Monte Carlo simulations of x-ray grating interferometry based imaging systems

S. Tessarini[a,b]
M. Fix[c], W. Volken[c], M. Stampanoni[a,b]

[a]Institute for Biomedical Engineering, University and ETH Zürich, 8092 Zürich, Switzerland
[b]Swiss Light Source, Paul Scherrer Institut, 5232 Villigen, Switzerland
[c]Division of Medical Radiation Physics and Department of Radiation Oncology, Inselspital University Hospital Bern and University of Bern, Bern, Switzerland

Goal

- Implementation of a Monte Carlo simulation tool for grating based imaging systems including quantitative dose estimations


Absorption


Phase


Dark field

Basic principle: Phase shift

- Light propagating through media picks up a phase shift
- The refractive index of the material, for x-rays:

$$n = 1 + \delta$$

- Consider 17 keV x-ray beam passing through a µm thick sheet of biological tissue
  - Phase shift of the order of π
  - Absorption of a few percent.
- This is used as a new source of contrast.

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- Understood by Fresnel diffraction

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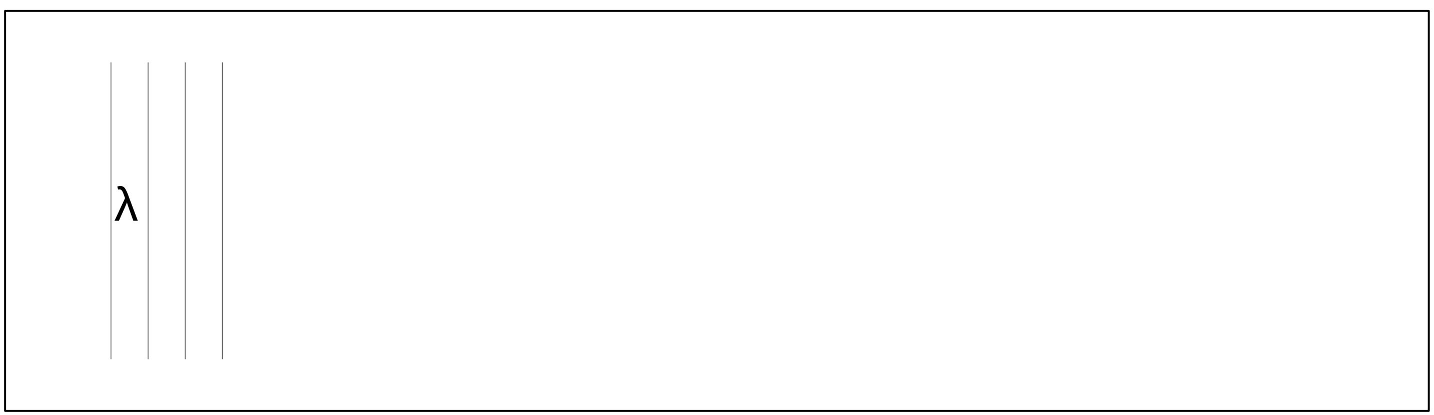

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- Absorption grating with period p (typically Au):
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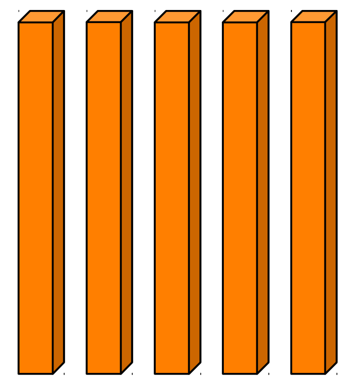

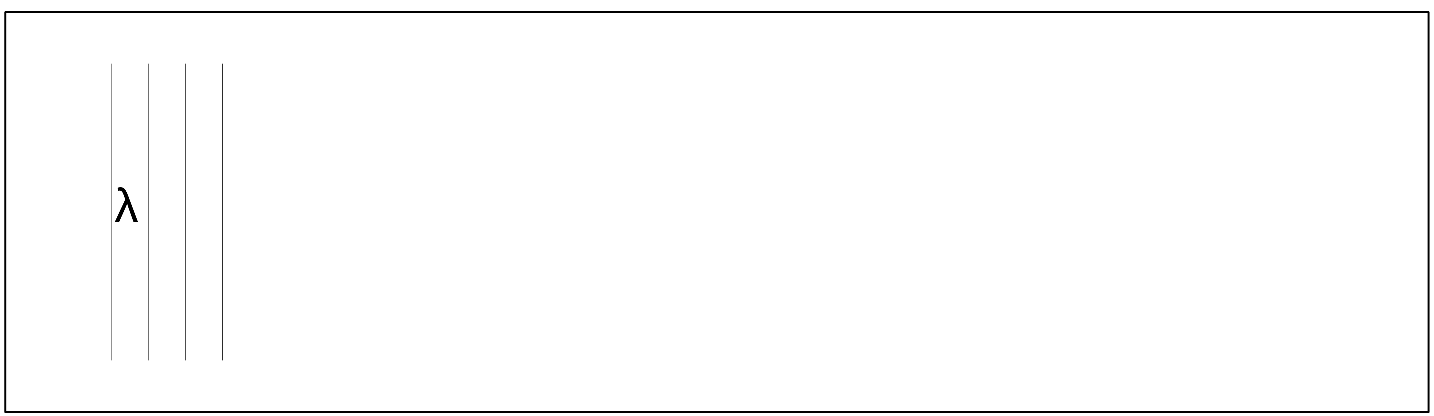

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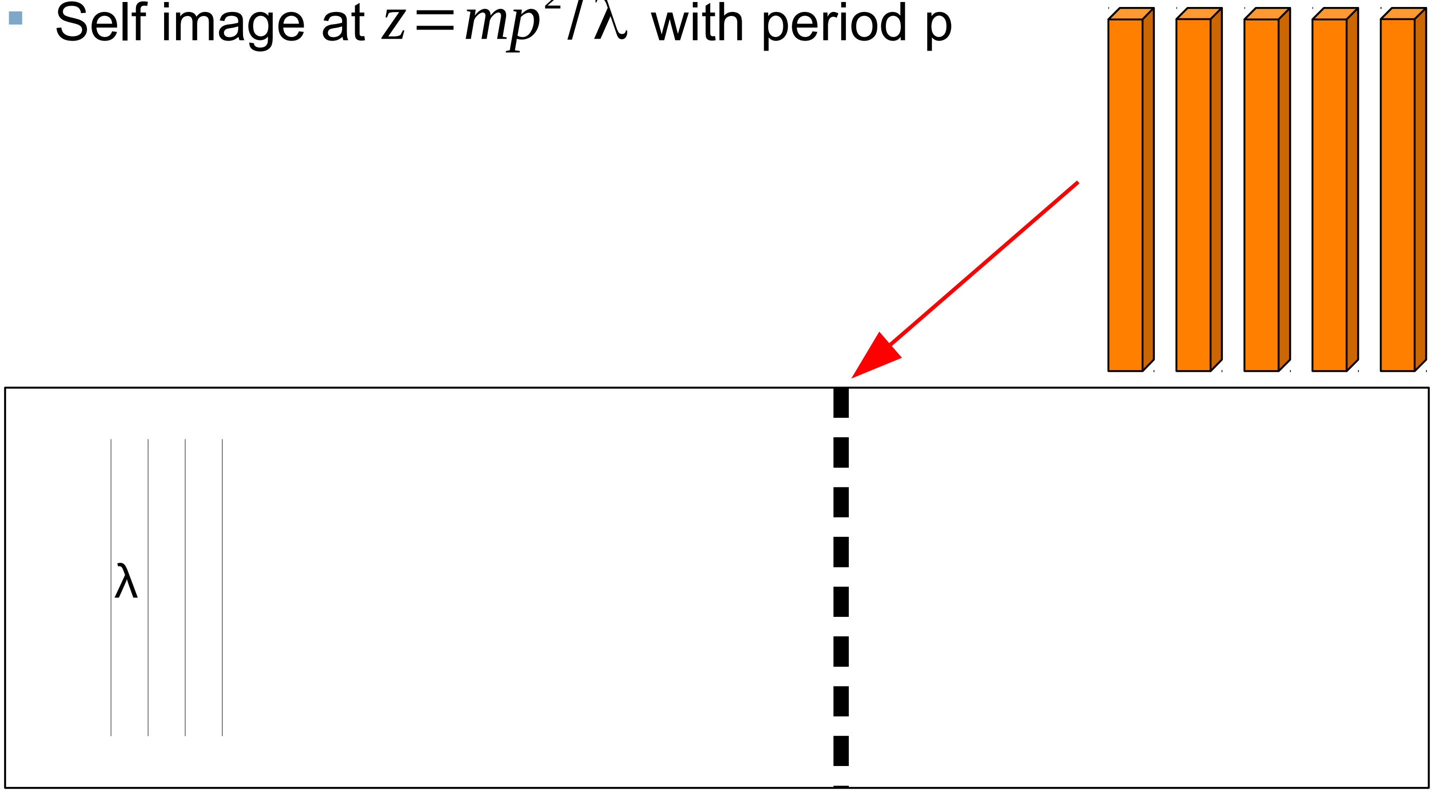

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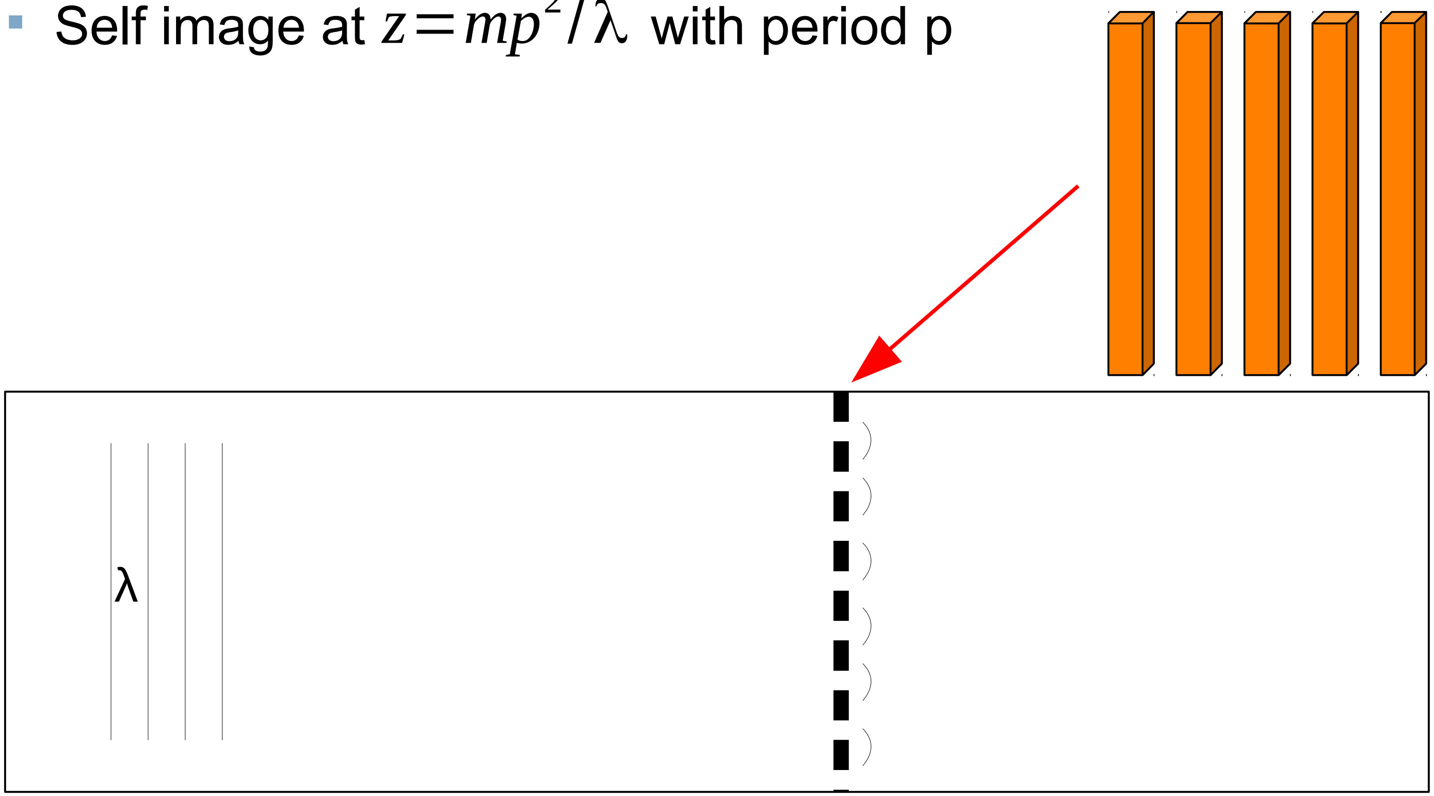

