Activities on targets fabrication and characterization at IJCLab

Online one-day meeting,
WP 2.5.2 Targets for Nuclear Physics
15 / 05 / 2025

Contact: Aurélie Gentils, aurelie.gentils@ijclab.in2p3.fr
Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France

IJCLab, a new lab since January 1st, 2020

https://www.ijclab.in2p3.fr

Laboratory of the Physics of the two infinities Irène Joliot-Curie

748 Collaborators
- 233 Researchers & Professors
- 344 Engineers & Technicians
- 4 Administrative Division
- 8 Support services
- 171 PhD and Post-docs
- 50 European and International Research Grants
- 150 National and Local Research Grants
- 150 People accredited to supervise PhD
- 600/y Articles in international peer-reviewed journals

7 Scientific Poles
- Accelerators physics
- Astroparticles, astrophysics and Cosmology
- **Energy and Environment**
- High energy physics
- Health physics
- Nuclear physics
- Theory

1 Engineering Pole

4 Research Platforms
- **ALTO**
- **MOSAIC**
- LaseriX
- Supratech

Targets fabrication and/or characterization

Fusion of 5 physics laboratories of the Orsay valley: CSNSM, IPNO, IMNC, LAL, LPT

Outline

- Targets fabrication at IJCLab
  - Targets fabricated by electrodeposition (at Energy and environment department)
  - Thin layers targets (at ALTO facility)
  - UC_x ISOL targets (at ALTO facility)
  - Deposition using *Sidonie* isotope separator (at MOSAIC facility)

- Targets characterization at IJCLab
  - Optical microscopy
  - Scanning Electron Microscopy, coupled to EDS
  - (Transmission Electron Microscopy)
  - Ion Beam Analysis (RBS, ERDA, PIXE, …)
  - X-Ray Diffraction
  - B.E.T theory
  - Pycnometry He
  - Porosimetry Hg

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Preparation of targets by electrodeposition

Technique:

Electroprecipitation in organic solvent (generally isobutanol) containing a fraction of water

→ Preparation of targets under hydroxide or oxide form but not metallic form

^{240}Pu target on C substrate (100 µg/cm^2)
for CENBG – LP2I, April 2017
Phys. Rev. Lett. **125** (2020) 122502

E&E Energie & Environnement Energy & Environment

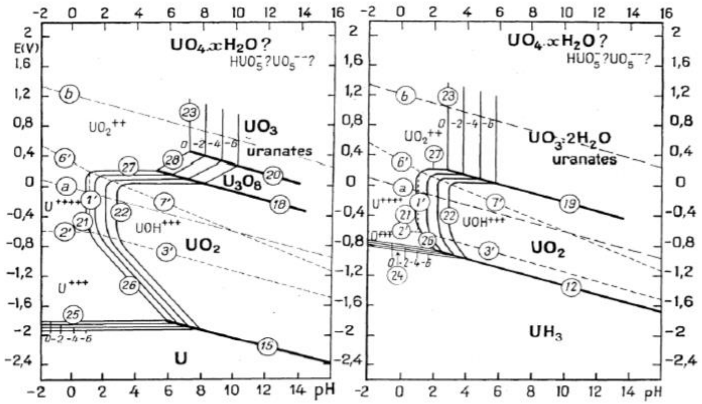
Contact : Céline Cannes
celine.cannes@ijclab.in2p3.fr

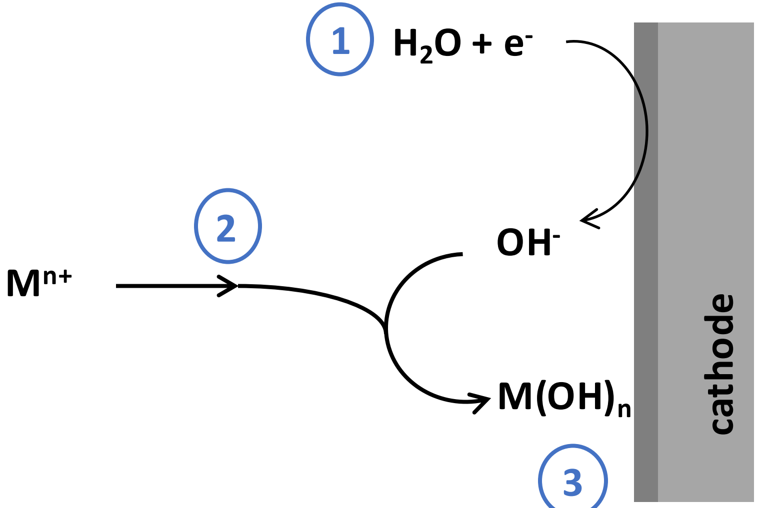
Targets fabrication are not
the topic of the research team
Collaboration possible from time
to time, to be discussed ;-)

^{235}U target on Be substrate (25 µm)
March 2023, IJCLab
Corentin Hiver PhD thesis, Université Paris-Saclay

Principle of electroprecipitation

Pourbaix diagram (potential-pH diagram in aqueous solution) calculated for uranium
from Deltombe, E., de Zoubov, N., Pourbaix, M. , Atlas d'Equilibres Electrochimiques, ed. M. Pourbaix, 256 (1963)



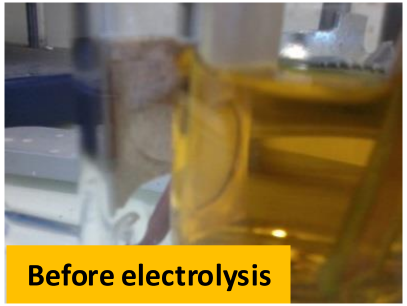


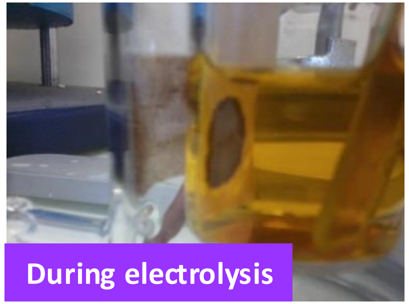
target

1. Reduction of water:

$$2H_2O + 2e \longrightarrow H_2 (g) + 2OH^-$$

Modification of pH at the substrate surface





Blue of bromophénol : yellow at acid pH and purple at basic pH

2. Diffusion of the element at the cathode

3. Formation of hydroxides and precipitation at the substrate surface:

$$M^{n+} + n\,OH^- \longrightarrow M(OH)_n$$

Experimental conditions of the electroprecipitation

High voltage generator
ΔE : 100 à 1000 V
or I : 1 à 10 mA/cm^2

2 electrodes set-up:

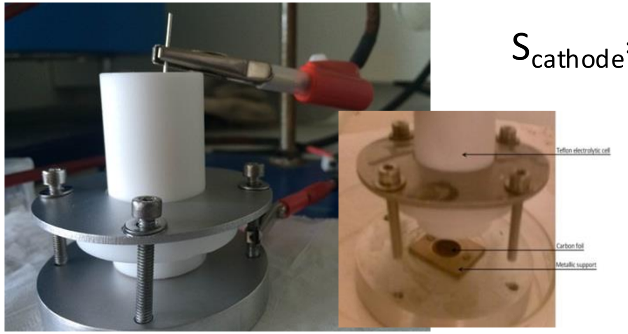
Cathode: Target substrate (Al, C, Ti)

Anode: inert metal (Pt)

Electrolyte :

Element (M^{n+}) of the target in isobutanol + H_2O or HNO_3

2 types of electrodeposition cell



$S_{cathode}$=0.95 cm^2

$S_{cathode}$=10 cm^2

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ALTO
Accélérateur Linéaire et Tandem à Orsay

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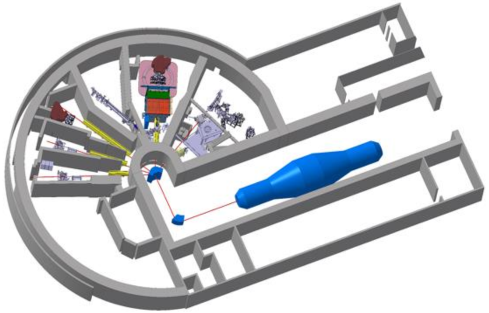
Targets and thin films development at ALTO



alto.ijclab.in2p3.fr

The target laboratory of ALTO provides thin targets and thin films for academic experiments and industrials clients. Every year 150 targets and 50 thin films are built at ALTO not only for experiments performed at ALTO but also in French, European and world wide facilities. About 50% of this production is done for industrial clients in France, Europe and other countries in the world.

