# Nanometer Scale Patterning and Processing

Spring 2016

## Lecture 23

## Nanofabrication with Focused Ion Beams – Overview & Ion Source and Optics

Only a small portion is lithography

# Nanofabrication with Focused Ion Beams

ECE 695, Spring 2016

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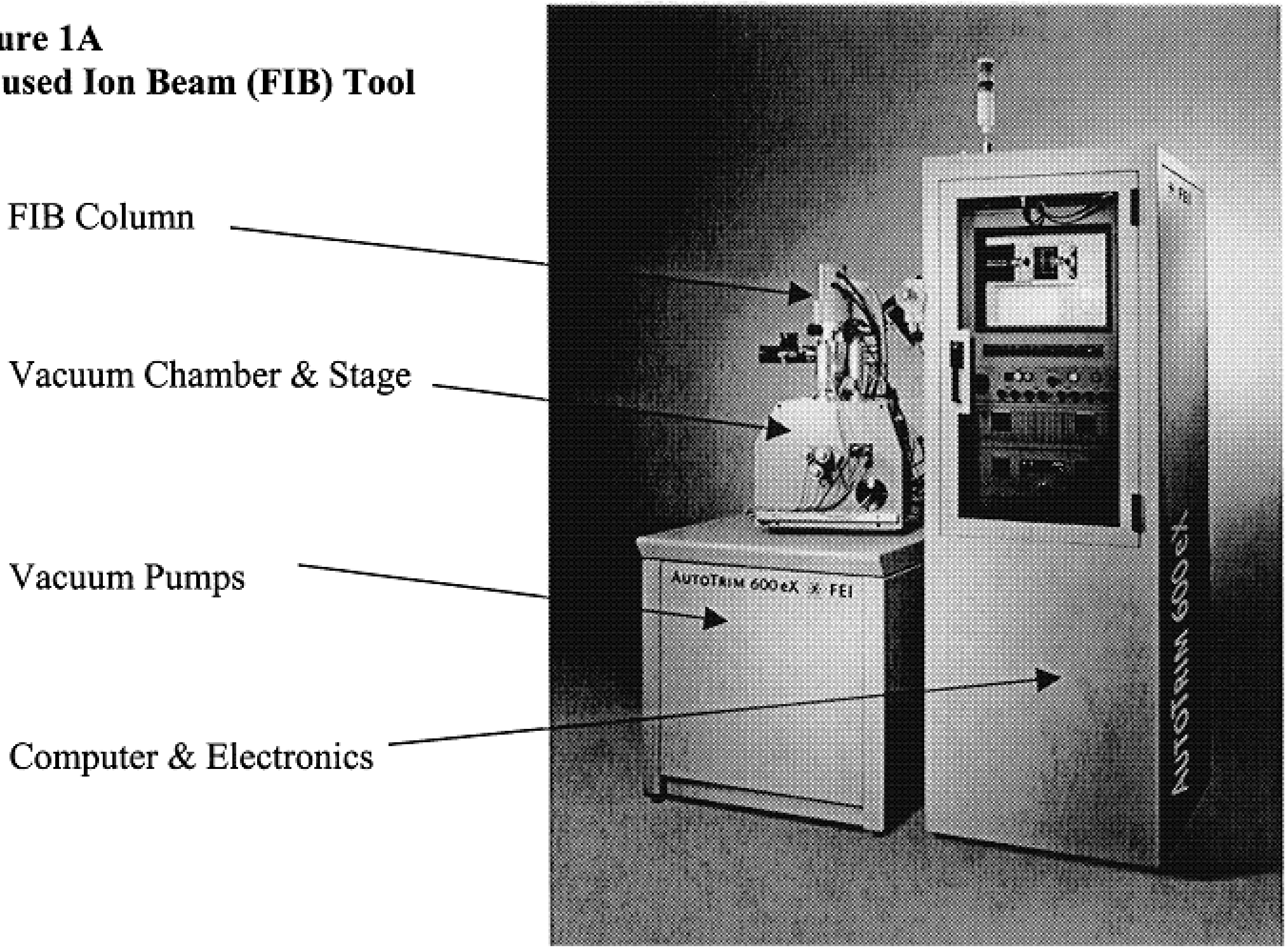
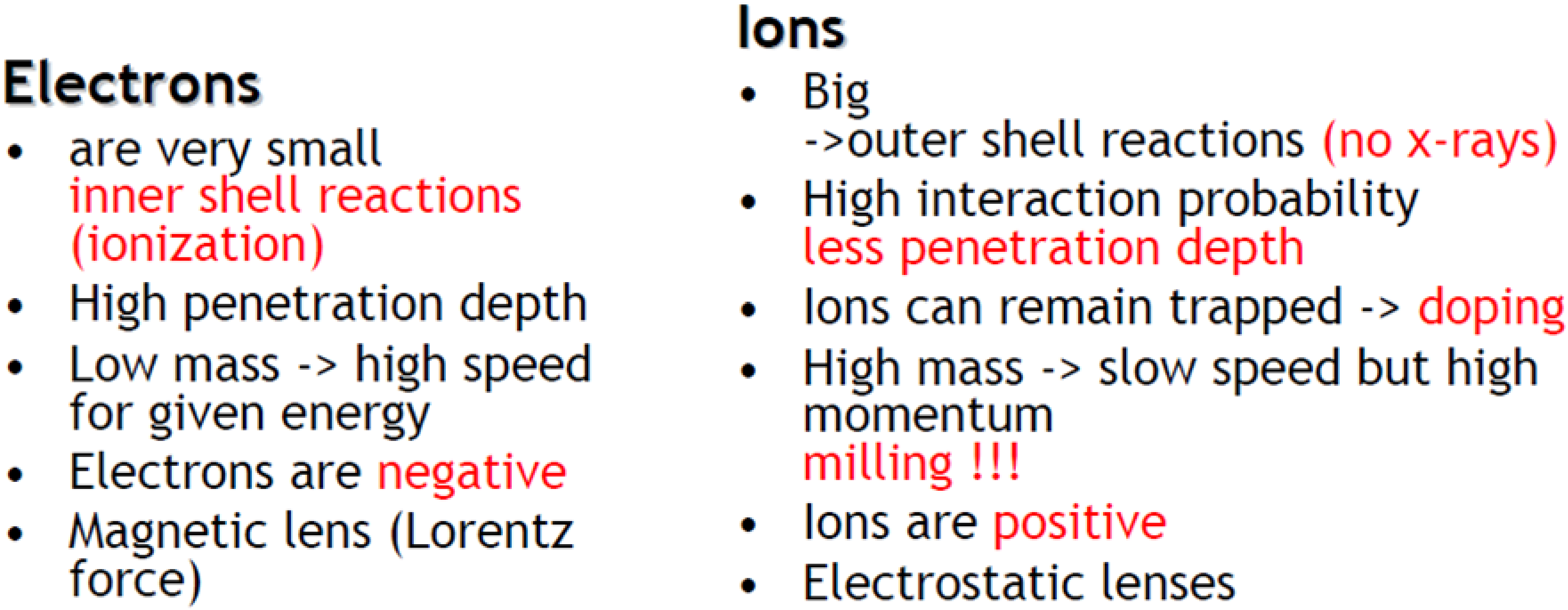
# An Early Focused Ion Beam Tool

