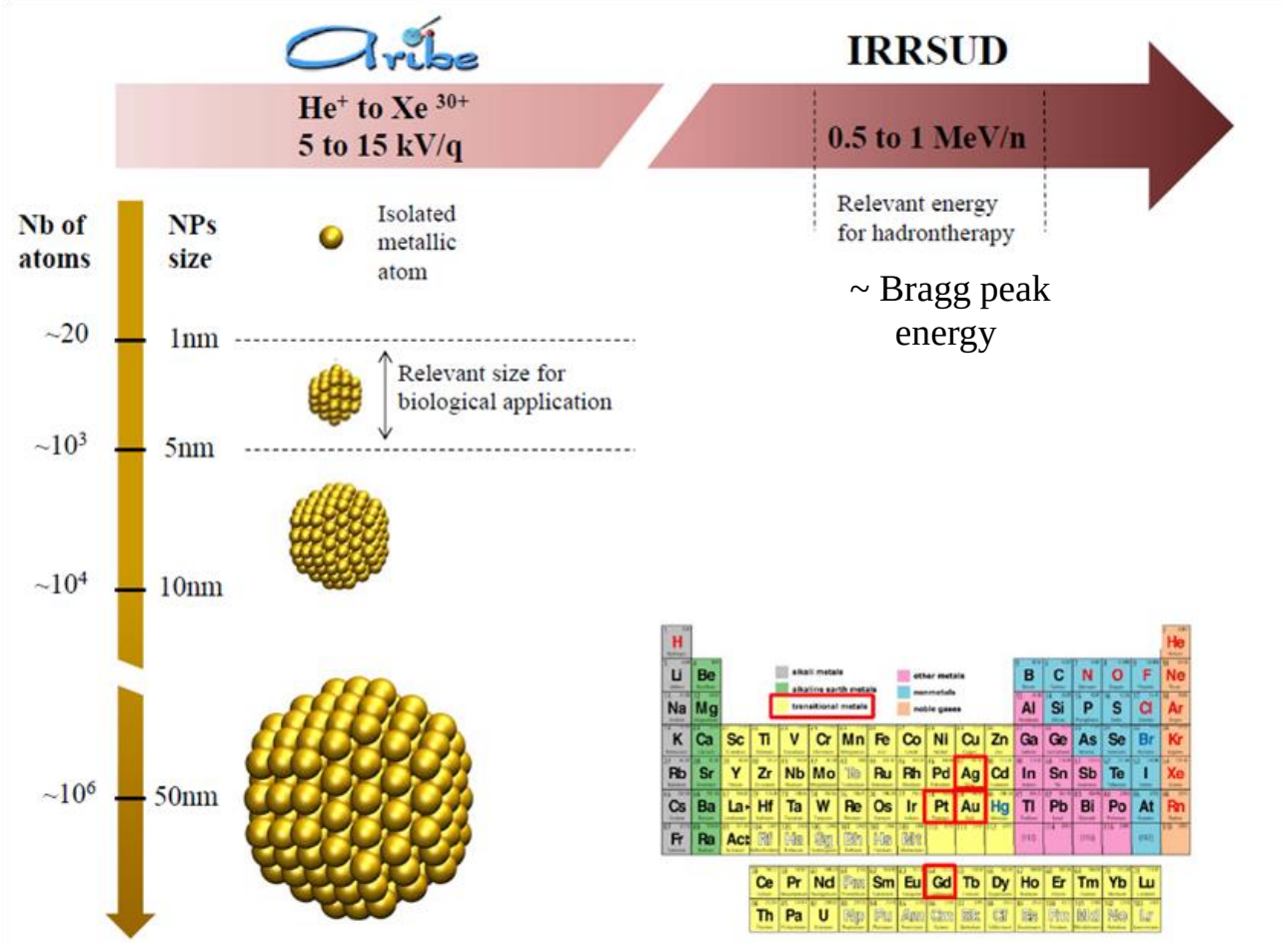

Effect of the projectile energy

→ keV to MeV

Effect of the size

→ from atom to NP

Effect of the material

→ Au, Ag, Pt, Gd

IMAGERI: Measure of electron emission

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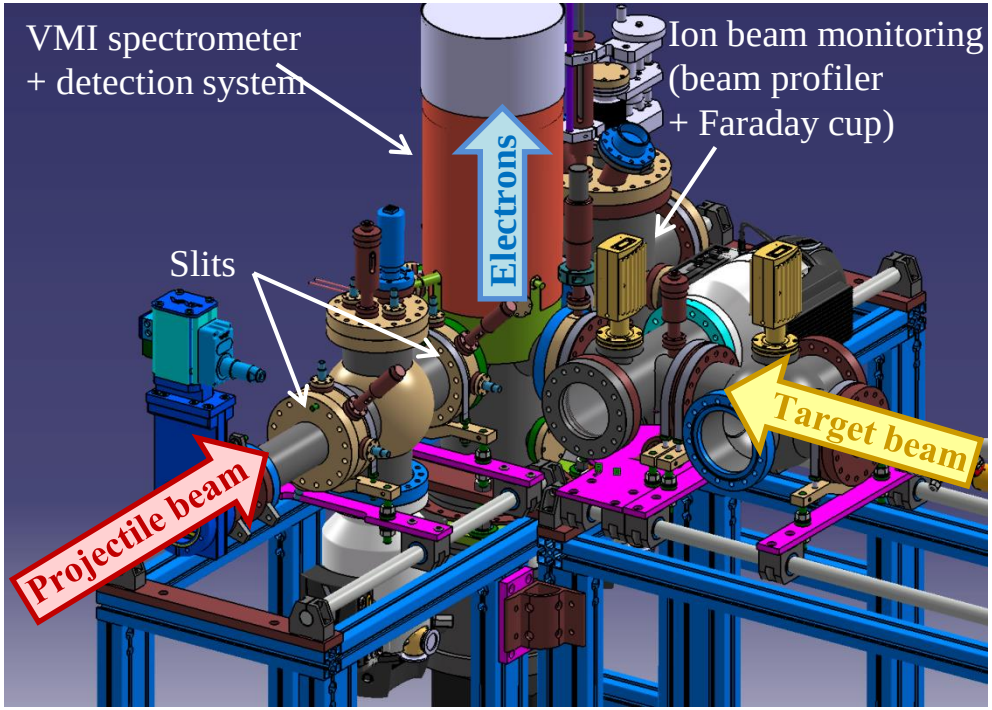
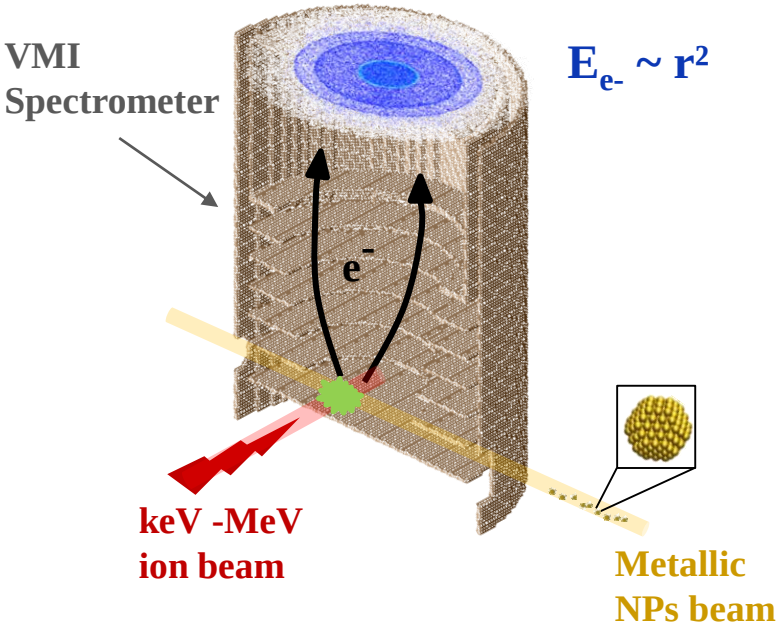
