

# 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

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## Ions for the industry

*Ion Sources : the accelerators versus the industry*

- Accelerators :

*Emittance, Intensity, Efficiency*

- Industry :

*Throughput, Tunability, Cost*

# Other Ion Sources - Ions for the industry

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## 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 Sputtering*

*Magnetron discharge & End Hall ion source*

## Other ion sources - Ions for the industry

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

- 1 - High brightness  $\sim 1 \text{ nm}^{-1} \mu\text{m}$  beam (FIB)
- 2 - High current  $\sim 1 \text{ cm}-30 \text{ cm}$  beam (Implanter)
- 3 - Broad beam  $\sim 30 \text{ cm}-10 \text{ m}$  beam/treatment (Coating)

## Other ion sources - Ions for the industry

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The good Units for the industrial purpose :

1 - Focused Ion Beam :  $\mu\text{m}^3/\text{s}$

2 - Implanter : Wafers/h

3 - Coating :  $\mu\text{m}/\text{m}^2/\text{h}$

## Other ion sources - Ions for the industry

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### Popular Ion Sources for the industry :

#### 1 - Focused Ion Beams

*LMIS, RF, Microwave*

#### 2 - Implanters

*Freeman, Bernas*

#### 3 - Coatings

*Broad beam, Magnetron, Gridless*

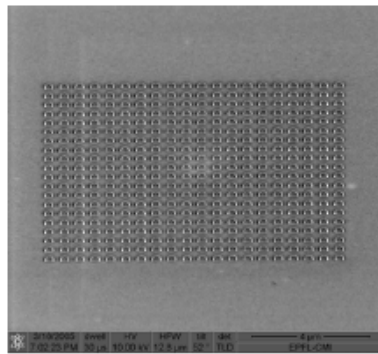
Other ion sources - Ions for the industry  
1 - Focused Ion Beam for the Nanotechnologies

The purpose of the Focused Ion Beam systems:

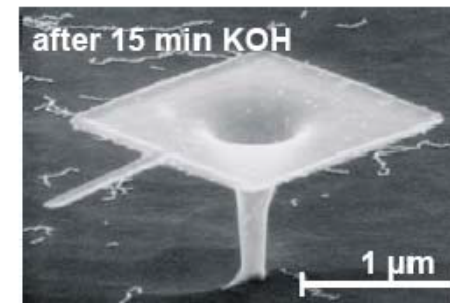
$1\ \mu\text{m}$   
to  $1\ \text{nm}$   
beam

$1\ \mu\text{A}$   
to  $1\ \text{nA}$   
beam

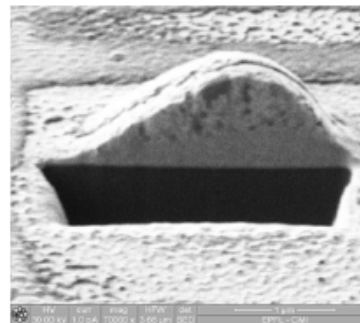
Milling



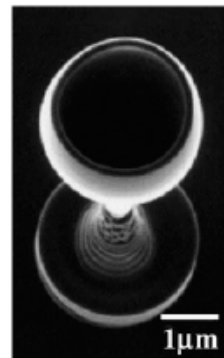
Doping



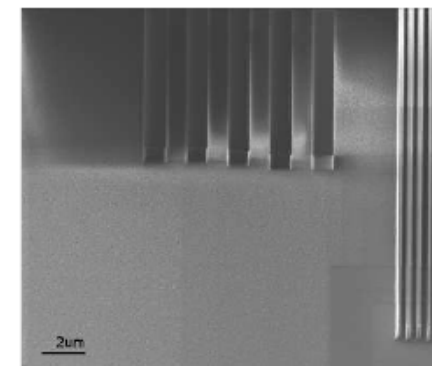
Imaging



Deposition

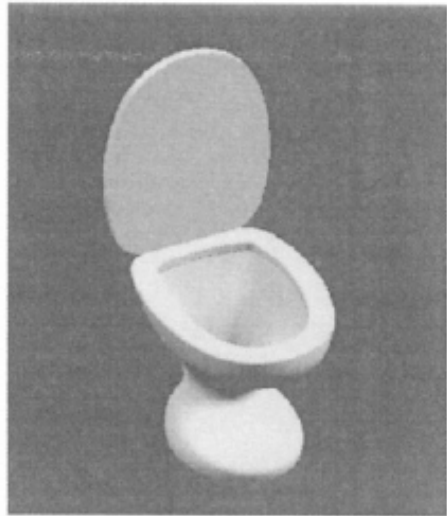


Lithography

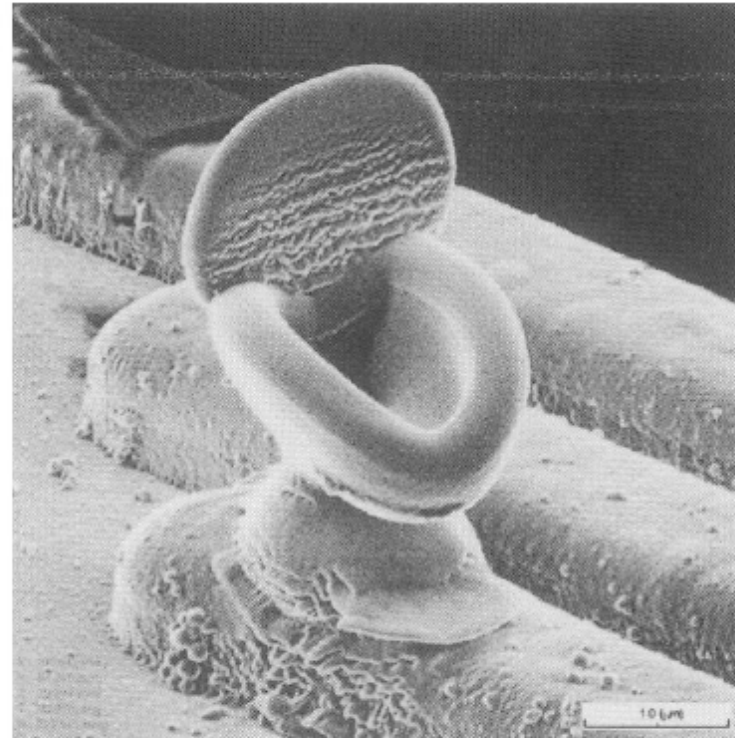


**Other ion sources - Ions for the industry**  
**1 - Focused Ion Beam for the Nanotechnologies**

**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.*



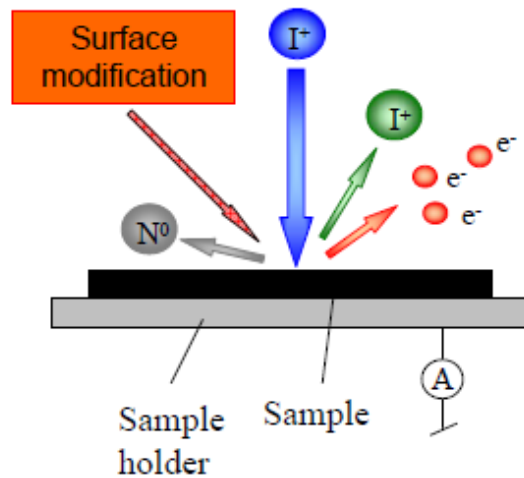
# Other ion sources - Ions for the industry

## 1 - Focused Ion Beam for the Nanotechnologies

### 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  $\gamma$

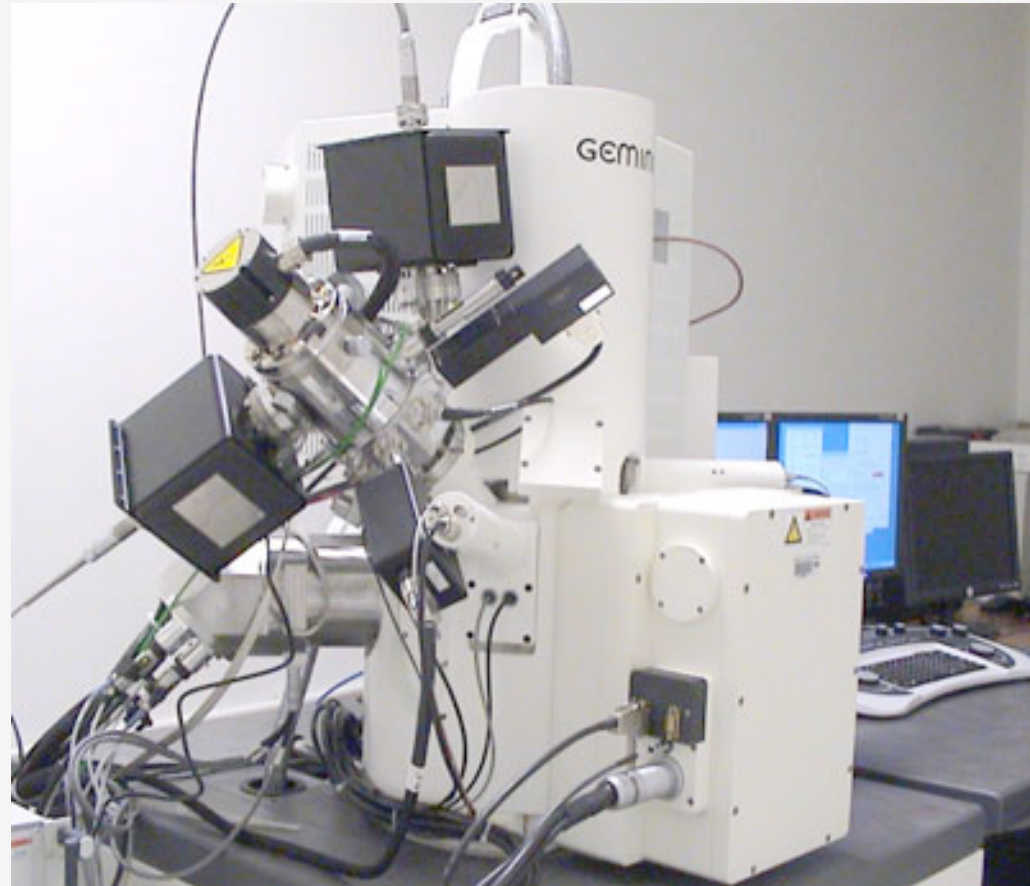
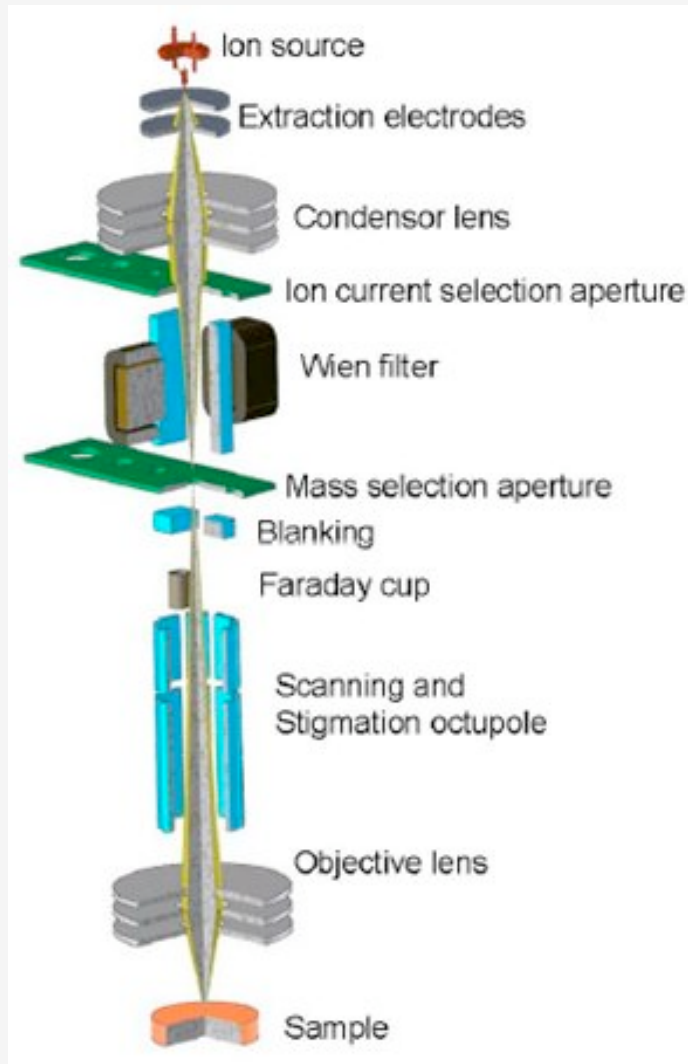
Moving the beam

⇒

Surface patterning

# Other ion sources - Ions for the industry

## 1 - Focused Ion Beam for the Nanotechnologies



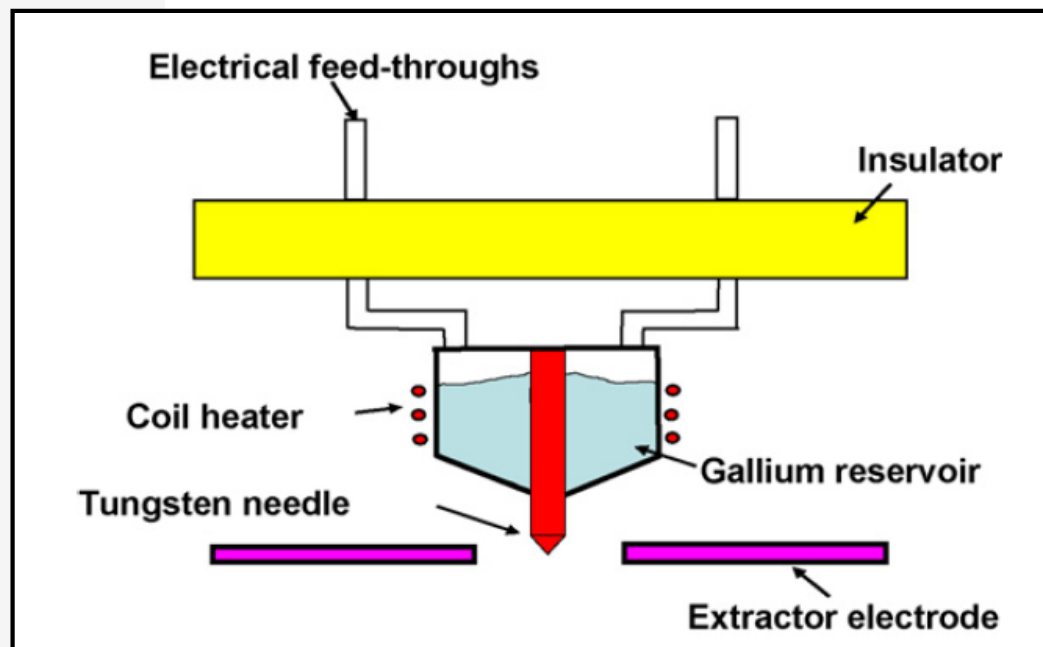
# Other ion sources - Ions for the industry

## 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<sup>+</sup> 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**  $F_s = 2\frac{\gamma}{r}$ ,  $\gamma$  : surface tension

inward force

- **Coulomb force**  $F_c = \frac{\epsilon_0 E^2}{2}$ ,  $E = \frac{q}{4\pi\epsilon_0 r^2}$

outward force

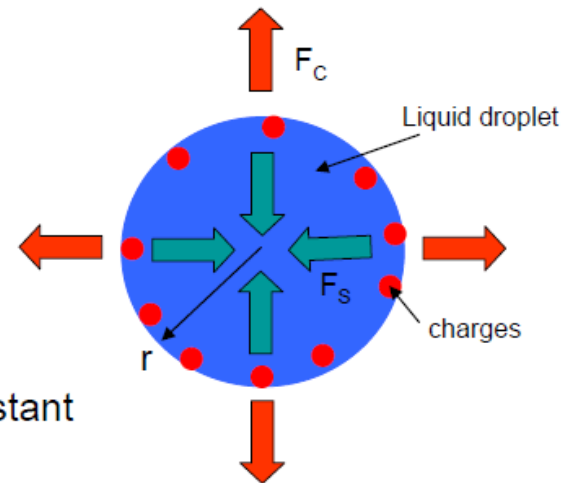
- Maximum charge may be placed on the surface

⇒ Rayleigh limit:

$$q_{Rh} = 8\pi\sqrt{\epsilon_0\gamma r^3}$$

$\epsilon_0 = 8.85 \cdot 10^{-12} \text{ C}^2/\text{J m}$  dielectric constant

- Formation of Taylor Cone



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

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

### Ion Source

#### Gas Field Ionisation Source (GFIS)

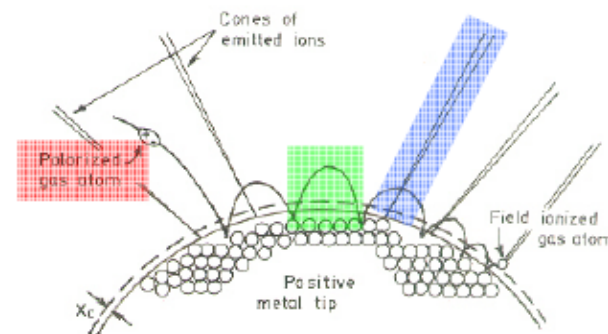
Low temperature (cryogenic)  
« LMIS » : 10-300 K

- atoms (molecules) are trapped by polarizations forces
  - Trapped atoms hop on the surface until they are ionised
- Ionisation: tunneling process with probability D:

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

I : Ionisation potential  
 $\Phi$  : Work function of emitter  
V : EI. Potential  
c : constant

- Ions are ejected from the surface



# Other ion sources - Ions for the industry

## 1 - Focused Ion Beam for the Nanotechnologies

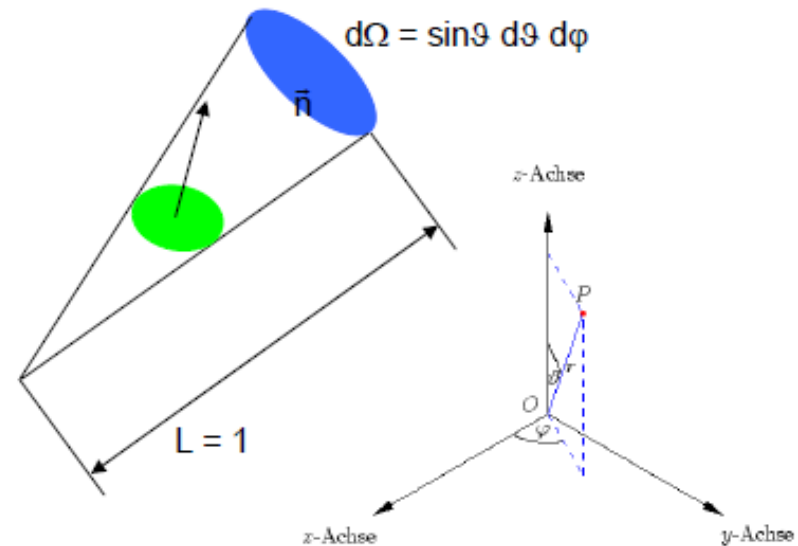
### Ion Source

#### Gas Field Ionisation Source (GFIS)

- Cooling the tip  $\Rightarrow$  higher residence time  $\tau_r$  leads higher ionisation rate

- Ions:  $H^+, He^+, Ne^+, \text{etc}$

- low current  $\frac{dI}{d\Omega} = 1 \mu A \text{ sr}^{-1}$  <sup>a)</sup>



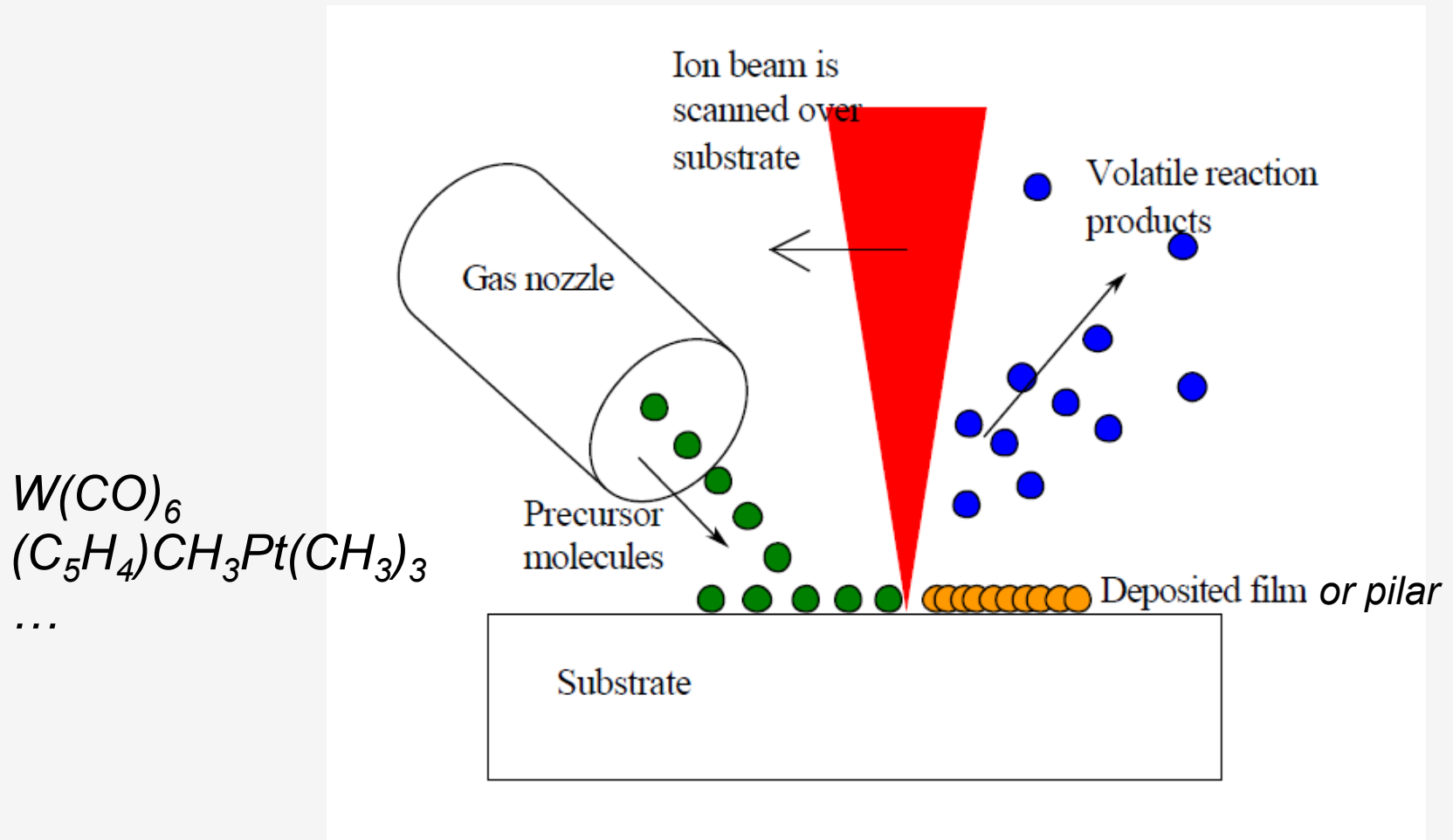
<sup>a)</sup> largest reported value (J. Orloff: High Resolution Focused Ion Beams, Kluwer Academic, 2003)



