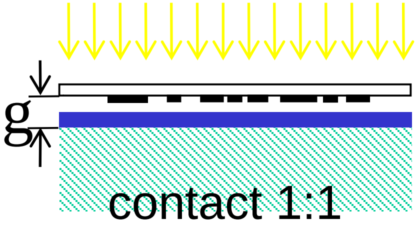
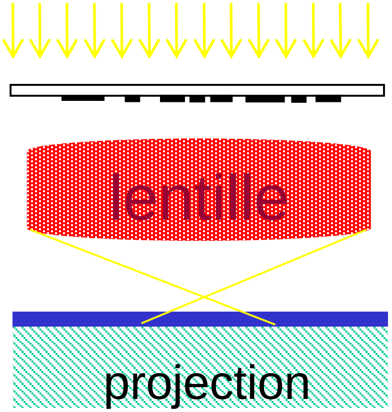
lithography

optical

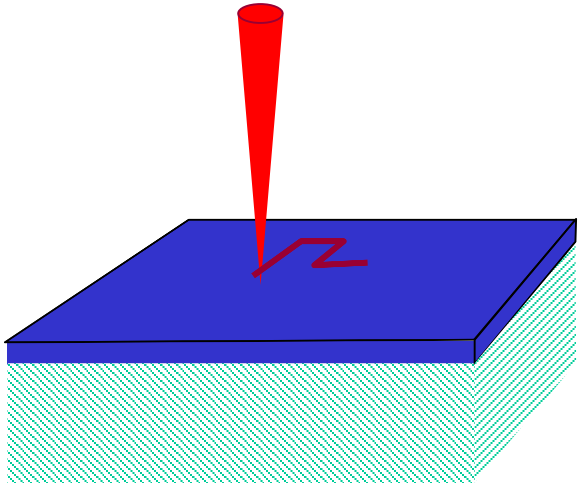


contact 1:1



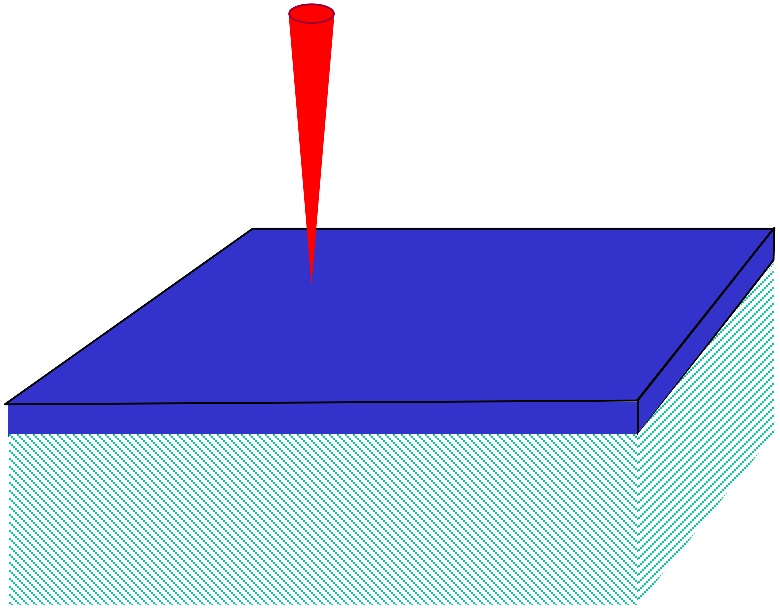
projection
1:5 to 1:20

Focused beam



Nanoimprint
1:1

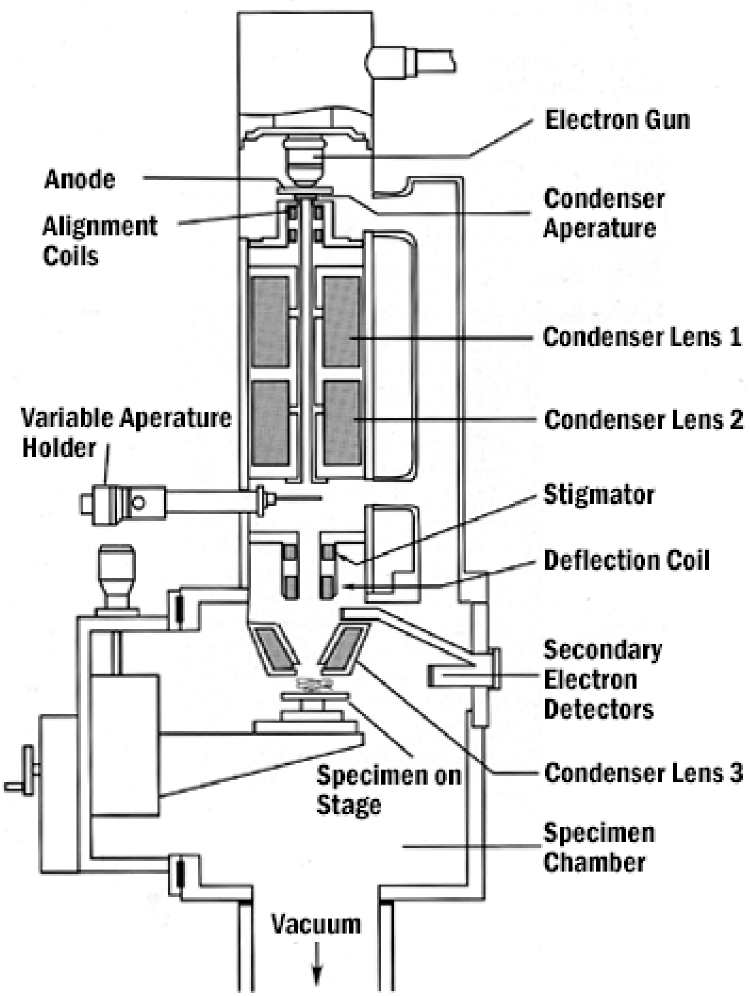
ebeam lithography



- We know how to focalize an electron beam : spot < 10nm
- wave length very small : no limitation due to diffraction
- direct writing: no mask needed
- sequential writing: very slow
- Very high resolution : depending on resist 1nm has been achieved

Electron beams are quite important in nanofabrication since their are also used to observed small samples by electron microscopy. So I will give some overview on focused electron beams.

A standard SEM



Electron gun

Thermo-ionic
Field effect
Schottky

Lens

Lens for demagnifying the source
Lens for focus on the sample
Lens for correcting astigmatism
Lens to scan the sample

Detectors

standard secondary electron detector
in-lens secondary electron detector

Electrons under a potential

An electron under a potential U acquire a speed : $v = \sqrt{2e\,U/m}$

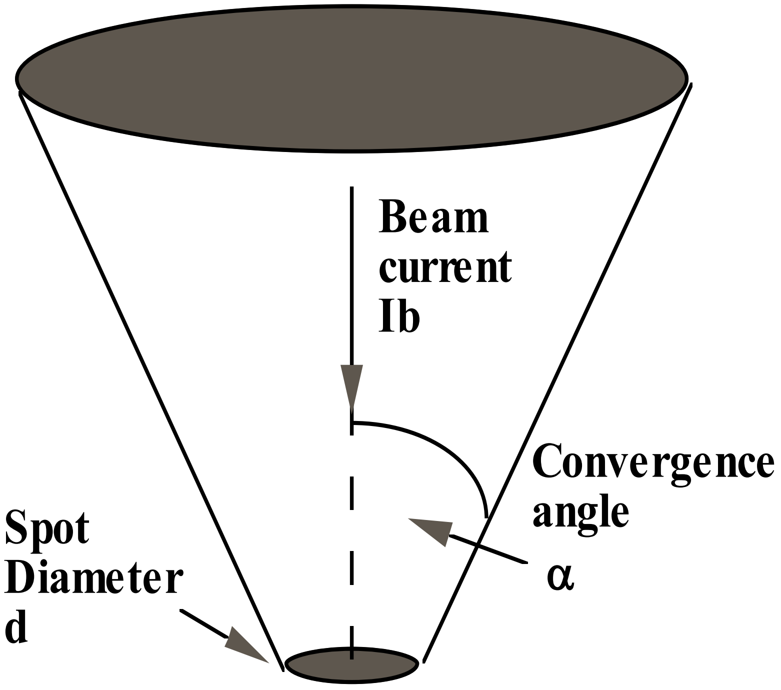
And a wavelength : $\lambda = \frac{h}{p} = \frac{h}{\sqrt{2meU}}$

Voltage kV	Speed km/s	Wavelength nm
1	18760	0,0386
10	59320	0,0122
20	83806	0,0086
50	132600	0,0054
100	187600	0,0037

Above 100kV needs relativitics corrections

Electron sources: source brightness β

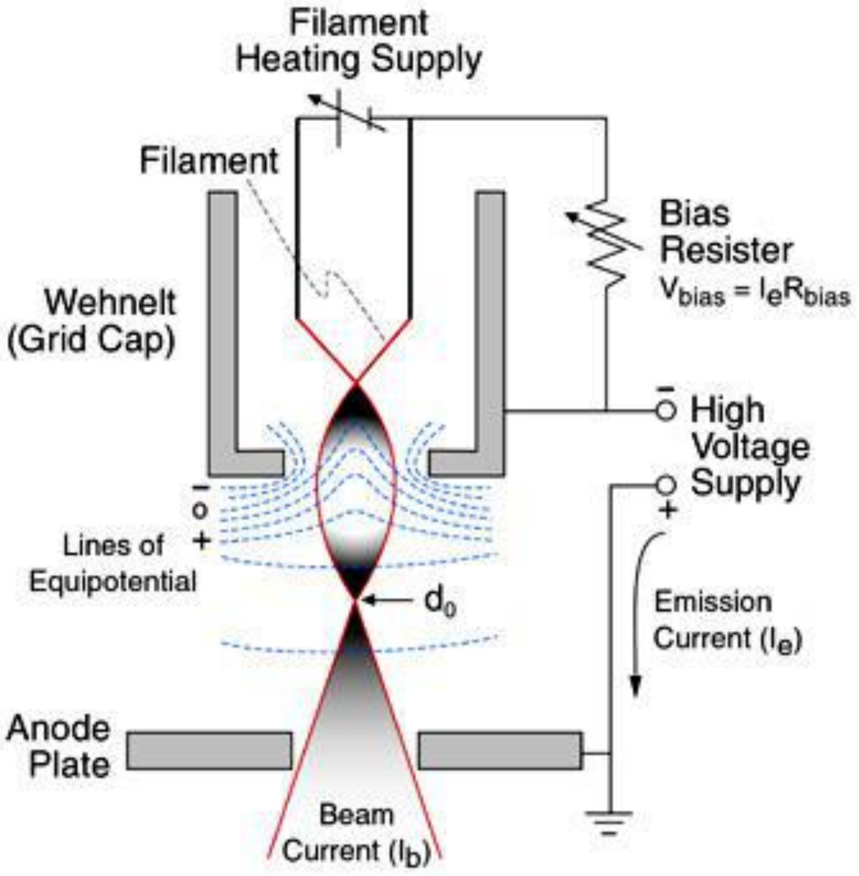
$$\beta = \frac{4I_b}{\pi^2\alpha^2 d^2}$$



- Brightness is defined as current per unit area per solid angle, with unit amp/cm^2/steradian.
- Brightness is the most useful measure of gun performance.
- High brightness is not the same as high current.
- E.g. thermionic emission can have very high beam current, but low brightness (due to large d).

wehnelt

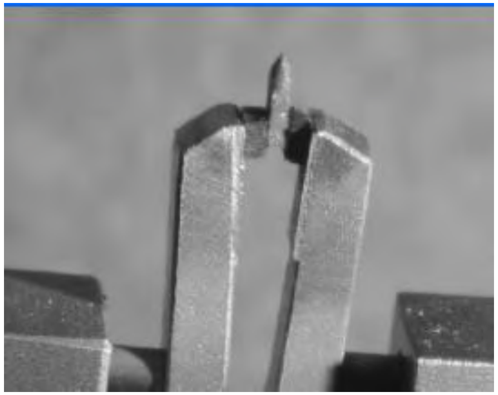
The wehnelt is a hollow cylinder, between the anode + and the filament – polarized to - 200V to -300V.



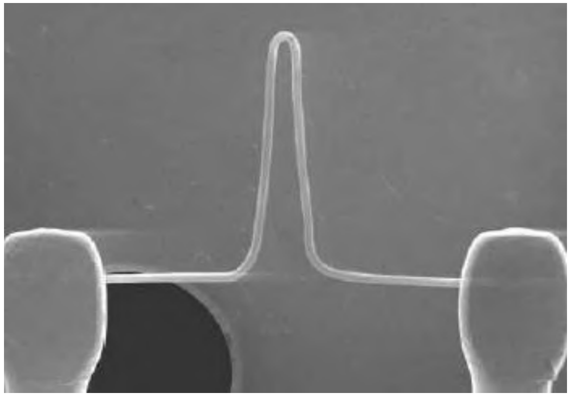
Wehnelt allows to reduce the spreading of the emission. It forms an image of the source d_0. It is an electrostatic lens. The stronger the emission the stronger the wehnelt acts. It stabilizes the emission

d0 is typically 40µm for W and 15µm for LaB6

Thermo-ionic sources



LaB6 crystal
Vacuum barrier : 2eV
T=1500°C
Min source size: 5nm
Ionic pump: 10^{-7}mBar

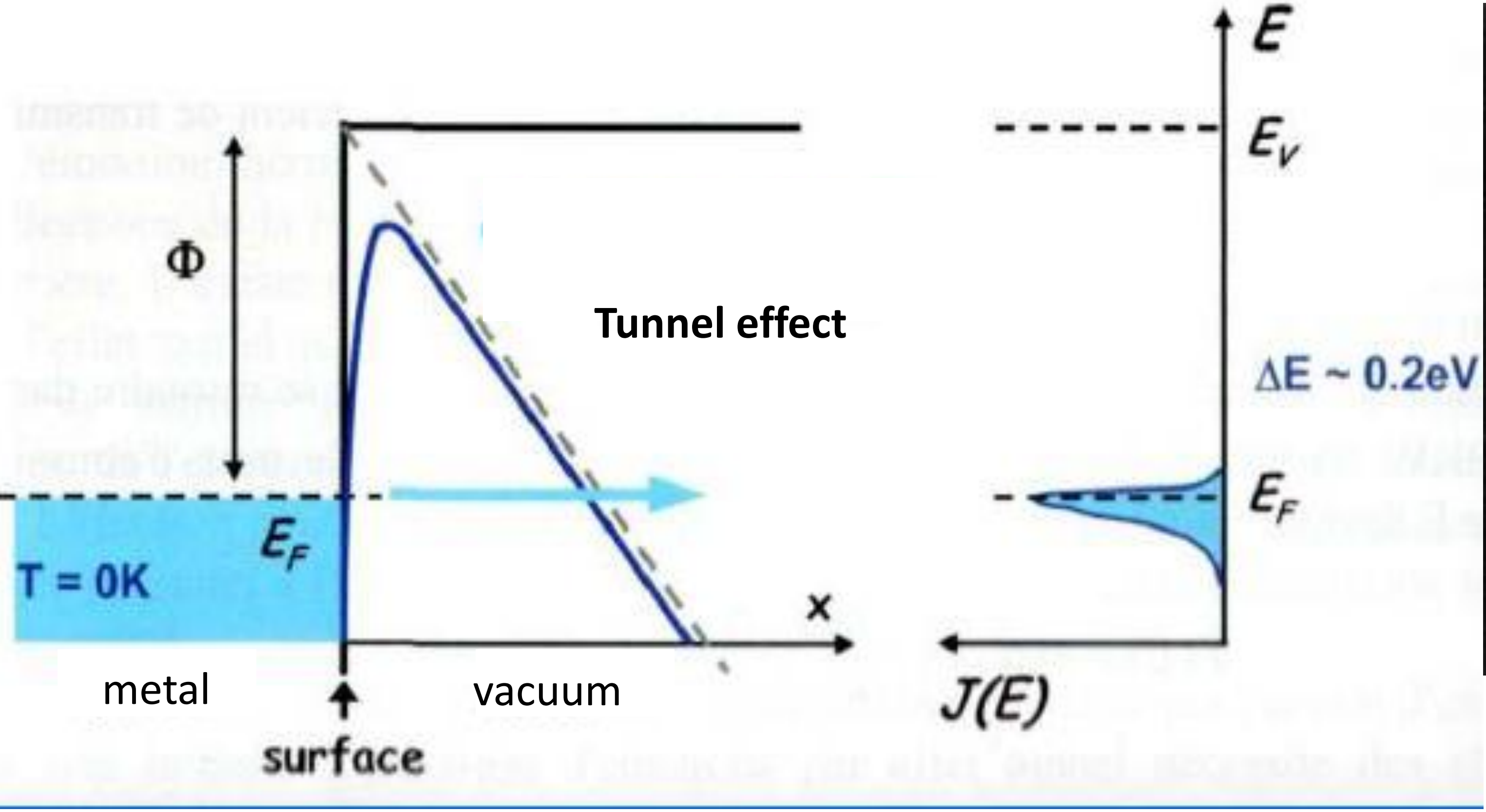


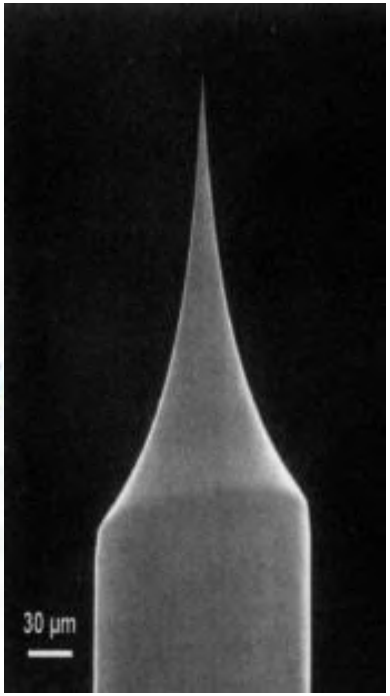
Tungsten
Vacuum barrier 4eV
T=2700°C
Min source size: 15nm
Turbo pumping 10^{-6}mBar

Very easy to handle
cheap
Good emission stability
Weak brighness:
W : 10^6 Acm^{-2}/str
LaB6 : 10^7Acm^{-2}/str
Small live time specially for W
Quite big virtual source size
Strong energy spread > 5 eV (chromatic aberration)

Field effect gun

Field effect gun : one use very sharp tip (~100nm) and strong voltage (~4kV) to obtain high field to lower the work function to get strong tunneling effect.
No heating (called cold cathode)





$$J_0 = AF^2 \exp\left[-\frac{B\Phi^{3/2}}{F}\right]$$

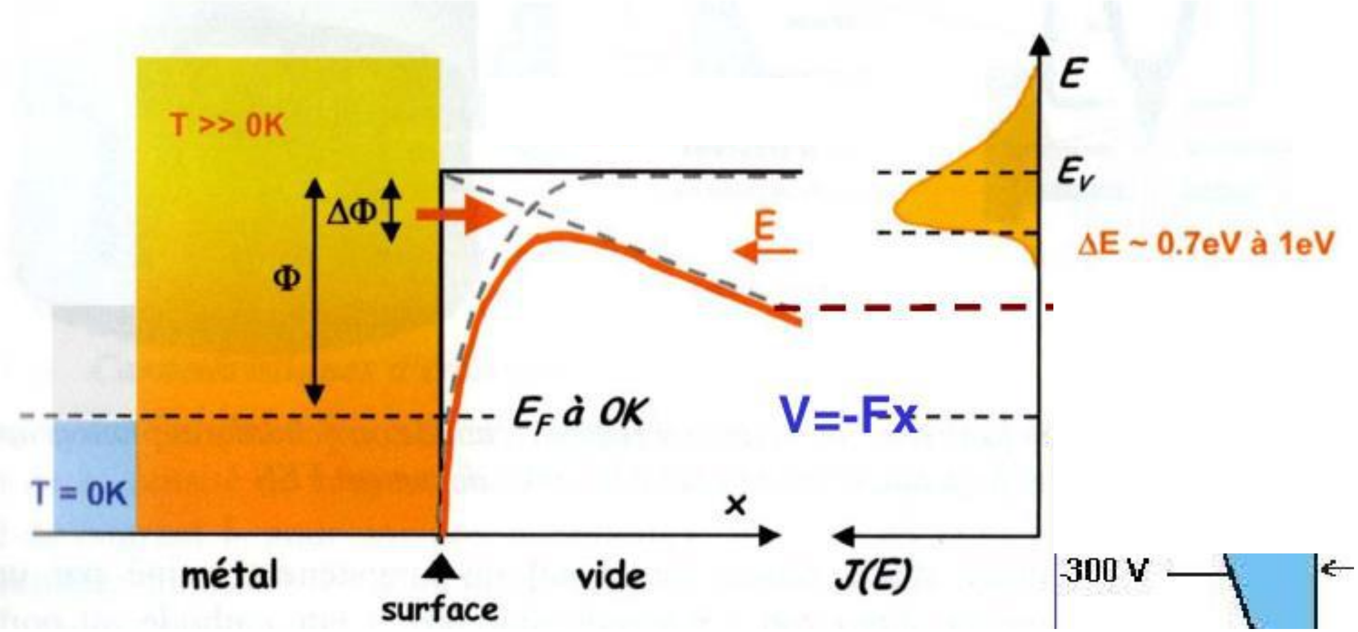
Very spatially localized small energy dispersion

Field effect gun

- High brightness : 10^9A/cm2/str
- Small source size
- Small energy spread : 0.2eV
- The tip must be very clean to perform properly as a field emitter.
- Even at 10^{-6}Torr, a monolayer of gas is deposited in just 1 sec.
- So tip needs higher vacuum, $\sim 10^{-10}$Torr vacuum (baking the gun assembly).
- Cleaning is performed by “flashing” - heating the tip for a few seconds to desorbs gas.
- The emission is never very stable, drift of typically few percent/hour
- This best for SEM imaging applications.
- Because of the current instability, cold FEG is not good choice for e-beam lithography,

Schottky source (hot cathode)

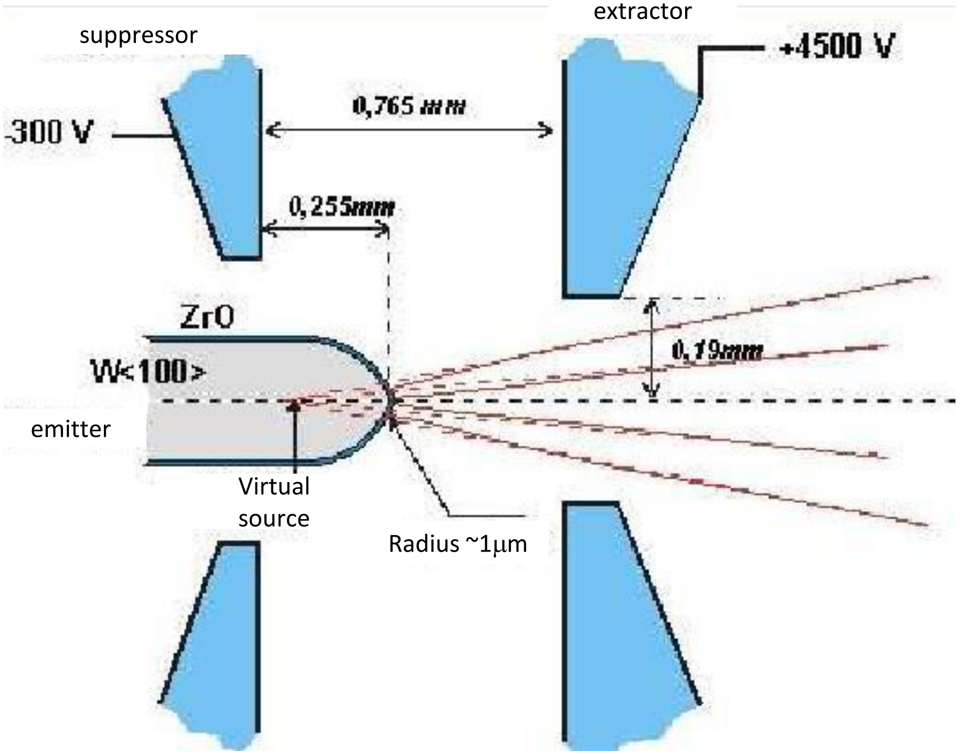
Source Schottky : combine thermo-ionic emission and field effect to increase stability and current emission compare to cold FEG. It is not a tunneling emission

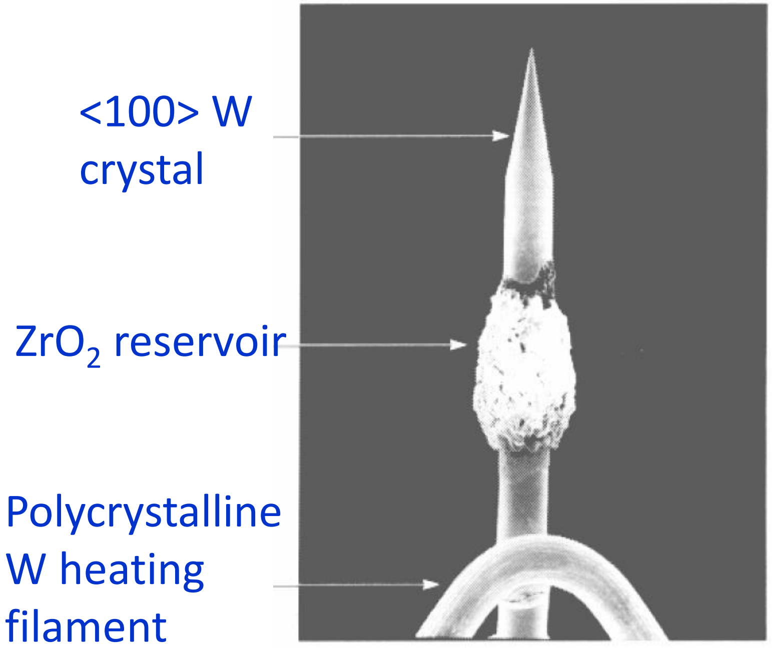


For Schottky emitter, the field F reduces the work function ϕ by an amount of $\Delta\phi = 3.80\times10^{-4}F^{1/2}$eV (e.g. $\Delta\phi$=0.5eV for 1.7×10^{6}V/cm).

T~1800°C

Schottky FEG

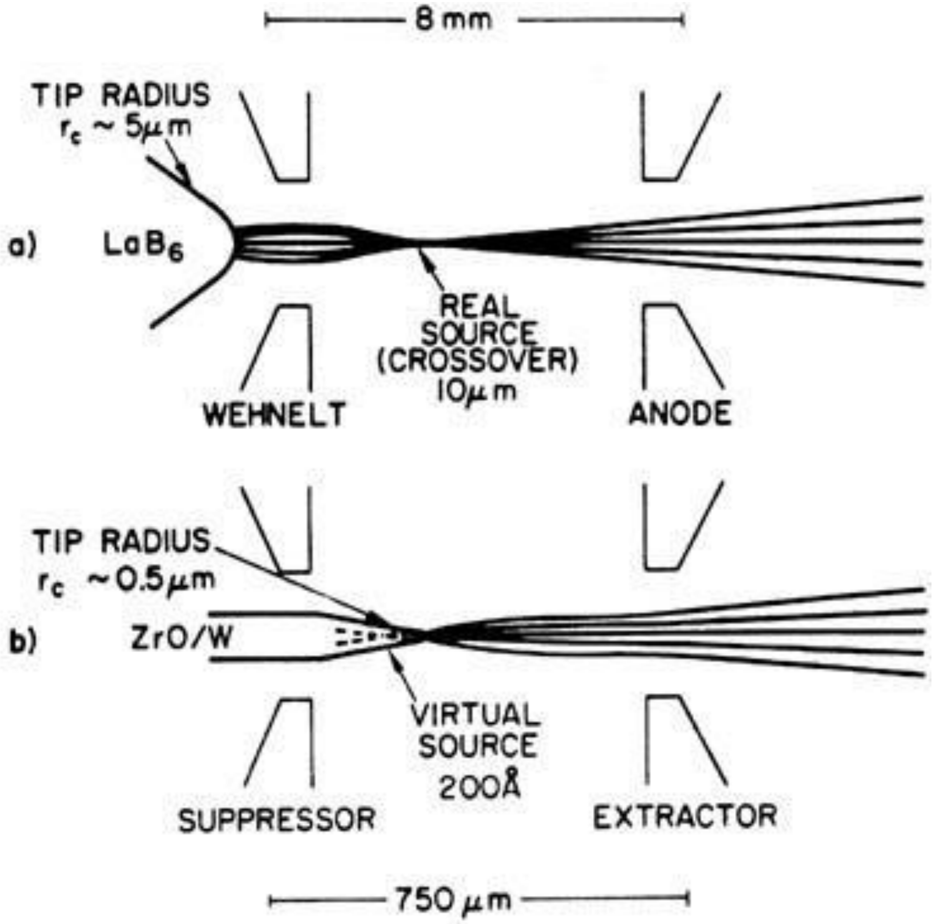




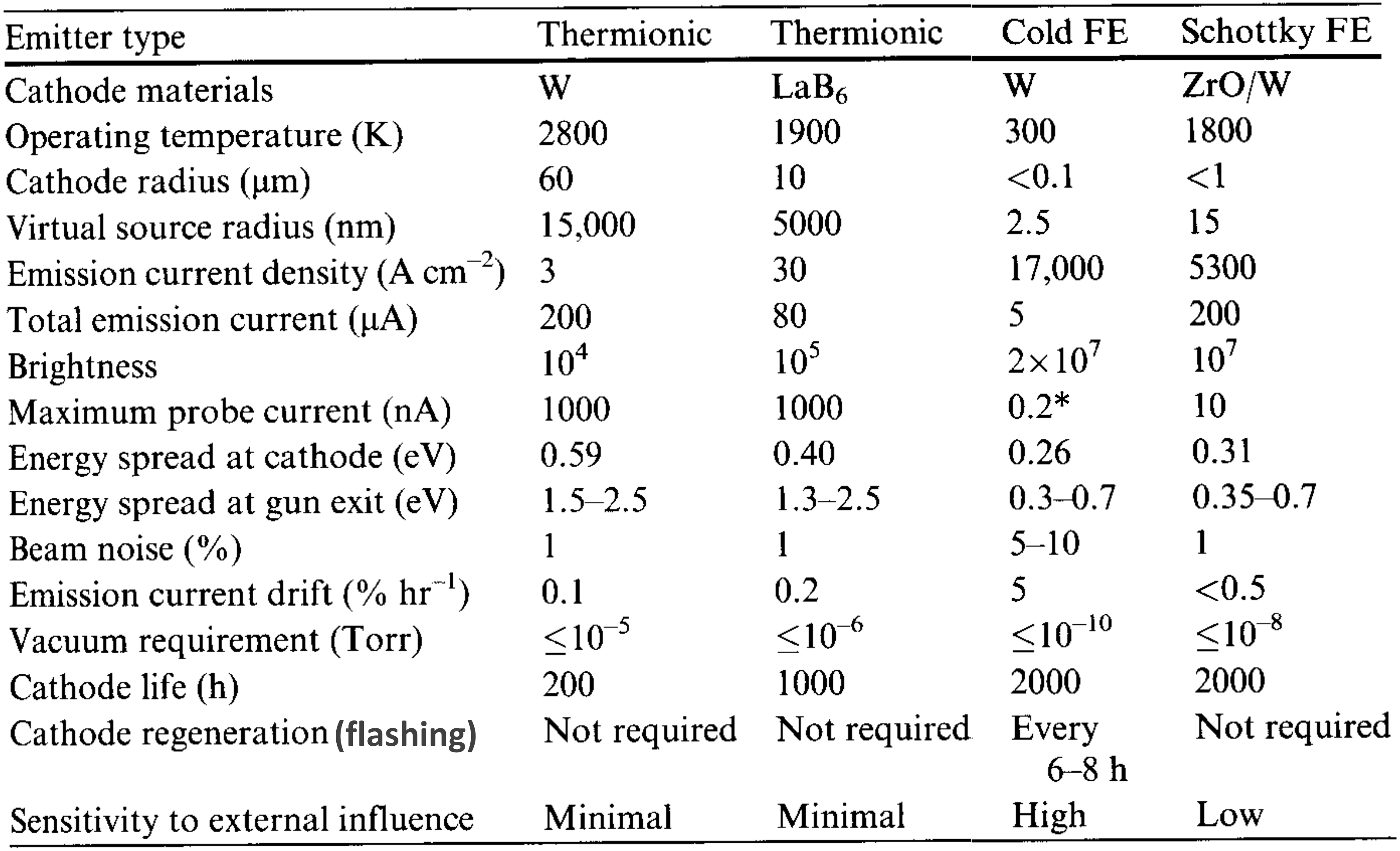
Z_r0_2 lower the work function. The suppressor negatively charged forces the emission toward the tip.