New experimental setup : crossed beam experiment with Velocity Map Imaging (VMI) spectrometer



2D projection of a 3D e- distribution
→ inverse Abel transform
→ energy/angular distribution

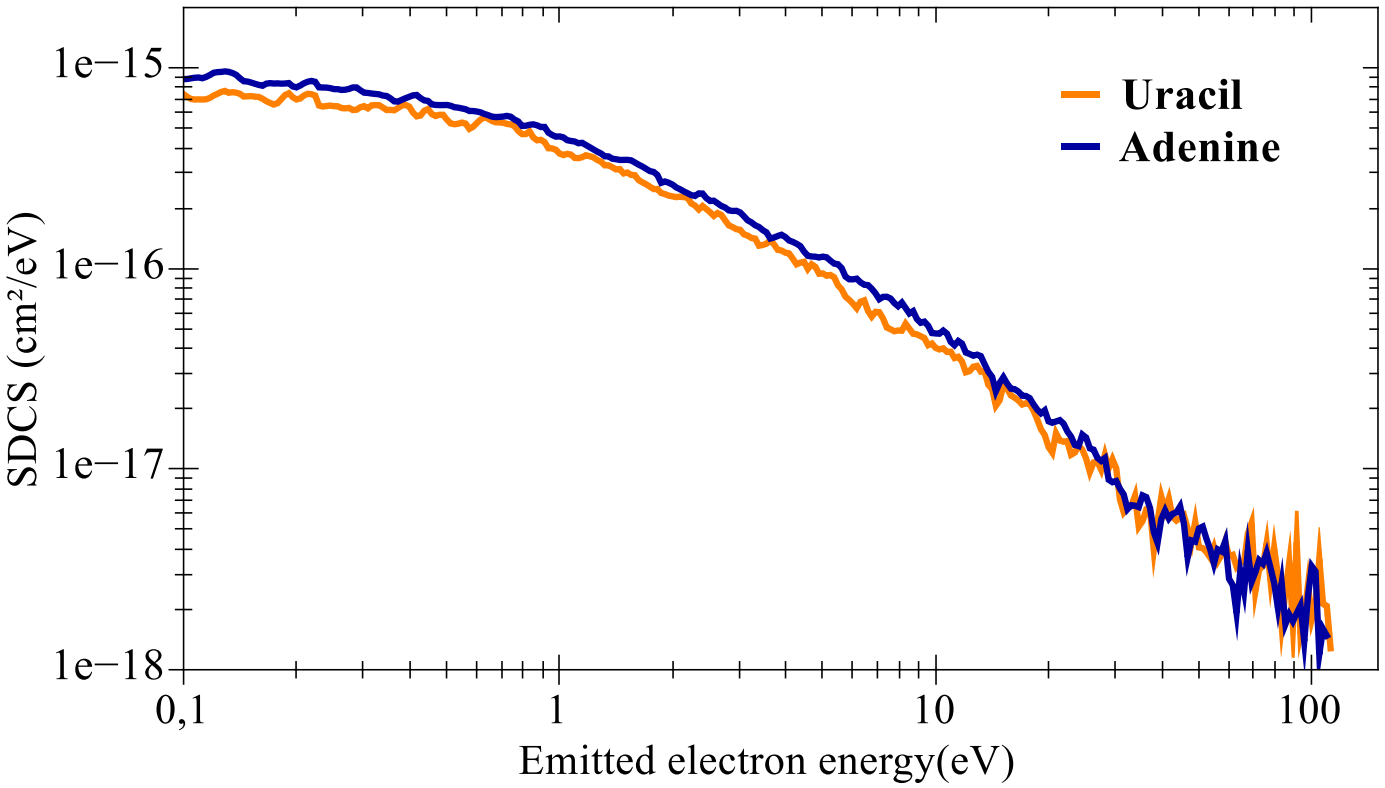


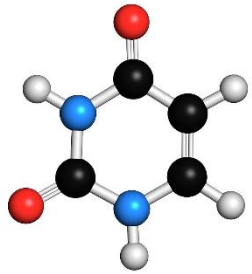
ANR AGENCE NATIONALE DE LA RECHERCHE
ANR JCJC 2016 (IMAGERI)

