PLASMA FIB: PRINCIPES ET APPLICATIONS

Guillaume Audoit, CEA Leti, Grenoble

PLAN DE LA PRÉSENTATION

- **Quelques rappels sur les FIBs**
- **Technologie FIB Gallium vs. technologie Plasma FIB**
  - Design des sources
  - Gamme des courants et échelles associées
- **Champs d'applications FIB et spécificités applicatives du PlasmaFIB**
- **Artefacts**
- **Conclusions**

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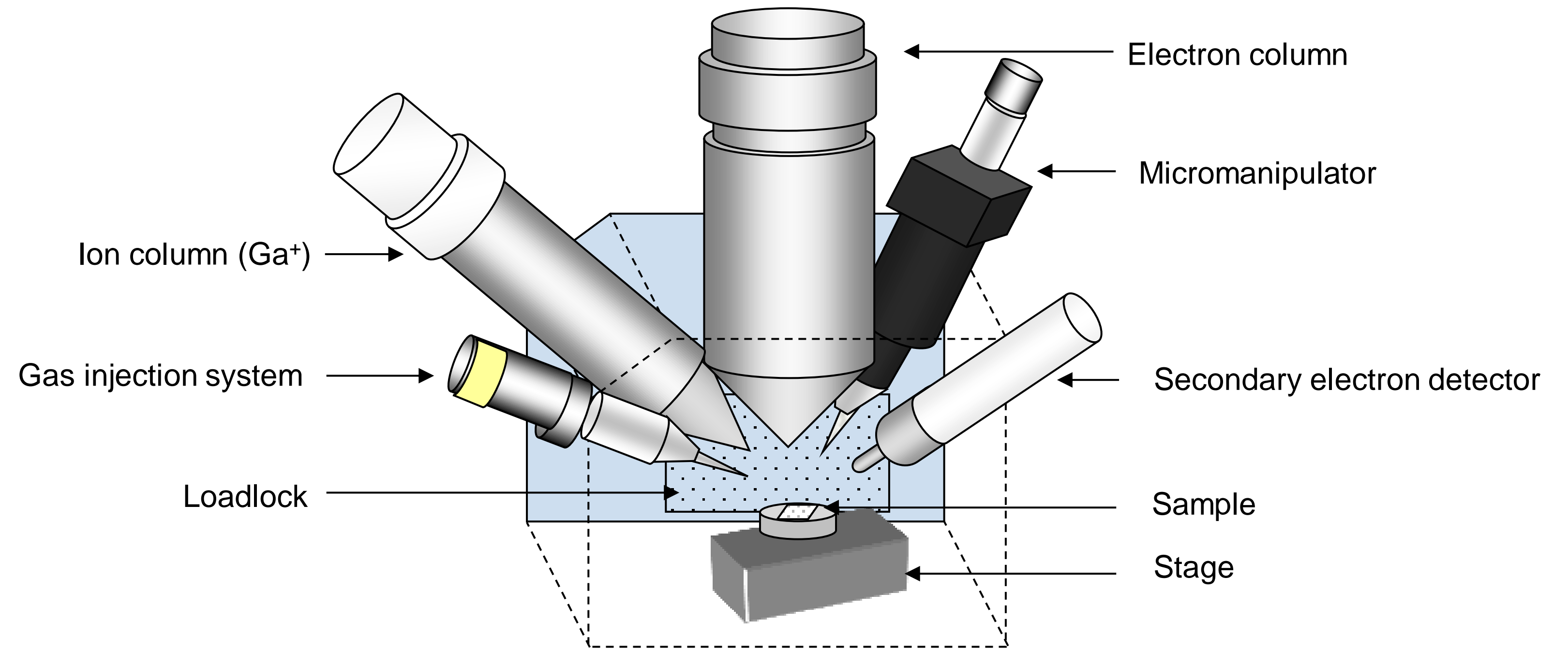
FIB: UN PEU D’HISTORIQUE

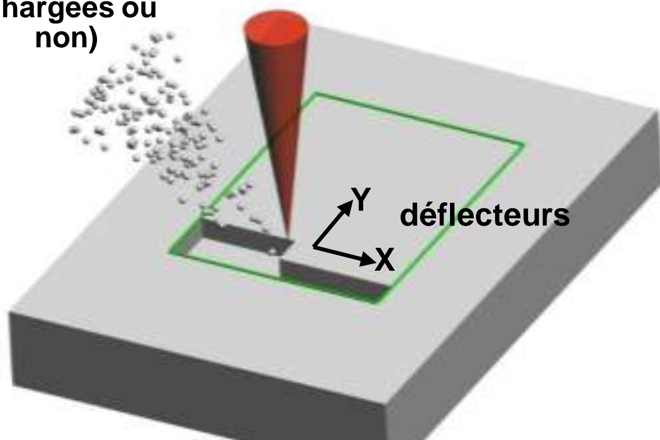
- **Premiers développements dans la fin des 70’s, début 80’s**
- **Premiers équipements commerciaux dans les 90’s, des FIBs à source gallium liquide**
- **Champs d’applications liés à l’industrie du semi-conducteur**
  - Contrôle procédés de fabrication,
  - Analyse de défaillance, retour client
  - Modification de circuit
- **Aujourd’hui, le FIB est utilisé dans de très nombreux domaines**
  - Métallurgie
  - Biologie
  - Prospection ressources (minières et pétrolifères)
  - Géologie
  - Dentaire
  - …

FIB: QUELQUES GÉNÉRALITÉS

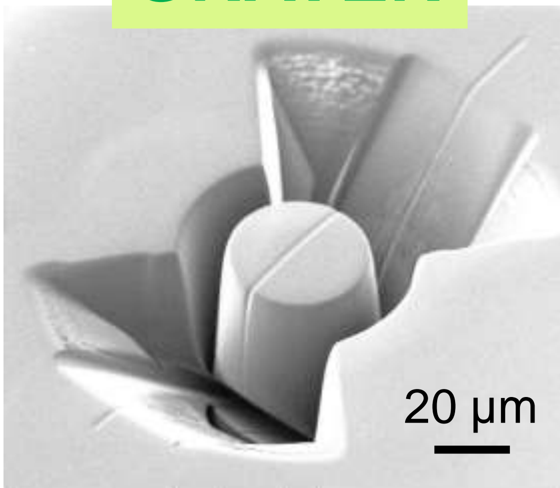


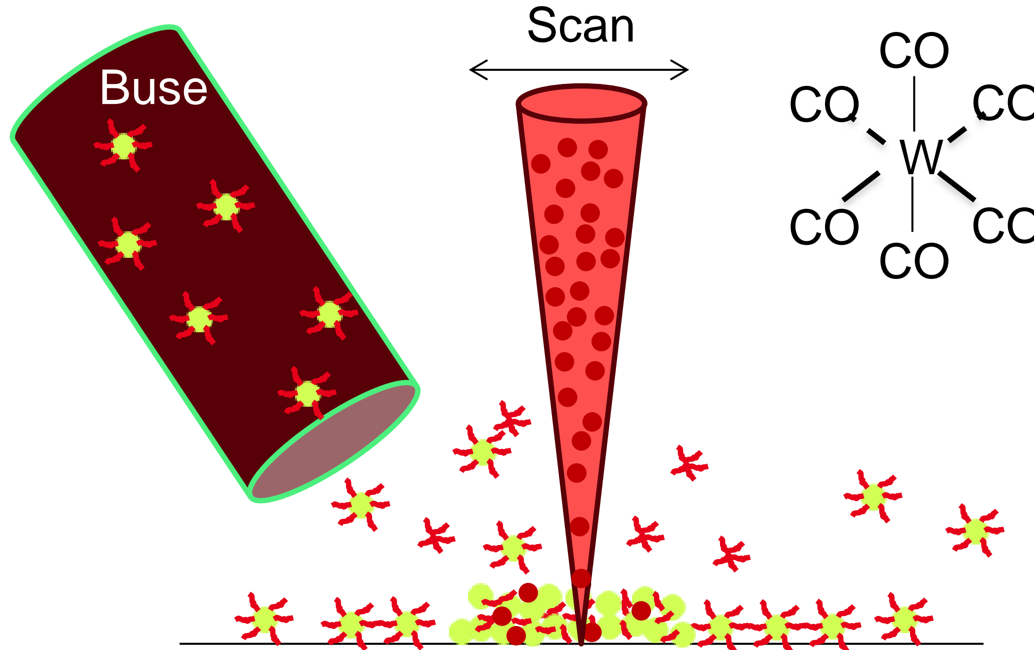
- Gravure
- Dépôts
- Manipulations
- Imagerie
- Local

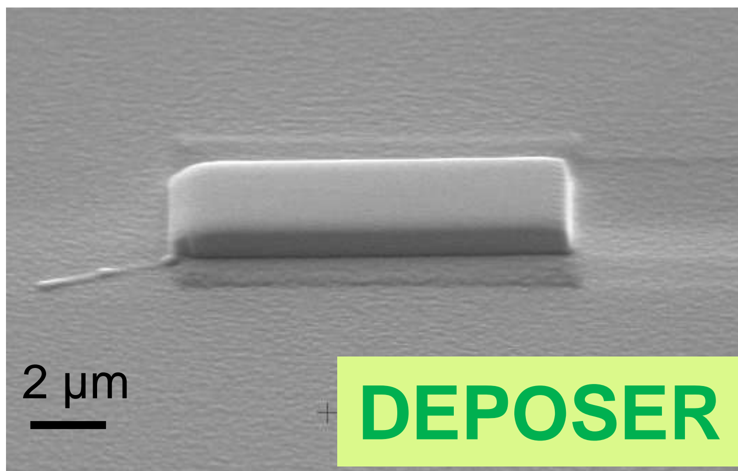
CAPACITÉS D'UN FIB



GRAVER

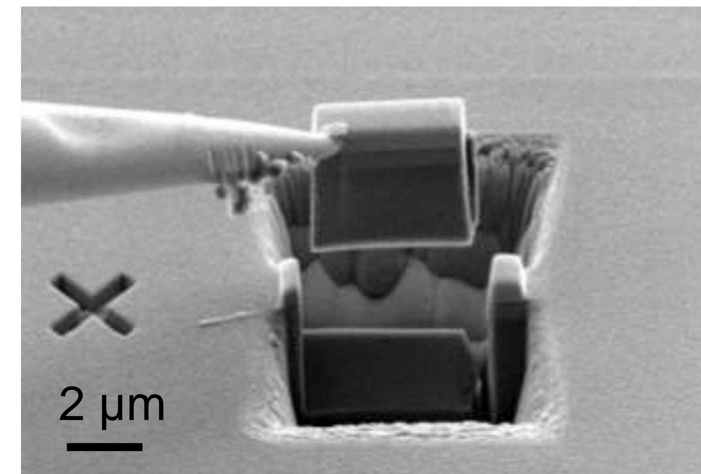






DEPOSER

MANIPULER



CHAMPS D'APPLICATIONS

FIB/SEM

Outil d'analyse

- Imagerie (SEM, STEM)
- Composition chimique :EDX
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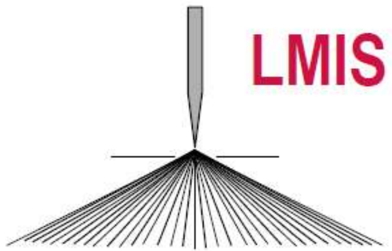
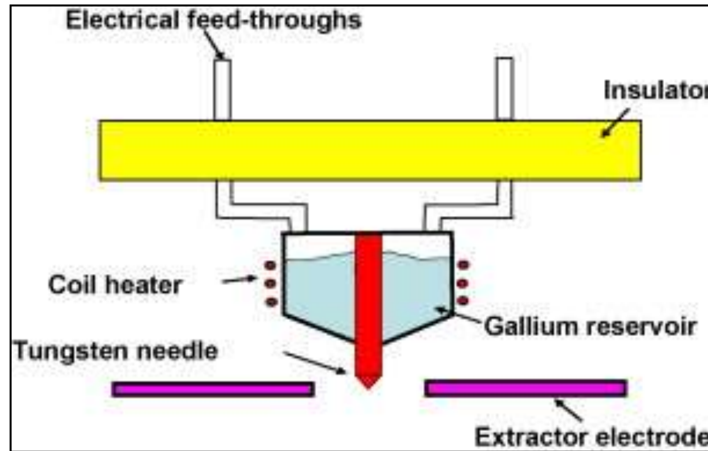
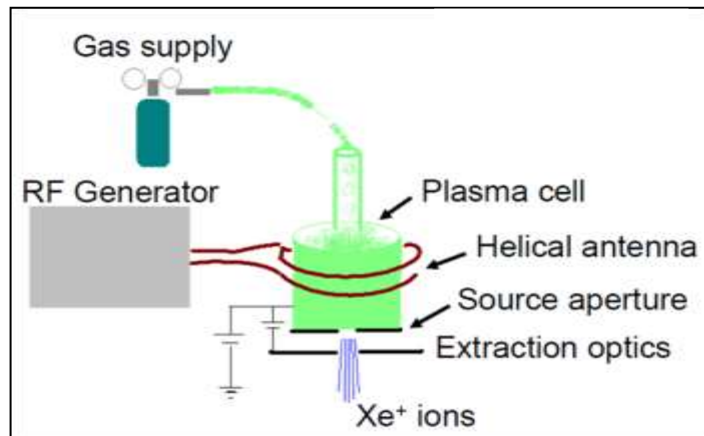
GALLIUM LIQUIDE VS. PLASMA XÉNON

