Other Ion Sources

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Other Ion Sources ???

Not : *ECR, EBIS, RF,*
Fusion, Laser, MEVVA,
Radioactive , Breeders,
Medical, Multi-beam …

What to do ???

Ions for the industry

Ion Sources : the accelerators versus the industry

- Accelerators :

Emittance, Intensity, Efficiency

- Industry :

Throughput, Tunability, Cost

Ion Sources for Industry : *the fields of use*

- 1 - Focused Ion Beams :

Focused Ion Beam for the nanotechnologies (FIB)

Ion beam figuring for optical components (IBF)

- 2 - High Intensity Beams for *MicroElectronics*

Ion Sources for implanters

- 3 - Broad Beam & "Ionic Machine" for *the Industrial Coating*

Ion Source for Sputterring
Magnetron discharge & End Hall ion source

Ion sources for the industry: *the orders of magnitude*

1 – High brigtness ~ 1 nm-1 µm beam (FIB)

2 – High current ~ 1 cm-30 cm beam (Implanter)

3 – Broad beam ~ 30 cm- 10 m beam/treatment (Coating)

The good Units for the industrial purpose :

1 – Focused Ion Beam : $\mu m^3/s$

2 – Implanter : Wafers/h

3 – Coating : $\mu m/m^2/h$

Popular Ion Sources for the industry :

1 – Focused Ion Beams

LMIS, RF, Microwave

2 – Implanters

Freeman, Bernas

3 – Coatings

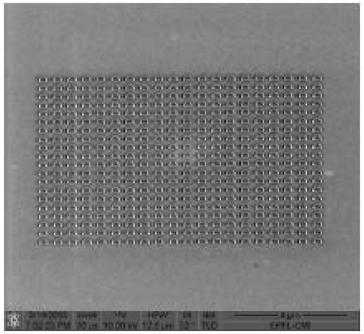
Broad beam, Magnetron, Gridless

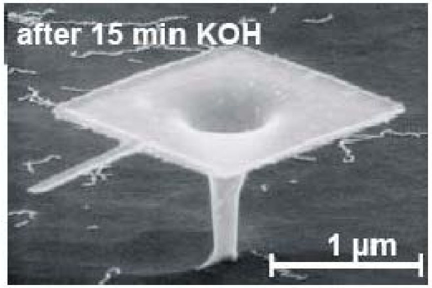
Other ion sources - Ions for the industry
1 - Focused Ion Beam for the Nanotechnologies

The purpose of the Focused Ion Beam systems:

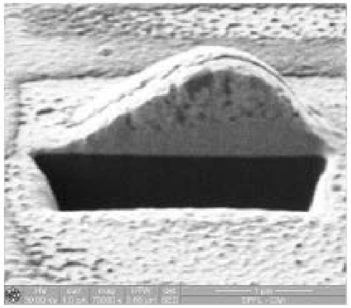
**1µm
to 1 nm
beam**

**1µA
to 1 nA
beam**

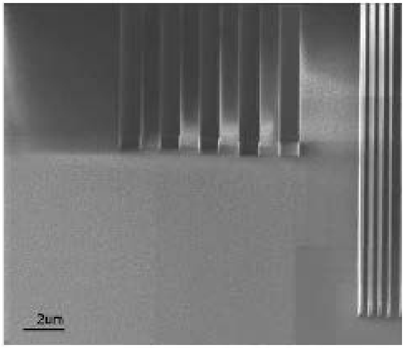

Milling



Doping


Imaging

Deposition



Lithography

Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies

The process with the Focused Ion Beam :

Figure 4-8. 3D CAD drawing of a feature.

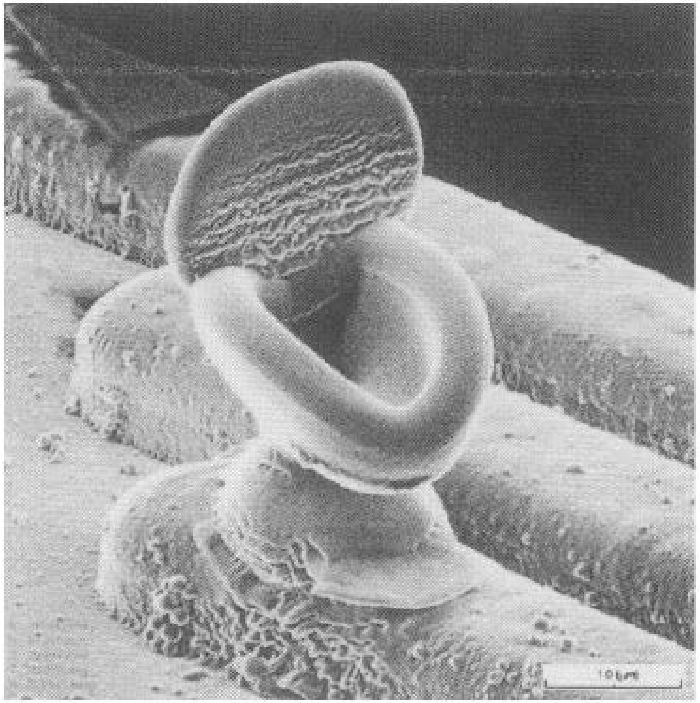
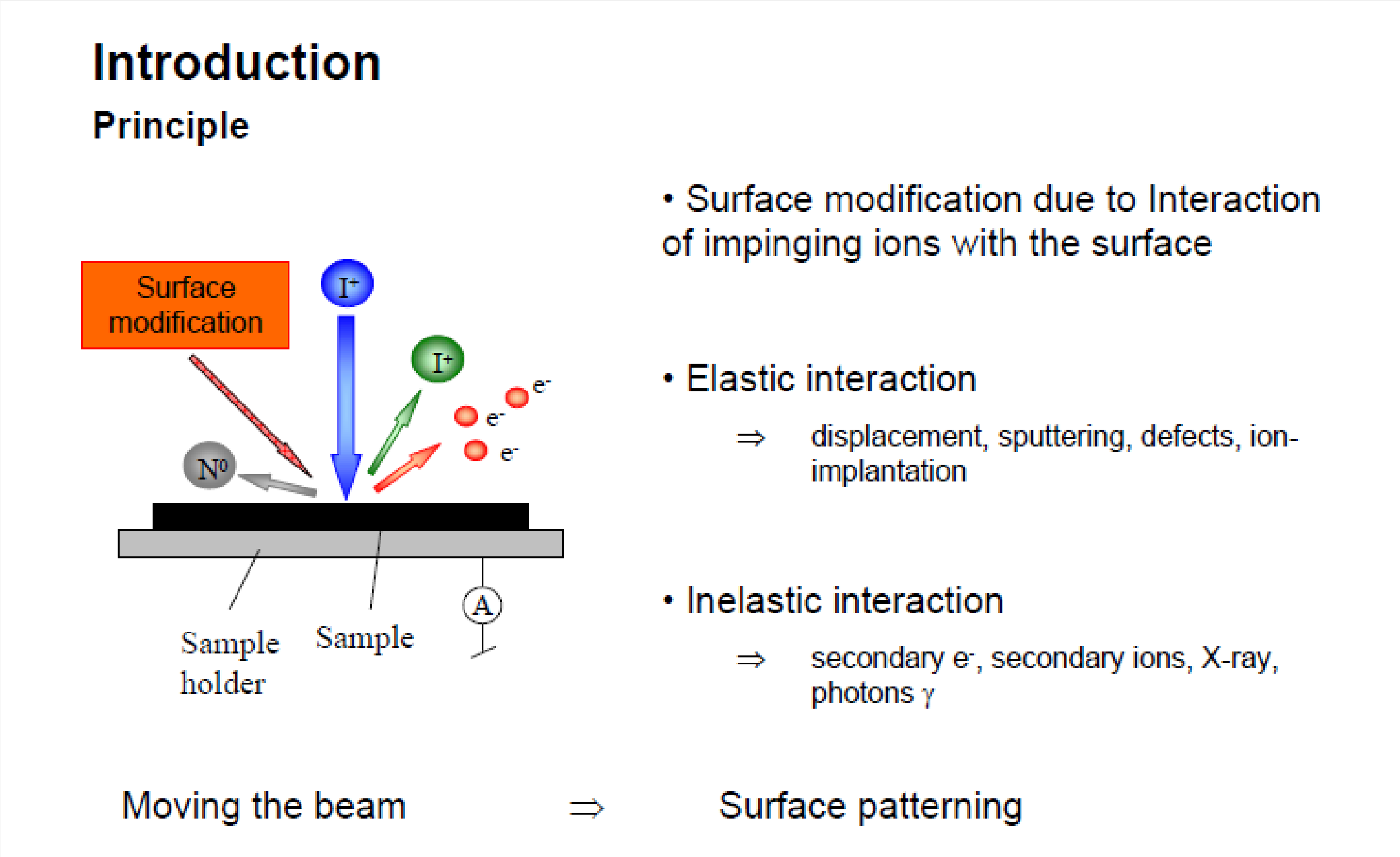


Figure 4-9. 3D FIB fabrication performed automatically from the CAD drawing in figure 8.

The process with the Focused Ion Beam :



Introduction

Principle

- Surface modification due to Interaction of impinging ions with the surface

- Elastic interaction

  ⇒ displacement, sputtering, defects, ion-implantation

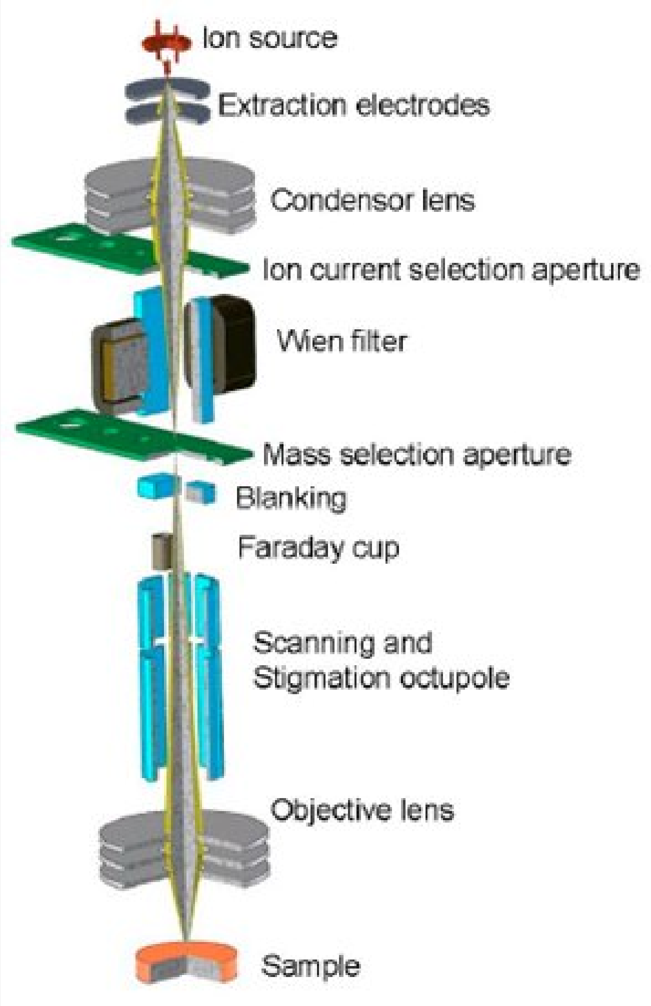
- Inelastic interaction

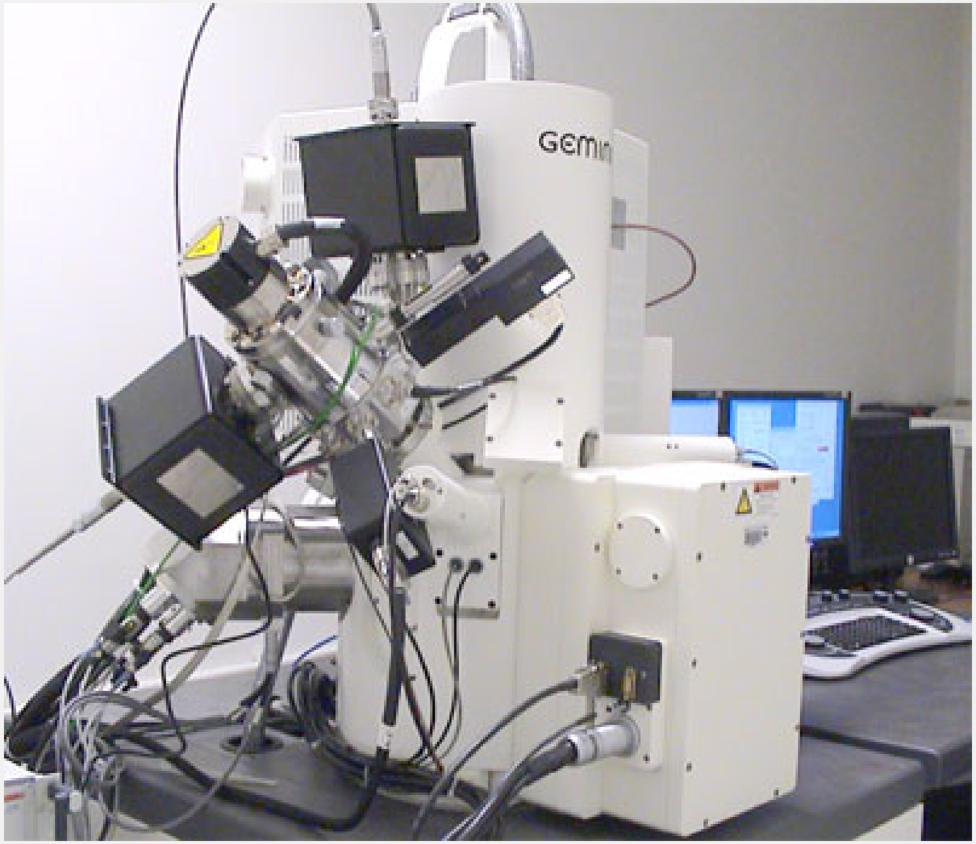
  ⇒ secondary e^-, secondary ions, X-ray, photons γ

Moving the beam ⇒ Surface patterning

Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies





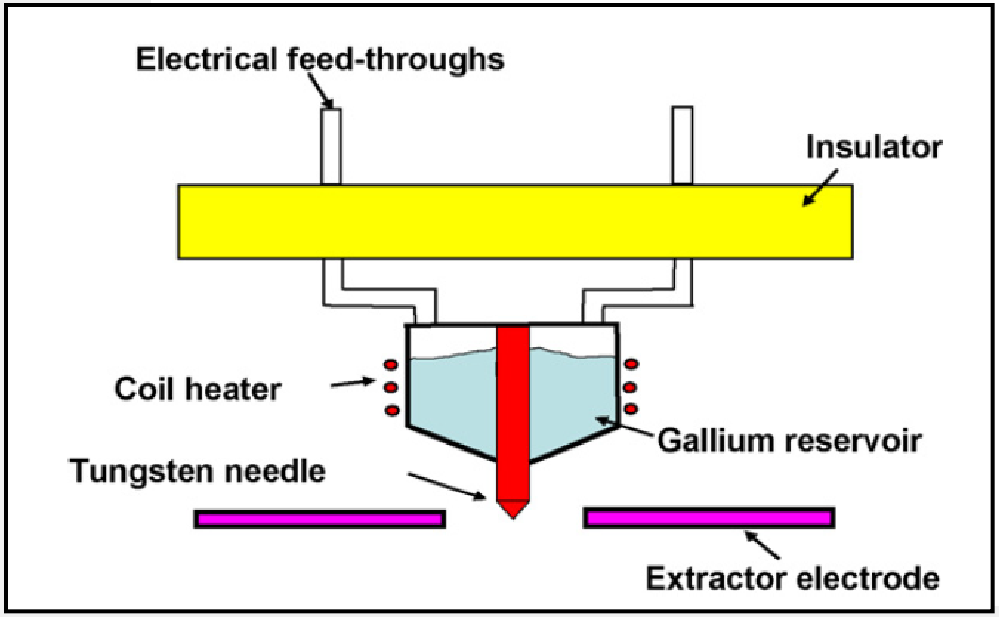
Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies

Ion Source

Liquid Metal Field Ionization Source (LMIS)

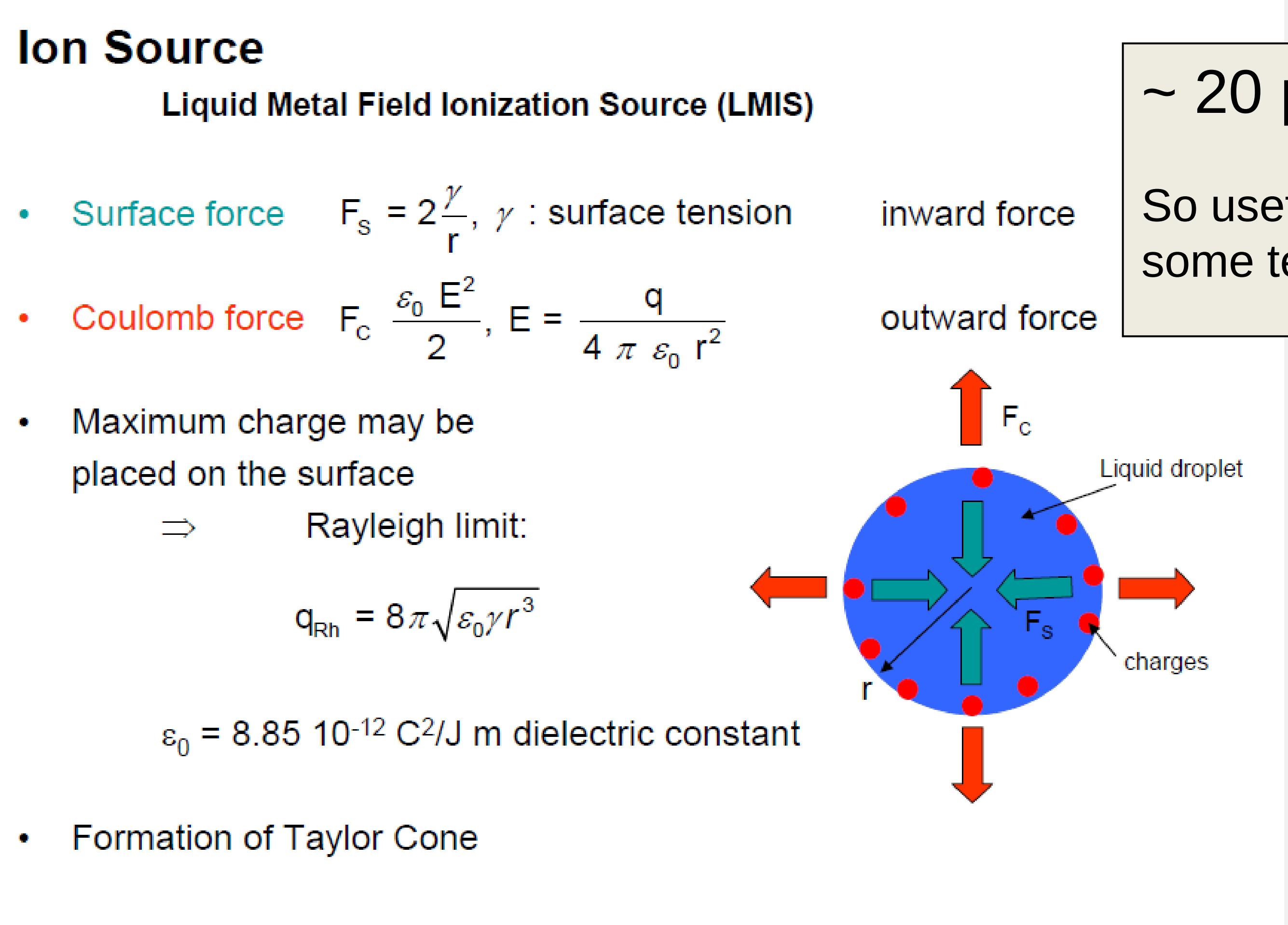
- High electrical fields at the apex of a rod leads to detachment of Ions
- Liquid metal film is drawn into conical shape of the rod (W or Rh)
- Wide variety of ion species including Al, As, Au, B, Be, Cs, Cu, Ga, Ge, Fe, In, Li, Pb, Si, Sn, U, and Zn



Ga^+ source from FEI

Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies



Ion Source

Liquid Metal Field Ionization Source (LMIS)

- Surface force $F_S = 2\frac{\gamma}{r}$, γ : surface tension inward force
- Coulomb force $F_C \; \frac{\varepsilon_0 E^2}{2}$, $E = \frac{q}{4\pi\varepsilon_0 r^2}$ outward force
- Maximum charge may be placed on the surface

  $\Rightarrow$ Rayleigh limit:

  $$q_{Rh} = 8\pi\sqrt{\varepsilon_0 \gamma r^3}$$

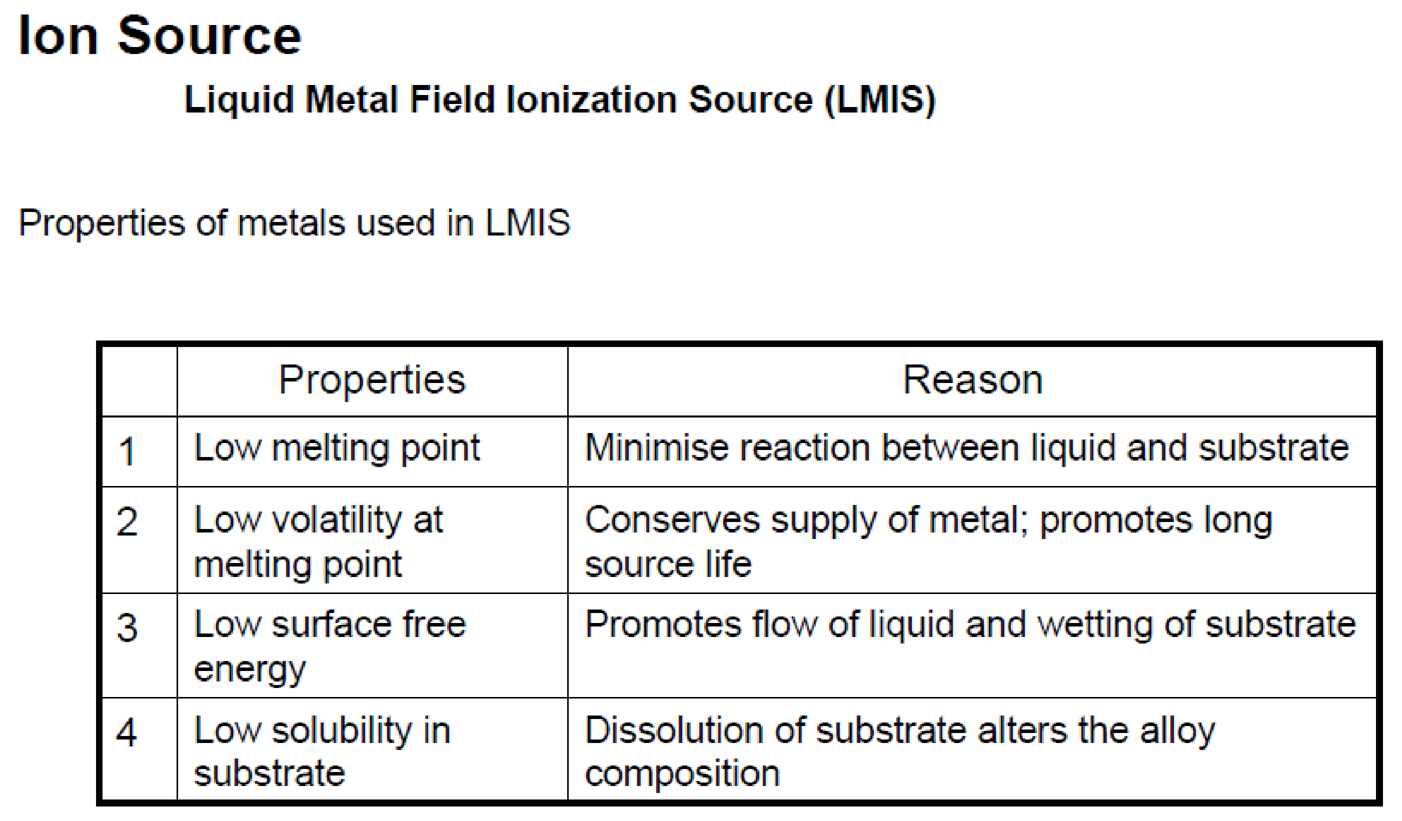
  $\varepsilon_0 = 8.85\ 10^{-12}\ C^2/J\ m$ dielectric constant
- Formation of Taylor Cone

