Performance of a Reflective Microscope Objective and Thin Scintillator in an X-ray Pinhole Camera

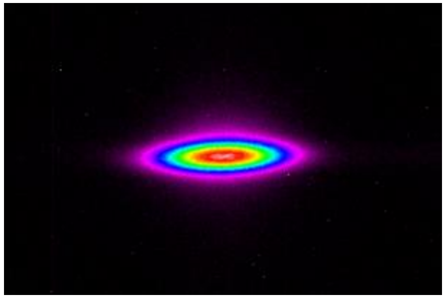
L. Bobb

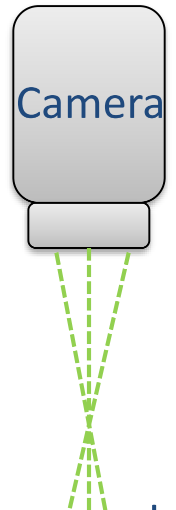
X-ray Pinhole Camera

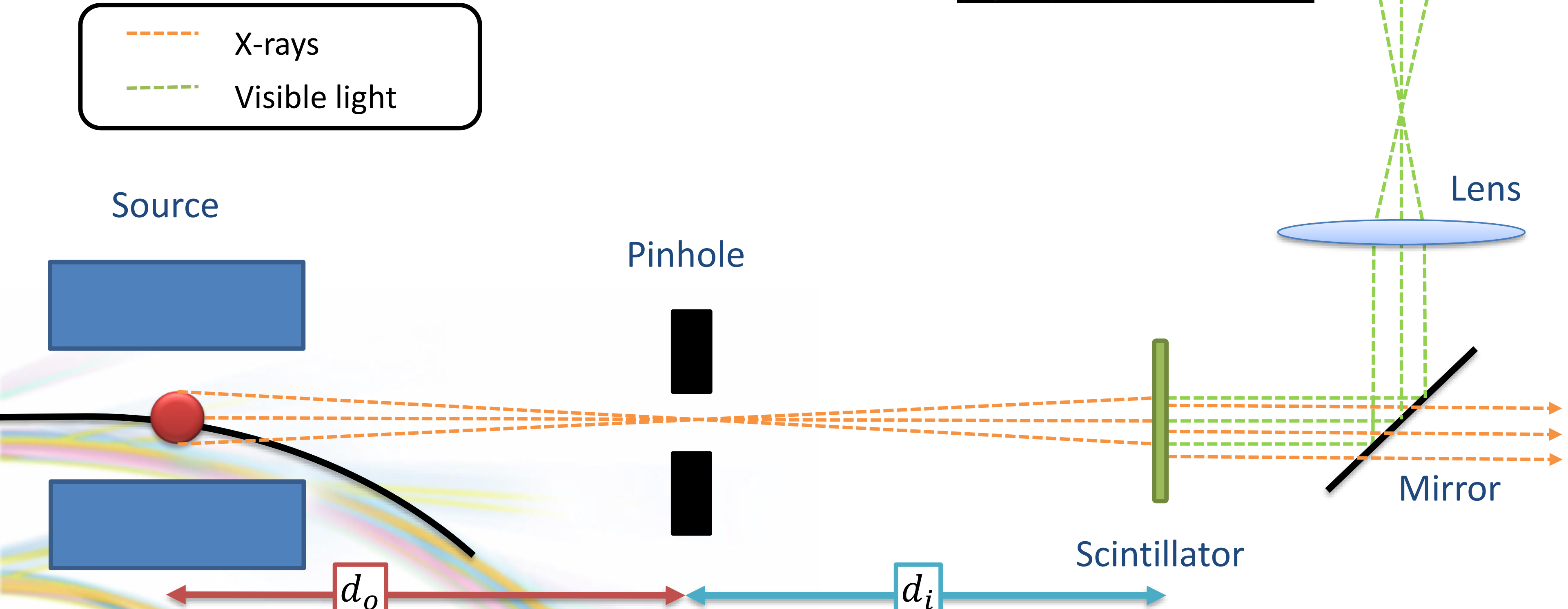
Transverse profile of the electron beam is measured using an X-ray Pinhole Camera

$$\text{Source–to–scintillator magnification } |M_1| = \left|-\frac{d_i}{d_o}\right|$$

$$\text{Scintillator–to–camera magnification } |M_2| \sim 1$$







Point Spread Function

Measured beam size is a convolution of the true beam size and the PSF (Gaussian approx.):

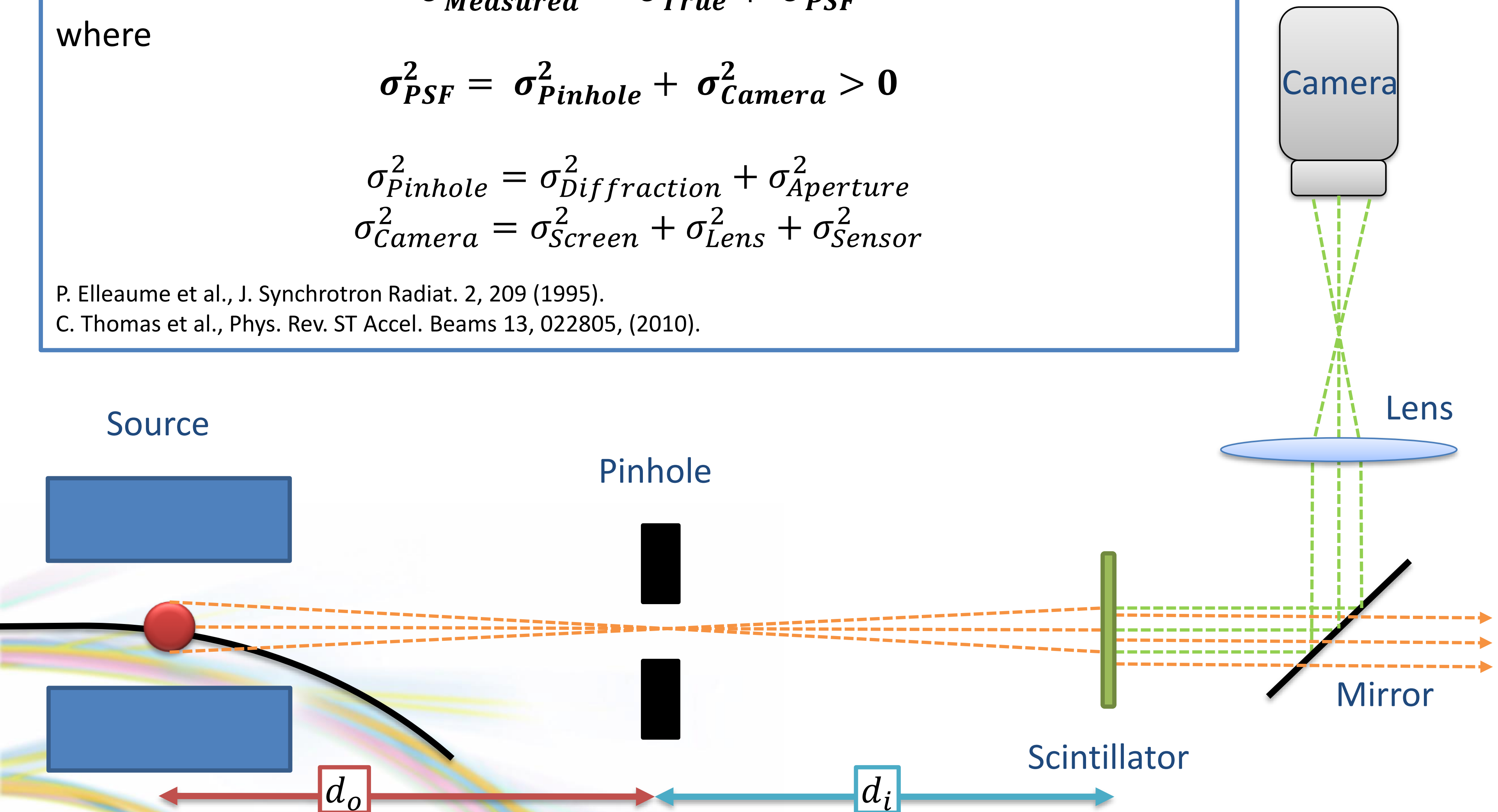
$$\boldsymbol{\sigma^2_{Measured} = \sigma^2_{True} + \sigma^2_{PSF}}$$

where

$$\boldsymbol{\sigma^2_{PSF} = \sigma^2_{Pinhole} + \sigma^2_{Camera} > 0}$$

$$\sigma^2_{Pinhole} = \sigma^2_{Diffraction} + \sigma^2_{Aperture}$$
$$\sigma^2_{Camera} = \sigma^2_{Screen} + \sigma^2_{Lens} + \sigma^2_{Sensor}$$