Brightness 10^8Acm^{-2}/str
Good stability
Strong current
Good life time > 5000h

Source size


8 mm
TIP RADIUS
$r_c \sim 5\mu m$
a)
LaB_6
REAL SOURCE (CROSSOVER) 10μm
WEHNELT
ANODE
TIP RADIUS
$r_c \sim 0.5\mu m$
b)
ZrO/W
VIRTUAL SOURCE 200Å
SUPPRESSOR
EXTRACTOR
750 μm

Comparaison between guns



Emitter type	Thermionic	Thermionic	Cold FE	Schottky FE
Cathode materials	W	LaB_6	W	ZrO/W
Operating temperature (K)	2800	1900	300	1800
Cathode radius (μm)	60	10	<0.1	<1
Virtual source radius (nm)	15,000	5000	2.5	15
Emission current density (A cm^{-2})	3	30	17,000	5300
Total emission current (μA)	200	80	5	200
Brightness	10^4	10^5	2×10^7	10^7
Maximum probe current (nA)	1000	1000	0.2*	10
Energy spread at cathode (eV)	0.59	0.40	0.26	0.31
Energy spread at gun exit (eV)	1.5–2.5	1.3–2.5	0.3–0.7	0.35–0.7
Beam noise (%)	1	1	5–10	1
Emission current drift (% hr^{-1})	0.1	0.2	5	<0.5
Vacuum requirement (Torr)	$\leq10^{-5}$	$\leq10^{-6}$	$\leq10^{-10}$	$\leq10^{-8}$
Cathode life (h)	200	1000	2000	2000
Cathode regeneration **(flashing)**	Not required	Not required	Every 6–8 h	Not required
Sensitivity to external influence	Minimal	Minimal	High	Low

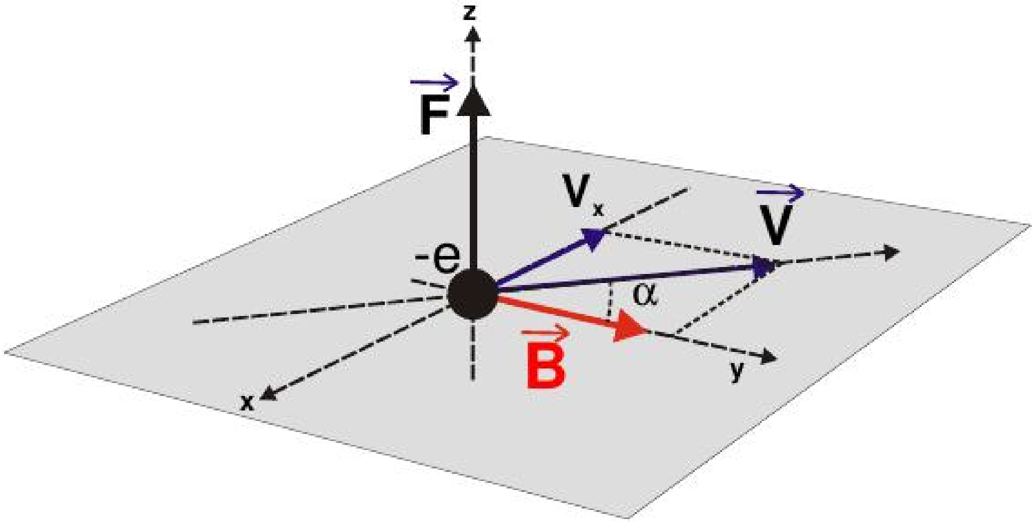
Electron lens

- Mvt electron in a B:

$$F = -e\vec{v} \wedge \vec{B}$$

- Force is perpendicular to v and B and its amplitude is proportional to the projection of v on the normal of B

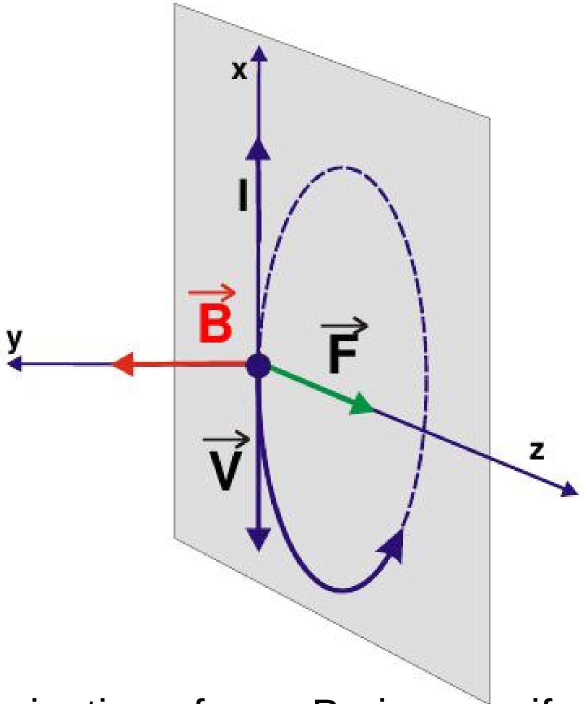
$$F = -e\,|\,v\,|\,B\sin(\alpha)$$

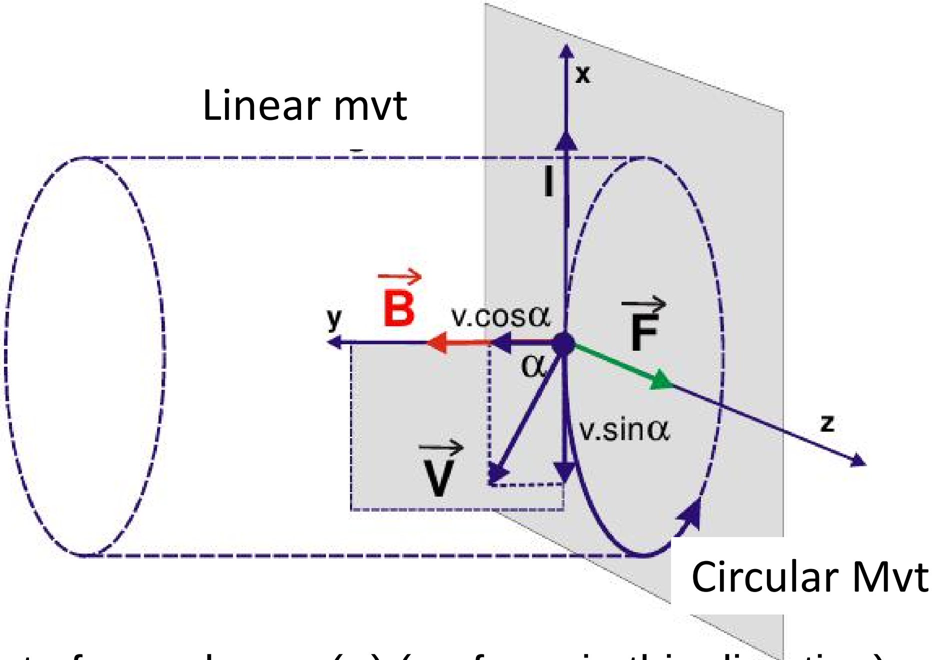


Electron in a magnetic field

The force direction change in a uniforme B which is not the case for a E field

If v is perpendicular to B then the mvt is circular with a radius : $R = \frac{mv}{eB}$



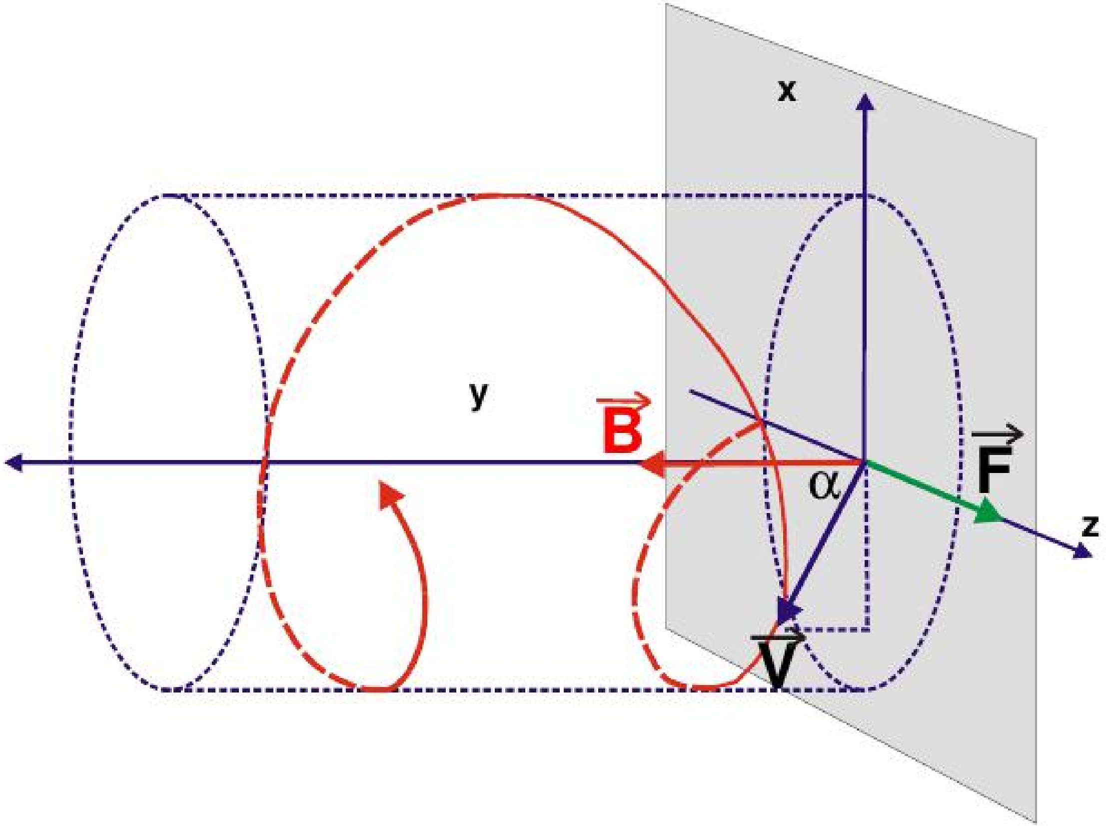


Linear mvt

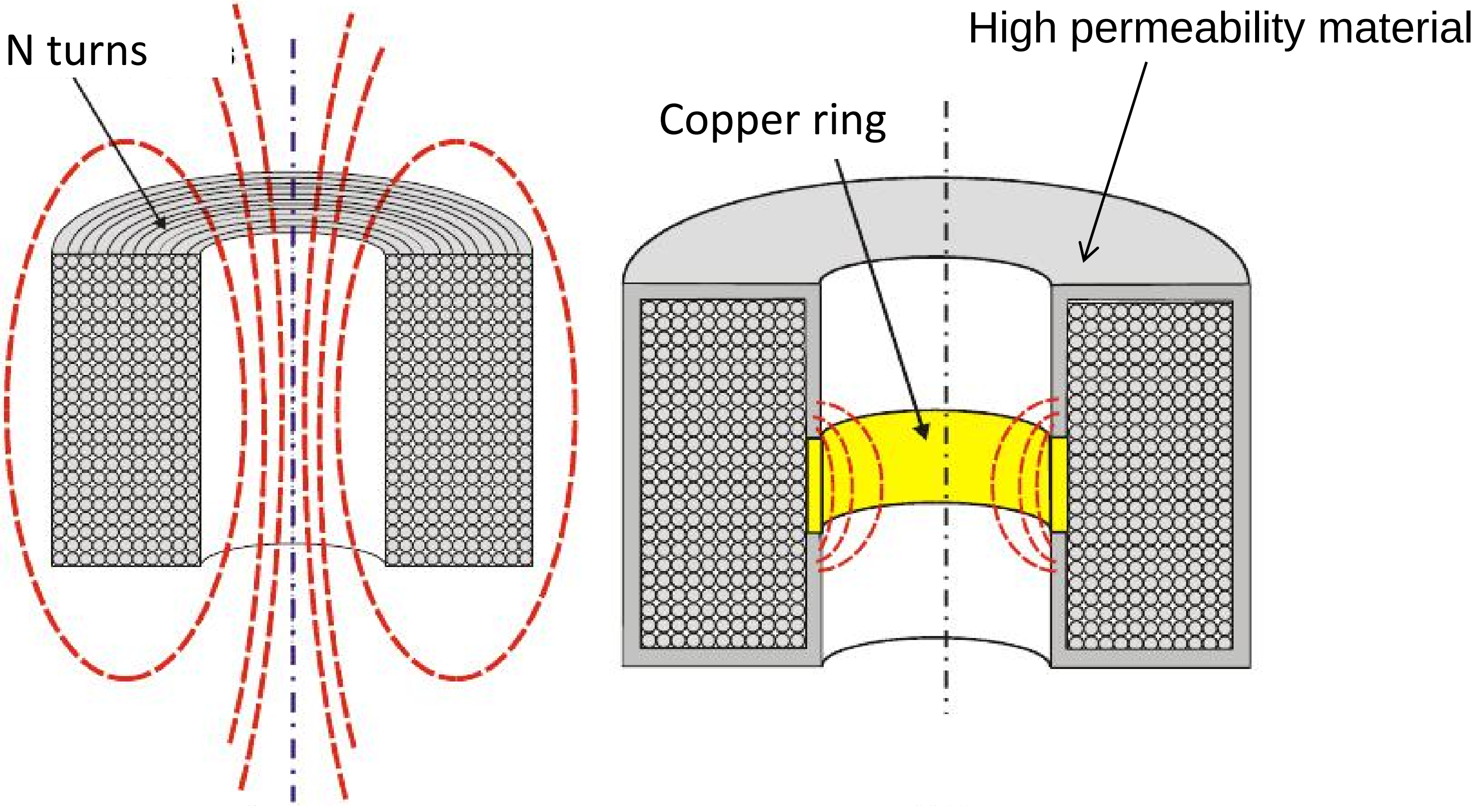
Circular Mvt

The projection of v on B give a uniforme mvt of speed vcos(α) (no force in this direction)

Helicoidal mouvement



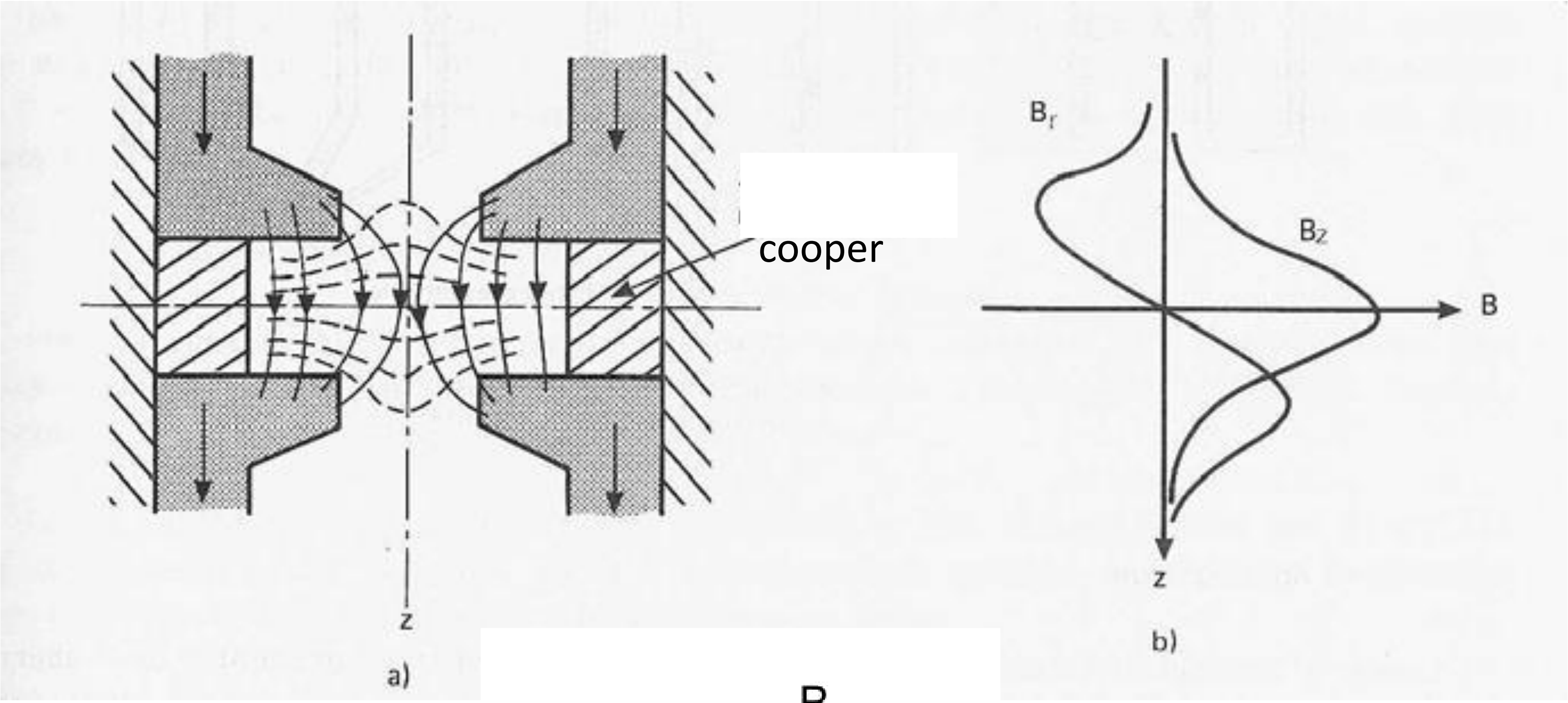
Magnetic lens :



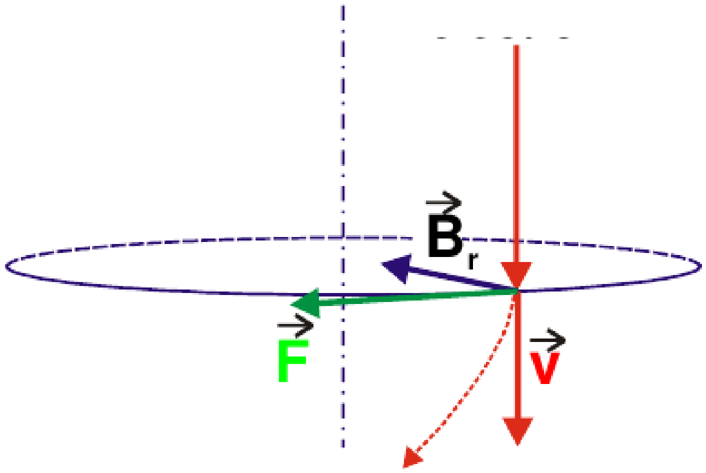
(a)

(b)

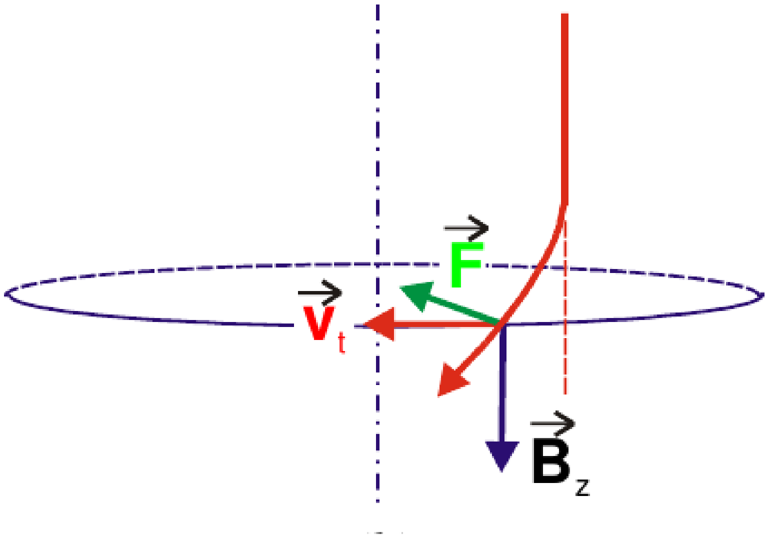
Magnetic lens : equipotentials



$$B(z)=\frac{B_0}{\left[1+\left(\frac{z}{a}\right)^2\right]^n}$$



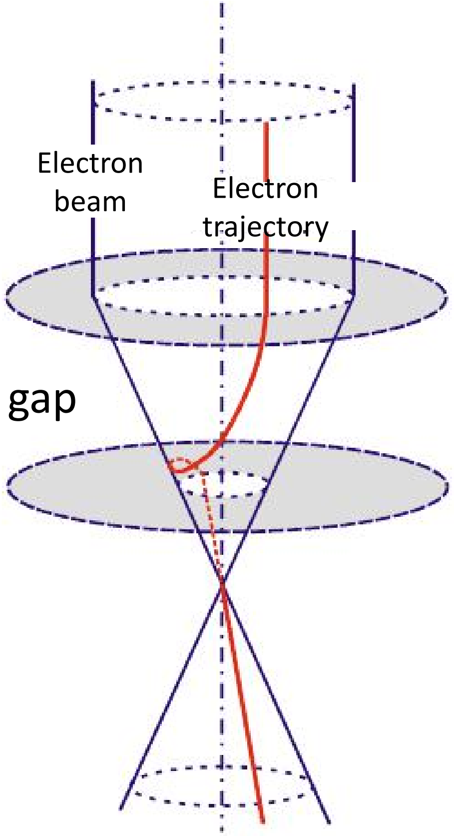
Radial component push electron out of the [B,v] plan



Normal component then push the electron toward the center

If far from center strong Bz the electron is strongly attracted toward the center: focusing lens

Focal lens



$$\frac{1}{f} = \frac{e}{8mU} \int_{-\infty}^{+\infty} B_z^2 dz = \frac{e}{8mU} \int_{-\infty}^{+\infty} \frac{B_0^2}{\left[1 + \left(\frac{z}{a}\right)^2\right]^2} dz$$

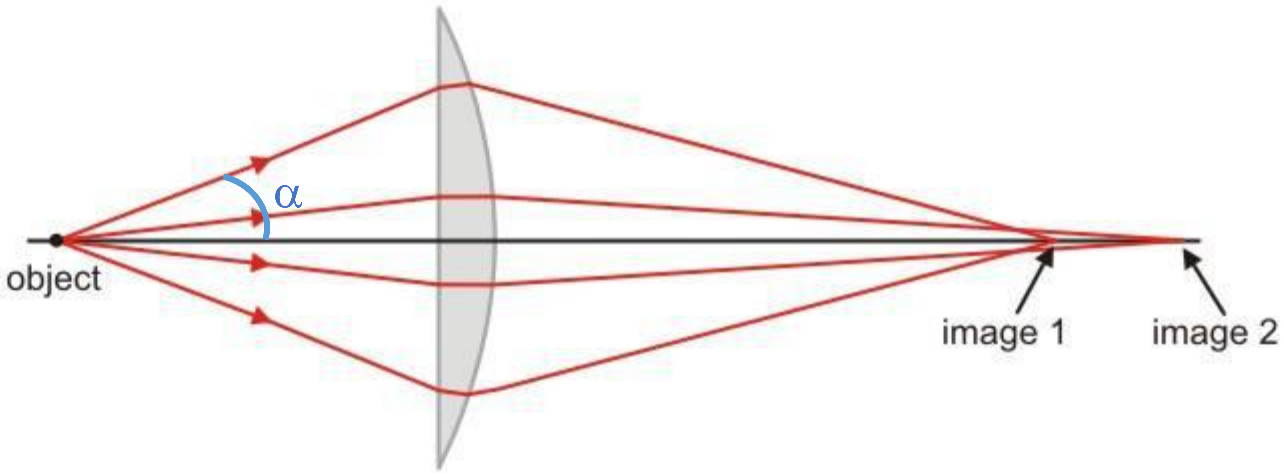
Focal length depends:

- Energy of electron
- B i.e. the current in the coil

It is a lens where you can easily change the focal length

Spherical aberration

The focus depends on the distance of the trajectory of the axis

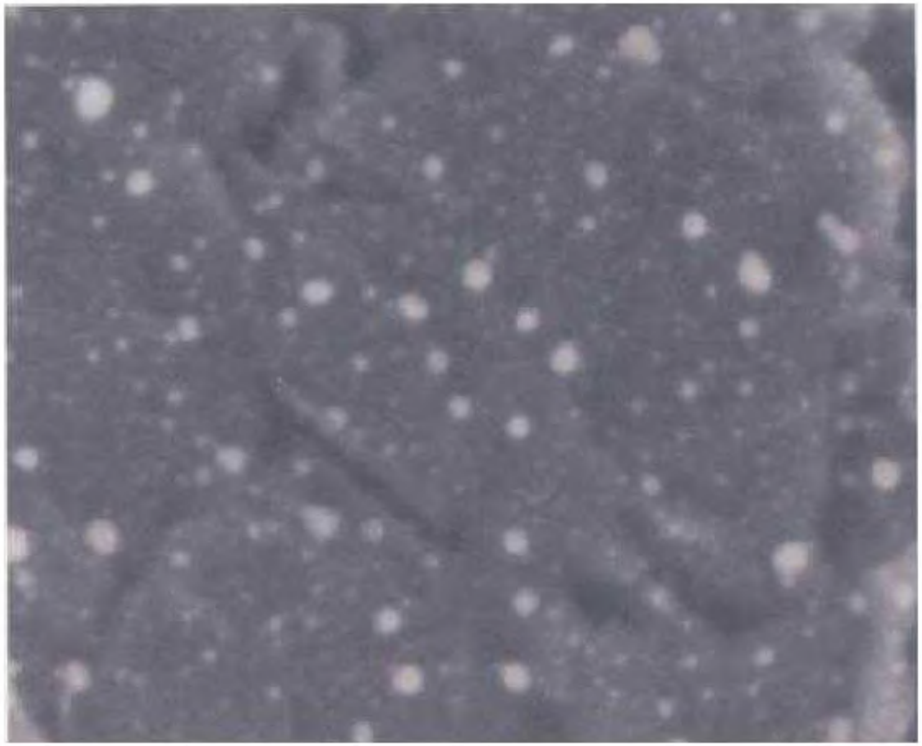


Links to imperfection of the geometry of the coil
Minimum spot size :

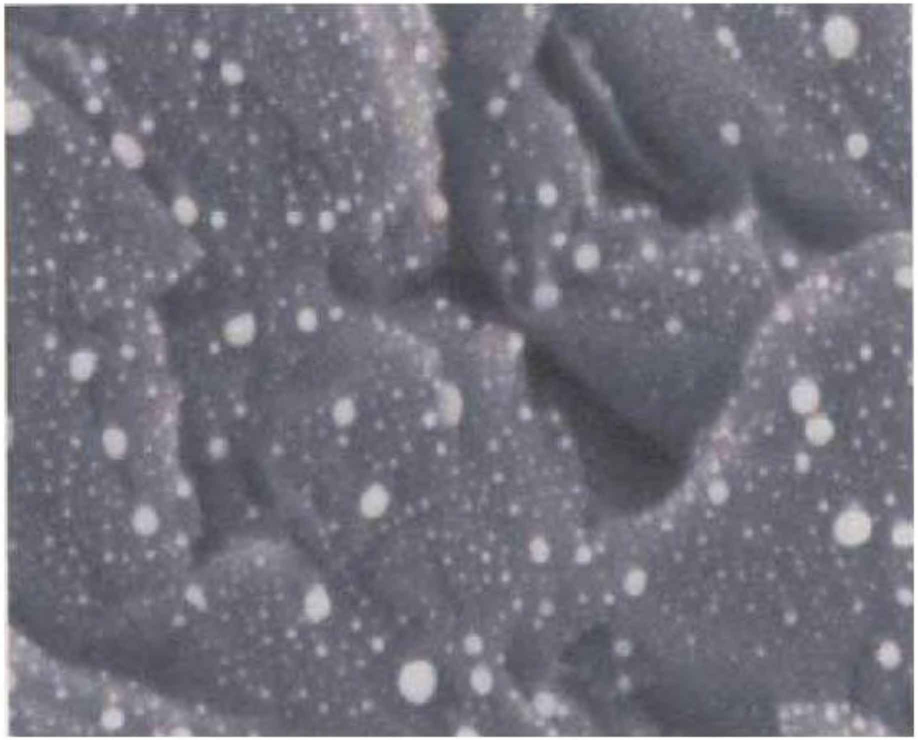
$d_s = 0.5C_s\alpha^3$ Cs depends on working distance

Need to decrease α but it decreases the current…
High resolution microscope -> correction by added coil and software

Spherical aberrations corrections

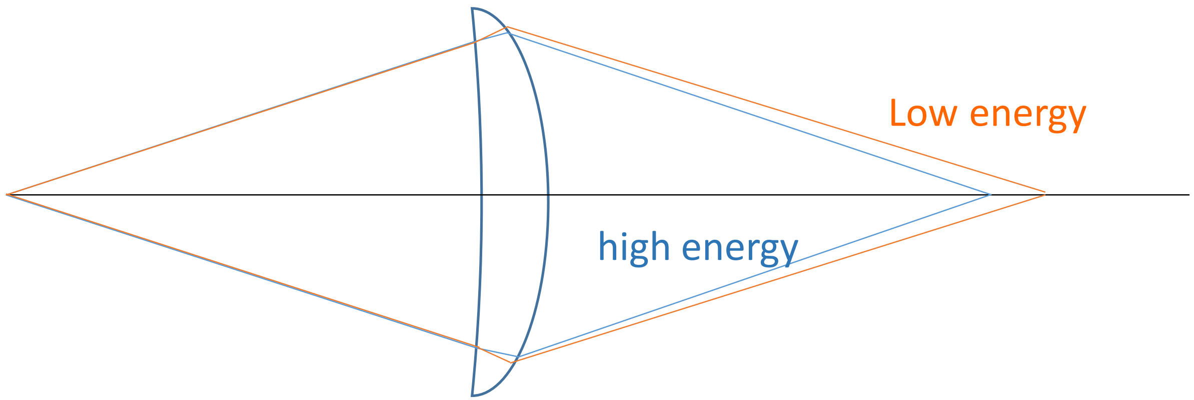


Without corrections



With corrections

Chromatic aberrations

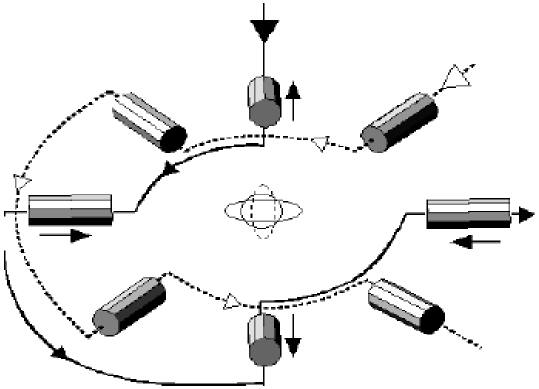


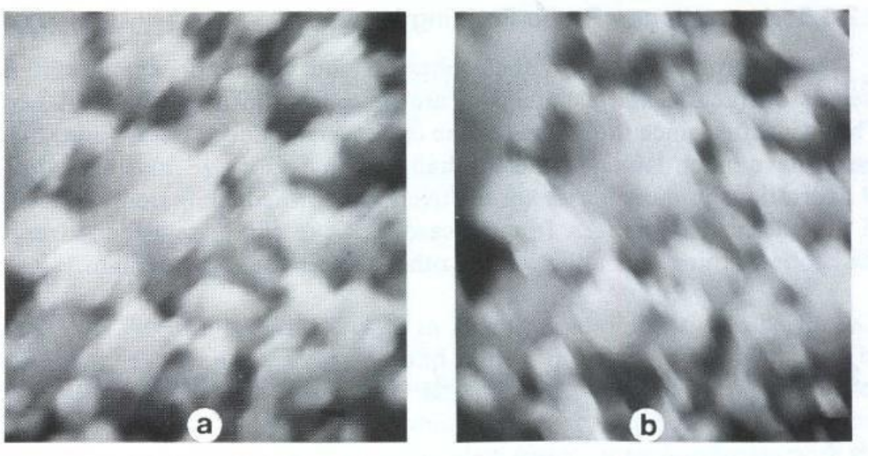
- The focal length of higher energy electrons is longer than that for lower energy electrons.
- The minimum spot size is

  $d_c = C_c \alpha \Delta E / E_0$ (or $\Delta V/V$) which increase at low energies E_0, or when using thermionic emitters with high energy spread ΔE.

