Status of X-ray Pinhole Cameras for 3GSLS

L. Bobb

Ancient meets State-of-the-Art

≈ 400 – 300 BC : Earliest written observations

Chinese philosopher Mozi [1].

“Why does the sun penetrating through quadrilaterals form not rectilinear shapes but circles, as for instance when it passes through wicker-work?”

Greek philosopher Aristotle (384-322 BC) [2].

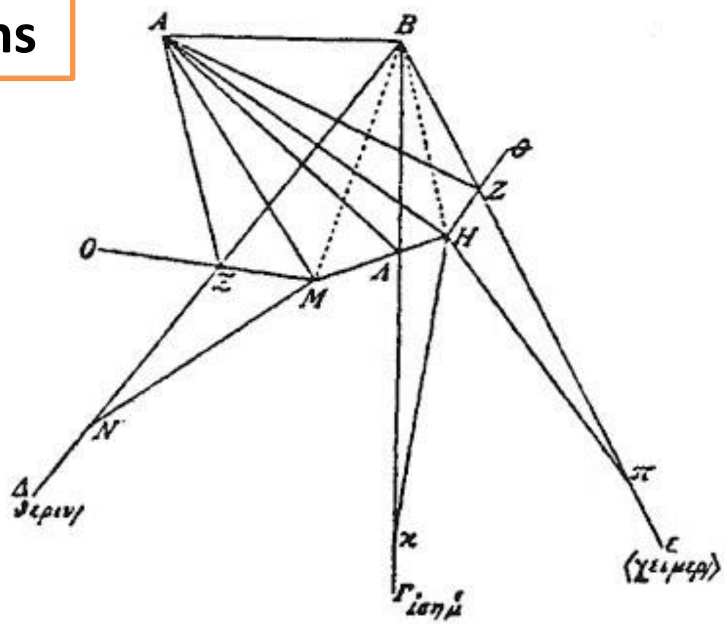
Time

Observation of a partial solar eclipse through overlapping fingers that Aristotle could not explain [3].

Ancient meets State-of-the-Art

≈ 400 – 300 BC : Earliest written observations

Light ray diagram by Anthemius of Tralles [3].



500 – 1100 AD : First experimental studies

555 AD: Ray-tracing diagram by Anthemius of Tralles (mathematician and co-architect of the Hagia Sophia) [3].

965 – 1039 AD: Optical scientist Ibn al-Haitham (Alhazen) describes imaging candles in a darkened room using a pinhole and states:

"The image of the Sun at the time of the eclipse, unless it is total, demonstrates that when light passes through a narrow, round hole and is cast on a plane opposite to the hole, it takes on the form of a moonsickle."

Ancient meets State-of-the-Art

≈ 400 – 300 BC : Earliest written observations

1100 – 1400 AD : Finding applications

Theodoric of Freiberg and Kamal al-Din al Farisi simultaneously and independently study the colour theory of sunlight using a pinhole.

≈1300 AD: Roger Bacon uses science to reaffirm religious belief [3].

Time

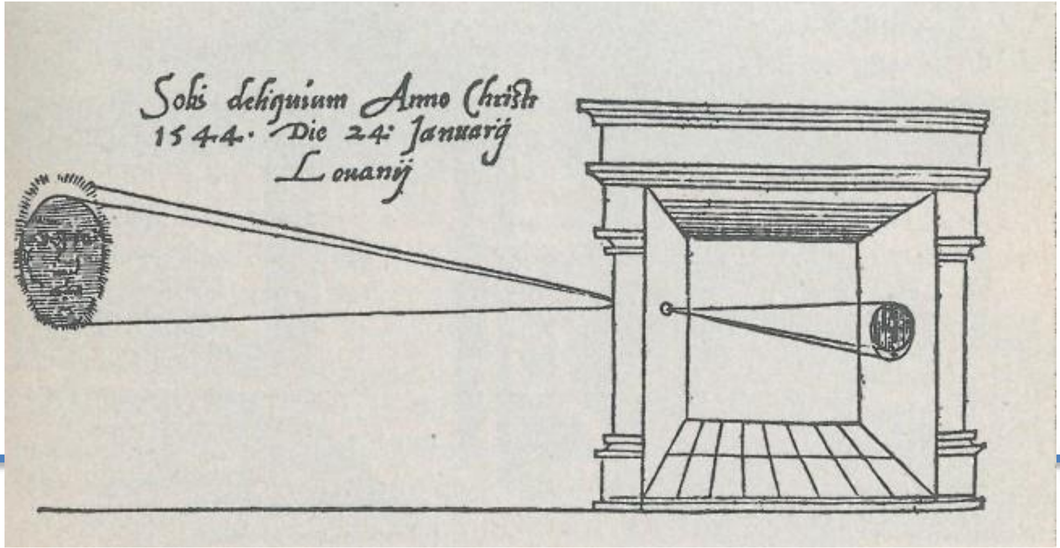
Drawing of a 3-tiered camera by Roger Bacon.

500 – 1100 AD : First experimental studies

Ancient meets State-of-the-Art

≈ 400 – 300 BC : Earliest written observations

1100 – 1400 AD : Finding applications



Schematic of a pinhole camera in 1545 [3].

1400 – 1600 AD : Renaissance of human understanding

Optical and astronomical experiments by Antonio de Dominus, René Descartes, Tycho Brahe, Johannes Kepler and Leonardo da Vinci.

