The JANNuS-Orsay / SCALP platform

Presentation at the Scientific Council of the National Institute of
Nuclear Physics and Particle Physics (IN2P3)

Tuesday 25th February 2020, Paris

SCALP **S**ynthesis and **C**haracterization using ion **A**cce**L**erators for **P**luridisciplinary research
JANNuS **J**oint **A**ccelerators for **N**anoscience and **Nu**clear **S**imulation

Operations manager: Dr Cyril Bachelet
Scientific leader: Dr Aurélie Gentils

Outline

Description of the platform

- Equipment
- Governance structure
- Networks
- Beam time allocation
- Resources
- Distribution of users and scientific themes

Scientific issues

- Nuclear materials
- Nuclear physics and astrophysics
- Radionuclides production for health
- Miscellaneous

Perspectives

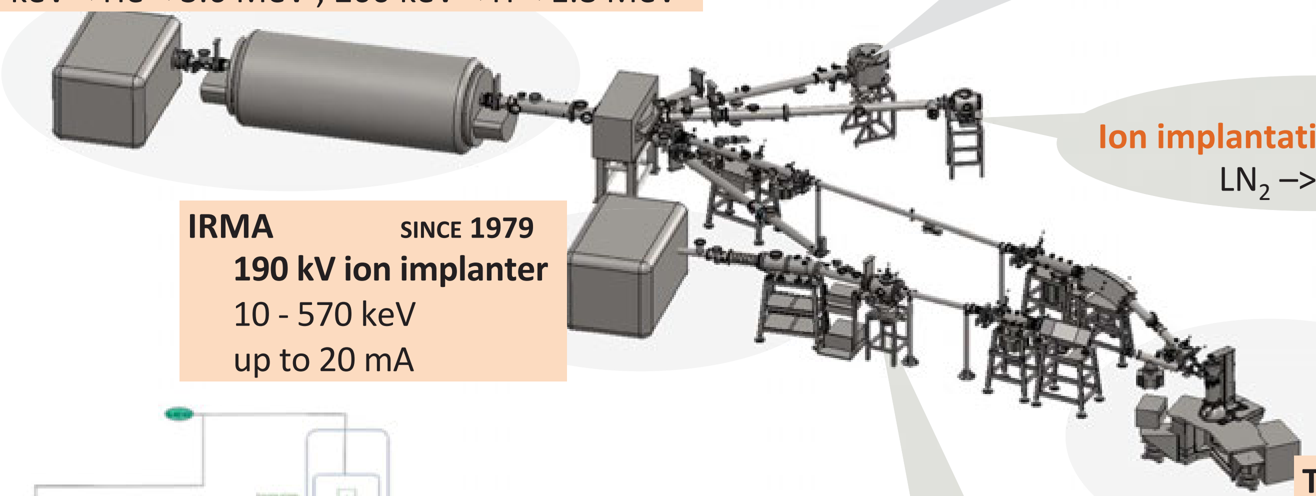
The JANNuS-Orsay / SCALP platform

✓ **Home-made ion accelerators**

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

Ion Beam Analysis
RBS, RBS/C, ERDA,
PIXE, *μPIXE, PIGE*

Ion implantation / irradiation
LN_2 –> 1000°C



IRMA SINCE 1979
190 kV ion implanter
10 - 570 keV
up to 20 mA

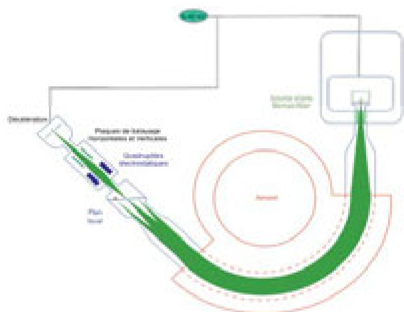
SCALP Synthesis & Characterization using ion AcceLerators for Pluridisciplinary research

JANNuS
Joint Accelerators for Nanoscience and Nuclear Simulation

***IN SITU* DUAL ION BEAM TEM**
SINCE 1980 UPDATED IN 2007

TRANSMISSION ELECTRON MICROSCOPE
200 kV *FEI Tecnai G² F20 Twin*
Resolution: 0.27 nm
Magnification range: x 70-700 000
EDX, GIF (EELS, EFTEM…), STEM
-170°C up to 1000°C

***in situ* RBS/C and ion impl.**
LN_2 –> 600°C



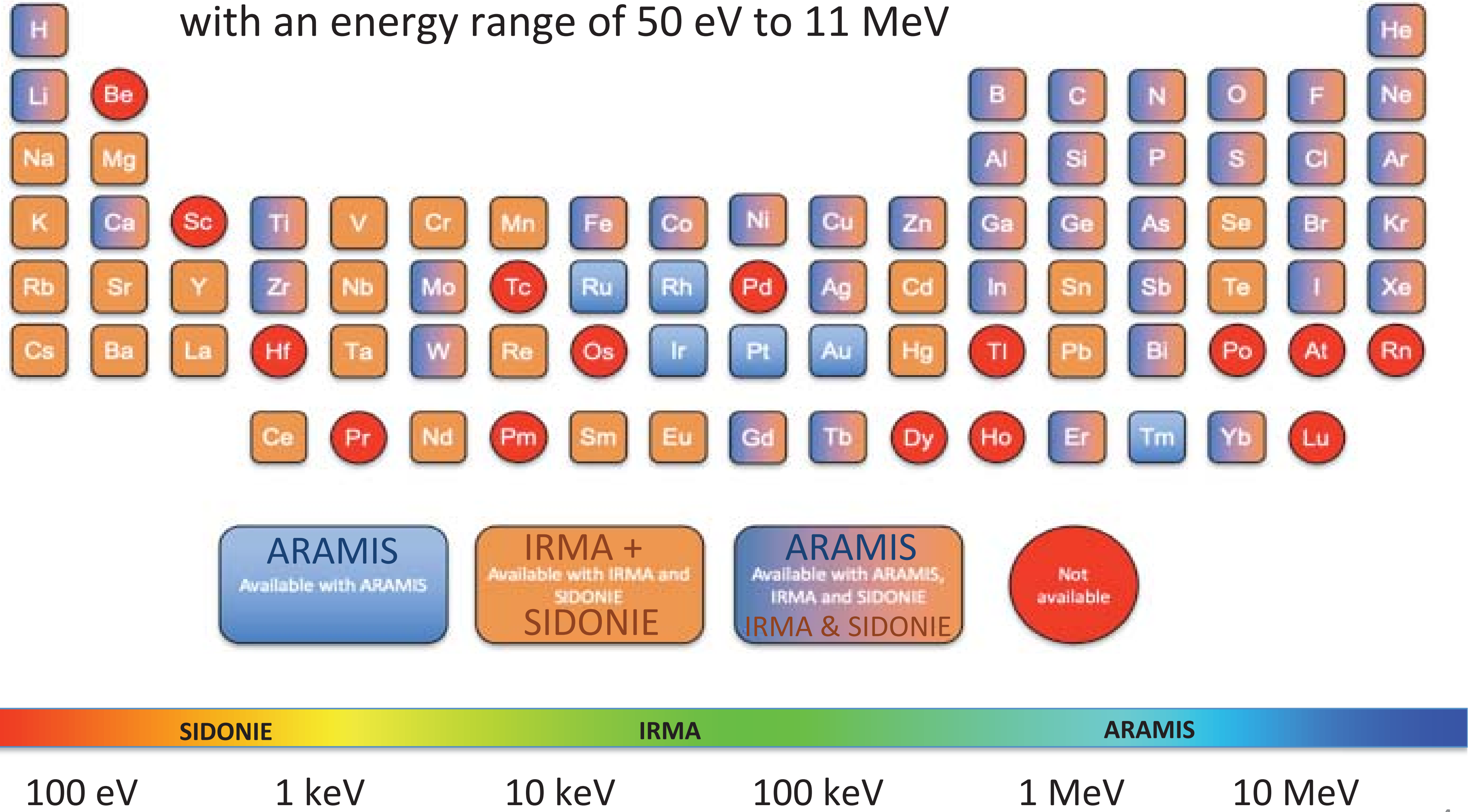
SIDONIE SINCE 1967
50 kV isotope separator
50 eV – 150 keV
up to 20 mA, M/ΔM>1000

✓ *In situ* measurements using IBA and TEM with one or two ion beams

Member of GIS **JANNuS** (**J**oint **A**ccelerators for **N**anoscience and **Nu**clear **S**imulation), Orsay & Saclay
Member of **EMIR&A** French Accelerators Federation for Irradiation & Analysis of Materials and Molecules

Large diversity of ions available (nature, energy)

71 chemical elements available,
with an energy range of 50 eV to 11 MeV



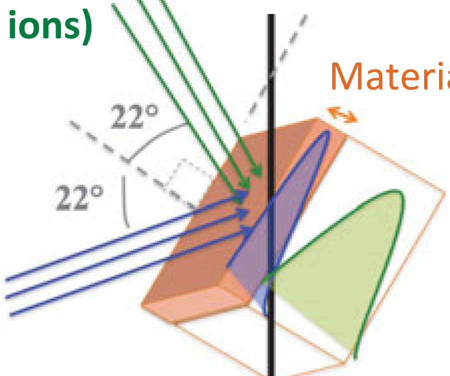
A unique *in situ* dual ion beam TEM

Transmission **E**lectron **M**icroscope

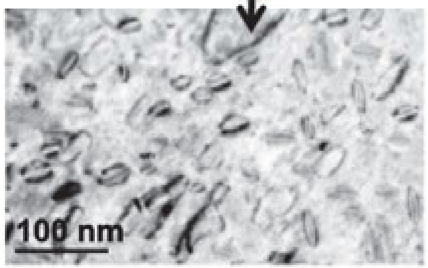
- 200 kV FEI Tecnai G² 20 TWIN
- **Electron source**: LaB_6 filament
- **Spatial resolution**: 0.27 nm
- **Analytical techniques** : **EDX** (Energy Dispersive X-rays), **EELS** (Electron Energy Loss spectroscopy), **EFTEM** (Energy Filter TEM), **STEM** (Scanning TEM), **HAADF** (High Angle Annular Dark field)

In situ observation of the atomic scale microstructure of materials submitted to one or two ion beams

- ✓ Dynamical observation (above 100 keV N ions)
- ✓ Raster scanned beam
- ✓ Ion beam dosimetry inside TEM: continuous flux measurement ≤ 3 cm sample, accuracy < 5%