IMAGERI: Measure of electron emission

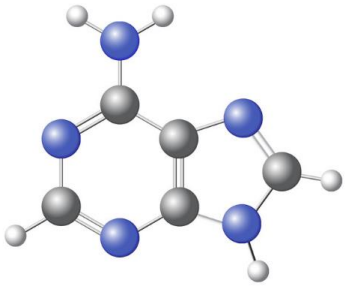
Radiosensitizers in ion beam therapy: Measure of absolute cross section for electron emission from metallic nanoparticles upon ion collision

First results with biologically relevant molecules (DNA /RNA bases)
→ IRRSUD C^{4+} @ 0.95 MeV/u (June 2019)





Uracil



Adenine

Prospect for interdisciplinary research

Development of new setups:

–> Broaden the ion beam capability

IRRSUD, LARIA, ARIBE,…..

PELIICAEN

–> Improve the understanding of ion/matter interaction

–> Emerging of new topics

IGLIAS

IMAGERI

–> Future: extreme grazing incidence, in-situ AFM/STM, PELIICAEN, …..

Prospect for interdisciplinary research

Hot topics

–>Astrophysical ices

Production and radioresistance of new species
Molecular complexification

–> Combine effect of potential energy/ electronic energy loss/ nuclear energy loss

–> Slow ion- Fast ion collision (Fit-FISIC)

–> Simulation of irradiation for nuclear industry or spatial applications

–> New material or new applications / Defect engineering

–> Radiobiology
- individualized and Combined treatment
- Molecular mechanisms in biologic response

–> …….

Prospect for interdisciplinary research

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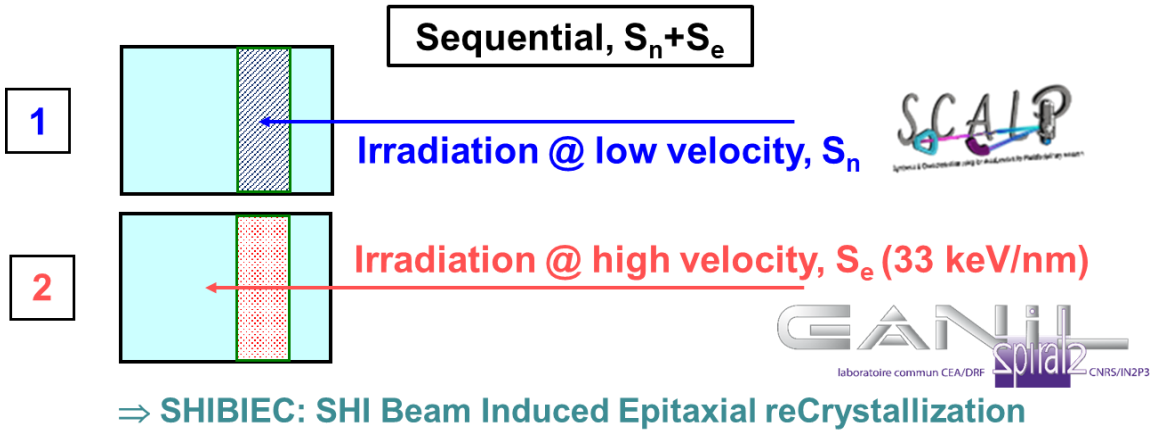
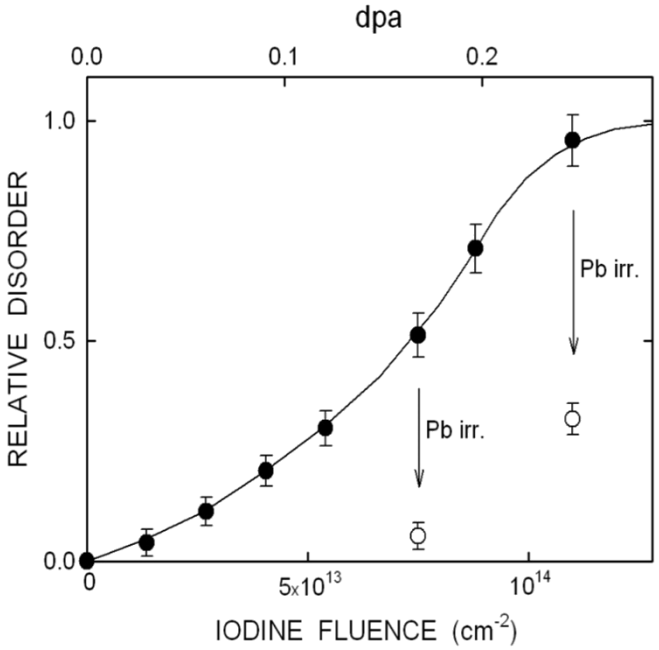
SiC: Coupled effect of Se, Sn

