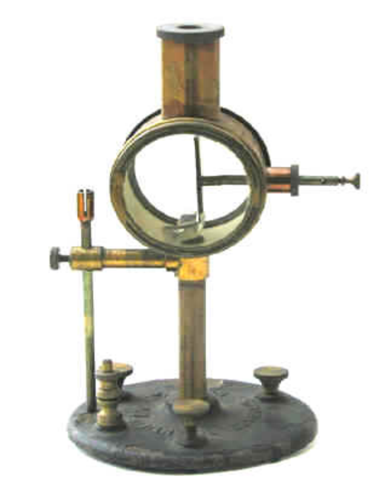
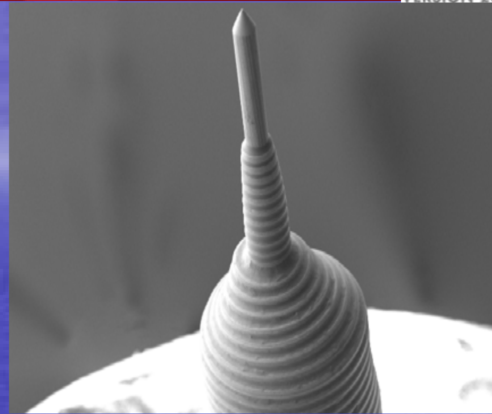
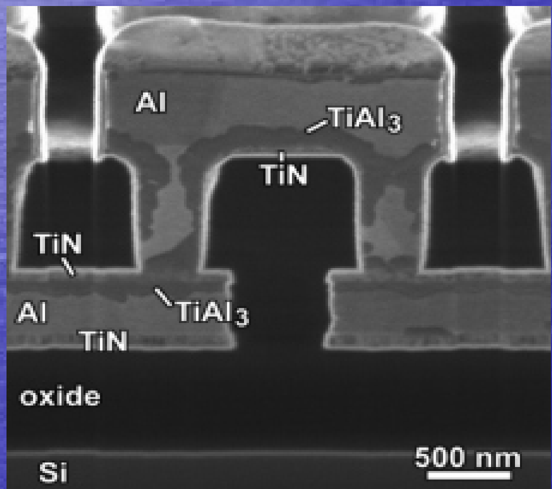
OUTLINE



⇨ History of LMIS / FIB

⇨ LMIS principles



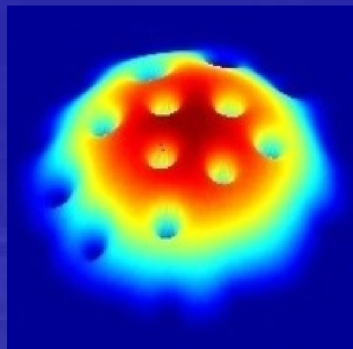


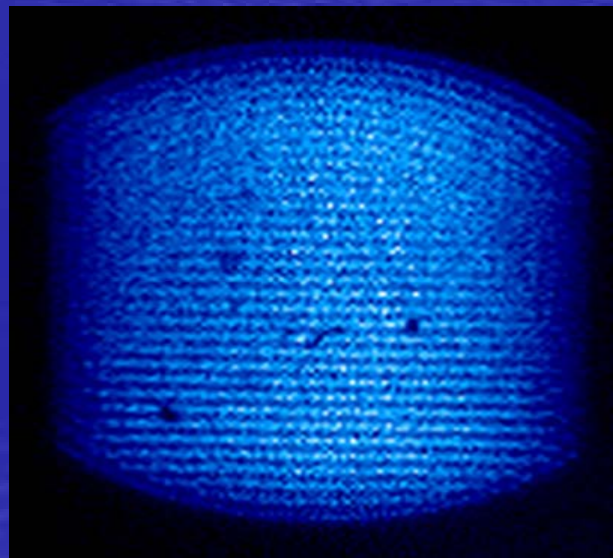
FIB cross-section through a hot Al via chain

© IMEC

⇨ F.I.B. technology

⇨ Future of FIB





Early observations

History of Taylor cones

Gilbert (1600)
fluid under high tension forms a cone

Zeleny (1914)
Observed and filmed cones and jets

Taylor (1964)
exactly conical solution to equations of Electro Hydro Dynamics (EHD)

Gilbert was the scientist (and probably lover) of Queen Elisabeth I, she was fond of physical phenomena.

From Joakim Reuteler
ETH - DMATL

NANOSOLUTIONS by ORSAYPHYSICS

Early work

THE

PHYSICAL REVIEW.

THE ELECTRICAL DISCHARGE FROM LIQUID POINTS, AND A HYDROSTATIC METHOD OF MEASURING THE ELECTRIC INTENSITY AT THEIR SURFACES.[1]

By John Zeleny.

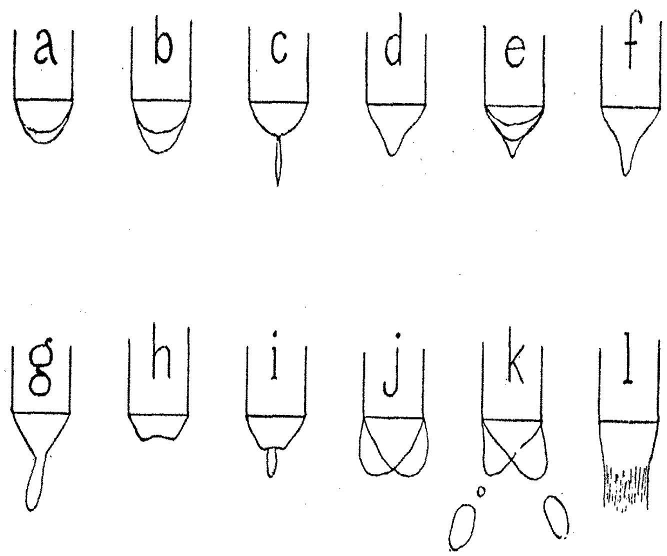


Fig. 3.

Oscillations of meniscus during intermittent discharge.

Zeleny 1914: he took excellent ultra fast pictures of TC moving the photo plaque with a rubber band! Inventor of Zeleny Electroscope (University of Minesota)

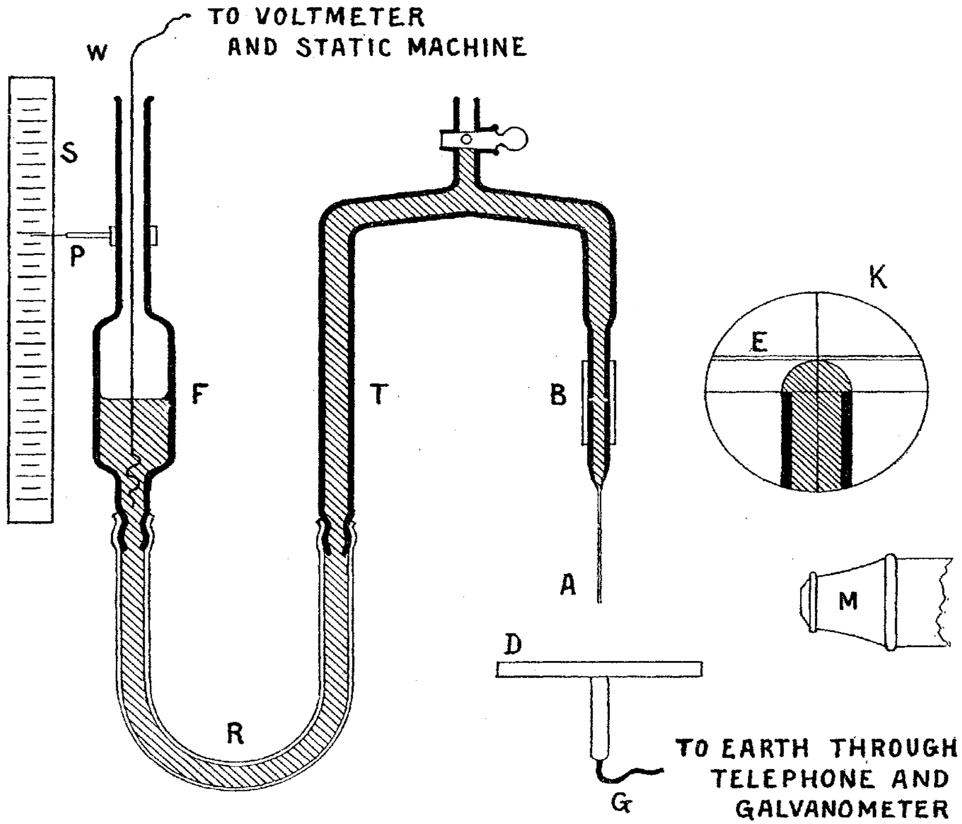


Fig. 1.

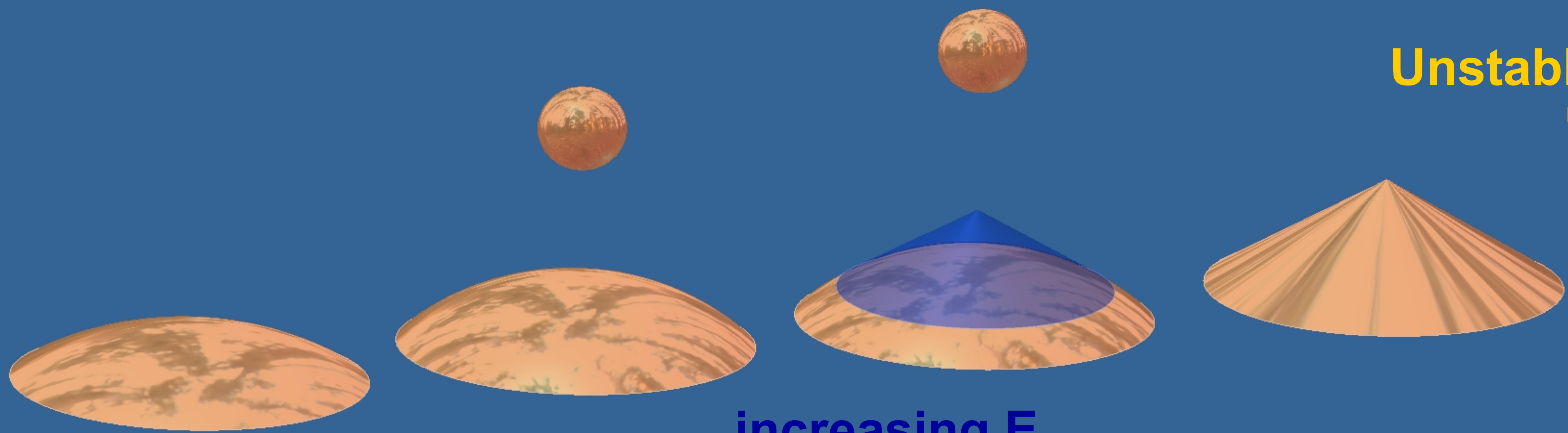
Diagram of apparatus.

History of LMIS

⇨Interaction Electric field - Liquid surface

Electrostatic energy and surface tension energy

Unstable ⇨



increasing E

E=0

Gibert-Taylor Cone

Droplets

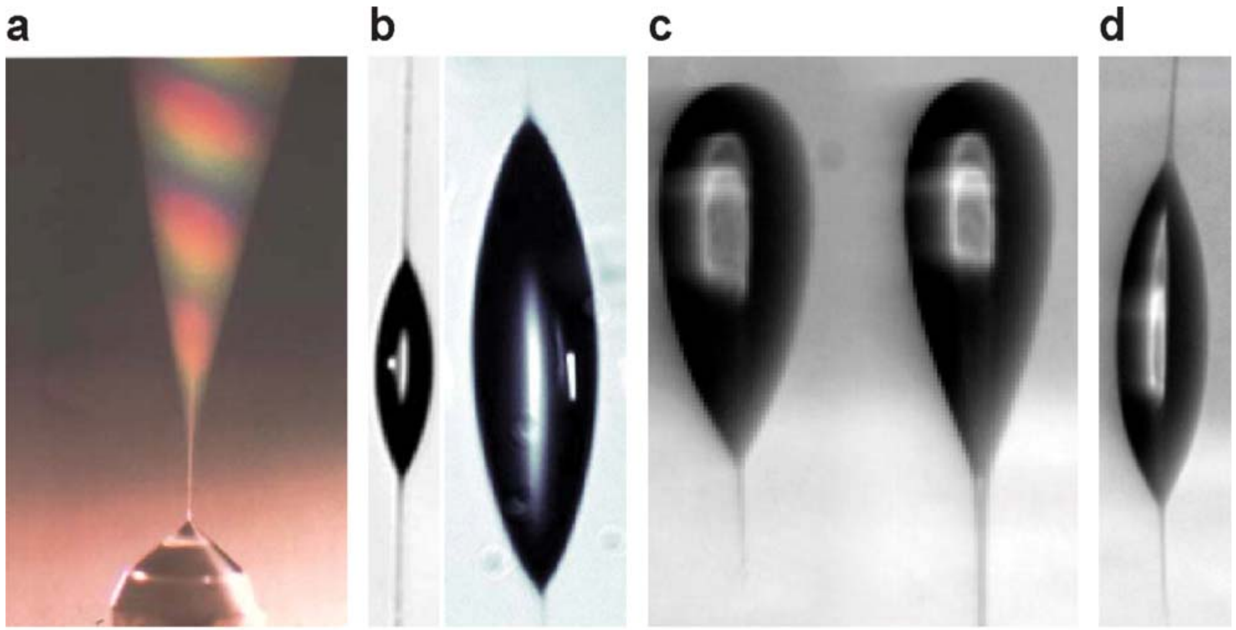
meniscus

Stable

Unstable

Stable

History of LMIS



Fernández de la Mora J. 2007.
Annu. Rev. Fluid Mech. 39:217–43

a: TC on capillary
b: ethylene-glycol Rayleigh explosion no external field
c: idem plus external field
d: no charge only external field

Role in thunderstorms formation!