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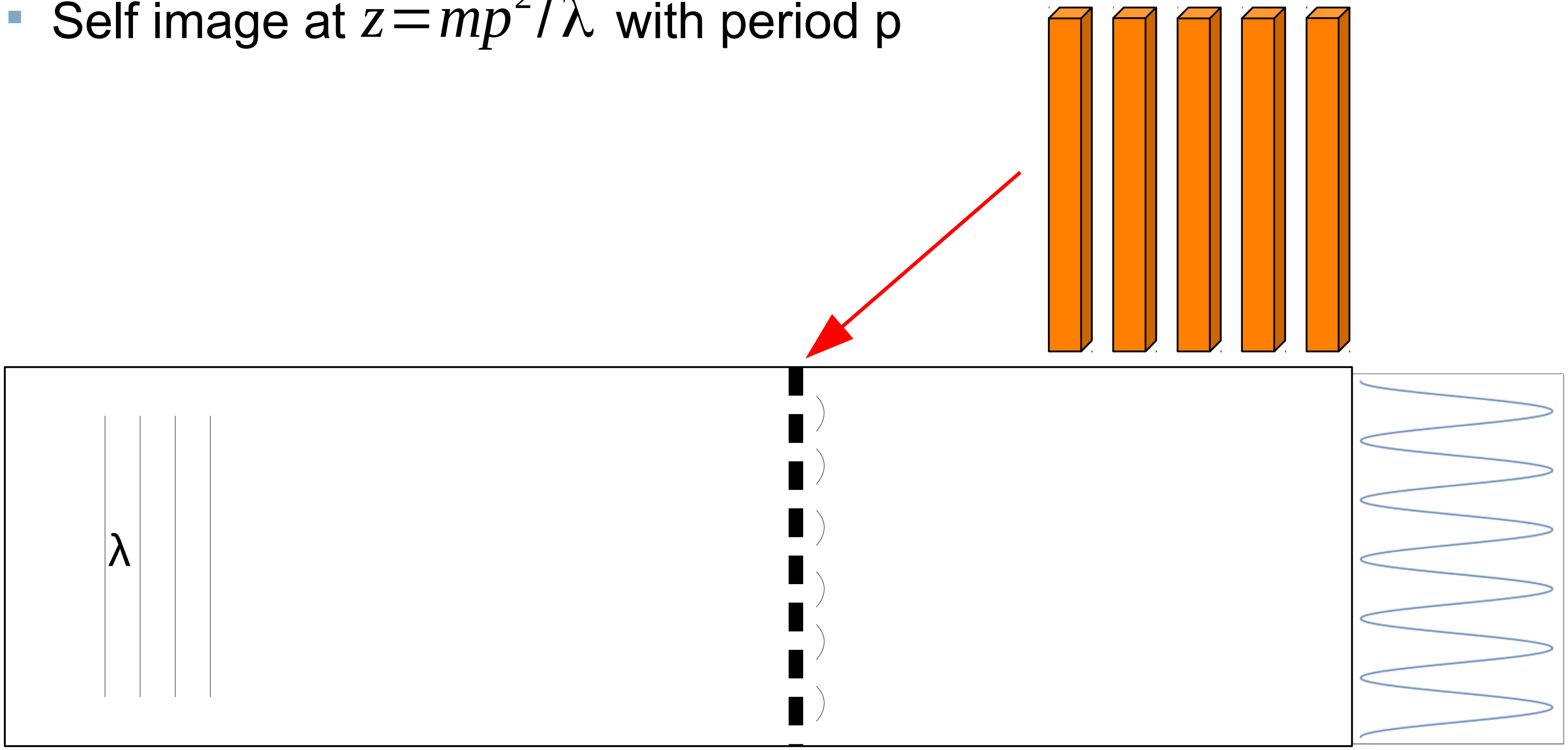

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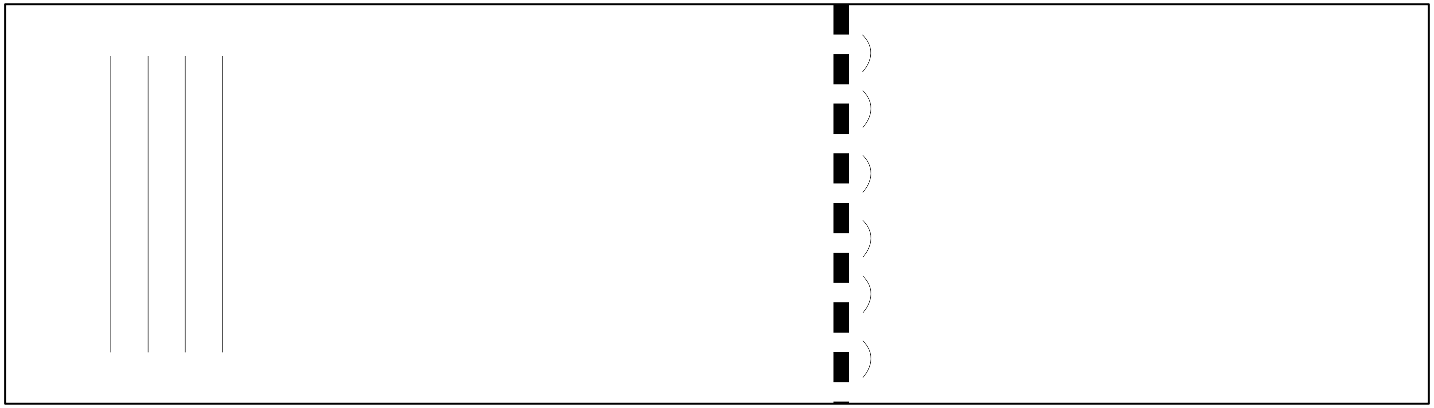

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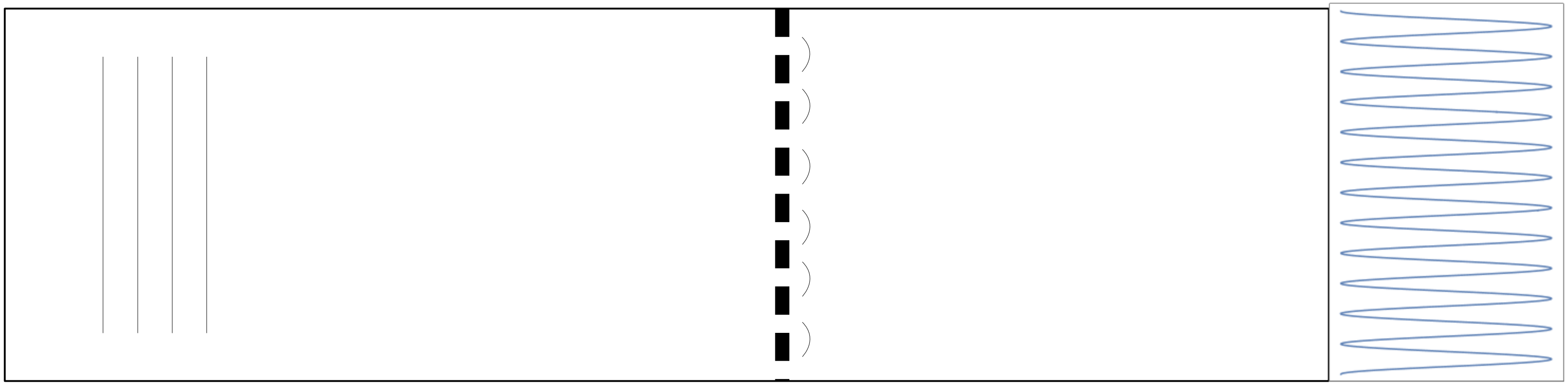
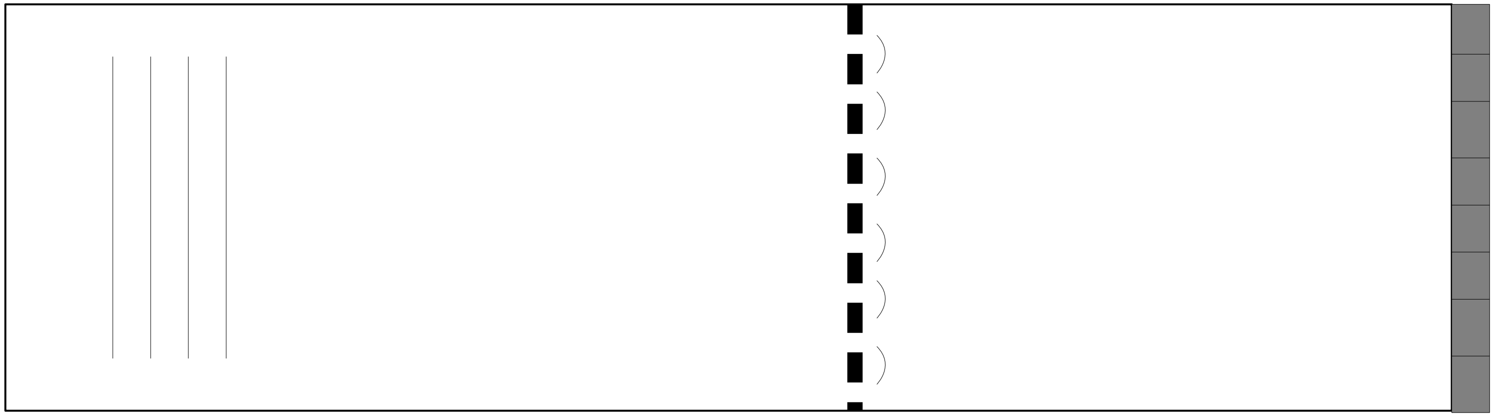


Measurement of the phase signal

- Typical period of the phase grating: 4 μm



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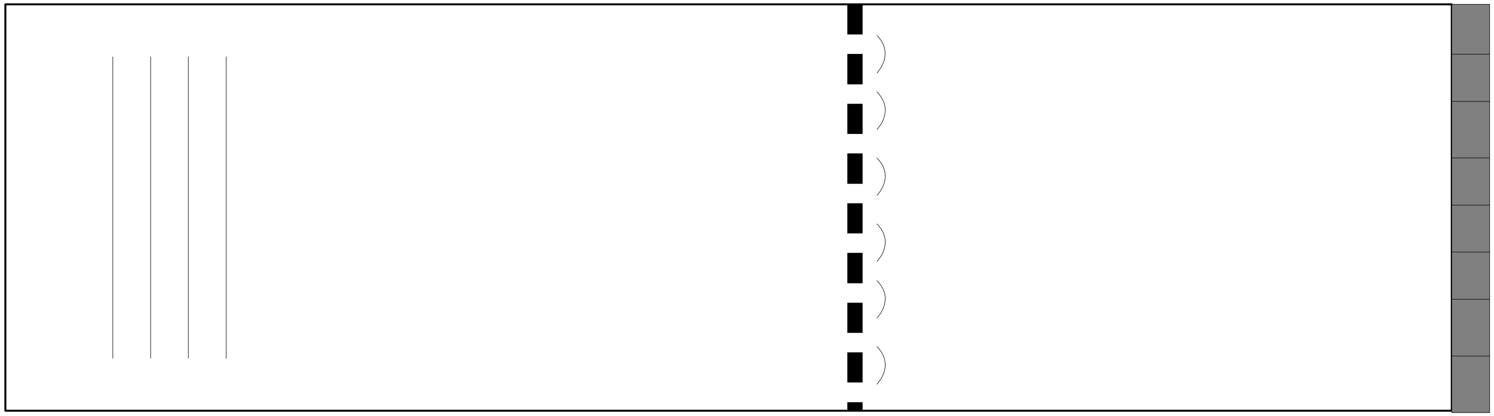

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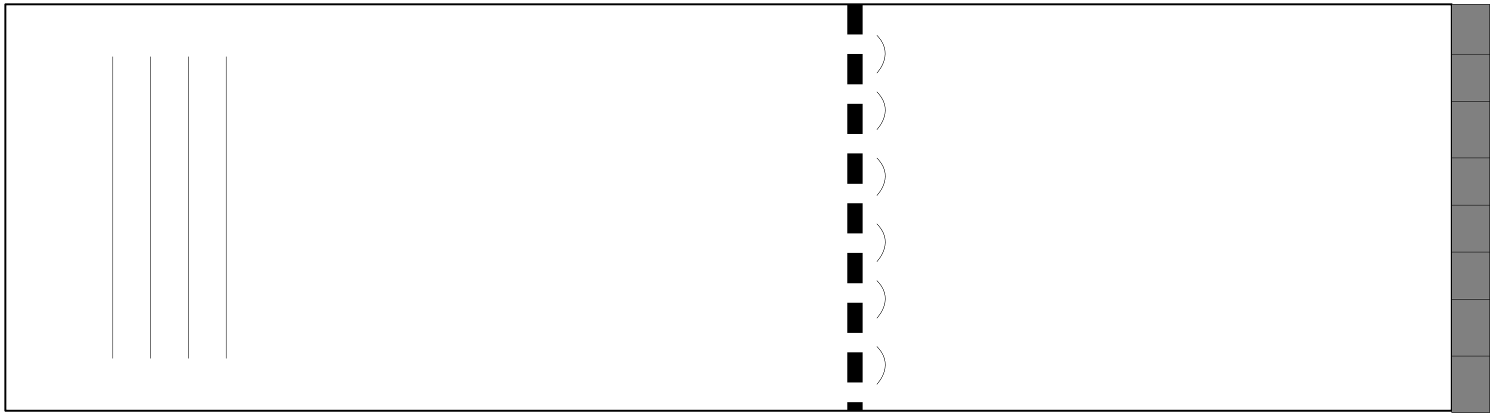

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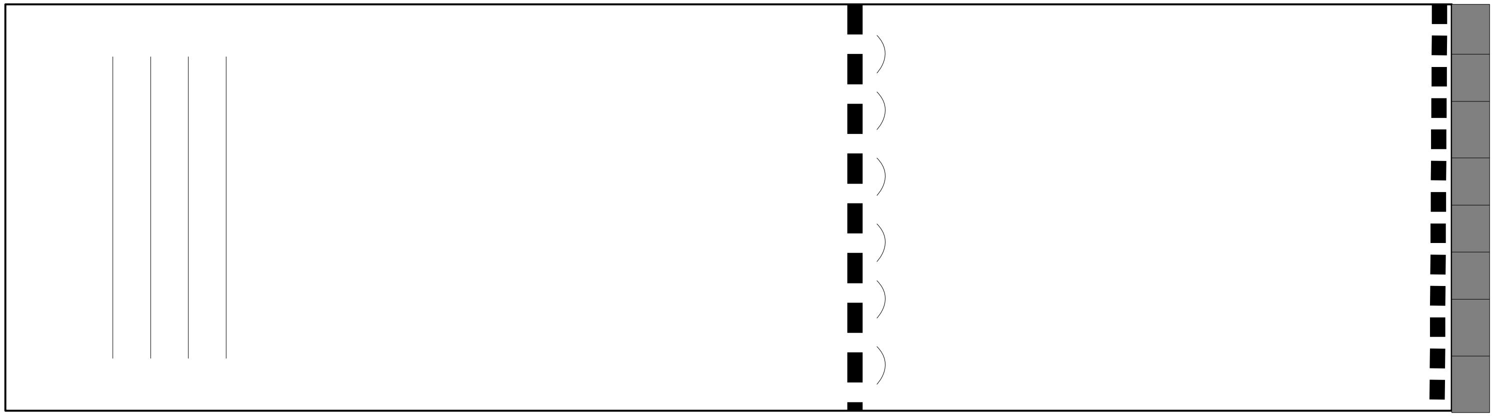

