Optical technologies, screen resolution and PSF

'Scintillation Screens and Optical Technology for transverse Profile Measurements'

ARIES-ADA topical workshop,
Krakow
1-3 April 2019

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Outline

- ***Motivation:*** *what's the challenge?*
- ***Optical technologies***
  - *Scintillator-camera geometries*
    - *Depth-of-field & Scheimpflug principle*
  - *Avoiding aberrations, key components*
    - *Telecentric lenses, filters*
  - *Analytic design and ray tracing*
- ***Resolution enhancement***
  - *Screen thickness*
  - *PSF and deconvolution*
- ***Background suppression***
  - *OTR, synchrotron light*

Motivation: what are the challenges when imaging a beam?

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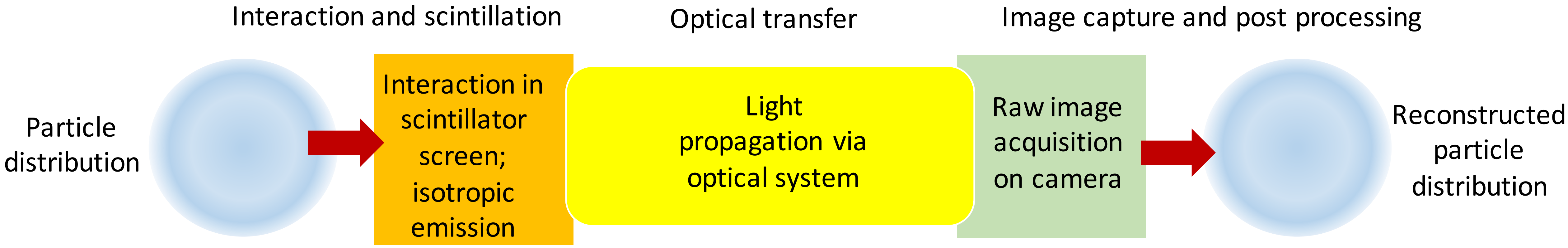
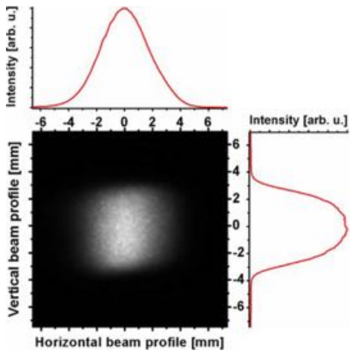
- Precise measurements of the **size**, **profile** and **position** of a particle beam striking a scintillator screen requires a carefully designed optical system to transfer scintillation light to the camera, so the true particle distribution can be reconstructed.



Motivation: what are the challenges when imaging a beam?

- Precise measurements of the **size**, **profile** and **position** of a particle beam striking a scintillator screen requires a carefully designed optical system to transfer scintillation light to the camera, so the true particle distribution can be reconstructed.
- Aim to capture a clean, sharply focused image of the scintillation plane, free of distortion, optical aberrations, non-linearity, or optical backgrounds (OTR).

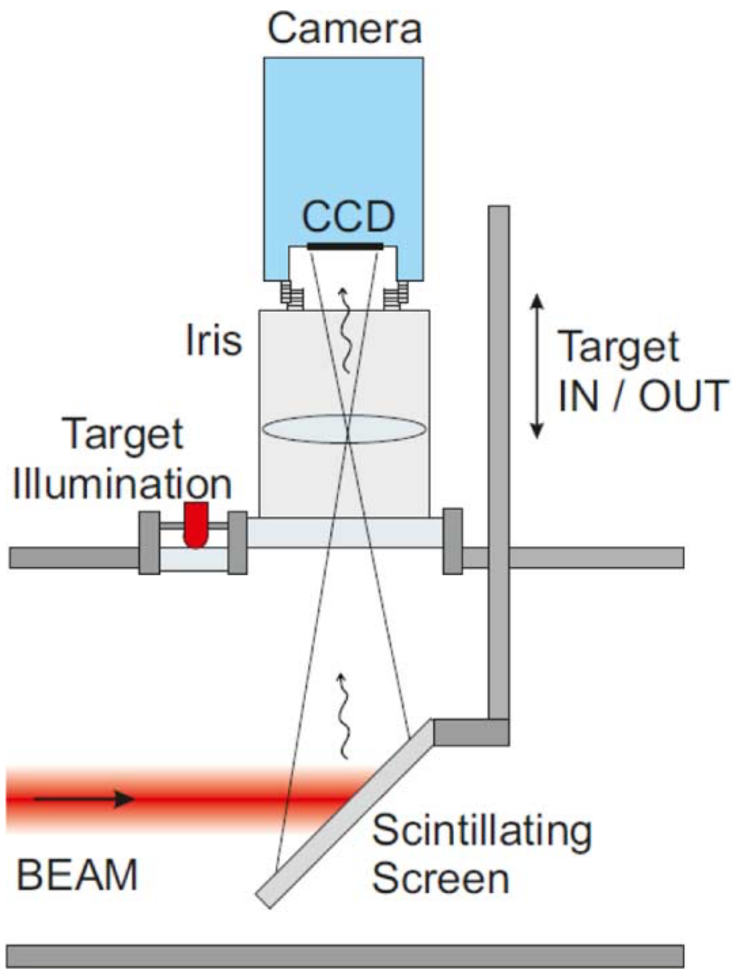
	Interaction and scintillation	Optical transfer	Image capture and post processing	
Particle distribution →	Interaction in scintillator screen; isotropic emission	Light propagation via optical system	Raw image acquisition on camera →	? Reconstructed particle distribution
Challenges:	*Refraction at scintillator boundary*	*Geometric distortion, focus, depth-of-field* *Diffraction effects* *Chromatic aberrations*	*Field-of-view at camera* *Resolution / pixel size* *Non-linearity*	



Scintillator-camera typical setup

- Particle beam impinges on flat scintillator screen, typically angled at 45 degrees.
- Camera is housed away from beam to reduce radiation, and views the angled screen through a vacuum window.
- A lens (system) is included to form an image of the screen on the sensor plane.
- Include light source to illuminate target.

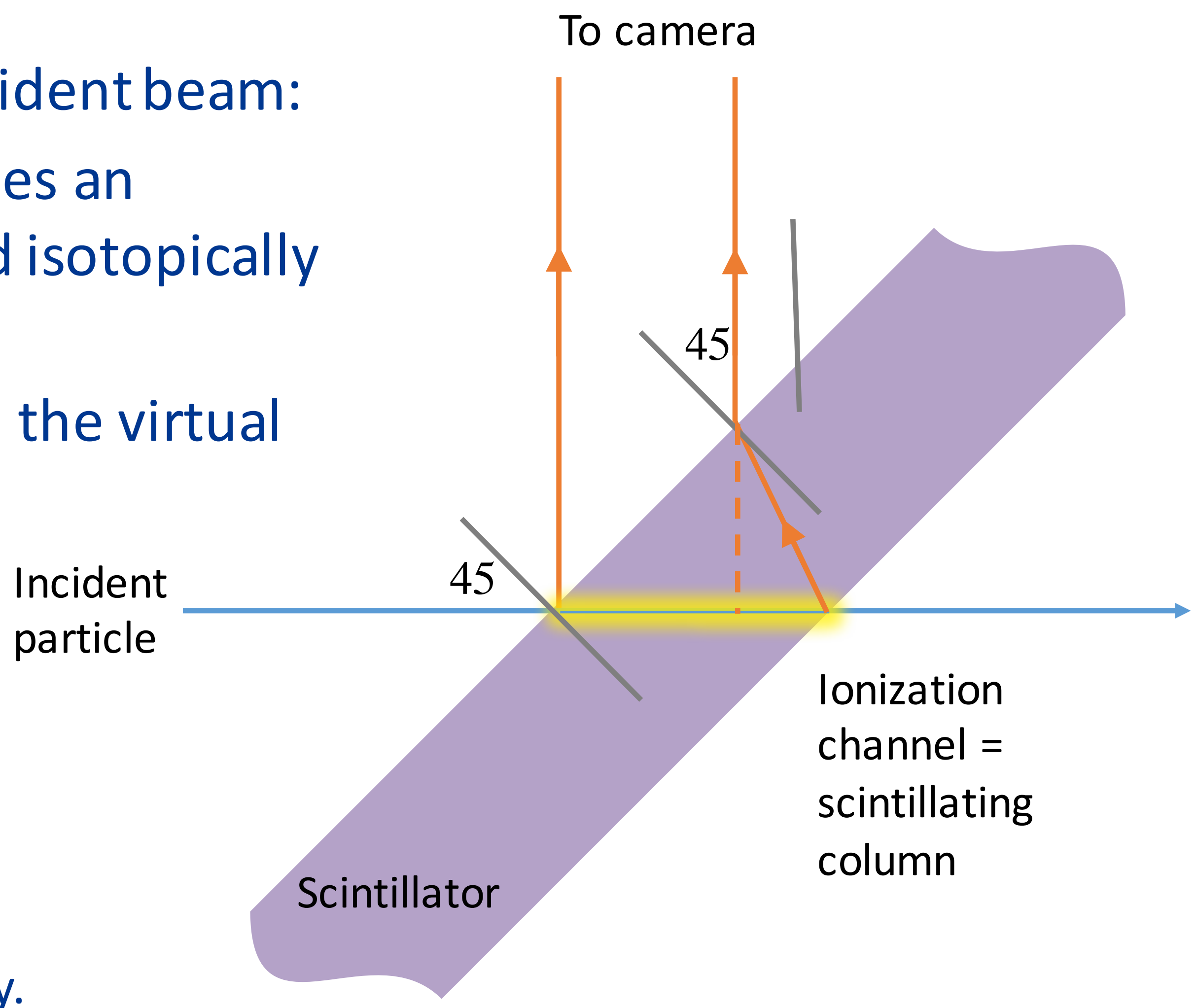
- Optical Transition Radiation (OTR):
  - Generated by charged particles traversing the vacuum / screen interface and can be reflected towards the camera.
  - Considered here as a background to the scintillation light signal



Walasek-Höhne and G. Kube, Proc. DIPAC'11, Hamburg (Germany), p.553

Light generation and refraction at scintillator-screen

- Consider scintillator screen at angle 45^o to incident beam:
- Each particle that crosses the scintillator creates an ionization channel, from which light is emitted isotopically within the volume.
- Refraction of this light at the boundary affects the virtual image size and achievable resolution.

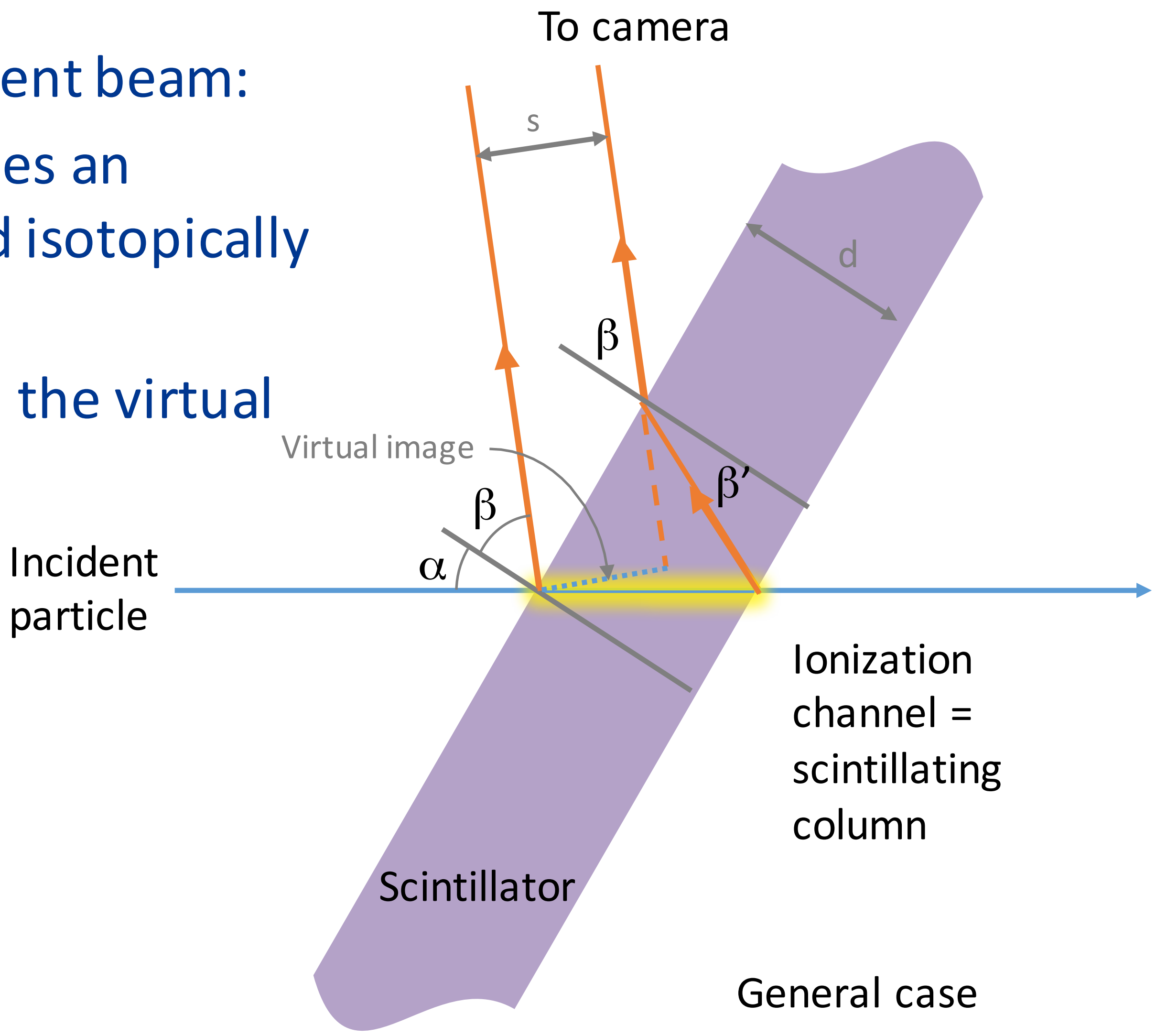


- Scintillator thickness is a trade-off :
  - Thinner screen for best resolution
  - Stability of screen mount, thermal effects.
  - Thicker screen provides more photons.
  - Choice also depends on bunch energy and intensity.