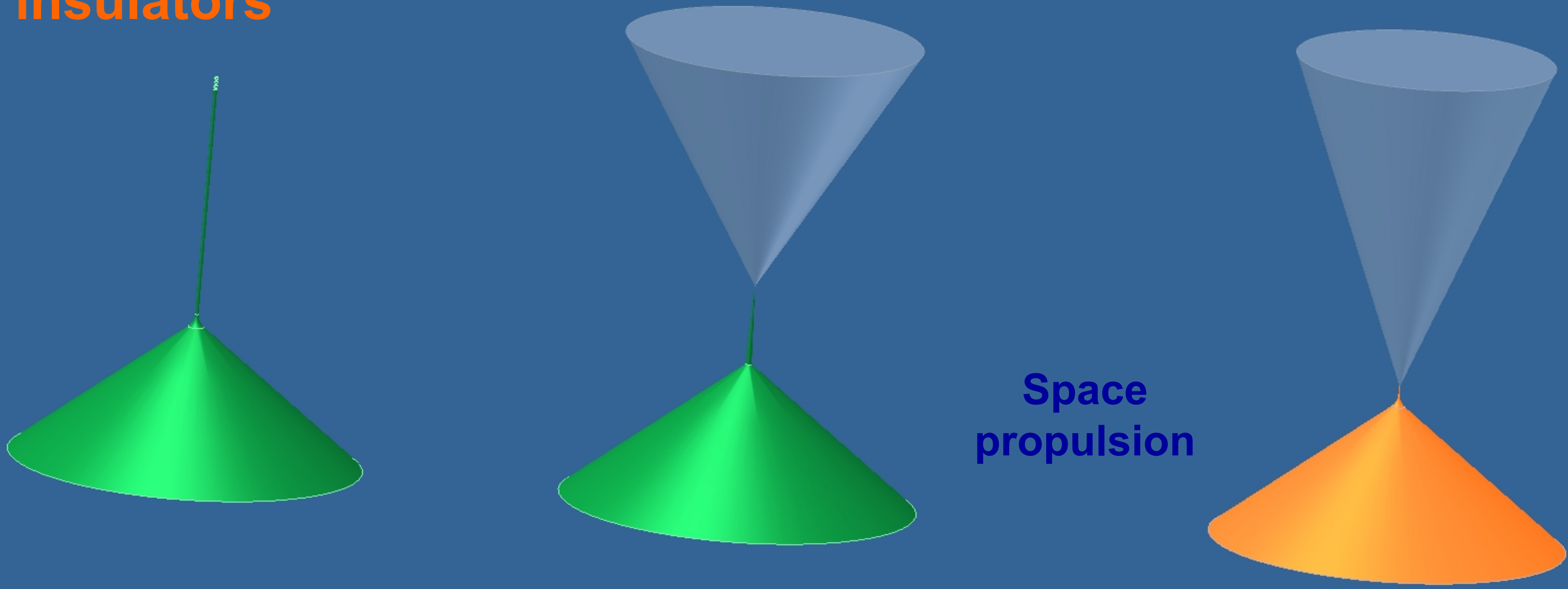
History of LMIS

Metals

electrolytes

Doped insulators

insulators



Space propulsion

(Printers)

Electro-spray MS

LMIS and FIB

L.M.I.S. principles

Some pionners of LMIS & FIB

Mahoney (1969)

Krohn Ringo (University of Chicago) 1975

Sudraud et al Paris XI Orsay (1974)

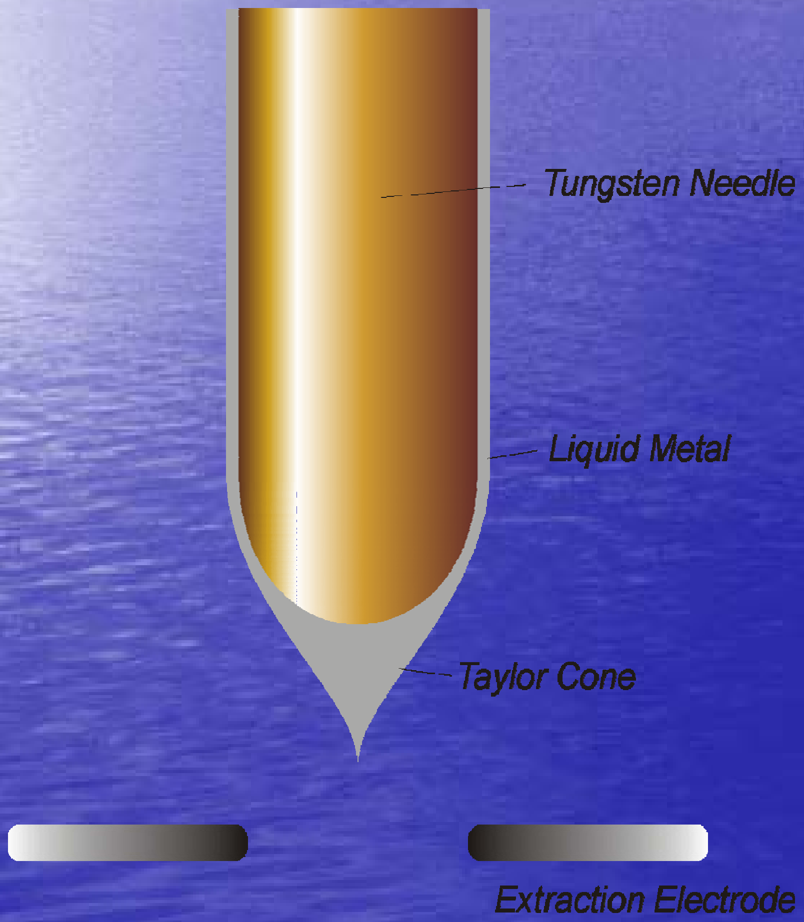
University of Oxford Mair (1980)

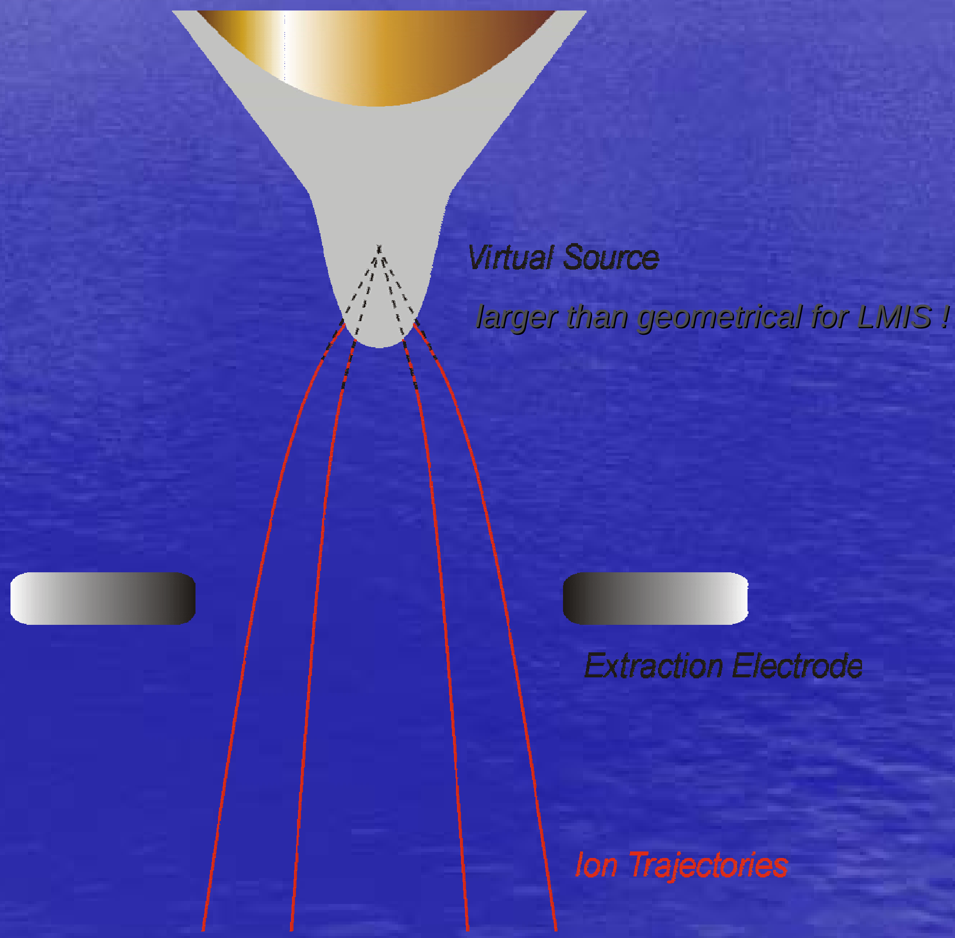
Culham UK,Roy Clampitt Prewett (1980)

Oregon Graduate Center L.Swanson (1980)

LMIS Technology

The L.M.I.S. (Liquid Metal Ion Source)





L.M.I.S. principles

LMIS concept

⇨ Substrate : Refractory, Wetting, insoluble, tip and reservoir

⇨ Temperature : Heater, T° higher than Mp

⇨ Liquid metal : low Mp, low vapor P, oxyde VP > metal VP

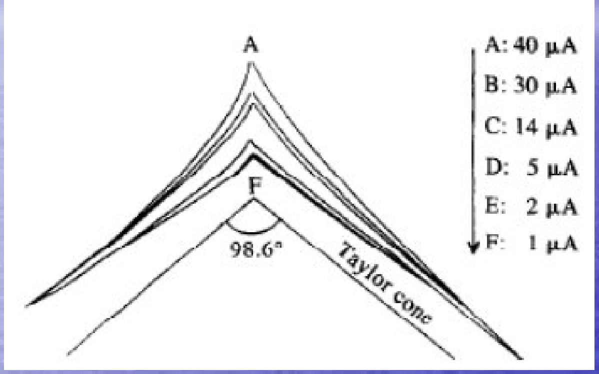
⇨ Tip : cone angle, apex radius

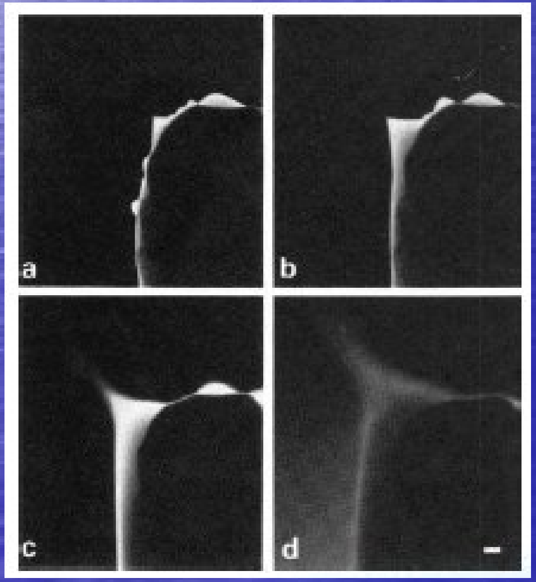
⇨ Liquid flow : surface compatibility

⇨ Reduced energy dispersion

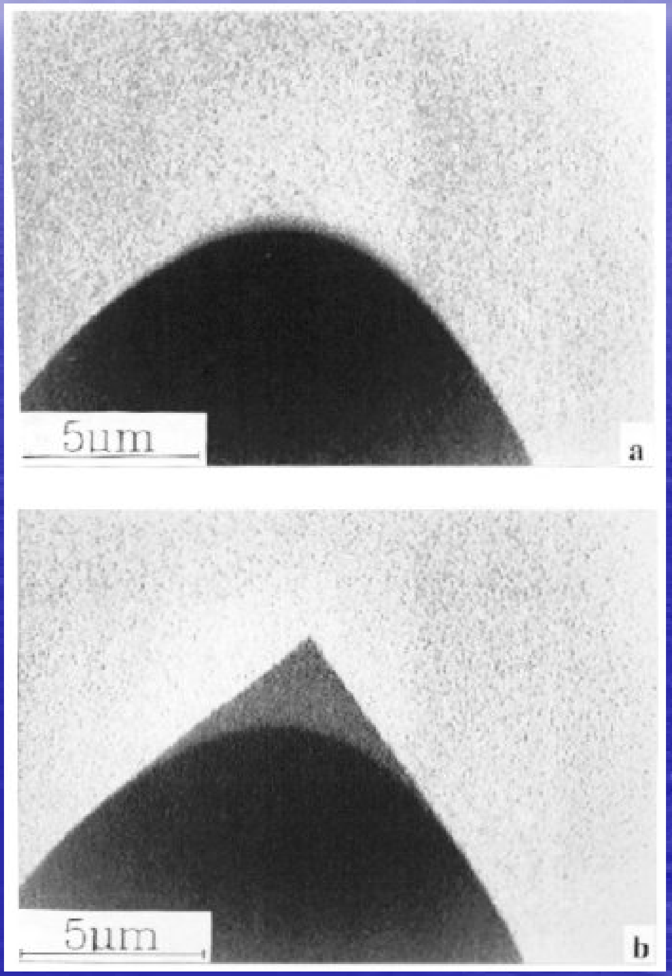
Gallium is a very good element !

L.M.I.S. (Liquid Metal Ion Source)





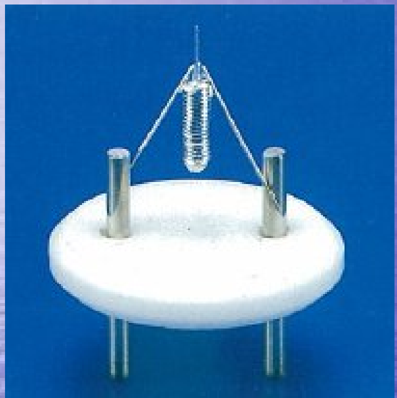
BenAssayag et al. – LPS Orsay
3 MeV TEM (1985)



Driesel et al. – MPI Halle
1MeV TEM (1996)

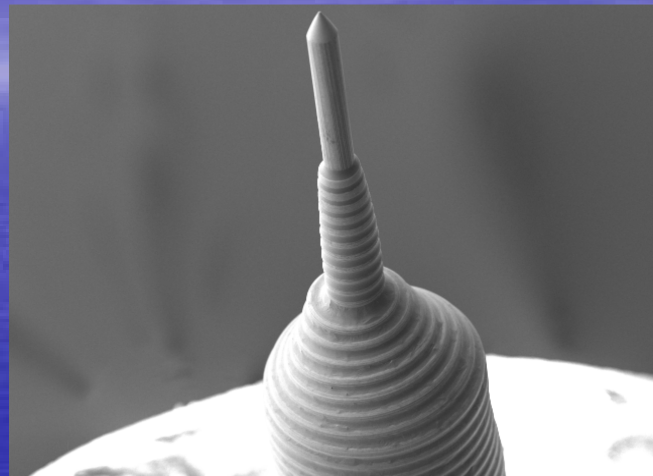
LMIS Technology

L.M.I.S. and L.M.A.I.S.



Denka Ga LMIS

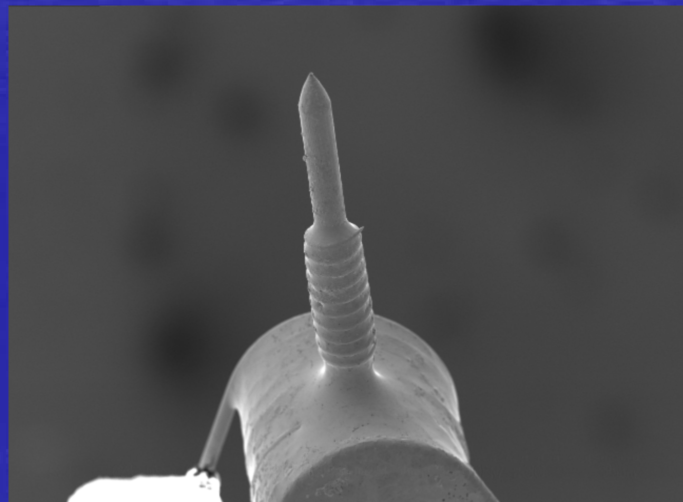
J.Gierak – LPN (F)



Orsay Physics Ga LMIS

Some geometries

L.Bischoff – FZR Dresden (D)