P. Elleaume et al., J. Synchrotron Radiat. 2, 209 (1995).
C. Thomas et al., Phys. Rev. ST Accel. Beams 13, 022805, (2010).



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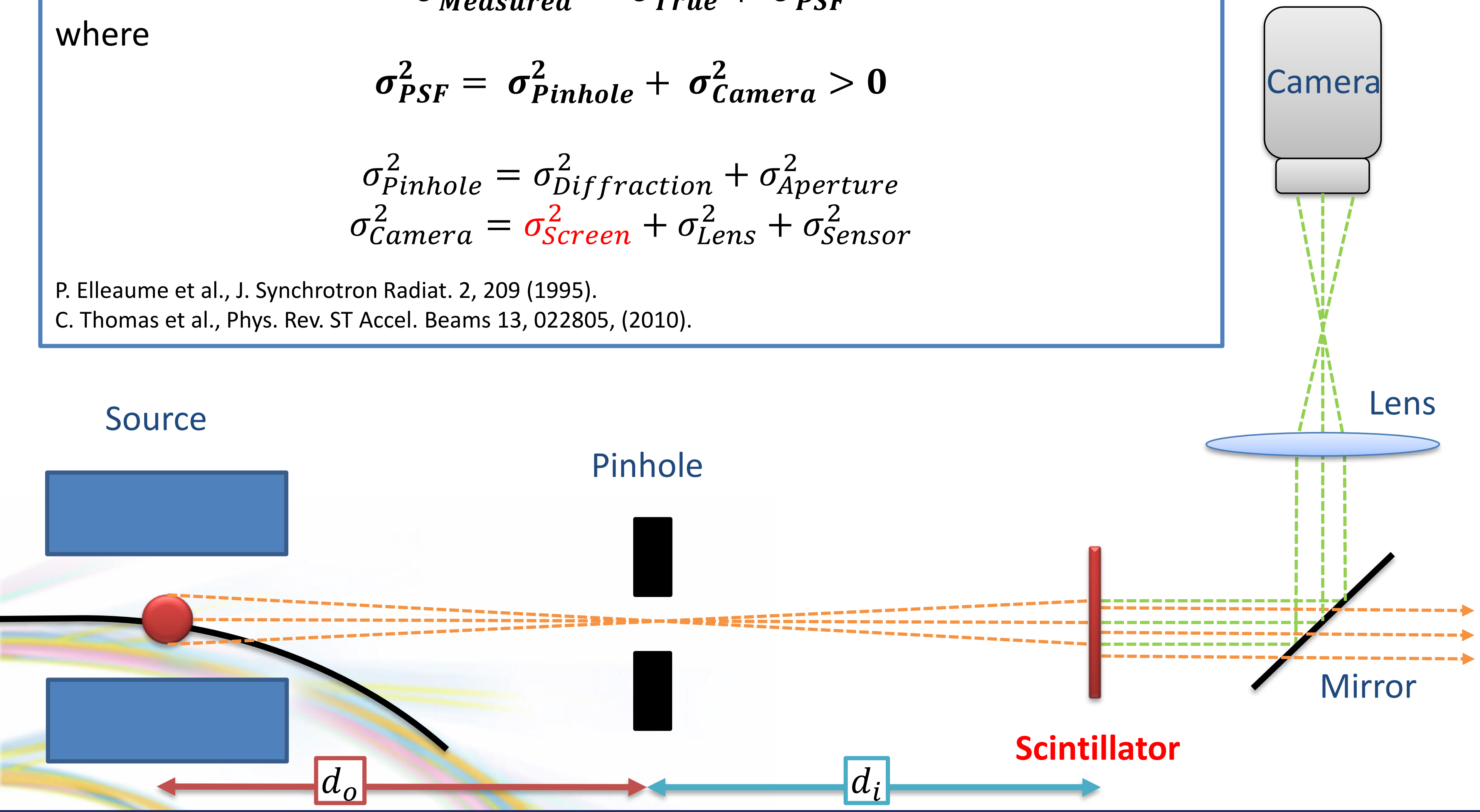


Reducing Scintillator Contribution to PSF

Spatial resolution is improved by reducing the scintillator thickness.

G. Kube et al., Proc. IBIC2015, Melbourne, Australia, p.330

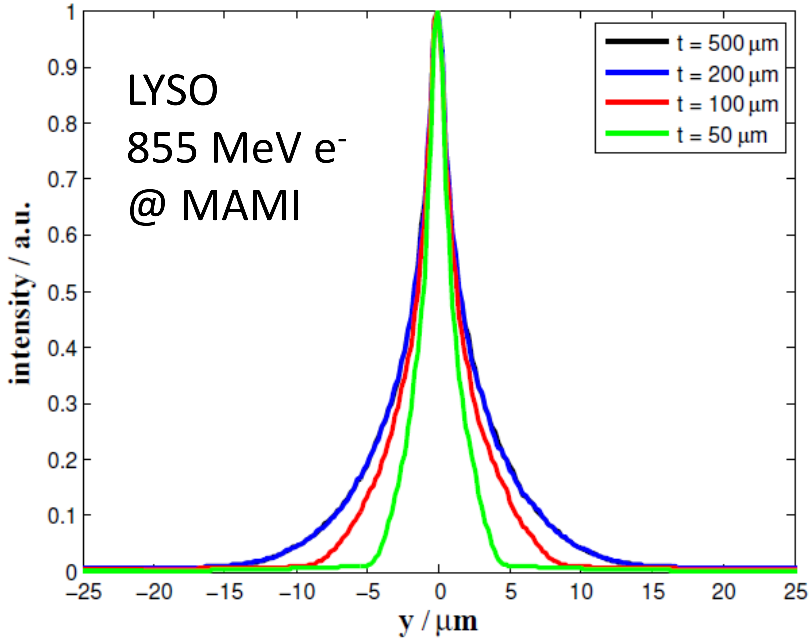


Figure 8: Simulated SPFs for different scintillator thicknesses. The simulations were performed for NA = 0.20 and $\lambda = 420$ nm.

