Diagnostics X-ray Beamline at Diamond Light Source

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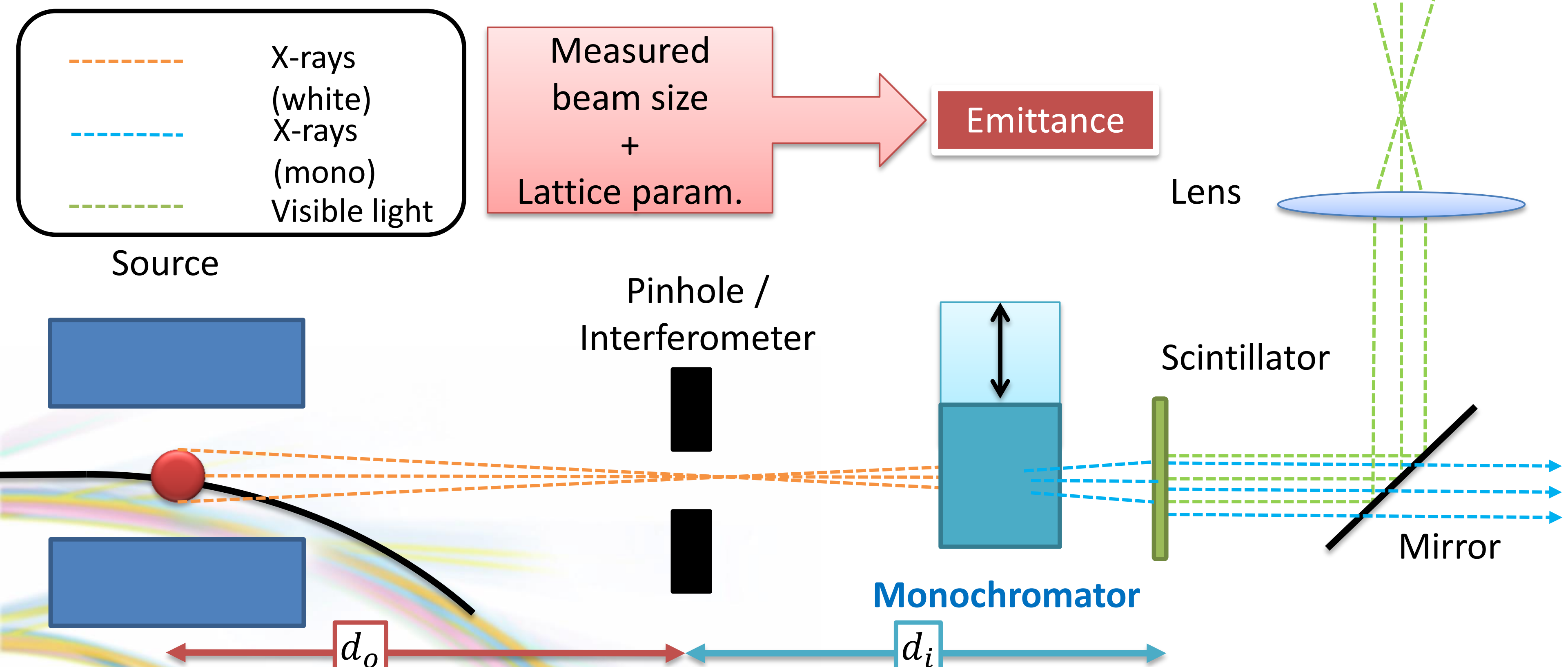
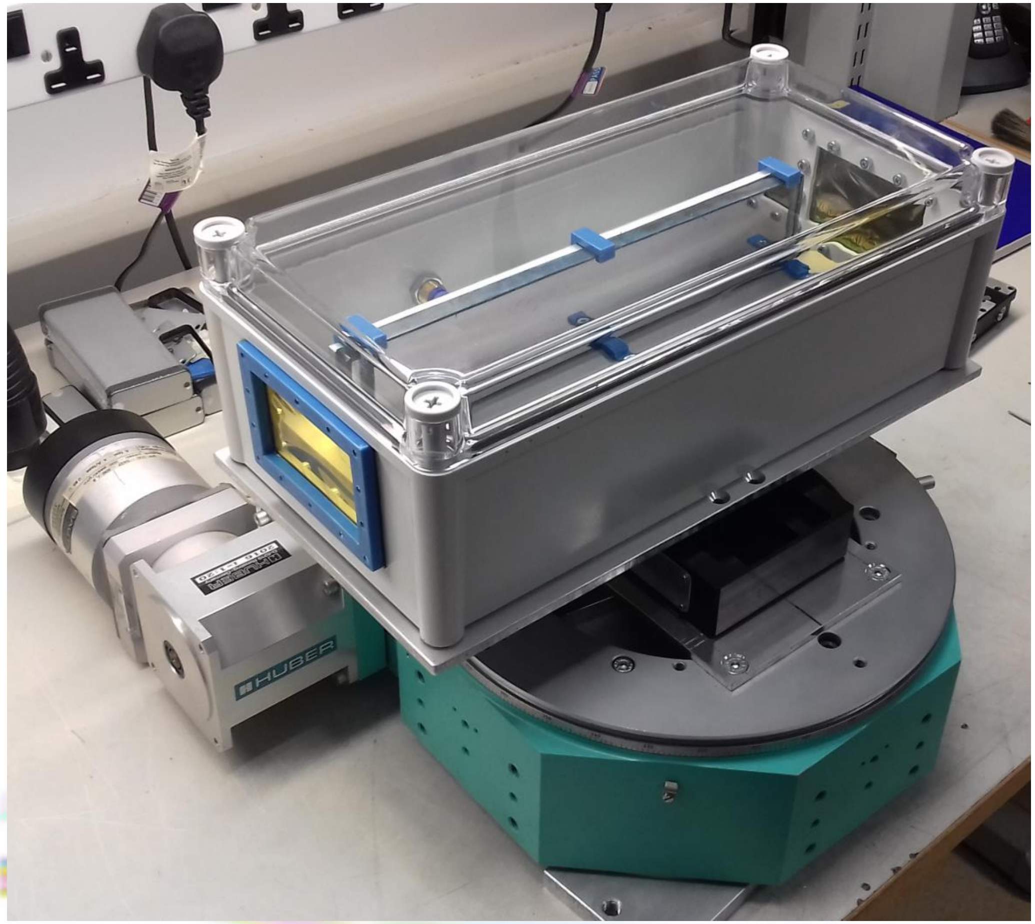
Small-scale X-ray beamline

- **Improve beam size resolution of X-ray pinhole camera:**
Monochromatic → Match pinhole size to energy → Minimise PSF
Best spatial resolution ~1 – 3 µm

- **Develop X-ray interferometer which can measure smaller beam sizes** (-requires monochromatic X-ray beam).