**Figure 1A**
**Focused Ion Beam (FIB) Tool**



Resolution vs throughput
Unique capabilities

# Electrons vs Ions



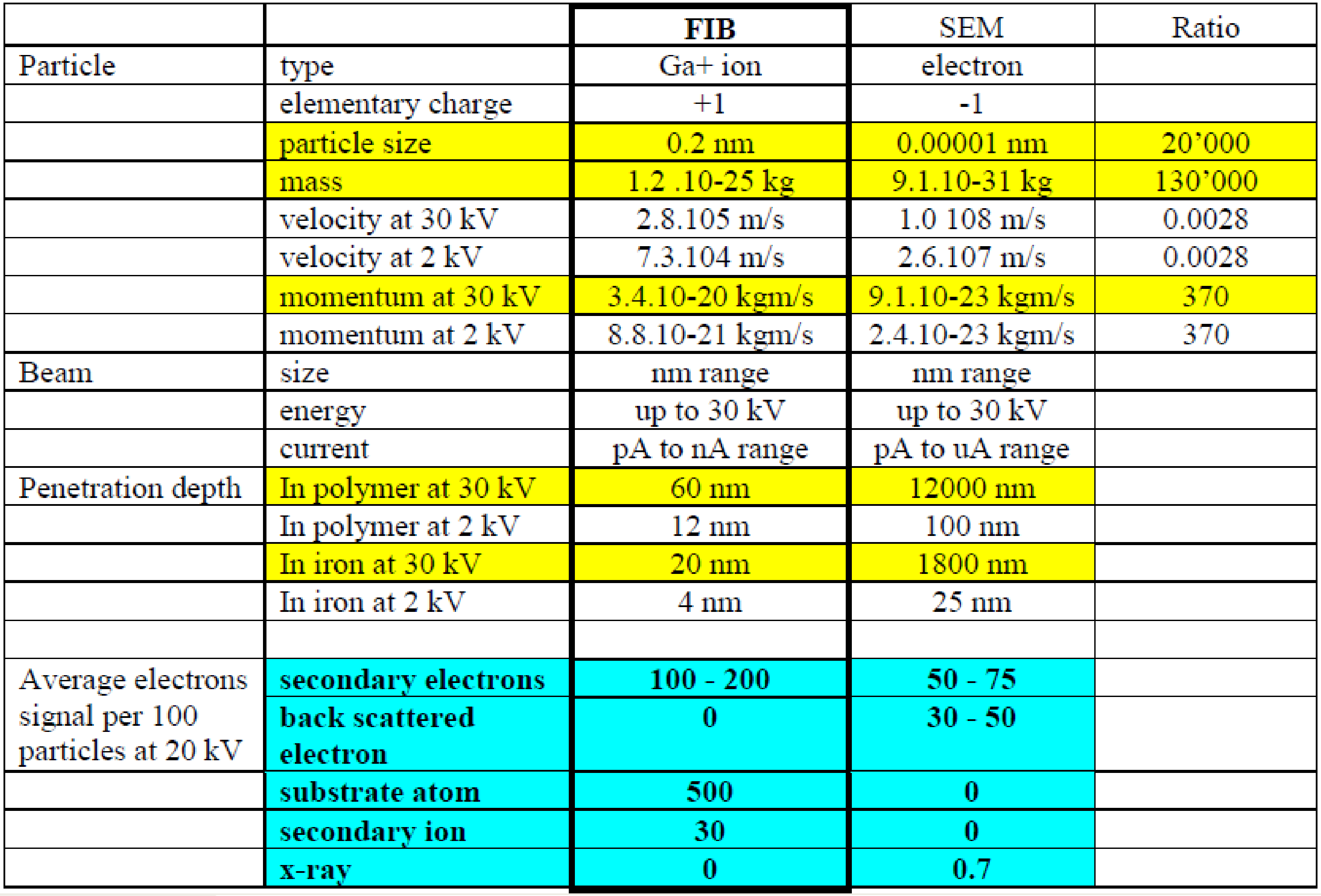
**Electrons**

- are very small
  inner shell reactions (ionization)
- High penetration depth
- Low mass -> high speed for given energy
- Electrons are negative
- Magnetic lens (Lorentz force)

**Ions**

- Big
  ->outer shell reactions (no x-rays)
- High interaction probability
  less penetration depth
- Ions can remain trapped -> doping
- High mass -> slow speed but high momentum
  milling !!!
- Ions are positive
- Electrostatic lenses