SPF = Single Particle Resolution Function

$$\text{Contrast} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

P.-A Douissard et al., 2012 JINST 7 P09016

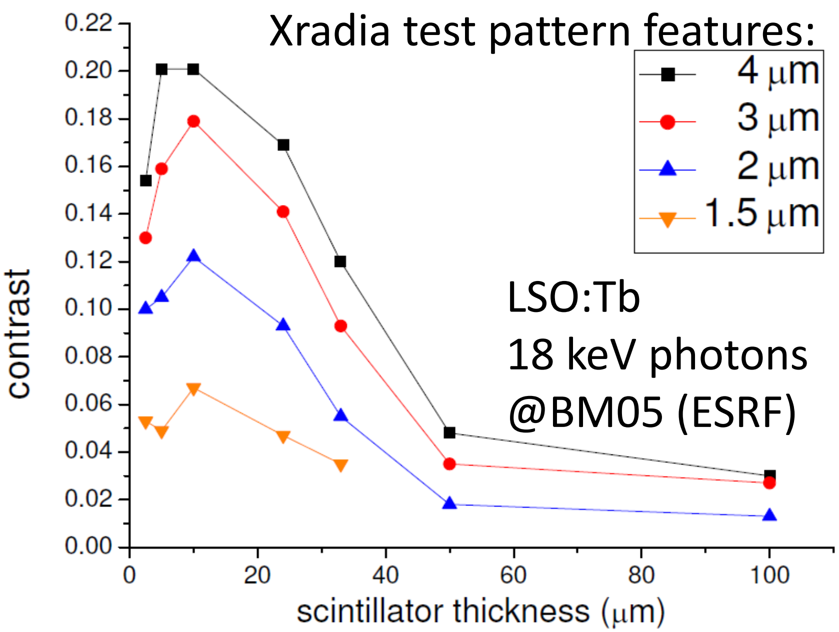


Figure 6. Influence of the thickness of the single crystal scintillator film on the contrast achievable in the image with a 10× (NA = 0.4) microscope objective (18 keV photon energy, different graphs represent results obtained by using differently sized features in the Xradia test pattern).

Dependence of Photon Yield

Spatial resolution is improved by reducing the scintillator thickness. However, a thin scintillator will emit fewer photons.

$$I = I_o e^{-t/\mu}$$

I_o = incoming intensity, I=outgoing intensity, μ= attenuation length, t=thickness

M. Ishii and M. Kobayashi, Prog. Crystal Growth and Charact. 1991, 23, 245-311

Table 1

M. Rutherford et al., J. Synchrotron Rad. (2016). 23, 685-693

Scintillator materials for hard X-ray detection on the sub-µs timescale.

Crystal	Density (g cm^{-3})	Emission maximum (nm)	Attenuation length (25 keV, 50 keV) (µm)	Light yield (photons MeV^{-1})	Dominant decay time (ns)
$Cs_2NaYBr_3I_3$:Ce	4.0	425	125, 252	43000	43
$Cs_2NaLaBr_3I_3$:Ce	4.0	438	138, 229	58000	68
$Cs_2LiLaBrCl$:Ce	4.1	419	143, 215	50000	55
K_2LaI_5:Ce	4.4	450	166, 195	52000	24
YAG:Ce†	4.6	550	122, 791	24000	96
YI_3:Ce	4.6	532	117, 176	99000	34
$Gd_3Al_2Ga_3O_{12}$:Ce	4.7	550	124, 869	55000	60
$RdGd_2Br_7$:5%Ce	4.7	430	77, 508	42000	45
GdI_3:5%Ce	5.2	552	114, 195	83000	33
LuI_3:Ce	5.6	540	91, 176	115000	33
$Lu_3Al_5O_{12}$:Ce†	6.7	525	66, 405	27000	61
$(LuY)Si_2O_5$:Ce†	7.1	420	75, 461	34000	41
$SrHfO_3$:Ce	7.6	410	45, 284	40000	42
$BaHfO_3$:Ce	8.5	400	52, 148	40000	25

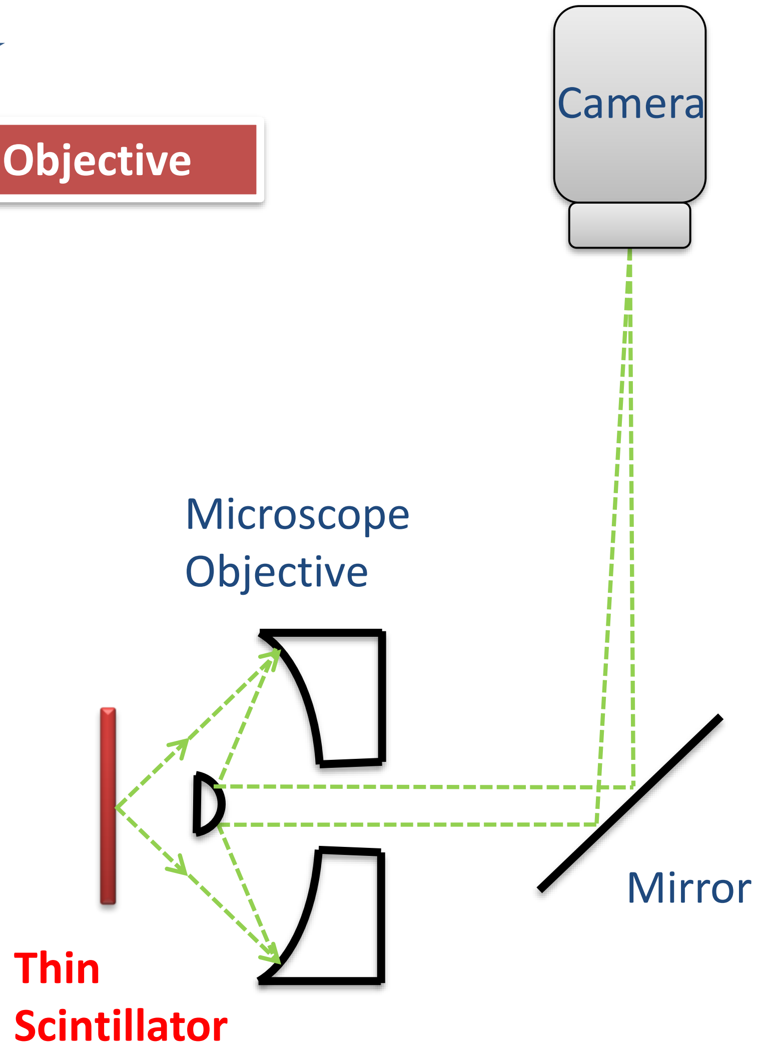
Microscope Objective

Therefore, the optical system must have a large numerical aperture (NA) to capture as many photons as possible from the thin scintillator.

Reflective Microscope Objective

- To **avoid browning from X-ray** exposure a reflective objective is used.
- For optimal spatial resolution, the **scintillator thickness must be matched to the NA** of the microscope objective.
- Not a novel idea! Commercially available ~£30k predominantly for beamlines. **It's now possible to build in-house at a fraction of the cost** since reflective objectives are available from Thorlabs and Newport.

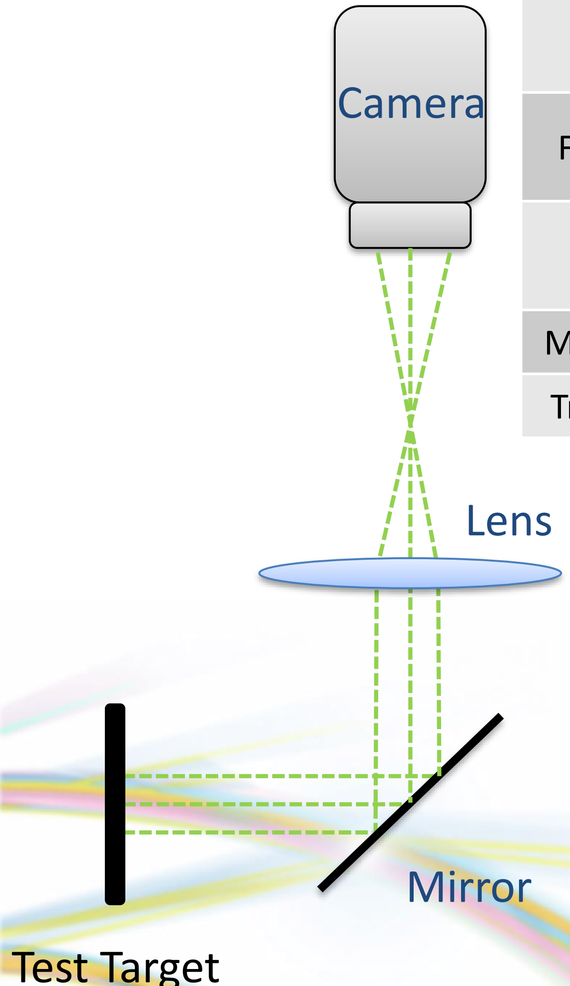
A. Koch et al., J. Opt. Soc. Am., (15) 7, 1998



