GenISys
Advancing the Standard

BEAMER

Training Webinar

Part 4: Standard Dose PEC - Intro

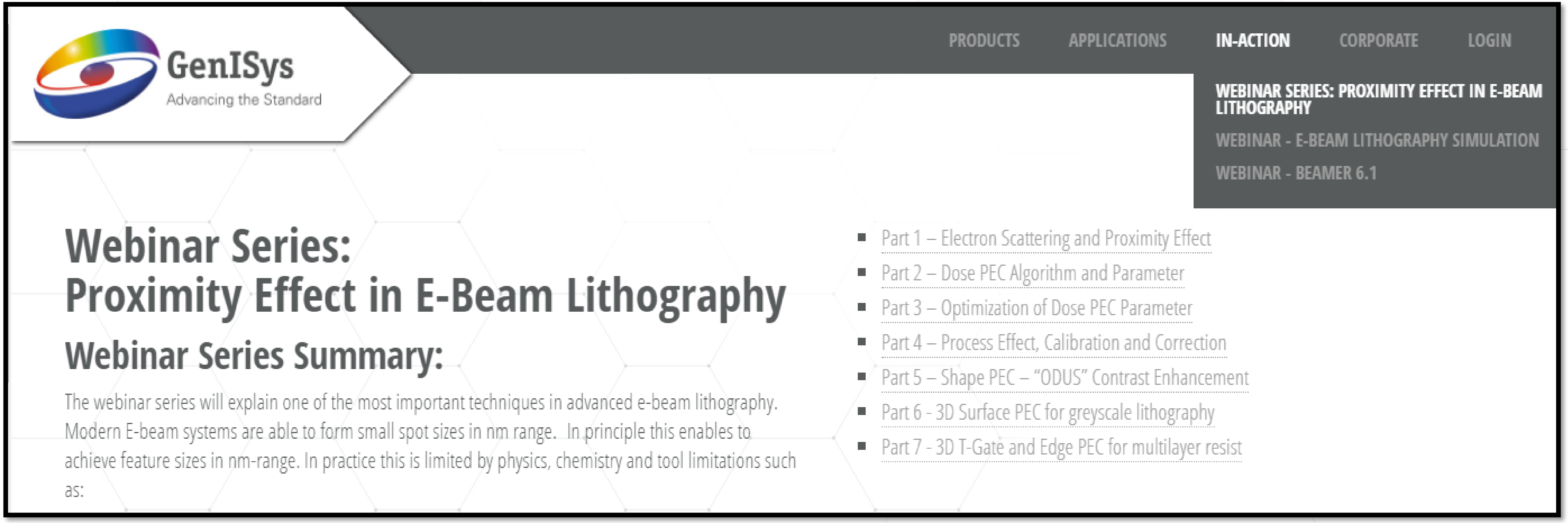
Agenda

- Proximity Effect
- Proximity Effect Correction by Dose modulation
- Inside the PEC window
- Summary
- Q&A

Focus: Website

Please visit our webinar series for more detail discussion on Proximity effect correction

https://www.genisys-gmbh.com



Webinar Series: Proximity Effect in E-Beam Lithography

Webinar Series Summary:

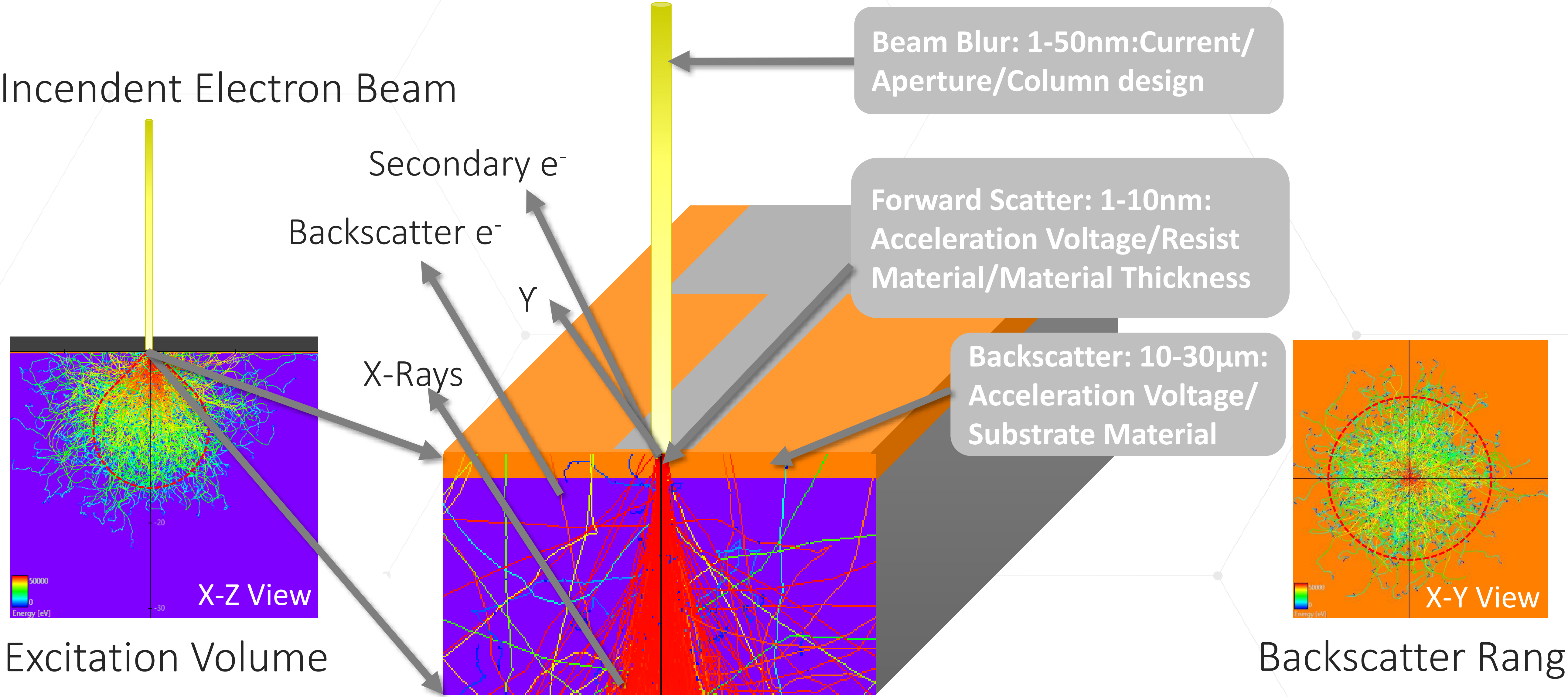
The webinar series will explain one of the most important techniques in advanced e-beam lithography. Modern E-beam systems are able to form small spot sizes in nm range. In principle this enables to achieve feature sizes in nm-range. In practice this is limited by physics, chemistry and tool limitations such as:

- Part 1 – Electron Scattering and Proximity Effect
- Part 2 – Dose PEC Algorithm and Parameter
- Part 3 – Optimization of Dose PEC Parameter
- Part 4 – Process Effect, Calibration and Correction
- Part 5 – Shape PEC – “ODUS” Contrast Enhancement
- Part 6 - 3D Surface PEC for greyscale lithography
- Part 7 - 3D T-Gate and Edge PEC for multilayer resist

Agenda

- Proximity Effect
  - Principle
  - Monte Carlo Simulation in TRACER
- Proximity Effect Correction by Dose modulation
  - Edge Equalization algorithm
  - Simulation comparing with and without correction
- Inside the PEC window
  - Why divide into Short, Mid, Long range
  - Effective Blur
  - Short – range correction
- Summary
- Q&A

Electron-Solid Interactions



Incendent Electron Beam

Secondary e^-

Backscatter e^-

Y

X-Rays

Beam Blur: 1-50nm:Current/ Aperture/Column design

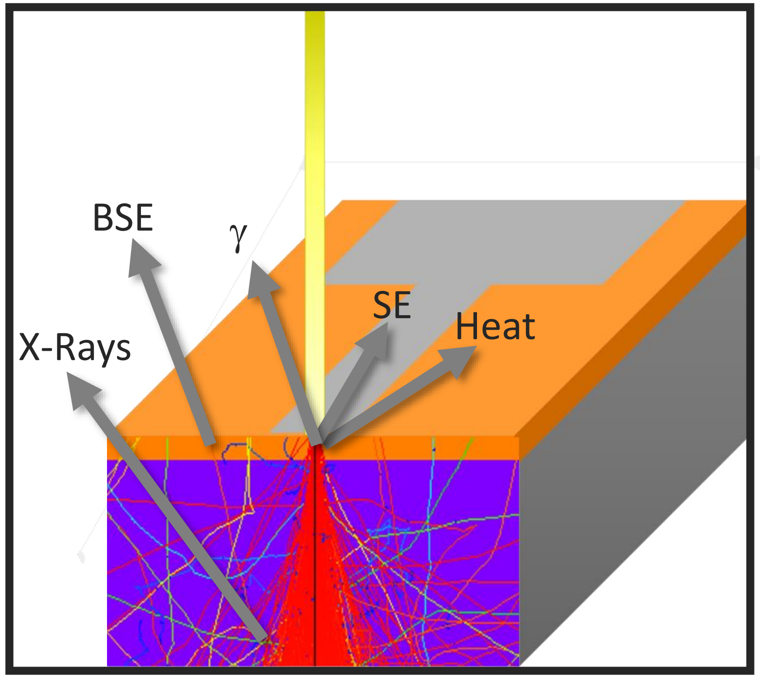
Forward Scatter: 1-10nm: Acceleration Voltage/Resist Material/Material Thickness

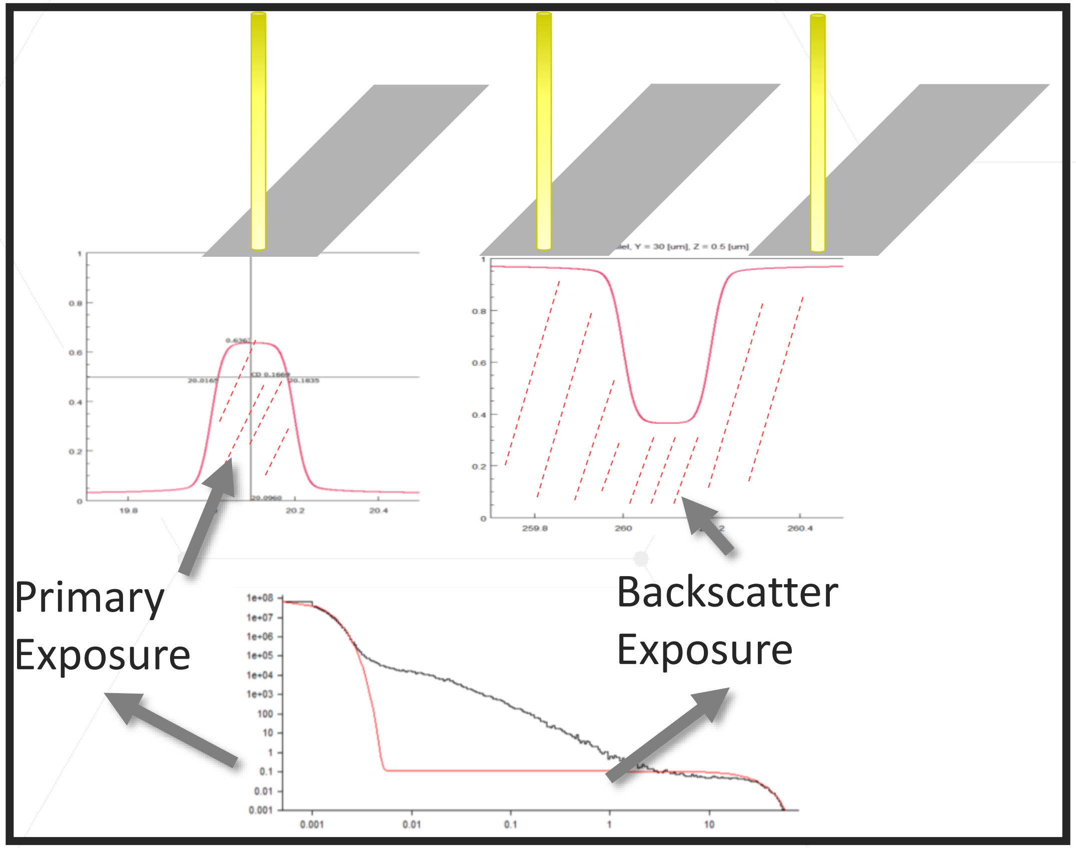
Backscatter: 10-30µm: Acceleration Voltage/ Substrate Material

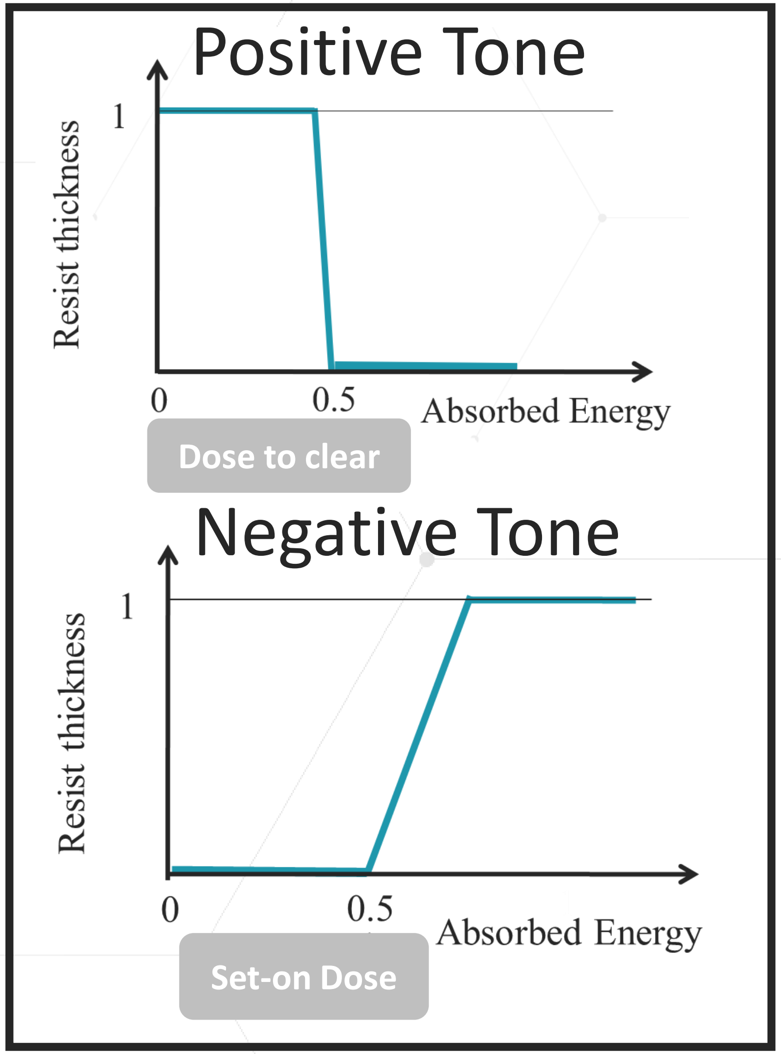
Excitation Volume

Backscatter Range

How do we write features with e-beam?