# Electrons vs Ions: More Detailed comparison

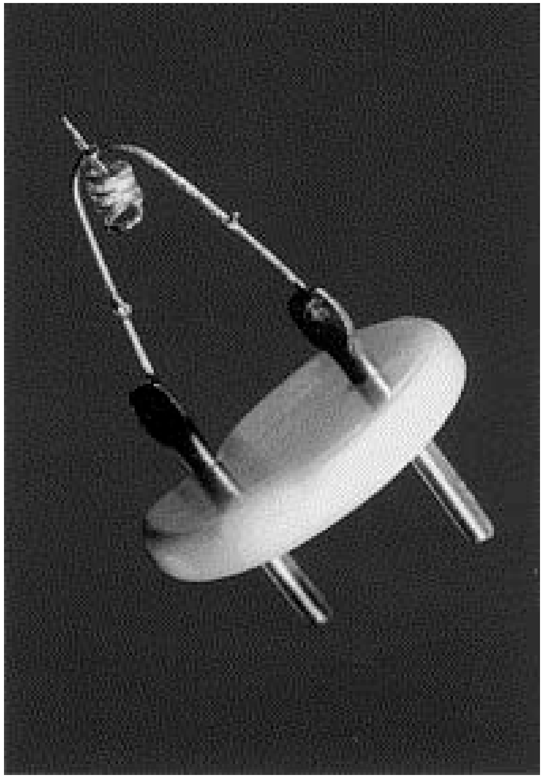


| | | **FIB** | SEM | Ratio |
|---|---|---|---|---|
| Particle | type | Ga+ ion | electron | |
| | elementary charge | +1 | -1 | |
| | particle size | 0.2 nm | 0.00001 nm | 20’000 |
| | mass | 1.2 .10-25 kg | 9.1.10-31 kg | 130’000 |
| | velocity at 30 kV | 2.8.105 m/s | 1.0 108 m/s | 0.0028 |
| | velocity at 2 kV | 7.3.104 m/s | 2.6.107 m/s | 0.0028 |
| | momentum at 30 kV | 3.4.10-20 kgm/s | 9.1.10-23 kgm/s | 370 |
| | momentum at 2 kV | 8.8.10-21 kgm/s | 2.4.10-23 kgm/s | 370 |
| Beam | size | nm range | nm range | |
| | energy | up to 30 kV | up to 30 kV | |
| | current | pA to nA range | pA to uA range | |
| Penetration depth | In polymer at 30 kV | 60 nm | 12000 nm | |
| | In polymer at 2 kV | 12 nm | 100 nm | |
| | In iron at 30 kV | 20 nm | 1800 nm | |
| | In iron at 2 kV | 4 nm | 25 nm | |
| | | | | |
| Average electrons signal per 100 particles at 20 kV | **secondary electrons** | **100 - 200** | **50 - 75** | |
| | **back scattered electron** | **0** | **30 - 50** | |
| | **substrate atom** | **500** | **0** | |
| | **secondary ion** | **30** | **0** | |
| | **x-ray** | **0** | **0.7** | |

# Focused ion beam (FIB)

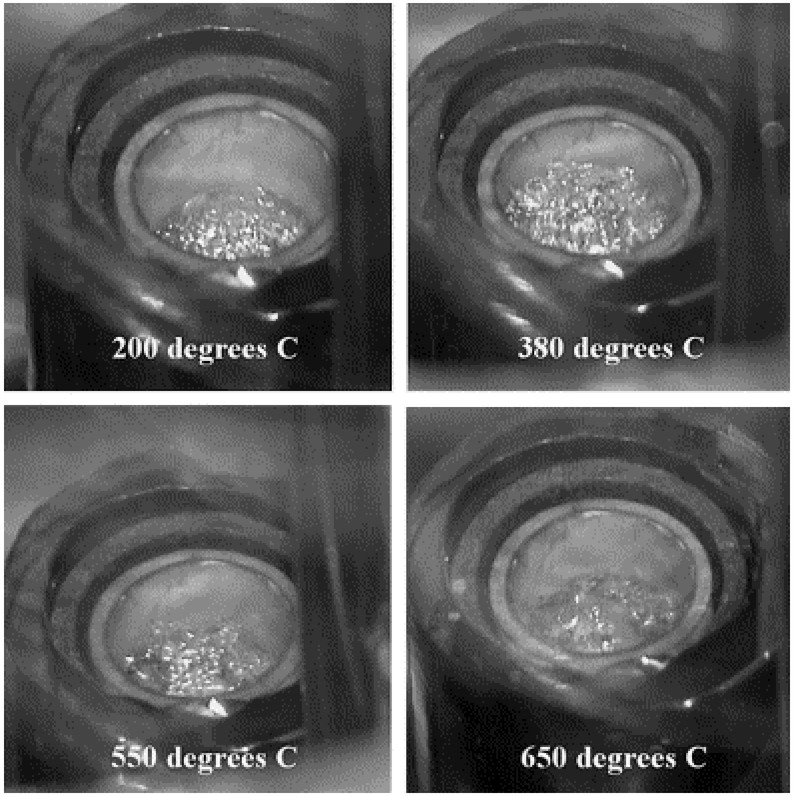
1. Overview.
2. Ion source and optics.
3. Ion-solid interaction, damage.
4. Scanning ion beam imaging.