Emmanuel Blanc is the responsible of the ALTO target Laboratory. Abdelhakim Said is the ALTO technical director and Enrique Minaya Ramirez is the ALTO Scientific Coordinator.

For all inquiries related to target production and thin films, please contact us at **altoprestations@ijclab.in2p3.fr**

Targets and thin films development at ALTO

- The ALTO target laboratory is able to provide thin films with a support (target) or without a support.
- The targets, filters and deposits range from a few µg to several mg.
- Many devices allow evaporating most of natural and isotopic materials.

The manufacture of thin-film targets and filters is based on the following three techniques :

Electron gun

For all type of materials and large targets (above 400 mm)

Electronic bombardment

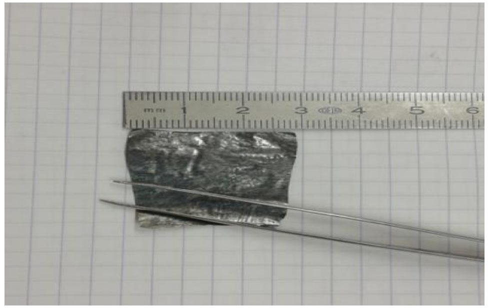
For rare isotopic materials from 100 µg/cm² to 1 mg/cm²

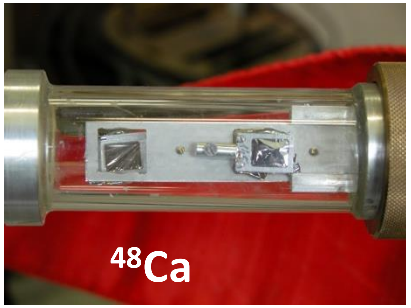
Joule heating effect

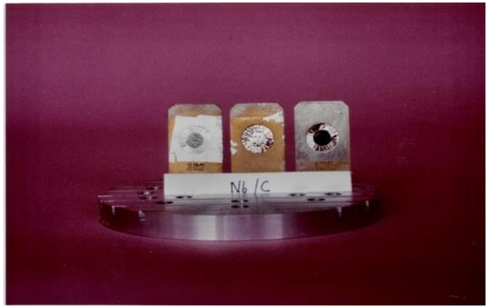
For all type of materials

Targets and thin films development at ALTO

Natural products (such as : Ag, Au, Al, C, Cu, Si...) or enriched products (such as : Ca, Ge, Mg, Ni, Sn...) can be used with this three techniques.



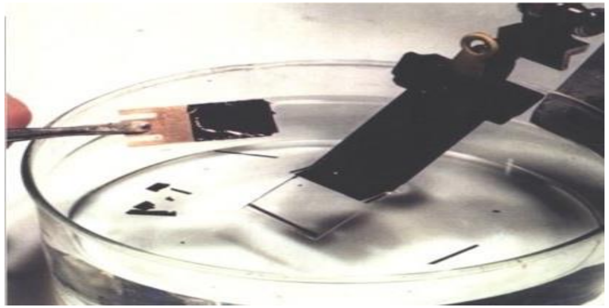




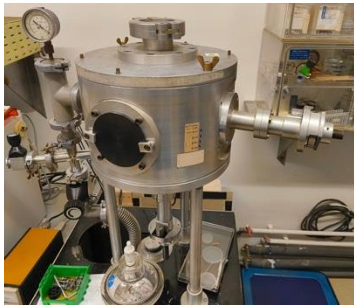
Different tools to characterise the target thin films

Rolling mill

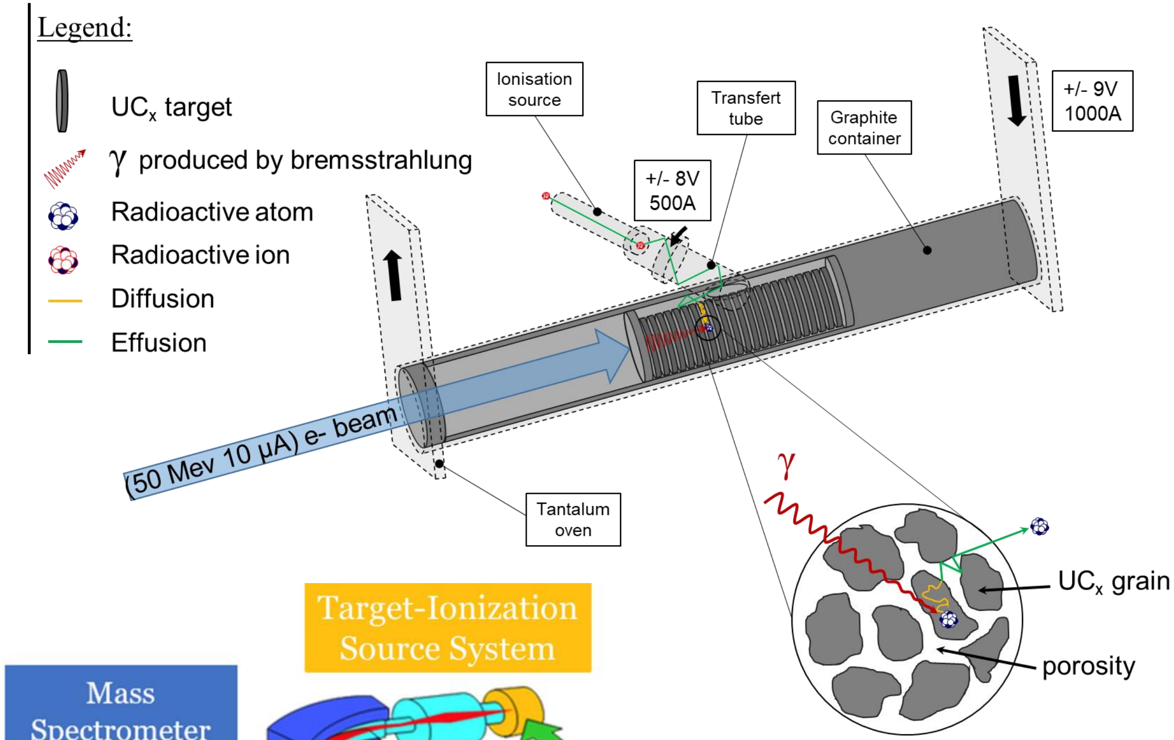
Lift-off thin films

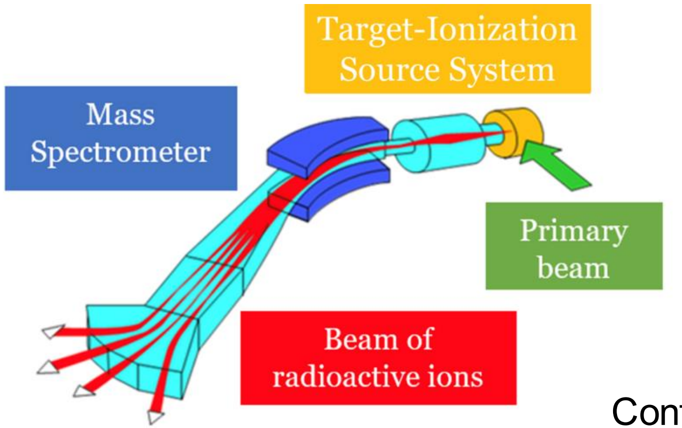


Thickness determination by α particle



Several targets were prepared for the ν-Ball2 campaign experiments at ALTO between April 2022 and June 2023