$\sim 20\ \mu A.sr^{-1}$

So useful current : some tens of nA max

Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies



Ion Source

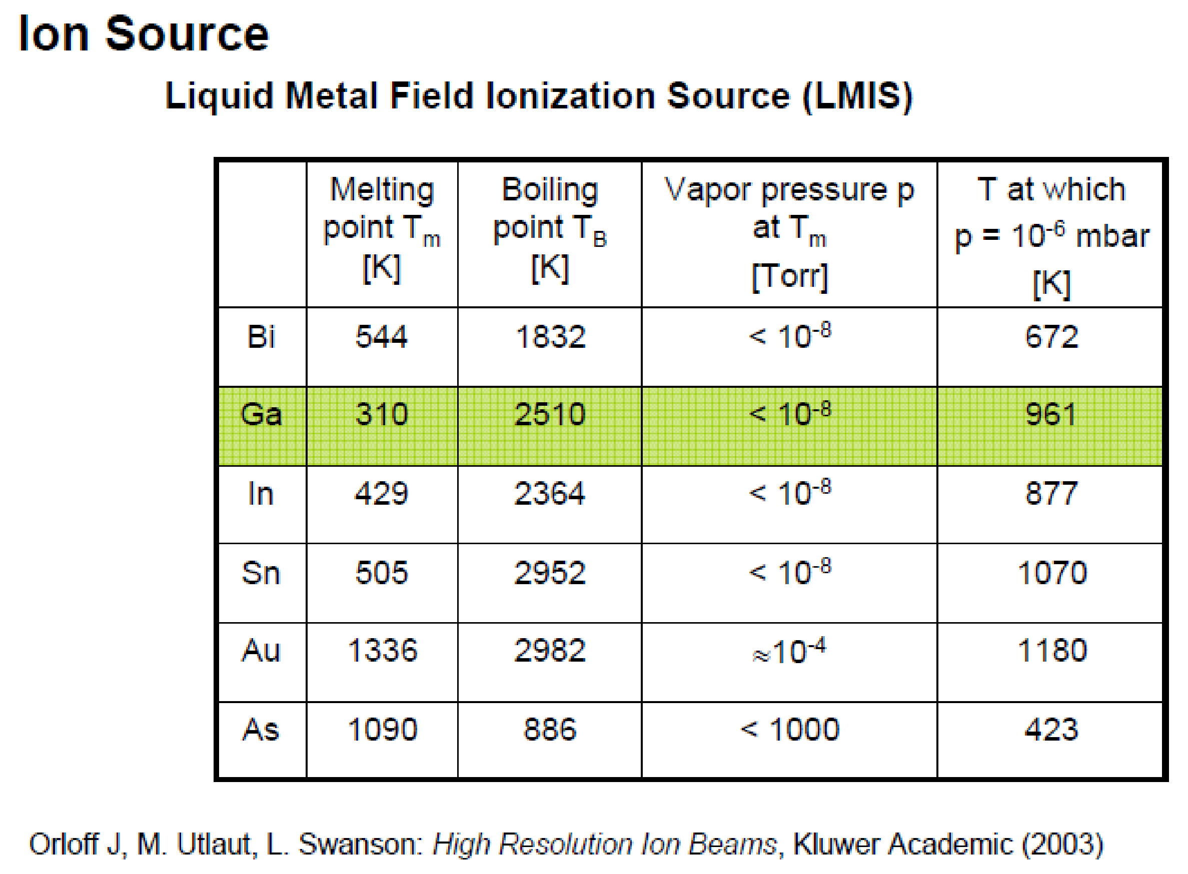
Liquid Metal Field Ionization Source (LMIS)

Properties of metals used in LMIS

	Properties	Reason
1	Low melting point	Minimise reaction between liquid and substrate
2	Low volatility at melting point	Conserves supply of metal; promotes long source life
3	Low surface free energy	Promotes flow of liquid and wetting of substrate
4	Low solubility in substrate	Dissolution of substrate alters the alloy composition

Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies



Ion Source

Liquid Metal Field Ionization Source (LMIS)

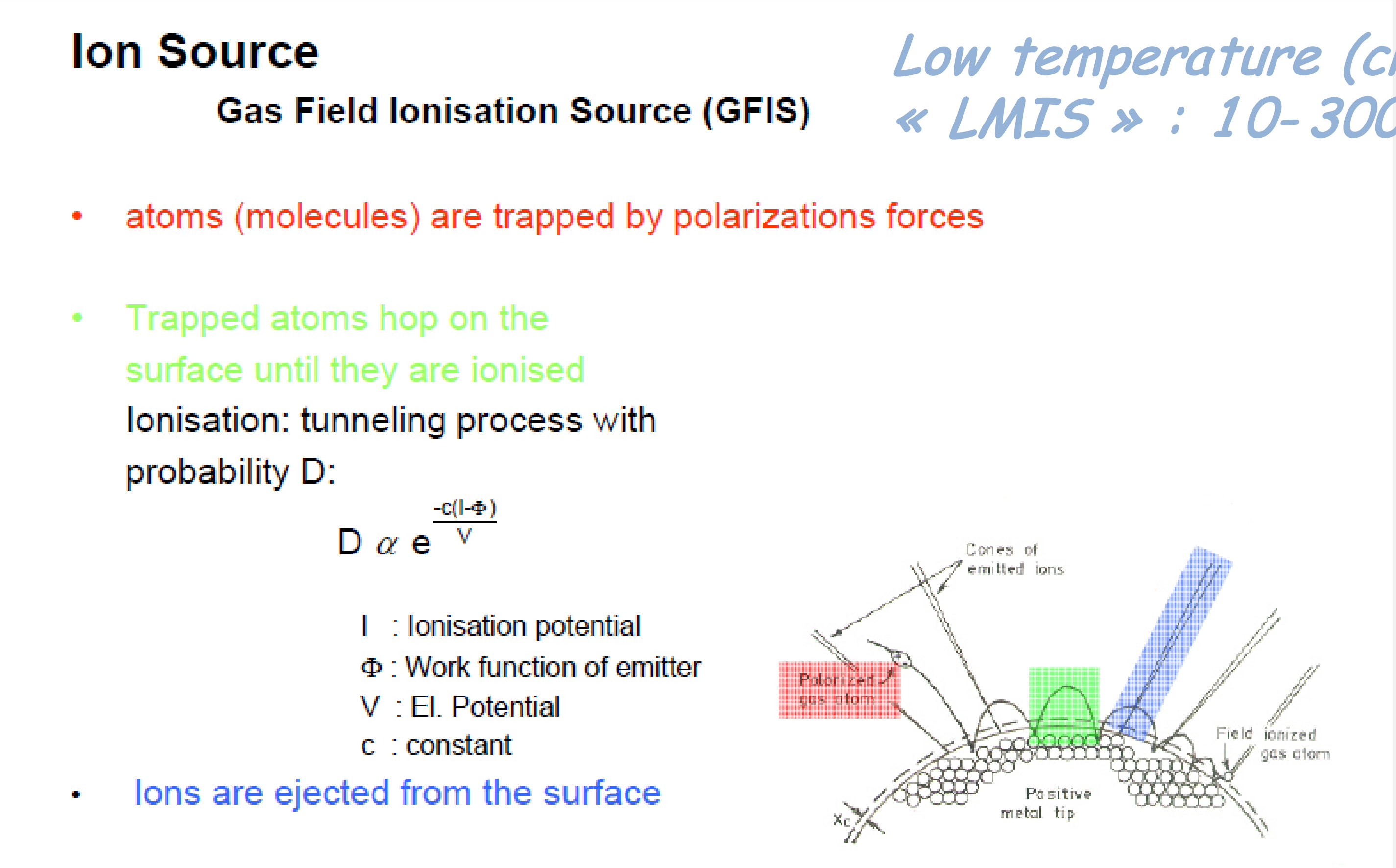
	Melting point T_m [K]	Boiling point T_B [K]	Vapor pressure p at T_m [Torr]	T at which $p = 10^{-6}$ mbar [K]
Bi	544	1832	$< 10^{-8}$	672
Ga	310	2510	$< 10^{-8}$	961
In	429	2364	$< 10^{-8}$	877
Sn	505	2952	$< 10^{-8}$	1070
Au	1336	2982	$\approx 10^{-4}$	1180
As	1090	886	< 1000	423

Orloff J, M. Utlaut, L. Swanson: *High Resolution Ion Beams*, Kluwer Academic (2003)

Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies

Low temperature (cryogenic) « LMIS » : 10-300 K



Ion Source

Gas Field Ionisation Source (GFIS)

- atoms (molecules) are trapped by polarizations forces
- Trapped atoms hop on the surface until they are ionised

  Ionisation: tunneling process with probability D:

$$D \alpha e^{\frac{-c(I-\Phi)}{V}}$$

I : Ionisation potential

Φ : Work function of emitter

V : El. Potential

c : constant

- Ions are ejected from the surface

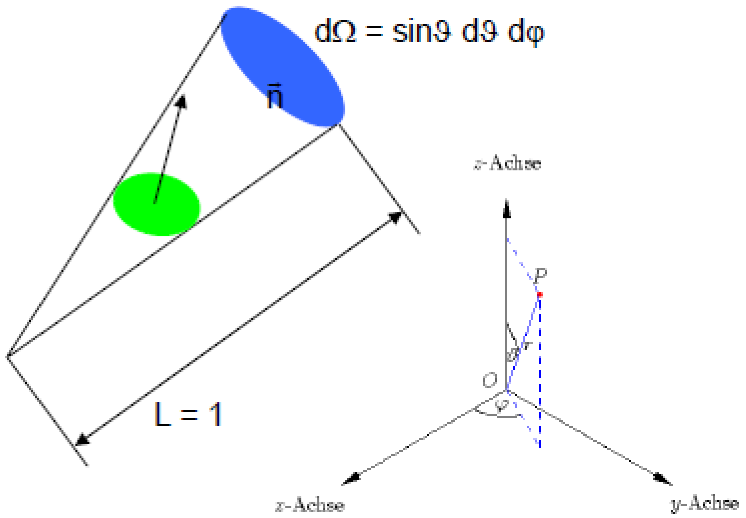
Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies

Ion Source

Gas Field Ionisation Source (GFIS)

- Cooling the tip ⇒ higher residence time τ_r leads higher ionisation rate
- Ions: H^+, He^+, Ne^+, etc
- low current $\frac{dI}{d\Omega} = 1\ \mu A\ sr^{-1}$ [a)]



[a)] largest reported value (J. Orloff: High Resolution Focused Ion Beams, Kluwer Academic, 2003)

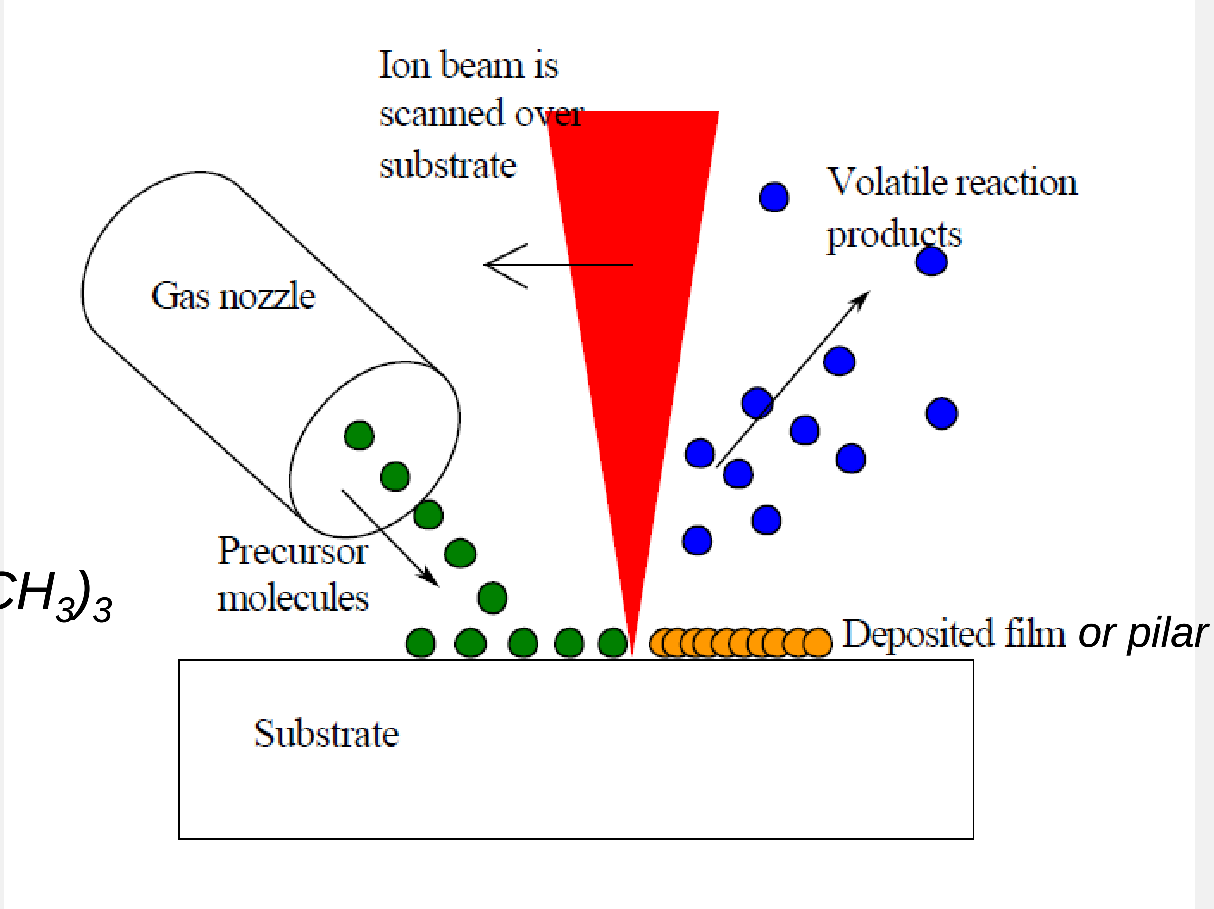
Other ion sources - Ions for the industry
1 - *Focused Ion Beam for the Nanotechnologies*

Deposited films induced by focused ion beam

$W(CO)_6$

$(C_5H_4)CH_3Pt(CH_3)_3$

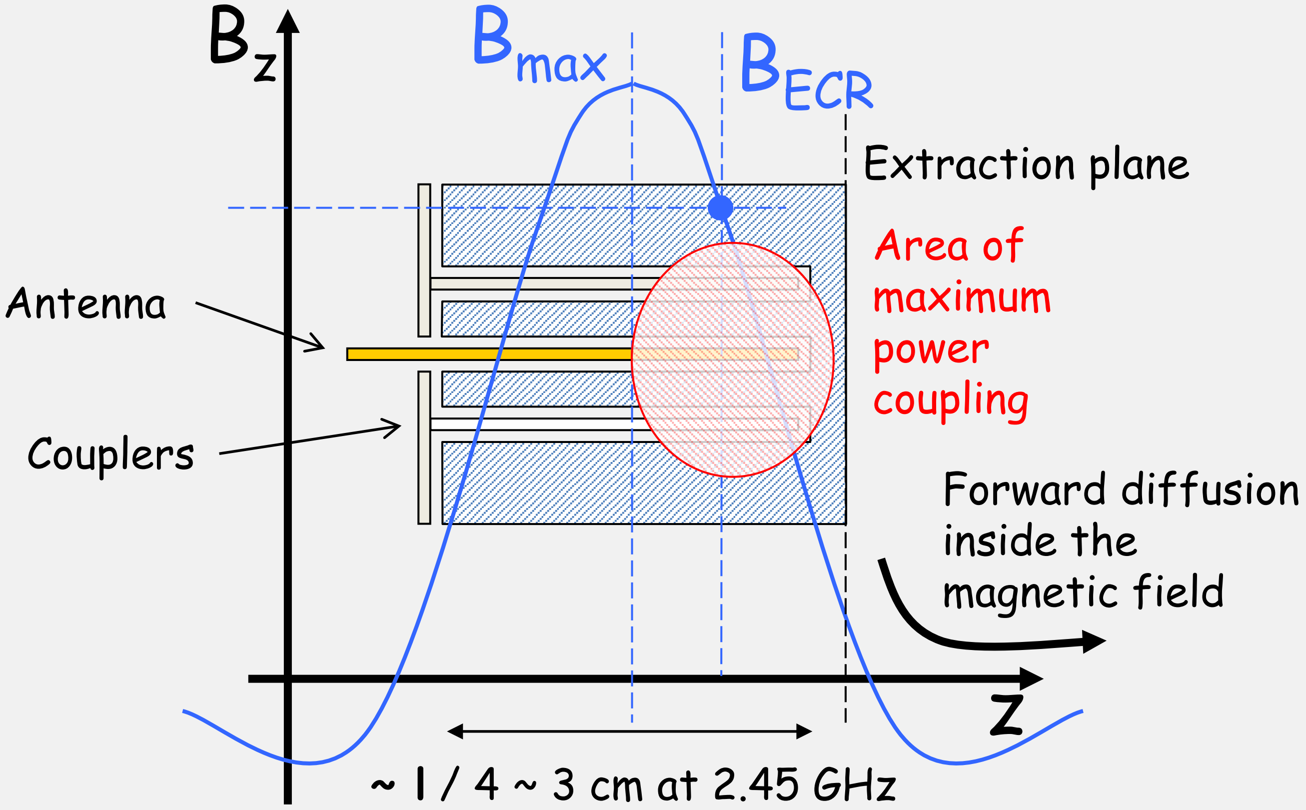
…



Other ion sources - Ions for the industry

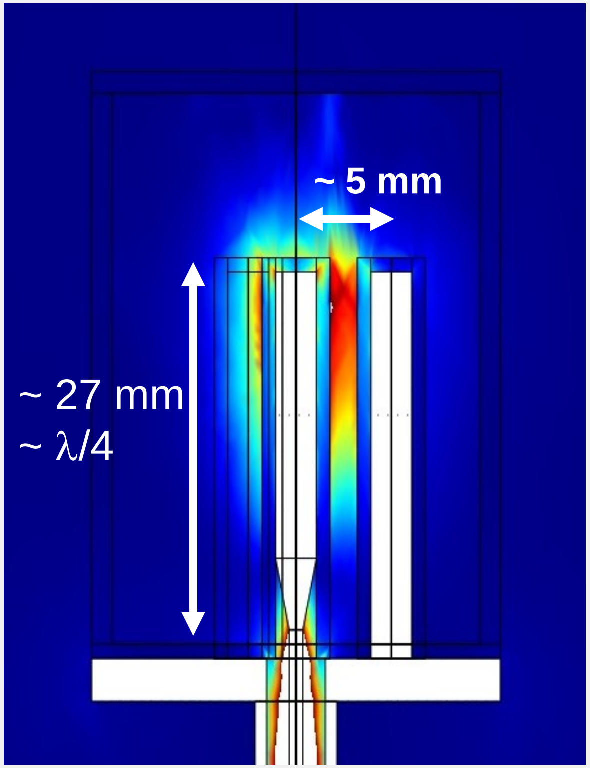
1 - Focused Ion Beam for the Nanotechnologies

Microwave source with “high brightness & high current” (μA):
The COMIC concept



Other ion sources - Ions for the industry

1 - *Focused Ion Beam for the Nanotechnologies*



Electric field amplitude distribution between the central antenna and couplers with quasi-coaxial geometry (COMSOL Calculation)

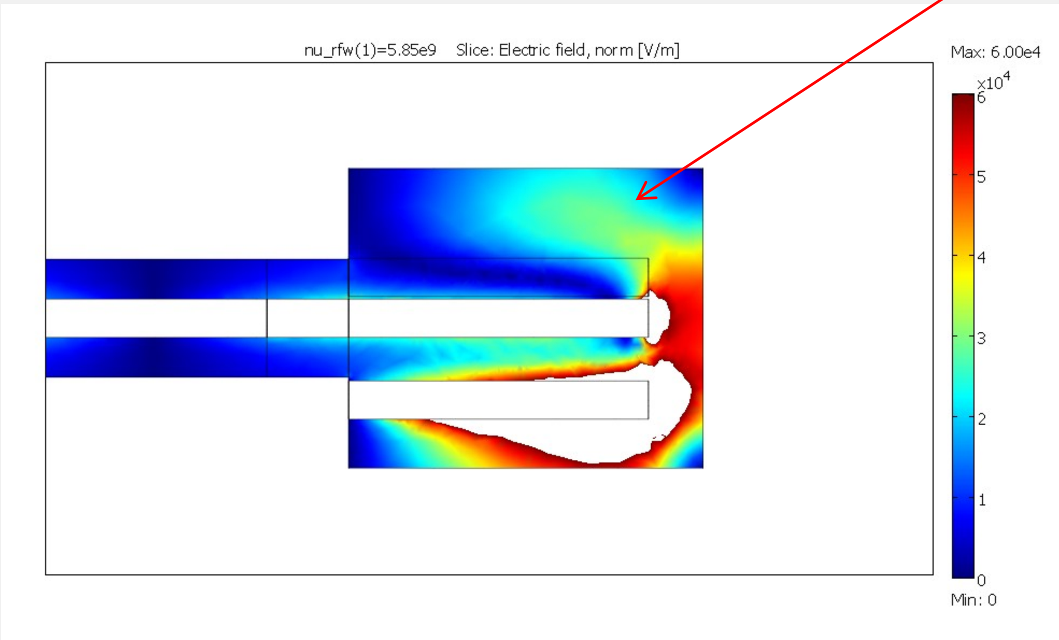
f_{hf} = 2.45 GHZ **Red > 10^4 V/m**

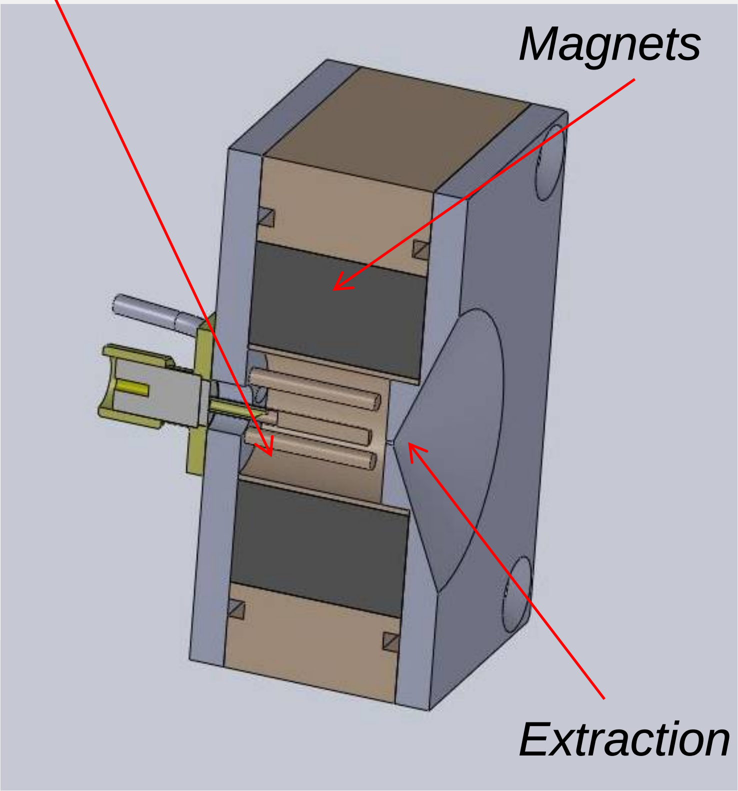
Distribution of light in a **Xenon** discharge (2 W) between the central antenna and the coupler with quasi-coaxial geometry

p ~ 10^{-2} mbar

Other ion sources - Ions for the industry
1 - Focused Ion Beam for the Nanotechnologies

Electric field amplitude inside a closed cavity



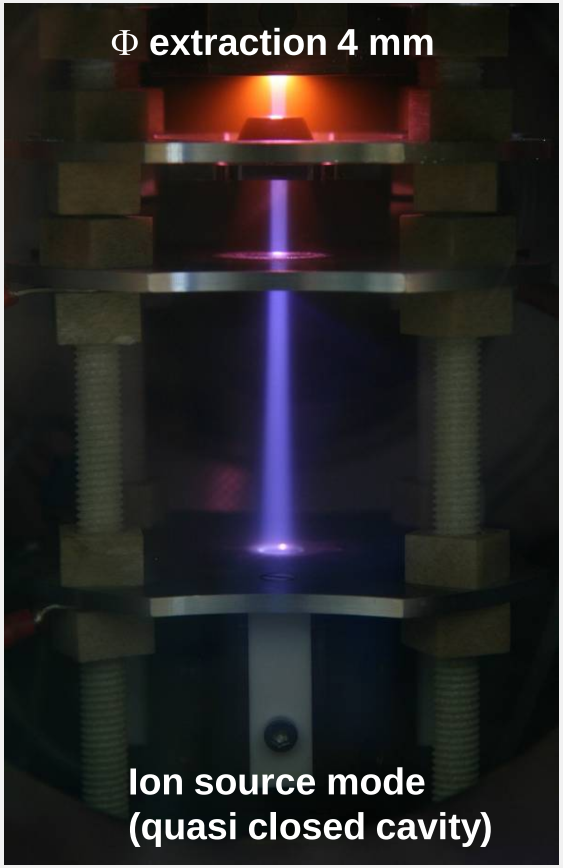


Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies

Plasma source mode
(semi closed cavity)