# Liquid Metal Ion Source (LMIS)



Picture of W tip coated with metal

Field induced ionization (electrons are repelled, and positive ions are extracted)

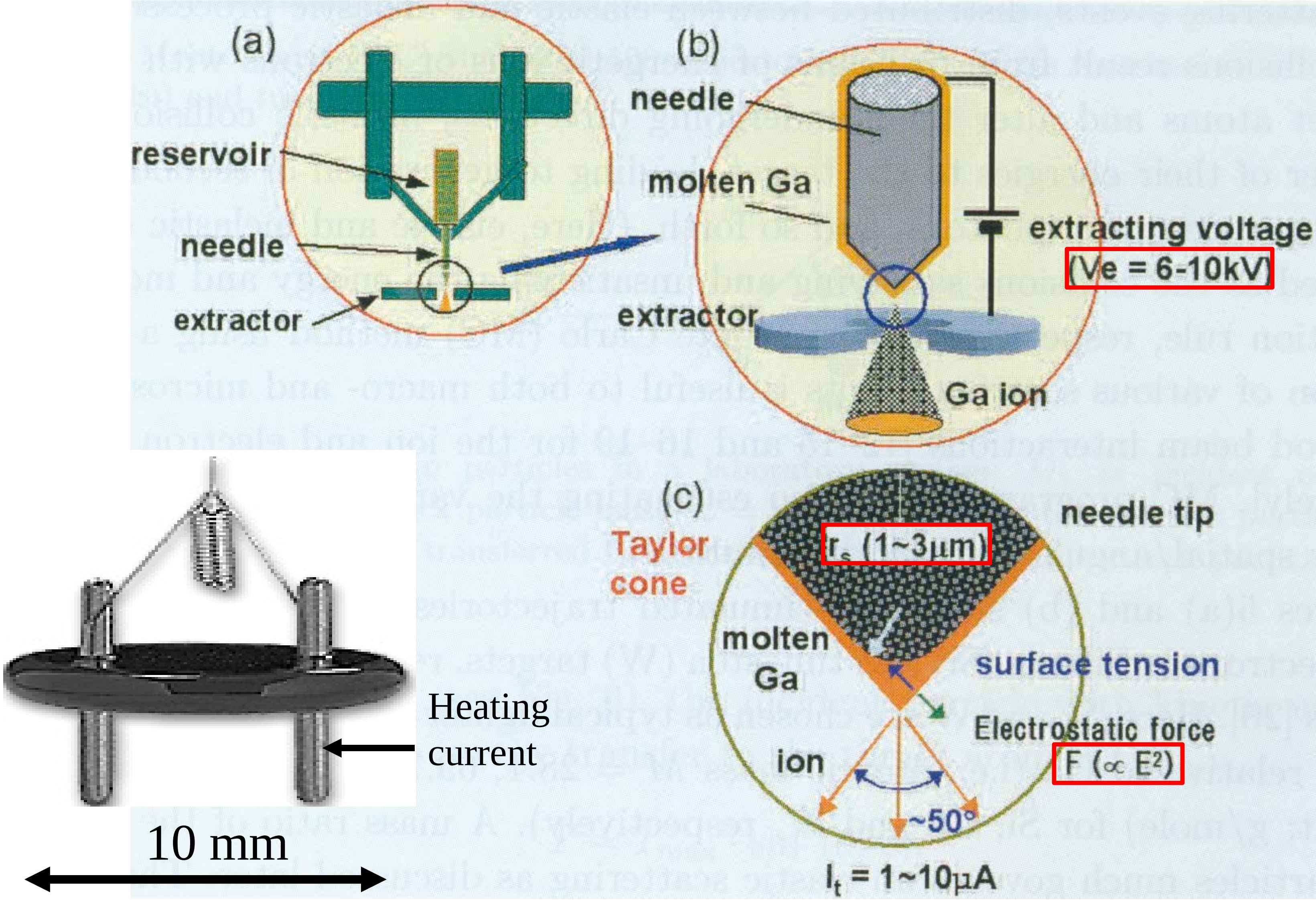


Crucible with melted metal alloys,

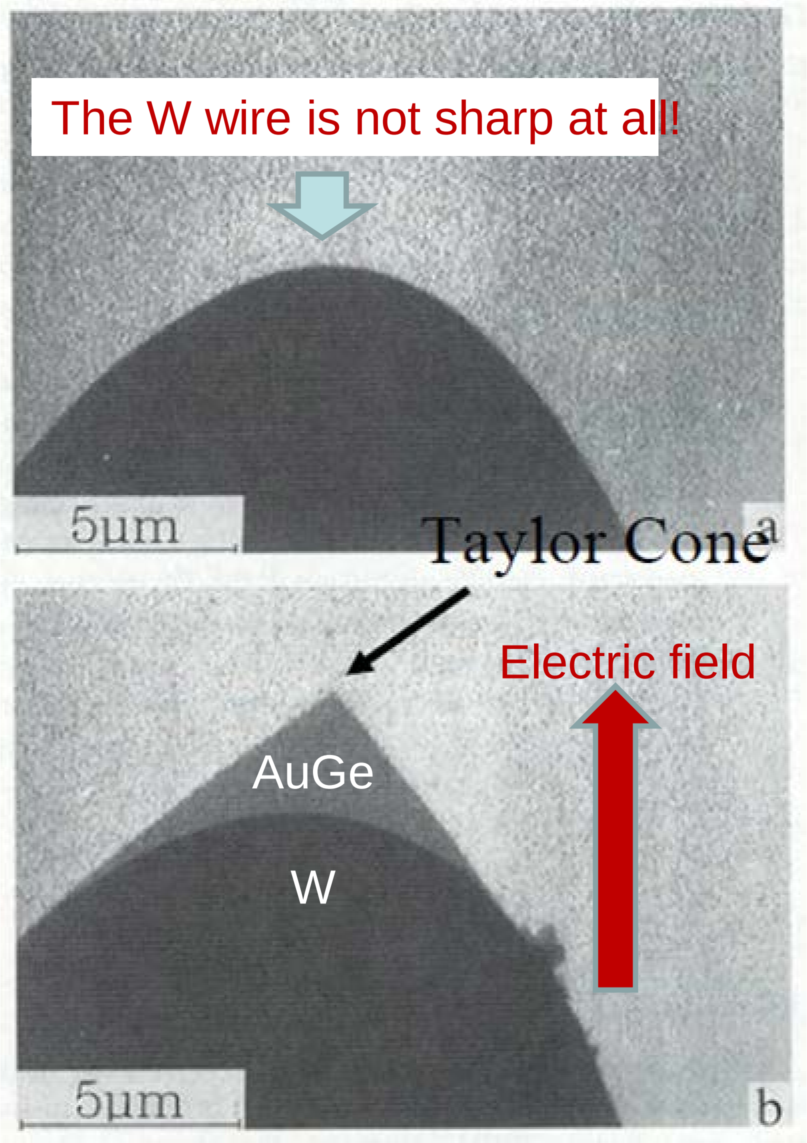
W tips dip into the metal melt.