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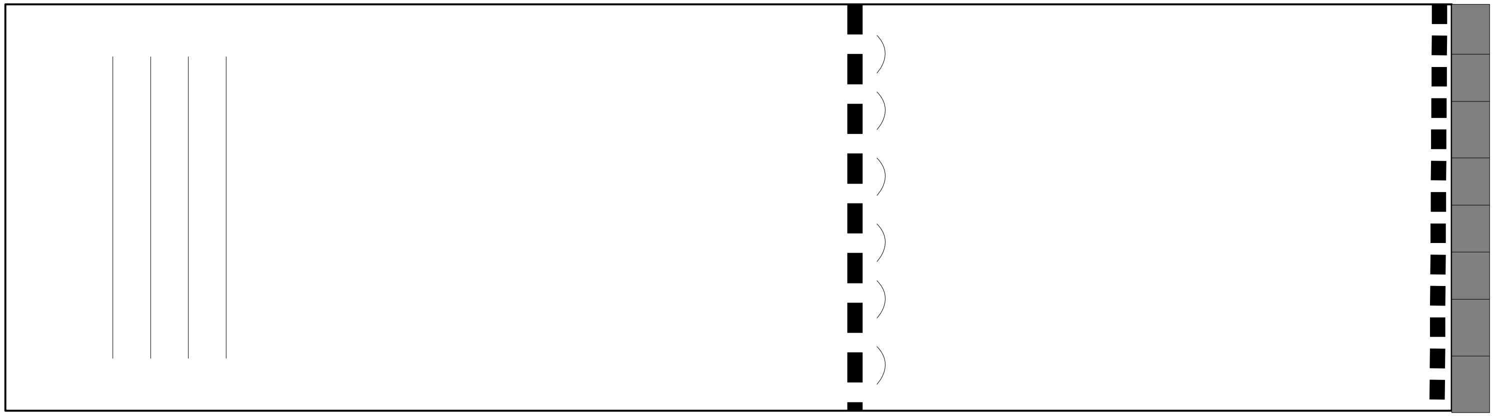

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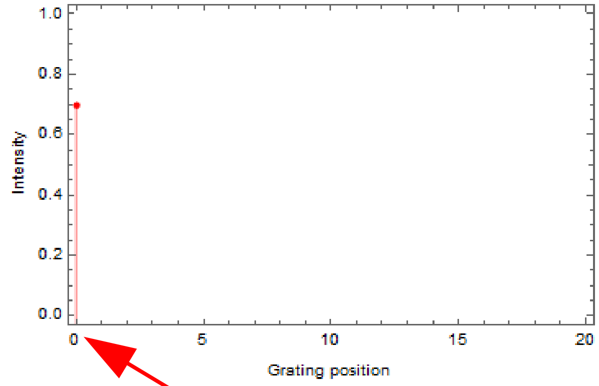

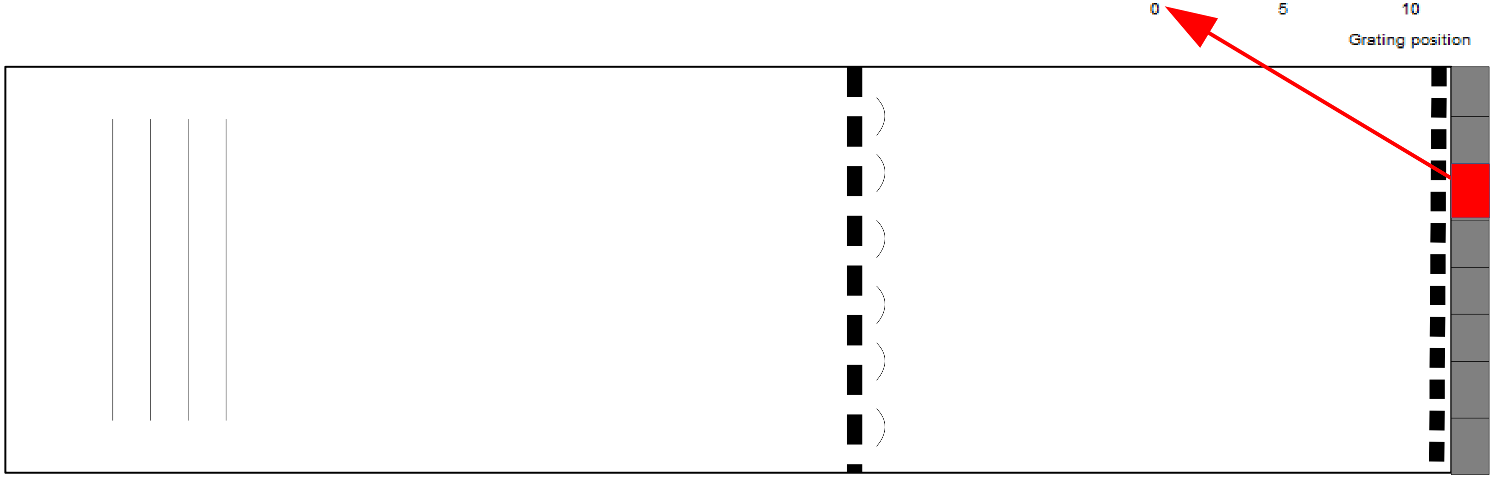

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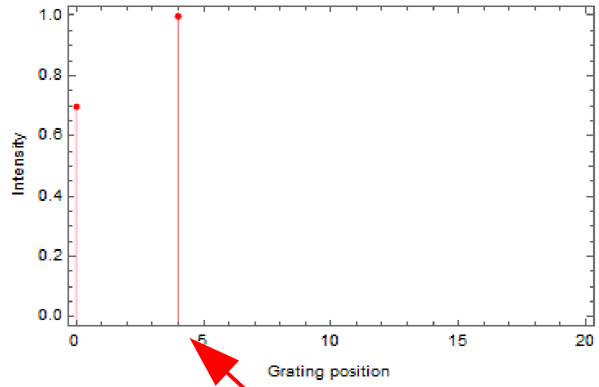

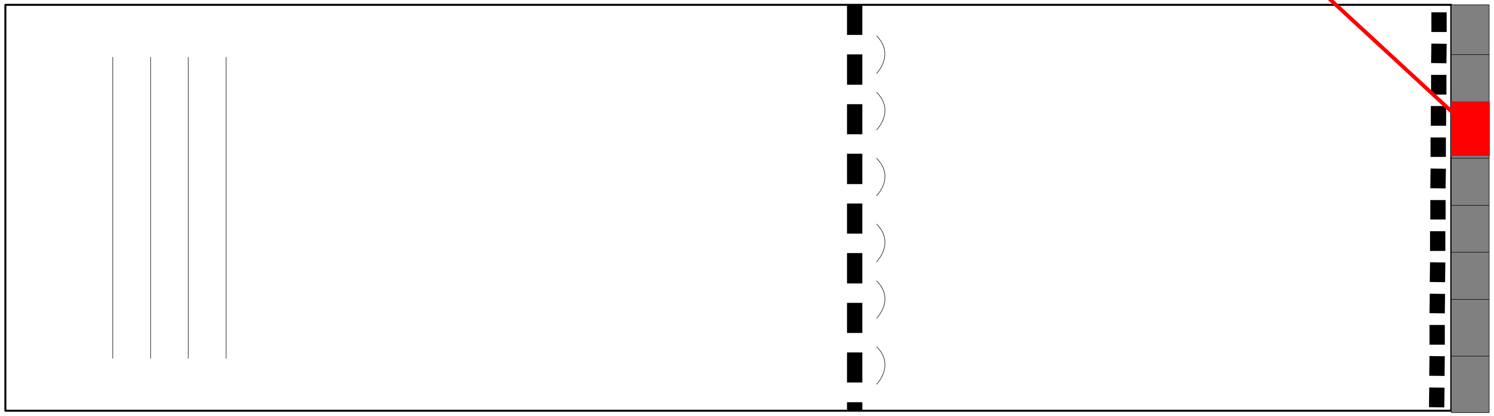

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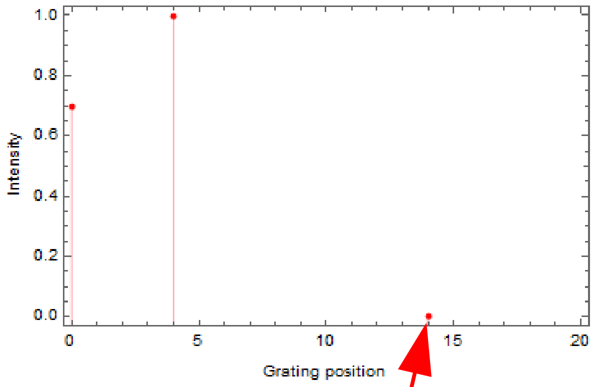

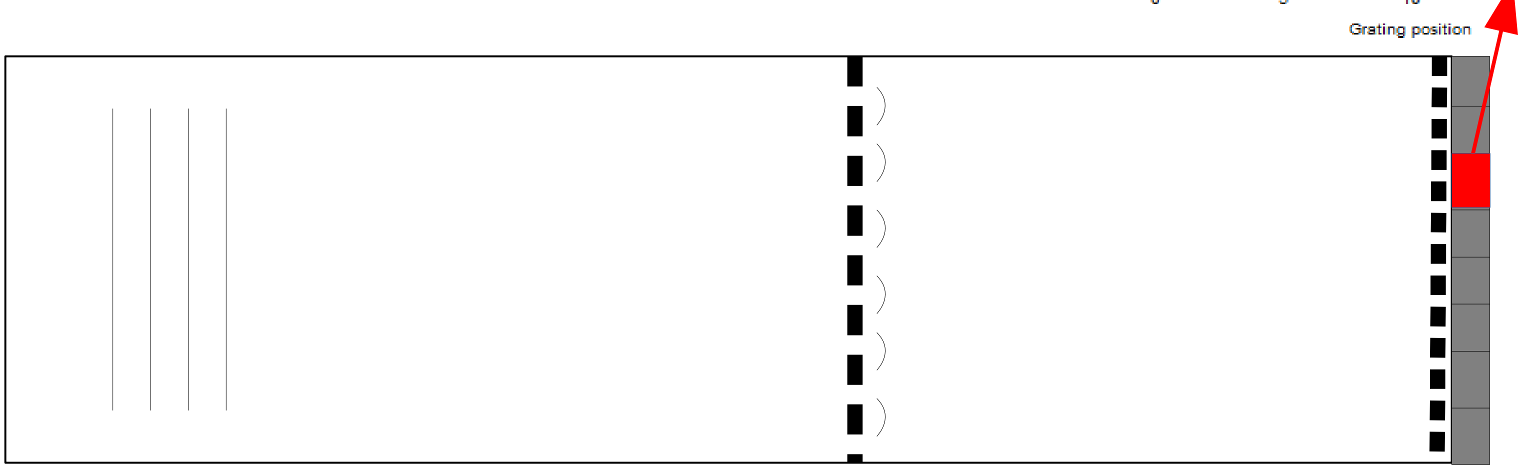

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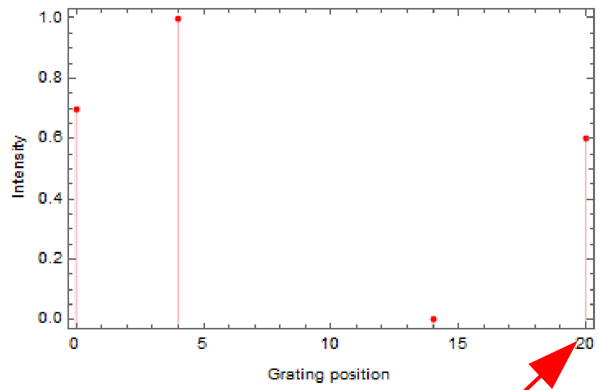

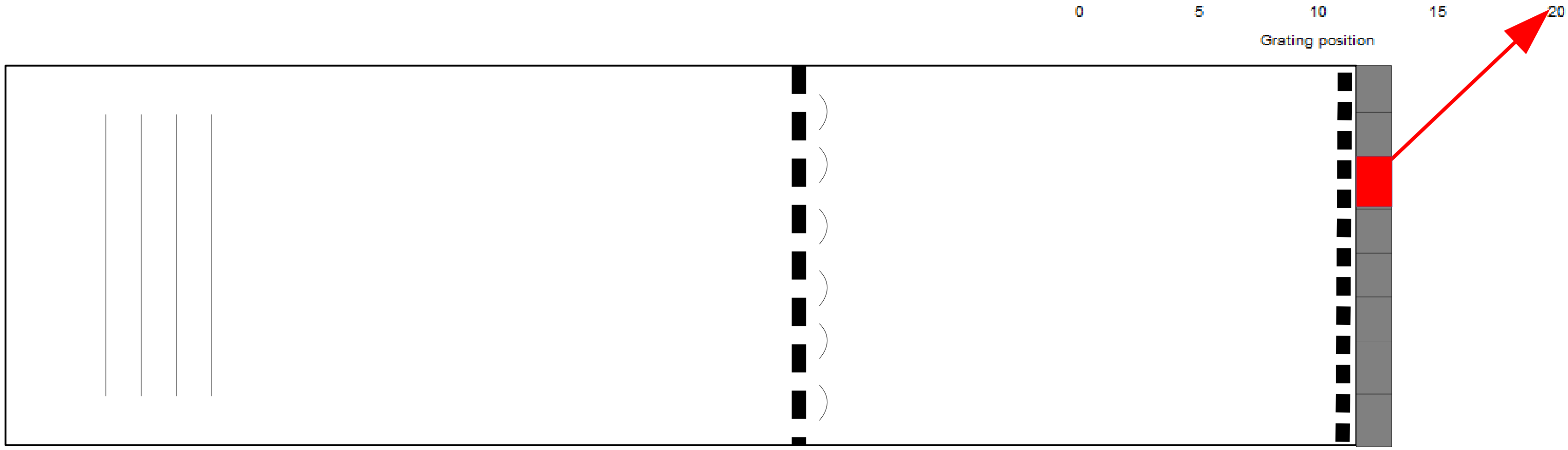

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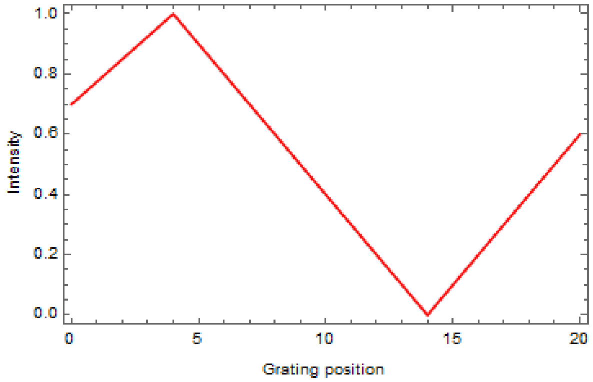

