Methods for sub-micron beam size measurements in circular accelerators

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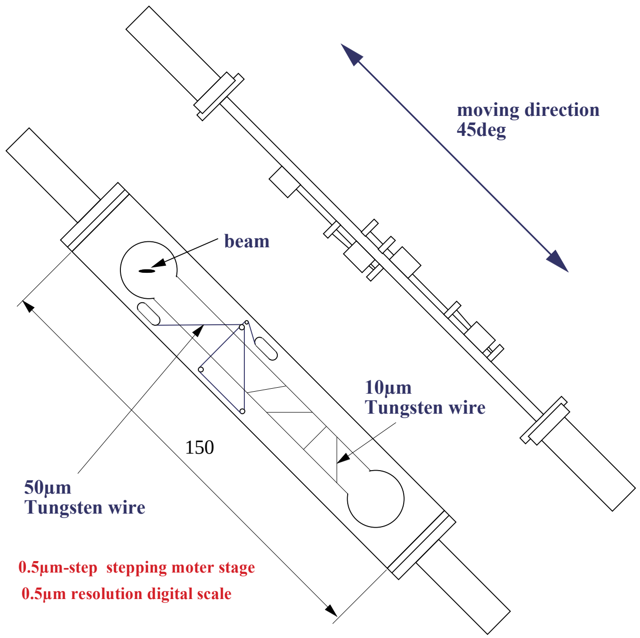
Introduction

- Interceptive methods
  - Wire scanner
  - Screen imaging (OTR, YAG etc.)
  - Screen interferometry

- Non intercepting
  - Synchrotron radiation imaging
  - Synchrotron radiation interferometry
  - Diffraction radiation
  - Laser wire scanner

Wire scanner

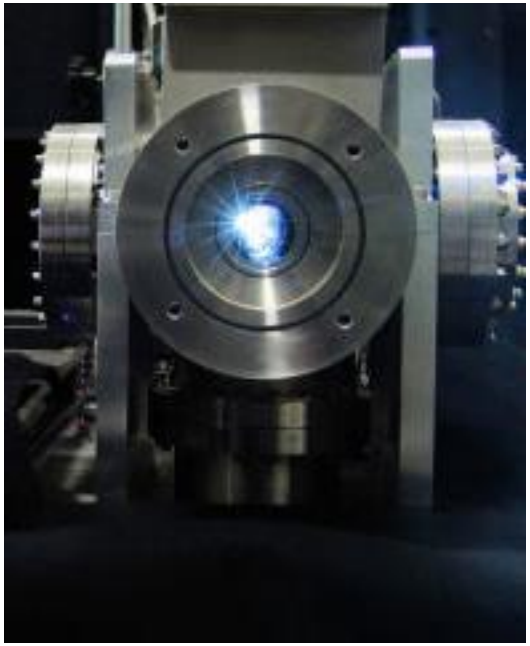
- Used as reference in many particle accelerators
- Few microns resolution achieved (SLC, ATF) on LINAC or transfer line [1]
- Difficult to use in rings due to wire damage



Ex.: for a 4 µm carbon wire moving at 1 m/s in a ring with rev. time of 1 µs and beam of $\sigma_{x,y}$ of 10 µm the limit is around 10^9 particles [2]

Synchrotron radiation

- Widely used for online monitoring of beam parameters in electron/positron rings
- Radiation generated in all bending magnets
- Need only an extraction viewport and an adequate optical system to obtain the image of the beam
- In most rings however the emitted radiation is diffraction limited

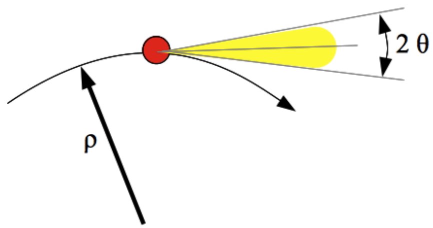


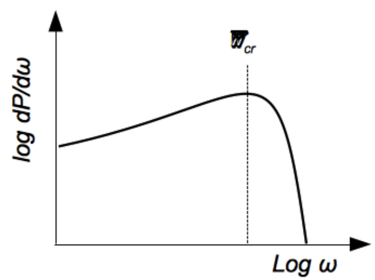
Synchrotron radiation imaging

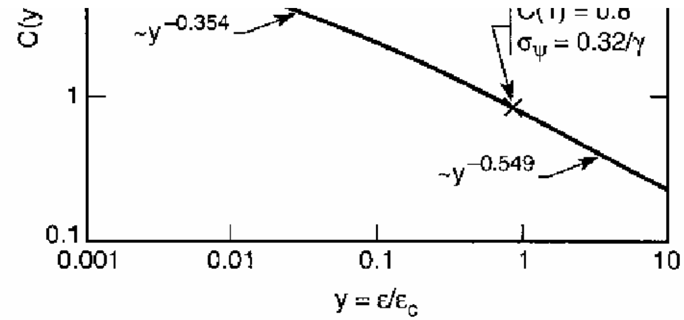
$$P = \frac{1}{4\pi\epsilon_0}\frac{2}{3}\frac{ce^2\gamma^4}{\rho^2}$$

$$\omega_{cr} = \frac{3}{2}\frac{c\gamma^3}{\rho}$$

$$\sigma_\theta = \frac{2}{\gamma\sqrt{2\pi}}C(y)$$







. 2-3. The function C(y). The limiting slopes, for $\varepsilon/\varepsilon_c$ << 1 and ε/ >> 1, are indicated.