Ge, Si, B, Be, GeMn, GeAs, AuSi, PtB, AuBeSi, Pt

# Field Induced Ionization



# Formation of the very Sharp Taylor Cone



LMIS emitter substrate

The W wire is not sharp at all!

But the "Taylor" cone of the liquid metal induced by electric field is very sharp.

As a result, electric field at cone apex is very high for field emission.

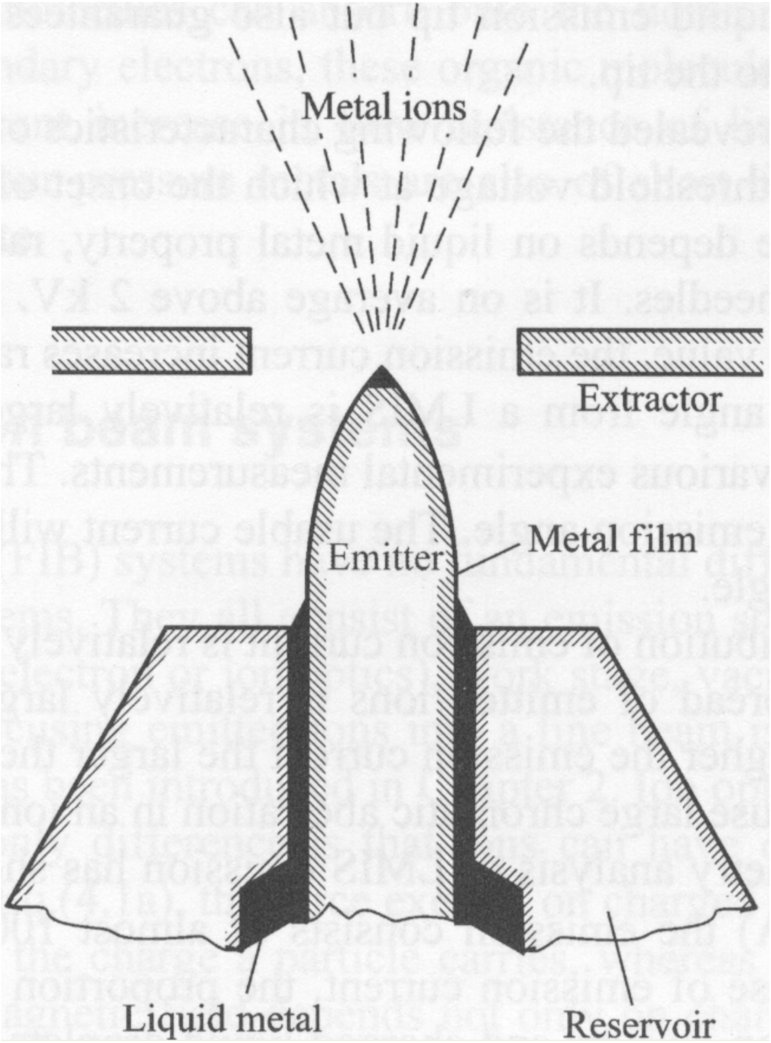
LMIS emitter substrate with AuGe Taylor cone

Driesel W, Dietzsch C, Muhle R, J. Vac. Sci. Technol. B, 14, 3367(1996)

# Characteristics of LIMS

Experiment has shown the following.

- There exists a threshold voltage (~2kV) for ion emission.
- The emission angle is large, around $30^o$.
- The angle distribution of emission current is rather uniform.
- Energy spread of emitted ions is large, ~15V, leading to large chromatic aberration in an ion optical system.
- At current <10μA, almost 100% ions are single charged.



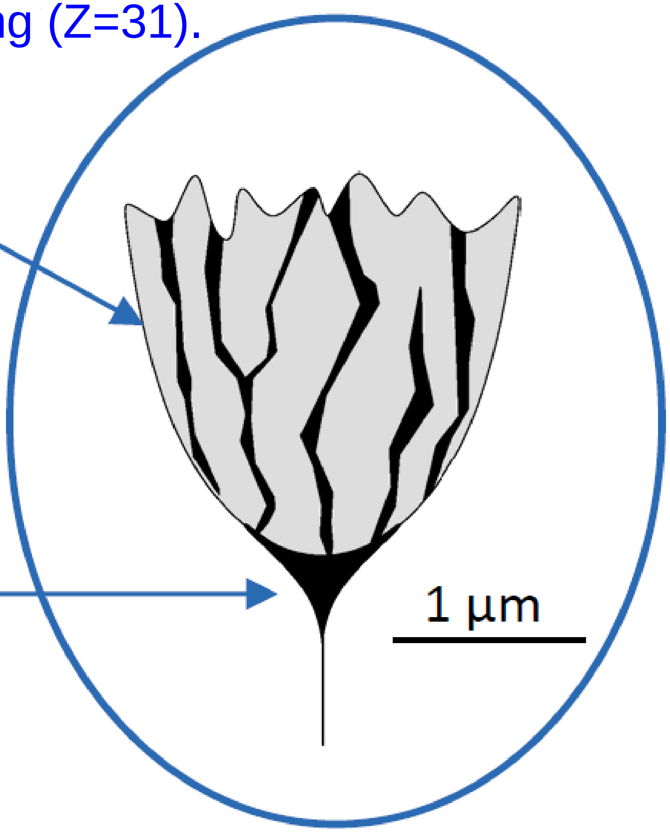
# Why $Ga^+$

- Melting point at 30°C → liquid around room temperature.
- Low vapor pressure → applicable in high vacuum.
- $[Ga^{2+}]/[Ga^{+}] \sim 10^{-4}$ at 10μA → narrow energy distribution.
- Long life (up to 1500 hr sources).
- Heavy ion for sputtering (Z=31).