The production of radioactive ion beams is done by ISOL technique. The intensity "I" of the particle beam is given by the following expression:

$$I = I_P.\sigma.N.\varepsilon_r.\varepsilon_{ion}.\varepsilon_{tr}$$

- $\mathbf{I_p}$, intensity of primary beam
- $\boldsymbol{\sigma}$, cross section
- **N**, number of target atoms
- $\boldsymbol{\varepsilon_r}$, $\boldsymbol{\varepsilon_{ion}}$, $\boldsymbol{\varepsilon_{tr}}$, efficiencies respectively of release, ionization and transport

The **main factors** on the study of UC_x is $\boldsymbol{\varepsilon_r}$ controlled by diffusion and effusion in the material:

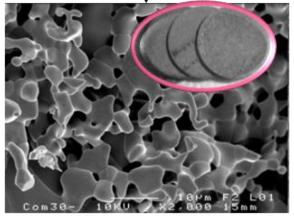
$$\varepsilon_{release} = \varepsilon_{(diffusion+effusion)}$$

Contacts at ALTO: Enrique Minaya Ramirez (Scientific Coordinator), Julien Guillot (Target R&D)

How to build a target ? Which characterization?

- **Synthesis of UC_x target:** $UO_2 + 6C \rightarrow (1-x)UC + xUC_2 + (3-x)C + 2CO_{(g)}$

Mixing of uranium and carbon precursor powders → Pressing ~ 220 MPa → Green Pellet → Carburization : 1800°C at 10^{-3} Pa → Carburized Pellet



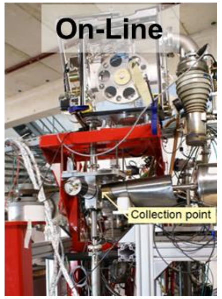
10 µm UC_x target

- **Techniques used for the physico-chemical characterization of UC_x targets :**

XRD | SEM | BET | He Pycnometry | Hg Porosimetry

- XRD: Analysis of phases
- SEM, BET: Grain and aggregate size
- He Pycnometry, Hg Porosimetry: Proportion and distribution of porosities

- **Equipment for measuring released fractions (off-line) and production (on-line) :**



https://alto.ijclab.in2p3.fr/installation/alto-leb/cibles/

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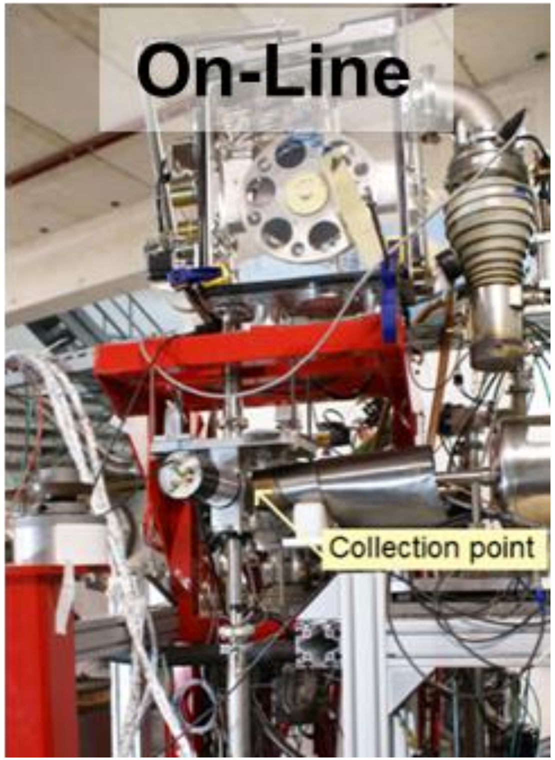
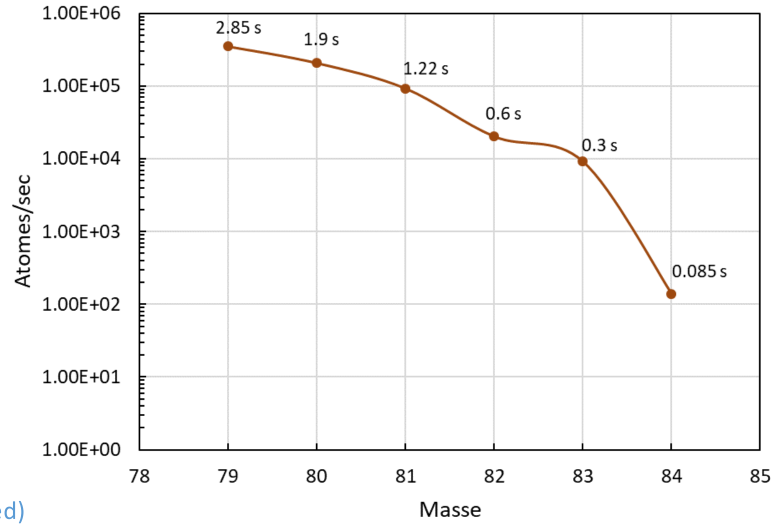


At ALTO, targets are irradiated with an electron beam to produce radioactive isotopes. After mass separation, the selected isotopes are collected on a decay station, where their activity is measured using a germanium detector. This allows us to quantify how much of each isotope is produced.

As an example, the production curve of gallium isotopes obtained during the 2023 irradiation campaign at ALTO:



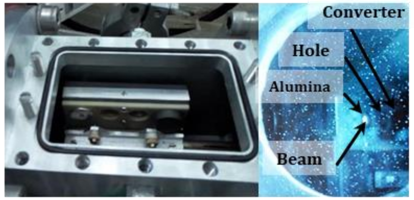
A. Segovia Miranda *et al.* Nuclear Instruments and Methods in Physics Research A (Submitted)
https://alto.ijclab.in2p3.fr/installation/alto-leb/production/

Setups for Measuring Release and Production Yields

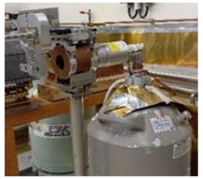
- **Equipment for measuring production (on-line) and released fractions (off-line) :**

off-Line method:

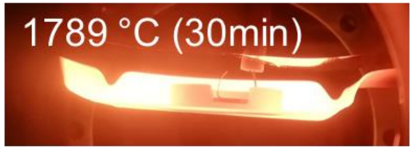
Irradiation:



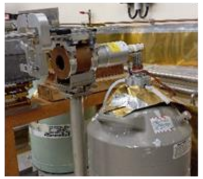
1st measurement :



Heating:



2nd measurement :



Irradiation conditions :

- Beam ^{2}H
- Energy 26 MeV
- Intensity 20 nA
- Time of irradiation 20 min

$$R = \frac{I_{P1}}{I_{P2}}$$

Temperature controlled by thermocouple

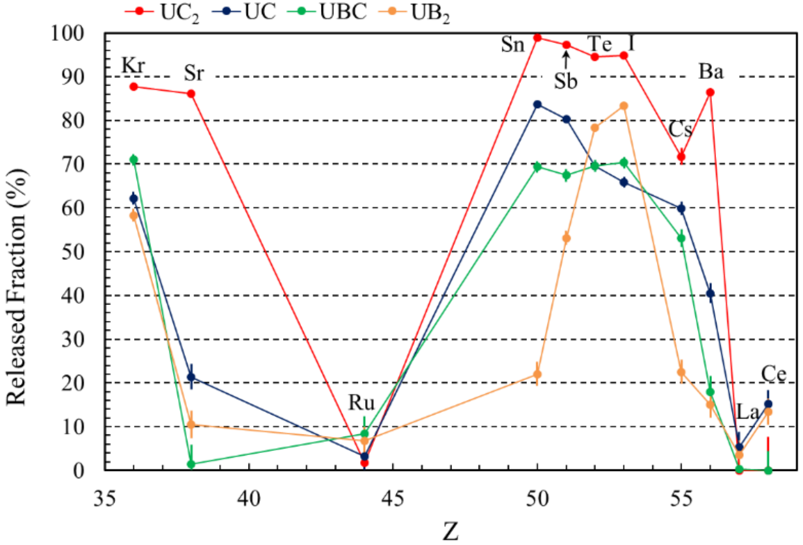
$$RF = 100\left(1 - \frac{I_{heated}}{I_{unheated}}\right)$$

$$\text{with } I_{unheated} = I'_{P2} \times R$$

$$\text{and } I_{heated} = I'_{P1}$$

We study how isotopes escape from the target material by irradiating small samples and measuring what comes out. This helps us understand how well the material releases useful isotopes.