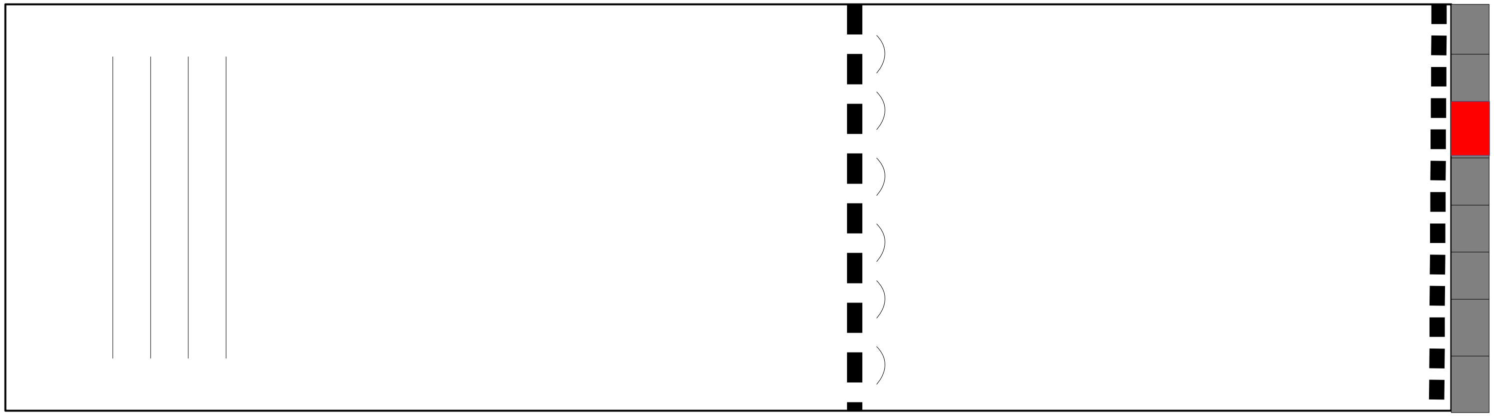

Measurement of the phase signal

- Inserting a sample introduces a phase shift
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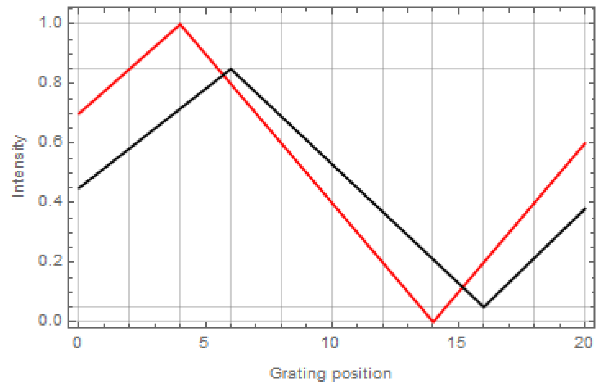

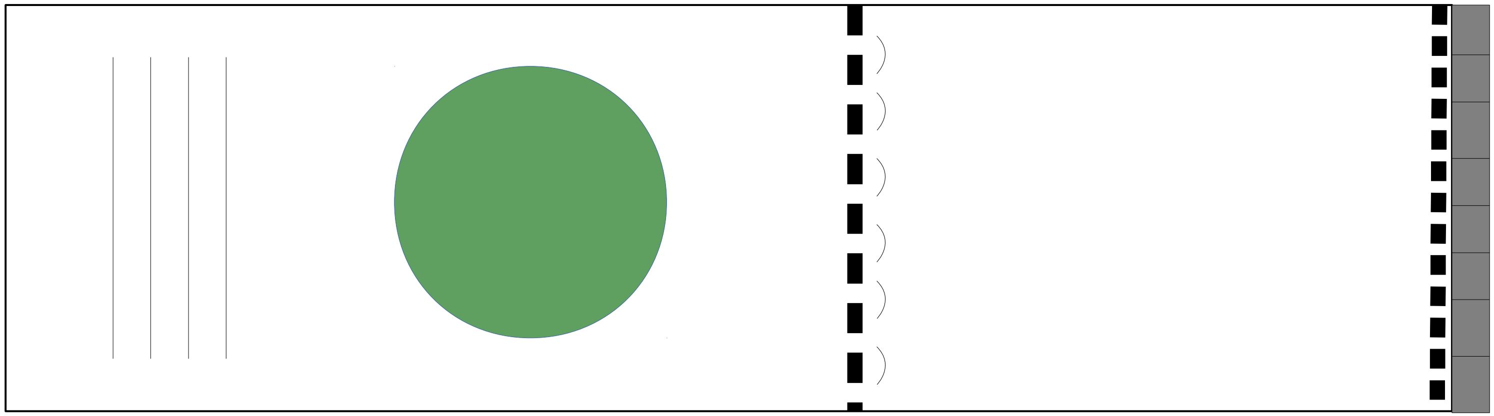

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- Inserting a sample introduces a phase shift
  - Distortion of the interference pattern
- Reduced mean value of the intensity
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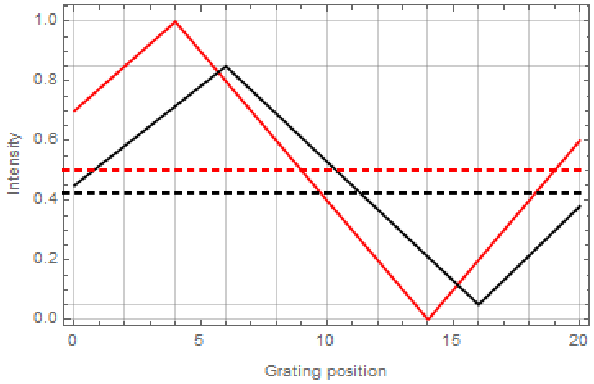

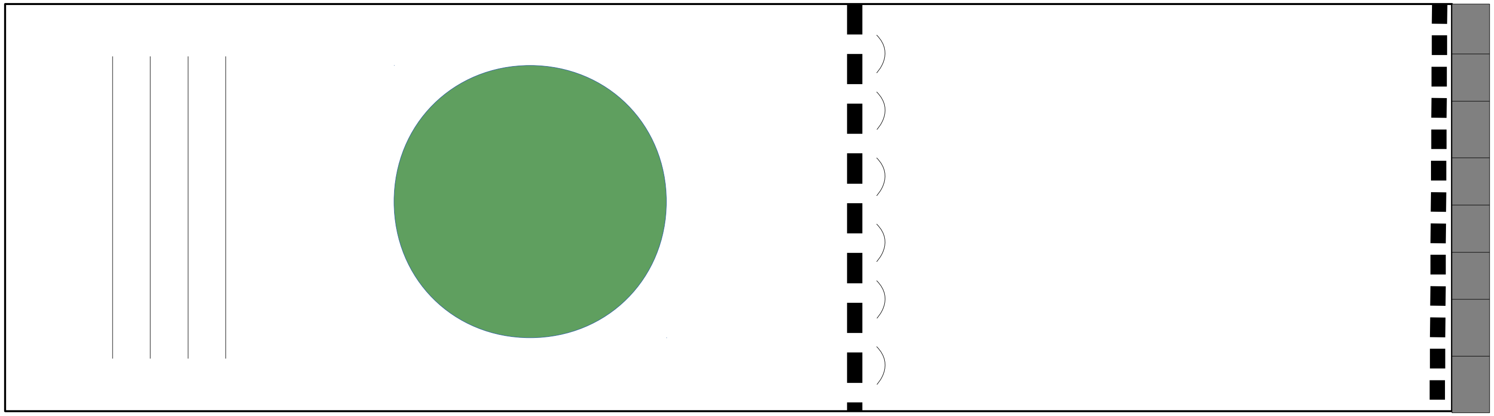

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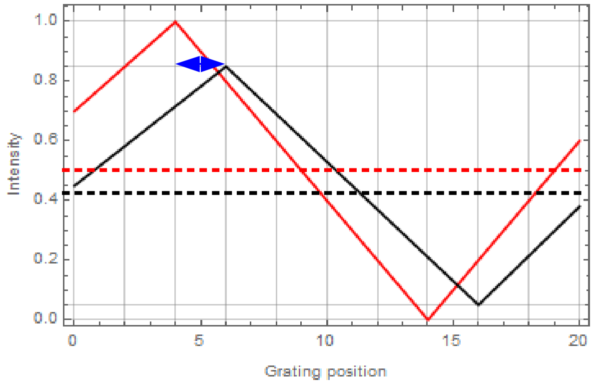