Photos of Monochromator

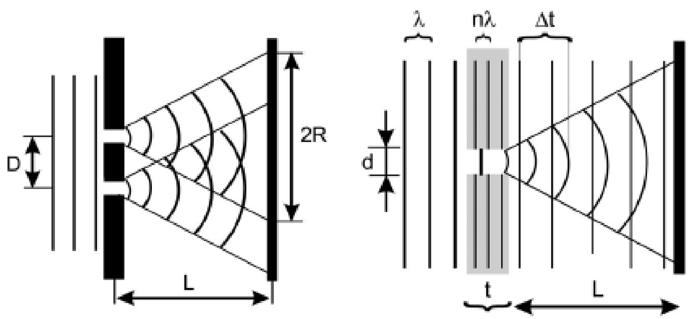


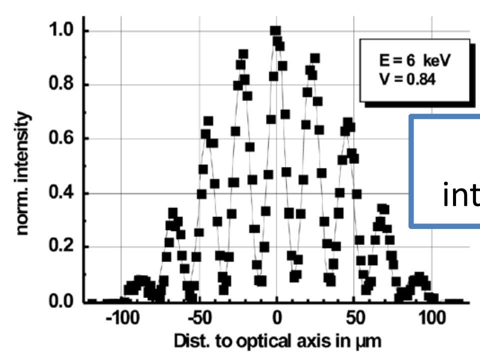
X-ray Interferometer

Owing to limited space in the experimental hutch the maximum distance between the double pinhole and the detector was $L_{exp} = 1.40$ m. This is a relatively small distance for the small diffraction angles occurring at this short wavelength. To observe interference of both diffracted waves they must sufficiently overlap each other after propagation from the pinholes to the detector. The width of the first diffraction minimum $2R$ in the distance L behind a pinhole of diameter d at a wavelength λ is given by the Airy criterion, $2R = 1.22L\lambda/d$. The degree of overlap, O, can be expressed as

$$O = 1 - \frac{D}{2R} = 1 - \frac{Dd}{1.22L\lambda} \quad (3)$$

(see Fig. 2). A complete overlap of the diffraction maxima of $O \simeq 1$ is reached for very large values of L. Let us assume an overlap of at least 0.8 to obtain an evaluable interference pattern from the

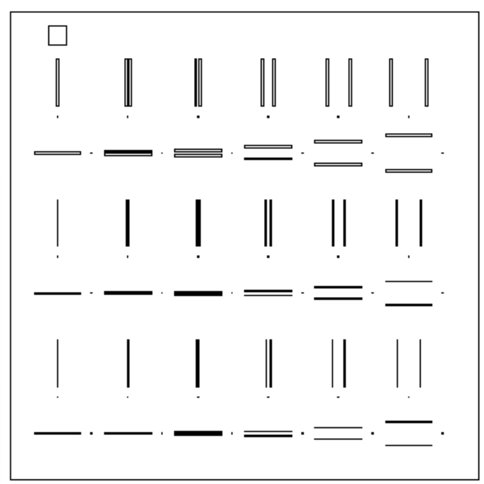


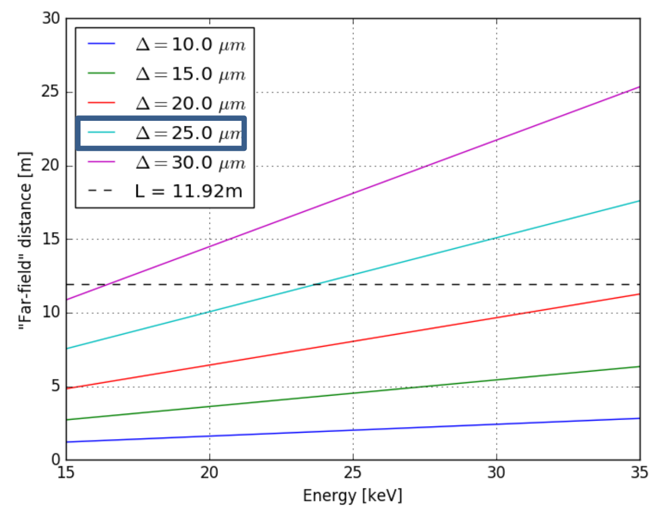


Example interferogram

Overlap @ 15 keV ≈ 0.79
Overlap @ 25 keV ≈ 0.66

Note that minimum distance for far-field is
$$\frac{\Delta^2}{\lambda} = L_{min},$$
however in reality $L_{min} \ll L$ which is not satisfied for all object sizes.





[1] Pinhole interferometry with coherent hard X-rays- Wolfram Leitenberger, Horst Wendrock, Lothar Bischoff and Timm Weitkamp

Multilayer Mono Parameters

	Borrowed from Optics group	Incoatec
Dimensions	300 mm x 50 mm	Approx 40mm x 100mm
D-spacing	4.8 nm	4 nm
Multilayers	Mo/Si with N=100 layer-pairs deposited on float glass	Tungsten/Boron Carbide (B4C) with 200 pairs
Comment	At 12 keV, it will have a Bragg angle of ~0.67 deg, giving a beam-deflection of ~23mm at 1m	