Lens Comparison in Lab

Refractive

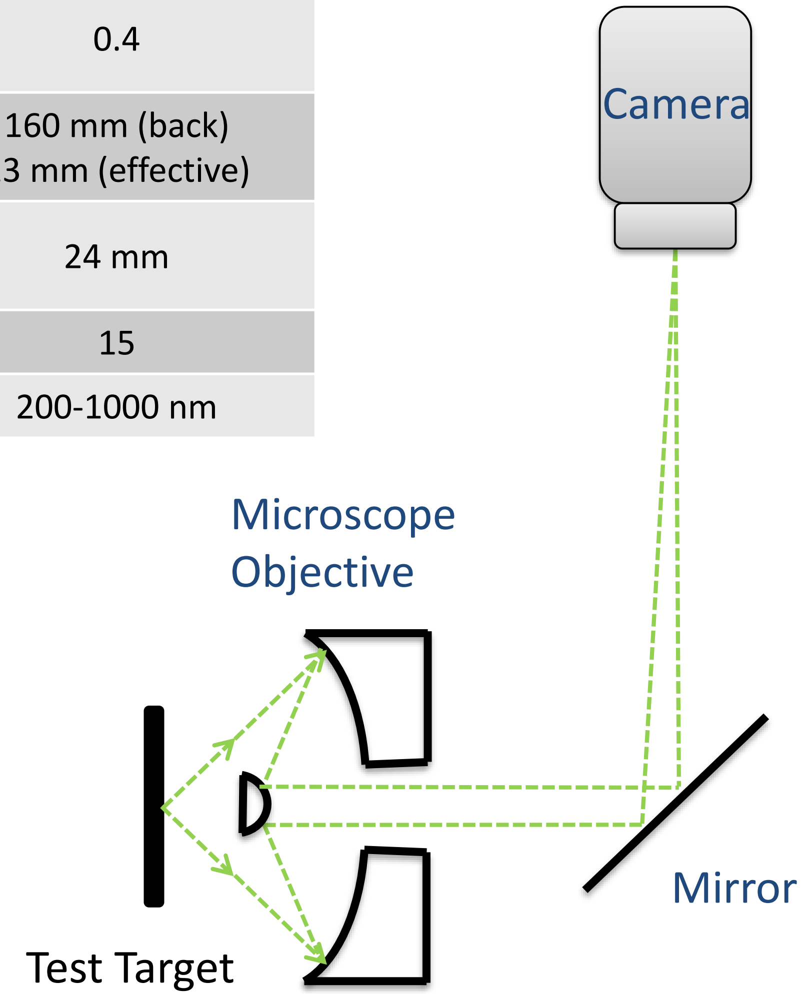
For thick (200µm) scintillator



	REFRACTIVE LENS	REFLECTIVE MICROSCOPE OBJECTIVE
F-number	2.8 to 8	1.25*
Numerical Aperture	0.18 to 0.06*	0.4
Focal length	50.2 mm	160 mm (back) 13 mm (effective)
Working distance	-	24 mm
Magnification	1	15
Transmission	400-700 nm	200-1000 nm

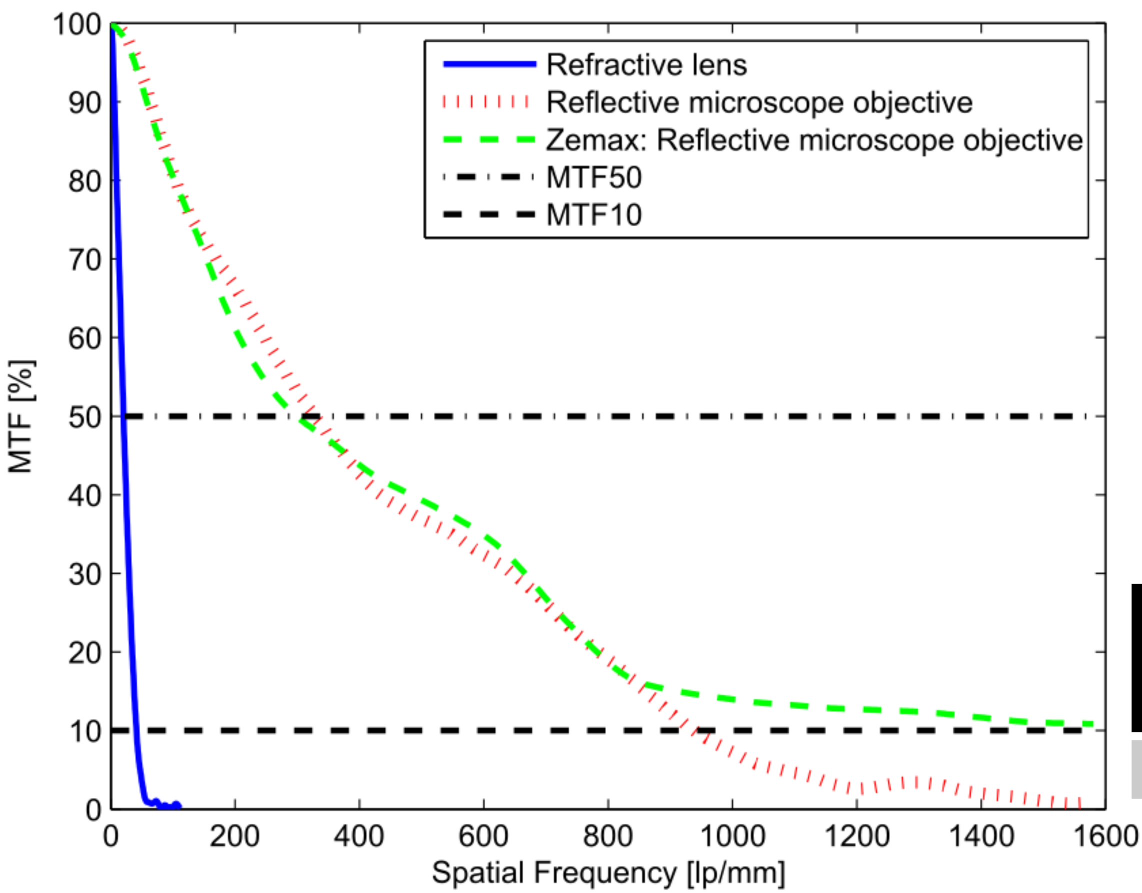
Reflective

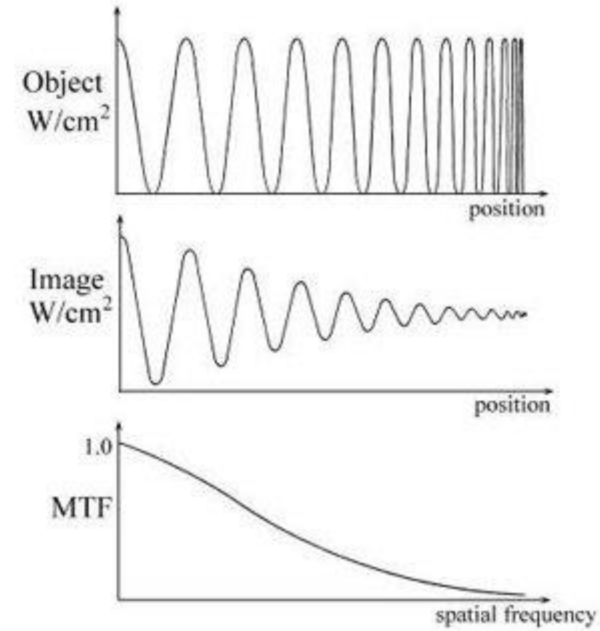
For thin (<50µm) scintillator



Modulation Transfer Function

The MTF (or spatial frequency response) is the magnitude response of the optical system to sinusoids of different spatial frequencies.