1545 AD: First published picture of a pinhole camera obscura in the book, *De Radio Astronomica et Geometrica,* by Gemma Frisius [3].

500 – 1100 AD : First experimental studies

Ancient meets State-of-the-Art

≈ 400 – 300 BC : Earliest written observations

500 – 1100 AD : First experimental studies

1100 – 1400 AD : Finding applications

1400 – 1600 AD : Renaissance of human understanding

1600 – 1900 AD : Replaced by lenses

Pinhole aperture replaced by a lens in the majority of camera obscuras.

David Brewster describes pinhole camera photography in his book, *The Stereoscope,* in 1856 [3].

Time

diamond

Ancient meets State-of-the-Art

≈ 400 – 300 BC : Earliest written observations

1100 – 1400 AD : Finding applications

1600 – 1900 AD : Replaced by lenses

Time

1900 – Now : Rise of scientific pinhole cameras

Pinhole cameras coupled with films, scintillators, lenses and modern camera sensors are used in high energy physics.

→ **Transverse profiling of particle beams in light sources.**

1400 – 1600 AD : Renaissance of human understanding

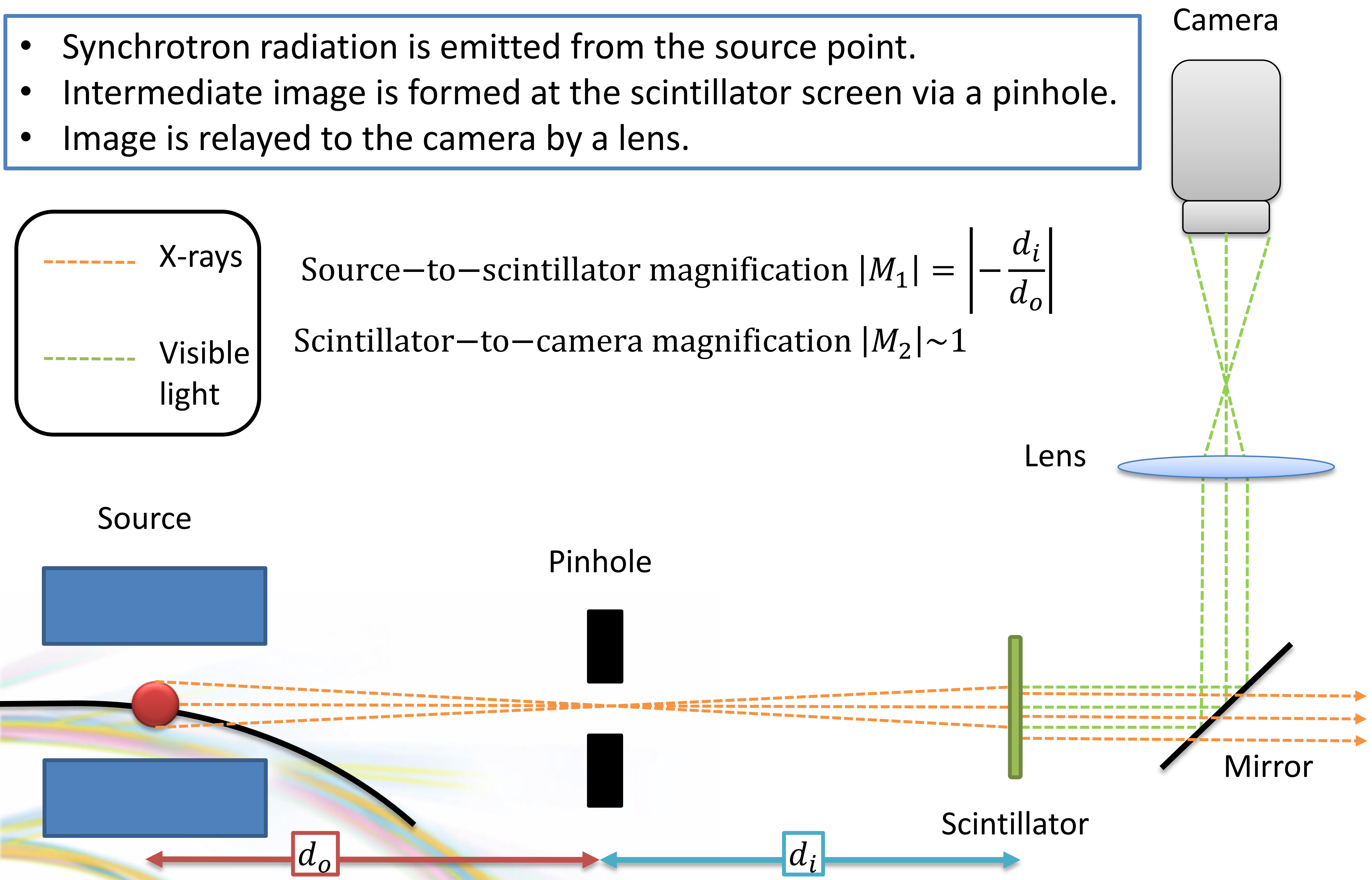
500 – 1100 AD : First experimental studies

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.