Argon 10^{-2} mbar / 5 W



Φ extraction 4 mm

Source
20 KV

1st elect.
16 KV

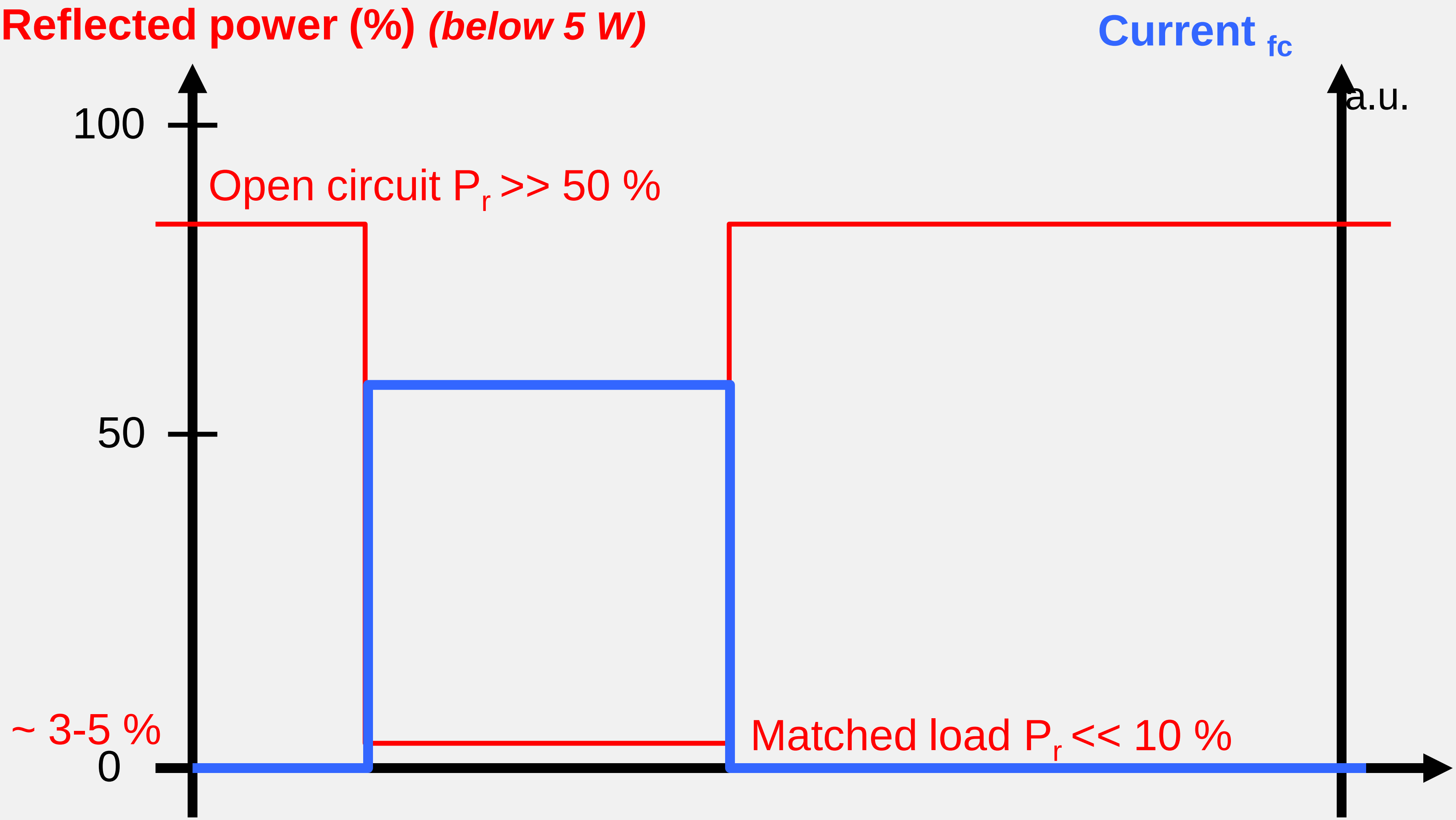
Grounded electrode
0 KV

Ion source mode
(quasi closed cavity)

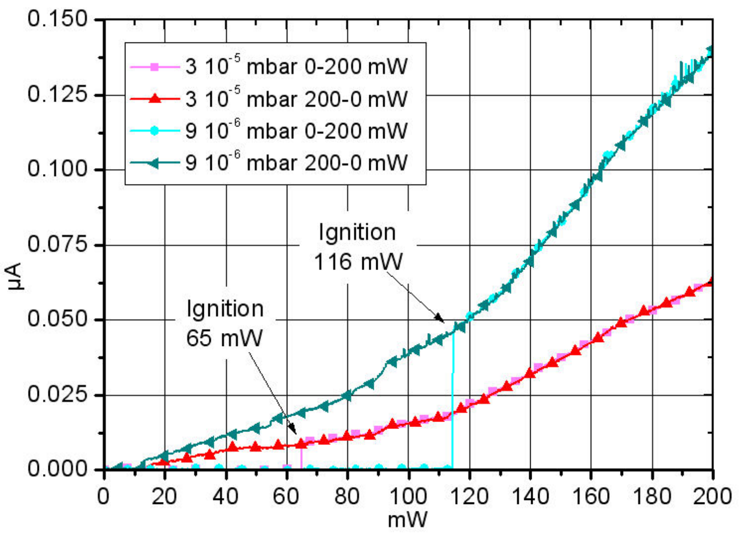
Nitrogen 5 10^{-5} mbar / 5 W
~ 500 µA ~ 4 mA/cm²

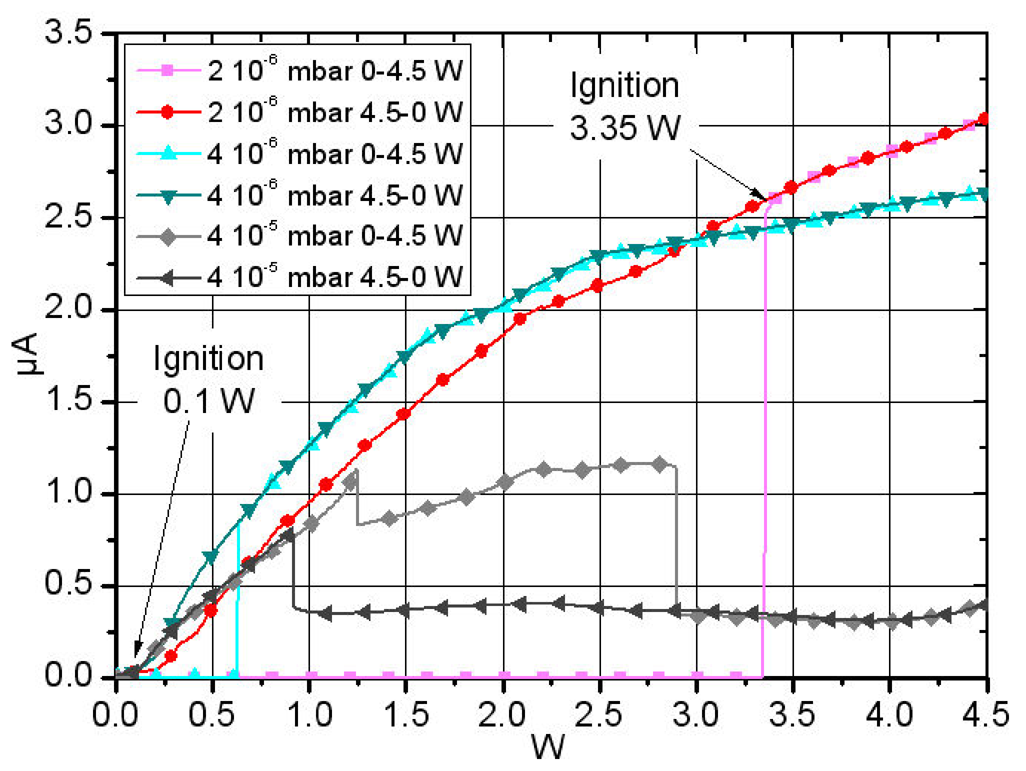
Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies



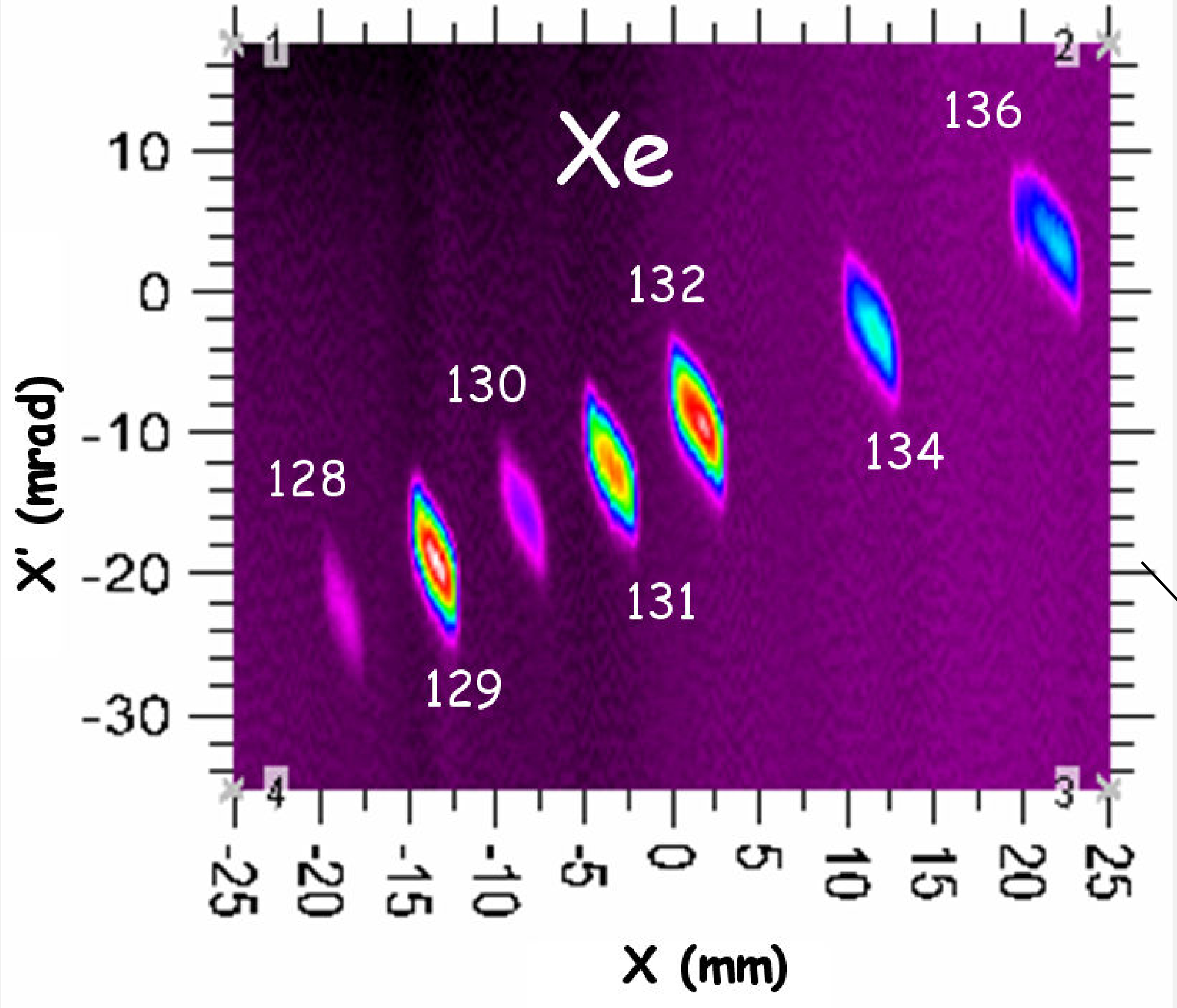
Other ion sources - Ions for the industry
1 - Focused Ion Beam for the Nanotechnologies





Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies



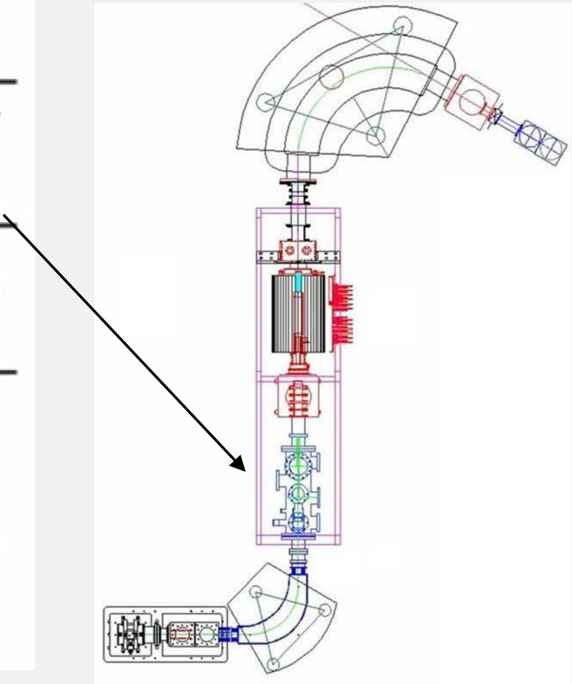
1 σ

1.2 π.mm.mrad

15 KV

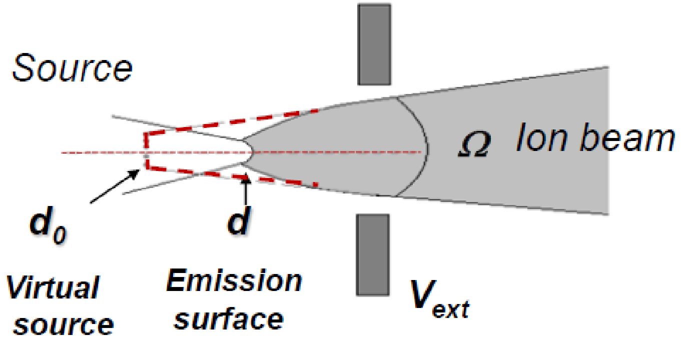
3/10 mm ext.

1.8 µAe total / 3 W / ext. *0.3* mm / 15 KV (12.5 *k*V élect. intermédiaire)



Other ion sources - Ions for the industry
1 - Focused Ion Beam for the Nanotechnologies

LMIS

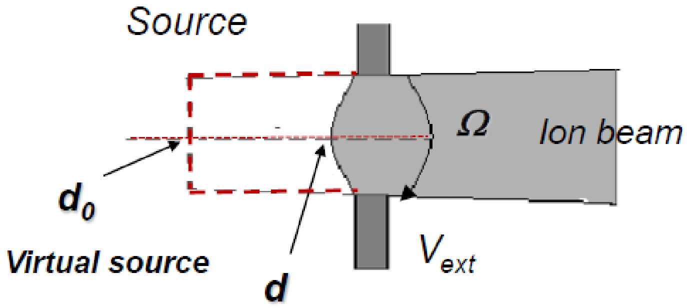


Virtual source size ≈ 50 nm

$\alpha \approx 20°$

Angular intensity ≈ 20 µA. sr-1

Plasma source

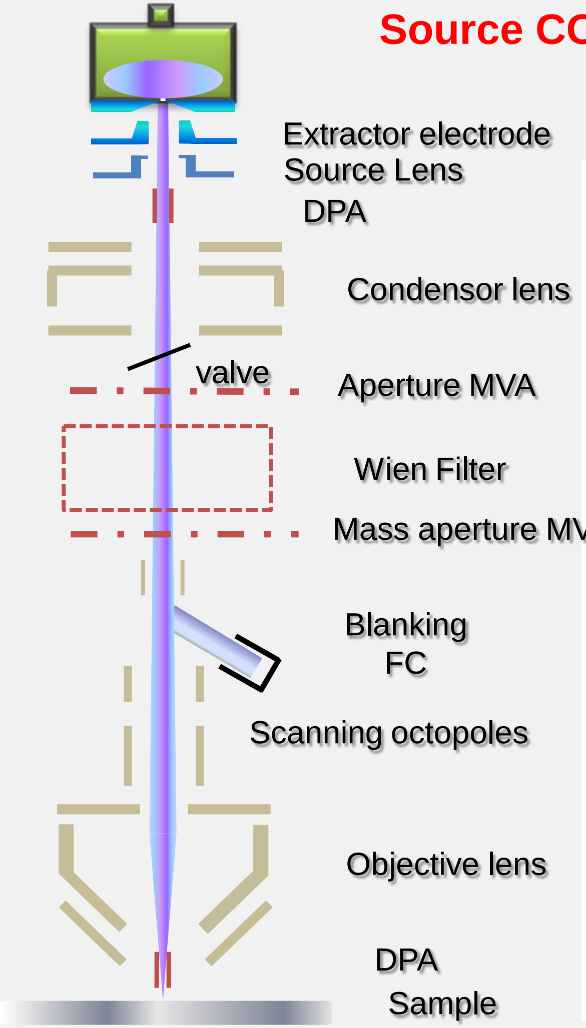


Virtual source size ≈ 15 µm

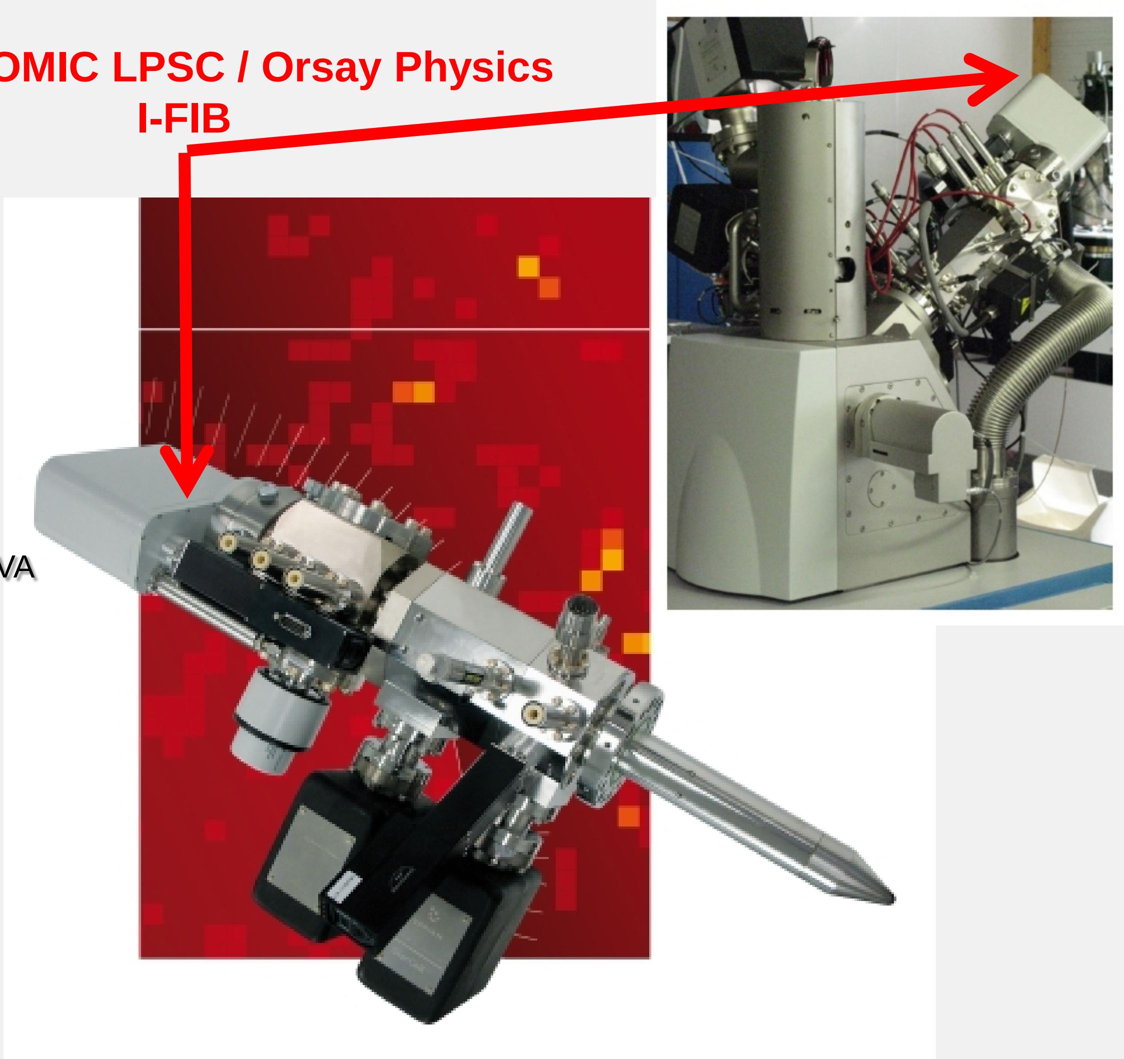
$\alpha \approx 1°$

Angular intensity ≈ 18 mA. sr-1

Other ion sources - Ions for the industry
1 - Focused Ion Beam for the Nanotechnologies

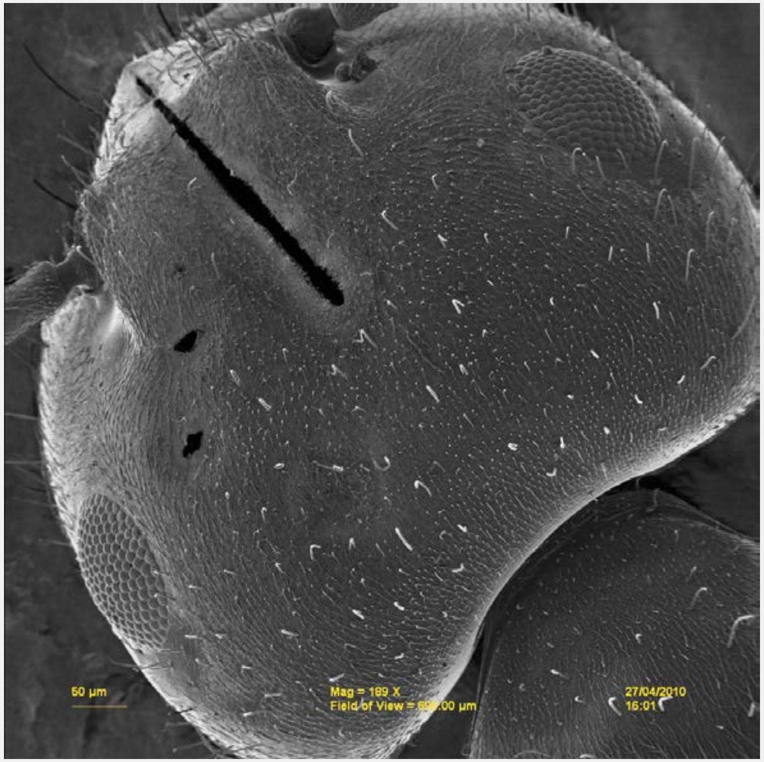


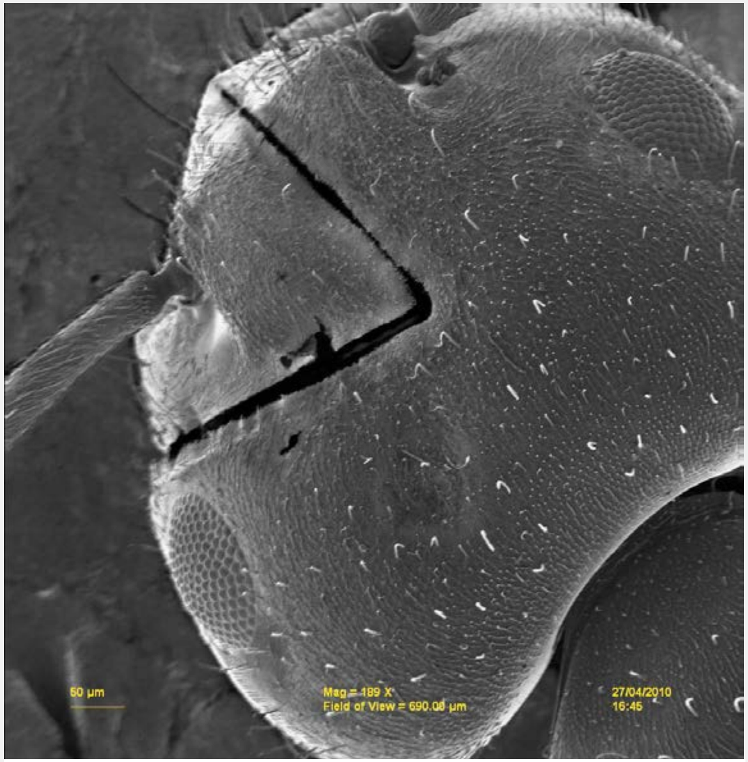
Source COMIC LPSC / Orsay Physics
I-FIB



Other ion sources - Ions for the industry
1 - Focused Ion Beam for the Nanotechnologies

Microsurgery of a ant head with the COMIC source





100 x 100 x 100 μm^3
15 hours with Ga (65 nA) = 40 minutes with Xe (1µA)