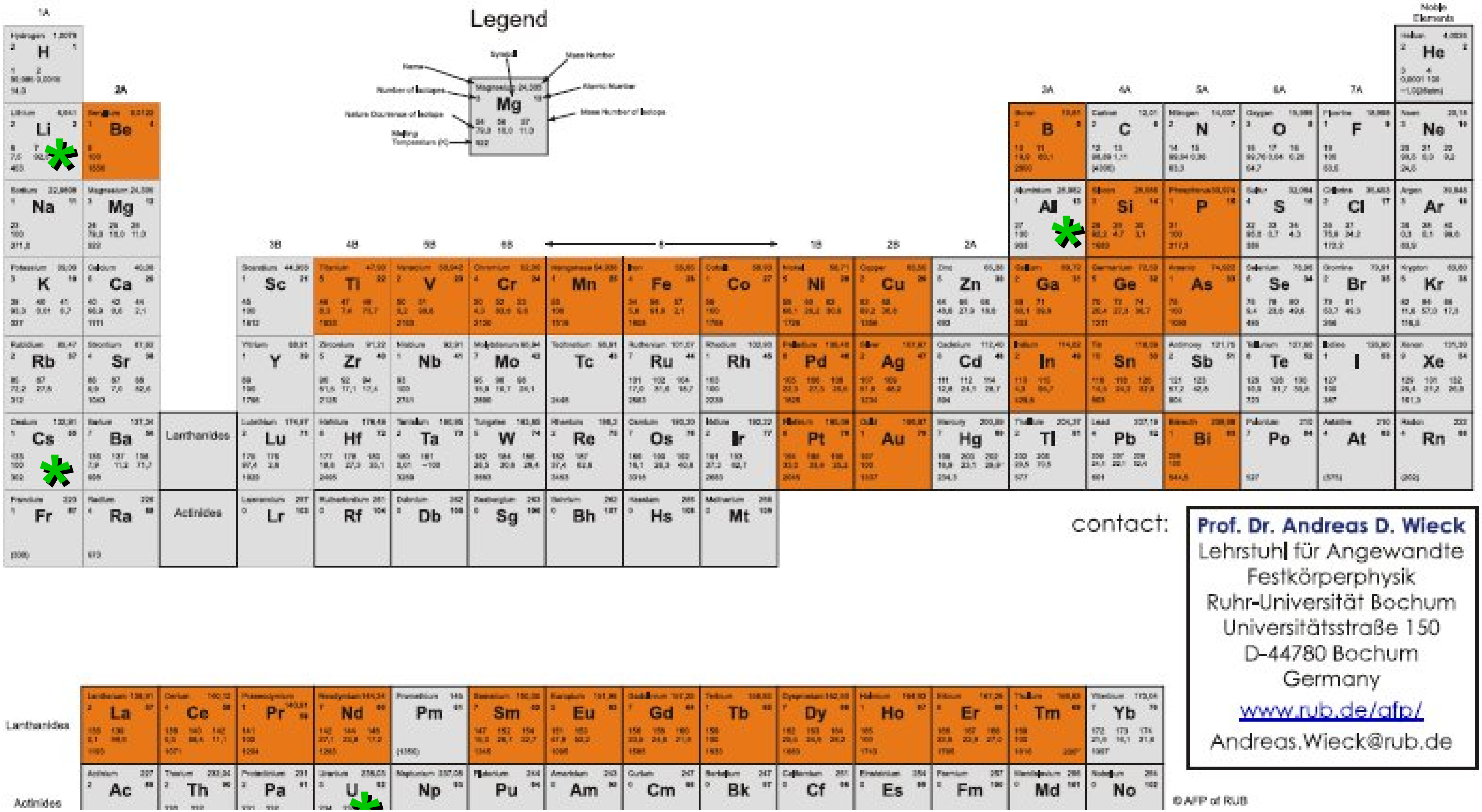


Orsay Physics alloy LMIS

NANOSOLUTIONS by ORSAYPHYSICS

LMIS Technology

Available Ion Species for Focused Ion Beam Implantation at Chair of Applied Solid State Physics of Ruhr-University of Bochum



contact:

Prof. Dr. Andreas D. Wieck
Lehrstuhl für Angewandte Festkörperphysik
Ruhr-Universität Bochum
Universitätsstraße 150
D-44780 Bochum
Germany
www.rub.de/afp/
Andreas.Wieck@rub.de

LMIS Technology

Non-exhaustive list of LMIS and LMAIS

Prof. A.Wieck - RUB

Other alloys, such as

AuSi, AuGe, GaBi, GaBiLi,

AsPdB, CoNd, MgGa,

GePd (Mühle et al, ETH)

etc…

are also available.

	Type of LMIS	Most intensive fraction of ions
1	AgGe	Ge^{++}, Ge^{+}, Ag^{+}
2	AgAuGe	Ge^{++}, Ge^{+}, $Ag^{+}(Au^{++})$, Au^{+}, $AuGe^{+}$
3	AuBeSi	Be^{++}, Be^{+}, Si^{++}, Si^{+}, Au^{++}, Au^{+}, Au_2^{+}
4	AuBGeNi	Ni^{++}, Ni^{+}, Ge^{++}, Ge^{+}, Au^{++}, Au^{+}, Au_2^{+}, $AuGe^{+}$, Au_2Ge^{+}
5	AuCeSi	Si^{++}, Si^{+}, Ce^{+++}, Ce^{++}, Ce^{+}, Au^{++}, Au^{+}, Au_2^{+}
6	AuCoGe	Co^{++}, Co^{+}, Ge^{++}, Ge^{+}, Au^{++}, Au^{+}, Au_2^{+}, $AuGe^{+}$, Au_2Ge^{+}
7	AuCrGe	Cr^{++}, Cr^{+}, Ge^{++}, Ge^{+}, Au^{++}, Au^{+}, Au_2^{+}, $AuGe^{+}$, Au_2Ge^{+}
8	AuDyGe	Ge^{++}, Ge^{+}, Dy^{+++}, Dy^{++}, Au^{++}, Au^{+}, $Au_2^{+}AuGe^{+}$
9	AuDySi	Si^{++}, Si^{+}, Dy^{+++}, Dy^{++}, Au^{++}, Au^{+}, Au_3^{++}, Au_2^{+}
10	AuErSi	Si^{++}, Si^{+}, Er^{+++}, Er^{++}, Au^{++}, Au^{+}, Au_2^{+}
11	AuEuSi	Si^{++}, Si^{+}, Eu^{++}, Au^{++}, Au^{+}, Au_2^{+}
12	AuFeGe	Fe^{++}, Fe^{+}, Ge^{++}, Ge^{+}, Au^{++}, Au^{+}, Au_2^{+}, $AuGe^{+}$, Au_2Ge^{+}
13	AuGdSi	Si^{++}, Si^{+}, Gd^{+++}, Gd^{++}, Au^{++}, Au^{+}, Au_2^{+}
14	AuGeMn	Mn^{++}, Mn^{+}, Ge^{++}, Ge^{+}, Au^{++}, Au^{+}, $AuGe^{+}$, Au_2^{+}, Au_2Ge^{+}
15	AuGeNi	Ni^{++}, Ni^{+}, Ge^{++}, Ge^{+}, Au^{++}, Au^{+}, Au_2^{+}, $AuGe^{+}$, Au_2Ge^{+}
16	AuGeV	V^{++}, Ge^{++}, Ge^{+}, Au^{++}, Au^{+}, Au_2^{+}, $AuGe^{+}$, Au_2Ge^{+}
17	AuHoSi	Si^{++}, Si^{+}, Ho^{+++}, Ho^{++}, Au^{++}, Au^{+}, Au_2^{+}
18	AuLaSi	Si^{++}, Si^{+}, La^{+++}, La^{++}, La^{+}, Au^{++}, Au^{+}, Au_2^{+}
19	AuNdSi	Si^{++}, Si^{+}, Nd^{++}, Au^{++}, Au^{+}, Au_2^{+}
20	AuSbSi	
21	AuSiSm	Si^{++}, Si^{+}, Sm^{++}, Au^{++}, Au^{+}, Au_2^{+}
22	AuSiTb	Si^{++}, Si^{+}, Tb^{+++}, Tb^{++}, Au^{++}, Au^{+}, Au_2^{+}
23	AuSiTm	Si^{++}, Si^{+}, Tm^{++}, Au^{++}, Au^{+}, Au_2^{+}
24	BPt	B^{++}, B^{+}, Pt^{++}, Pt^{+}
25	Bi	Bi^{++}, Bi^{+}, Bi_3^{++}, Bi_2^{+}, Bi_5^{++}, Bi_3^{+}, Bi_4^{+}, Bi_5^{+}
26	BiGaIn	Ga^{+}, Bi^{+}, In^{+}
27	CoDy	Co^{++}, Co^{+}, Dy^{++}, Dy^{+}
28	CuP	$P^{+}(Cu^{++})$, Cu^{+}
29	CuPPt	P^{++}, $P^{+}(Cu^{++})$, Cu^{+}, Pt^{++}, PtP^{++}, PtP^{+}, Pt^{+}
30	DyNi	Ni^{++}, Ni^{+}, Dy^{++}, Dy^{+}
31	Ga	Ga^{+}
32	GaIn	Ga^{+}, In^{+}
33	GaZn	
34	GeNiTi	Ti^{++}, Ni^{++}, Ge^{++}, Ti^{+}, Ni^{+}, Ge^{+}
35	HoNi	Ni^{++}, Ni^{+}, Ho^{++}
36	In	In^{+}
37	Sn	Sn^{++}, Sn^{+}, Sn_2^{+}, Sn_3^{+}, Sn_4^{+}, Sn_5^{+}

F.I.B. principles

Probe formation

- ⇨ Minimize radius
- ⇨ Maximize current
- ⇨ Optimize I distribution
- ⇨ Beam purity

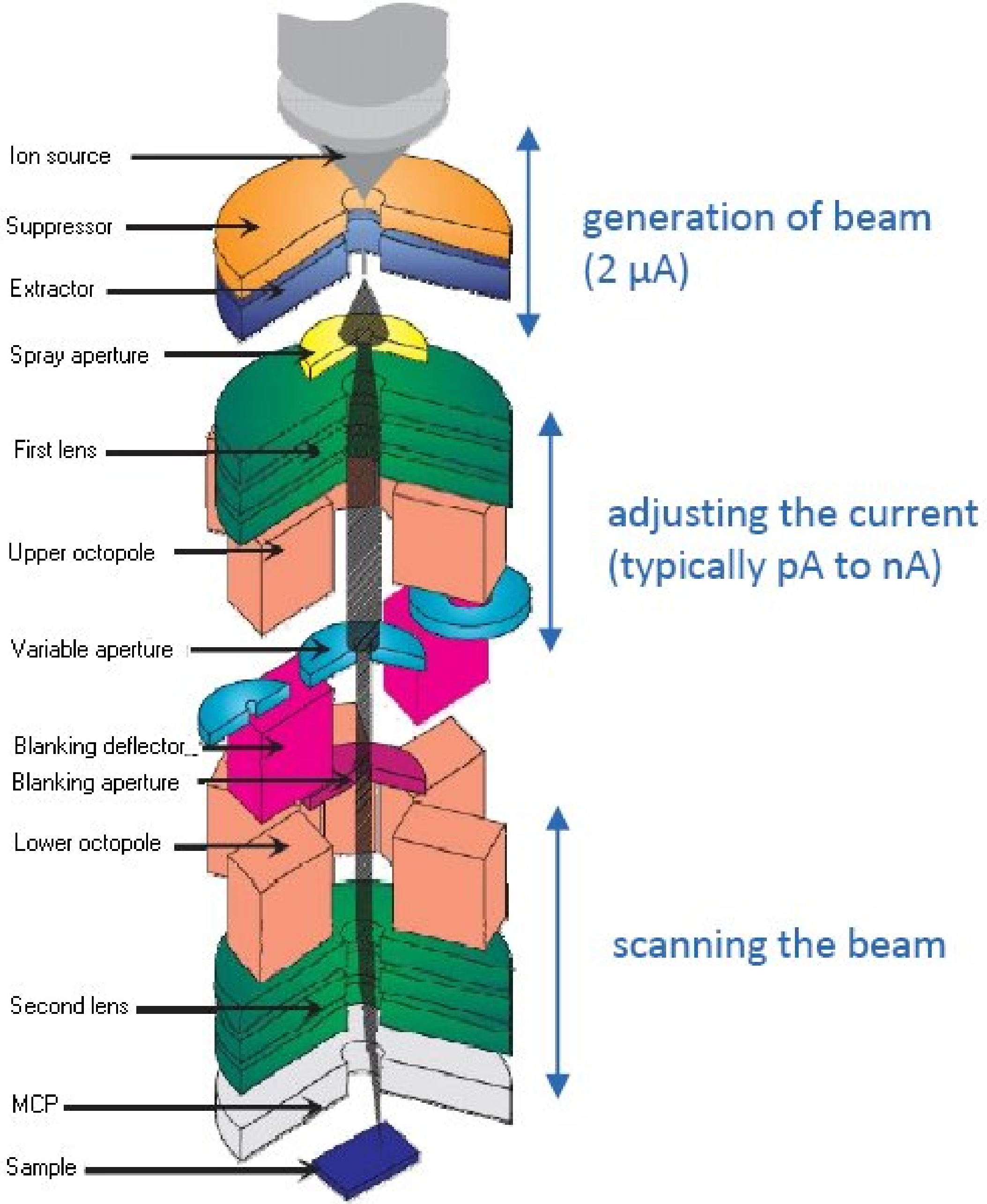
Ion optics

- ⇨ Minimize lenses aberrations
- ⇨ Chromatic linked with source ΔE
- ⇨ Spherical (large I)
- ⇨ Coma, alignment

Environment optimization

- ⇨ Electric and magnetic noises
- ⇨ Vibrations, accoustic noise
- ⇨ Thermal shifts (long working times)
- ⇨ Software automation

FIB Technology



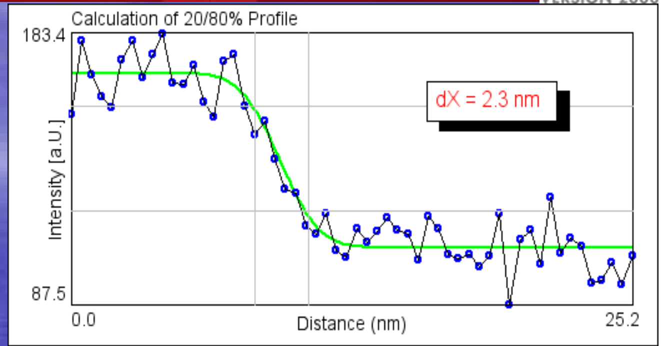
Other FIB columns :

-Sidewinder from FEI

-Cobra-FIB from OP

Typical FIB column geometry (SII Zeta) from J.Reuteler ETH Zürich

High Resolution Imaging



Resolution measurement ?

⇨SEM separation (subjective)of two objects

⇨FIB more difficult

⇨Fast scan: bad signal to noise ratio

⇨Slow scan: milling while imaging

⇨Measured in % of contrast:

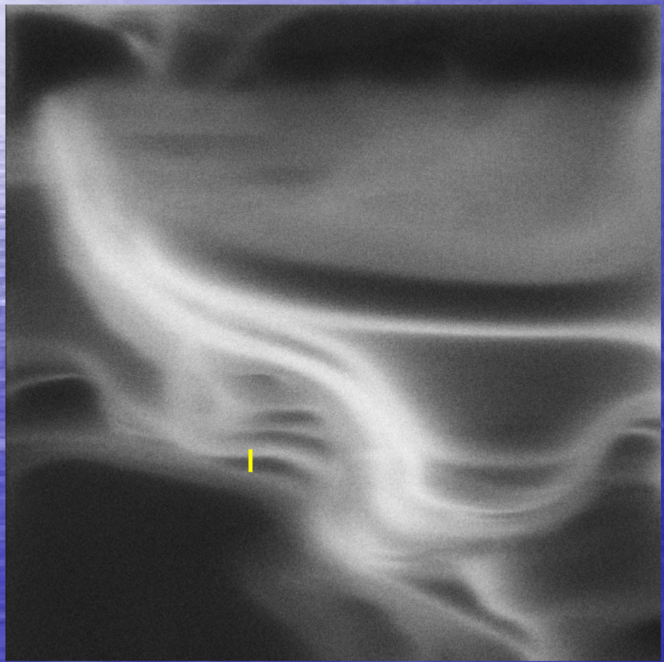
35/65%;16/84%;20/80%;25/75% or Δx_{50}

High Resolution Imaging

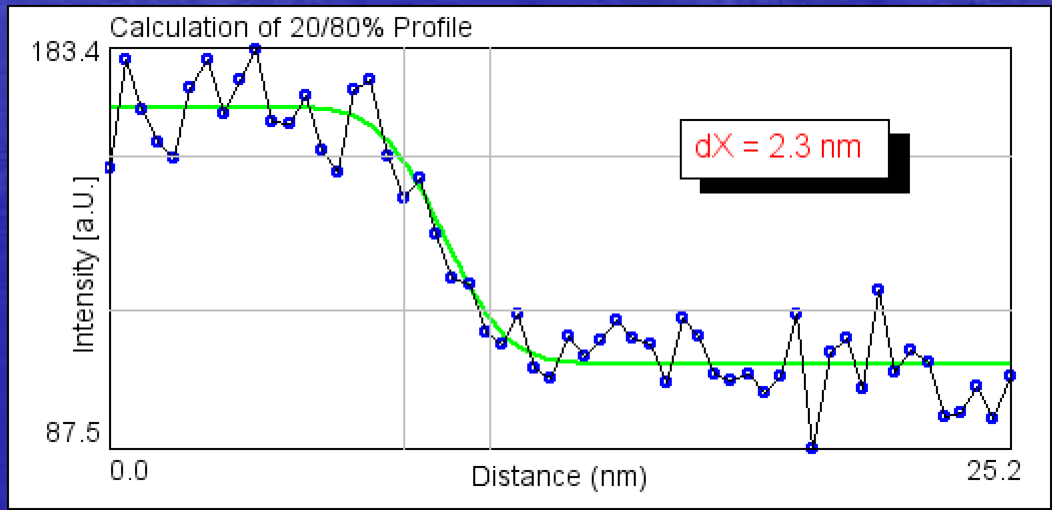
New COBRA-FIB column

Dr. Anne Delobbe
Dr. Bernard Rasser

⇨ E= 30 kV
⇨1 pA probe current



⇨ Resolution < 2.5 nm



⇨FOV = 780 nm

1,7 nm resolution has been performed at 20-80 with Cobra-FIB

Resolution measurement

« It is interesting that you should be running into beam-specimen interactions that limit resolution. Mark Utlaut, Lyn Swanson and I, made prediction for imaging resolution for a Ga FIB based on specimen damages and S/N considerations. This issue becomes even more acute now that beam sizes decrease so much. »