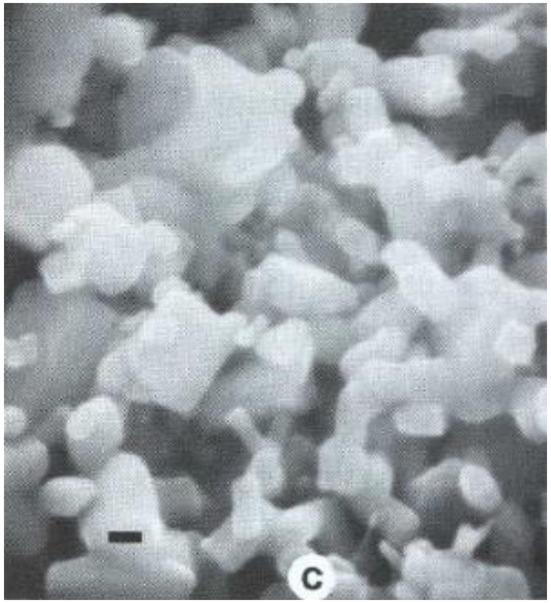
astimatism

Astigmatism : non circular spot link to imperfection in the coils or dust in the column (that charges). One can correct them using octopole lens.





Defocus below and above focal point



Corrected image

Final spot size

$$d = \sqrt{d_g^2 + d_s^2 + d_c^2 + d_d^2}$$

$$d_g = \frac{d_v}{M}$$

d_v: virtual source diameter

M: demagnefication

$$d_s = \frac{1}{2} C_s \alpha^3$$

Spherical aberration

$$d_c = C_c \alpha \frac{\Delta V}{V}$$

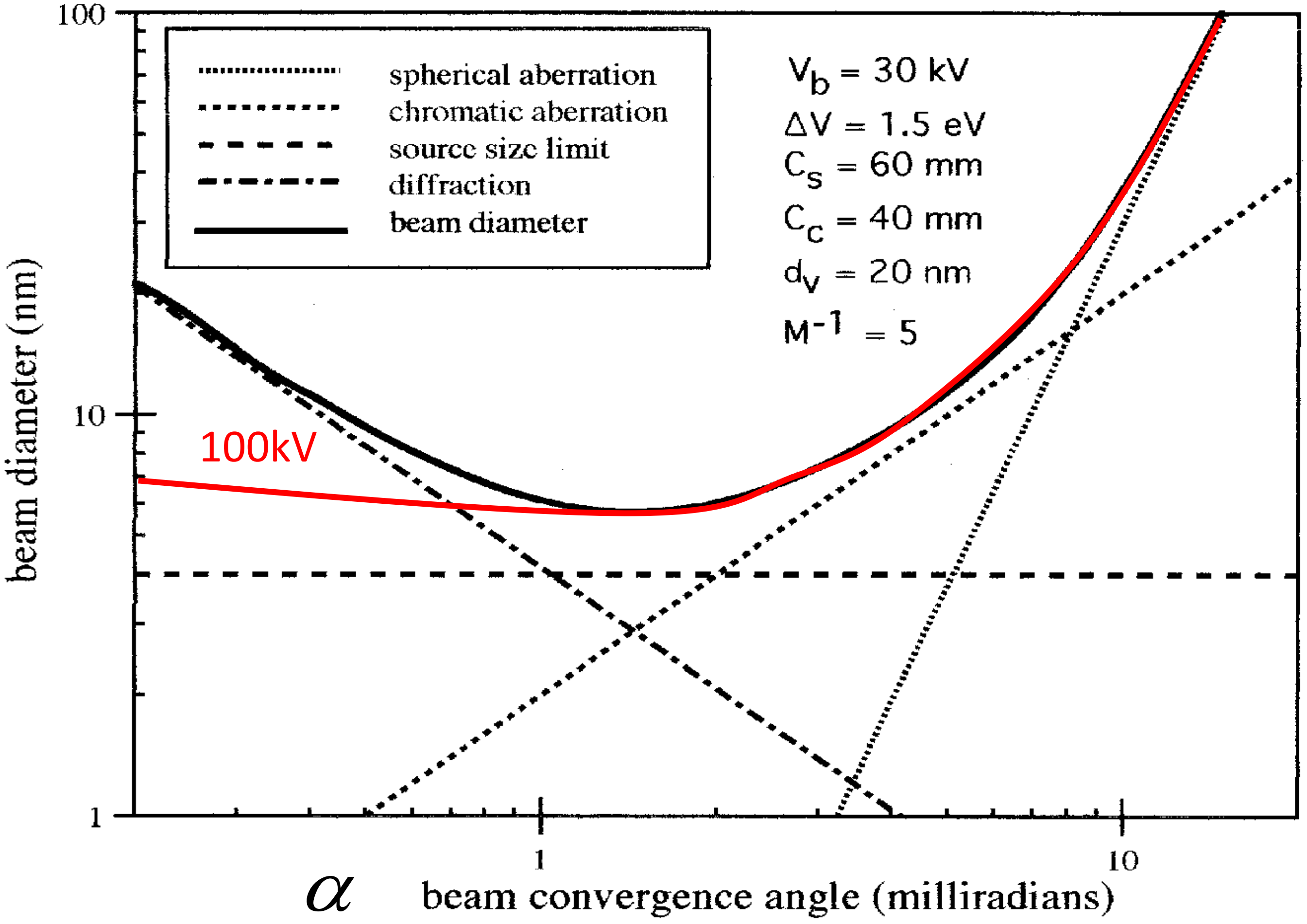
Chromatic aberration

$$d_d = 0.61 \frac{\lambda}{\alpha}, \lambda = \frac{1.2}{\sqrt{V}} nm$$

Diffraction (remember optical lithography)

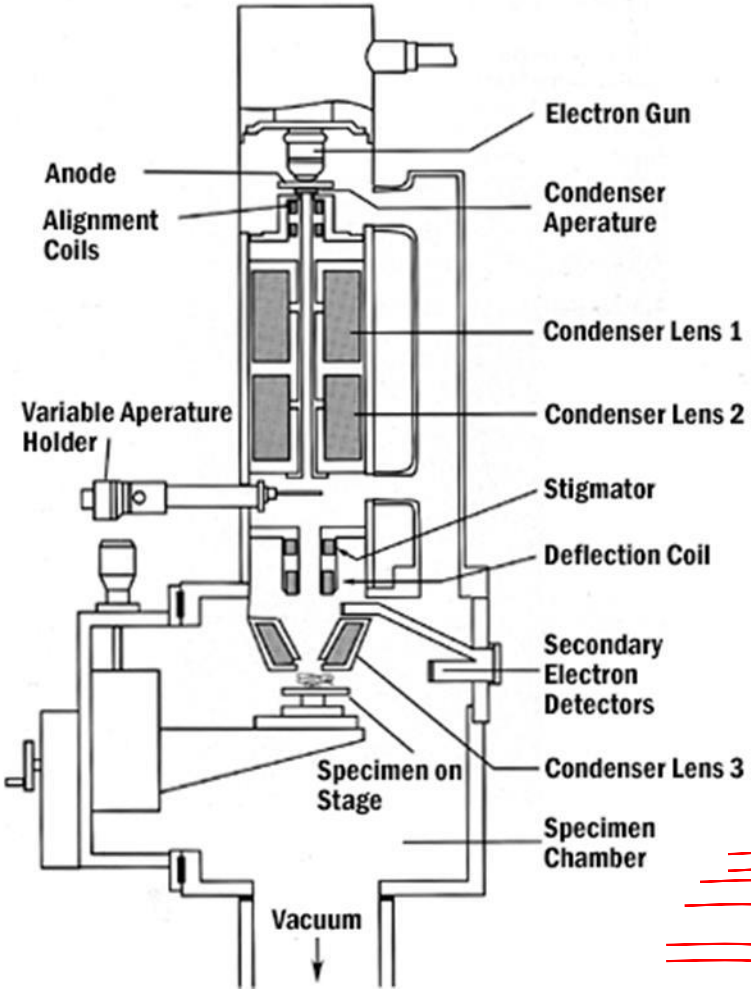
- Beam spot size depends on acceleration voltage, because higher voltage leads to: smaller chromatic aberration, and shorter λ thus smaller diffraction.
- This is particular true for thermionic emission guns, where high resolution (~5nm) can only be achieved at 30kV.
- Such resolution can be achieved at ~5kV for field emission (cold and Schottky) guns.

practical exemple



On can adjust a by playing with aperture at cross over. But reducing a decrease current

SEM



Condenseurs demagnify the virtual image source

The image is obtained by a TV scanning of the beam on the sample while recording electrons re-emmitted by the material.

Spot size fixes the resolution

Magnification is obtained by decreasing the sweep area since the screen is the same.

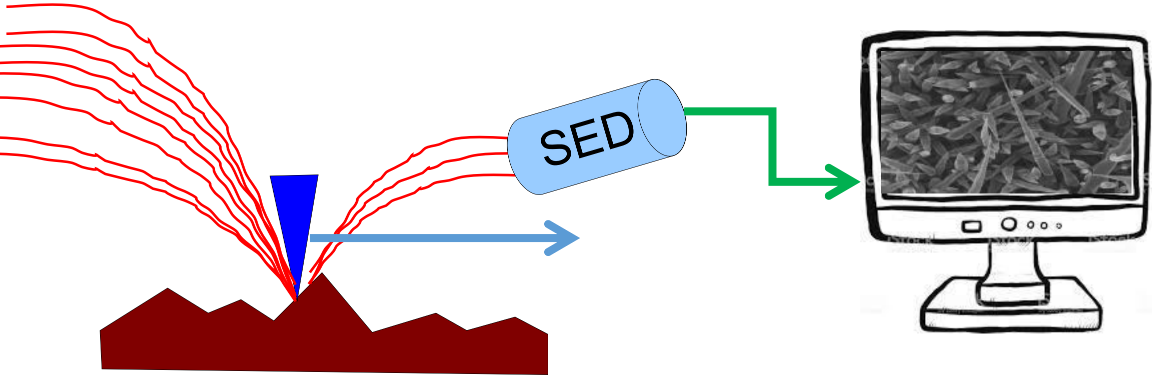
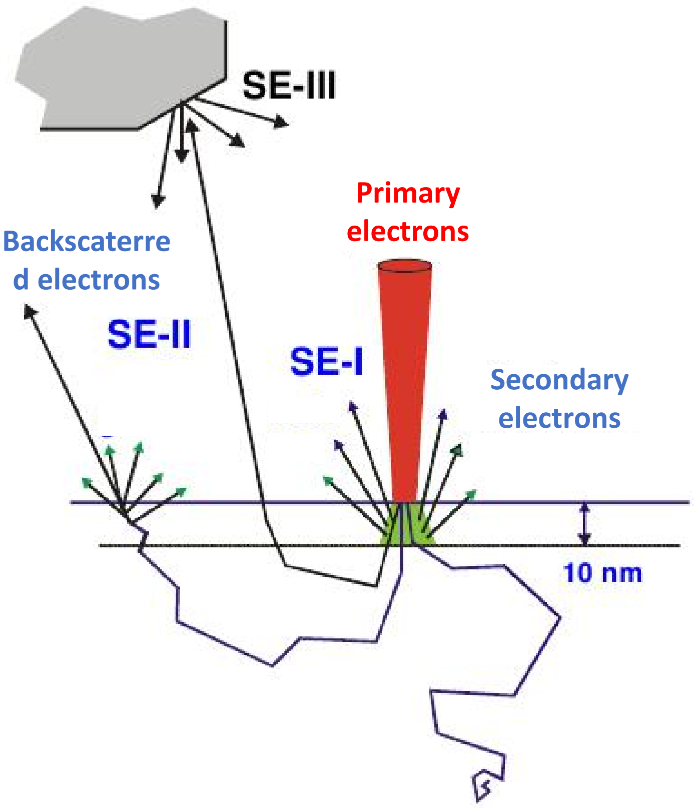
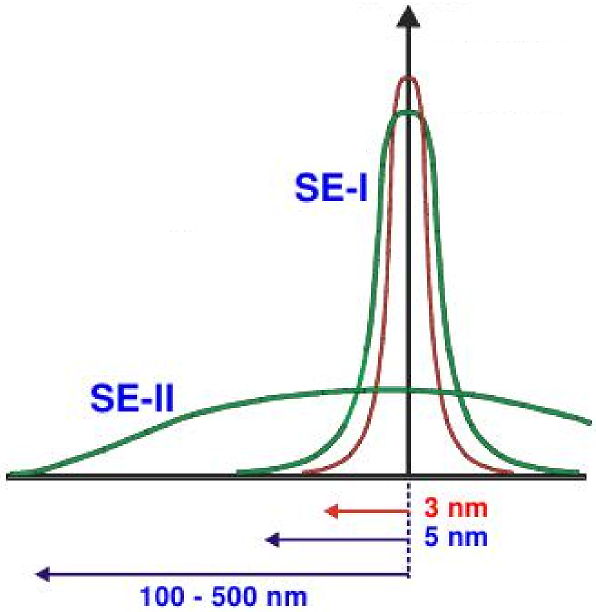


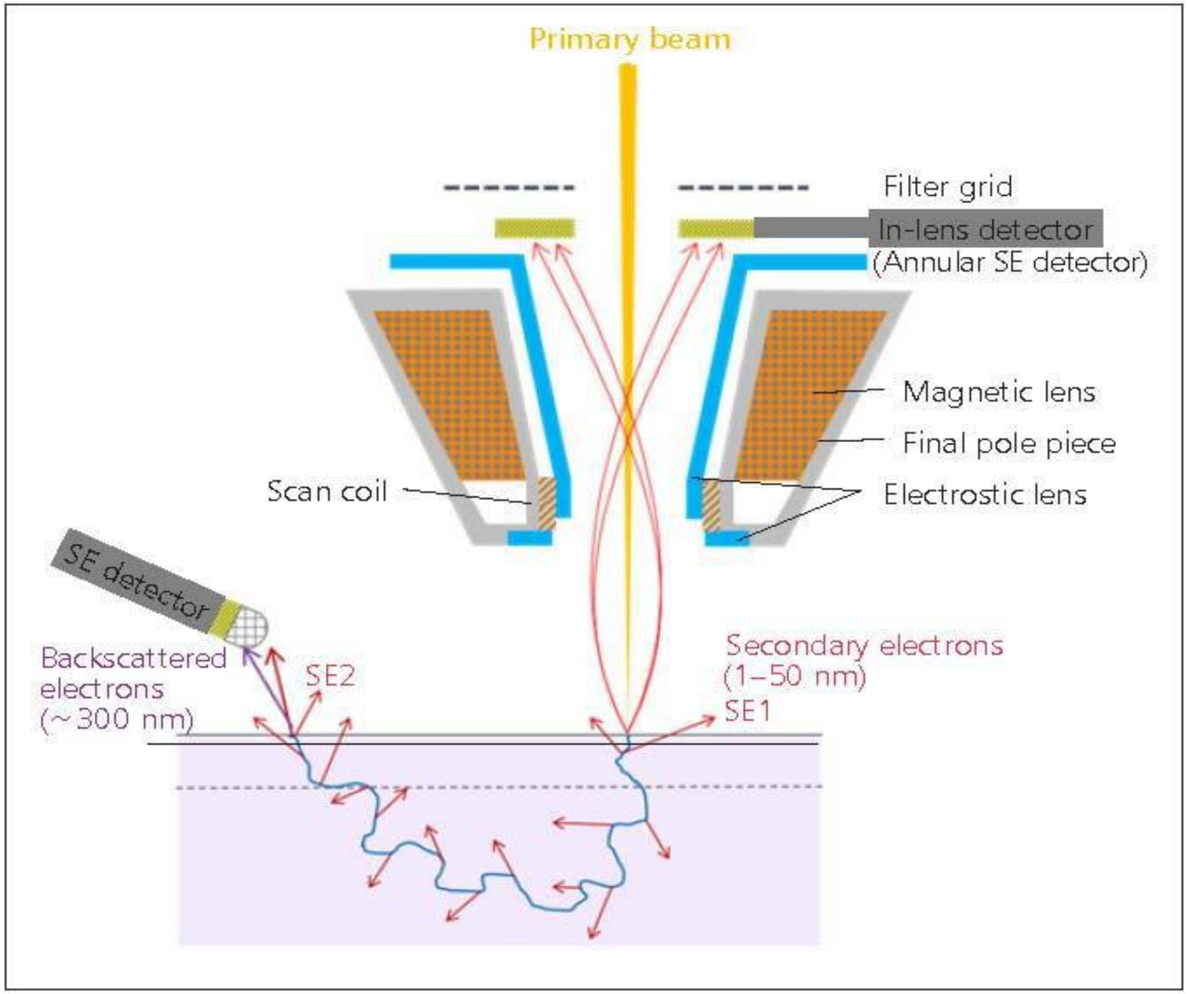
Image formation



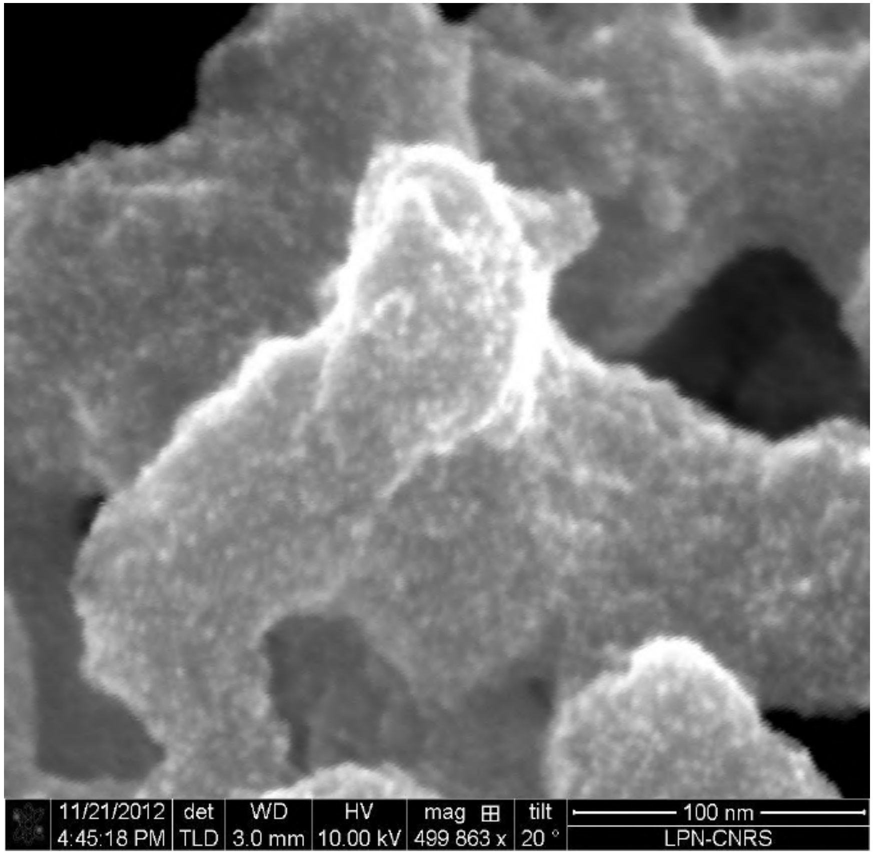


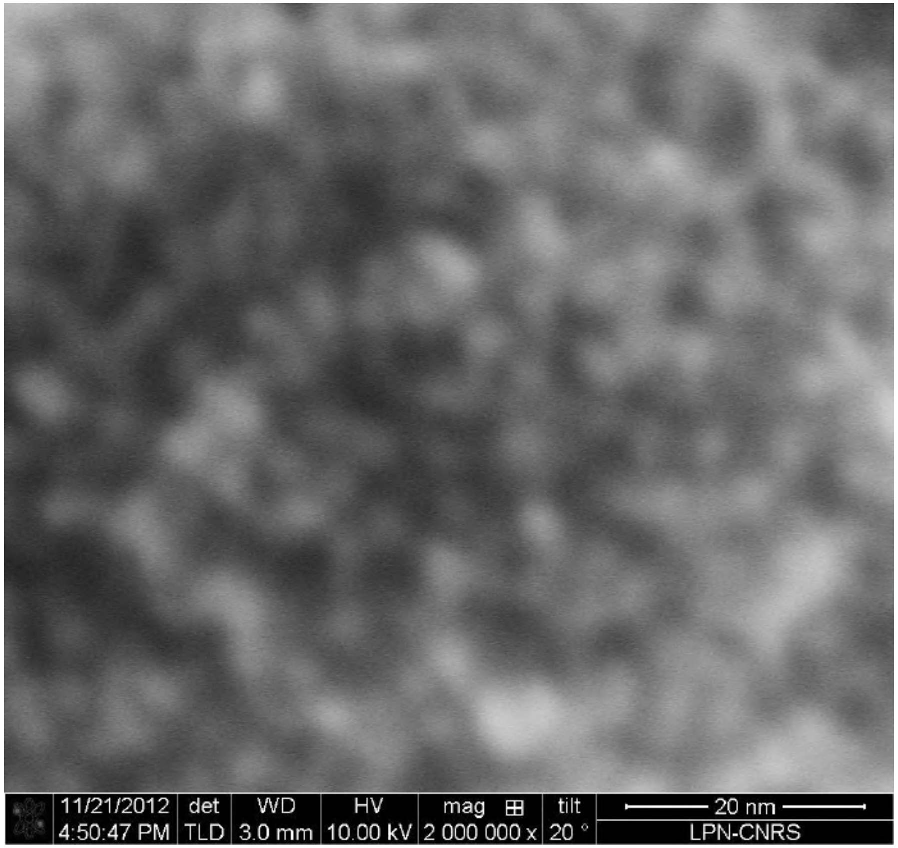
Using a grid at positive voltage one can filter the secondary electrons and change the contraste of the image.

In lens detection



The strong field at the final lens acts as a lens to collect efficiently the secondary electrons and give a strong S/N . Very helpful at small current i.e. high resolution


11/21/2012
4:45:18 PM
det
TLD
WD
3.0 mm
HV
10.00 kV
mag ⊞
499 863 x
tilt
20 °
100 nm
LPN-CNRS


11/21/2012
4:50:47 PM
det
TLD
WD
3.0 mm
HV
10.00 kV
mag ⊞
2 000 000 x
tilt
20 °
20 nm
LPN-CNRS

Electron beam lithography

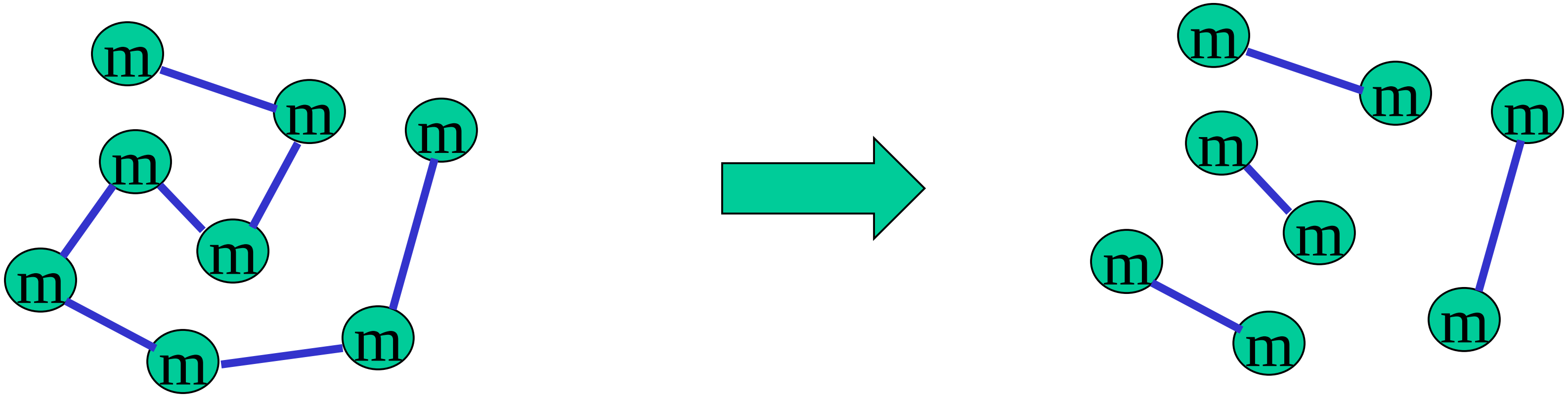
Now we understand how we can have a nice small electron beam

Let’s use it to pattern a resist.

Need to understand electron resist interaction

electron-resist interaction

Organic resist (PMMA)



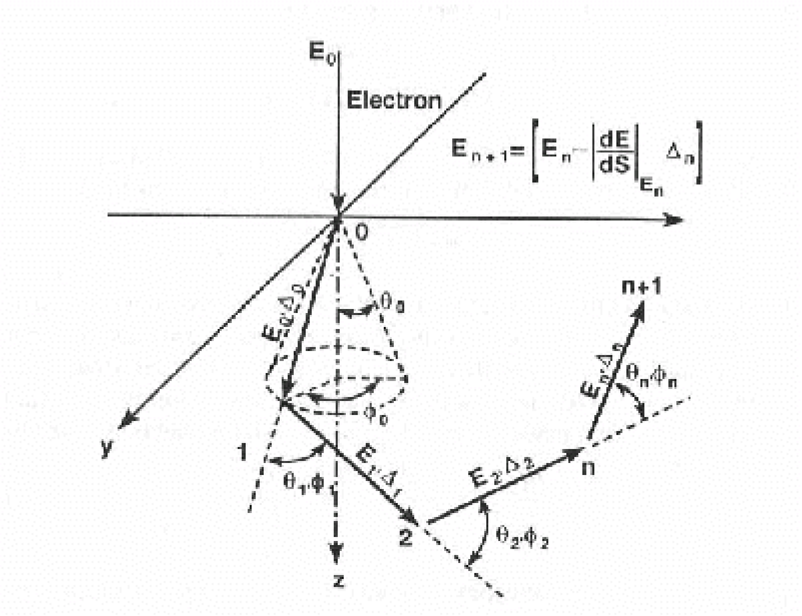
non soluble

soluble

Typical energy to break a bond: 10eV
Typical energy of the beam: several 10keV

One needs to know how the electron looses its energy down to zero energy!