Electrons hit sample

- Exposure from primary electrons
- Exposure from backscattered electrons
- SE‘s, Heat, X-Rays, Photons, …
  - Elastic + inelastic scattering

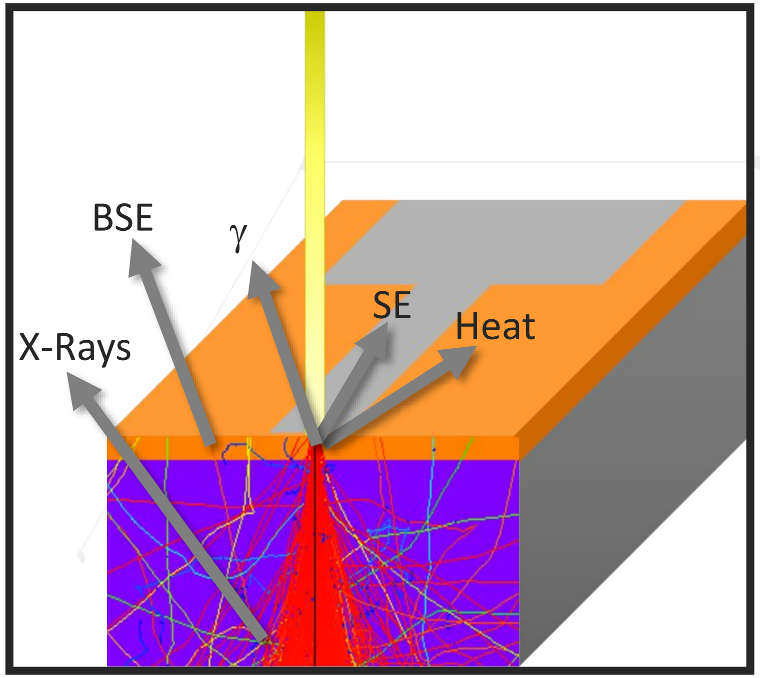
Energy deposition

- Local (primary exposure)
- Proximity (backscattering)

Threshold = 0.5

Base dose = 1

How an E-Beam transforms to structures



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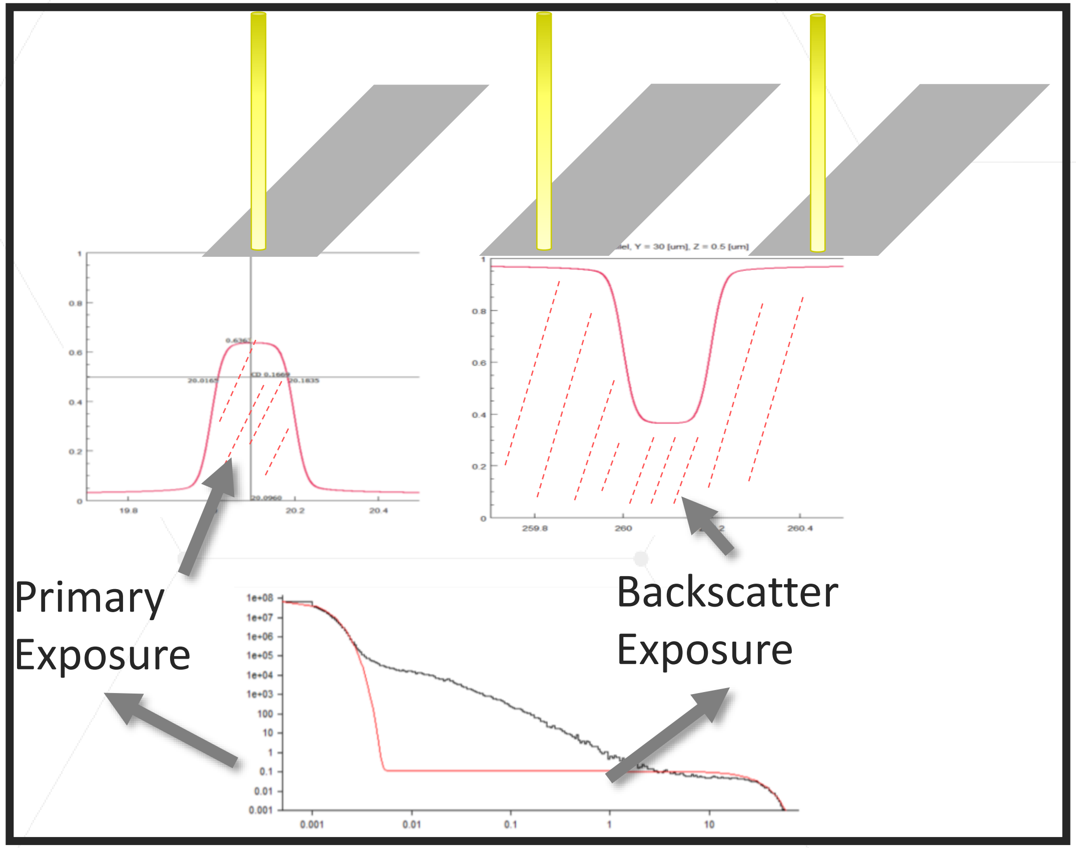

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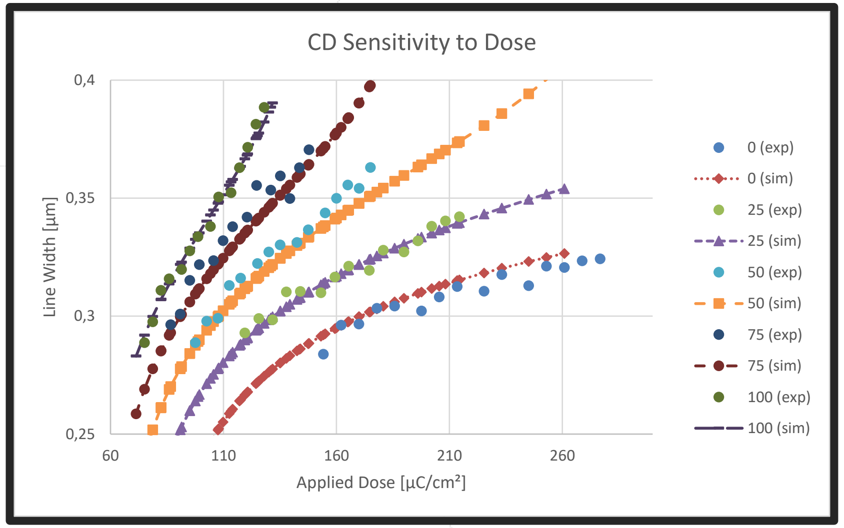


Courtesy Pennstate University

Printed Features

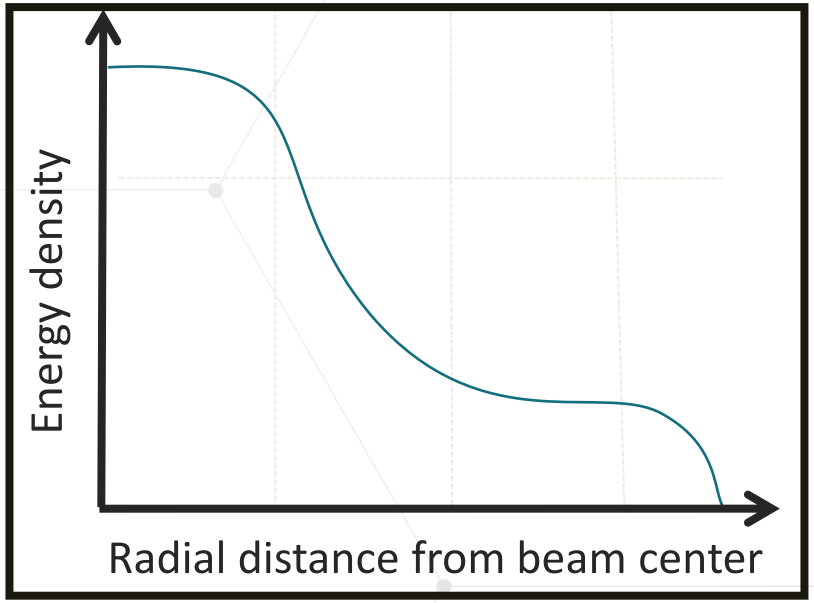
- CD = f(Dose, Density)
- Iso-features require more dose
- Dense features at degraded EL

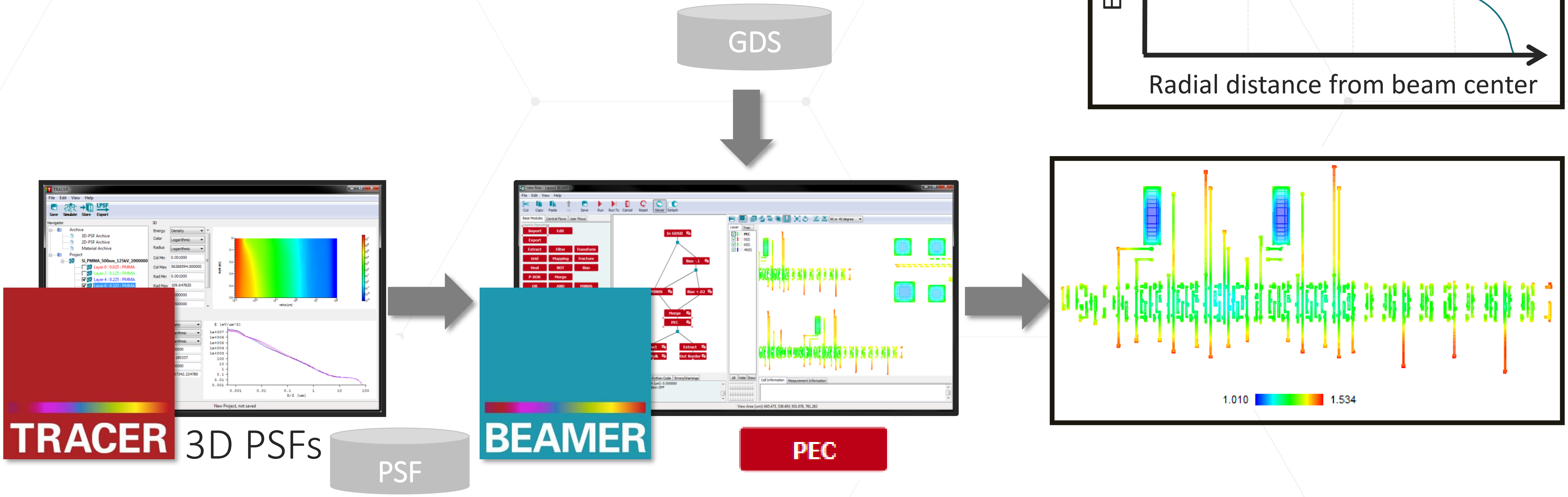
Scattering → Energy Deposition → Printed Feature

How do we quantify electron scattering?

TRACER Monte Carlo simulation to generate Electron point spread functions

- Plots the absorbed energy density in the resist vs the radial distance from the beam center




GDS

TRACER

3D PSFs

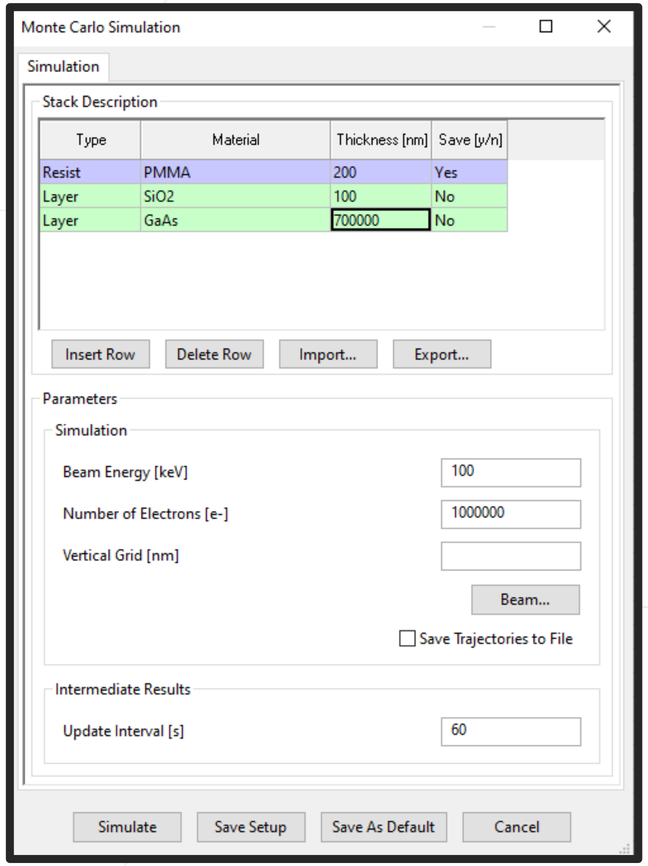
PSF

BEAMER

PEC

Live Demo: Monte Carlo Simulation

- Define the Stack
  - Start with subrate material, e.g. GaAs wafer
    - Material data are coming from database
    - Adding new material:
      - Define Stoichiometries
      - Define mass density (from literature or measure)
      - Excitation Energy determined automatic by database, or entered manually
  - Add coating (layer) onto the substrate
  - Add the resist on top (special layer market Resist)



Stack Description

Type	Material	Thickness [nm]	Save [y/n]
Resist	PMMA	200	Yes
Layer	SiO2	100	No
Layer	GaAs	700000	No

Parameters

Simulation

Beam Energy [keV]: 100

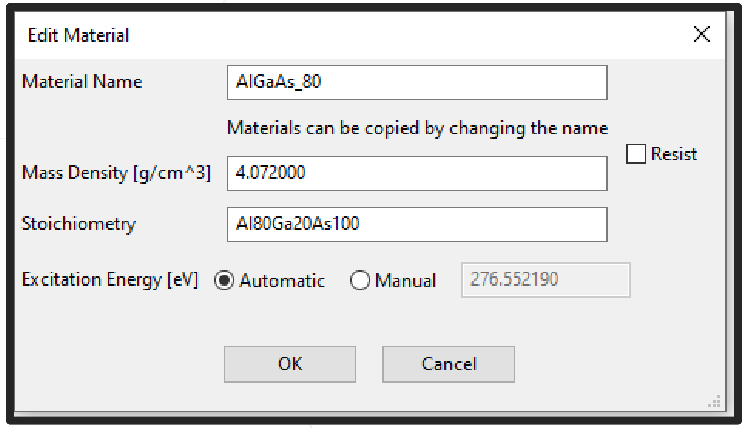
Number of Electrons [e-]: 1000000

Vertical Grid [nm]:

☐ Save Trajectories to File

Intermediate Results

Update Interval [s]: 60



Material Name: AlGaAs_80

Materials can be copied by changing the name

☐ Resist

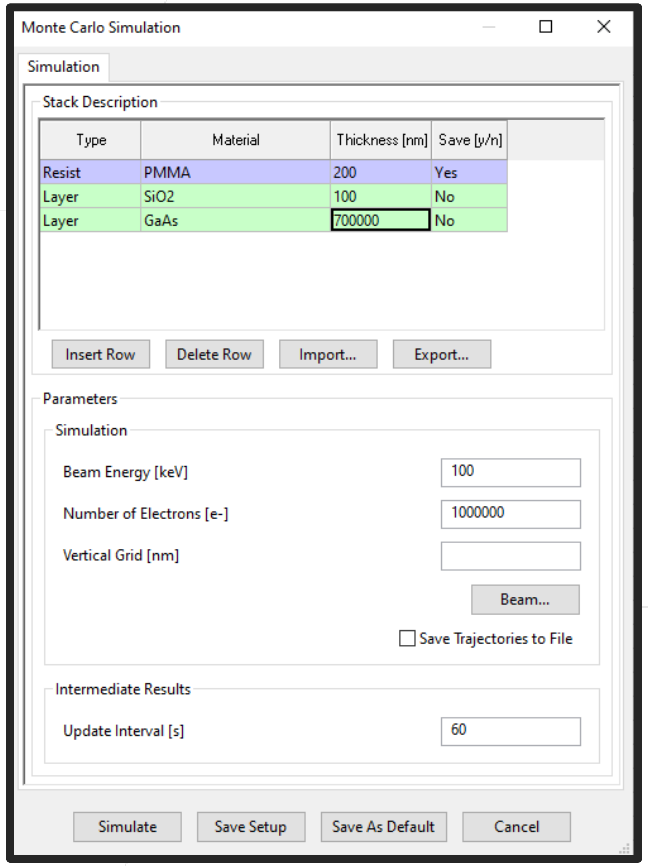
Mass Density [g/cm^3]: 4.072000

Stoichiometry: Al80Ga20As100

Excitation Energy [eV]: ● Automatic ○ Manual 276.552190

Live Demo: Monte Carlo Simulation

- Define Beam Energy, e.g. 100keV
- Define number of electron, e.g. 2 million
  - More electron give better statistics (quality for PSF)
  - 2+ million are recommended for good quality
- Save Trajectories, only for a nice presentation plot
- Click Simulate, wait a couple minutes



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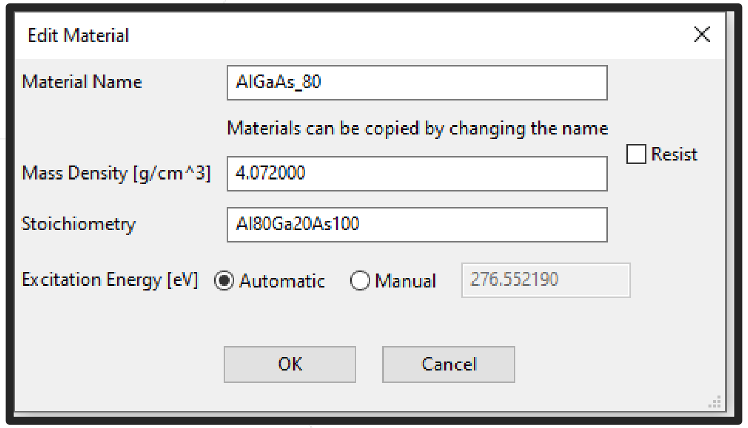

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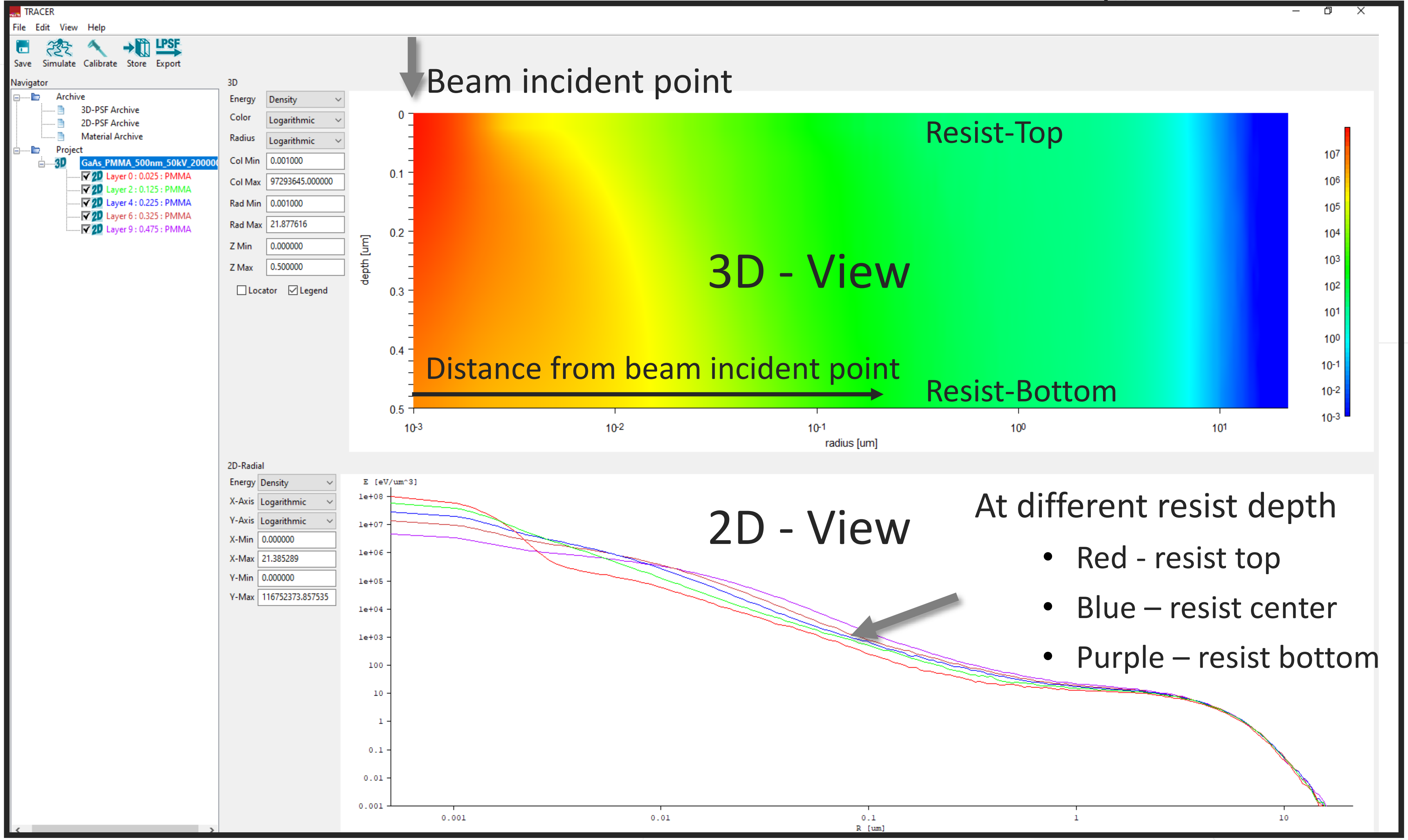
Simulation Result