From Jon Orloff to P.Sudraud, June 26, 2008

Resolution and current with gaussian distribution

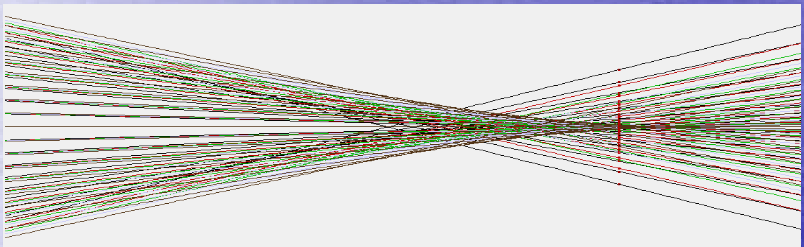
Contrast	D/sigma	I/It
10-90%	2,565	0,561
12-88%	2,355	0,5
16-84%	1,989	0,39
20-80%	1,685	0,299
25-75%	1,35	0,204
35-65%	0,771	0,072

Large current spots

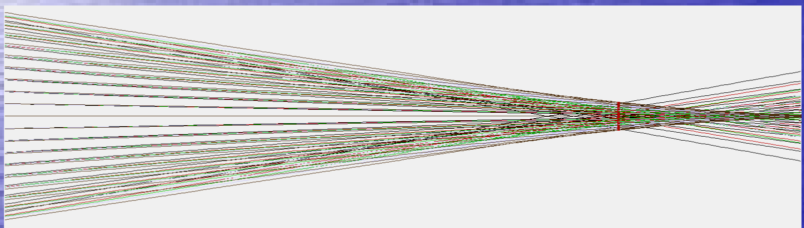
Focusing adjustment

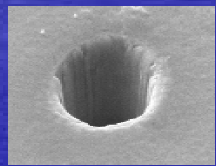
15 nA

Dr.Anne Delobbe
Dr.Bernard Rasser

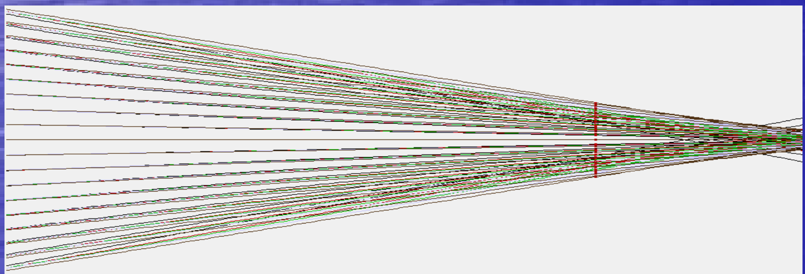


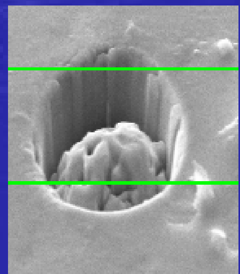
a) focus





b) - 60 V





c) - 110 V

In a) imaging resolution is optimum but milling is not sharp

In b) imaging resolution is poor, but milling is optimum.

Milling rate

Ion-solid interaction at some keV:
It involves mostly elastic collisions.
A very small quantity of heat is produced.

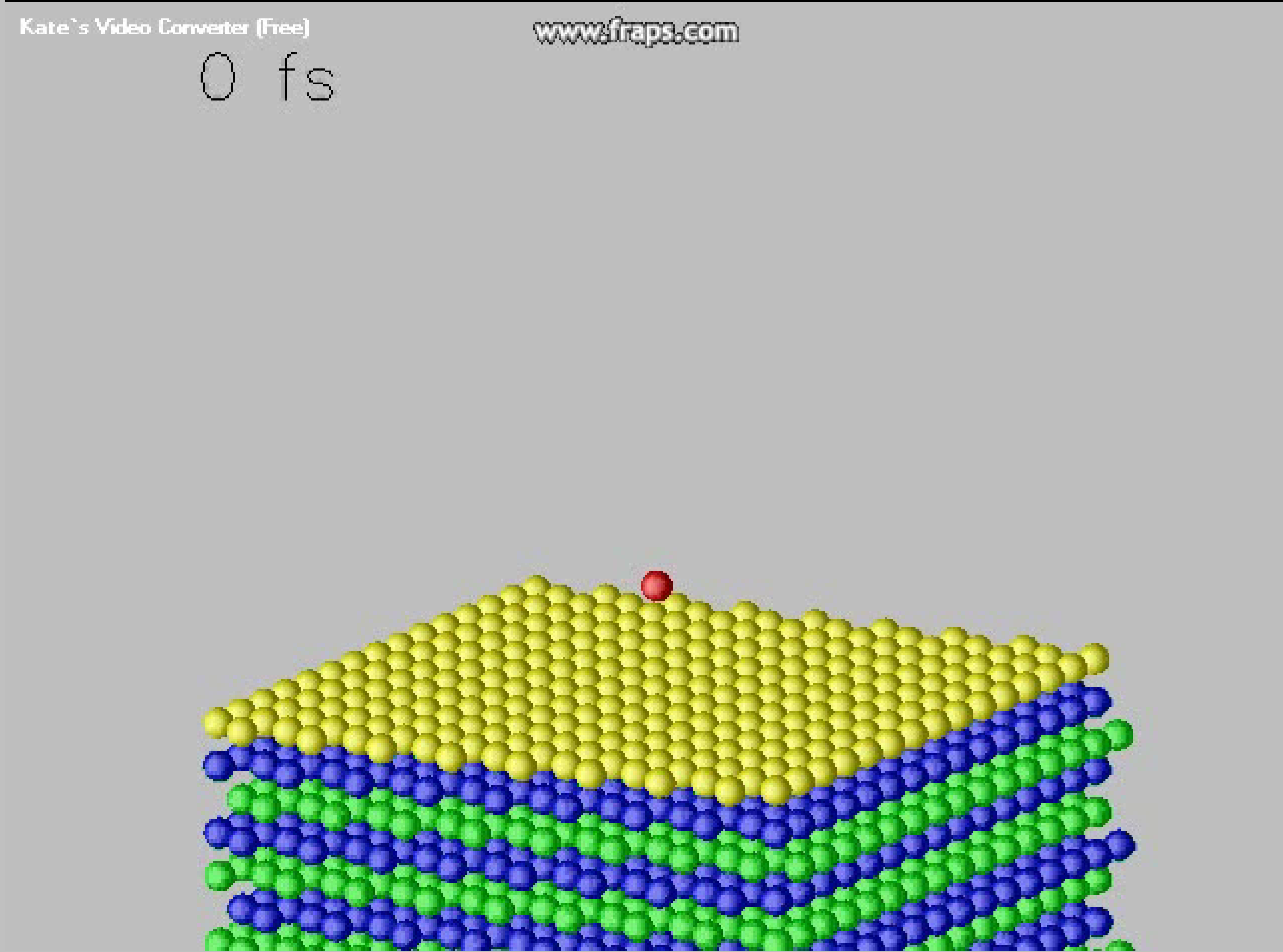
One could imagine that it is a « quiet » mechanism??

Milling rate

Ion-solid interaction is not so quiet !

Lets see some simulations from Prof. Dr A.Wucher group at Duisburg Universität to be convinced !

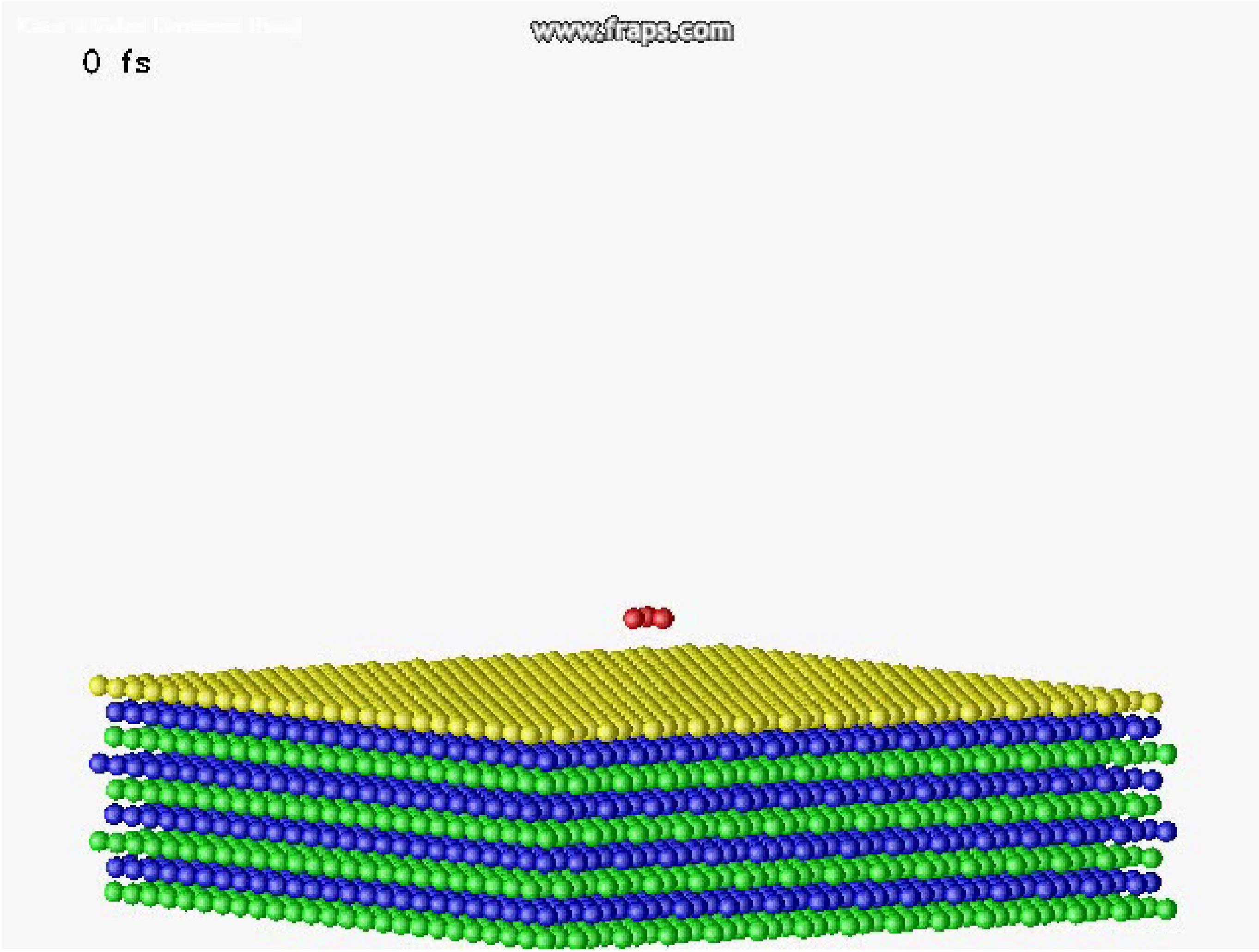
Simulation of particle impact



5 keV Ag on Ag (111)

Prof. Dr A.Wucher group – Duisburg Universität

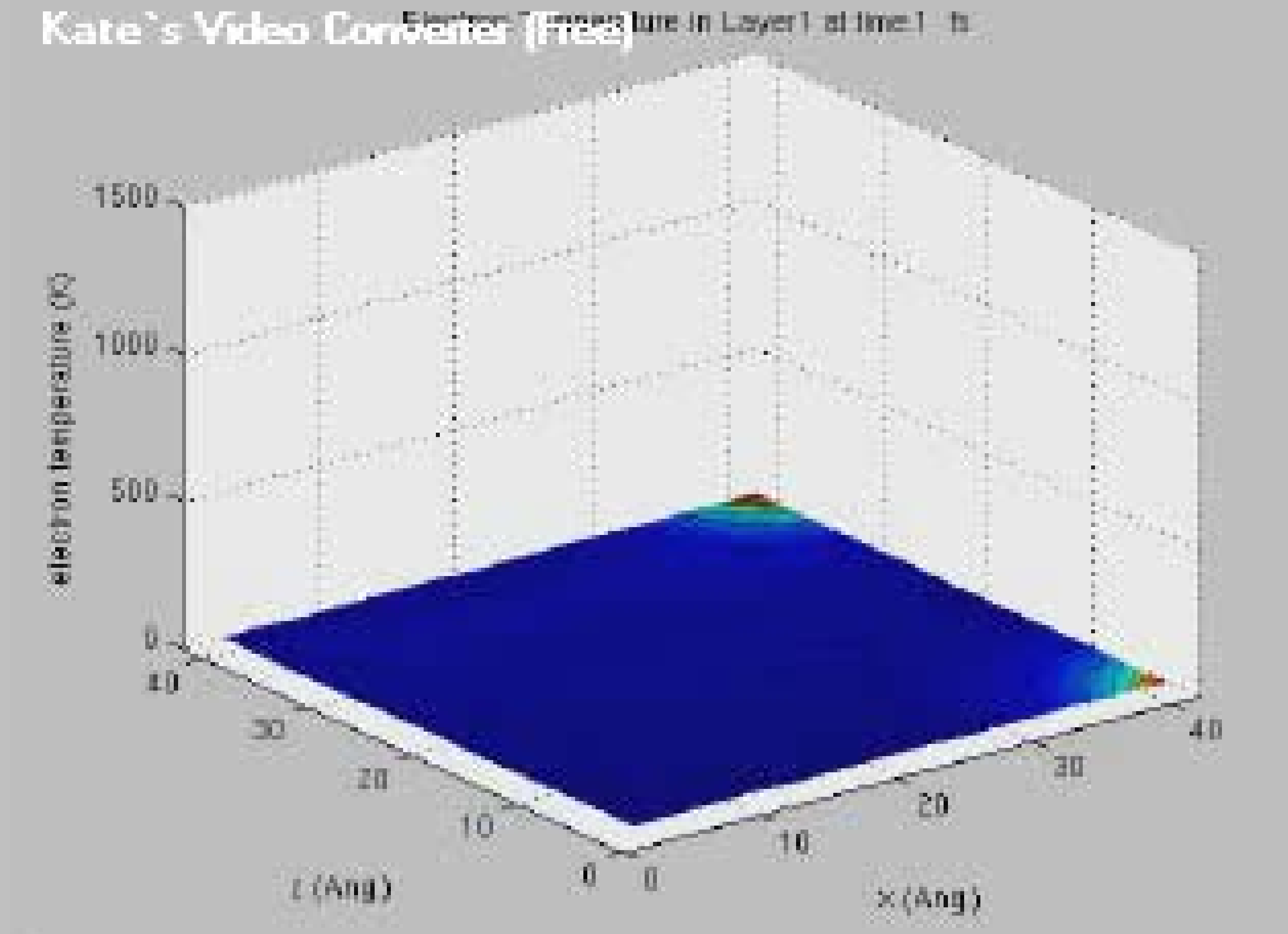
Simulation of particle impact



6 keV Ag_3 on Ag (111)