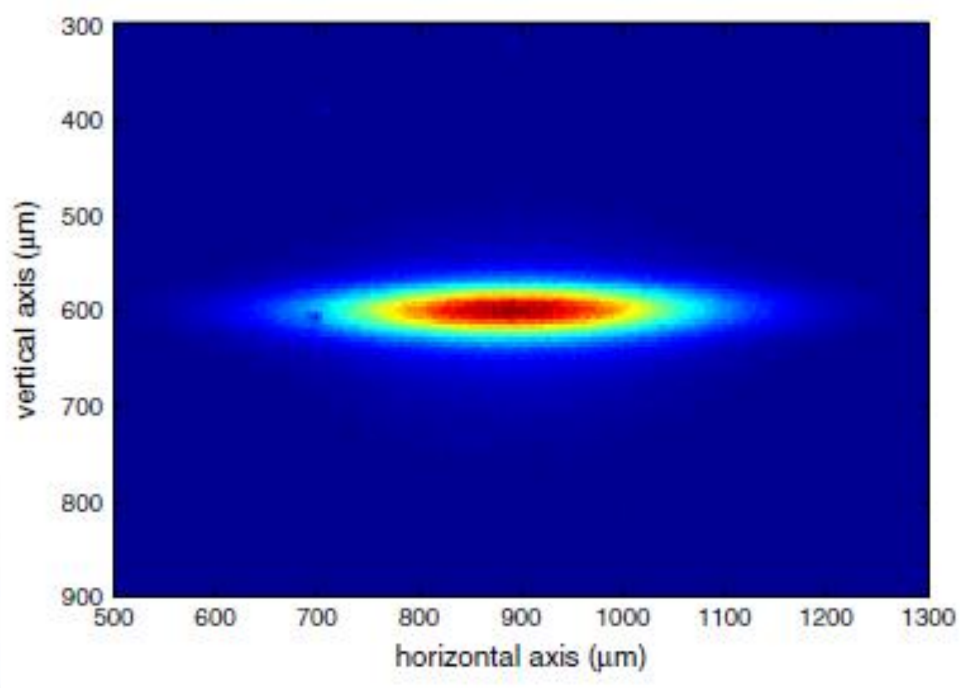
Source−to−scintillator magnification $|M_1| = \left|-\frac{d_i}{d_o}\right|$

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:

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

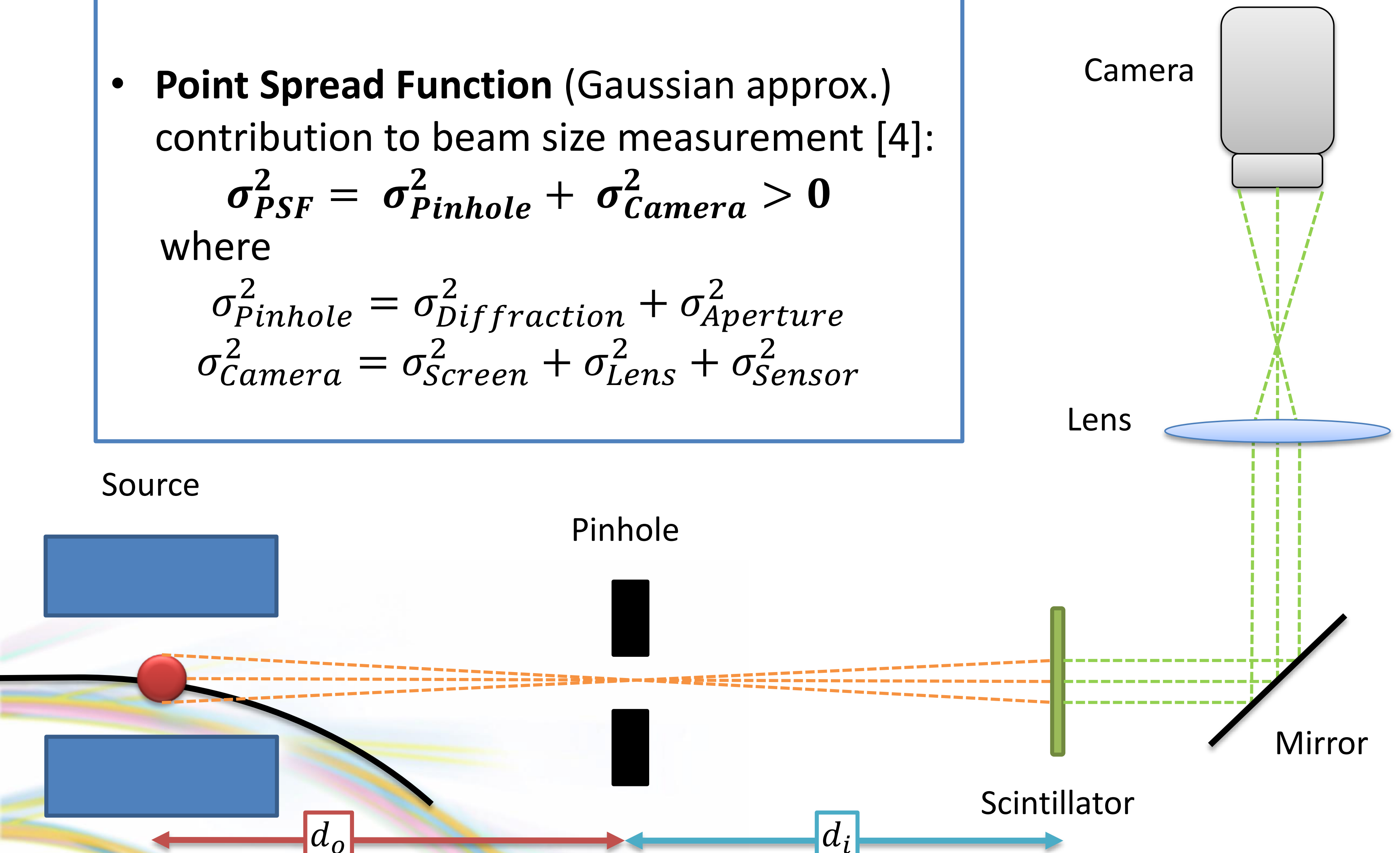
Fundamental Limitations

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

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

where

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



Fundamental Limitations

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

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

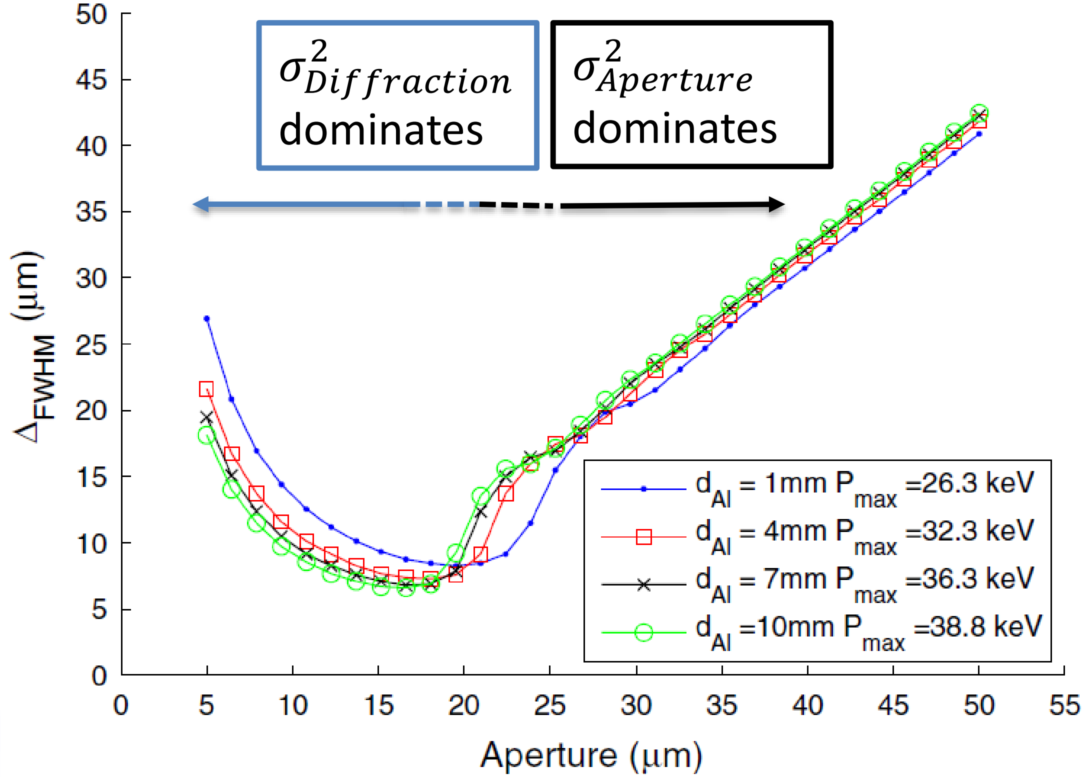
$$\frac{\left(\frac{\Delta_{FWHM}}{2.35}\right)}{|M_1|} \sim \frac{\left(\frac{6\ \mu\text{m}}{2.35}\right)}{2.65} \sim 1\ \mu\text{m}$$

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

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)