Monte Carlo simulation

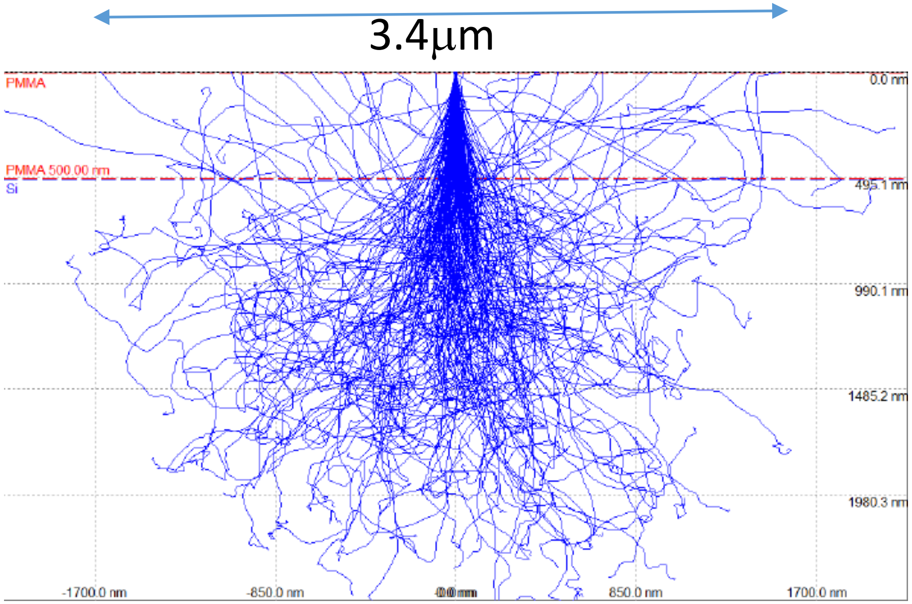


Elastic collisions: Bethe approx the energy lost between two collisions is proportional to the lenght Λ (radiation like dissipation) and depends on E and the material.

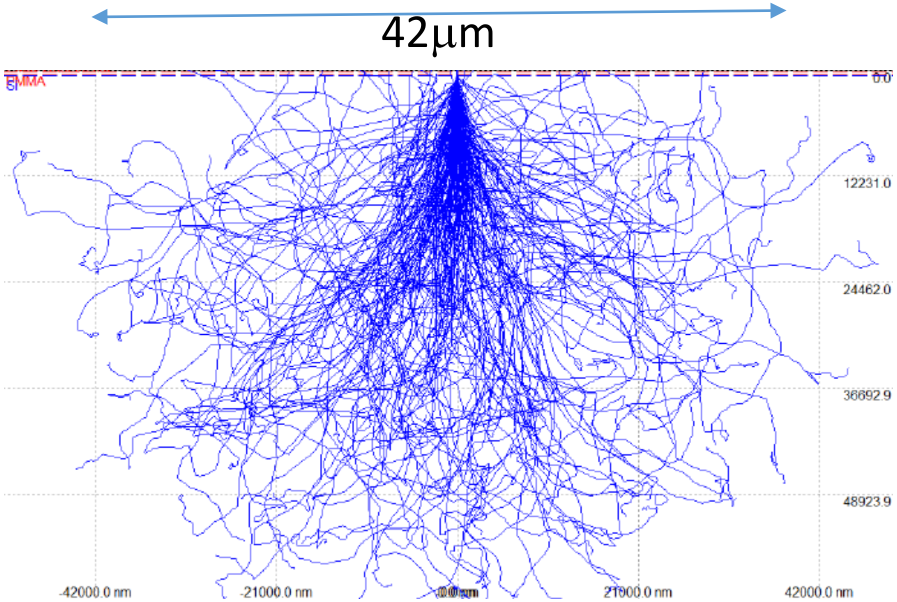
Λ depends on energy and taken in a distribution

Θ and ϕ are taken in a ditribution following a screened Rutherford cross section depending on Z and E

Monte Carlo resist on InP 200 electrons



15kV

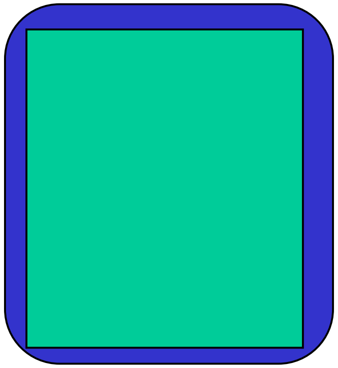


100kV

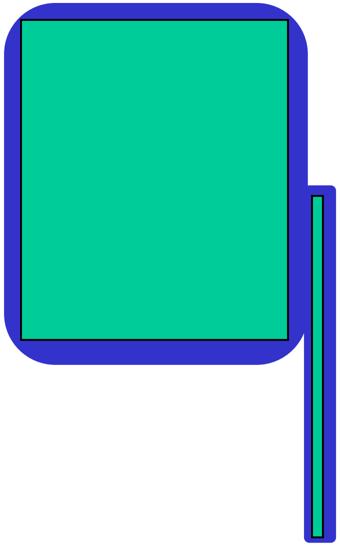
Forward scattering → Divergence of the beam, degrade resolution

Back scattering → Energy far from the impact of electron
Proximity effect

Proximity Effect

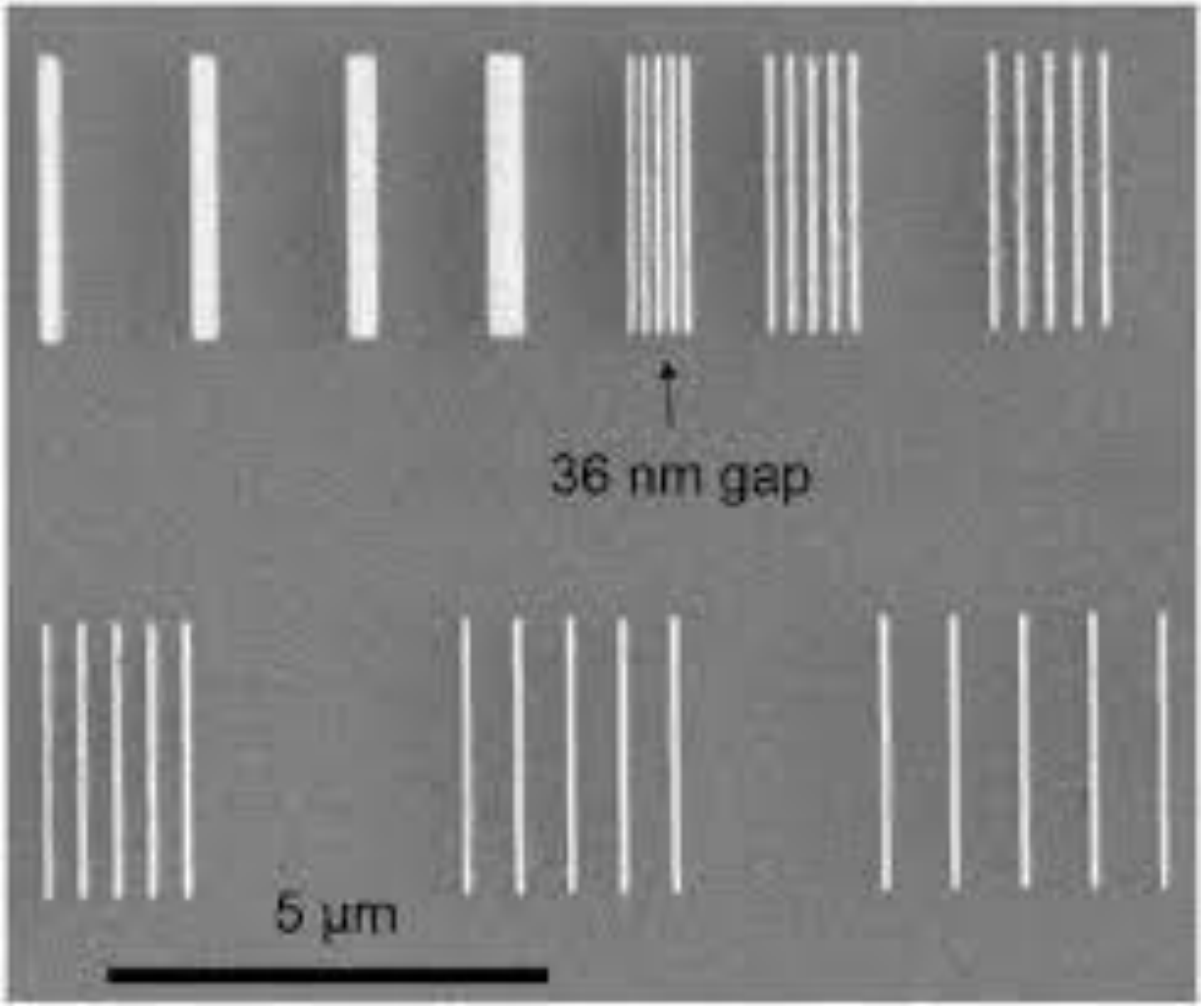


Dose depends on the
pattern: intra-proximity

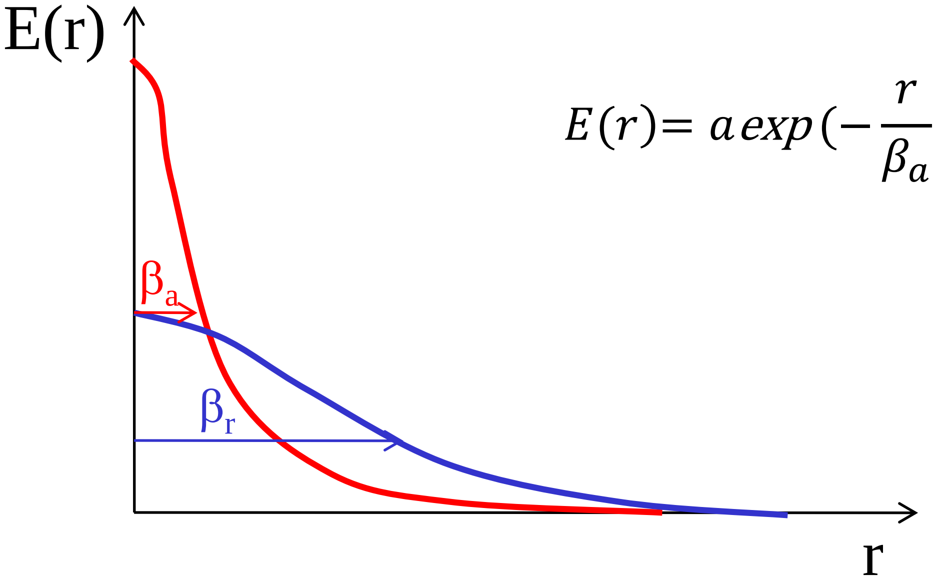


Dose depends on the surrounding of
the pattern: inter-proximity

Example: difficult to produce dense pattern



Double Gaussian model



$$E(r) = a\,exp\left(-\frac{r}{\beta_a}\right)^2 + b\,exp\left(-\frac{r}{\beta_b}\right)^2$$

Tension kV	β_a(μm)	β_r (μm)
20	0.08	2
50	0.04	9
60	-	13
120	-	43

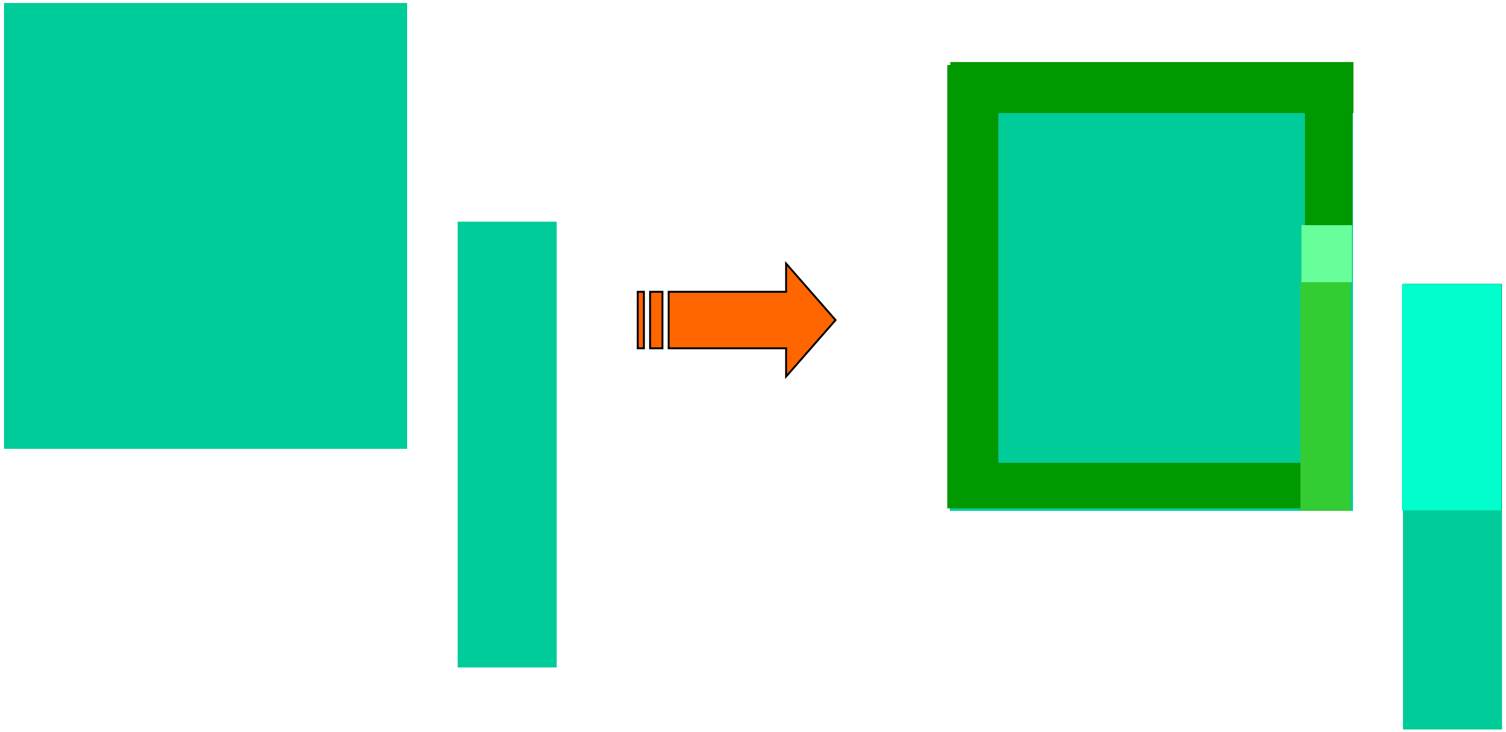
Substrate Si

β_a forward scattering:
Depends essentially on the voltage
β_r backscattering:
Depends on the voltage and the Z of the substrate

How to fight against proximity effect

- Vary the dose at a point to take into account its surrounding
- Use very low Z substrate – multilayer technique
- Use high energy to dilute the backscattered in a large area
- Use resists only sensitive to high energies – backscattered have lost quite energy
- Write on membranes – not always possible!
- Use very low energy (no back scattering) but large forward scattering : STEM lithography

Varying the dose

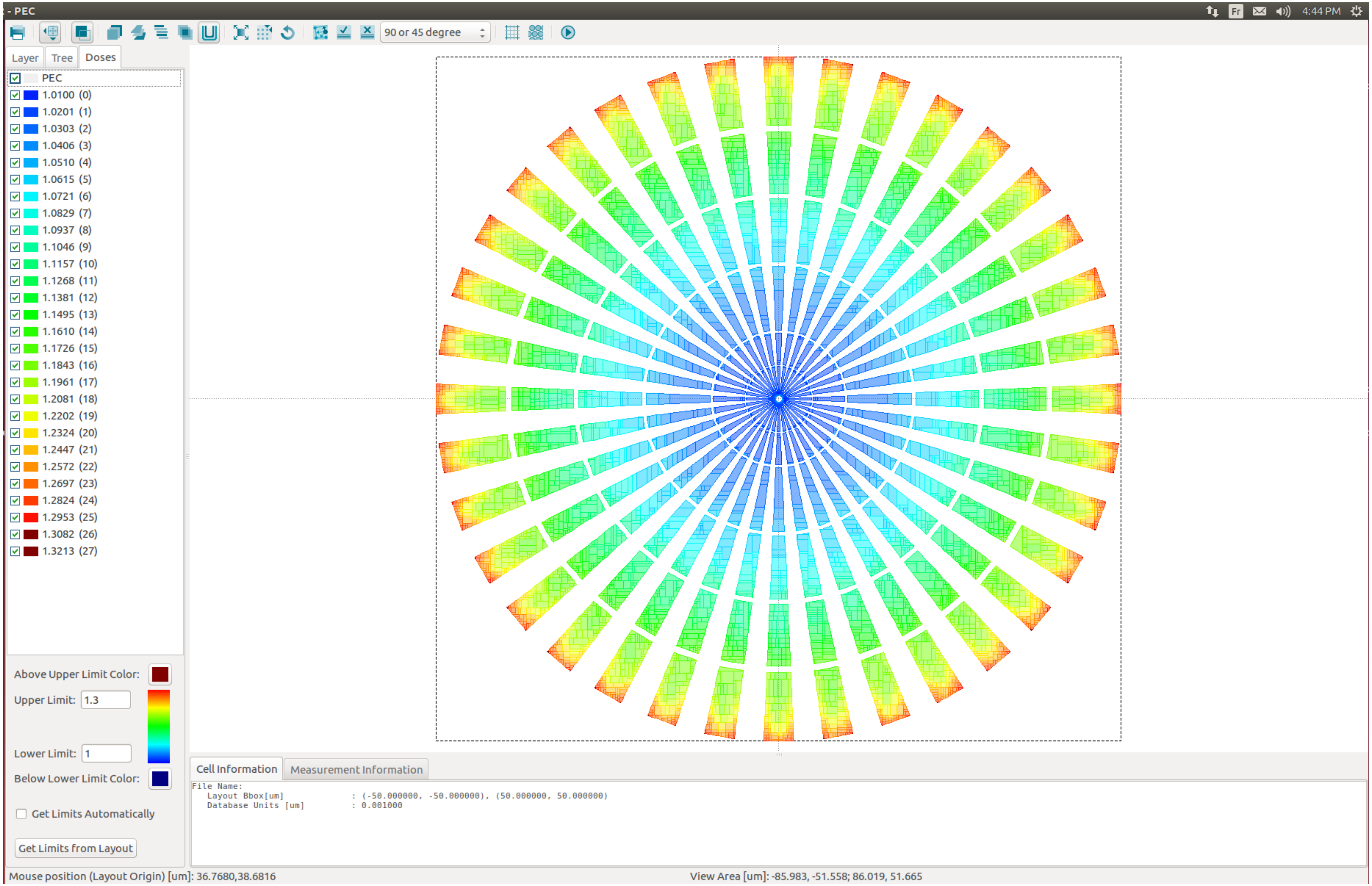


Commercial software

Not always possible(negative dose!)

Still difficult to fabricate very dense line array

Example of proximity effect correction



☑ PEC
☑ 🟦 1.0100 (0)
☑ 🟦 1.0201 (1)
☑ 🟦 1.0303 (2)
☑ 🟦 1.0406 (3)
☑ 🟦 1.0510 (4)
☑ 🟦 1.0615 (5)
☑ 🟦 1.0721 (6)
☑ 🟦 1.0829 (7)
☑ 🟩 1.0937 (8)
☑ 🟩 1.1046 (9)
☑ 🟩 1.1157 (10)
☑ 🟩 1.1268 (11)
☑ 🟩 1.1381 (12)
☑ 🟩 1.1495 (13)
☑ 🟩 1.1610 (14)
☑ 🟩 1.1726 (15)
☑ 🟩 1.1843 (16)
☑ 🟩 1.1961 (17)
☑ 🟨 1.2081 (18)
☑ 🟨 1.2202 (19)
☑ 🟨 1.2324 (20)
☑ 🟧 1.2447 (21)
☑ 🟧 1.2572 (22)
☑ 🟧 1.2697 (23)
☑ 🟥 1.2824 (24)
☑ 🟥 1.2953 (25)
☑ 🟫 1.3082 (26)
☑ 🟫 1.3213 (27)

Above Upper Limit Color: 🟫

Upper Limit: 1.3

Lower Limit: 1

Below Lower Limit Color: 🟦

☐ Get Limits Automatically

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File Name:
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   Database Units [um]       : 0.001000
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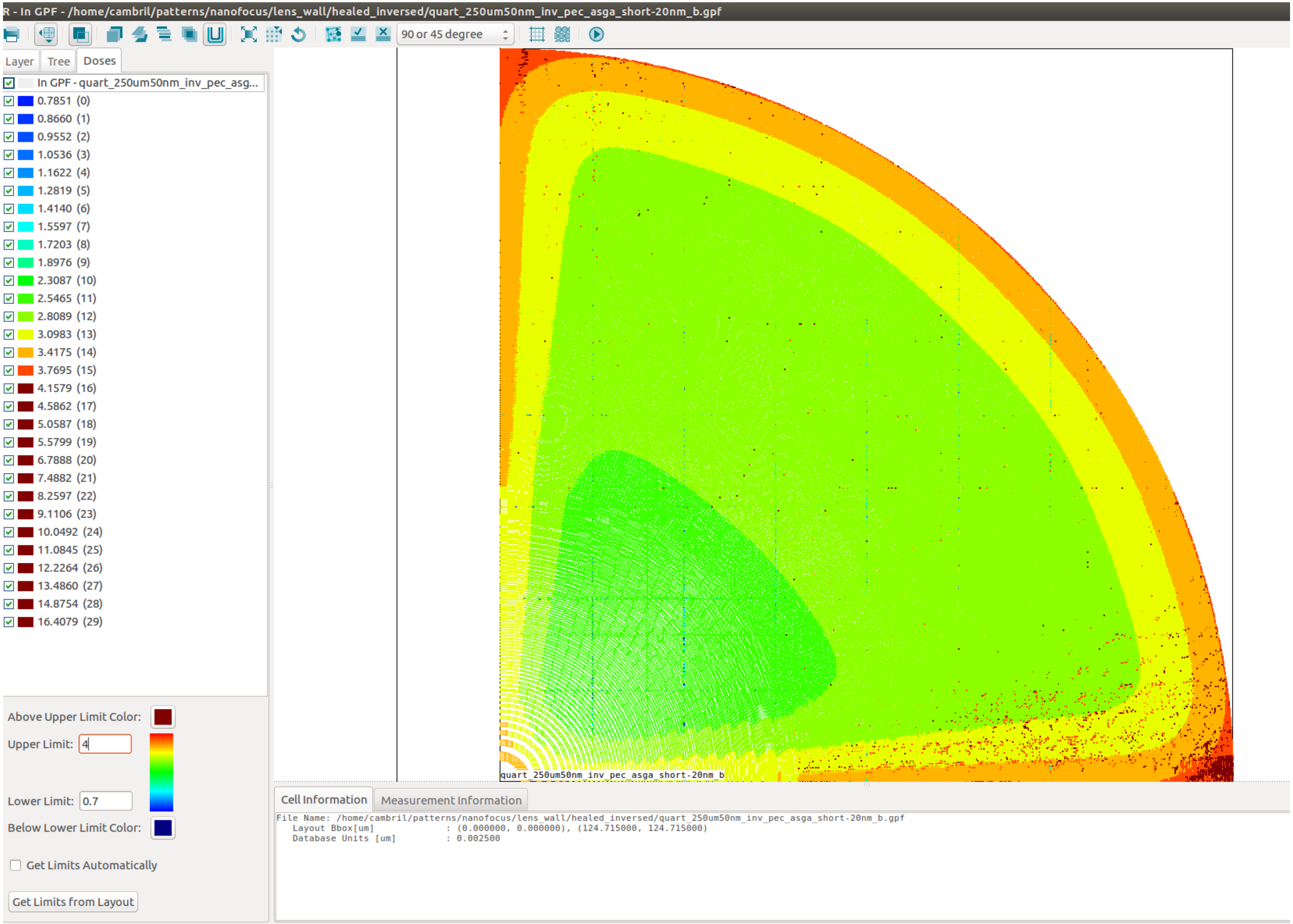
Mouse position (Layout Origin) [um]: 36.7680,38.6816

View Area [um]: -85.983, -51.558; 86.019, 51.665

Example of proximity effect correction



R - In GPF - /home/cambril/patterns/nanofocus/lens_wall/healed_inversed/quart_250um50nm_inv_pec_asga_short-20nm_b.gpf

90 or 45 degree

Layer | Tree | Doses

☑ In GPF - quart_250um50nm_inv_pec_asg...
☑ 🟦 0.7851 (0)
☑ 🟦 0.8660 (1)
☑ 🟦 0.9552 (2)
☑ 🟦 1.0536 (3)
☑ 🟦 1.1622 (4)
☑ 🟦 1.2819 (5)
☑ 🟦 1.4140 (6)
☑ 🟦 1.5597 (7)
☑ 🟩 1.7203 (8)
☑ 🟩 1.8976 (9)
☑ 🟩 2.3087 (10)
☑ 🟩 2.5465 (11)
☑ 🟩 2.8089 (12)
☑ 🟨 3.0983 (13)
☑ 🟧 3.4175 (14)
☑ 🟥 3.7695 (15)
☑ 🟥 4.1579 (16)
☑ 🟥 4.5862 (17)
☑ 🟥 5.0587 (18)
☑ 🟥 5.5799 (19)
☑ 🟥 6.7888 (20)
☑ 🟥 7.4882 (21)
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☑ 🟥 12.2264 (26)
☑ 🟥 13.4860 (27)
☑ 🟥 14.8754 (28)
☑ 🟥 16.4079 (29)

Above Upper Limit Color: 🟥
Upper Limit: 4
Lower Limit: 0.7
Below Lower Limit Color: 🟦

☐ Get Limits Automatically

Get Limits from Layout

quart_250um50nm_inv_pec_asga_short-20nm_b

Cell Information | Measurement Information

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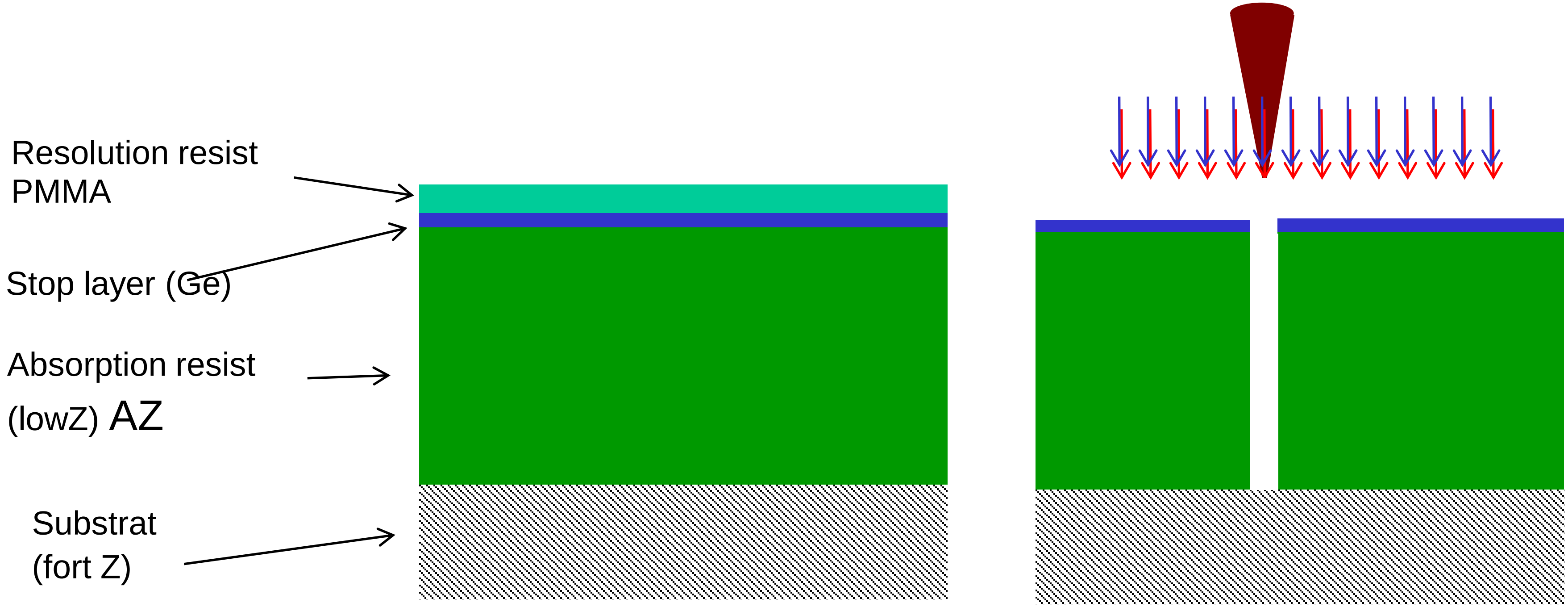
Multilayer Techniques



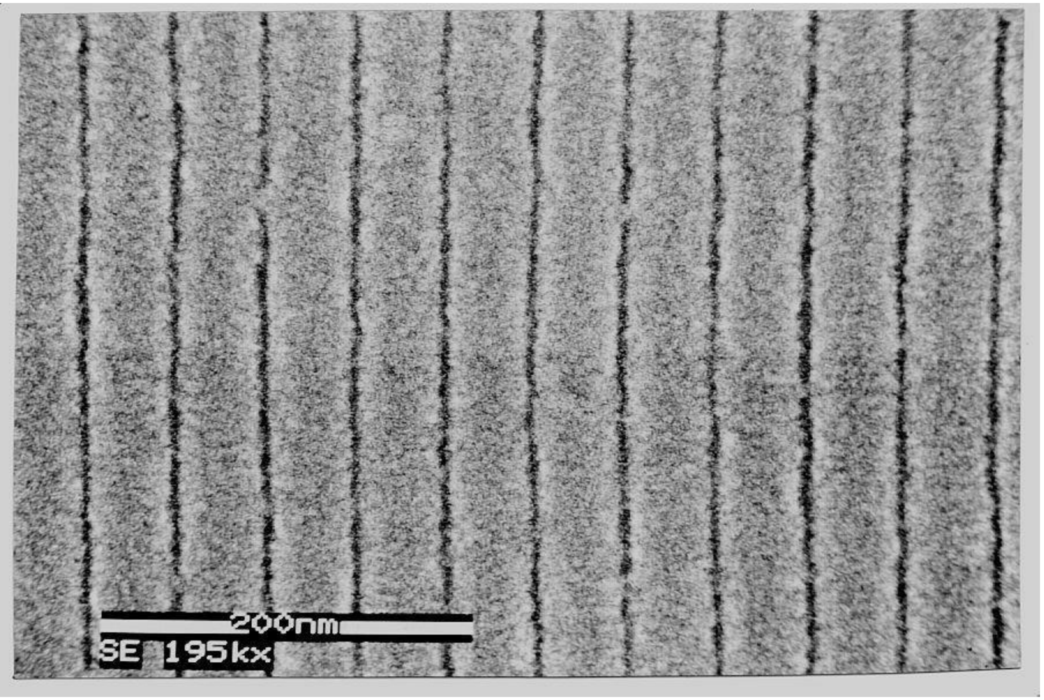
Resolution resist
PMMA

Stop layer (Ge)