# Other ion sources - Ions for the industry

## 1 - Focused Ion Beam for the Nanotechnologies

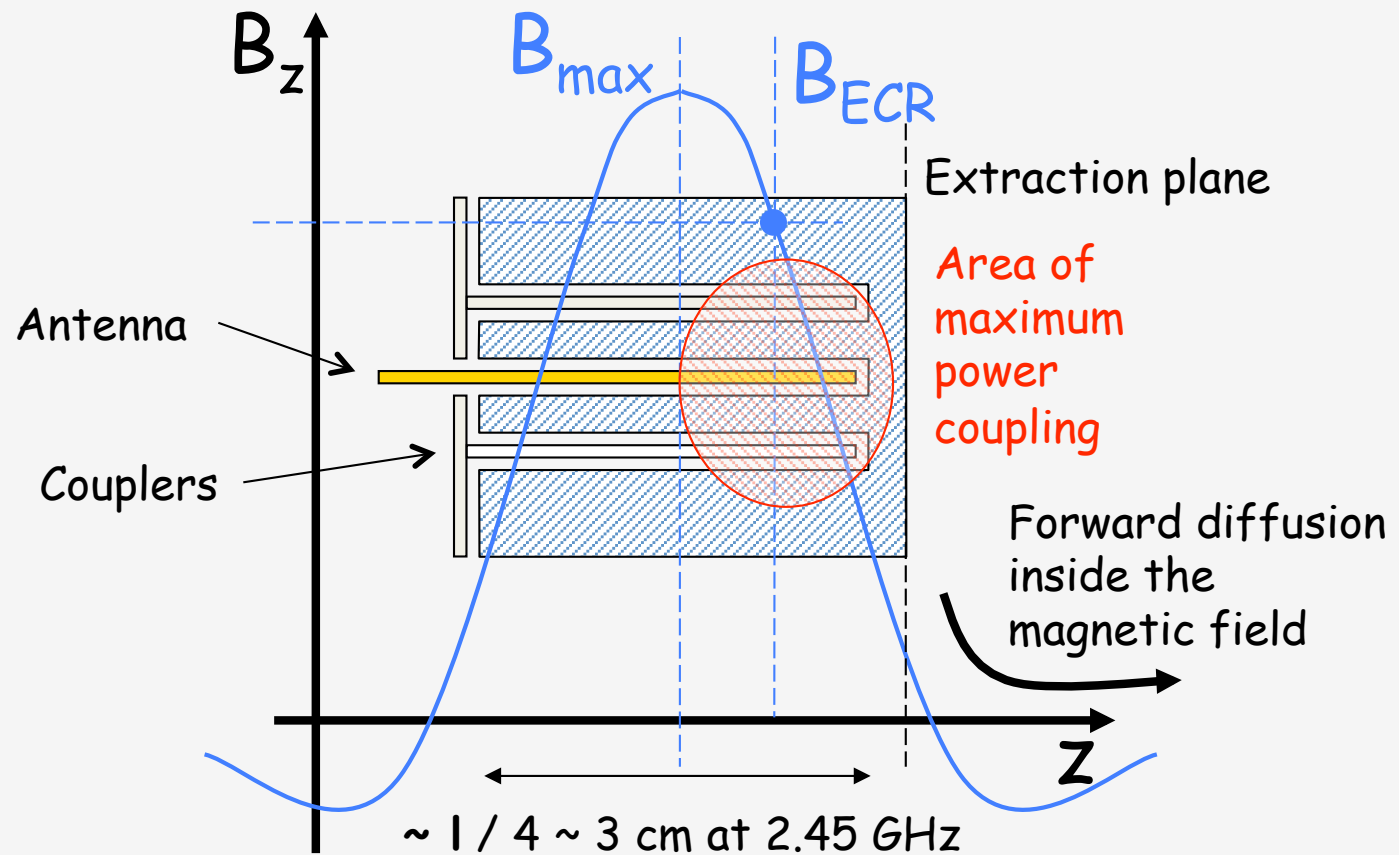
### Deposited films induced by focused ion beam



# Other ion sources - Ions for the industry

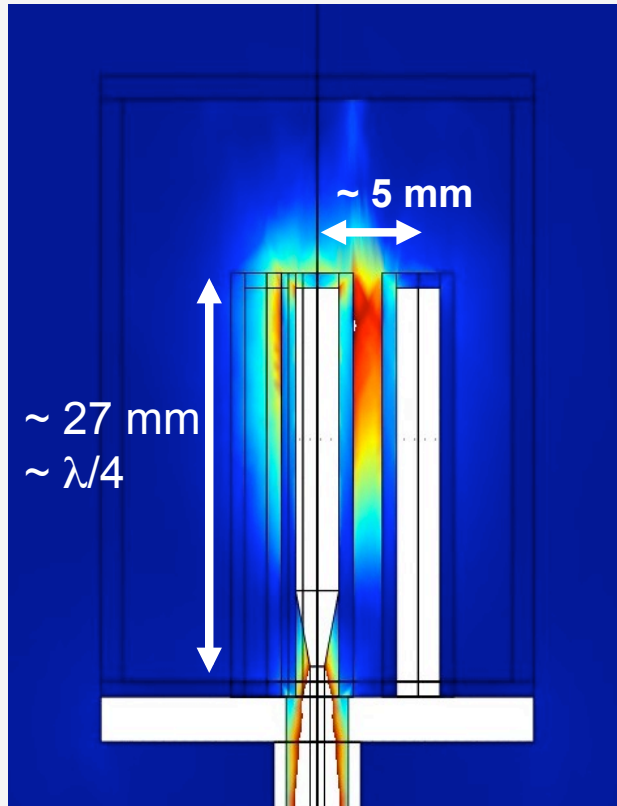
## 1 - Focused Ion Beam for the Nanotechnologies

Microwave source with "high brightness & high current" ( $\mu\text{A}$ ):  
*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 )

$$f_{hf} = 2.45 \text{ GHz} \quad \text{Red} > 10^4 \text{ V/m}$$



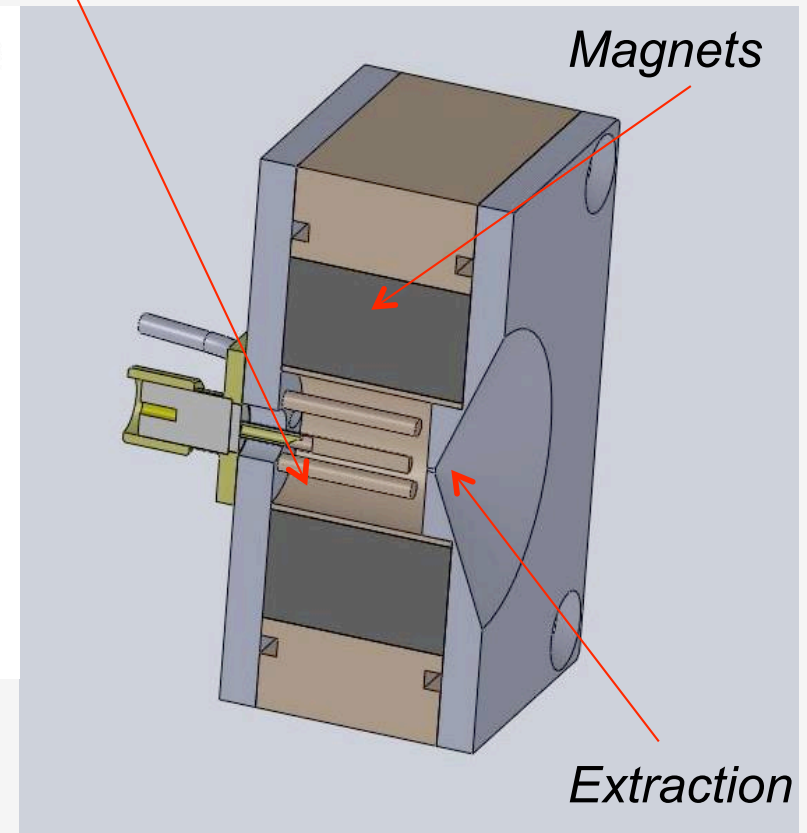
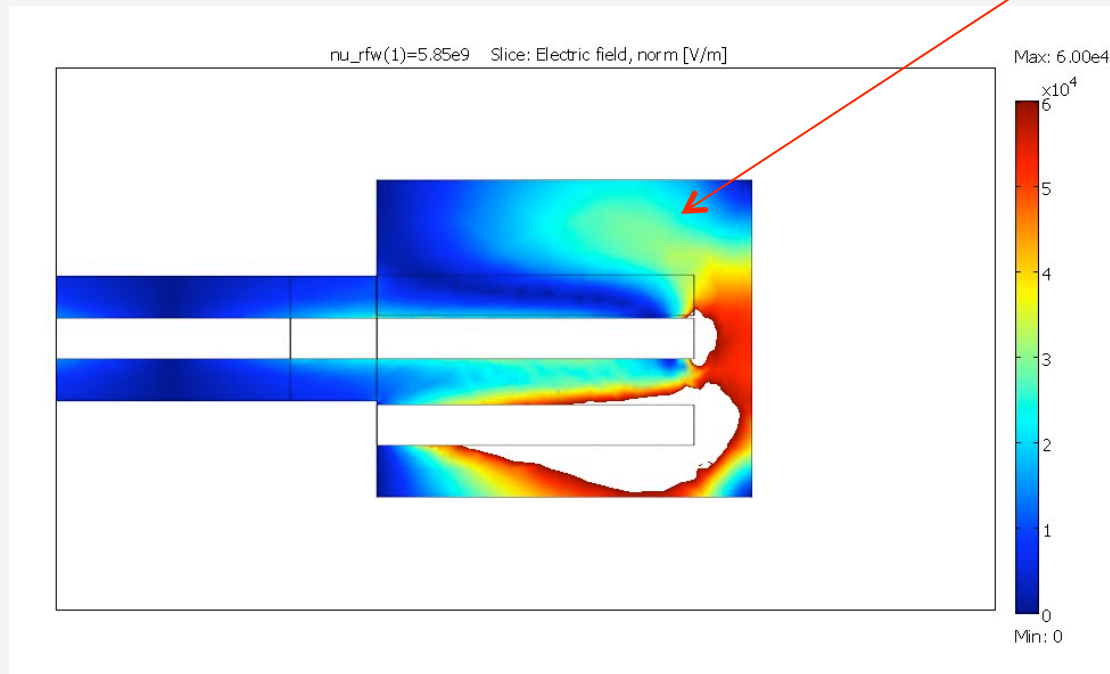
Distribution of light in a  
**Xenon** discharge (2 W)  
between the central  
antenna and the coupler  
with quasi-coaxial  
geometry

$$p \sim 10^{-2} \text{ mbar}$$

# Other ion sources - Ions for the industry

## 1 - Focused Ion Beam for the Nanotechnologies

*Electric field amplitude inside a closed cavity*

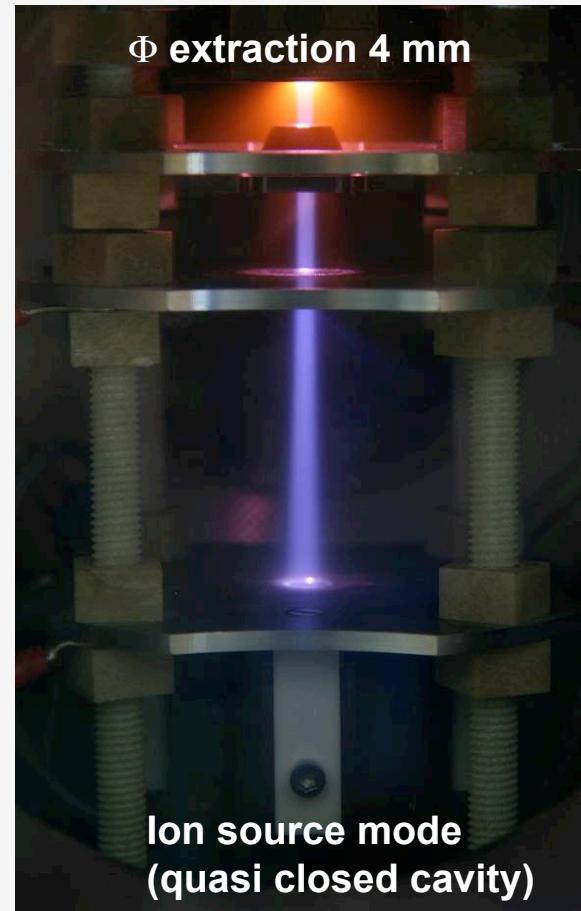


## Other ion sources - Ions for the industry

### 1 - Focused Ion Beam for the Nanotechnologies



*Argon  $10^{-2}$  mbar / 5 W*



*Nitrogen  $5 \cdot 10^{-5}$  mbar / 5 W*  
 *$\sim 500 \mu\text{A} \sim 4 \text{ mA/cm}^2$*

Source  
20 KV

1<sup>st</sup> elect.  
16 KV

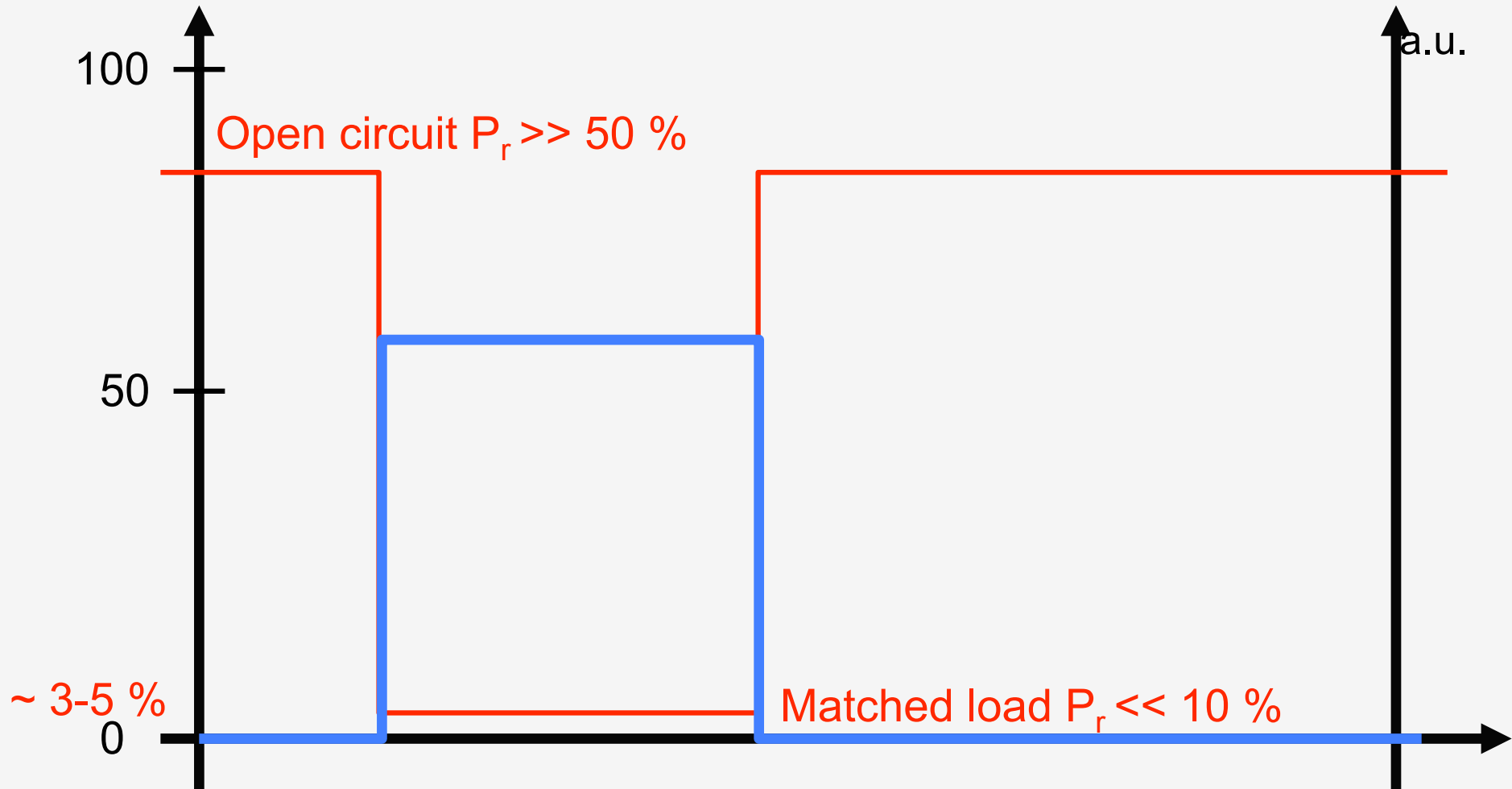
Grounded electrode  
0 KV

# Other ion sources - Ions for the industry

## 1 - Focused Ion Beam for the Nanotechnologies

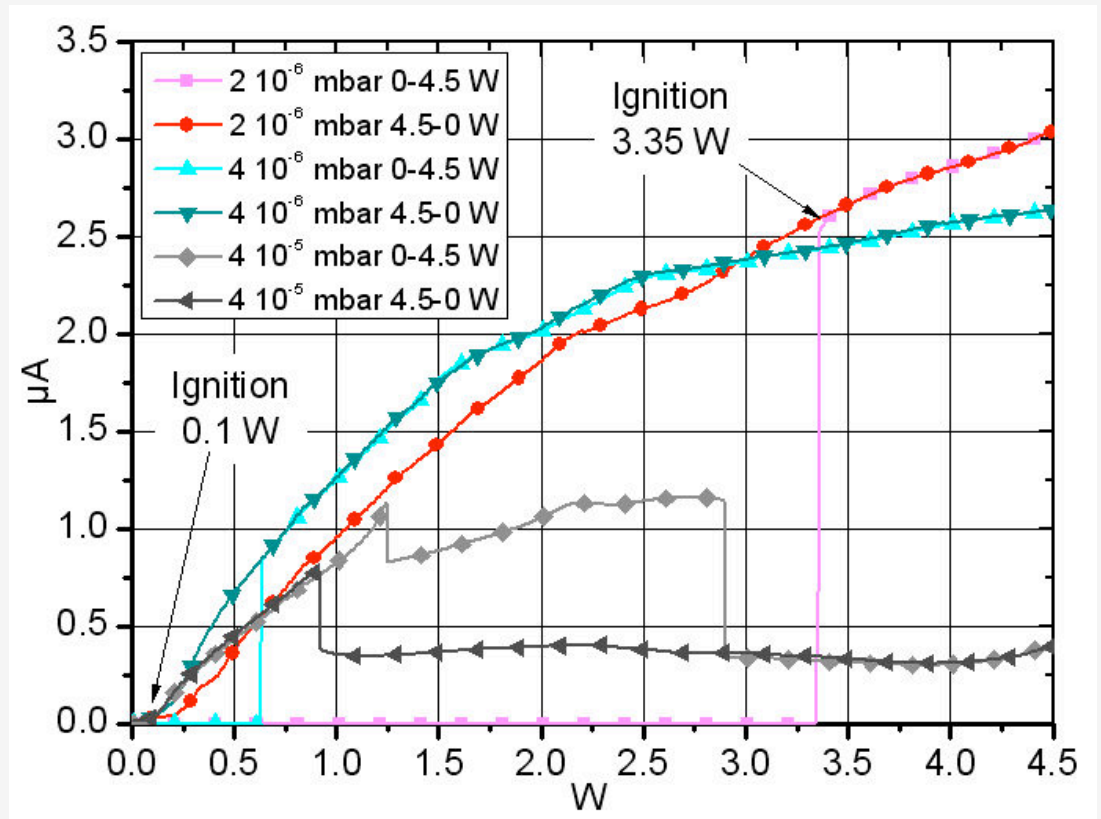
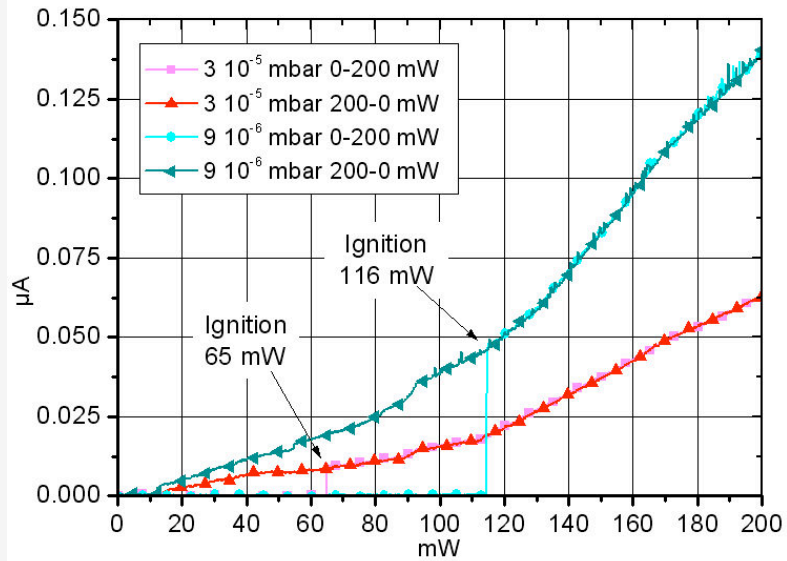
Reflected power (%) (below 5 W)

Current  $i_c$



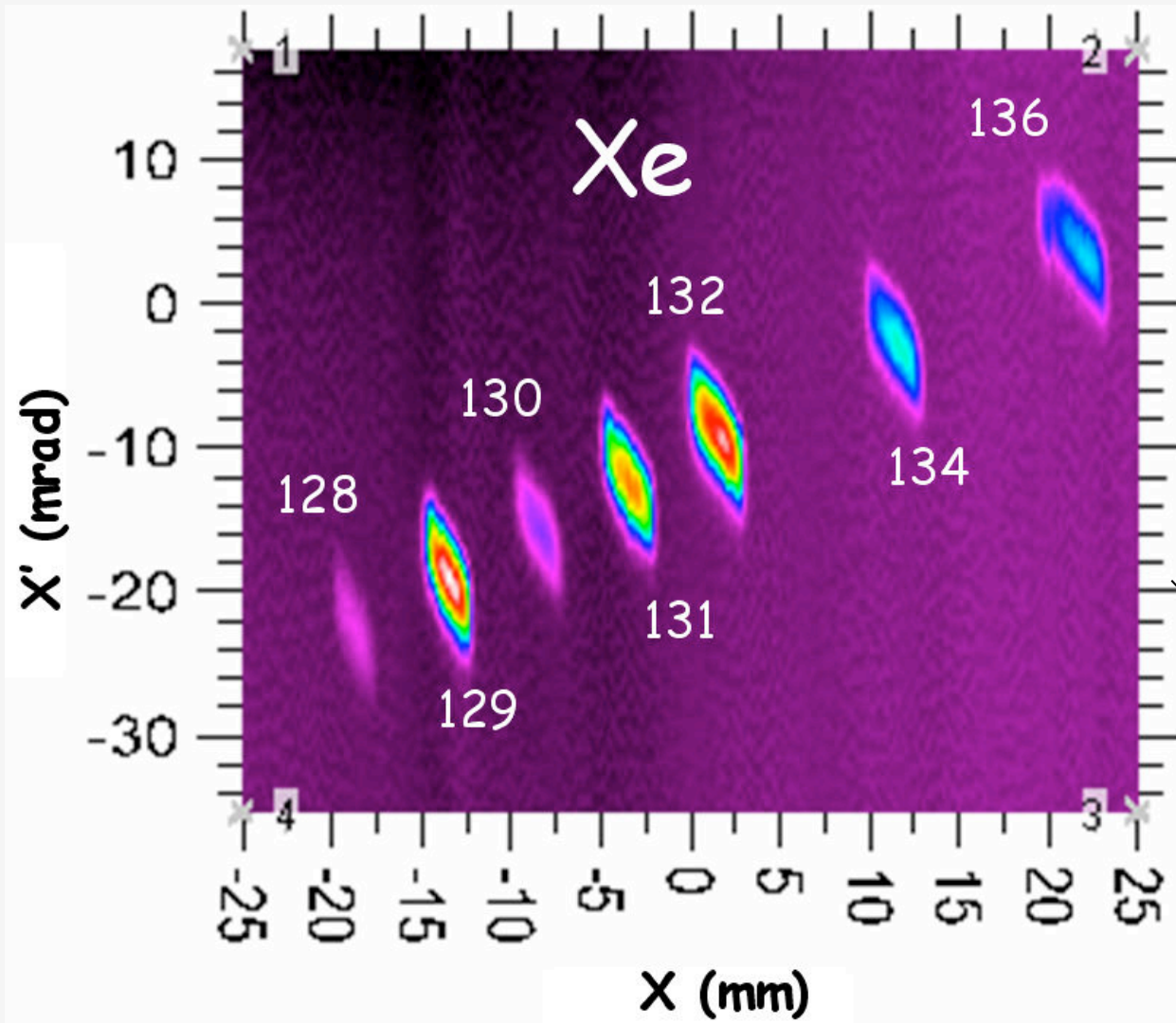
# Other ion sources - Ions for the industry

## 1 - Focused Ion Beam for the Nanotechnologies



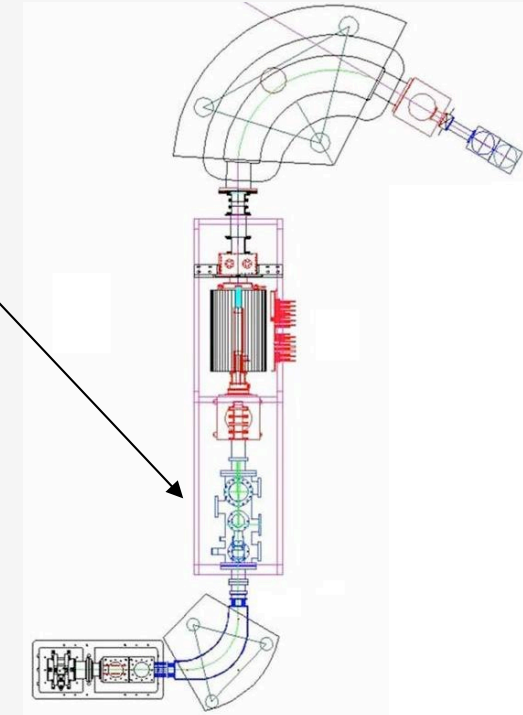
# Other ion sources - Ions for the industry

## 1 - Focused Ion Beam for the Nanotechnologies



$1 \sigma$   
1.2  $\pi$ .mm.mrad  
15 KV  
3/10 mm ext.