Light generation and refraction at scintillator-screen

- Consider scintillator screen at angle α to incident beam:
- Each particle that crosses the scintillator creates an ionization channel, from which light is emitted isotopically within the volume.
- Refraction of this light at the boundary affects the virtual image size and achievable resolution.

$$s = d\cos\beta \cdot \sqrt{\frac{1}{1-\frac{\sin^2\beta}{n^2}} + \frac{1}{\cos^2\alpha} - 2\frac{\cos\left[\arcsin(\frac{\sin\beta}{n}) + \alpha\right]}{\sqrt{1-\frac{\sin^2\beta}{n^2}}\cos\alpha}}$$



See PRSTAB 18 082802 (2015) (note sign)

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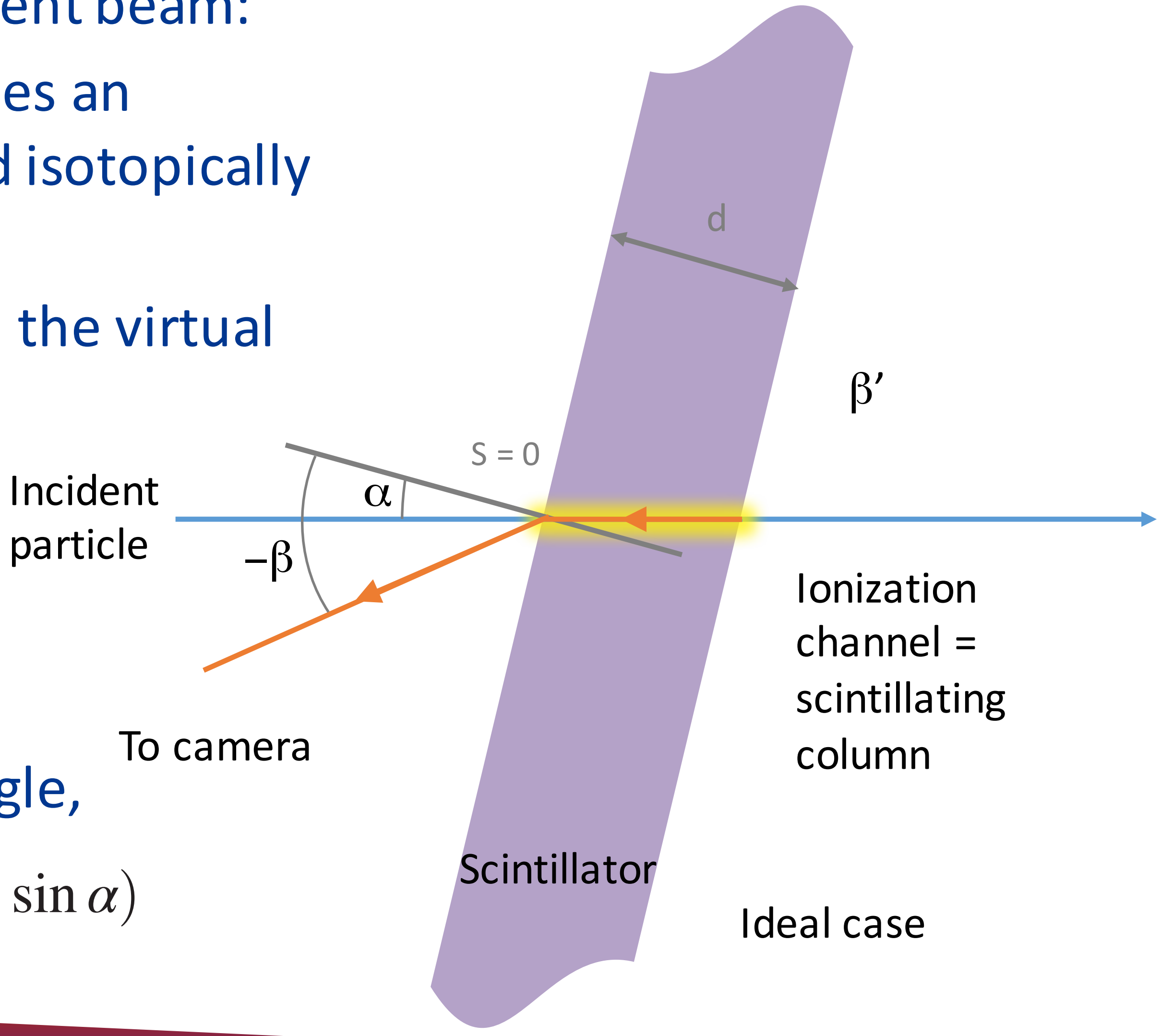


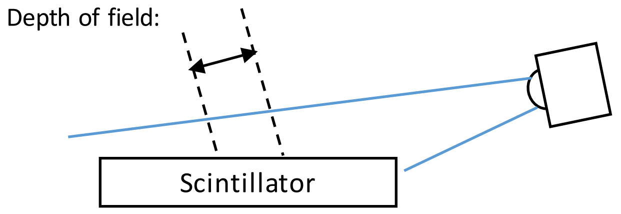
- Apparent size is zero (s = 0) when viewing angle,

$$\beta_{\text{ideal}} = -\arcsin(n\sin\alpha)$$

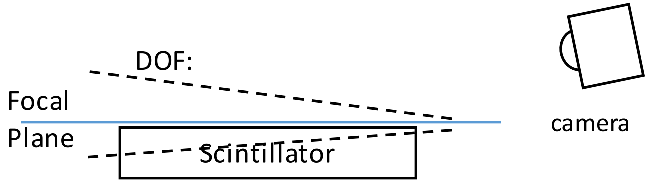
See PRSTAB 18 082802 (2015) (note sign)

Depth of field

- In the typical setup, the camera-lens must focus on a scintillator plane surface that is at an oblique angle…
- This works for very small electron beams of only 10 μm or so, when the distribution is well within the depth-of-field of the lens.
- However, for larger beams only part of the scintillator plane will be in focus:



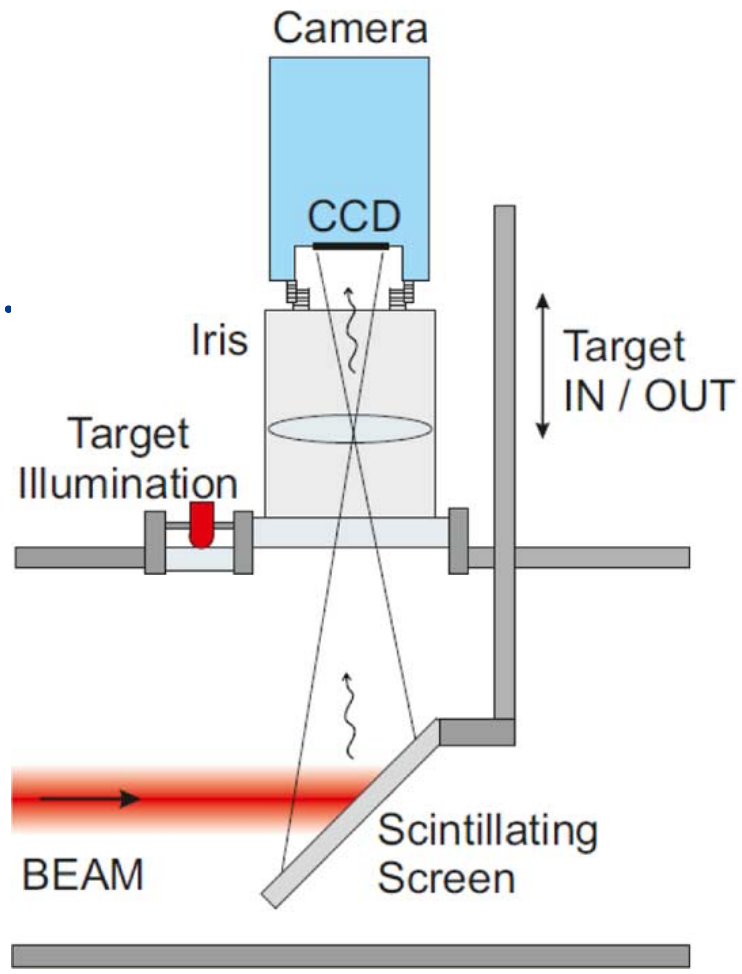
- What we really need is this:



IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 59, NO. 5, OCTOBER 2012

TABLE I
SIMPLIFIED OVERVIEW OF SCINTILLATOR USAGE IN BEAM DIAGNOSTICS AND HIGH ENERGY PHYSICS

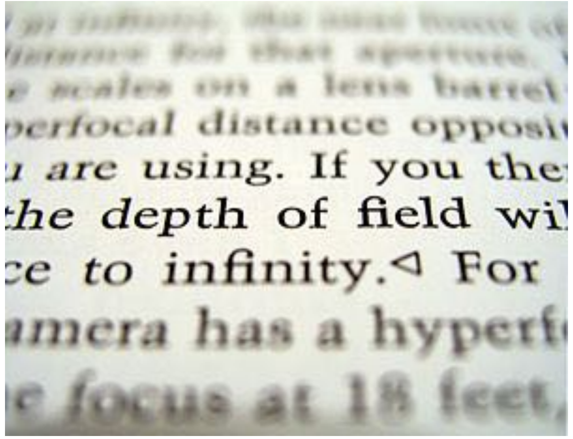
	Ion Diagnostic	Electron Diagnostic	High Energy Physics
Application	Primary beam on screen Transverse beam profile		Detection of secondary particles, tracking, timing
Particle energy	1 keV – 100 GeV/u	100 keV – 10 GeV	up to 10 GeV
Spot size	1 mm – cm	10 μm – mm	1 cm – 100 cm
Particle rate	very high	very high	low
Dose rate	very high	high	low
Energy deposition	very large	medium	low
Saturation	expected	possible	none
Modification	expected	possible	low



Walasek-Höhne and G. Kube, Proc. DIPAC'11, Hamburg (Germany), p.553

Depth of field: the view camera

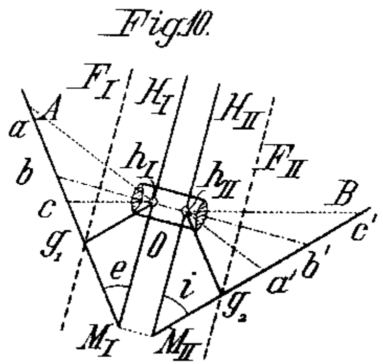
How to focus on ***all the Wawel wall of Krakow?***



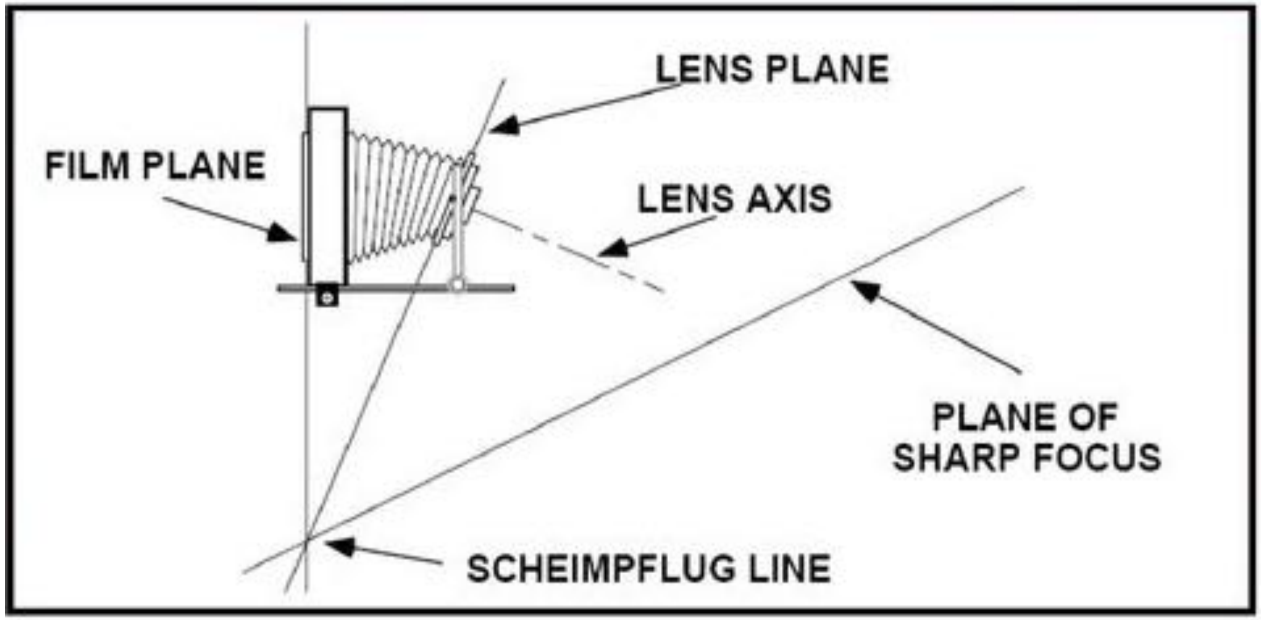
- Fortunately, this is a solved problem in photography and is the basis of the “view camera”

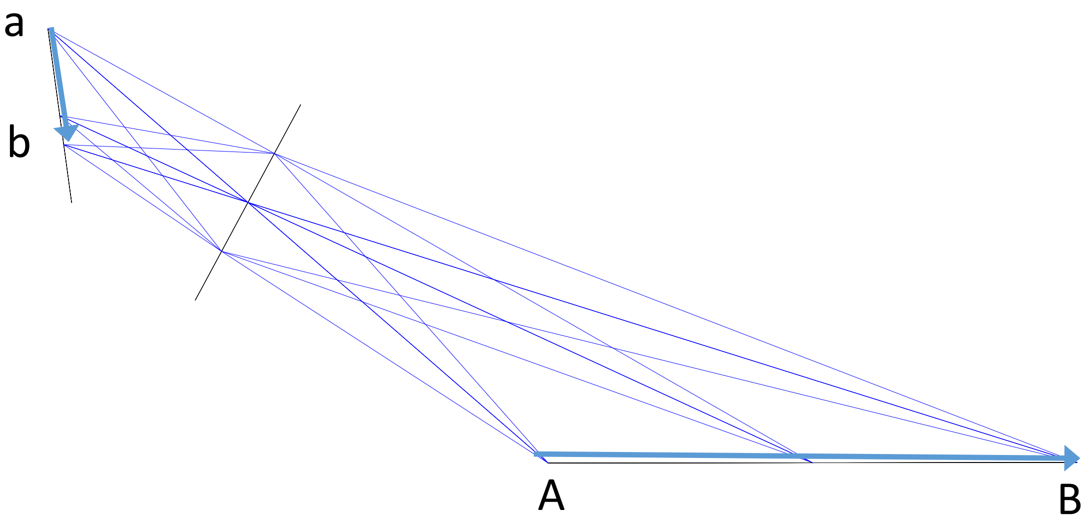
- View cameras can move the lens in x & y tilt, and z translation; and are still made today:

The Schiempflug Principle



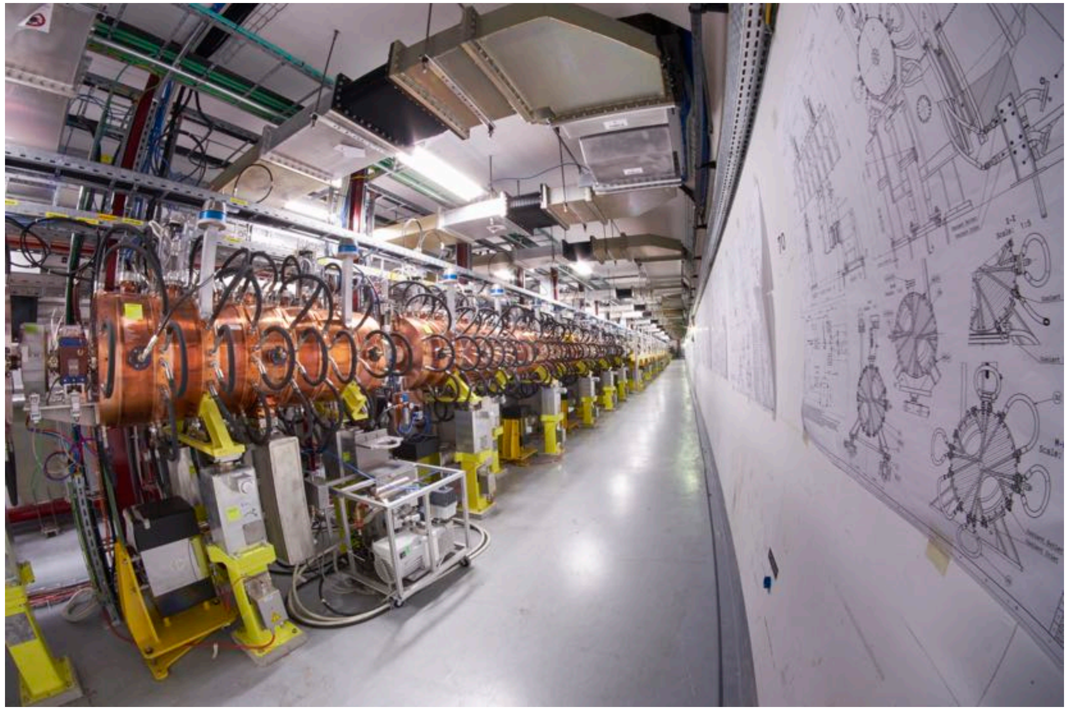
- Captain Theodor Scheimpflug was an Austrian Army & Navel officer who used aerial photography to make accurate maps with undistorted images from balloon-suspended cameras (not pointing straight down).
- His principle states that if subject plane, lens plane and image plane intersect in a single line as shown, then the subject plane is completely in sharp focus.





http://www.trenholm.org/hmmerk/download.html
https://en.wikipedia.org/wiki/Scheimpflug_principle

Depth of field: the view camera



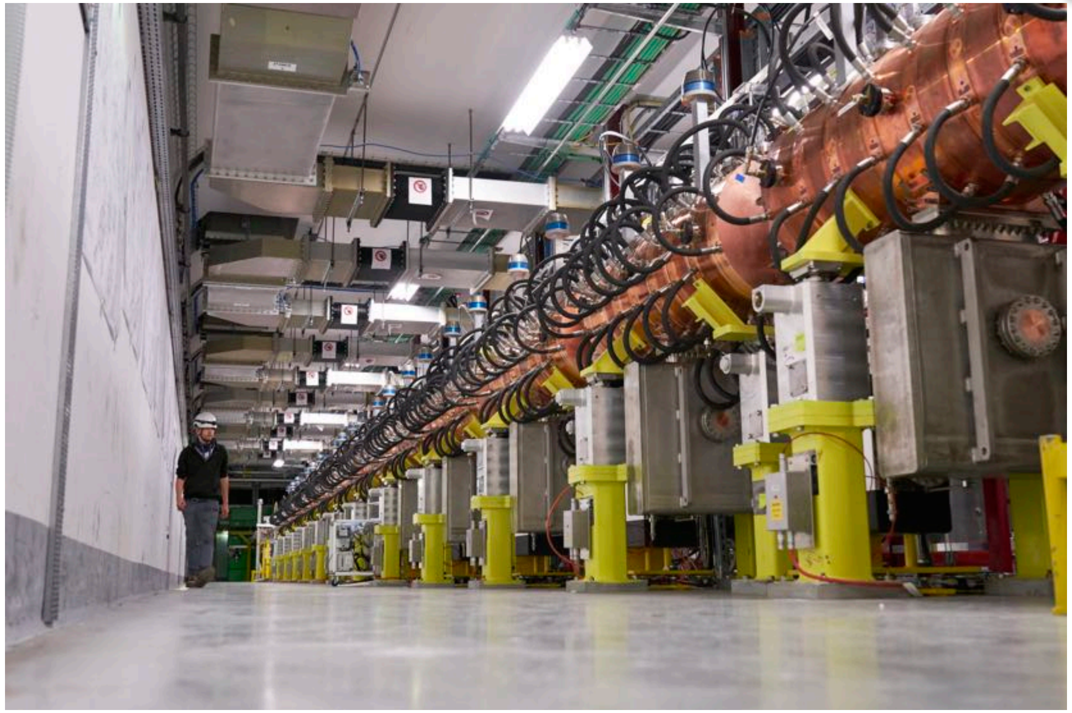


Photo by J-E Nyström, Helsinki, Finland

A modern Scheimpflug mount

MCSM1-01X is a variable macro lens expressly designed for 3D measurement and imaging applications where the object plane is not perpendicular to the optical axis. A precise built-in adjustment mechanism allows the lens to accurately meet the Scheimpflug condition and to image tilted planes in perfect focus. This lens offers a wide range of magnifications and view angles. It can be interface with any structured light source to build up extremely accurate 3D imaging systems. Image sharpness is maintained even when the lens is tilted by a wide angle, since the Scheimpflug adjustment tilts around the horizontal axis of the detector plane. The tiltable mount is compatible with any C-mount camera.