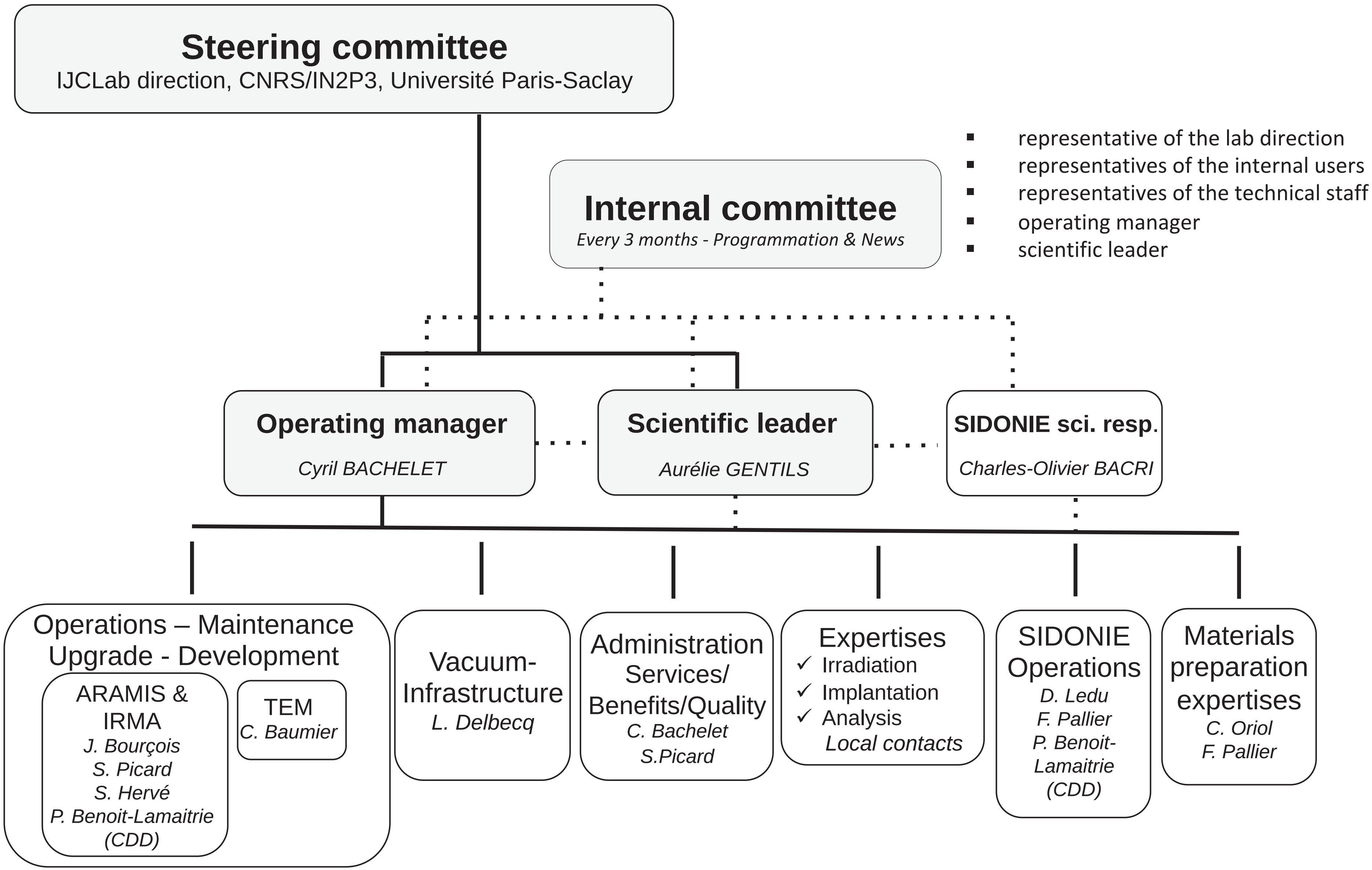


At a chosen T
LN_2 → 1000°C



Nature, size and density of defects, impurities, nanoprecipitates, crystallographic structure, chemical composition….

Governance structure of JANNuS-Orsay / SCALP



Networks

JANNuS is a founding member of **EMIR** French Accelerators network (2009)
CNRS Federation (FR 3618) since 2014
EMIR&A since 2019

ARAMIS
IRMA
TEM

COUPLING

ACCESS

European programmes (EUROfusion)

Scientific Interest Group (GIS) JANNuS (2005)

Joint **A**ccelerators for **N**ano-science and **Nu**clear **S**imulation

JANNuS-Orsay

JANNuS-Saclay
CEA Paris-Saclay, DEN/DMN/SRMP

French accelerators network for Irradiation and Analysis of Materials and Molecules (EMIR&A)

Nathalie Moncoffre's talk

CEMHTI Orléans, CIMAP Caen, IJCLab Orsay, LSI Palaiseau, CEA Saclay SRMP et SRMA, INSP Paris, LCP Orsay

EMIR&A President:
N. Moncoffre (IP2I Lyon)
President of the scientific committee:
R. Schaeublin (ETH Zurich)

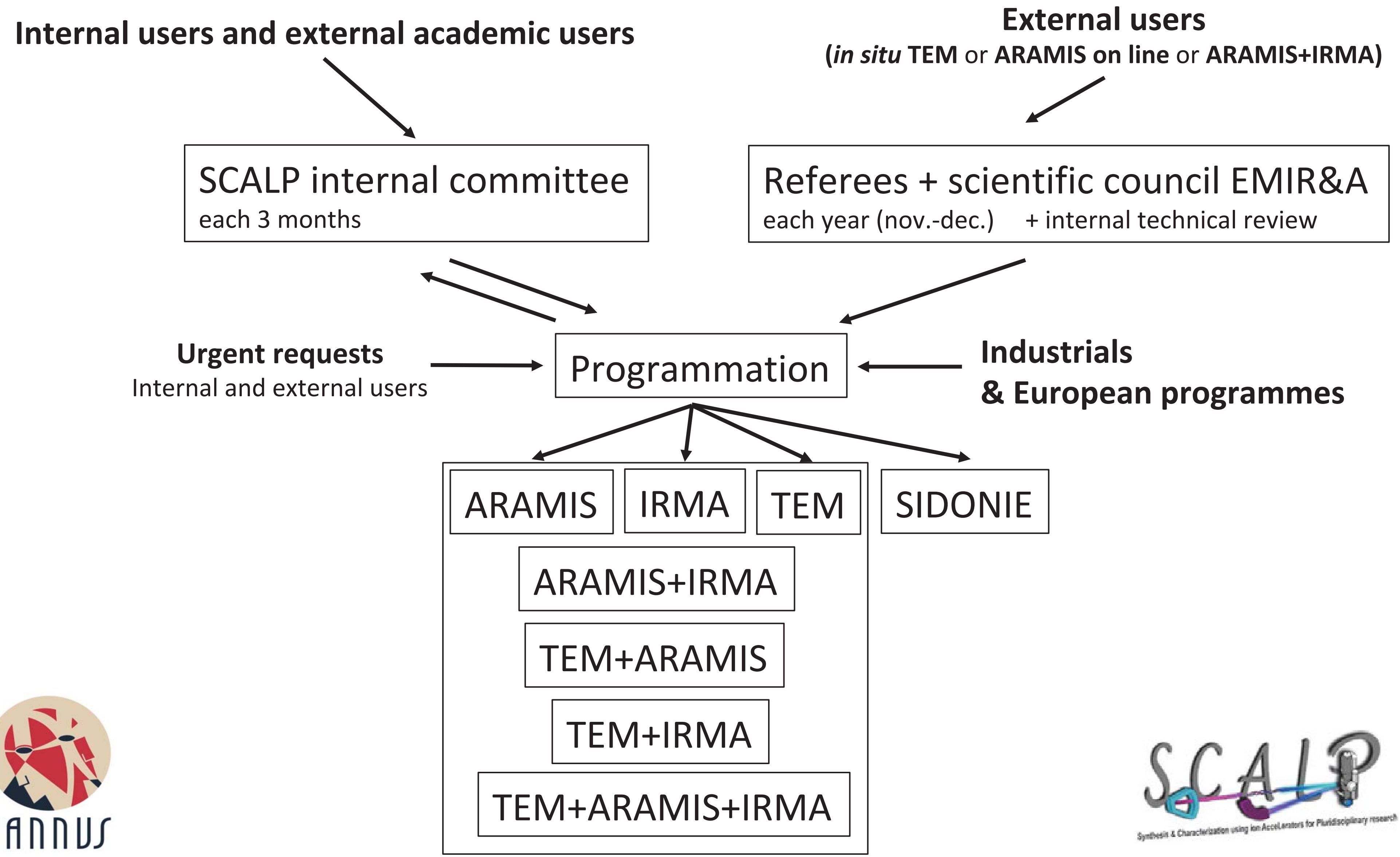
http://jannus.in2p3.fr

JANNUS

http://emir.in2p3.fr

emir&A
National network of accelerators for irradiation and analysis of molecules and materials

Beam time allocation: proposal procedure



8h per day from Monday to Friday

Resources

Human resources: approx. 11 FTE (IN2P3)

Operations and dev. technical staff	9.4 FTE
Engineering pole technical help	≈ 1 FTE
Local contacts and scientific leading	≈ 1 FTE

Financial model:

- ✓ ~ 85 % of own resources coming from chargeable services for industries and external users
- ✓ Annual operating cost is in average 85-115 k€ per year

Strongly dependant on economical context

Example – average on the last 3 years :