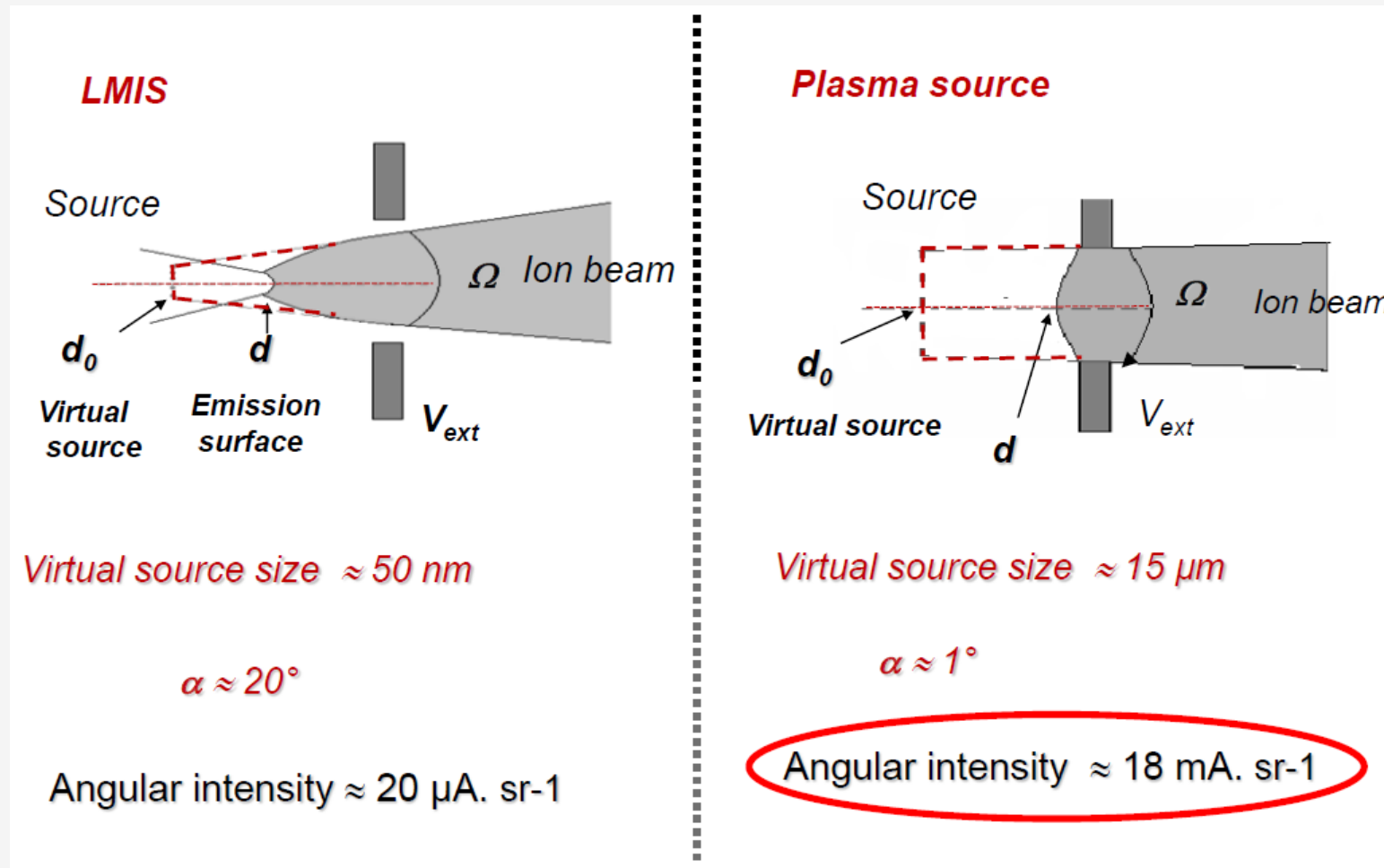
1.8  $\mu$ Ae total / 3 W / ext. 0.3 mm / 15 KV  
(12.5 kV élect. intermédiaire)





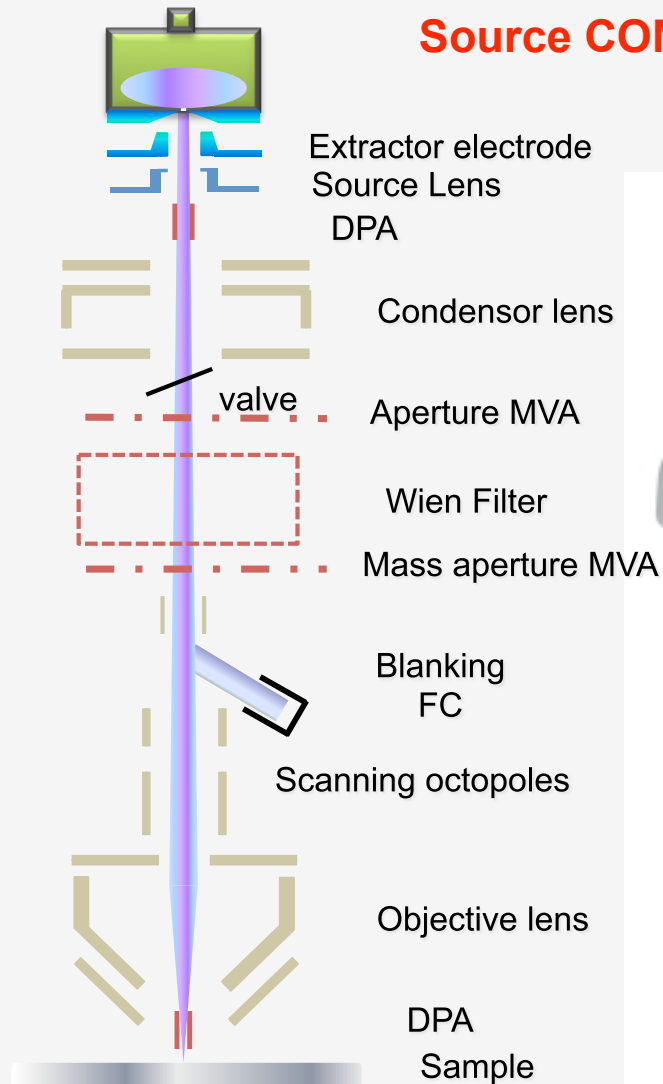
# Other ion sources - Ions for the industry

## 1 - Focused Ion Beam for the Nanotechnologies

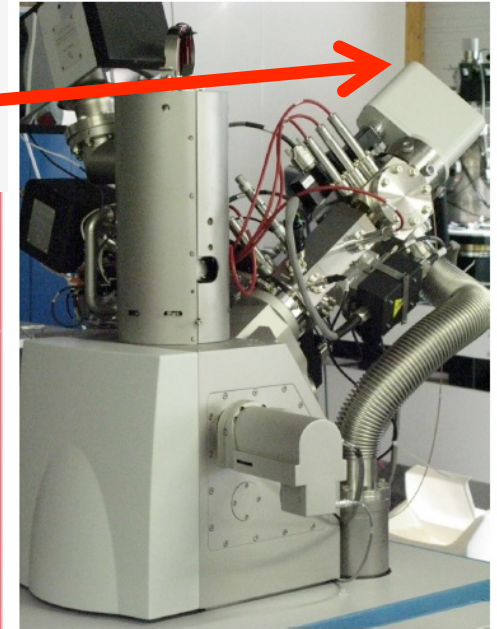
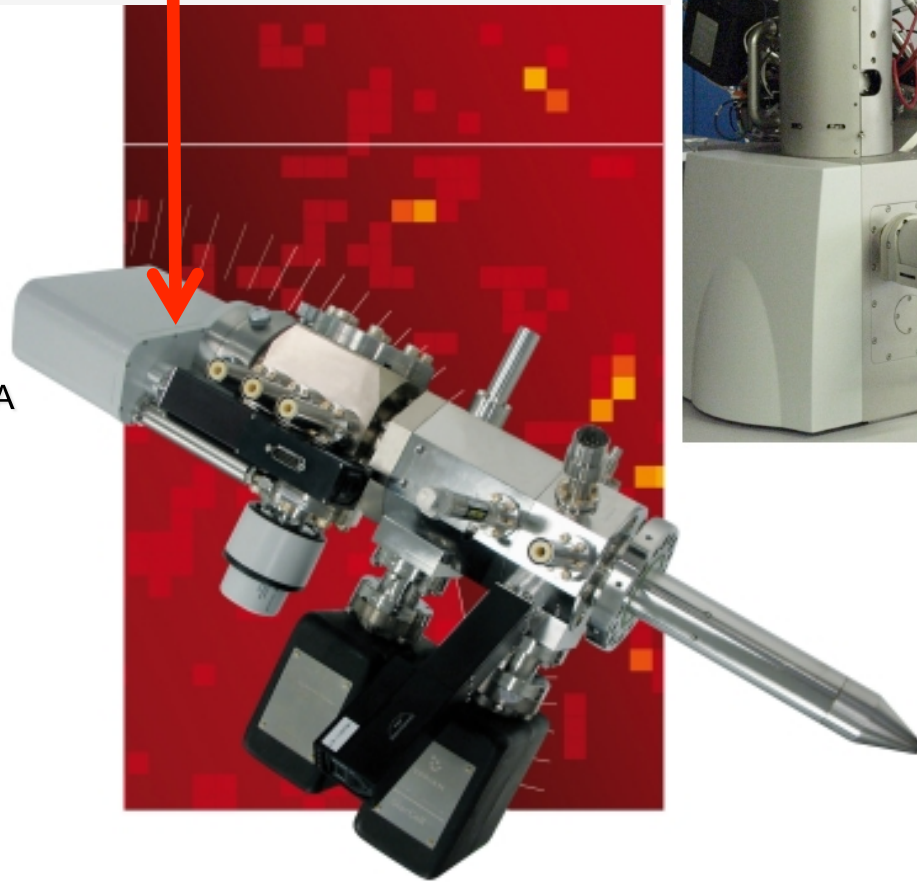


# Other ion sources - Ions for the industry

## 1 - Focused Ion Beam for the Nanotechnologies



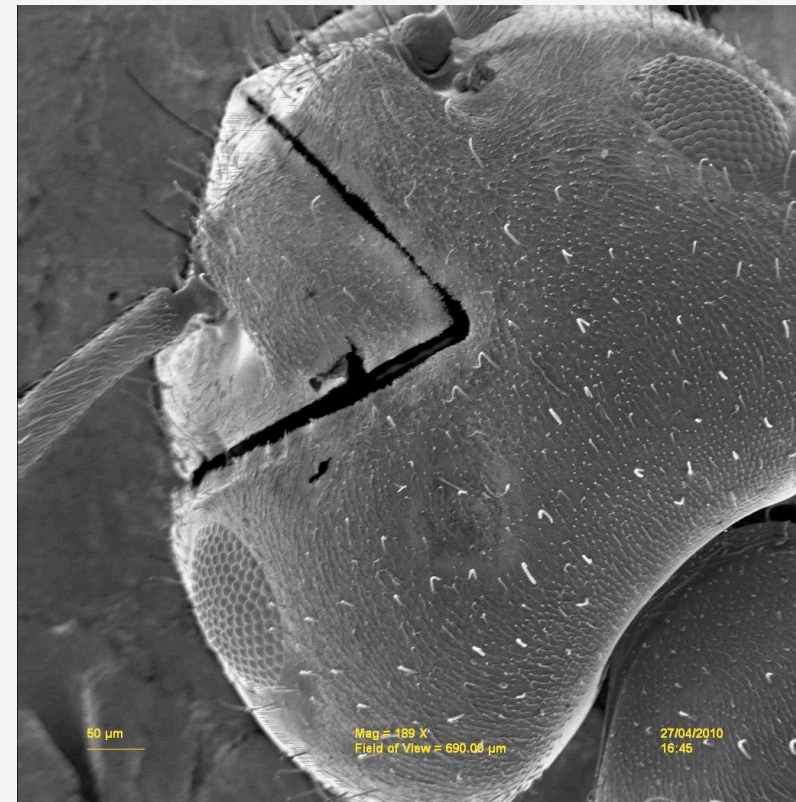
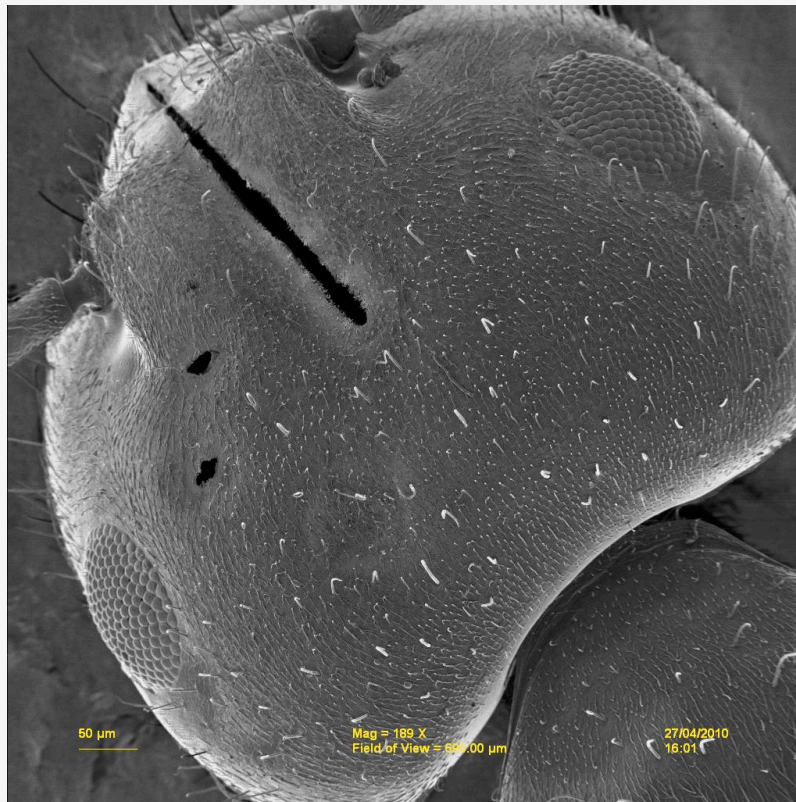
Source COMIC LPSC / Orsay Physics  
I-FIB



# Other ion sources - Ions for the industry

## 1 - Focused Ion Beam for the Nanotechnologies

### Microsurgery of a ant head with the COMIC source



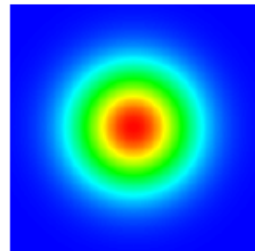
100 x 100 x 100  $\mu\text{m}^3$   
15 hours with Ga (65 nA) = 40 minutes with Xe (1  $\mu\text{A}$ )

# Other ion sources - Ions for the industry

## 1 - Ion Beam Figuring of the Optic Industry

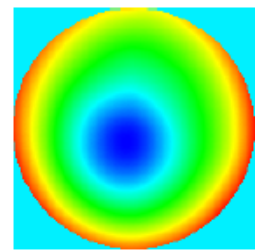
### The purpose of the Ion Beam Figuring :

*The beam*



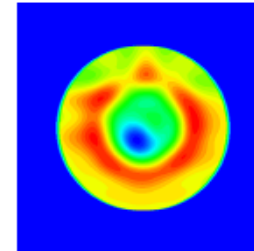
Mesure du profil d'érosion du faisceau

*The profil Defaults :*  
*> 1mm and*  
*<1 μm*



Mesure de la surface optique (par interférométrie)

Traitement mathématique sur ordinateur

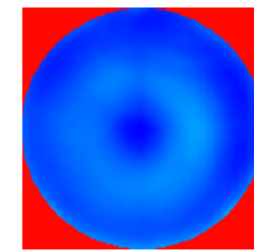


*The pulverisation*

Temps de séjour

Trajectoires

Séquence IBF sous vide (érosion des défauts)



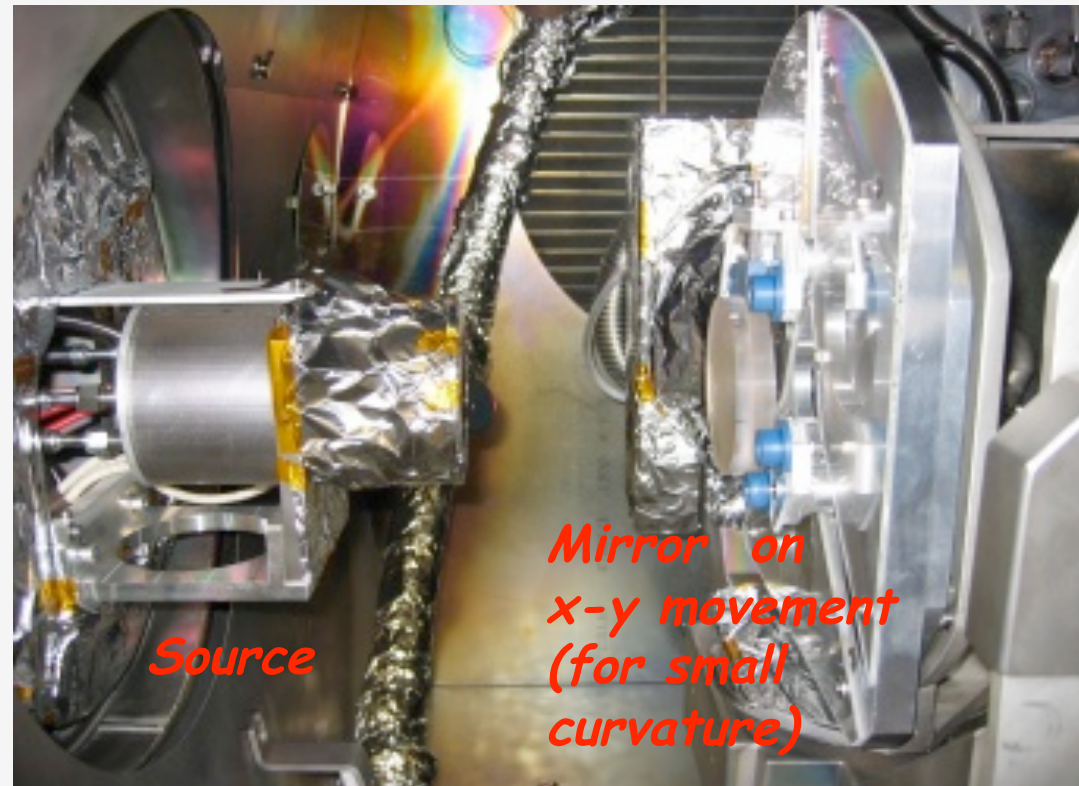
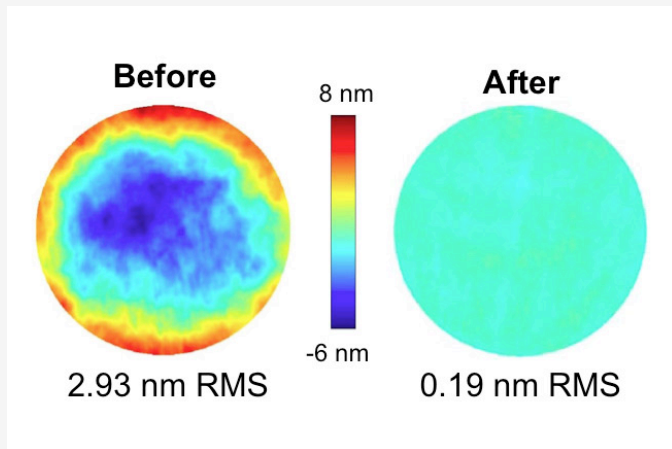
Simulation des erreurs résiduelles

Mesure de la surface optique (contrôle)

## 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**

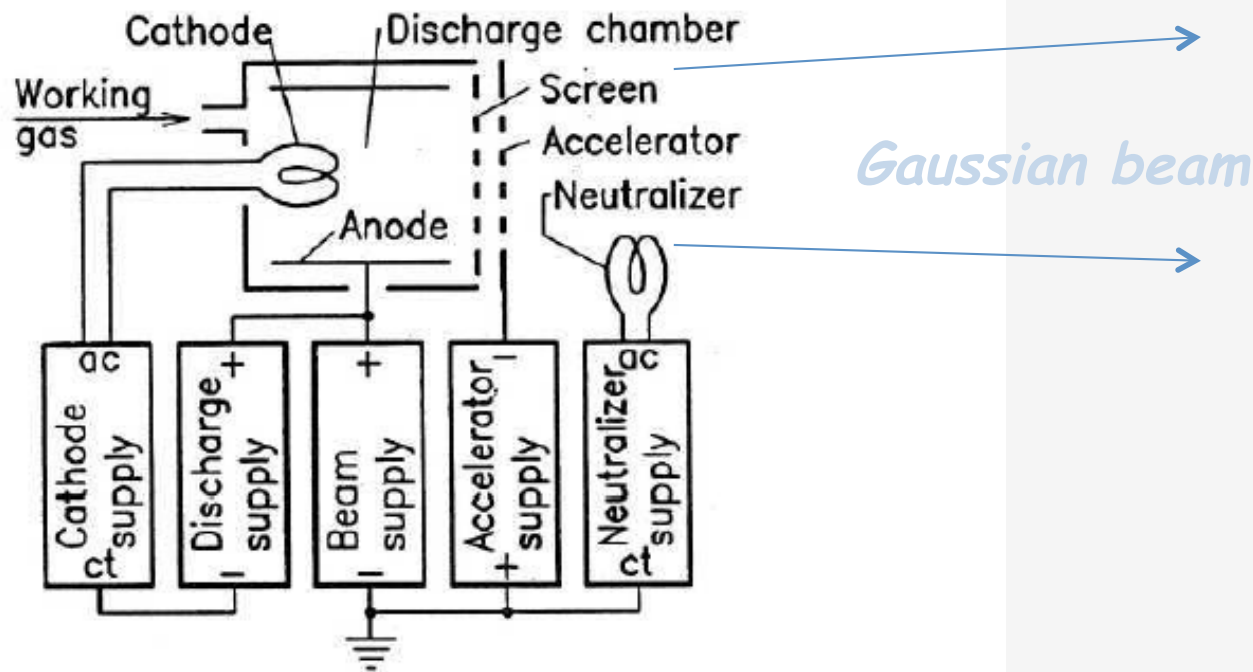
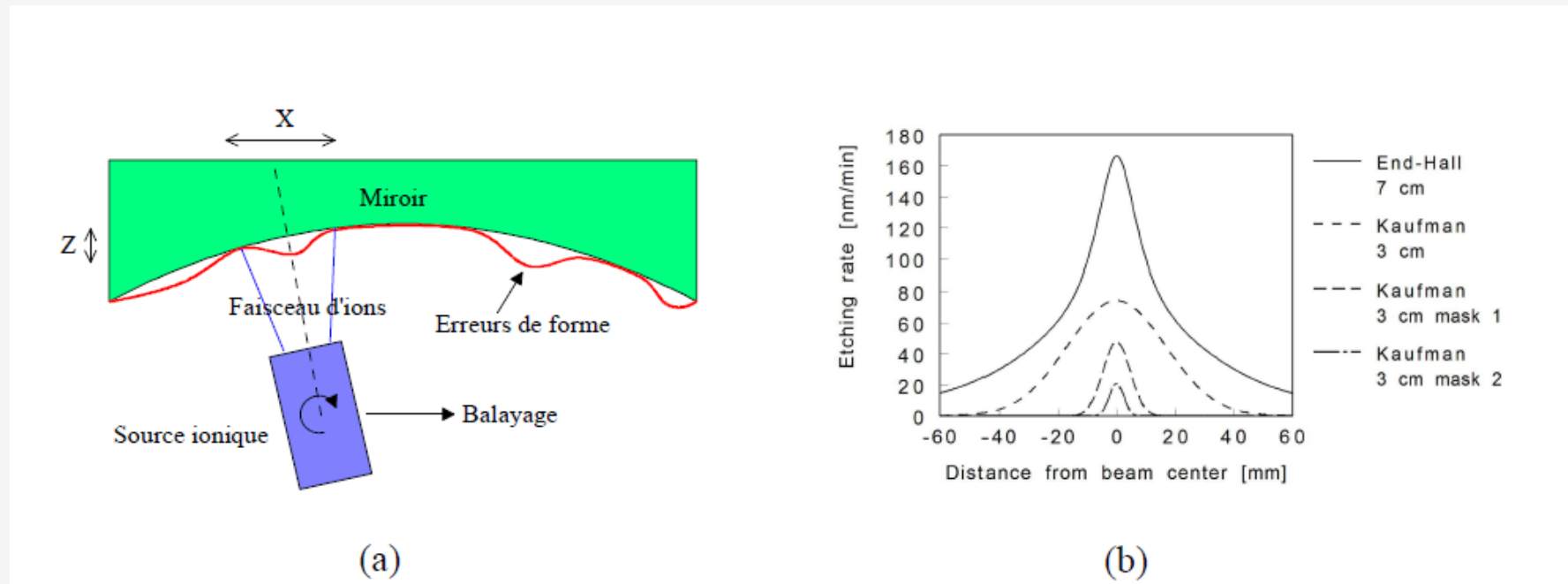