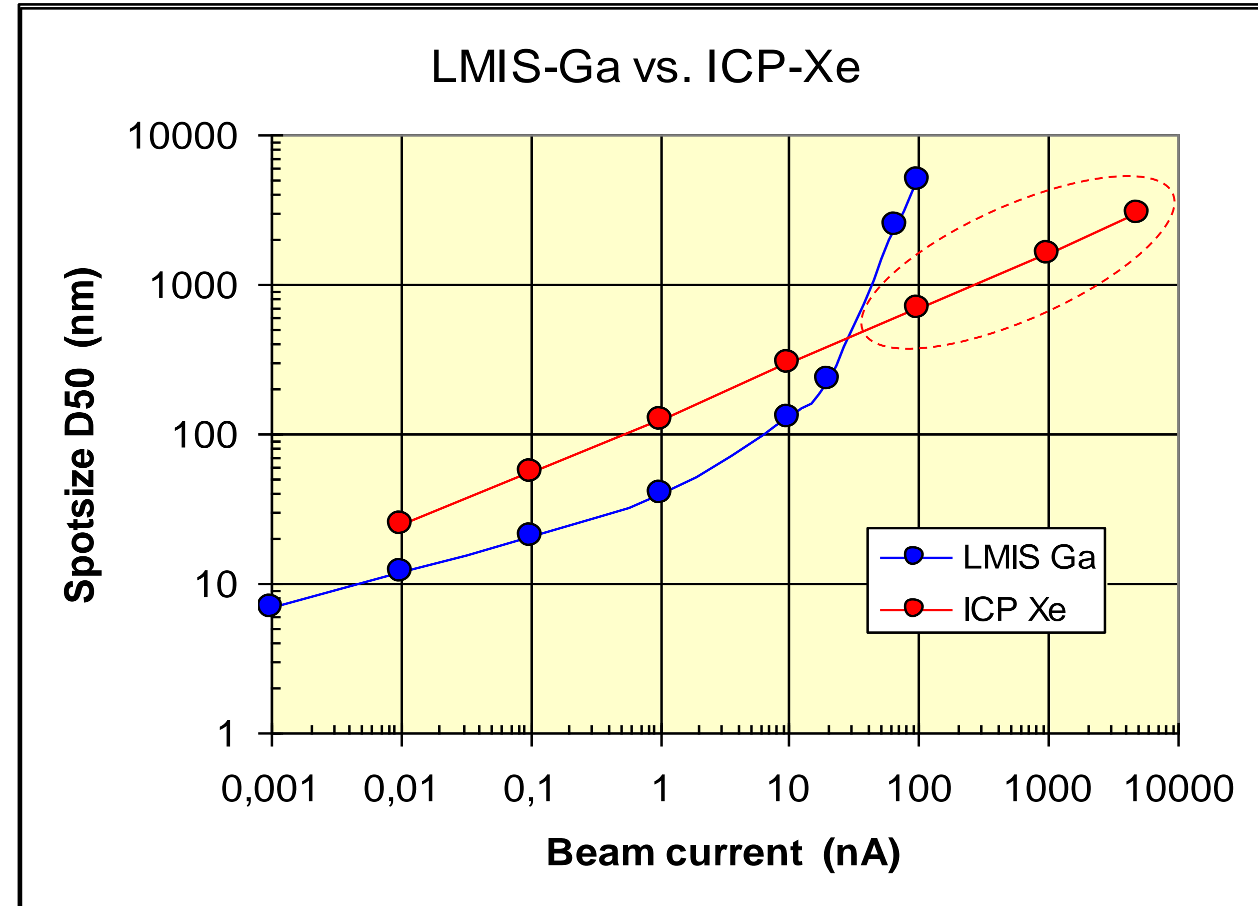
ThermoFisher SCIENTIFIC

Kwakman et al., M&M 2011



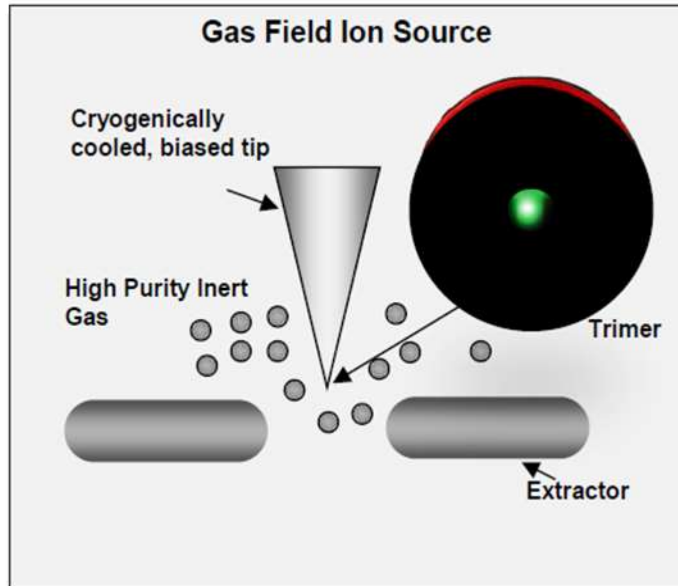


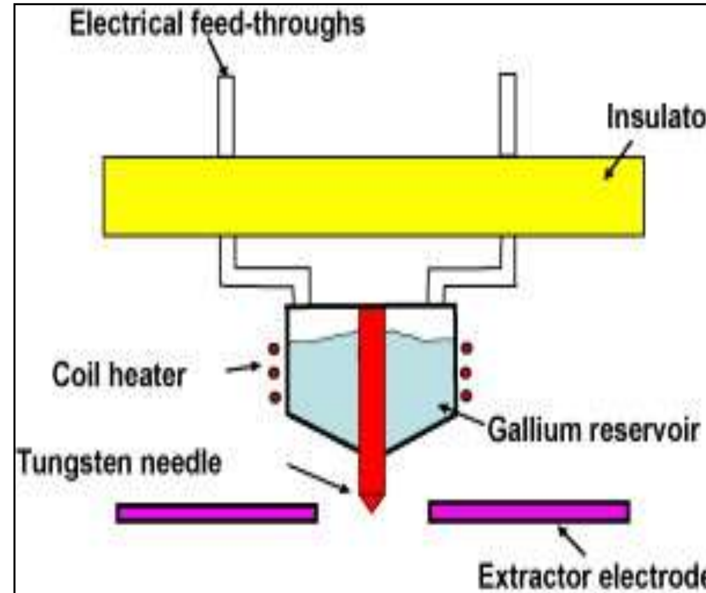


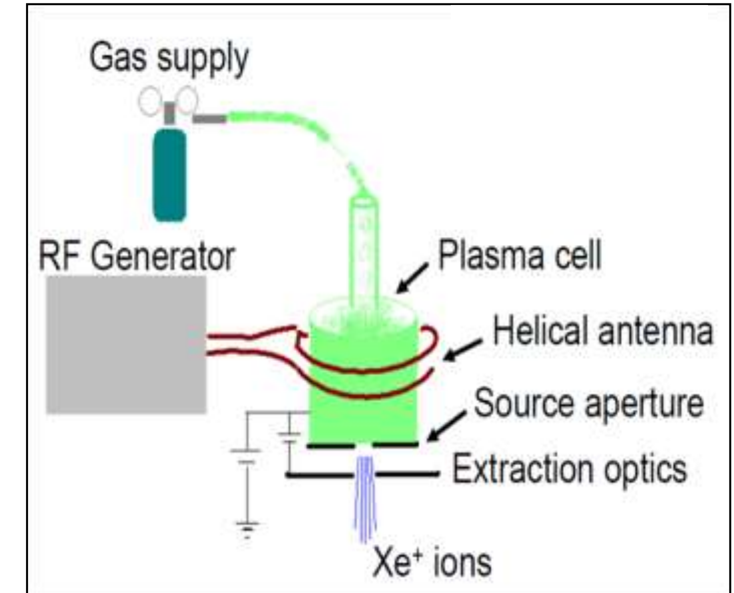


SOURCES IONIQUES

Microscope ionique Hélium	FIB à source Gallium liquide	Plasma FIB Xénon







	Microscope ionique Hélium	FIB à source Gallium liquide	Plasma FIB Xénon
Taille de faisceau:	0,35nm	5nm	20nm
Echelle de travail:	qq nm à qq µm	qq 100nm à qq 10µm	qq µm à qq 100µm

ThermoFisher SCIENTIFIC

Kwakman et al., M&M 2011

SOURCE IONIQUE PLASMA

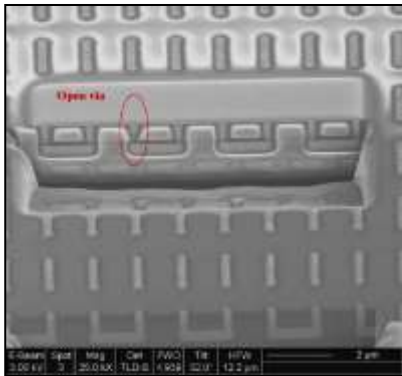
- Intensité des courants jusqu'à quelques µA (vs 100nA pour LMIS Ga)
- Le Xénon est plus lourd que le gallium

Plasma FIB Xénon

Un PFIB grave plus vite

Ou plutôt

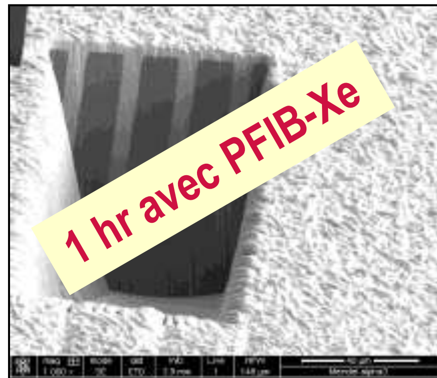
A temps égal, de plus grand volumes peuvent être gravés



More Moore:

Volumes: 10 x 10 x 10 μm^3

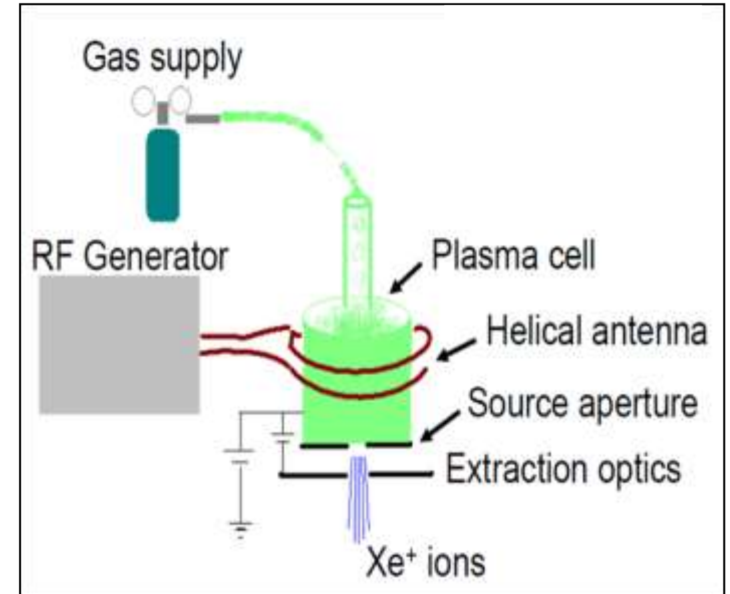
Temps total ~ **3-10 min avec FIB-Ga**



More than Moore:

Volumes: 100 x 100 x 100 μm^3

Temps total ~ **50 hrs avec FIB-Ga**



Kwakman et al., M&M 2011

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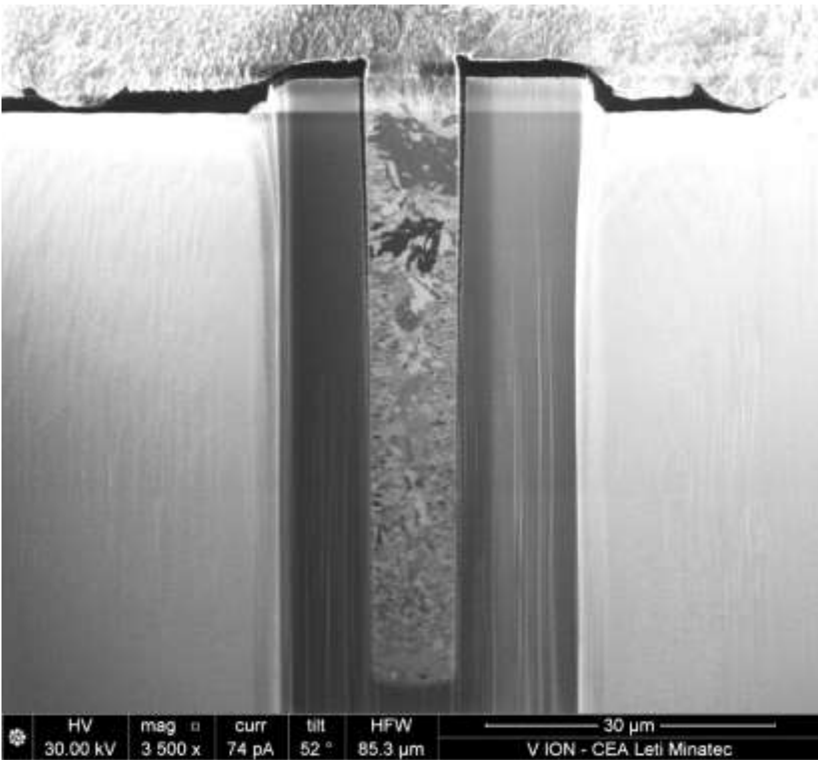
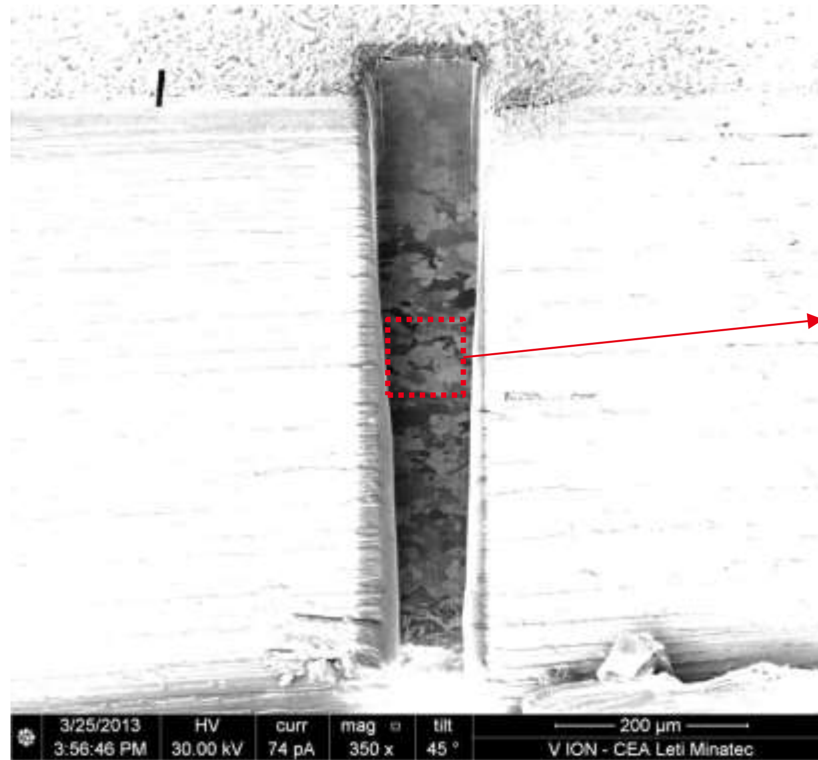
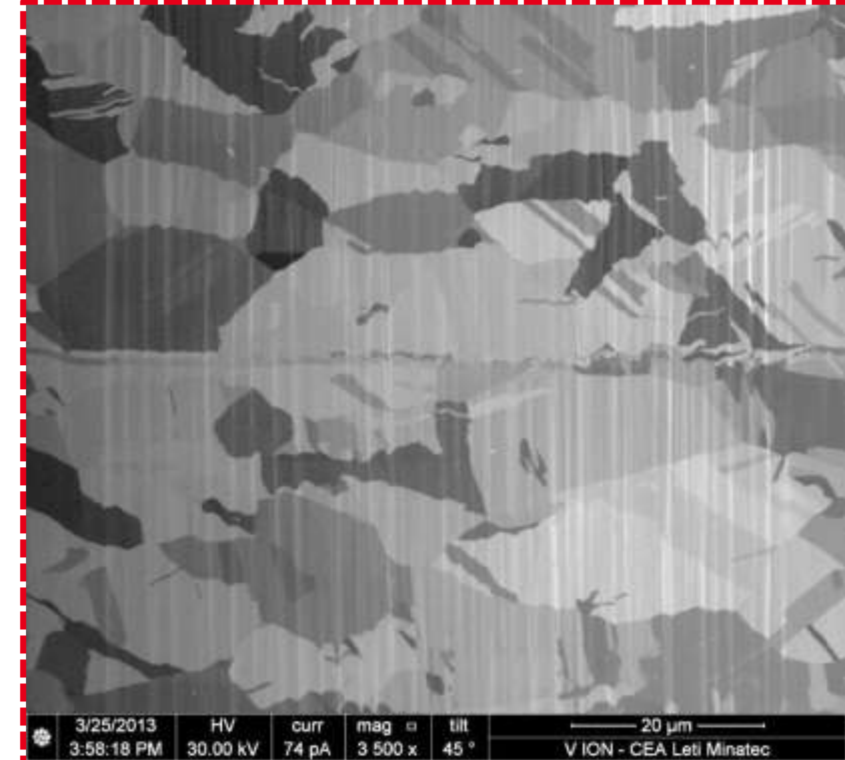
VUE EN COUPE: GRANDE PROFONDEUR



Through Silicon Via
Connection en Cuivre dans du silicium
10µm x 100µm
2hr de coupe



Collage moléculaire Cuivre/Cuivre
Coupe en bord d'échantillon
1mm d'épaisseur
2hr de coupe



Imagerie ionique de l'interface
de collage

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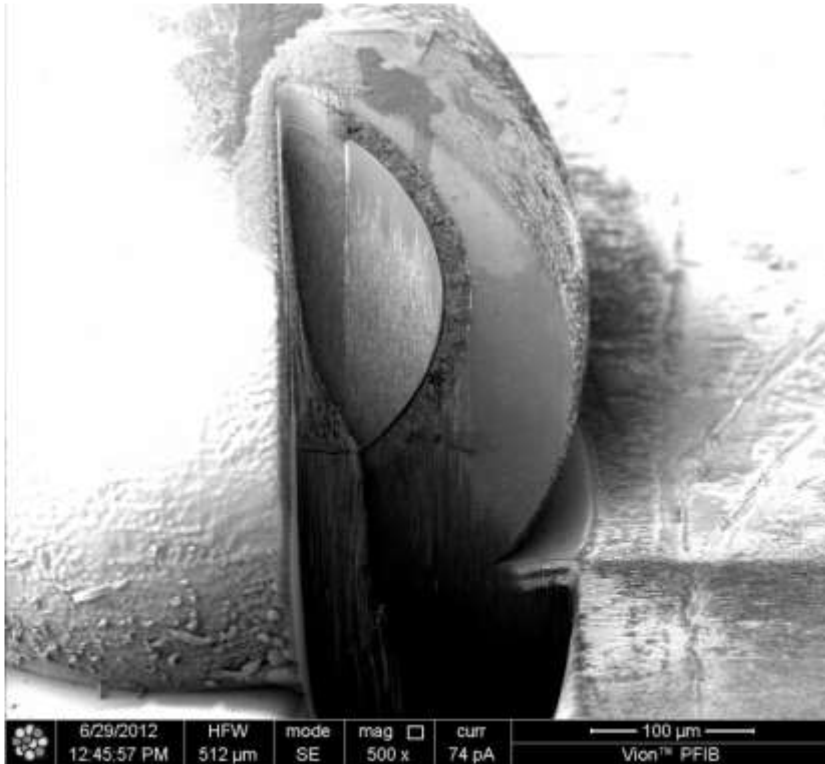
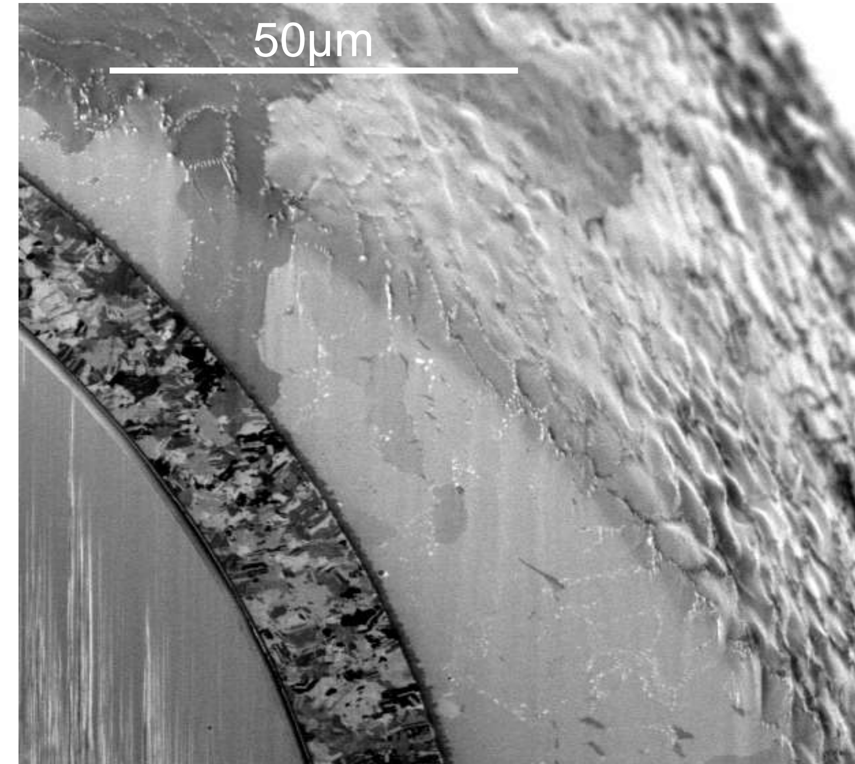
VUE EN COUPE