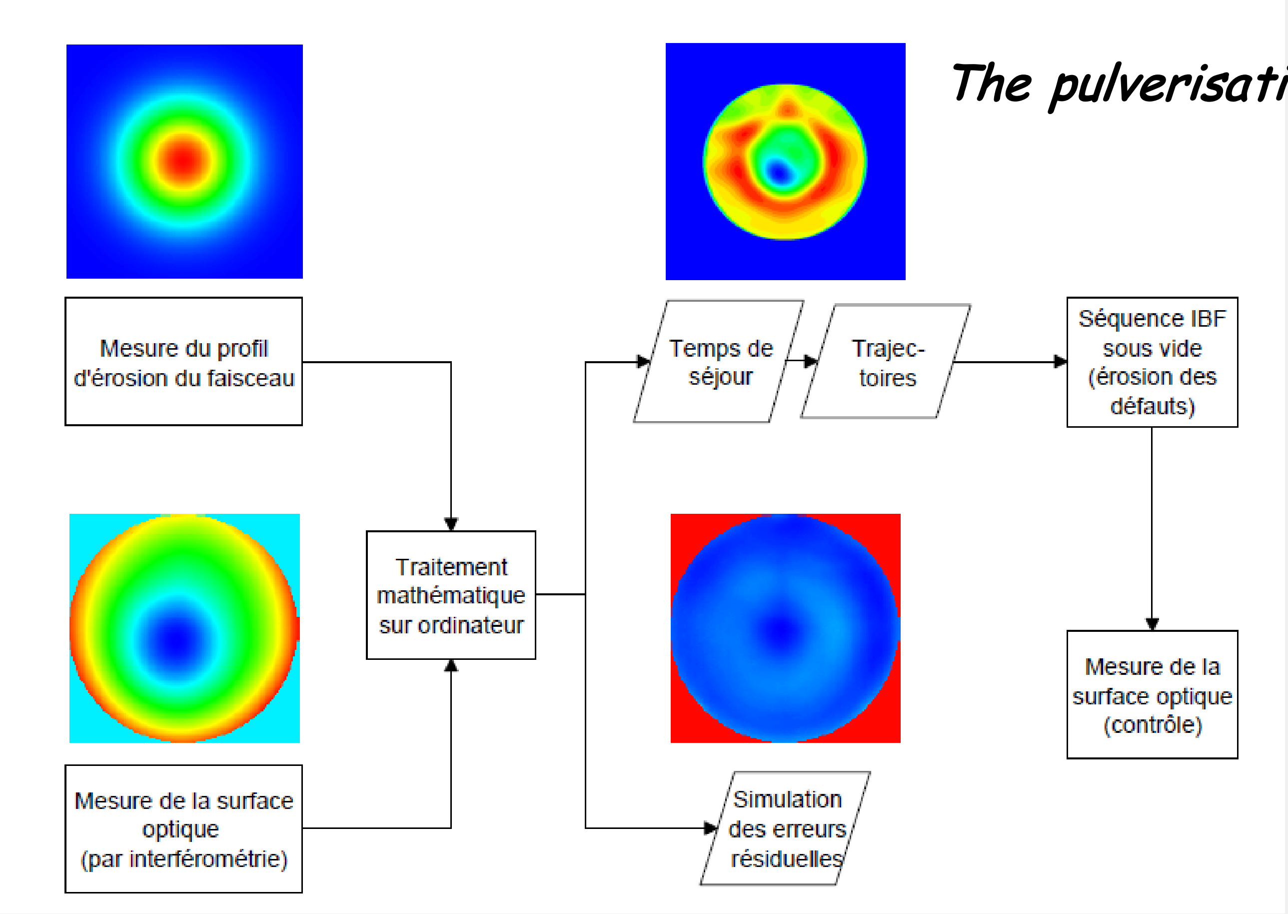
Other ion sources - Ions for the industry
1 - Ion Beam Figuring of the Optic Industry

The purpose of the Ion Beam Figuring :

The beam

The pulverisation

The profil Defaults :
> 1mm and
<1 µm



Mesure du profil d'érosion du faisceau

Mesure de la surface optique (par interférométrie)

Traitement mathématique sur ordinateur

Temps de séjour

Trajec-toires

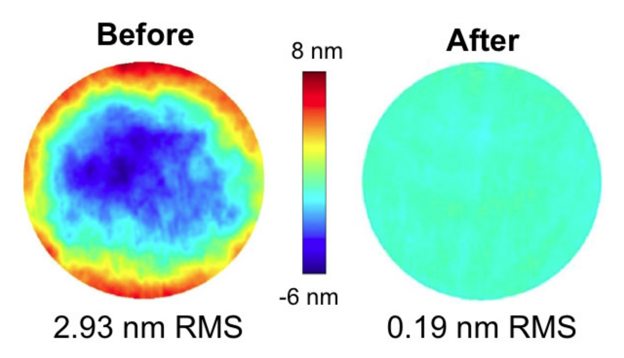
Séquence IBF sous vide (érosion des défauts)

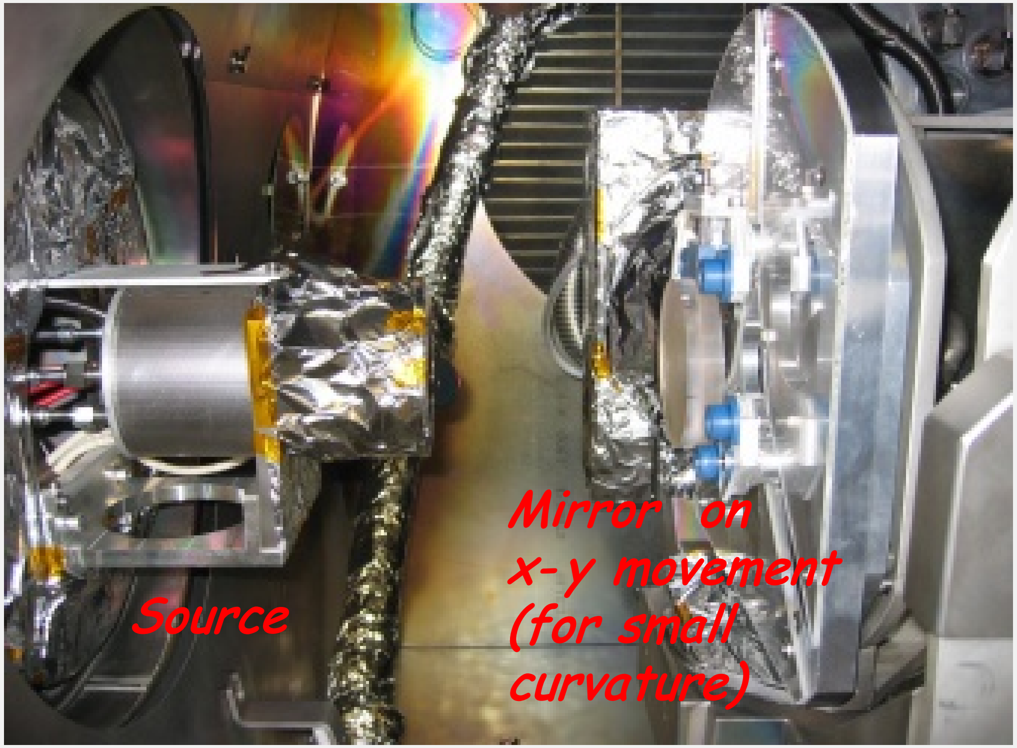
Mesure de la surface optique (contrôle)

Simulation des erreurs résiduelles

Other ion sources - Ions for the industry
1 - Ion Beam Figuring of the Optic Industry

Ion Beam Figuring machine:





+ No pressure : very thin optics
+ Determinist
- Under vacuum (heating)
- Rugosisy modification

Other ion sources - Ions for the industry
1 - Ion Beam Figuring of the Optic Industry

Broad beam (20-40 mm) Kaufman filament source with grid extractor

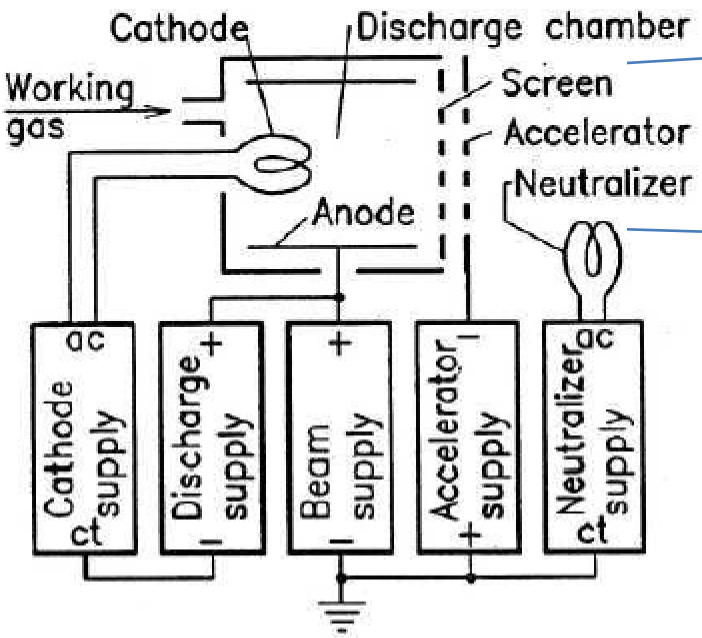


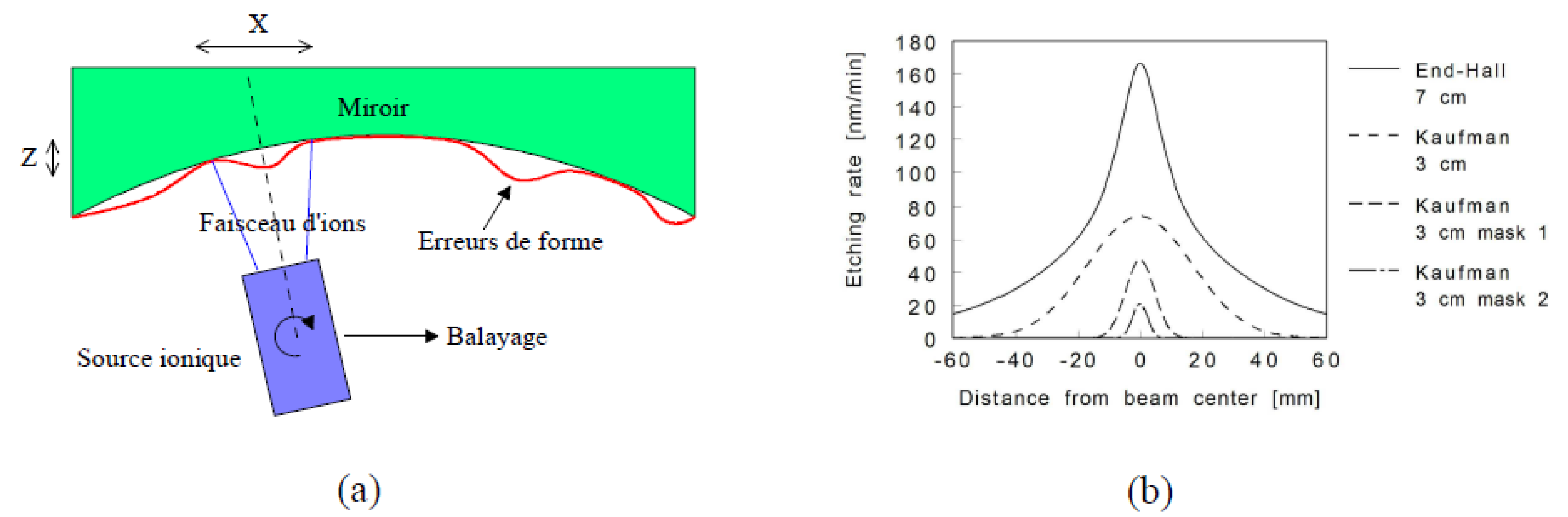
Schéma de principe d'une source ionique de type « Kaufman »

Gaussian beam

Other ion sources - Ions for the industry

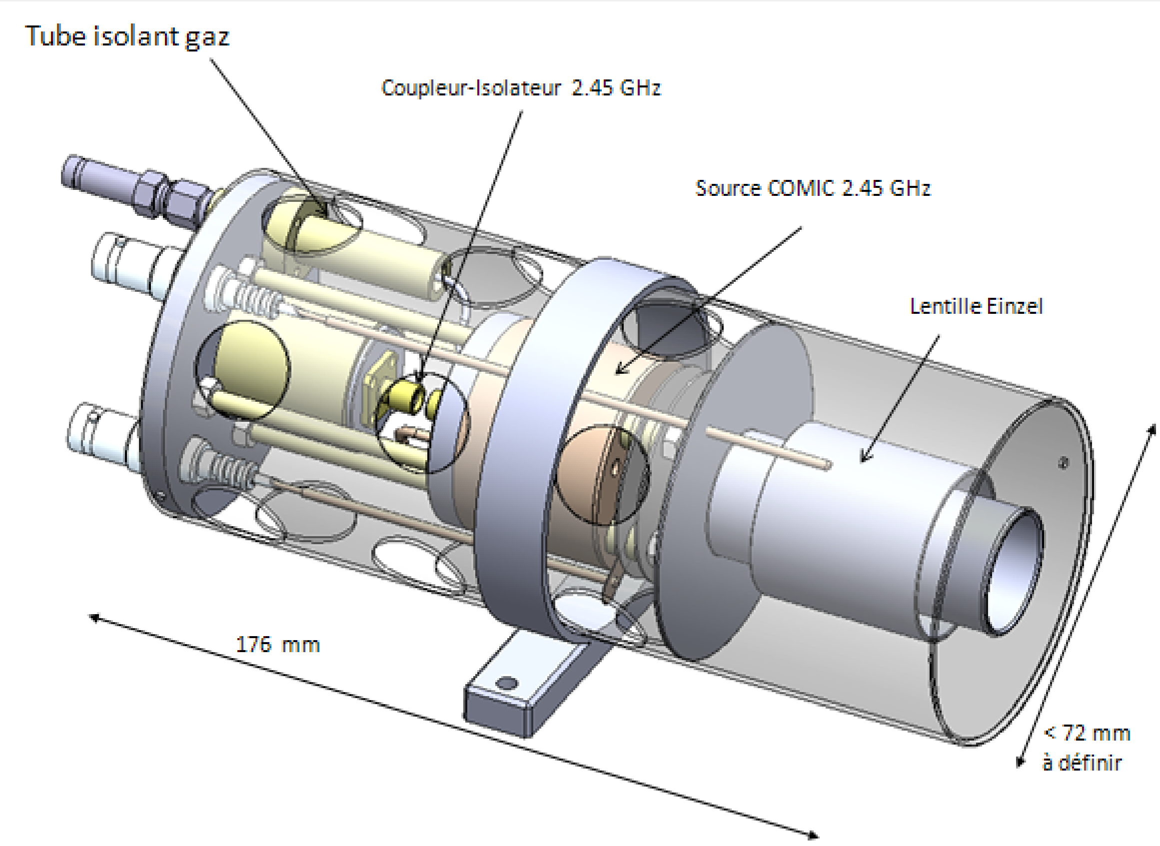
1 - Ion Beam Figuring of the Optic Industry

Matching of the beam size to a characteristic lenght of the defaults:

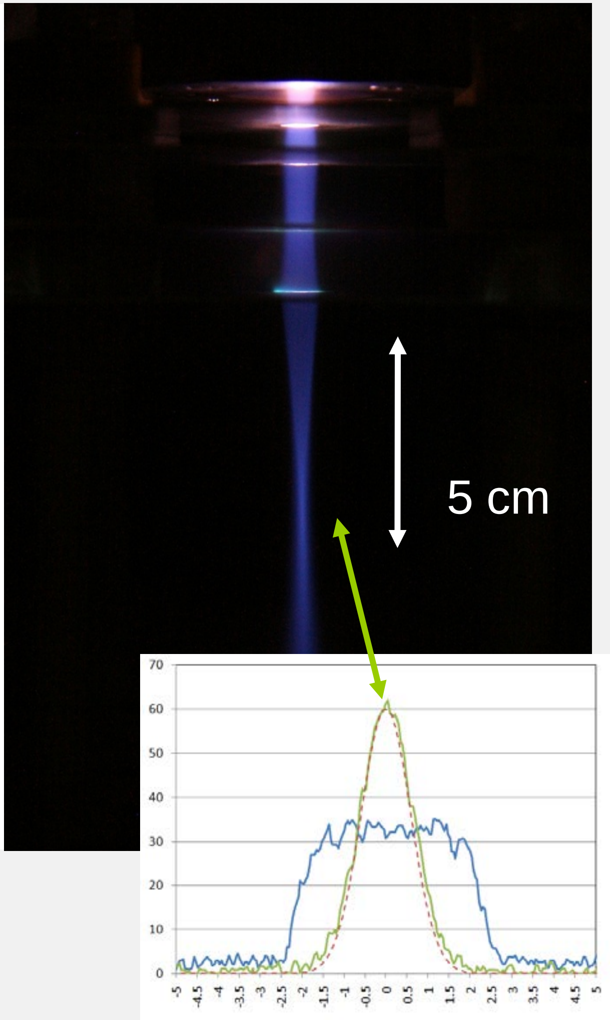


(a) (b)

Other ion sources - Ions for the industry
1 - Ion Beam Figuring of the Optic Industry



Ar – 150 µA – 1.4 KV – σ ~ 0.6 mm



High brightness gaussian millimeter beam size with COMIC

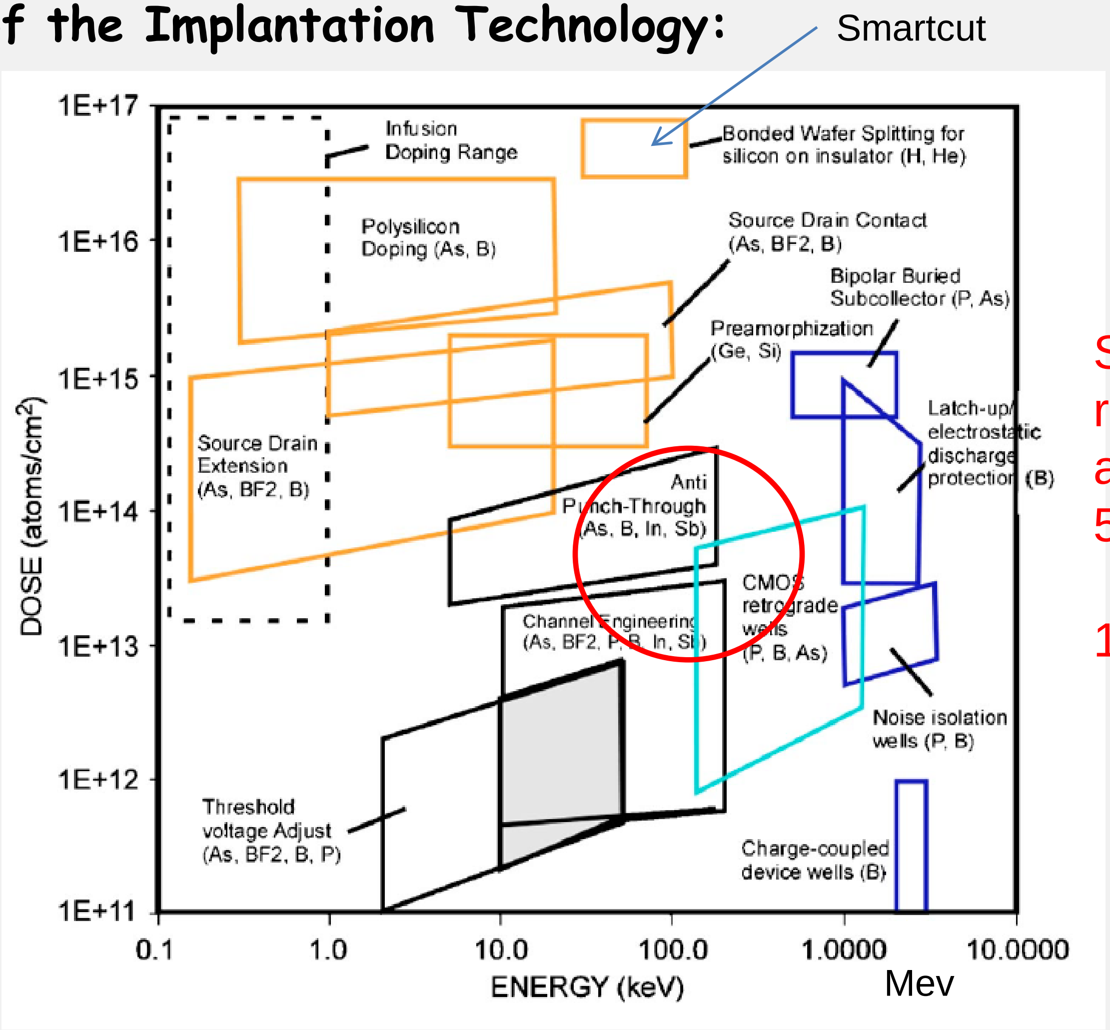
Other ion sources - Ions for the industry
2 - High Intensity Beams for MicroElectronics

The purpose of the Implantation Technology:

High current
~ 10 mA acc.

Medium current
~ 1 mA acc.

Low current



Standard requirement area
50-200 Kev

10^{14} at./cm2

Φ 300 mm
~ 700 cm^2

Other ion sources - Ions for the industry

2 - *High Intensity Beams for MicroElectronics*

The demand for the Implantation Technology:

Boron (z=5): BF_3, B_2H_6

Phosporus (z=15) : P(solid), PF_3, PH_3

Arsenic (z=33) : AsH_3

↓

gas

↓

B, P, As

↓

solid

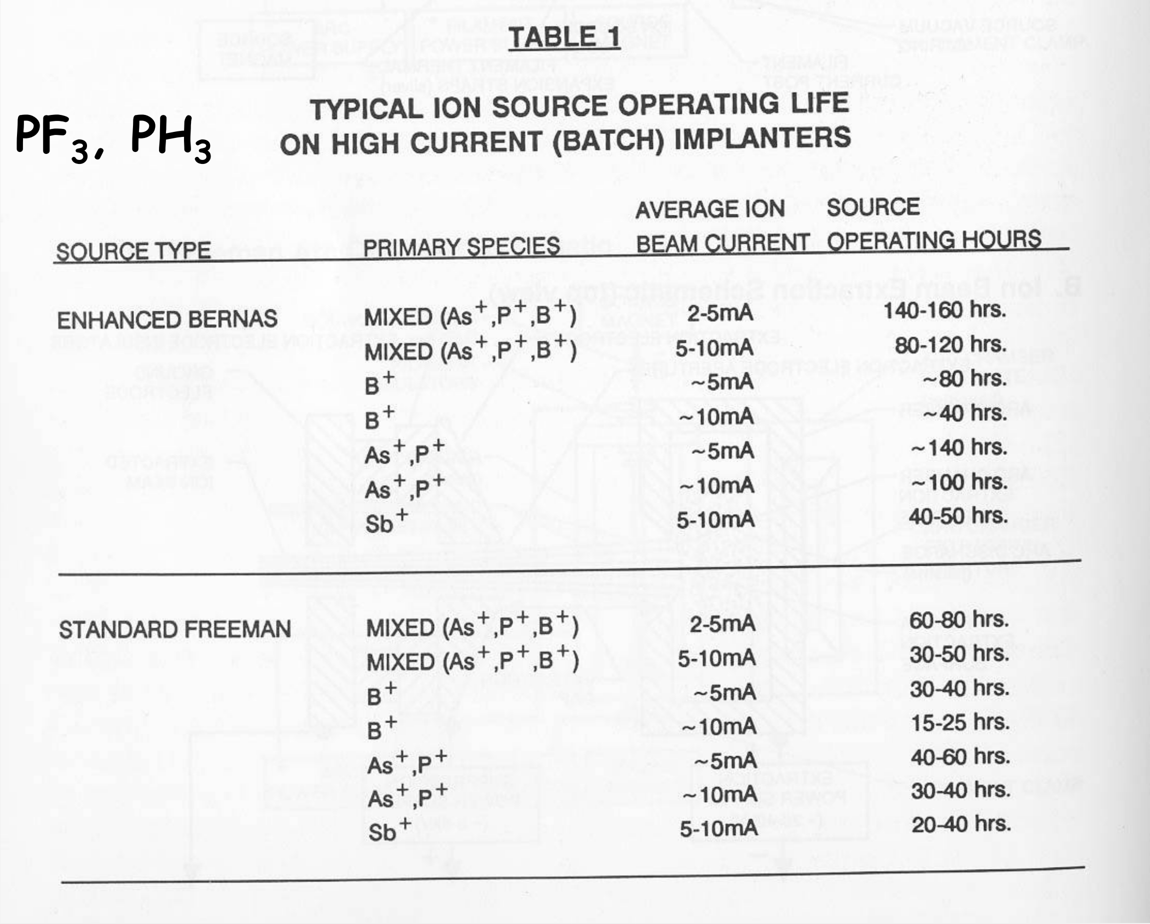


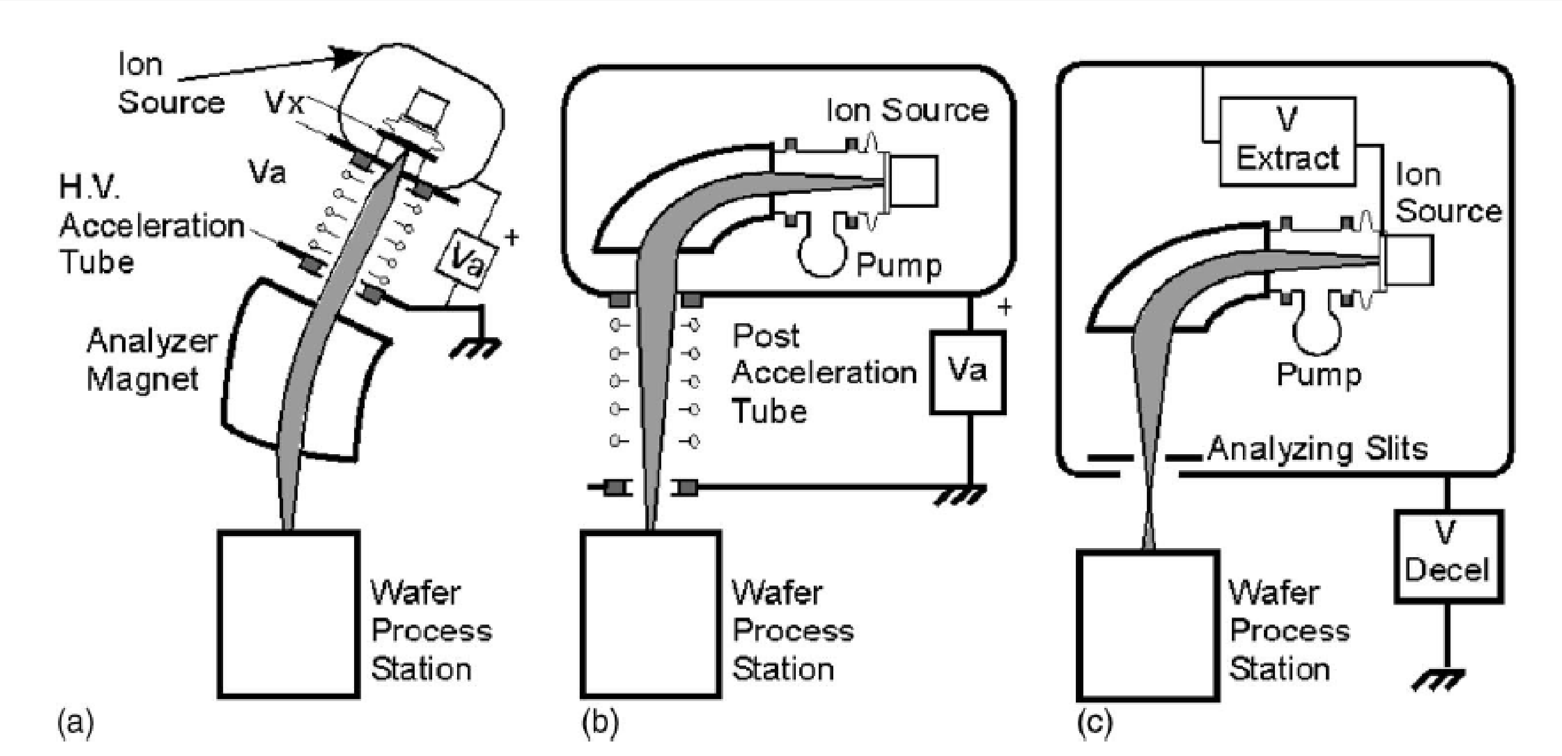
TABLE 1

TYPICAL ION SOURCE OPERATING LIFE ON HIGH CURRENT (BATCH) IMPLANTERS

SOURCE TYPE	PRIMARY SPECIES	AVERAGE ION BEAM CURRENT	SOURCE OPERATING HOURS
ENHANCED BERNAS	MIXED (As^+,P^+,B^+)	2-5mA	140-160 hrs.
	MIXED (As^+,P^+,B^+)	5-10mA	80-120 hrs.
	B^+	~5mA	~80 hrs.
	B^+	~10mA	~40 hrs.
	As^+,P^+	~5mA	~140 hrs.
	As^+,P^+	~10mA	~100 hrs.
	Sb^+	5-10mA	40-50 hrs.
STANDARD FREEMAN	MIXED (As^+,P^+,B^+)	2-5mA	60-80 hrs.
	MIXED (As^+,P^+,B^+)	5-10mA	30-50 hrs.
	B^+	~5mA	30-40 hrs.
	B^+	~10mA	15-25 hrs.
	As^+,P^+	~5mA	40-60 hrs.
	As^+,P^+	~10mA	30-40 hrs.
	Sb^+	5-10mA	20-40 hrs.

Other ion sources - Ions for the industry
2 - High Intensity Beams for MicroElectronics

The purpose of the Implantation Technology:



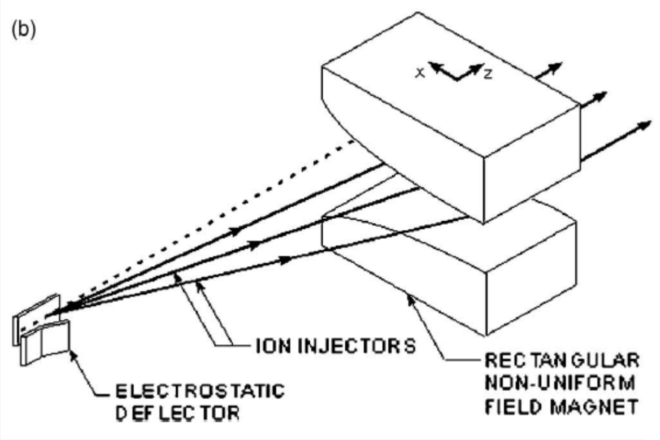
Medium current
Medium energy

High current
Medium energy

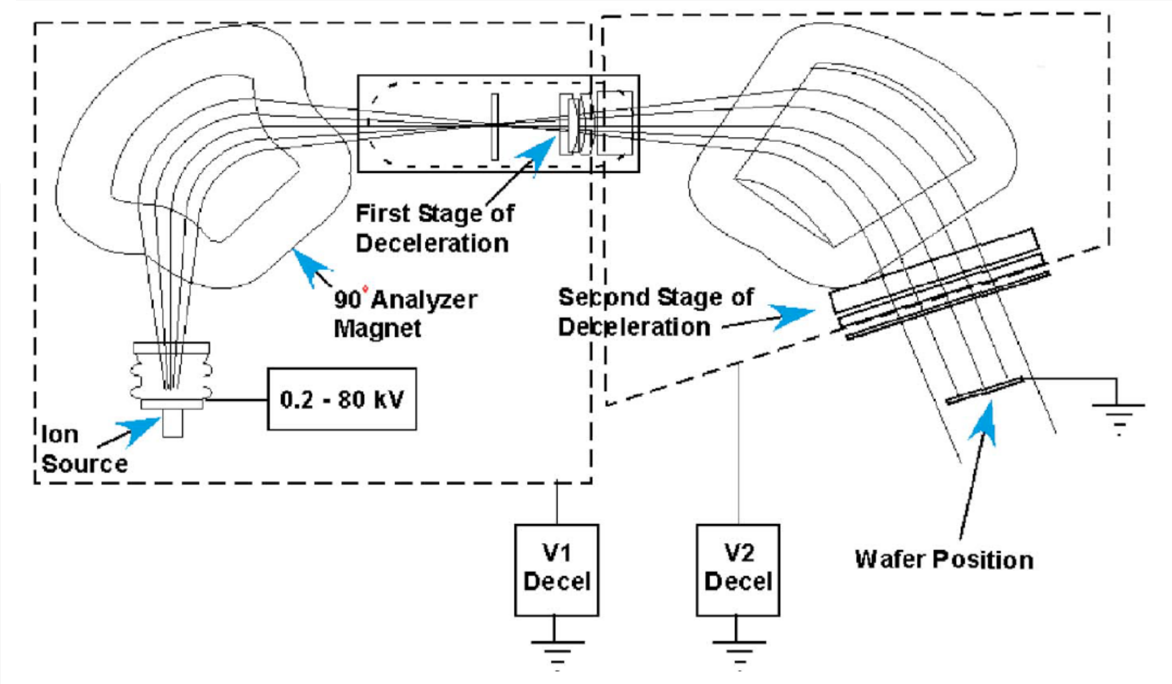
High current
Low energy

Other ion sources - Ions for the industry
2 - High Intensity Beams for MicroElectronics

The purpose of the Implantation Technology: Ribbon beam generation



Scanning of a parallel beam

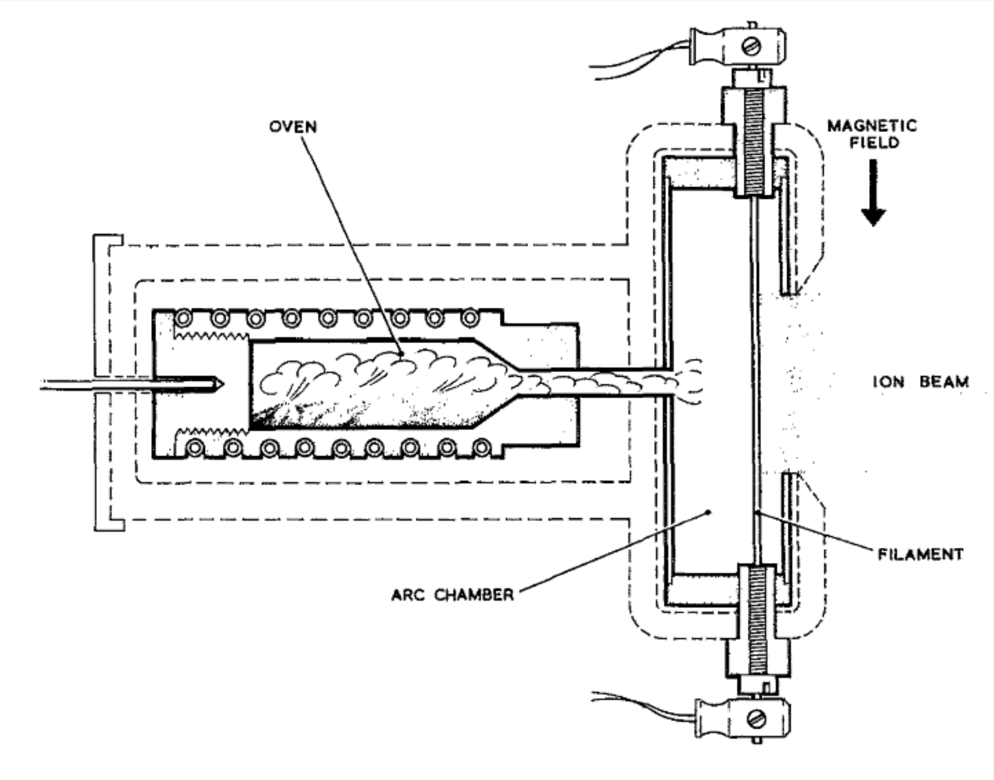


Generation of the ribbon beam

Other ion sources - Ions for the industry

2 - High Intensity Beams for MicroElectronics

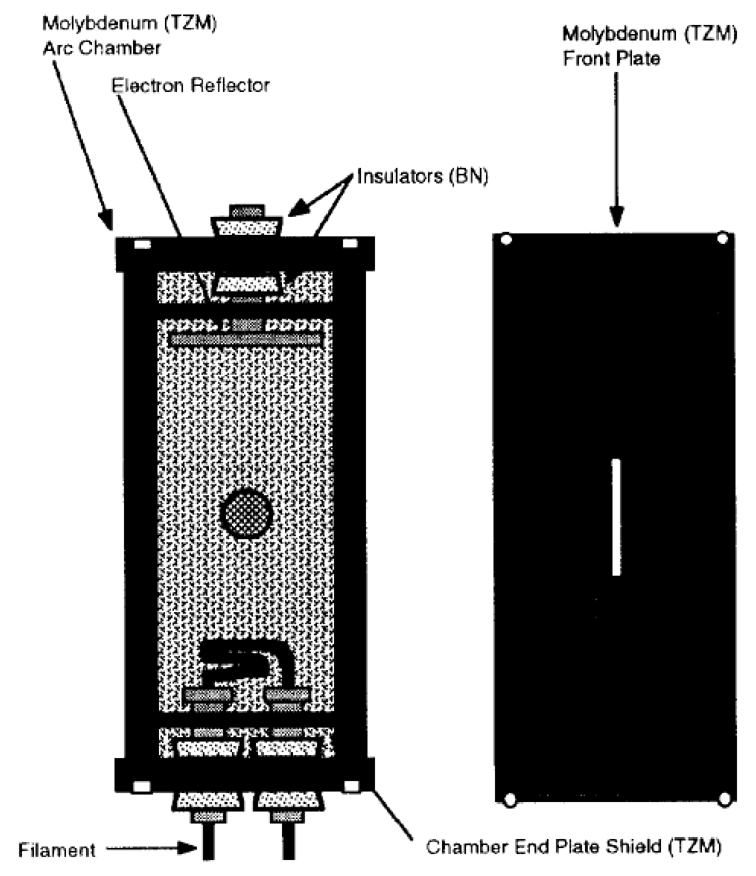
The Freeman Ion Source:



Other ion sources - Ions for the industry

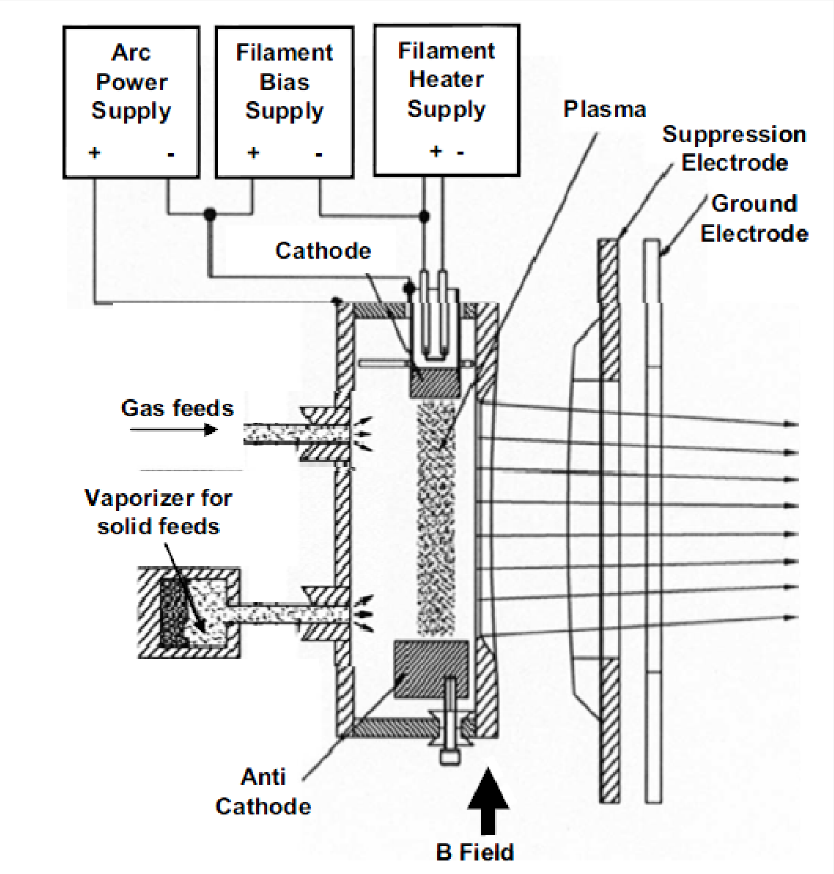
2 - High Intensity Beams for MicroElectronics

The Bernas Ion Source:



Other ion sources - Ions for the industry
2 - High Intensity Beams for MicroElectronics

The Indirectly Heated Cathode Ion Source (IHC):

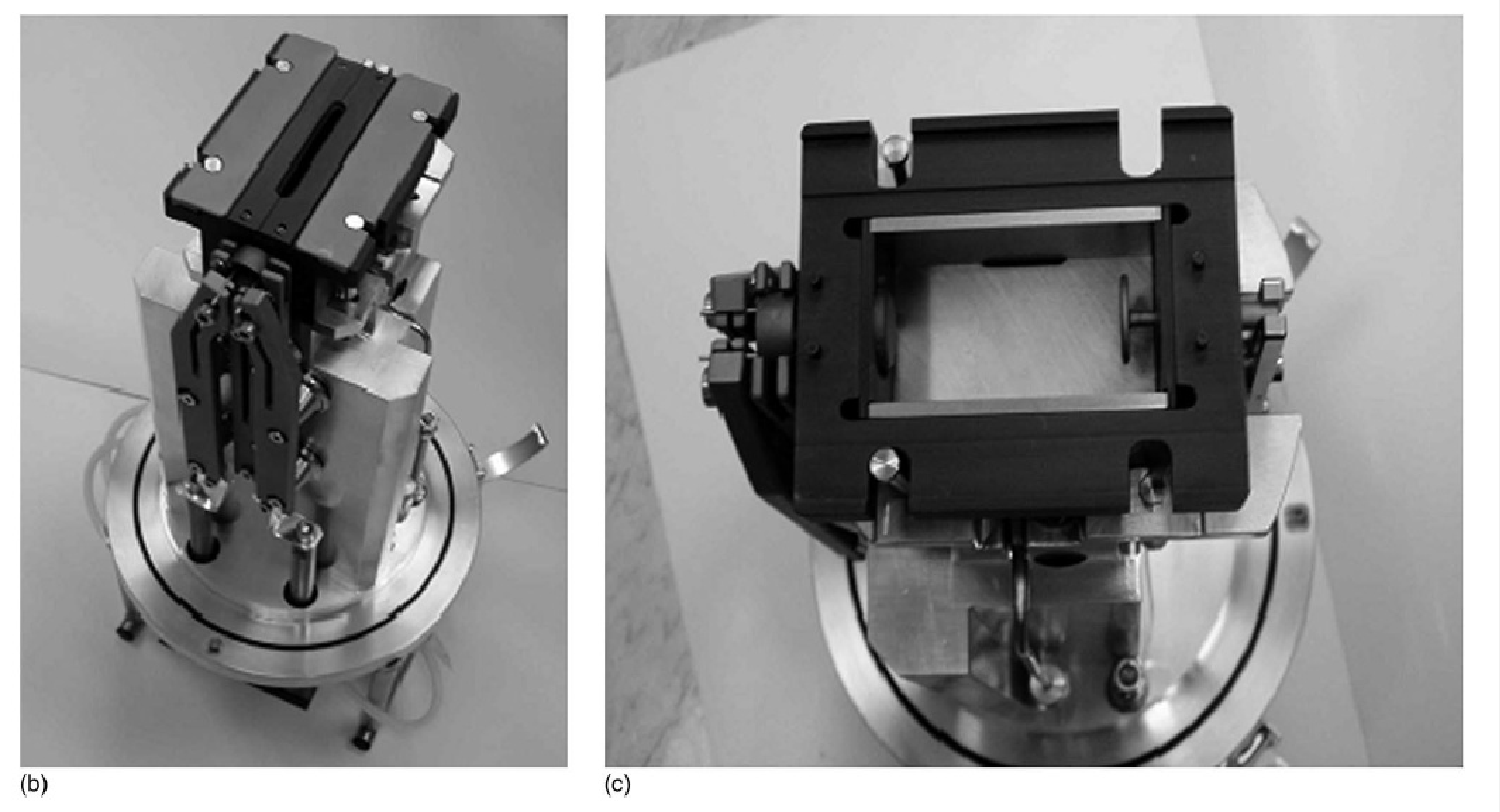


Lifetime > 500 h
Strongly depending of the tuning

Other ion sources - Ions for the industry

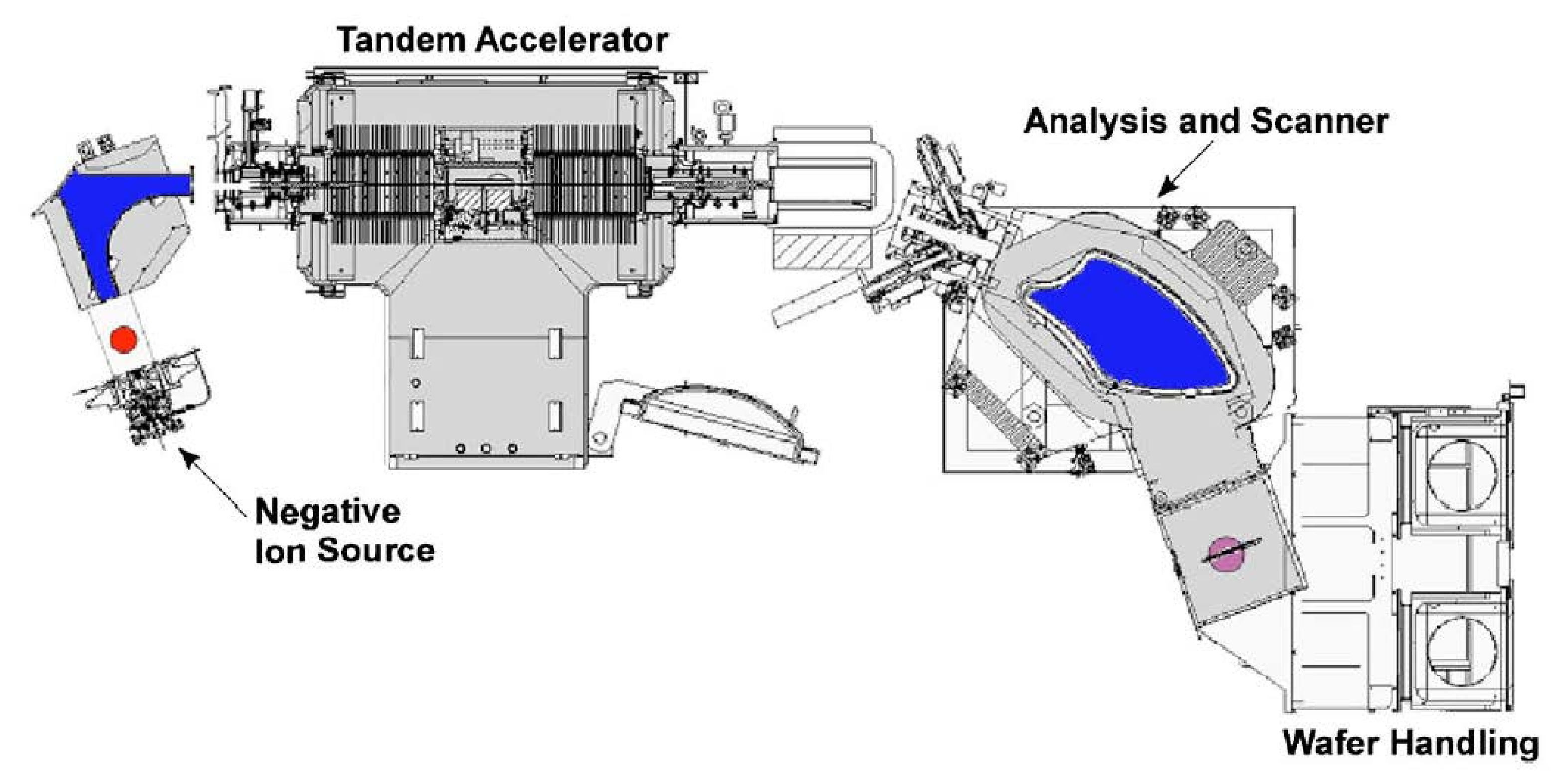
2 - High Intensity Beams for MicroElectronics

The Indirectly Heated Cathode Ion Source (IHC):



Other ion sources - Ions for the industry
2 - High Intensity Beams for MicroElectronics