Simulation Result for GaAs wafer with 500nm PMMA resist exposed at 50keV exposure



TRACER

File Edit View Help

Save Simulate Calibrate Store Export

Navigator

- Archive
  - 3D-PSF Archive
  - 2D-PSF Archive
  - Material Archive
- Project
  - 3D GaAs_PMMA_500nm_50kV_20000
    - ☑ 2D Layer 0 : 0.025 : PMMA
    - ☑ 2D Layer 2 : 0.125 : PMMA
    - ☑ 2D Layer 4 : 0.225 : PMMA
    - ☑ 2D Layer 6 : 0.325 : PMMA
    - ☑ 2D Layer 9 : 0.475 : PMMA

3D

Energy: Density
Color: Logarithmic
Radius: Logarithmic
Col Min: 0.001000
Col Max: 97293645.000000
Rad Min: 0.001000
Rad Max: 21.877616
Z Min: 0.000000
Z Max: 0.500000
☐ Locator ☑ Legend

2D-Radial

Energy: Density
X-Axis: Logarithmic
Y-Axis: Logarithmic
X-Min: 0.000000
X-Max: 21.385289
Y-Min: 0.000000
Y-Max: 116752373.857535

Beam incident point

Resist-Top

3D - View

Distance from beam incident point

Resist-Bottom

2D - View

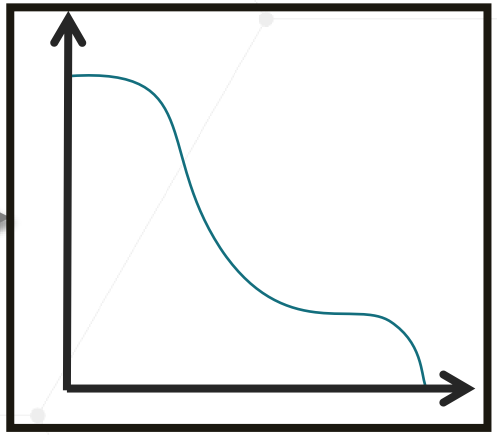
At different resist depth

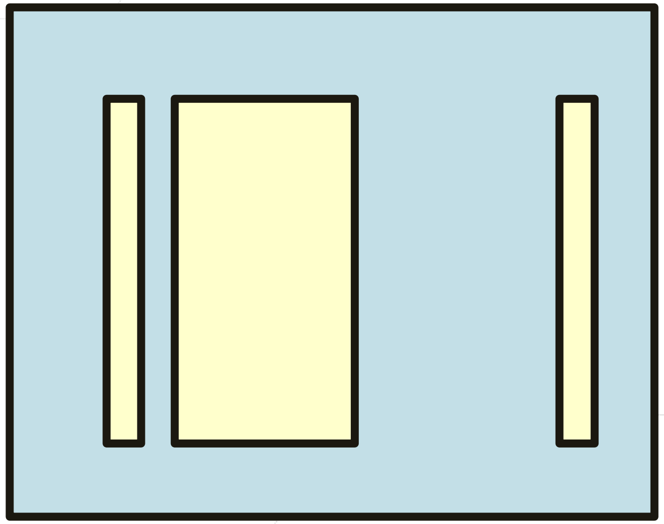
- Red - resist top
- Blue – resist center
- Purple – resist bottom

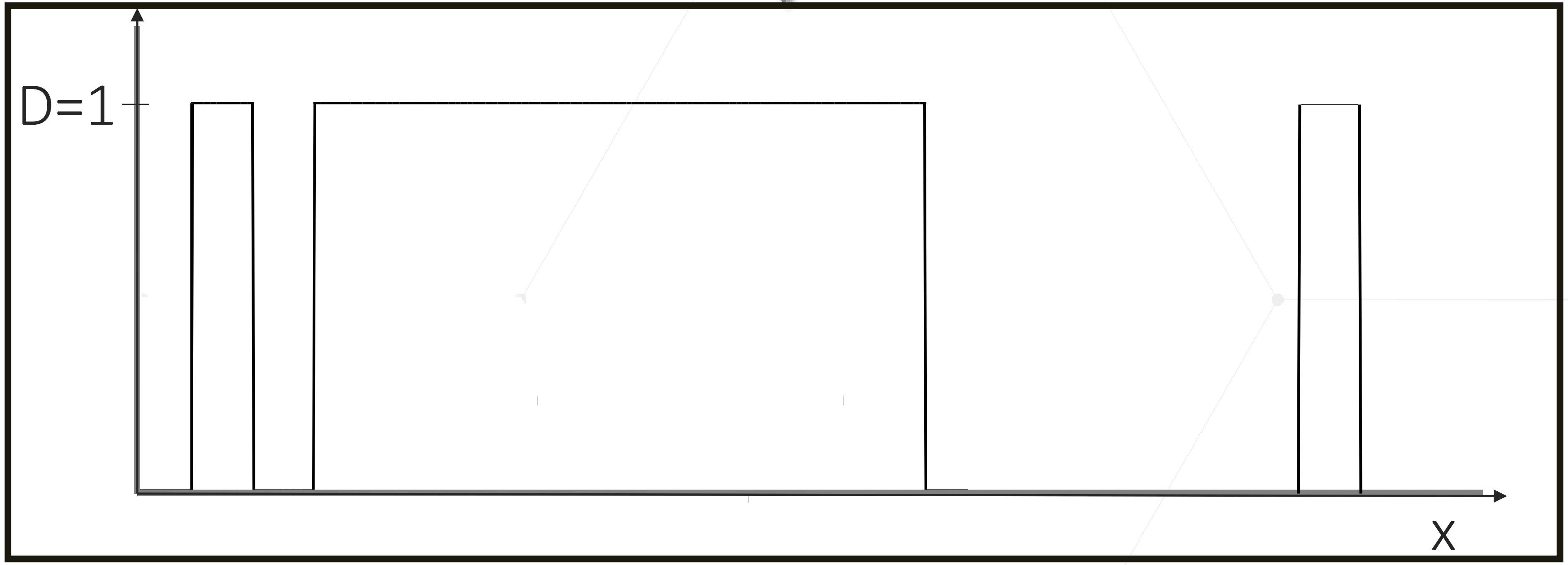
Calculation of Absorbed Energy

Knowing the PSF, the absorbed energy at any position *x* can be calculated:

$E(x) = P(x) \otimes \mathrm{PSF}$







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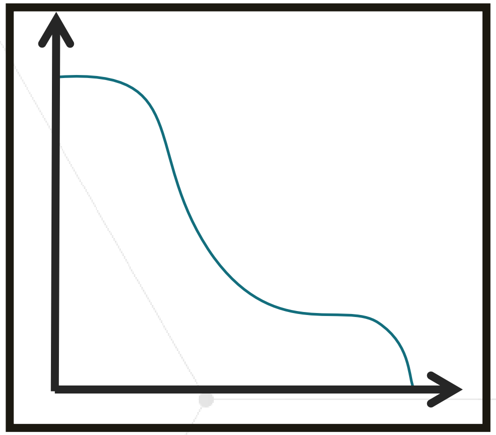

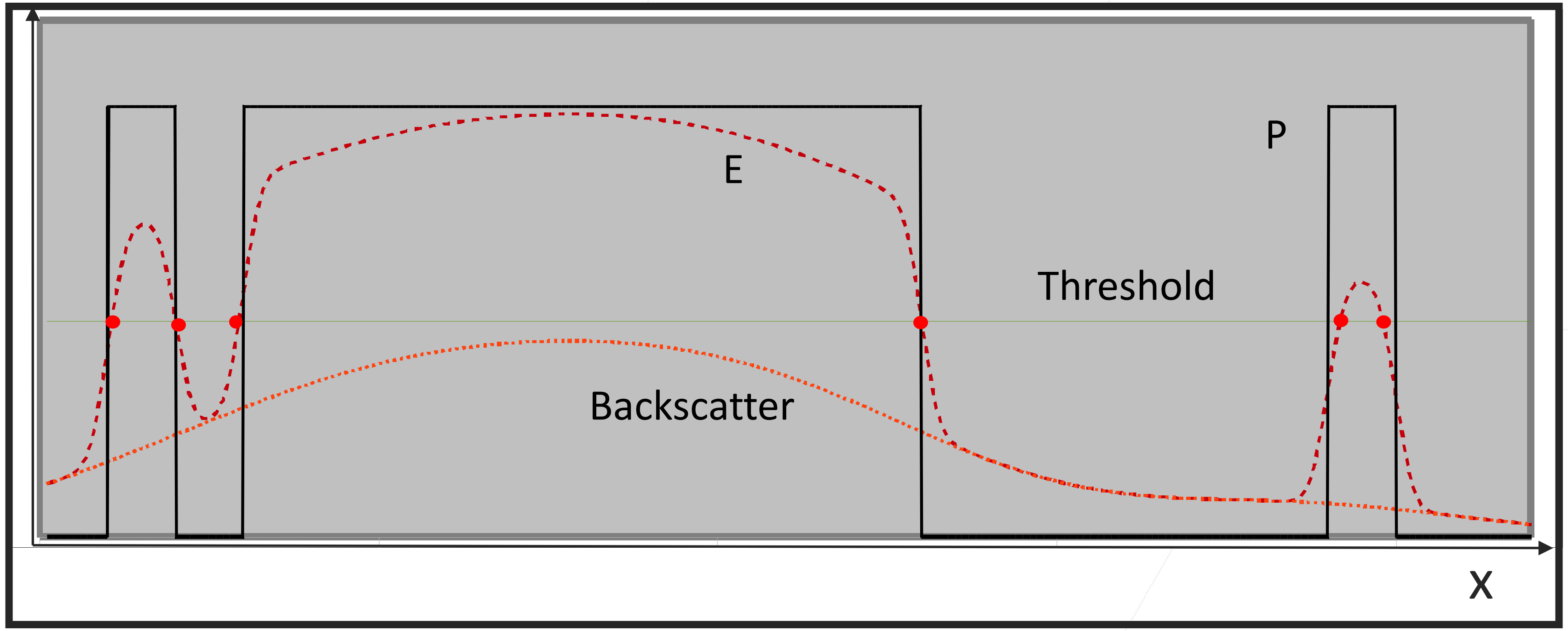

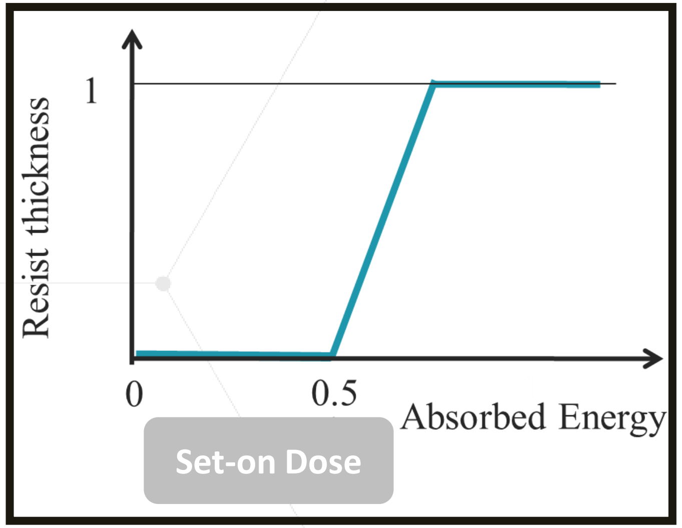

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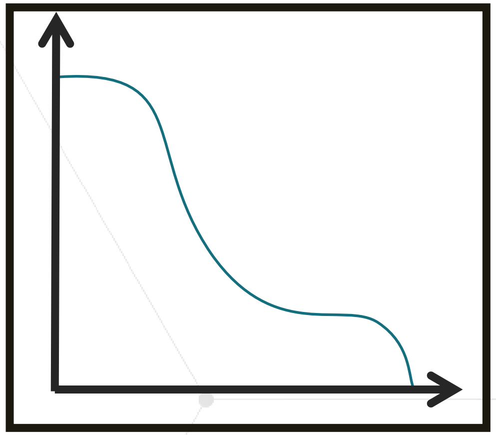