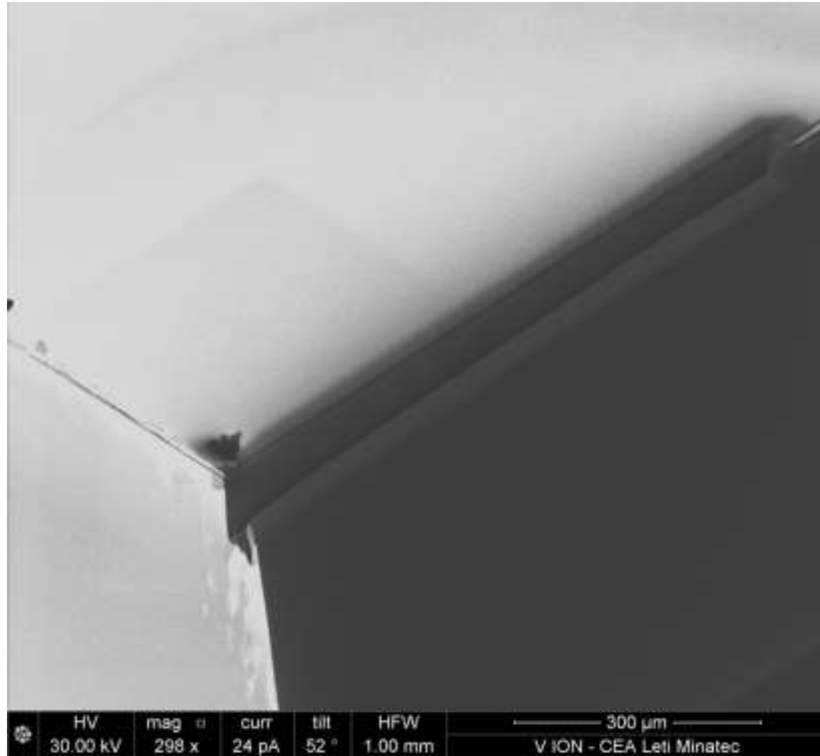


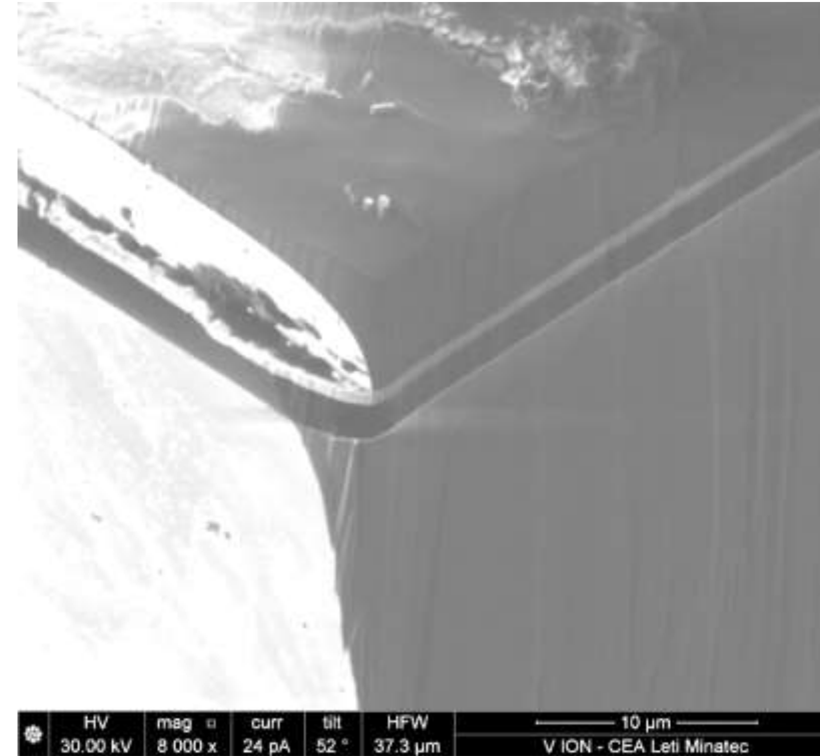
Bille diametre 500µm
Connection en Cuivre dans du silicium
10µm x 100µm
2hr de coupe



Imagerie ionique de la structure périphérique

VUE EN COUPE: LONGUE DISTANCE



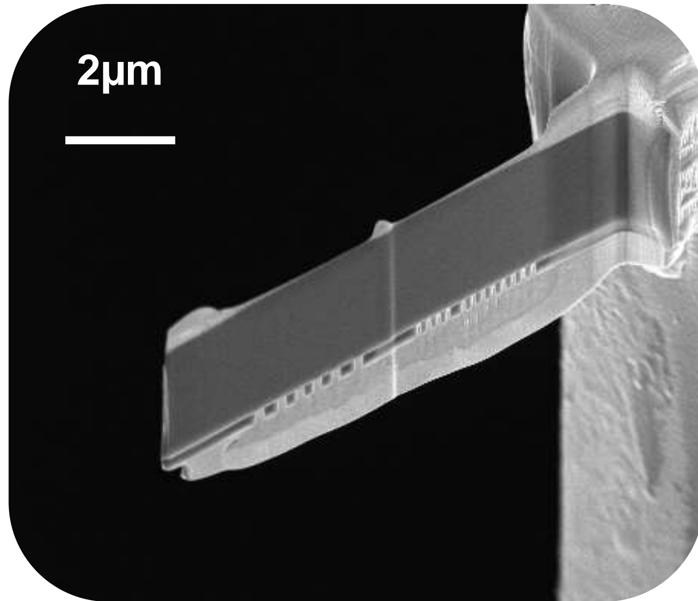


Recherche de défauts sur une “longue” distance
Coupe en bord d’échantillon sur 1 mm de long
2h

LAMES TEM

- **Obtenir une grande lame**

ThermoFisher SCIENTIFIC
Kwakman et al., M&M 2011



10 x 5 µm
LMIS Ga FIB

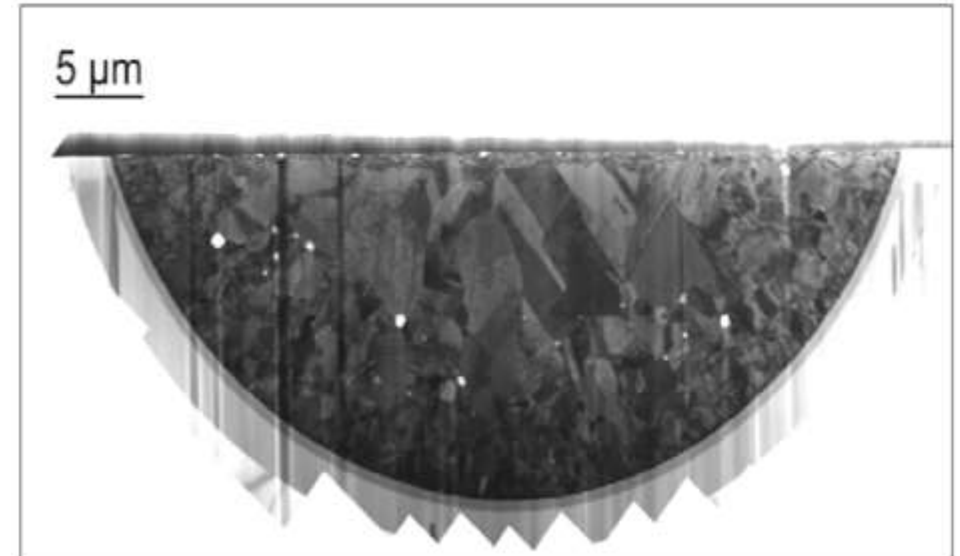
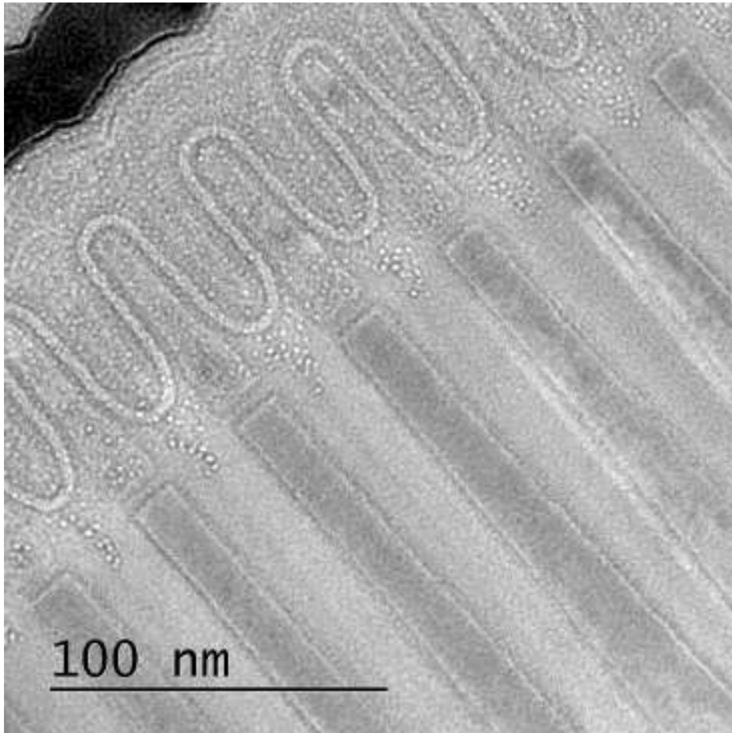
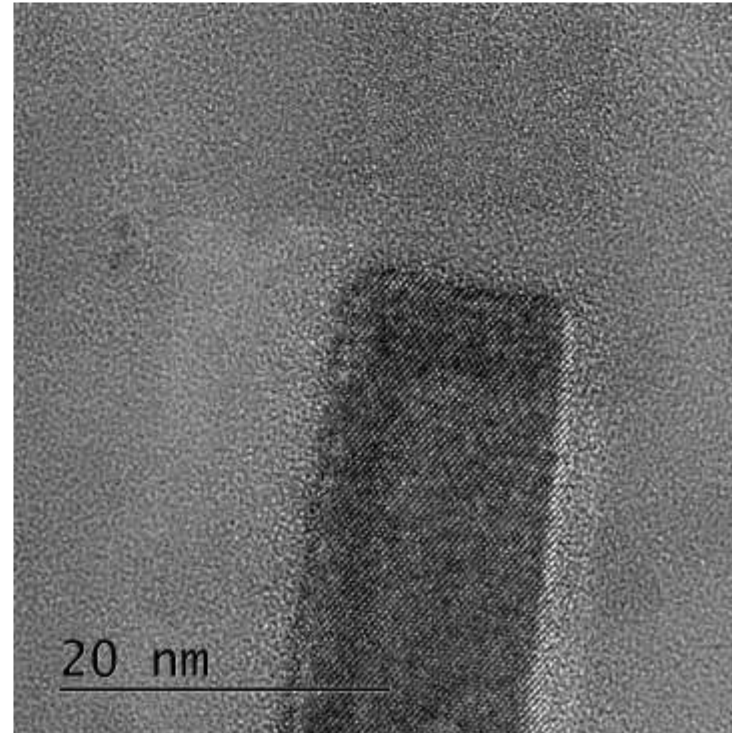


Figure 16: PFIB TEM lamella (60 x 30 µm²) creation and TEM inspection of a TSV. Backscatter electron contrast measurements indicate a 100-200 nm lamella thickness.

LAMES TEM

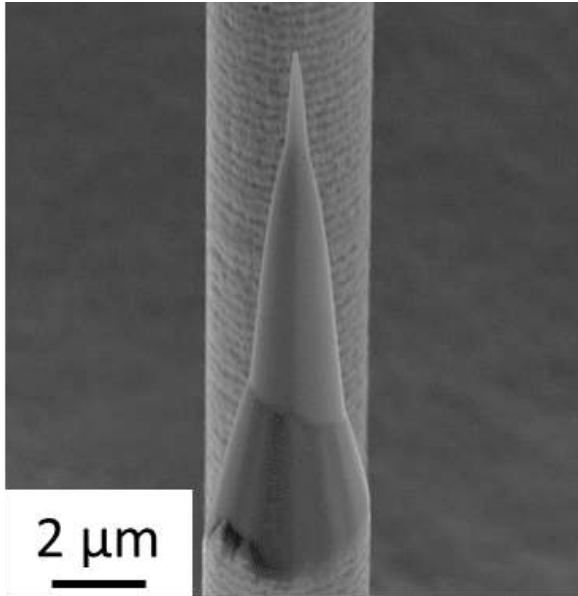
- **Utiliser des ions Xénons au lieu du Gallium**
  - Réactivité des espèces Xe vs. Ga





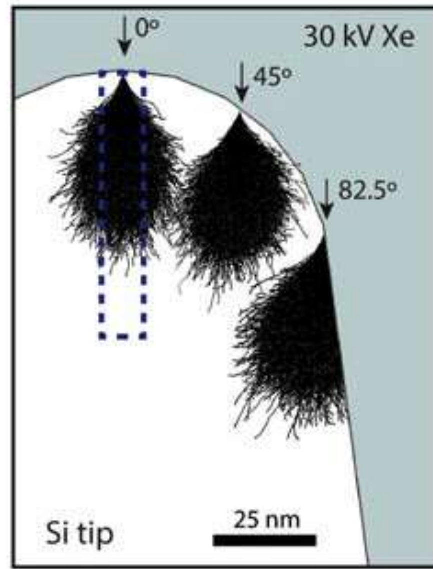
Hrncir et al., ISTFA 2015

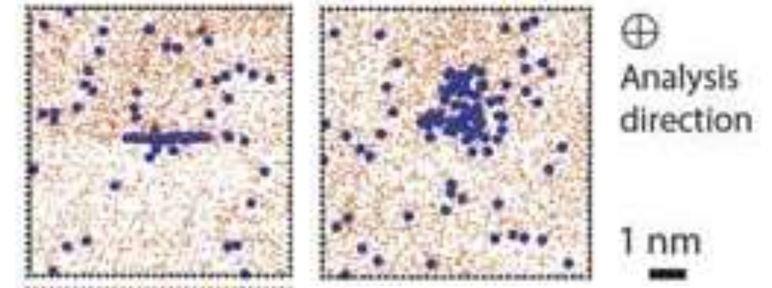
POINTES POUR SONDE ATOMIQUE TOMOGRAPHIQUE

