CHALLENGES OF HIGH-SPEED EUV DEFECT INSPECTION

MP0601: Short Wavelength Laboratory Sources

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EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

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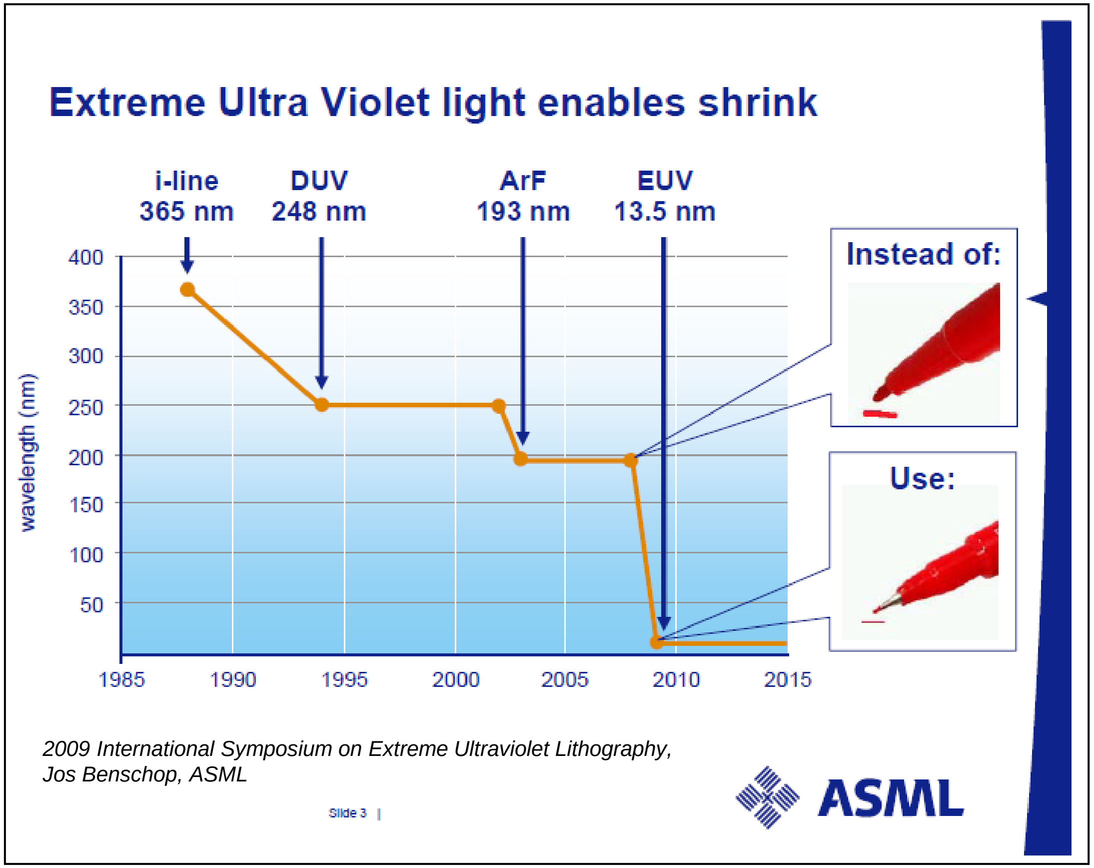
LEHRSTUHL FÜR TECHNOLOGIE OPTISCHER SYSTEME

Outline

1. Motivation
2. Experimental setup
3. Experimental results
4. Limitations
5. Alternative detector concepts
6. Extendability
7. Conclusion & Outlooks

1. Motivation

- Lithography => smaller structures (2011: 22nm HP) => shorter wavelength



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1. Motivation

- Transition to EUV (13.5nm) => fundamental changes:
  - Vacuum required
  - No transmission masks, due to short penetration depth (<1µm) => reflection masks => multilayer mirrors
- Masks => mask blanks => both: defect free => critical defect size: 30nm
- Mask blank: 150x150mm^2 (143x143mm^2 to inspect), inspection time $\leq$ 45min
  - Resolving inspection => great sensitivity to defects, but $t_{inspection} \cong 2$ month
  - Inspect with large FOV => $t_{inspection}$ gets short, but sensitivity drops
- solution: sensitivity to small defects (=> dark field mode) but low resolution (=> big FOV), zooming option as a 2nd inspection step
- Parameters of: source/collector, object, objective, detector => **which are suitable for the task?**

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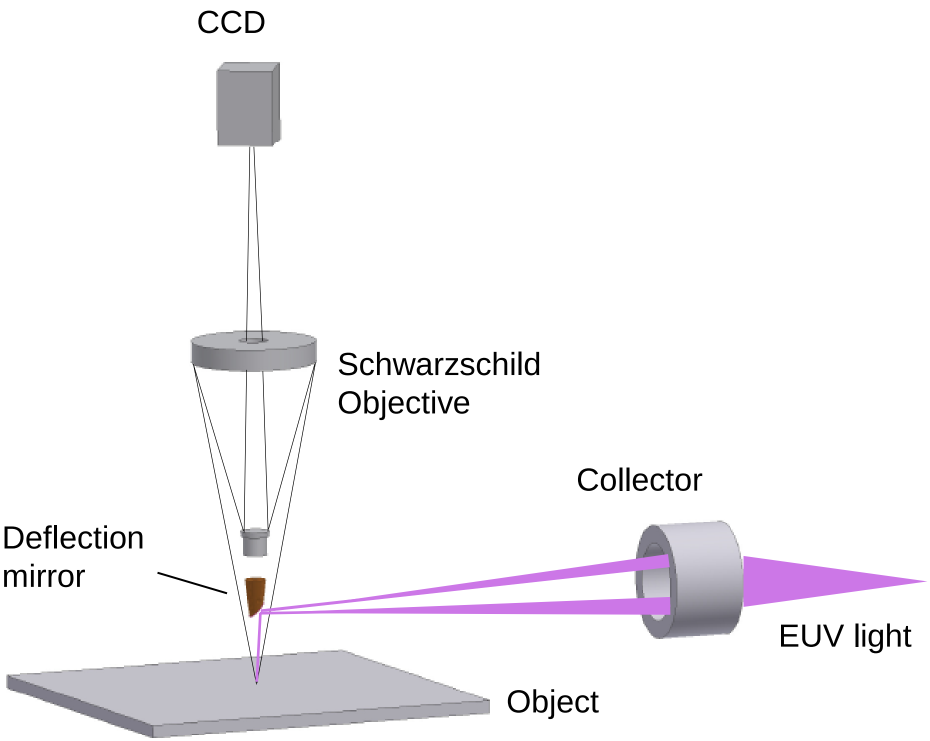
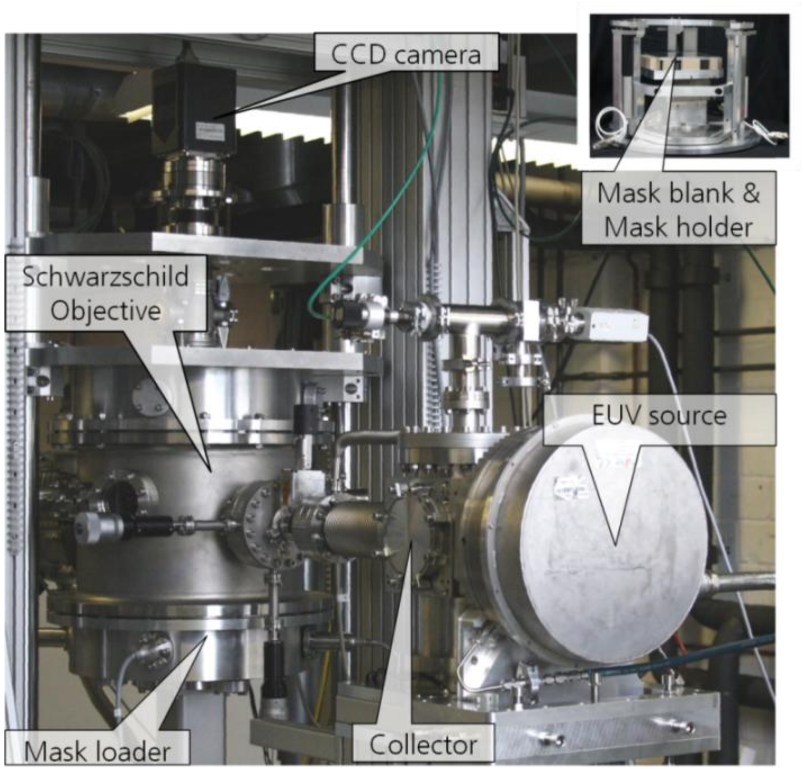
2. Experimental setup