Annual costs	**106,7 k€**
Operation costs	93,1 k€
Developments	13,6 k€

Income :
IN2P3 15 k€ / year
+ chargeable services

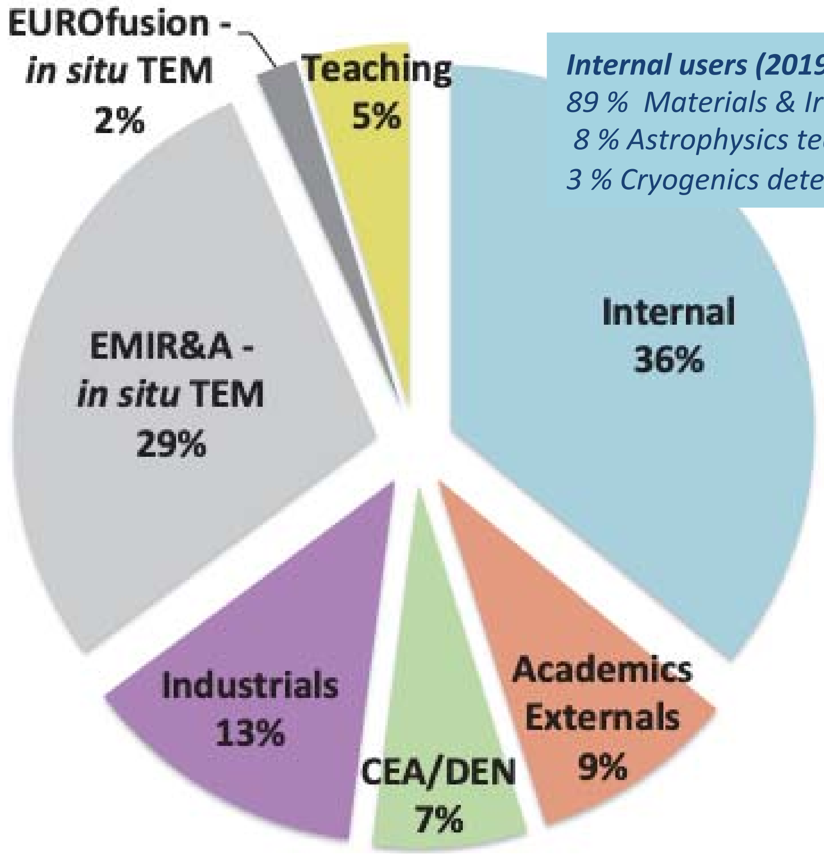
Distribution of users

ion beam modification and ion beam analysis of materials

IRMA-ARAMIS-TEM JANNuS

Internal users (2019):
89 % Materials & Irradiation team
8 % Astrophysics team
3 % Cryogenics detectors team

Poles:
E&E
AAC
AAC



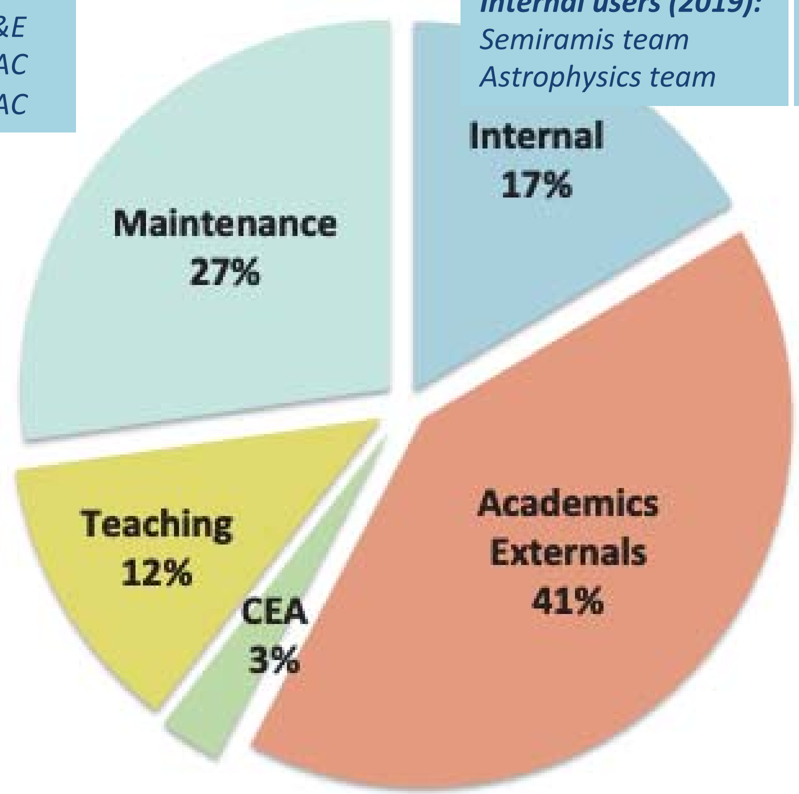
Year 2019
170 days of beam time, 130 distinct experiments, 30 users