ere σ_ψ is given by

$$\sigma_\psi = \frac{2}{\gamma\sqrt{2\pi}}C(y) = 0.408\frac{C(y)[\text{mr}]}{E[\text{GeV}]} \quad (7)$$

X-Ray data booklet

Diffraction limit

$$\sigma_{diff} \simeq 1.22\frac{\lambda}{8\sigma_\theta}$$

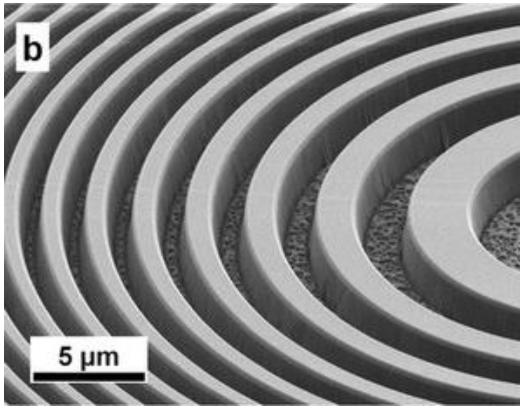
For E= 2 GeV (γ~ 4000) λ= 400 nm and ρ= 10 m
E_{cr}=1.7 keV
resolution is around 25 μm (240 μm using 1/γ)

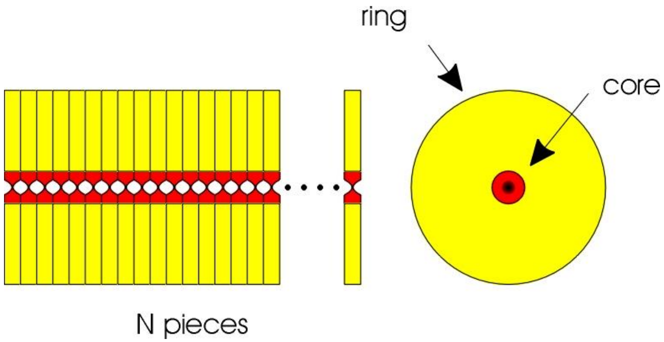
X-rays imaging

- Reducing the wavelength we can improve the diffraction limit

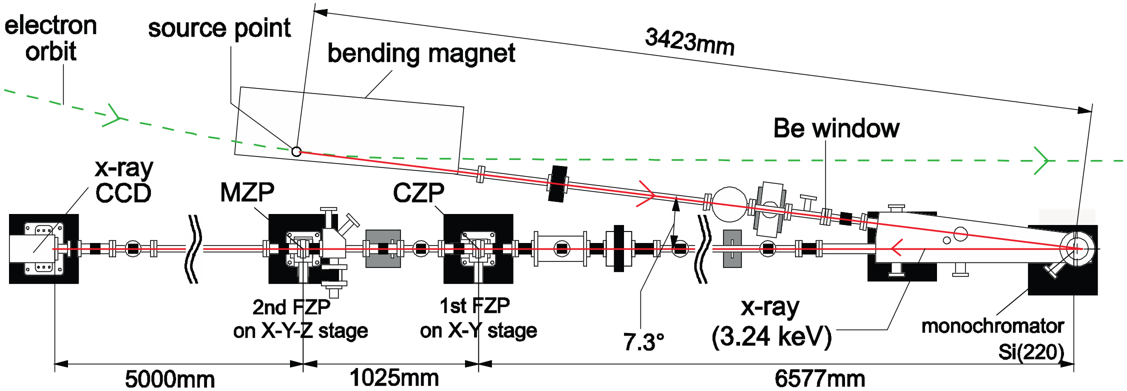
  For E= 2GeV (γ= 4000) ρ= 10 m and λ= 0.4 nm (3 keV) the diffraction limit is around 0.5 μm