1/3" TO 2/3" SENSORS

KEY ADVANTAGES

Precision Scheimpflug mount
Image focus is retained across any tilted plane.

Compatible with any C-mount cameras
The back focal length meets the C-mount standard.

Application flexibility
Supports a wide range of magnification factors and viewing angles.

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A modern Scheimpflug mount

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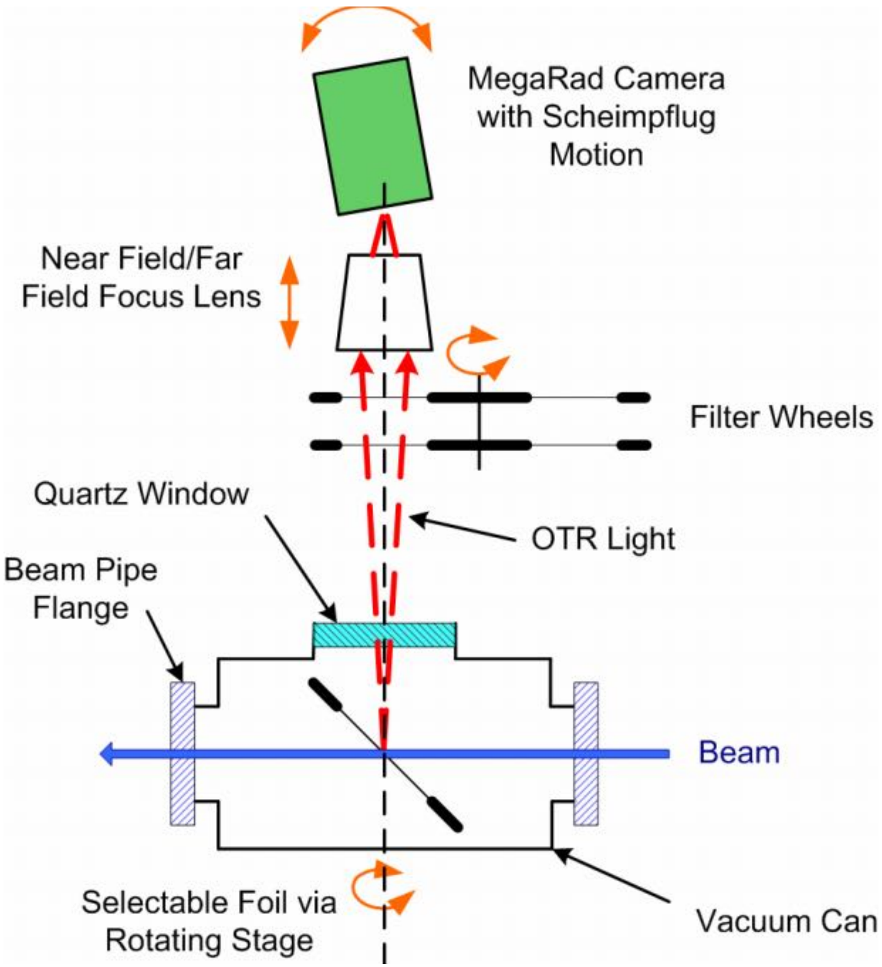
Example of Scheimpflug beam diagnostic (for OTR)



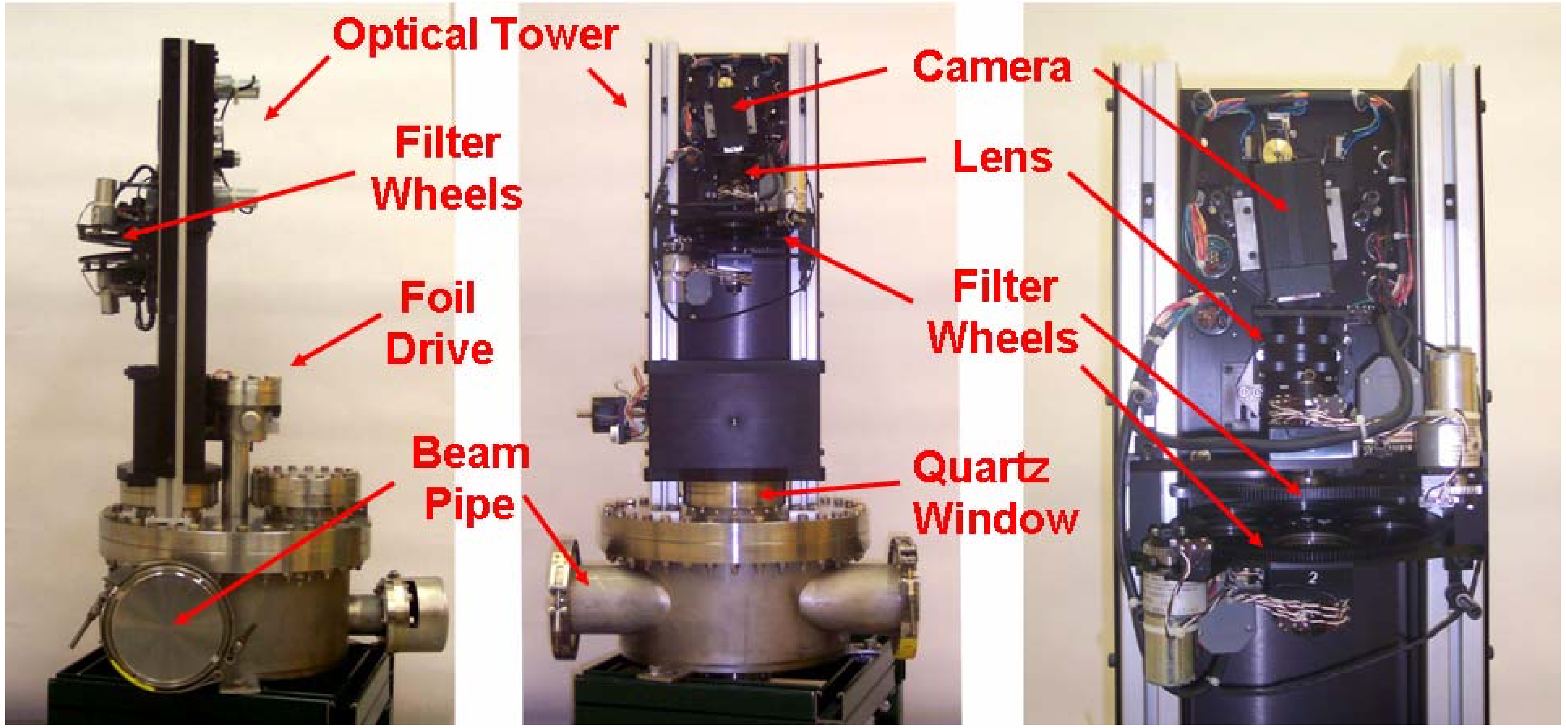


Figure 2: The OTR detector. Left image shows beam line view of detector. Center image shows side of detector. Right image shows magnified view of optical tower with camera, lens and filter wheel assembly.

V. Scarpine, Proc of PAC 2005

Common scintillator layouts

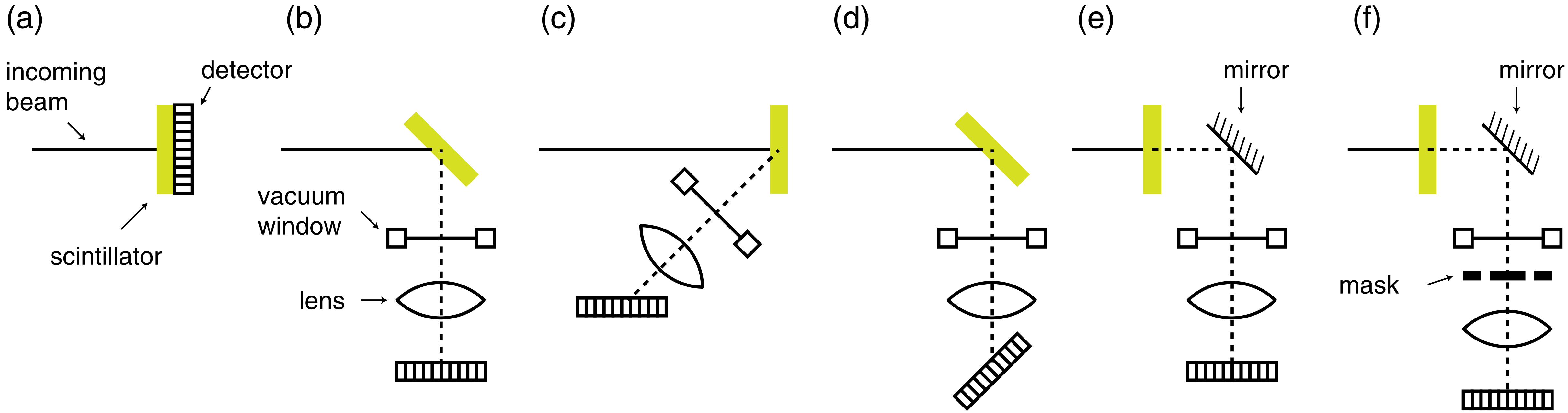


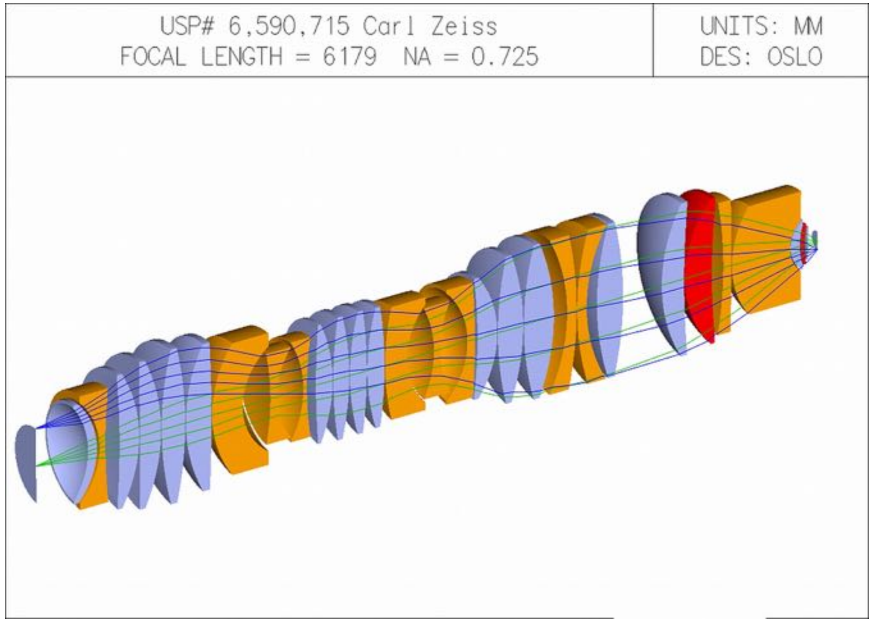
FIG. 1. Commonly used layouts to image fluorescent light onto a detector. (a) Direct detection of the light, (b) and (c) imaging the light through a vacuum window, (d) observing the Scheimpflug imaging geometry, (e) using an additional in-vacuum mirror, and (f) with an additional mask to block coherent transition radiation.

PRSTAB 18 082802 (2015)

Optical design with ray tracing software

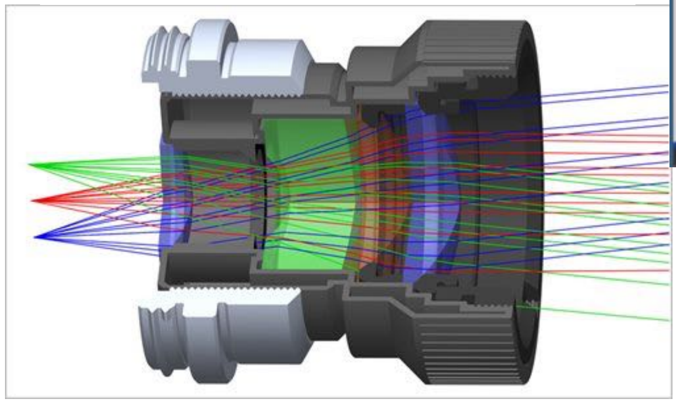
- *Ray tracing divides the real light field into discrete monochromatic rays that are propagated through the system. Can input real light distribution.*
- *Several professional software suites available, e.g.*

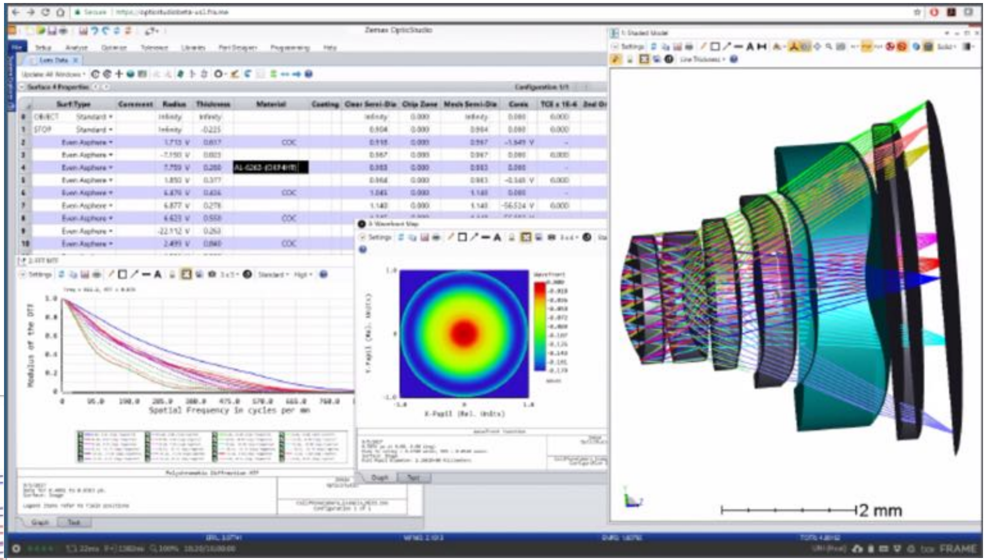
OSLO: Optics Software for Layout and Optimization
https://www.lambdares.com/oslo/