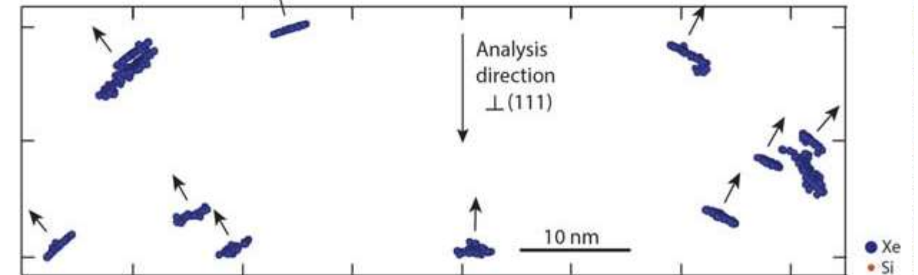


Pointe sur Silicium – PFIB Xe 30kV

Cluster de Xe dans la pointe

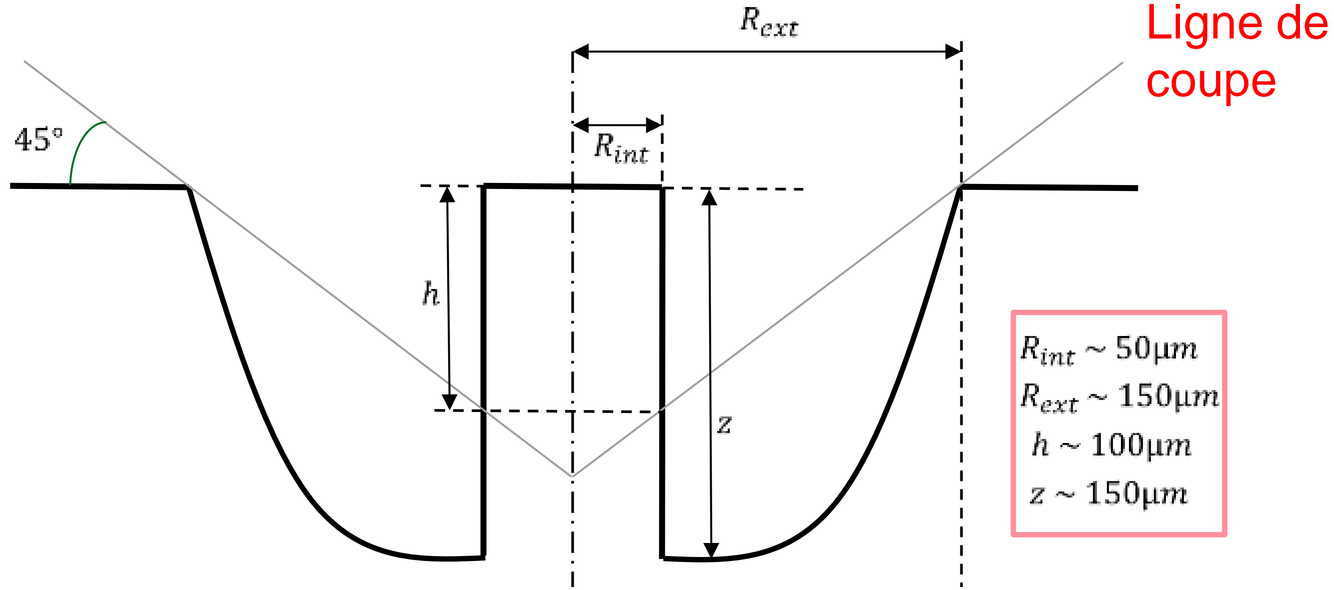


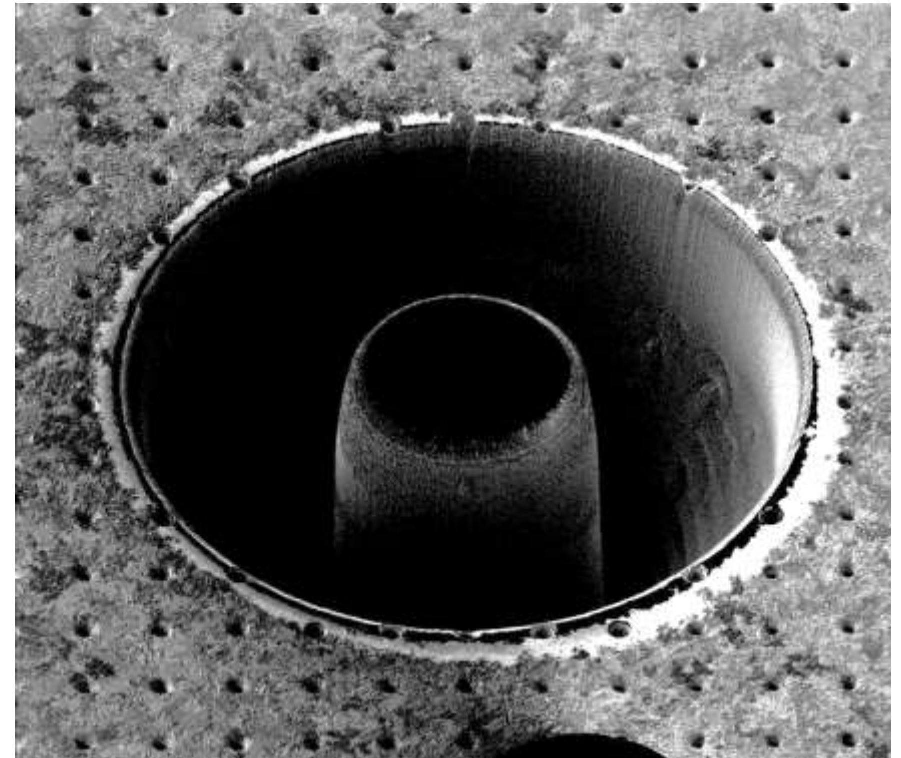




Estivill et al., M&M 2016

PILIERS POUR TOMOGRAPHIE X



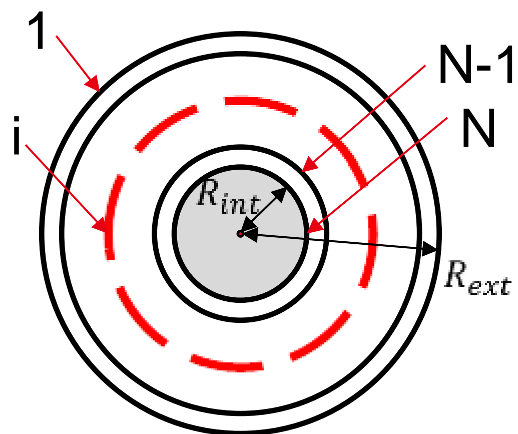


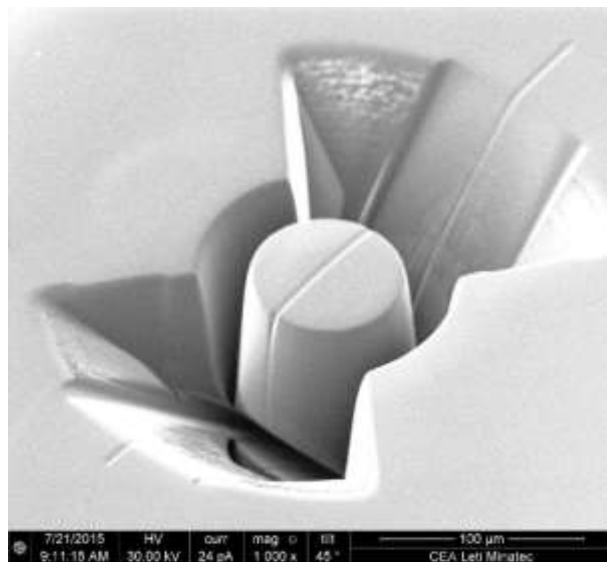
Volume à graver ~ 5.10^6 μm^3
Avec un FIB Ga at 30kV/65nA ---------- ~ 10 days at 5μm³/sec
On a Xe PFIB at 30kV/2μA ---------- ~ 5 hours at 60μm³/sec

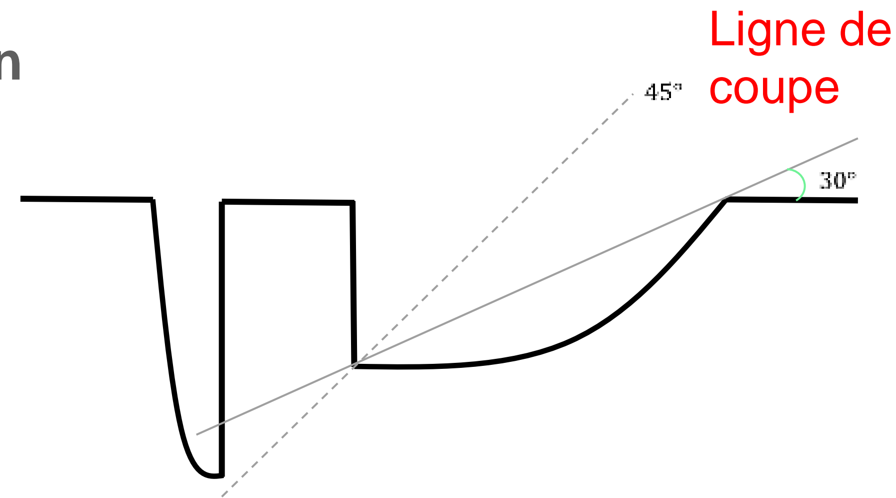
Audoit et al., ISTFA 2016

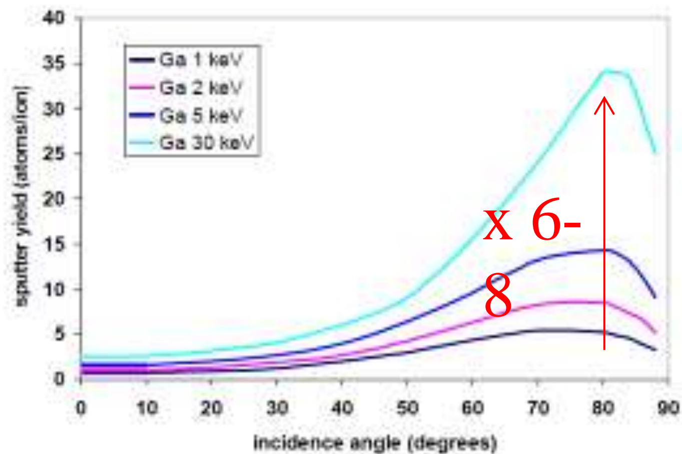
PILIERS POUR TOMOGRAPHIE X

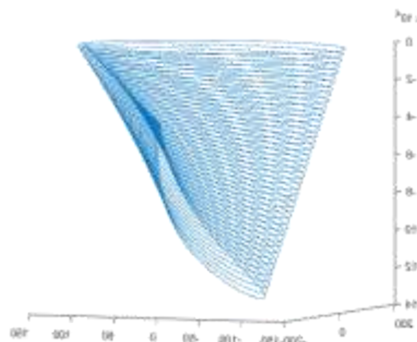
- Optimisation de la stratégie de scan du faisceau Xénon



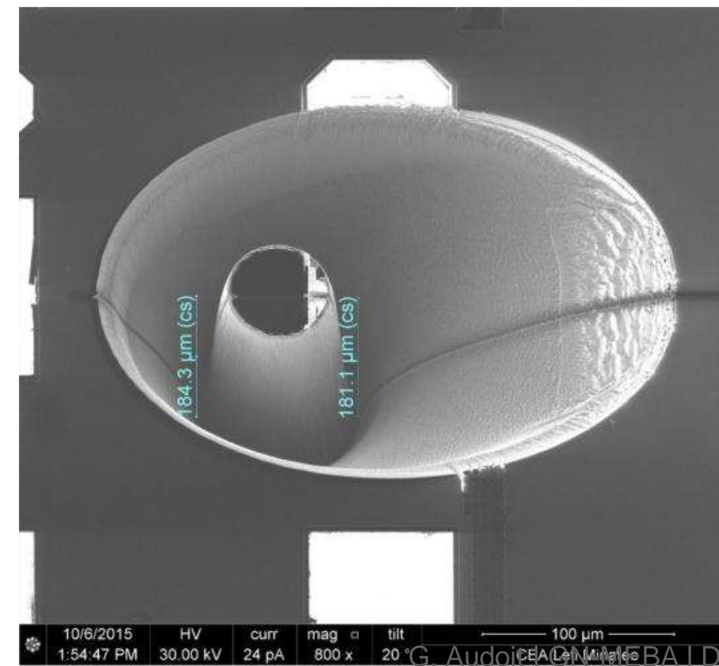








Patent FEI - LETI, n°20180143110



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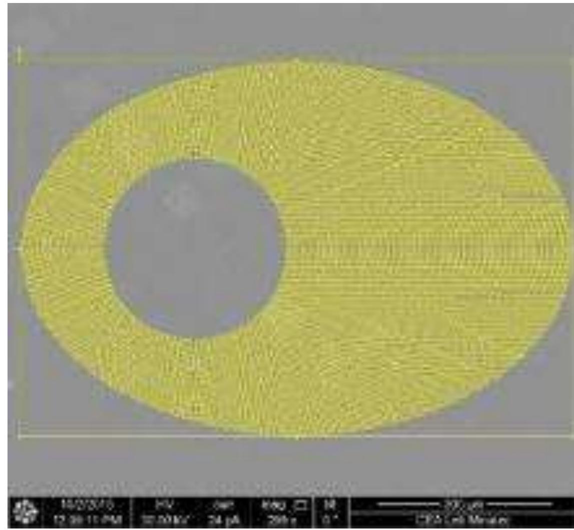
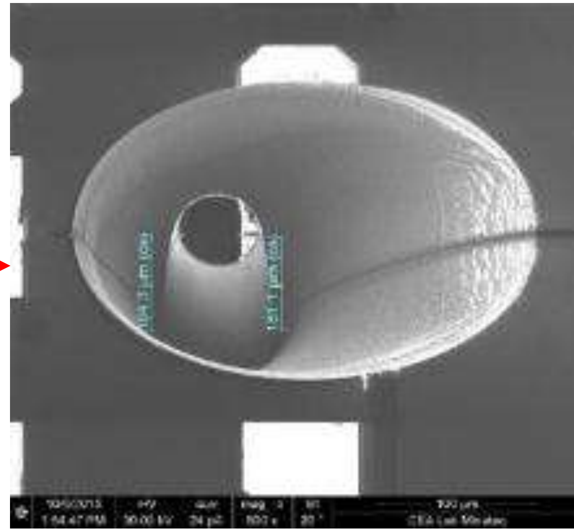
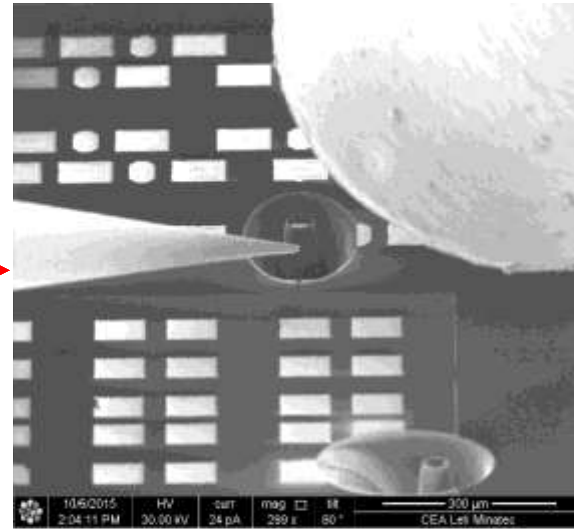
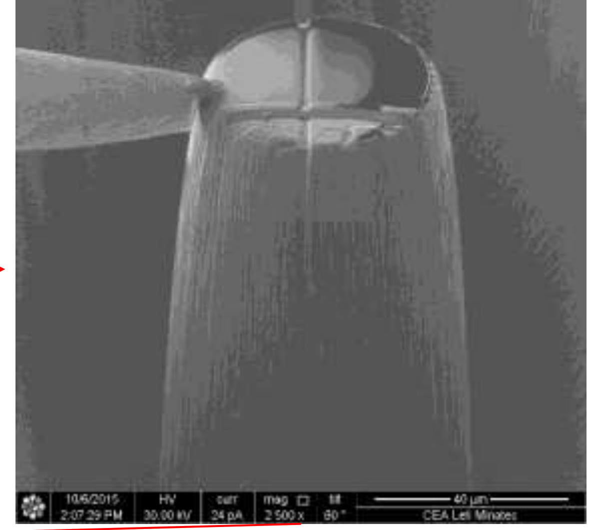
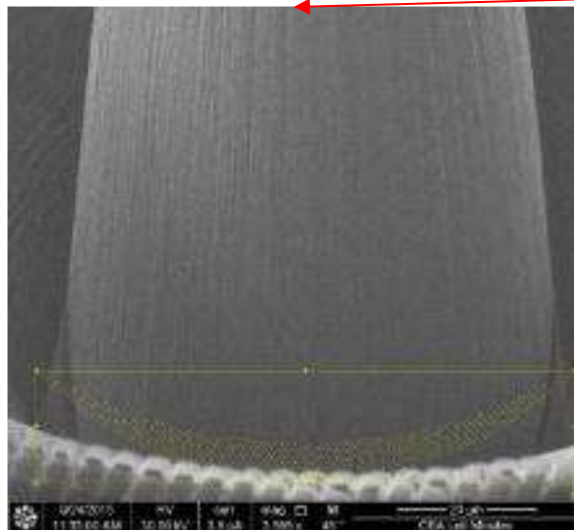
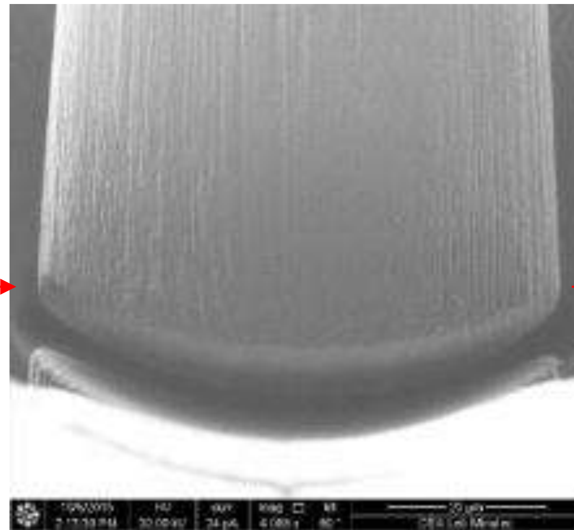
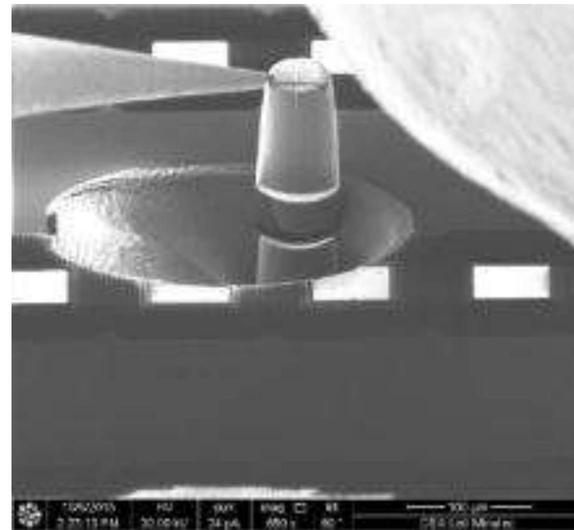
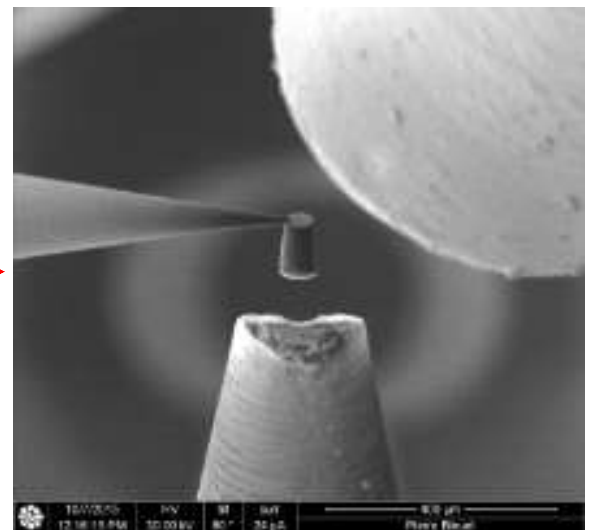