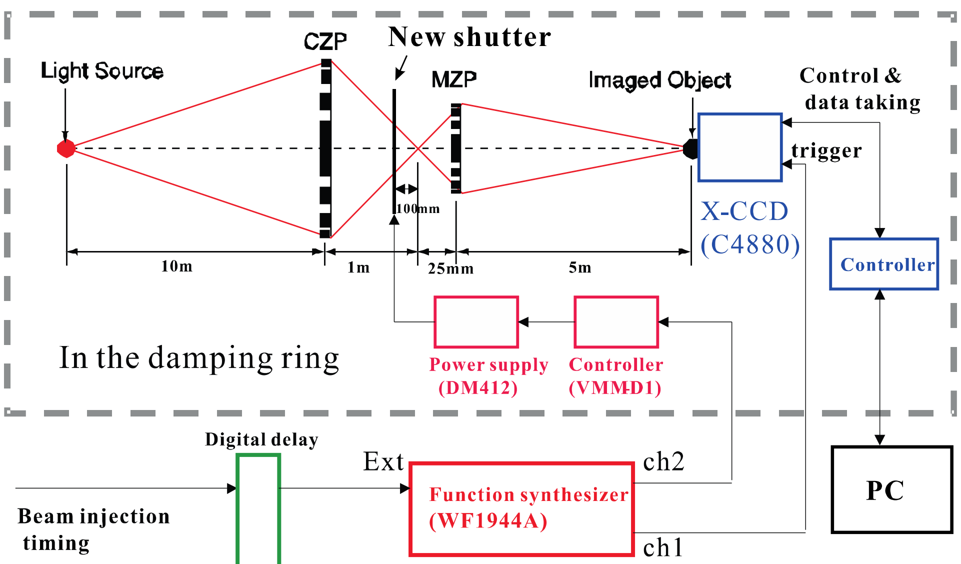
- Still need an optical system for X-rays with very good optical properties
- Fresnel plates
- Compound refractive lenses
- Pin-hole

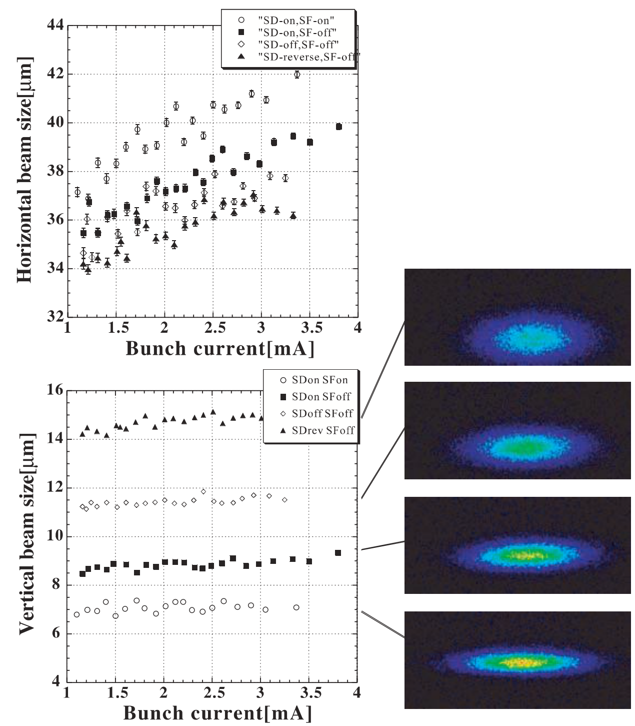




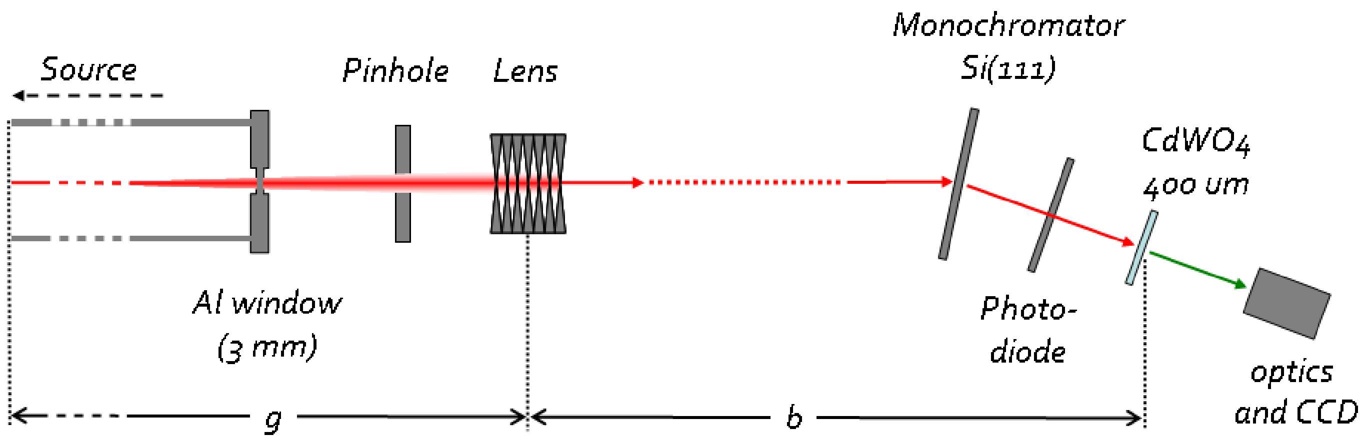
SR imaging using FZP at ATF [3]