$He^+$

$m=2$

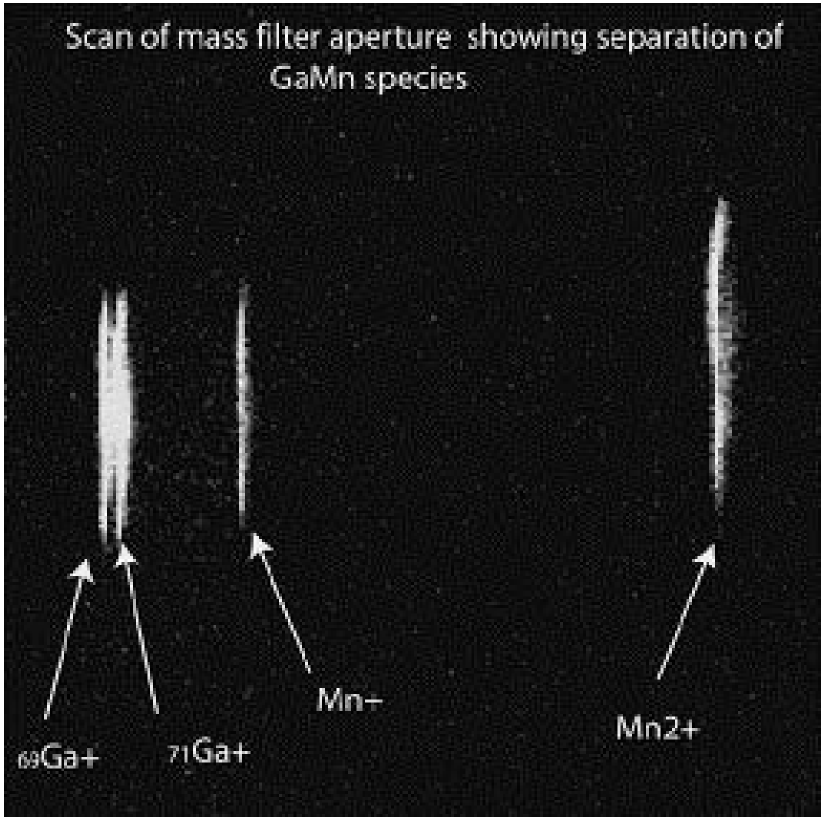
$Z=2$



Blunt W with *grated* surface for Ga transport

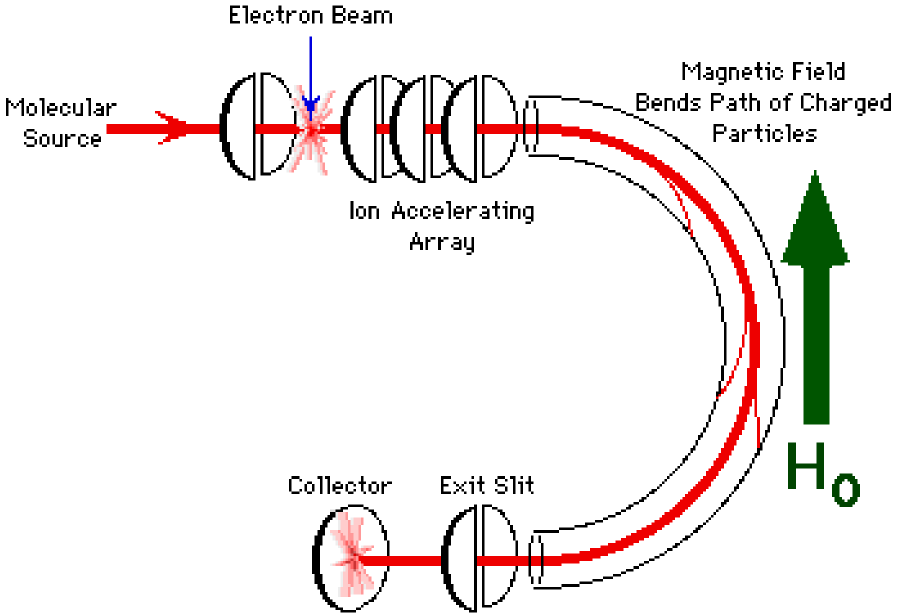
Ga forms a Taylor-Gilbert cone

# Different Ions can be separated from alloys

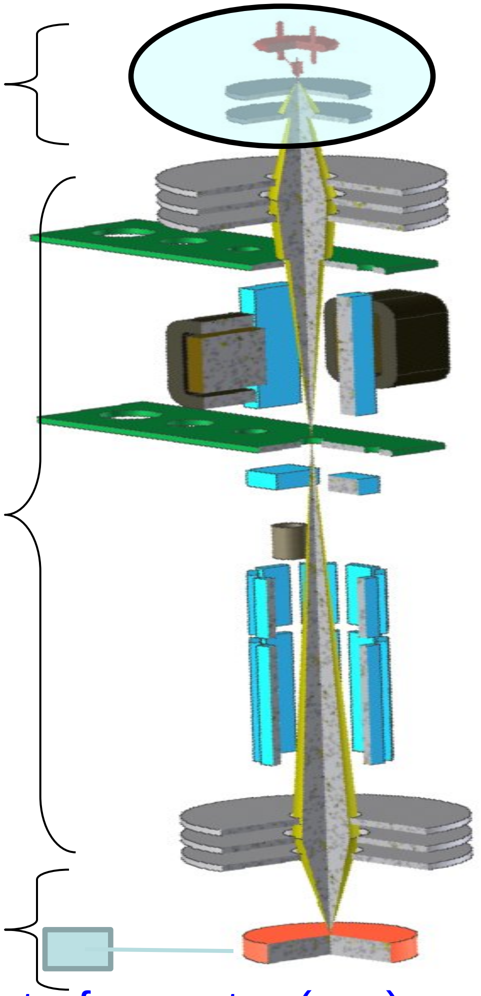


Based on e/m ratio

Similar to mass spectroscopy



# Electro-Optic Column



Gun with LMIS ion source

Ion optics

Chamber

Ion source

Extraction electrodes

Accelerator (10-200 kV)

Condensor lens

Ion current selection aperture

Wien filter (Mass spectrometer)

Mass selection aperture

Blanking plates

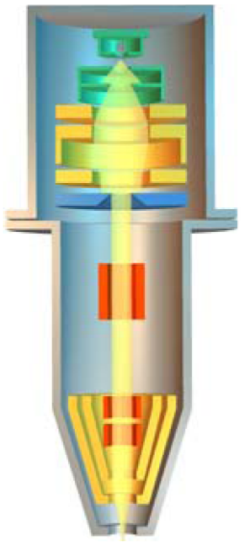
Faraday cup

Scanning and Stigmation octupole

Electrostatic objective lens

Sample stage (z, R, and tilt)

Laser Interferometer (x, y)