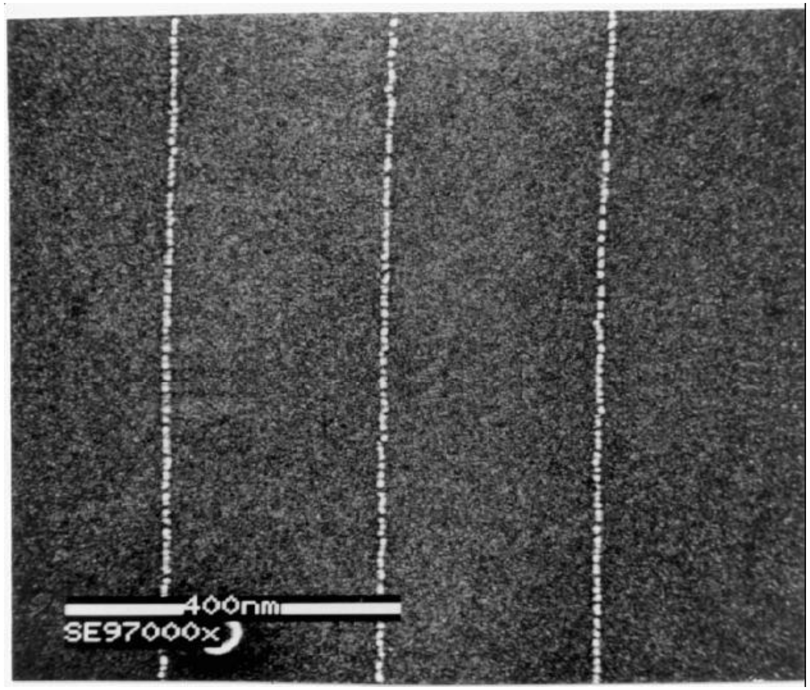
Absorption resist
(lowZ) AZ

Substrat
(fort Z)

High voltage :200kV e-beam lithography on PMMA

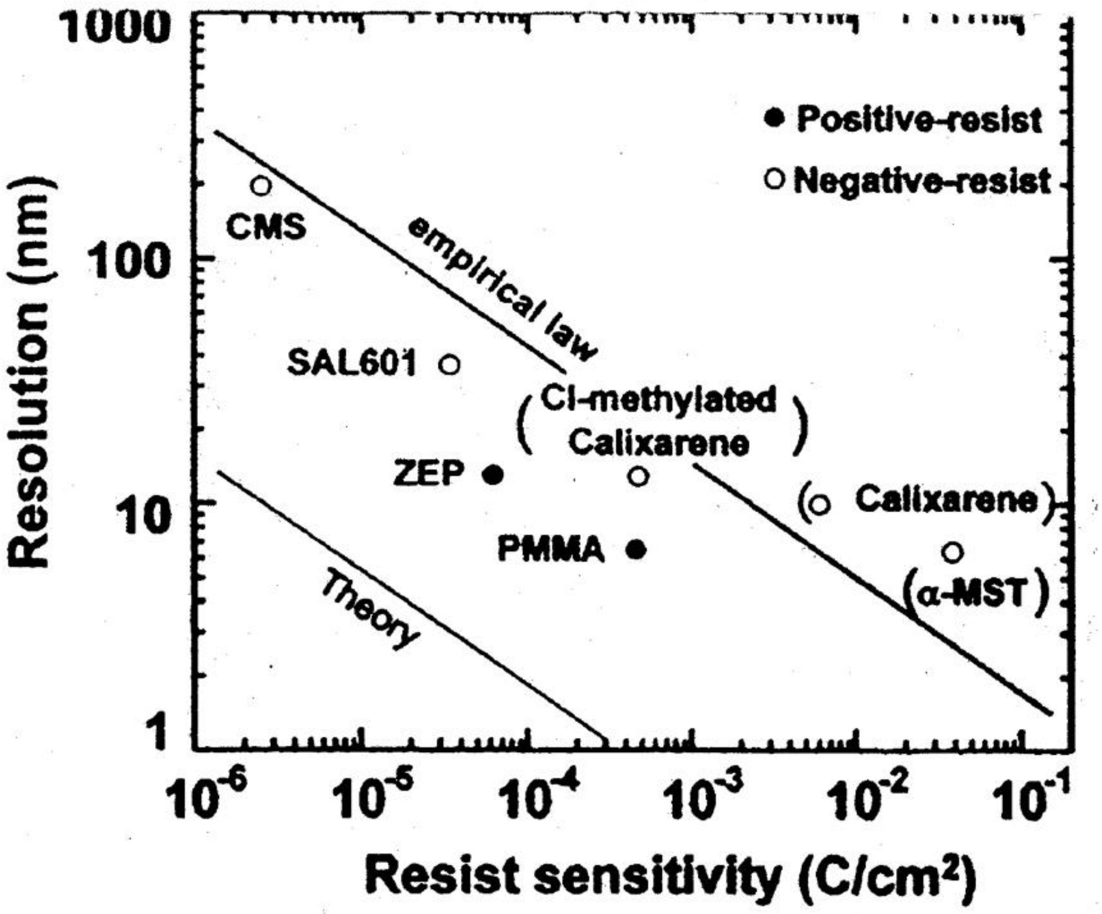


Line <10nm



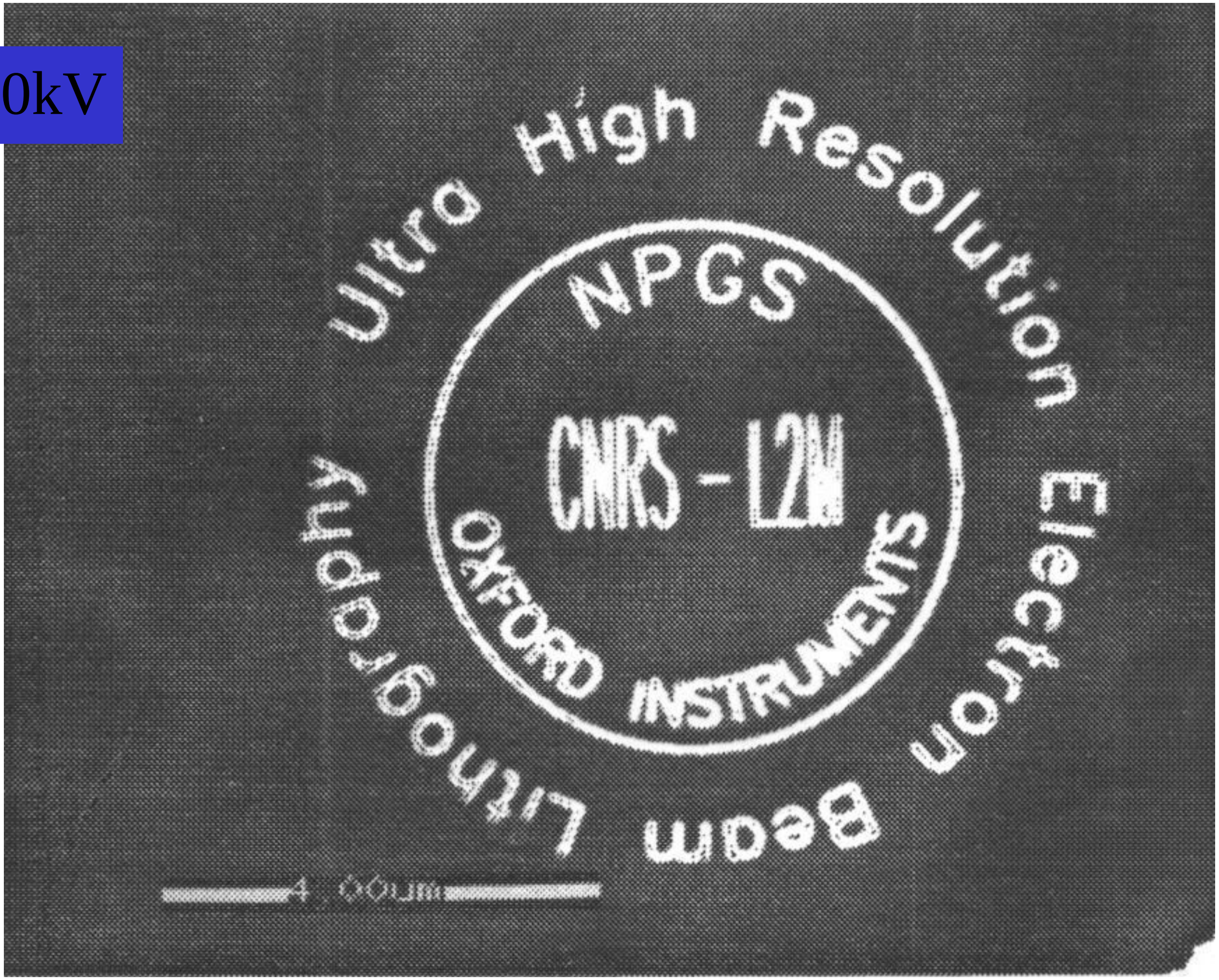
lift-off granular gold

Organic resist resolution



Inorganic resist

AlF$_3$ at 200kV



Electron beam lithography

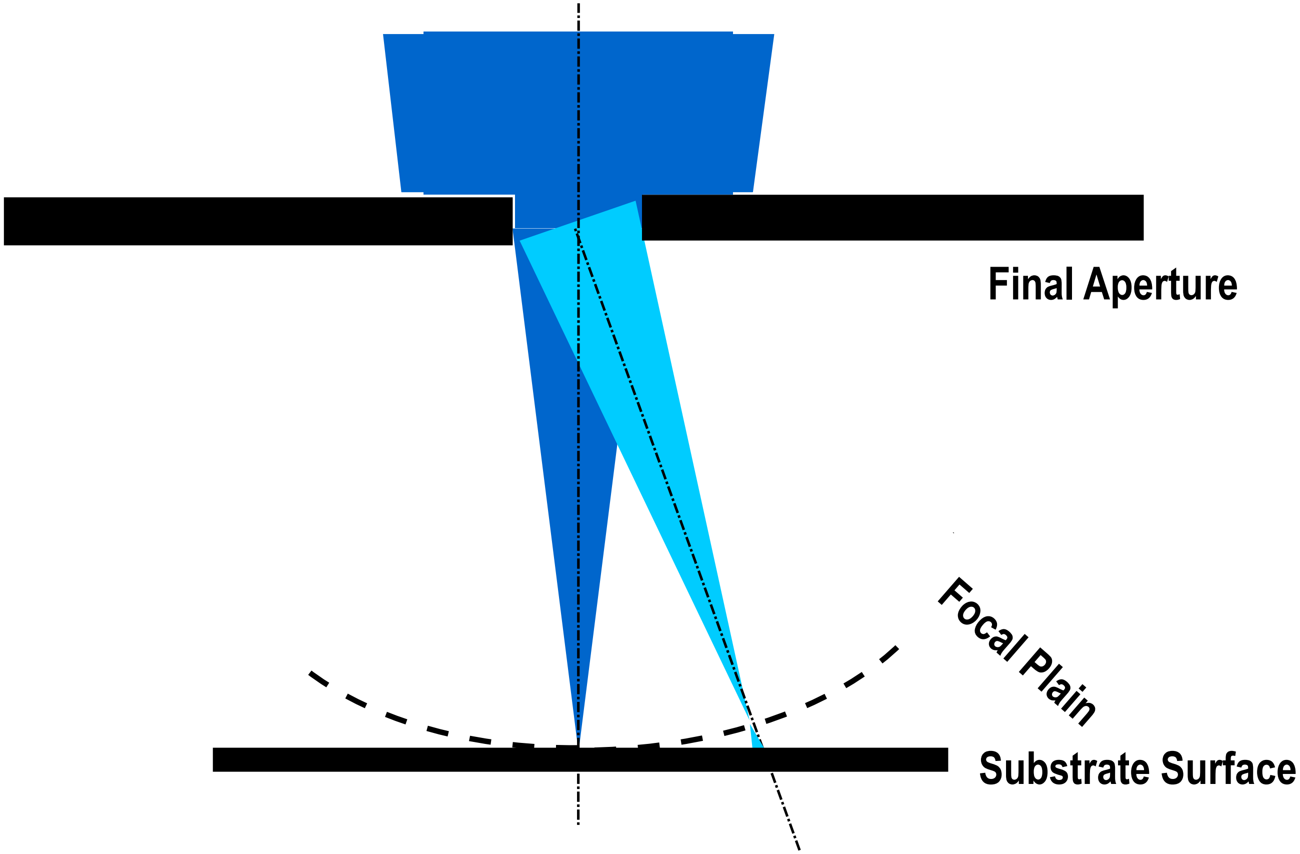
- High resolution

- No mask needed

- Slow : not compatible for microelectronics

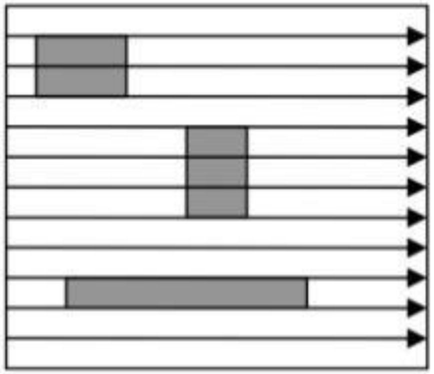
- Intermediate cost
- 200k€-500k€ for an SEM based equipment
- 2M€-3M€ for an E beam writer

Writing strategy



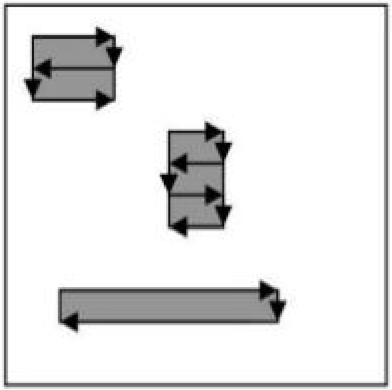
Need to divide the pattern into writing field

Scanning methods



Raster Scan

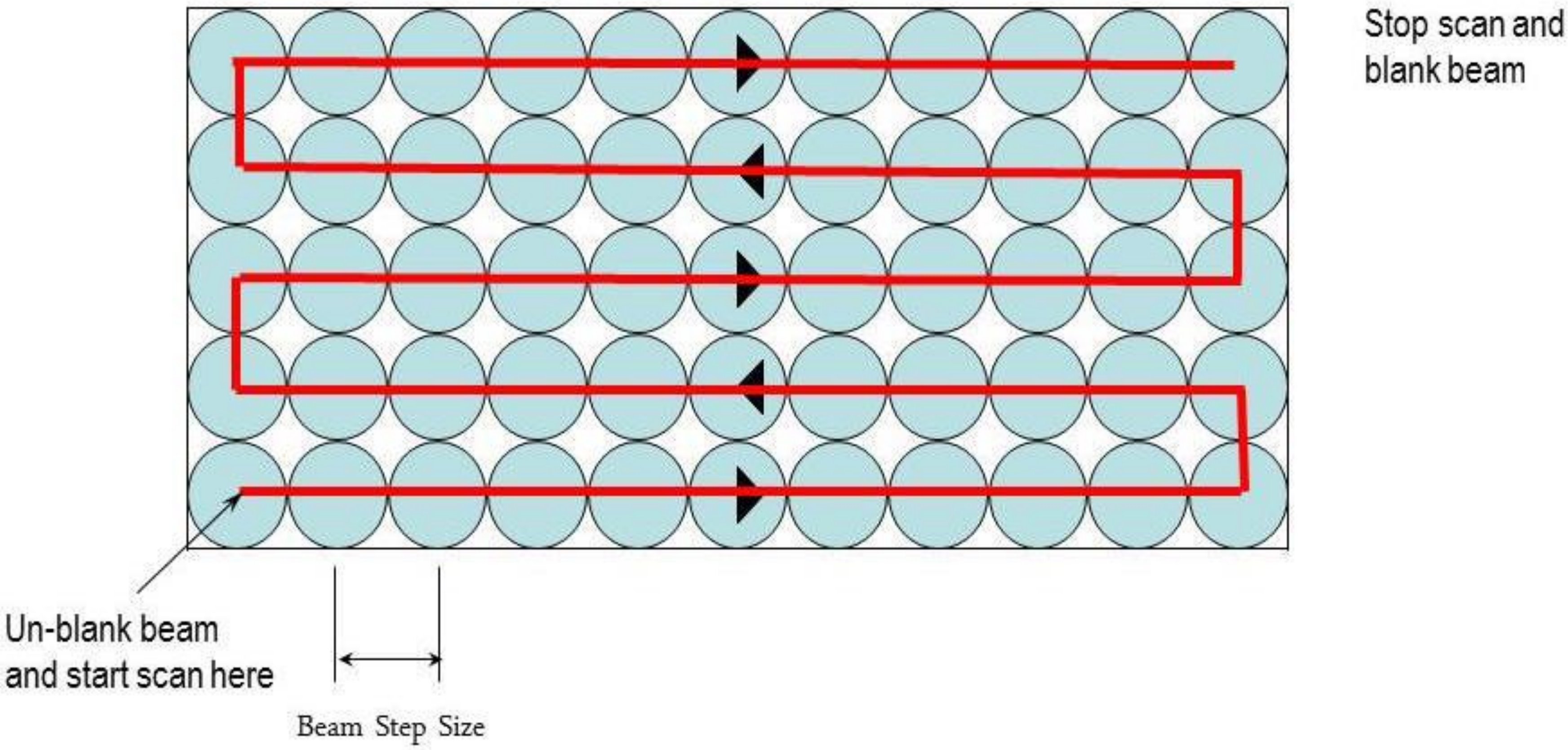
- The whole field is scanned
- The beam is turn on and off
- Time for a field is always the same whatever is the filling factor of the pattern
- Difficult to change the dose inside a field



Vector Scan

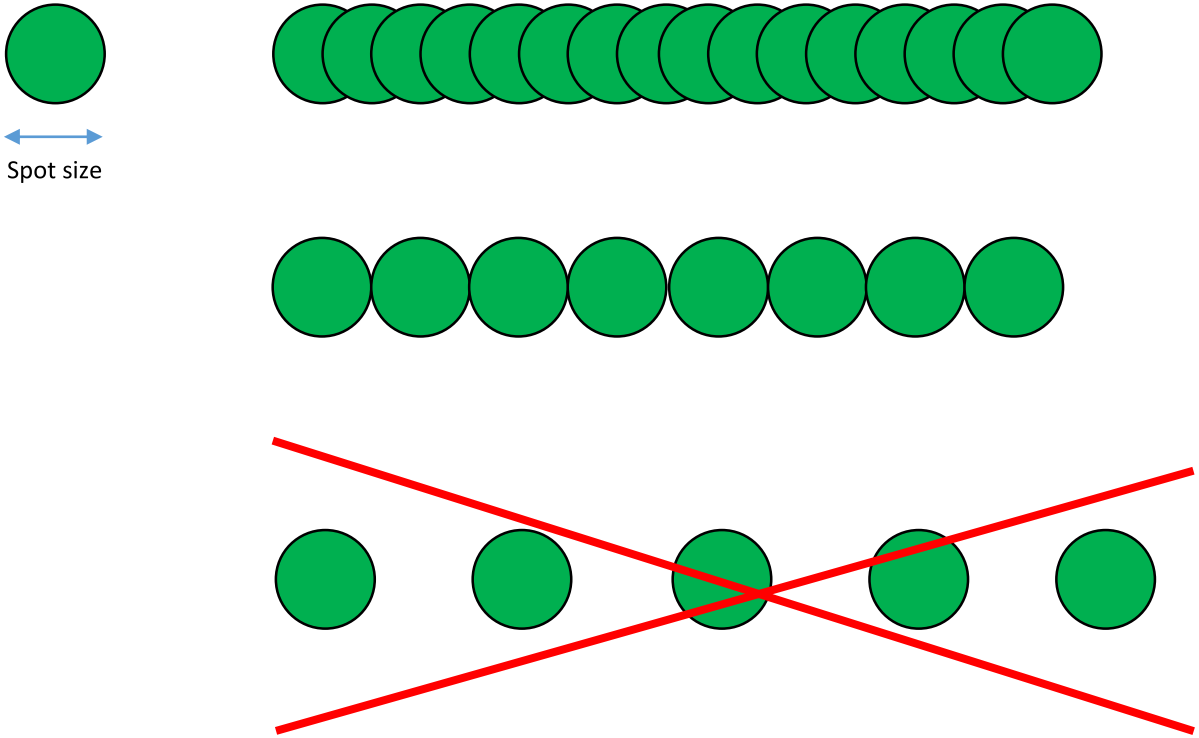
- The beam scan only the patterned area
- Easy to change the dose inside a field.
- Fast if small filling factor
- Need accurate placement of the beam

Beam step size



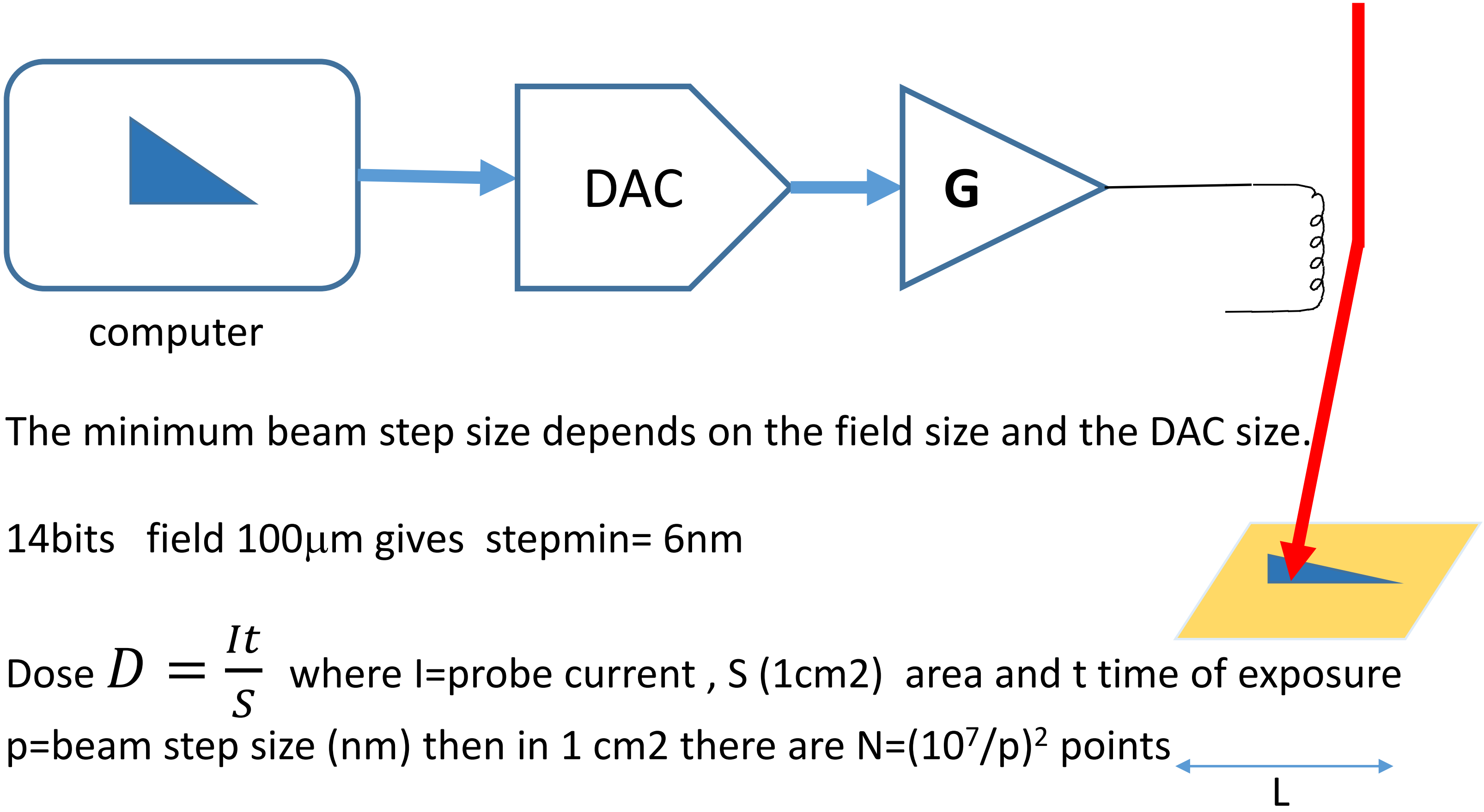
Beam step size needs to be adjust with the beam spot size

Beam step size



Need also to be consistent with the maximum speed of the scanning and the minimum beam step size

Scanning speed and minimum beam step size



The minimum beam step size depends on the field size and the DAC size.

14bits field 100µm gives stepmin= 6nm

Dose $D = \frac{It}{S}$ where I=probe current , S (1cm2) area and t time of exposure

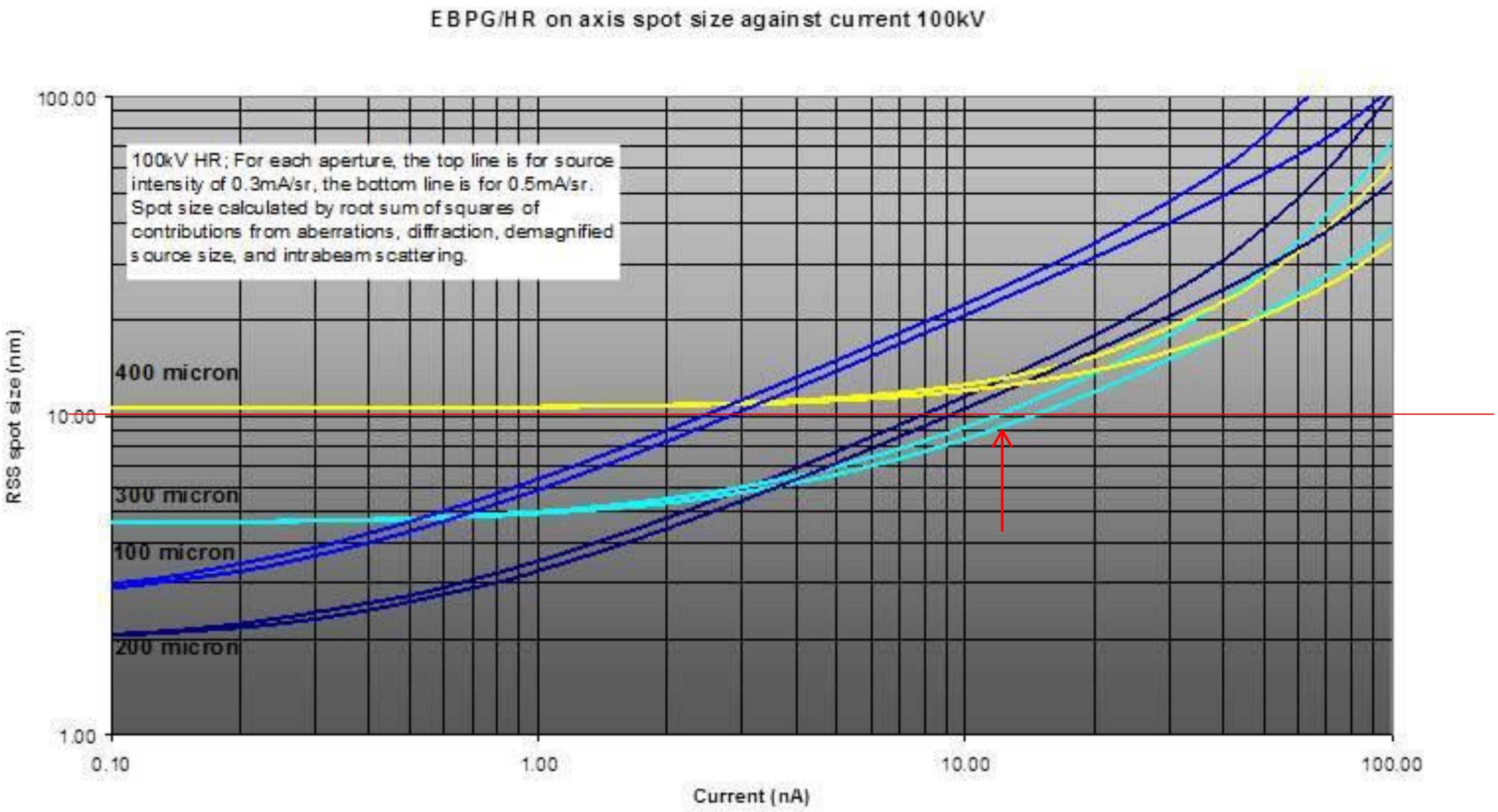
p=beam step size (nm) then in 1 cm2 there are N=$(10^7/p)^2$ points

Time between two pixels: $t = \frac{D}{I} \times \frac{p^2}{10^{14}}$ or max frequency of the DAC

$$f_{max} = \frac{I \times 10^{14}}{D \times p^2}$$

Example: 14bits DAC I=1nA D= 500uC/cm2 p=1nm fmax = 200MHz!

Choosing writing parameters



100kV HR; For each aperture, the top line is for source intensity of 0.3mA/sr, the bottom line is for 0.5mA/sr. Spot size calculated by root sum of squares of contributions from aberrations, diffraction, demagnified source size, and intrabeam scattering.