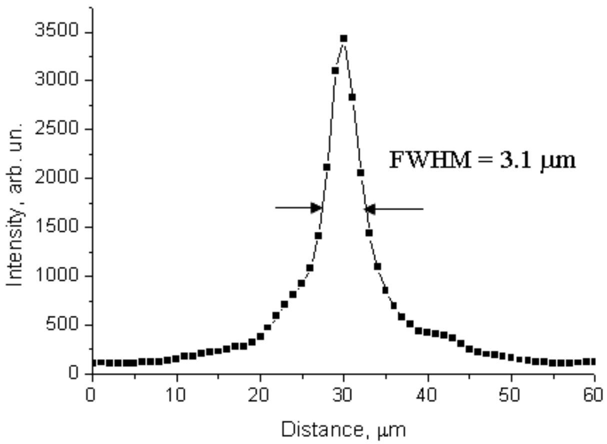






SR imaging at ESRF [4]



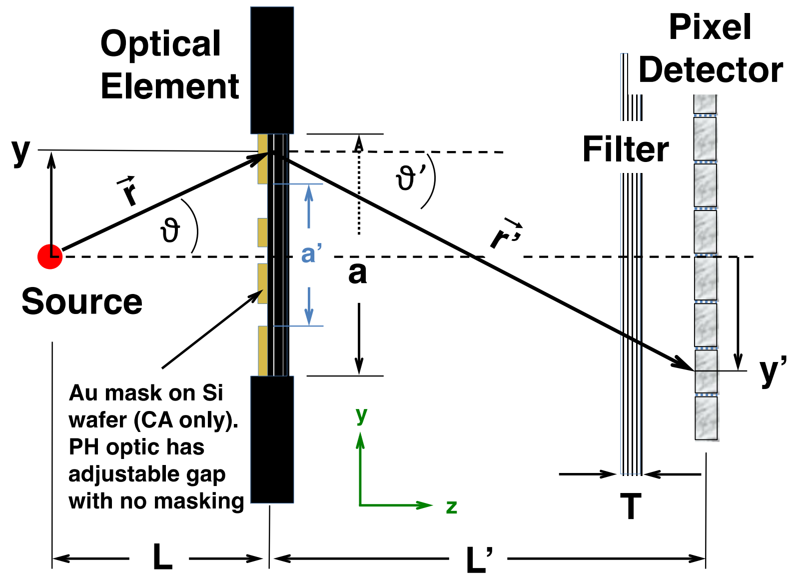


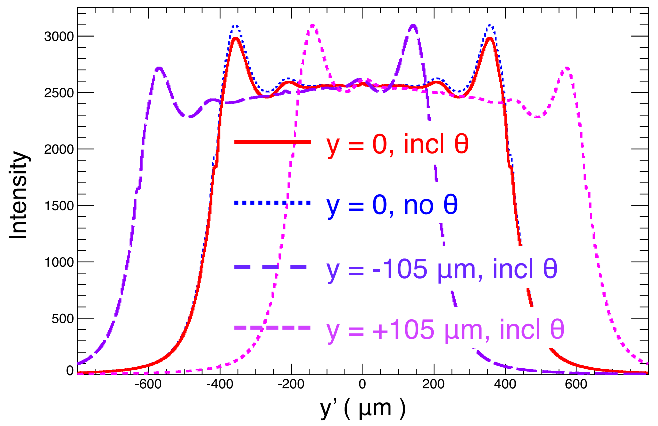
Vertical beam profile obtained with 12.5 keV photons and 5 Al lenses of 49µm curvature radius

29 lenses are used at 45.6 keV for a focal length of 3.3 m

SR imaging at CeSR-TA [5]

- Pin-hole camera
  - Single slit 50-1000 μm
  - Coded aperture
- 1 keV to 10 keV photons
- Measured beam of 12 μm with 0.5 μm error
- Complex deconvolution of PRF
- Can do single turn single bunch acquisitions
- array of 32 InGaAs photodiodes with 50 μm pitch