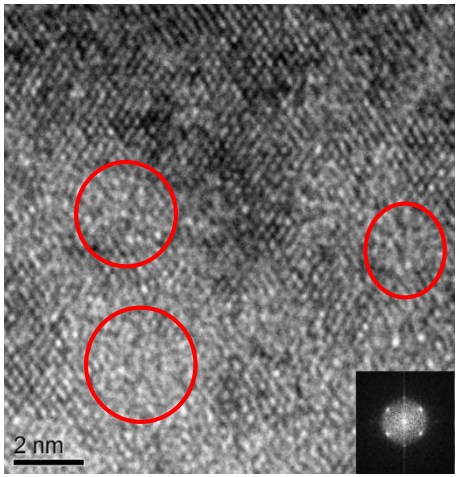


For partially amorphous state before SHI

⇒ SHIBIEC: SHI Beam Induced Epitaxial reCrystallization

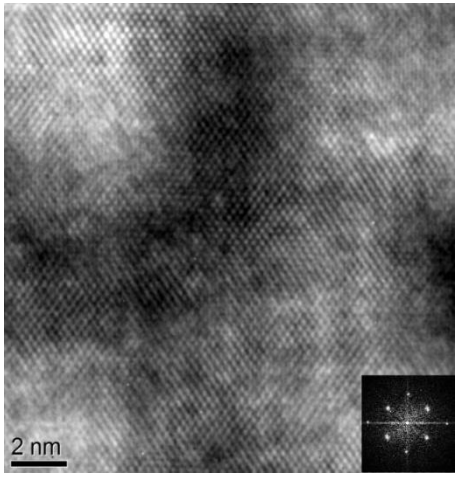


Before SHI



Highly defective crystals containing amorphous pockets

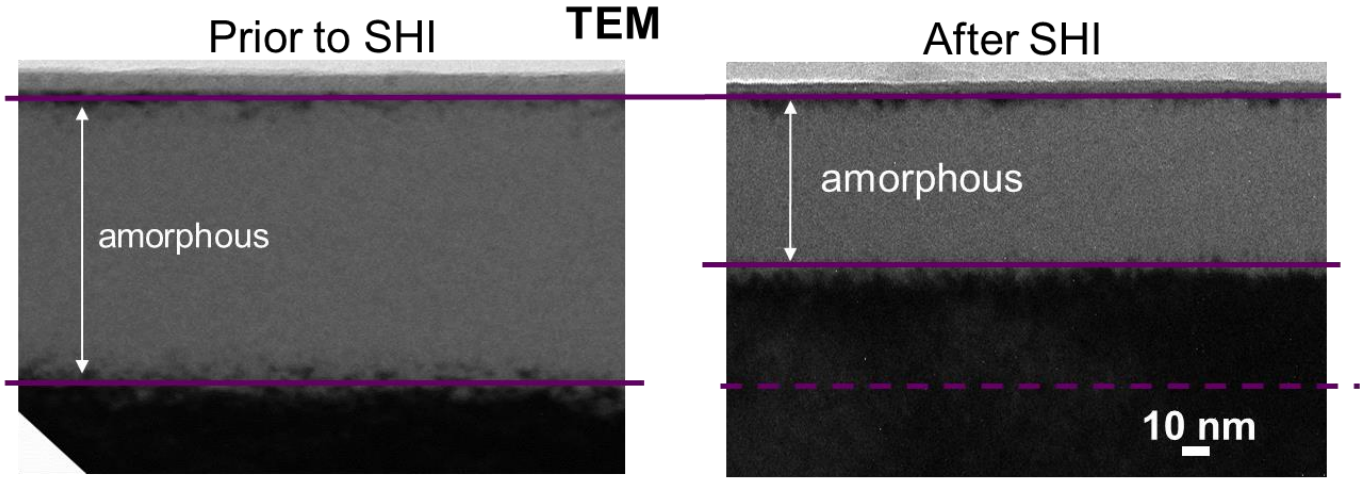
After SHI

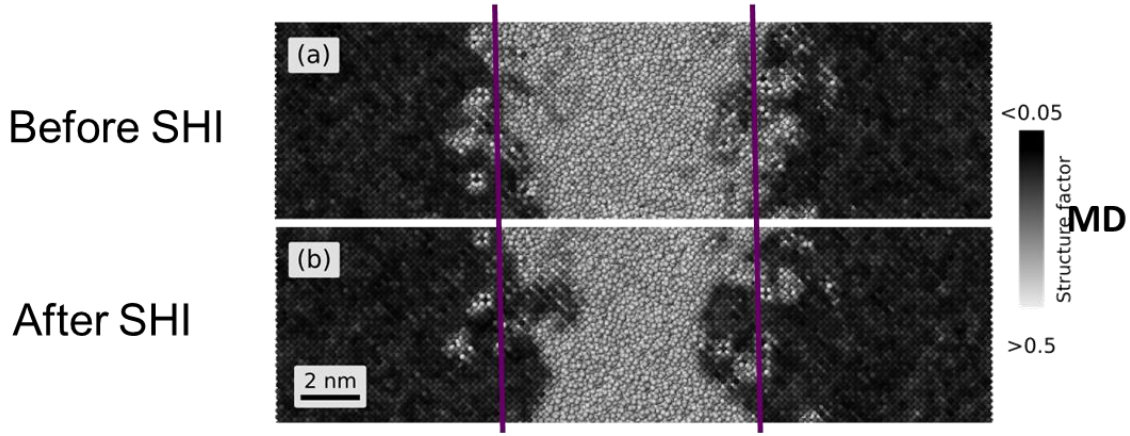


Weakly defective crystals

SiC: Coupled effect of Se, Sn

For fully amorphous layer after the low velocity ion irradiation





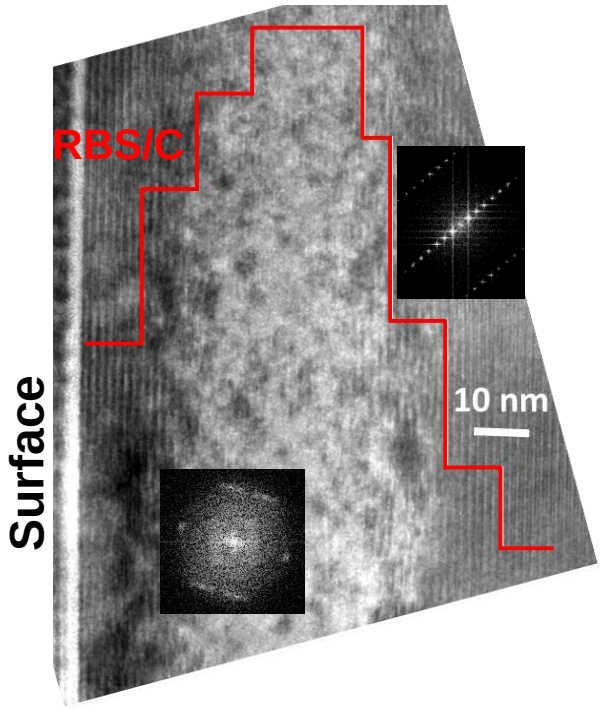
⇒ **Recrystallization occurs at the a/c interfaces**