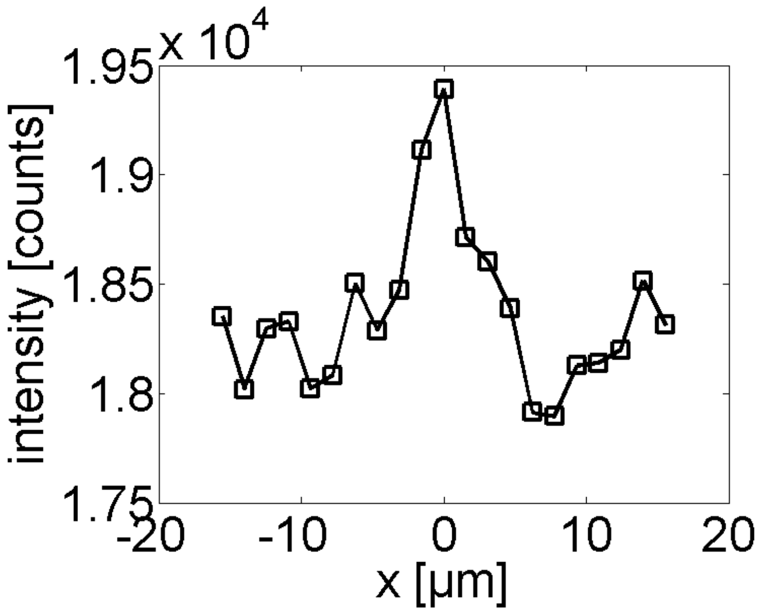




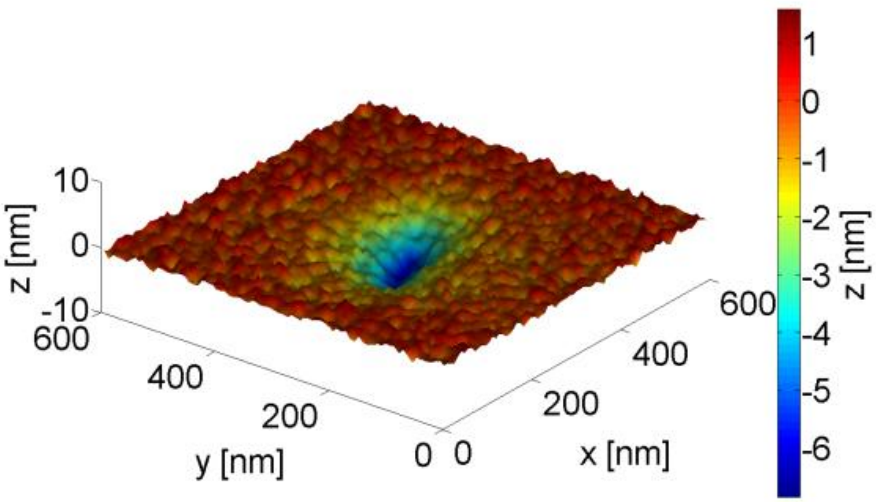
3. Experimental results

- Programmed structures (bumps and pits) and natural defects both on multilayer mirrors investigated by EUV microscope and characterized by Atomic Force Microscope
- Smallest structure: diameter = 45 nm, depth = 7 nm (equivalent sphere)

Profile – EUV Microscope



Atomic Force Microscope



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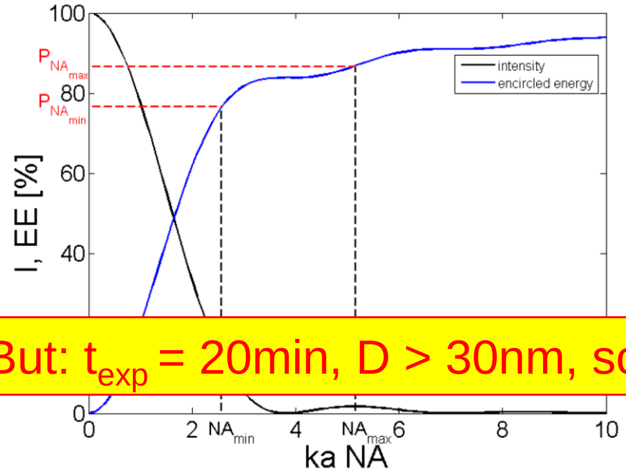
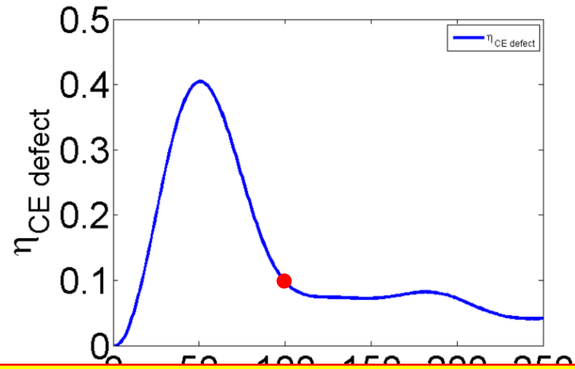
3. Experimental results

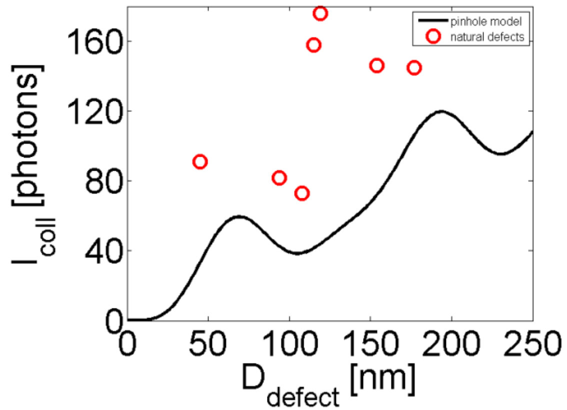
Pinhole approach for simulation of defects scattering distribution:





But: t_{exp} = 20min, D > 30nm, scanable area 25x25mm^2, **system not suitable**!