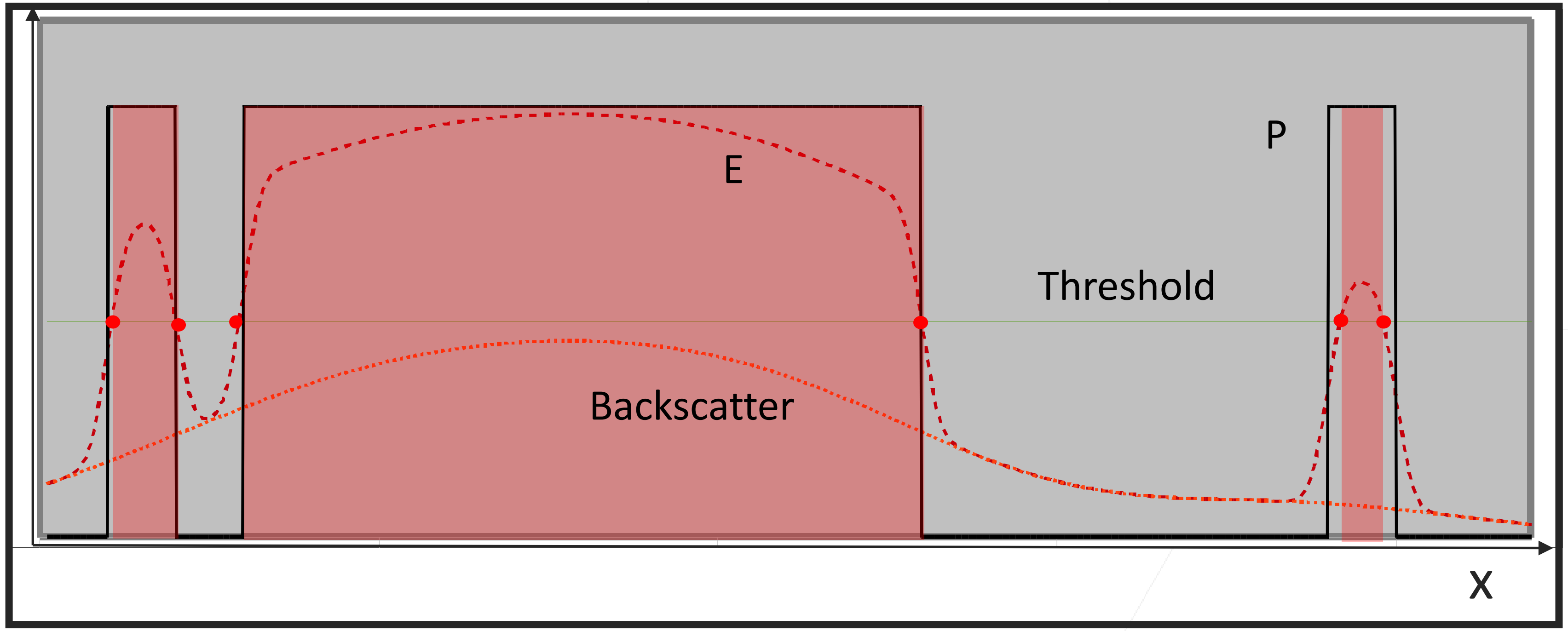

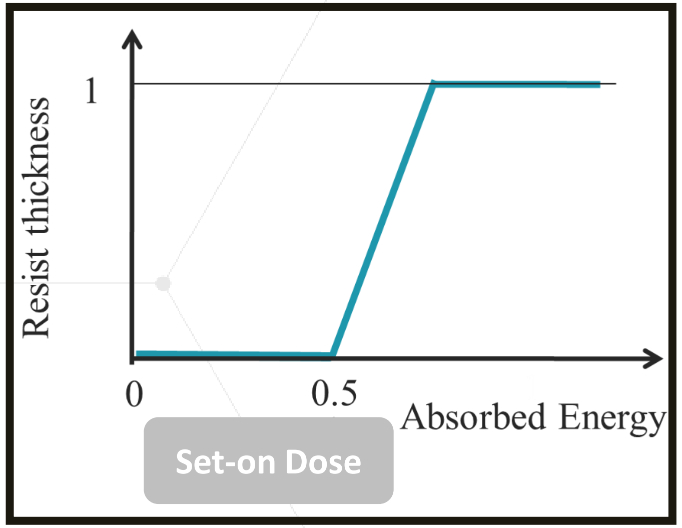

Agenda

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- Proximity Effect Correction by Dose modulation
  - Edge Equalization algorithm
  - Simulation comparing with and without correction
- Inside the PEC window
- Summary
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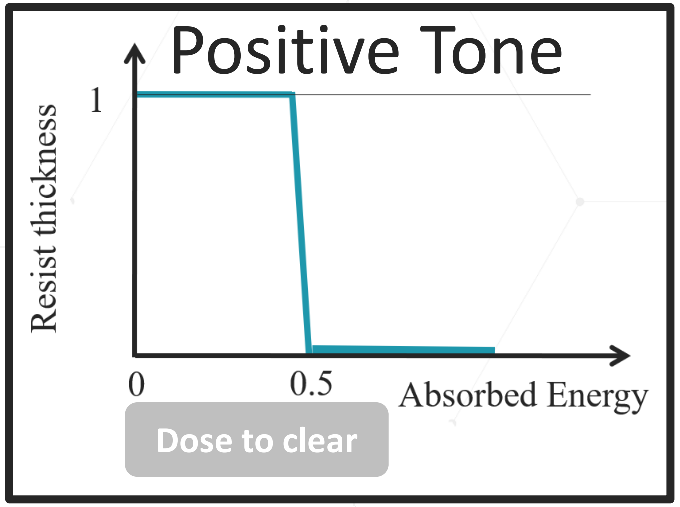
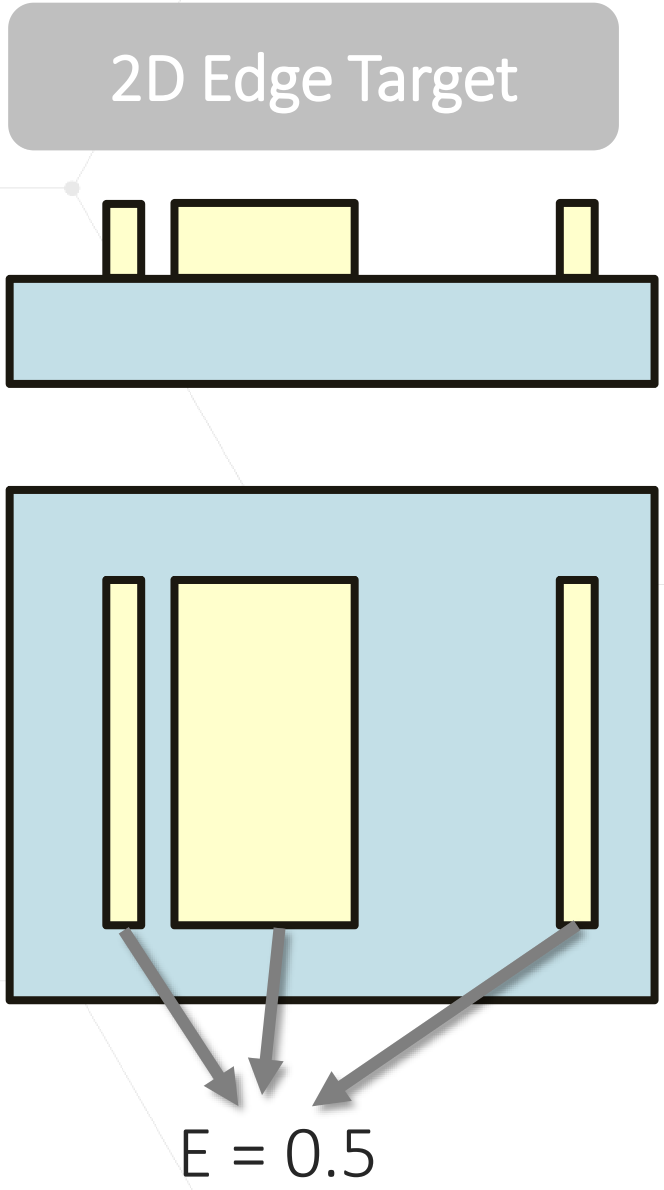
Proximity Effect Correction

- Edge Equalization-Target of correction:
  - Adjust all feature edges to the same absorbed energy: Dose of clear for positive tone resist
- E(x)>Dose to clear:
  - Resist will develop away
- E(x)<Dose to clear:
  - Resist will remain
- E(x)=0.5=Resist Edge
- Correction Equation:

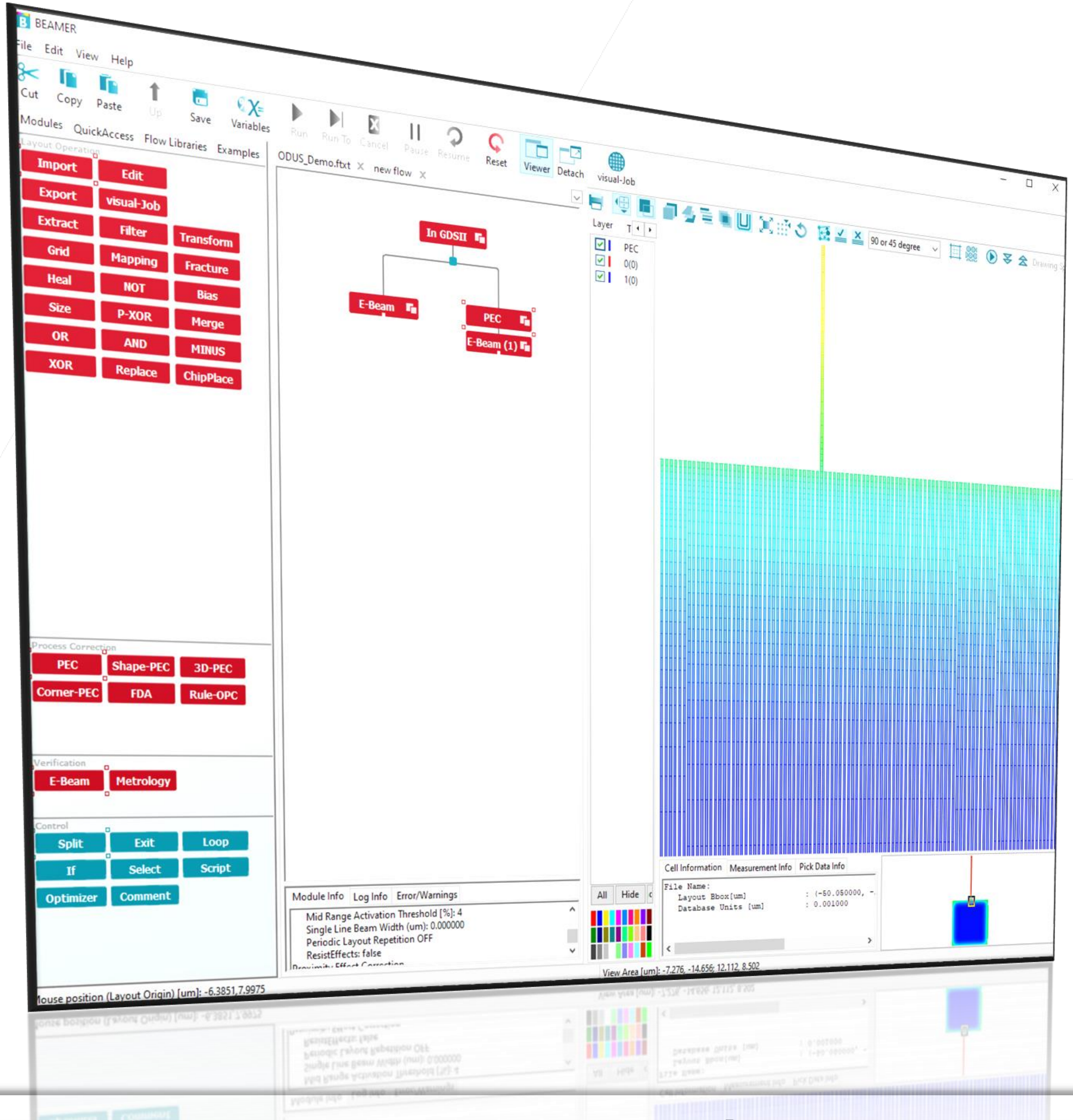
  $E(edge) = 0.5 = D(x) \otimes PSF$
- There is a large number of PEC Algorithms.
- The strongest algorithms are based on:

J. Pavkovich, J. Vac. Sci. Techmol., B. Vol 4, No.1, Jan/Feb 1986





Live Demo: Proximity Effect Correction



Mid Range Activation Threshold [%]: 4
Single Line Beam Width (um): 0.000000
Periodic Layout Repetition OFF
ResistEffects: false

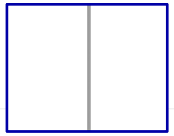
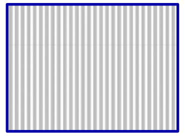
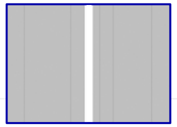
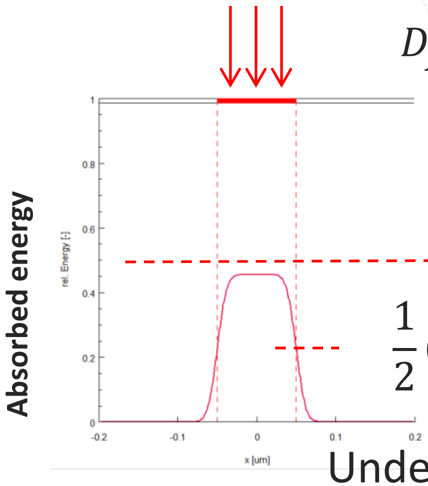
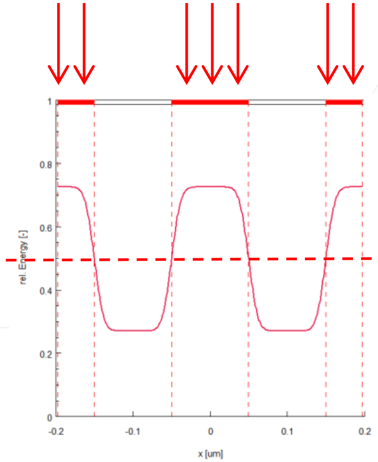
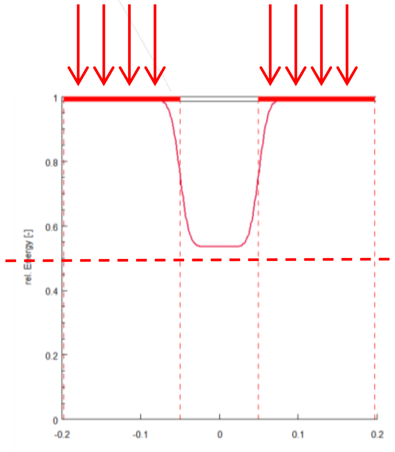
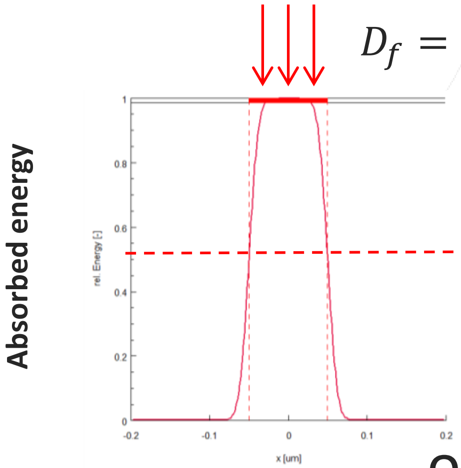
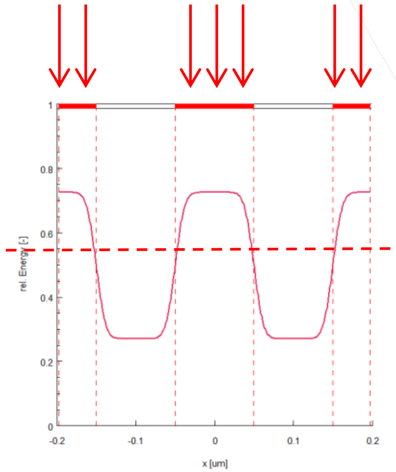
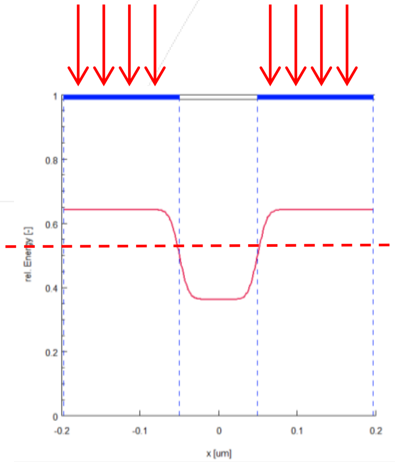
```
File Name:
  Layout Bbox[um]            : (-50.050000, -
  Database Units [um]        : 0.001000
```

View Area [um]: -7.276, -14.656; 12.112, 8.502

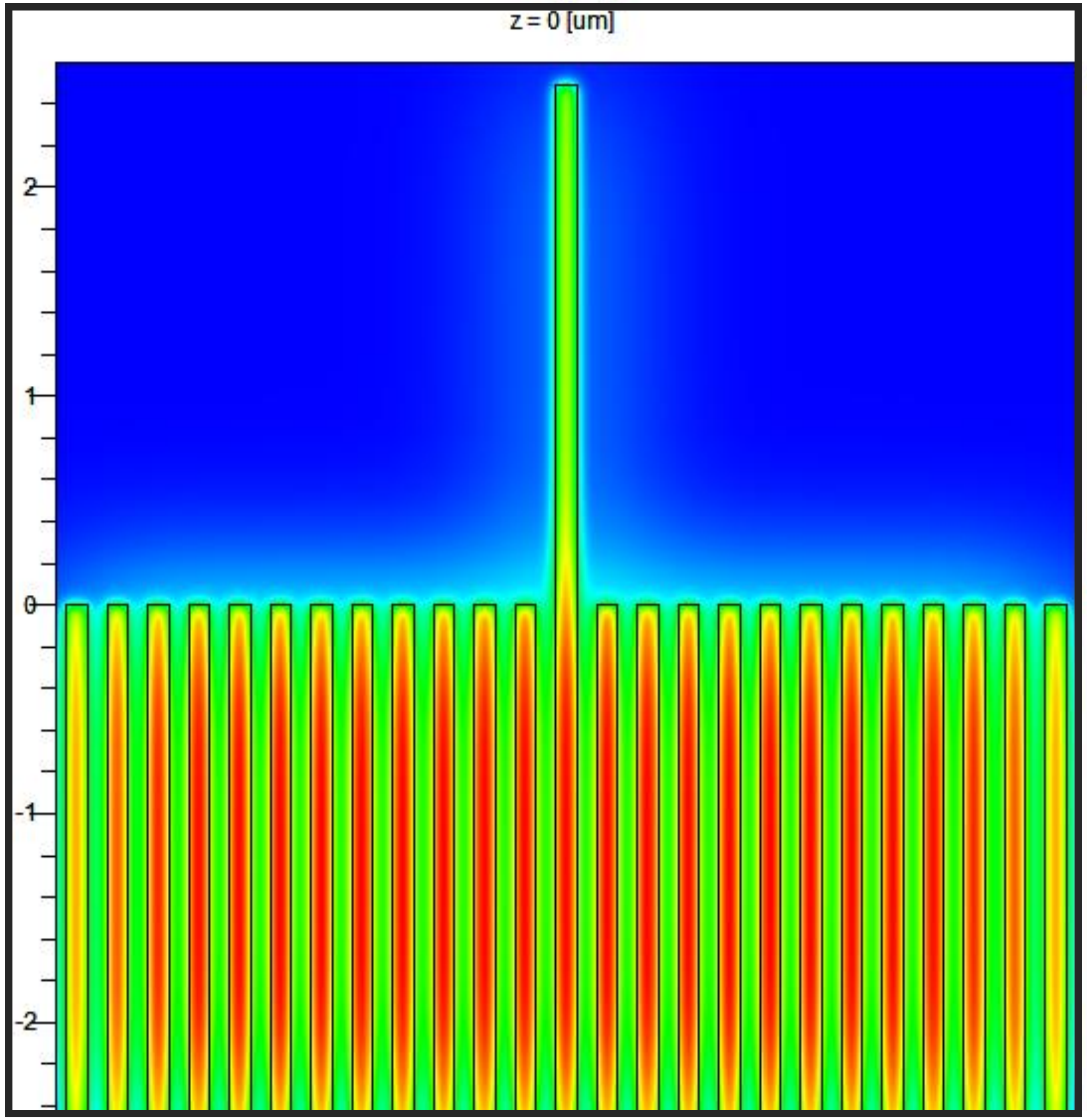
Mouse position (Layout Origin) [um]: -6.3851,7.9975