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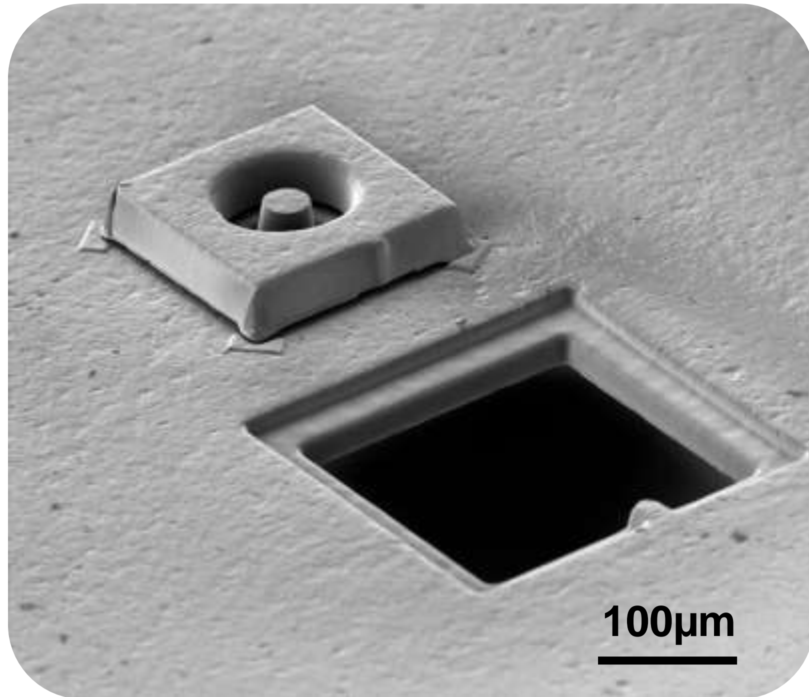
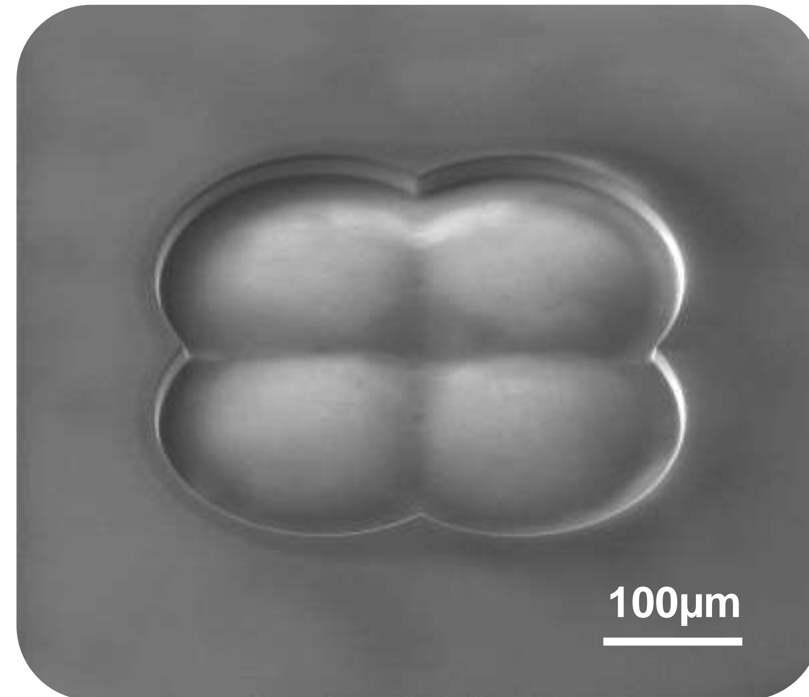
OUTIL DE PROTOTYPAGE ET DE MANIPULATION IN-SITU

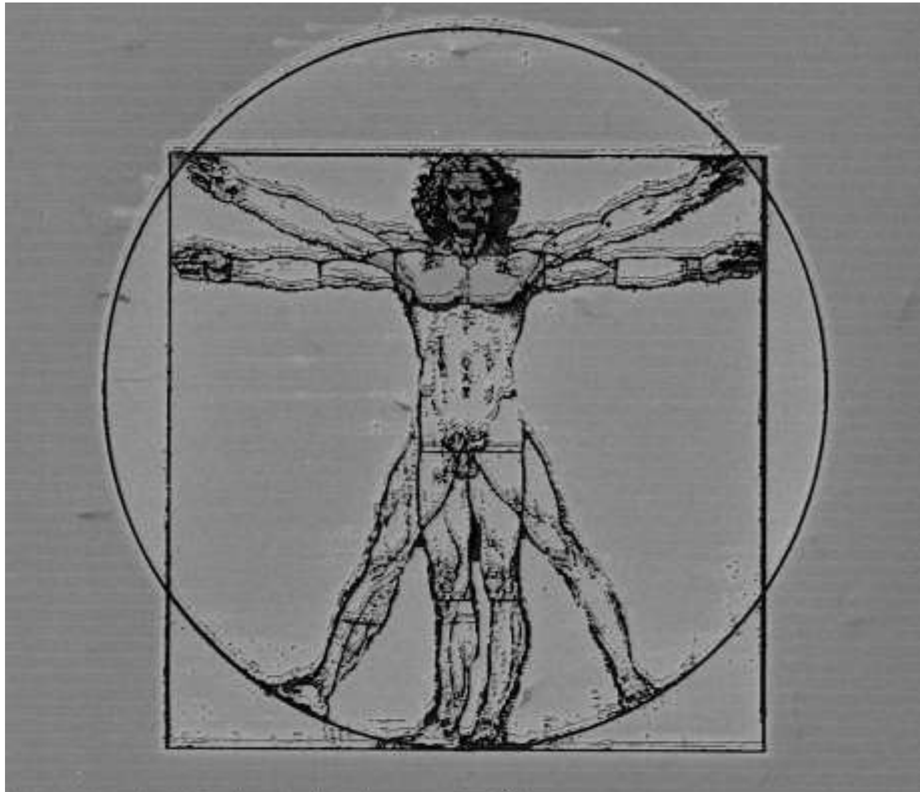
- Echelle sup-100µm





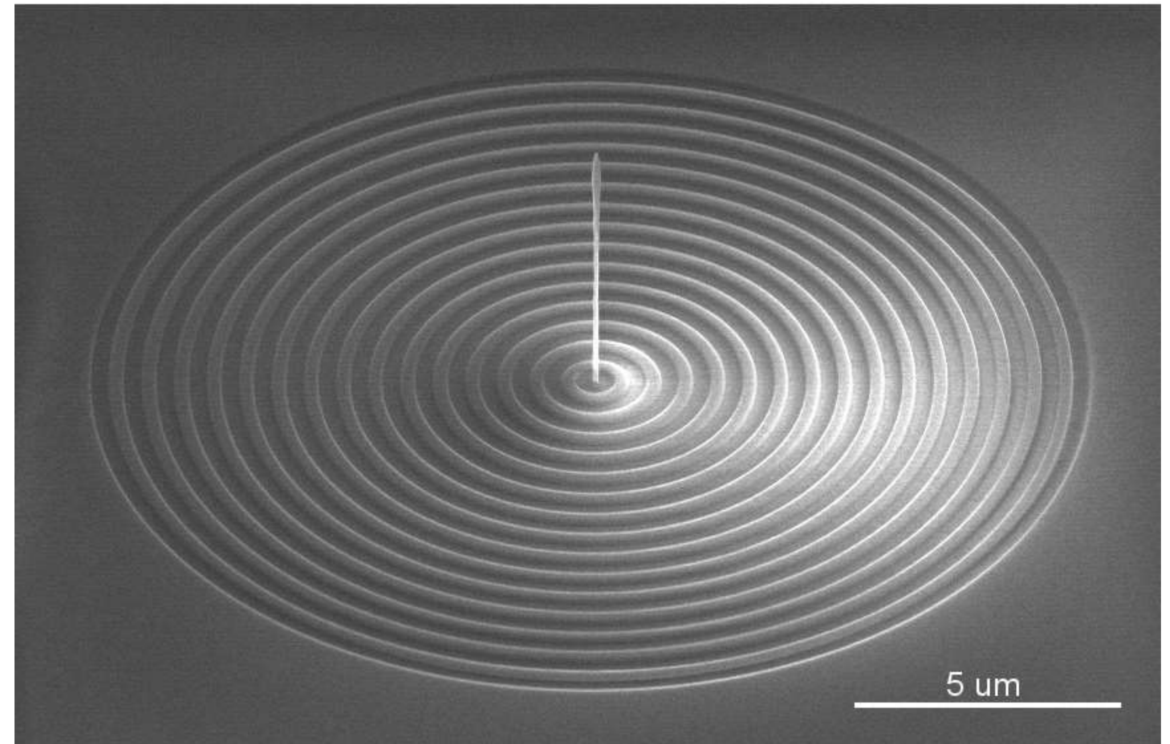
OUTIL DE PROTOTYPAGE ET DE MANIPULATION IN-SITU

- **Prototyping system**



50 µm champ de vue

PFIB



Ga FIB

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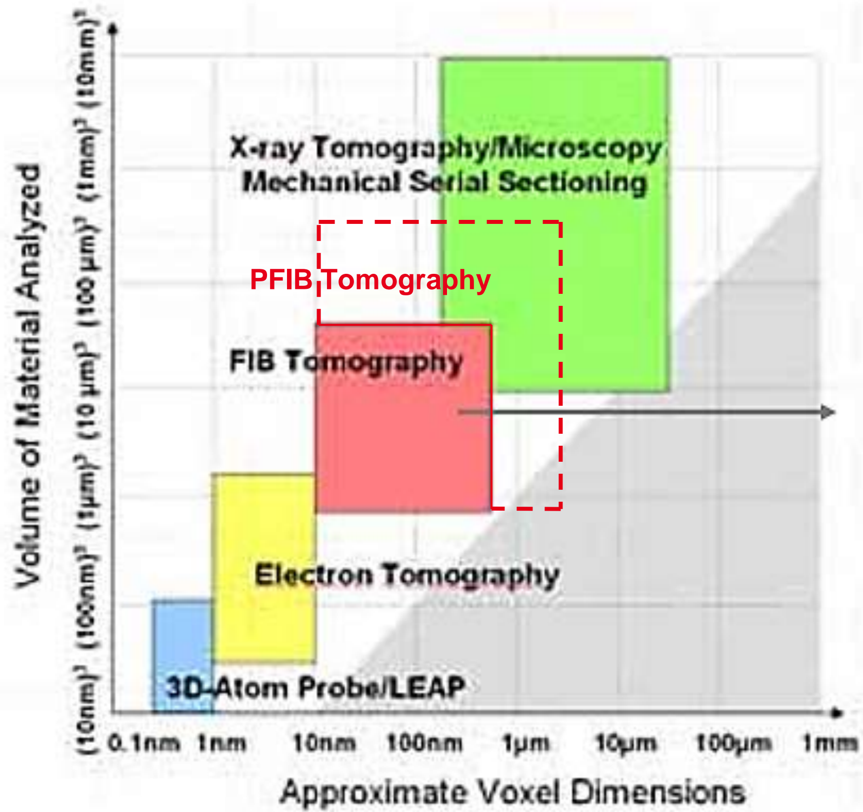
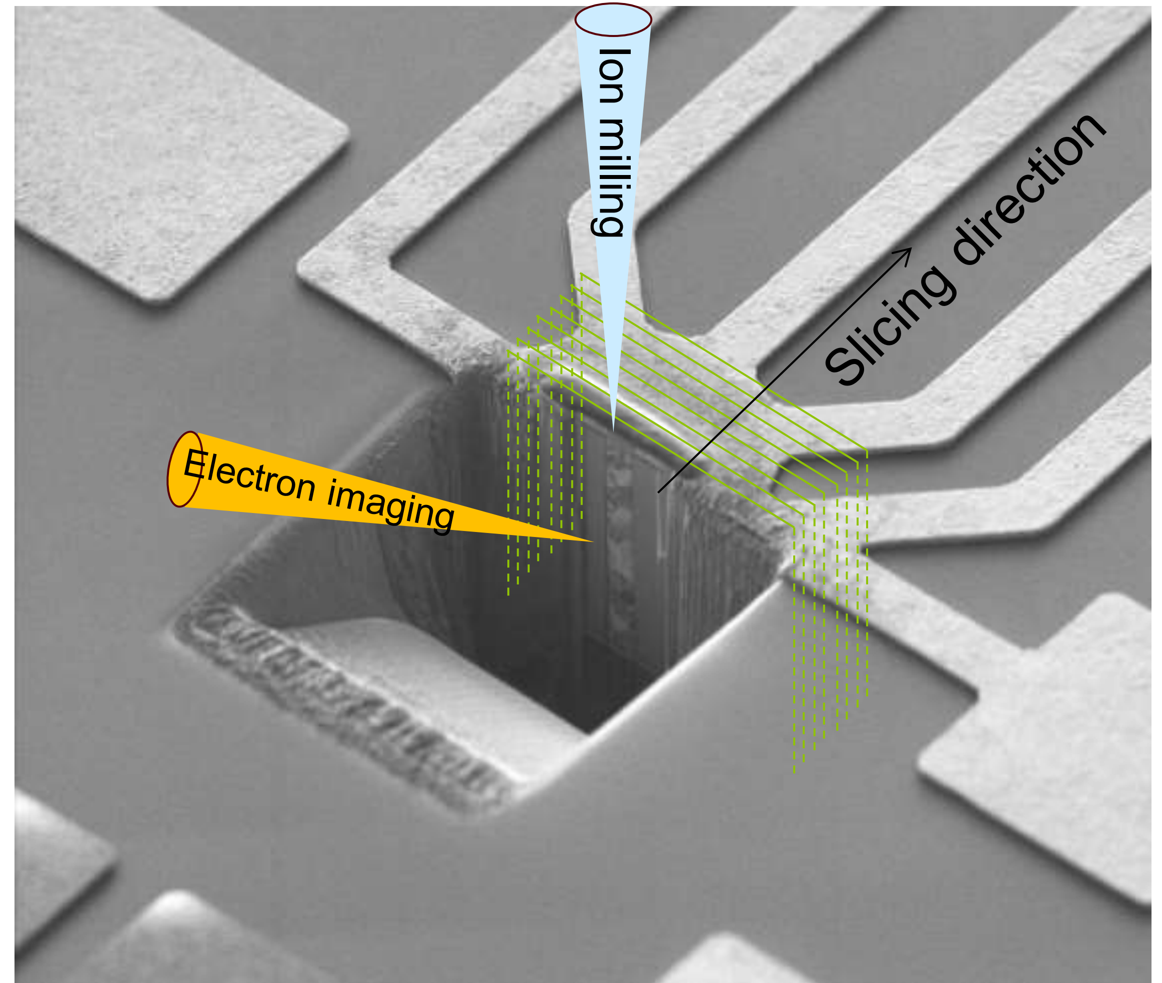
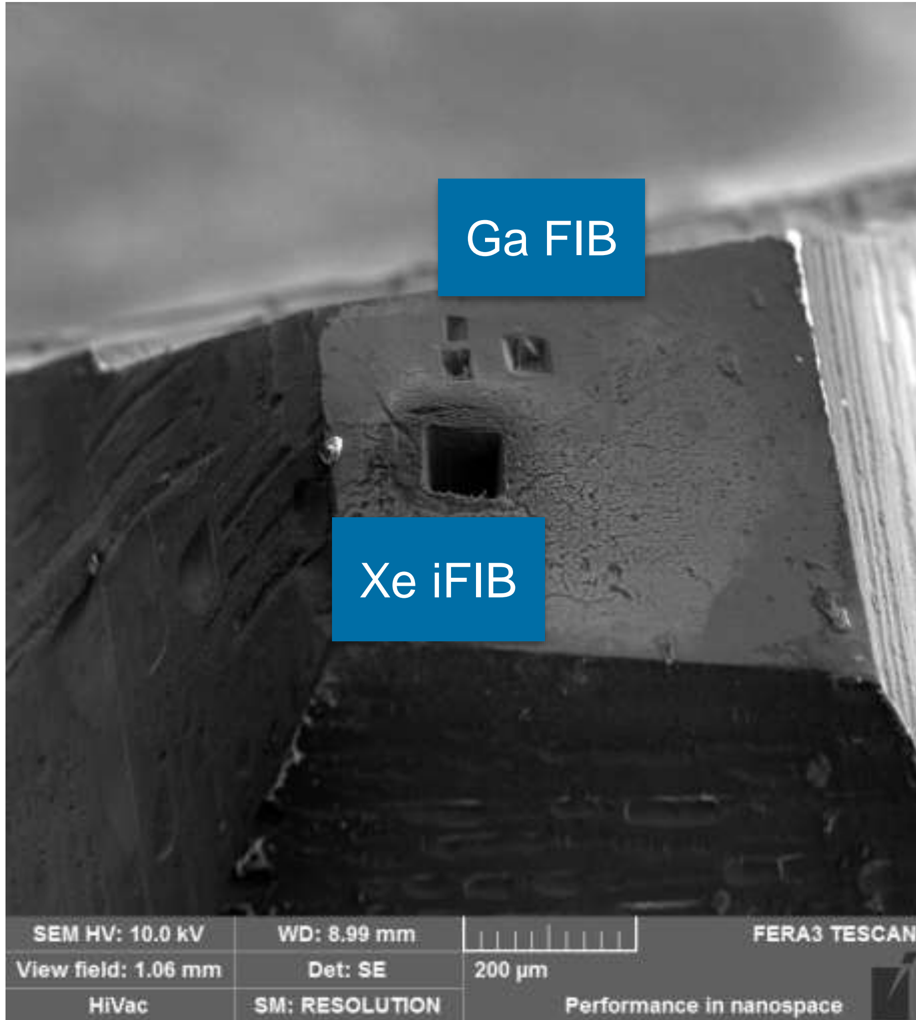
TOMOGRAPHIE