Schéma de principe d'une source ionique de type « Kaufman »

# Other ion sources - Ions for the industry

## 1 - Ion Beam Figuring of the Optic Industry

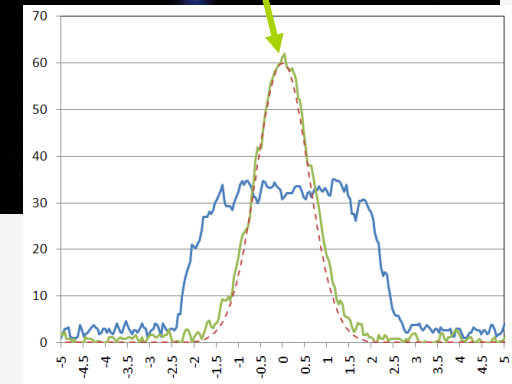
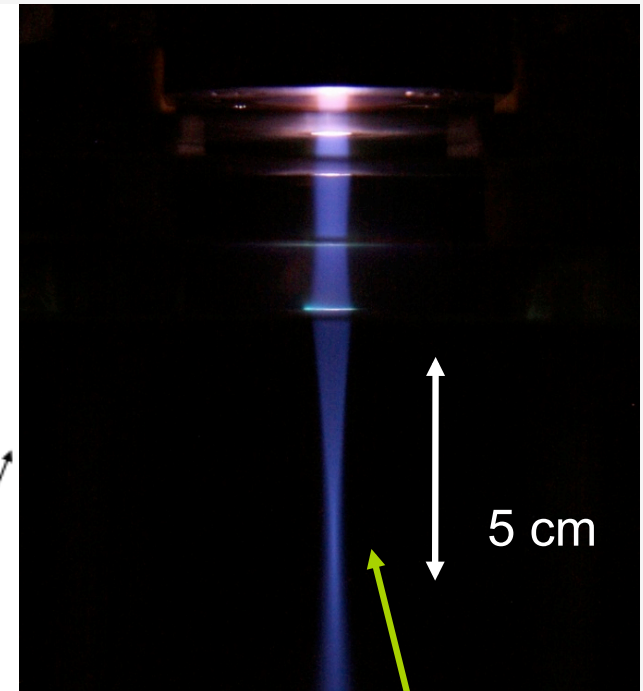
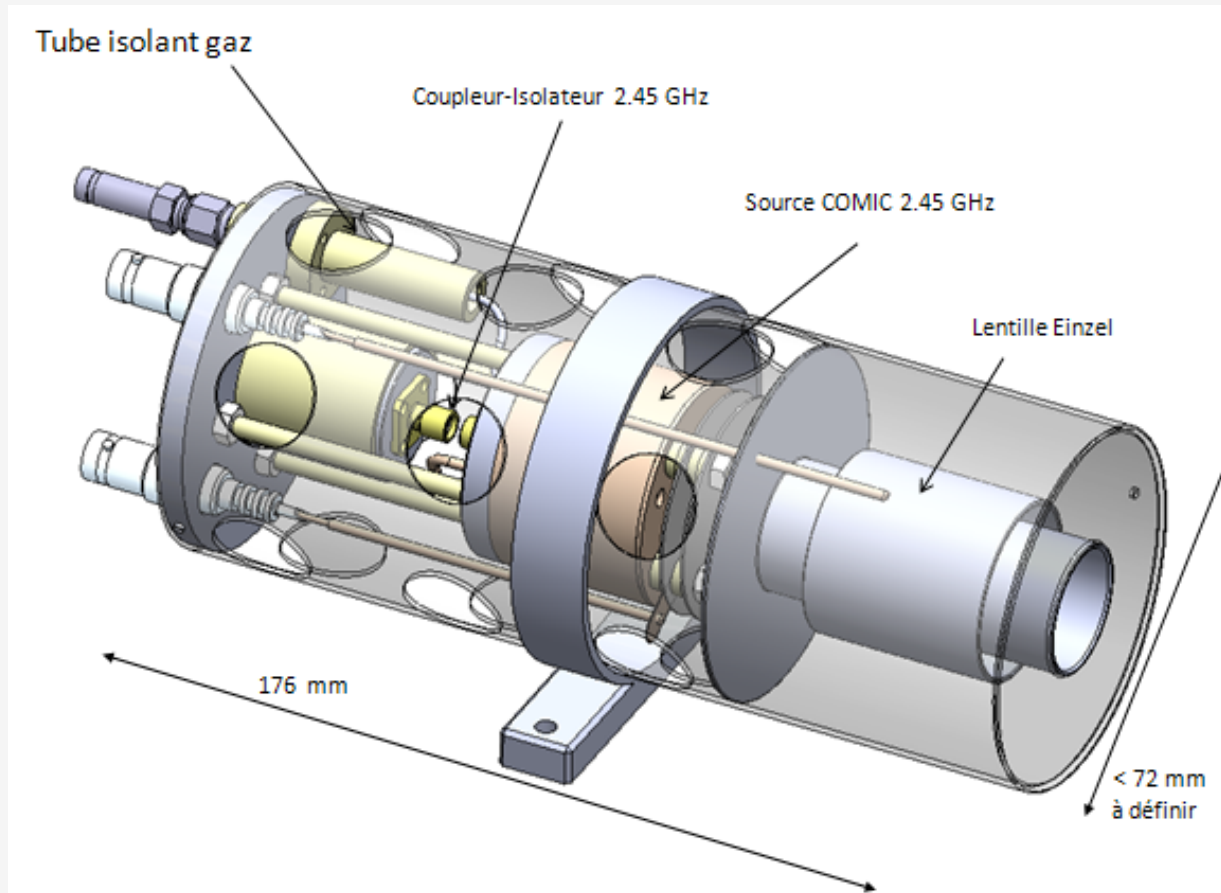
*Matching of the beam size to a characteristic length of the defaults:*



# Other ion sources - Ions for the industry

## 1 - Ion Beam Figuring of the Optic Industry

Ar – 150  $\mu$ A – 1.4 KV –  $\sigma \sim 0.6$  mm



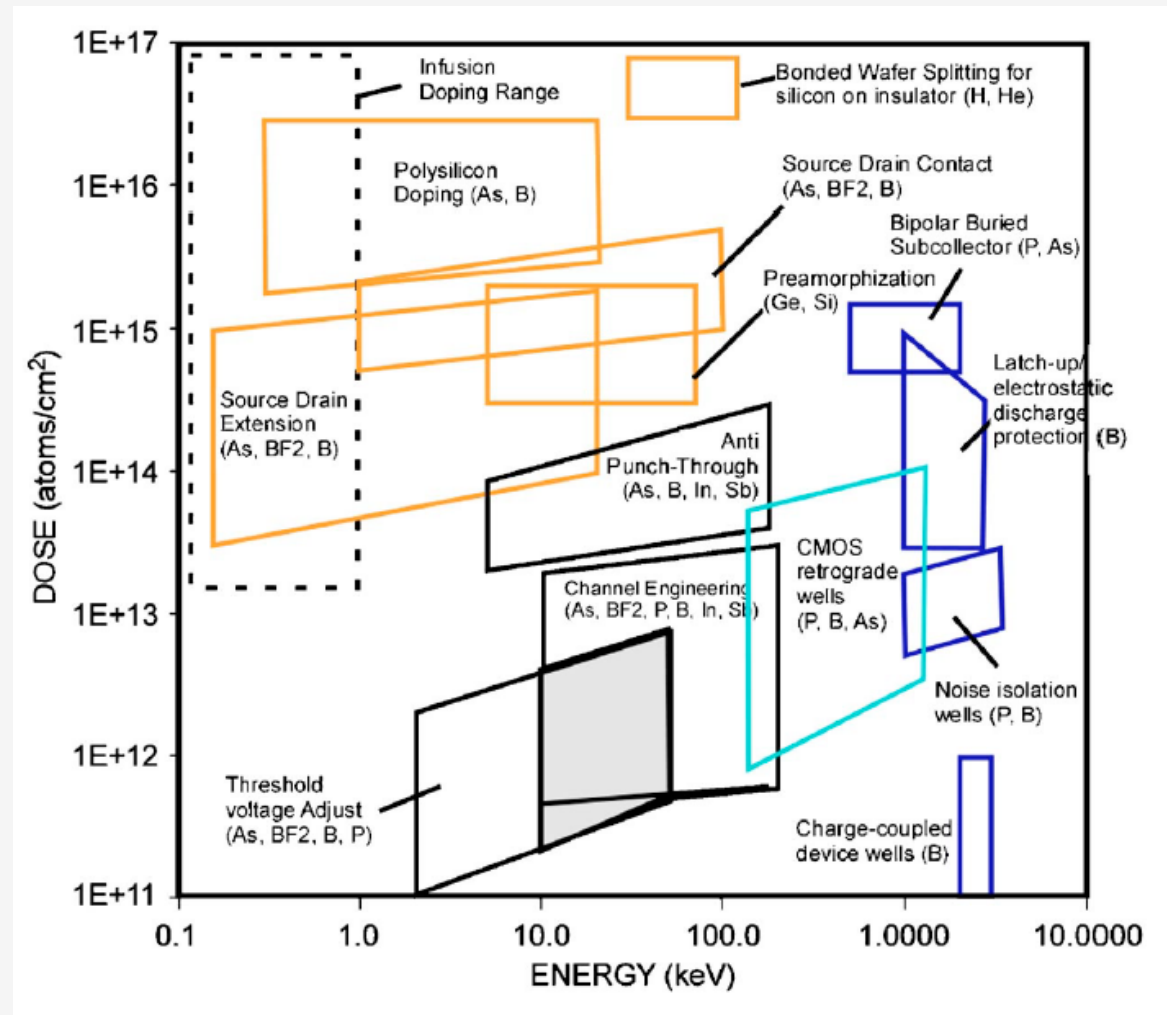
*High brightness gaussian millimeter beam size with COMIC*



## Other ion sources - Ions for the industry

### 2 - High Intensity Beams for MicroElectronics

The purpose of the Implantation Technology:



## Other ion sources - Ions for the industry

### 2 - High Intensity Beams for MicroElectronics

The demand for the Implantation Technology:

Boron :  $\text{BF}_3$ ,  $\text{B}_2\text{H}_6$

Phosphorus : P (solid) ,  $\text{PF}_3$ ,  $\text{PH}_3$

Arsenic :  $\text{AsH}_3$

TABLE 1

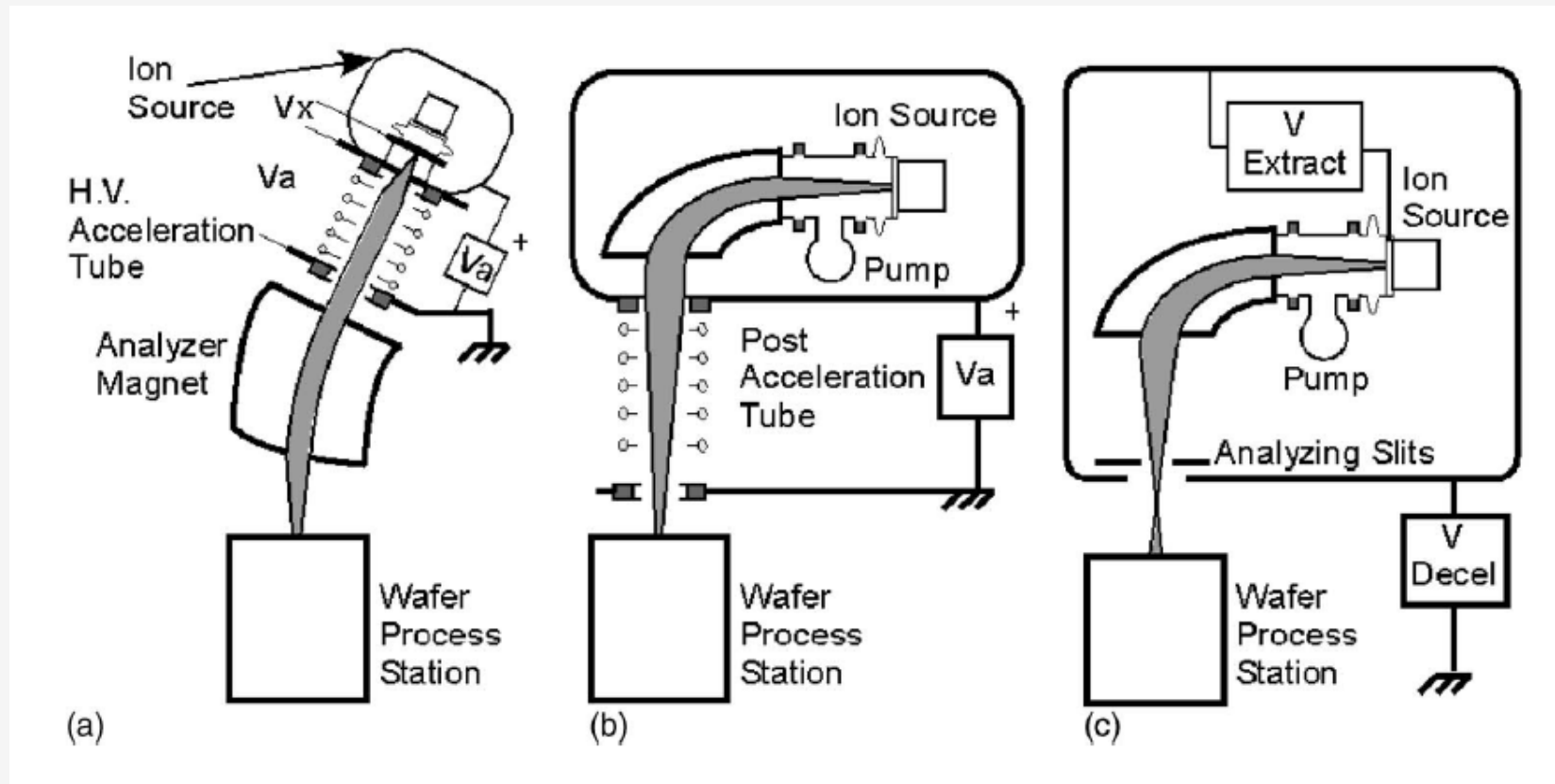
TYPICAL ION SOURCE OPERATING LIFE  
ON HIGH CURRENT (BATCH) IMPLANTERS

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

## Other ion sources - Ions for the industry

### 2 - High Intensity Beams for MicroElectronics

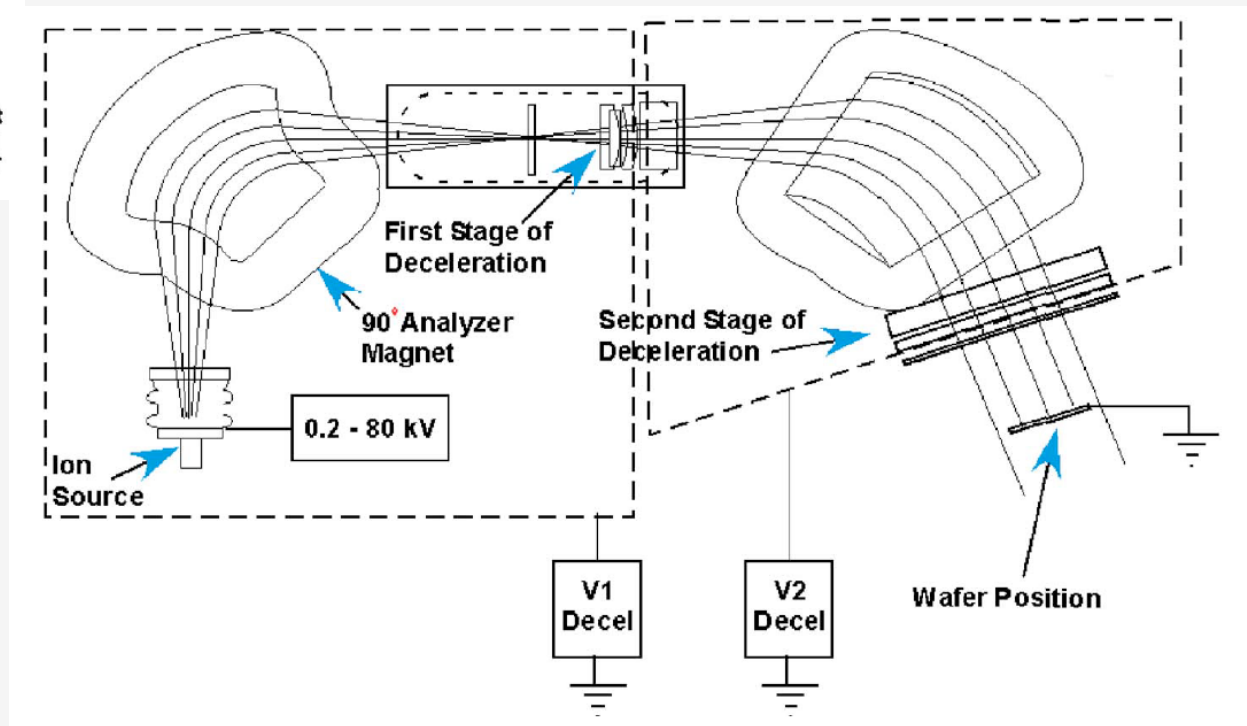
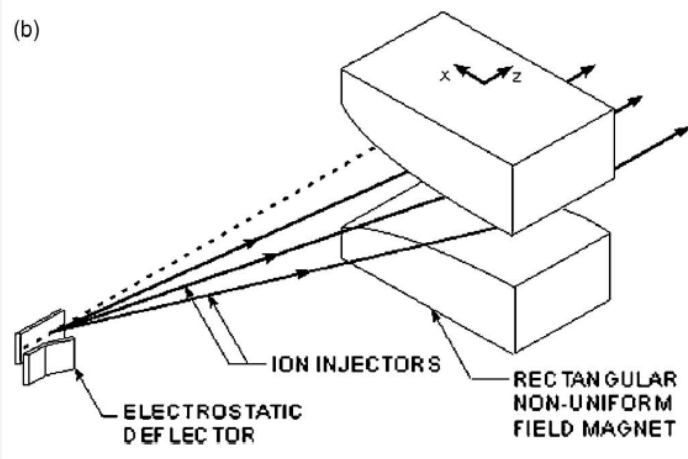
The purpose of the Implantation Technology:



## Other ion sources - Ions for the industry

### 2 - High Intensity Beams for MicroElectronics

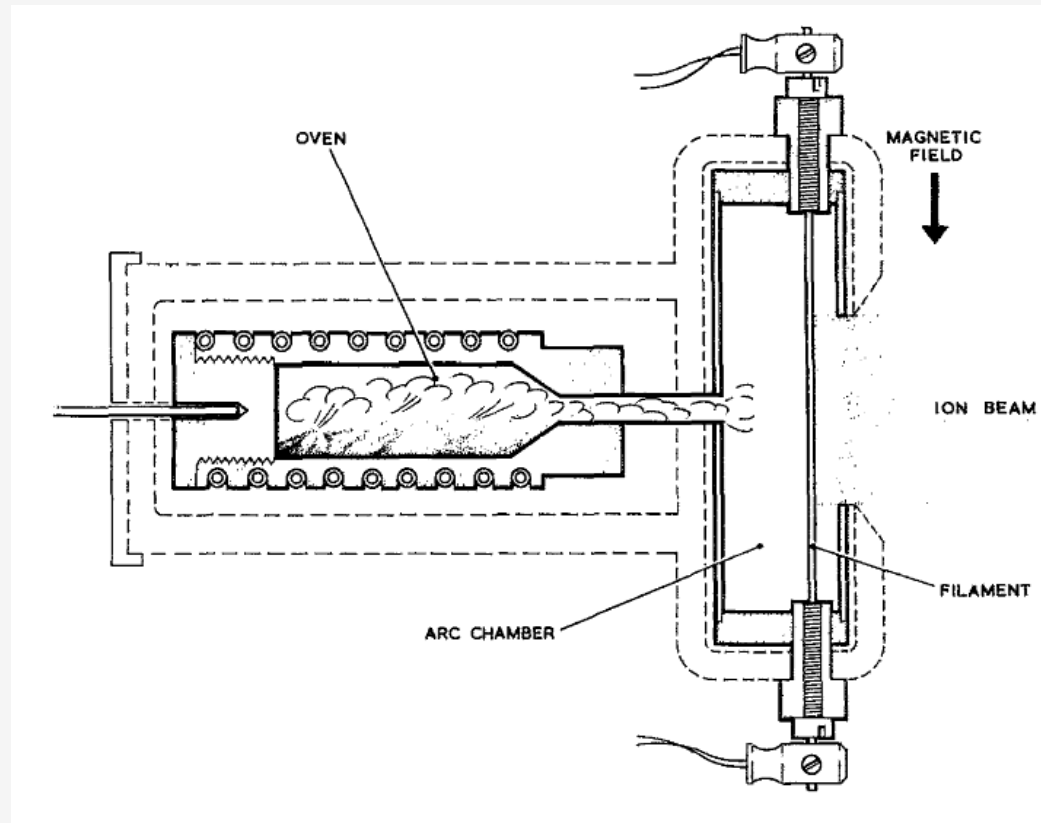
The purpose of the Implantation Technology: Ribbon beam generation