Comparison between experiment and simulation:



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4. Limitations

Three main categories can limit the tools performance due to the industrial requirements:

1) **Sensitivity** (object roughness, objective collection efficiency)
2) **Scan rate** (Sample mechanics, detector read out speed)
3) **Light flux** (source power, collector efficiency)

Parameter	Worst case	Expected case	Best case
η_{QE}	0.40		0.60
$\eta_{scatt-flare}$	0.02	0.015	0.01
$\eta_{scatt-defect}$	0.40		
$\eta_{collect-flare}$	0.15	0.20	0.25
$\eta_{collect-defect}$	0.20	0.25	0.30
R_{SO}	0.36		
d_{pixel} [μm]	13		
R_{defl}	0.45		
T_{filter}	0.30		
T_{gas}	0.70		
R_{coll}	0.45		
$\varphi_{obj-coll}$ [°]	5		
M_{coll}	6		
d_{source} [μm]	400		
P_{source} [W/2π/2%b.w.]	30		

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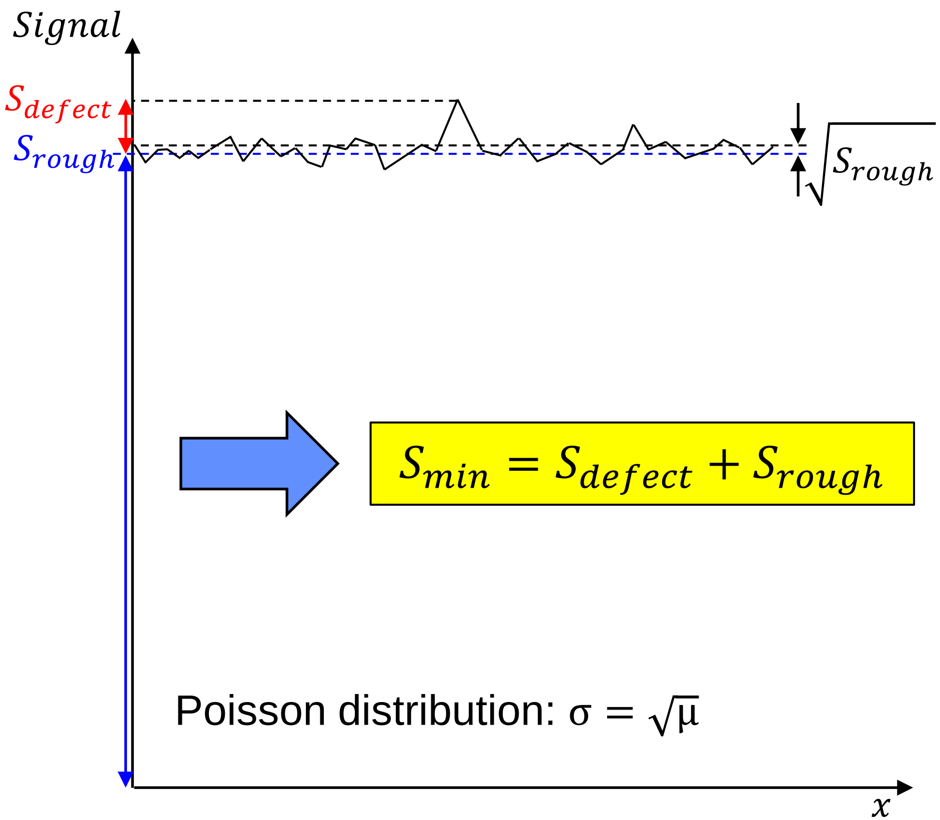
4. Limitations

1) Sensitivity:



$$SNR = \frac{S_{defect}}{\sqrt{S_{rough}}}$$

Rose criteria: SNR ≥ 5

$$S_{defect} \geq SNR \cdot \sqrt{S_{rough}}$$

$$S_{min} = S_{defect} + S_{rough}$$

$$S_{min} \propto \frac{1}{M_{SO}{}^4} \qquad Scanspeed \propto M_{SO}{}^2$$

Which is the optimal M_{SO}?

Poisson distribution: $\sigma = \sqrt{\mu}$

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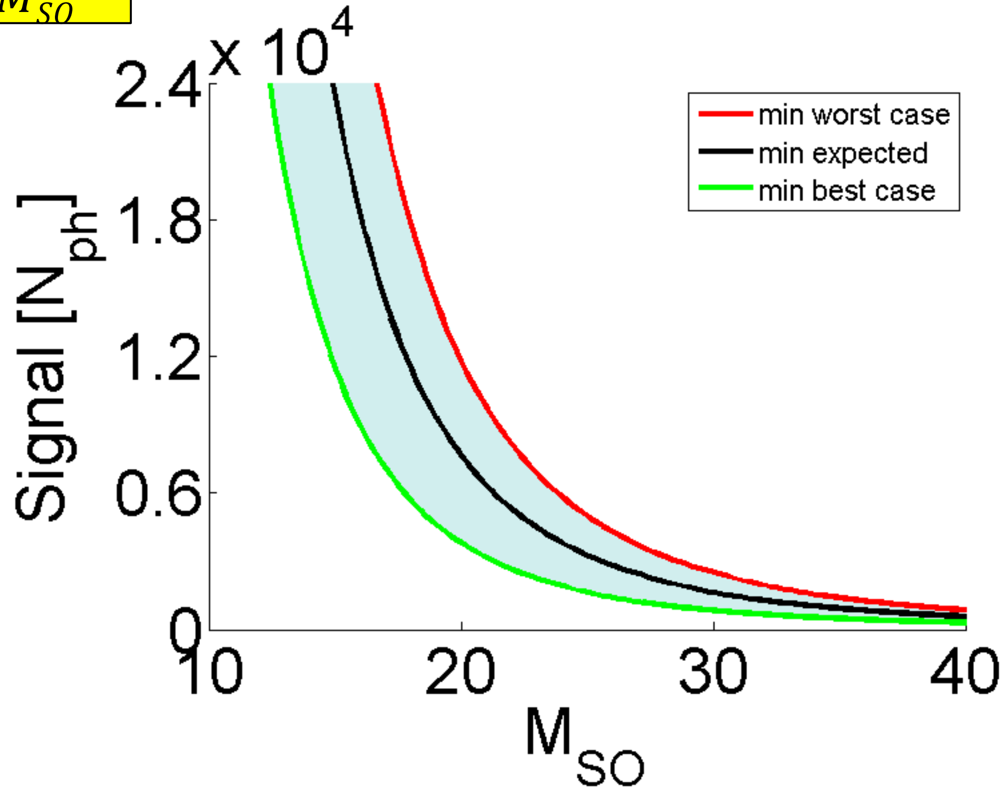
4. Limitations