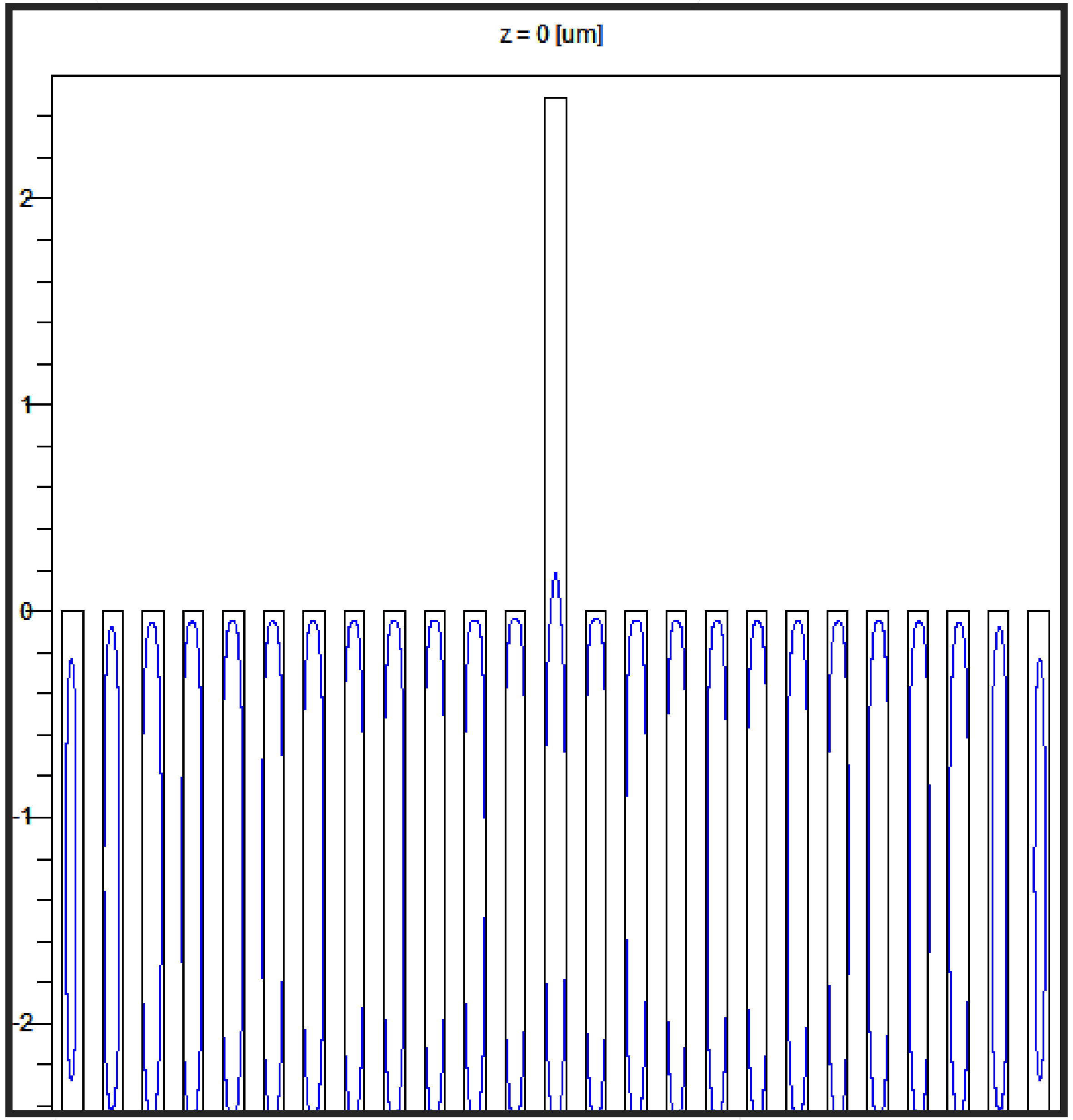
- Simulation comparing with and without PEC
- PEC module general tab with selecting PSF

Edge Equalization

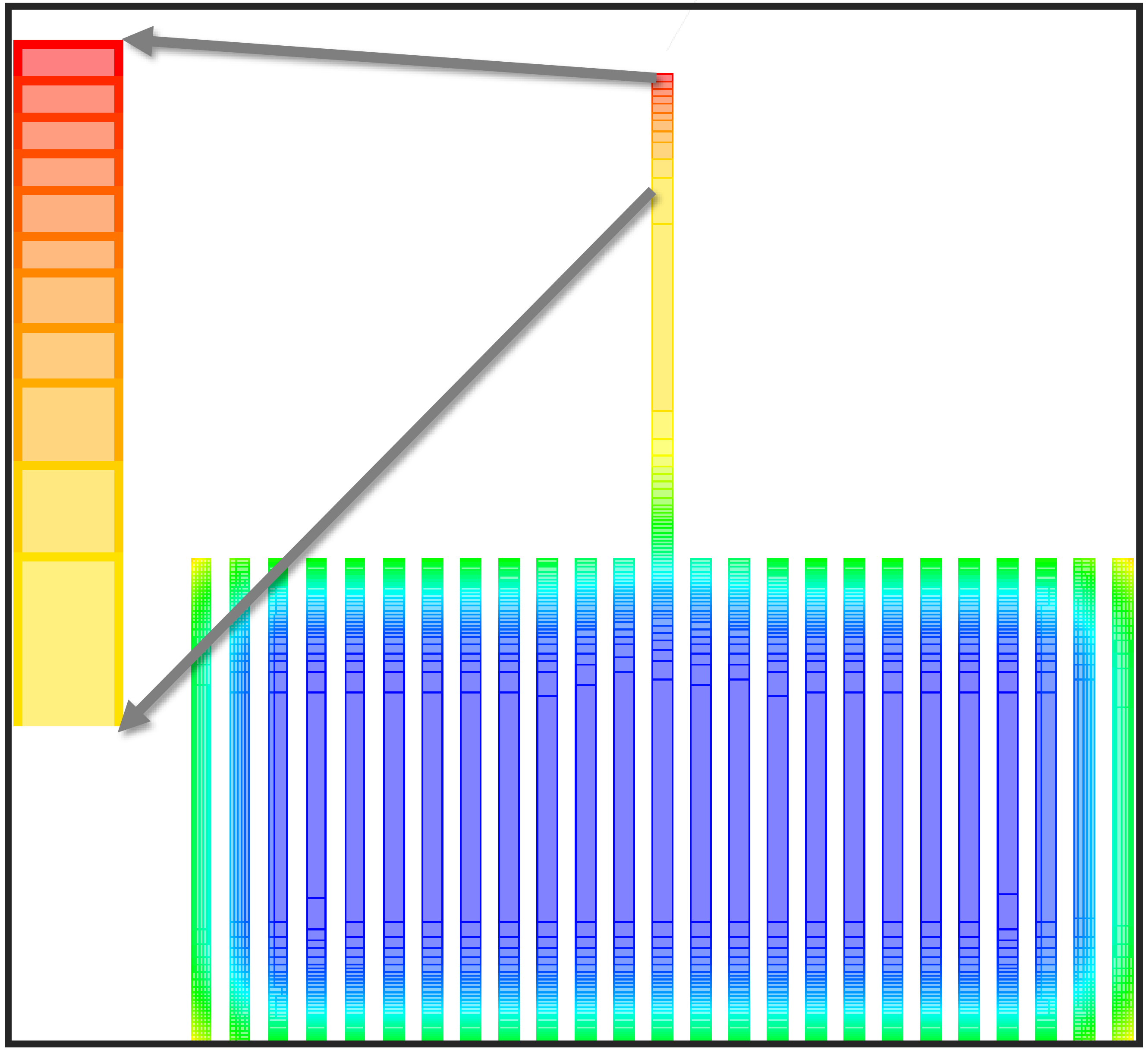
PMMA on GaAs at 100keV	 Case 1. Narrow line	 Case 2. Lines & Spaces (50%)	 Case 3. Narrow gap (w << b)
No PEC $D_f = 1$	 $D_f = 1$ $\frac{1}{2}(1 - BE)$ Under -developed!	 $D_f = 1$ Just on size	 $D_f = 1$ $\frac{1}{2} + \frac{1}{2}BE$ Dose to Clear Over- developed!
PEC	 $D_f = \frac{1}{1 - BE}$ on size	 $D_f = 1$ on size	 $D_f = \frac{1}{1 + BE}$ Dose to Clear on size

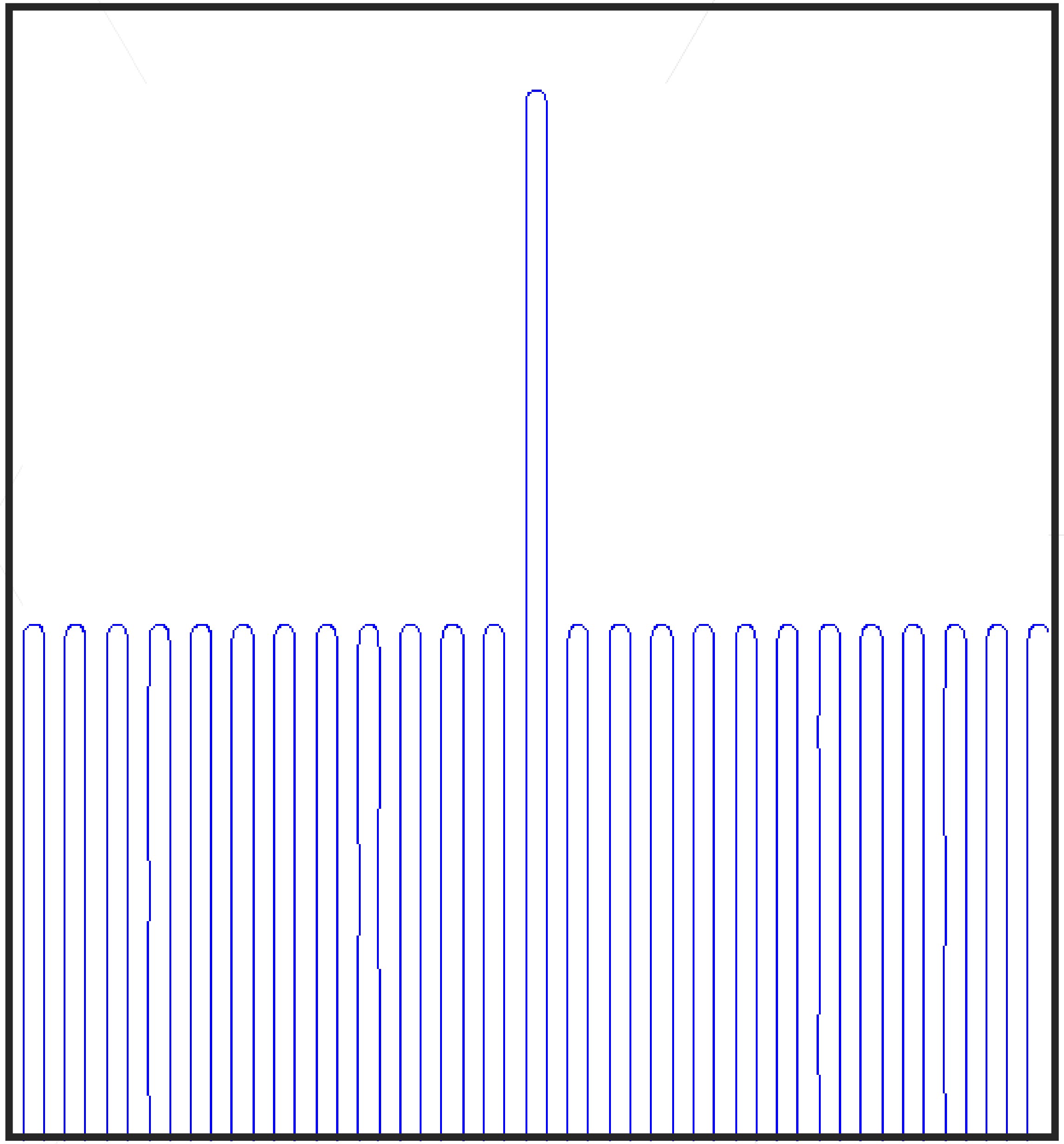
Absorbed Energy in Resist





PEC -> Contour





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    - Why divide PSF into Short, Long range
    - Effective Blur
    - Short – range correction
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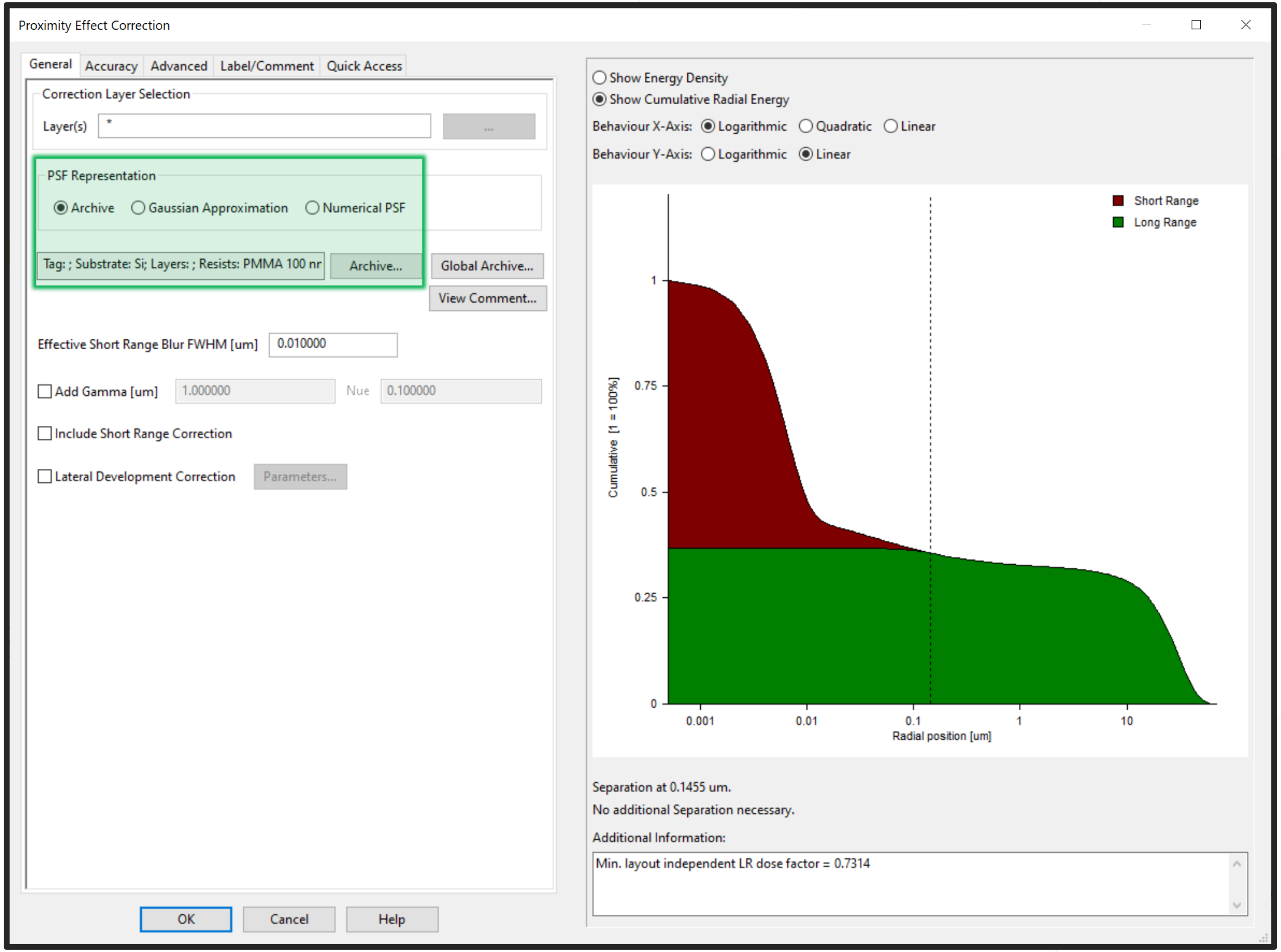
Inside the PEC window



Proximity Effect Correction

Correction Layer Selection

Layer(s) *

PSF Representation

● Archive ○ Gaussian Approximation ○ Numerical PSF

Tag: ; Substrate: Si; Layers: ; Resists: PMMA 100 nr

Effective Short Range Blur FWHM [um] 0.010000

☐ Add Gamma [um] 1.000000 Nue 0.100000

☐ Include Short Range Correction

☐ Lateral Development Correction

○ Show Energy Density

● Show Cumulative Radial Energy

Behaviour X-Axis: ● Logarithmic ○ Quadratic ○ Linear

Behaviour Y-Axis: ○ Logarithmic ● Linear

Separation at 0.1455 um.