	REFRACTIVE LENS	REFLECTIVE MICROSCOPE OBJECTIVE
MTF10	42 lp/mm	936 lp/mm

G.D. Boreman, "Modulation Transfer Function in Optical and Electro-Optical Systems", SPIE Press, Bellingham, WA (2001)
www.thorlabs.com

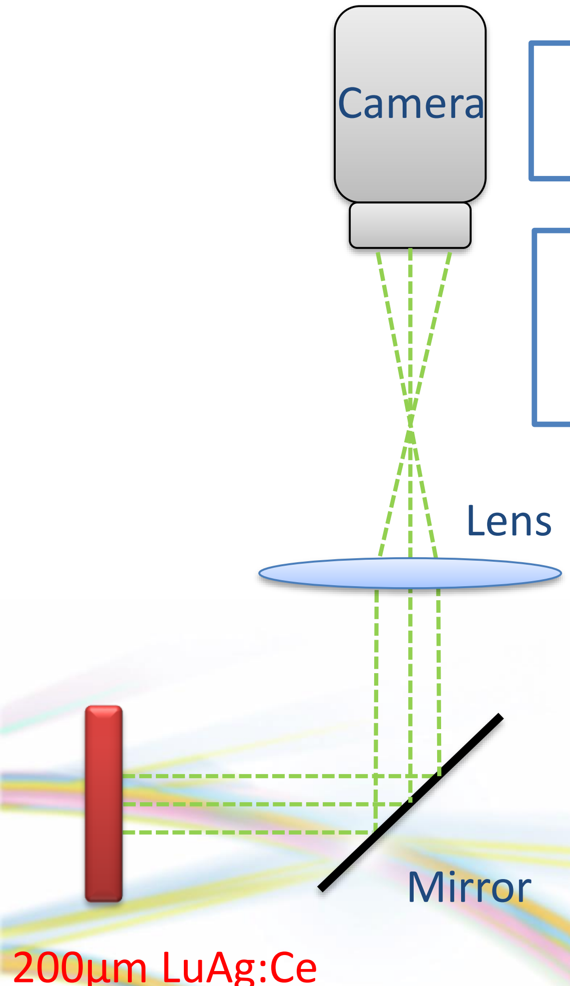
Comparison of Thick vs Thin Scintillator + Optics

Ideally, the **scintillator contribution to the PSF** would be measured **using the knife-edge** technique with X-ray exposure.

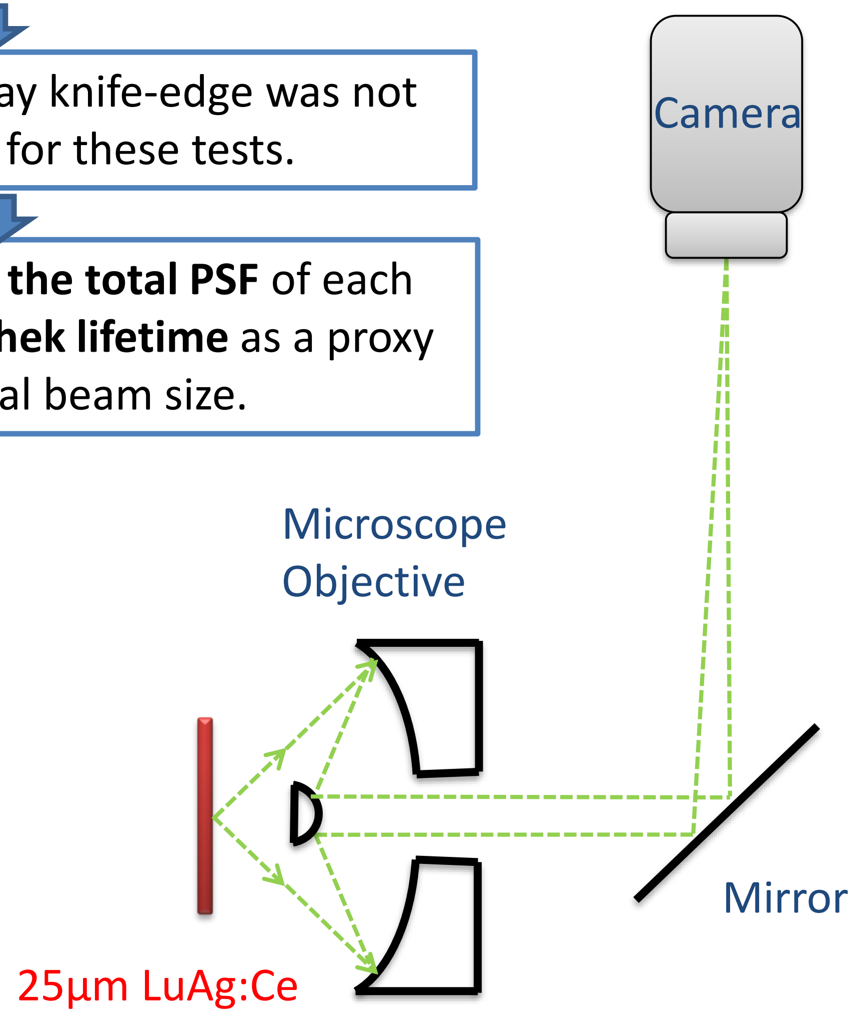
However a suitable X-ray knife-edge was not available in time for these tests.

Instead, we **measured the total PSF** of each system **using the Touschek lifetime** as a proxy for true vertical beam size.

Refractive



Reflective



PSF Measurement using Touschek Lifetime

In the **Touschek dominated regime** (400 bunch, 200 mA) the measured **beam lifetime** (or condition) τ **is used as a proxy measurement for the true beam size** σ_y as:

$$\sigma_y = k\tau \quad (1)$$

where k is a scaling factor.

Subtraction in quadrature given a Gaussian beam profile and PSF σ_{PSF} gives the measured beam size σ_M as:

$$\sigma_M = \sqrt{\sigma_y^2 + \sigma_{PSF}^2} \quad (2)$$

Substituting Eq. (1) into (2):

$$\boldsymbol{\sigma_M = \sqrt{(k\tau)^2 + \sigma_{PSF}^2}} \quad (3)$$

A. Piwinski, "The Touschek effect in strong focusing storage rings", DESY 98-179, 1998
L.M. Bobb et al., Proc. of IBIC2016, Barcelona, Spain, WEPG63.

Experiment

The refractive and reflective microscope imagers were installed on X-ray pinhole camera 3 in the storage ring tunnel to ensure all other PSF contributions are identical.