$$S_{min}(M_{SO}) = \frac{1}{SNR^2} \cdot A^2 \cdot \frac{1}{{M_{SO}}^4} + A \cdot \frac{1}{{M_{SO}}^2}$$



$$A = \frac{SNR^2 \cdot \eta_{SE\_rough} \cdot A_{pix}}{\eta_{SE\_defect} \cdot A_{defect}} \cdot \frac{\eta_{CE\_rough}}{\eta_{CE\_defect}}$$

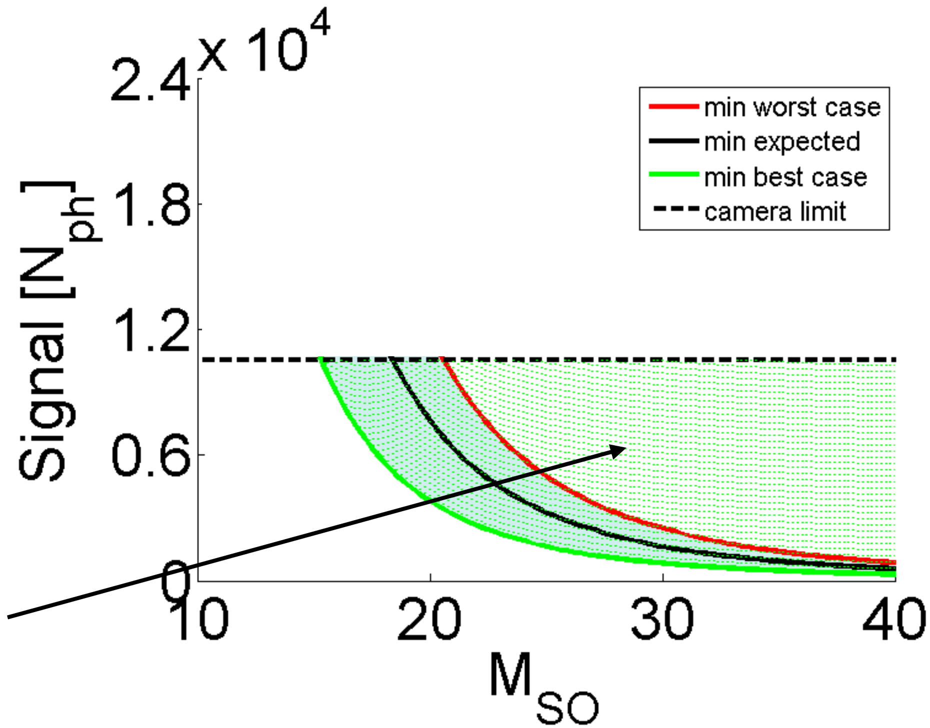
4. Limitations

Detector dynamic range: 16bit:

$$16\ bit = 2^{16} = 65536$$

$$\text{typical XUV CCD: } \frac{counts}{ph} \approx 6$$

$$S_{min}(M_{SO}) \leq 10561$$



workable area

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4. Limitations

2) Scan rate (SR):

Required:

$$SR_{req} = \frac{A_{blank}}{A_{FOV} \cdot t_{blank}} = \frac{{M_{SO}}^2 \cdot A_{blank}}{A_{pix} \cdot N_{pix} \cdot t_{blank}} \quad \Rightarrow \quad SR_{req}(M_{SO}) \propto {M_{SO}}^2 \quad unit: fps$$

$$reference: 1\ MP\ camera$$

Sample Movement speed:

$$SR_{table} = \frac{1}{t_{exp} + t_{step}} \qquad t_{exp} \Rightarrow 0 \quad \Rightarrow \quad SR_{table\_max}(M_{SO}) = 37 fps^{*}$$

*concerning a commercial movement table with a step size of 1mm and a load of 1kg

Detector read out speed:

commercial full frame CCD: 4.6 fps

custom made frame transfer CCD: 9.8 fps

$$\Rightarrow \quad SR_{detector\_max}(M_{SO}) = 9.8 fps$$

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4. Limitations

$$SR_{req}(M_{SO}) \propto M_{SO}^2$$

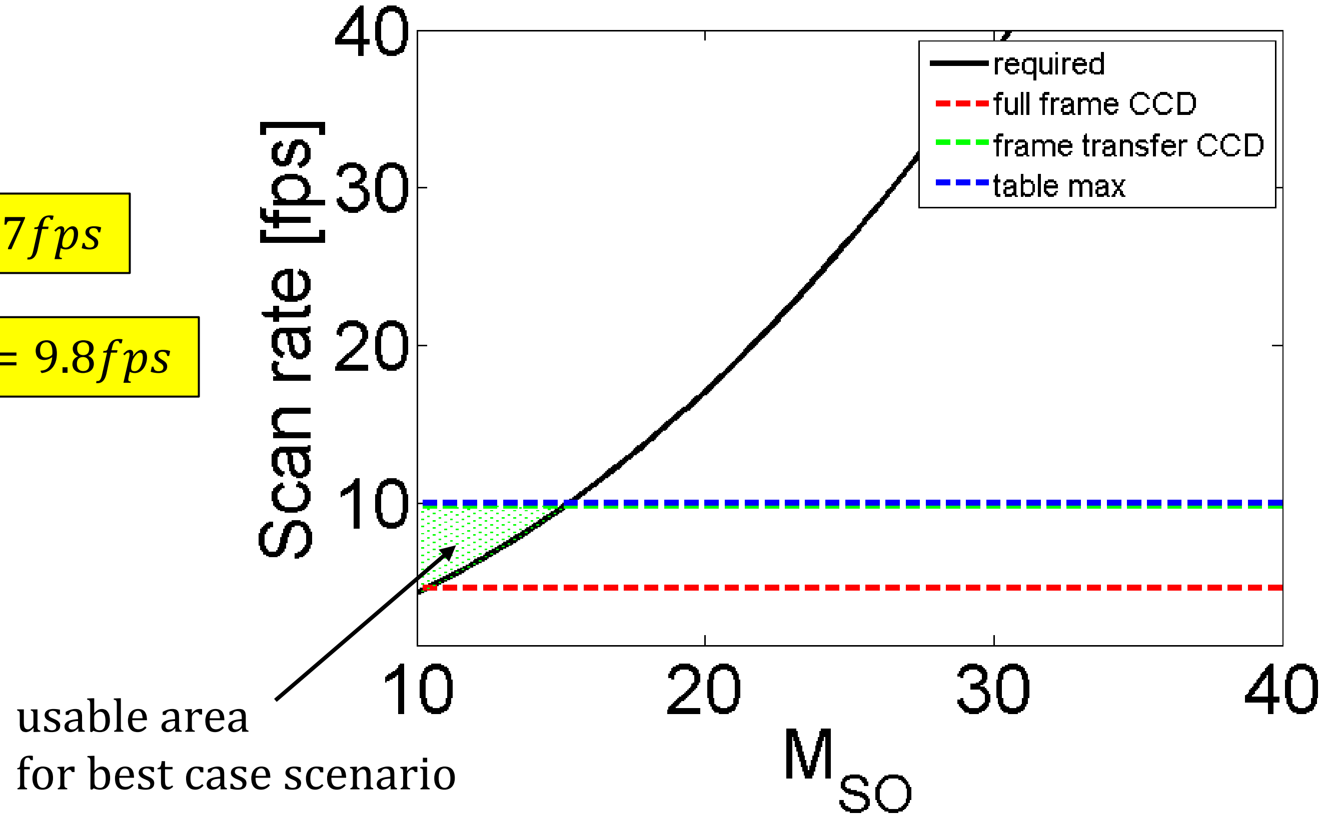
$$SR_{table\_max}(M_{SO}) = 37 fps$$

$$SR_{detector\_max}(M_{SO}) = 9.8 fps$$

$$SR_{table} = \frac{1}{t_{exp} + t_{step}}$$

$$t_{exp} = 0\ ms$$

$$t_{exp} = 73\ ms$$



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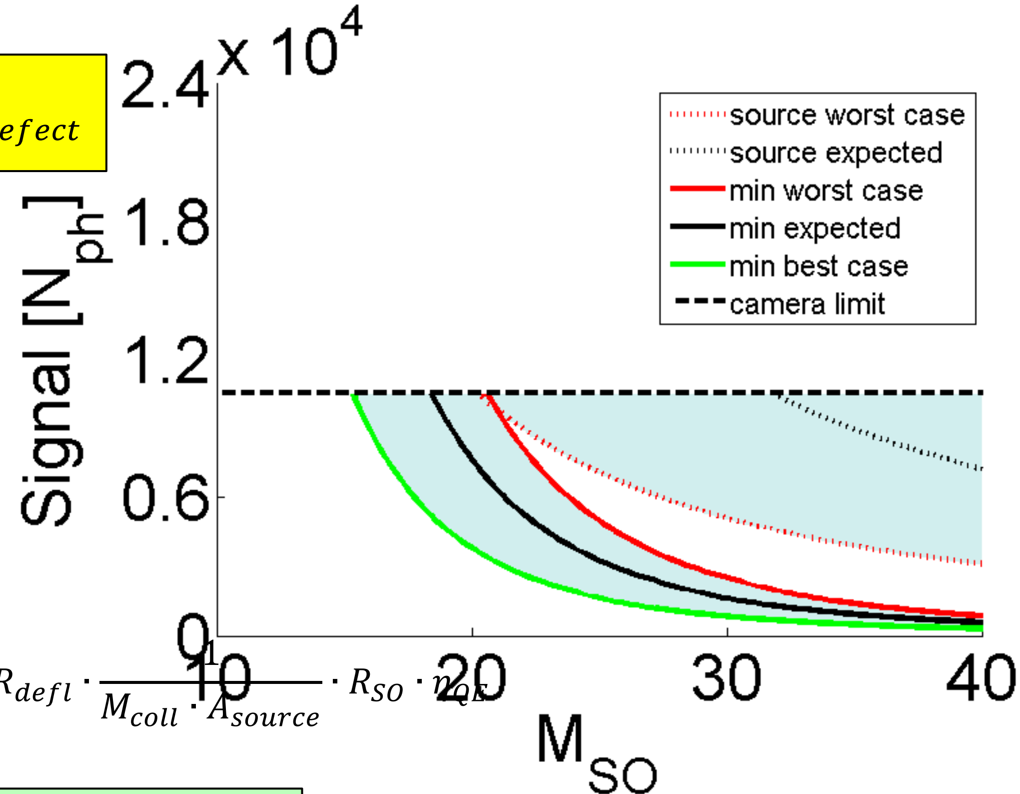
4. Limitations

3) Light Flux:

$$S_{source}(M_{SO}) = B \cdot C_{rough} \cdot \frac{1}{{M_{SO}}^2} + B \cdot C_{defect}$$

$$SR_{table} = \frac{1}{t_{exp} + t_{step}}$$

$$t_{exp} = 8\ ms$$



$$B = N_{ph\_source} \cdot T_{gas} \cdot \eta_{CE\_coll} \cdot R_{coll} \cdot T_{filter} \cdot R_{defl} \cdot \frac{1}{M_{coll} \cdot A_{source}} \cdot R_{SO} \cdot \eta_{QE}$$

$$C_{rough} = A_{pix} \cdot \eta_{SE\_rough} \cdot \eta_{CE\_rough}$$

$$C_{defect} = A_{defect} \cdot \eta_{SE\_defect} \cdot \eta_{CE\_defect}$$

⇒ adapted to sensitivity requirement!

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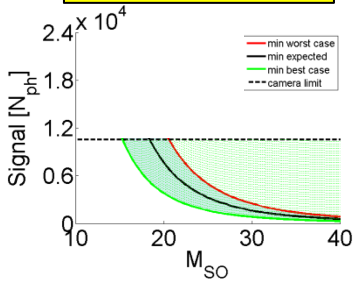
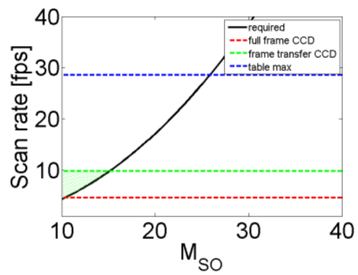
4. Limitations

Process window:

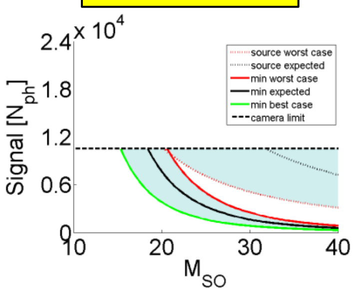
Sensitivity

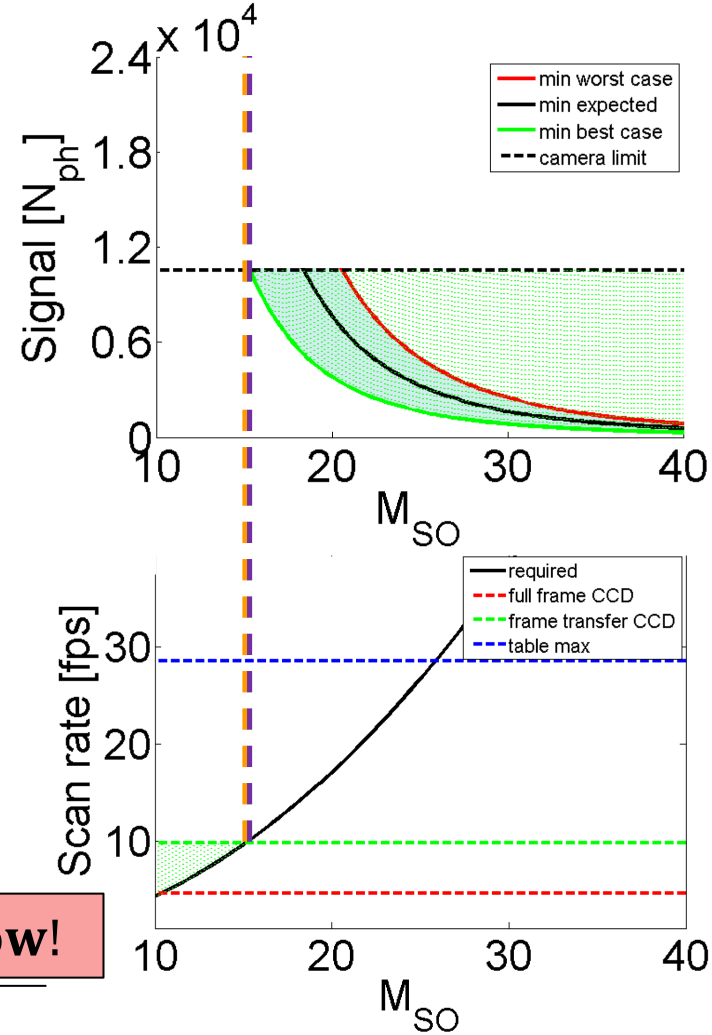


Scan Rate



Source





no process window!

4. Limitations

No window achieved – what now?

- Required scan time: 45min

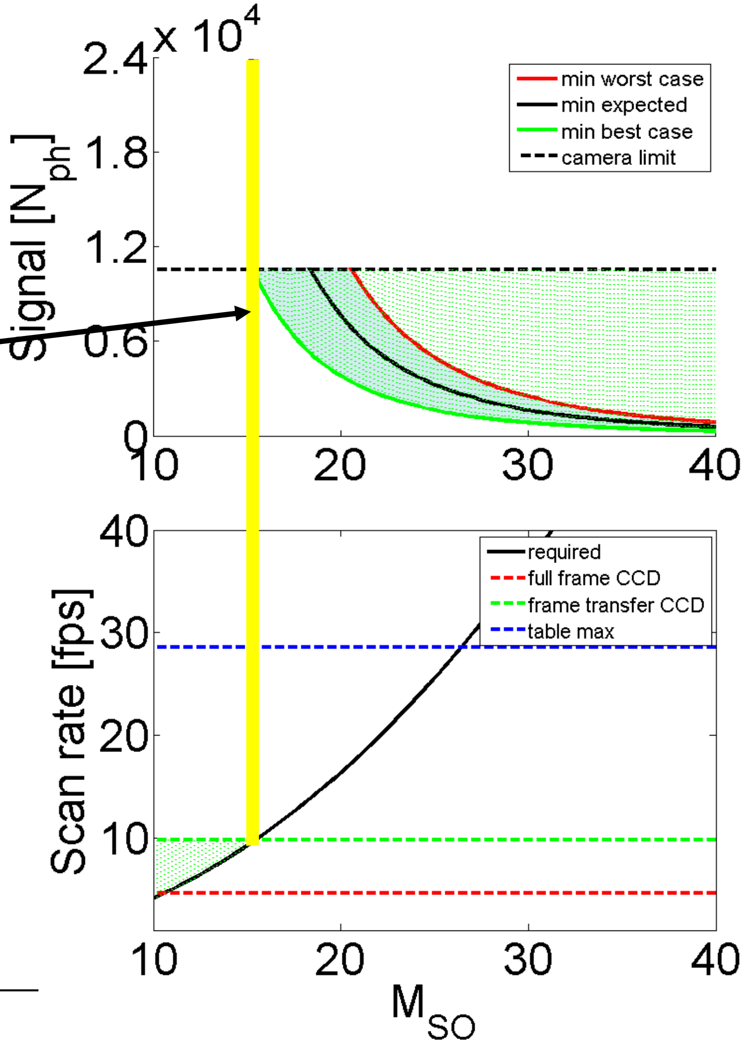
  => expand to 47min:

tiny process window
$$15.22 < M_{SO} < 15.42$$

- But only counts for best case scenario!
- Limitation is detector read out speed and sensitivity