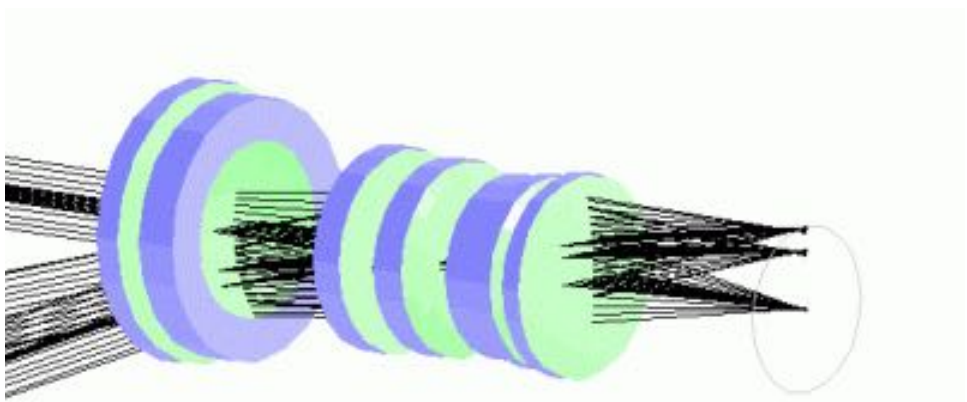


ZEMAX
https://www.zemax.com/

LensMechanix







WinLens3D - lens design & optimization software
http://www.opticalsoftware.net/index.php/how_to/lens_design_software/winlens3d/

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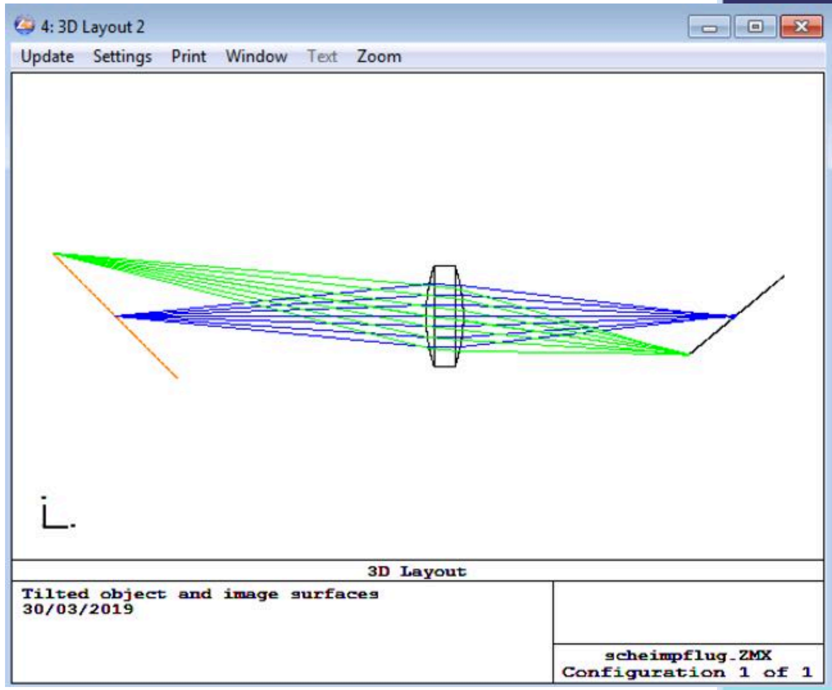
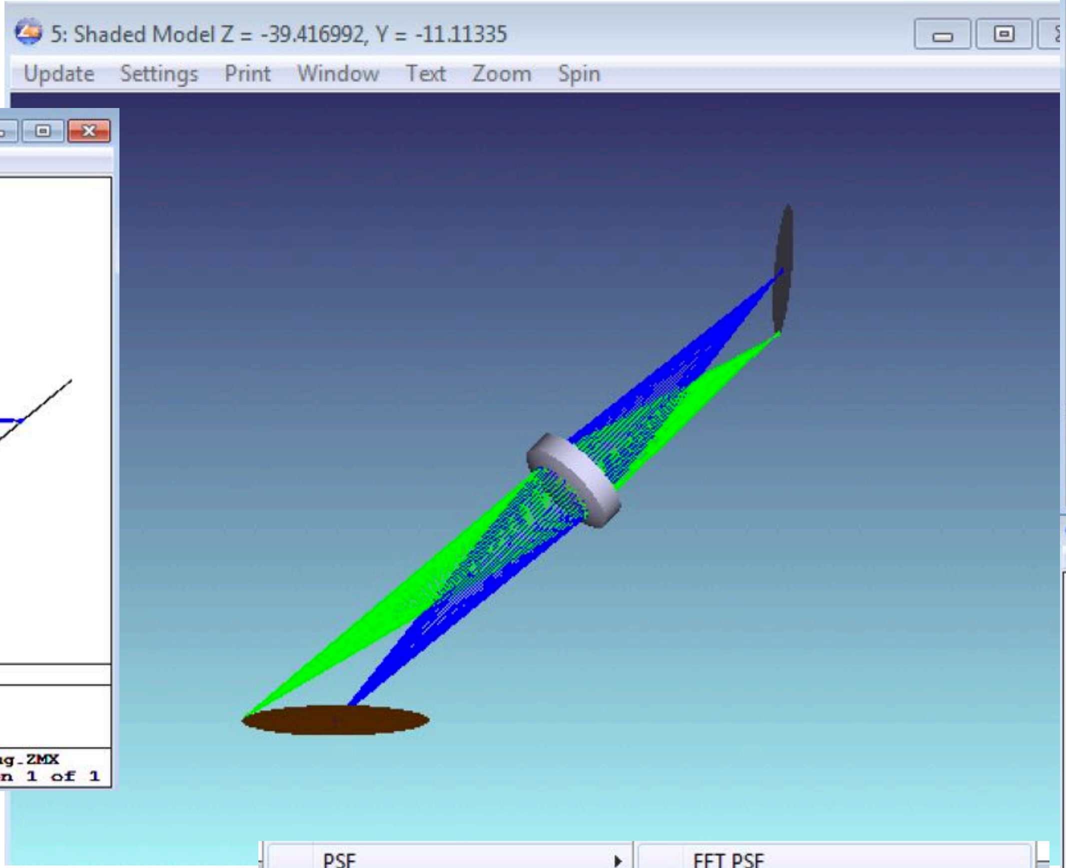
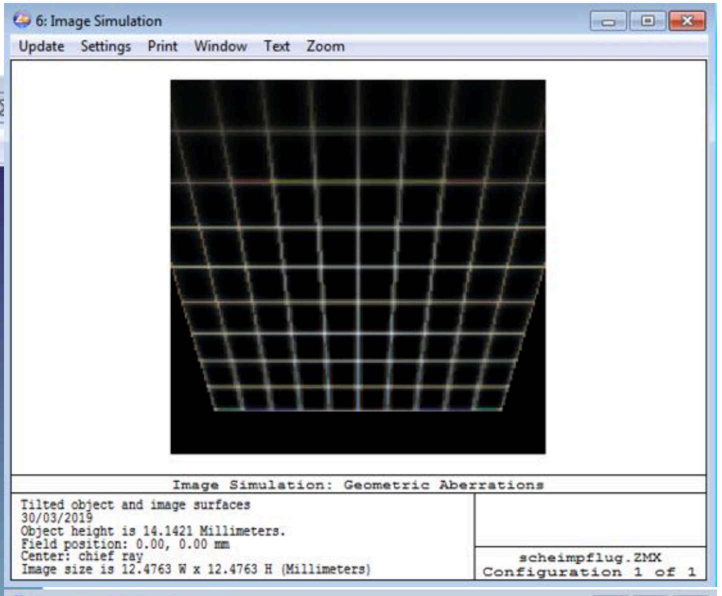
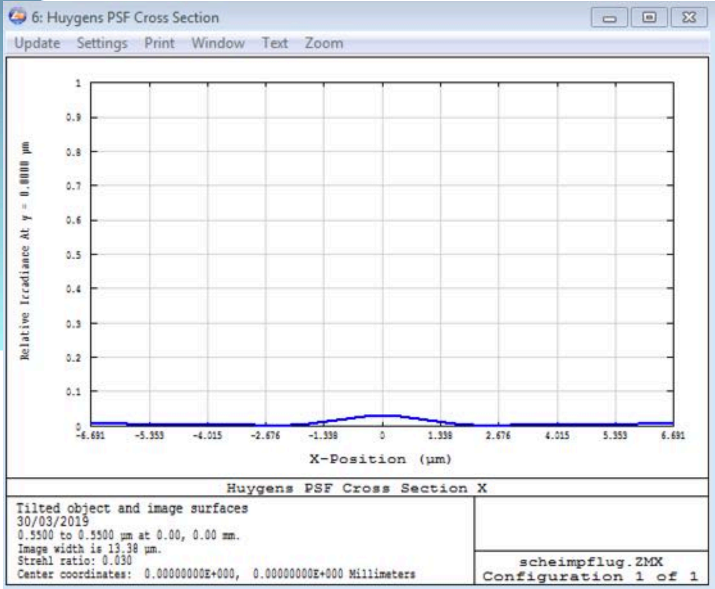
e.g. Scheimpflug principle in Zemax

- *Tilted object and image planes with respect to lens*



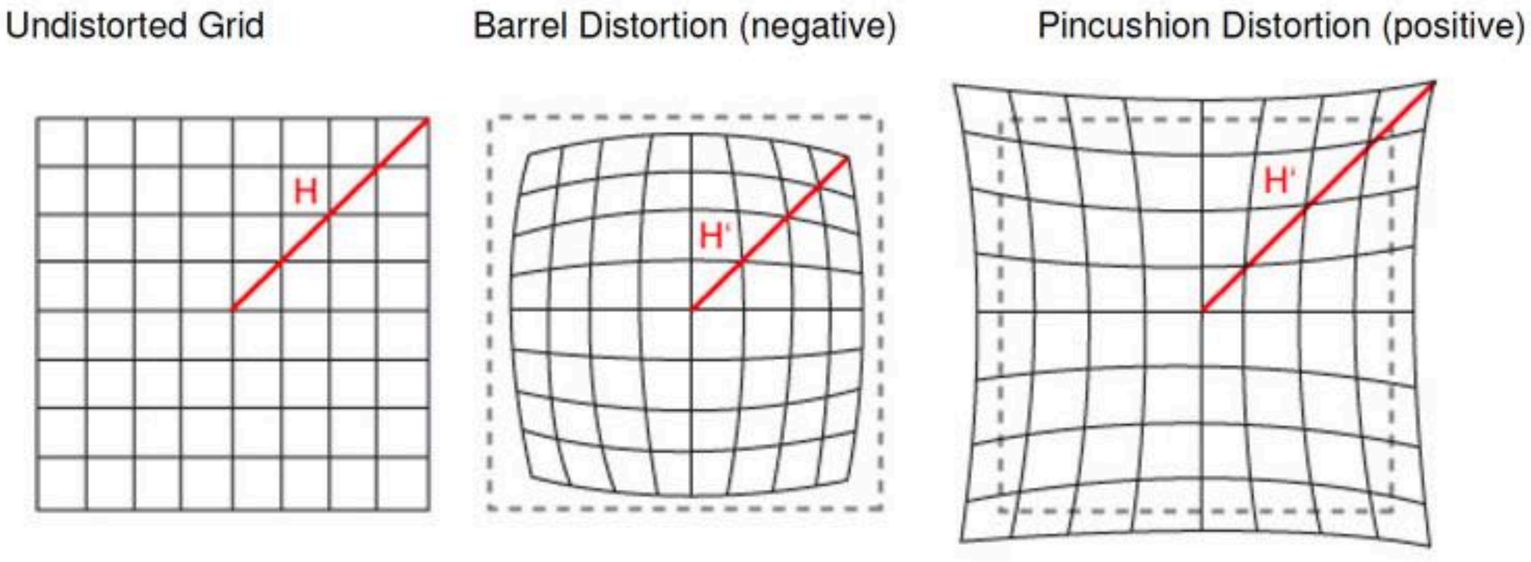






Zemas can calculate: e.g. image simulation, point spread function.

Image distortion



Lens Geometric Distortion Definition

The lens geometric distortion is defined as

$$LGD = 100 \cdot \frac{(H` - H)}{H}$$

H' = dot distance from center of image

H = undistorted dot position

- Barrel distortion: magnification increases with distance from optical axis
- Pincushion distortion: magnification decreases with distance from optical axis

Spotted on a visit to KEK

Scale for calibration of magnification and distortion

- Illuminated target screen with graticule

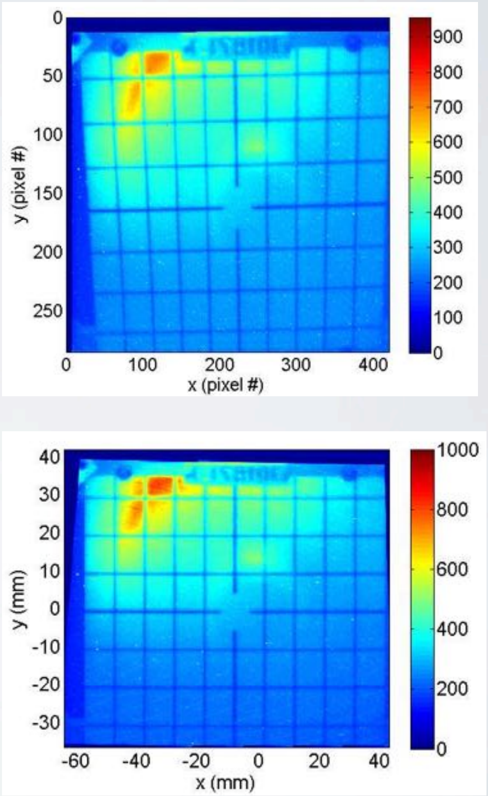
U Raich, CAS Frascati
2008 Beam Diagnostics

- Image distortion can be calibration by adding a known network of lines or dots on the target: e.g. keystoned (trapezoid) image may be post-processed to compensate for distortion

Scale for calibration of magnification and distortion

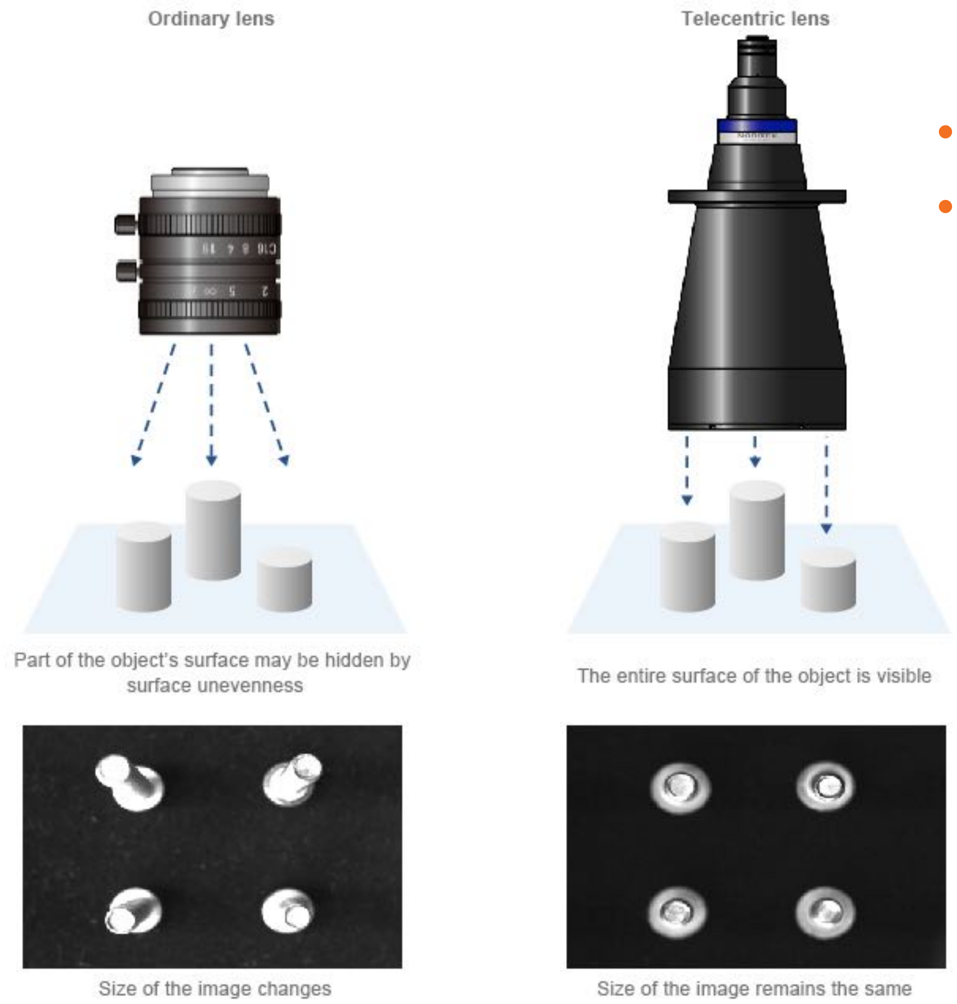
IMAGE DEFORMATIONS

- Usually screens are tilted at 45° or similar
- This introduces the "trapeze" aberration
- Need to calculate and apply a correction algorithm