## Other ion sources - Ions for the industry

### 2 - High Intensity Beams for MicroElectronics

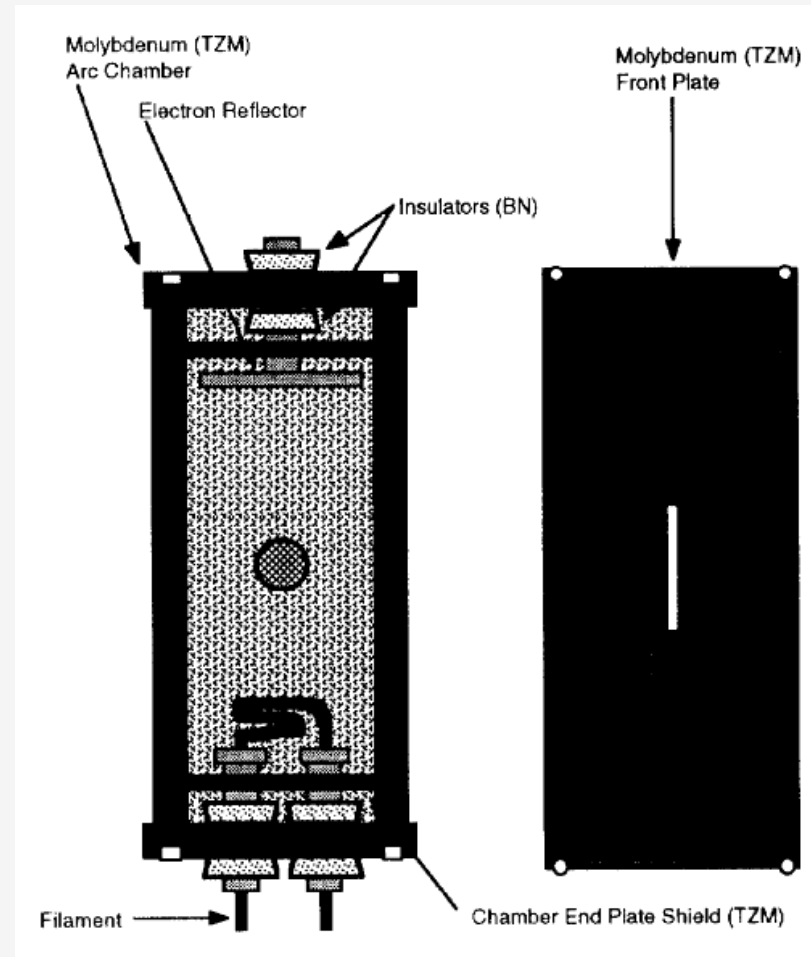
The Freeman Ion Source:



## Other ion sources - Ions for the industry

### 2 - High Intensity Beams for MicroElectronics

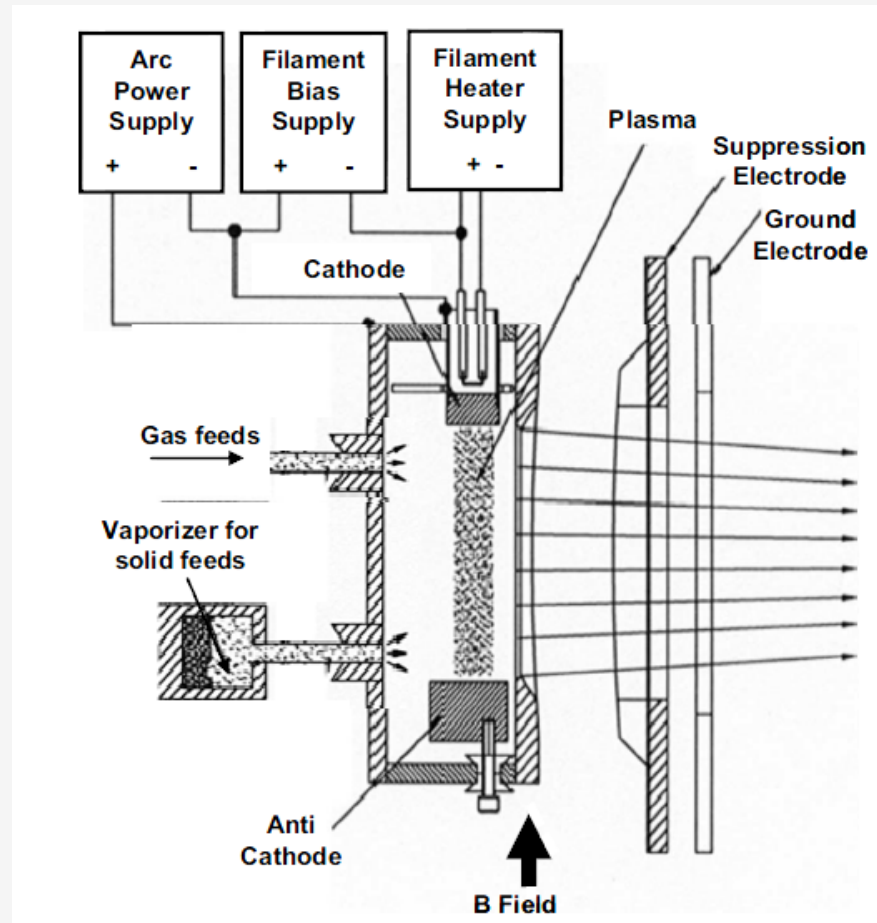
#### The Bernas Ion Source:



## Other ion sources - Ions for the industry

### 2 - High Intensity Beams for MicroElectronics

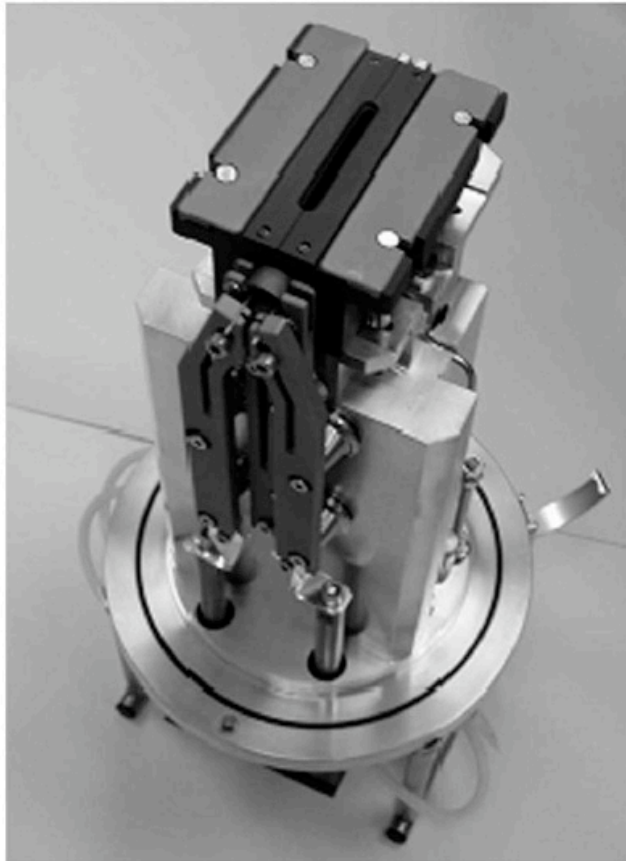
#### The Indirectly Heated Cathode Ion Source (IHC):



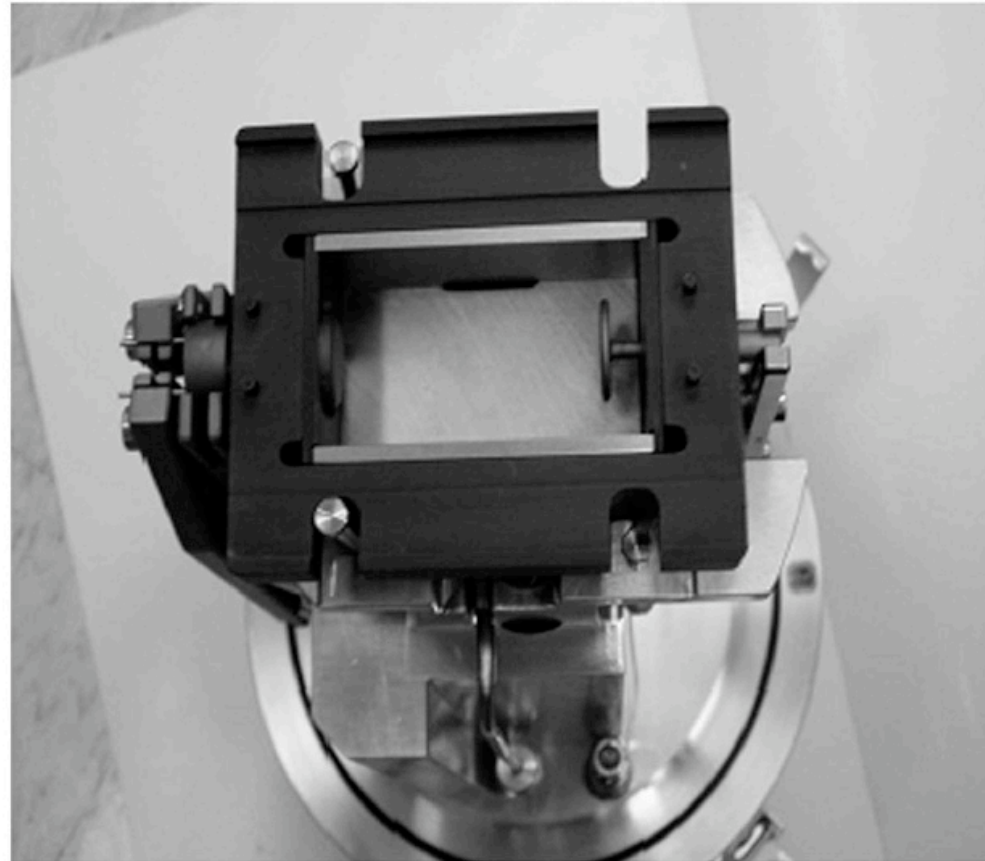
## Other ion sources - Ions for the industry

### 2 - High Intensity Beams for MicroElectronics

The Indirectly Heated Cathode Ion Source (IHC):



(b)



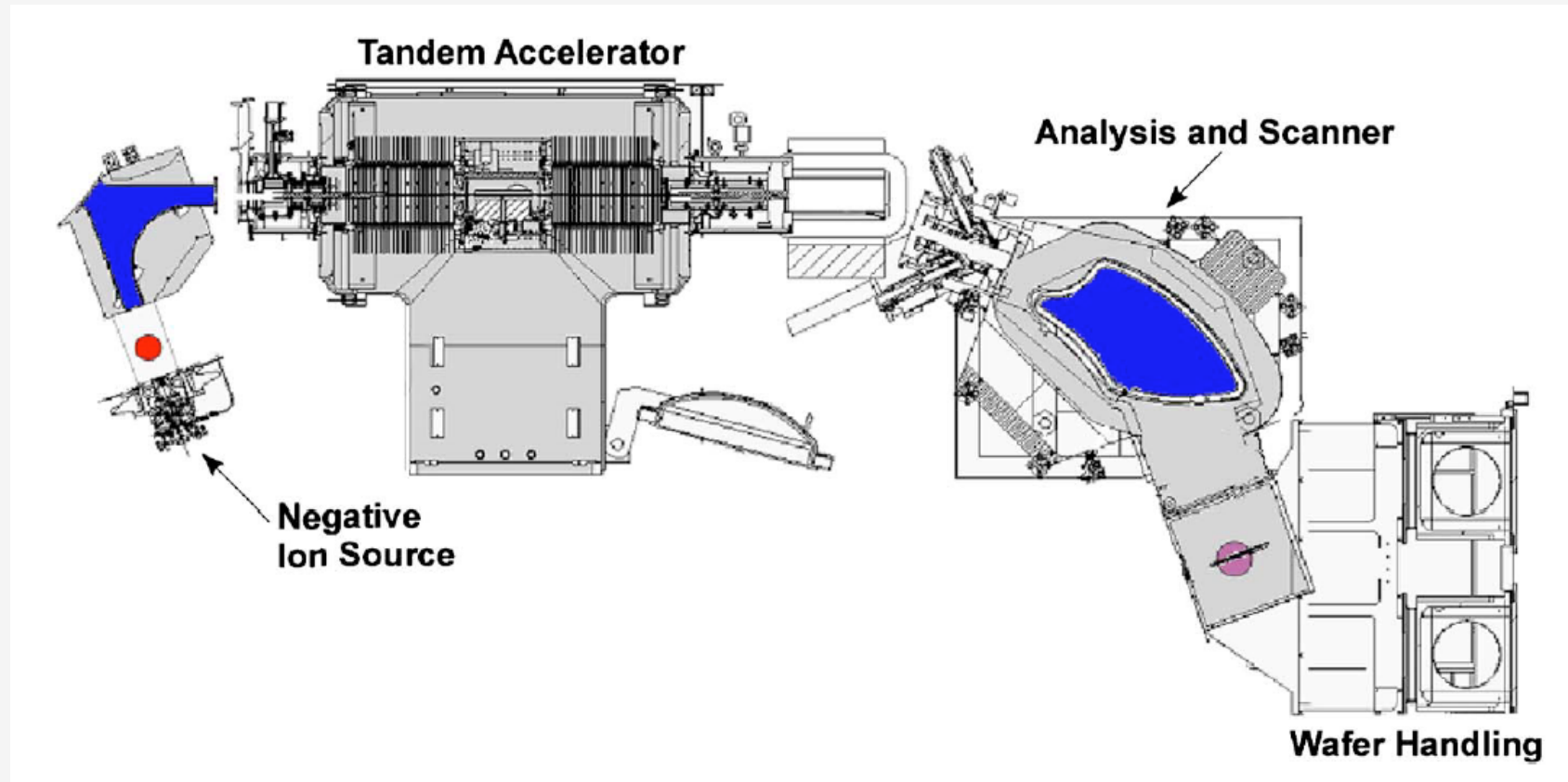
(c)



## Other ion sources - Ions for the industry

### 2 - High Intensity Beams for MicroElectronics

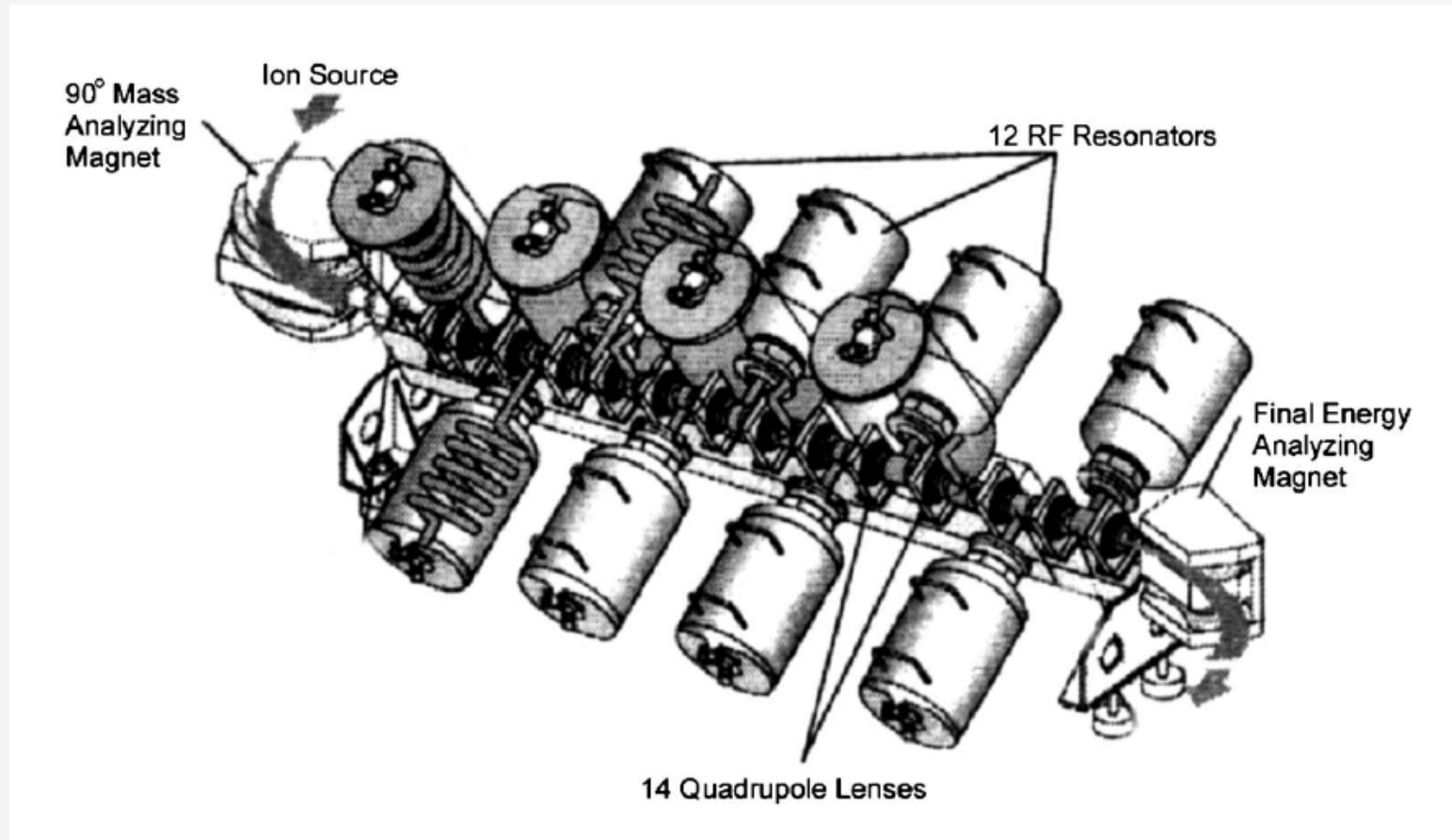
#### High energy implantation : Negative ion source and Tandem



## Other ion sources - Ions for the industry

### 2 - High Intensity Beams for MicroElectronics

#### High energy implantation : Positive ion source and Linac

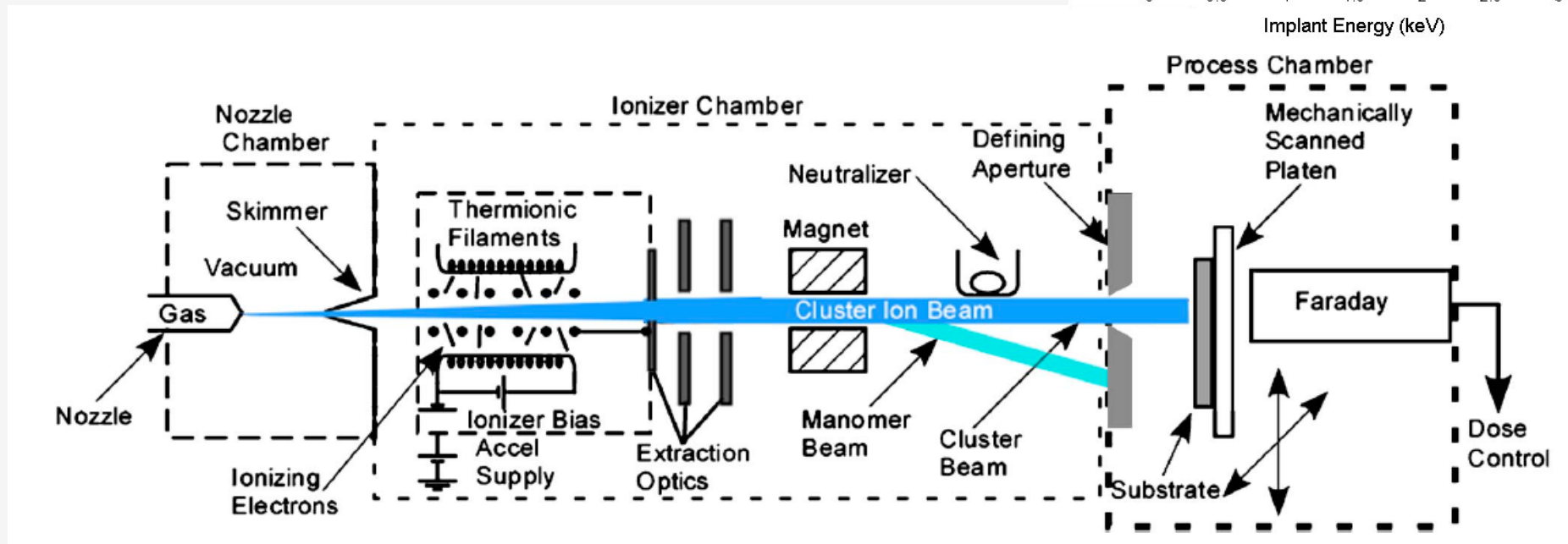
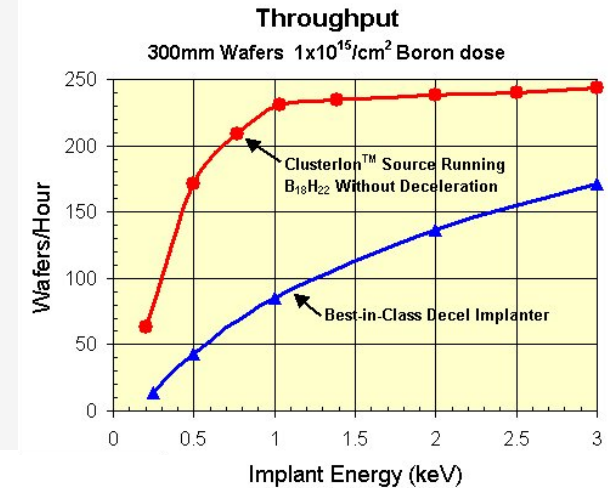


## Other ion sources - Ions for the industry

### 2 - High Intensity Beams for MicroElectronics

Low energy implantation :  
**Complex Molecular ion and Cluster**

$B_{18}H_{22}$ ,  $C_{16}H_{10}$   
 followed by annealing ( $\sim 1000^{\circ}C$ )



## 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<sup>+</sup>, 2<sup>+</sup> & 3<sup>+</sup> compact, low cost and upgreadeable*
- 2 - *> 5 mA CW of B<sup>-</sup>, P<sup>-</sup>, As<sup>-</sup> with lifetime > 168 h*
- 3 - *Large area implantation : < 1% over  $\Phi$  500 mm*
- 4 - *Low mainteance ion source*  
*(without any monodification 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

