ICFA FLS 2006
37th ICFA Advanced Beam Dynamics Workshop on Future Light Sources

Synchrotron Radiation based transverse Emittance Diagnostics at Light Sources

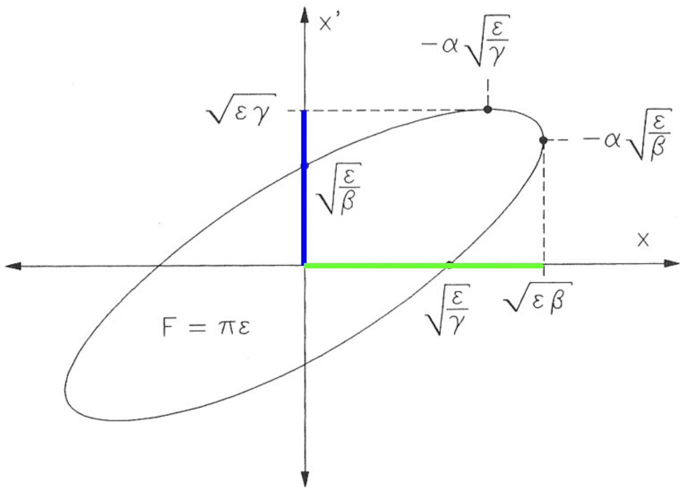
Gero Kube
DESY / MDI
gero.kube@desy.de

- storage rings
- bending magnets
- standard systems

HELMHOLTZ GEMEINSCHAFT
DESY

Beam Emittance

- projected area of transverse phase space volume
- emittance ε not directly accessible for beam diagnostics



- beam size

$$\sigma = \sqrt{\varepsilon\,\beta}$$

- beam divergence

$$\sigma' = \sqrt{\varepsilon\,\gamma}$$

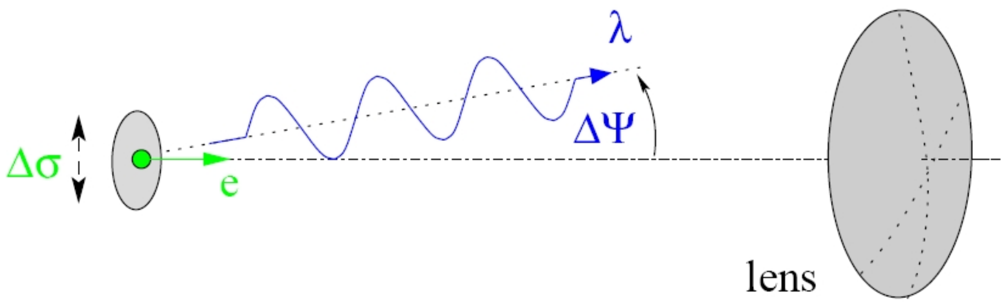
- dispersion: $\sigma = \sqrt{\varepsilon\,\beta + (\eta\,\Delta p / p)^2}$ $\sigma' = \sqrt{\varepsilon\,\gamma + (\eta'\,\Delta p / p)^2}$
- influence of radiation properties σ_{rad}
- monitor resolution σ_{mon}

÷ photon beam spot σ_{ph} ÷ $\varepsilon(\beta, \gamma, \eta, \eta', \Delta p / p, \sigma_{\text{ph}}, \sigma_{\text{mon}}, \sigma_{\text{rad}})$

measure calculate

Resolution Limits

- direct approach: imaging of beam profile



uncertainty principle:

$$\Delta\sigma \approx \frac{\lambda}{2\Delta\Psi}$$

- synchrotron radiation: small vertical emission angle G\

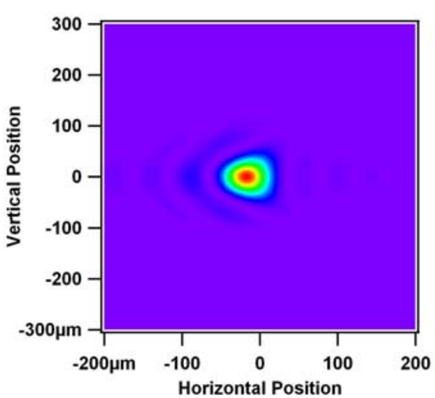
typical half opening angle $(\lambda \geq \lambda_c)$:

$$\Delta\Psi = \frac{1}{\gamma}\left(\frac{\lambda}{\lambda_c}\right)^{1/3}$$

÷ resolution fully limited by uncertainty principle

- example: HERA monitor

near field calculation of PSF including resolution broadening and depth of field at ○@ 500 nm