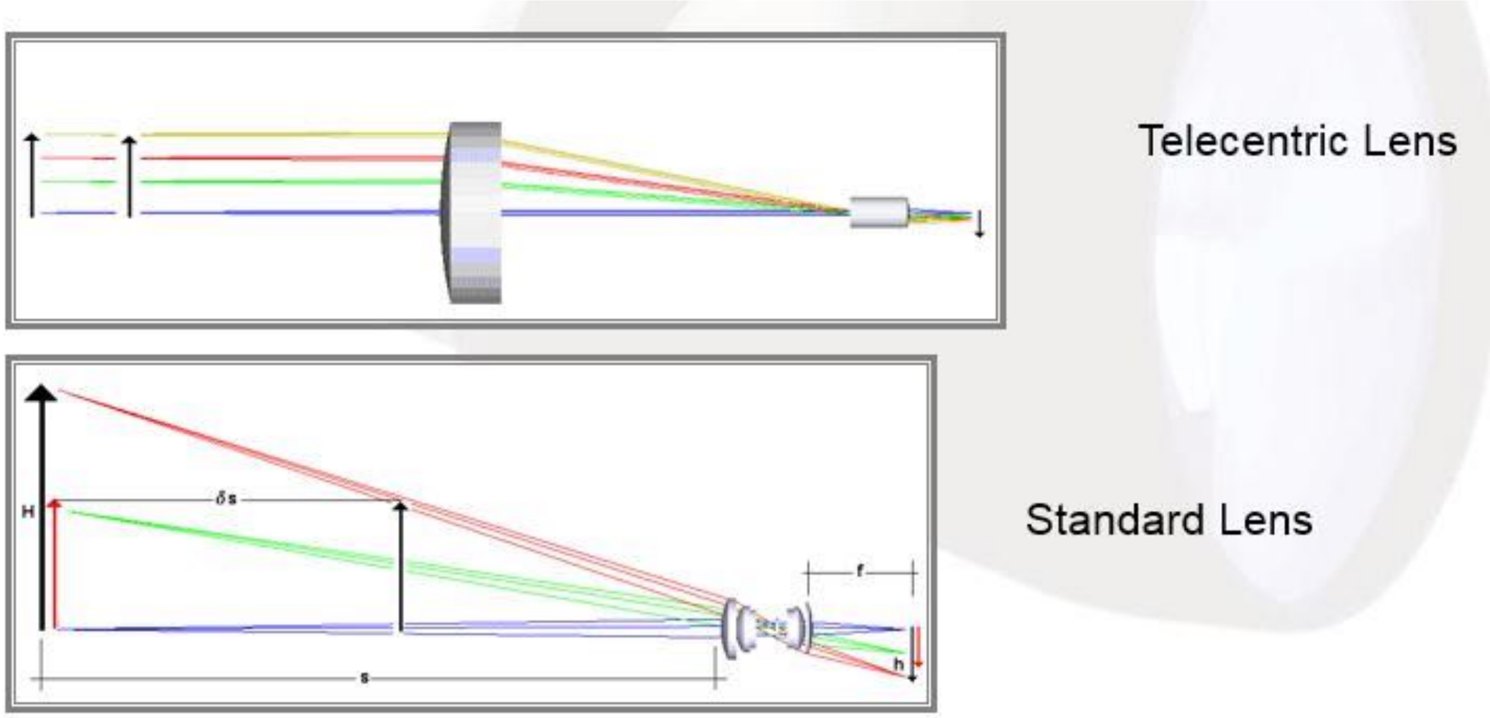


Enrico Bravin, Proc. of Scintillation workshop at GSI, 2011

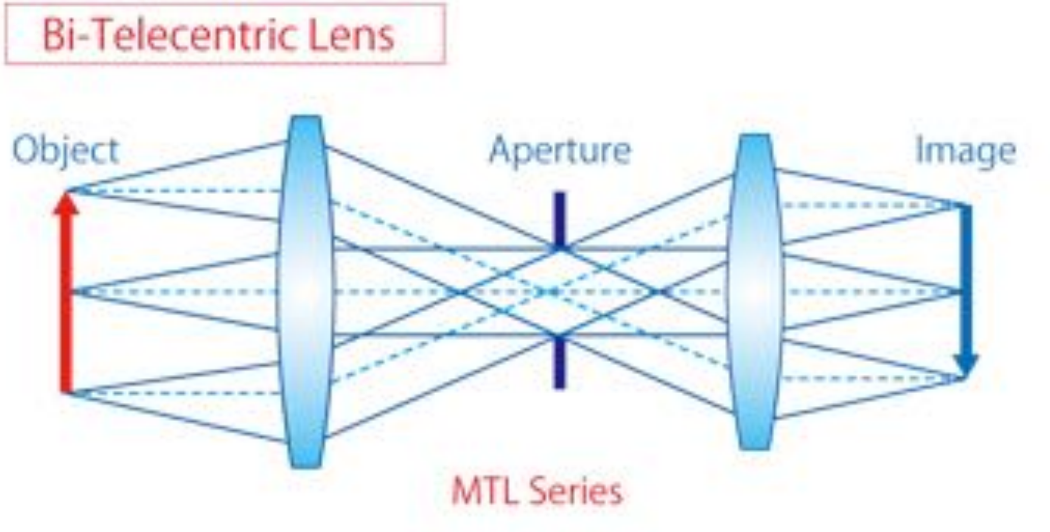
Telecentric lens

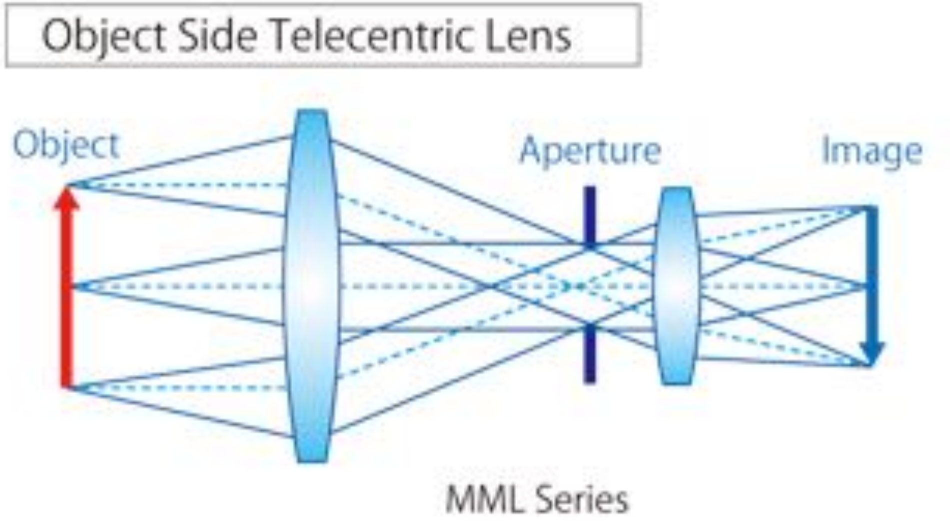


- Unlike a standard lens, the magnification of a telecentric lens does not change with the object distance.
- Such lenses are often useful in machine vision applications:
- When measuring dimensions, a telecentric lens will yield the same measurement regardless of changes in object distance or position.



Bi-telecentric lens with Scheimpflug adjustment





- In a bi-telecentric lens, the principle rays are parallel to the optical axis at the object **and** the image.
- Thus the magnification in independent of the object or image distance.
- Can combine this lens with Schiempflug adjustment:

TCSM080

3D bi-telecentric lens with Scheimpflug adjustment

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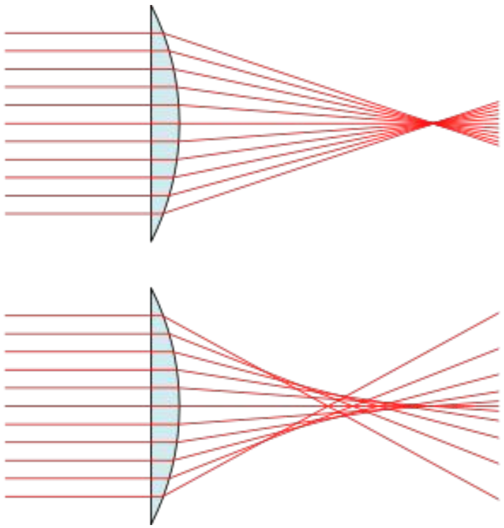
Other common optical aberrations

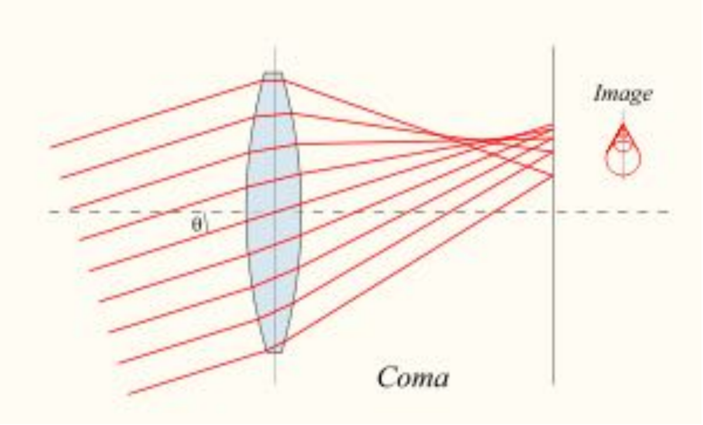
- For an ideal optical system, every point in an object space corresponds to a point in image space: a stigmatic image, which typically cannot be perfectly achieved.

- ***Spherical aberration:***
  - off axis rays focus as different distances.

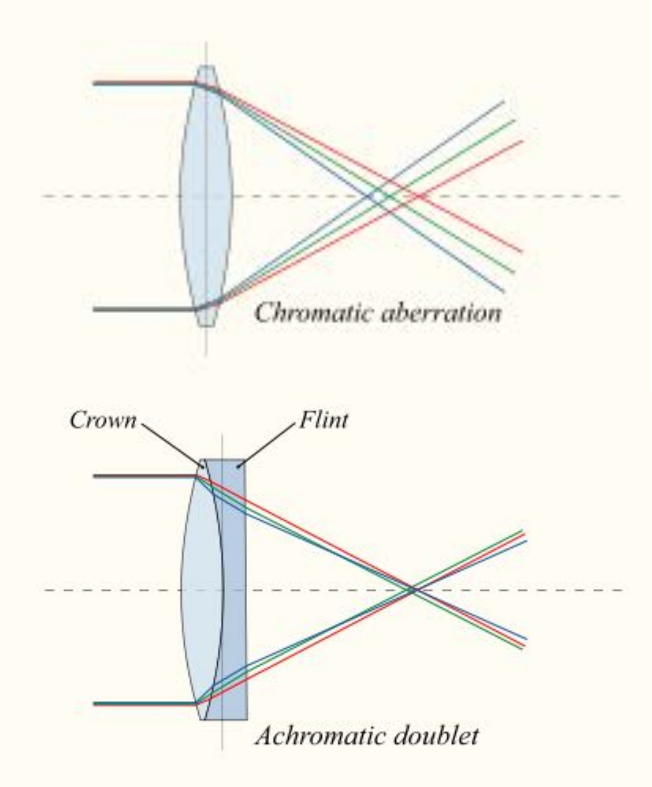


  - Can be corrected with Schmitt plate (aspheric lens)

- **Comatic aberration or coma**
  - A wavefront distortion appears for object points off-axis: comet like spread.



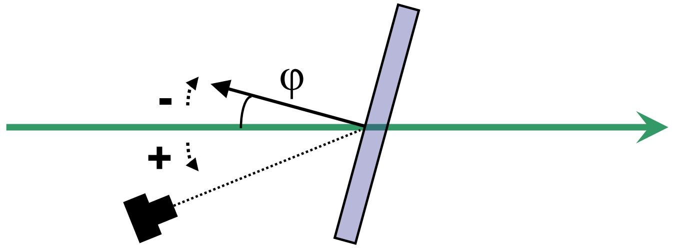
Chromatic aberration: colours refract by different angles due to dispersion. Correct with achromatic doublet.



Screen Resolution: observation geometry

- As we have already seen in Gero's talk this morning, the observation geometry including the tilt of the scintillator and camera wrt the beam axis will strongly influence the ***resolution***:

- experiment: scintillator tilt vs. beam axis

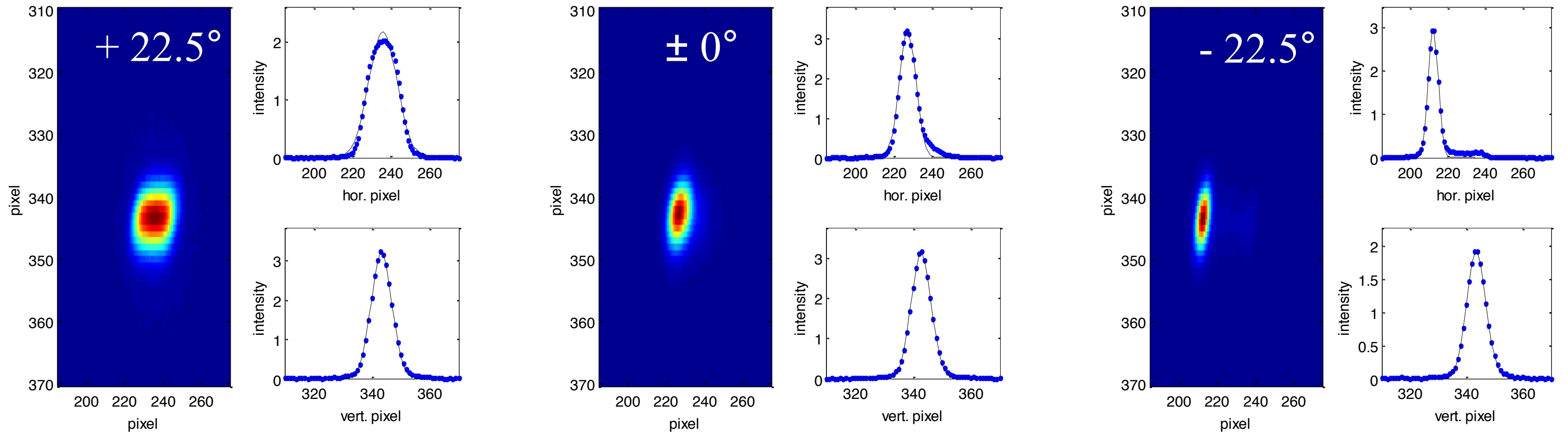


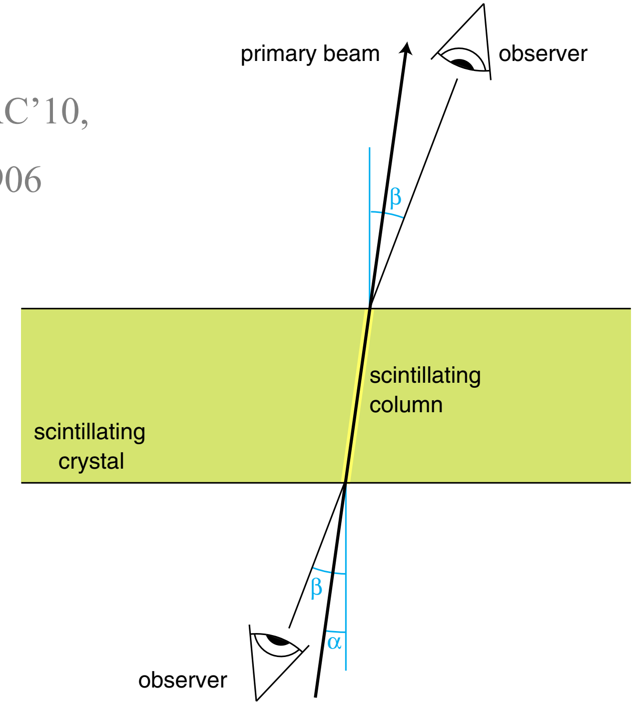
BGO crystal

micro-focused electron beam

I = 3.8 nA

G. Kube et al., Proc. IPAC'10, Kyoto, Japan (2010), p.906





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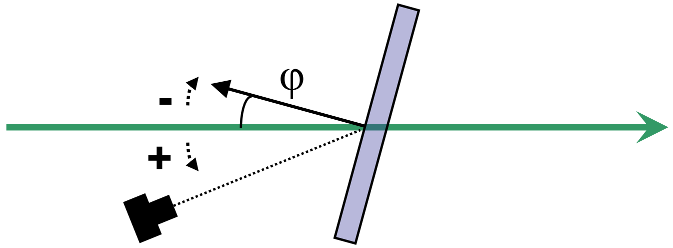