⇒ **Simulation of thermal spike allows reproducing experimental findings**

SiC: Coupled effect of Se, Sn and temperature

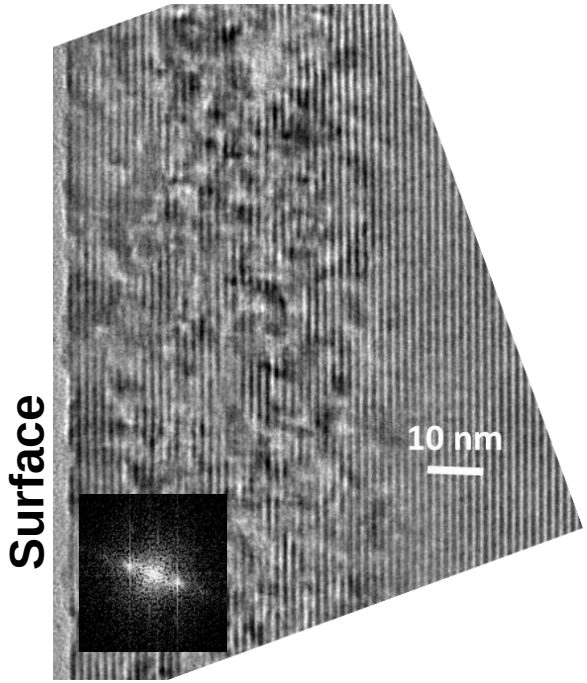
TEM pictures of irradiated SiC crystals

Before SHI



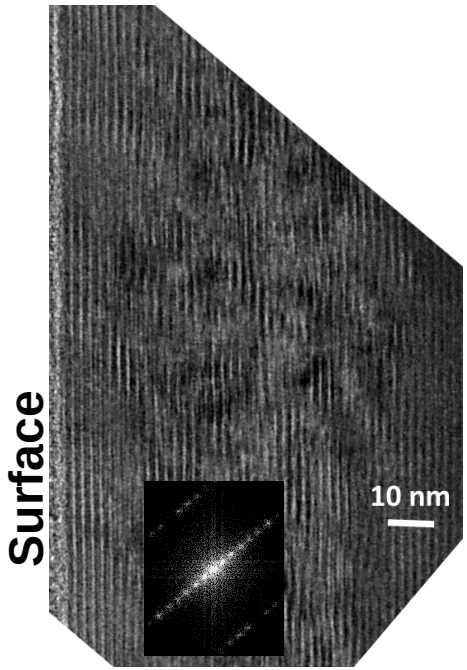
Defective crystals with high-density amorphous regions

After SHI, LT ($4x10^{13}$ cm^{-2})



Defective crystals with low-density amorphous regions

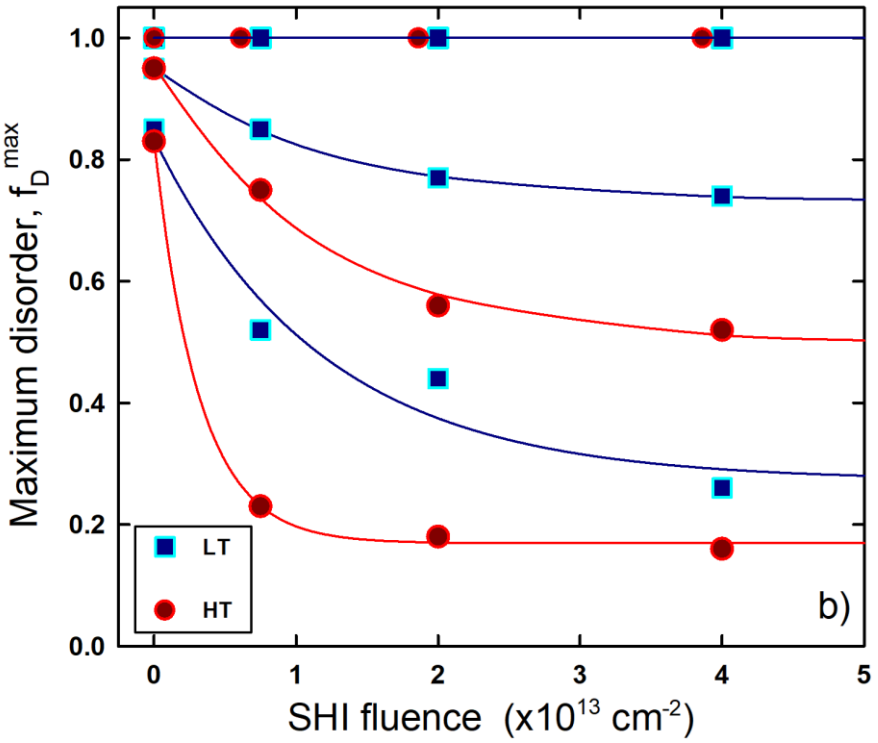
After SHI, HT ($4x10^{13}$ cm^{-2})



Defective crystals

⇒ **Microstructure of SHI-irradiated crystals depends on T°**

SiC: Coupled effect of Se, Sn and temperature



- **Recovery efficiency increases with ↗ temperature and ↘ initial disorder**
- **Yet, thermal load (500 °C / 15h) alone does lead to significant crystal recovery**
- Irradiation temperature is insignificant as compared to temperature inside the ion track, so why does it have an influence on the recovery???