isotopes and targets production

SIDONIE

Internal users (2019):
Semiramis team
Astrophysics team

Poles:
Health
AAC

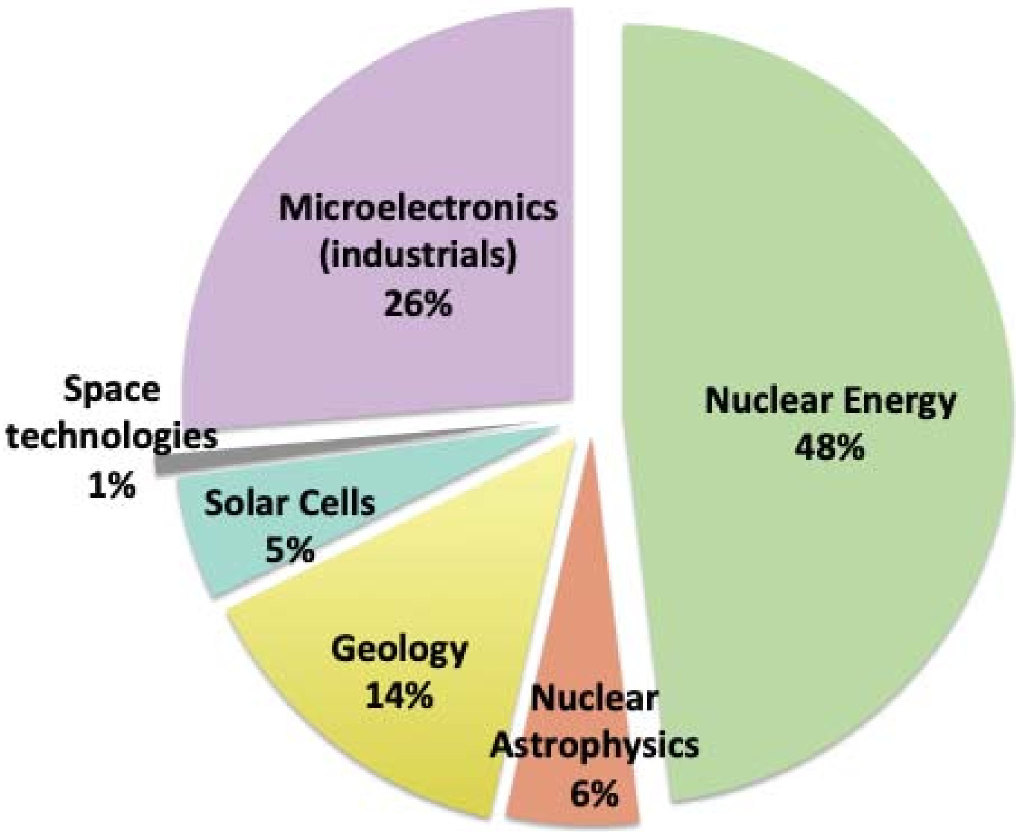


Years 2017-2019
36 days of beam time per year in average

Overview of scientific themes

ion beam modification and ion beam analysis of materials

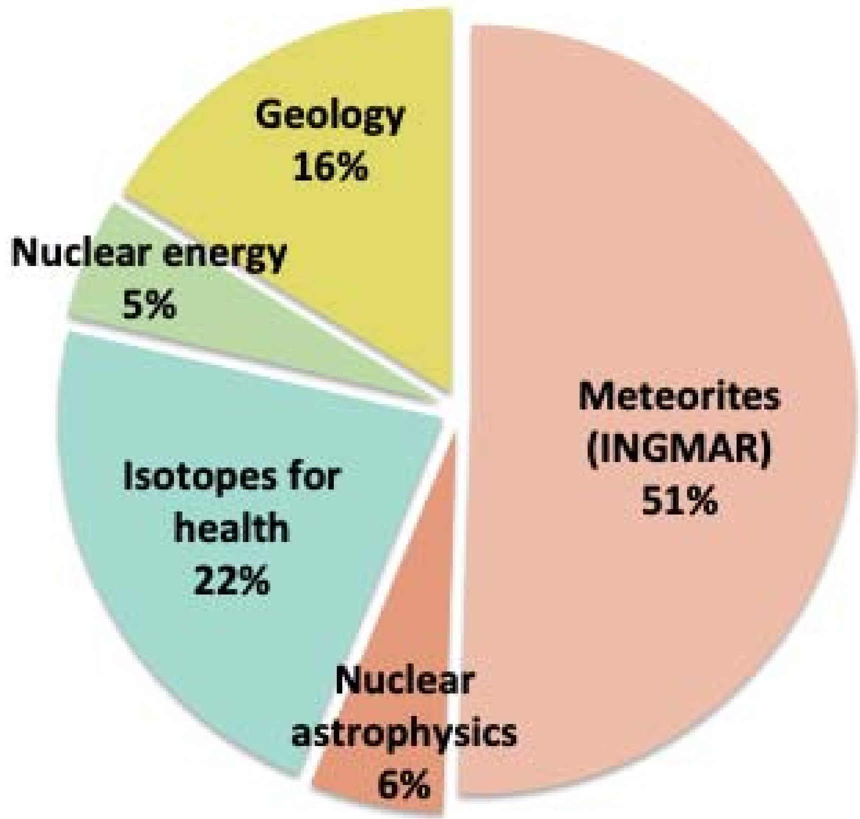
IRMA-ARAMIS-TEM JANNuS



Year 2019
170 days of beam time, 130 distinct experiments, 30 users

isotopes and targets production

SIDONIE



Years 2017-2019
36 days of beam time per year in average

Scientific issues – some examples

Materials for nuclear energy

Irradiation of austenitic steels – *in situ* TEM + ARAMIS

Light gas in ODS steels – *in situ* TEM + IRMA

Ion beam synthesis of nano-oxides - IRMA and TEM

Irradiation of UO_2 - *in situ* RBS/C analysis using IRMA+ARAMIS

Astrophysics

Meteorites and ices - INGMAR setup on SIDONIE

Radionuclides production for health

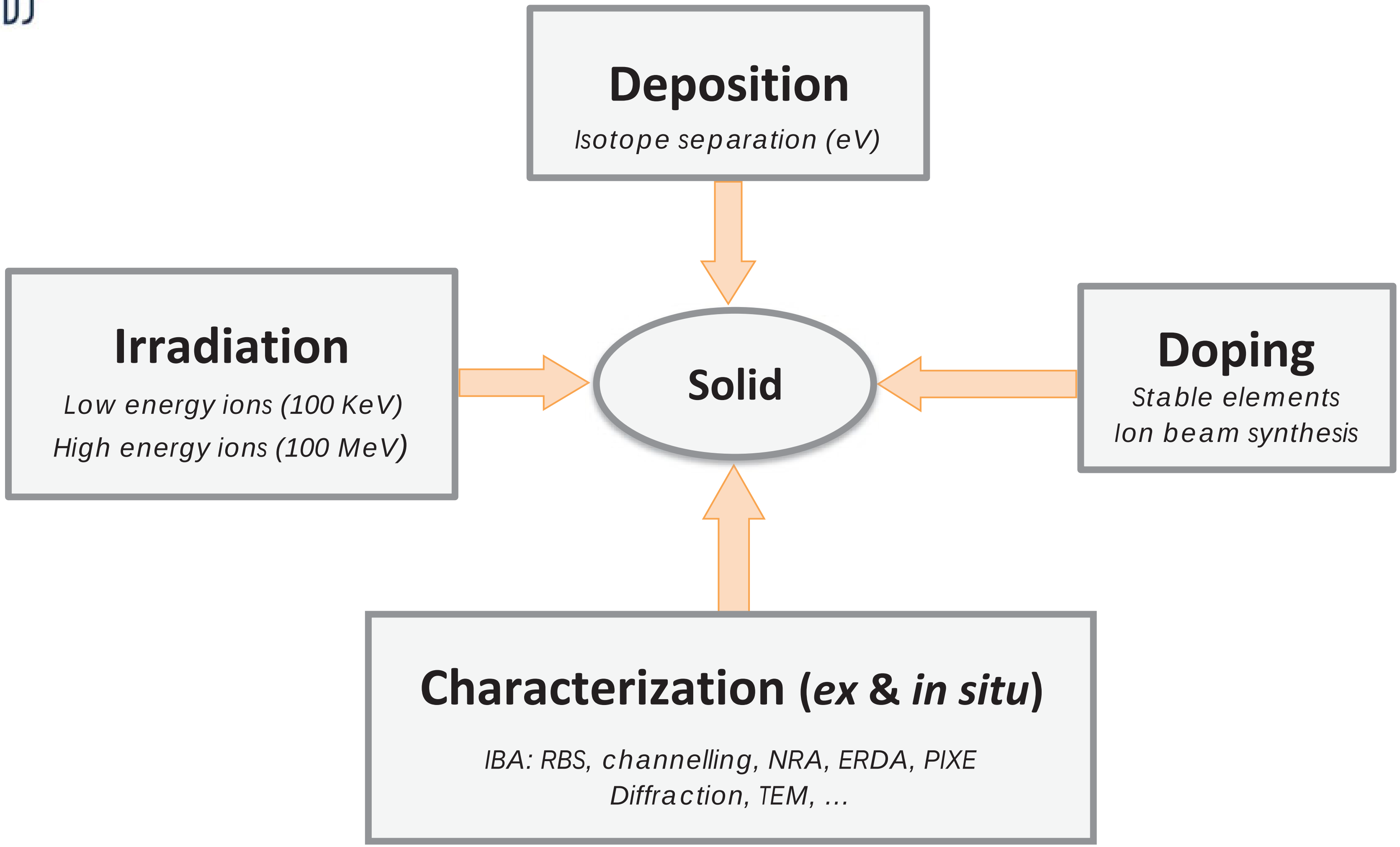
Production of Gd for theragnostic − SIDONIE

Miscellaneous

Helium in geological minerals - ERDA analysis on ARAMIS

SNEEL effect - RBS/C analysis on ARAMIS

Ion beams for material science



Irradiation-induced defects, atomic diffusion,
physical and chemical properties, etc, using JANNuS / SCALP facility

Behaviour under irradiation of model austenitic steels

<u>Objective:</u> get a better understanding of the effect of solutes, Ti and Cr, on the irradiation behaviour of austenitic structure, i.e. Face Centered Cubic (FCC) structure

***In situ* TEM irradiation with ARAMIS (JANNuS-Orsay)**

2 MeV Ni ions, $\Phi = 4\times10^{11}$ ions.cm^{-2}.s^{-1} during 3’40’’

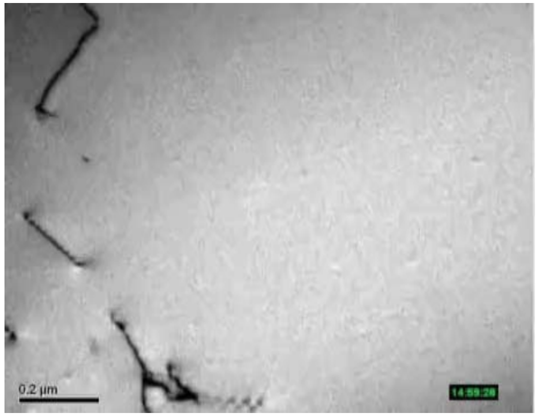
0.07 dpa (displacements per atom), RT

Clear influence of an addition of Cr or Ti on loop growth and mobility

PhD thesis of Kan Ma, 2017-2020, unpublished results

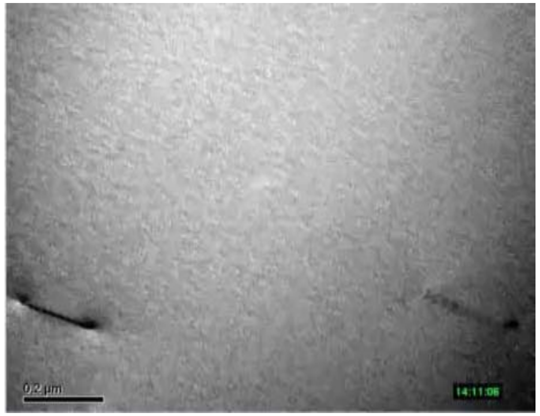
x16 play speed

Ni



Ni-0.4Cr

Ni-0.4Ti



Kan MA[1], Marie LOYER-PROST[1], Thomas JOURDAN[1], Brigitte DECAMPS[2], Anna FRACZKIEWICZ [3], Frédéric PRIMA[4]

[1] CEA Paris-Saclay, DEN/DANS/DMN/SRMP
[2] Université Paris-Saclay, CNRS/IN2P3, IJCLab
[3] CNRS/UMR5307/ENSMSE/LGF
[4] IRCP/CNRS/UMR 8247-Chimie Paristech

The authors thank the RMATE (CEA) and NEEDS project (ARMADA) for their financial support; the JANNuS-Orsay team for the irradiations and their welcome. This experiment was supported by the EMIR French accelerator network.

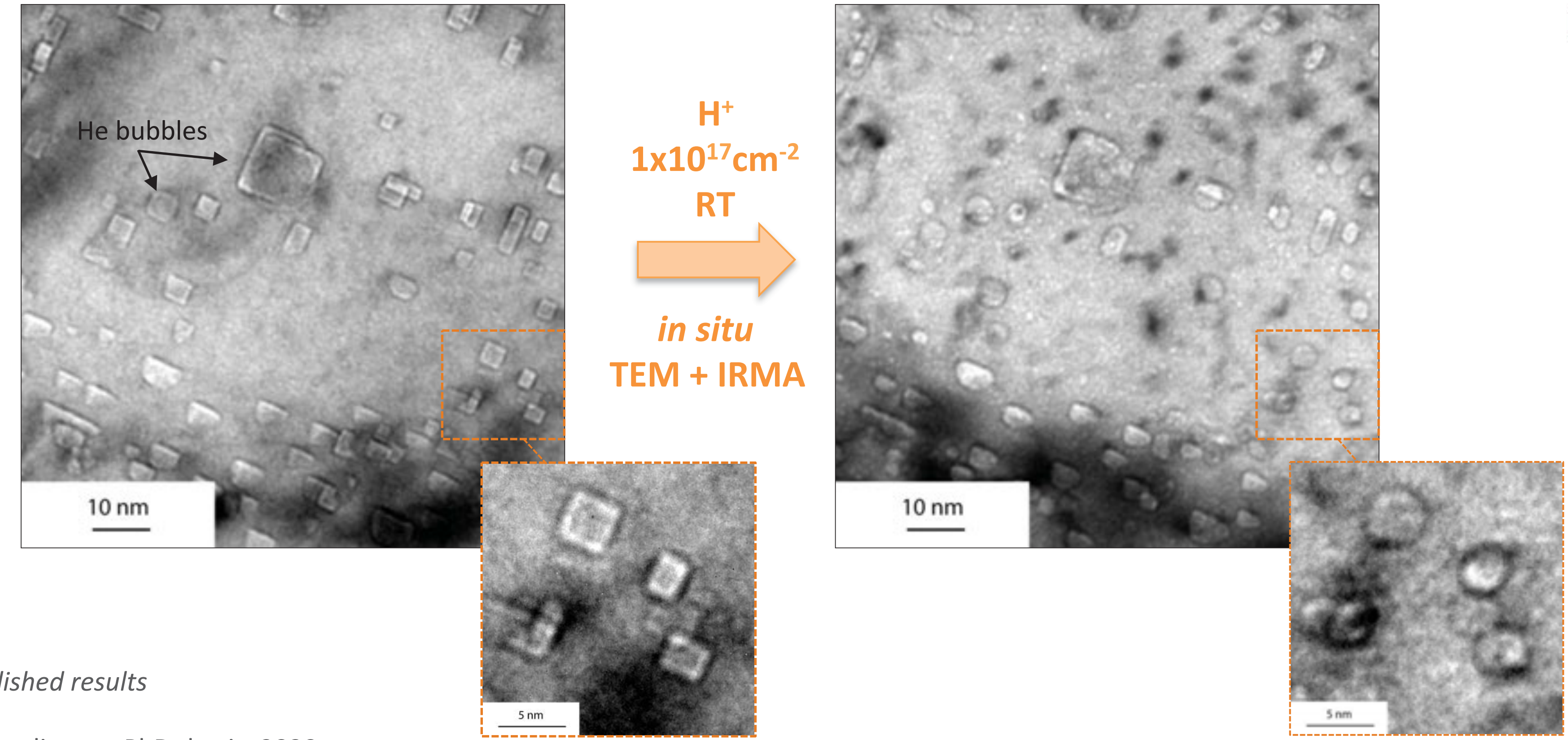
Synergetic effect of He and H gas in ODS FeCr EUROFER steels

Influence of light gas accumulation in Oxide Dispersed Strengthened (ODS) FeCr steels microstructure ?