Here is an example of a release fraction measurement performed in 2023, where the release of 11 elements was studied to investigate the impact of UC_2, UC, UBC, and UB_2 target compositions on the release of fission products.



Hy *et al.* Nuclear Instruments and Methods in Physics Research B 288 (2012) 34-41
J. Guillot *et al.* Nuclear Instruments and Methods in Physics Research B 559 (2025) 165600

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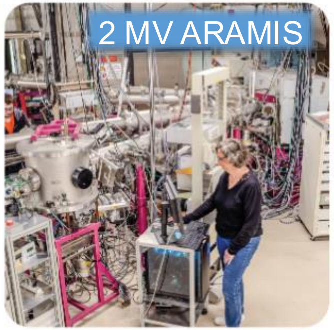
MOSAIC, a multidisciplinary platform with complementary equipment

Ion beams for …



… synthesis, modification, and analysis of materials,

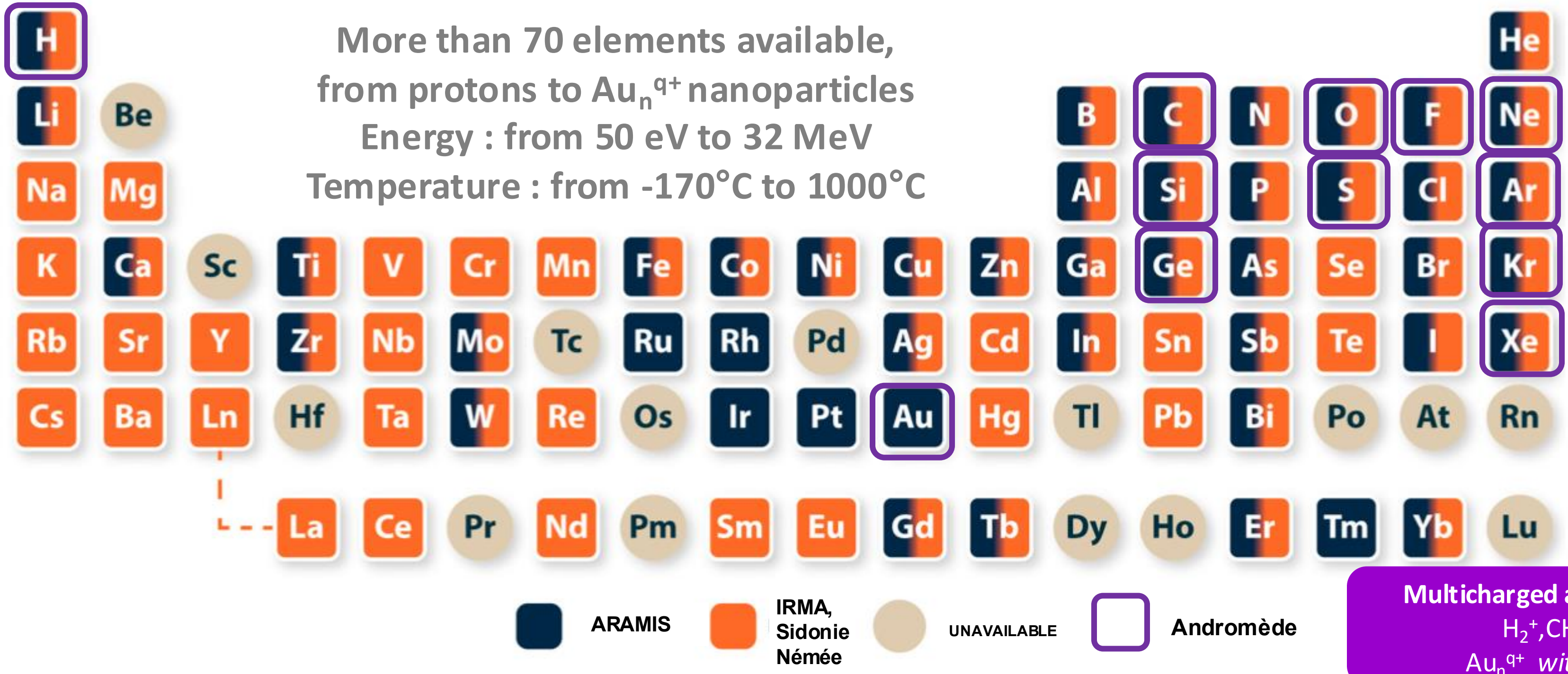
Facility open to
industrials
academics
students

… and ion-matter interactions studies

A large variety of elements available

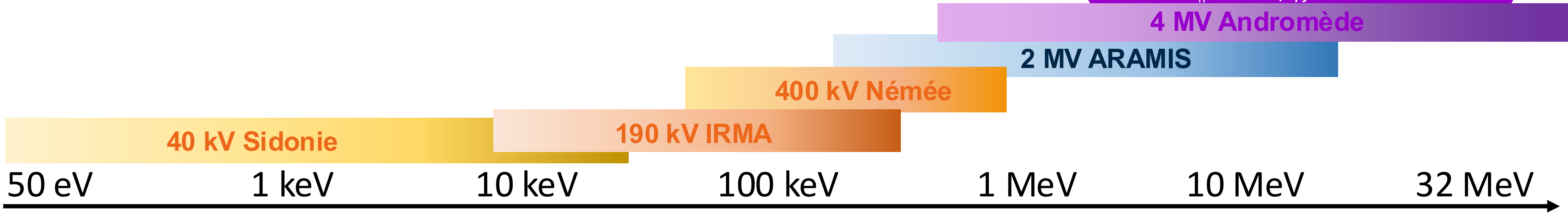
mosaic

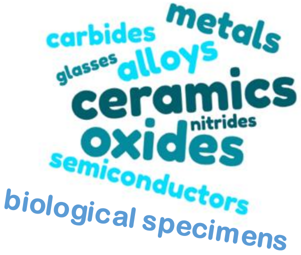
More than 70 elements available,
from protons to Au_n^{q+} nanoparticles
Energy : from 50 eV to 32 MeV
Temperature : from -170°C to 1000°C



Complementary ion sources

Multicharged atomic and molecular ions
H_2^+, CH_n^{q+}, $C_2H_5^+$, SFn^+, …
Au_n^{q+} *with n/q from 1 to 1600*





Deposition
High purity isotope deposition (eV)

Doping
Stable elements
Ion beam synthesis

Solid

Irradiation
Low energy ions (KeV)
'High' energy ions (MeV)

Ion-matter interactions
Nuclear reactions

Elemental and molecular composition, evolution of the microstructural modifications at the nanoscale