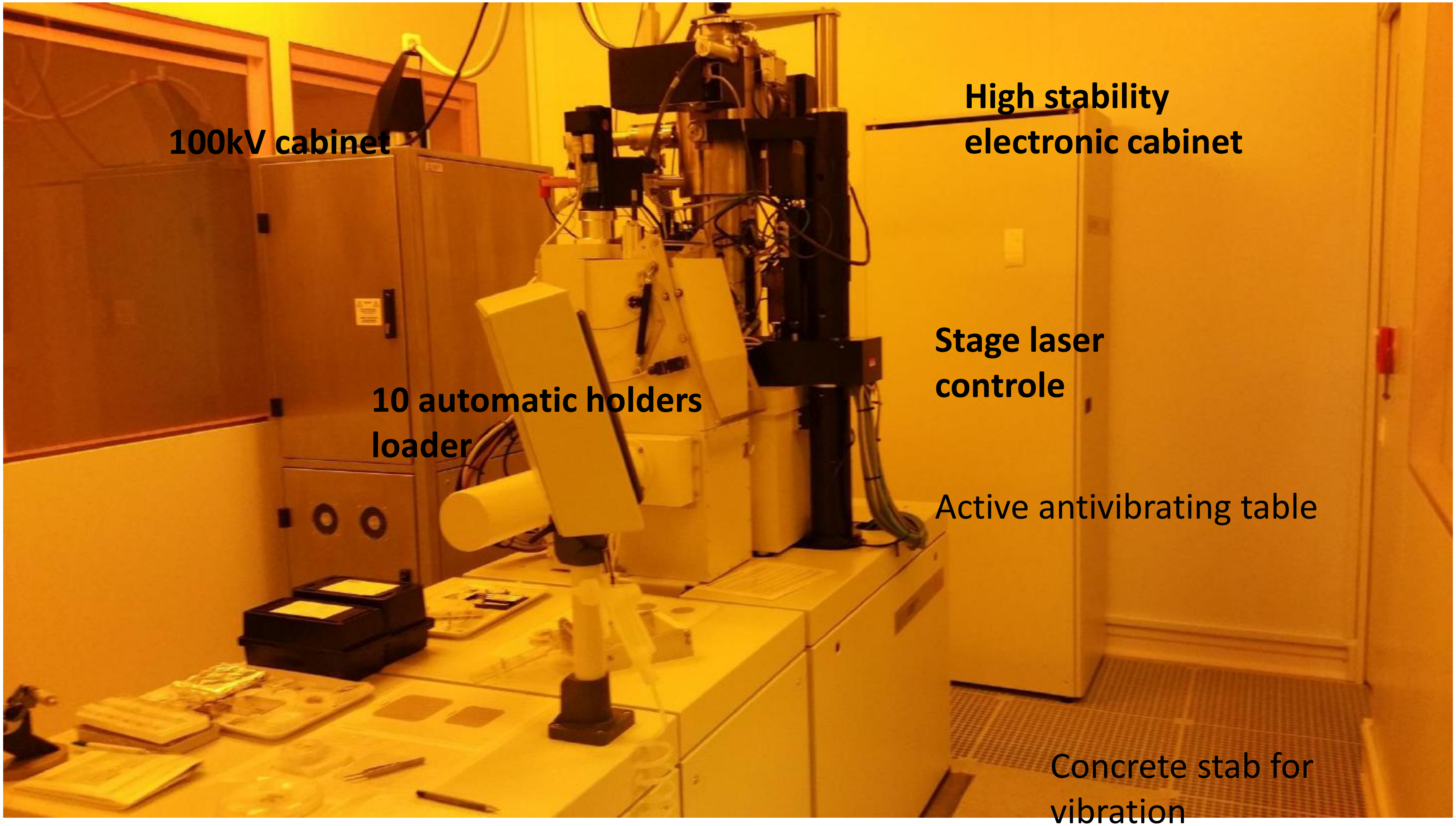
First one chooses a spot size according to the minimum feature of the pattern
This will fix a maximum beam step size
Then one chooses the highest current in order to short the writing time keeping the DAC frequency below the max.
Example D=500 $\mu C/cm^2$ Line 100nm → spot 10nm → beam step 5nm
Diaph 300 I=12nA → freq = 96MHz
Diaph 400 I= 2,5nA → freq = 20MHz or idem with beam step 8nm freq = 7,8MHz

SEM based writer

- Low voltage system 30kV
- Need a dedicated scan generator
- Need to add a beam blanking
- One field writing
- High inductance coil :
  - Hysteresis
  - Dwell time stabilisation
  - Low speed
- Thermal and mechanical stability (enough to make a picture)
- Field distorsions
- Stability of the DC amplifiers (drift, temperature)

cost: 400k€ to 1M€ if more dedicated equipment

The e-beam writer



100kV cabinet

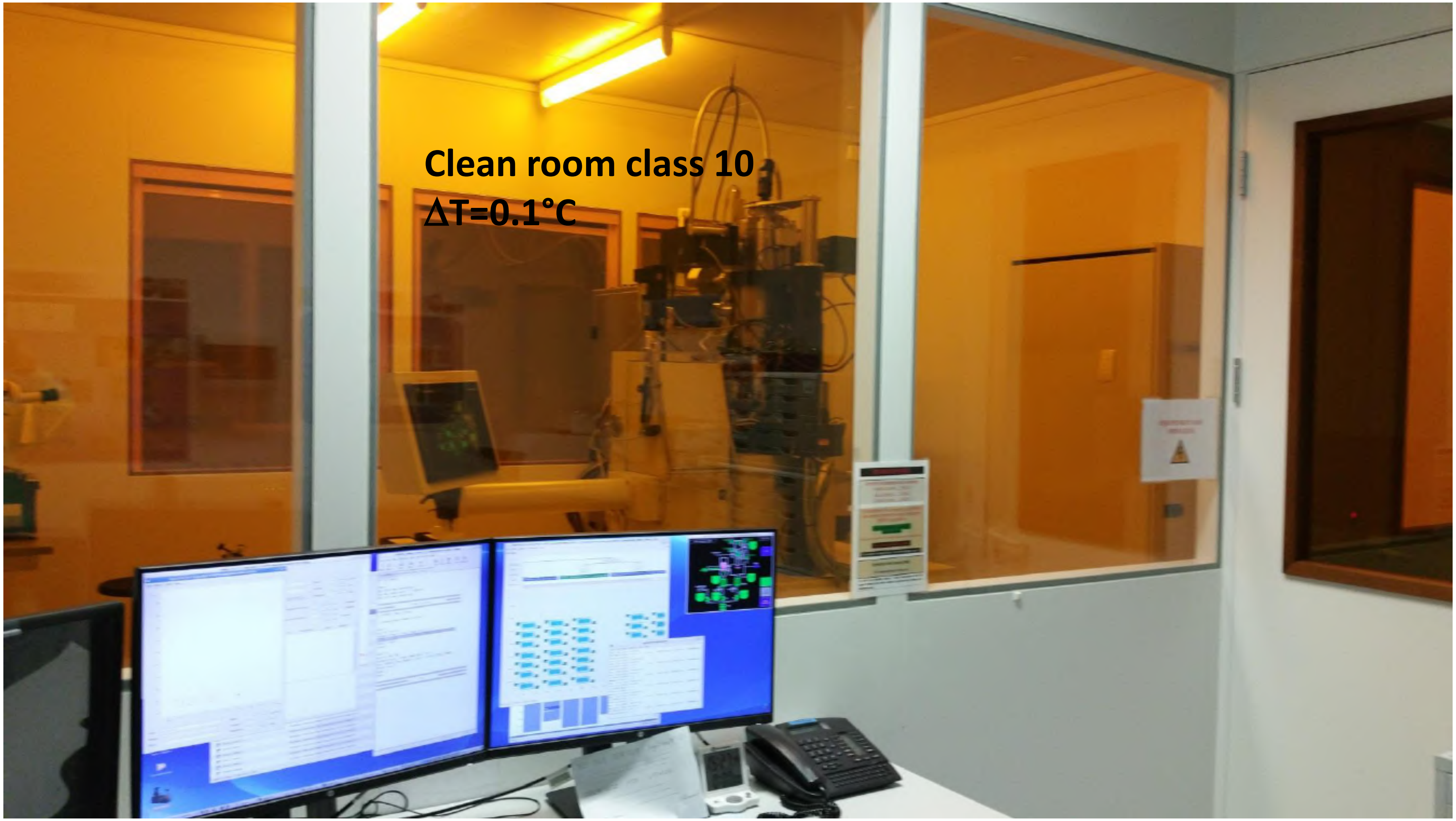
High stability electronic cabinet

Stage laser controle

10 automatic holders loader

Active antivibrating table

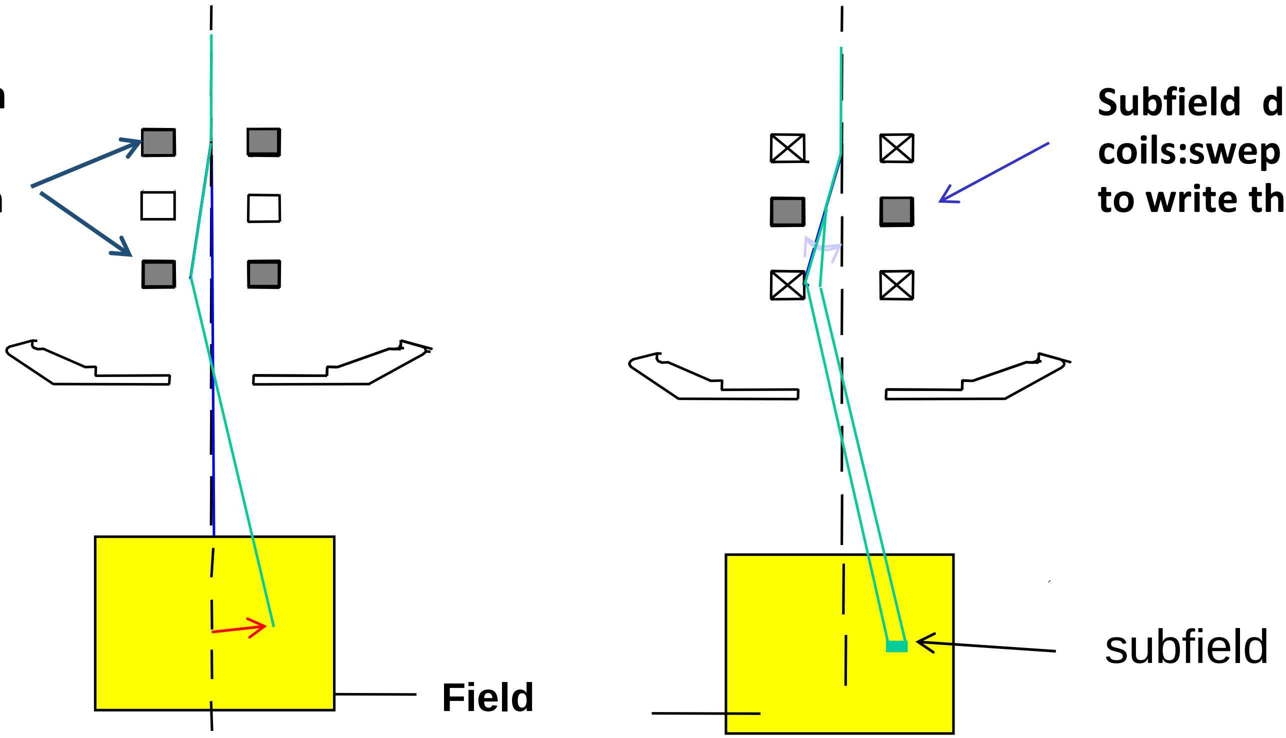
Concrete stab for vibration



Clean room class 10
ΔT=0.1°C

Cost : 2M€ to 3M€
Maintenance of an equipment ~7% of the price/year

Writing strategy



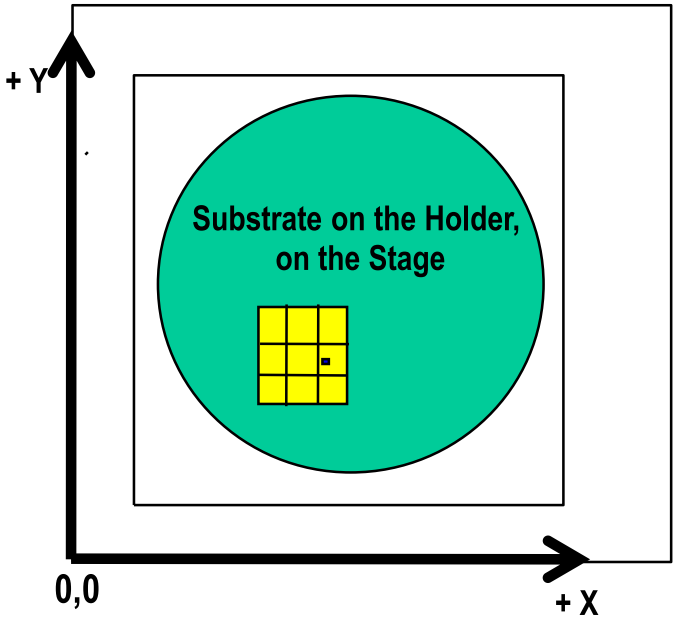
Main field deflection coils: place the spot in a given position in the field. Beam blanked

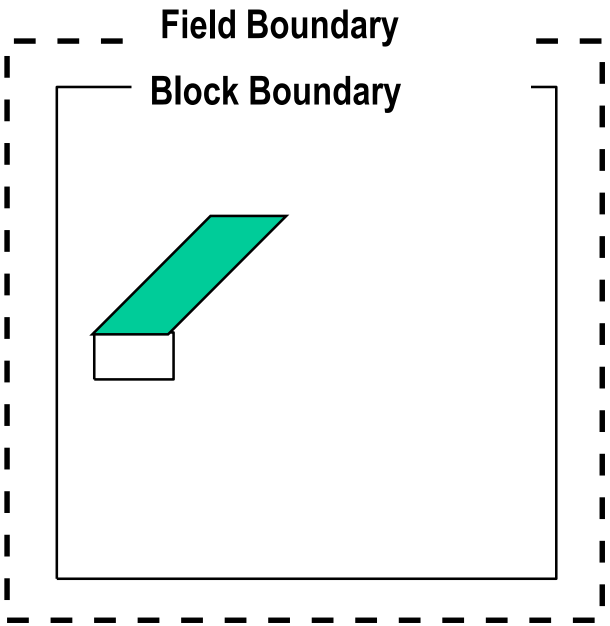
Subfield deflection coils:swep the beam to write the pattern

Main DAC doesn’t need to be fast one can uses a high accuracy DAC 24bits
Subfield small doesn’t need large DAC but fast one : 14bits 50MHz
Small subfield → small current in coils → small hysteresis, no heating

Typical size:
Field :300µmx300µm -> 1mmx1mm mechanical displacement from field to field
Subfield : 2µmx2µm -> 10µmx10µm depending on beam step size

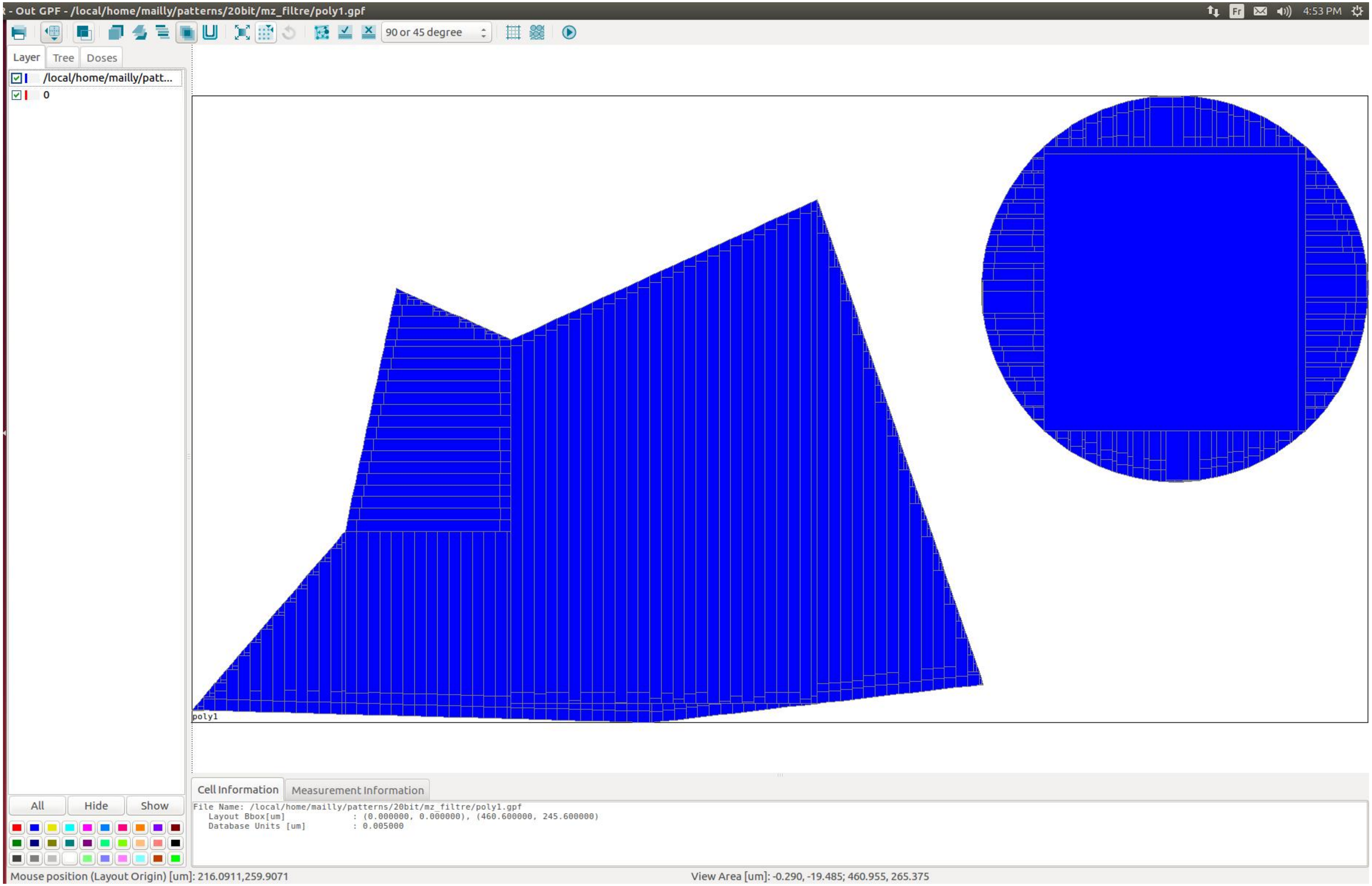
Writing strategy





Trapezia
- Positioned by main deflection
- Written by Trapezia Scan

Exemple of subfield fractionning



- Out GPF - /local/home/mailly/patterns/20bit/mz_filtre/poly1.gpf

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   Database Units [um]           : 0.005000
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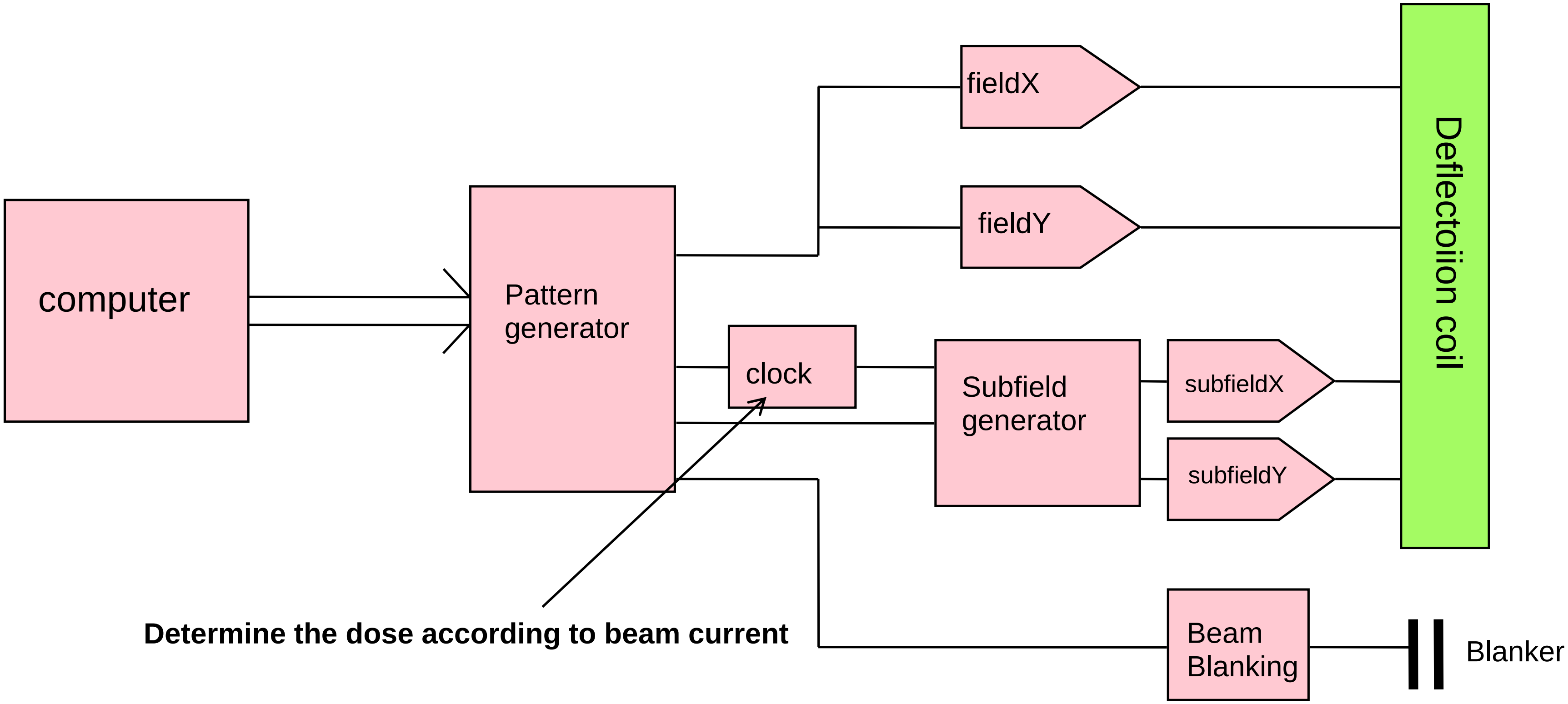
Mouse position (Layout Origin) [um]: 216.0911,259.9071

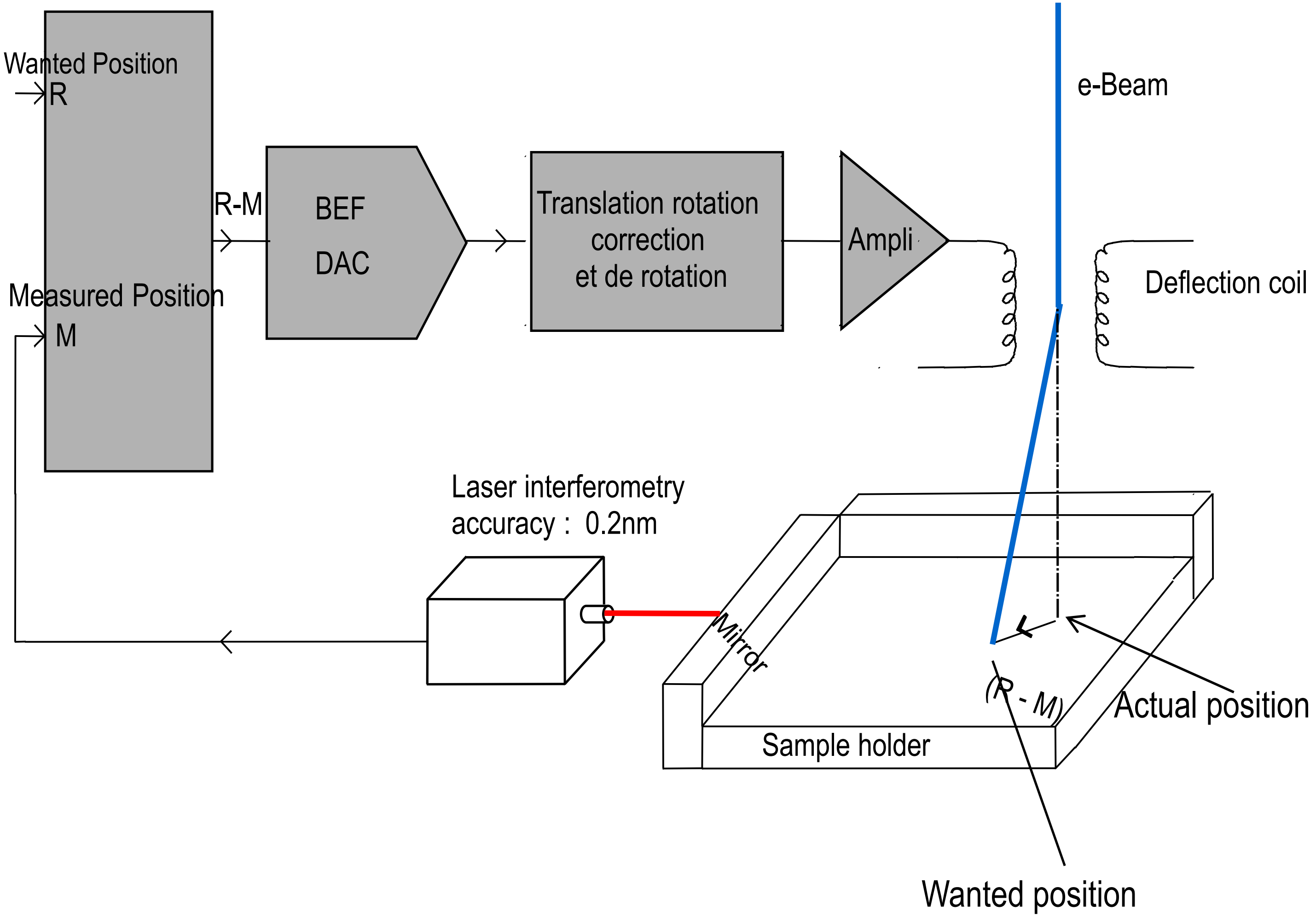
View Area [um]: -0.290, -19.485; 460.955, 265.375

schematic



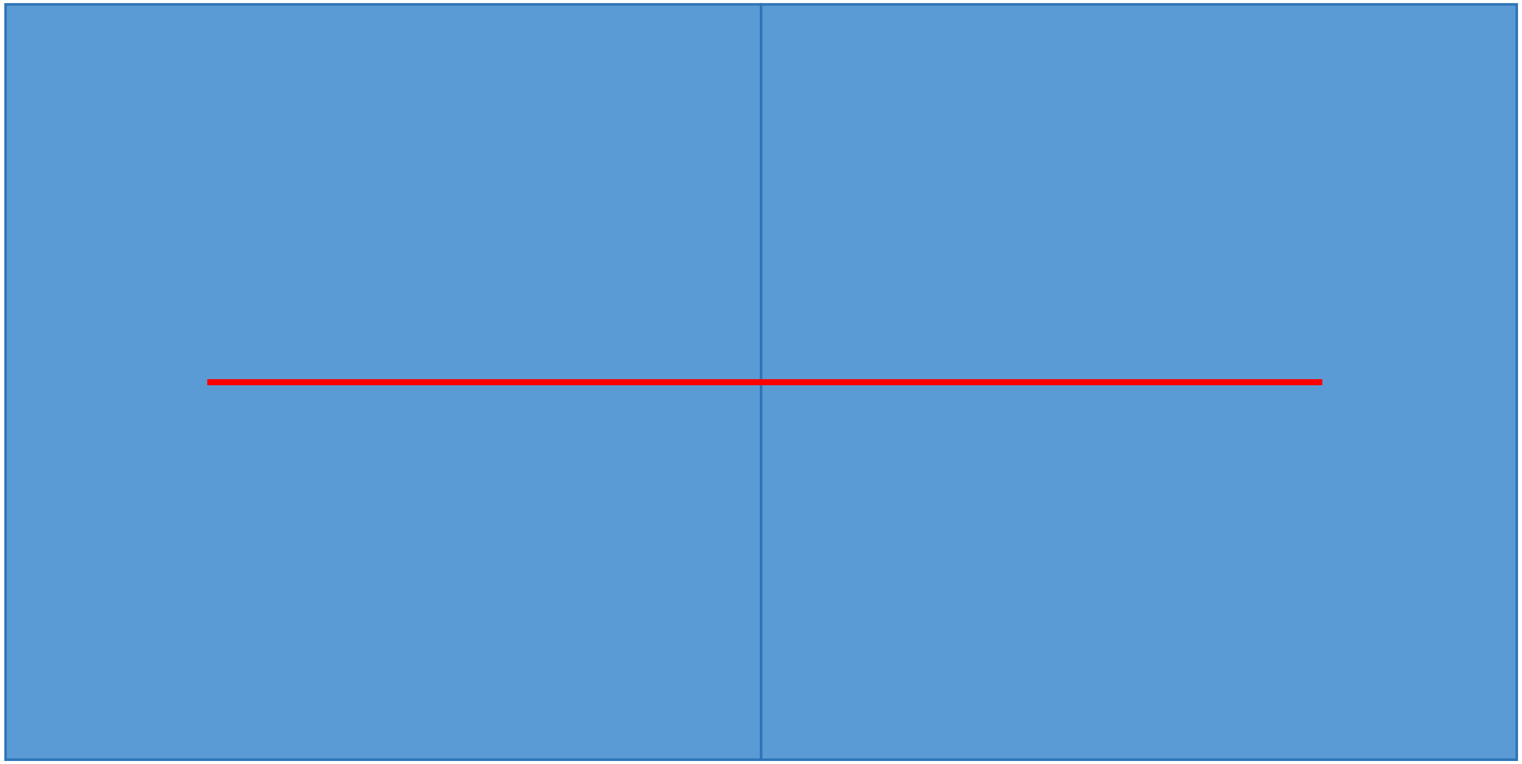
Determine the dose according to beam current

Sample displacement : stiching

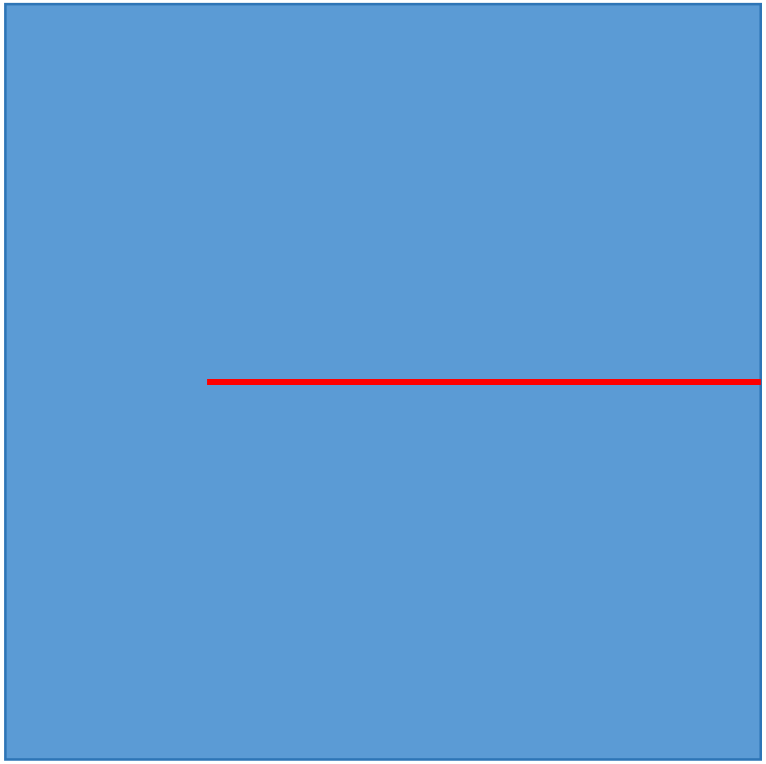


One does not control the displacement of the motors but correct the error by the beam deflection : conserve a very fast displacement.