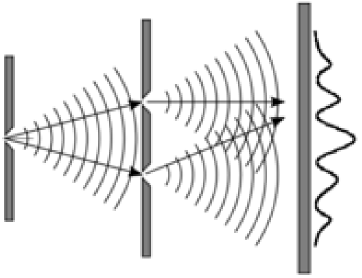


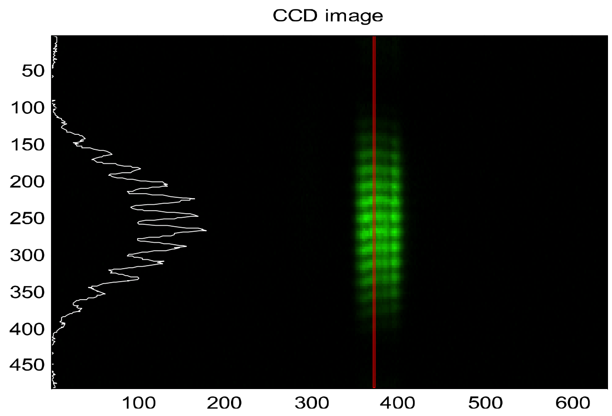
SR interferometry

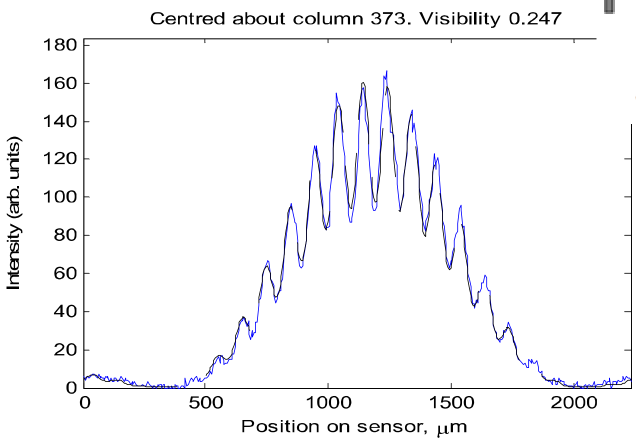
- Alternative to imaging
- Interference fringes produced by SR passing trough two slits (Young's interferometer)
- Visibility of fringes depends on source (beam) size

$$I(y,D) = (I_1 + I_2)\cdot\left\{\mathrm{sinc}\left(\frac{\pi\cdot a\cdot y\cdot\chi(D)}{\lambda\cdot f}\right)\right\}\cdot\left\{1+\gamma\cdot\cos\left(k\cdot D\cdot\left(\frac{y}{f}+\psi\right)\right)\right\}$$

$$\gamma = \left(\frac{2\sqrt{I_1\cdot I_2}}{I_1+I_2}\right)\left(\frac{I_{max}-I_{min}}{I_{max}+I_{min}}\right),\quad \psi = \tan^{-1}\frac{S(D)}{C(D)}$$



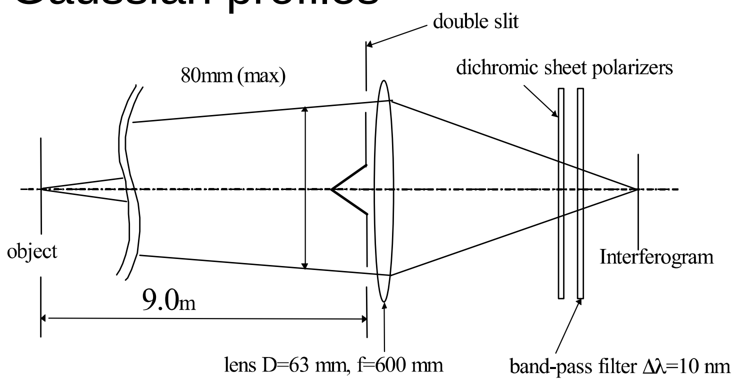


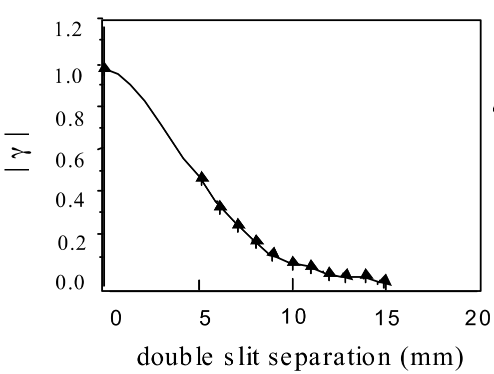


SR interferometer at KEK [6]

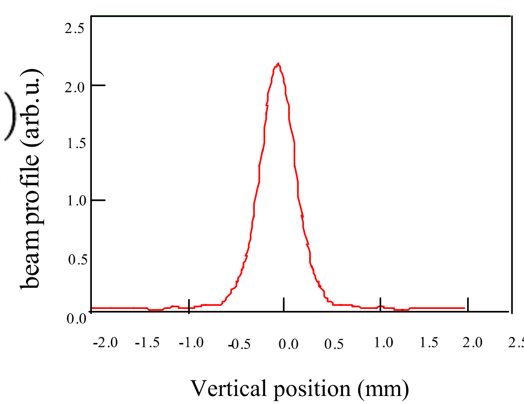
Developed by Toshi Mitsuhashi at the KEK Photon Factory. Works at 500 nm

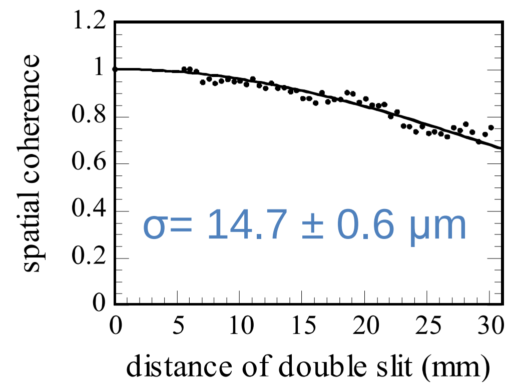
Very small beams can be measured assuming Gaussian profiles