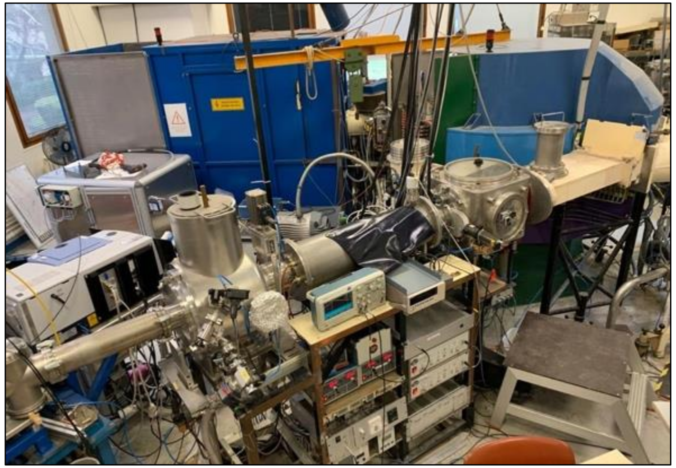
Characterization (*ex* & *in situ*)
Ion Beam Analysis (RBS, channelling, ERDA, PIXE)
In situ RBS-C (with implantation)
Transmission Electron Microscopy (TEM)
In situ TEM (single/dual ion beam)
Mass spectrometry analysis (ToF-SIMS with MeV gold nanoparticles)
Surface analysis (SEM, AFM) & sample preparation

mosaic
ion beam facility
https://mosaic.ijclab.in2p3.fr

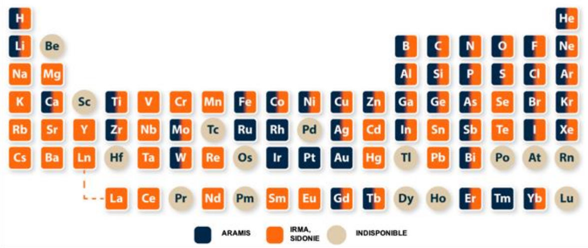
SIDONIE **SINCE 1967**
40 kV isotope separator
up to 20 mA, M/ΔM>1800

Isotopic Purity > 99,8 %

J. Camplan et al., NIM 84 (1970) 37
K. Alexandre et al., NIM 84 (1970) 45
N. Chauvin et al., NIM A521 (2004) 149



Energy between 50 eV→ 40 keV

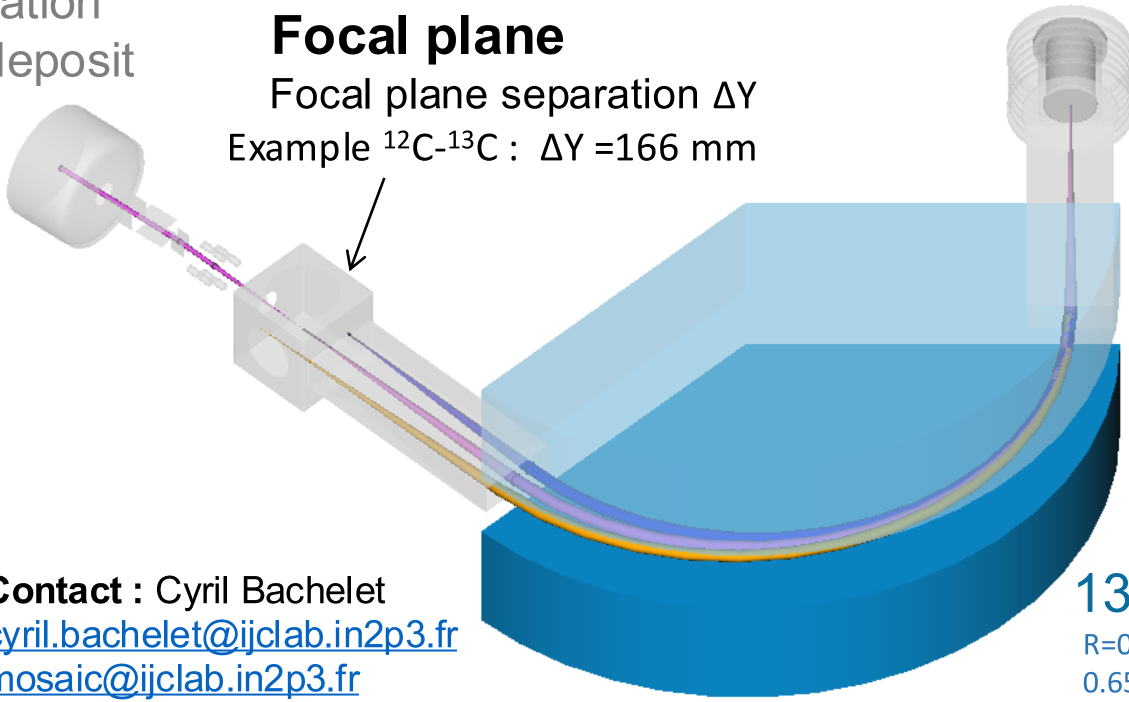


Bernas ion source

10 kV→ 40 kV

Deceleration for ion deposit

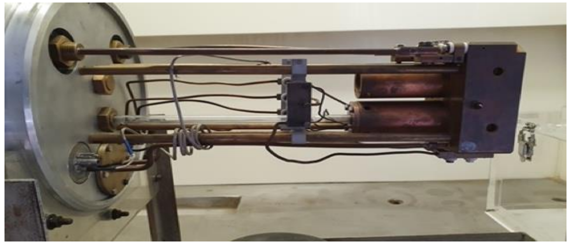
Focal plane
Focal plane separation ΔY
Example ^{12}C-^{13}C : ΔY =166 mm



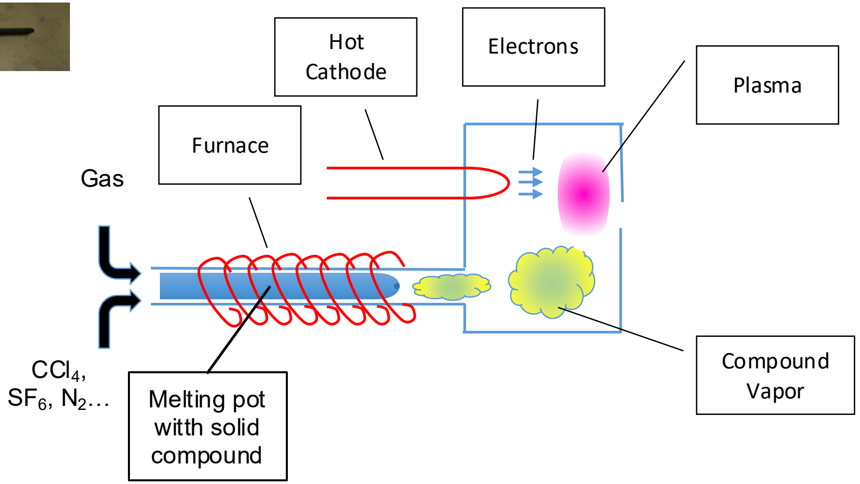
135° magnet
R=0.85m
0.65 T Max

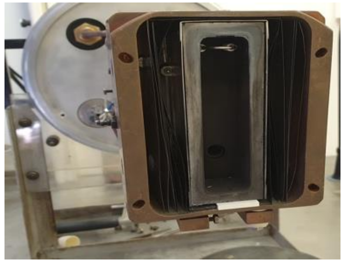
Contact : Cyril Bachelet
cyril.bachelet@ijclab.in2p3.fr
mosaic@ijclab.in2p3.fr