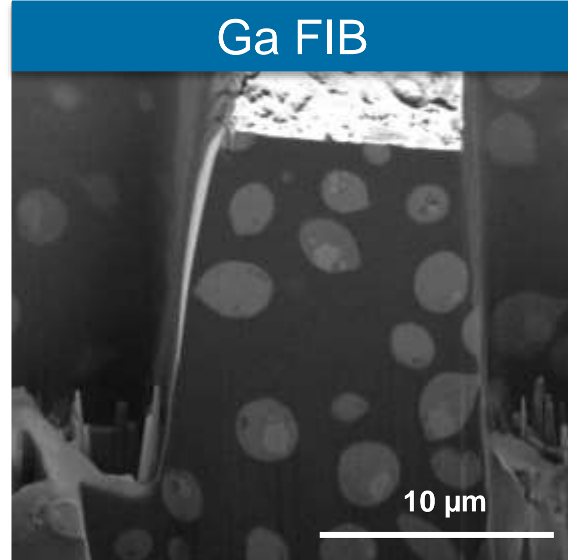
- Principle





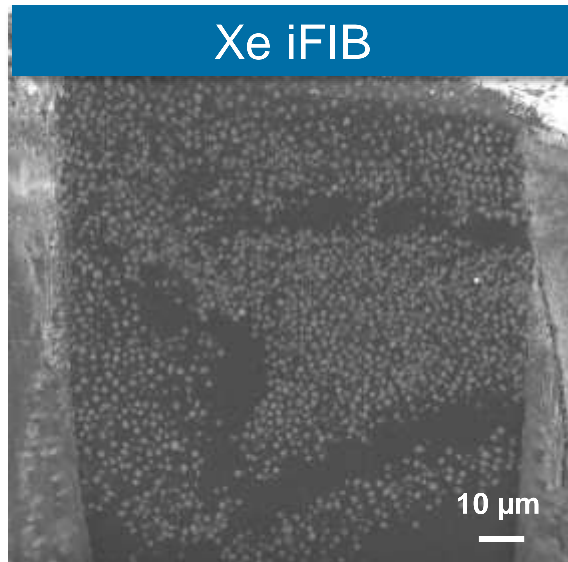
OUTIL D'ANALYSE: PFIB 3D





20µm x 20µm

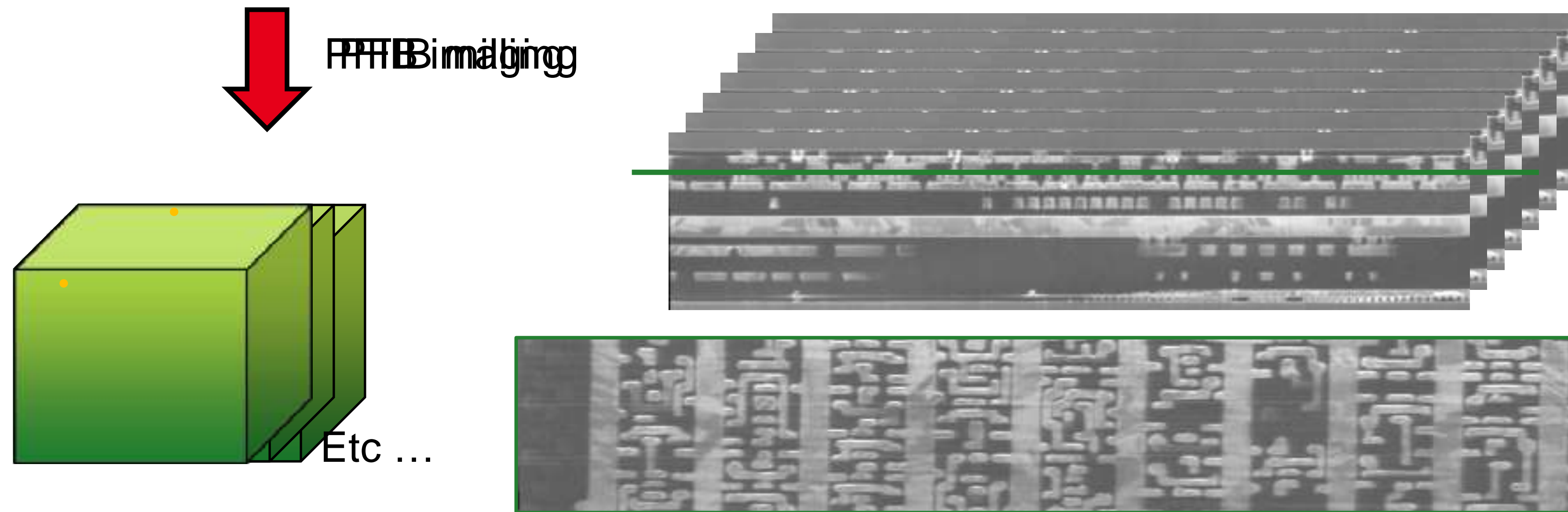
Données fournies par Tomáš Hrnčíř
Tescan Brno



100µm x 100µm

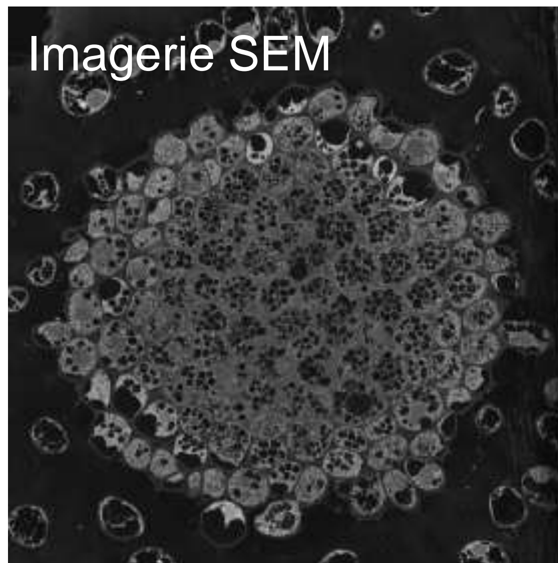
OUTIL D’ANALYSE: PFIB 3D

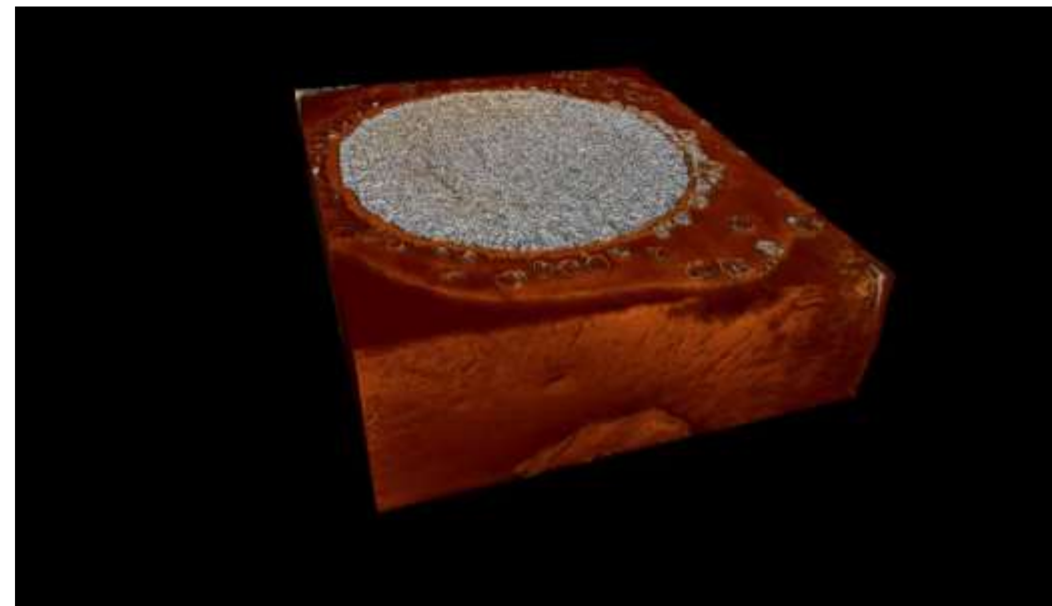
- **PFIB/PFIB 3D**

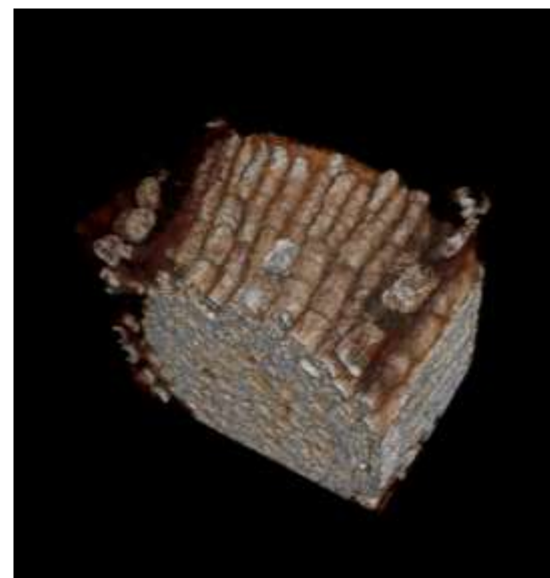


Thèse Alexandra Fraczkiewicz, CEA Leti, 2017

PFIB/SEM 3D SUR RACINE D'ORGE







TESCAN
PERFORMANCE IN NANOSPACE

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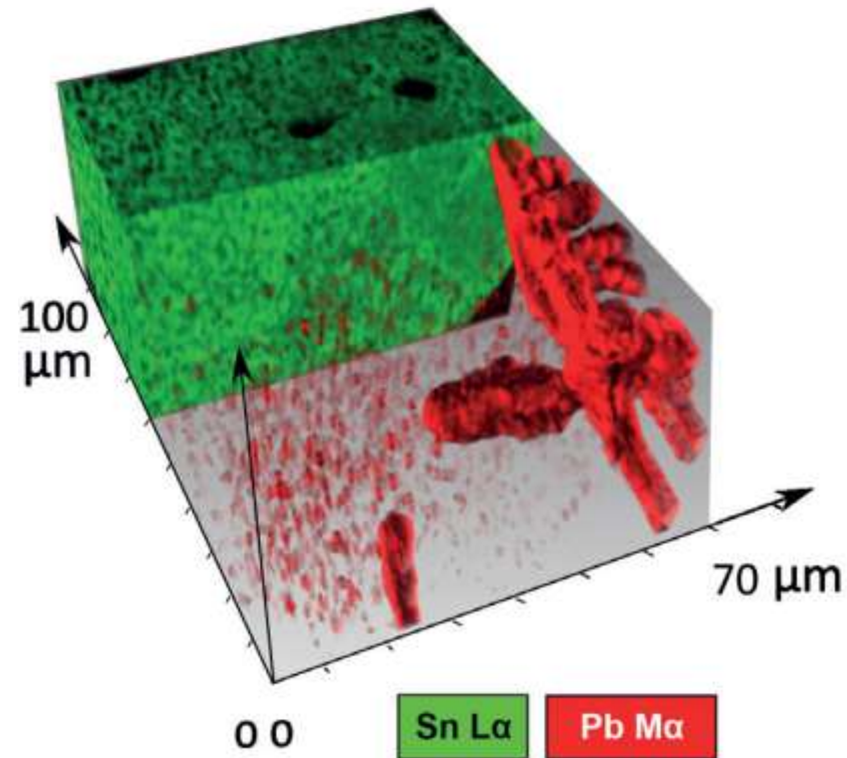
PFIB/SEM 3D + EDX

- **Possibilité de coupler l'imagerie avec**
  - Analyse chimique par EDX

Soudure SnPb

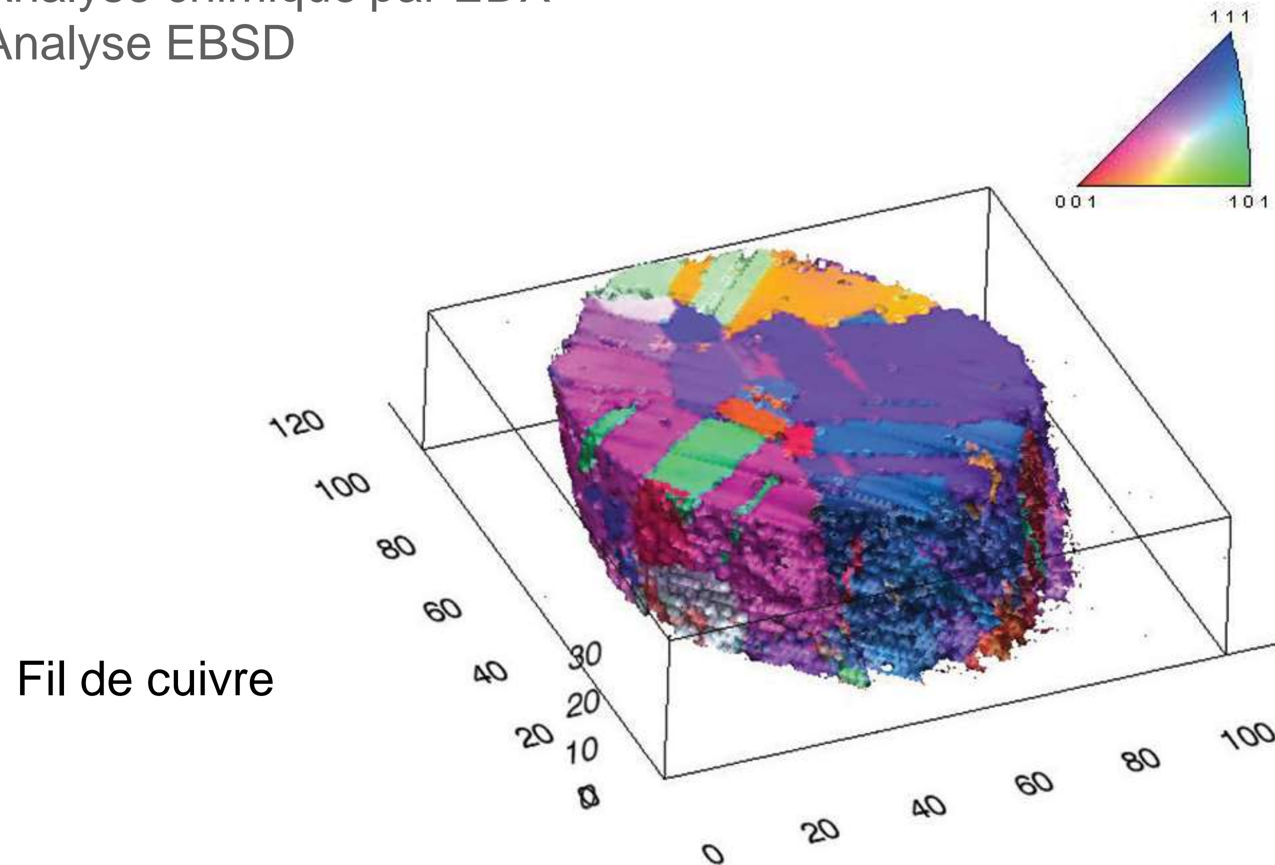


100 x 70 x 45 µm3
2,5 h acquisition
45 tranches

Données fournies par Tomáš Hrnčíř
Tescan Brno

PFIB/SEM 3D + EBSD

- **Possibilité de coupler l'imagerie avec**
  - Analyse chimique par EDX
  - Analyse EBSD



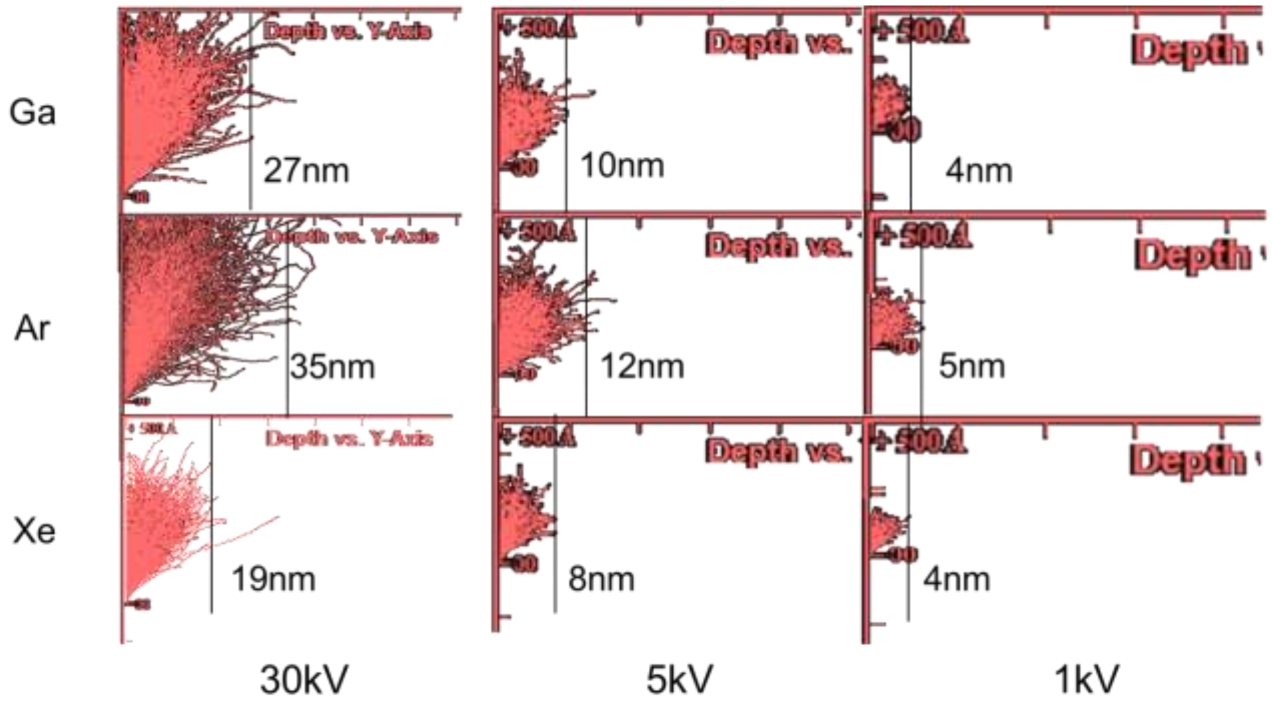
Fil de cuivre

100 x 100 x 30 µm3
2,5 h acquisition
30 tranches
1 min de coupe + 4 min acquisition EBSD