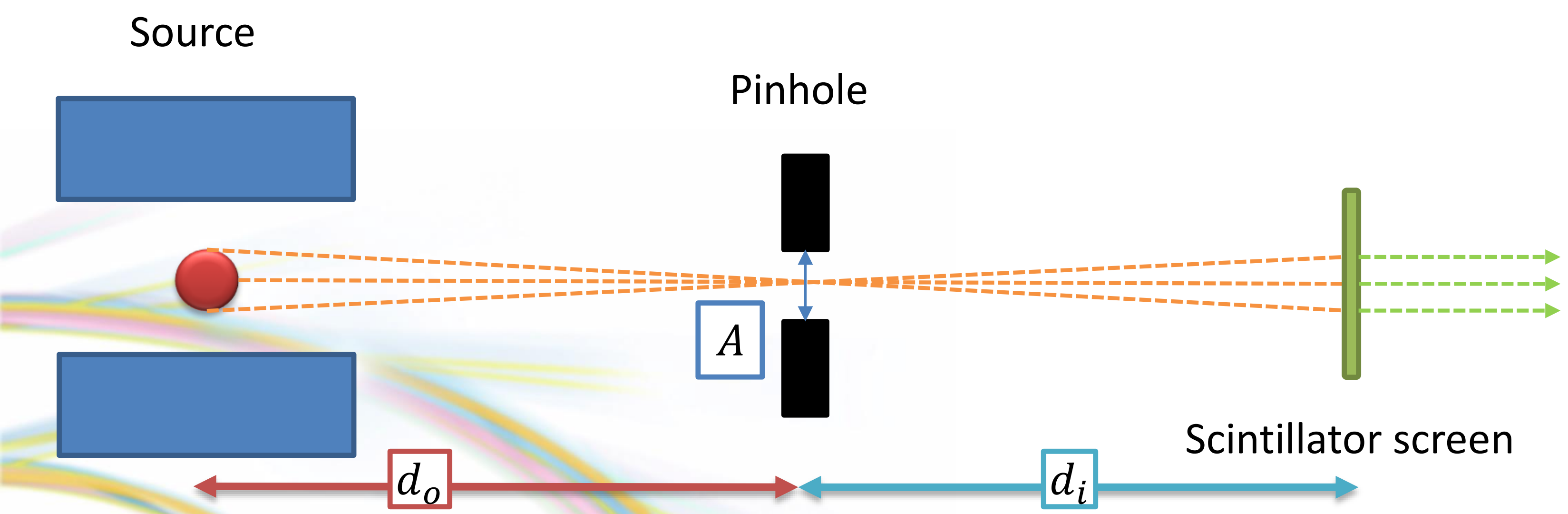
Practical Challenges

- Spatial constraints
  - For sufficient source-to-screen magnification ($|M_1| = \left|-\frac{d_i}{d_o}\right| \geq 2$):

    → X-ray path length $(d_o + d_i) \geq 10\text{m}$

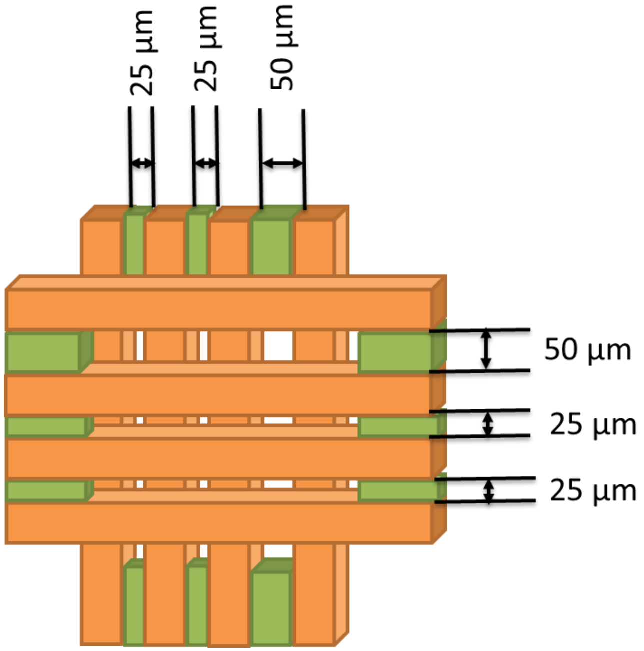
  - Diffraction contribution to PSF from pinhole worsens with distance given a fixed aperture size A :

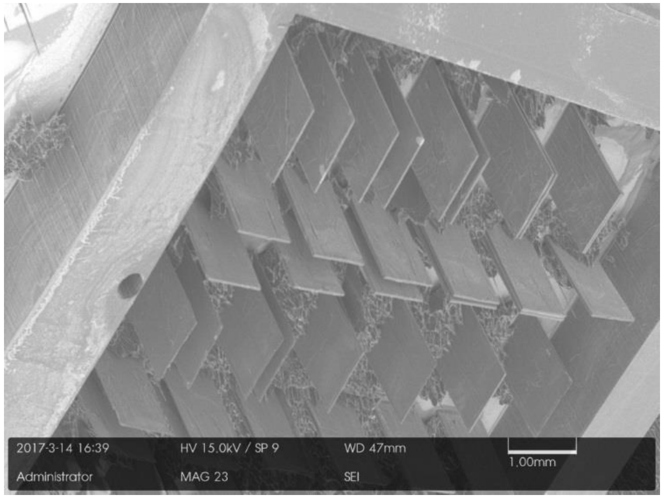
$$\sigma_{Diffraction} = \frac{\sqrt{12}}{4\pi}\frac{\lambda d_i}{A}$$ for wavelength λ [5].