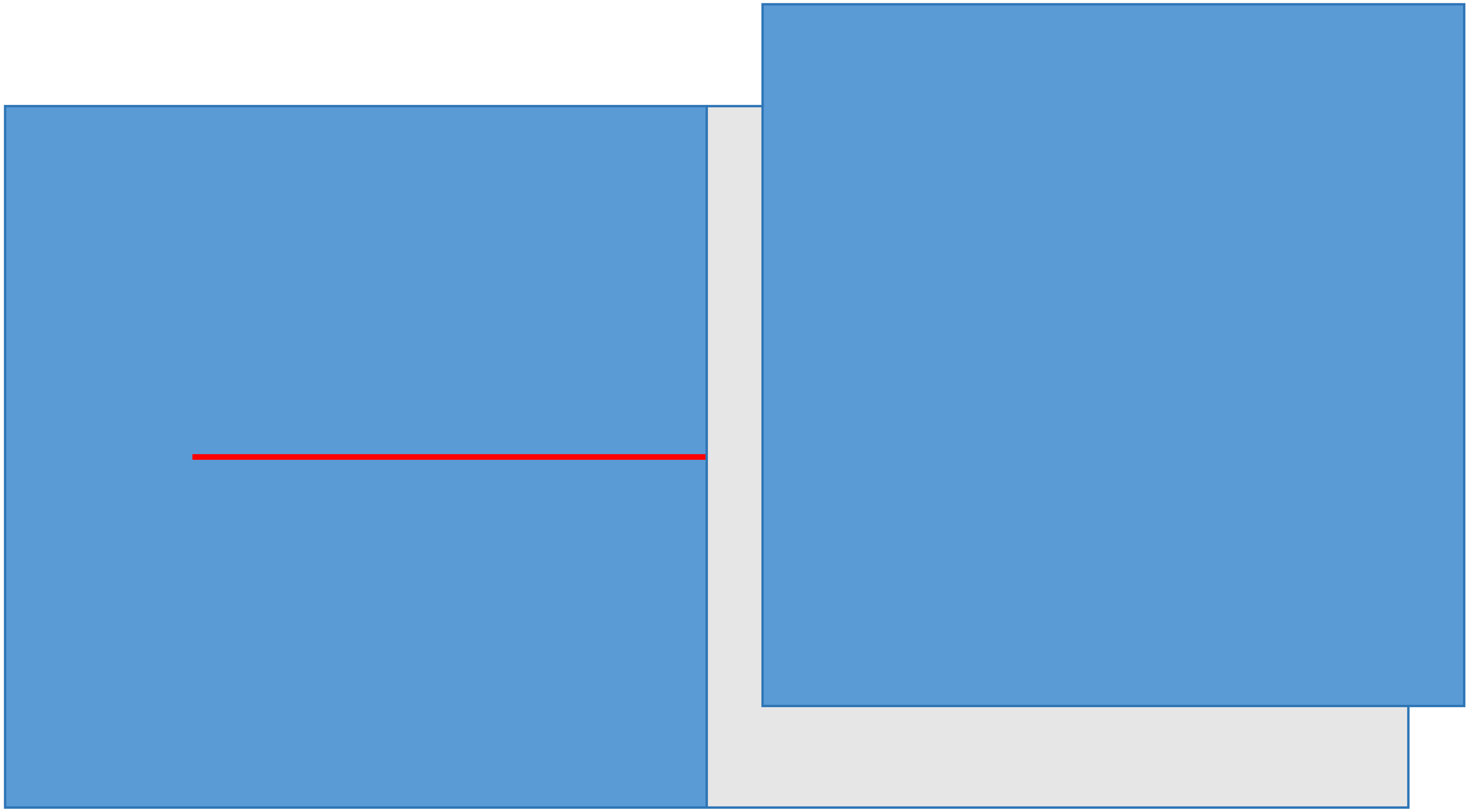
Example a line over two fields



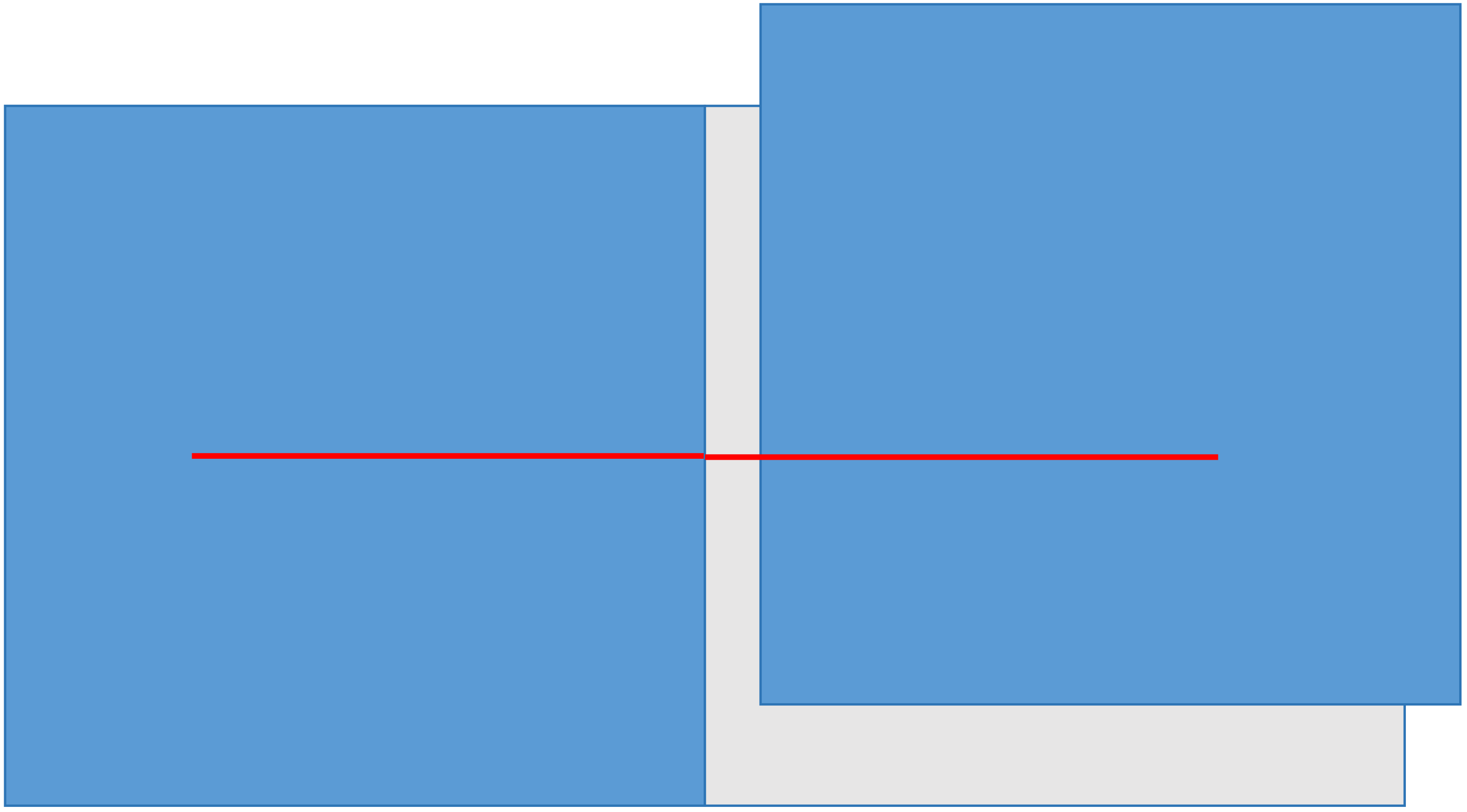
First field



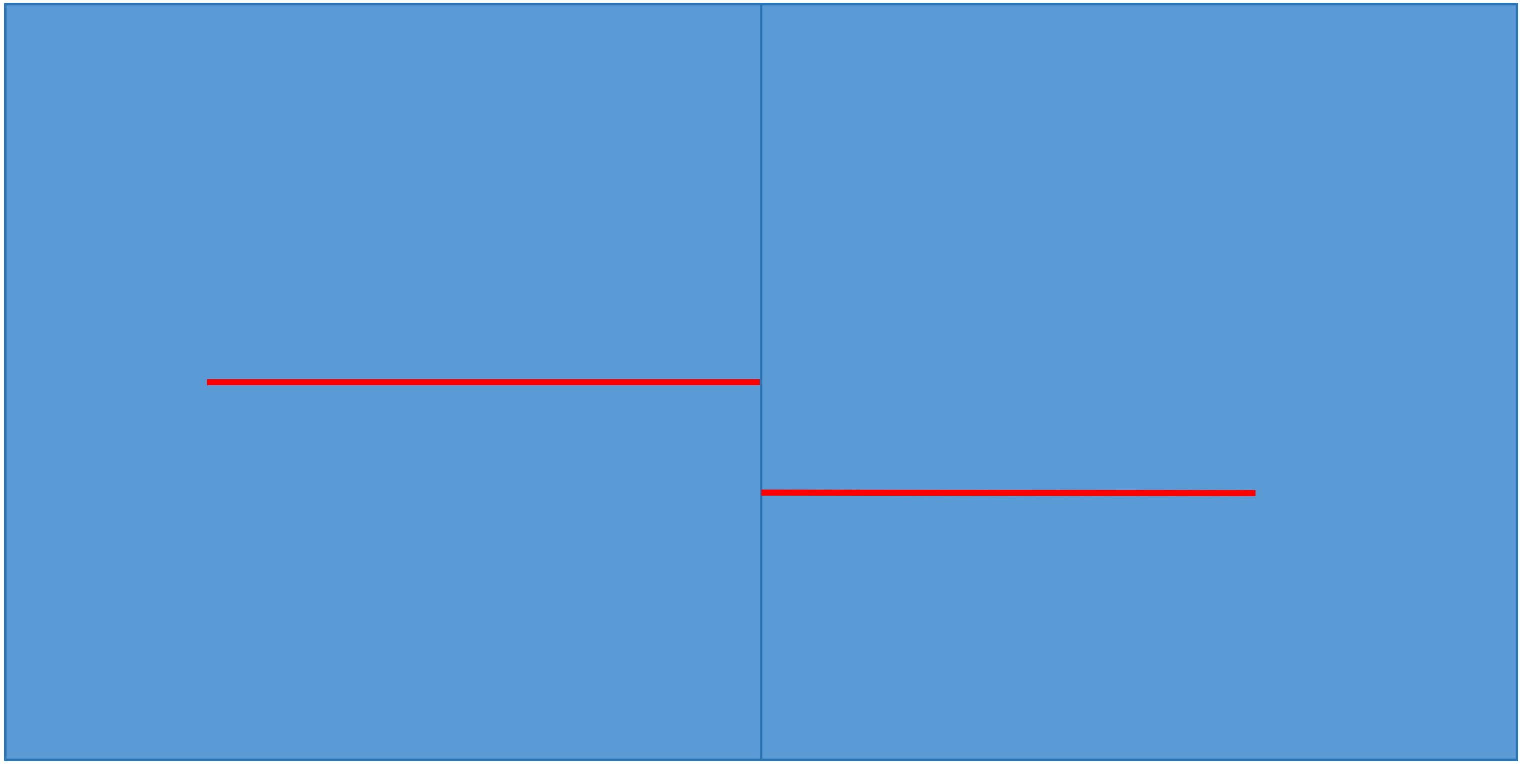
Second field no correction



Second field no correction

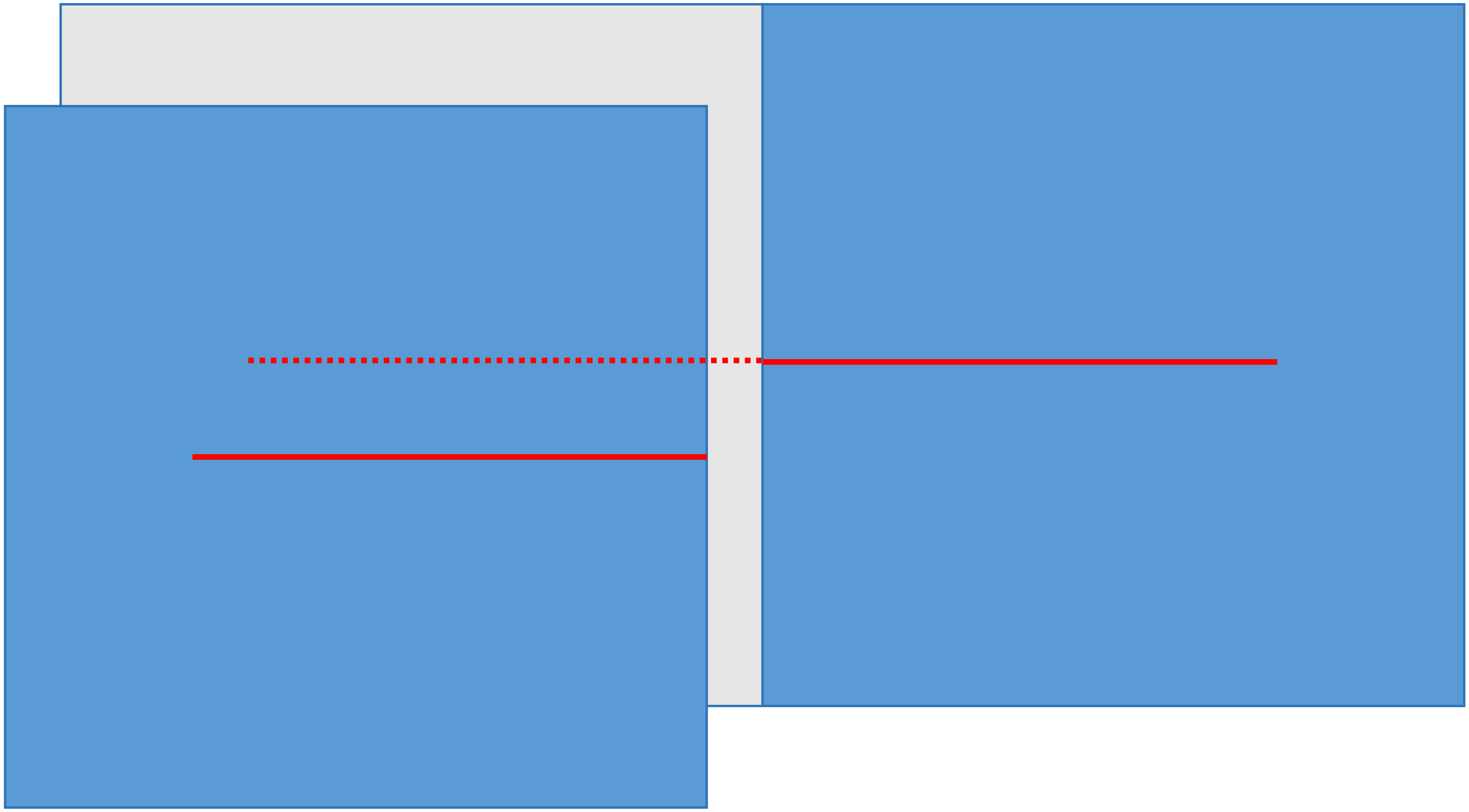


Second field no correction

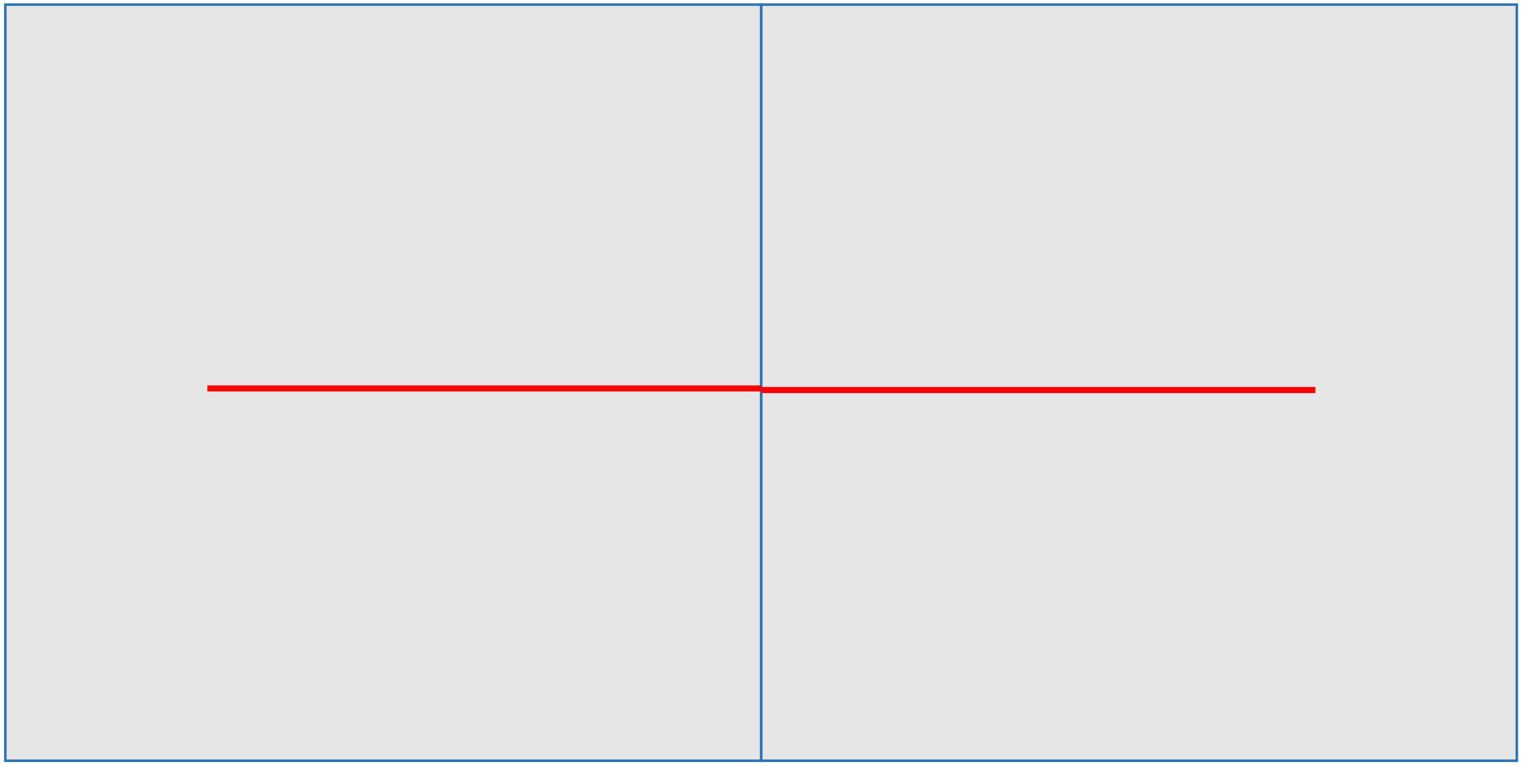


Second field no correction

Second field beam correction



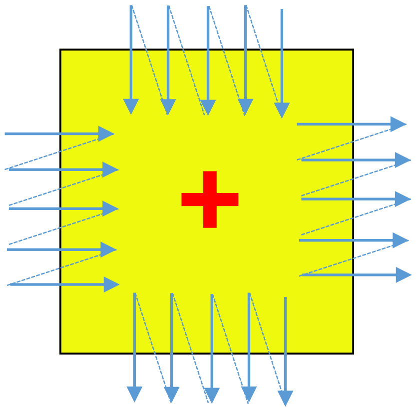
Second field with beam correction

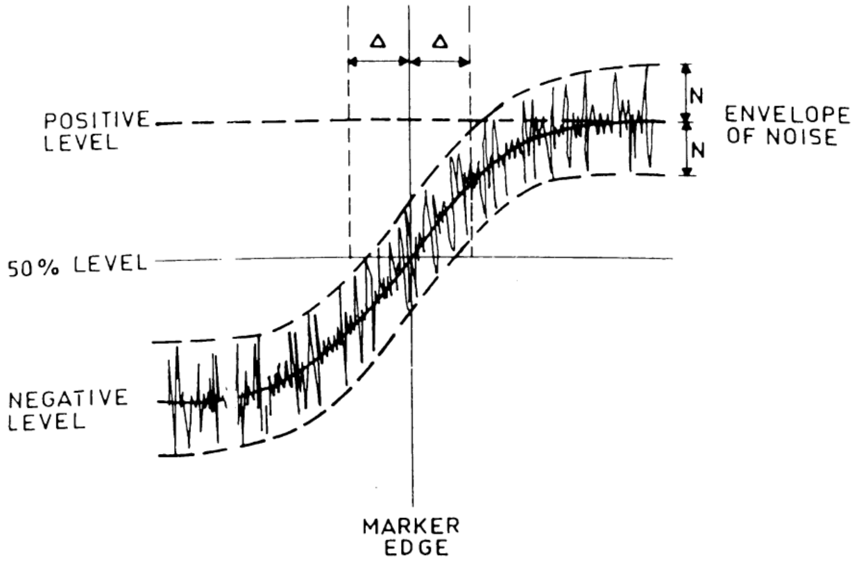


Stiching accuracy is 20nm at 3σ

Mark registration

Mark detection by scanning the beam



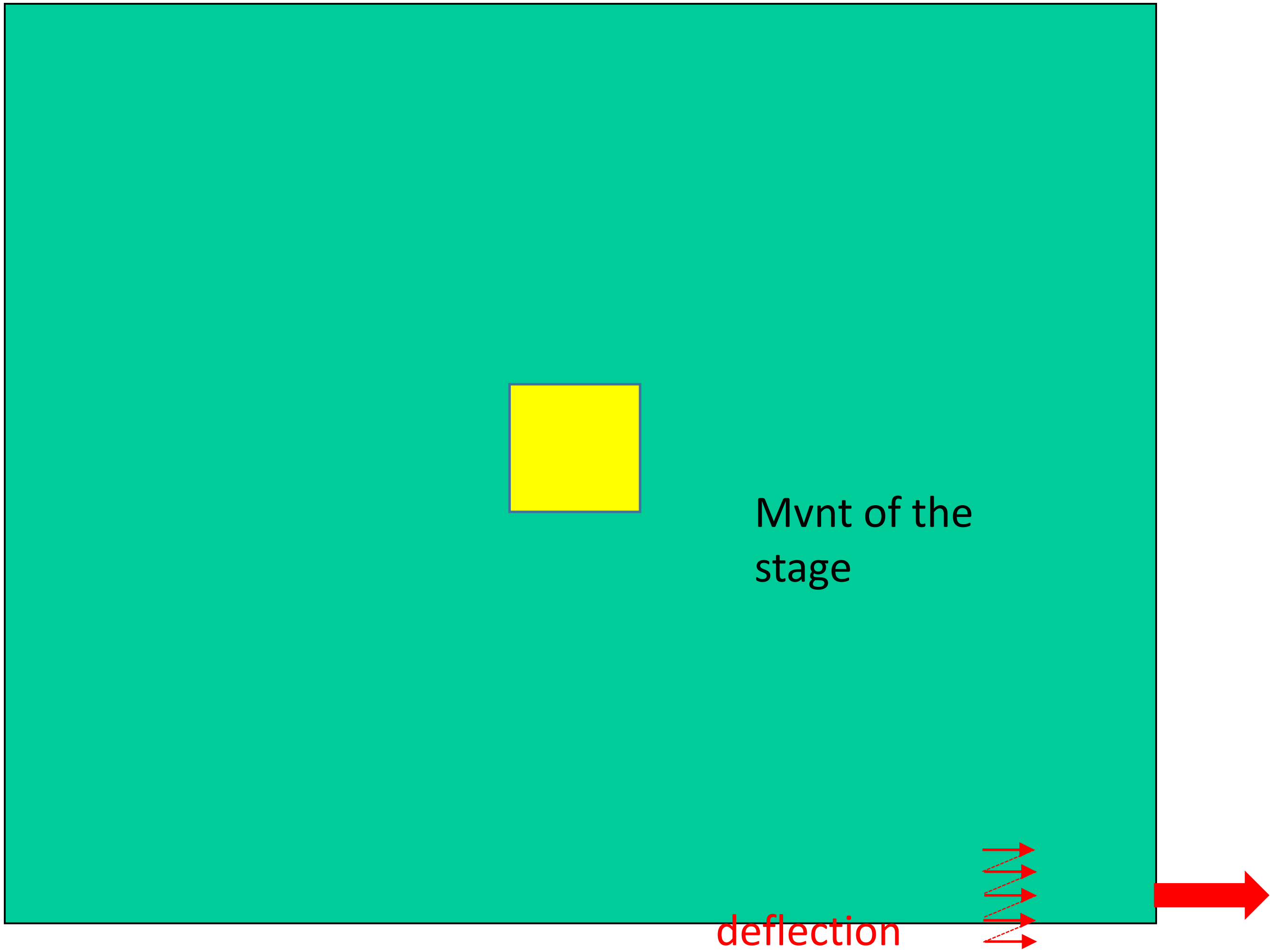


Signal on the SE detector

Allows to precisely determine the center of the mark

Will be used to align two layers

Deflection calibration



Mvnt of the stage

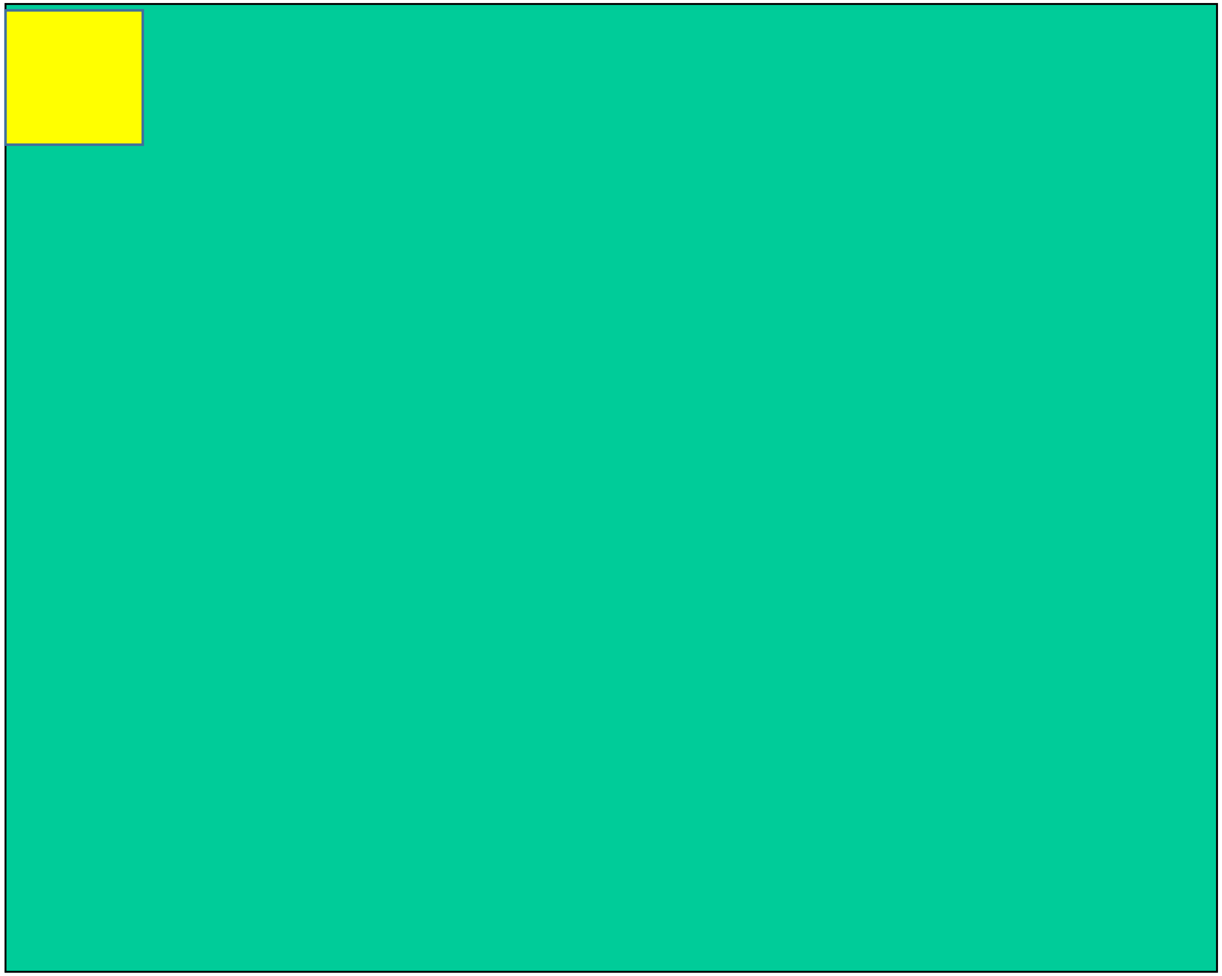
deflection

Measure of error

Deflection calibration

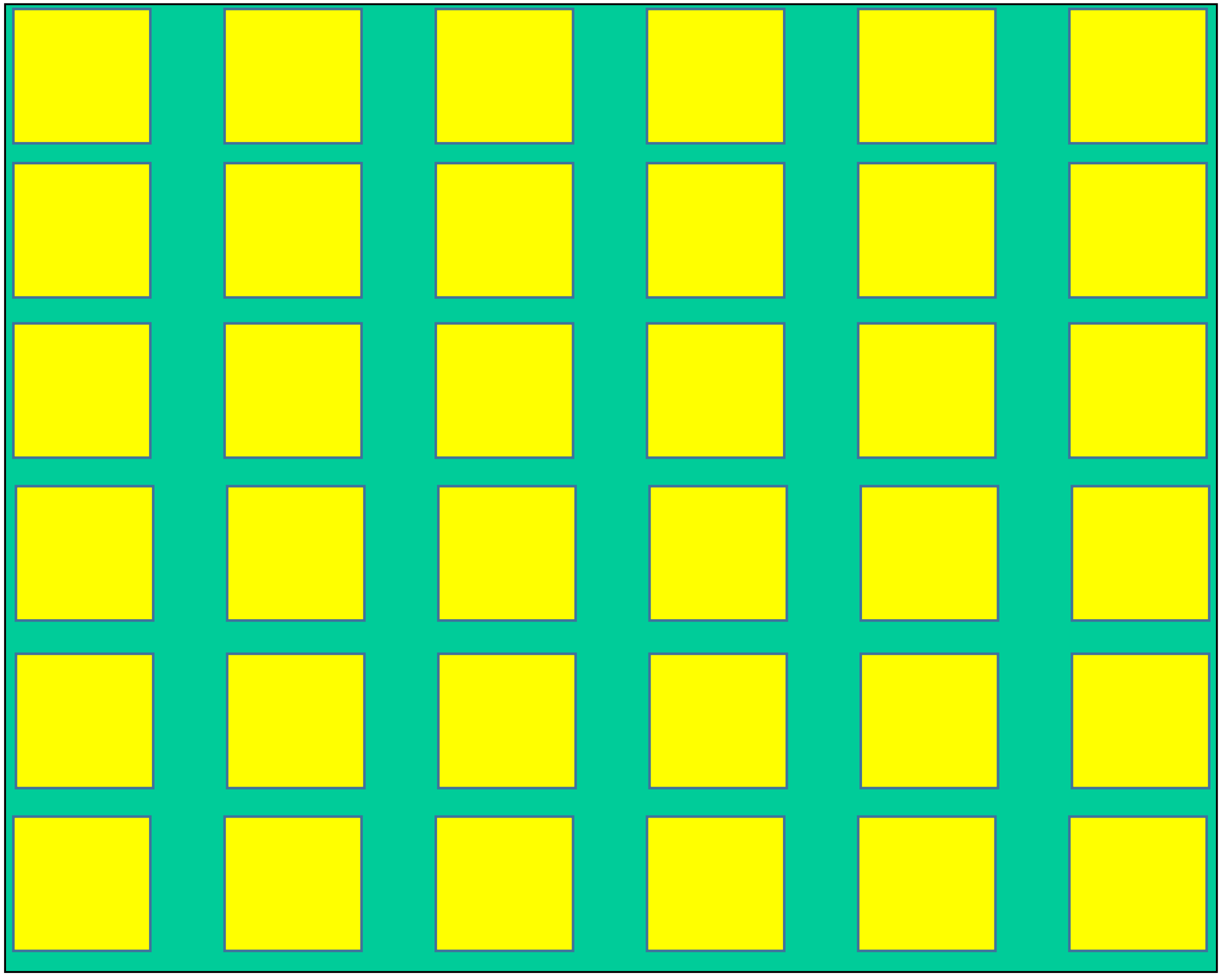
Deflection calibration

Deflection calibration



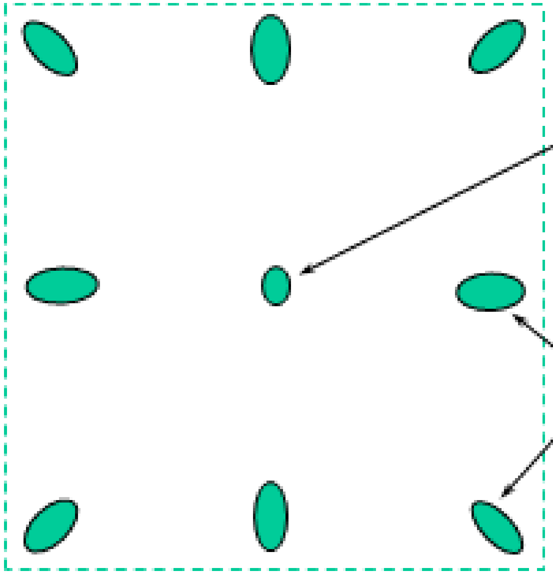
Allows a precise calbration of the deflection amplifiers for gain and rotation

Distorsion correction



Allows to corrrect the distorsion in each part of the field (spherical aberrations)

Effect of Beam Deflection on the Focus

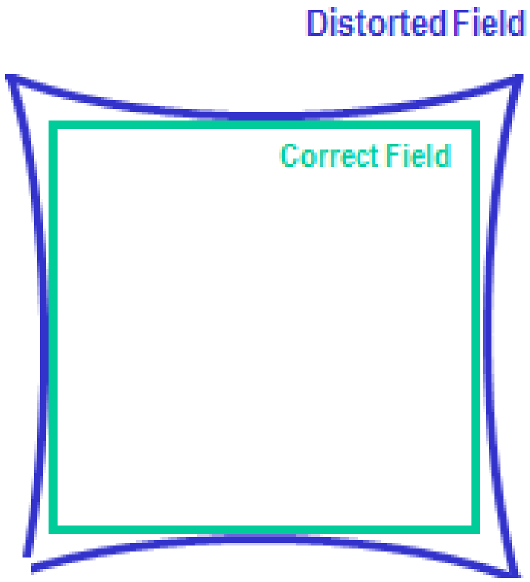


Beam focused to form
round spot at Field centre.