Application to fusion reactor conditions (He+H)

- ✓ He/H ion implantation results in pronounced evolution of the cavities shape associated with all types of the sinks
- ✓ Possible changes could be associated with H accumulation on the inner surface of the cavities

He^+, 550 °C, up to $1x10^{16} cm^{-2}$ (IRMA)



unpublished results

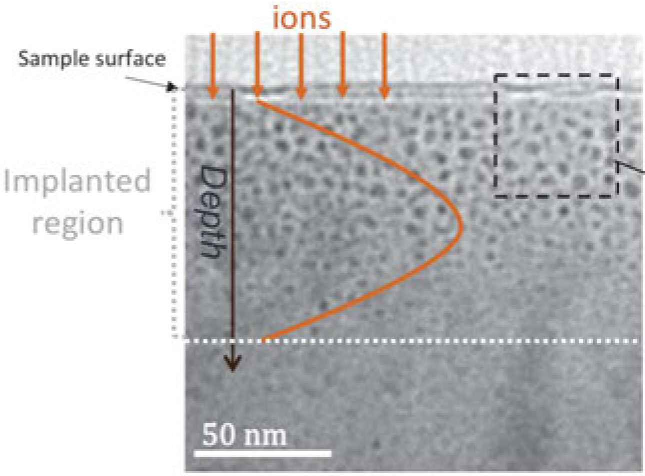
Olga Emelianova PhD thesis, 2020
Université Paris-Saclay / National Research Nuclear University MEPhI
Co-supervision: A. Gentils (IJCLab), M. Ganchenkova and V.A. Borodin (NRNU MEPhI et NRC Kurchatov Inst., Moscow, Russia)
Fundings: NRNU MEPhI, Univ Paris-Sud, AP ODS IN2P3, FR FCM, Renatech

Ion beam synthesis of (Y,Ti) nano-oxides in high purity FeCr

Optimisation of the Oxide Dispersed Strengthened (ODS) steels industrial fabrication
Application to future reactors (Gen IV fission, fusion)

→ Model experiments with high purity Fe-10Cr alloy (size, structure, chemistry of the nano-oxides)
→ Understanding the involved mechanisms on a nanometric scale

Ion implantations (Y, Ti, O…)
ex situ (IRMA)
⇩
Thermal treatments
(*in* or *ex situ*)
⇩
TEM characterization
Any particle ? Size ? Structure ? Composition ?



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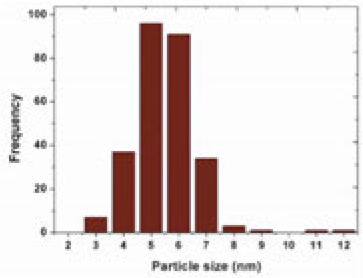
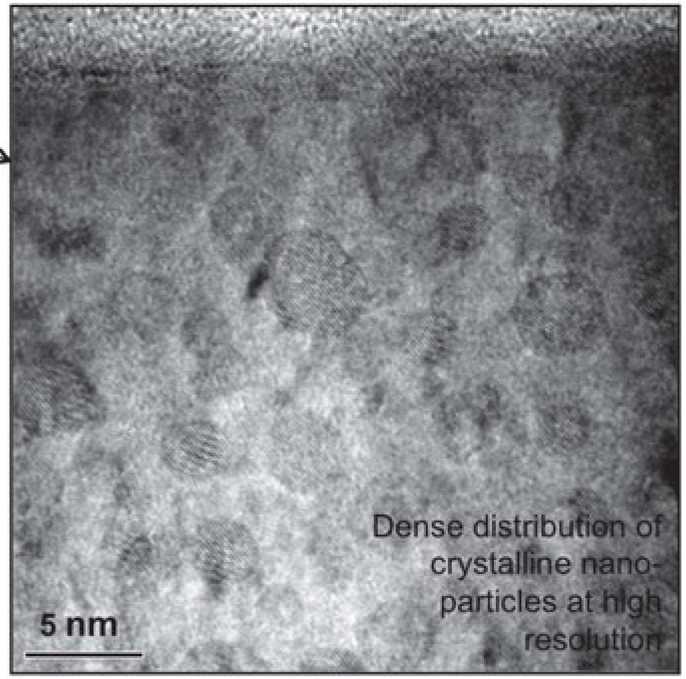




Y + O ions, annealed 1100°C

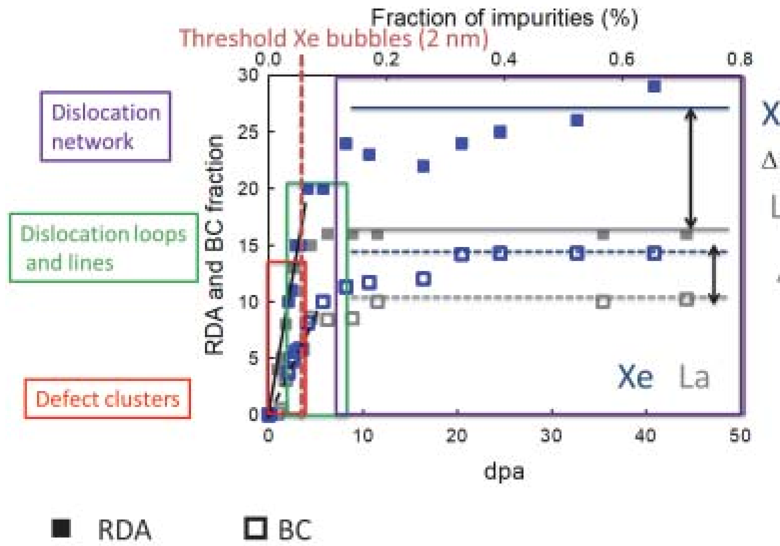
- Average particle size ≈ 6 nm
- Particle density ≈ 10^{23} m^{-3}
- Crystallographic structure (not shown): *fcc* and *bcc* Y_2O_3-type structure

unpublished results

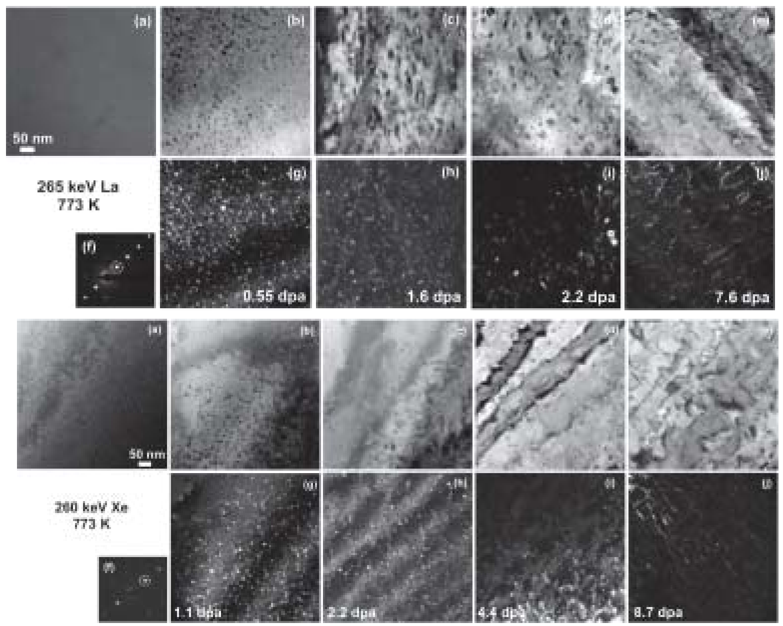
Martin Owusu-Mensah PhD thesis, 2019
Université Paris-Saclay
Co-supervision: A. Gentils and S. Jublot-Leclerc (IJCLab)
Coll. CEA Saclay, IM2NP Marseille, NCSU USA, NRC Kurchatov Inst. Russia
Fundings: Univ Paris-Sud (ED PHENIICS), AP ODS IN2P3, FR FCM, Renatech, METSA

Experimental simulation of High Burnup Structure (HBS) in UO_2

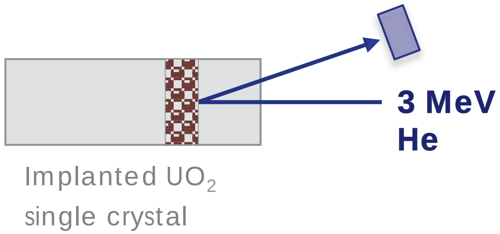
- Formation mechanisms of the HBS at the fuel periphery (high porosity, small grain size; local increase of the Pu content)
- Parametric approach : burnup, T, chemistry of impurities, radiation defects and damage
- UO_2 single crystal as model system
- *In situ* irradiation/RBS-C or TEM at 773 K

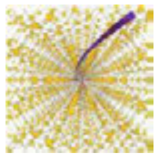


- Two steps in the fuel destabilisation
  - First is ballistic (radiation damage): same dpa for Xe and La, same evolution (clusters, dislocations, network)
  - Second: dramatic role of FP solubility – polygonization induced by nanometer-sized gas bubbles



SCALP





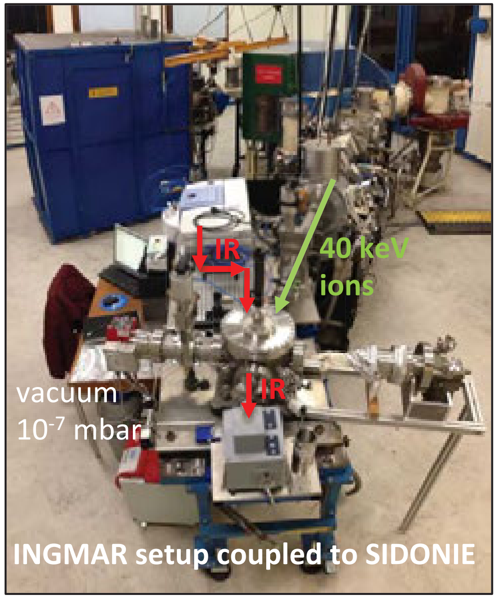
JANNuS

PhD thesis of Yara Haddad (2014-2017) - Supervisor F. Garrido (CSNSM)