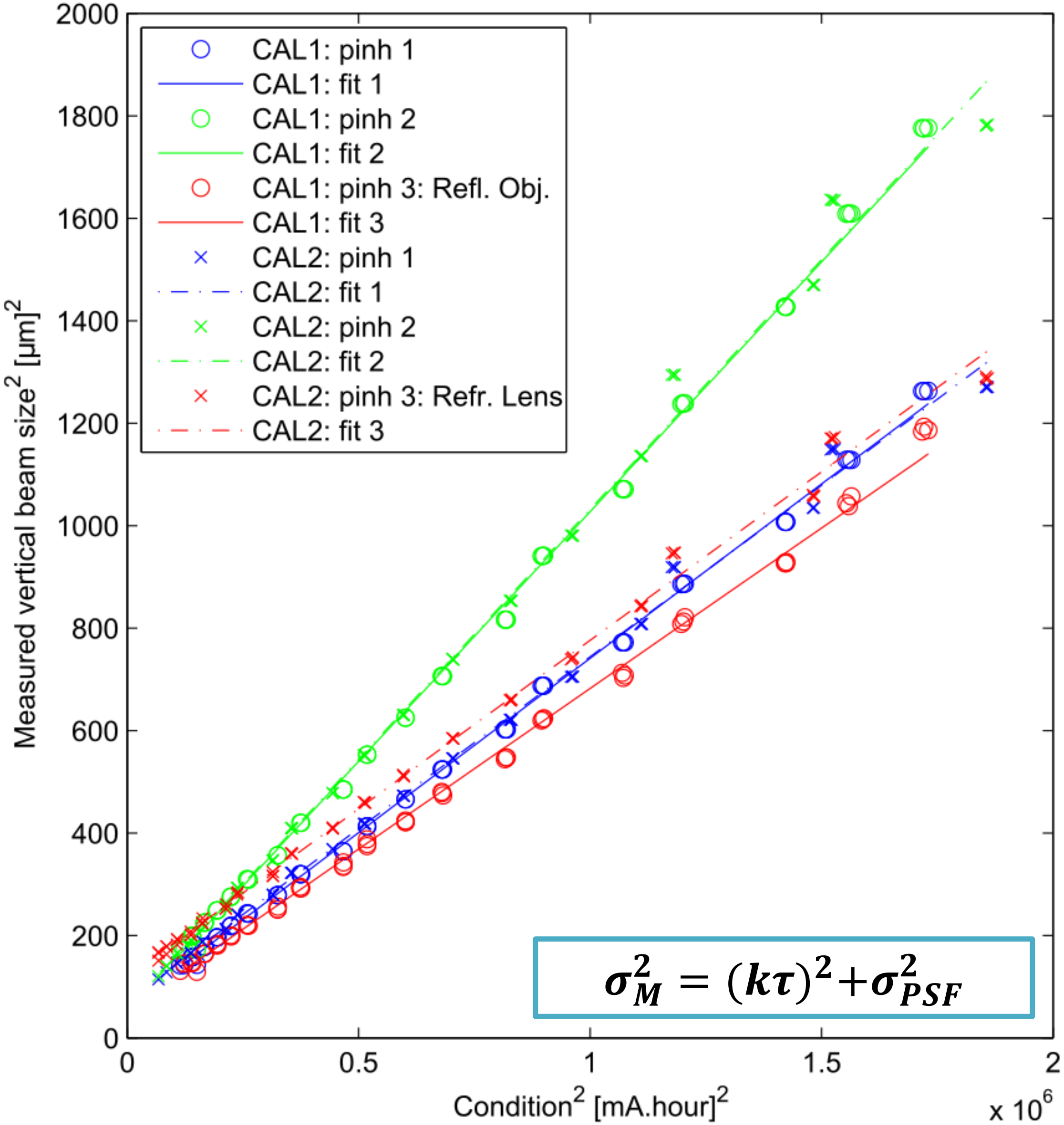
X-ray Pinhole Camera	Scintillator	Source-to-scintillator magnification	Scintillator-to-camera magnification	Optical setup
1	200 µm Prelude 420: LYSO:Ce	2.39	1	**Refractive lens**
2		2.65	1	
3	**200 µm LuAg:Ce**	**2.47**	**1**	
	25 µm LuAg:Ce		**11**	**Microscope**

Since the two setups on pinhole 3 could not be calibrated simultaneously, X-ray pinhole cameras 1 and 2 were used to verify that the beam conditions did not change between the consecutive PSF measurements using the Touschek lifetime.

L. Bobb and G. Rehm, Proc. of IBIC2018, Shanghai, China, WEPB18.

PSF results (1)

L. Bobb and G. Rehm, Proc. of IBIC2018, Shanghai, China, WEPB18.



PSF results (2)

PINHOLE CAMERA	CALIBRATION 1		CALIBRATION 2	
	$\boldsymbol{k}$ [µm mA^{-1} h^{-1}]	$\boldsymbol{\sigma_{PSF}}$ [µm]	$\boldsymbol{k}$ [µm mA^{-1} h^{-1}]	$\boldsymbol{\sigma_{PSF}}$ [µm]
1	0.026	7.8	0.026	8.6
2	0.031	7.2	0.031	7.5
	Reflective microscope imager with thin 25µm scintillator		Refractive lens imager with thick 200µm scintillator	
3	0.025	**7.4**	0.026	**10.9**

Using a thin scintillator resulted in a 30% improvement to total PSF

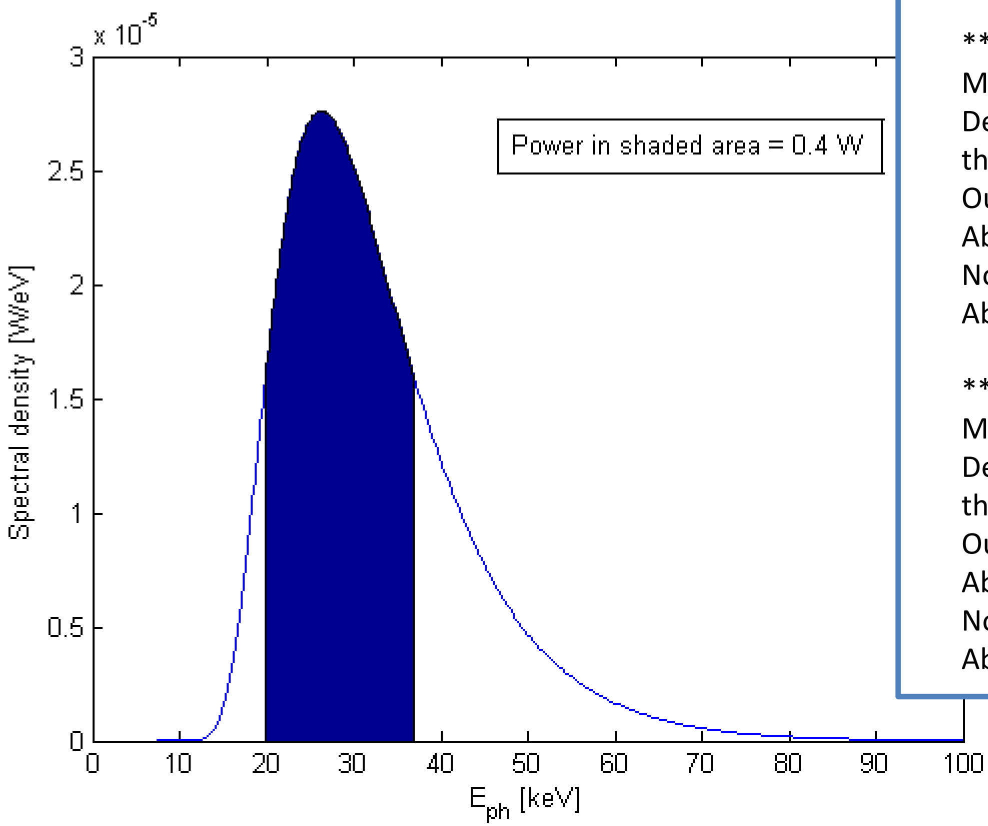
L. Bobb and G. Rehm, Proc. of IBIC2018, Shanghai, China, WEPB18.