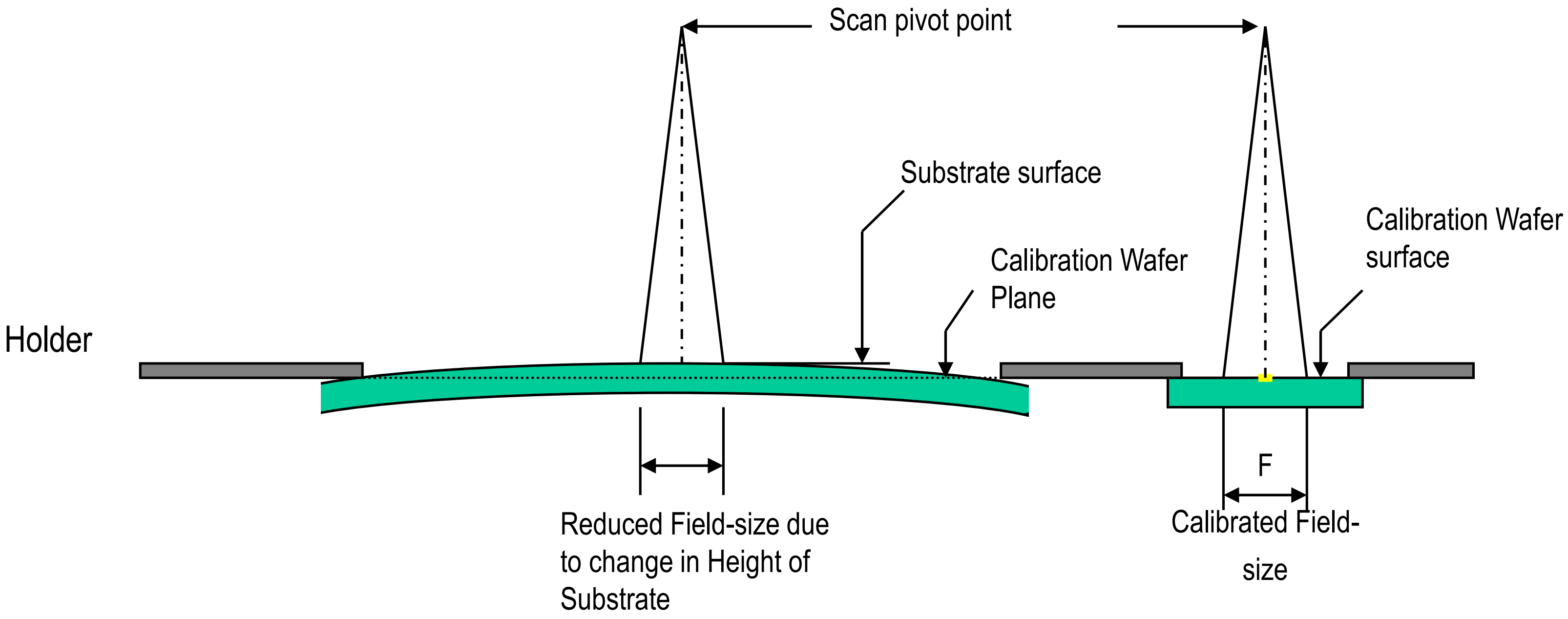
Spot defocused and astigmatic
when deflected from centre.

Field Distortion caused by Beam Deflection

Field distortion is removed by applying corrections to the Main and Subfield scanning system



Effects of Substrate Height Variation

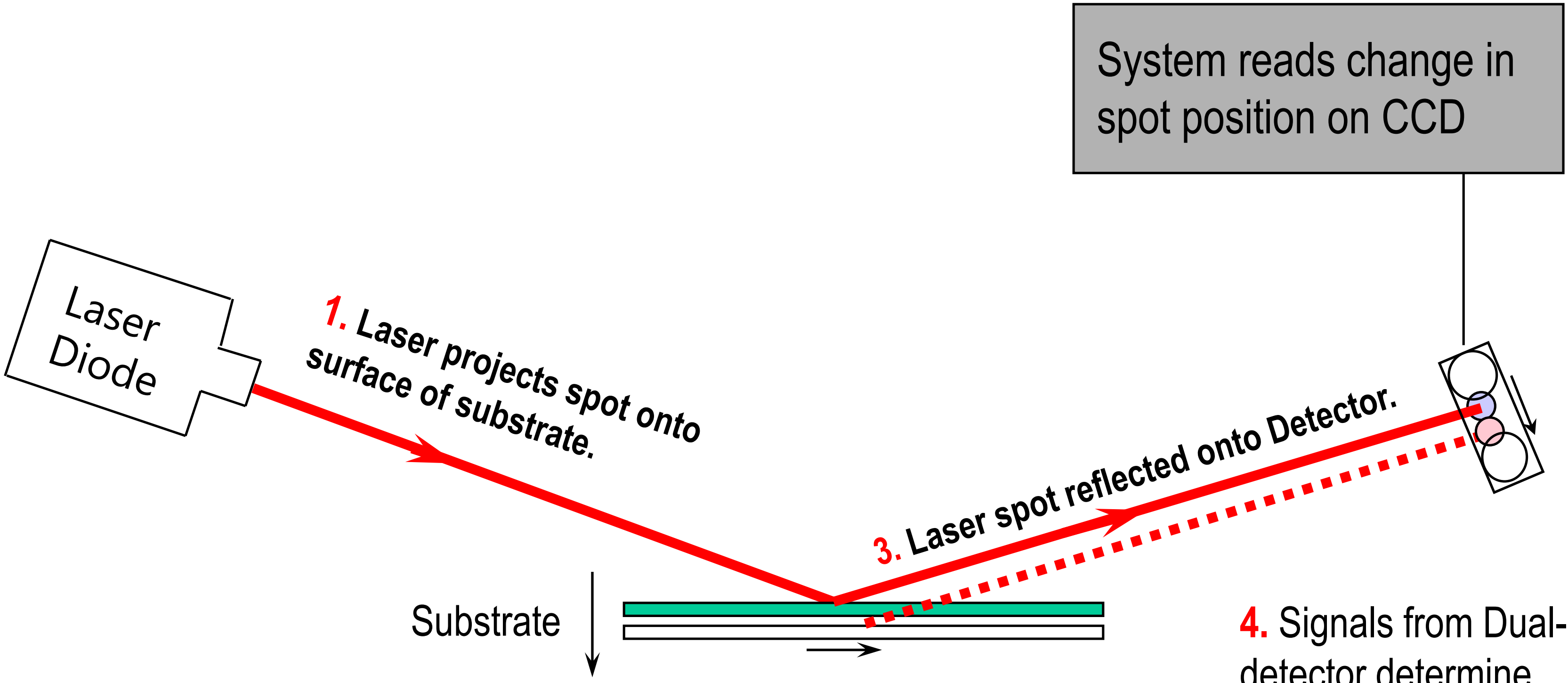


Changes in Substrate surface height relative to plane of the Calibration wafer result in

a) Incorrect Field/Block/trapezia size

b) Defocused beam

Principles of Laser Height Sensor



System reads change in spot position on CCD

1. Laser projects spot onto surface of substrate.

3. Laser spot reflected onto Detector.

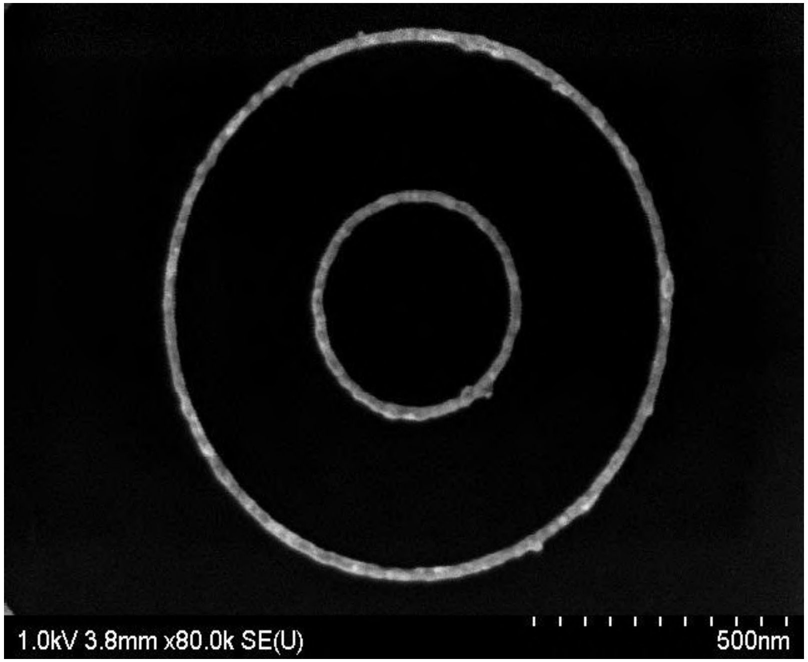
Substrate

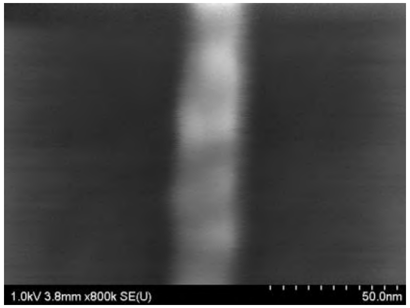
2. Laser spot movement due to change in height of substrate surface.

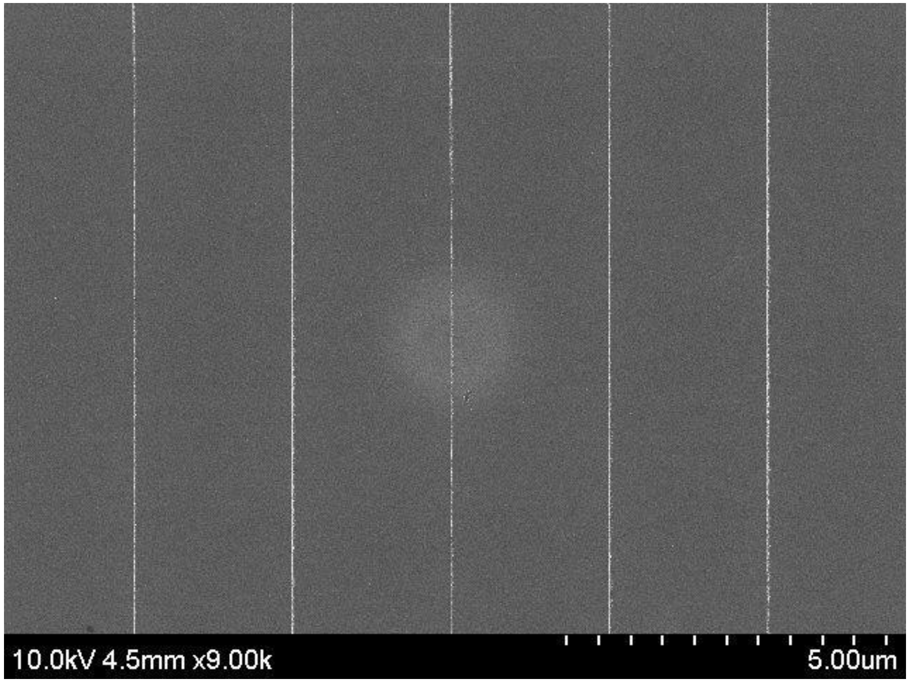
4. Signals from Dual-diode detector determine distance moved by laser beam.

Correction up to 50μm defocusing

Examples


1.0kV 3.8mm x80.0k SE(U)
500nm

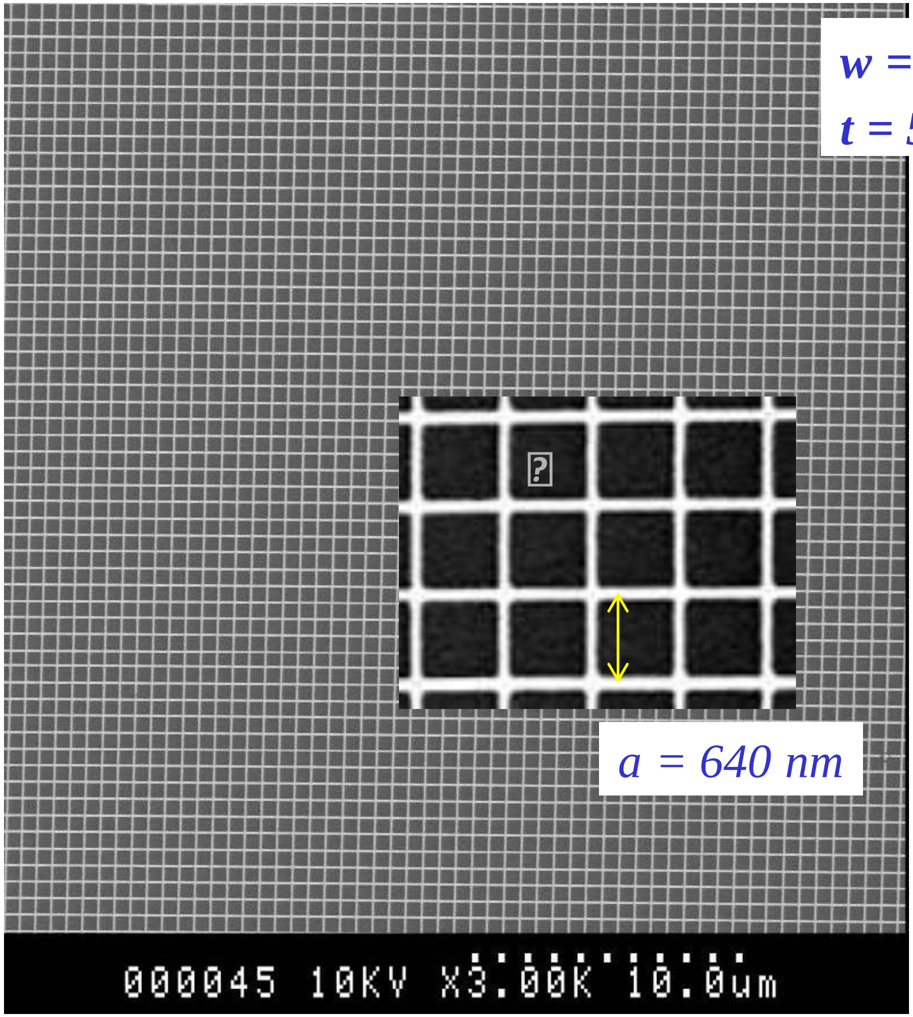

1.0kV 3.8mm x800k SE(U)
50.0nm


10.0kV 4.5mm x9.00k
5.00um

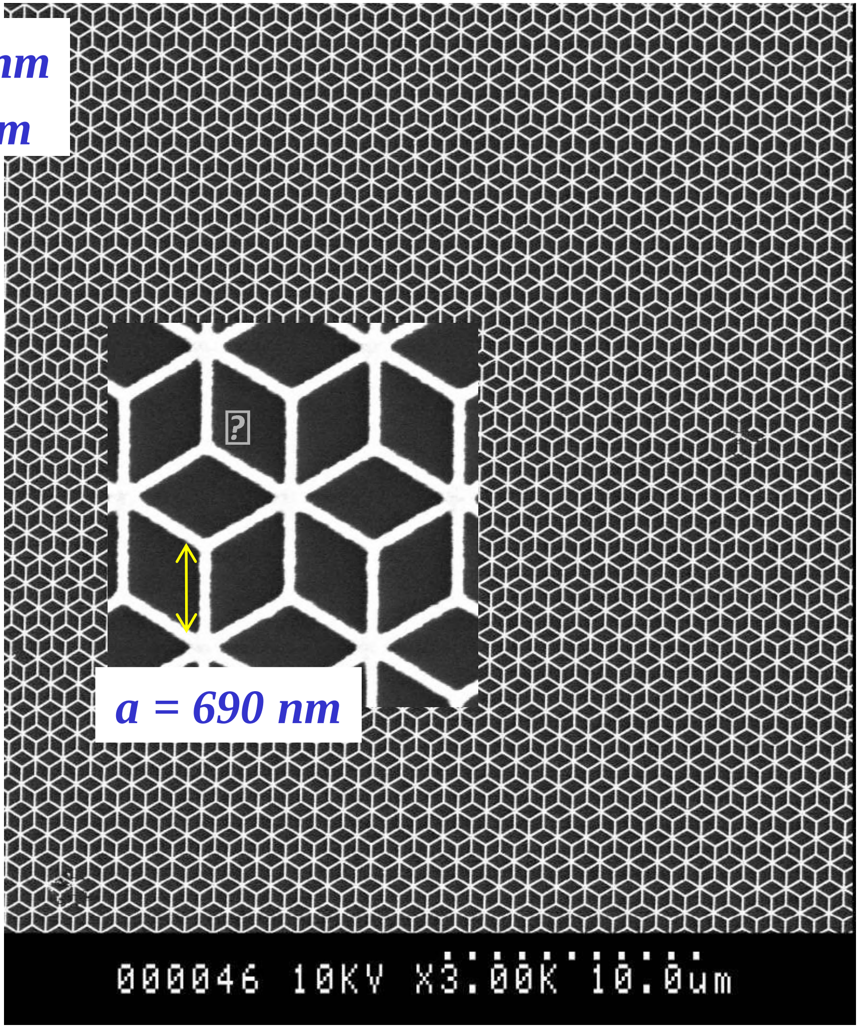
Examples: large area

w = 60 nm

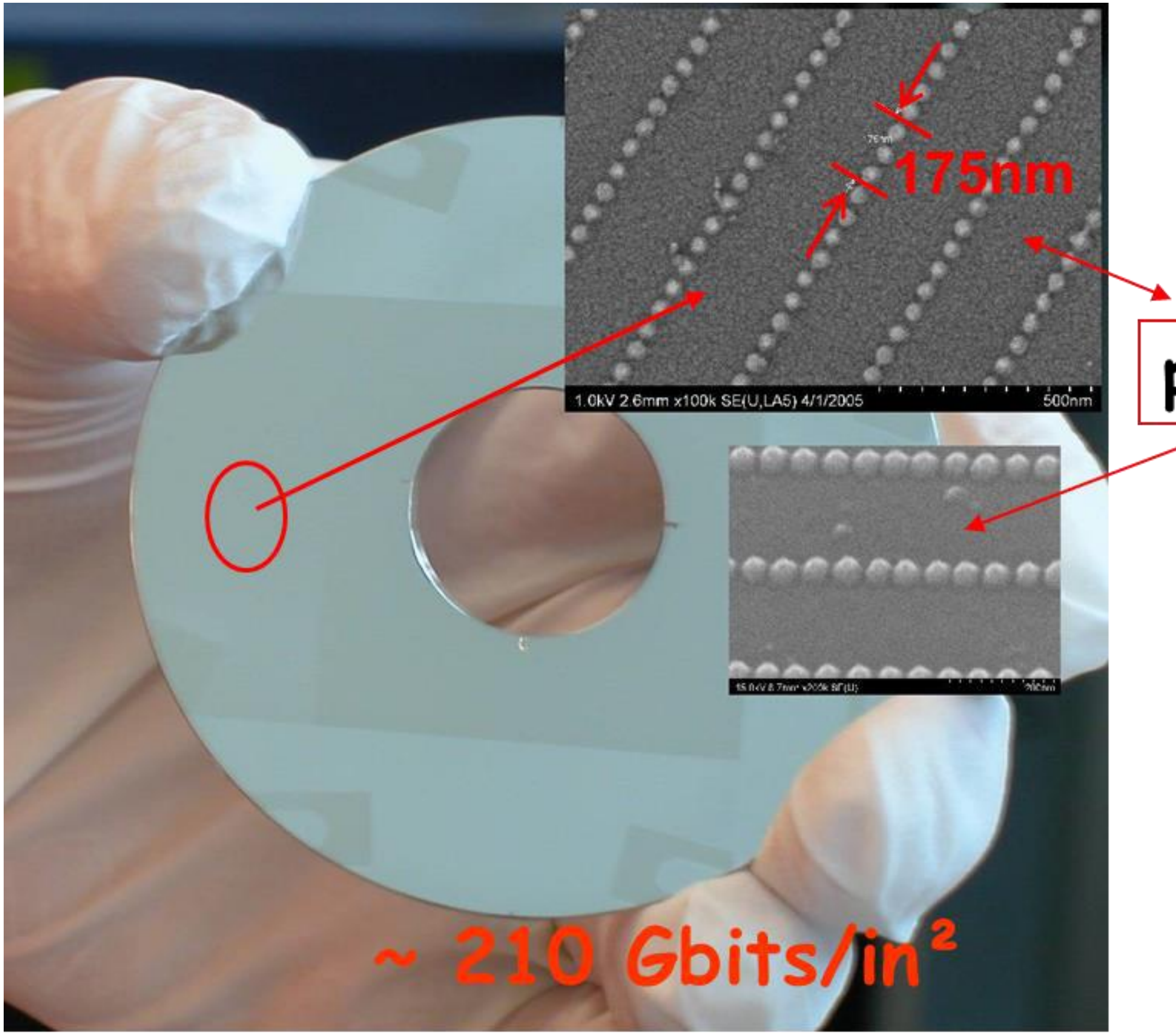
t = 50 nm



a = 640 nm



a = 690 nm



pitch ~ 60nm

~ 210 Gbits/in^2

Improving the throughput

Large collimated electron beam

Variable shape beam

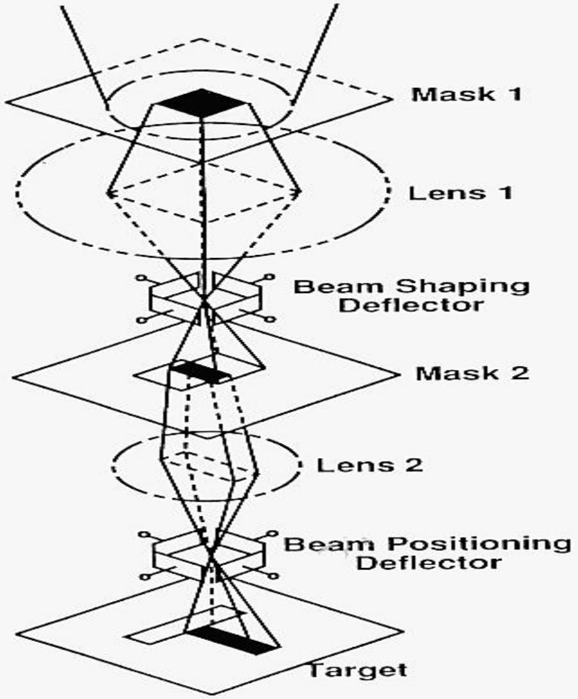


Figure 71. Schematic of a compound-shape electron-beam system.

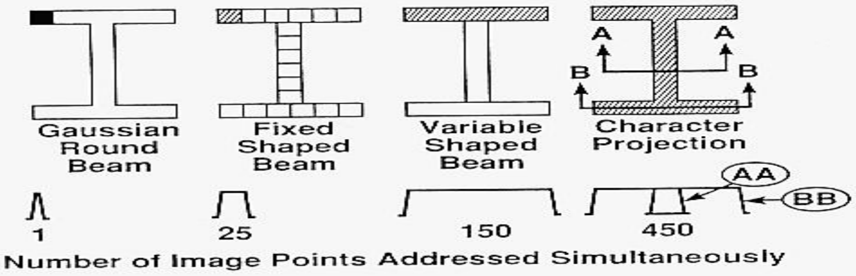


Figure 72. Comparison of pattern generation techniques and resultant profiles.

Simple geometrical shapes are produces through aperture system

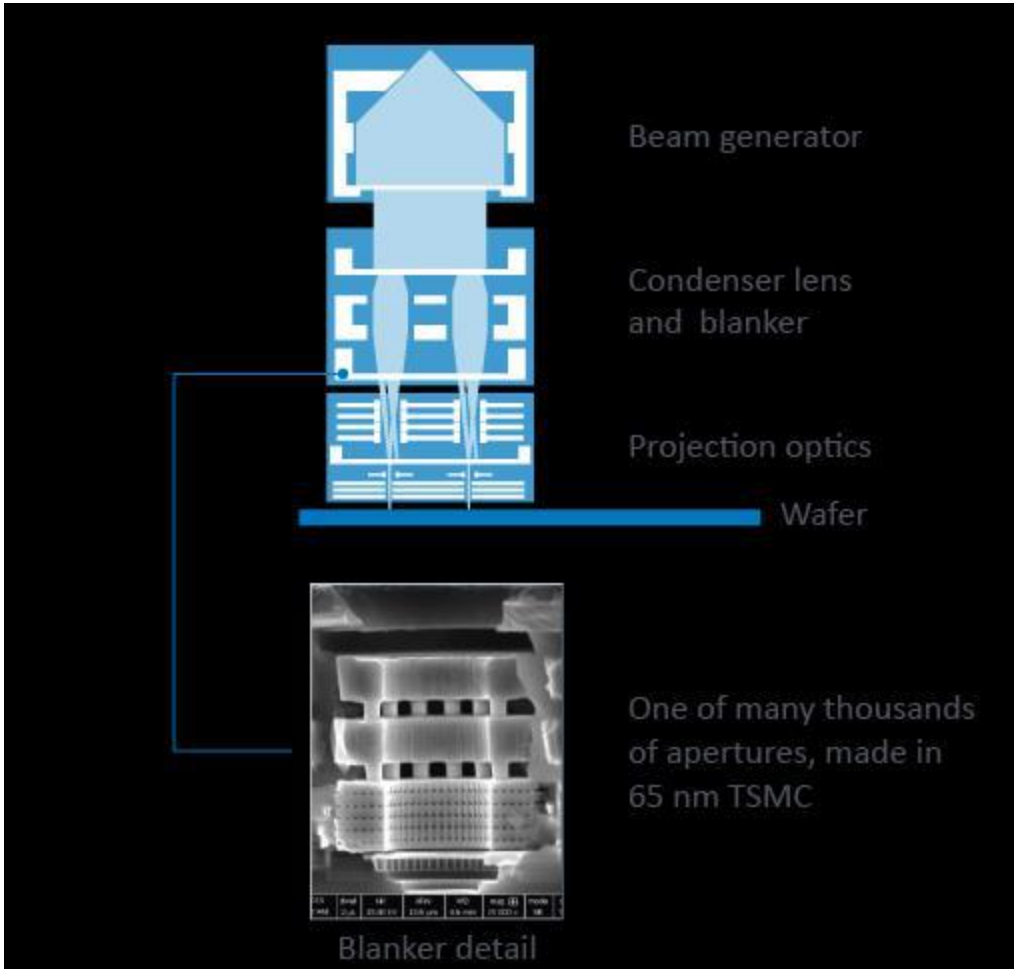
(mask 1 et mask 2)

Example: Leica ZBA 31/32

Resolution about 100nm

Use for mask making

Multi-beams technique : Mapper



A large (3cm) 5kV beam is produced

A module split this beam into 6500 beamlets with individual blanker (raster scan)

projection optics micro-lens array with thousands of electrostatic lenses

deflectors scan the beamlets over a 2 µm range so the whole area can be covered

Spot size on the wafer 25nm

MEMS technology for the optics

Extension to 650000 beams for 40 wafers/h production

Mapper results