SiC: Coupled effect of Se, Sn and temperature

Recovery process in SiC subjected to (intense) electronic energy deposition:

⇒ **Ionization-induced, thermally-assisted process**

⇒ **Recovery is a two-step process:**

(1) defect annealing induced by intense electronic energy deposition that locally ↗ temperature

(2) further annealing due to macroscopic T° (relaxation time of defects is ms in SiC)

⇒ Occurs even at low temperature but may be enhanced with temperature

⇒ Modify the cascade final state or the cascade debris itself

⇒ **Same physical mechanism whatever the energy deposition sequence**

Prospect for interdisciplinary research

Hot topics

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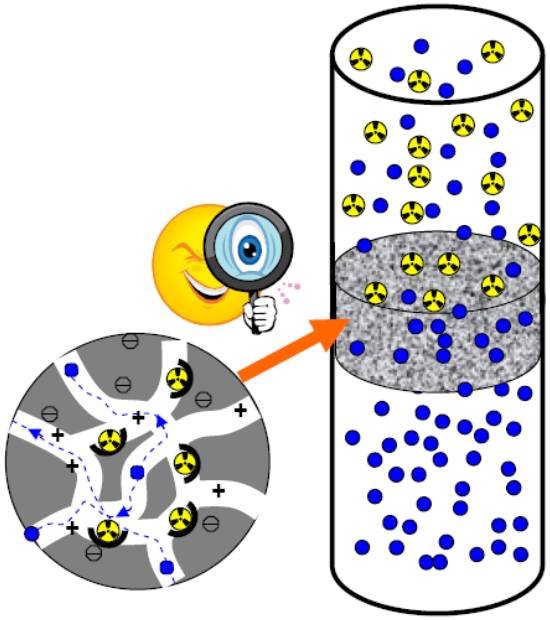
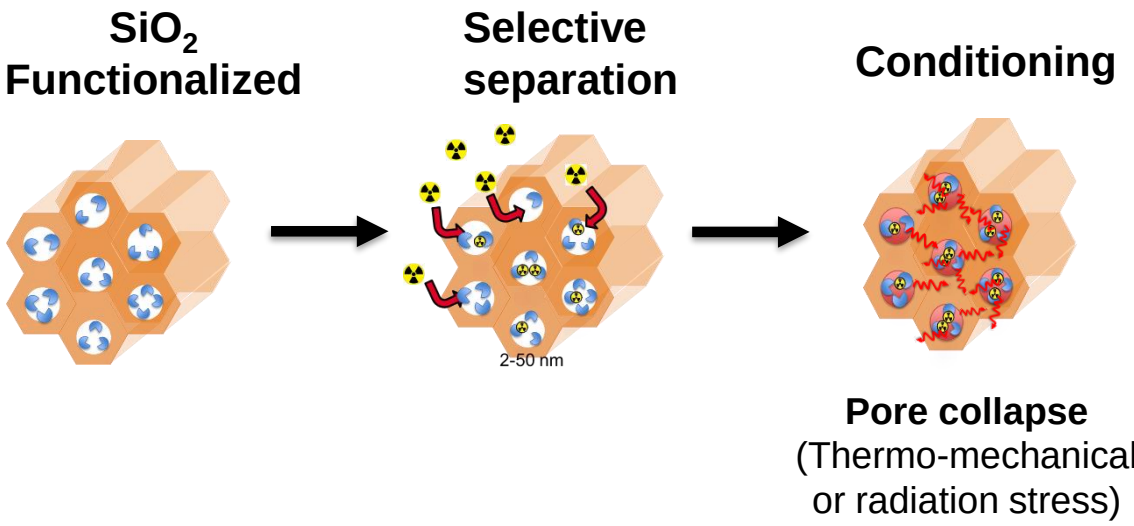
–> …….

Separation – conditioning process

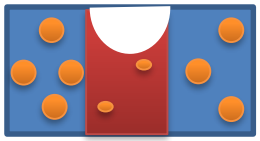
- **Nuclear waste management**
  - Adsorption of the selected radionuclide
  - Encapsulation of the radionuclide by subsequent collapse of the structure (Thermal stress, chemical stress…)





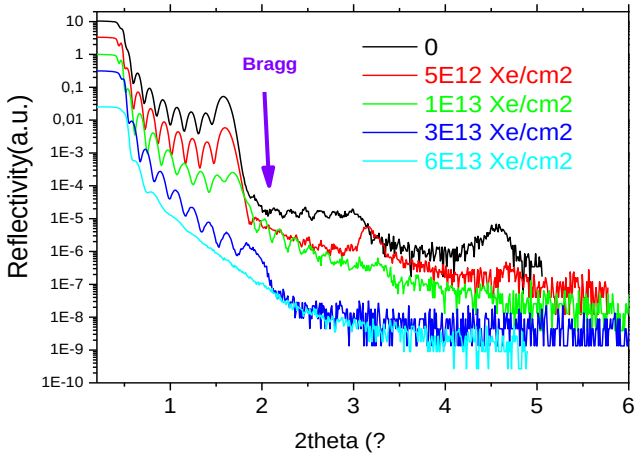
- **Field of application**
  - Outflows coming from dismantling sites