Other Experiences at Diamond

L. Bobb

SR from Dipole

Useful energy range once the attenuation in air is also included = 20 to 37 keV
Power in this range = 0.4 W



************************ Xpower Results ****************

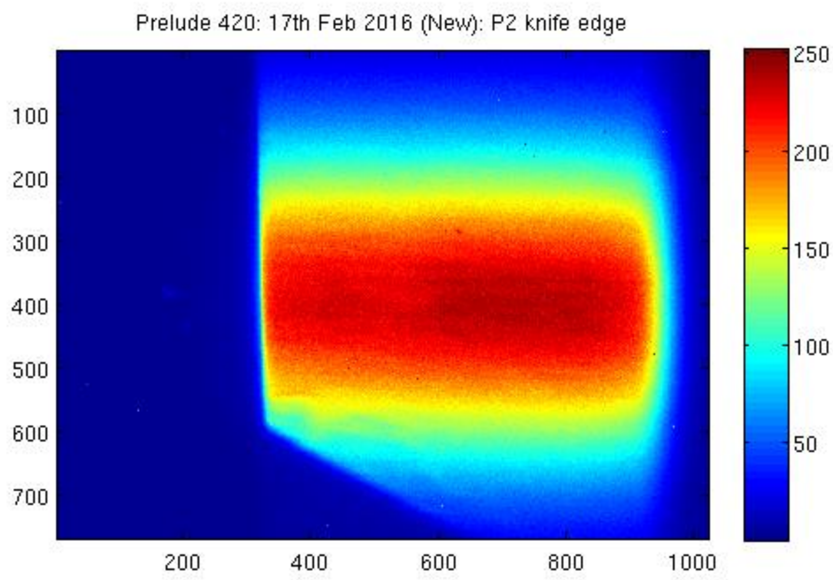
Calculations using DABAX files: CrossSec_XCOM.dat and f1f2_Windt.dat

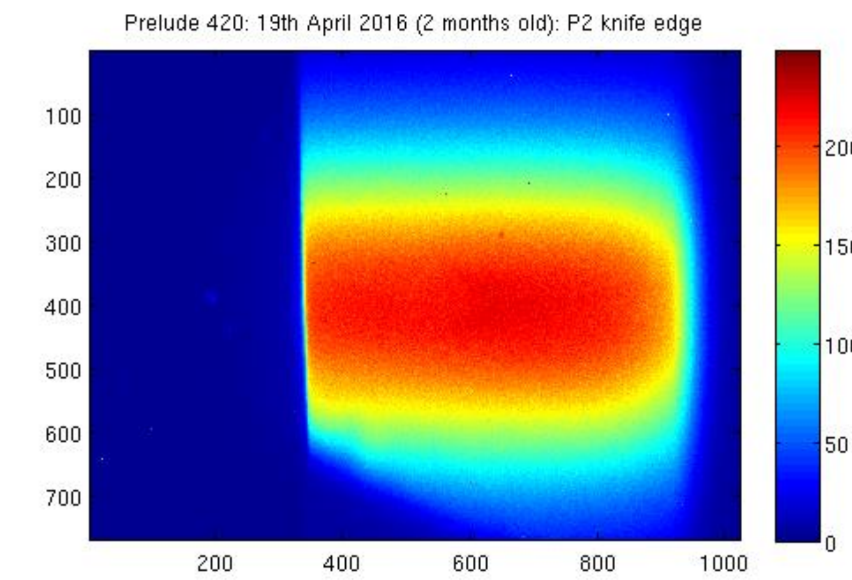
Source energy (start,end,points): 100.000, 100000., 1000
Number of optical elements: 2
Incoming power [source integral]: 11.9806
Normalized Incoming power: 1.00000

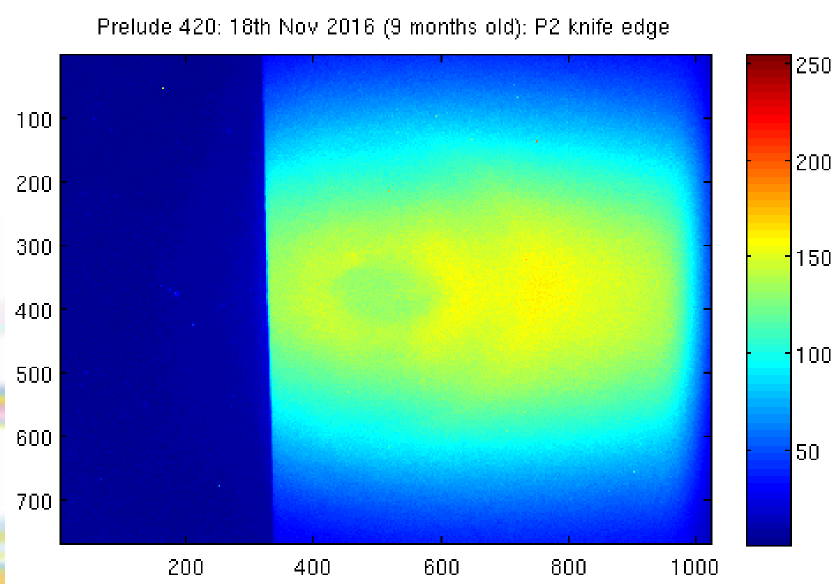
***** oe 1 [Filter] ************
Material: Al
Density [g/cm^3]: 2.7000000
thickness [mm] : 1.00000
Outcoming power: 1.58626
Absorbed power: 10.3944
Normalized Outcoming power: 0.132402
Absorbed dose Gy.(mm^2 beam cross section)/s: 3849763.5

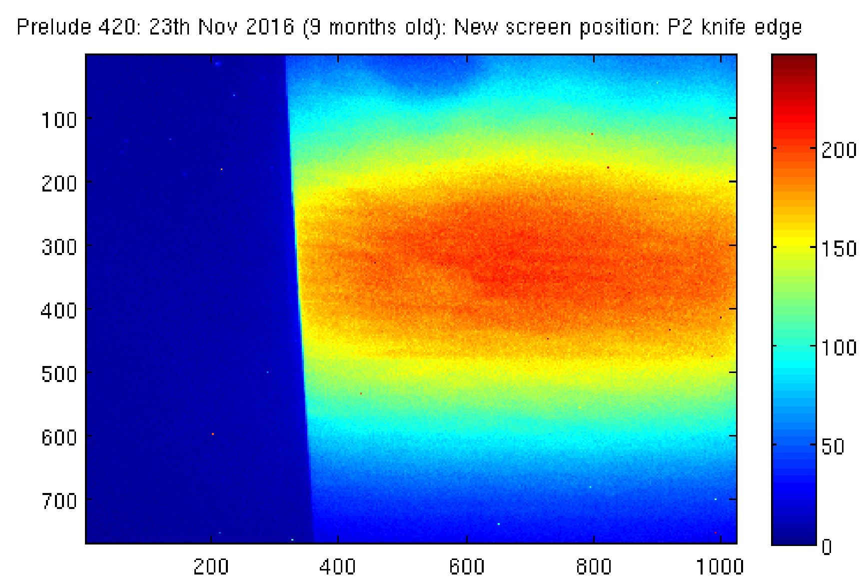
***** oe 2 [Filter] ************
Material: air
Density [g/cm^3]: 0.0012047000
thickness [mm] : 16420.0
Outcoming power: 0.601784
Absorbed power: 0.984480
Normalized Outcoming power: 0.0502298
Absorbed dose Gy.(mm^2 beam cross section)/s: 49768.520