Prof. Dr A.Wucher group – Duisburg Universität

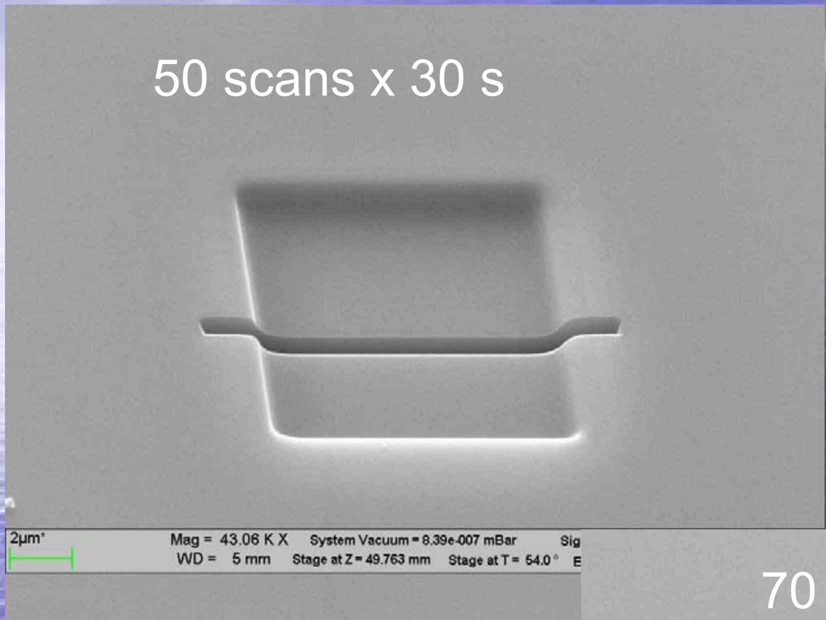
Simulation of particle impact



Electronic excitation

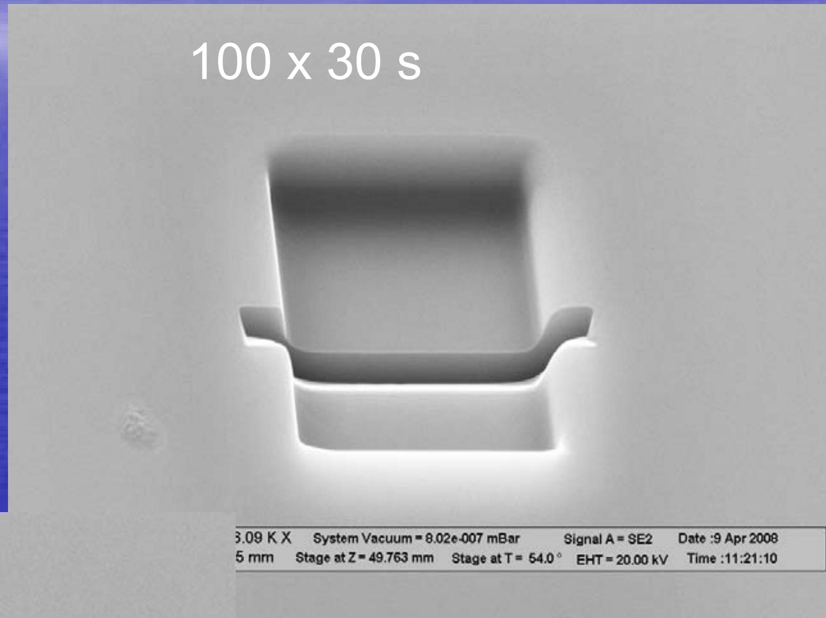
Prof. Dr A.Wucher group – Duisburg Universität

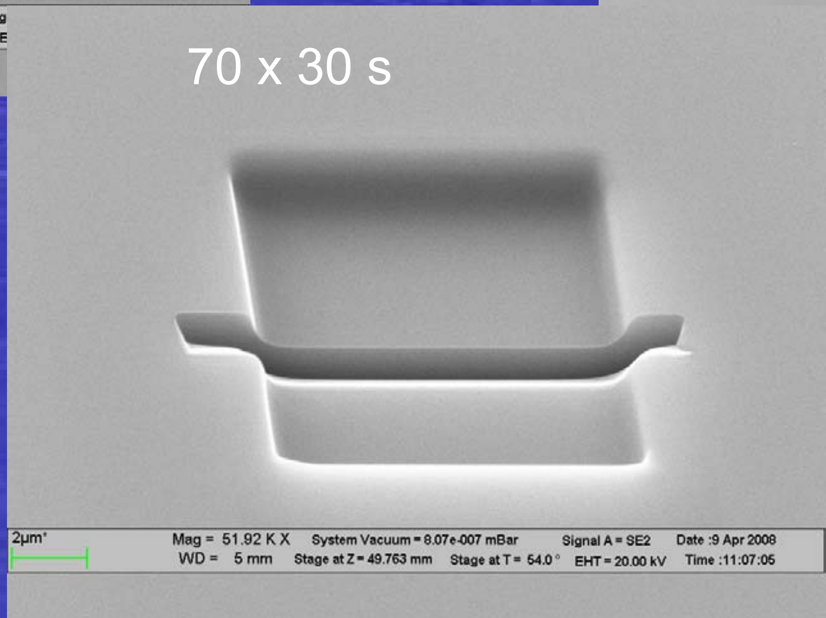
Milling rate at 5kV



271 pA

10 µm x 10 µm





Sputtering rate measurement

3 different times

For linearity control

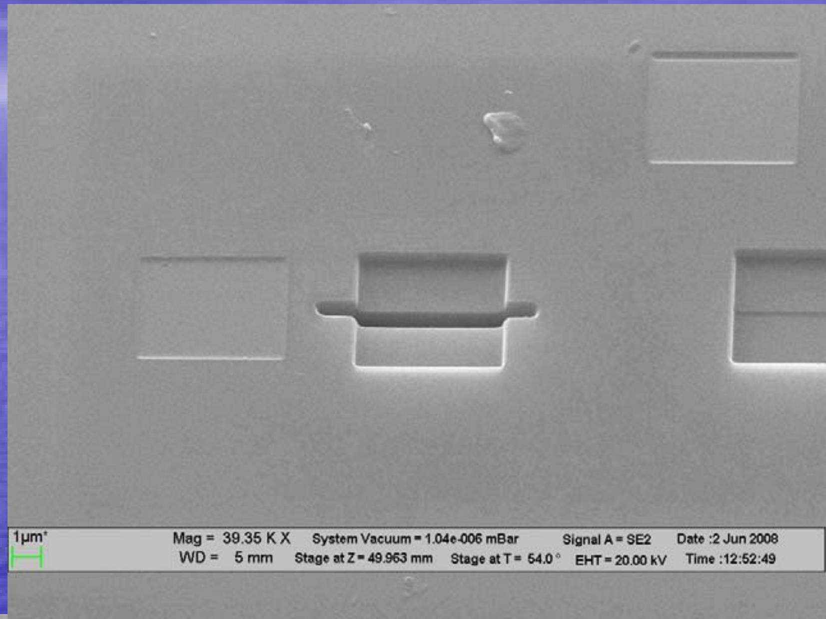
Milling rate

⇨ Ga+ on Si

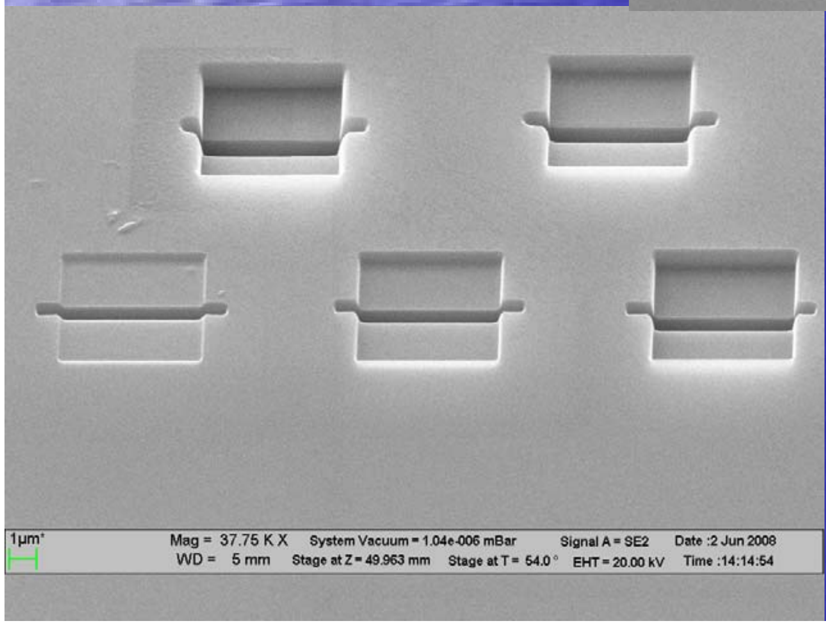
⇨ 30 kV : 2.4 atoms/ion
⇨ 15 kV : 2.0 atoms/ion
⇨ 5 kV : 1.4 atoms/ion