*Suppressor & LMIS*

*Extractor Cap*

*Beam Acceptance Aperture*

*Lens 1*

*Beam Defining Aperture*

*Beam Blanking*

*Deflection Octopole*

*Lens 2*

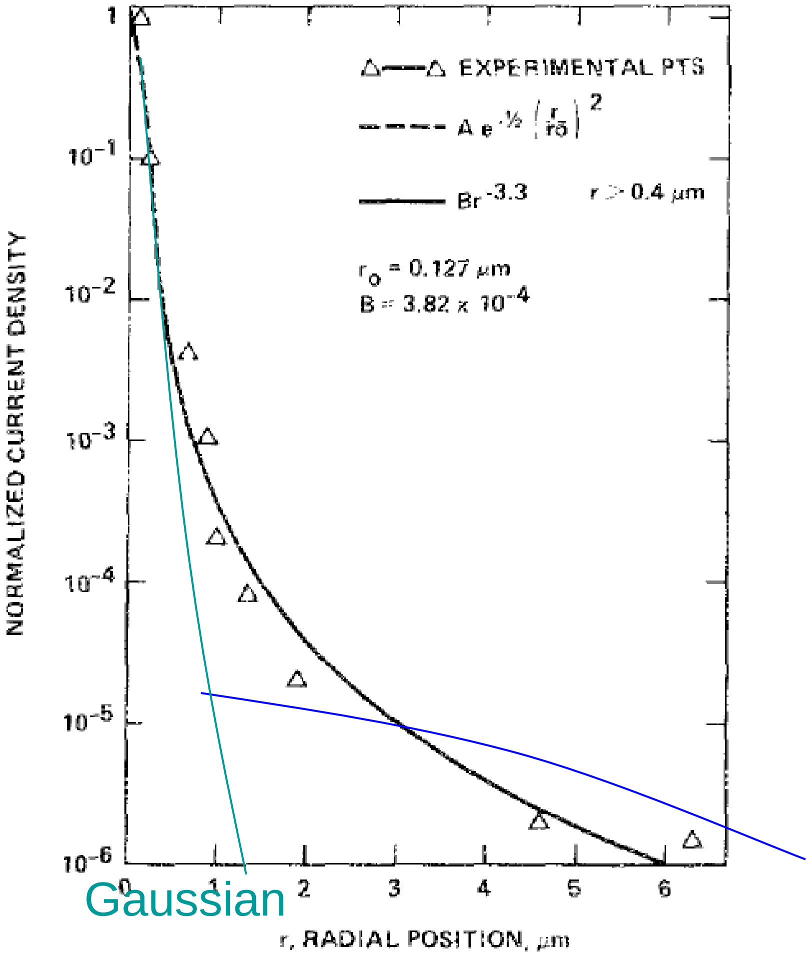
Newer dual beam column focuses both electrons and positive ions

Magnetic lenses have little effect on heavy ions

# Electrostatic Lenses

- Much stronger focusing effect for heavy ions.
- Chromatic and spherical aberration coefficients 7-10 times larger than magnetic lenses (focusing effect relies on fine shape of the electrode).
- Divergence angle < $10^{-4}$ rad ($10^{-2}$ rad for electrons).
- Fast focus and stigmation adjustment are limited
- Not optimal for lithography! (high resolution, large-deflection field, placement accuracy, uniformity, etc.)