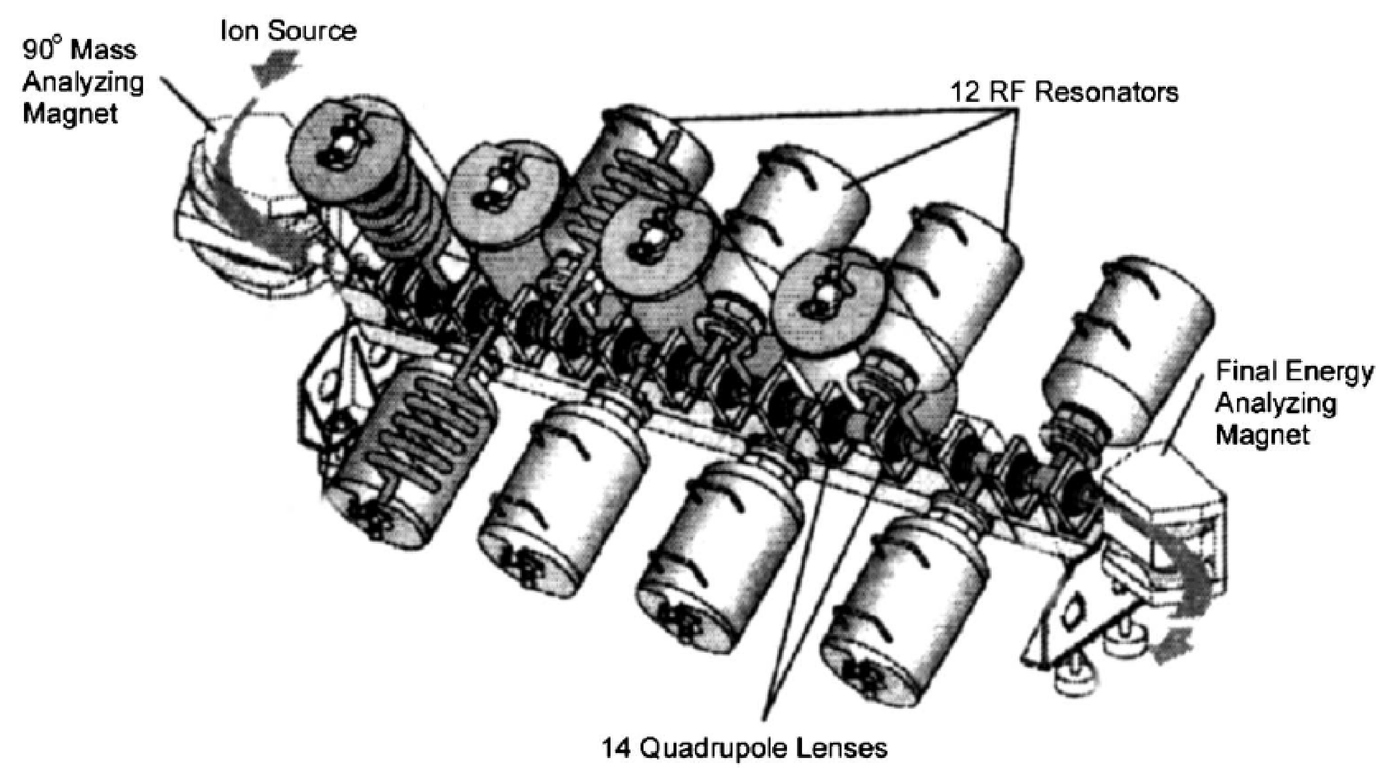
High energy implantation : Negative ion source and Tamdem



Other ion sources - Ions for the industry

2 - High Intensity Beams for MicroElectronics

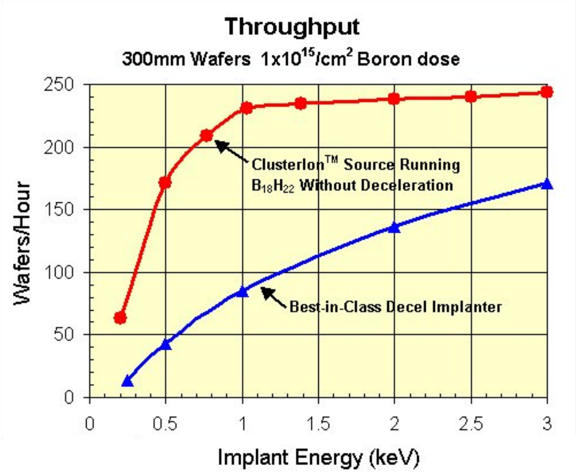
<u>High energy implantation</u> : Positive ion source and Linac

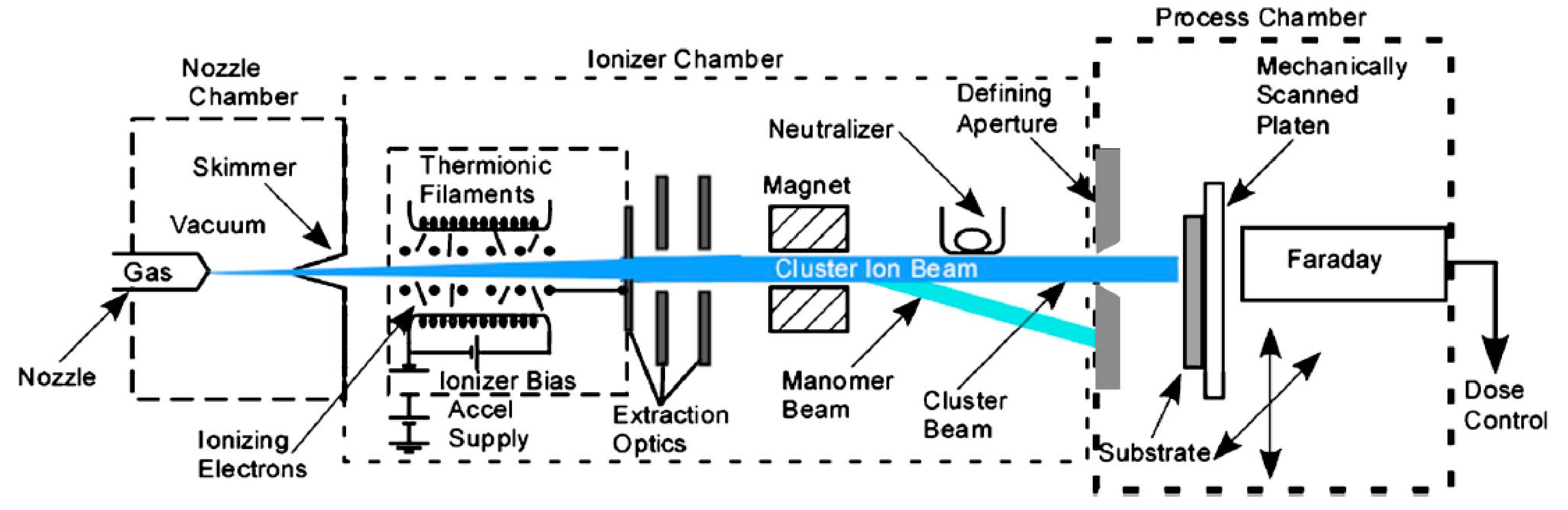


Other ion sources - Ions for the industry
2 - High Intensity Beams for MicroElectronics

Low energy implantation :
Complex Molecular ion and Cluster

$B_{18}H_{22}$, $C_{16}H_{10}$
followed by annealling (~ 1000°C)





Other ion sources - Ions for the industry

2 - High Intensity Beams for MicroElectronics

Problems already open in the implantation technology :

(from A. Renau, Varian Semiconductor Equipment Associates
35 Dory Rd, Gloucester, Massachusetts 01930, USA, RSI, 81, 02B907, 8 February 2010)

1 - > 5 mA CW of 1^+, 2^+ & 3^+ compact, low cost and upgreadeable

2 - > 5 mA CW of B^-, P^-, As^- with lifetime >168 h

3 – Large area implantation : < 1% over Φ 500 mm

4 – Low maintenance ion source

(without modification inside the beam line optics)

Other ion sources - Ions for the industry

3 - *Broad Beam & "Ionic Machine" for the Industrial Coating*

The industrial field of use : the PVD coating

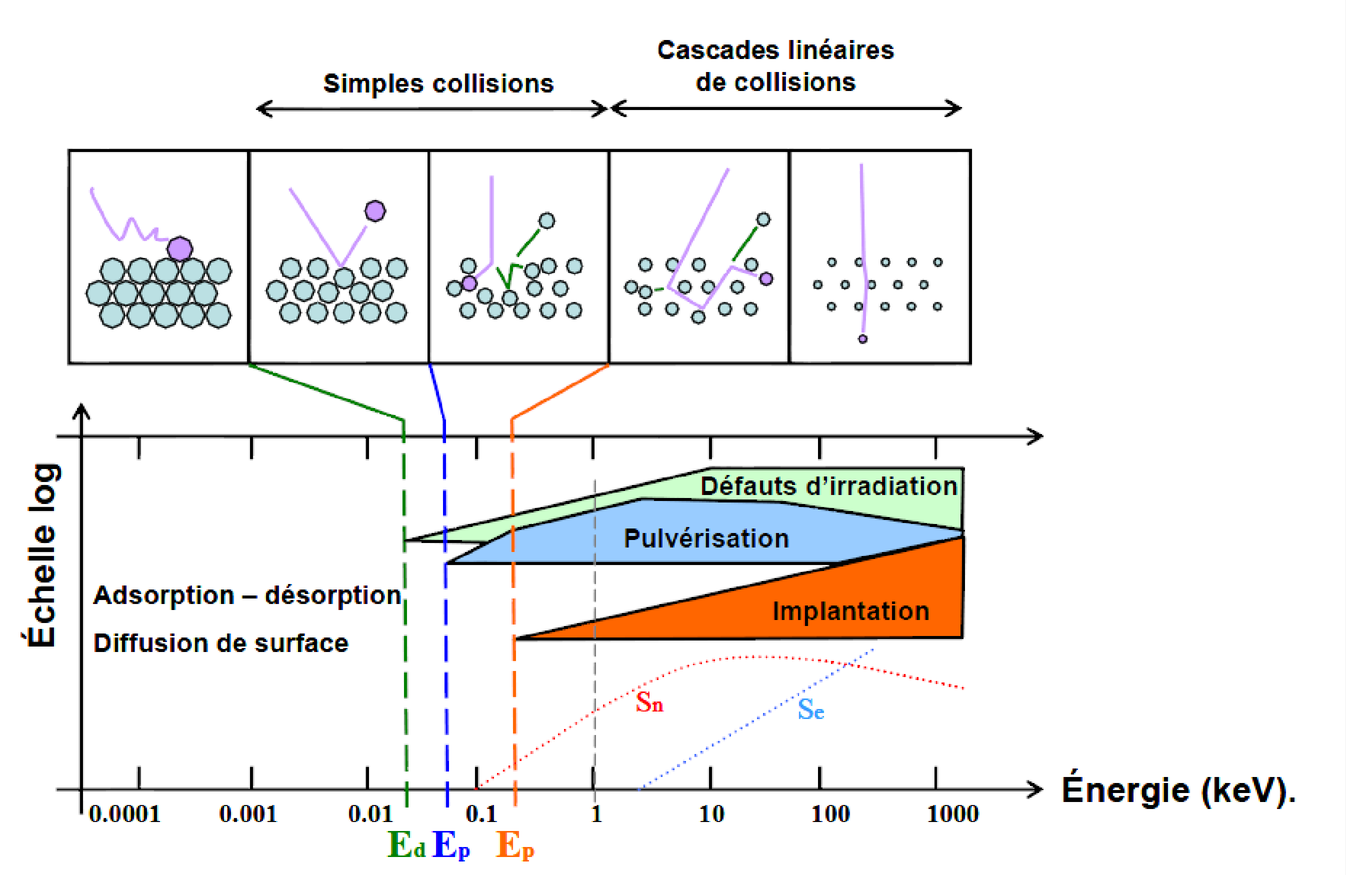
(Physical Vapor Deposition)

- *Hardness modification (cutting tools, tribology)*
- *Solar (large area deposition)*
- *Optical component (laser and large optical miror)*
- *Decorative coating (watchmaking,...)*

Other ion sources - Ions for the industry

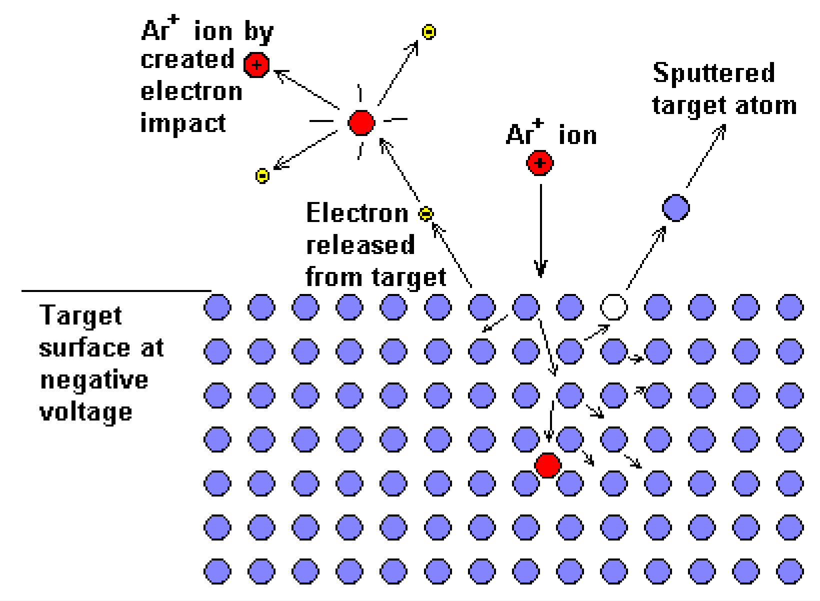
3 - Broad Beam & "Ionic Machine" for the Industrial Coating

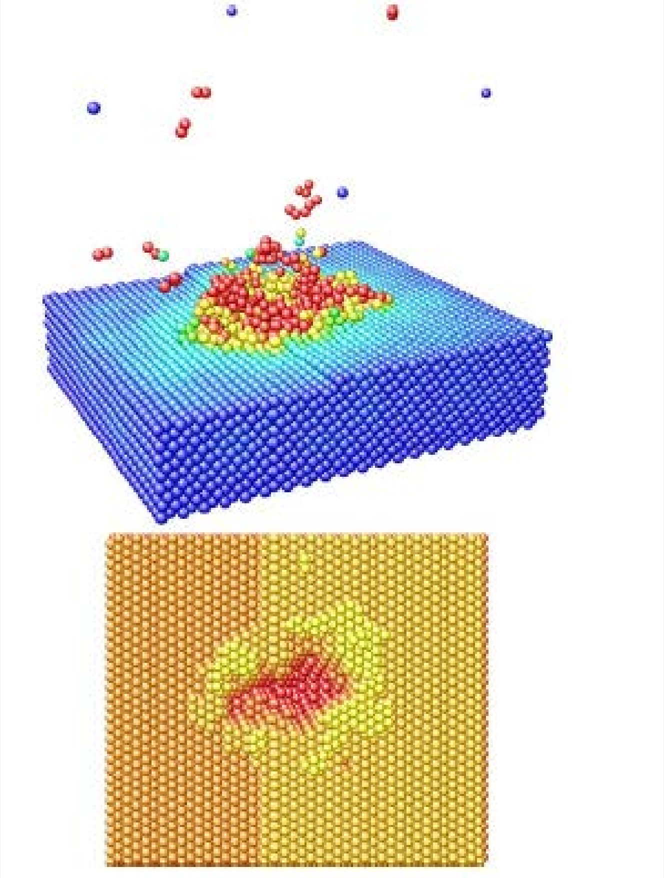
Ionic modification of matérial :



Other ion sources - Ions for the industry
3 - *Broad Beam & "Ionic Machine" for the Industrial Coating*

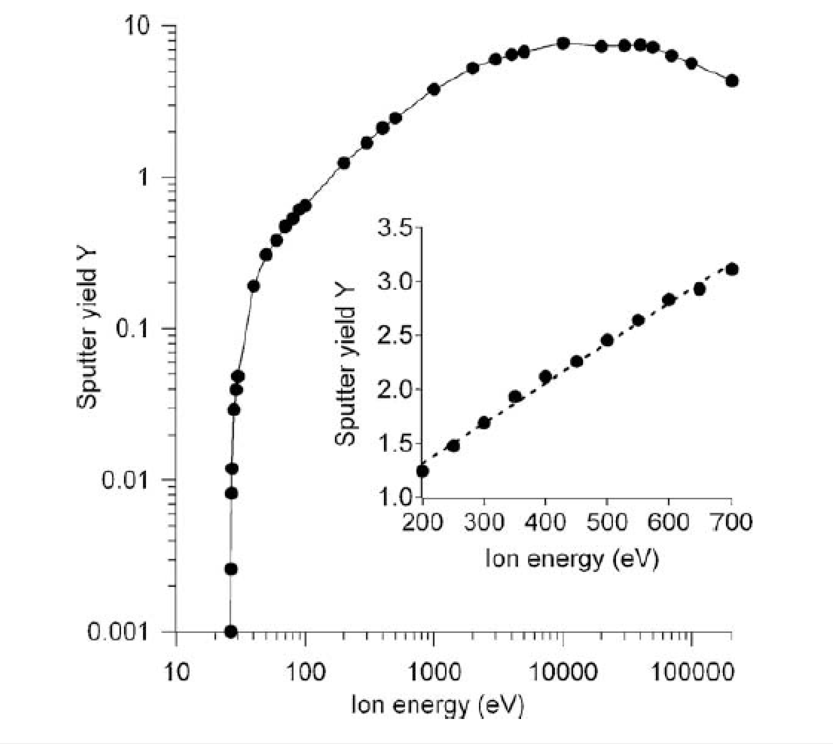
The sputtering process : (Ar$^+$, 5 kV at 83° / surf., 2.5 ps)



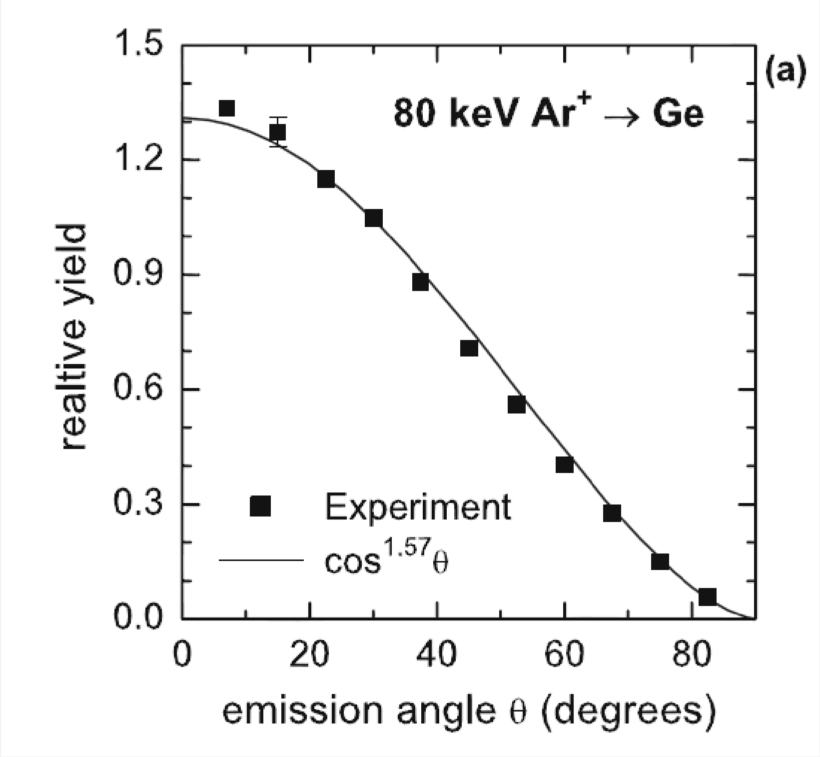


Other ion sources - Ions for the industry

3 - Broad Beam & "Ionic Machine" for the Industrial Coating

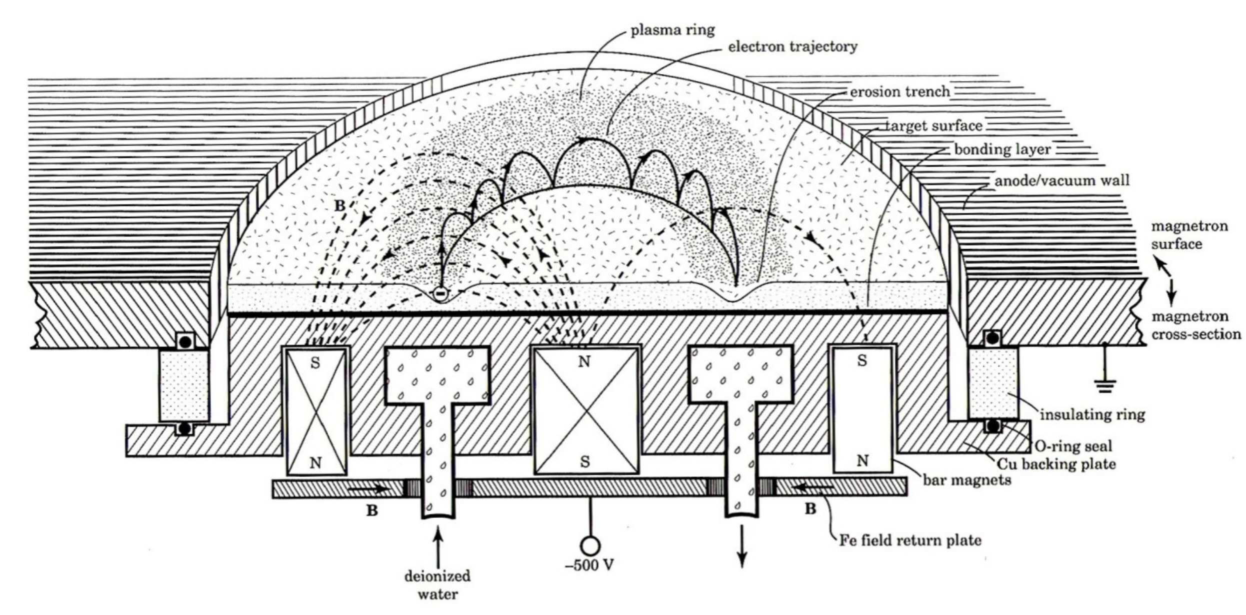


Ar → Si



Other ion sources - Ions for the industry
3 - *Broad Beam & "Ionic Machine" for the Industrial Coating*

The Magnetron Sputerring (MS) :

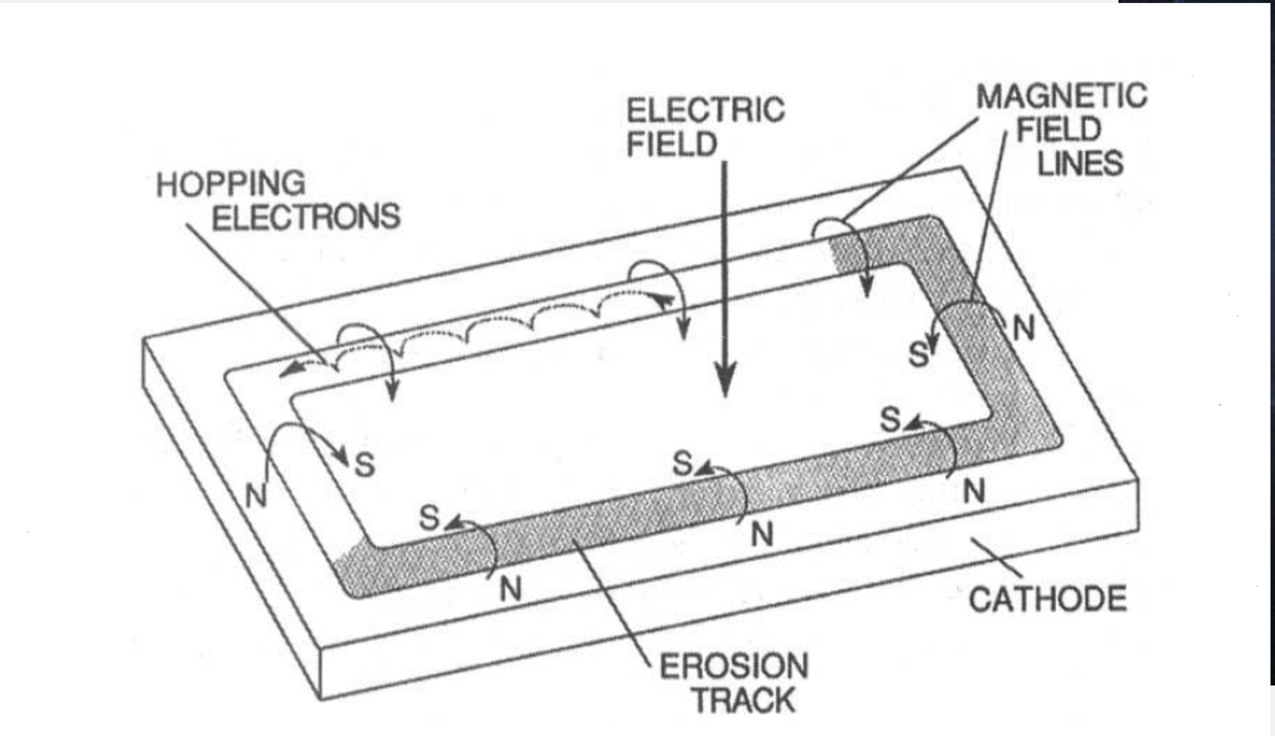


~ 300-700 V
~ 10^{-3} mbar
Ar

Other ion sources - Ions for the industry

3 - Broad Beam & "Ionic Machine" for the Industrial Coating

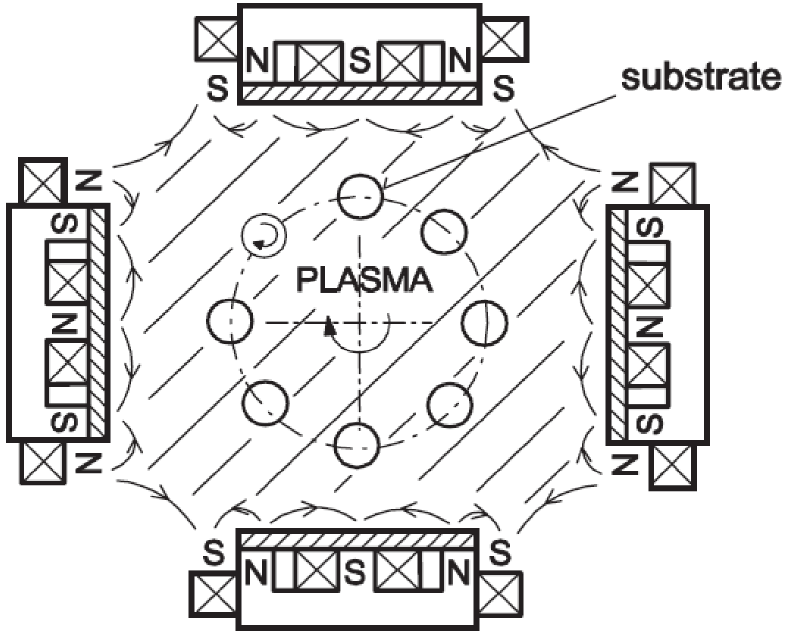
The Magnetron Sputerring (MS) :