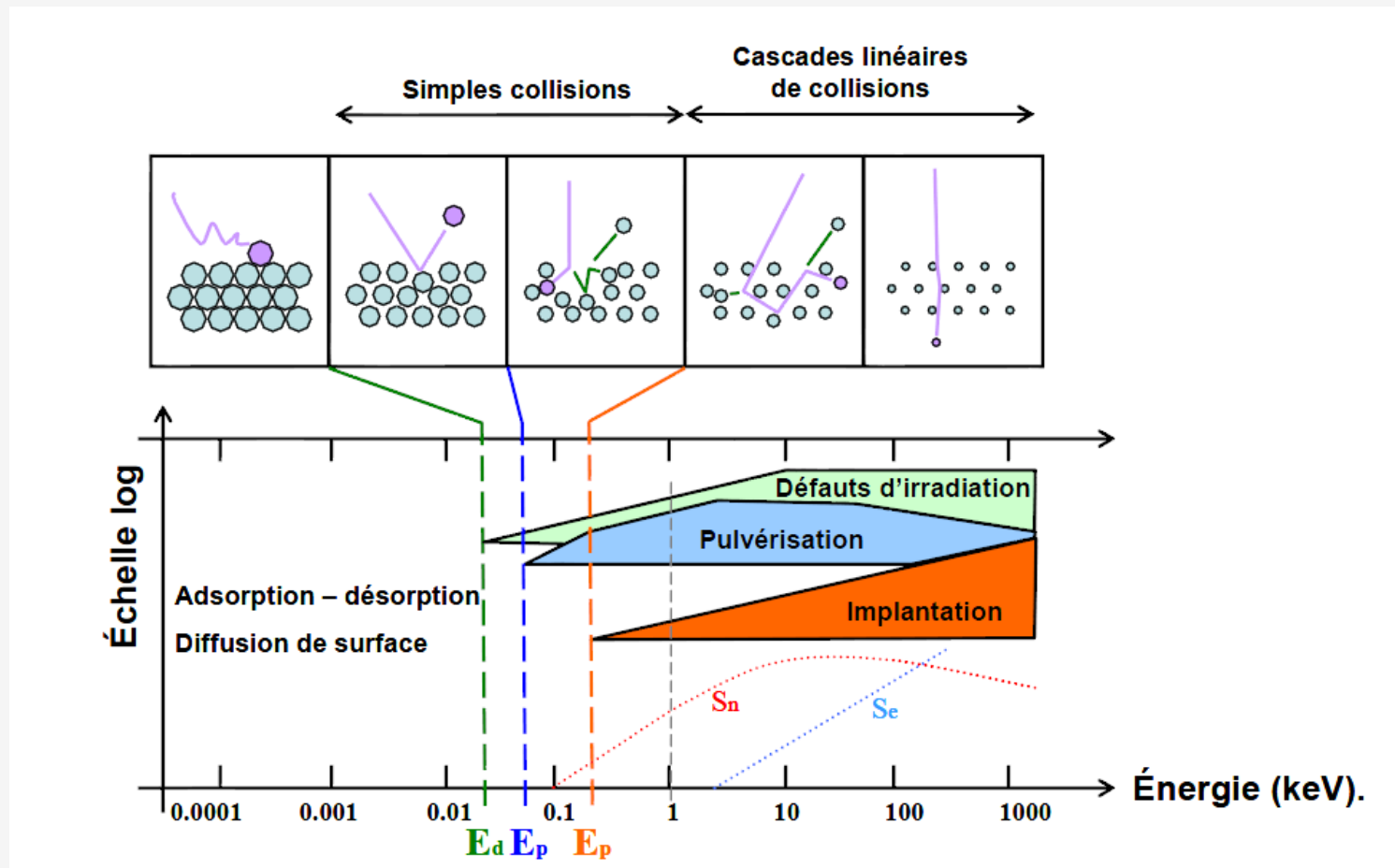
*(Physical Vapor Deposition)*

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

# Other ion sources - Ions for the industry

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

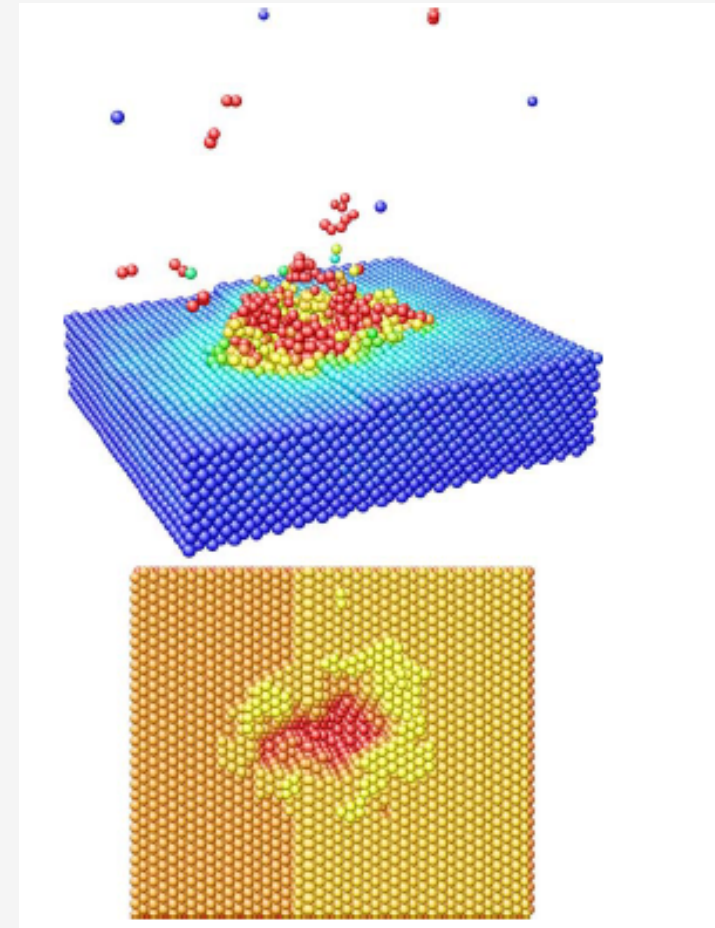
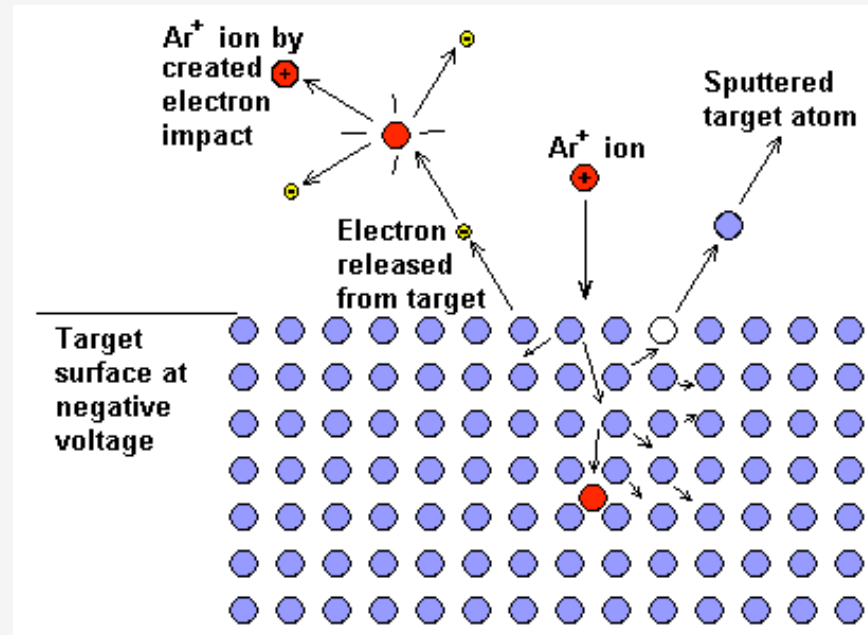
### Ionic modification of matériel :



## Other ion sources - Ions for the industry

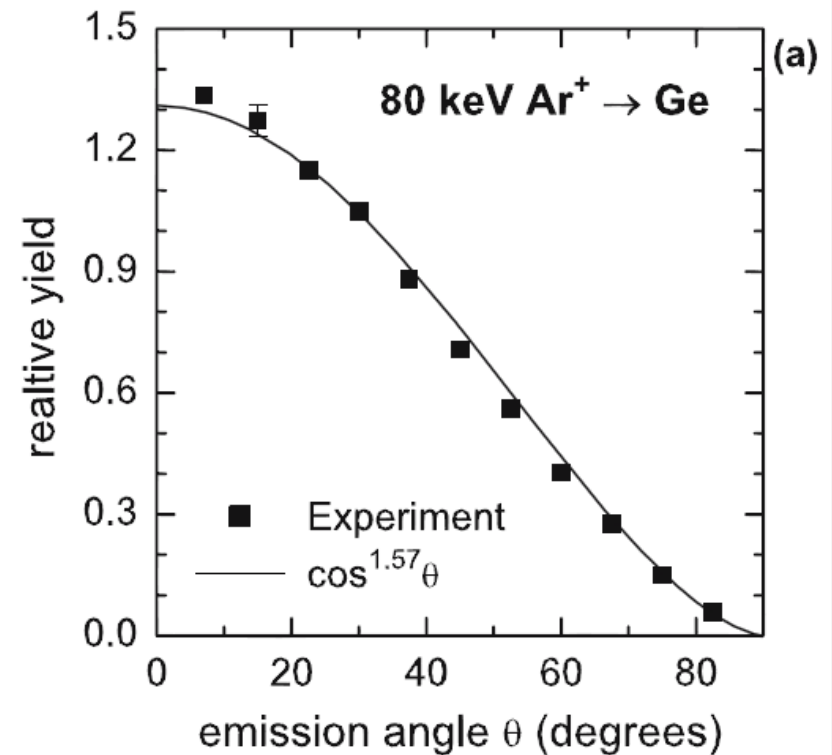
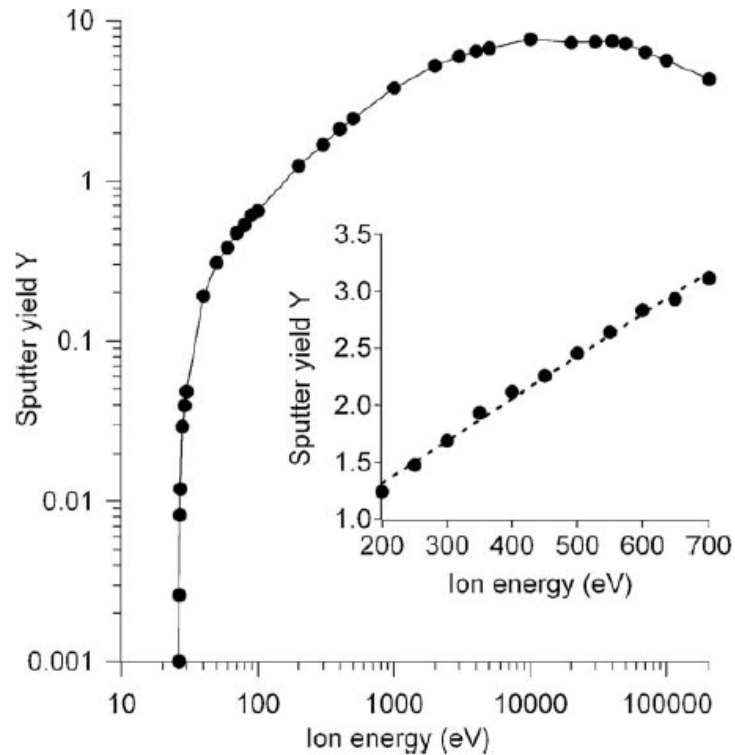
### 3 - Broad Beam & "Ionic Machine" for the Industrial Coating

The sputtering process : ( $\text{Ar}^+$ , 5 kV at  $83^\circ$  / surf., 2.5 ps)



## Other ion sources - Ions for the industry

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

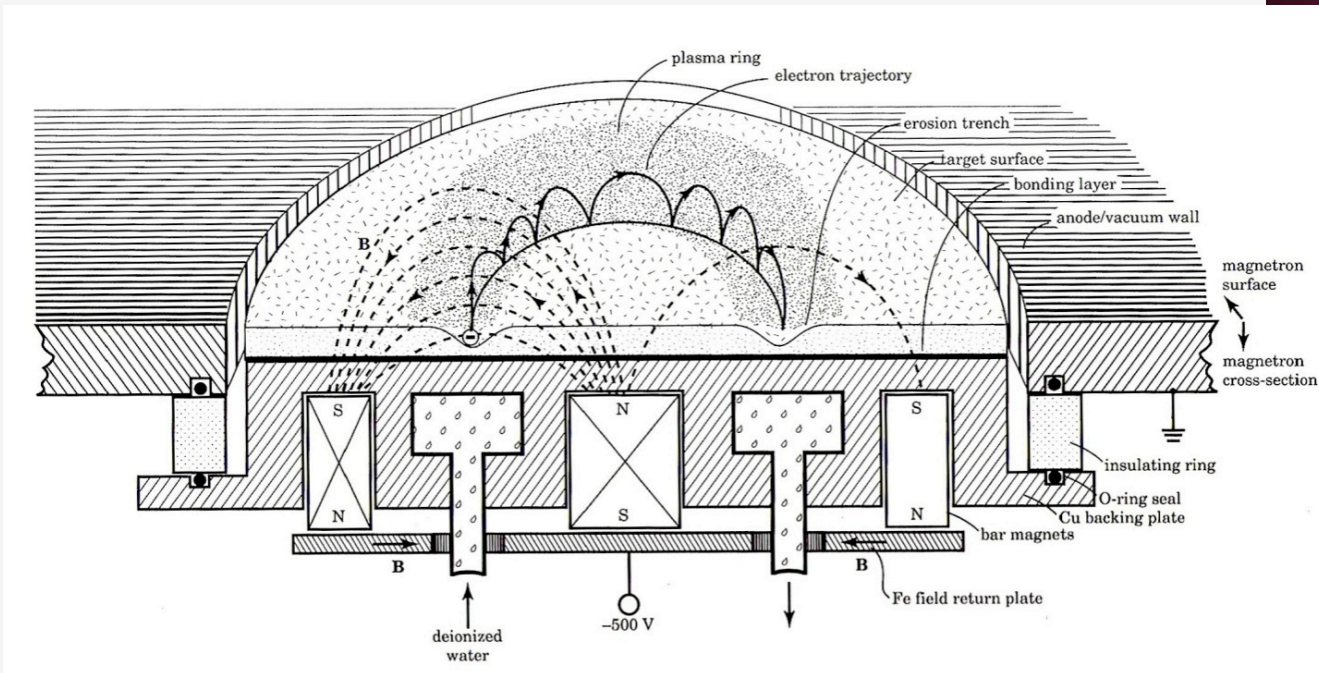




## Other ion sources - Ions for the industry

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

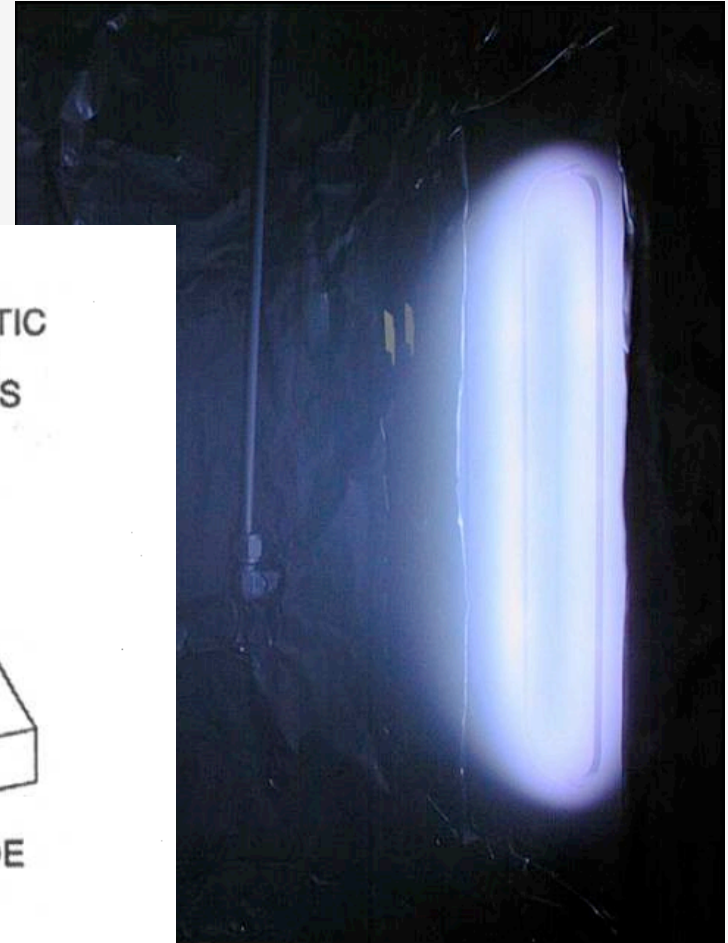
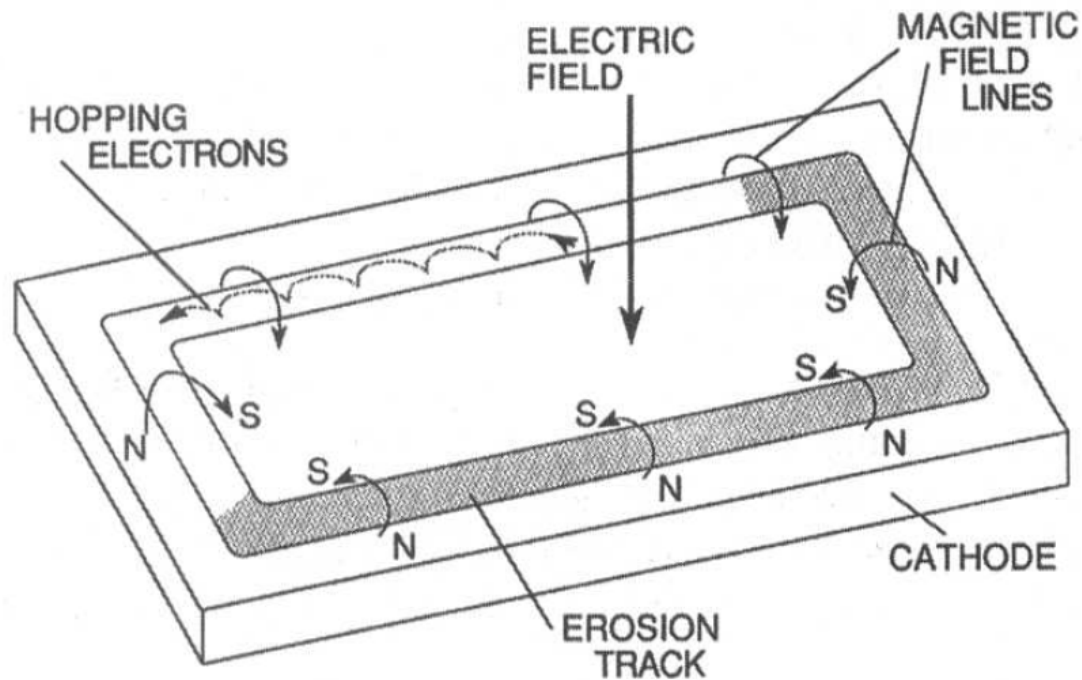
## The Magnetron Sputtering (MS) :



## Other ion sources - Ions for the industry

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

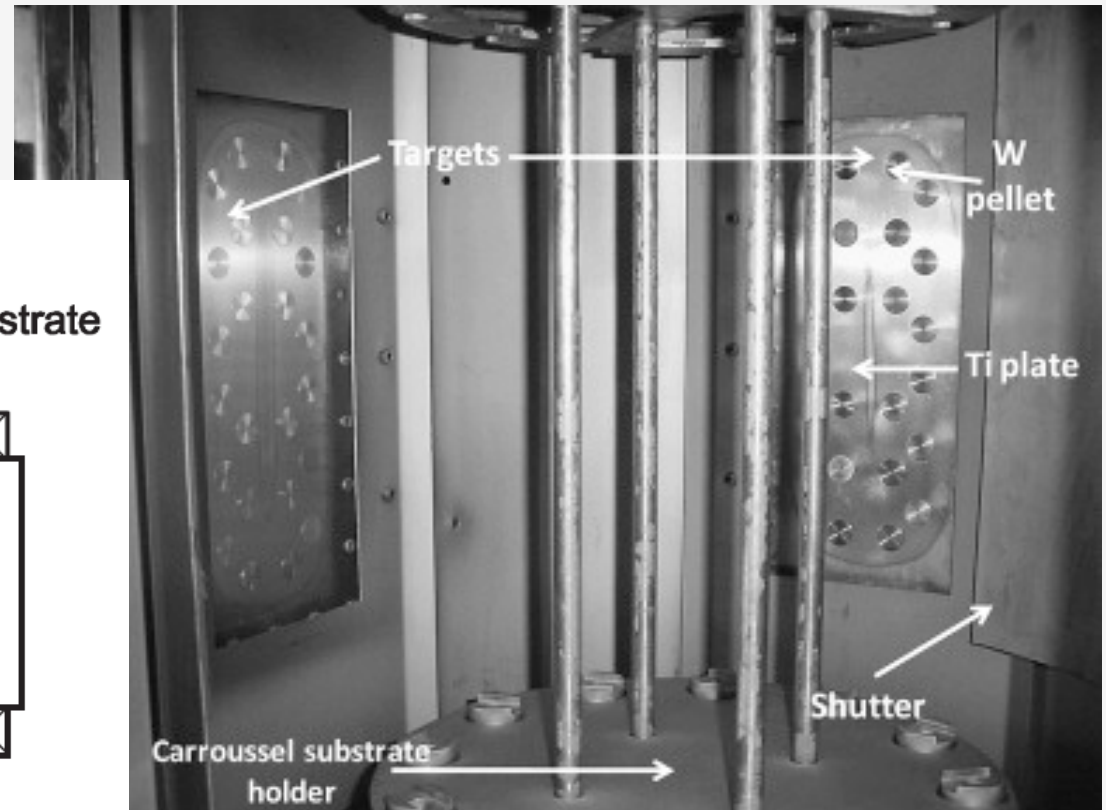
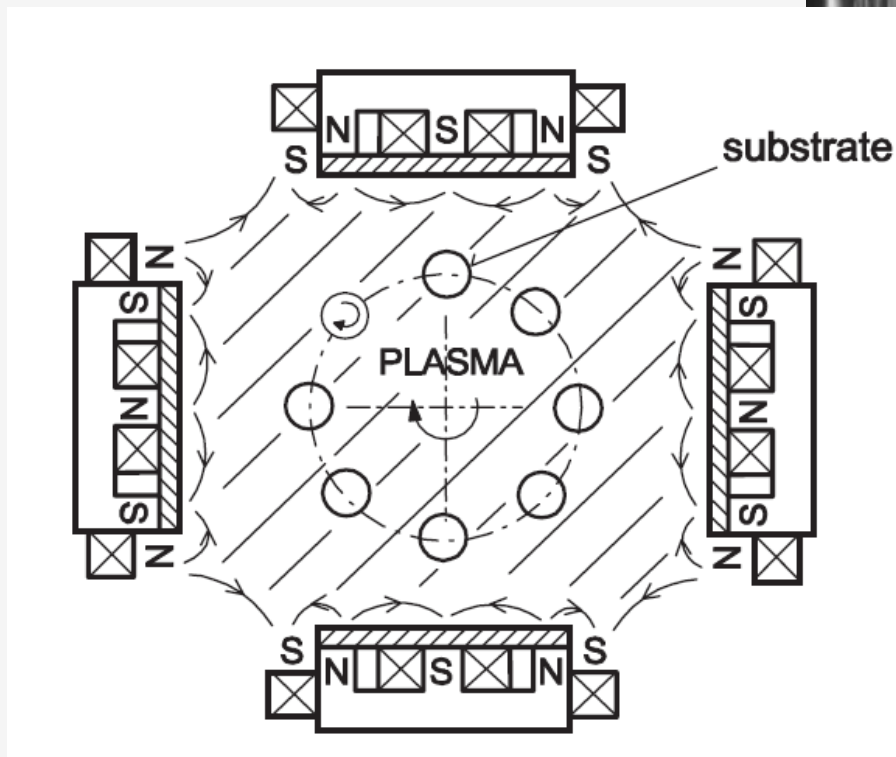
The Magnetron Sputtering (MS) :



## Other ion sources - Ions for the industry

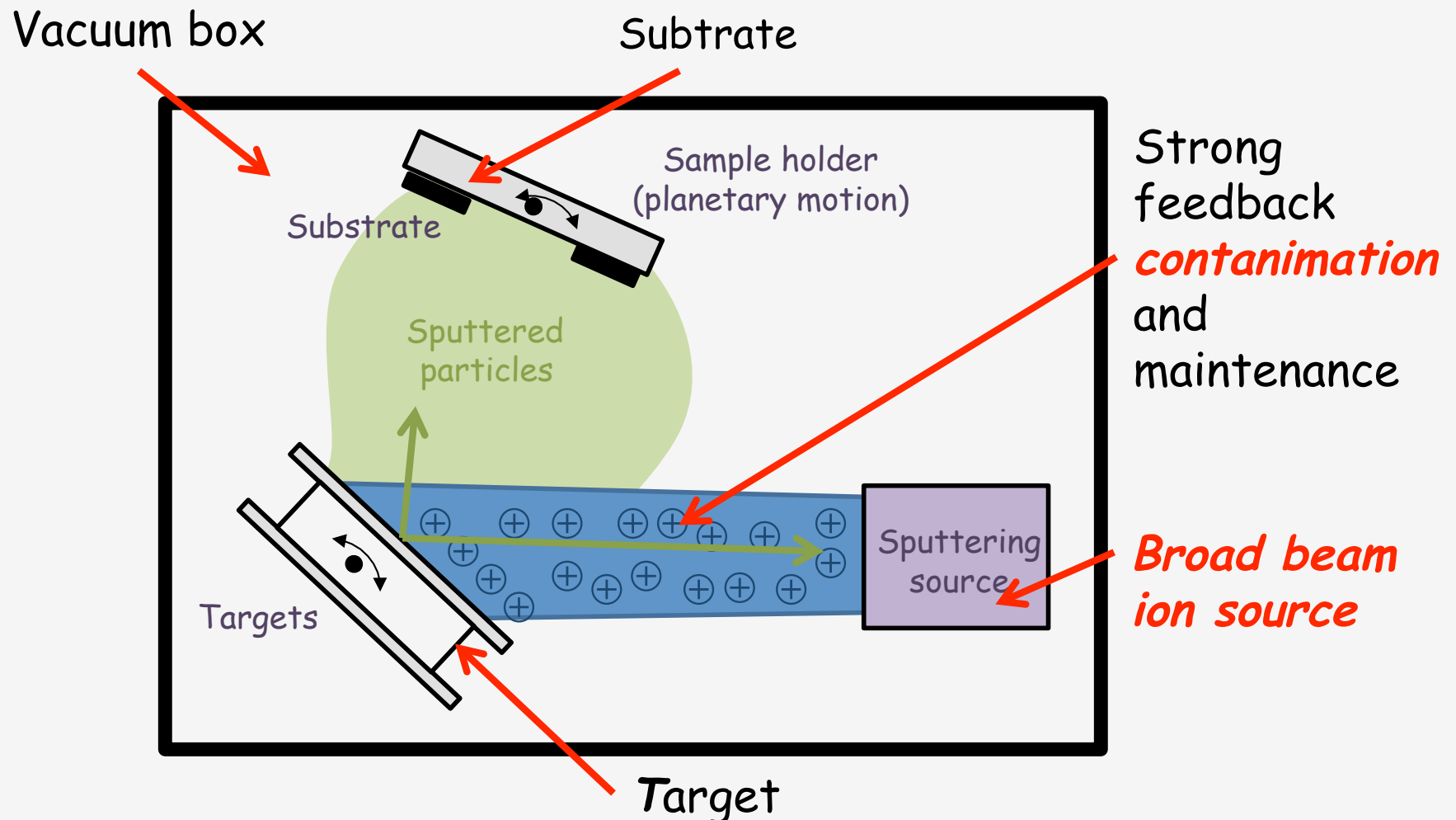
### 3 - Broad Beam & "Ionic Machine" for the Industrial Coating