Practical Challenges

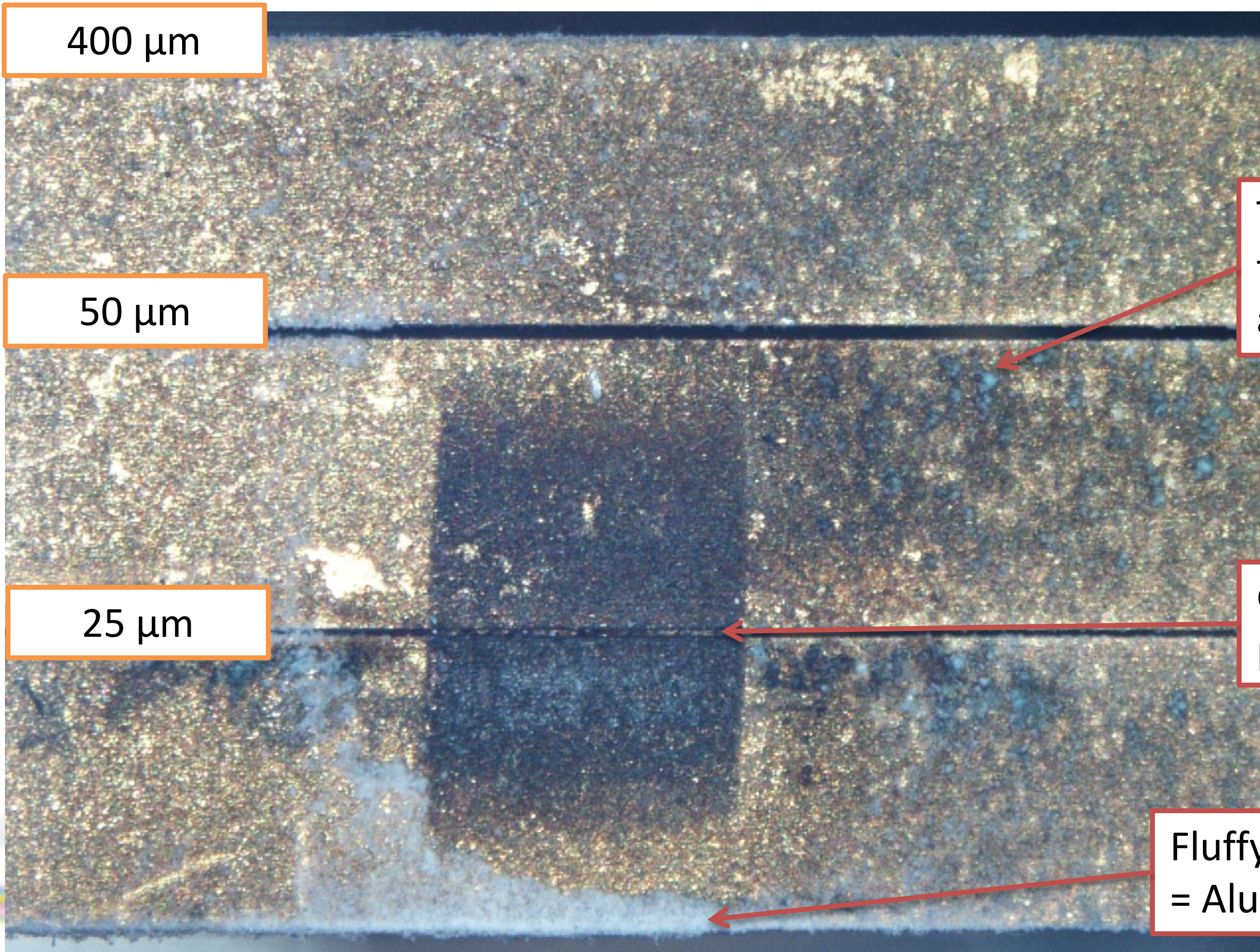
- Pinhole fabrication
  - For the pinhole to be opaque to keV X-rays a high Z material is required e.g. 1mm thick Tungsten.
  - Often these materials are difficult to machine.
  - Especially given the high aspect ratio 10 µm (aperture): 1mm (thickness)
    → 1:100





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

Nov 2014: Gold Plated Tungsten Blades



Upstream view of Pinhole 2

Practical Challenges

- Low photon flux through pinhole
  - Monochromatic vs white beam? Attenuation?
  - Generally a multi-turn diagnostic given tens of ms exposure time
- Knowledge of the lattice parameters
  - Errors on the lattice parameters from LOCO will propagate to the error on the obtained emittance
- PSF contribution
  - $\sigma_{PSF} > 0$
  - Thus some post-processing deconvolution is needed
  - Simulation of the PSF is not trivial
- Cost

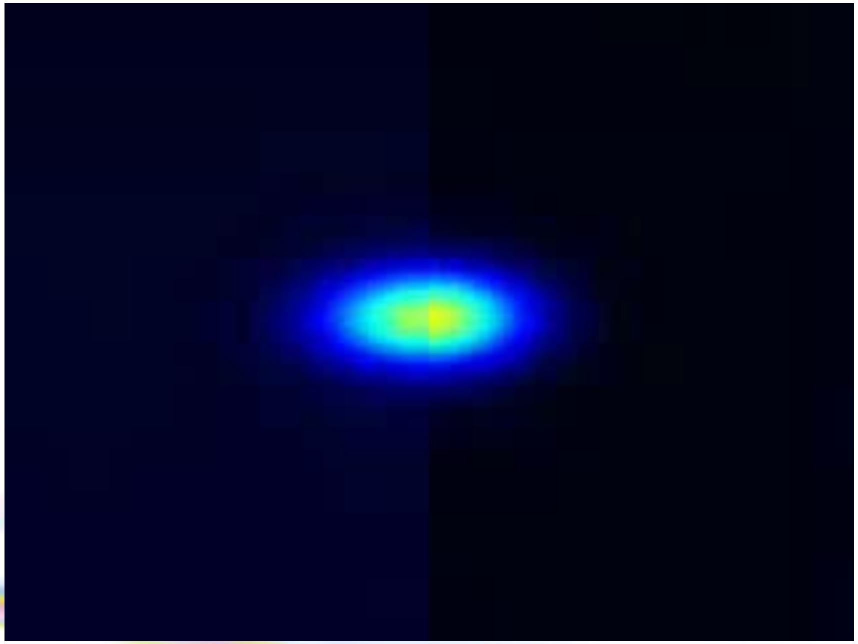
Now tell us the perks!

- 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.