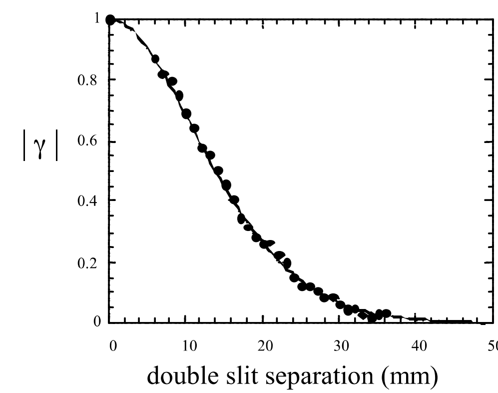




$\mathcal{F}(D)$



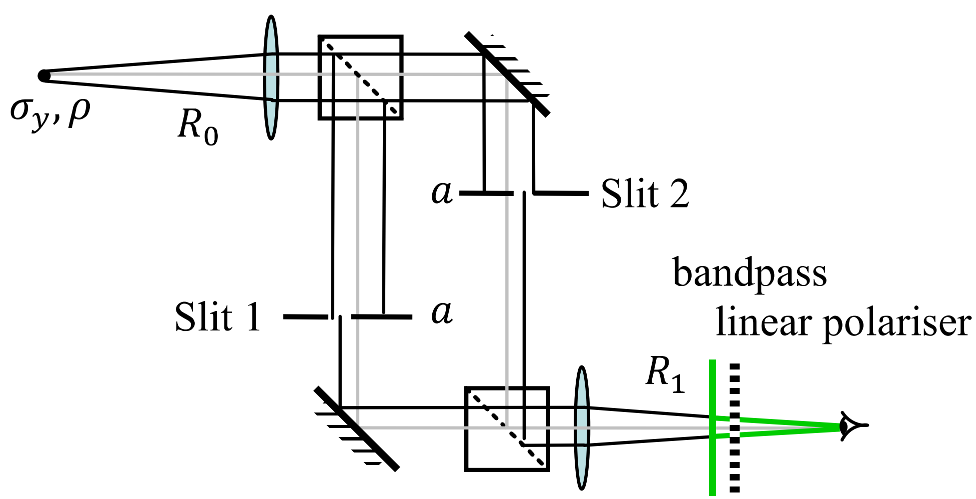


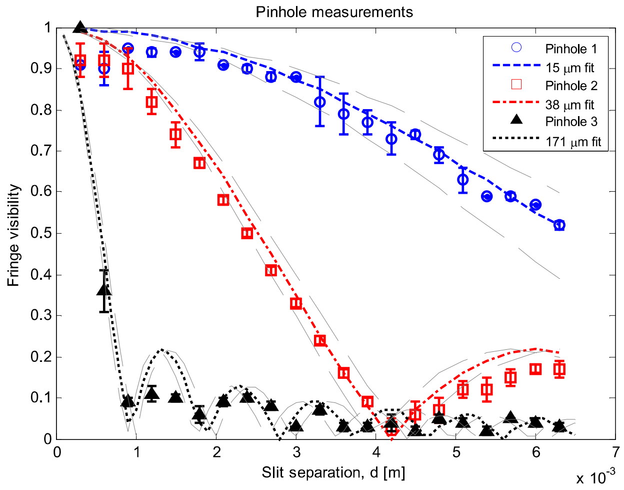


σ= 39 ± 1 μm

Another slit solution [7]

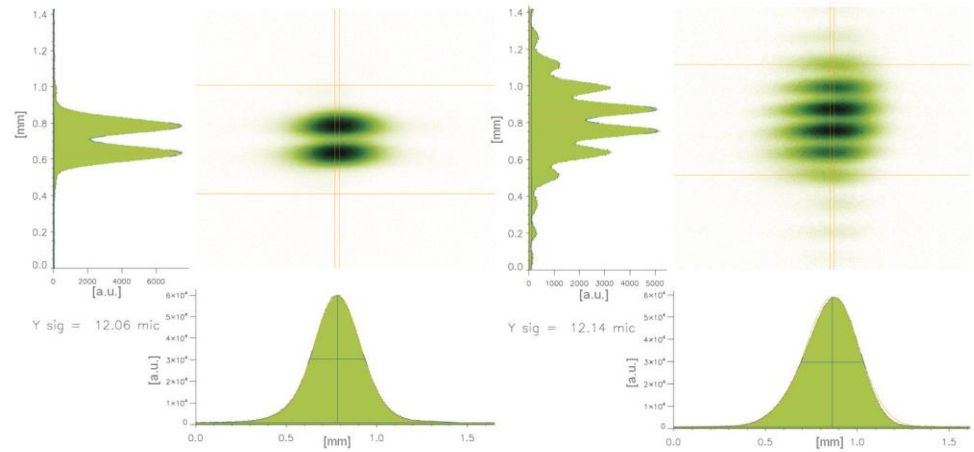
- Solution implemented at the Australian synchroton
- No mechanical limit on the distance between slits
- Designed for 532 nm
- Demonstrated pin-hole measurement 15 ±2 μm