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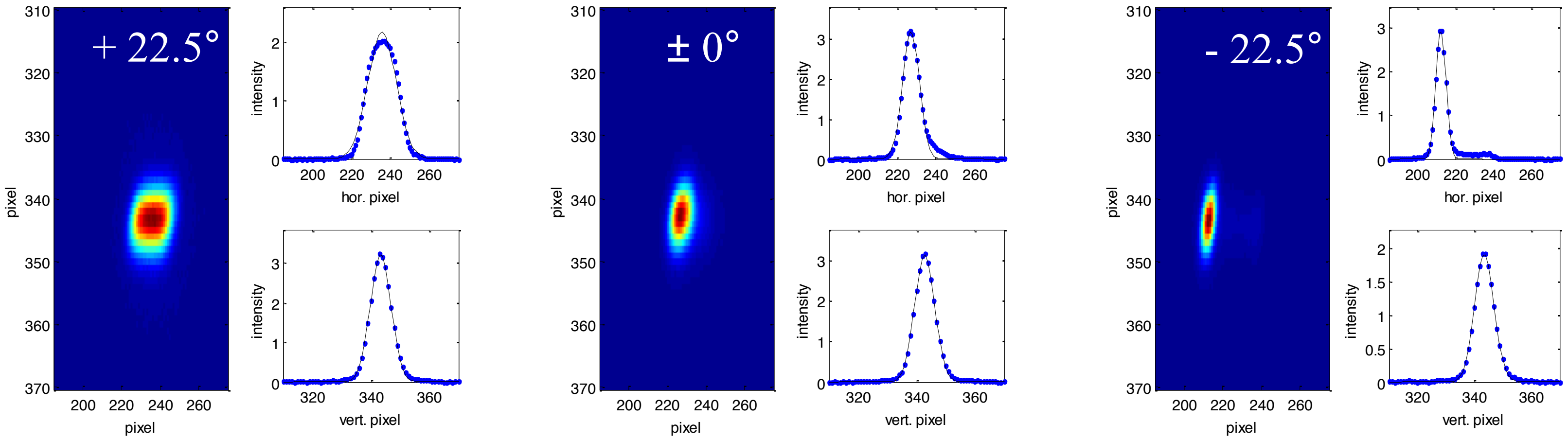
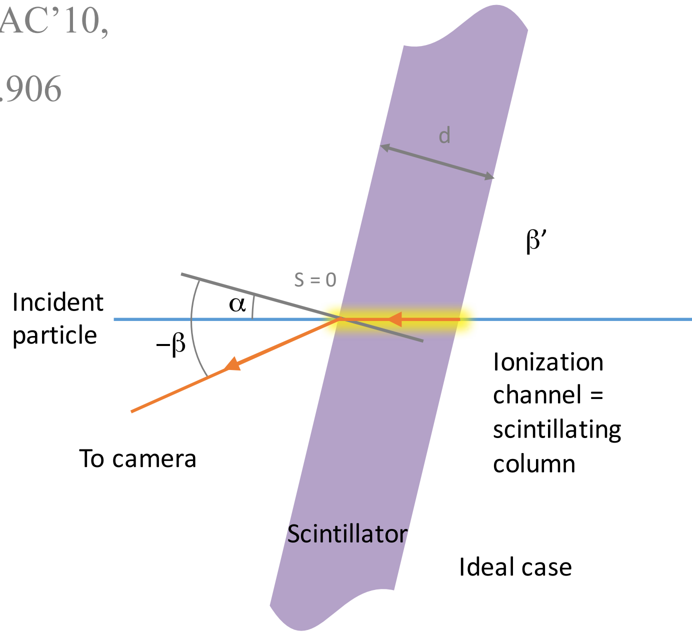




Ideal case:

$$\beta_{\text{ideal}} = -\arcsin(n \sin\alpha)$$

Screen Resolution and PSF

- In addition to observation geometry, the resolution at the image plane will be influenced by diffraction at any restrictive apertures, around bstructions (dust), or aberrations due to lens imperfections or refractive index variations in the optical system.
- An important parameter to determine is the ***Point Spread Function*** (PSF): the optical response of the system to a single point of light at the object plane
- In the case of a bunch profile, this is the passage of one charged particle through the scintillator.
- Knowledge of the PSF can be used to the enhance the image resolution.

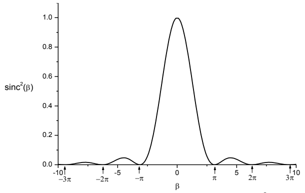
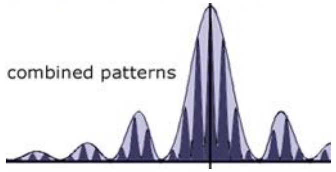
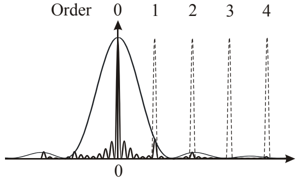
- But first, a quick reminder on diffractive optics and convolution.

General Fraunhofer Diffraction in 1D

- *To calculate the far field diffraction pattern take the **Fourier Transform** of the transmission function of the diffracting aperture:*

$$I(\theta_x) = \left|E_{res}(\theta_x)\right|^2 = \left|\int_S A(x_s)\exp\left[-ikx_s\sin\theta_x\right]dx_s\right|^2$$

Common examples

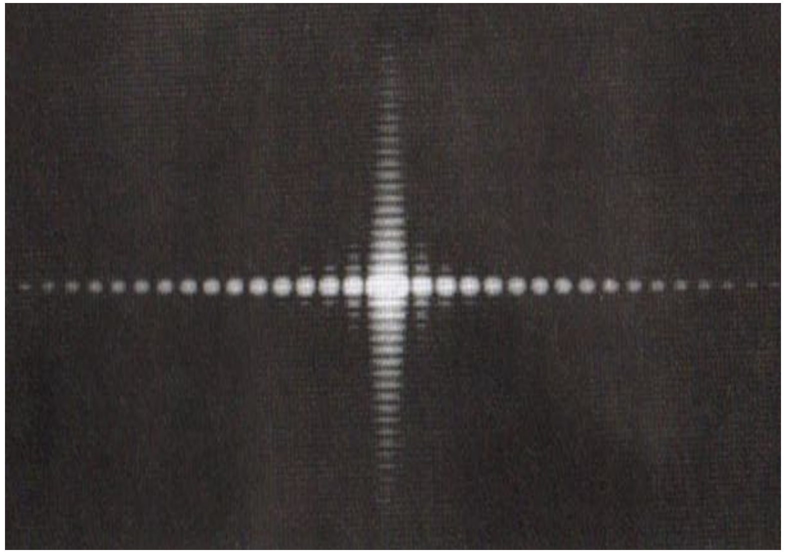
Intensity integral, FT of aperture function	Solution	Definitions
Single slit: $I(\theta_x) = \left|E_{res}(\theta_x)\right|^2 = \left|\int_{-a/2}^{a/2} A_0\exp\left[-ikx_s\sin\theta_x\right]dx_s\right|^2$	$I = A_0^2\dfrac{\sin^2\alpha}{\alpha^2}$ 	$\alpha = \dfrac{\pi}{\lambda}a\sin\theta_x$
Double slit: $I(\theta_x) = \left|\int_{-b/2-a}^{-b/2} A(x_s)\exp\left[-ikx_s\sin\theta_x\right]dx_s + \int_{b/2}^{b/2+a} A(x_s)\exp\left[-ikx_s\sin\theta_x\right]dx_s\right|^2$	$I = A_0^2\dfrac{\sin^2\alpha}{\alpha^2}\cos^2\dfrac{\delta}{2}$ 	$\alpha = \dfrac{\pi}{\lambda}a\sin\theta_x$ and $\delta = \dfrac{2\pi}{\lambda}(a+b)\sin\theta_x$
N-slit grating: $I(\theta_x) = \left|\int_{-a/2}^{a/2} Ae^{-ikx_s\sin\theta_x}dx_s + \int_{d-a/2}^{d+a/2} Ae^{-ikx_s\sin\theta_x}dx_s + \int_{2d-a/2}^{2d+a/2} Ae^{-ikx_s\sin\theta_x}dx_s + \ldots + \int_{(N-1)d-a/2}^{(N-1)d+a/2} Ae^{-ikx_s\sin\theta_x}dx_s\right|^2$	$I = A_0^2\dfrac{\sin^2\alpha}{\alpha^2}\dfrac{\sin^2 N\beta}{\sin^2\beta}$ 	$\alpha = \dfrac{\pi}{\lambda}a\sin\theta$ *and* $\beta = \dfrac{\delta}{2} = \dfrac{\pi}{\lambda}d\sin\theta$

Diffraction in 2D

- *Rectangular slit:*

$$I(\theta_x) = \left| \int_{-a/2}^{a/2} \int_{-b/2}^{b/2} A(x_s) \exp[-ikx_s \sin\theta_x] \exp[-iky_s \sin\theta_y] dx_s\, dy_s \right|^2$$

$$I = A_0^2 \frac{\sin^2 \alpha}{\alpha^2} \frac{\sin^2 \beta}{\beta^2}, \quad \text{where } \alpha = \frac{\pi}{\lambda} a \sin\theta_x \text{ and } \beta = \frac{\pi}{\lambda} b \sin\theta_y$$

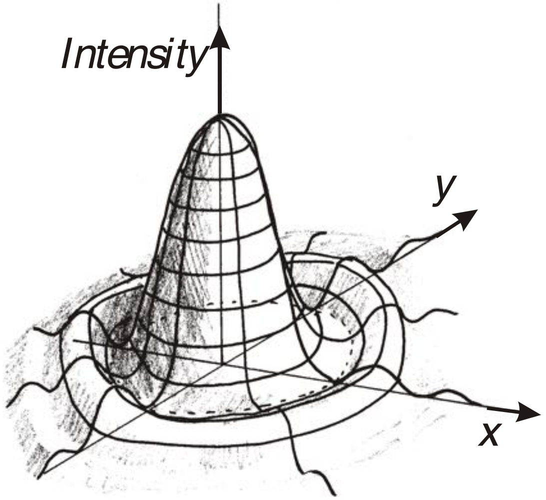


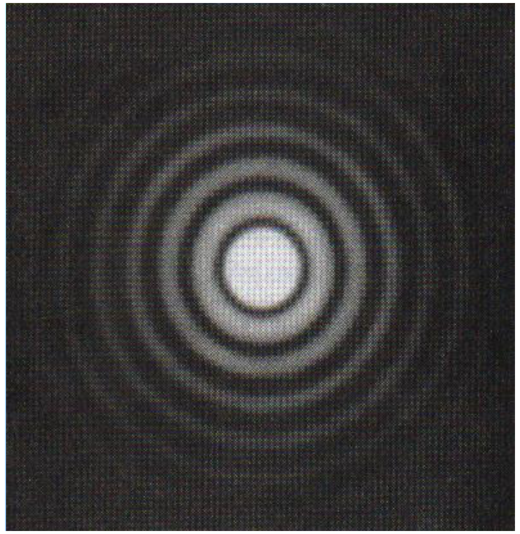
- *Circular aperture:*

$$E_{res}(\rho_d, \theta_d) = \int_0^{\bar{\rho}} \int_0^{2\pi} A(x_s) \rho_s \exp\left[-\frac{ik}{L} \rho_s \cdot \rho_d \cdot \cos(\theta_s - \theta_d) \right] d\rho_s\, d\theta_s$$

$$E_{res} = A_0^2 \frac{J_1^2(\alpha)}{\alpha^2}, \text{ where } \alpha = \frac{ka\rho_d}{L}$$

$$\theta = \frac{1.22 \cdot \lambda}{\rho_d}$$



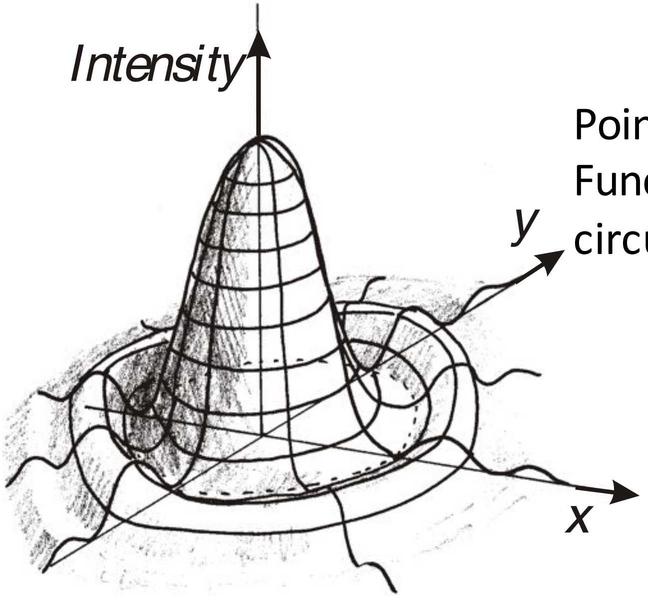


e.g. Telescope resolving power from PSF:

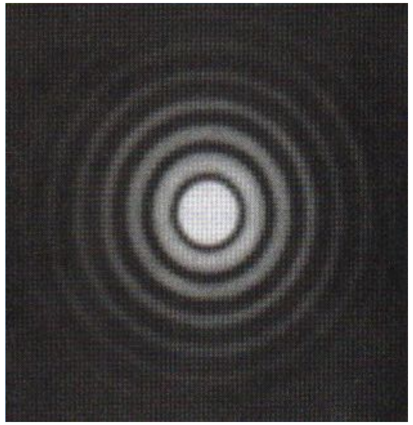
- *In general the resolution is defined by the diffraction pattern which is the Point Spread Function*
  - *the response of an imaging system to a point source*