Degradation of Prelude 420





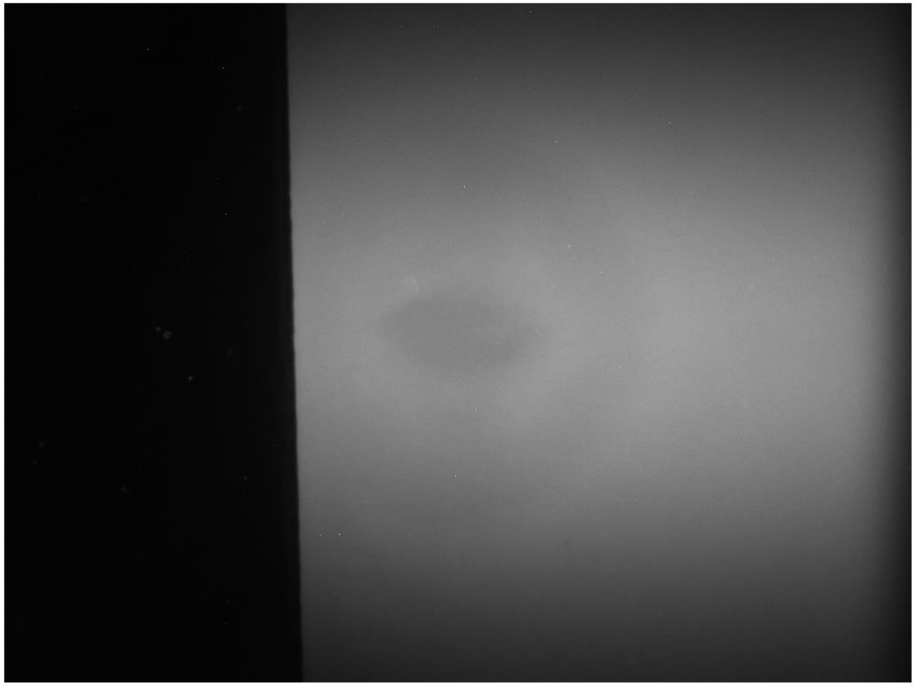




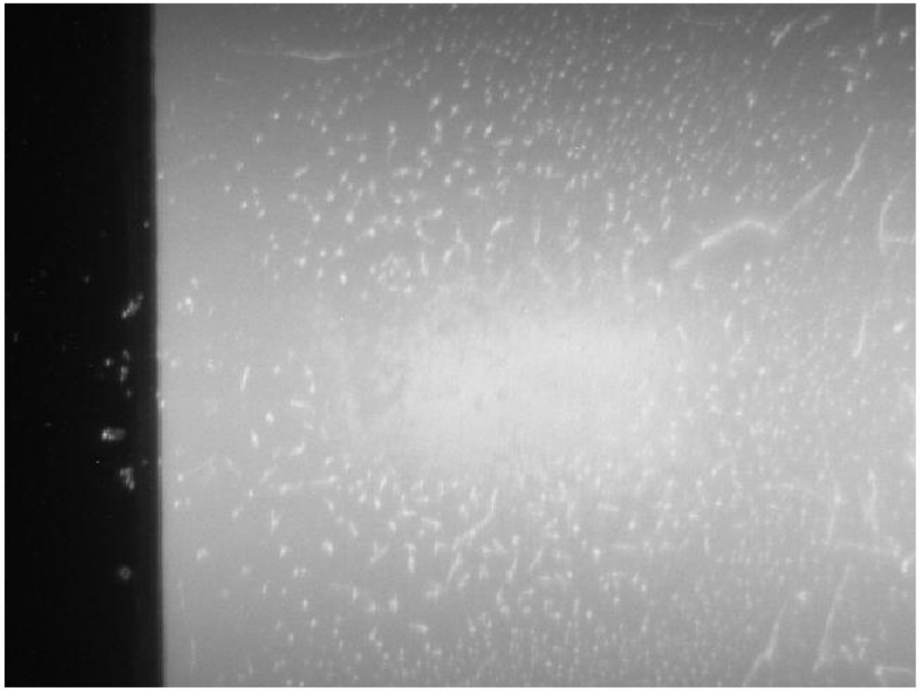
Radiation Damage

200 µm Prelude 420

Prelude 420: 18th Nov 2016 (9 months old): P2 knife edge



200 µm LuAg:Ce



LuAg:Ce Degradation

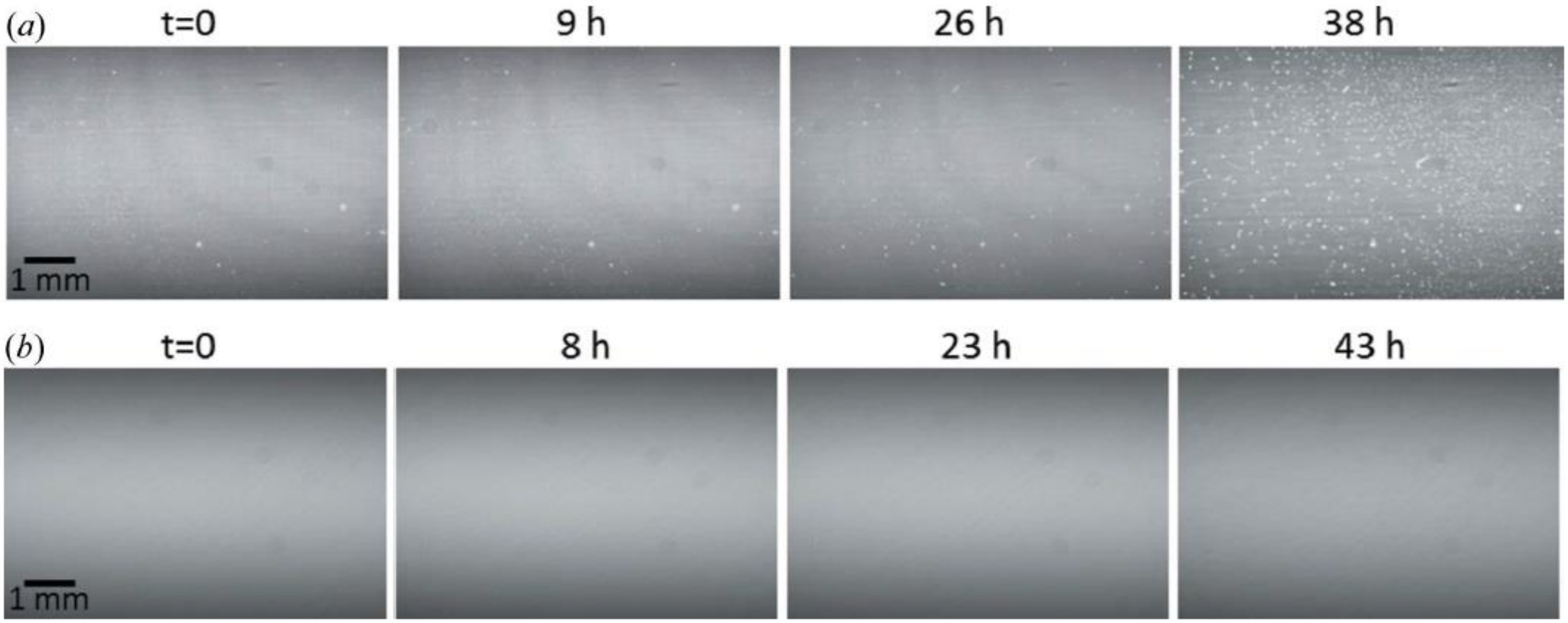


Figure 3
Flat-field image taken after scintillator is exposed with a pink beam (*a*) without and (*b*) with nitrogen gas flow.

T. Zhou *et al.* J. Synchrotron Rad. (2018). **25**, 801-807

Conclusion

- Reducing the scintillator thickness improves spatial resolution.
- For optimal resolution, the numerical aperture of the lens must be matched to the scintillator thickness.
- Here the PSF reduction using a thin scintillator and microscope is compared to the nominal refractive imager setup.
- For those at X-ray light sources, there are numerous publications in the beamline community, including the development of new scintillator materials.
- Scintillator degradation seems to occur differently for different scintillator materials. For LuAg:Ce, it has been found that using nitrogen can reduce the rate of degradation.

Thank you for your attention!