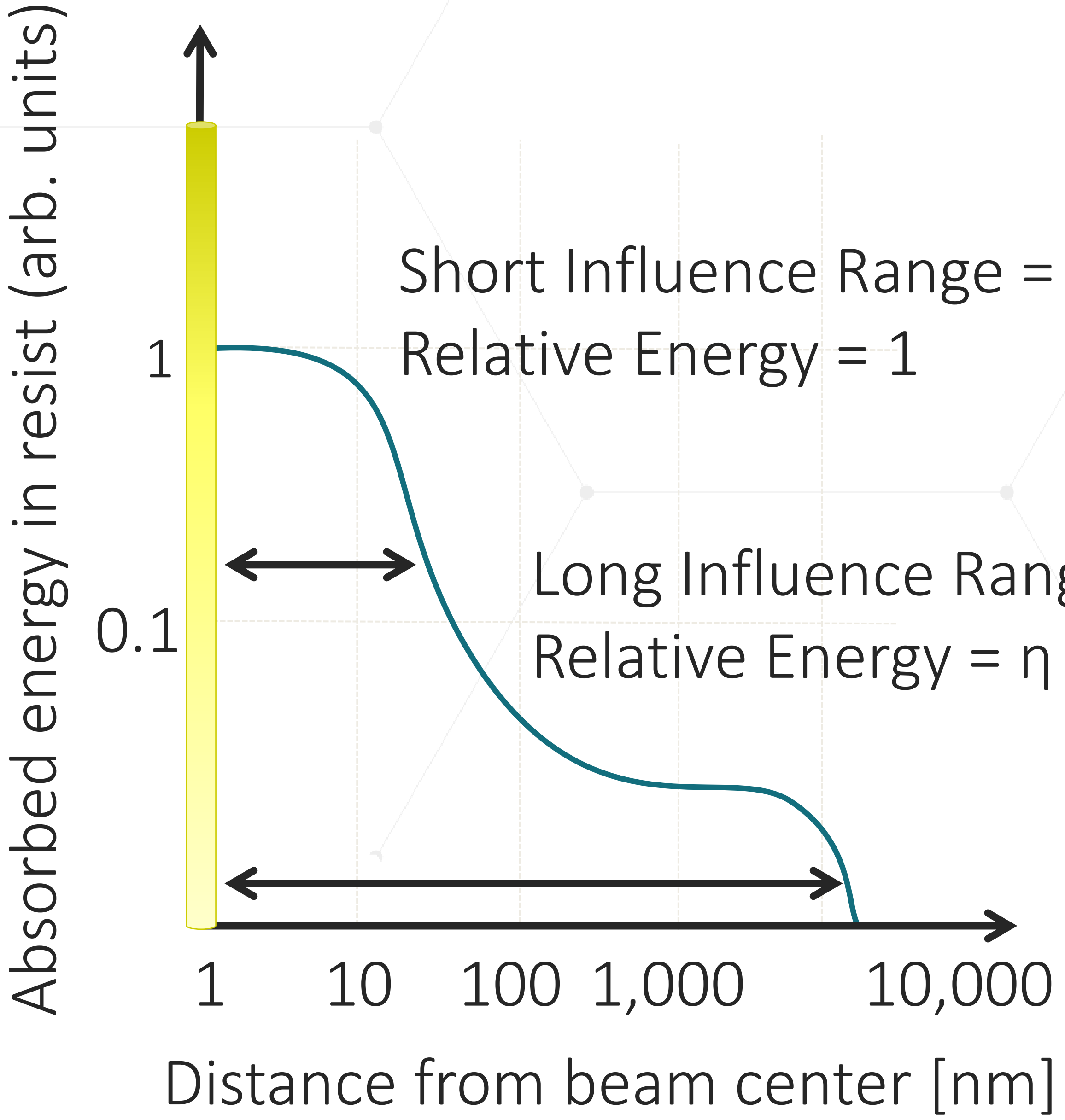
No additional Separation necessary.

Additional Information:

Min. layout independent LR dose factor = 0.7314

- PEC influence ranges
  - SR & LR PSF parts treated differently (computational complexity)
- Basic parameters : PSF, Effective Blur, Base Dose

Point Spread Function - PSF



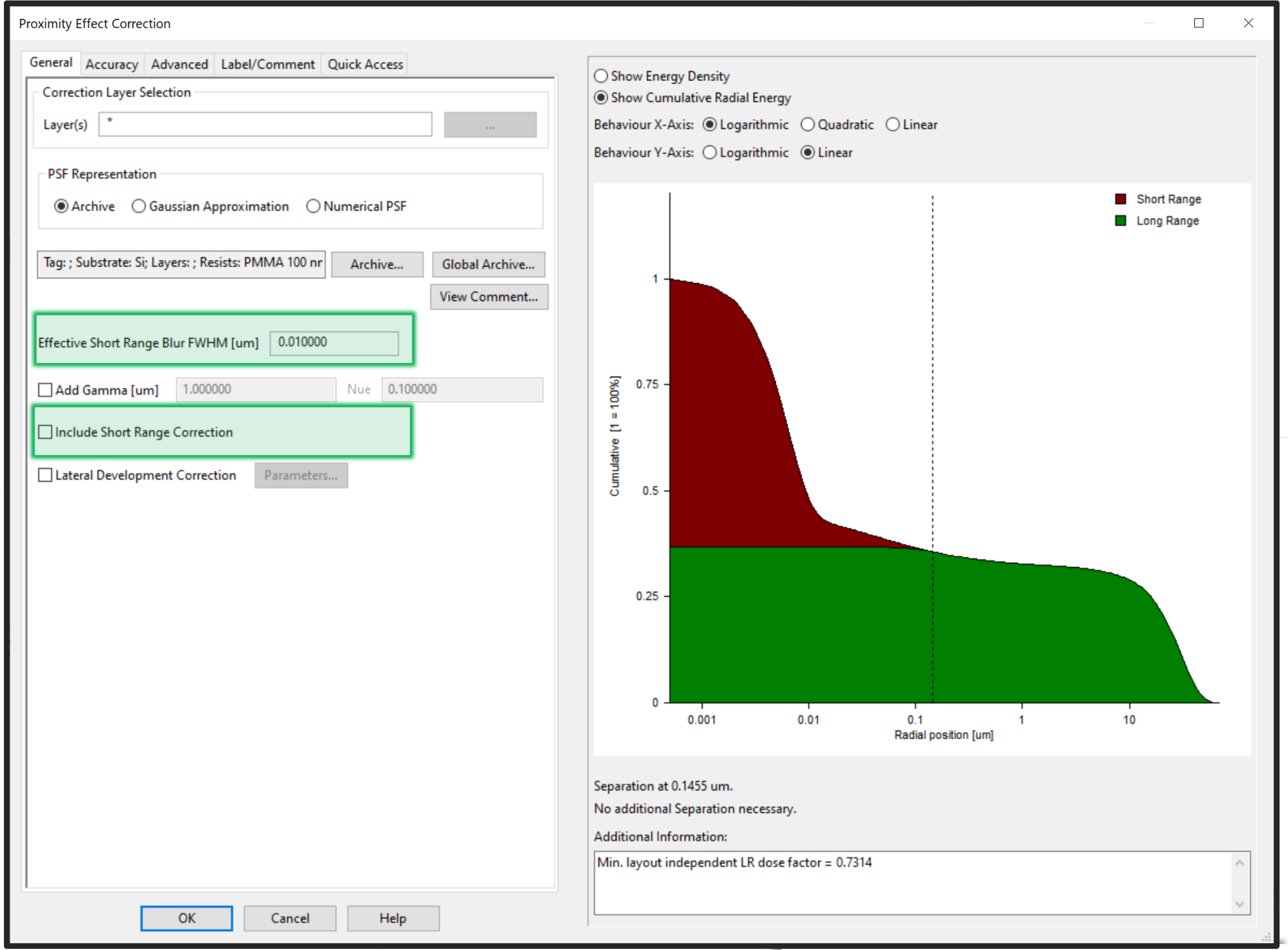
Short Influence Range = α
Relative Energy = 1

Long Influence Range = β
Relative Energy = η

$$PSF(r) = \frac{1}{\pi(1+\eta)}\left[\frac{1}{\alpha^2}e^{-\frac{r^2}{\alpha^2}} + \frac{\eta}{\beta^2}e^{-\frac{r^2}{\beta^2}}\right]$$

Effective blur and short range

- Typical range of Effective Blur (FWHM) ~ 10 nm to 100 nm
- Include short range correction:
  - If Feature size < 2 x Effective blur



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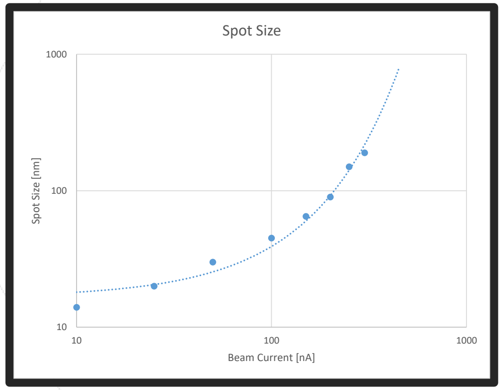
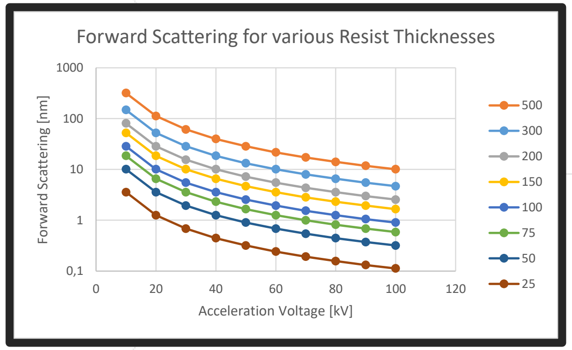
Total Effective Blur

$\mathrm{Spot}_{\mathrm{eff}} = \mathrm{Spot}_{\mathrm{Beam}}$ ← depends on current, 2-100nm

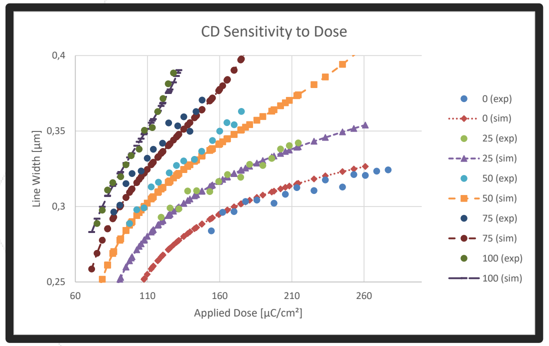


⊗ Jitter ← noise dominated

⊗ Forward Scattering ← 1-10nm



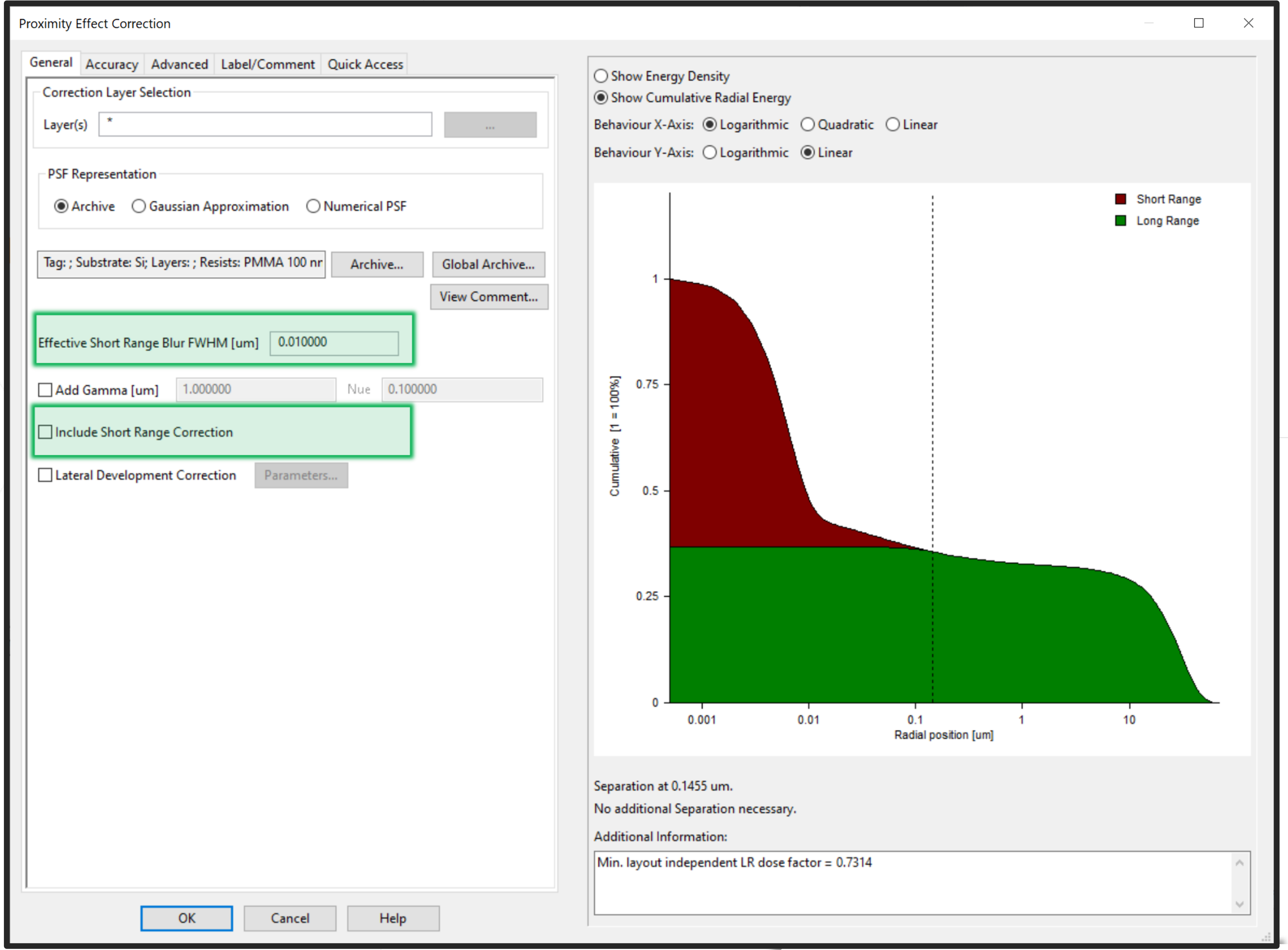
⊗ Back Scattering ← reduced EL for dense



⊗ Resist Effects ← diffusion, lateral development, …

Effective blur and short range

- Typical range of Effective Blur (FWHM) ~ 10 nm to 100 nm
- Include short range correction:
    - If Feature size < 2 x Effective blur



Proximity Effect Correction

Correction Layer Selection

Layer(s): *

PSF Representation

● Archive ○ Gaussian Approximation ○ Numerical PSF

Tag: ; Substrate: Si; Layers: ; Resists: PMMA 100 nr

Effective Short Range Blur FWHM [um]: 0.010000

☐ Add Gamma [um]: 1.000000 Nue: 0.100000

☐ Include Short Range Correction

☐ Lateral Development Correction

○ Show Energy Density
● Show Cumulative Radial Energy

Behaviour X-Axis: ● Logarithmic ○ Quadratic ○ Linear

Behaviour Y-Axis: ○ Logarithmic ● Linear

Separation at 0.1455 um.

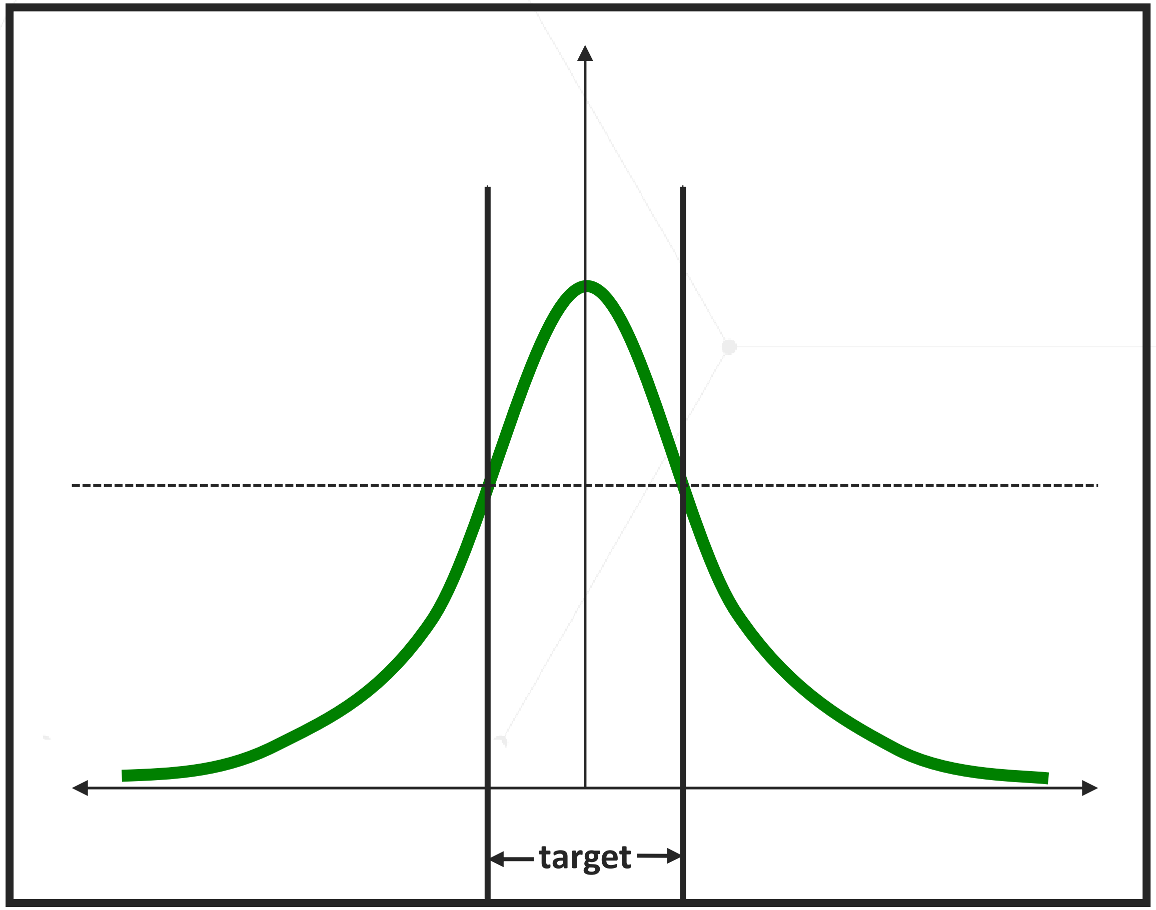
No additional Separation necessary.