a) smoother sample

b) faster camera



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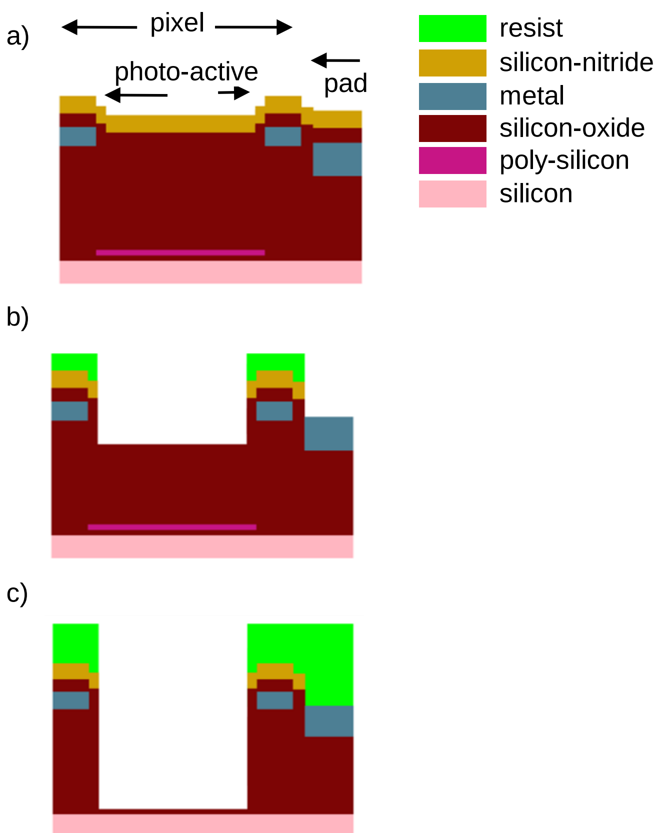
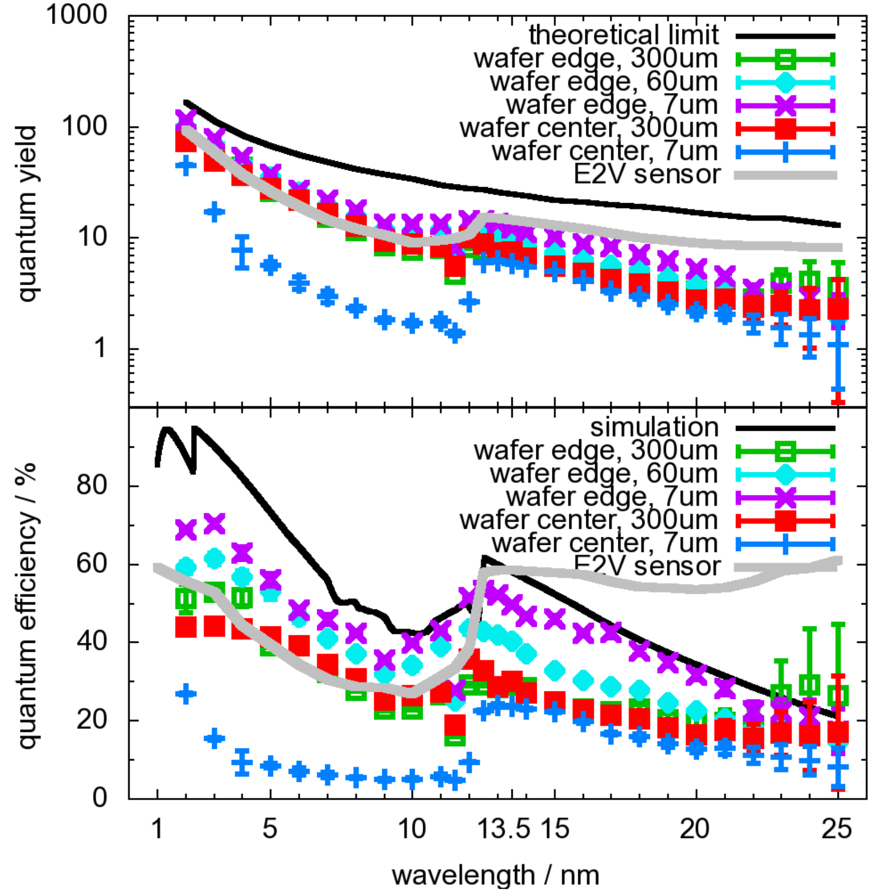
5. Alternative detector concepts

Concept	Price [k€]	Read out [fps]	QE [%]	Spatial resolution [µm]	Pixel Well Depth [ke⁻]	Noise [e⁻ rms] @ t_{exp}=100ms	Remarks
XUV CCD full frame (Andor iKon-M)	21	4.6	40-60	13	100	20	
XUV EMCCD frame transfer (Andor, custom made)	100	9.8	40-60	13	100	1	
XUV CCD Time Delay Integration[1]	-	6[a]	-	-	-	-	- Complex synchronization
VIS CCD (Andor Clara) + scintillator[2] + objective[2]	14	21	2.1	6.5	18	7	
VIS sCMOS (Andor Neo) + scintillator[2] + objective[2]	17	553	3.6	6.5	25	1	- Fill factor (?)
VIS sCMOS (Andor Neo) + scintillator[2] + fiber coupler (Proxitronic)	22	553	5.3	6.5	25	1	- Fill factor (?)
VIS sCMOS (Andor Neo) + Micro Channel Plate (Del Mar Photonics)	10-20	553	10-20	30	25	1	- Complex periphery, Fill Factor (?)
backside illuminated XUV wide bandgap CMOS[3]	-	>200[b]	5[c]	10	-	-	+ no VIS filter, no cooling, - fill factor (?)
backside illuminated XUV backthinned CMOS Hybrid[4]	-	1	30	10	-	25-33	- Fill factor (?)
frontside illuminated XUV open electrode CMOS[5]	<10	245.8	25-55	12	200	116	- Fill factor 50%

Open Electrode CMOS:





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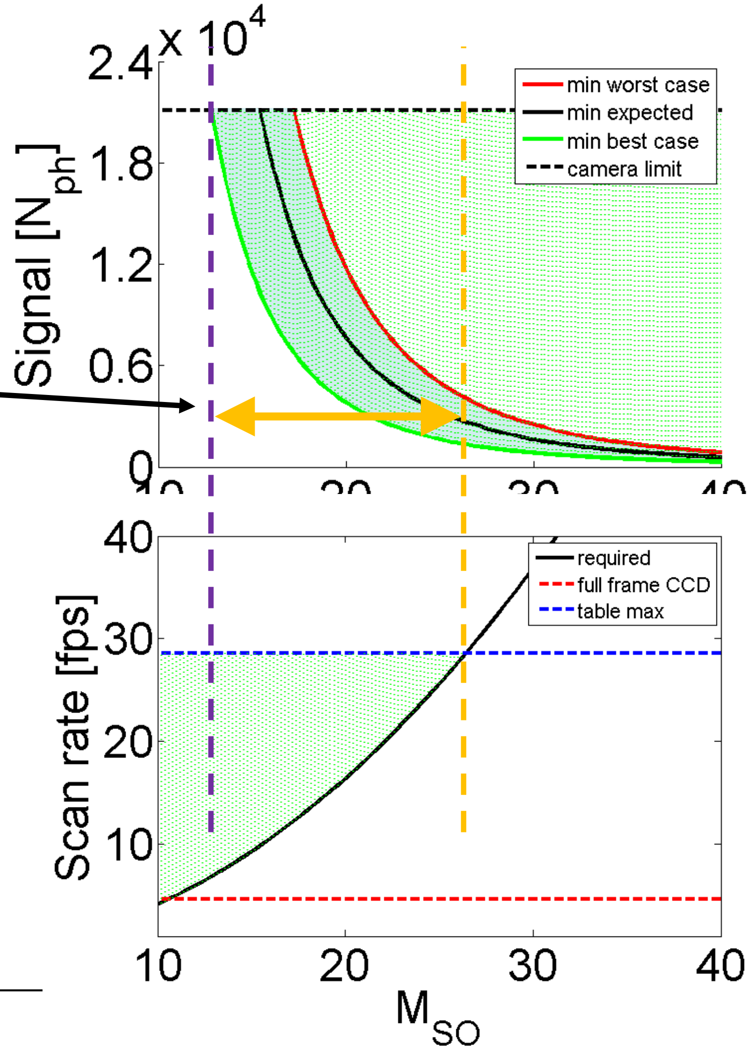
4. Limitations

Process window with DOSE camera:

- $N_{ph,max}$ ≈ twice higher
- Scanrate ≈ 25x higher

large process window!