Resolution Improvements

ESRF: E = 6 GeV, o$_c$= 0.35 nm

o@ 833 nm ÷ Gv$_v$@ 593 pm

+v$_v$@ 63 pm)

uncertainty principle:

$$\Delta\sigma_V \approx \gamma\, \lambda^{2/3}\, \lambda_c^{1/3} / 2$$

1.) decrease of wavelength

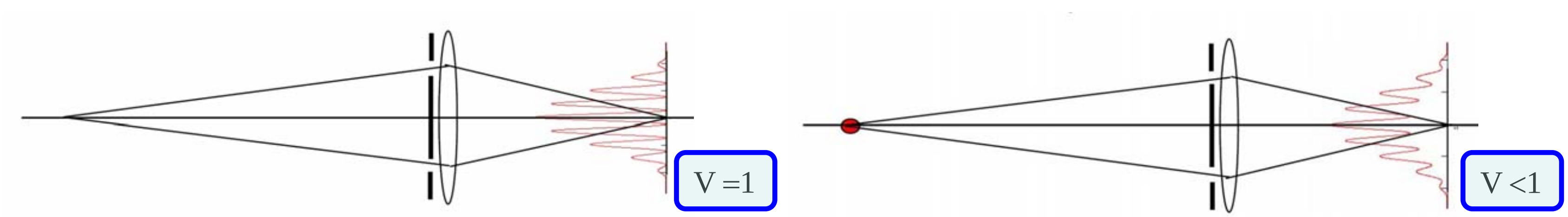
÷ VUV, soft X-ray, hard X-ray, …

o@ 31.457 nm (10 keV photons) ÷ Gv$_v$@ 4 pm

2.) interferometric approach (T. Mitsuhashi , Proc. of PAC 1997, p.766)

visibility: $$V = \frac{I_{max} + I_{min}}{I_{max} - I_{min}}$$

H. Fizeau, C.R.Acad.Sci. Paris 66 (1868) 934

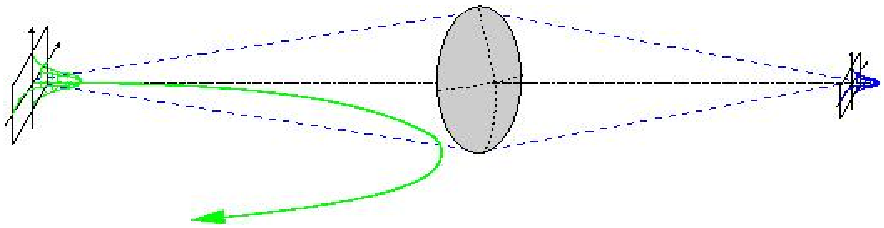


Classification

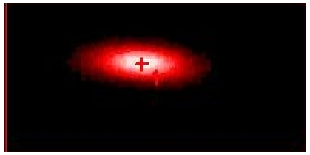
O. Chubar: *Novel Applications of Optical Diagnostics*, Proc. EPAC 2000, p.117

beam spot | wavefront manipulation | spatial resolving detector (CCD) | ÷ signal :

imaging :

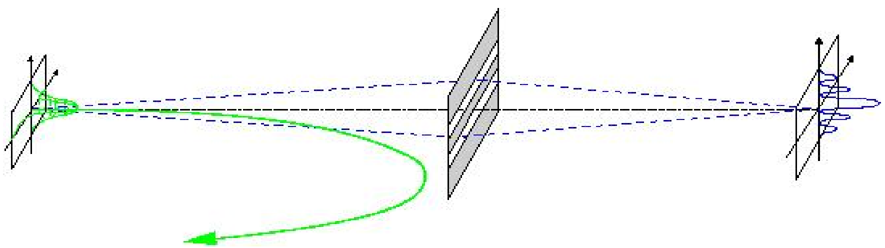


size of beam image

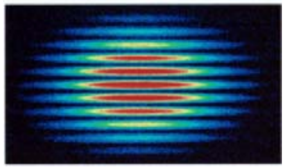


DORIS

interference :