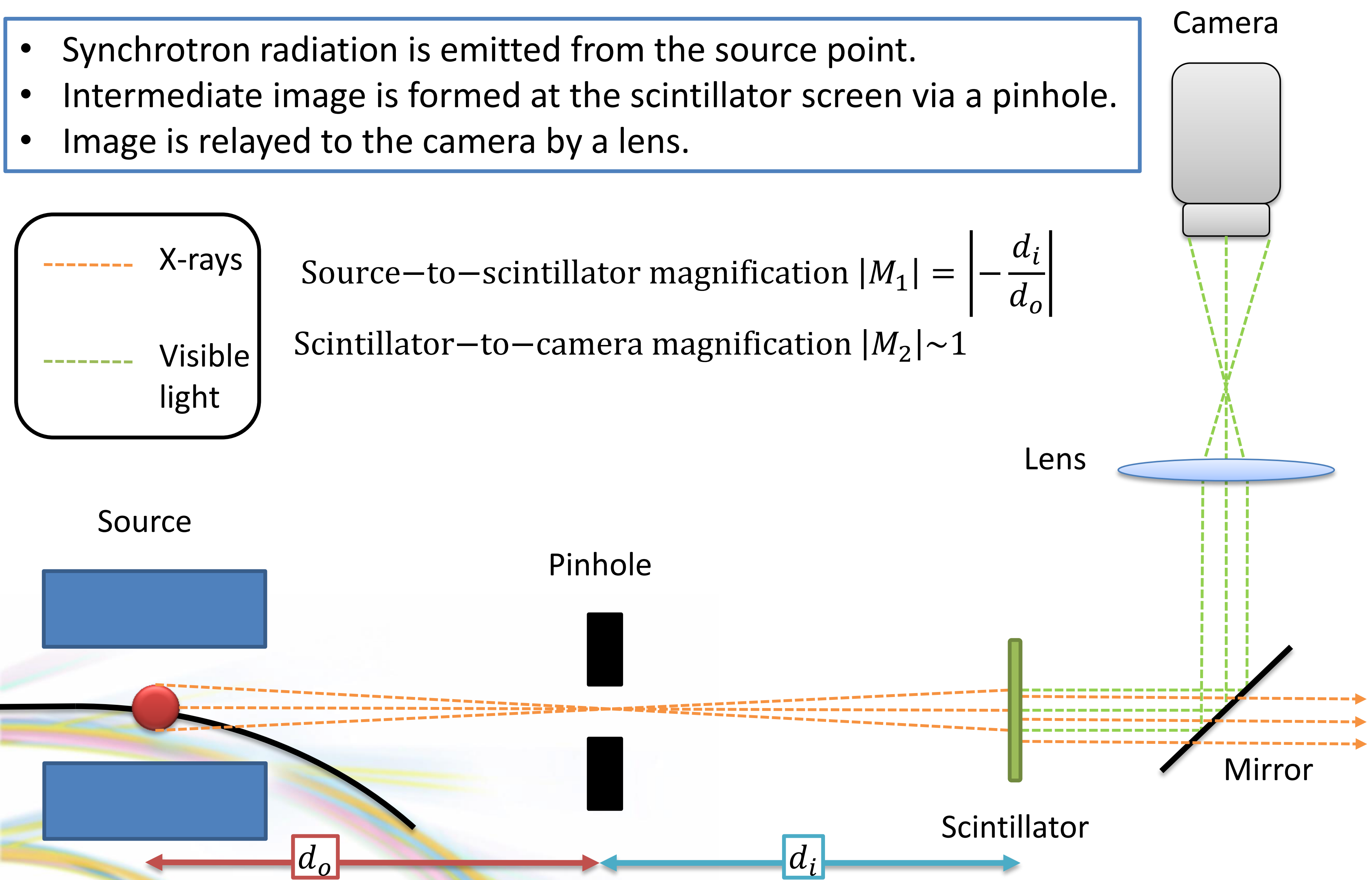
Extra Slides

Principle of Operation

- Synchrotron radiation is emitted from the source point.
- Intermediate image is formed at the scintillator screen via a pinhole.
- Image is relayed to the camera by a lens.

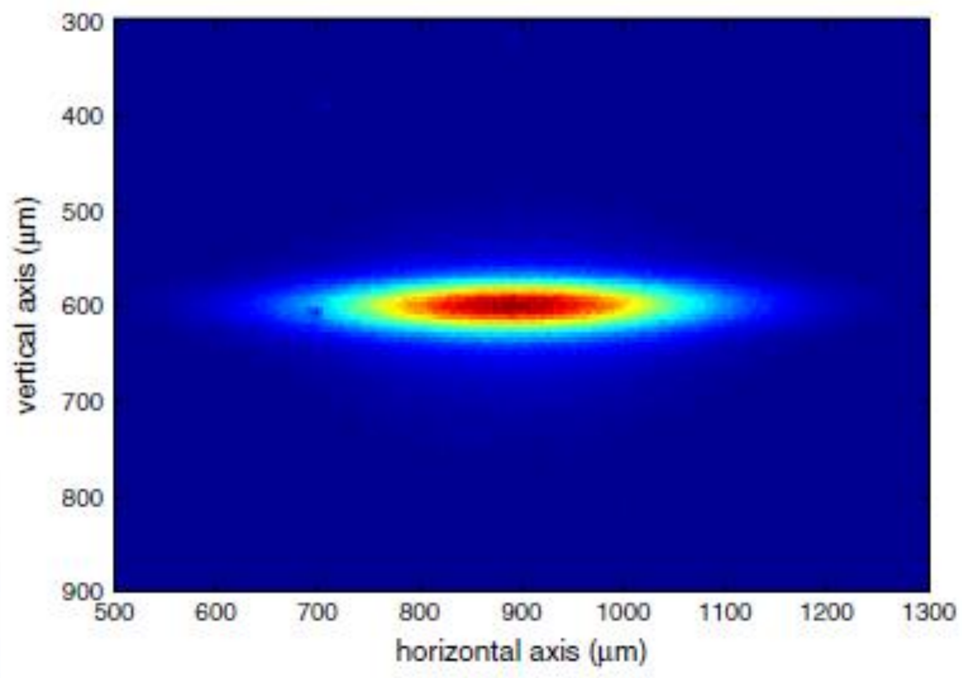
Source−to−scintillator magnification $|M_1| = \left|-\frac{d_i}{d_o}\right|$

Scintillator−to−camera magnification $|M_2| \sim 1$



Emittance Calculation

X-ray pinhole cameras **measure the transverse profile** of the beam, **from which the emittance may be calculated.**



Example image from Diamond Light Source in 2010, from which the emittance can be calculated [4, 5].

Emittance Calculation

At Diamond using two pinhole cameras at different locations:

1. Fit a 2D Gaussian to obtain horizontal and vertical imaged sizes $\sigma_{x_{1,2}}^{image}$ and $\sigma_{y_{1,2}}^{image}$ respectively.