# Beam spot size of Focused Ions



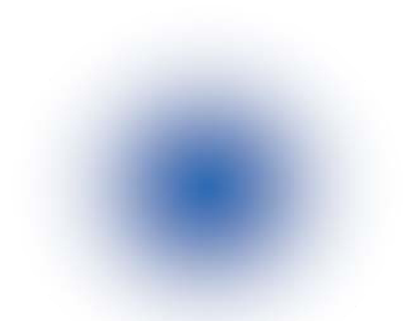
Gaussian

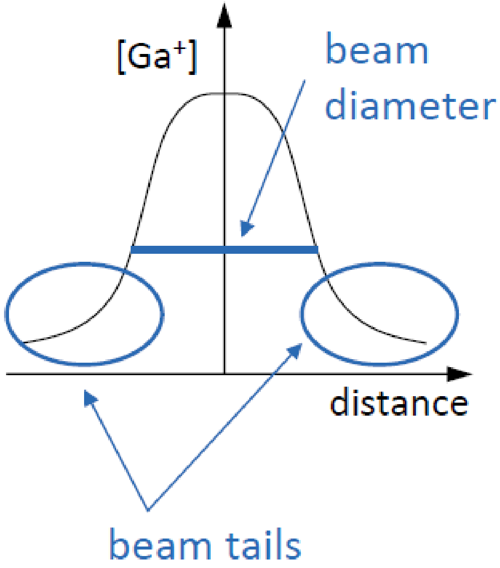
Second Gaussian in e-beam lithography

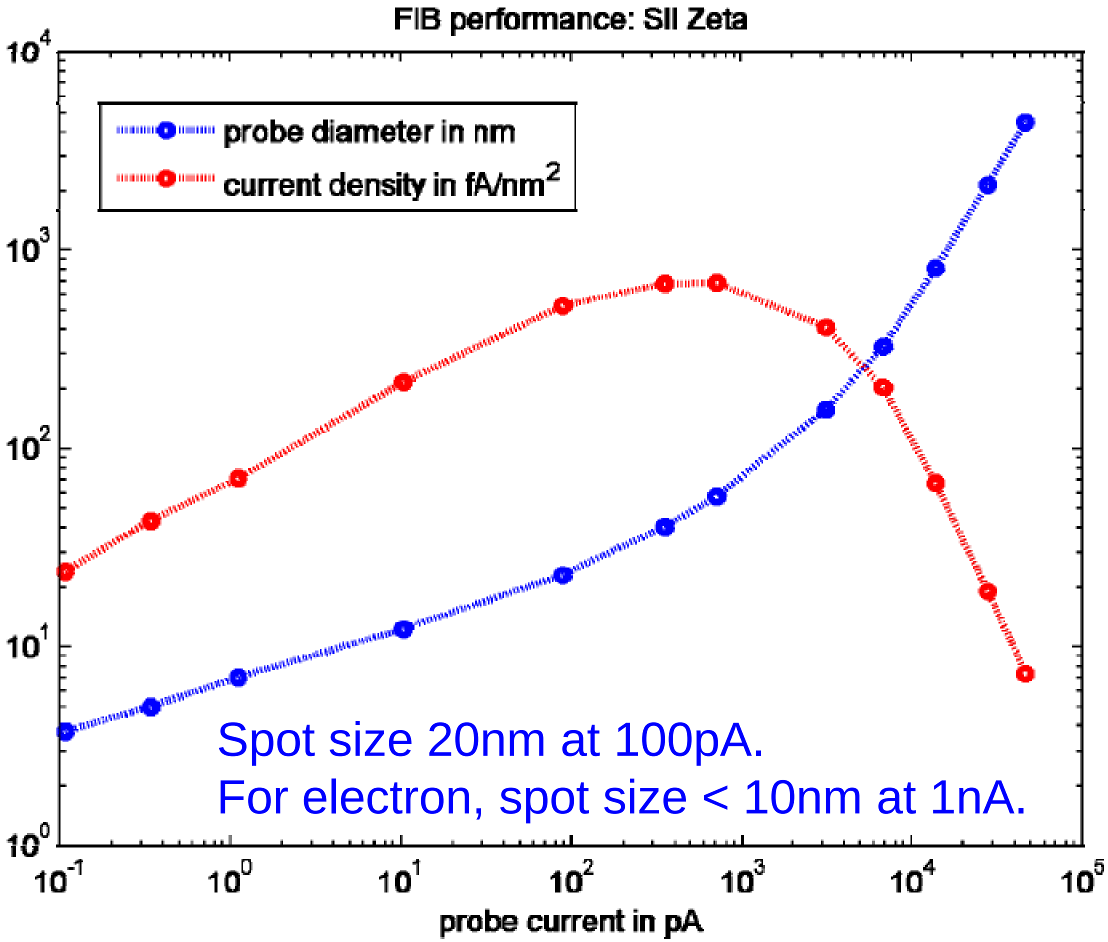
- Broader than Gaussian distribution
- Limits the resolution

Ward, et. al. J. Vac. Sci. Technol. B Vol 5, p167, (1987).

# Beam size vs. current







Spot size 20nm at 100pA.
For electron, spot size < 10nm at 1nA.

- Source spot size is about 50nm (fixed).
- Small aperture → small beam current (slow) and narrow beam (high resolution). Need a tradeoff.
- Beam tails can extend up to some μm, is one limiting factor when milling deep high aspect ratio (depth/width) trenches/holes (the other factor is re-deposition of sputtered material).

# Ion optics: overview

- Similar to electron optics.
- But use only electrostatic lens and deflectors to focus and deflect ion beam, because for magnetic lens (though they have superior optics):
  - o The focusing plane depends on mass/charge ratio.
- There is not much room for improvement in electrostatic lens performance given that working distances must remain ≥ 10 mm to allow room for gas injectors etc.
- Large energy spread (5-15eV) and thus large chromatic aberration.
- Enlarged focused ion beam.
- State-of-the-art FIB has focal spot size below 5nm at current of few pA.
- At medium current (60pA, 1mrad), chromatic aberration ($=C_c \cdot \alpha \cdot dE/E$) dominates.
- At large current (5nA, 10mrad), spherical aberration ($=0.5Cs \cdot \alpha^3$) dominates.

$F_e = qE$ Force independent of m, same for electron and ion.

$F_m = qv \times B$ v is speed, much smaller for ions than for electrons; so much smaller force, need impractically large B to focus.

$v = \sqrt{\frac{2qV}{m}}$ V is acceleration voltage.