Y. Haddad, L. Delauche, A. Gentils, F. Garrido, NIM B 435 (2018)
Y. Haddad, T.H. Nguyen, A. Gentils, L. Nowicki, C. Bachelet, J. Bourçois, S. Picard, S. Resnouf, F. Garrido, to be submitted

Simulating asteroid surface alteration process

INGMAR setup : IrradiatioN de Glaces et Météorites Analysées par Réflectance VIS-IR



Visible et IR in situ spectroscopy
(0.4 – 15 µm, transmission and reflectance)

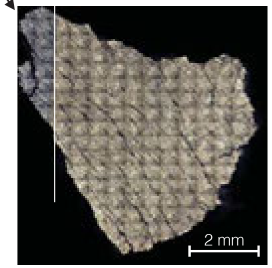
Study of surfaces alteration
from cosmic radiation and/or solar wind
Interpretation of spectra obtained on ground or onboard instruments

Amorphization: modification of the structure of the grains
Radiolysis: variation of the chemical composition
Sputtering: erosion

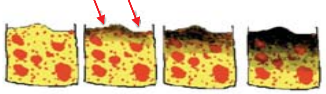
Brunetto et al. 2014 (Icarus)
Lantz et al. 2015 (A&A)
Lantz et al. 2017 (Icarus)
Brunetto et al. 2018 (PSS)
Lantz et al. 2018 (Icarus)

Non irradiated

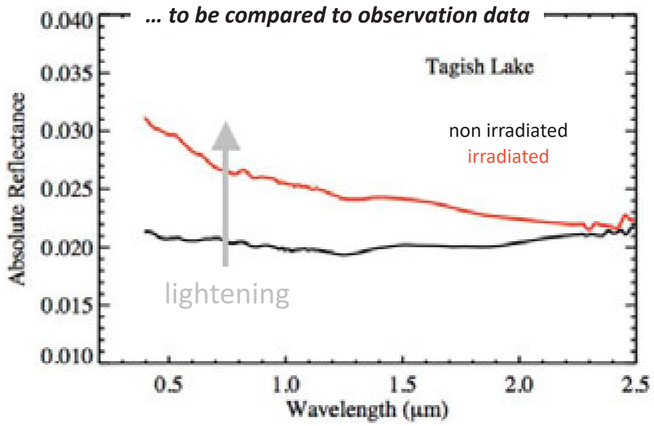
Irradiated
(He^+ 20 keV ; 6 10^6 ions/cm^2)



solar wind ions



Pattern of asteroid surface



Labex P2IO, Univ. Paris-Sud, DIM-ACAV, PNP, ANR, …

Radionuclides production for health physics

PRISM PROJECT
PRODUCTION D'ISOTOPES ET SÉPARATION POUR LE MÉDICAL
ISOTOPE PRODUCTION AND SEPARATION FOR THE MEDICAL SECTOR

Theranostic : One element (same chemistry) …
with at least 2 isotopes (therapy and diagnostic)

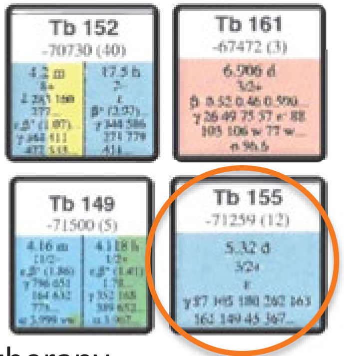
Development of a complementary method to produce pure isotope for the medical sector

The Right Drug to the Right Patient for the Right Disease at the Right Time with the Right Dosage

Pure stable isotope production

« small accelerator » → Transmutation
isotope production with small $T_{1/2}$ → Elimination of potential contaminant (chemical purification)

TEP imaging



β^- therapy

α therapy

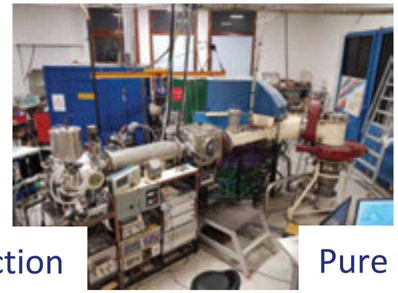
SPECT imaging

$^{155}Gd(p,n)$ ^{155}Tb production at ARRONAX

σ measurement

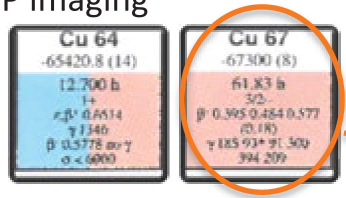
Pure ^{155}Gd production

Proof of concept experiment on SIDONIE



TEP imaging

β^- therapy



radioimmuno therapy

$^{68}Zn(\gamma,p)$ ^{67}Cu production at ALTO

σ measurement

Pure ^{68}Zn production

FIRST RESULT (2019)

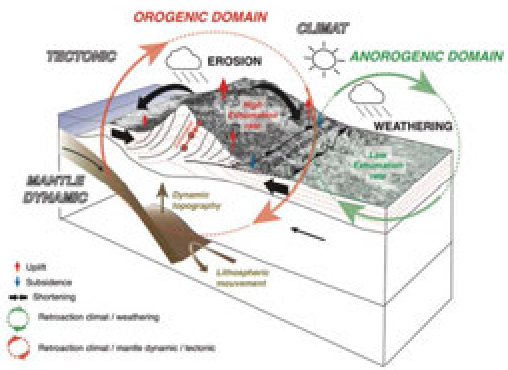
(coll. ARRONAX, ILL) part of K. Kamalakannan M2 internship (2019)
« proof of concept » experiment
^{155}Gd production of $^{155}Gd(p,n)^{155}Tb$ cross section measurement

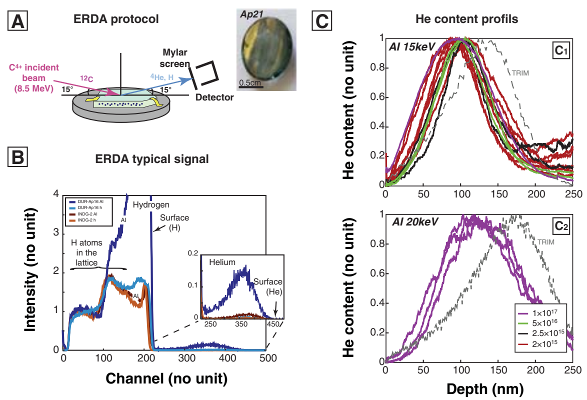
$^{155}Gd^{1+}$ target
3 10^{18} at/cm^2 on 0.95 cm^2
≈ 40 irradiation hours

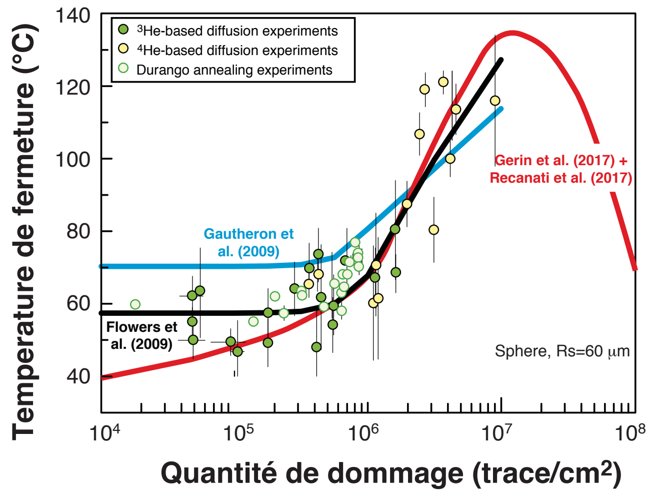
C.O. Bacri *et al.*
coll. with

Helium diffusion in apatite for thermochronology (U-Th)/He

- Method based on the production rate and diffusion of He
- Age measurement based on the accumulation of He during a rock-dependant time-temperature
- Role played by radiation-induced defects on the He diffusion simulated by 20-keV He implantation
- Measurement of He diffusion by ERDA (8.5-MeV C, ARAMIS)





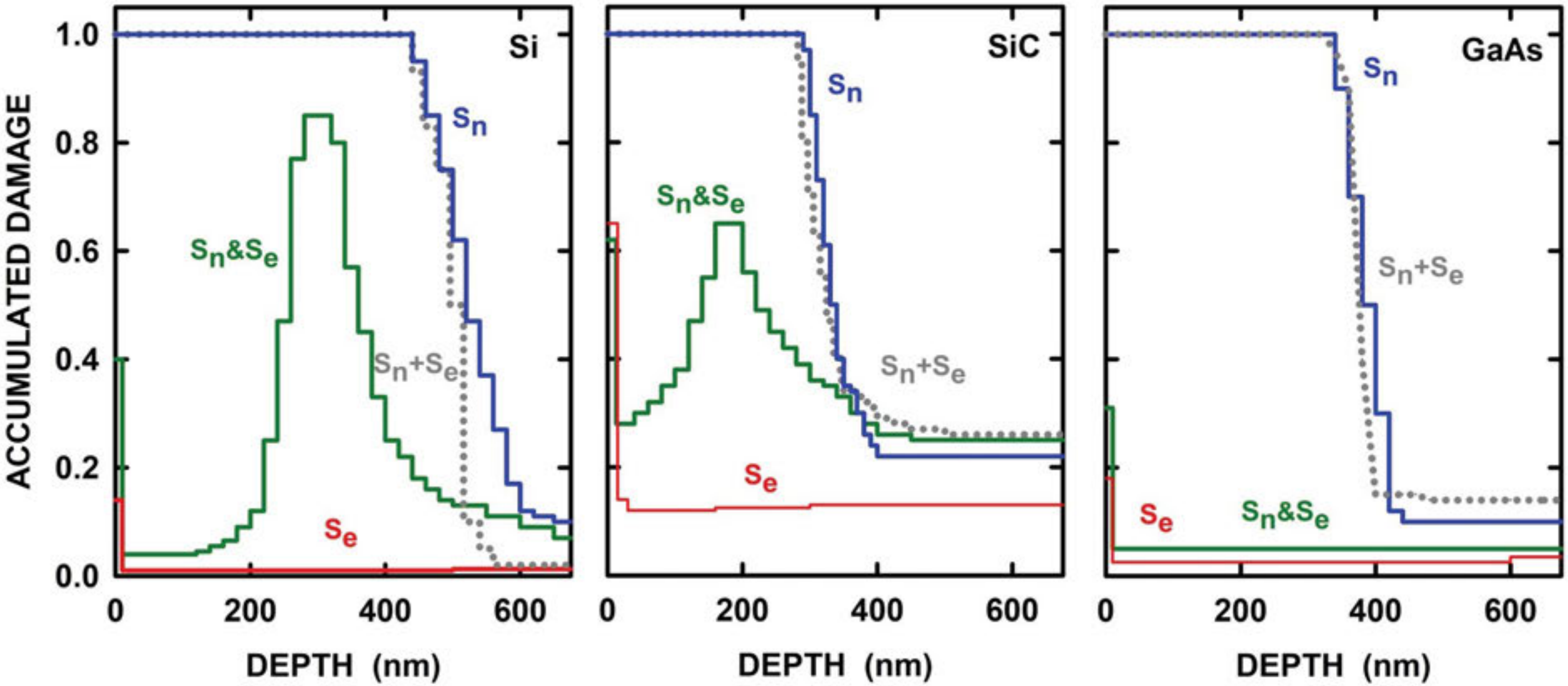


C. Gérin, C. Gautheron, E. Oliviero, C. Bachelet, D. Mbongo Djimbi, A-M. Seydoux-Guillaume, L. Tassan-Got, P. Sarda, J. Roques, F. Garrido, Geochimica et Cosmochimica Acta **197** (2017)