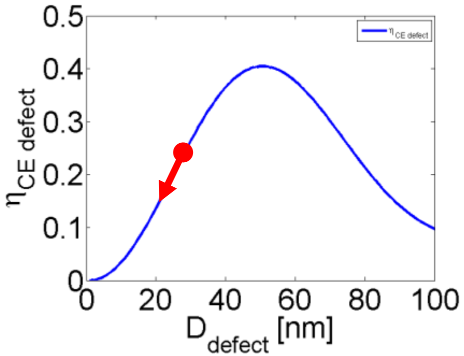


- 45min achievable
- Process window works for all scenarios
- Limitations now: sensitivity and sample scan speed

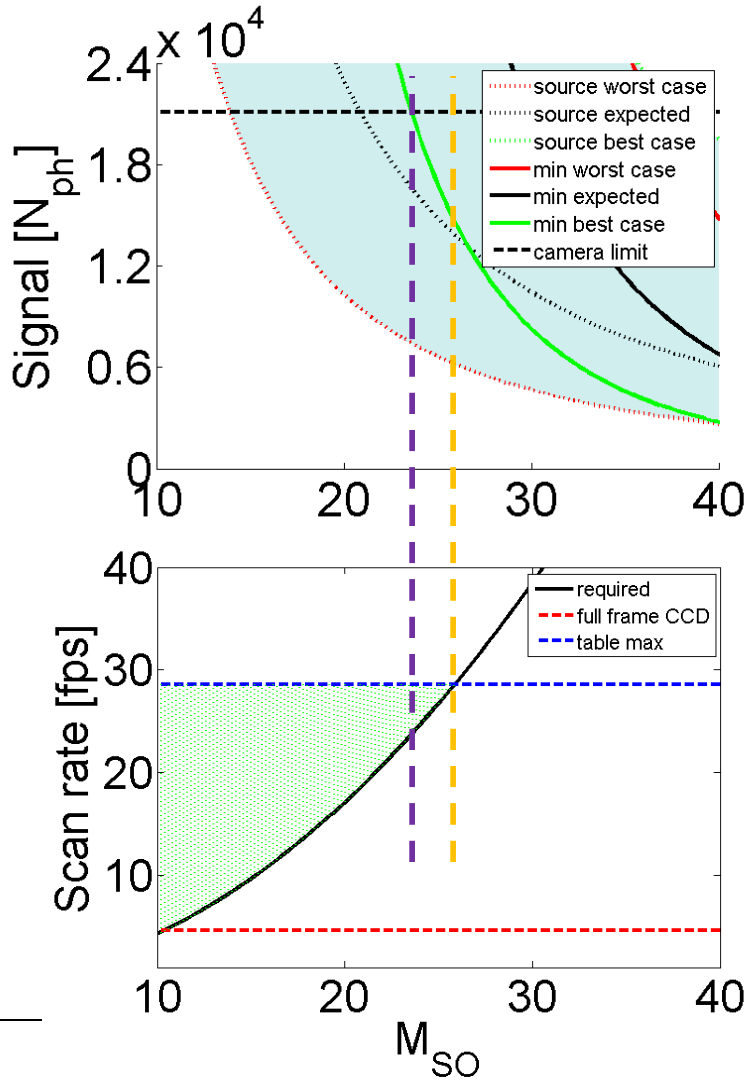
6. Extendability

Next critical defect size: 20nm

- Change in η_{CE_defect}:



- Scanrate remains the same
- Signal is shifted to higher M_{SO}
- Process window only work for best case scenario => adaptions required…



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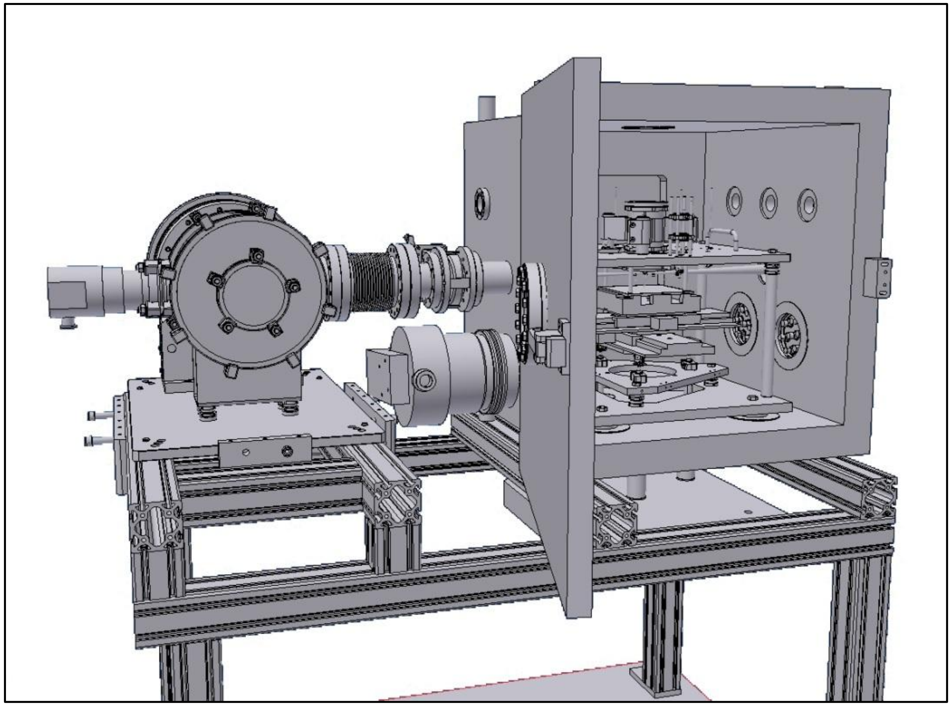
7. Conclusion & Outlook

Conclusion:

- Process window can be opened for best case scenario in the present setup
- The main limiting component is the detector, no suitable detector available to date
- Open electrode CMOS shows promising potential to be suitable
- Extendability to 20nm possible with faster camera



Outlook:

- New defect inspection setup will be commissioned in spring 2012
- New setup offers enlarged metrology spectrum: reflectivity monitoring, dark AND bright field operation and dose monitoring

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Acknowledgements & References

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PTB Berlin
Christian Laubis, Frank Scholze

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[3] *AlGaN photo-detectors for applications in the extreme ultraviolet (EUV) wavelength range, Proc. of SPIE Vol. 7003 70030N-1, 2008*

[4] *EUV and Soft X-Ray Quantum Efficiency Measurements of a Thinned Back-Illuminated CMOS Active Pixel Sensor, IEEE Electron Device Letters, Vol. 32. No. 3, 2011*

[5] *Quantum efficiency determination of a novel CMOS design for fast imaging applications in the extreme ultraviolet, IEEE Transactions on Electron Devices, accepted*

Thank you for your attention!

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