2. Deconvolve and scale using magnification to obtain the electron beam sizes e.g. Gaussian subtraction in quadrature:

$$\sigma_{y_1} = \frac{\sqrt{(\sigma_{y_1}^{image})^2 - \sigma_{PSF}^2}}{M_1}$$

3. Given the lattice parameters, solve the following matrix equation to obtain the horizontal and vertical emittances $\varepsilon_{x,y}$, and energy spread σ_e:

$$\begin{bmatrix} \sigma_{x_1}^2 \\ \sigma_{x_2}^2 \\ \sigma_{y_1}^2 \\ \sigma_{y_2}^2 \end{bmatrix} = \begin{bmatrix} \beta_{x_1} & 0 & \eta_{x_1}^2 \\ \beta_{x_2} & 0 & \eta_{x_2}^2 \\ 0 & \beta_{y_1} & \eta_{y_1}^2 \\ 0 & \beta_{y_2} & \eta_{y_2}^2 \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \sigma_e^2 \end{bmatrix}$$

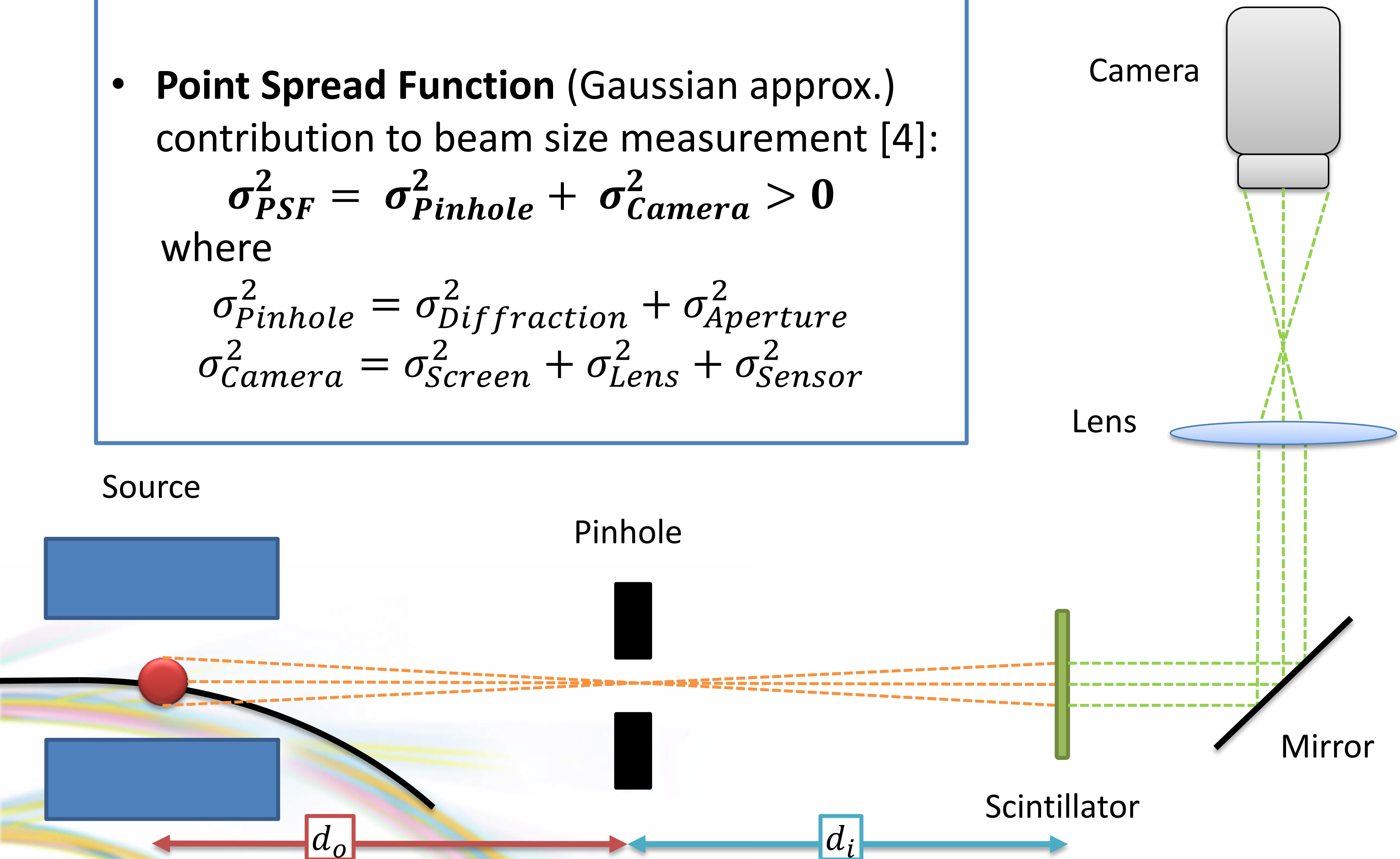
Fundamental Limitations

- **Indirect emittance measurement**
- **Point Spread Function** (Gaussian approx.) contribution to beam size measurement [4]:

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

where

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



Fundamental Limitations

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

Source resolution for optimised pinhole camera, given current spatial constraints at Diamond:

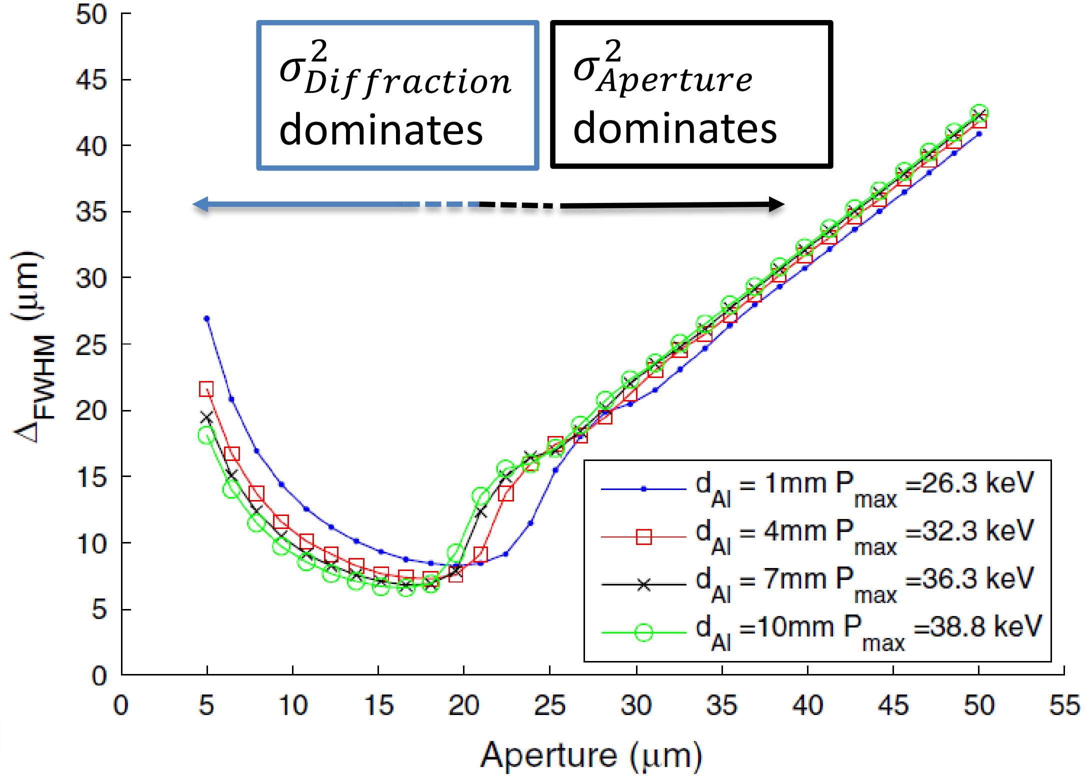
$$\frac{\left(\frac{\Delta_{FWHM}}{2.35}\right)}{|M_1|} \sim \frac{\left(\frac{6\ \mu\text{m}}{2.35}\right)}{2.65} \sim 1\ \mu\text{m}$$