SNEEL – Synergy between Nuclear & Electronic Energy Losses

- Solid irradiated with either single or dual beam
- SNEEL leads to a strong healing by Se of the damage created by Sn
- SNEEL mostly observed in semiconductors but also in MgO, $KTaO_3$
- Important result for applications: synergistic S_n/S_e effects lead to a strong reduction of the damage production in irradiated devices

JANNUS



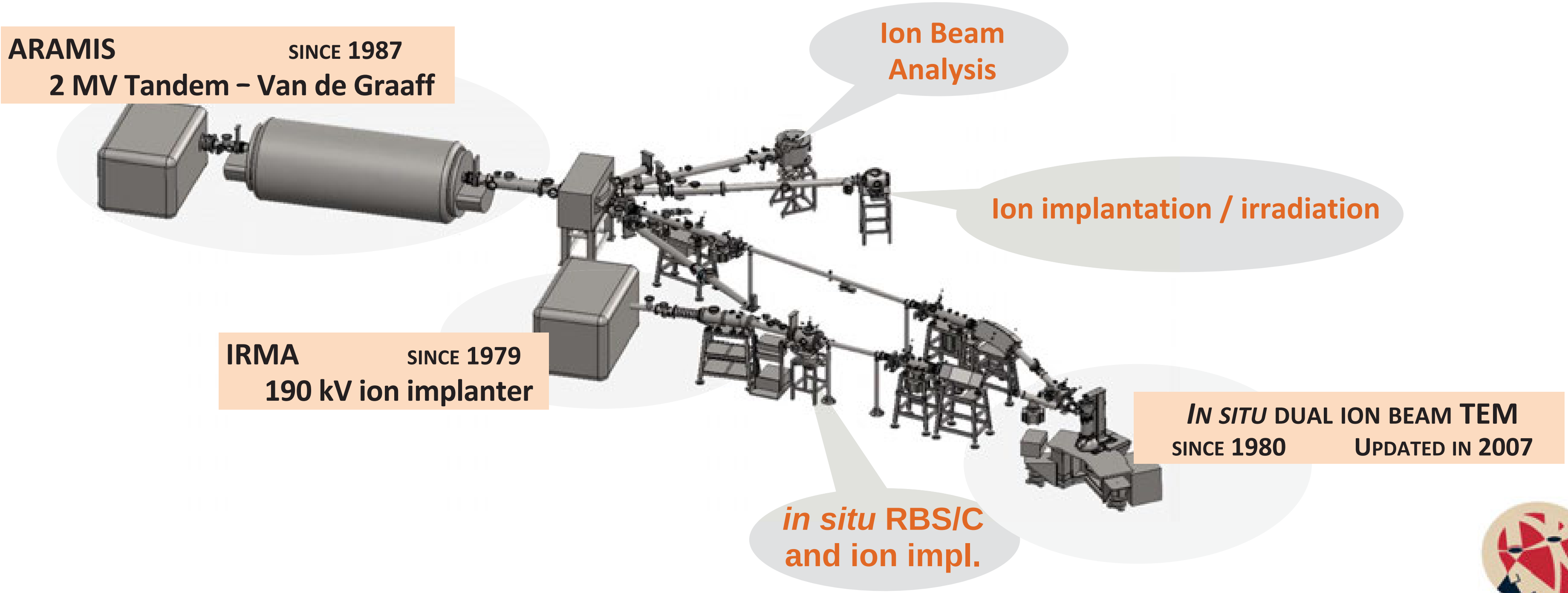
Damage profiles from RBS/C spectra on solids irradiated with either low-energy (S_n), high-energy (S_e) or dual (S_n&S_e) ion beams

L. Thomé, A. Debelle, F. Garrido et al., Appl. Phys. Lett. 102 (2013) ; L. Thomé, G. Velisa, S. Miro, A. Debelle, F. Garrido et al., J. Appl. Phys. 117 (2015)
L. Thomé, G. Gutierrez, I. Monnet, F. Garrido, A. Debelle, J. Mater. Sci. (2020)

Perspectives

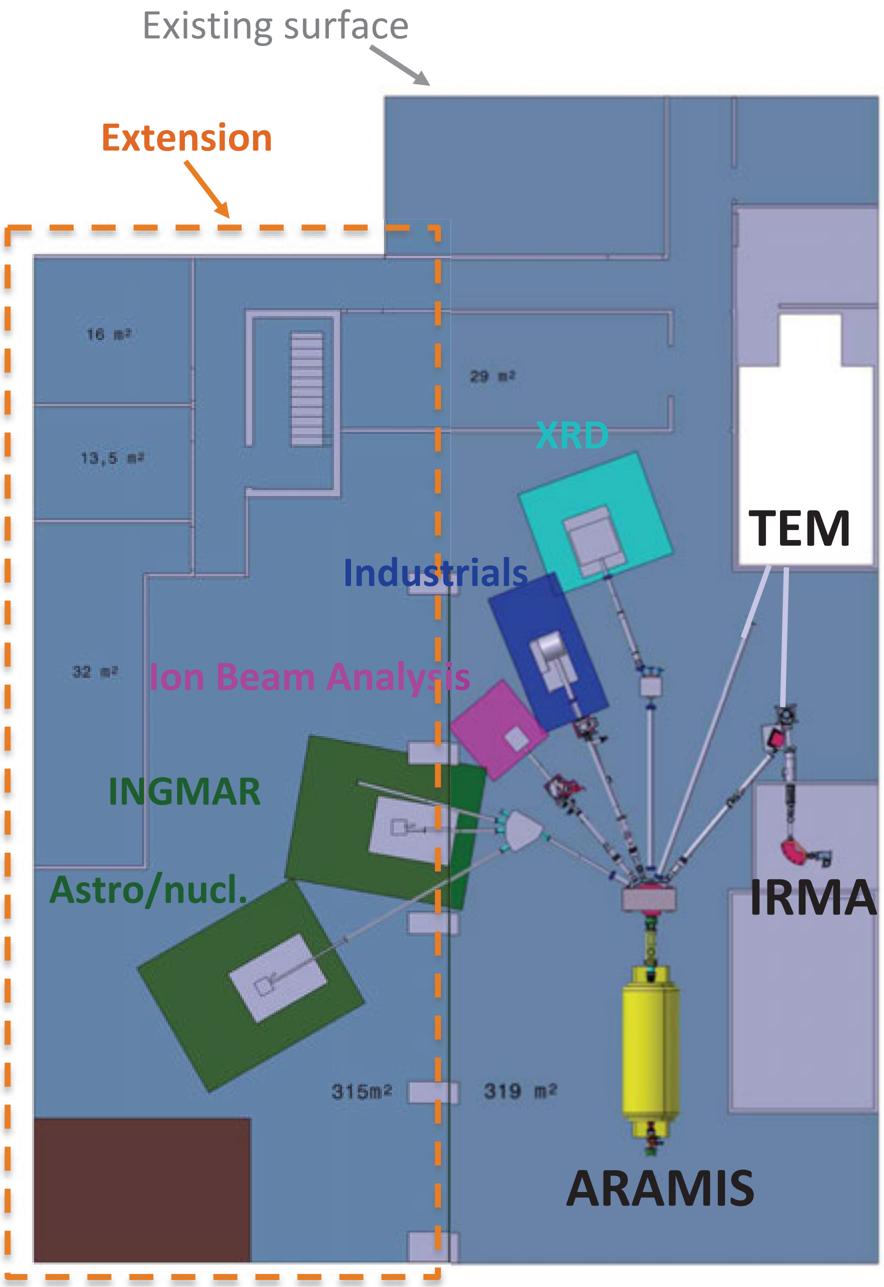
Extension of the experimental hall (ARAMIS-IRMA-TEM)

- ✓ Creation of an *in situ* XRD beam line
- ✓ Need for a new *in situ* TEM



JANNUS

Perspectives – Building extension

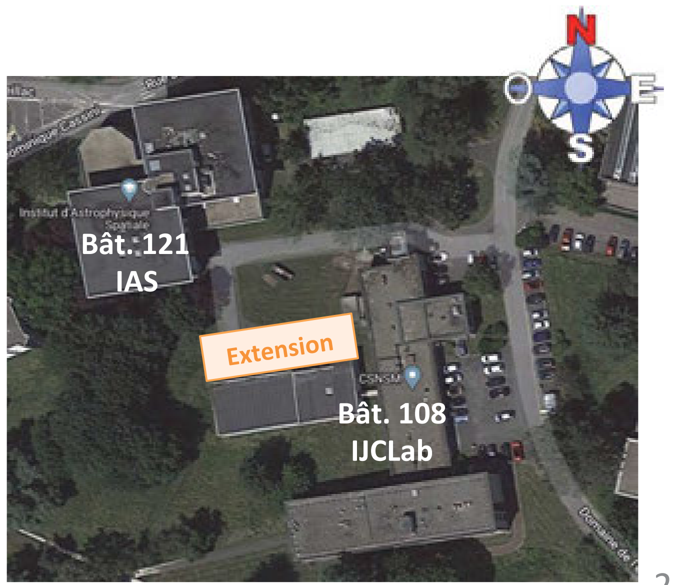


- ✓ **New ion beam lines on ARAMIS**
  - *In situ* X-Ray Diffraction line
  - γ analysis line (astro/nucl. physics)
  - Infra-Red *in situ* Spectrometry (INGMAR setup)
  - …
- ✓ **Practical work** with dedicated beam time and data analysis room (Masters MNE, GI, OSAE, …)
- ✓ **Industrials - Valorization**