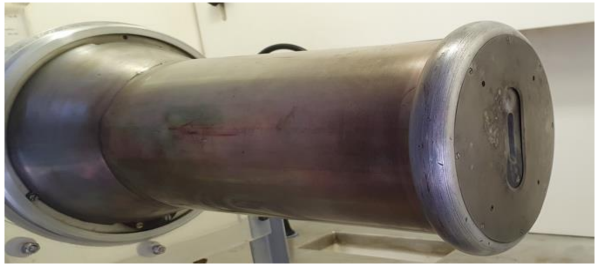
Bernas ion source



35 cm length





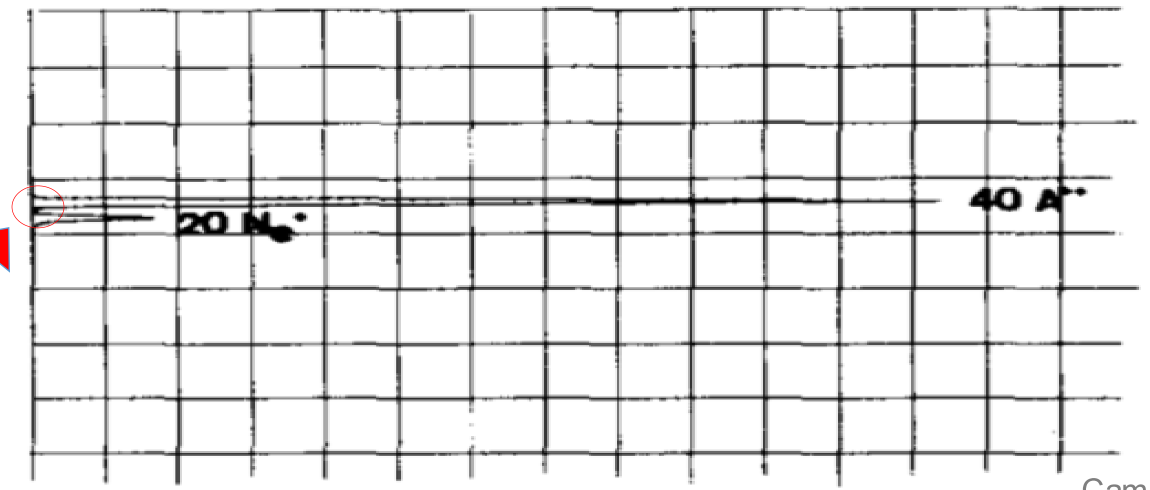


- Charge state up to 3+

- Gas: use of a pure element or a compound bottle + eventually another gas to enhance electrons density

- Solid: use the pure element or compound depending of the melting temperature 400°C $\lesssim$ T $\lesssim$ 1200°C + eventually a corrosive gas if melting point too high

Best separation with Sidonie



Important details !

Camplan *et al.*, *NIM* ***84*** *(1970) 37-44*

$^{20}Ne^{+}$ M/q=19,99244 AMU/e - $^{40}Ar^{2+}$ M/q = 19,98119 AMU/e

ΔM/q= 1.1E-2 AMU/e ➟ R>1800

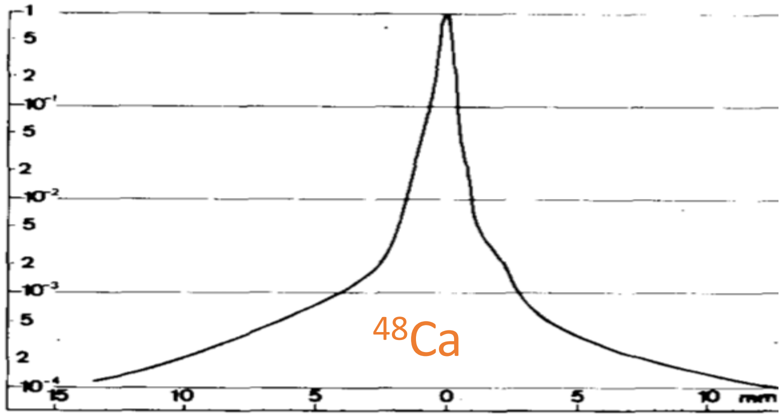
Separation and pollution at Sidonie in the ^{48}Ca case

^{46}Ca is the closer natural isotope to ^{48}Ca

$\Delta Y(^{46}Ca-^{48}Ca) \simeq 70mm$

^{46}Ca somewhere far away

Relative Intensity

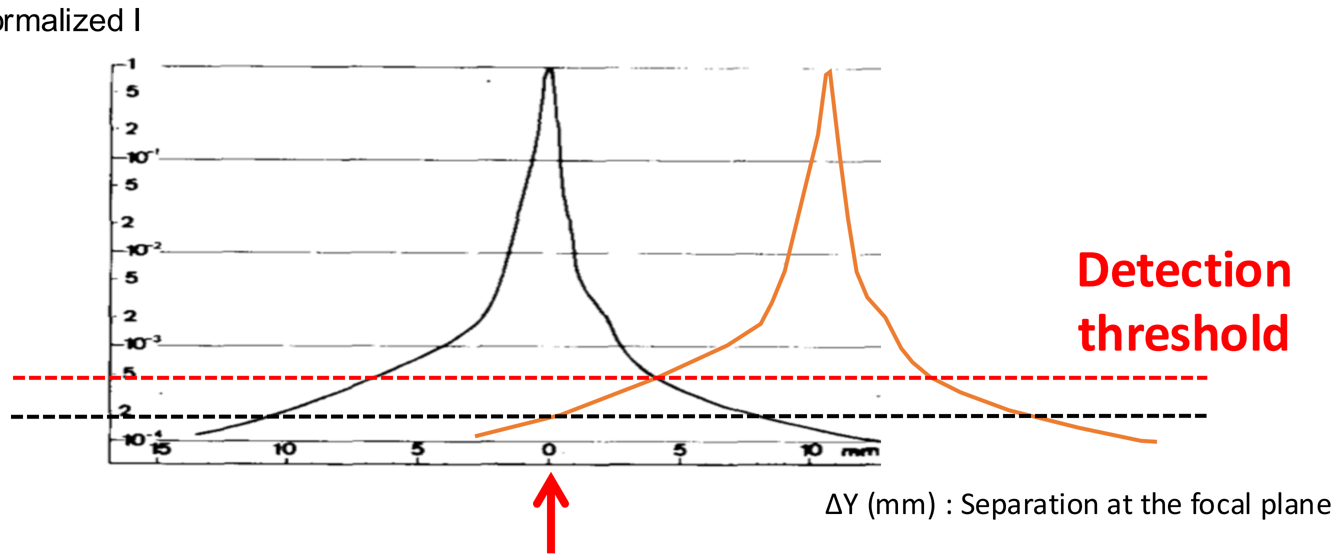


Camplan *et al.*, *NIM* ***84*** *(1970) 37-44*

^{46}Ca contamination should be << 10^{-4} * abundance ratio (0.004/0.187)

Separation and pollution in ^{155}Gd Case

$\Delta Y(^{155}Gd-^{156}Gd) = 11mm$



Camplan *et al.*, *NIM* ***84*** *(1970) 37-44*

^{156}Gd contamination should be << $1.5x10^{-4}$ * abundance ratio (^{156}Gd/^{155}Gd)

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ALTO
Accélérateur Linéaire et Tandem à Orsay

mosaic

E&E Energie & Environnement
Energy & Environment

Characterization of targets - overview

- Optical microscopy
- Atomic Force Microscopy → topography
- Scanning Electron Microscopy, coupled to EDS → surface and elemental composition
- (Transmission Electron Microscopy) → defects at the nanoscale, elemental composition, …
- Ion Beam Analysis (RBS, ERDA, PIXE, …) → layer thickness, elemental composition, …
- X-Ray Diffraction → amorphous/crystalline phases, crystallographic structure
- B.E.T theory → grain size
- Pycnometry He → proportion of porosities
- Porosimetry Hg → distribution size of open porosity
- …

available mainly at mosaic and ALTO (Accélérateur Linéaire et Tandem à Orsay) facilities

Contacts : MOSAIC: Cyril Bachelet / Cédric Baumier / Florian Pallier / Aurélie Gentils (mosaic@ijclab.in2p3.fr)
ALTO : Julien Guillot julien.guillot@ijclab.in2p3.fr, Enrique Minaya Ramirez