Additional Information:

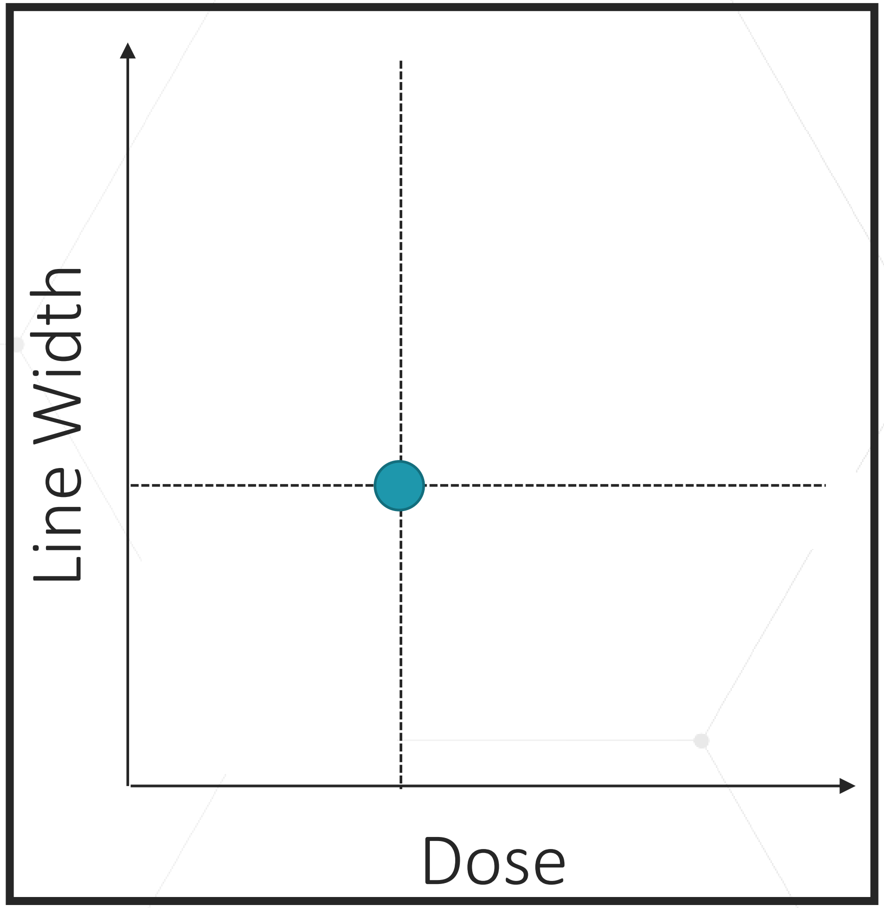
Min. layout independent LR dose factor = 0.7314

CD and Dose Sensitivity

Absorbed Energy



Exposure Latitude



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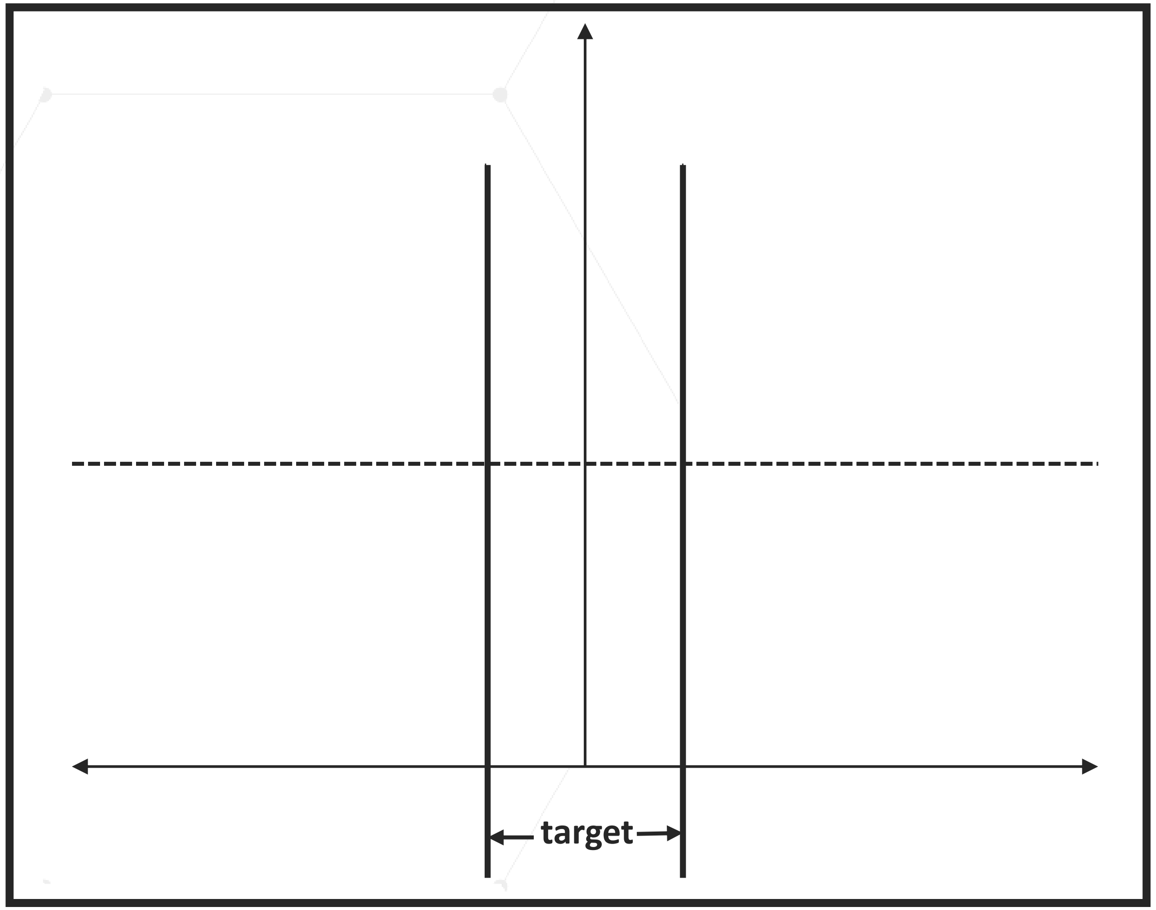
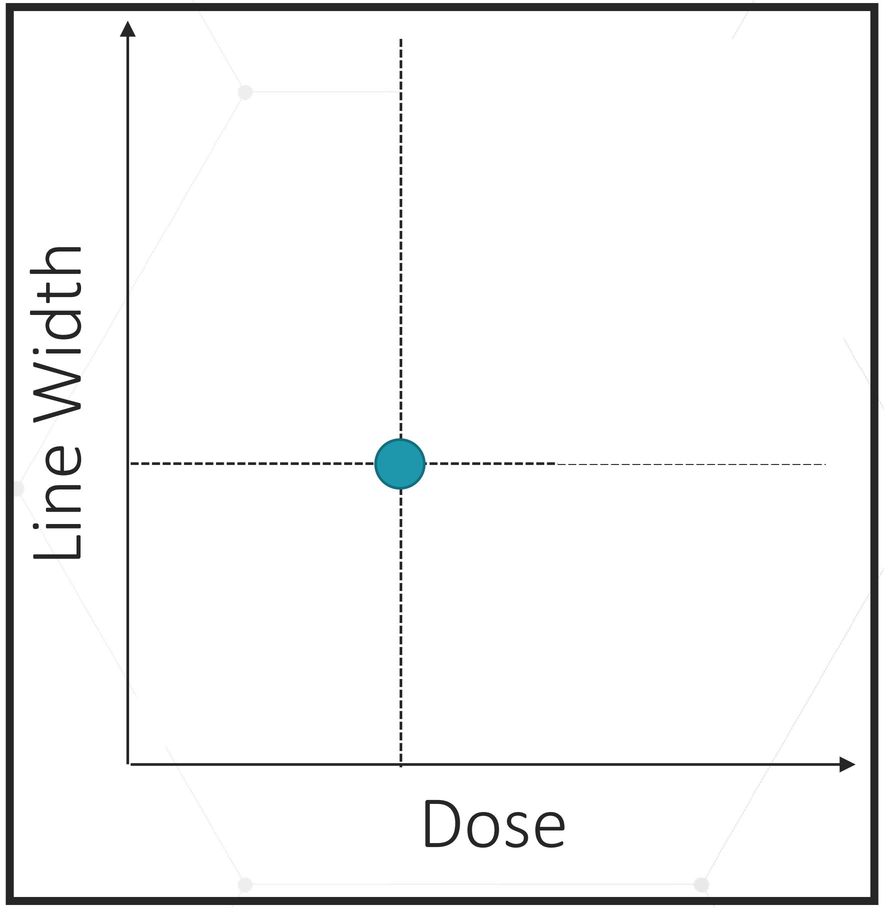
CD and Dose Sensitivity

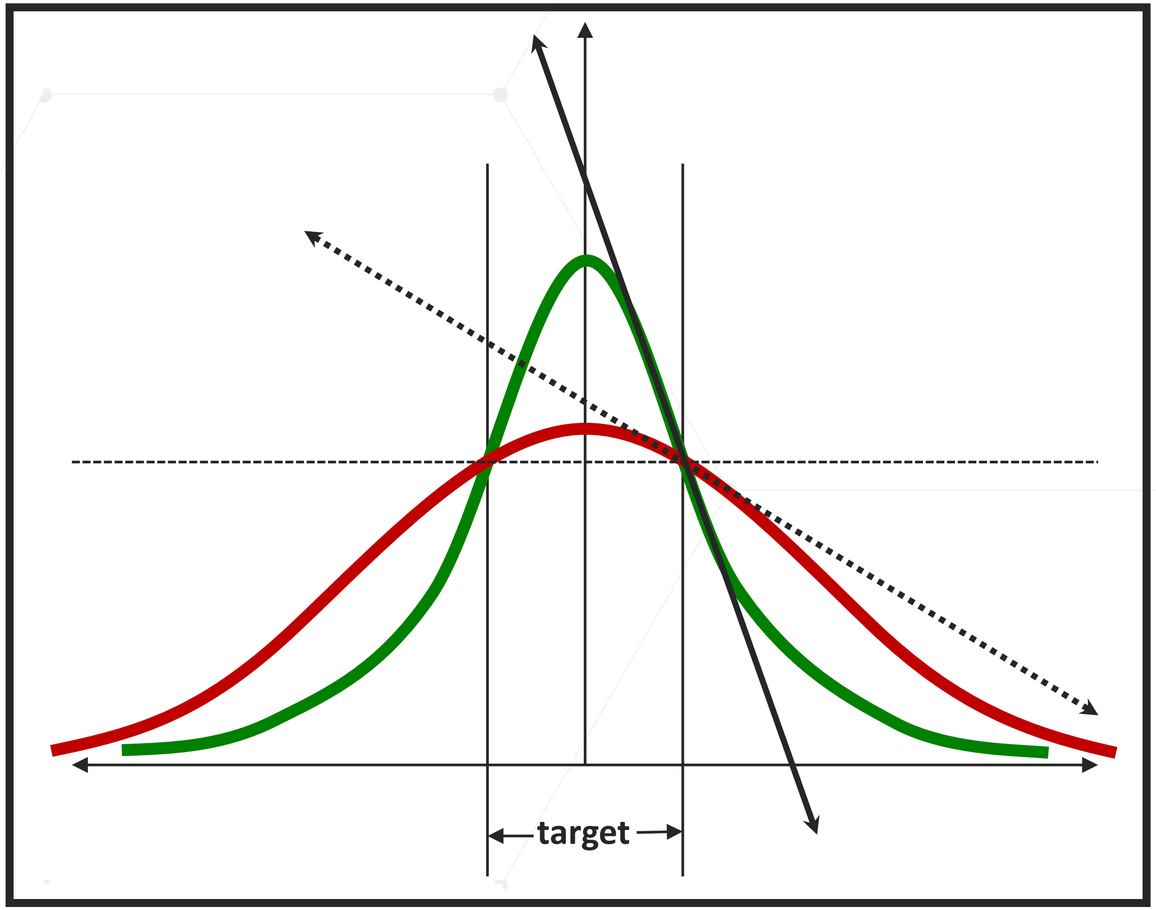


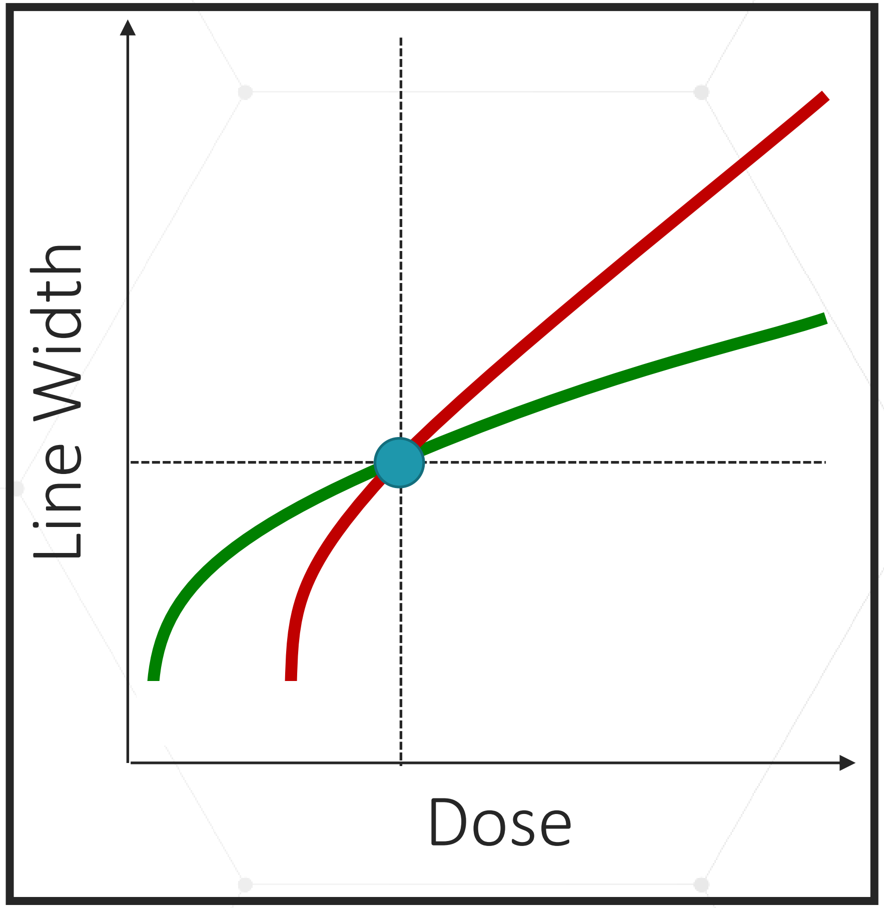
Absorbed Energy



Exposure Latitude

CD and Dose Sensitivity





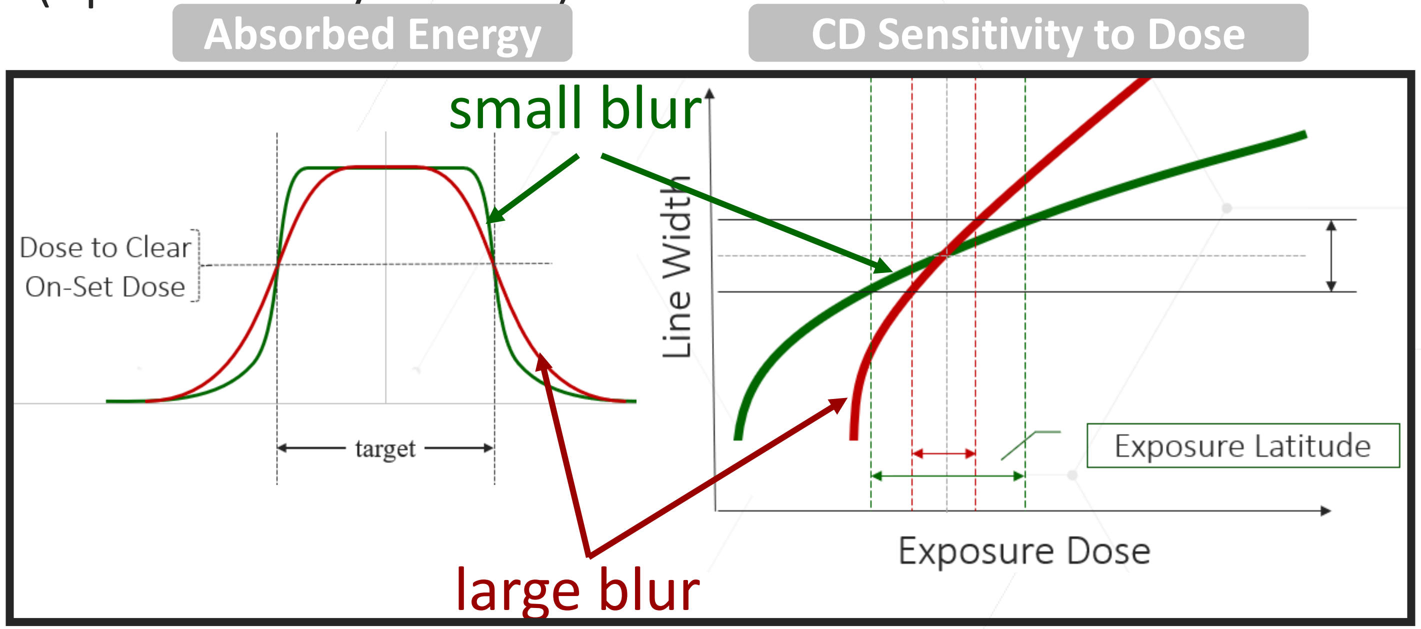
Absorbed Energy

Exposure Latitude

Larger spots magnify dose errors - CD sensitivity to dose gets worse

Blur couples Dose to CD

- Impact of proximity effect on lithography result depends on tool + process parameters
  - The effective short range blur transfers absorbed energy variation to CD variation
  - The effective beam size depends on e-beam tool parameters
    - beam current, apperture, focus (variation), noise
    - Reasonable exposure time and exposure quality ask for higher beam curent
  - The process (specifically resist) is another contributor to effective short range blur