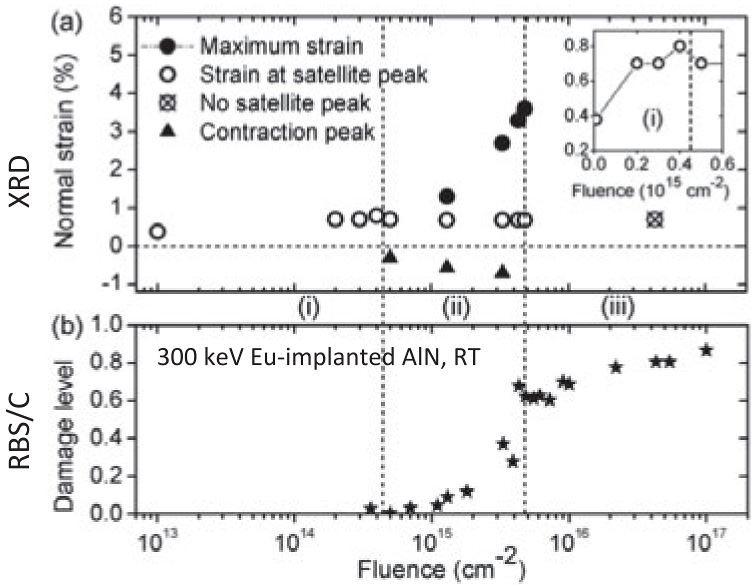
CPER-P2IO

SCALP

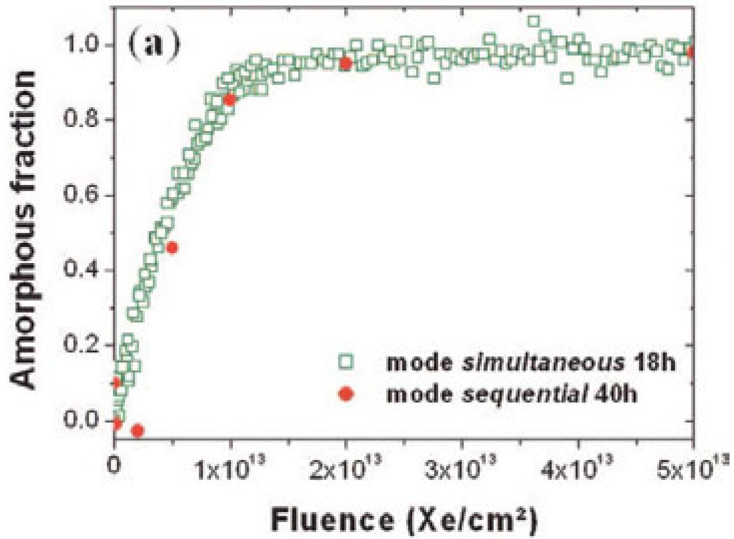
JANNUS



Perspectives – Need for an *in situ* X-Ray Diffraction (XRD) setup



S. Leclerc et al., J. Appl. Phys. ***112*** *(2012) 073525*



C. Grygiel et al., Review of Scientific Instruments ***83*** *(2012) 013902*

Use of X-Ray Diffraction to characterize structural ion-induced modifications

- ✓ Phase transformation (amorphization, …)
- ✓ Elastic strain (sensitivity to point defects)

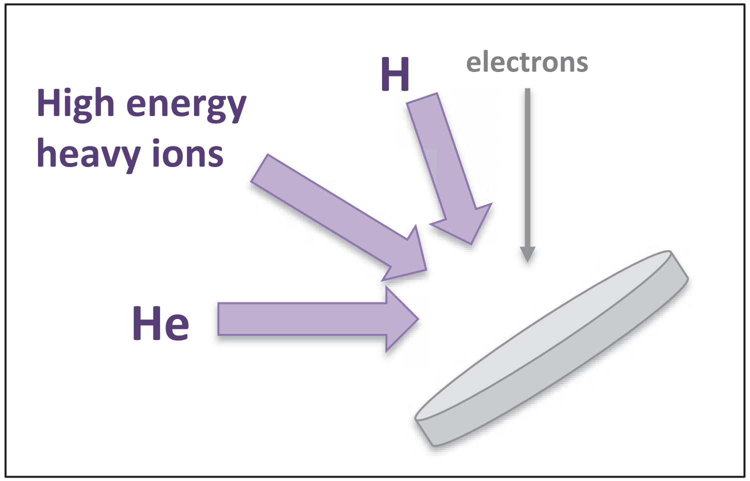
→ *Complementary to TEM and RBS at low damage level*

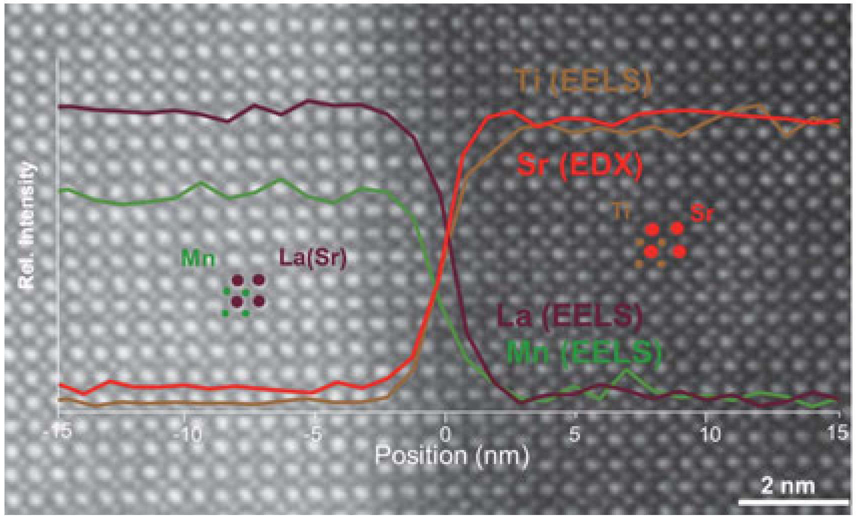
→ *Non destructive method*

In situ **measurement with ion irradiation**

- ✓ Inhomogeneity of the specimens, high cost, low availability
- ✓ Kinetics vs. fluence (more precision)
  - → *More reliability on the interpretation*
- ✓ Kinetics possible at a chosen temperature
- ✓ Time saving

Perspectives – Need for a new *in situ* Transmission Electron Microscope (TEM)





HAADF-STEM image of a $La_{1-x}Sr_xMnO_3/SrTiO_3$ interface with the individual atomic columns well resolved across the interface. Overlaid is an EELS/EDX intensity profile across this interface.
P.M. Leufke and D. Wang et al., Thin solid films 520 (2012) 5521-5527

Synergetic effects → 3 ion beams needed

- ✓ Unique in the world ! (fluence accuracy)
- ✓ Simultaneous observation and irradiation for low energy light ions (not possible today)
- ✓ Materials for fusion (He + H + irradiation)

Higher performances for structural and chemical characterization

- ✓ High resolution (HRTEM) → interfaces and nanostructured materials, precise identification of nanostructures and defects
- ✓ Highly-resolved elemental analysis (STEM-EDX/EELS, STEM-HAADF, ABF-STEM, iDPC, …)

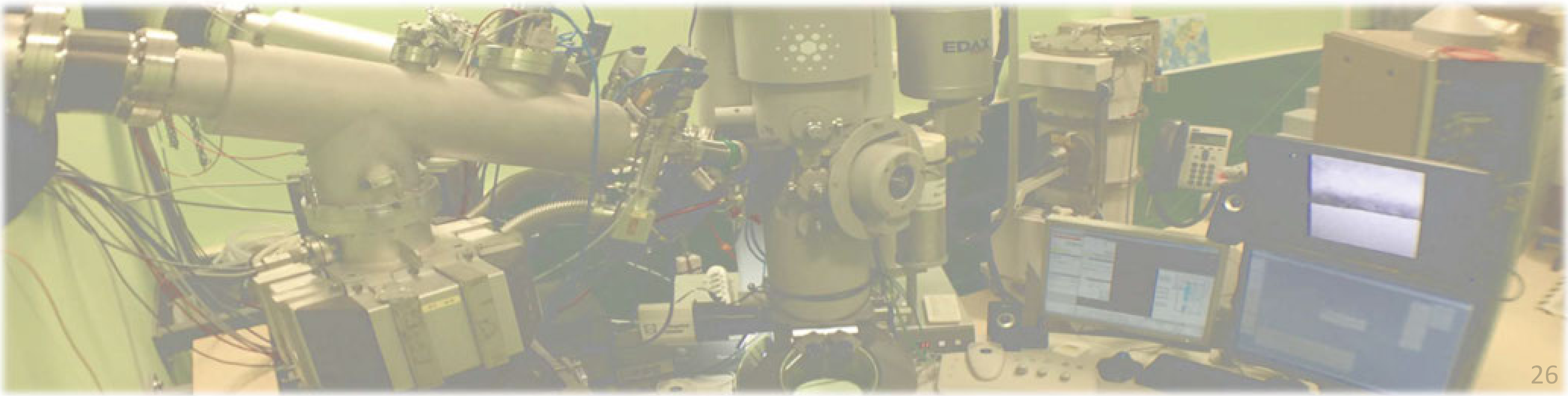
Keep the existing microscope (LaB_6 filament)

- ✓ Ideal for conventional observations and dislocation-like defects imaging (becomes rare)

Perspectives – *equipment needs*

2020-21	2020-2021	2021-22 ?	2021-22 ?	2022-23 ?	202x ?
Building extension work 1,3 M€ (CPER P2IO)	SIDONIE renovation under review @ IJCLab	**New high speed camera** for the TEM access to low doses observations *in situ*	**New ion beam line** for XRD connection	***In situ* XRD** No equivalent in Europe for this ion energy range	**New *in situ* TEM** Keep a state-of-the art equipment

Time →



Acknowledgments

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