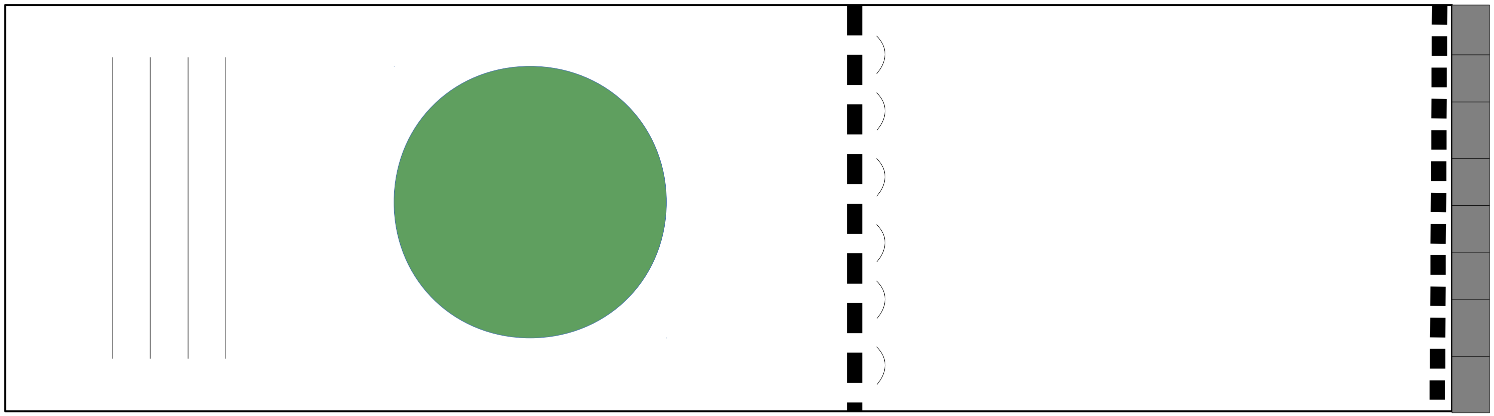

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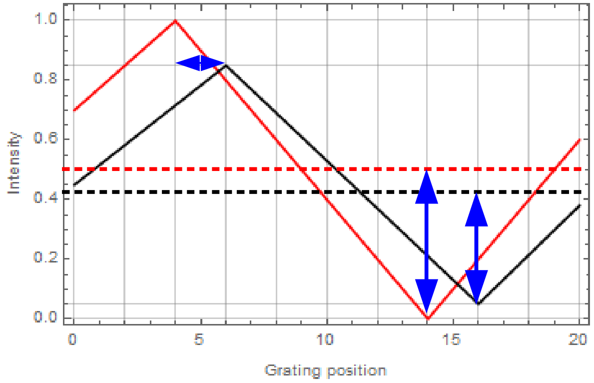
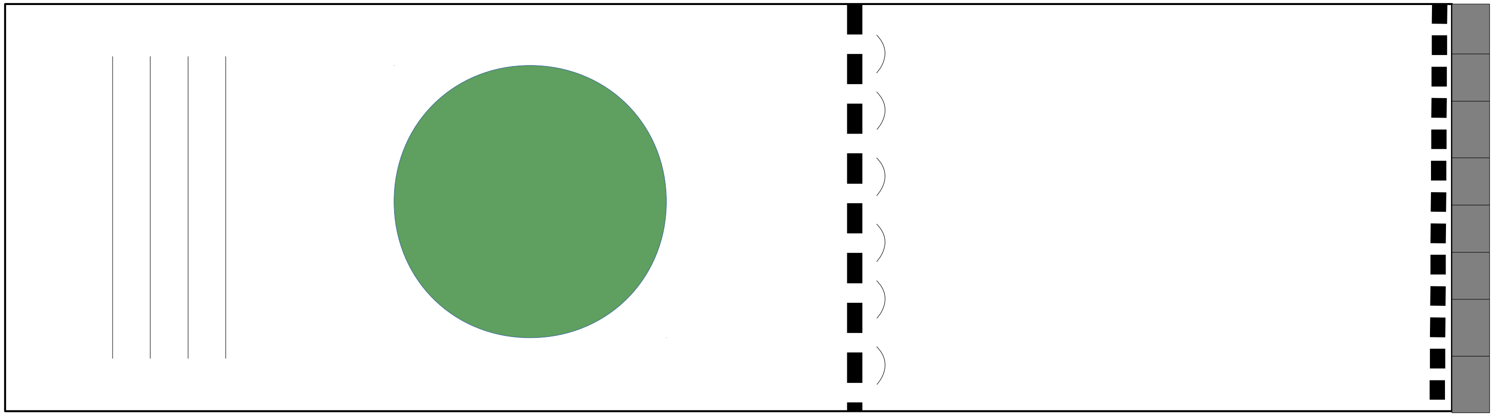
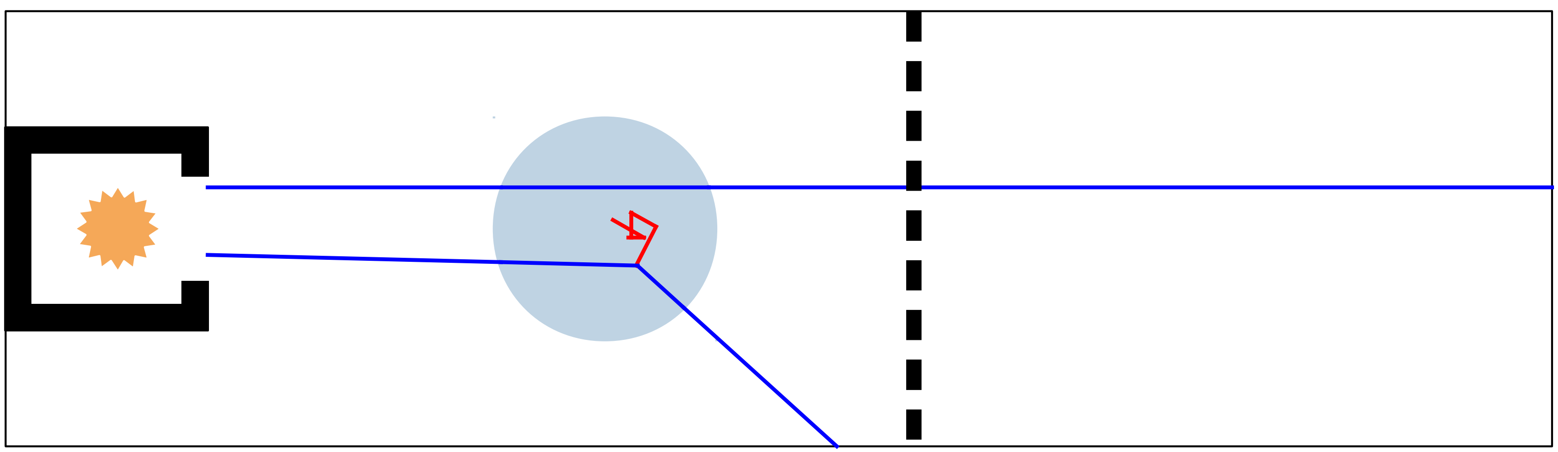
  - Phase signal
- Decrease of the amplitude
  - Dark field signal





Particle transport in EGSnrc: the missing parts



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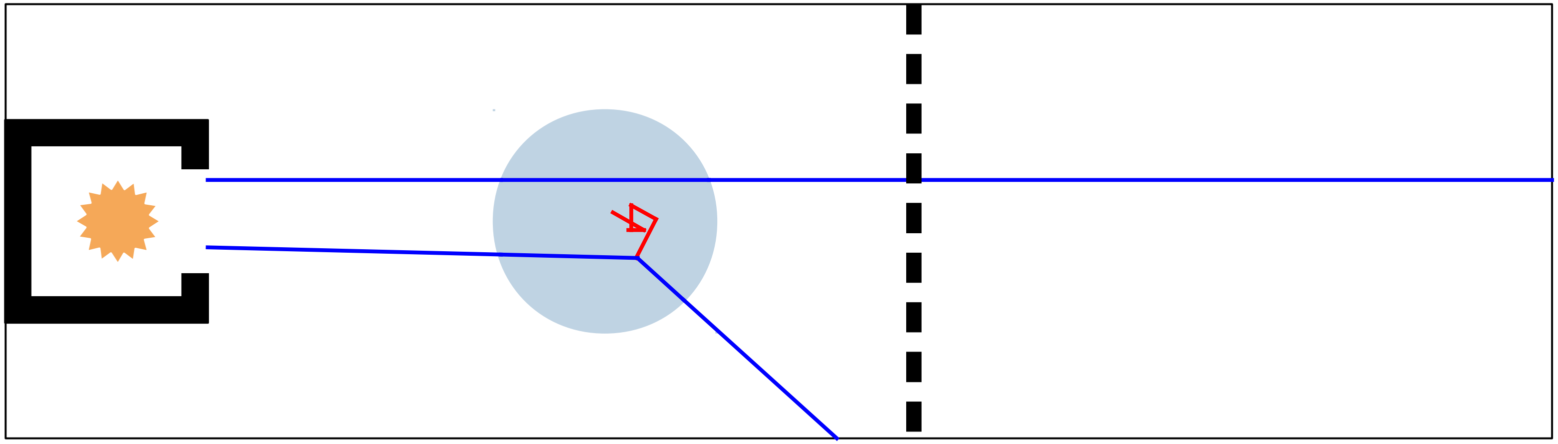

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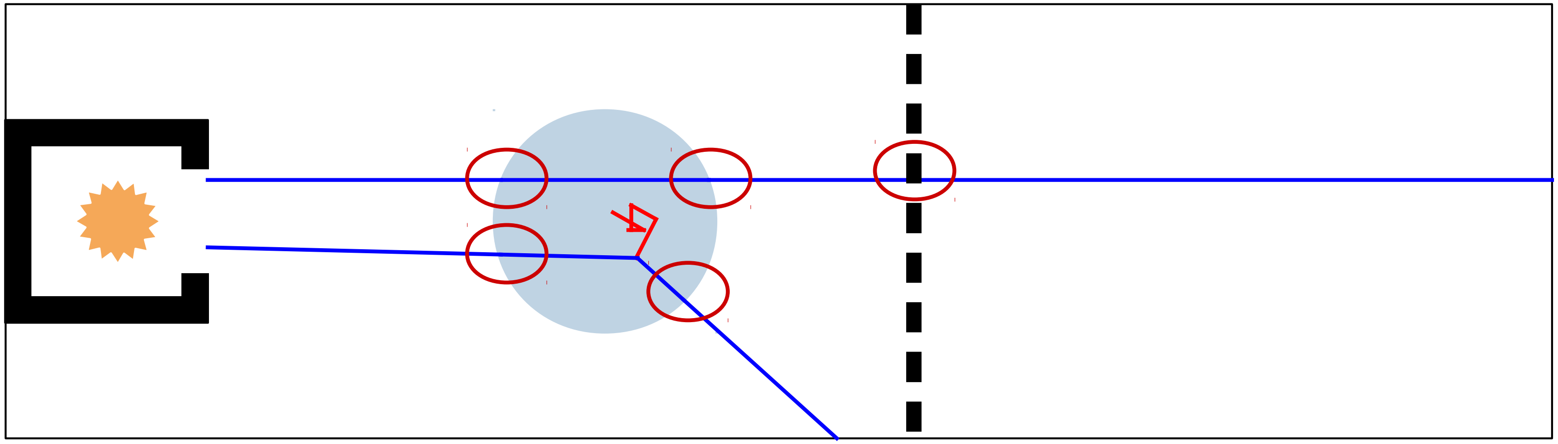

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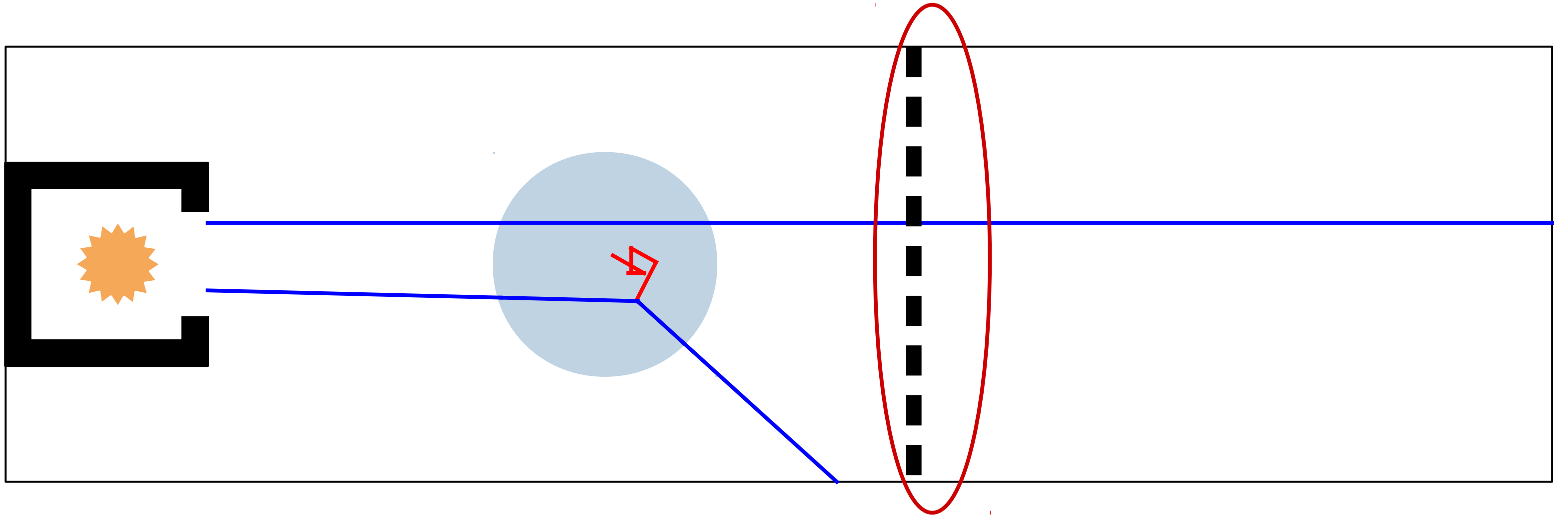

Particle transport in EGSnrc: the missing parts

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- Diffraction
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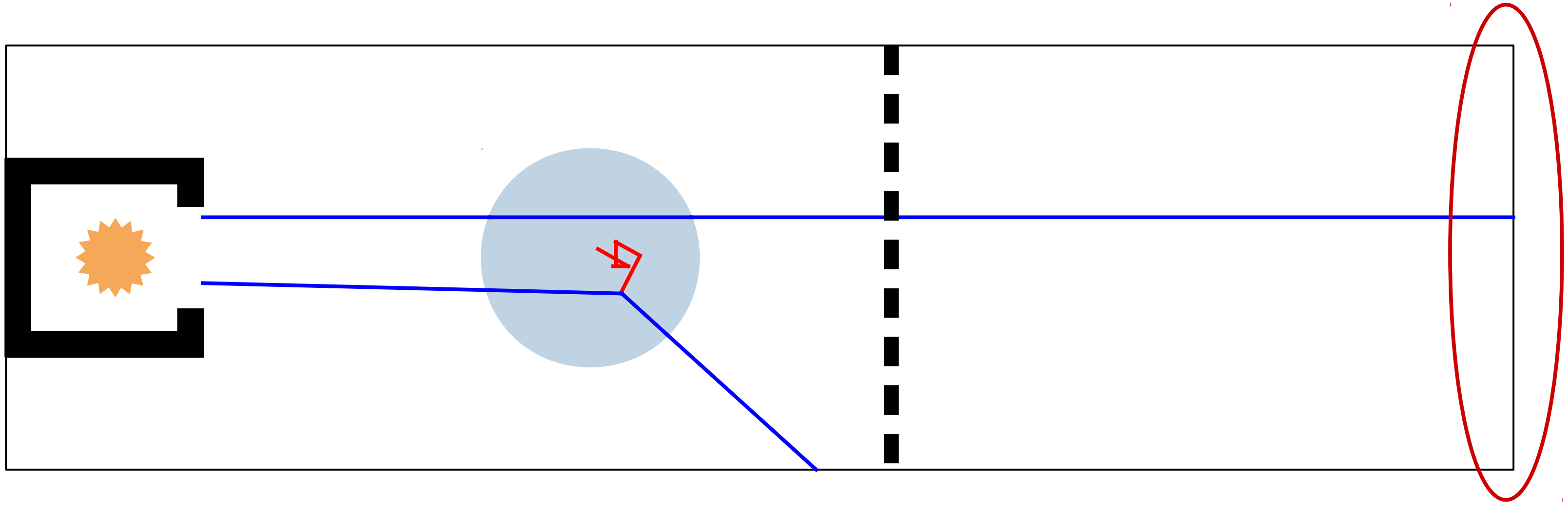

Modeling the missing parts

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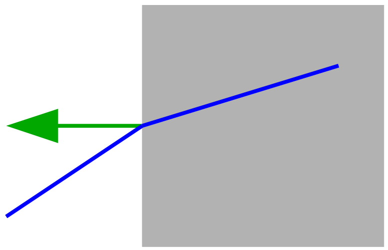

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- Diffraction at the grating
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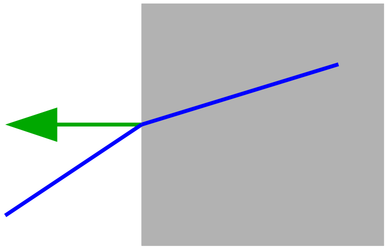

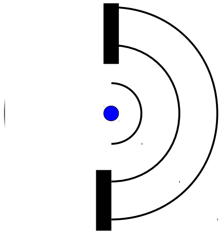

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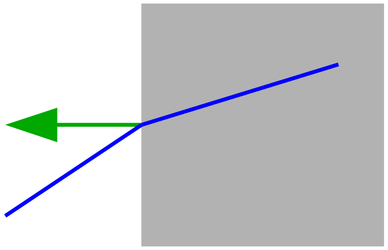