Au milling rate on Si

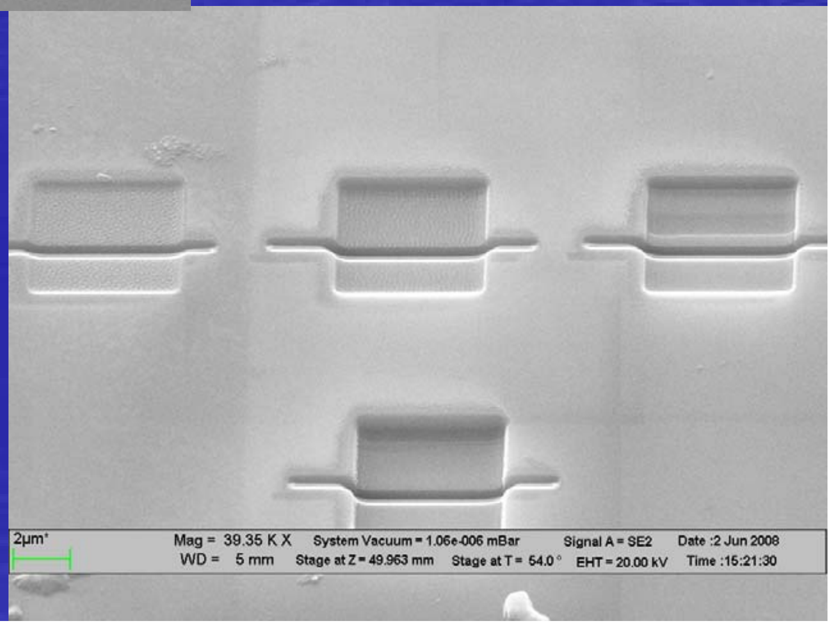
Au^{+} sur Si



Au^{++} sur Si



Au_2^{+} sur Si



Au milling rate on Si

⇨ Au on Si

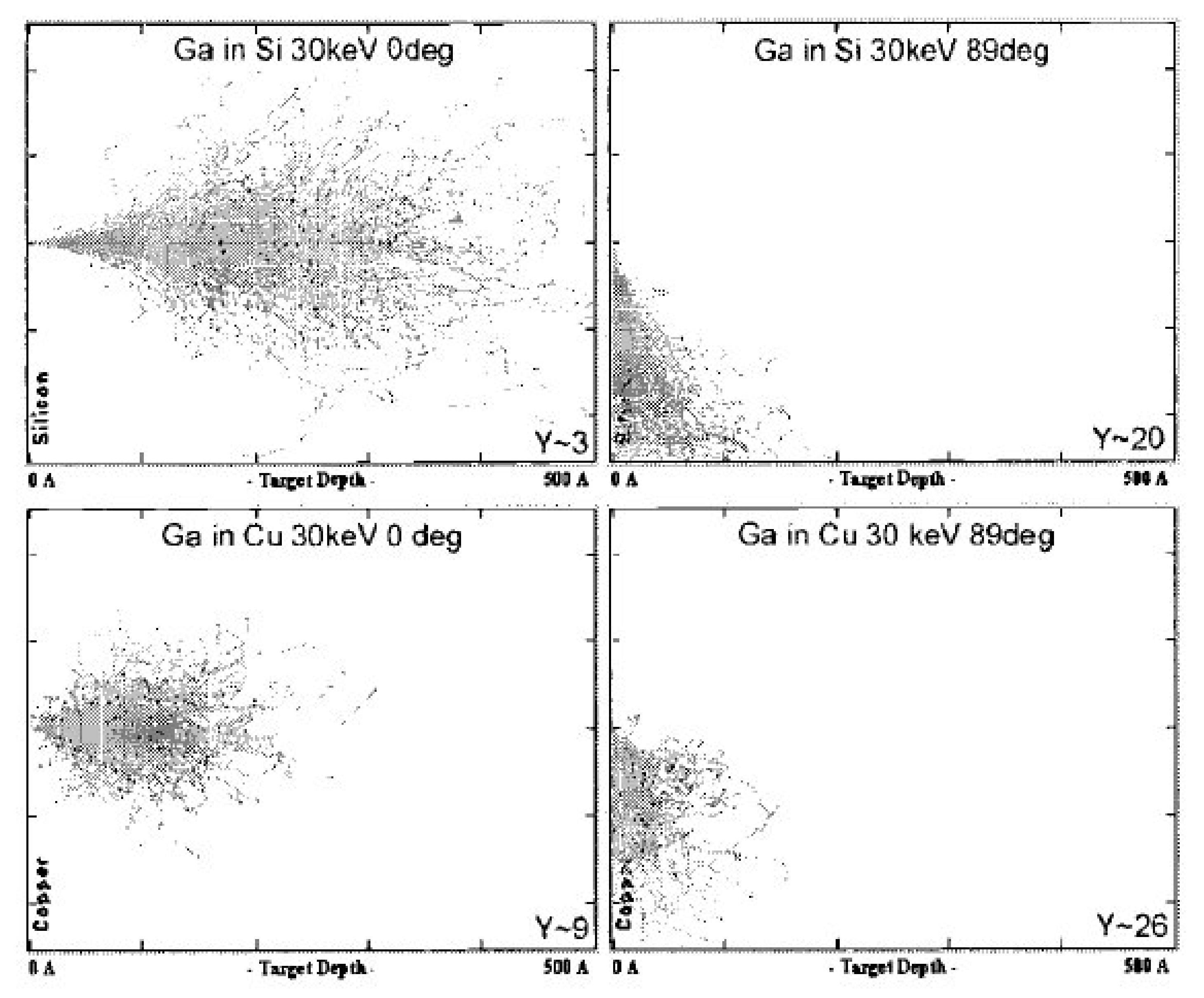
Incidence angle 90°

⇨ Au^{+} : 5.2 atoms/ion

⇨ Au^{++} : 5.6 atoms/ion

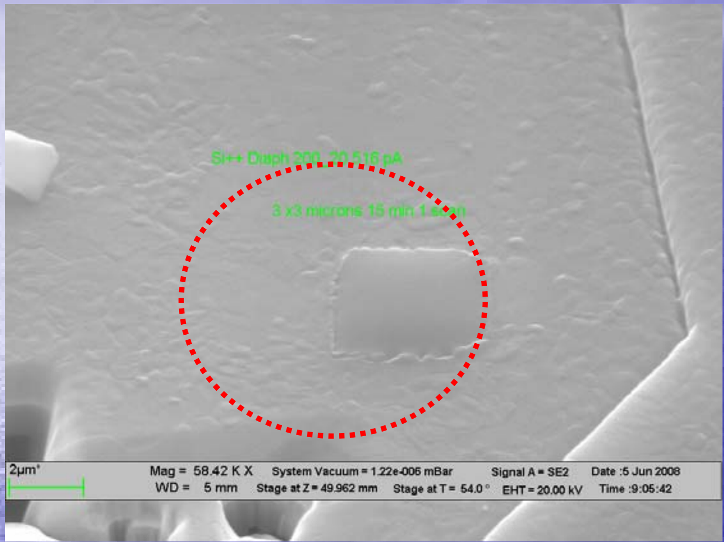
⇨ Au_2^{+} : 9.5 atoms/ion

Milling rate at 30 keV

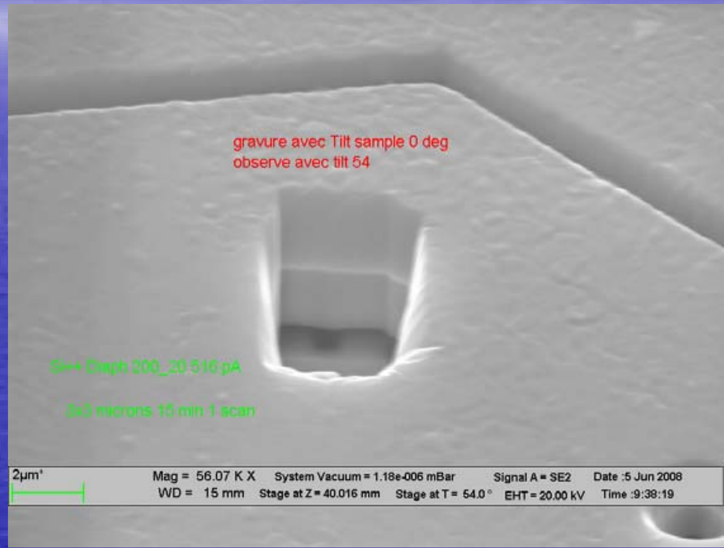


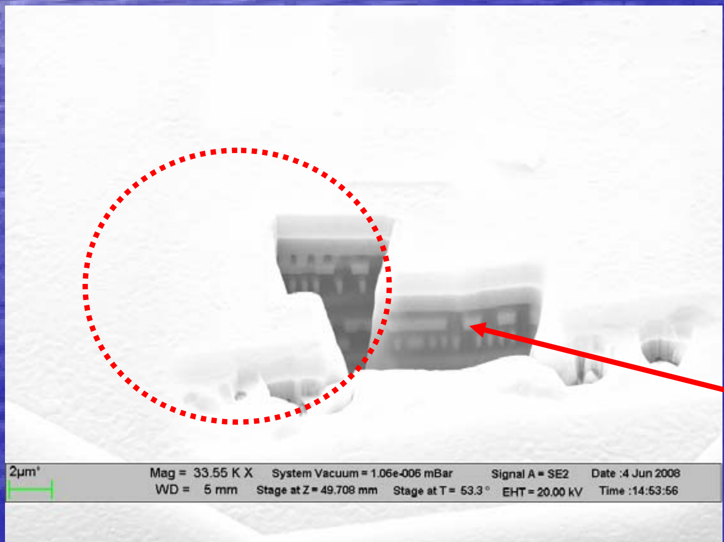
Si^{++} milling on Si

90 ° incidence



36 ° incidence



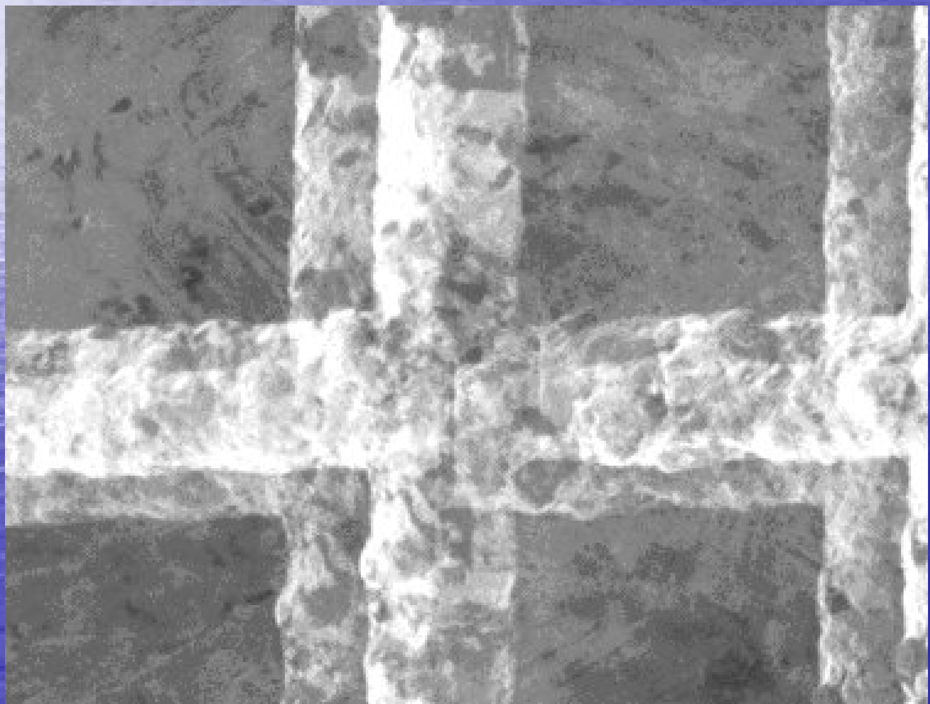


Same conditions
at different angles

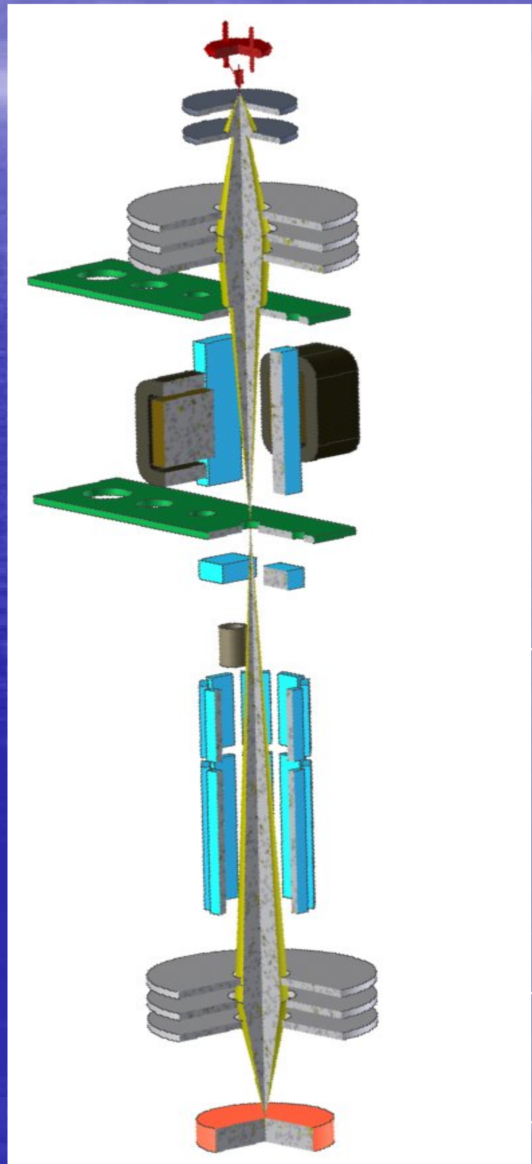
Polishing of existing
cross section

Mass filtered FIB with alloy sources

CANION 31X FIB column



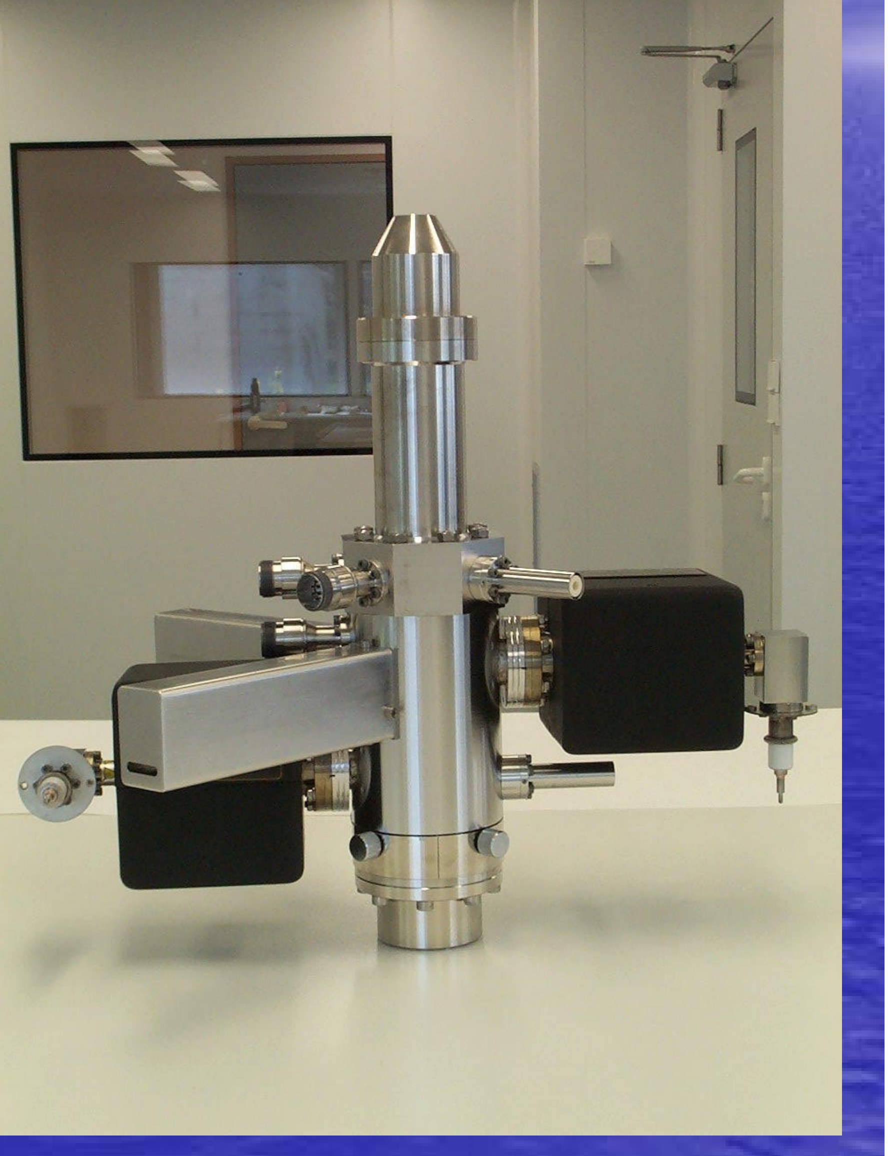
Separation of the two Ga isotopes



Coaxial ion/photon column

OPTIFIB column

- ✓ Patented concept
- ✓ Coaxial ion / photon beams
- ✓ Visible and I.R. imaging capabilities
  Resolution < 0,5 μm
  F.O.V. = 250 x 250 μm^2
- ✓ Ion resolution < 8 nm
  F.O.V. = 400 x 400 μm^2
  Beam current : 1 pA to 20 nA



NANOSOLUTIONS by ORSAYPHYSICS

Some FIB manufacturers

DCG Systems

Applied Materials Revolutionizes Defect Review with Industry's First Automated In-Line SEM/FIB System. (Photo: Business Wire)

APPLIED MATERIALS®

ZEISS

FEI COMPANY™

ULVAC
ULVAC-PHI, INC.

TESCAN
DIGITAL MICROSCOPY IMAGING

Raith
INNOVATIVE SOLUTIONS FOR NANOFABRICATION AND SEMICONDUCTOR NAVIGATION

FB-2100 FIB System

HITACHI
Inspire the Next

SII

JEOL

Future of FIB ?

Some industrial requirements

Non reactive elements (in-line FIB)

Low energy FIB (M.Rauscher's work)

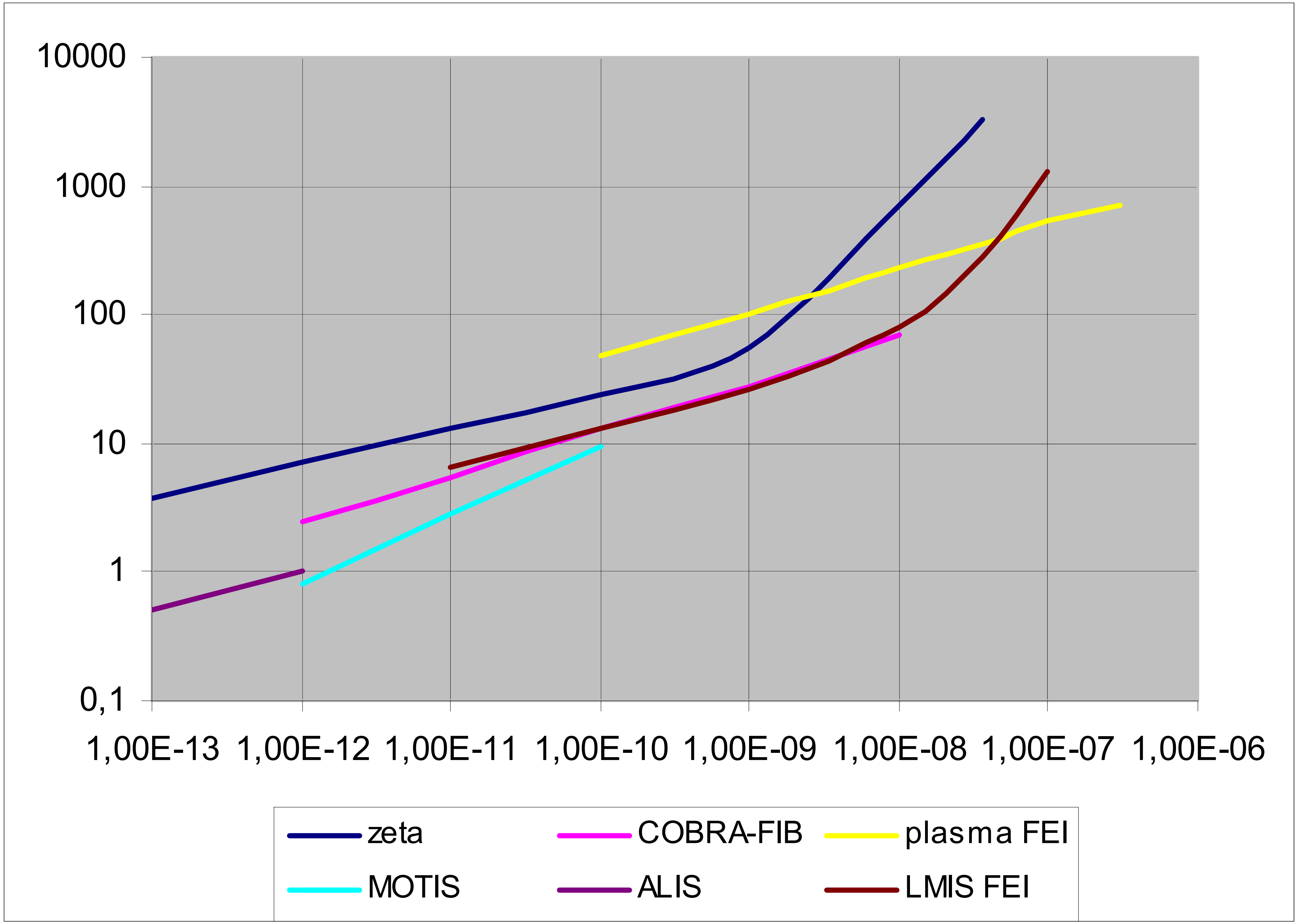
Nanometric and atomic (?) scale

Large volumes (MEMS)