with $\boldsymbol{\sigma^2_{Camera} = 0}$.

Source resolution incl. contribution from camera using a 5µm P43 screen [4]:

$$\sim 3\ \mu\text{m}$$

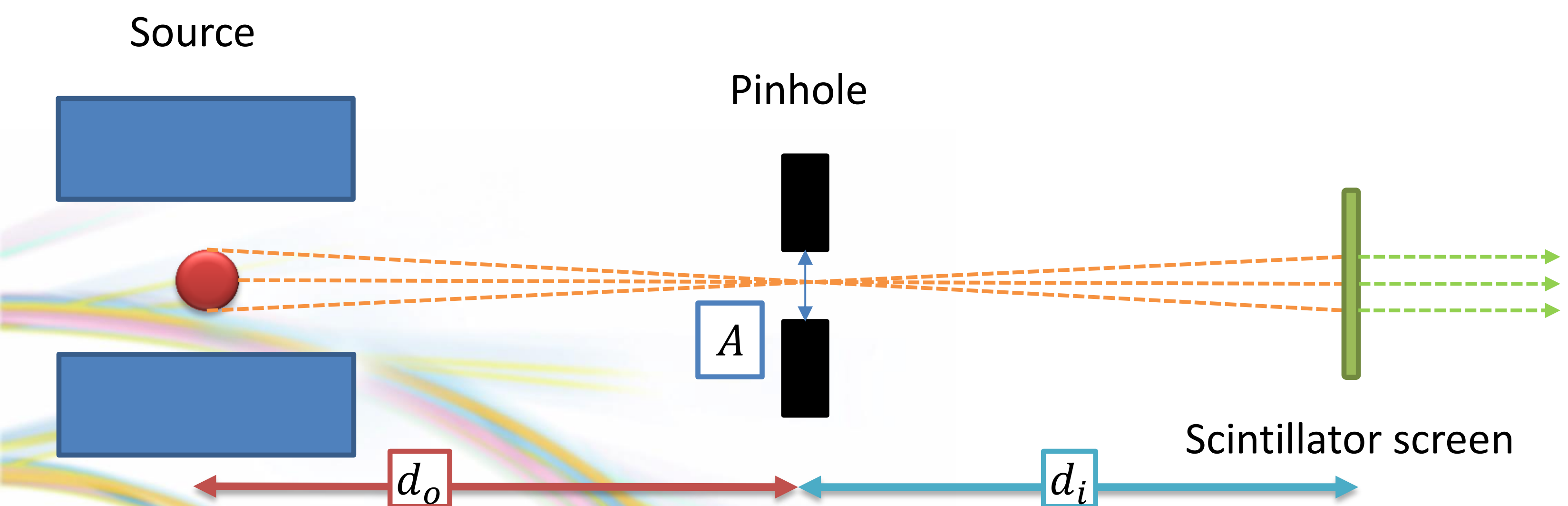
Phys. Rev. ST Accel. Beams **13**, 022805 (2010)



Practical Challenges

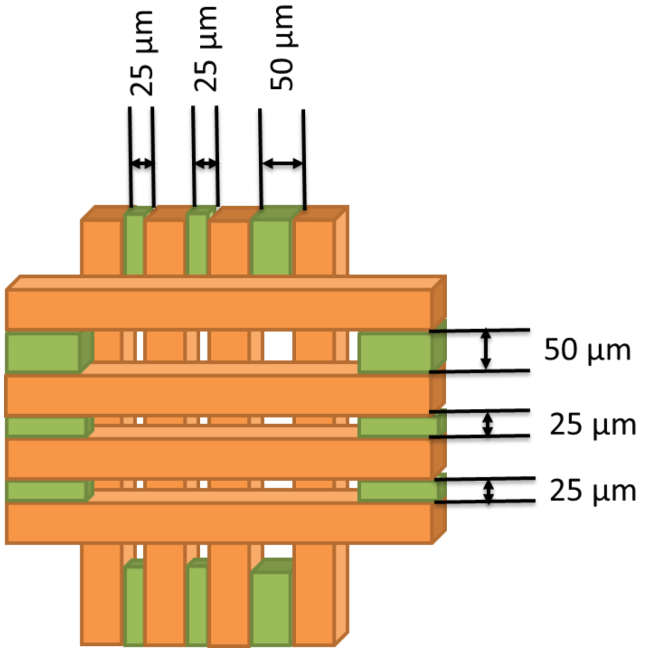
- Spatial constraints
  - For sufficient source-to-screen magnification ($|M_1| = \left|-\frac{d_i}{d_o}\right| \geq 2$):
    → X-ray path length $(d_o + d_i) \geq 10\text{m}$
  - Diffraction contribution to PSF from pinhole worsens with distance given a fixed aperture size A :

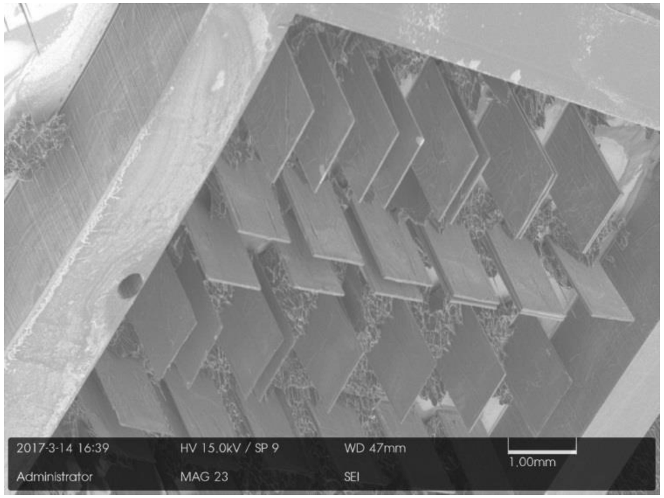
$$\sigma_{Diffraction} = \frac{\sqrt{12}}{4\pi}\frac{\lambda d_i}{A}$$ for wavelength λ [5].