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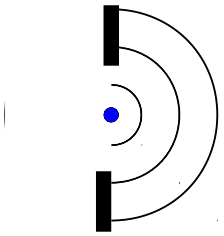
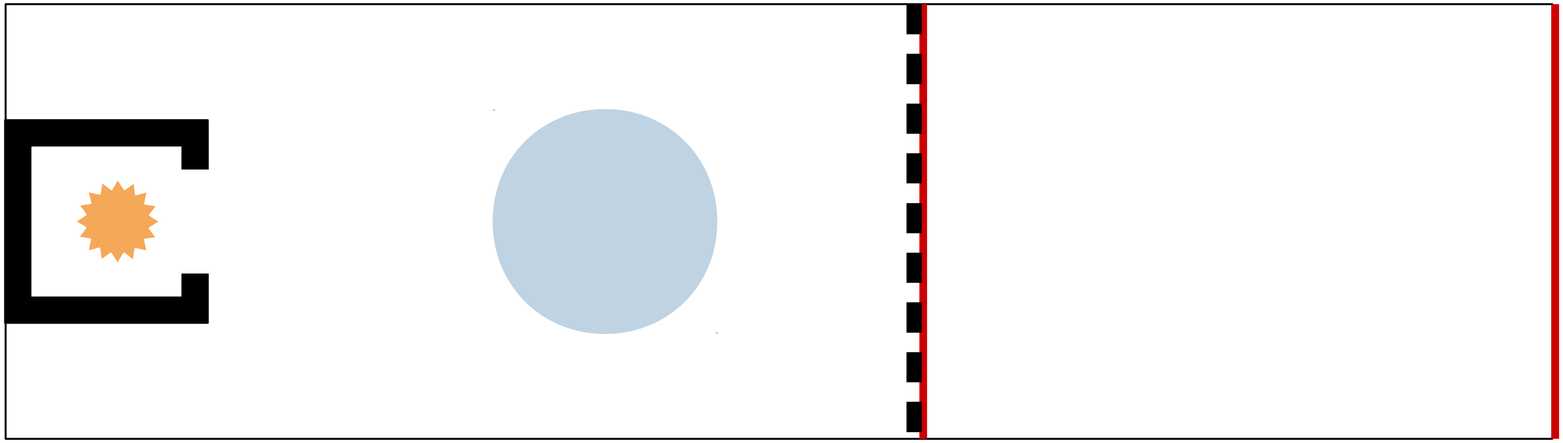


- Detector
  - Scoring a complex valued signal at the detector

Particle histories in the modified EGSnrc



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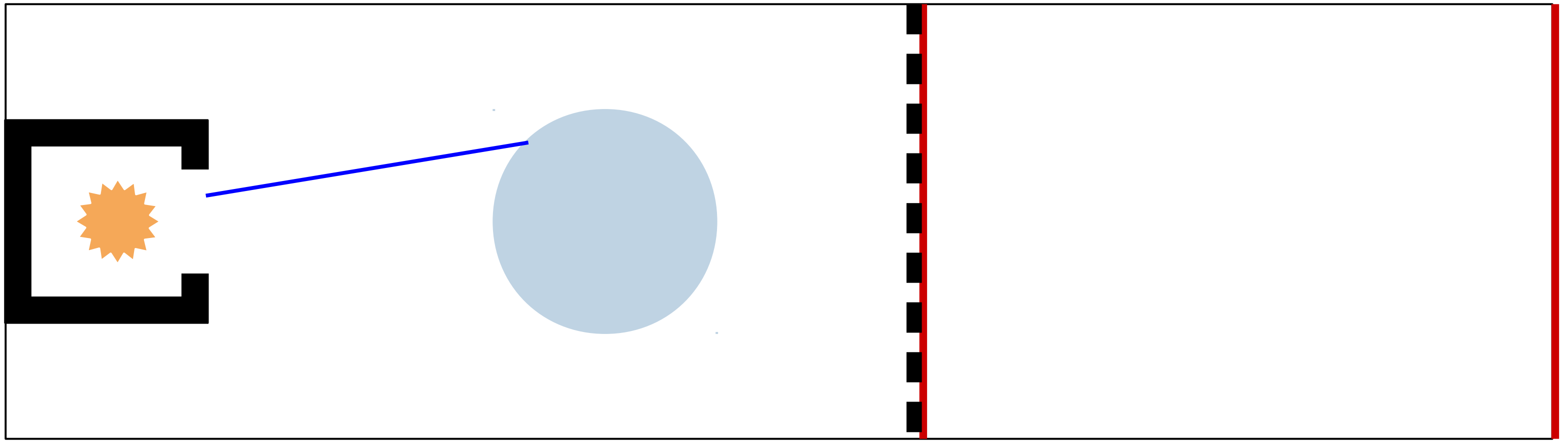

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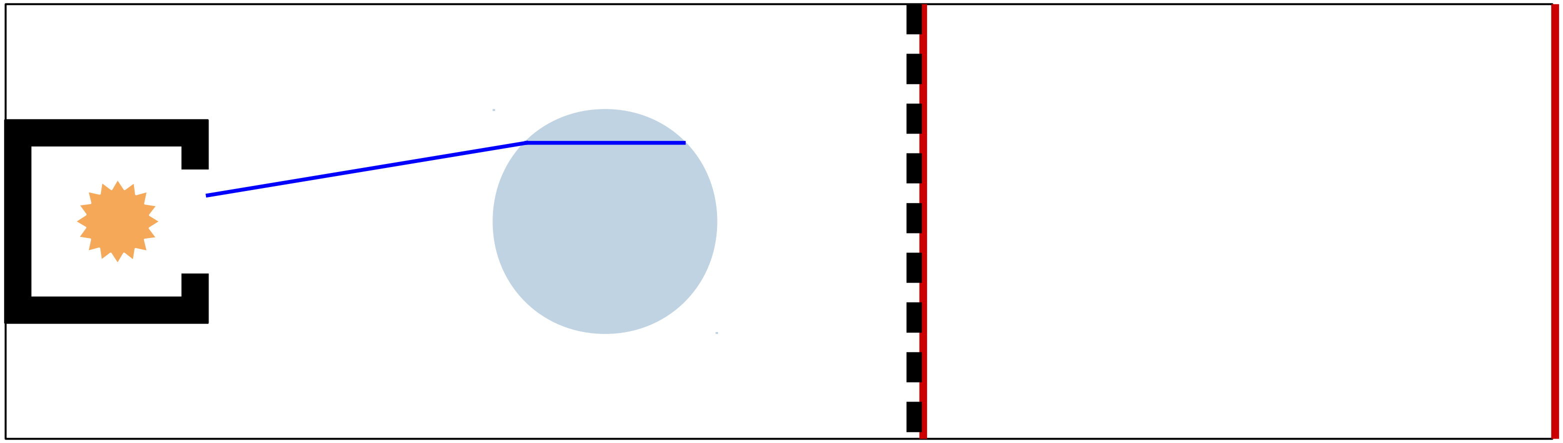

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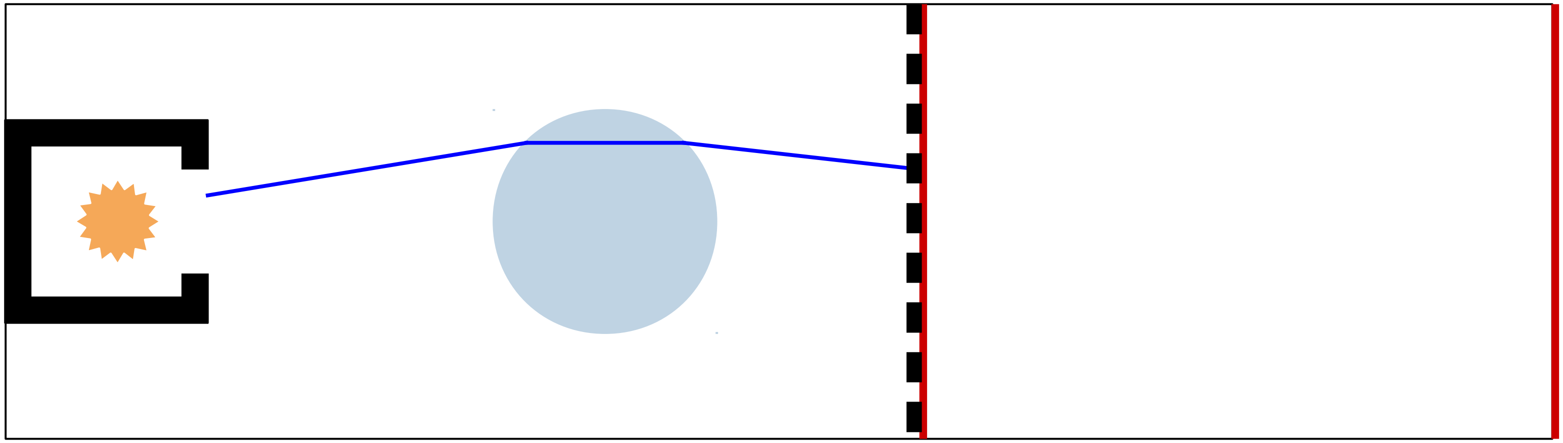

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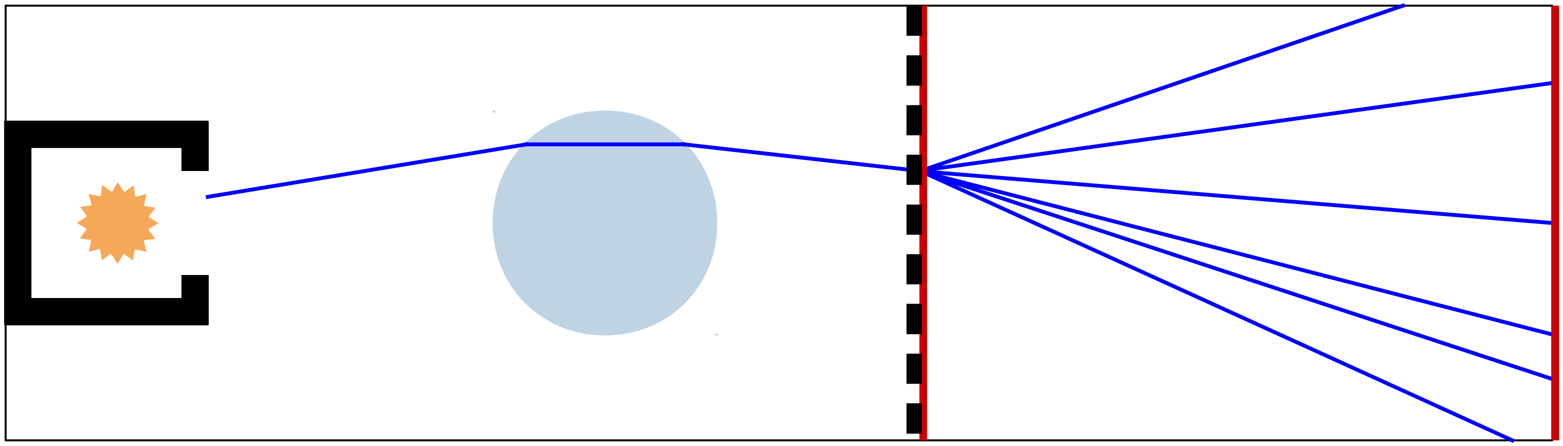

Particle histories in the modified EGSnrc

- Phase shift
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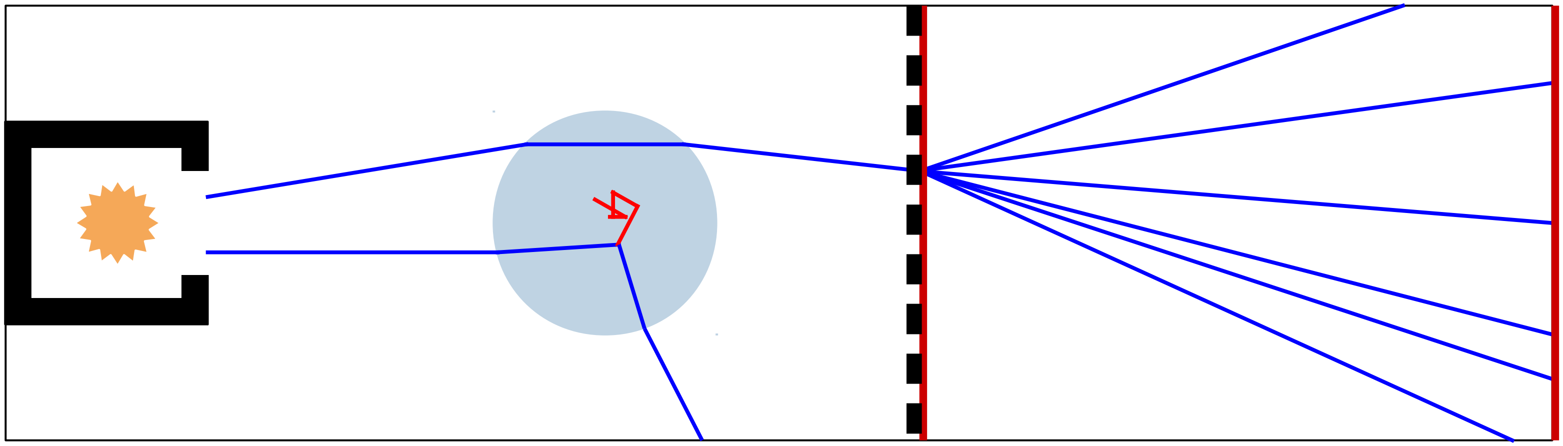
- Interactions (EGSnrc)