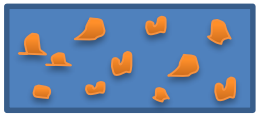
Mesoporous silica under irradiation



- Xe 92MeV

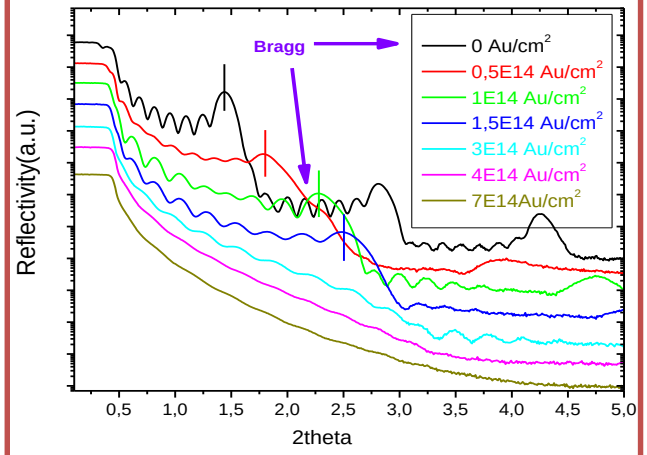
Electronic irradiation
track condition

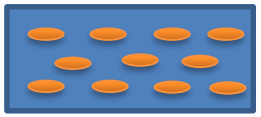




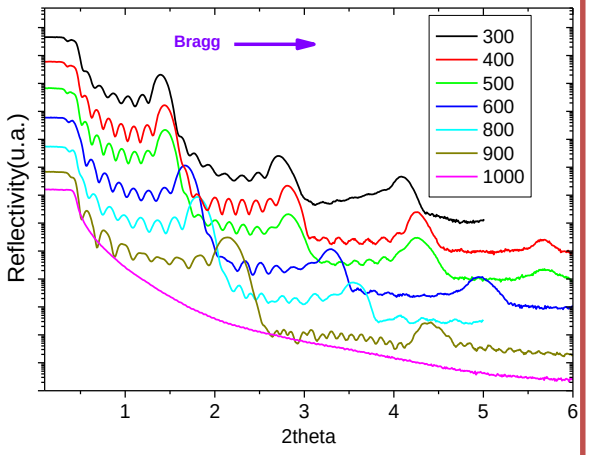
- Au 0,5MeV

Mainly ballistic effect





- Pure thermal sintering

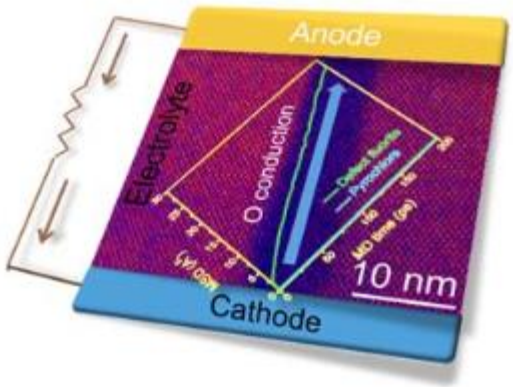


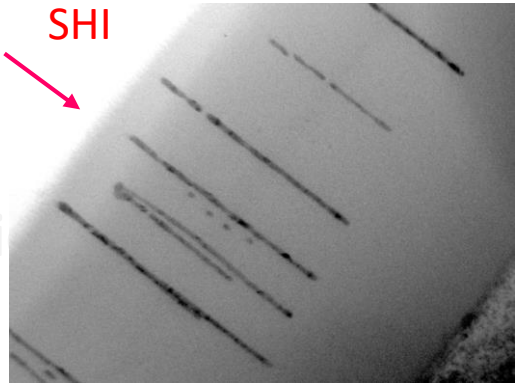
- Electronic irradiation (track): local damage
- Ballistic irradiation: extended damage
- Thermal sintering: homogeneous pore shrinkage

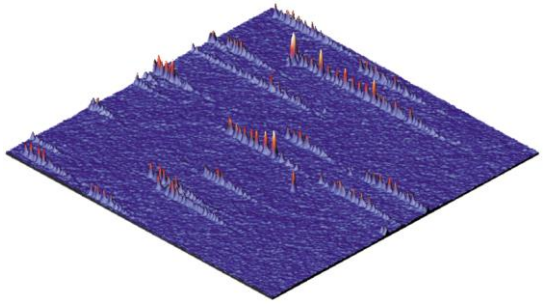
Prospect for interdisciplinary research

Hot topics

2D materials
Mott Insulator
High gap semiconductors
….
Surface Nanostructuration

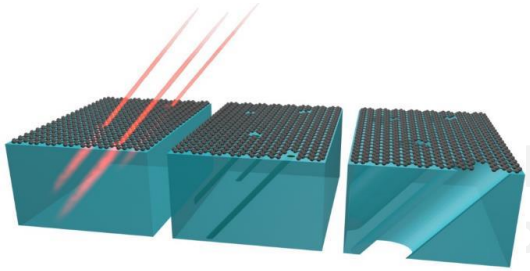


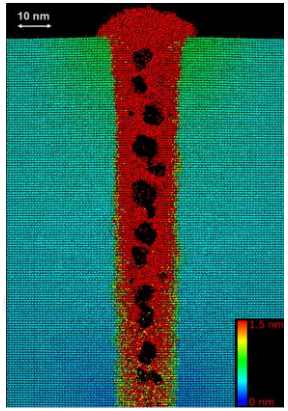




–> New material or new applications

Defect engineering





–> .....

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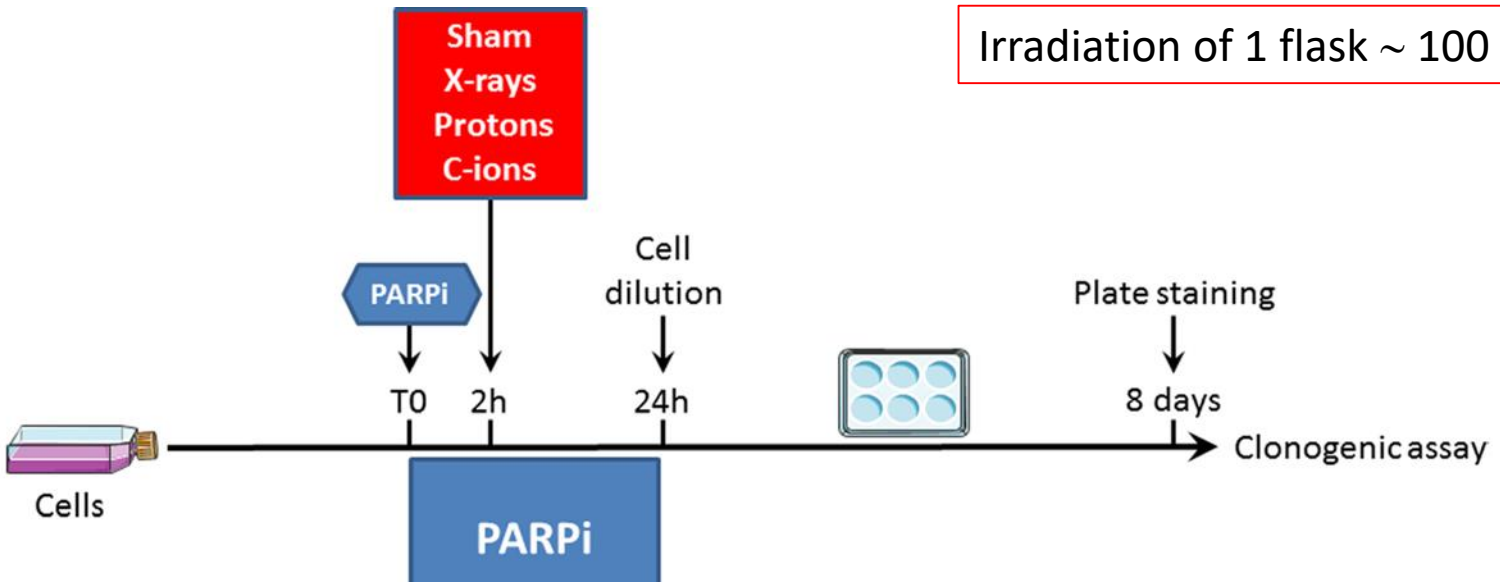
–> …….