Données fournies par Tomáš Hrnčíř
Tescan Brno

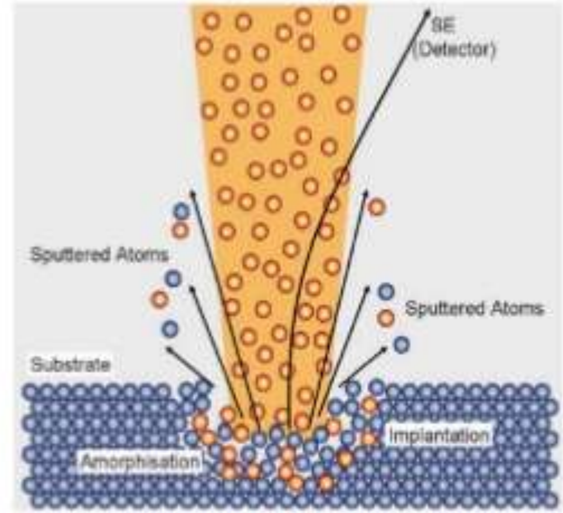
ARTEFACTS

- Perte de la structure cristalline (amorphisation)



- Implantation des espèces ioniques (Xénons)

- Génération de phonons: augmentation locale de la température



Stopping and range of ions in matter
Monte Carlo simulation

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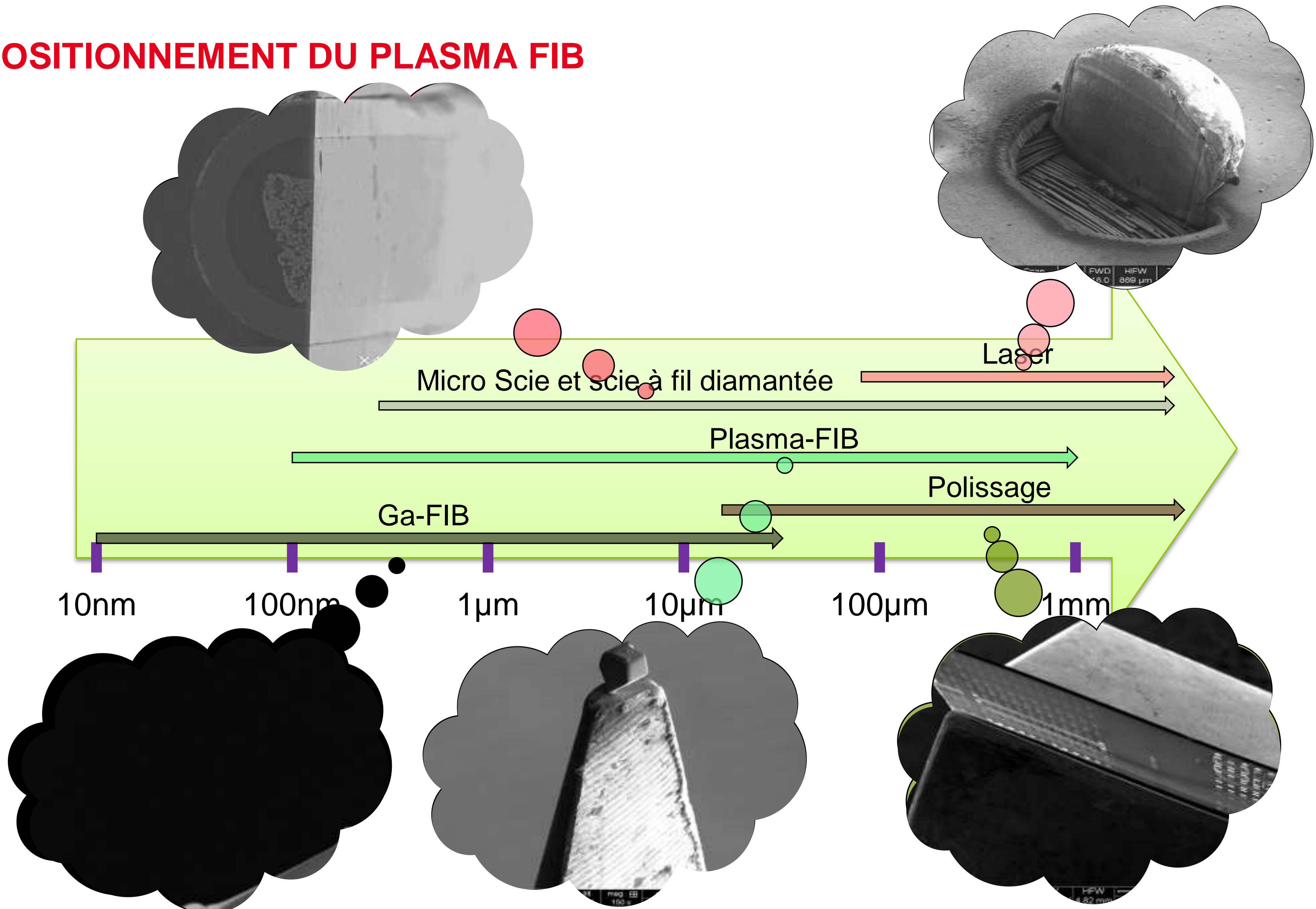
RÉSUMÉ ET FICHE PRATIQUE

- **Un Plasma FIB permet:**
  - D'atteindre des zones enterrées (sub100µm), localisée ou non
  - D'analyser de larges zones
  - D'avoir plus de statistique

- **Quand utiliser le PFIB:**
  - Sur un échantillon difficile ou impossible à polir
    - Sensible à l'eau
    - Fragile ou cassant
    - Matériau mou qui tartine
    - Empilement de matériaux très inhomogènes
  - Pour des préparations spécifiques
    - Cylindres pour la tomographie R-X
    - Lames TEM
    - Pointes SAT
  - Lorsque les coupes au FIB Gallium pose problème (matériaux chimiquement sensibles au gallium)

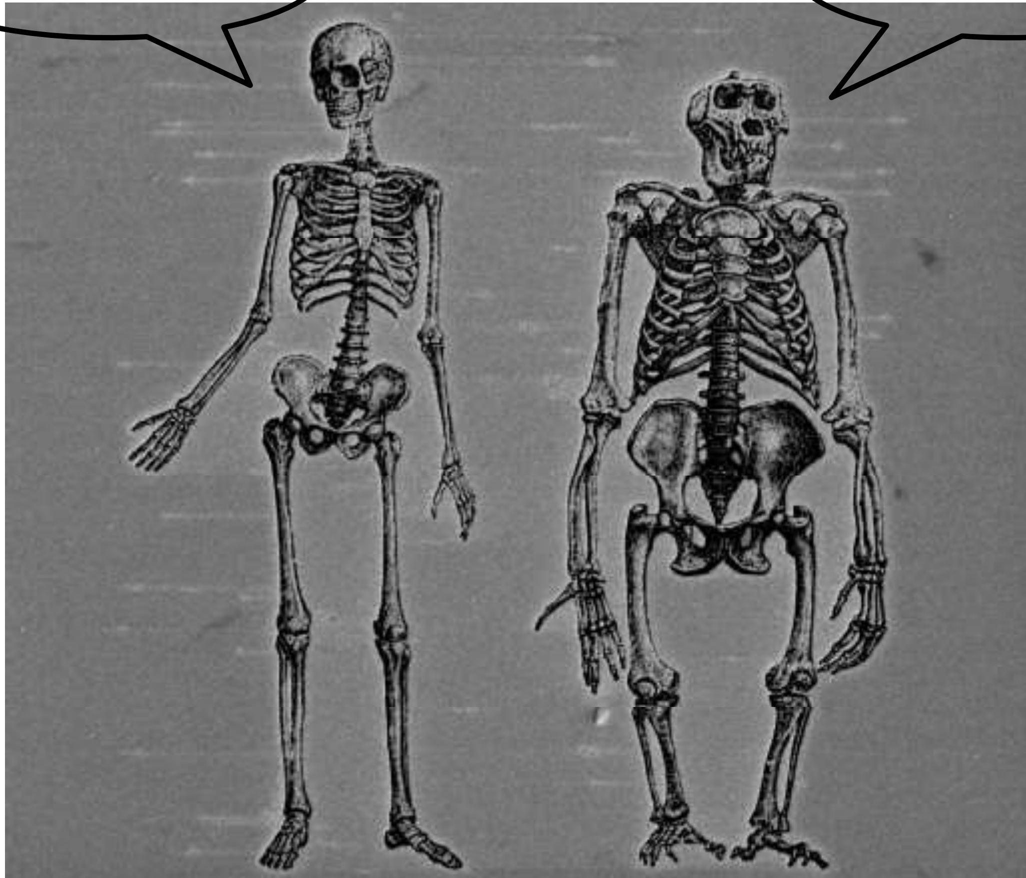
- **Nouvelle perspectives instrumentales annoncées (IMC '18): source modulable multi-gaz (Xe, O, N, Ar)**

POSITIONNEMENT DU PLASMA FIB



Questions ?

Anyone ?



Troisième workshop du réseau FIB européen

12-14 juin 2019
Dresde, Allemagne

www.eu-f-n.org

Contact: guillaume.audoit@cea.fr

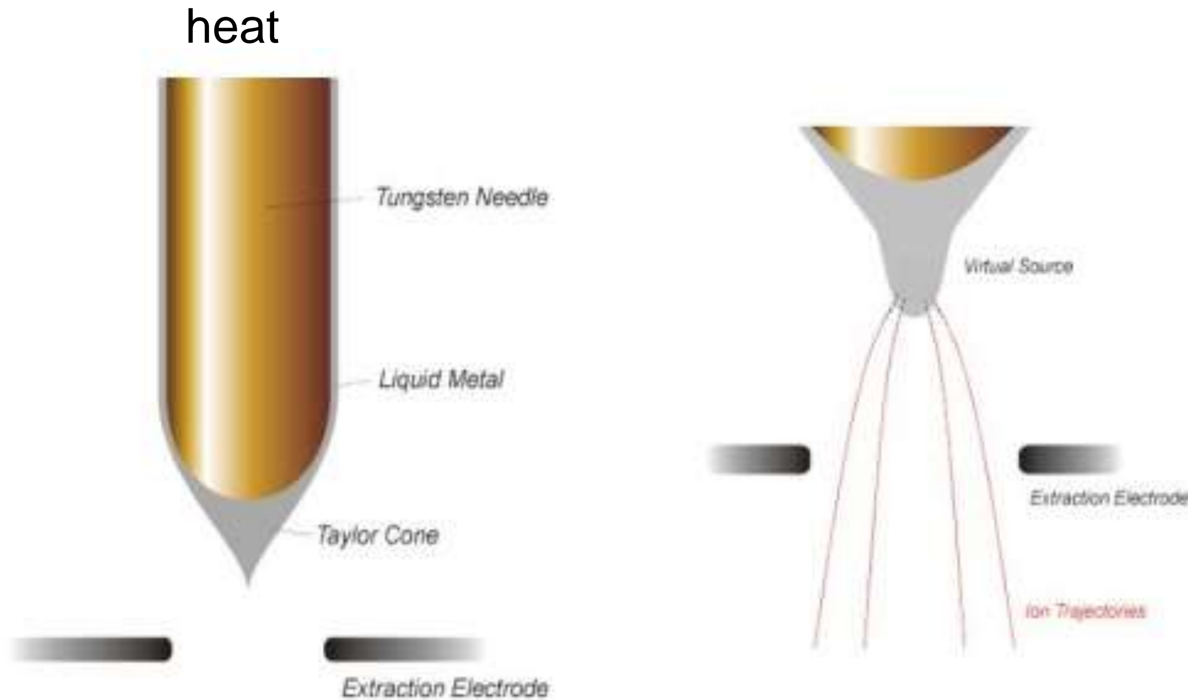
Merci à

Leti, technology research institute
Commissariat à l'énergie atomique et aux énergies alternatives
Minatec Campus | 17 rue des Martyrs | 38054 Grenoble Cedex | France
www.leti.fr

LIQUID METAL ION SOURCE

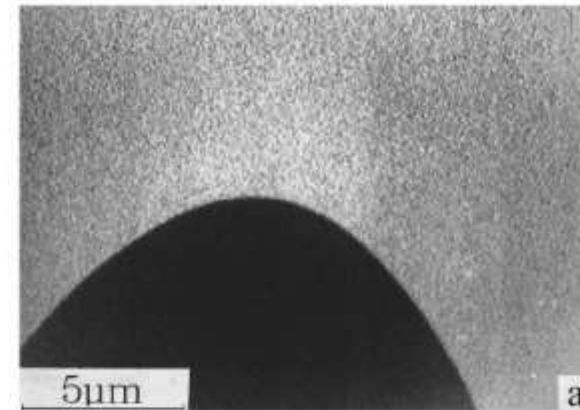
- Principe

heat

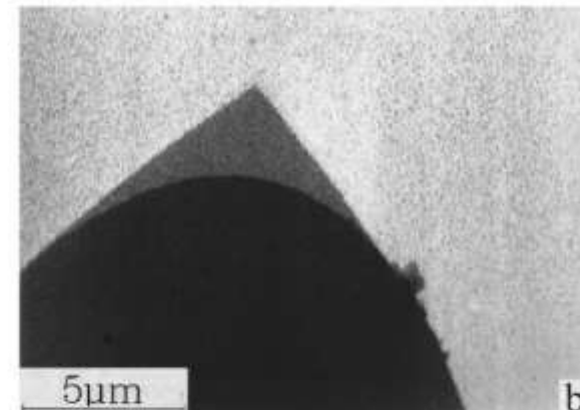


Extraction voltage

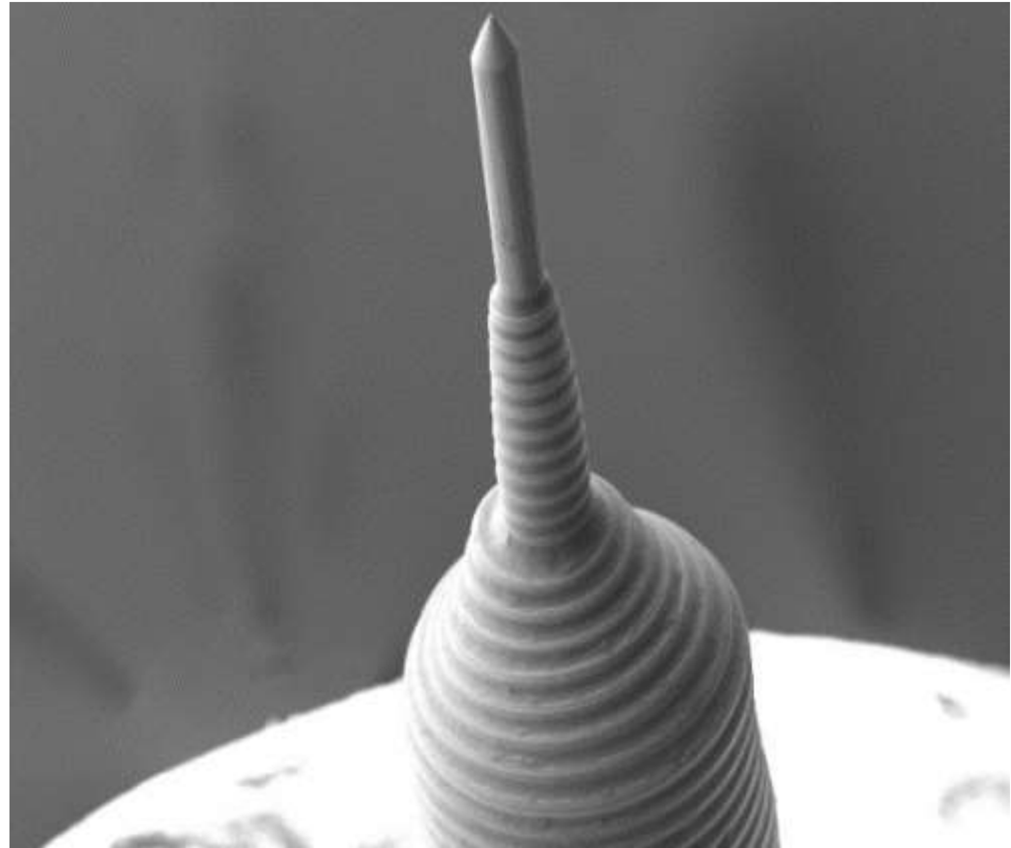
Taylor cone + Electric field 10 V / nm
Point source 2 - 5 nm in diameter



in less than 1/50 second…



LIQUID METAL ION SOURCE



LIQUID METAL ION SOURCE

- **LMIS's have been made from many materials**
- **Requirements:**
  - Low melting point (29.8°C for Ga) → no interdiffusion
  - Low volatility at the melting point
  - Low surface energy free energy (viscous behavior)
  - Low vapor pressure (pure form, no evaporation)
  - Excellent mechanical, electrical, vacuum properties
  - Good emission characteristics

H																	He
Li	**Be**											**B**	C	N	O	F	Ne
Na	Mg											**Al**	**Si**	**P**	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	**Fe**	Co	Ni	**Cu**	**Zn**	**Ga**	**Ge**	**As**	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	**Pd**	Ag	Cd	**In**	**Sn**	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	**Au**	Hg	Tl	**Pb**	**Bi**	Po	At	Rn
Fr	Ra	Ac	Unq	Unp	Unh												
		Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		
		Th	Pa	**U**	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr		

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FOCUSED ION BEAM SOURCE

- **FIB column**
  - Ion source : bright, small (~50nm)
  - Electrostatic lenses,
  - Beam deflectors and a stigmator
  - Operating currents

Beam current (pA)	Spot Size (nm)
1	7
10	12
30	16
50	19
100	23
500	39
3000	81
20000	427