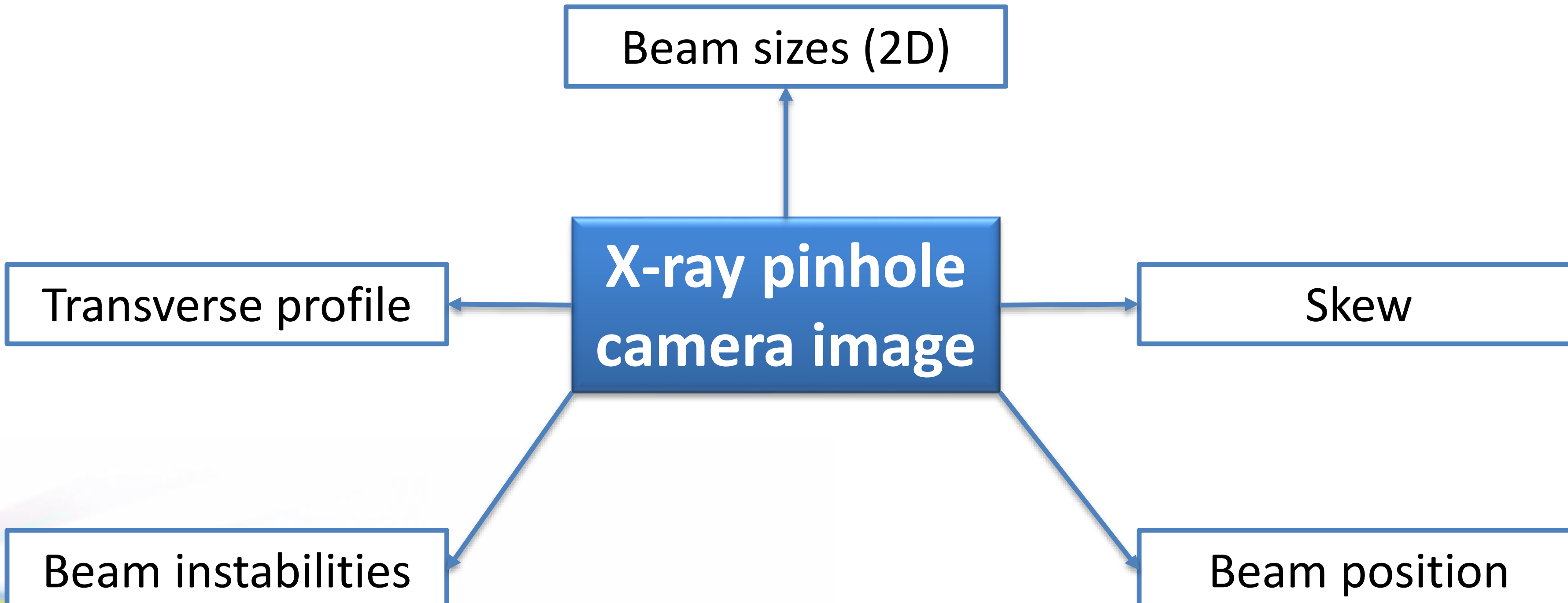


Injection at Diamond 2015

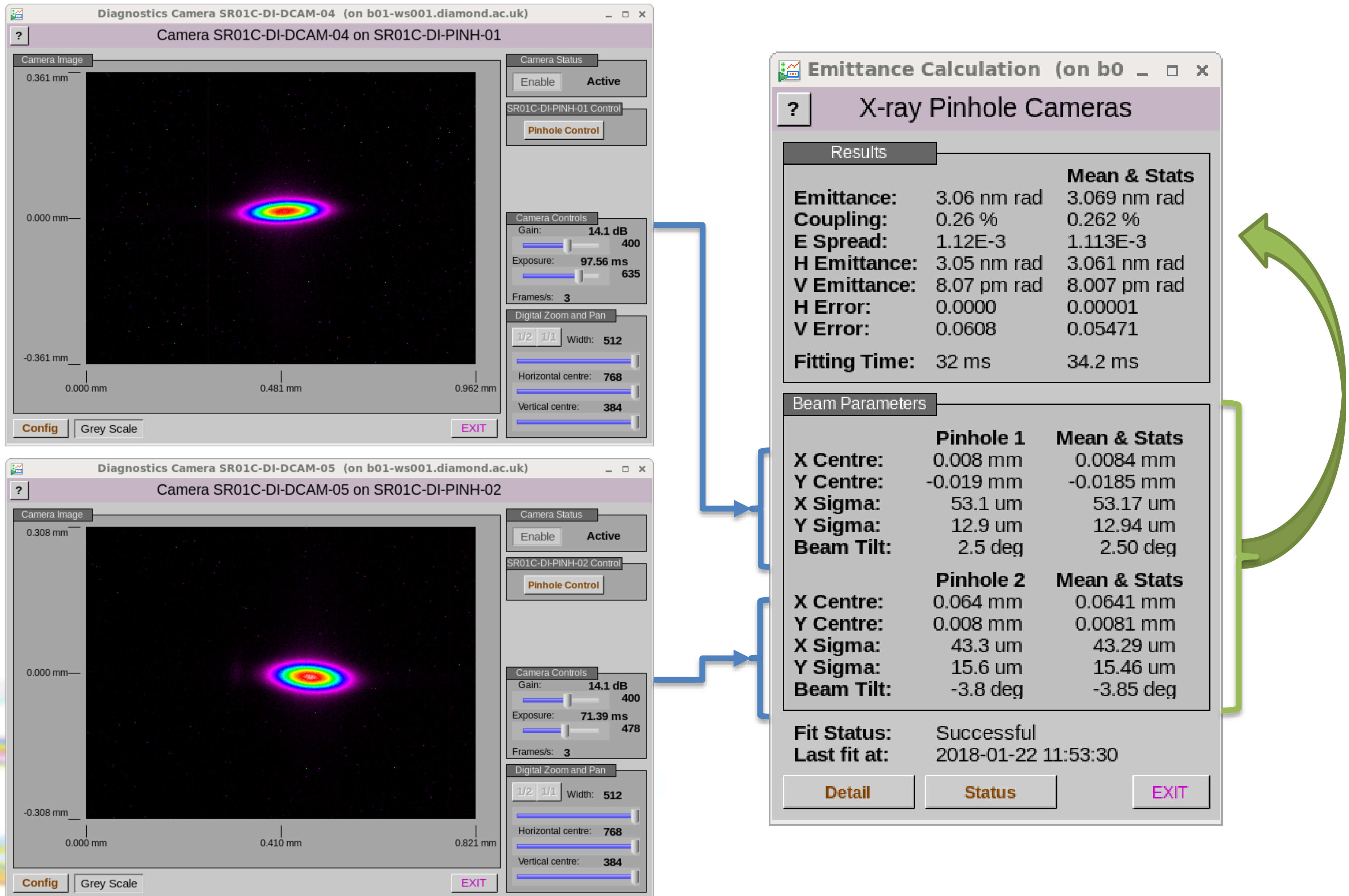
TMBF at Diamond 2015

Dual Purpose Diagnostic

Emittance Monitoring + **CCTV**

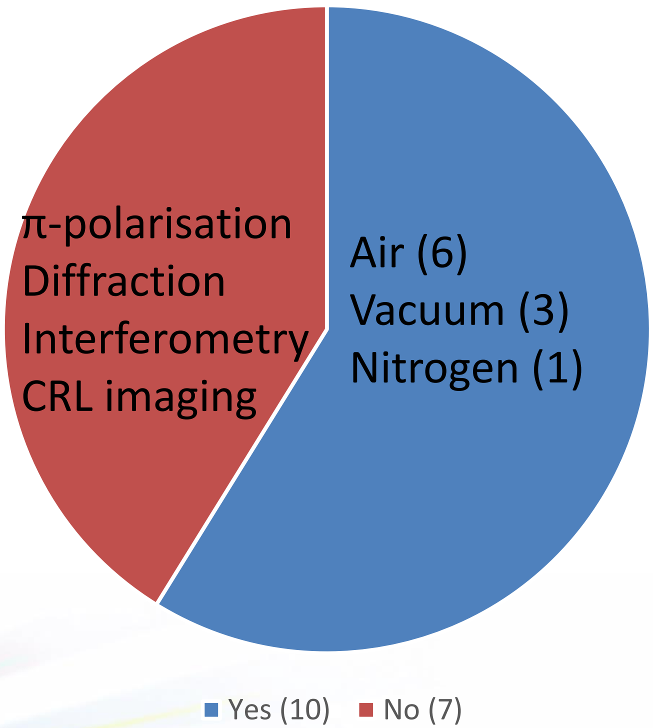


In Operation

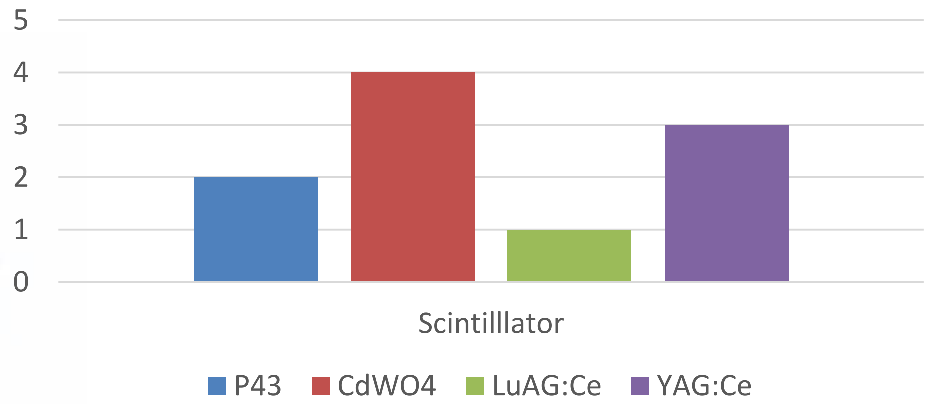


"Snapshot" of Current Status

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

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[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.

Acknowledgements

Thank you for your attention.

Thanks to the Diamond Diagnostics group and to all those who participated in the survey!

Ximenes Rocha Resende	Brazilian Synchrotron Light Laboratory	Kuo-Tung Hsu	TPS/NSRRC
Åke Andersson	MAX IV Laboratory	Marcel Schuh	KARA / KIT
Volker Schlott	PSI	Suntao Wang	CESR/CHESS
Yongbin	SSRF/SINAP	Friederike Ewald	ESRF
Shiro TAKANO	SPring-8	Marie Labat	SOLEIL
Rohan Dowd	Australian synchrotron	Gero Kube	DESY
Akash Deep Garg	RRCAT Indore INDIA	Ubaldo Iriso	ALBA
Oleg Meshkov	BINP	Jeff Corbett	SLAC

END

Not Limitations… "Challenges!"

Challenge	Potential Solutions
Spatial constraints	Dedicated diagnostic beamlines?
Pinhole fabrication	Investigate alternative techniques e.g. LIGA [6], 3D printing and materials that can be machined [7].
Environment	Solutions are already available depending on desired accessibility and cost.
Low intensity	Increase numerical aperture to intensified camera? Use a new scintillator material with greater photon yield (see talk by G. Kube).
Error on lattice parameters	Improve LOCO?
PSF	Reduce PSF through upgrading components. Lucy-Richardson deconvolution algorithm given accurate simulation on PSF?