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- Interference pattern at different grating to detector distances
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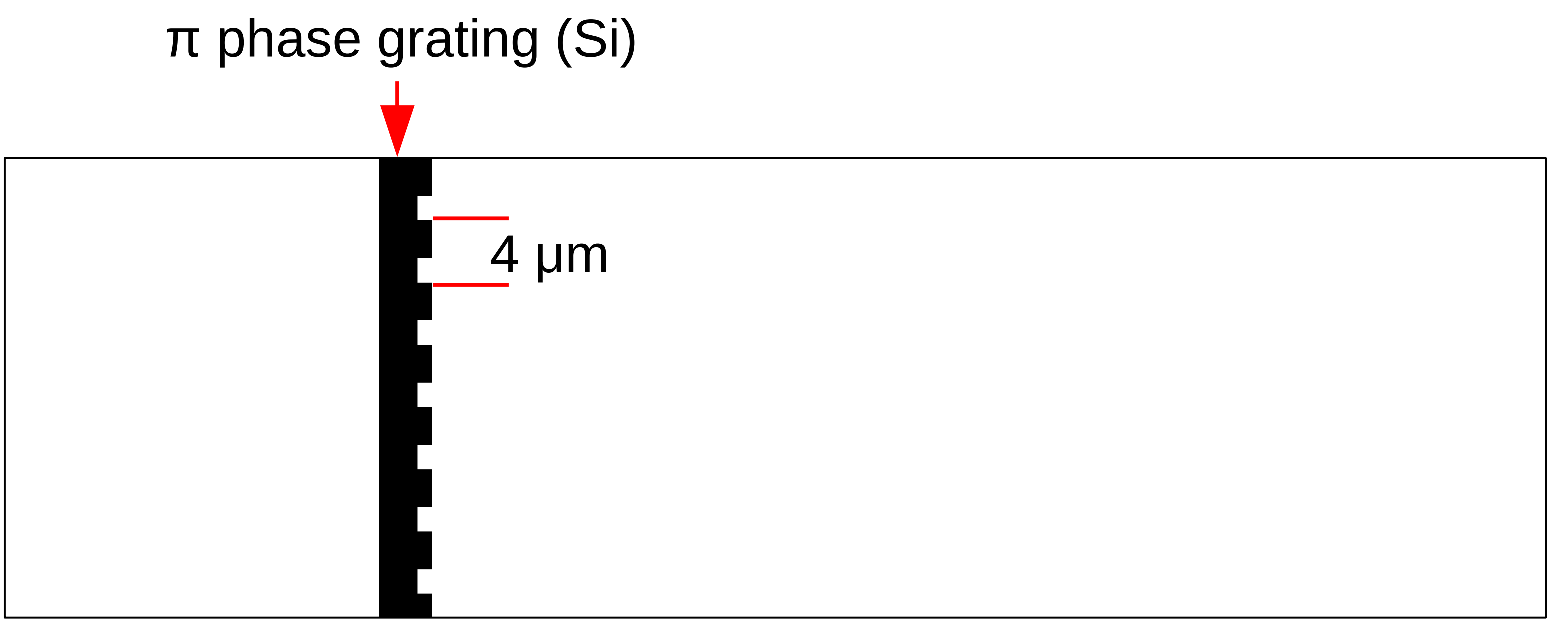

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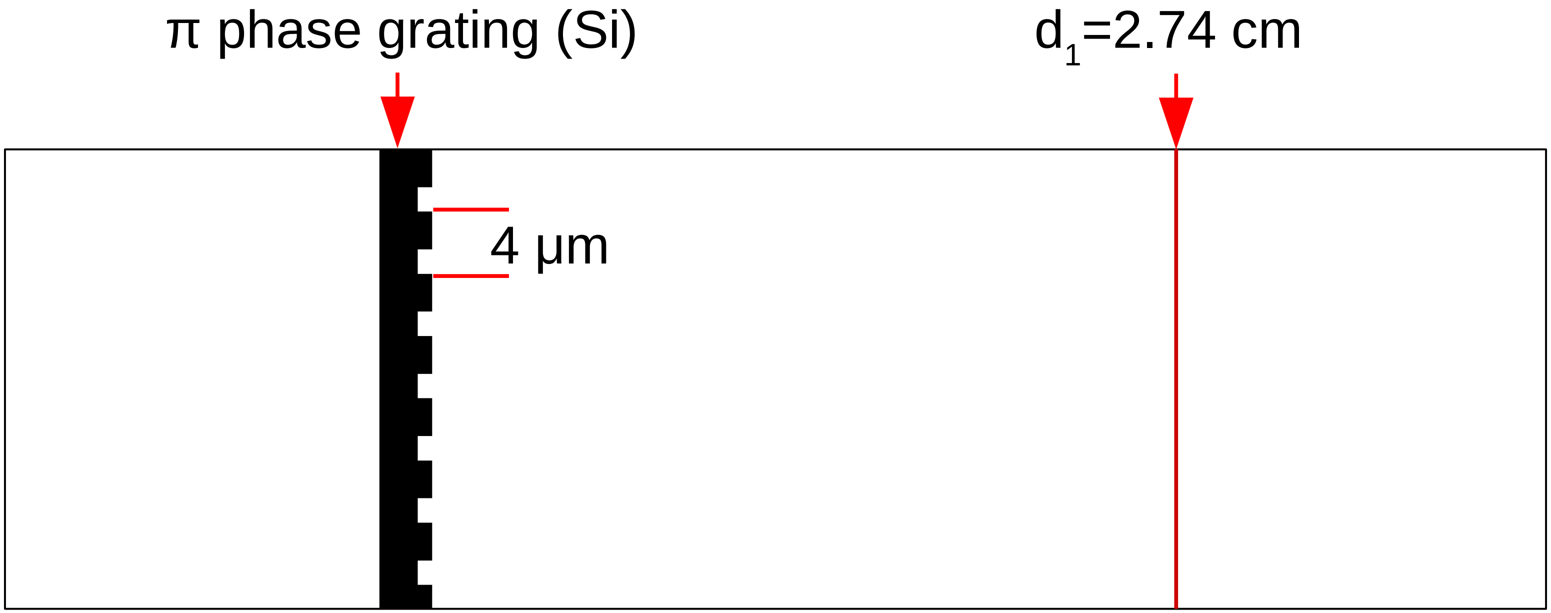

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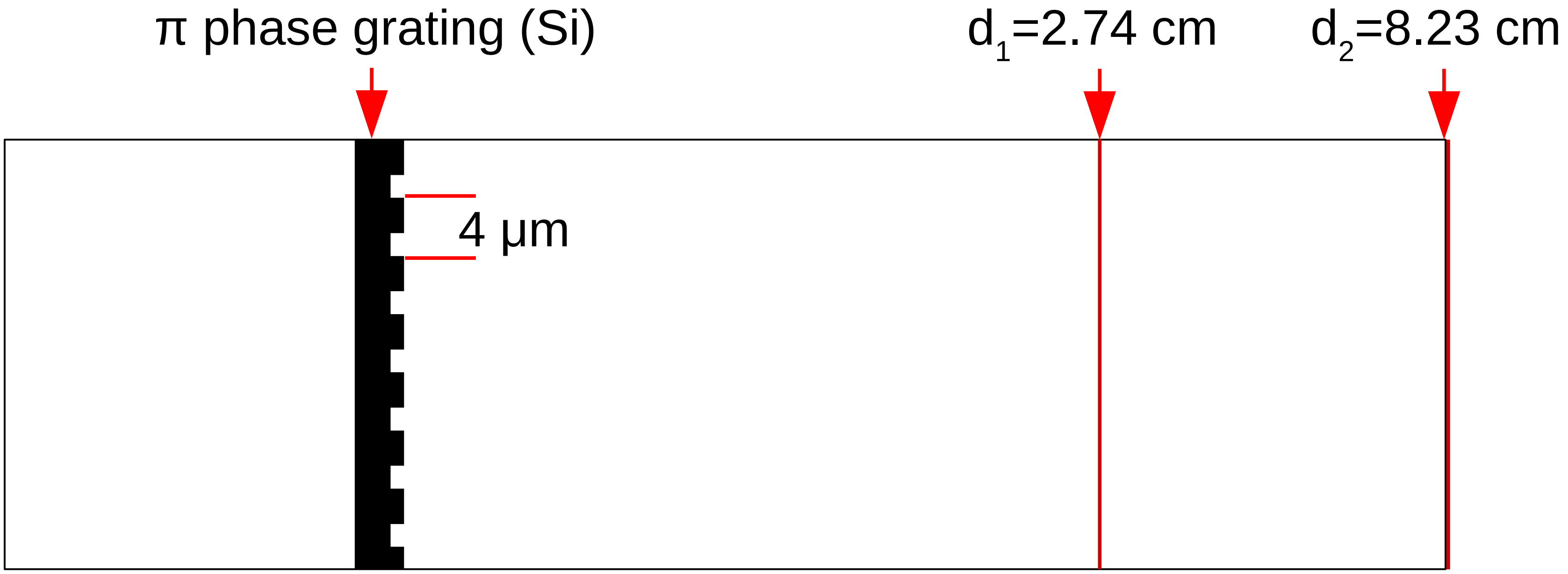

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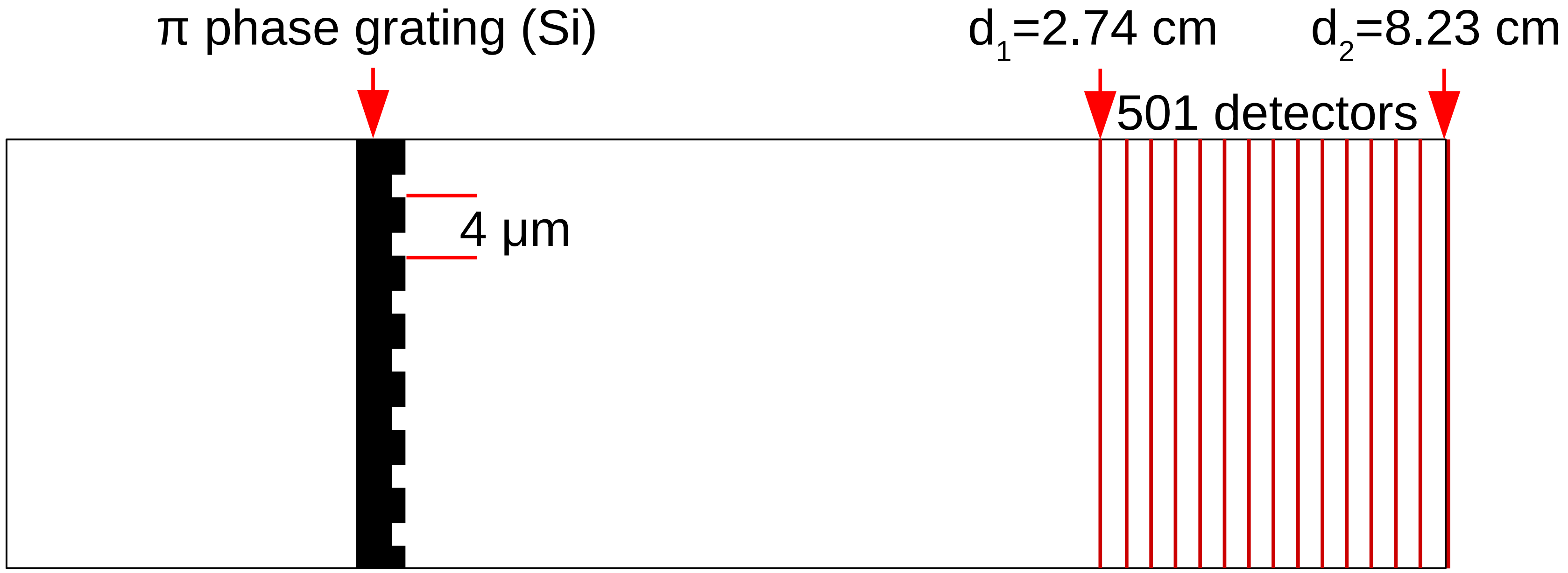

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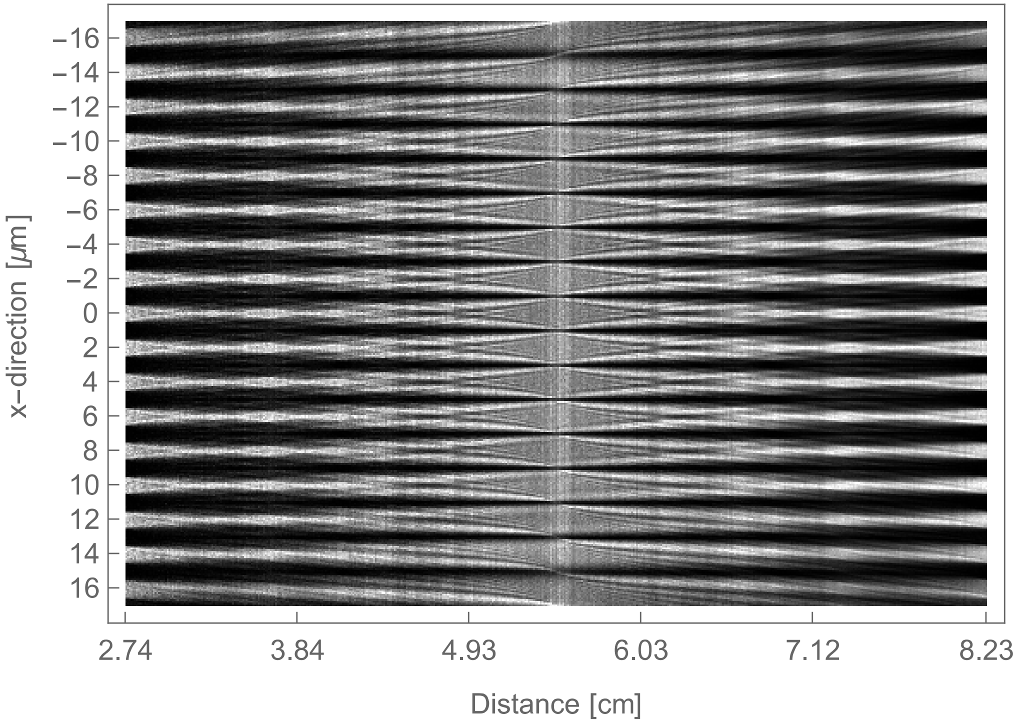
Results and Discussion

- The resulting Talbot carpet
  - Intensity pattern along middle line of the detectors plotted for each detector
- Observation
  - Self images of the phase grating at d_1 and d_2
  - Periodic patterns except for regions near the boundary
    - Boundary effect
  - Nearly flat signal in the middle of d_1 and d_2