Characterization of targets - overview

- Optical microscopy
- Atomic Force Microscopy → topography
- **Scanning Electron Microscopy, coupled to EDS** → surface and elemental composition
- (Transmission Electron Microscopy) → defects at the nanoscale, elemental composition, …
- **Ion Beam Analysis (RBS, ERDA, PIXE, …)** → layer thickness, elemental composition, …
- X-Ray Diffraction → amorphous/crystalline phases, crystallographic structure
- B.E.T theory → grain size
- Pycnometry He → proportion of porosities
- Porosimetry Hg → distribution size of open porosity
- …

Examples

available mainly at mosaic and ALTO (Accélérateur Linéaire et Tandem à Orsay) facilities

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The JANNuS-Orsay experimental hall at MOSAIC facility

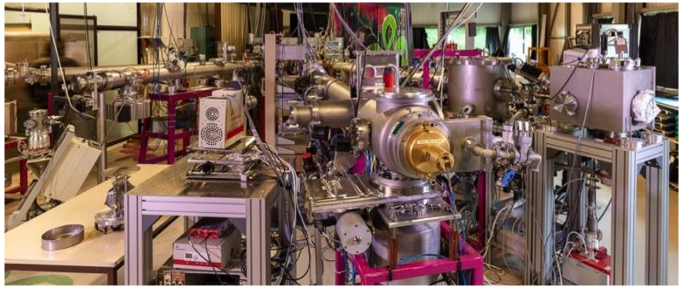
mosaic

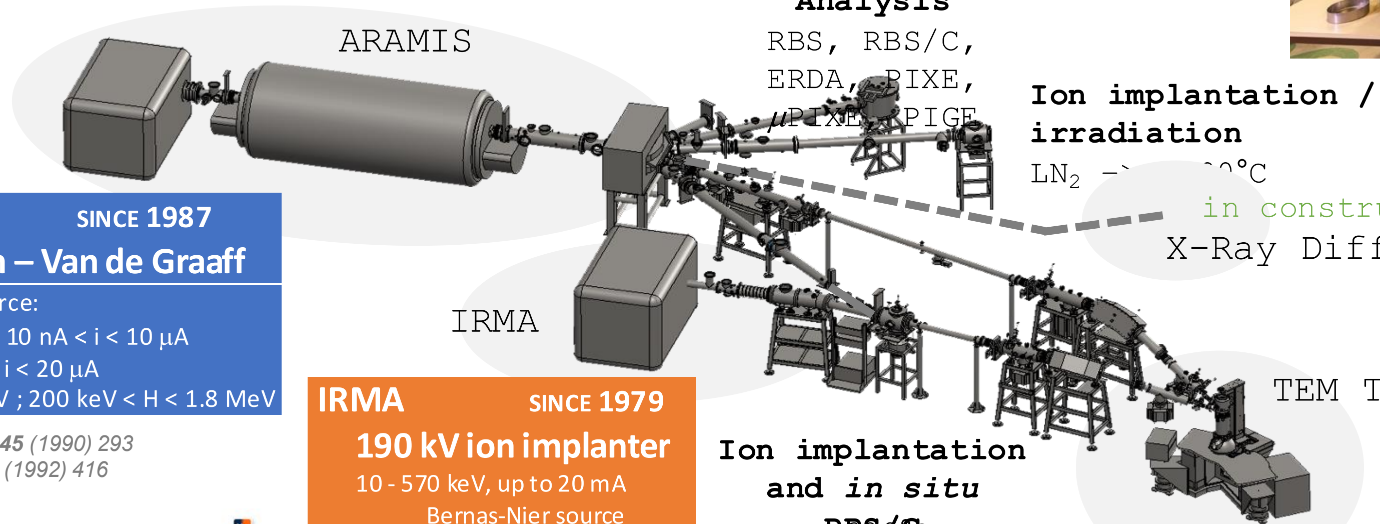
JANNuS

Joint Accelerators for Nanosciences and Nuclear Simulation

Home-made ion accelerators

Groupement d'Intérêt Scientifique (GIS) avec le CEA, ISAS/DES/SRMP, JANNuS-Saclay, depuis 2005





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

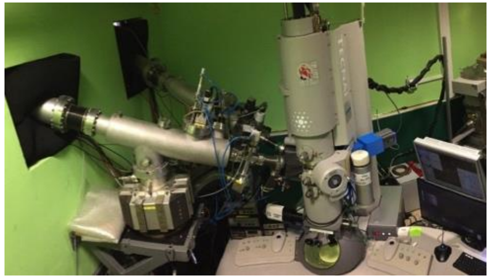
10 - 570 keV, up to 20 mA
Bernas-Nier source

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

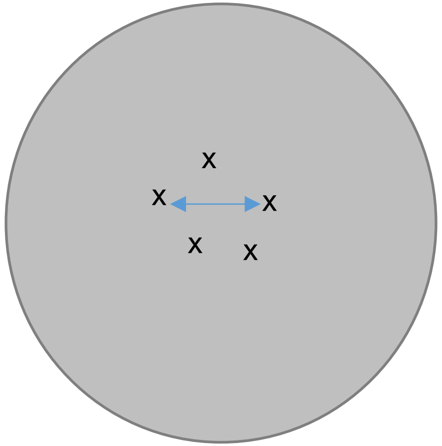
***IN SITU* DUAL ION BEAM TRANSMISSION ELECTRON MICROSCOPE**

SINCE 1980 UPDATED IN 1994, 2007

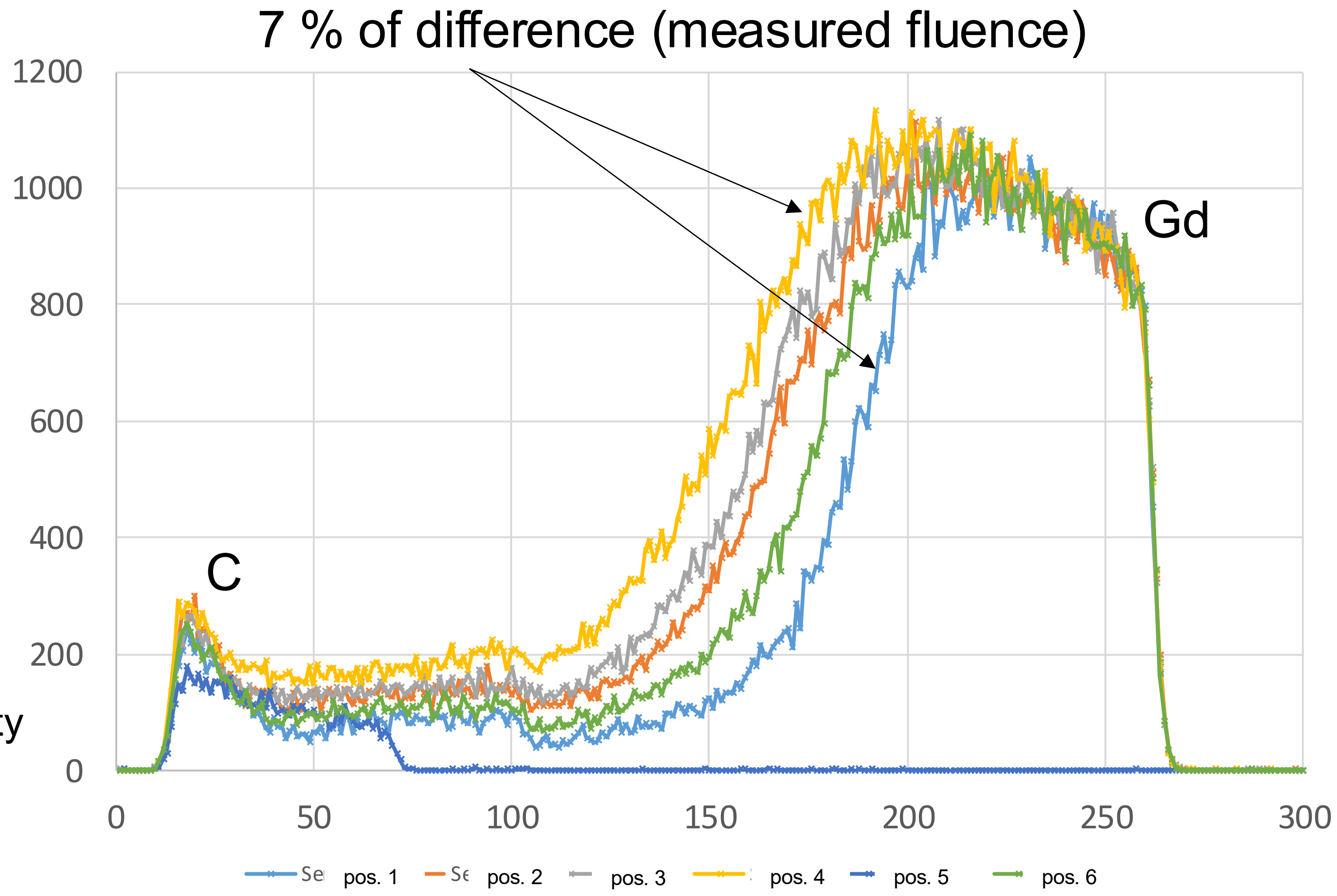
M.-O. Ruault et al., J. Mater. Res. ***20*** *(2005) 1758*
A. Gentils et al., NIMB ***447*** *(2019) 107*