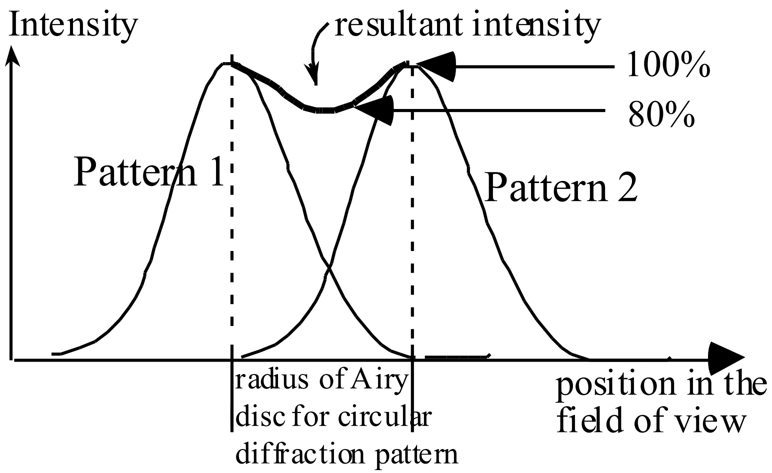
$$E_{res} = A_0^2 \frac{J_1^2(\alpha)}{\alpha^2}, \text{ where } \alpha = \frac{ka\rho_d}{L}$$

$$\theta = \frac{1.22 \cdot \lambda}{\rho_d}$$



Point Spread Function of a circular aperture





- *When considering diffraction patterns or the diffraction limited case (e.g. viewing through a telescope) we use the **Rayleigh Criterion:***
- *The **Rayleigh Criterion** states that two diffraction patterns with equal intensities may be said to be resolved when the central maximum of one pattern is not nearer than the position of the centre of the first minimum of the neighbouring pattern.*

$$\sin\theta_R = \frac{\lambda}{a}$$

Single slit

$$\sin\theta_R = 1.22\frac{\lambda}{a}$$

Circular aperture

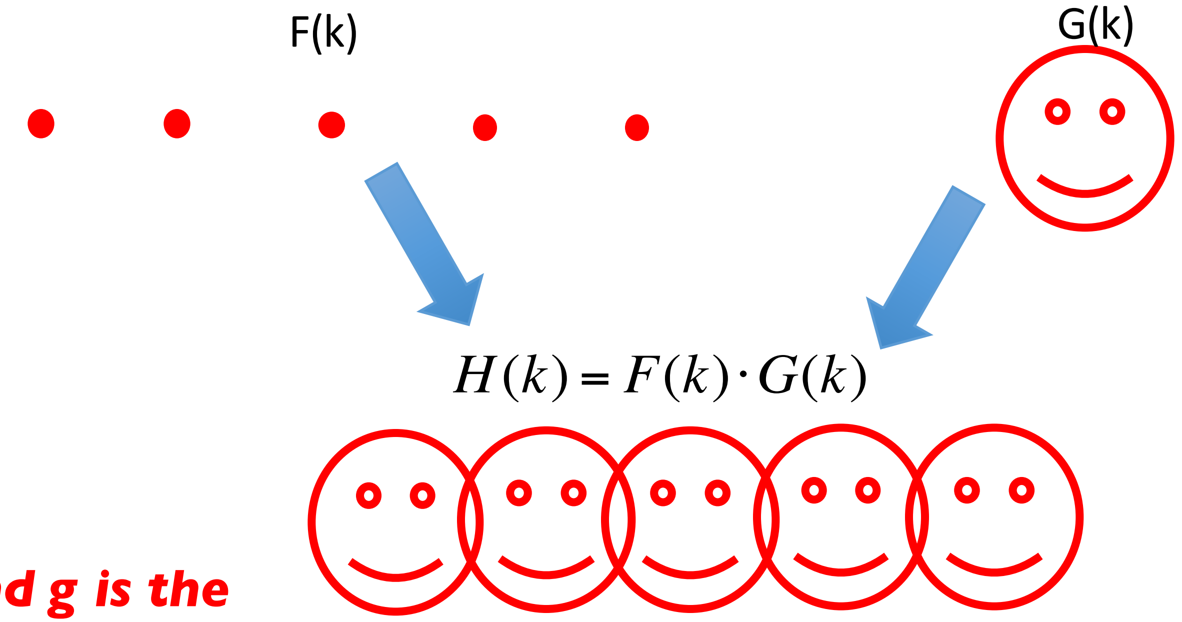
Convolution visualized

- *The convolution function:*

$$h(x) = f(x) \otimes g(x) = \int_{-\infty}^{\infty} f(x')g(x'-x)\,dx'$$

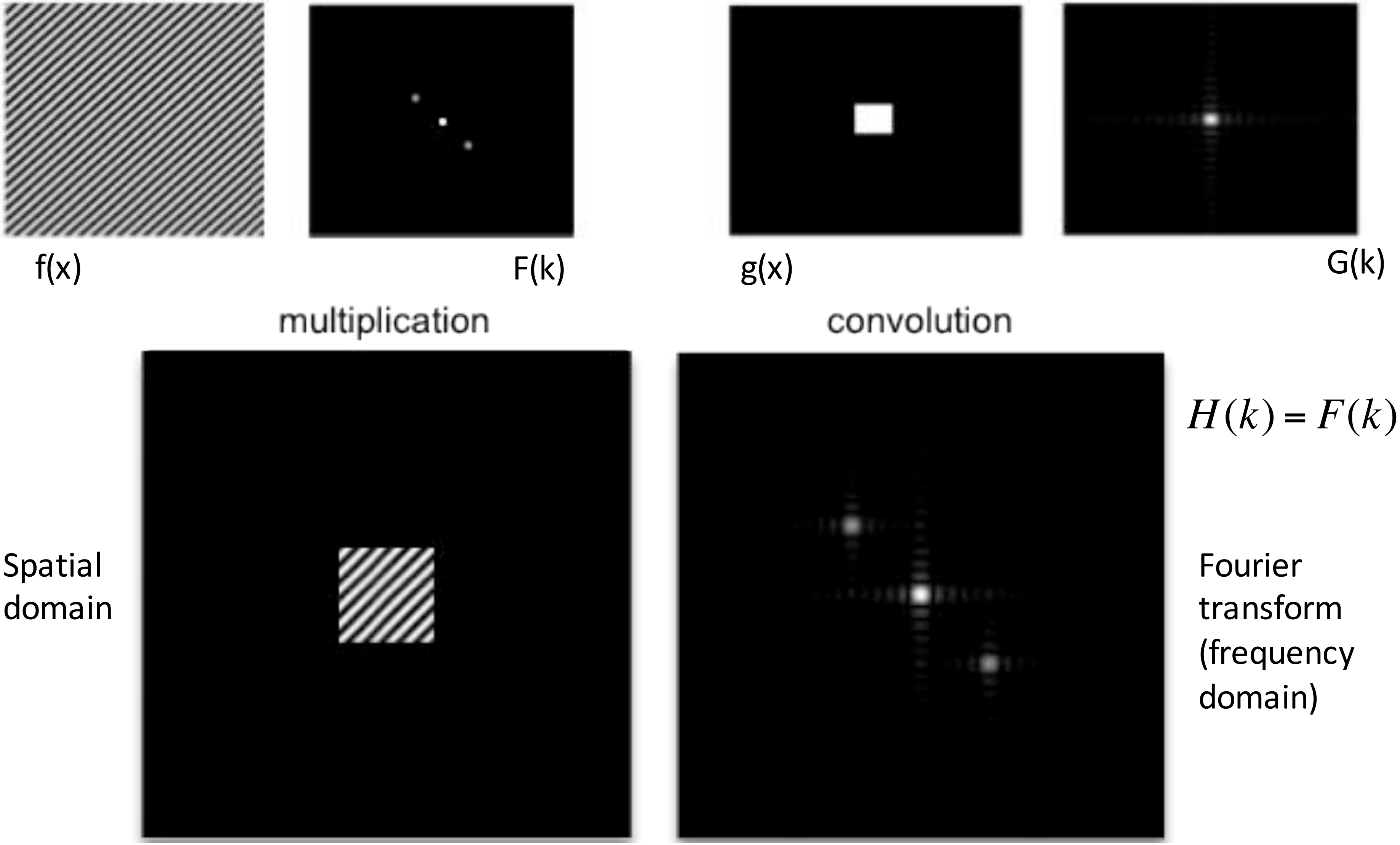
- *The convolution theorem:*
  - F(k) is the Fourier Transform of f(x)
  - G(k) is the Fourier Transform of g(x)
  - H(k) is the Fourier Transform of h(x)
  - Then:

$$H(k) = F(k) \cdot G(k)$$



  - ***The Fourier transform of a convolution of f and g is the product of the Fourier transforms of f and g***

Convolution theorem



$$H(k) = F(k) \cdot G(k)$$

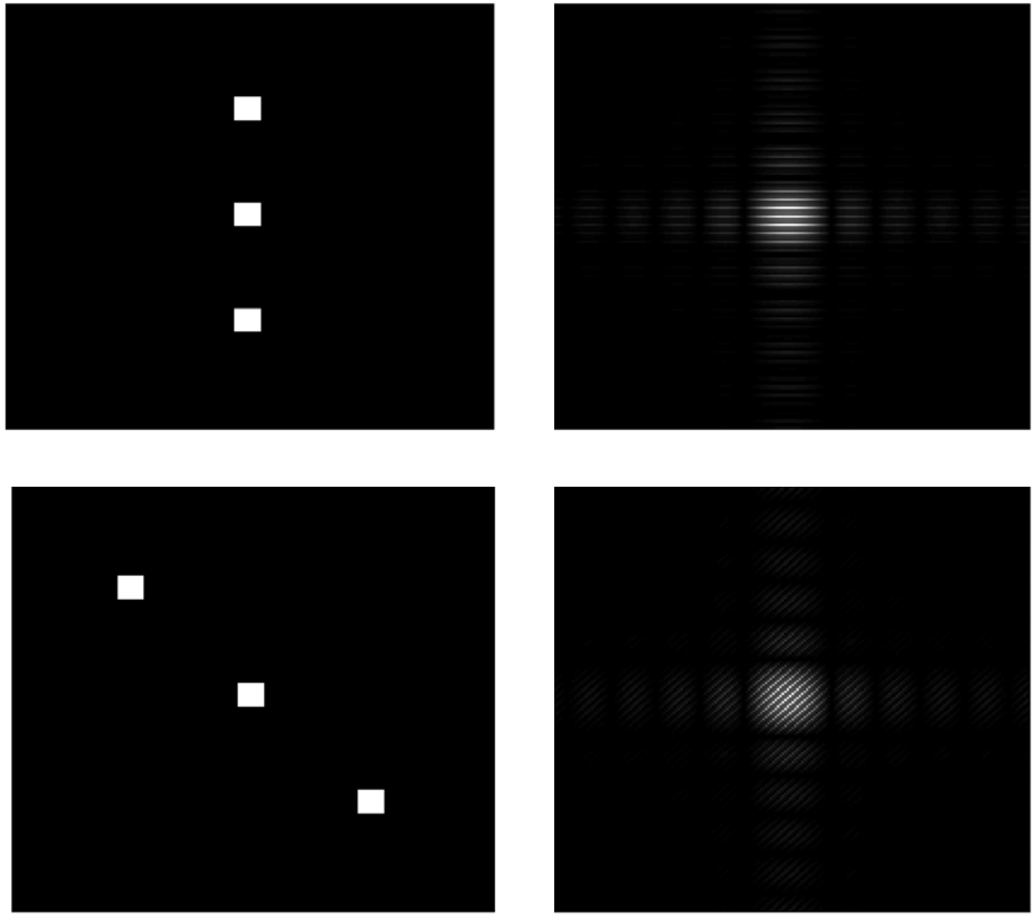
Spatial domain

Fourier transform (frequency domain)

Shift theorem in Fourier transform domain

- The PSF is independent of position in the image plane (shift theorem)

Spatial domain

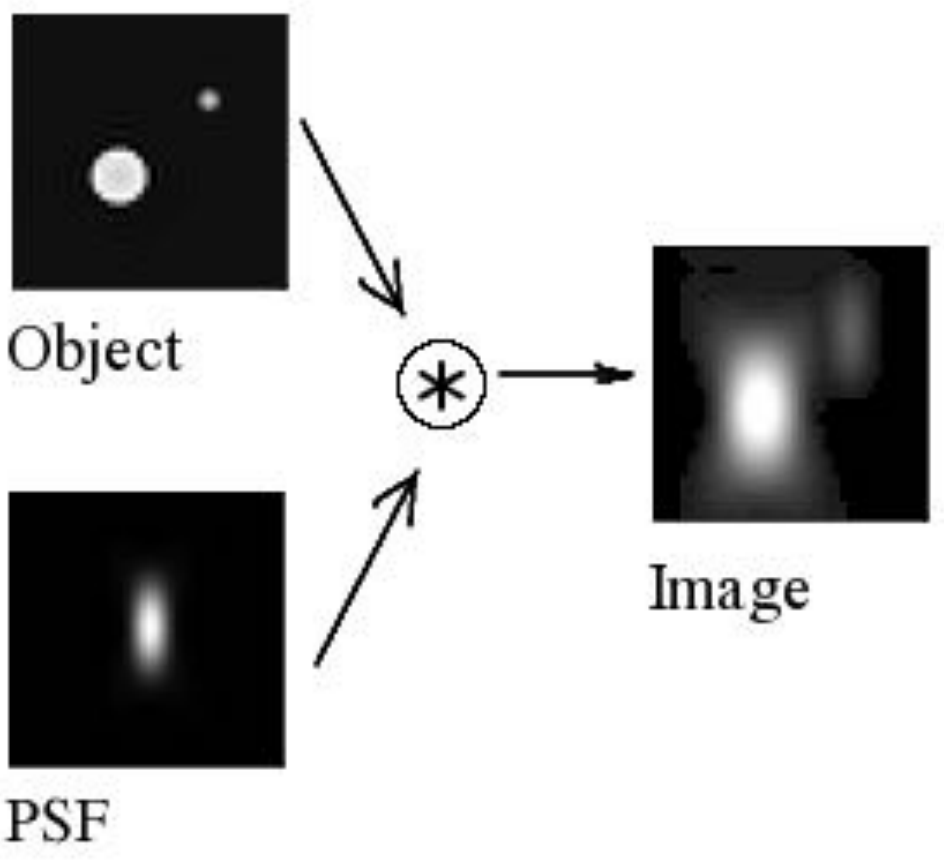


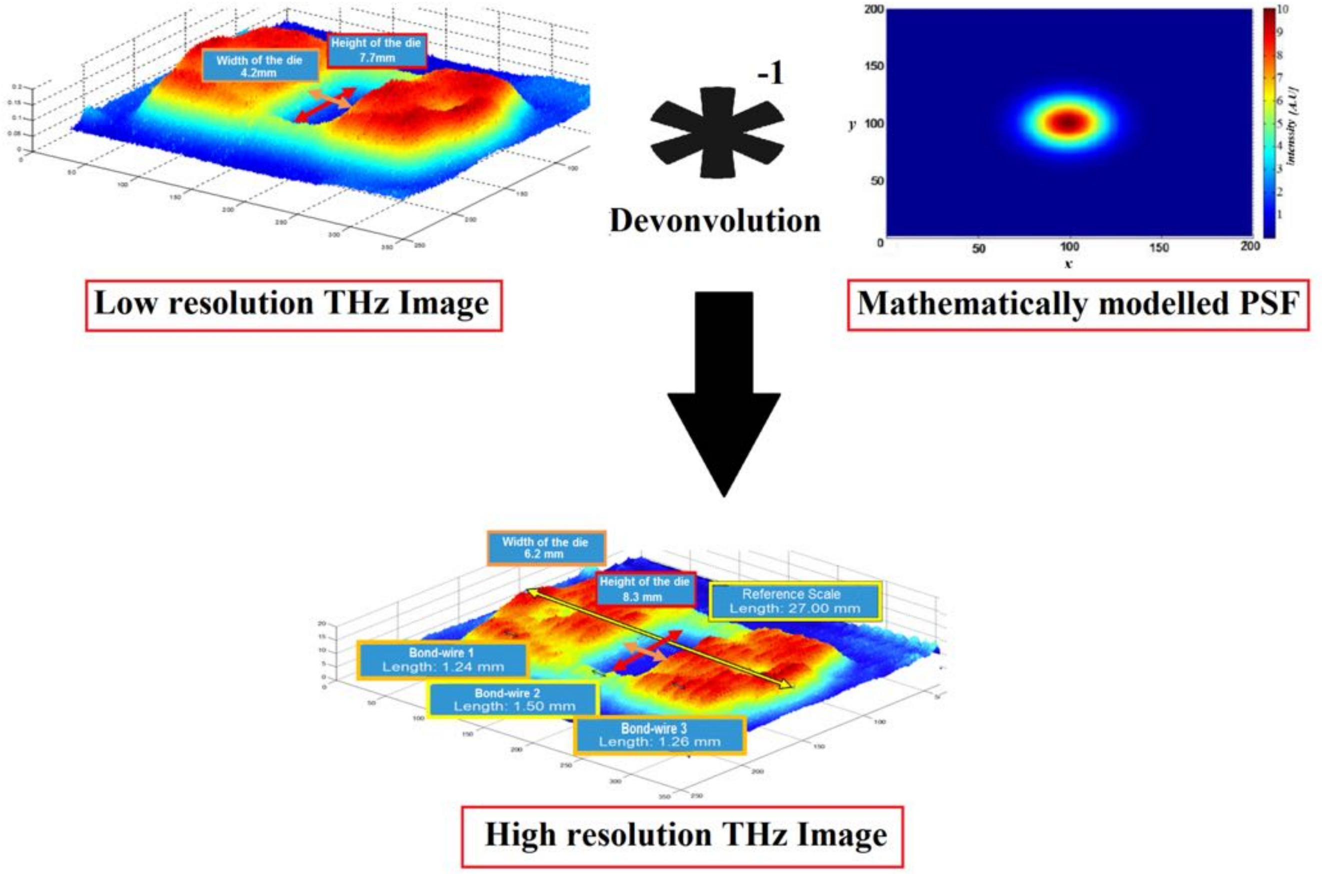
Fourier transform (frequency domain)

$$\mathcal{F}\left\{g\left(x-a,y-b\right)\right\}=\exp\left\{2\pi\left(au+bv\right)\right\}G(u,v)$$

Deconvolution of the PSF

- The PSF is independent of position in the image plane (shift theorem), so a deconvolution can be applied to enhance the resolution of the image.