Practical Challenges

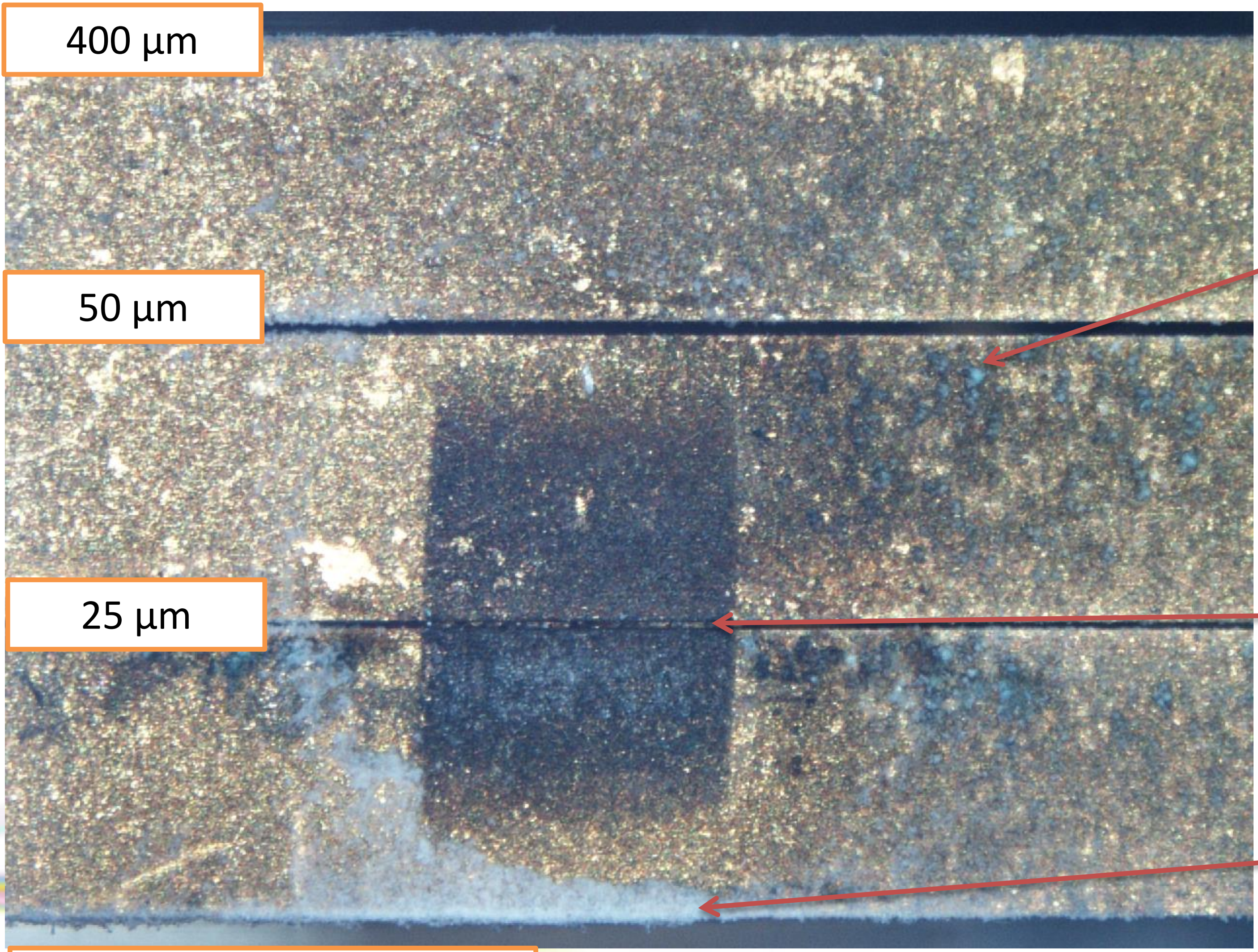
- Pinhole fabrication
  - For the pinhole to be opaque to keV X-rays a high Z material is required e.g. 1mm thick Tungsten.
  - Often these materials are difficult to machine.
  - Especially given the high aspect ratio 10 µm (aperture): 1mm (thickness)
    → 1:100





- Environment and oxidation
  - Air, nitrogen or vacuum?
  - Lifetime and maintenance considerations

Nov 2014: Gold Plated Tungsten Blades



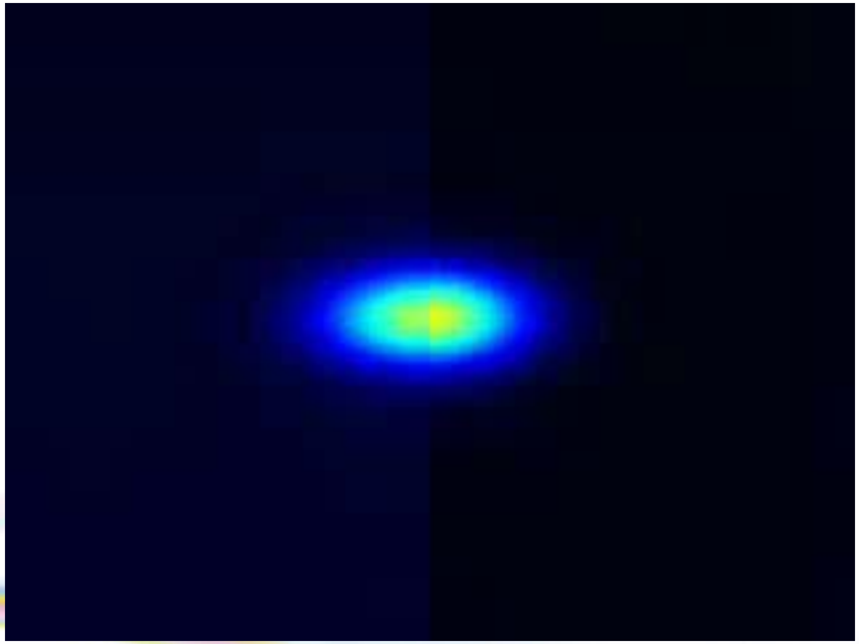
Now tell us the perks!