#### The Magnetron Sputtering (MS) :



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

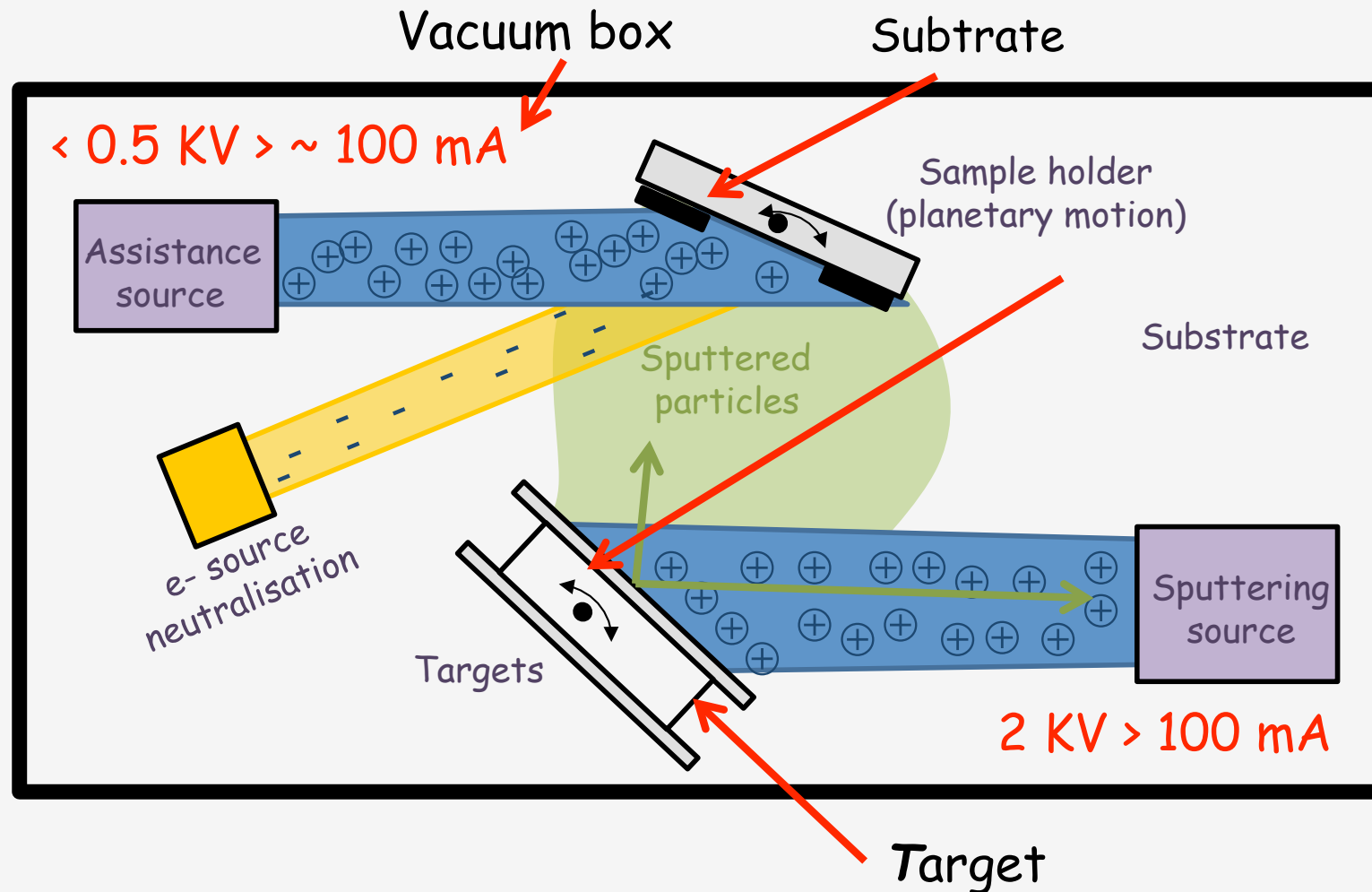
The Ion Beam Sputtering (IBS) :



## Other ion sources - Ions for the industry

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

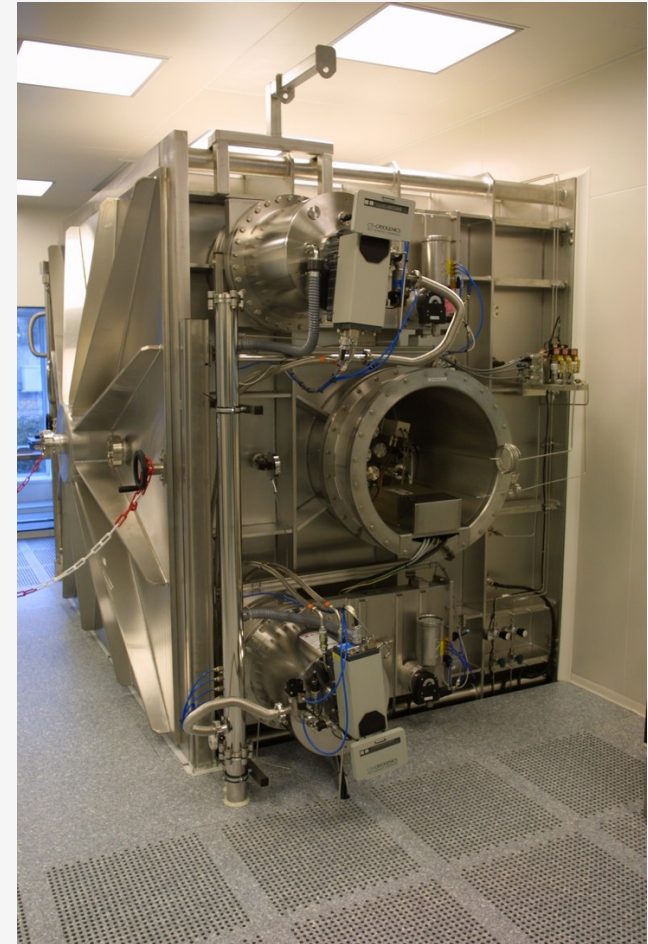
The Double Ion Beam Sputtering (DIBS) and assistance ion source :



## Other ion sources - Ions for the industry

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

The Double Ion Beam Sputtering (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":

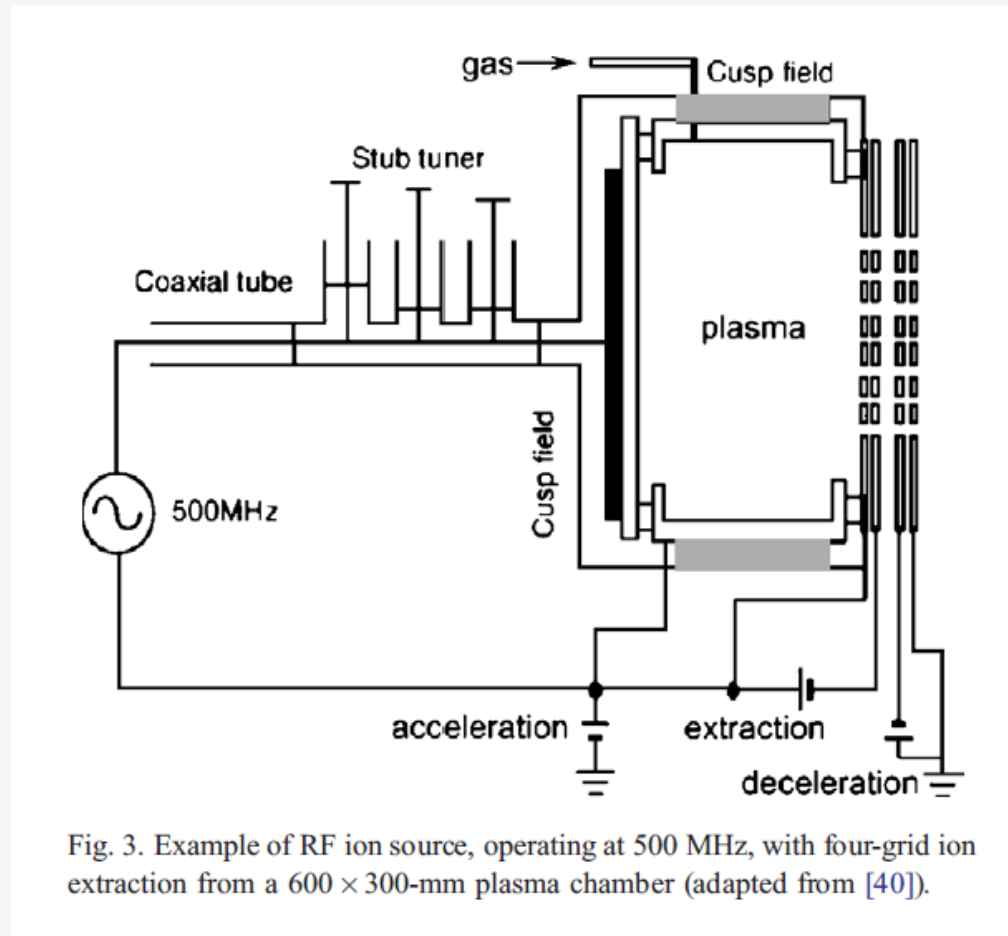
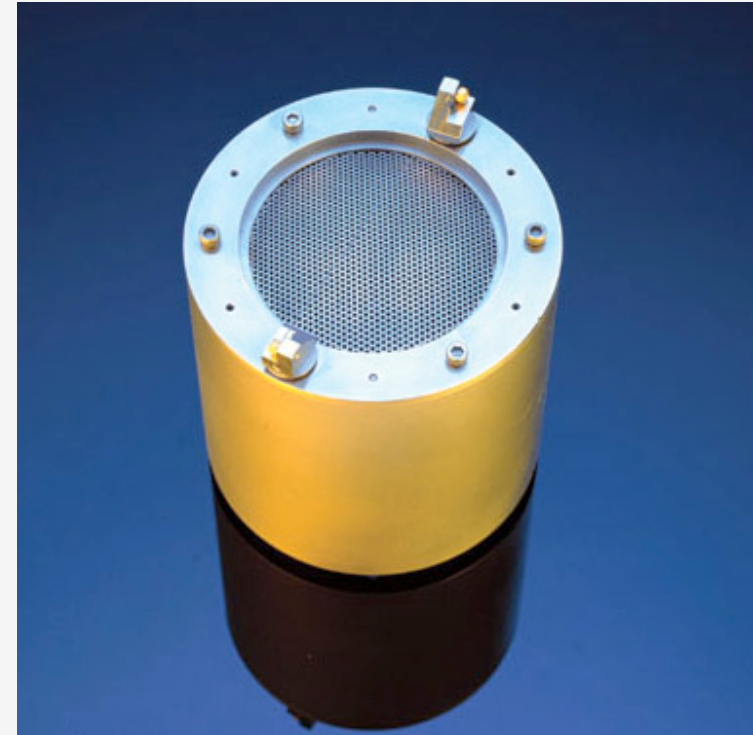


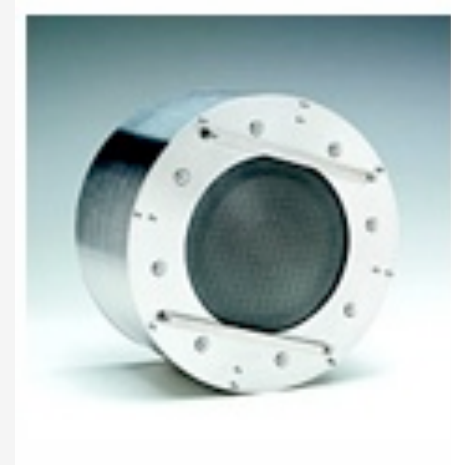
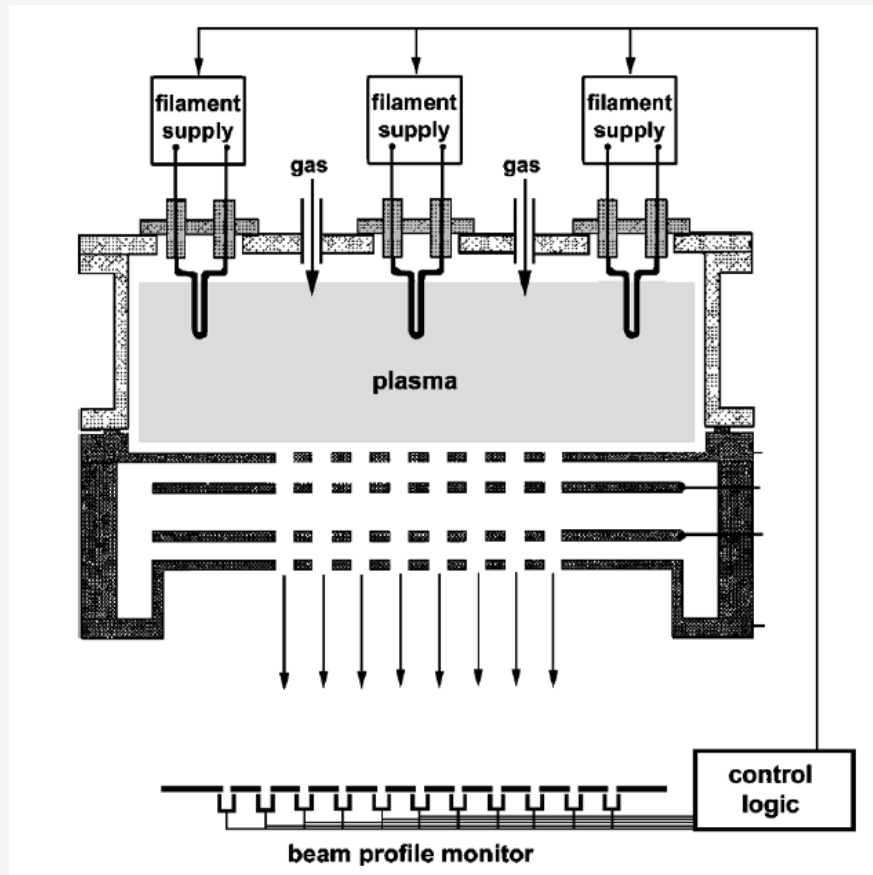
Fig. 3. Example of RF ion source, operating at 500 MHz, with four-grid ion extraction from a 600 × 300-mm plasma chamber (adapted from [40]).



## Other ion sources - Ions for the industry

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

The DC broad beam "gridded":

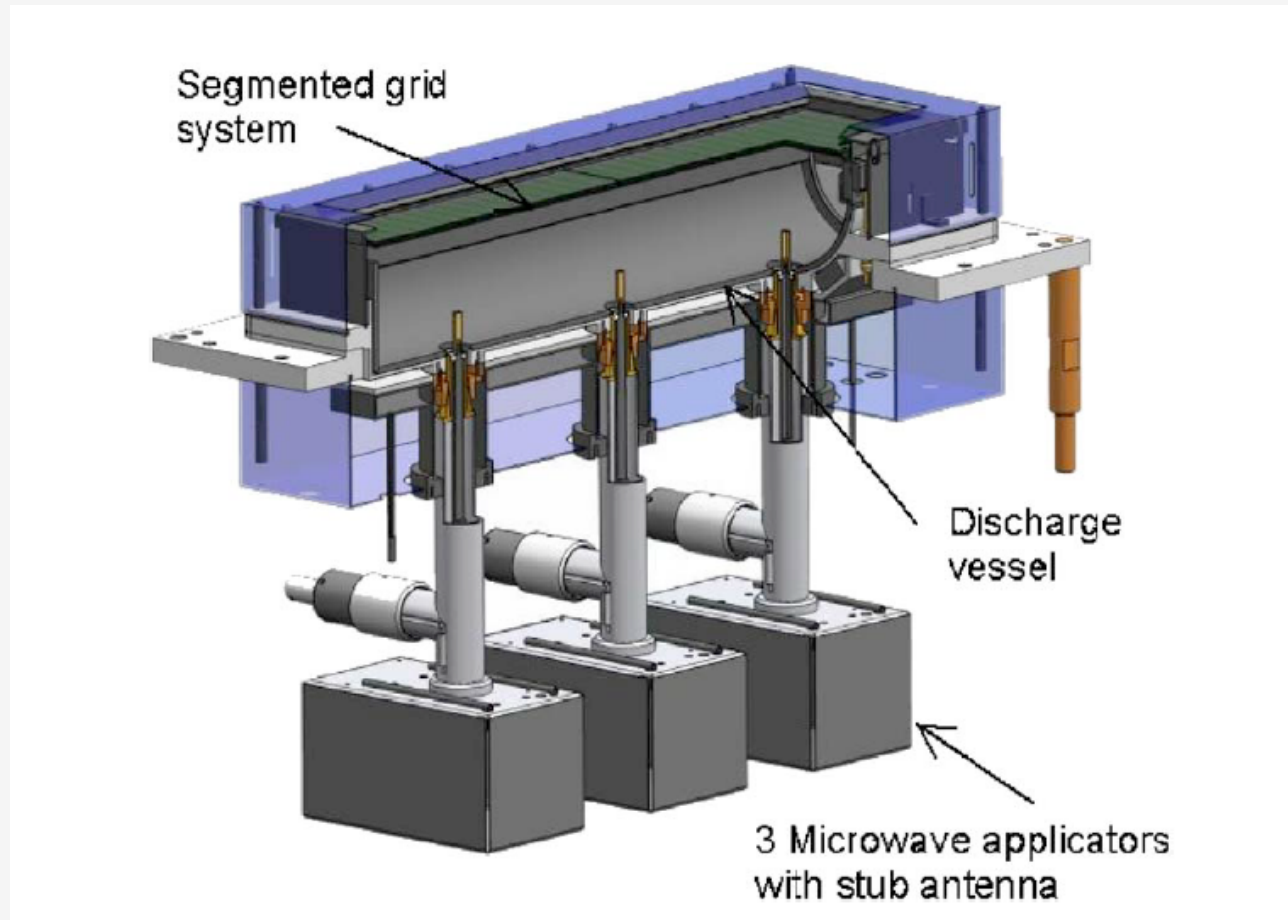




## Other ion sources - Ions for the industry

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

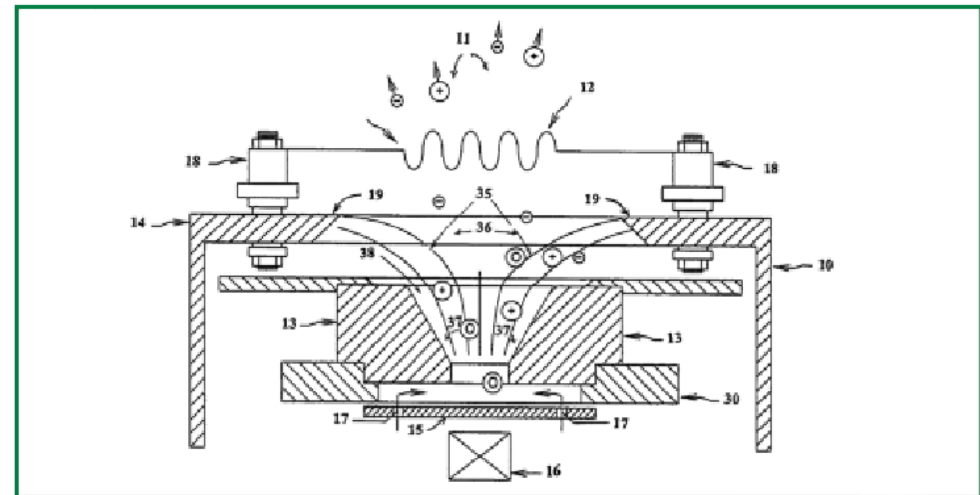
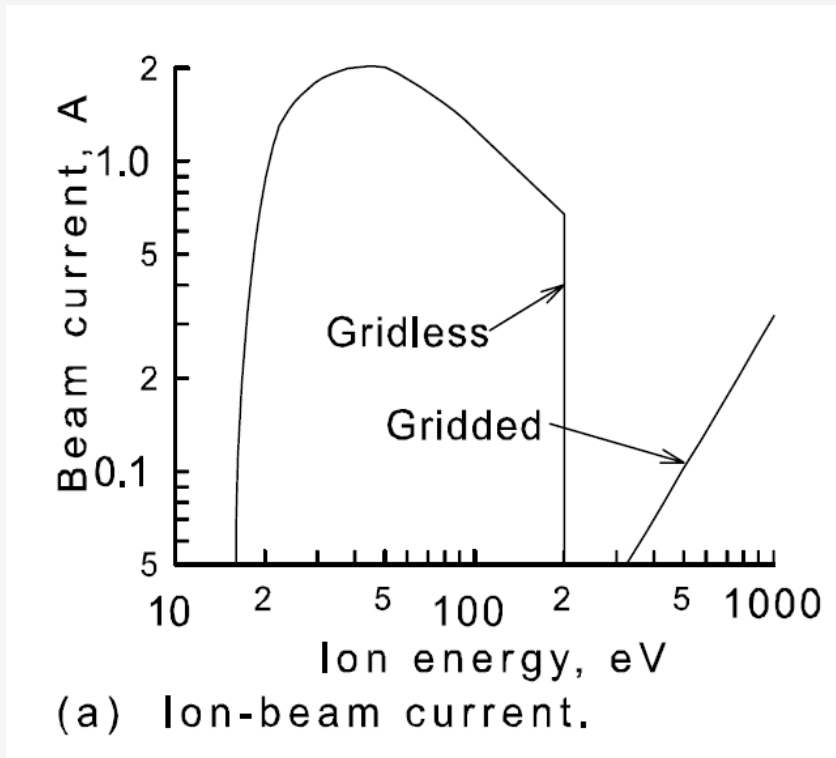
#### The Microwave Linear ECR (2.45 GHz) :



## Other ion sources - Ions for the industry

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

The industrial broad beam "gridless":



**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 separating 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":