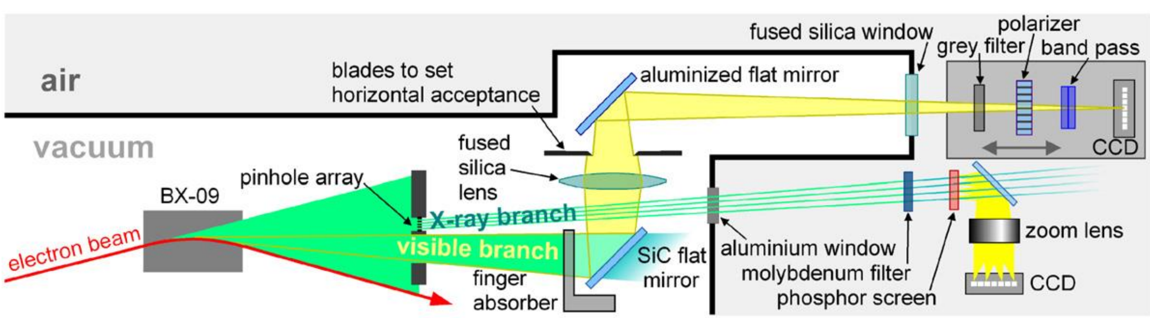


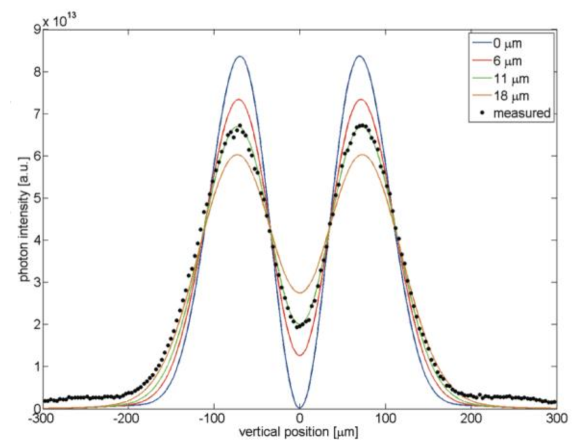


Alternative interferometry at SLS [8]

- Uses the two lobes of the π polarization to create a “natural” interferometer
- Possible to insert a mask between the lobes to increase the visibility
- Measured 3.6 ± 0.6 μm

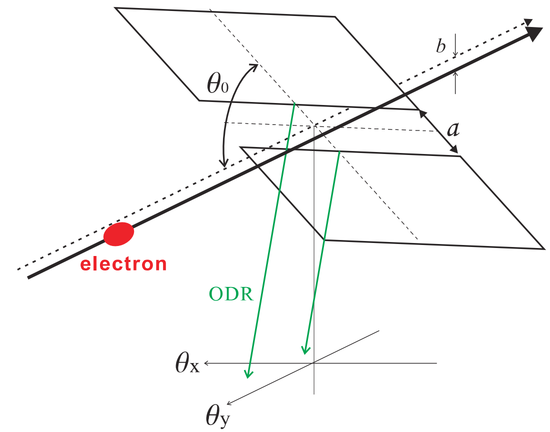


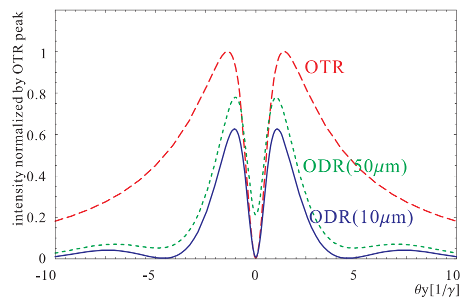




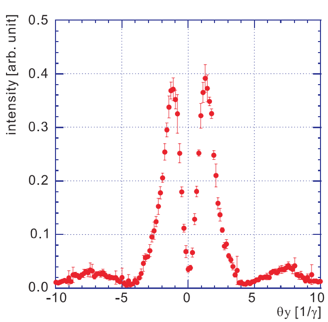
Diffraction radiation [9]

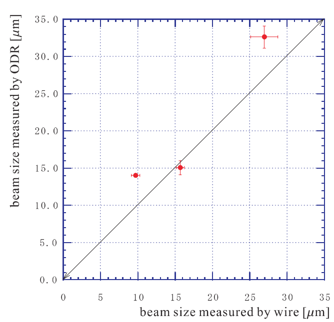
- Based on the analysis the angular distribution of the “vertical” polarization of the optical diffraction radiation

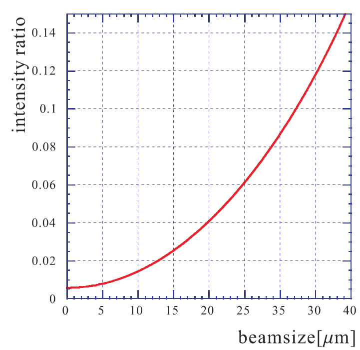




$$\frac{dW_y}{d\omega d\Omega} = \frac{\alpha\gamma^2}{2\pi^2}\frac{\exp\left(-\frac{2\pi a\sin\theta_0}{\gamma\lambda}\sqrt{1+t_x^2}\right)}{1+t_x^2+t_y^2}\times$$
$$\left\{\exp\left(\frac{8\pi^2}{\gamma^2\lambda^2}\sigma_y^2\left(1+t_x^2\right)\right)\cosh\left(\frac{4\pi b}{\gamma\lambda}\sqrt{1+t_x^2}\right)\right.$$
$$\left.-\cos\left(\frac{2\pi a\sin\theta_0}{\gamma\lambda}\theta_y+\psi\right)\right\} \qquad (1)$$