Deconvolution of PSF in medical imaging

- X-ray scintillator exhibits scattering which is modelled, then used to deconvolute a chest X-ray:

$I * PSF = B$, $I = B * PSF^{-1}$

I = clear image, B = blurred image, PSF = point spread function, PSF^{-1} = inverse PSF, * = convolution

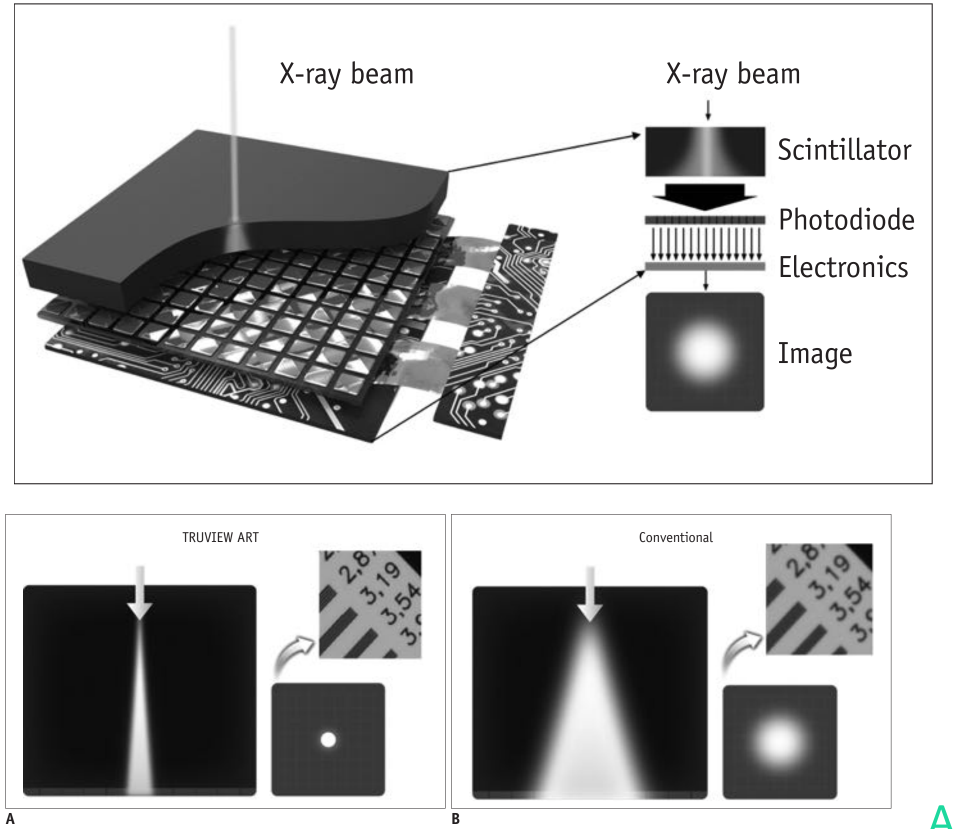


Fig. 2. Reconstructed image with and without TRUVIEW ART (DRTECH Corp.).
A. By elimination of scattering effects applying TRUVIEW ART, blurred image can be seen more clearly. **B.** Without TRUVIEW ART, light scattering occurs by light spread of conventional scintillator, and image looks blurred.

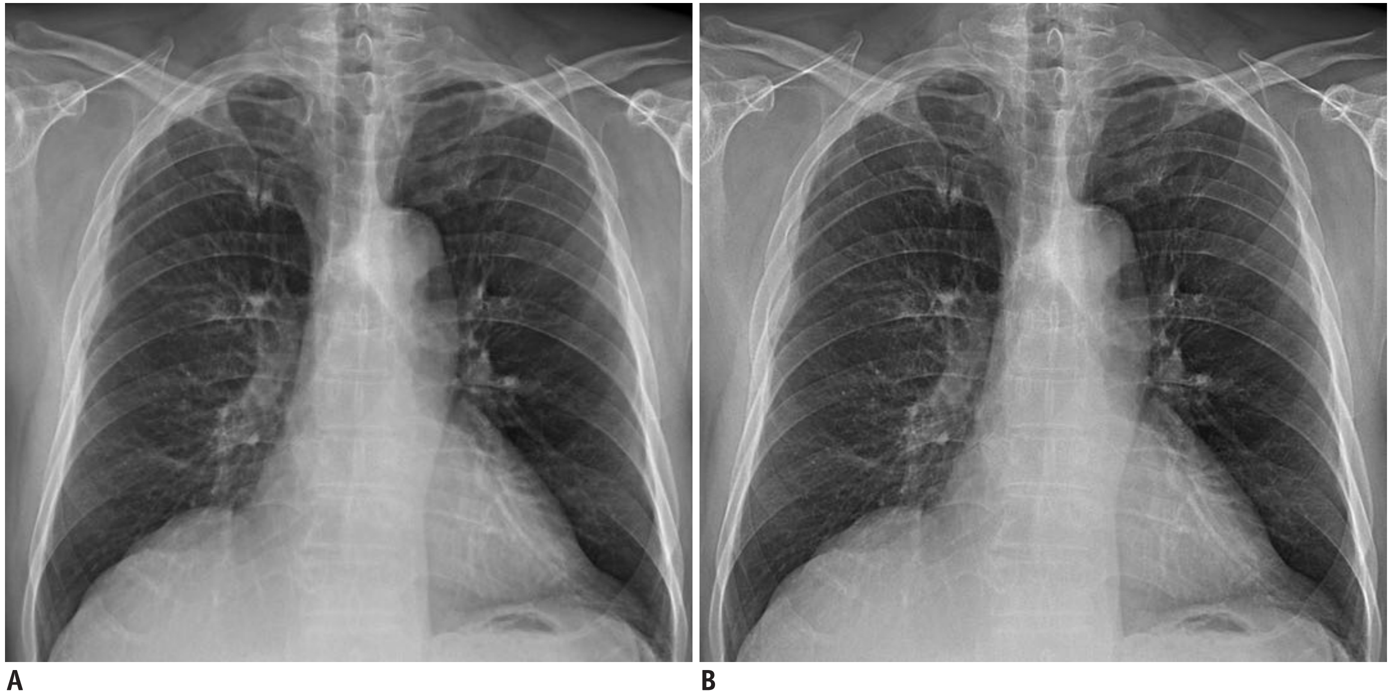


Fig. 3. 75-year-old man with coronary artery disease.
Compared with original chest radiography **(A)**, TRUVEIW ART applied chest radiography **(B)** shows better depiction in overall image quality.

Application of Deconvolution Algorithm of Point Spread Function in Improving Image Quality: An Observer Preference Study on Chest Radiography

Kum Ju Chae, MD[1,2], Jin Mo Goo, MD, PhD[1,3], Su Yeon Ahn, MD[1], Jin Young Yoo, MD[1], Soon Ho Yoon, MD[1,3]

Korean J Radiol 2018;19(1):147-152

PSF for pin-hole measurements of synchrotron light

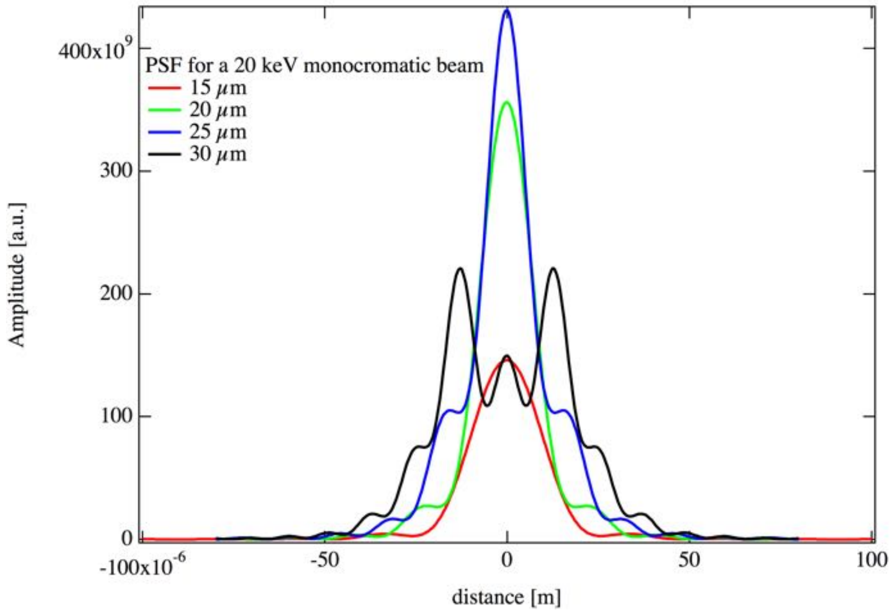
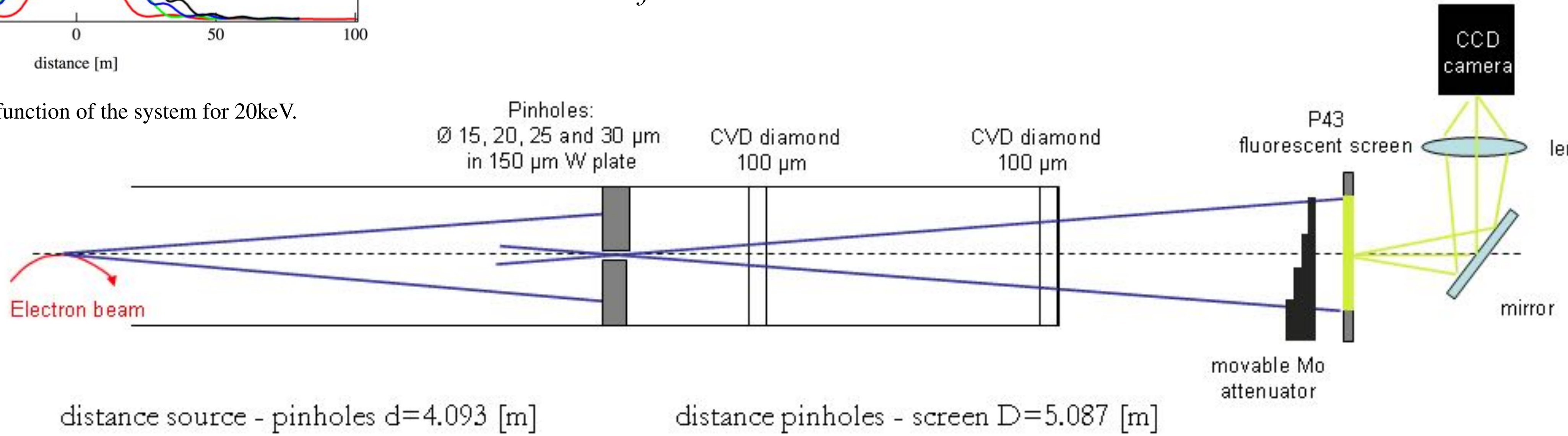


Figure 6: Point spread function of the system for 20keV.

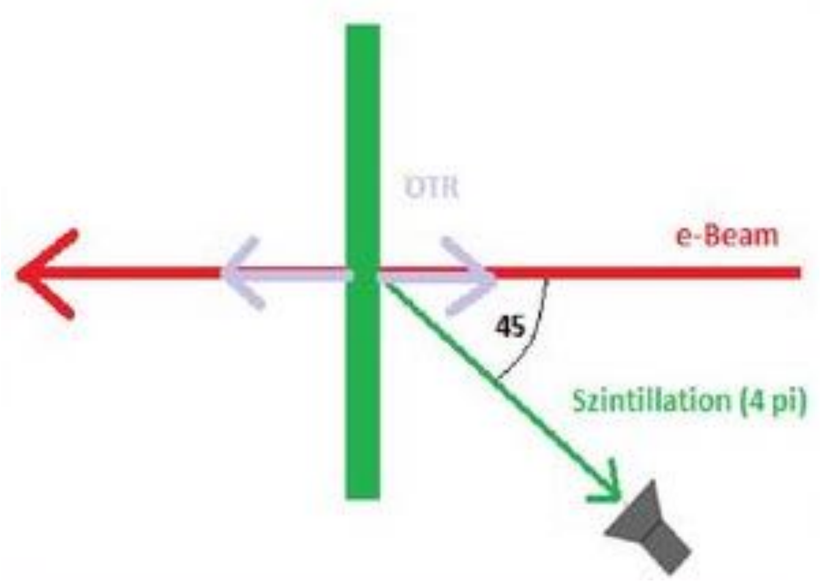
- PSF is dominated by diffraction at the pin-hole and Frensel pattern depends strongly on the pin-hole size, 15 -30 μm. [Swiss Lightsource, PSI]

Natalia Milas, Angela Saa Hernandez, *Calculation of the Point Spread Function for the X09DA Pinholes in SLS.*

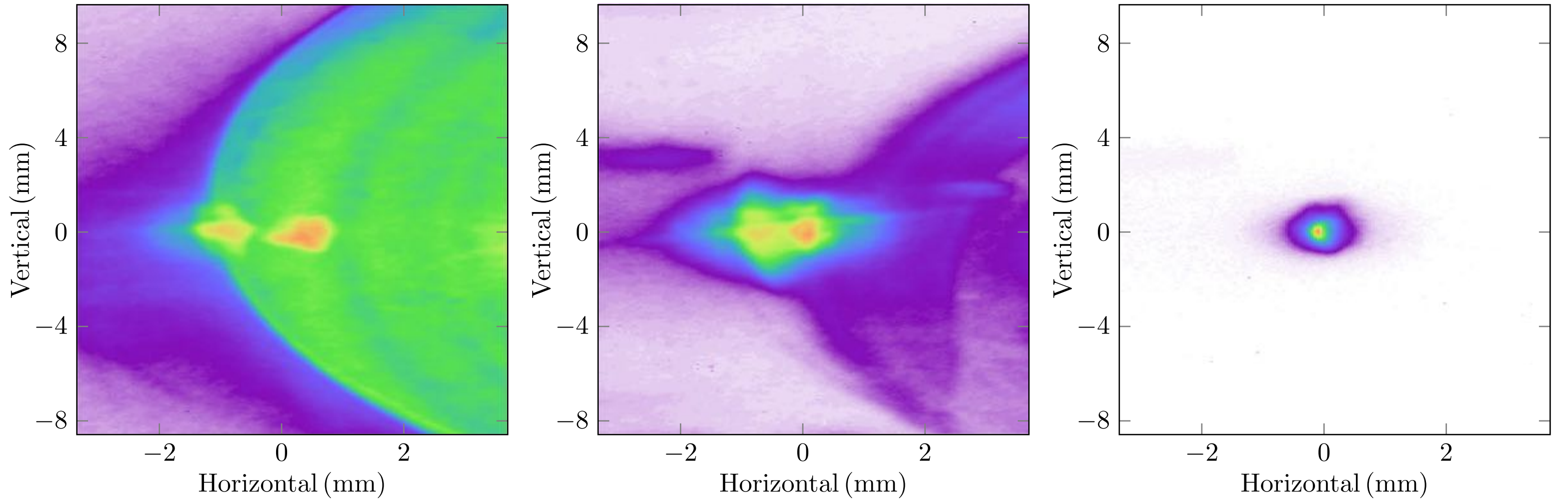


Background suppression:

- OTR can be a source of background in scintillation light
- OTR background can be suppressed by changing the viewing geometry, so it is not reflected toward the camera:



- Or a gated camera can be used to distinguish the fast OTR from the delayed scintillation light.
- ICCD (a) and scintillation without (b) and with (c) delay:



(a) OTR screen, no time delay. (b) LuAG screen, no time delay. (c) LuAG screen, time delay.

Electron beam profile imaging in the presence of coherent optical radiation effects

Christopher Behrens,[1,*] Christopher Gerth,[1] Gero Kube,[1] Bernhard Schmidt,[1] Stephan Wesch,[1] and Minjie Yan[1,2]

Phys. Rev. ST Accel. Beams **15,** 062801 (2012)

Summary

- The observed distribution at the camera is a convoluted measure of the particle distribution:
  - The optical system must be calibrated and/or understood to map between the particle coordinate at the scintillator screen and the detector plane.
- Various optical technologies can help to improve image quality:
  - Scheimpflug geometry to obtain sharp focus over complete object plane.
  - Bi-telecentric lens to eliminate dependence of magnification on object (and image) distance, hence reducing image distortion.
  - Aberrations may be corrected by careful optical design in Zemax or similar software, e.g. by using achromatic, or catadioptirc components.
- Resolution depends on the observation geometry, screen tilt and viewing angle.
- Measurement and/or calculation of the PSF allows a deconvolution of the image to enhance the resolution.

Thanks to Beate, Isabel and Peter for the excellent organization!