- Simple design. Simple alignment. Simple maintenance. Simple analysis. Simple…
  - Quick to commission e.g. < 1 week at Diamond (2006)
  - So simple, a human can learn a lot just by looking…!
- Provides 2D transverse profile.
- Non-invasive.
- Cheap options are available.
- Possible to custom build the imager to optimise for spatial resolution, turn-by-turn acquisition, dynamic range etc.
- Fast image processing, thus suitable for feedback systems.

Dual Purpose Diagnostic

Emittance Monitoring + **CCTV**

While we have human operators, the importance of easy human interpretation shouldn't be overlooked.

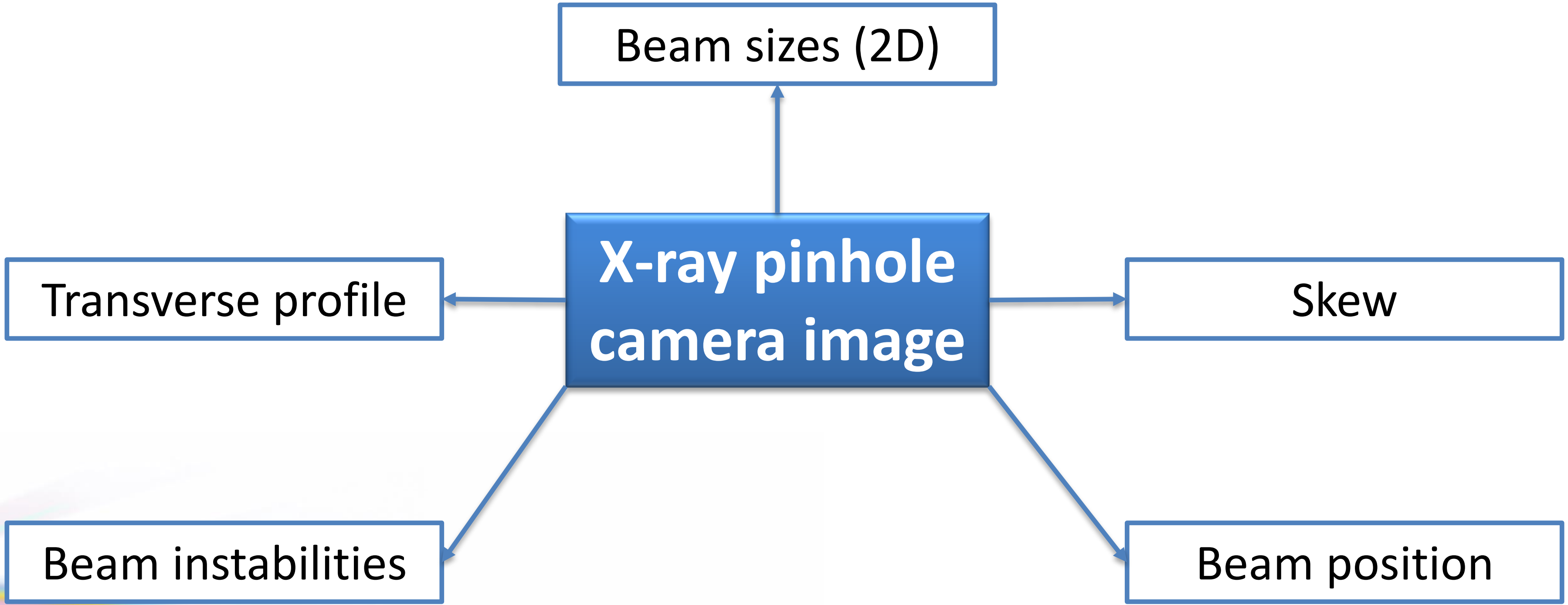


Injection at Diamond 2015

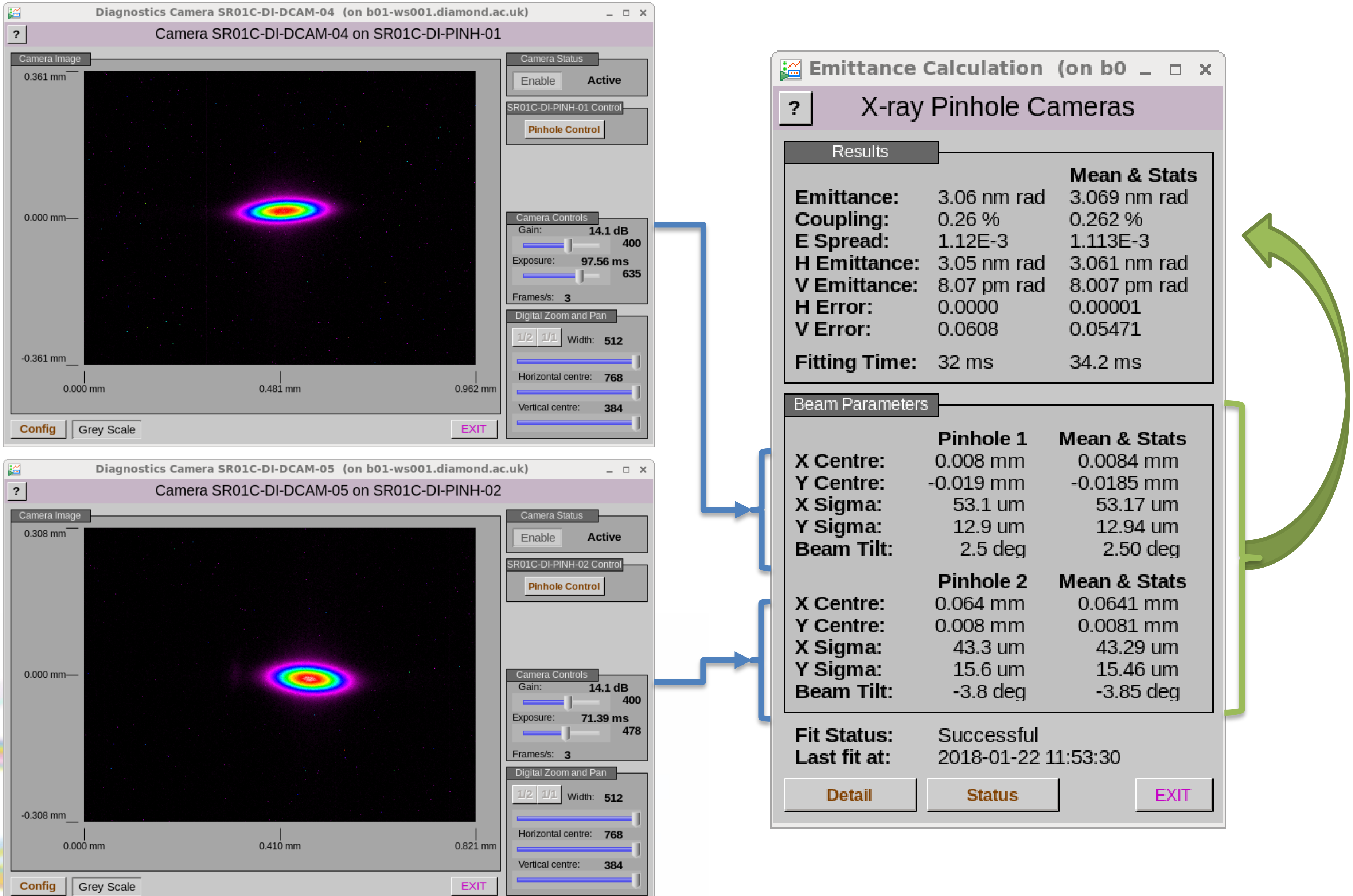
TMBF at Diamond 2015

Dual Purpose Diagnostic

Emittance Monitoring + **CCTV**

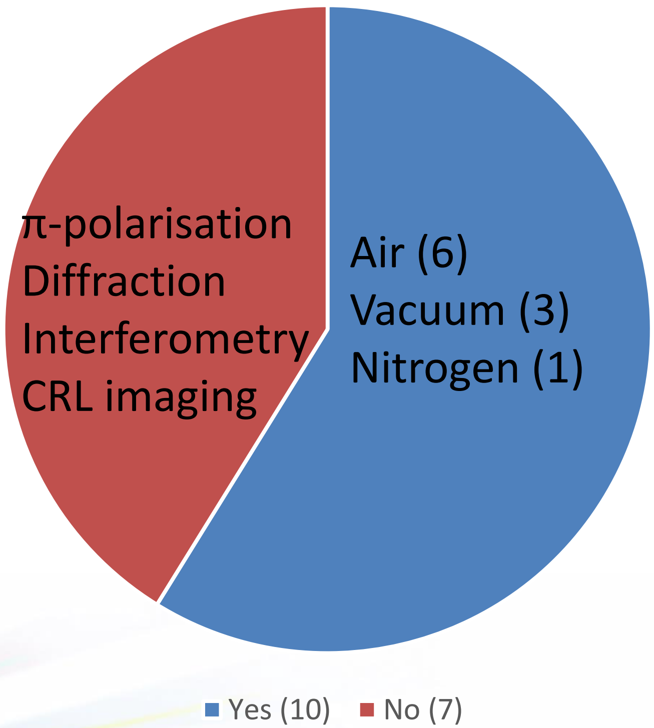


In Operation

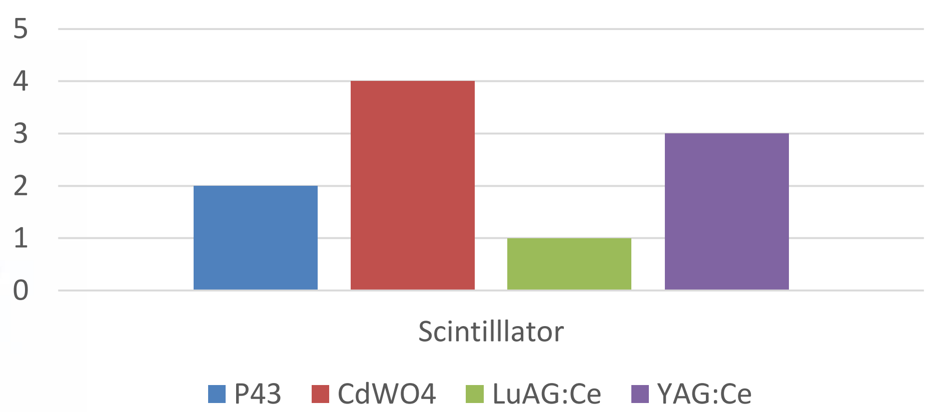


"Snapshot" of Current Status

Do you use X-ray pinhole cameras for emittance measurement?



Parameter	Average
Aperture	23 μm
X-ray energy	29 keV
$\left(\frac{\sigma_{PSF}}{\sigma_y}\right) \times 100$	32 %
Source-to-screen magnification	1.6
Screen-to-camera magnification	1.8



Summary

- Simple! → Easy to commission → Easy maintenance