Absorbed Energy

CD Sensitivity to Dose

Effective Blur: Beam Size + Scattering + Process

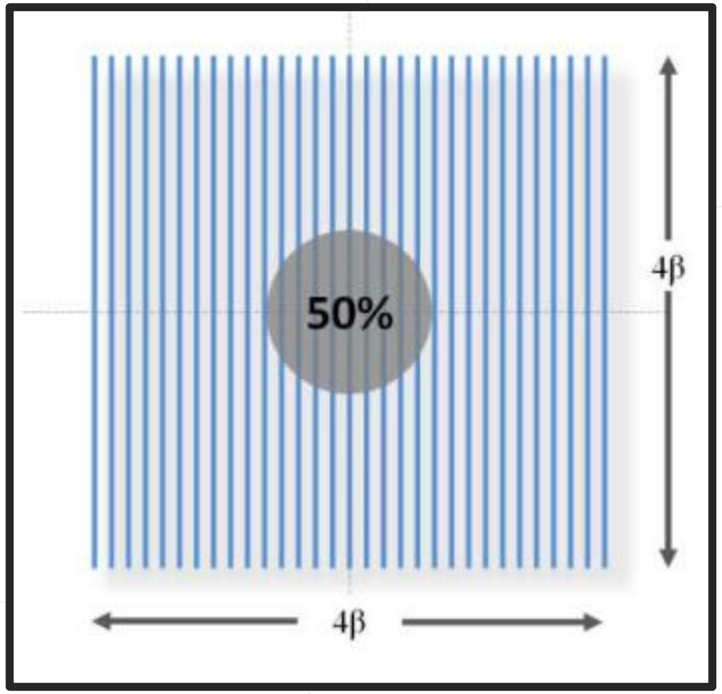
How to determine Effective Blur

- Quick and fast approximation
  - Expose an isolated line with a dose variation around dose to size
  - Measure CD for each dose change
  - Blur (FWHM) = 0.76 * ΔCD / Δ%dose
- Use Tracer Process Calibration to determine the Blur taking the entire process into account

Base Dose Determination

1. Correct base dose can be found by measuring the center of a 1:1 Line Space Grating
   200 nm lines in 4B x 4B grating

BEAMER takes dose factor 1 as the base dose of your experiment



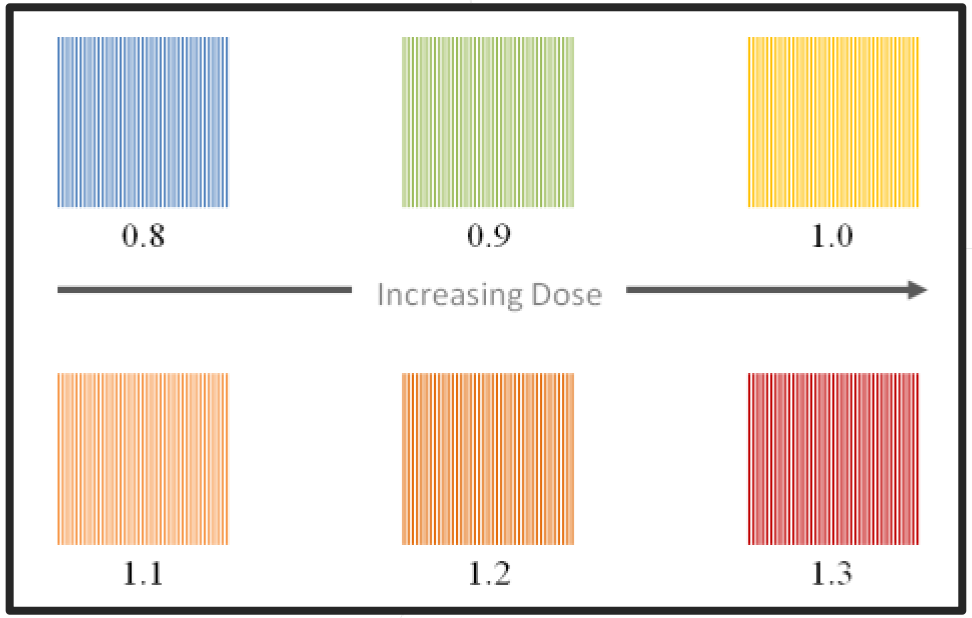
Base Dose Determination

1. Correct base dose can be found by measuring the center of a 1:1 Line Space Grating

   200 nm lines in 4B x 4B grating

2. Expose the grating at increasing dose in a dose matrix

BEAMER takes dose factor 1 as the base dose of your experiment



Base Dose Determination

1. Correct base dose can be found by measuring the center of a 1:1 Line Space Grating
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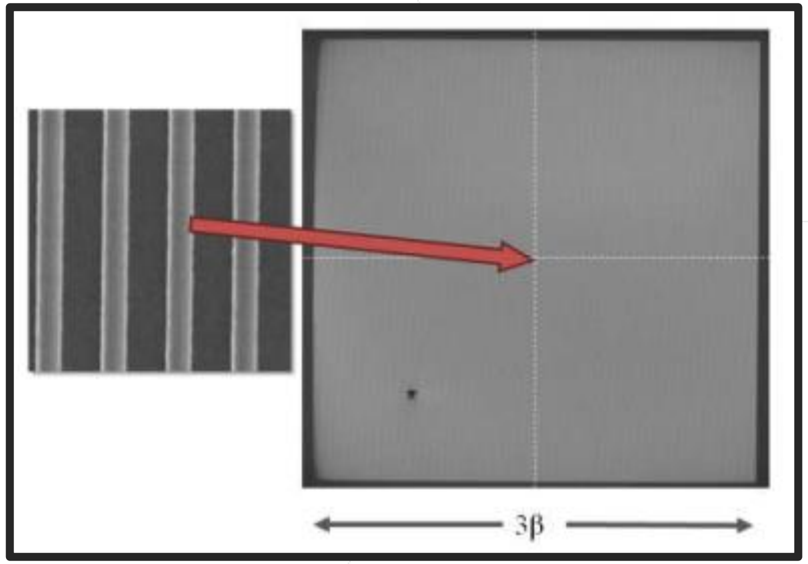
2. Expose the grating at increasing dose in a dose matrix
3. Measure the center of the pattern where pattern density is exactly 50%

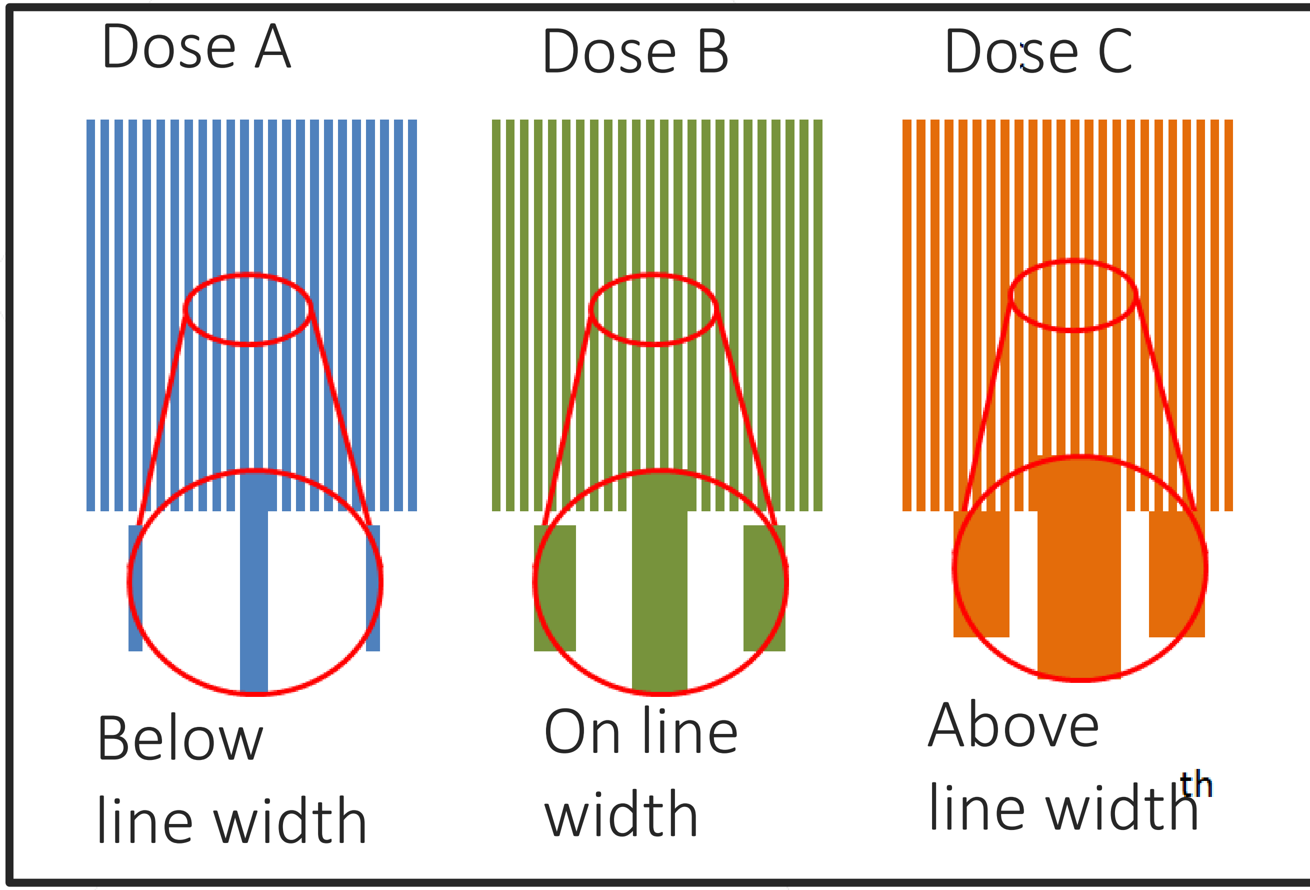
BEAMER takes dose factor 1 as the base dose of your experiment



Base Dose Determination

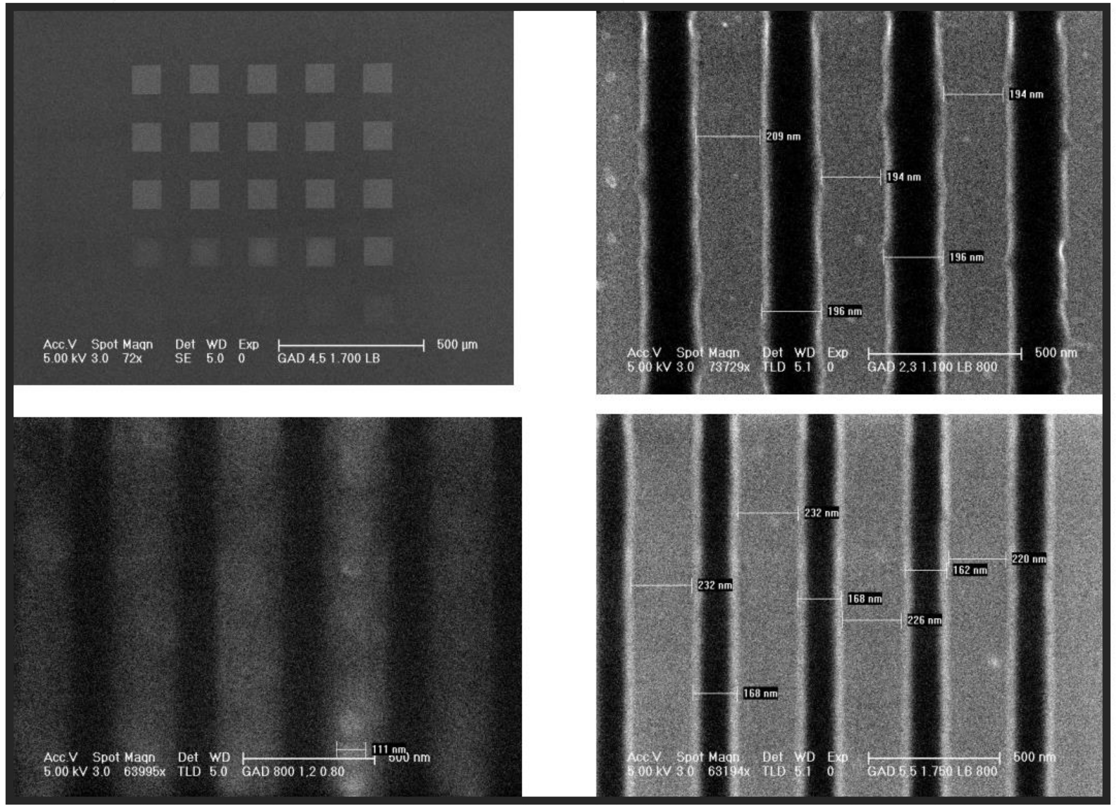
1. Correct base dose can be found by measuring the center of a 1:1 Line Space Grating
   200 nm lines in 4B x 4B grating
2. Expose the grating at increasing dose in a dose matrix
3. Measure the center of the pattern where pattern density is exactly 50%
4. Choose dose where line and space are same width

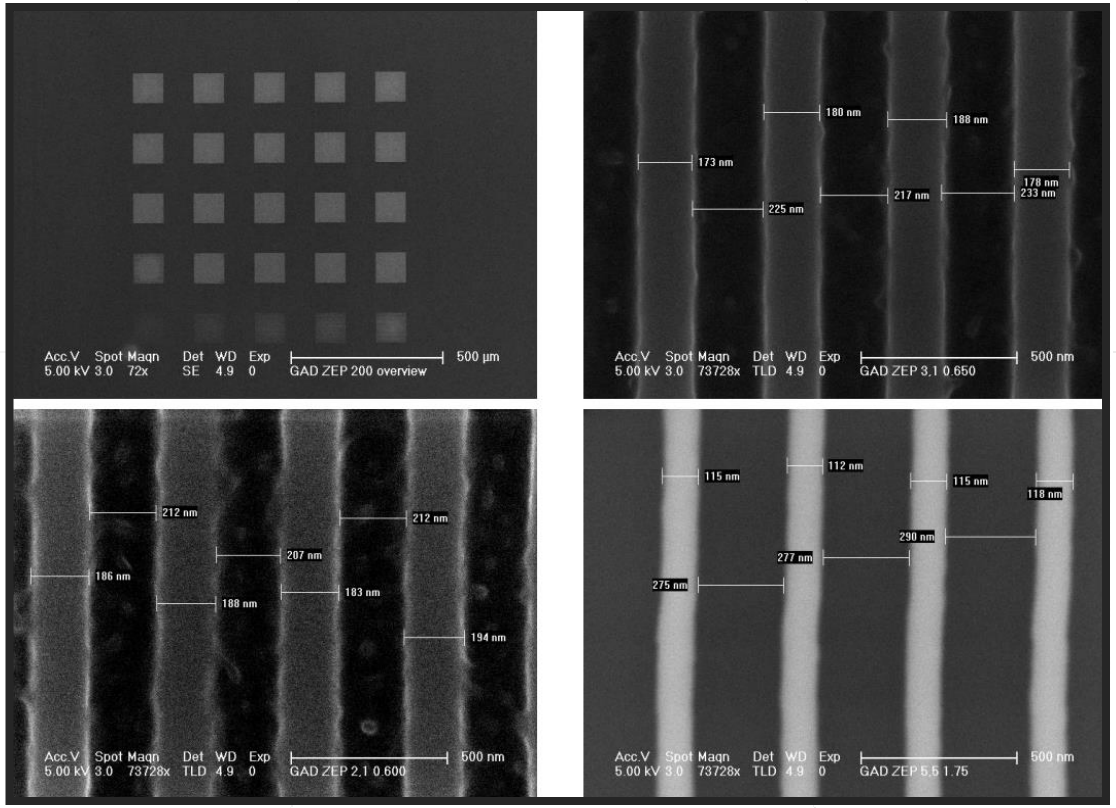
BEAMER takes dose factor 1 as the base dose of your experiment



Base Dose found

The dose without any residue is the base dose!





Agenda

- Proximity Effect
- Proximity Effect Correction by Dose modulation
- Inside the PEC window
- Summary
- Q&A

Summary

Standard Dose PEC – Introduction

- Proximity Effect
  - Principle – electron scattering, CD = f(Dose, Density)
  - Monte Carlo Simulation in TRACER
- Proximity Effect Correction by Dose modulation
  - Edge Equalization algorithm
  - Simulation comparing with and without correction
- Inside the PEC window
  - Why divide into Short, Long range – Computationally treated differently
  - Effective Blur – sources of origin
  - Short-range correction – when its required
  - Base dose determination

Outlook

- PSF definition
  - PSF Stack / PSF with Gaussian
- Process parameters
  - Base dose / Effective blur / Lateral development
  - TRACER process calibration
- Advanced Parameters
  - Dose assignment / Fracturing

Thank You!

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PEC: Why 0.5?

- A e-beam direct write tool has a Gaussian spot beam
  - Energy from exposure can represented with a Gaussian distribution
- Pattern definition is considered binary – either on or off
  - Can be represented with a step function
- The exposure is convolving a step function with a Gaussian, with the result that the applied energy is exactly 50% of the total energy at the pattern edge
- In BEAMER, 0.5 is the correction target – it is an edge correction