Typical radiobiology experiment

Setup of experiments : an example of limitation of using living cells



Irradiation of 1 flask ~ 100 s

The weeks before beam time: cell culture (hundred of flasks)

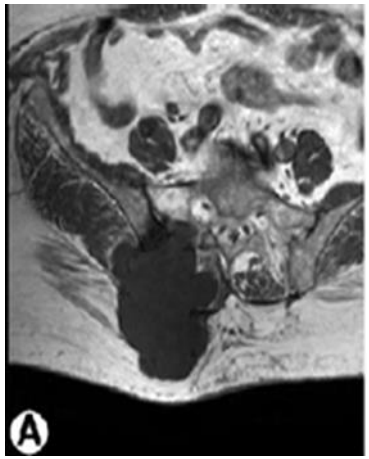
The day of the beam time:

addition of the drug **two hours** before irradiation (can not be less or more)

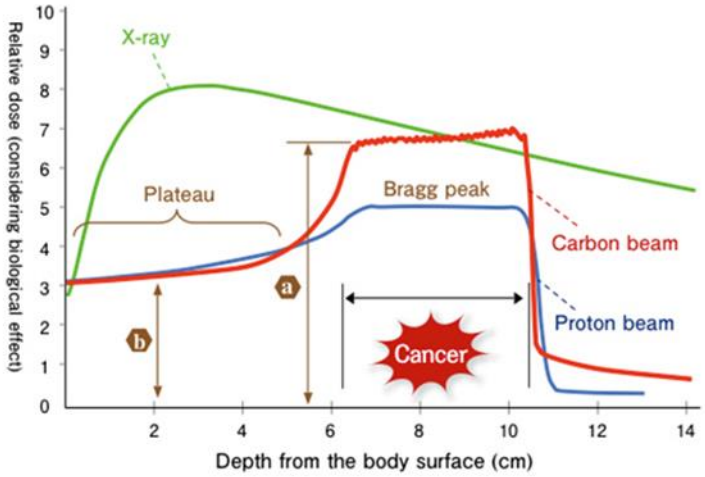
cell dilution **24 hours** after addition of the drug

plate staining **8 days** after irradiation

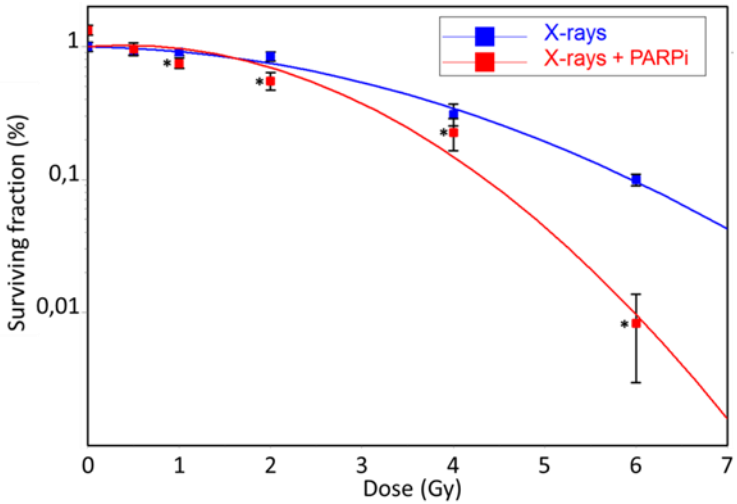
Chondrosarcoma / pre-clinical experiments



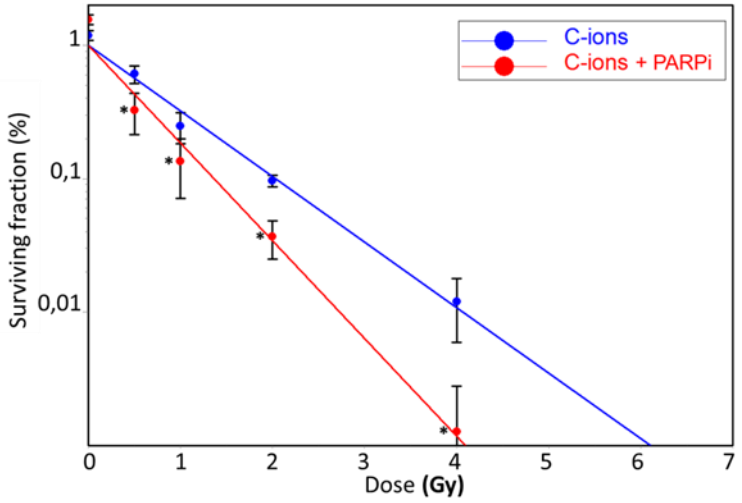
Chondrosarcoma
malignant tumor of cartilage with bad prognostic - highly radio-resistant => use of hadrontherapy ?



Clonogenic assays: comparison between X-rays and C-ions (+/- PARPi)



Cell survival (%) is a mean +/- SD of 3 independent experiments performed in triplicate



Comparison of C-ions and X-rays: Relative Biological Effectiveness 2,95

M. Cesaire, J. of bone oncology 17 (2019) 100246

Acknowledgments

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Thanks to CIRIL platform for interdisciplinary physics at GANIL