Very reactive elements (SIMS, local chemistry)

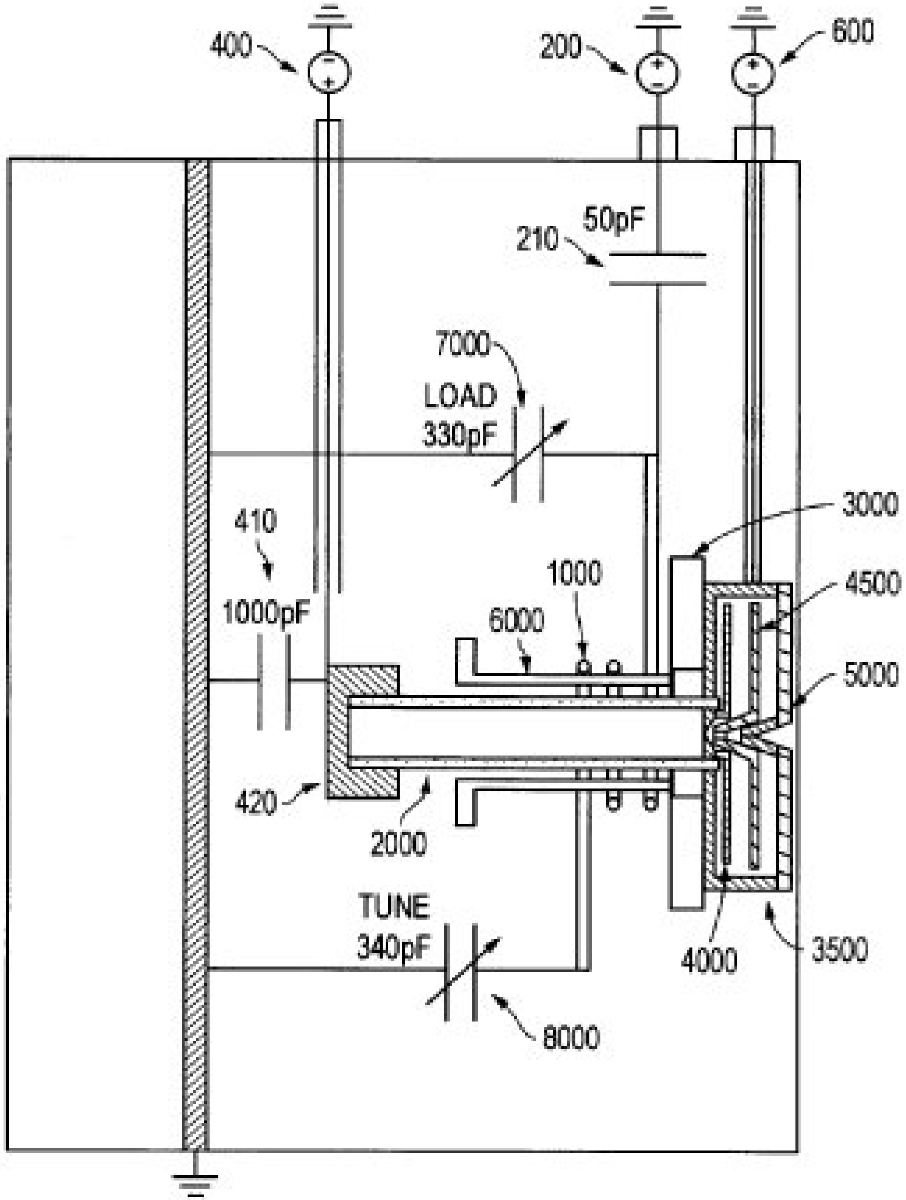
Light elements (imaging, analysis)

Future of FIB



Current and future FIB Technology

Future of FIB
High currents



Patent J. Keller N.Smith et al (FEI)

Inductively coupled plasma

Argon or Xenon (clean FIB)

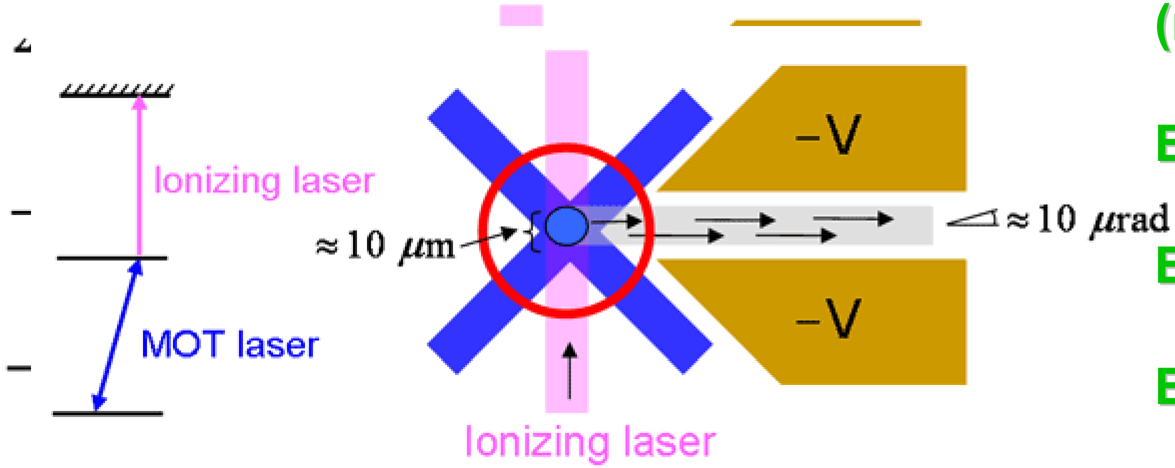
ΔE 7 eV (Xenon)

Angular intensity X 10^3 LMIS

For I > 50nA better than LMIS

Future of FIB

Magneto optical trap ion source (motis)



Enlarges ion pannel (reactive & non-reactive)

Extremely low ΔE (0.1eV)

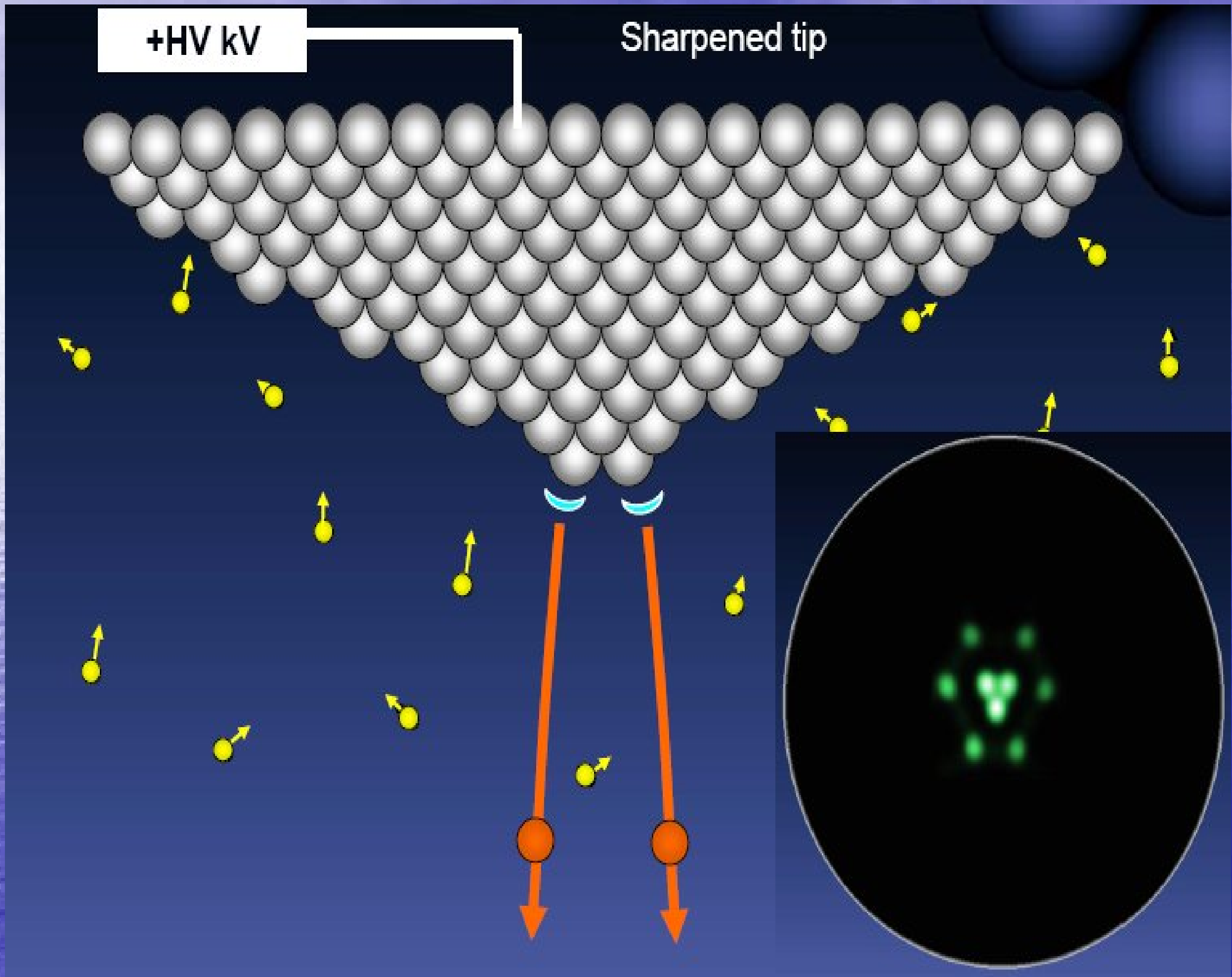
Extremely low divergence

Brighteness > 10 ^{5}A m^{-2} sr $^{-1}$ V $^{-1}$

Expensive

CNST – NIST
Orsay-Physics - Orsay Paris XI Univ.
Dept of Applied Physics Eindhoven Univ.
FEI

Future of FIB
GFIS Alis – Zeiss Orion



Very High Brightness

Atomic Virtual Source Size

Low energy spread

Diffraction < SEM

Sub nanometric d

Helium ions

Low current

Limited number ion species

Patented

NANOSOLUTIONS by ORSAYPHYSICS

Microscopic
Liquid Ionic Compound Ion Source

MI.LICIS provides reactive ions

Cs^+

$(CsCl)Cs^+$

$(CsNO_3)Cs^+$

NO_3^-

$(CsNO_3)O_2^-$

Cl^-

Both polarities

High brightness

$B \approx 10.^5 A.cm^2.sr^{-1}$

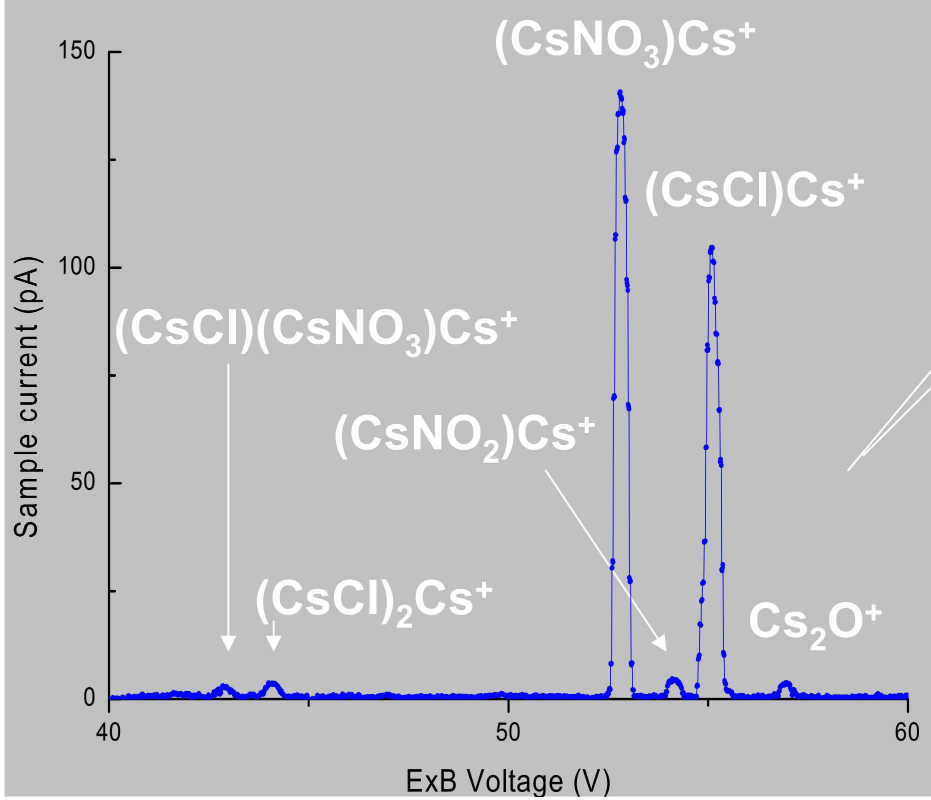
Olivier Salord
Dr. A. Houel
Dr. Pierre Sudraud