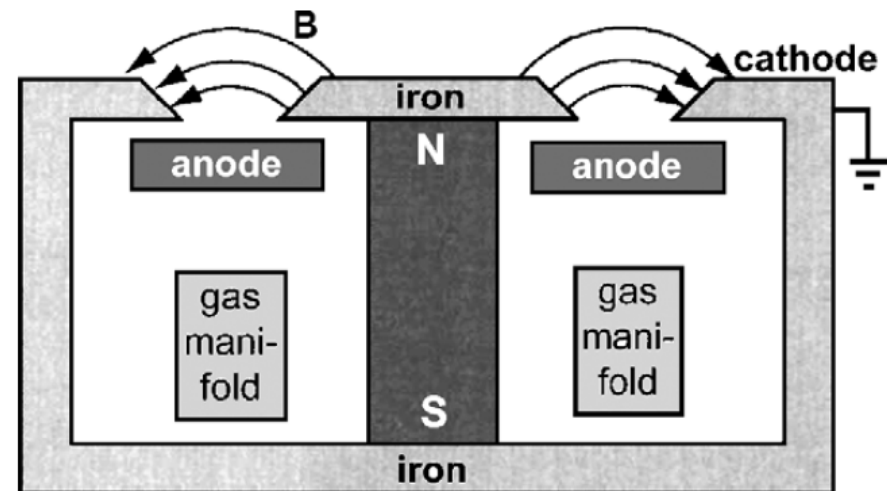
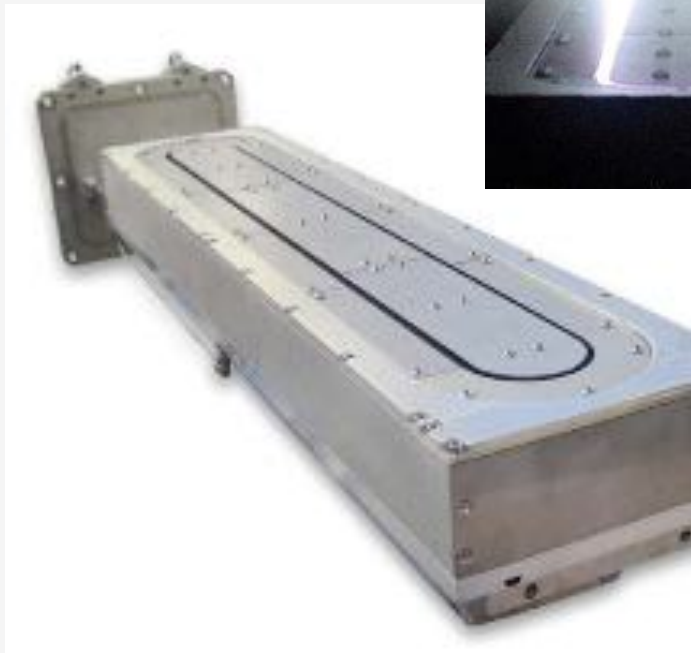
## Other ion sources - Ions for the industry

### 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

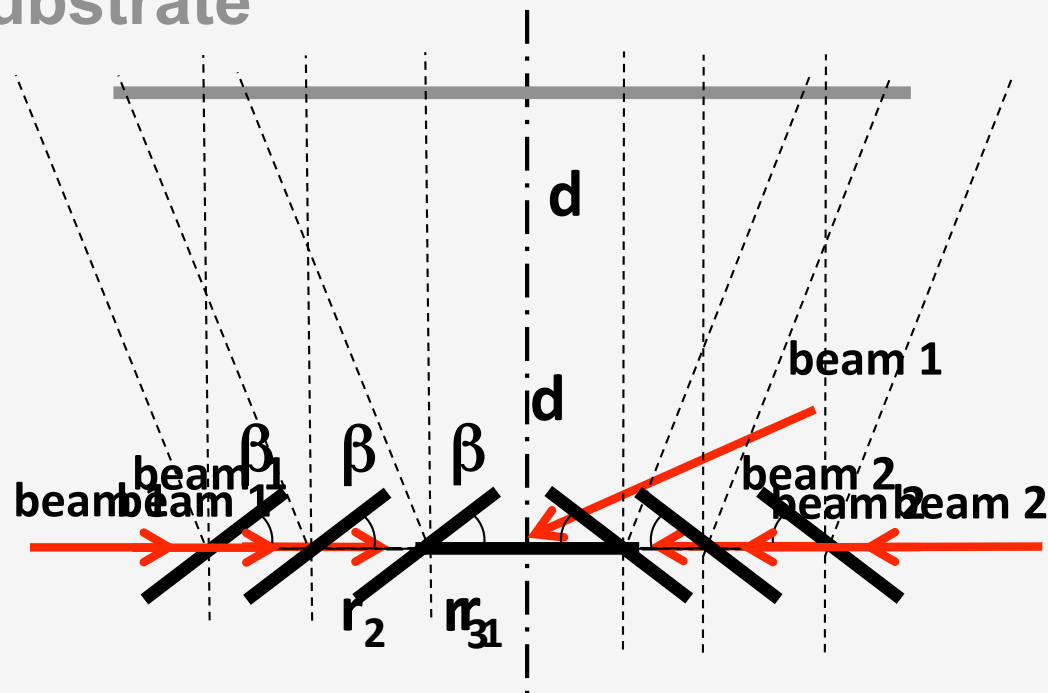


## Other ion sources - Ions for the industry

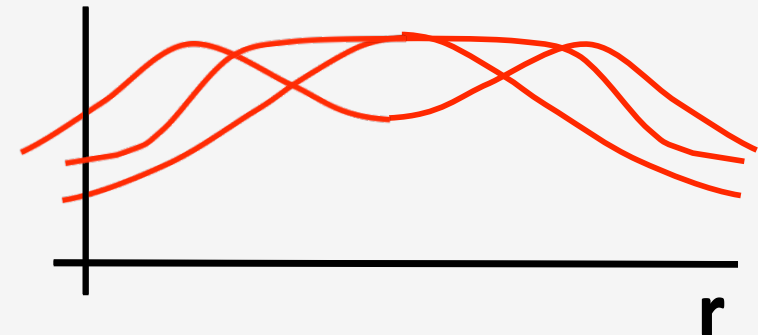
### 3 - Broad Beam & "Ionic Machine" for the Industrial Coating

The Principle of multi beam devices :

Substrate

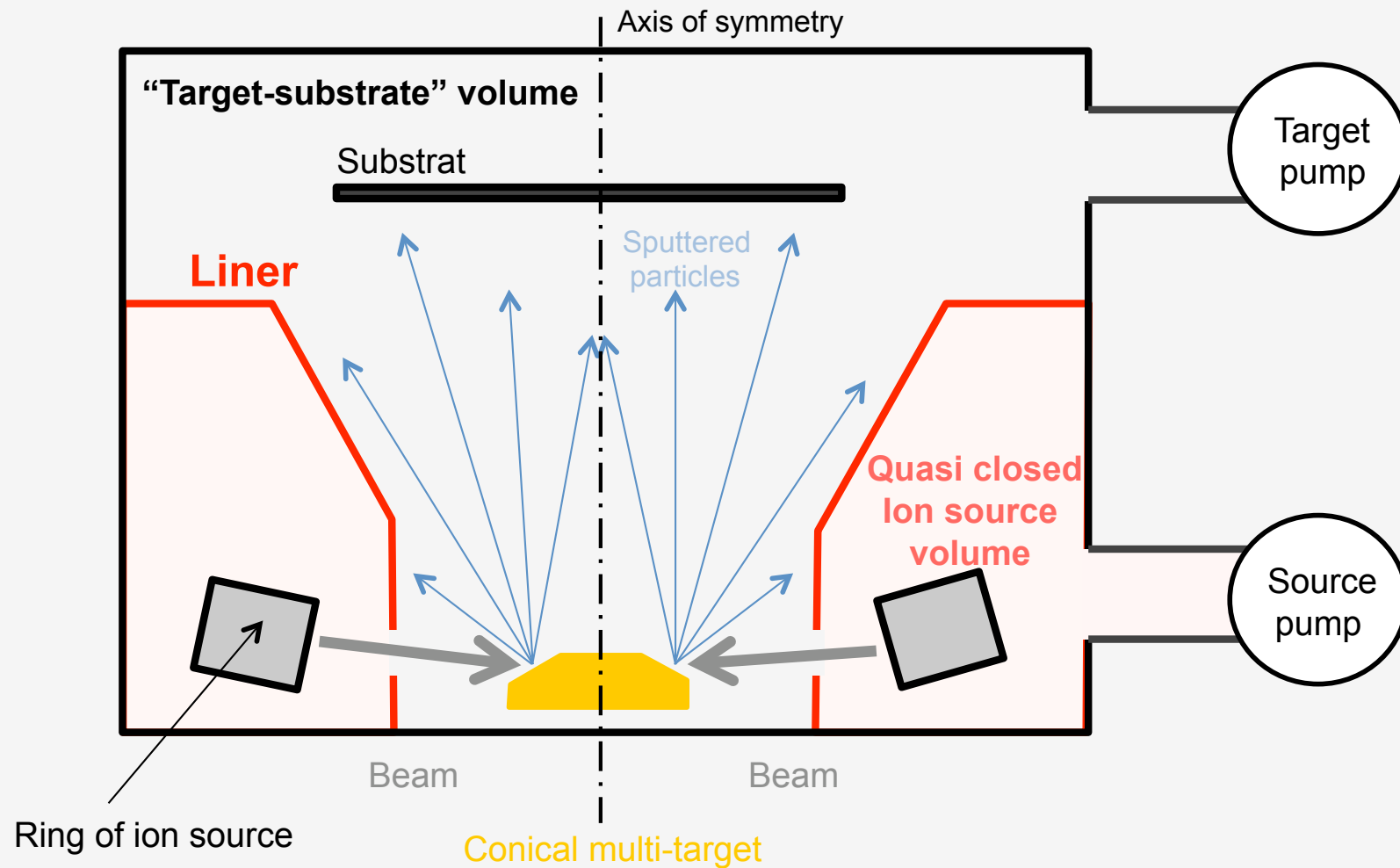


Flux on the substrate



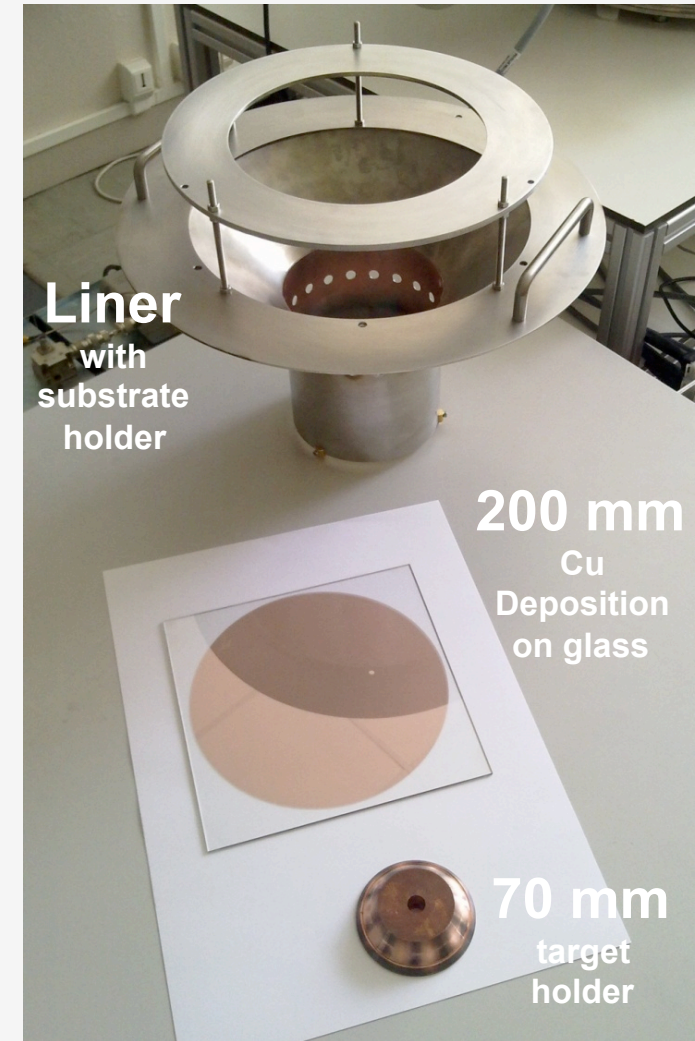
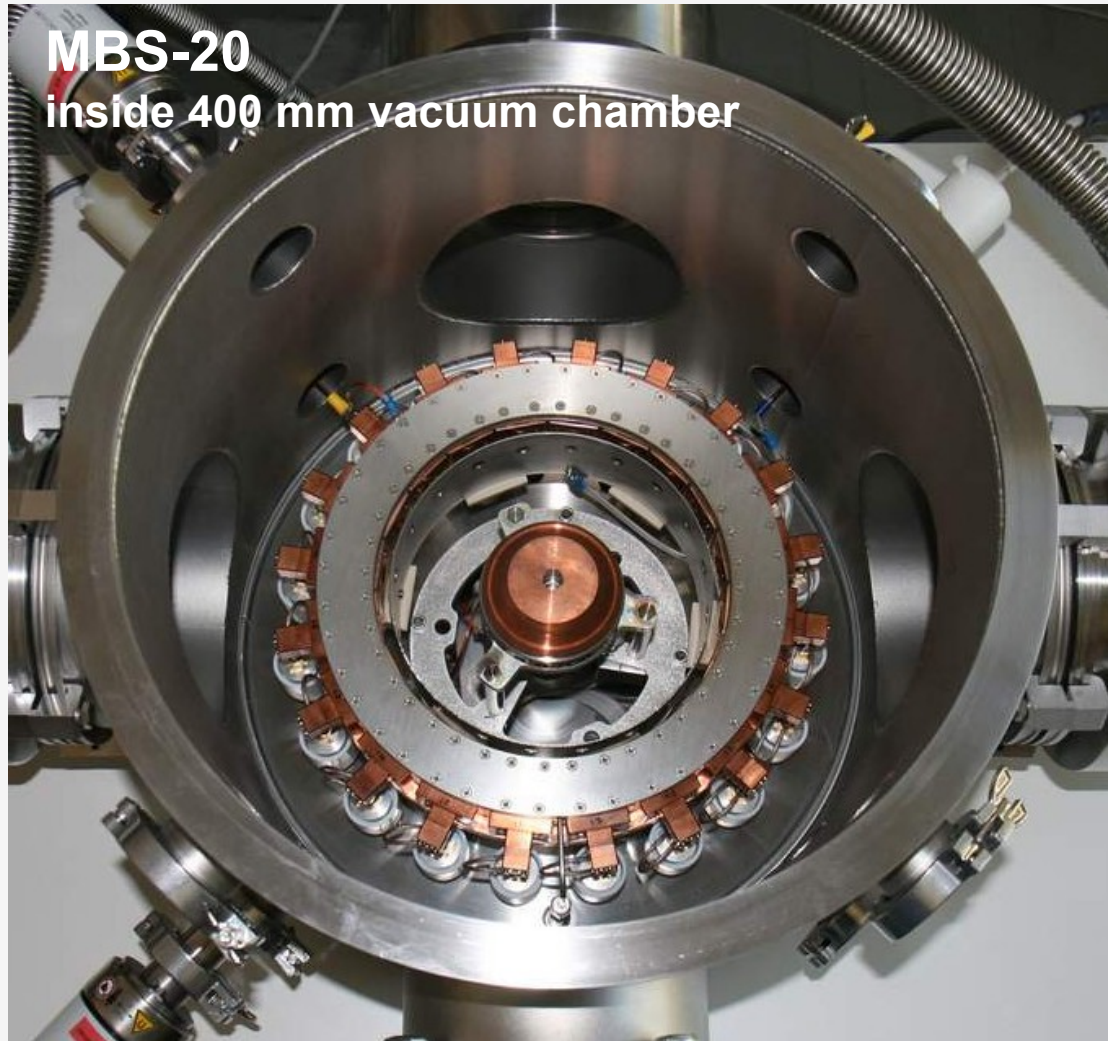
# Other ion sources - Ions for the industry

## 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

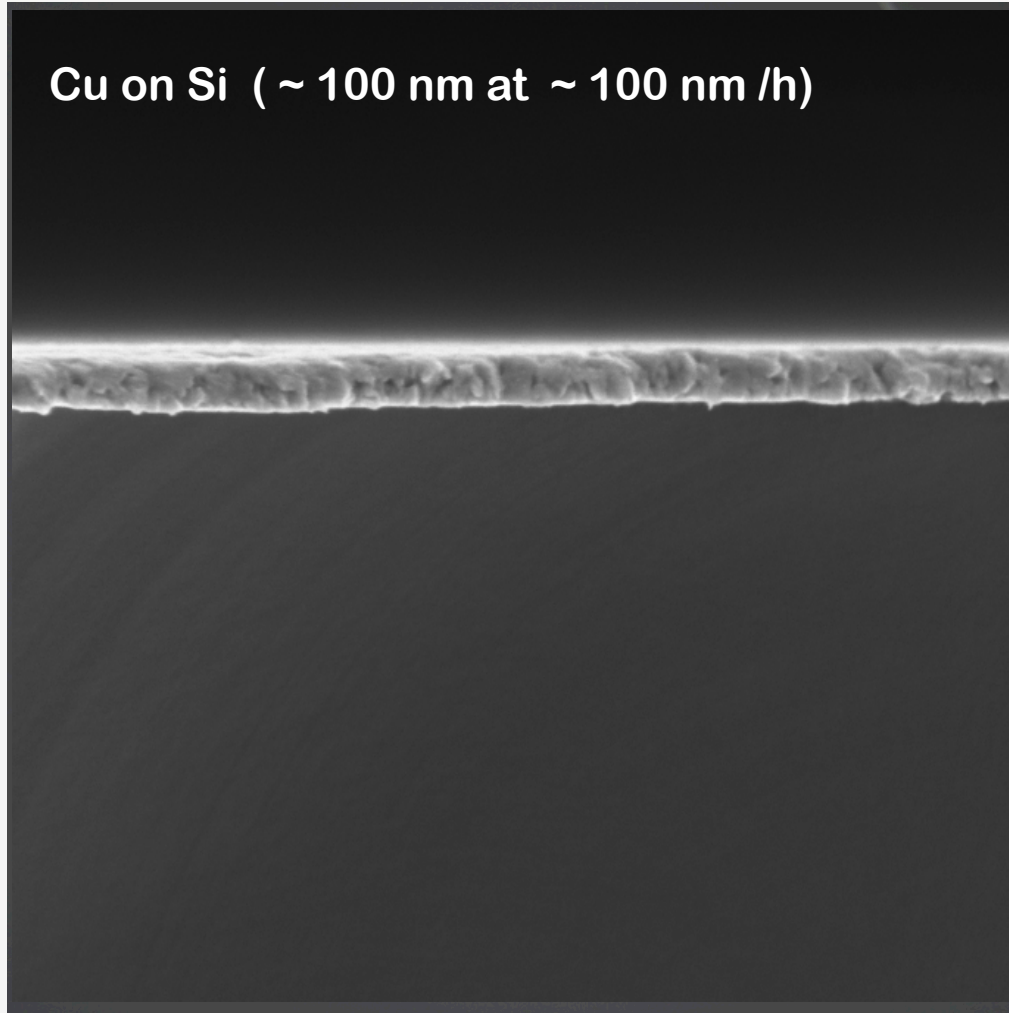




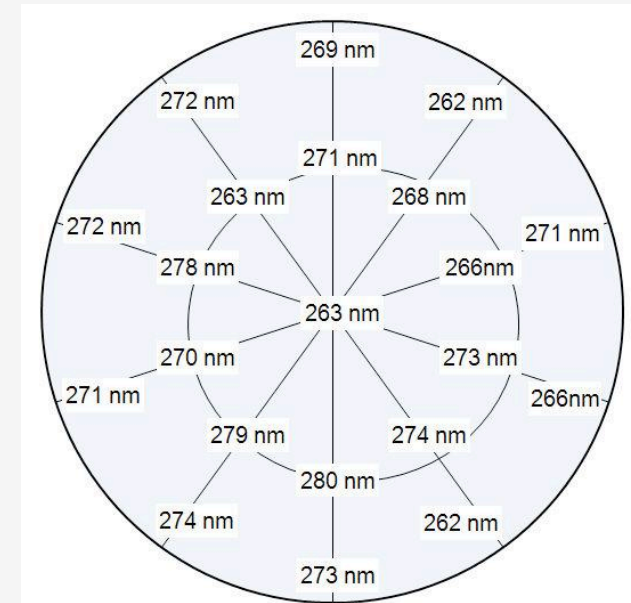
## Other ion sources - Ions for industry

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

146 mm



100 mm



263 +/- 7 nm

Profilometer measurements

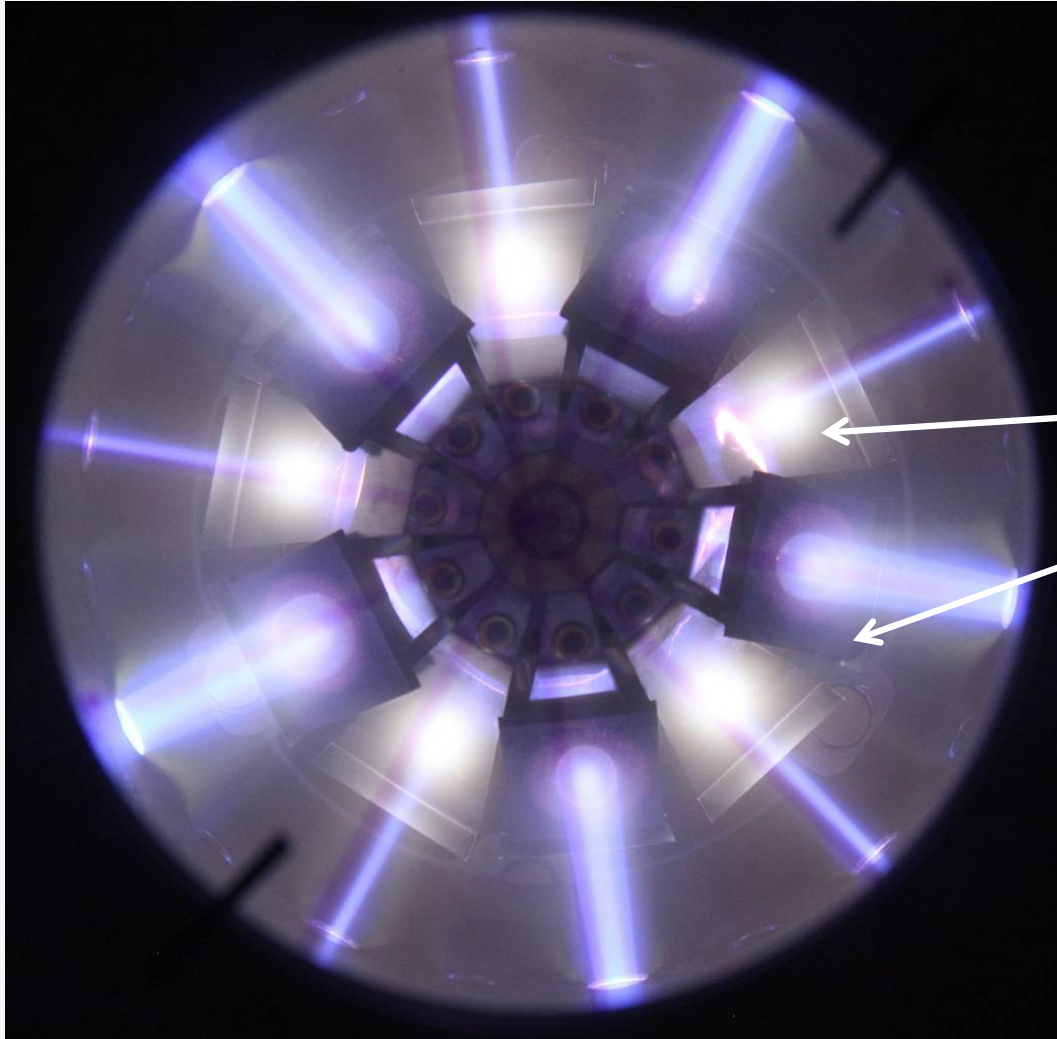
*Static substrate*

*Ta<sub>2</sub>O<sub>5</sub> on Silicium*

*(Ta target under O<sub>2</sub>)*

## Other ion sources - Ions for the industry

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

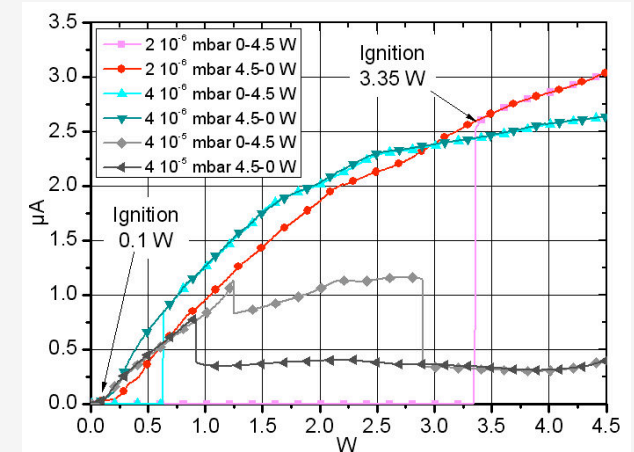


Multi beam (10)

Multi target (Ta and C)

Multi current (25 and 500  $\mu\text{Ae}$ )

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.*

- **2 - High Intensity Beams for *MicroElectronics***

*Knowhow for high intensity transportation  
(beam line feeded with plasma)*

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

*Multi beam machine for beam merging*