^{155}Gd target fabricated at Sidonie (on graphite) for PRISM project



Rutherford Backscattering Spectrometry analysis (using ARAMIS accelerator) to check the Gd quantity and its homogeneity
- also possible to measure the thickness

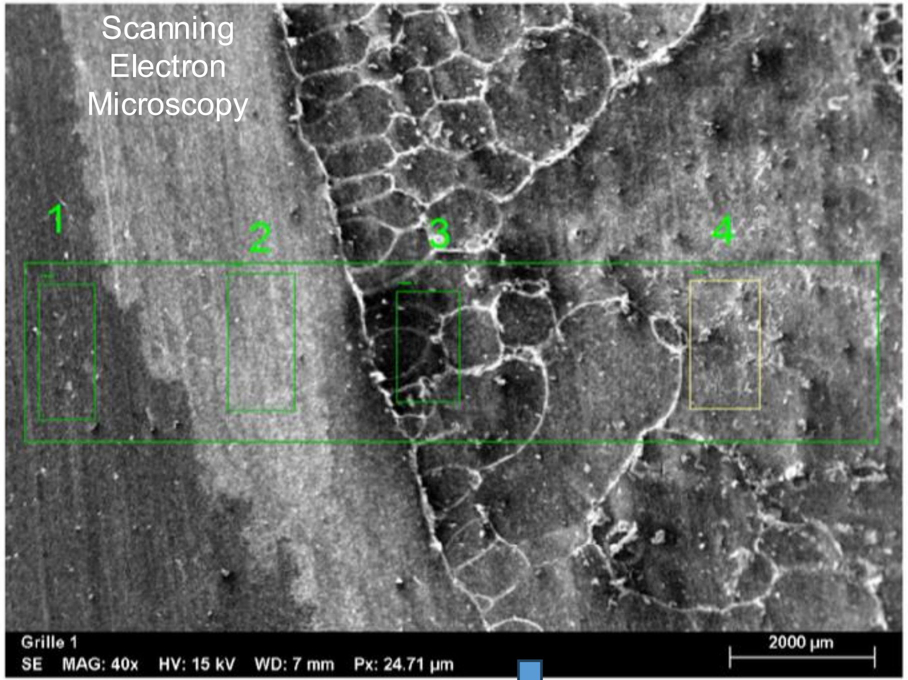


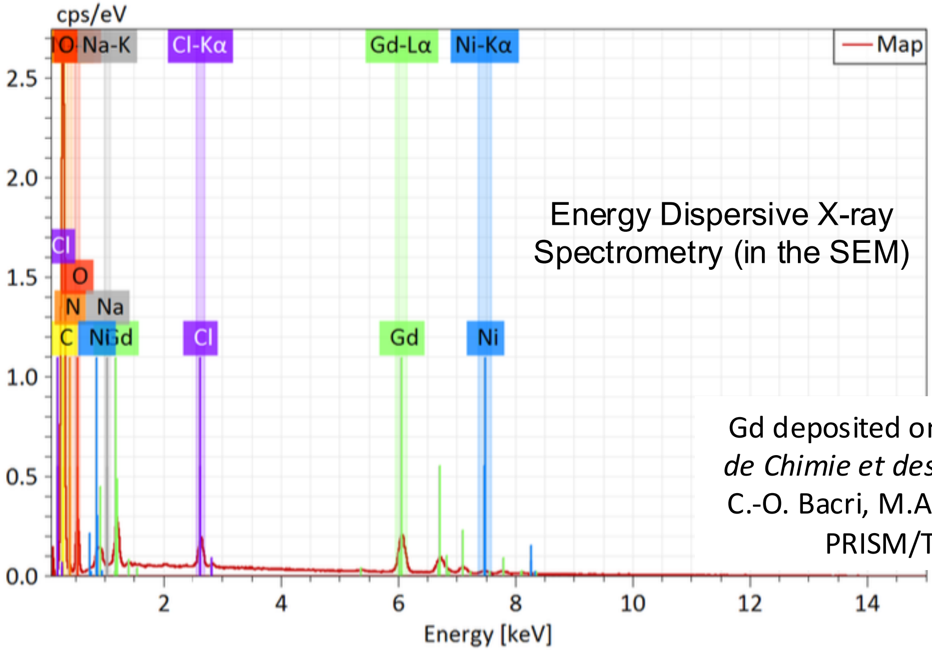
Contact : Cyril Bachelet
cyril.bachelet@ijclab.in2p3.fr, mosaic@ijclab.in2p3.fr

Characterization of targets at MOSAIC – SEM-EDX example

Chemical composition
Topography

Contact : Cédric Baumier
cedric.baumier@ijclab.in2p3.fr
mosaic@ijclab.in2p3.fr





Energy Dispersive X-ray Spectrometry (in the SEM)

Gd deposited on graphite at *Institut de Chimie et des Matériaux Paris-Est*
C.-O. Bacri, M.A. Duval *et al* (IJCLab)
PRISM/TTRIP project

Atomic concentration [%]

Spectrum	Carbon	Nitrogen	Oxygen	Sodium	Chlorine	Nickel	Gadolinium
mapedx 1	92.49	4.65	2.69	0.01	0.02	0.02	0.12
mapedx 2	90.83	4.40	4.16	0.01	0.05	0.07	0.48
mapedx 3	70.47	9.88	16.75	0.24	0.55	0.20	1.90
mapedx 4	55.42	13.25	23.75	0.12	2.30	0.62	4.54
Mean	**77.30**	**8.05**	**11.84**	**0.10**	**0.73**	**0.23**	**1.76**
Sigma	**17.69**	**4.29**	**10.14**	**0.11**	**1.07**	**0.27**	**2.01**
SigmaMean	**8.85**	**2.15**	**5.07**	**0.05**	**0.54**	**0.14**	**1.00**

at.%

A wide range of techniques for targets' fabrication and characterization !

- ✓ Targets fabricated by electrodeposition
- ✓ Thin layers targets at ALTO
- ✓ UC_x ISOL targets at ALTO
- ✓ Deposition using *Sidonie* isotope separator

- ✓ Optical microscopy
- ✓ Scanning Electron Microscopy, coupled to EDS
- ✓ (Transmission Electron Microscopy)
- ✓ Ion Beam Analysis (RBS, ERDA, PIXE, …)
- ✓ X-Ray Diffraction
- ✓ B.E.T theory
- ✓ Pycnometry He
- ✓ Porosimetry Hg
- ✓ …

ALTO
Accélérateur Linéaire et Tandem à Orsay

mosaic

E&E Energie & Environnement
Energy & Environment