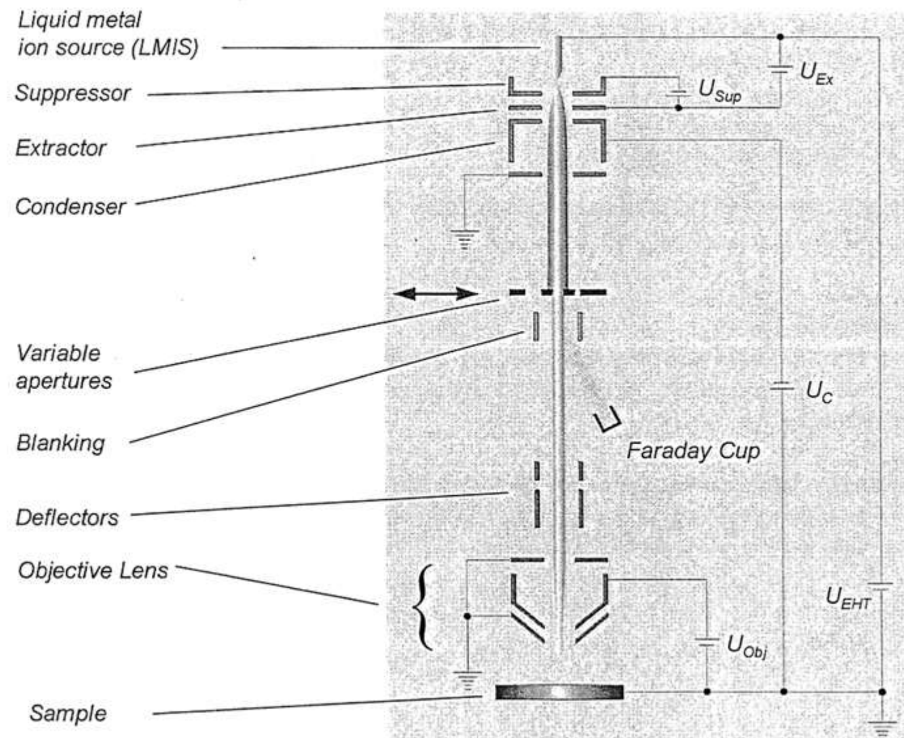
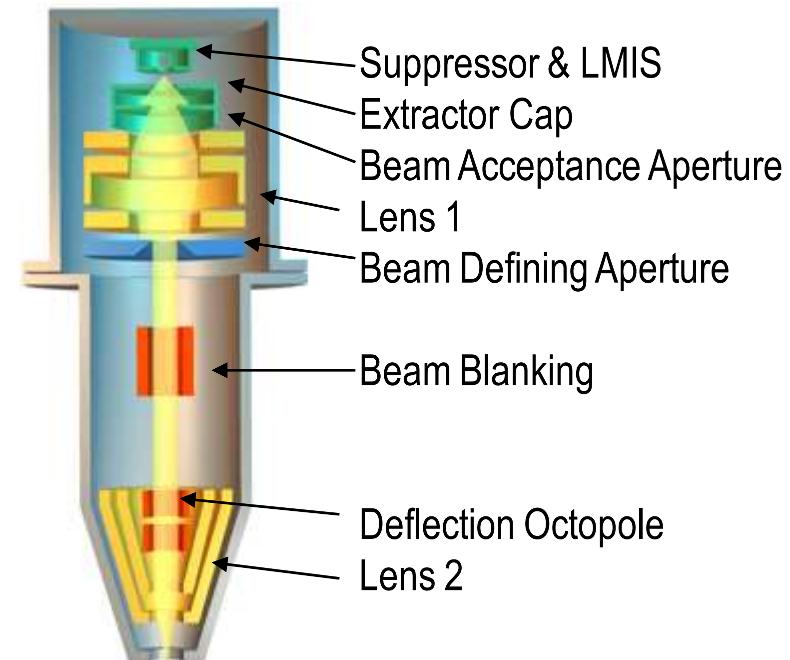


Fig. 2-1 Overview over the ion column



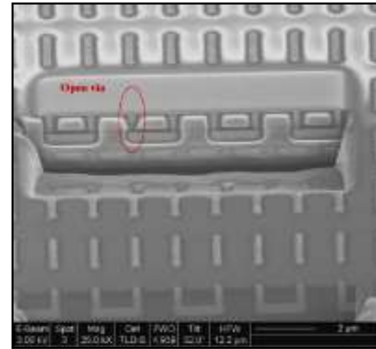
GALLIUM LIQUIDE VS. PLASMA XENON

- Intensité des courants jusqu'à quelques µA (vs 100nA pour LMIS Ga)
- Le Xénon est plus lourd que le gallium

Un PFIB grave plus vite

Ou

A temps égal, de plus grand volumes peuvent être gravés

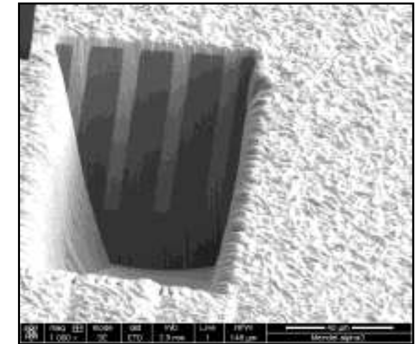


More Moore:

Typical volumes: 10 x 10 x 10 µm^3

Standard FIB mill rate < 5 µm^3 /s

Total Mill time ~ **3-10 min with Ga-FIB**



More than Moore:

Typical volumes: 100 x 100 x 100 µm^3

Standard FIB mill rate < 5 µm^3 /s

Total Mill time ~ **50 hrs with Ga-FIB**
1 hr with Xe-FIB

ThermoFisher SCIENTIFIC

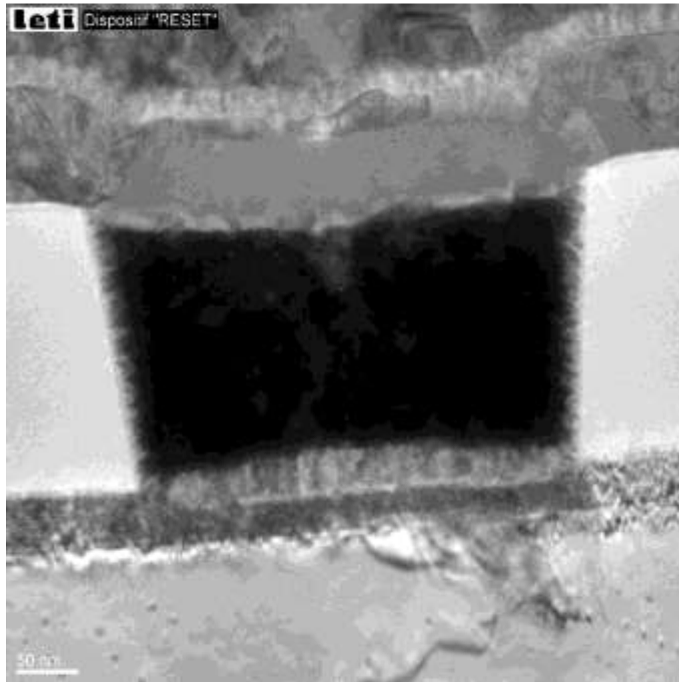
FOCUSED ION BEAM ARTIFACTS AND LIMITATIONS: TEMPERATURE

[Ref]	Beam type	Conditions	Measure	Material	Temp (° C)
[1]	i-Beam	FIB, Ga+, 30kV/1nA FIB, Ga+, 30kV/0,1nA FIB, Ga+, 30kV/0,01nA	Nano-thermoprobe	Amorphous Si	1000 ° C 350° C 250° C
[2]	i-Beam	PIPS, Ar+, 6kV, 80° incidence	Thermo-couple	Glass, SiO2	330° C
[3]	e-Beam	SEM all tension and current	Monte Carlo	GaAs	Up to few 100° C
[4]	i-Beam	PIPS, Duo Mill, Ar+, 5kV	TEM imaging (structure)	Al	230 to 400° C
[5]	i-Beam	FIB, 30kV	Laser model simulation	Si, GaAs SiO2	100° C 1000° C

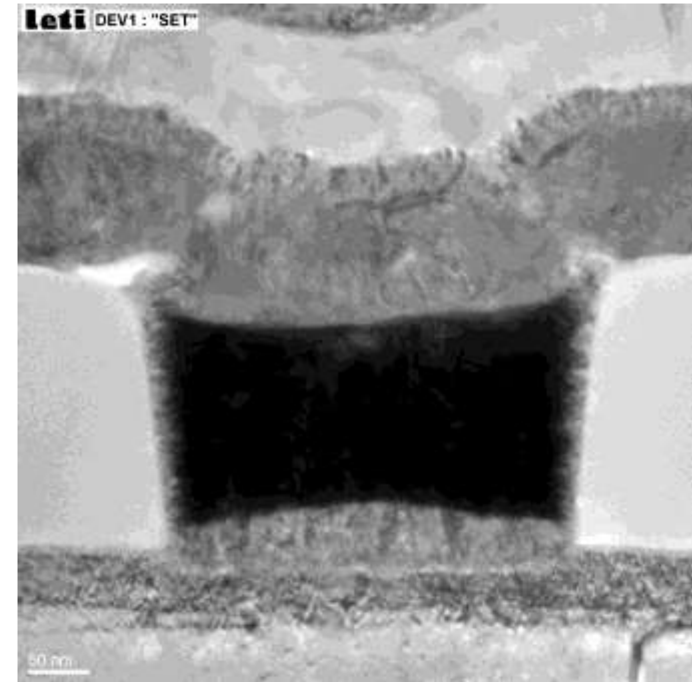
[1] Study of temperature rise during focused Ga ion beam irradiation using nanothermo-probe, Appl Surf Sc, **2009**
[2] Measurement and estimation of temperature rise in TEM sample during ion milling, Ultramicroscopy, **2007**
[3] Monte Carlo model of the temperature rise at a GaAs surface under en electron beam, Surf & Int An, **2006**
[4] Heating of TEM specimens during ion milling, Ultramicroscopy, **2001**
[5] Calculation of local temperature rise in FIB sample preparation, J. Electron. Micr., **1995**

FOCUSED ION BEAM ARTIFACTS AND LIMITATIONS: TEMPERATURE

- Example of temperature generated artifact: phase change memories material



GeTe amorphous
RESET

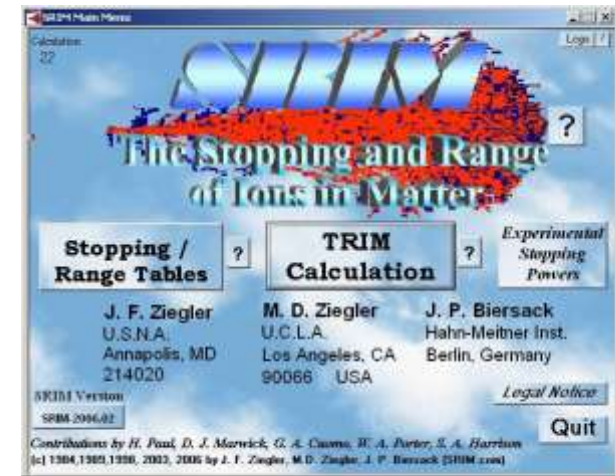


GeTe cristalline
SET

LAMES TEM

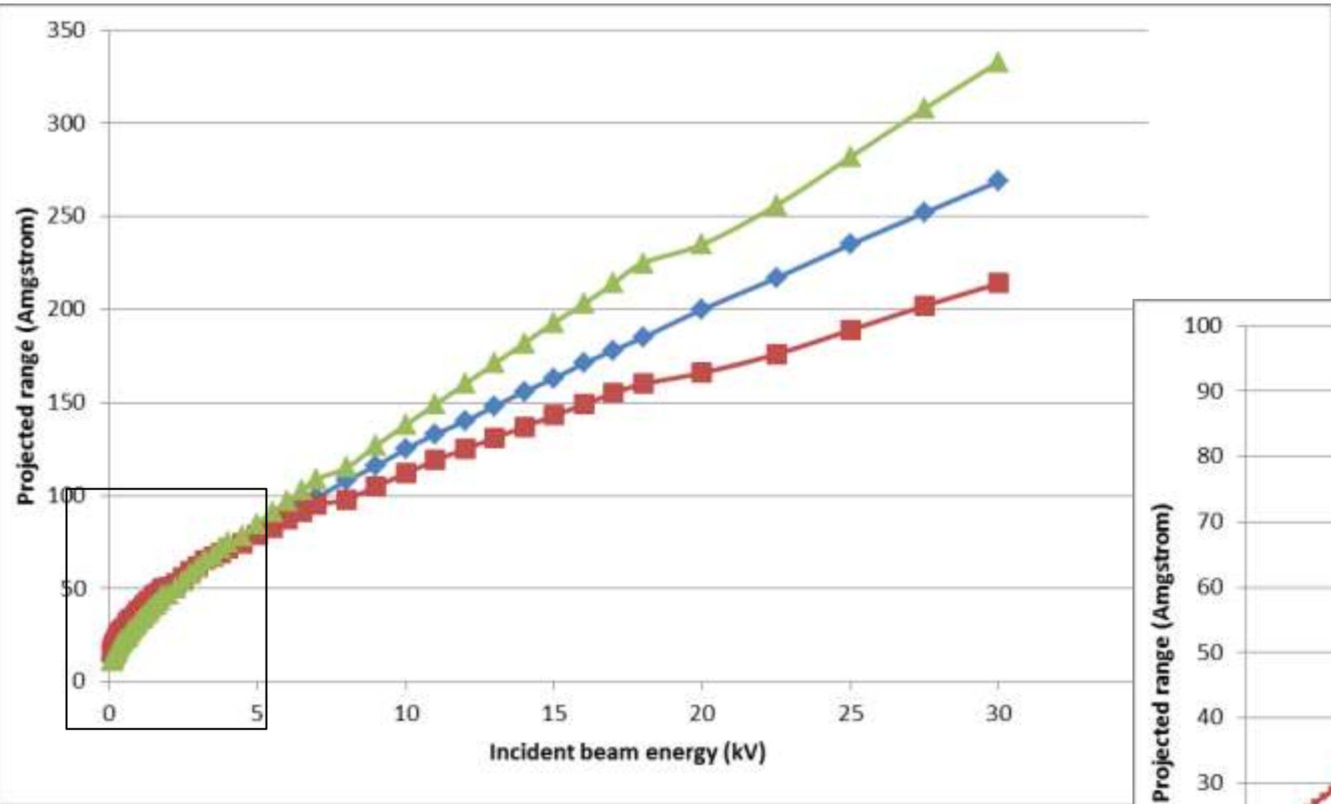
- **Utiliser des ions Xénons au lieu du gallium**
  - Amorphisation et implantation

	30kV	5kV	1kV
Ga	27nm	10nm	4nm
Ar	35nm	12nm	5nm
Xe	19nm	8nm	4nm

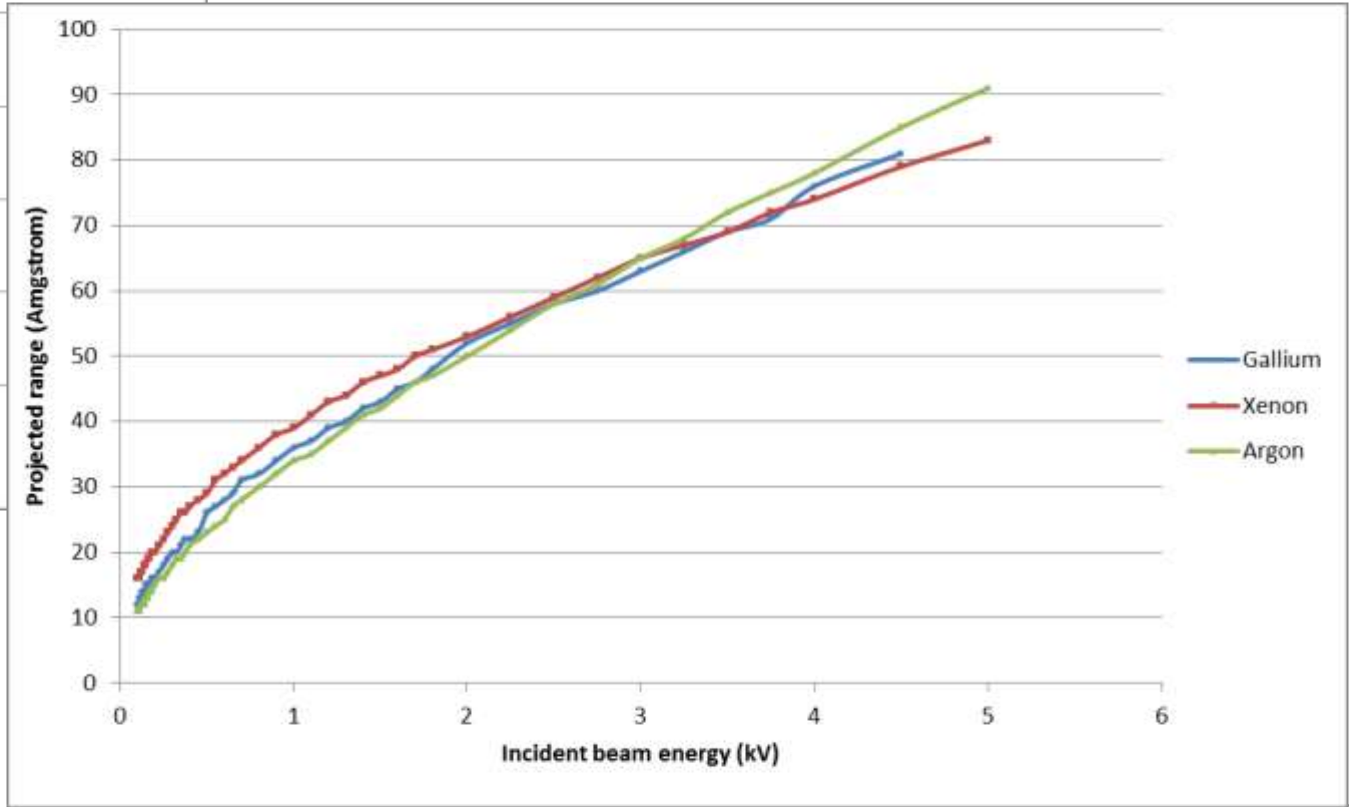


Stopping and range of ions in matter
Monte Carlo simulation

Hrncir et al., ISTFA 2015



350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
Projected range (Amgstrom)
Incident beam energy (kV)



100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
Projected range (Amgstrom)
Incident beam energy (kV)
Gallium
Xenon
Argon