- Survey shows primary instrument for emittance monitoring
- Fundamental limitations, given space and 30 keV X-rays etc., mean sub-micron beam size measurements are not possible.
- Many practical challenges are being improved with technological advances.
- Complementary general diagnostic → CCTV
- Suitable for emittance feedback
- Easy human interpretation

References

[1] V. Popovic *et al.*, Design and Implementation of Real-Time Multi-Sensor Vision Systems, Springer, 2017.

[2] E. S. Forster, Problemata by Aristotle, translated to English, Vol VII, 912b, 1927.

[3] E. Renner, Pinhole Photography from Historic Technique to Digital Application, Fourth Ed., Focal Press, 2009.

[4] C. Thomas *et al., X-ray pinhole camera resolution and emittance measurement,* Phys. Rev. ST Accel. Beams **13**, 022805 (2010).

[5] P. Elleaume *et al.*, J. Synchrotron Radiat. 2, 209 (1995).

[6] M. Madou, ``Chapter 10: Micromolding Techniques - LIGA'', Fundamentals of Microfabrication and Nanotechnology, Vol. 2, Third Ed., CRC Press, 2012, p.591-642.

[7] L.M. Bobb et al., ``Performance Evaluation of Molybdenum Blades in an X-ray Pinhole Camera'', Proc. IBIC2016, p. 796-799.

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