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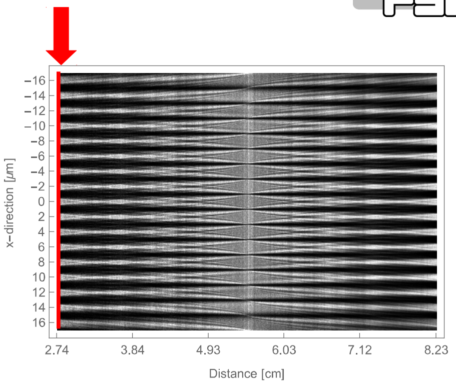
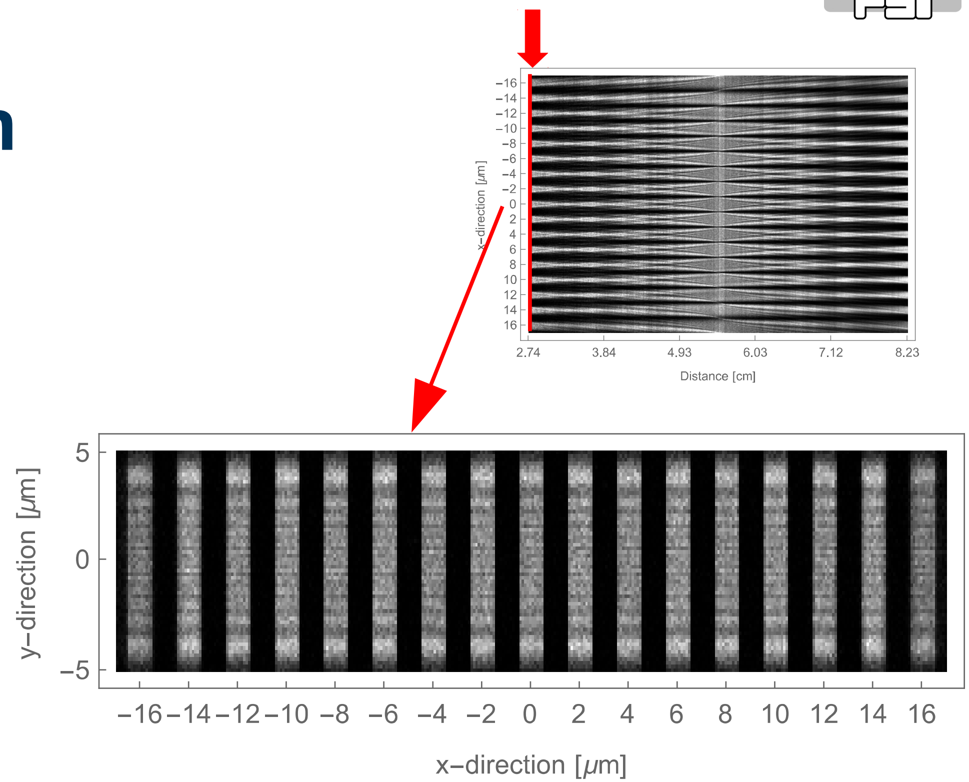
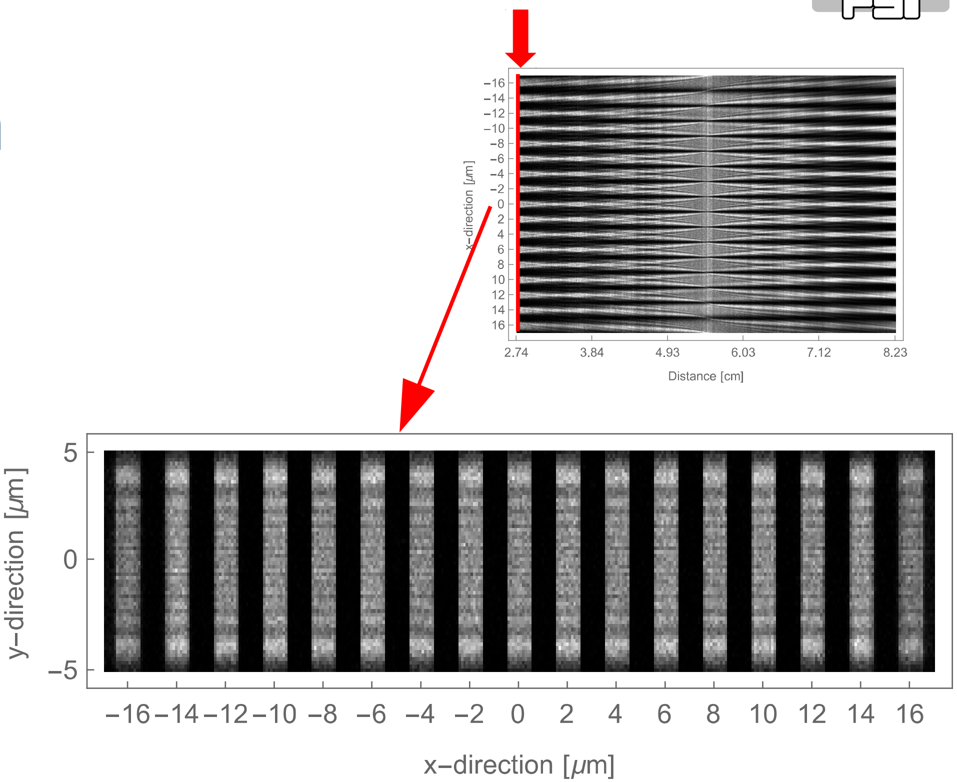


Results and Discussion



Results and Discussion

- Periodic line pattern in x-direction with 2 µm period
- Slightly faded signal close to the boundaries
  - Boundary effect
- Line pattern in y-direction
  - Boundary effect
  - Small grating dimensions



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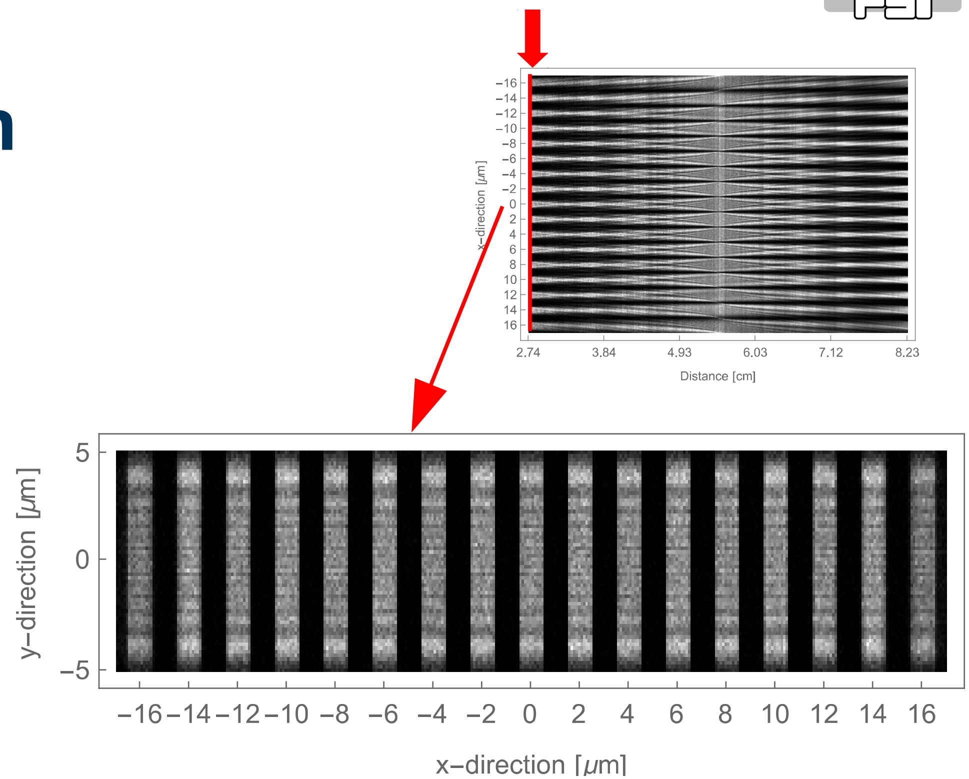
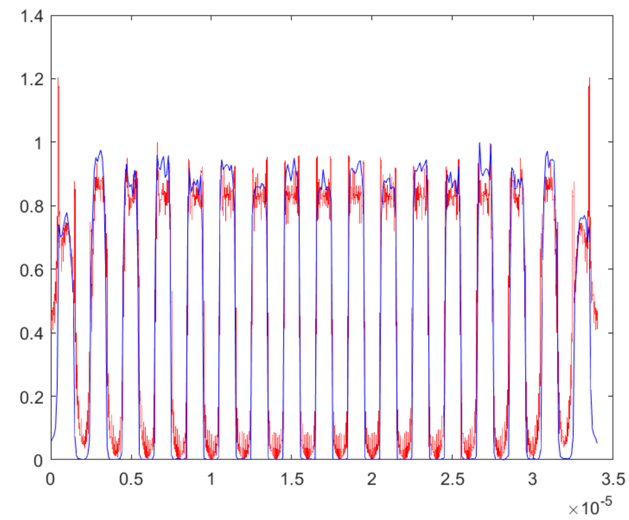




Conclusion

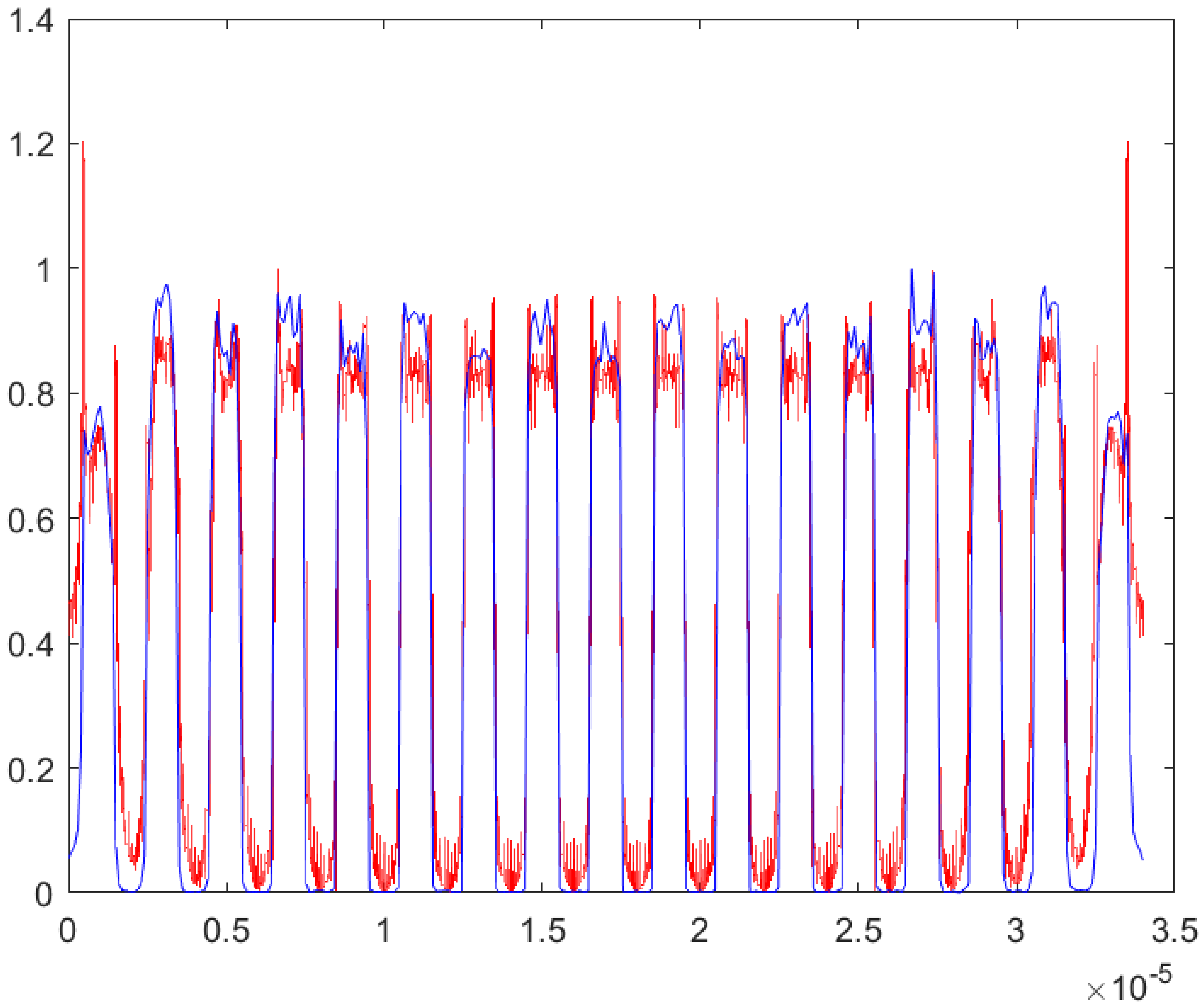
- Preliminary results
  - Algorithm feasible to model interference patterns occurring at a phase grating
  - Boundary effects
- Short term developments
  - Extend to finite source sizes and polychromatic sources
  - More efficient splitting algorithms
- Outlook
  - Implement dark field signal
  - Develop realistic source models

Acknowledgments

- Silvia Peter
- Tomcat team
- Carolina Arboleda
- AMS team at Inselspital Bern
- Reto Küng
- Silvan Müller
- Daniel Frei

Computations

- Ubelix linux cluster of university of Bern
  - Nodes: 273
  - CPU: 5828
- Simulation of a single detector
  - Parallelized on 41 nodes
  - Computation time for $20*10^6$ histories with 32044 splittings per particle: 1-2 hours
- Talbot Carpet
  - Separate job for each of the 501detectors
  - $20*10^6$ histories per job
  - 32044 splittings per particle on the grating
  - Computation time ~ 2.5 days per job


1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
3.5
$\times 10^{-5}$