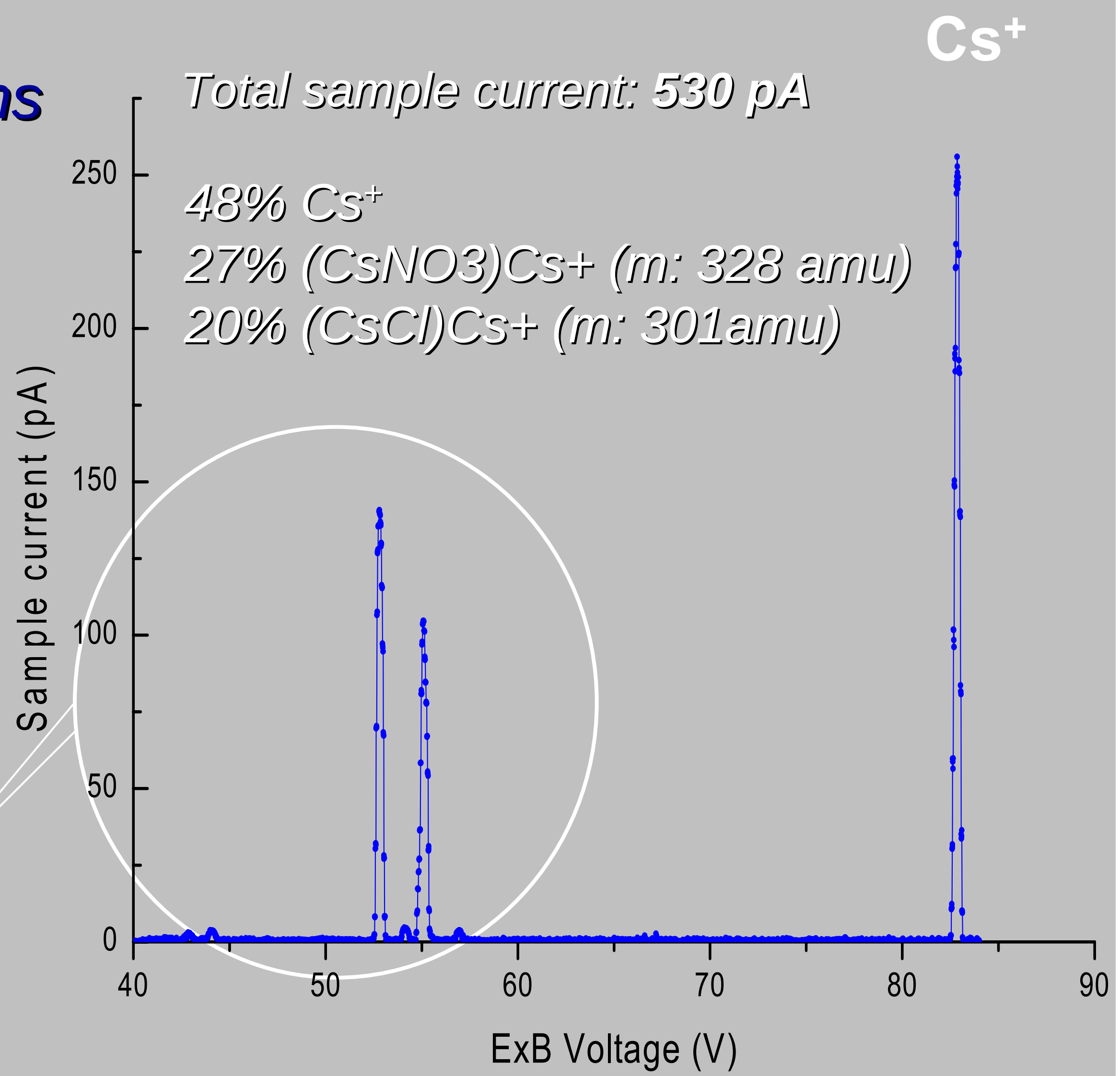
Patented

NANOSOLUTIONS by ORSAYPHYSICS

MI.L.I.C.I.S

Mass spectrum of Positive ions



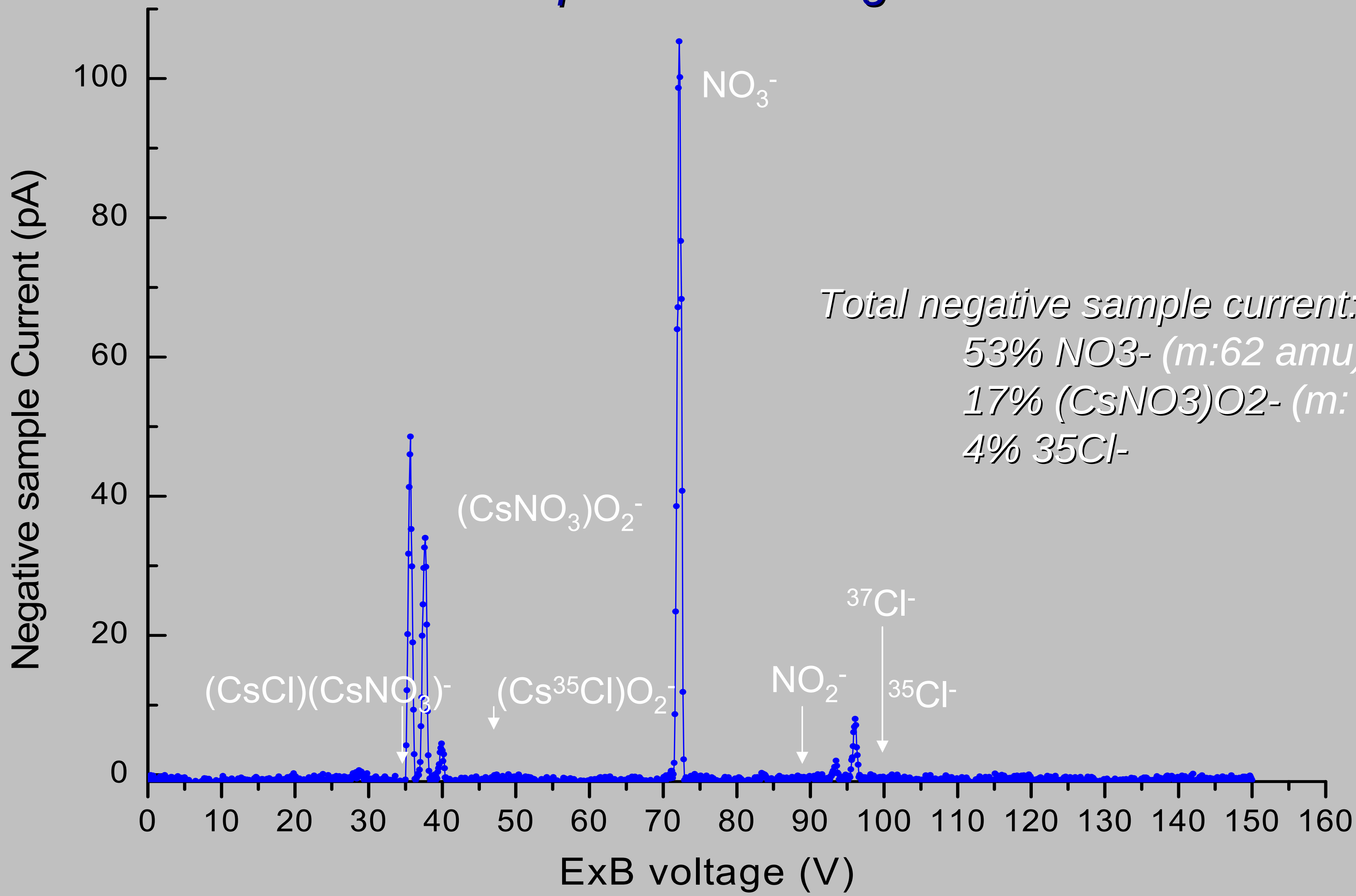


Patented

NANOSOLUTIONS by ORSAYPHYSICS

MI.L.I.C.I.S

Mass spectrum of Negative ions



Total negative sample current: 200 pA

53% NO3- (m:62 amu)

17% (CsNO3)O2- (m: 227 amu)

4% 35Cl-

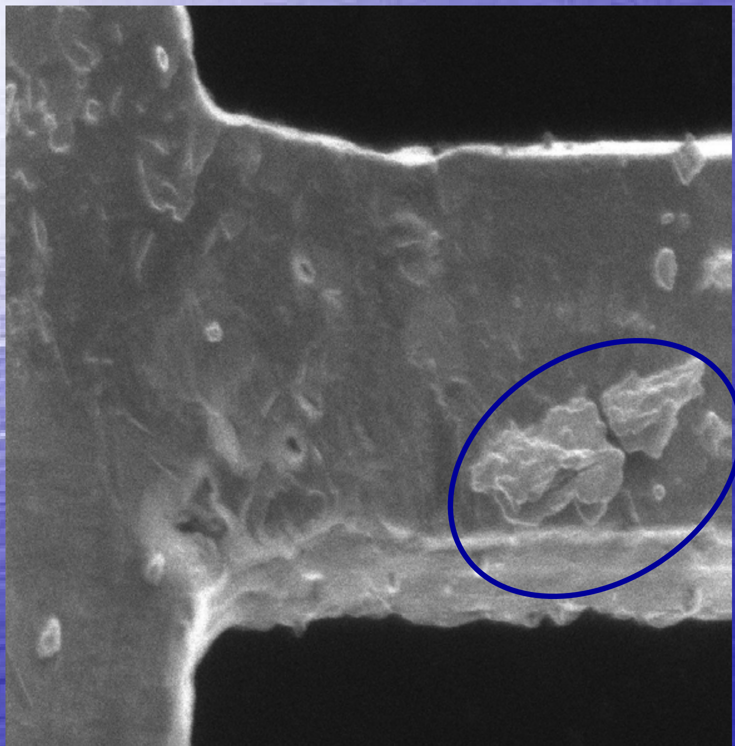
Patented

NANOSOLUTIONS by ORSAYPHYSICS

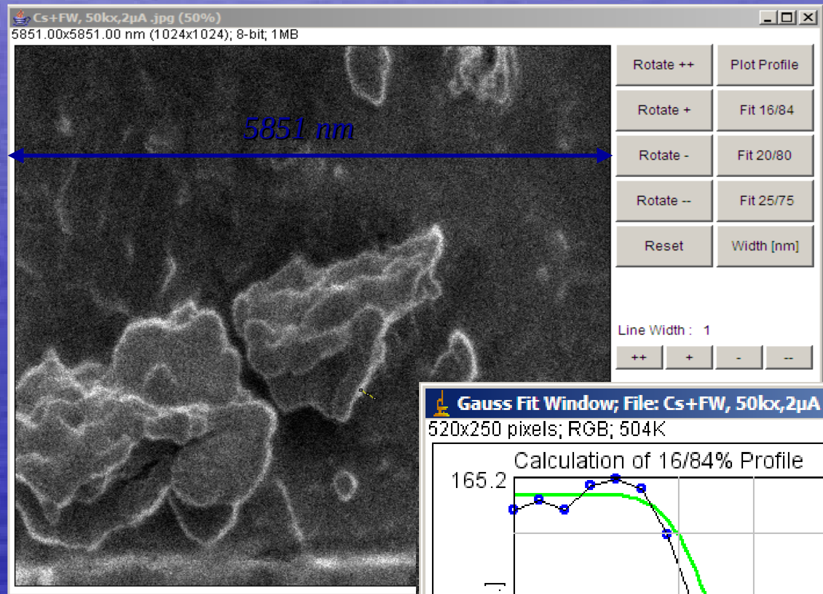
MI.L.I.C.I.S

Resolution at 30kV obtained with experimental setup

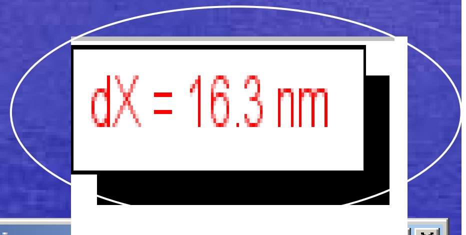
Positive ion beam filtered by O.P ExB Wien filter: **Cs^+** imaging

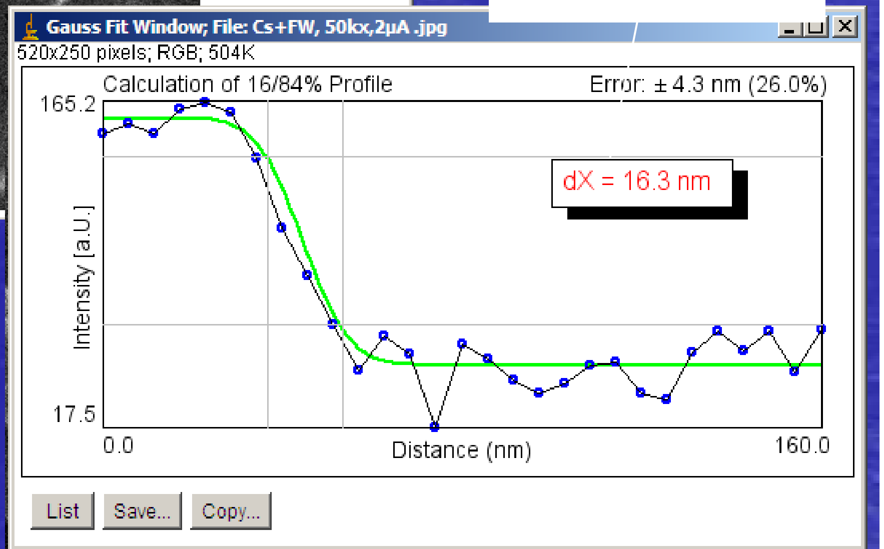


Mag 20kx



Mag 50kx





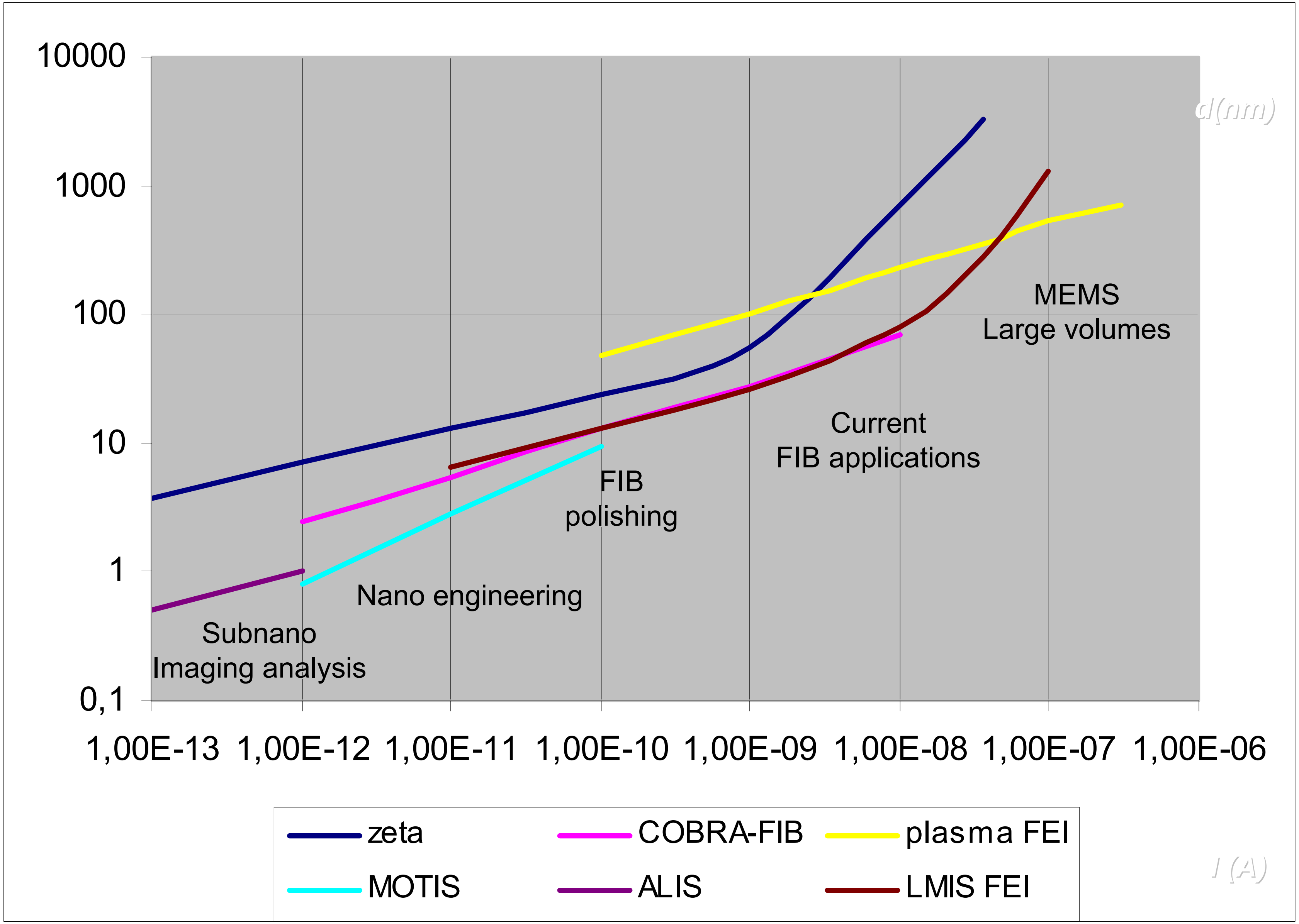
Nominal energy: 30kV

Acceptance aperture : 150µm, Mass aperture: 20 µm

I_{sample}=**10pA**; I_{em}=2µA

Olivier Salord

Future of FIB



Current and future FIB Technologies

Future of FIB

Prospective of FIB:
a panel of complementary technologies ?

ICRF plasma for clean high currents FIB

LMIS FIB could kept many applications

MOTIS for clean low energy nanometric FIB
MOTIS and MILICIS for HR SIMS

GFIS FIB for imaging analysis and assisted processing at sub-nanometric scale

Thank you for your attention