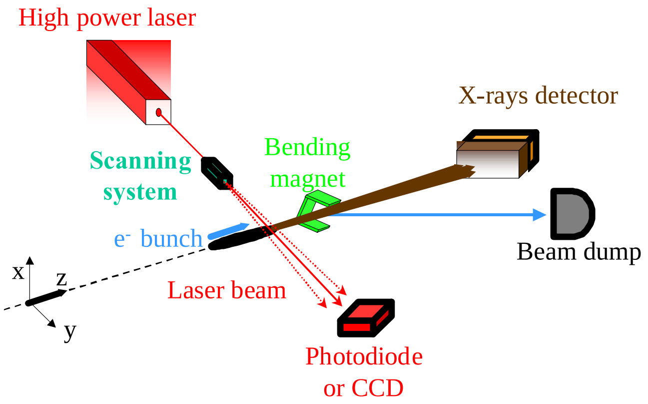


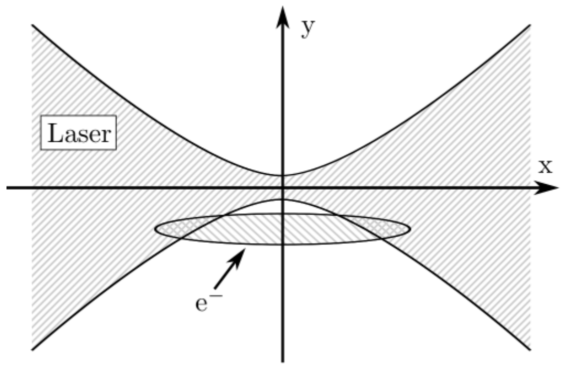


ATF: E=1.28 GeV, λ= 550 nm

Laser wire scanner

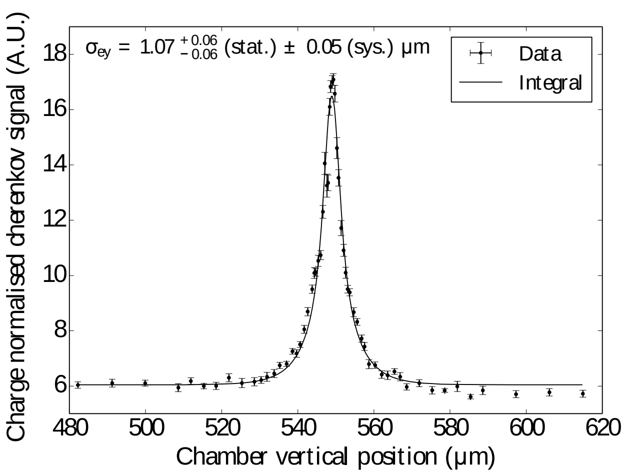
- Scan a collimated laser beam across the electron beam and observe the X-Rays/γ-Rays produced in the inverse Compton scattering process
- Difficult to measure small beams with high aspect ratio (Rayleigh range)

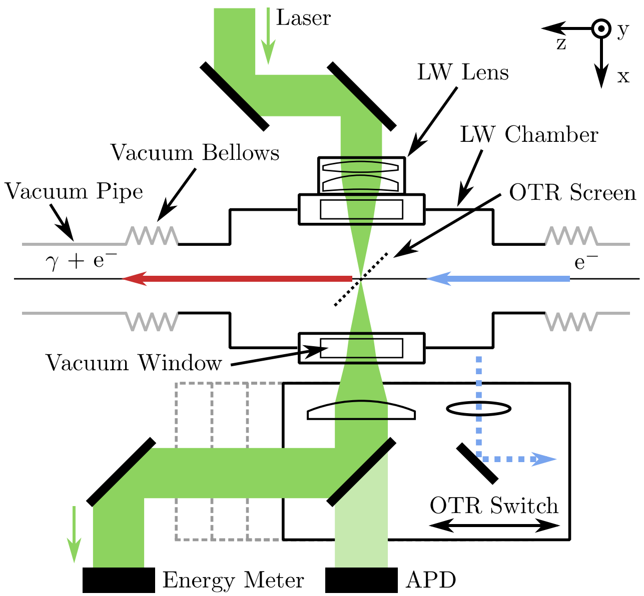




LWS at ATF [10]

- 1.28 GeV beam on extraction line of ATF
- Vertical beam size around 1μm
- Horizontal size 100μm
- Laser 532 nm focused to 1μm
- Fit data with complex model





Conclusions

- A selection of methods presented with relative examples
- Measuring small (microns) beams is possible
- Measuring small (microns) beams is difficult
- For circular machines methods based on synchrotron radiation are the most indicated

But … if you really need to measure sub-micron beams
T. Shintake et al.,
"EXPERIMENTS OF NANOMETER SPOT SIZE MONITOR AT FFTB USING LASER INTERFEROMETRY"

References

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