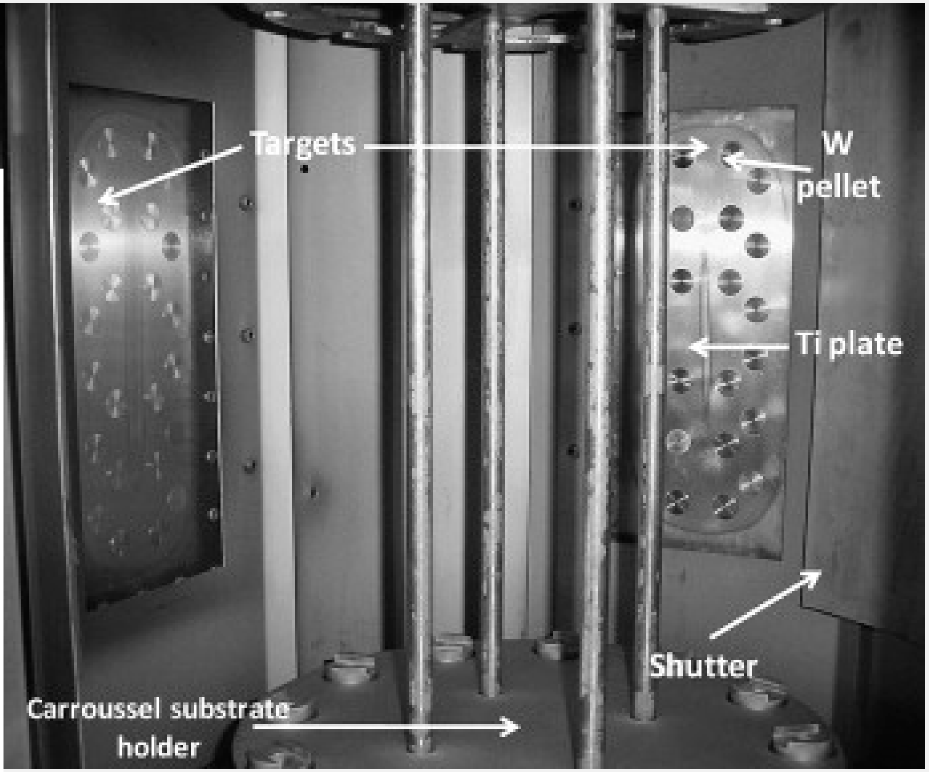


Other ion sources - Ions for the industry

3 - *Broad Beam & "Ionic Machine" for the Industrial Coating*

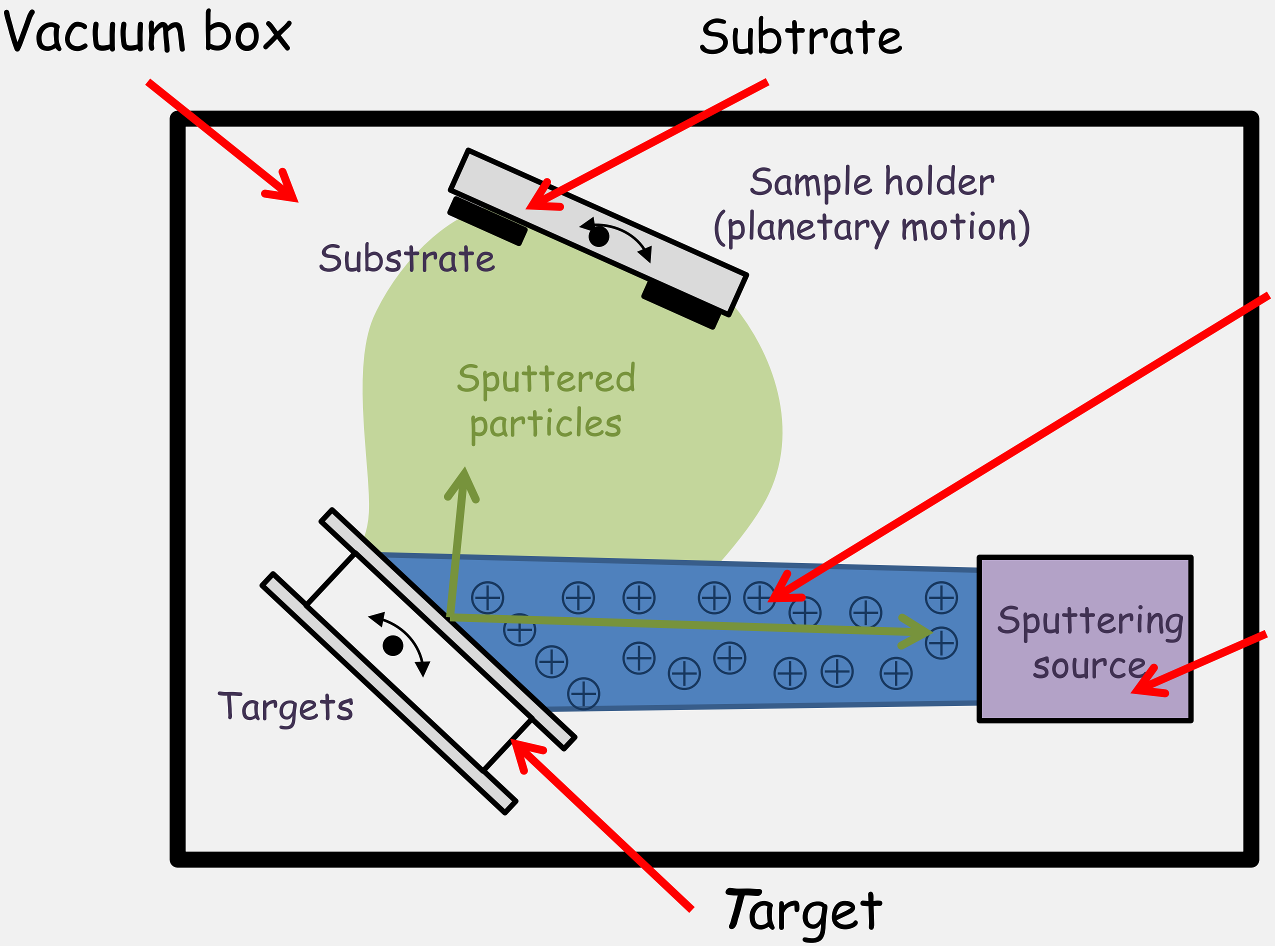
The Magnetron Sputerring (MS) :





Other ion sources - Ions for the industry
3 - Broad Beam & "Ionic Machine" for the Industrial Coating

The Ion Beam Sputerring (IBS) :



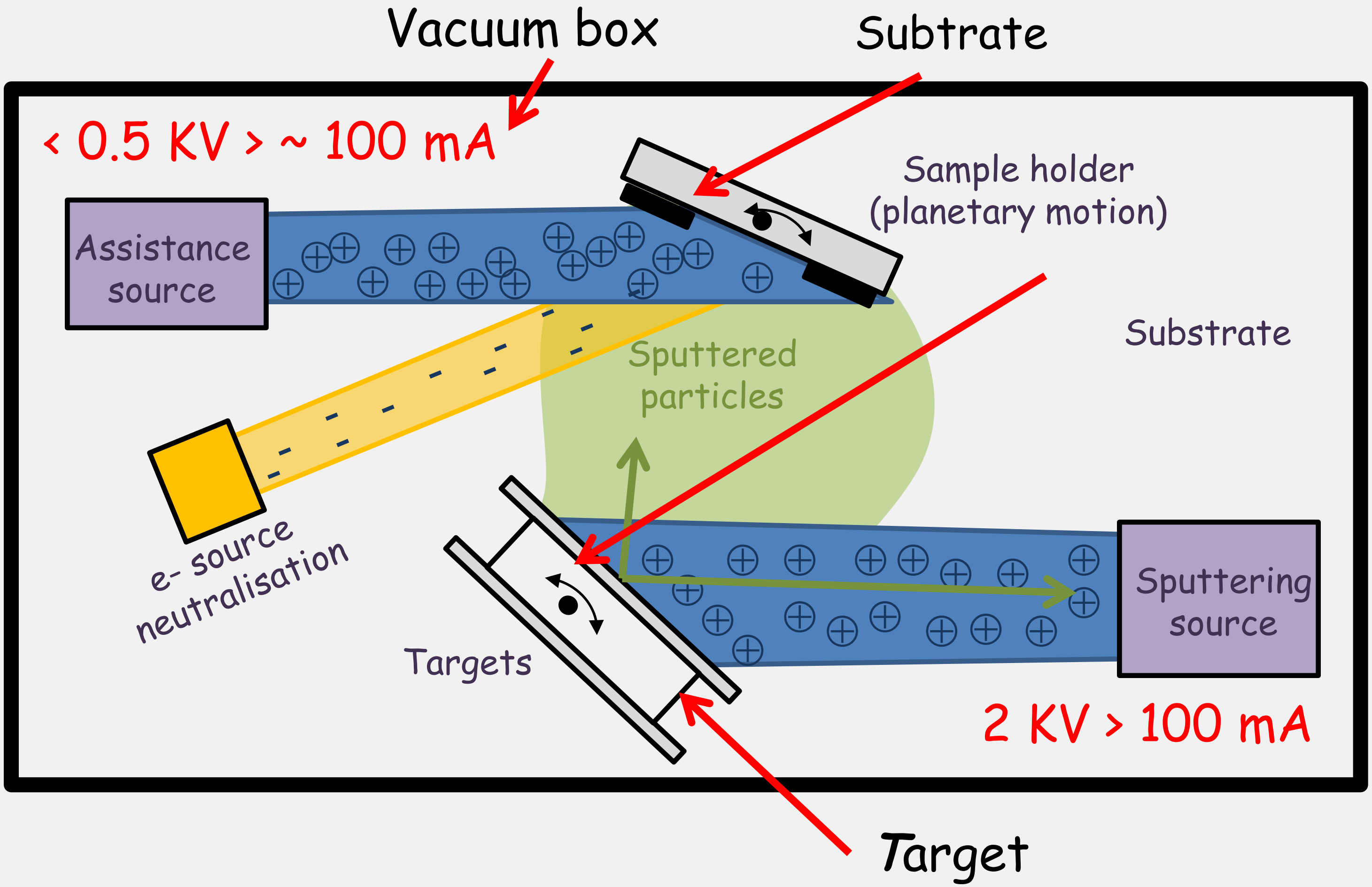
Strong feedback ***contamination*** and maintenance

Broad beam ion source

Other ion sources - Ions for the industry

3 - Broad Beam & "Ionic Machine" for the Industrial Coating

The Double Ion Beam Sputerring (DIBS) and assistance ion source :



Other ion sources - Ions for the industry
3 - Broad Beam & "Ionic Machine" for the Industrial Coating

The Double Ion Beam Sputerring (DIBS) and assistance ion source :

Other ion sources - Ions for the industry
3 - Broad Beam & "Ionic Machine" for the Industrial Coating

The RF broad beam "gridded":

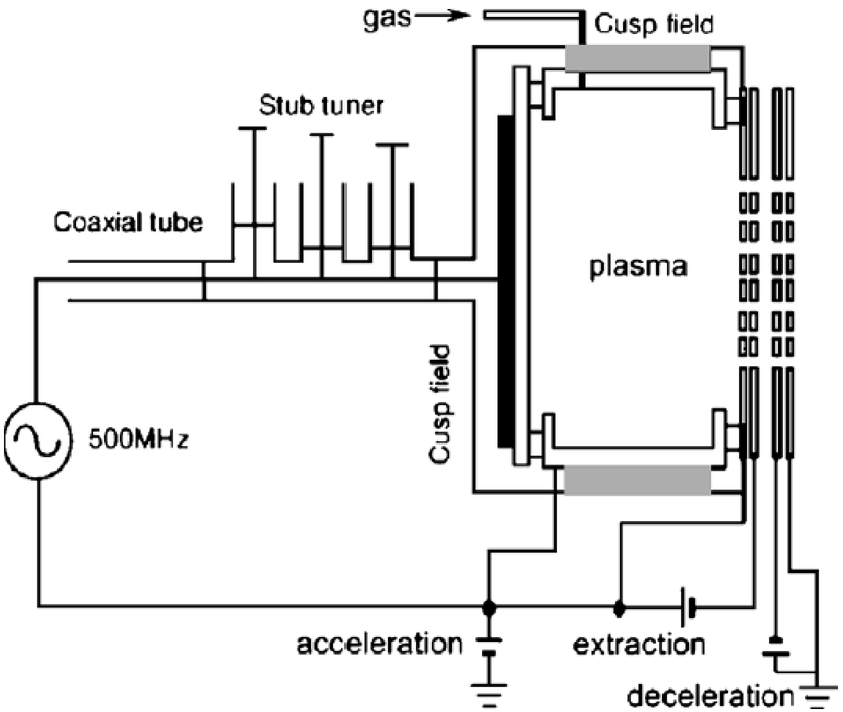
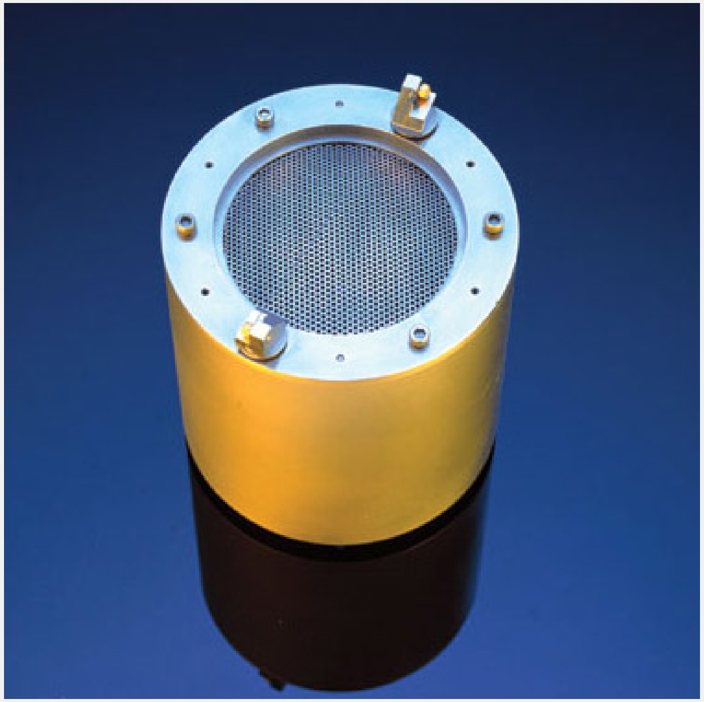
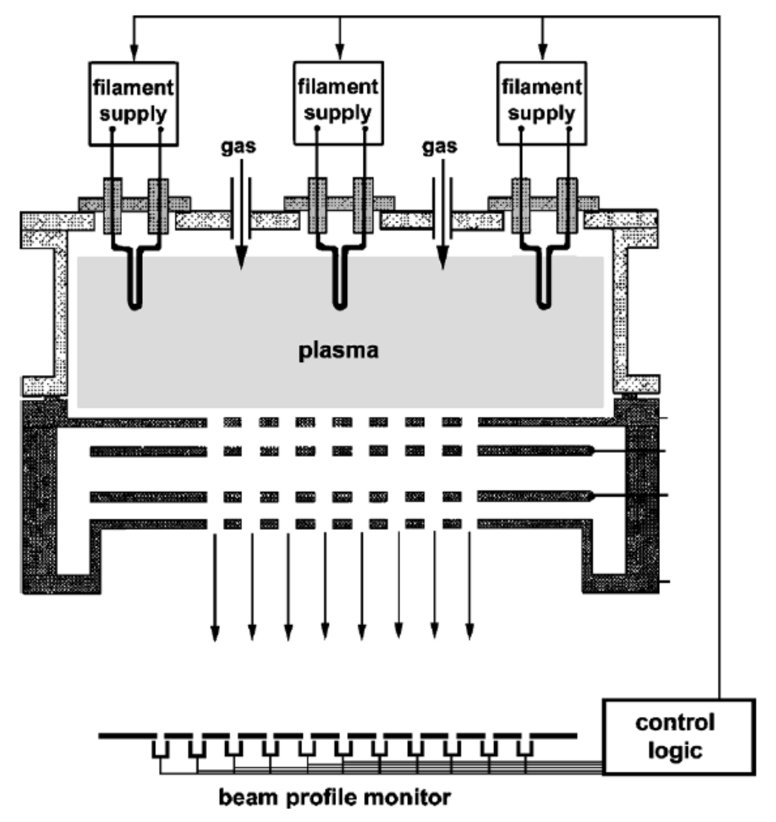


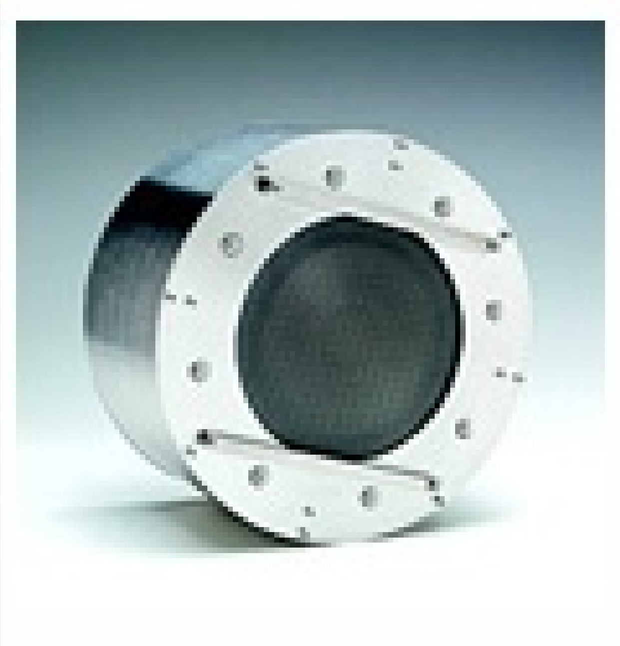
Fig. 3. Example of RF ion source, operating at 500 MHz, with four-grid ion extraction from a 600 × 300-mm plasma chamber (adapted from [40]).



Other ion sources - Ions for the industry
3 - Broad Beam & "Ionic Machine" for the Industrial Coating

The DC broad beam "gridded":

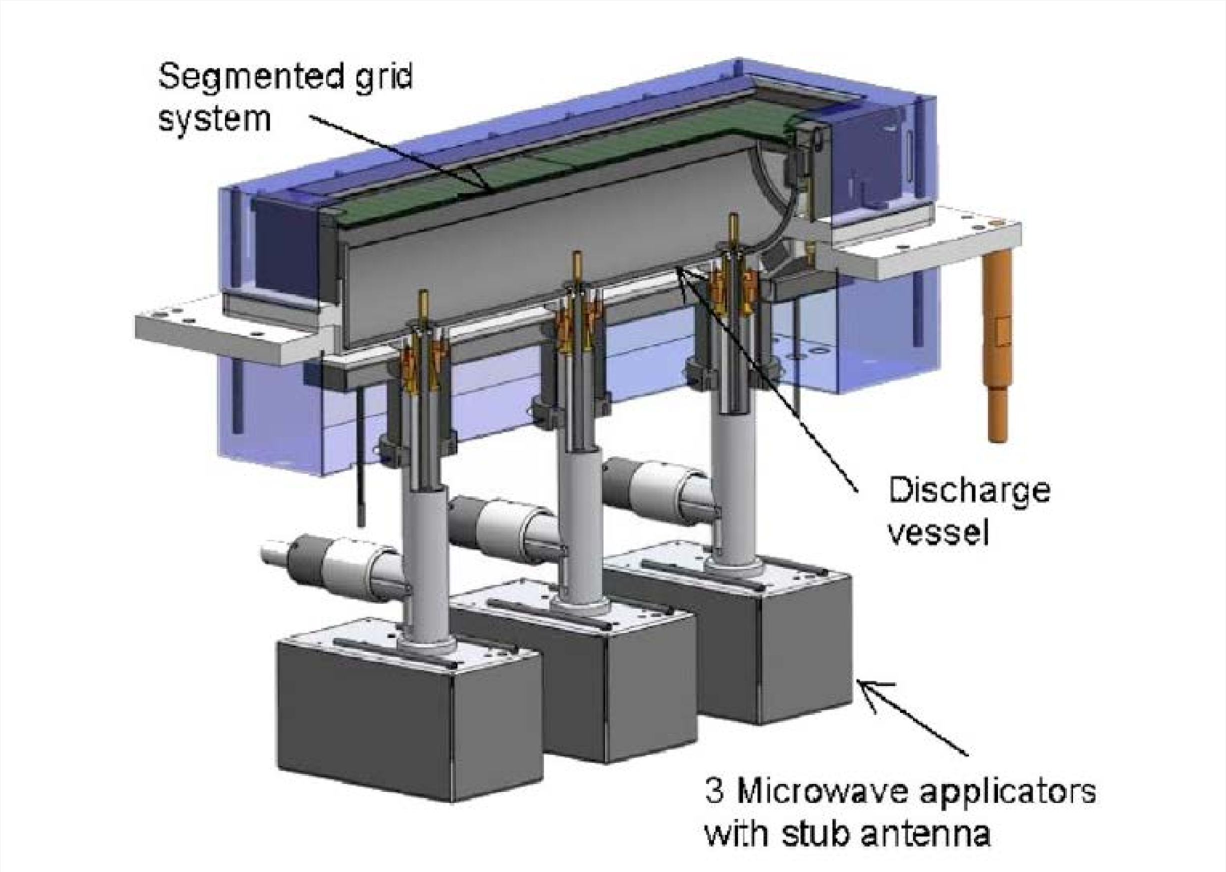




Other ion sources - Ions for the industry

3 - Broad Beam & "Ionic Machine" for the Industrial Coating

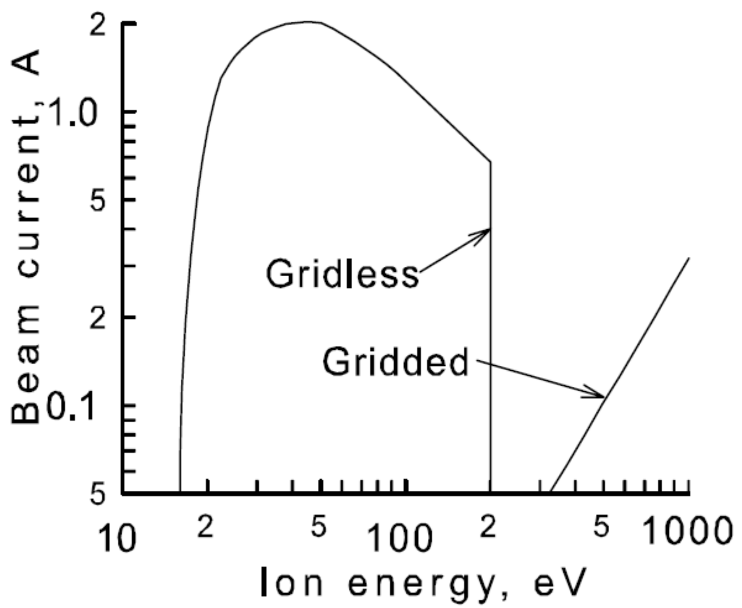
The Microwave Linear ECR (2.45 GHz) :



Other ion sources - Ions for the industry

3 - Broad Beam & "Ionic Machine" for the Industrial Coating

The industrial broad beam “gridless”:



(a) Ion-beam current.

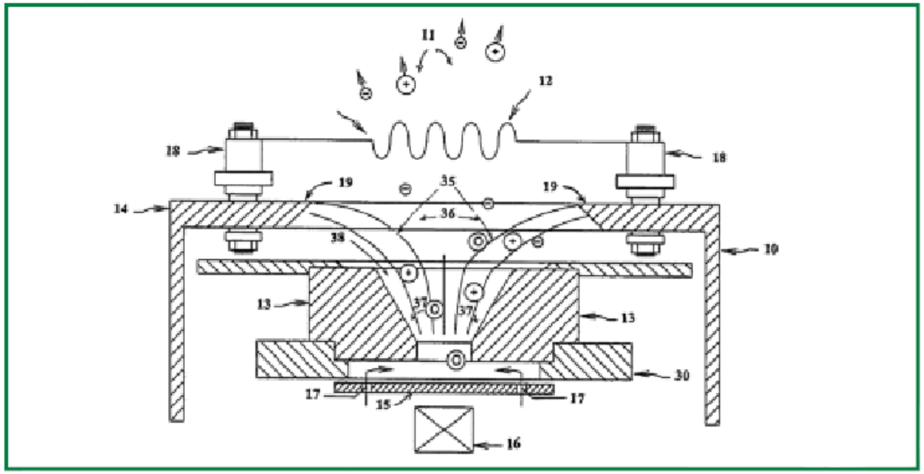


Figure 2. End-Hall ion source schematic: 10 - ion source; 11 - ion beam; 12 - Hot Filament cathode; 13 - anode; 14 - magnetic system; 15 - gas distributor - reflector; 16 - magnet; 17 - holes for working gas supply; 18 - cathode supports; 19 - magnetic pole; 30 - dielectric separarting plate; 35 - magnetic field lines; 36-37 - discharge channel.

Other ion sources - Ions for the industry
3 - Broad Beam & "Ionic Machine" for the Industrial Coating

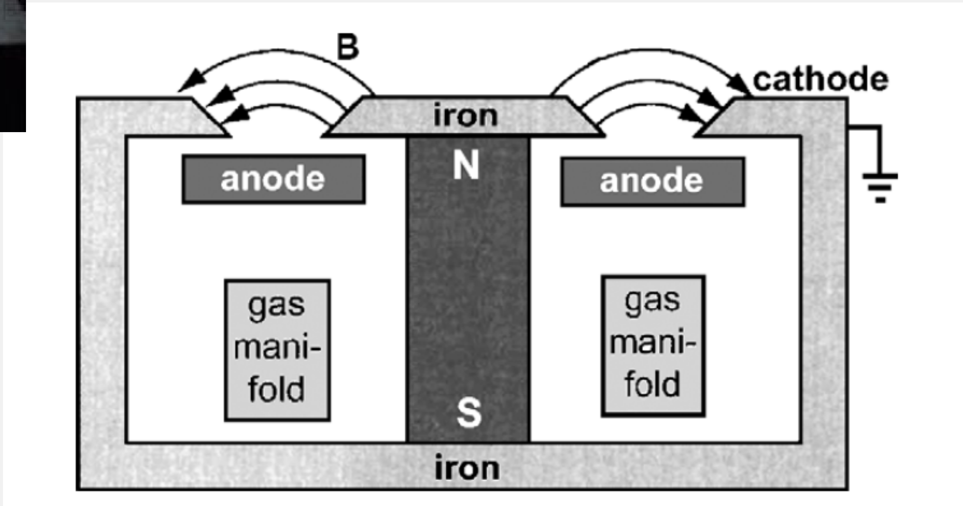
The industrial broad beam "gridless":

Other ion sources - Ions for the industry

3 - Broad Beam & "Ionic Machine" for the Industrial Coating

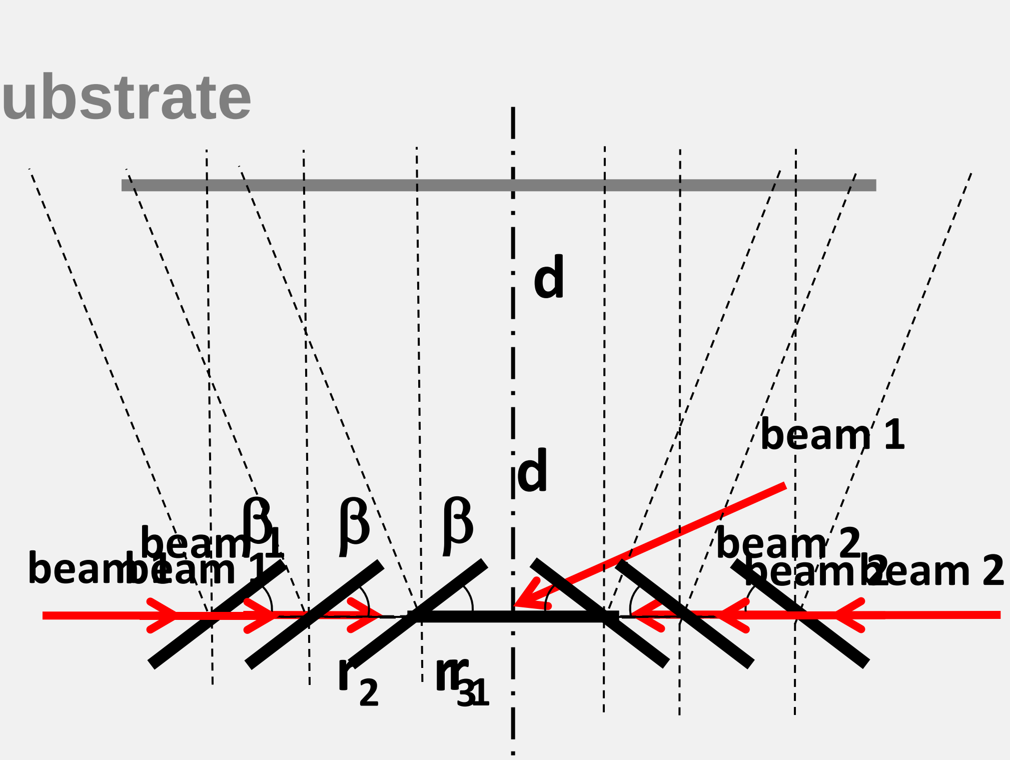
The industrial broad beam "gridless ion source" :
Anode layer ion source / *the reverse of the magnetron*

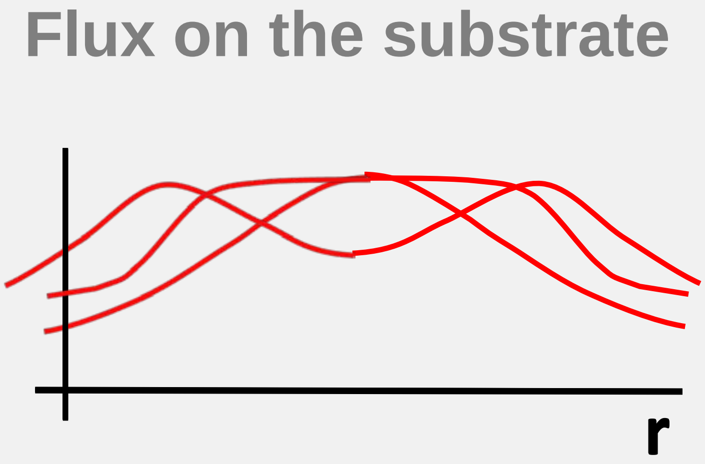
For cleaning
Surface preparation
Etching



3 - *Broad Beam & "Ionic Machine" for the Industrial Coating*

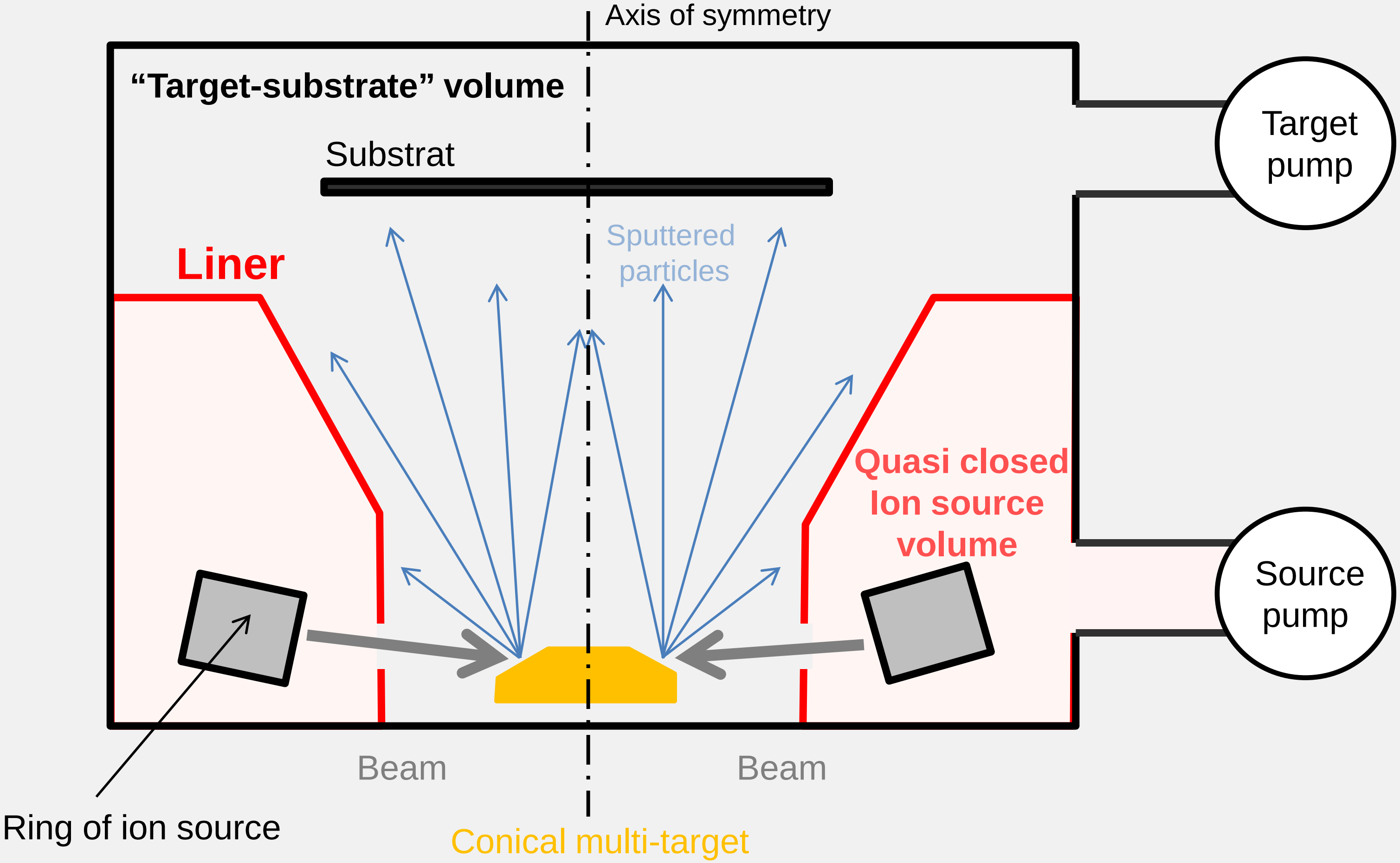
The Principle of multi beam devices :



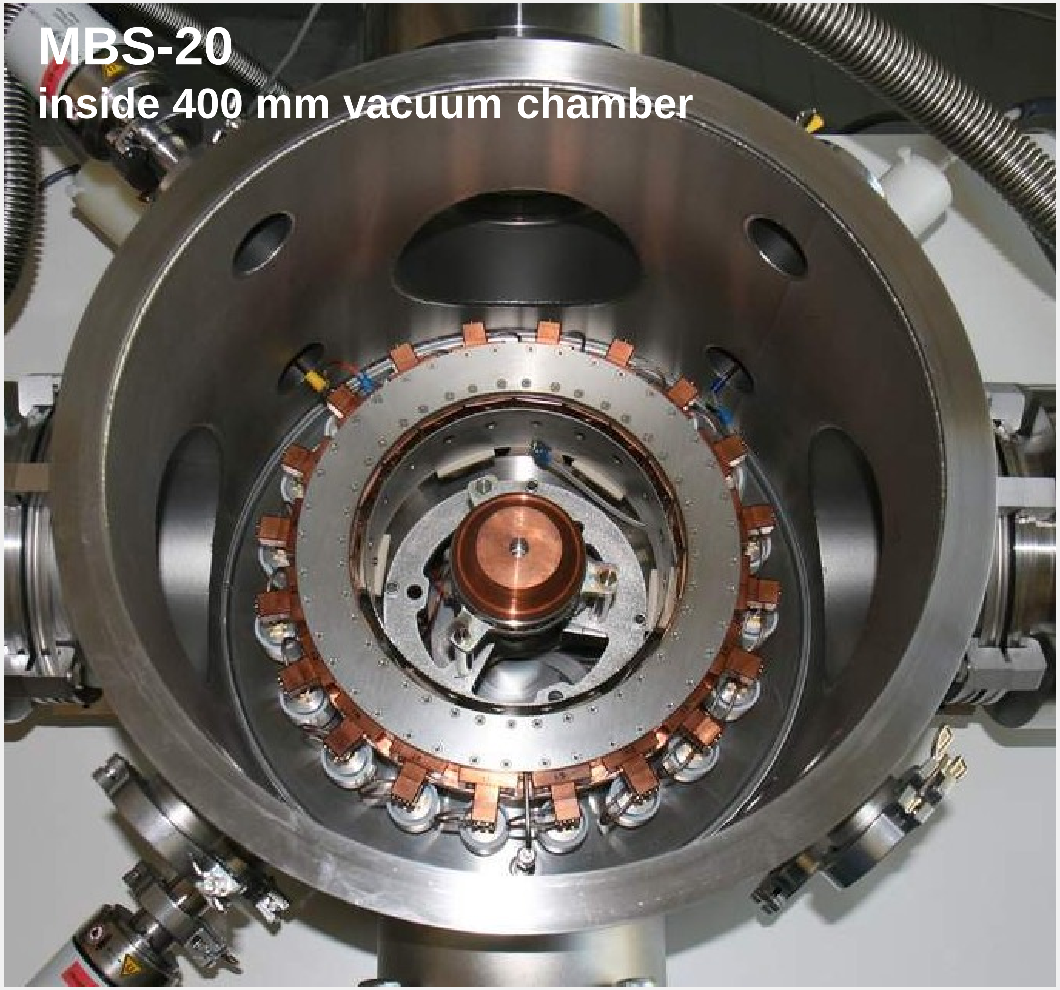


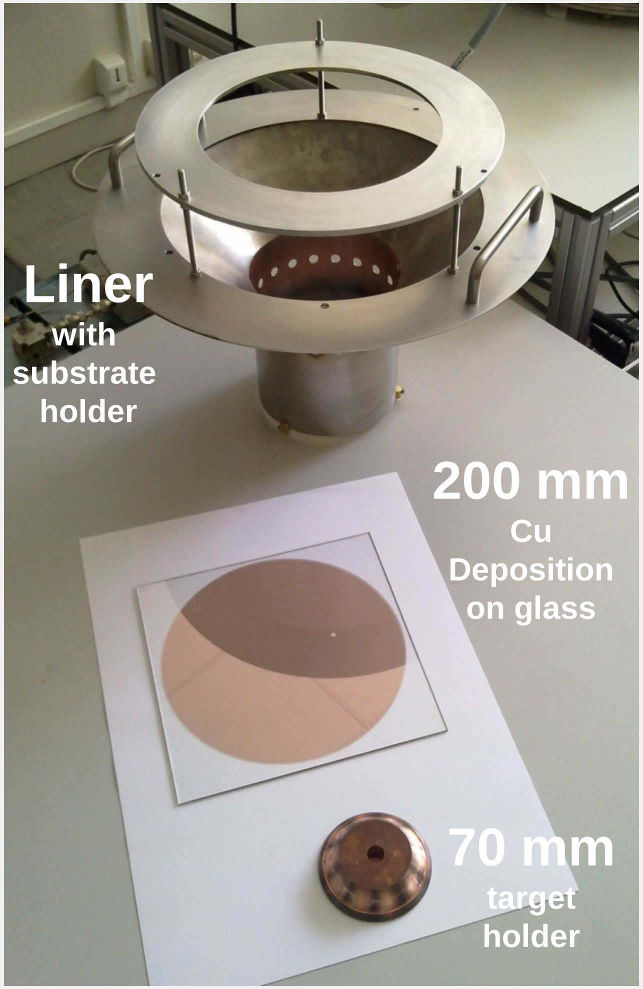
Other ion sources - Ions for the industry

3 - Broad Beam & "Ionic Machine" for the Industrial Coating



Other ion sources - Ions for the industry
3 - Broad Beam & "Ionic Machine" for the Industrial Coating

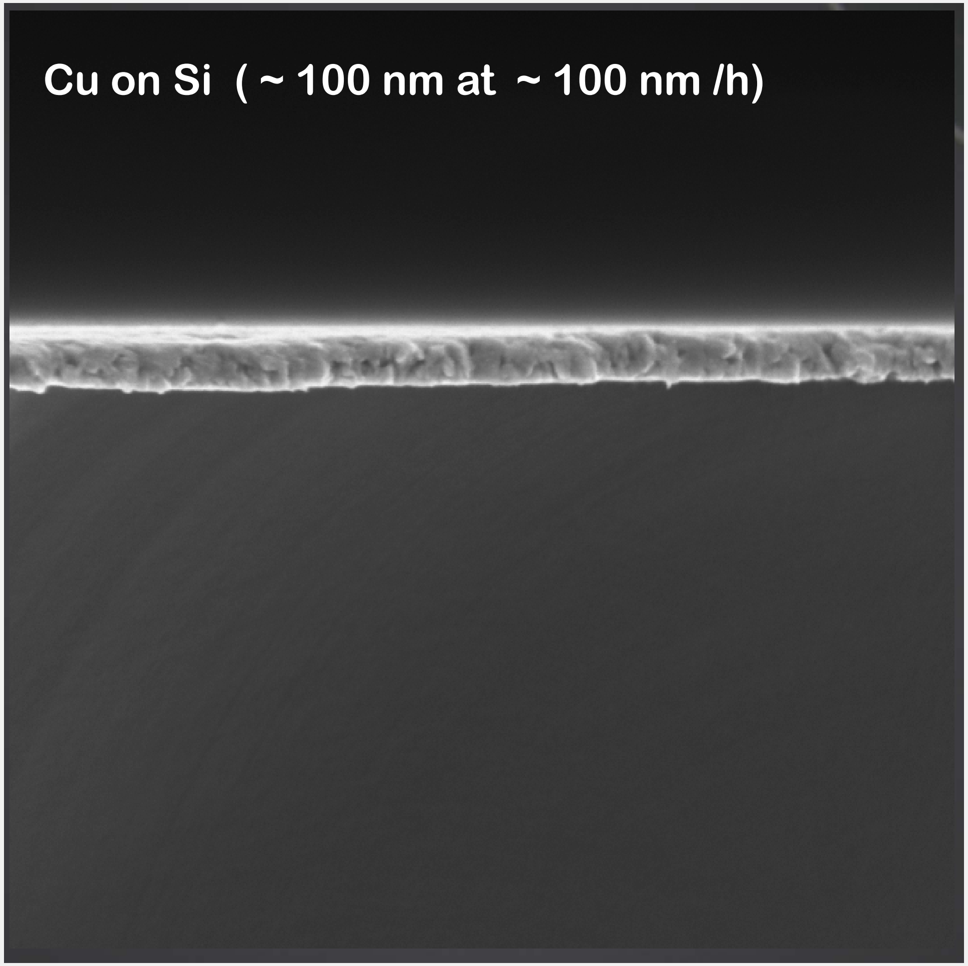




Other ion sources - Ions for the industry
3 - Broad Beam & "Ionic Machine" for the Industrial Coating

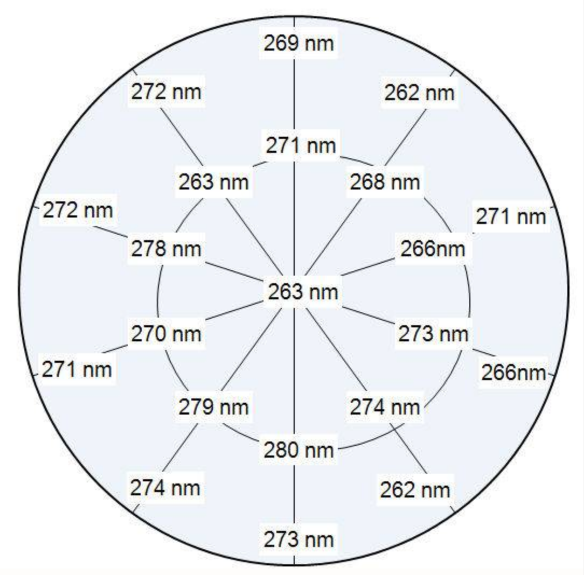
Other ion sources - Ions for industry
3 - Broad Beam & "Ionic Machine" for the Industrial Coating

146 mm



Cu on Si (~ 100 nm at ~ 100 nm /h)

100 mm



263 +/- 7 nm

Profilometer measurements

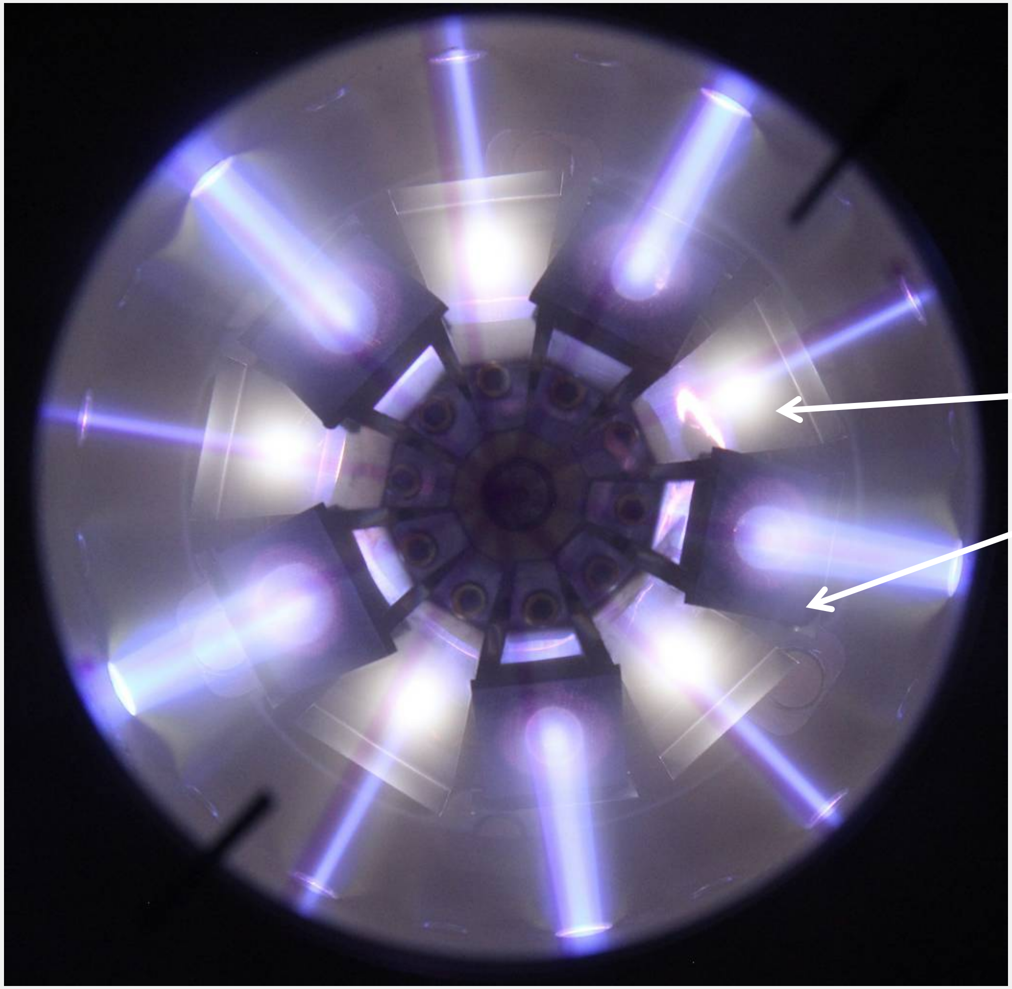
Static substrate

Ta_20_5 on Silicium

(Ta target under O_2)

Other ion sources - Ions for the industry

3 - Broad Beam & "Ionic Machine" for the Industrial Coating

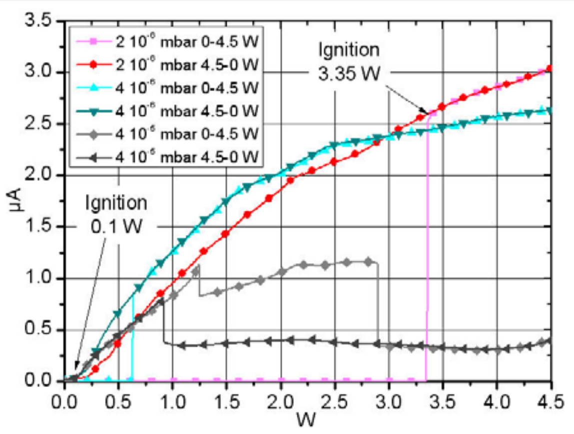


Multi beam (10)

Multi target (Ta and C)

Multi current (25 and 500 µAe)

Simultaneous Argon beams on
Ta
and
C
targets



Other ion sources - Ions for the industry

Conclusion

Ion Source for Industry : ***possible bridges between industry and accelerator technology***

- 1 - Focused Ion Beams :

High quality beam for AMS, radioactive ions, electrostatic acc. cyclotron injection, …

- 2 - High Intensity Beams for *MicroElectronics*

Knowhow for high intensity transportatio n
Ion source for molecular ions …

- 3 - Broad Beam & "Ionic Machine" for *the Industrial Coating*

Multi beam machine for beam merging, superconducting matérial deposition , …