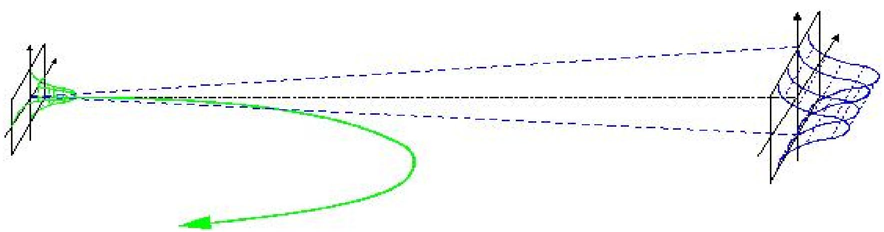


interference pattern (visibility)

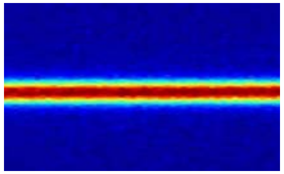


AURORA (courtesy T. Mitsuhashi)

projection :



angular distribution



ESRF (courtesy K. Scheidt)

Imaging: X-Ray Optics

complex index of refraction (X-rays):

$$n = 1 - g + i\, e$$

refractive index decrement g: $\delta \approx 10^{-6}$

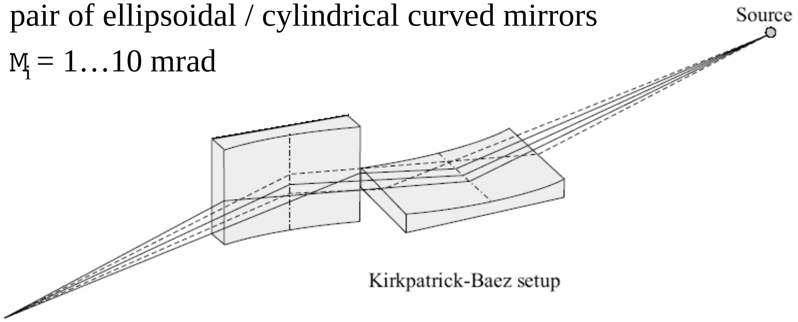
- reflective optics
- diffractive optics
- refractive optics

Imaging: X-Ray Optics

- grazing incidence optics: Kirkpatrick-Baez mirrors

pair of ellipsoidal / cylindrical curved mirrors

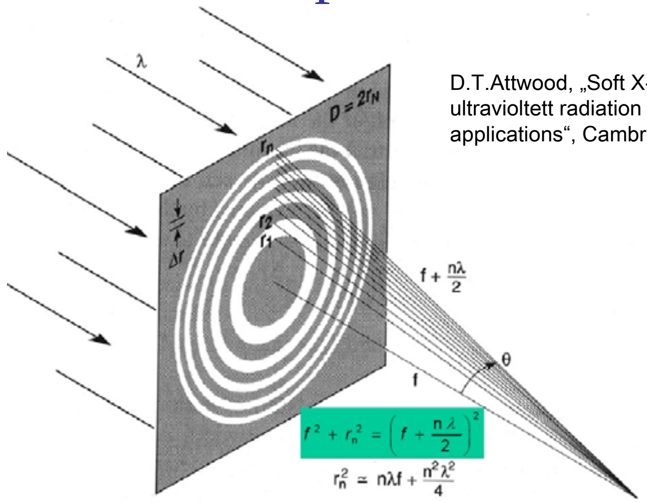
M_i = 1…10 mrad



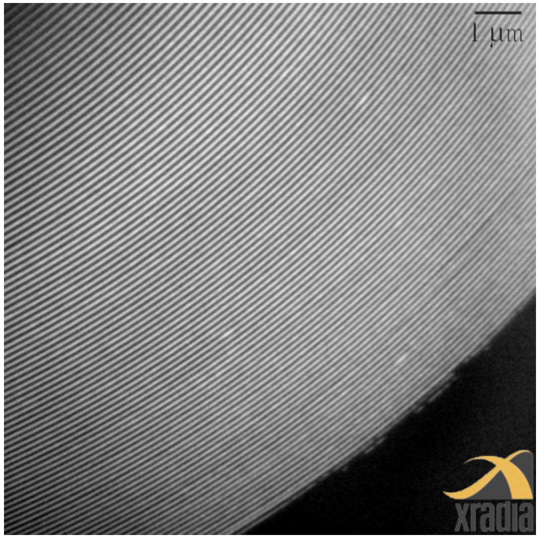
J. Tümmler: doctoral dissertation (2000), RWTH Aachen

Xradia: www.xradia.com

- Fresnel zone plates



D.T.Attwood, „Soft X-rays and extreme ultravioltett radiation principles and applications“, Cambr.Univ.Press 2000



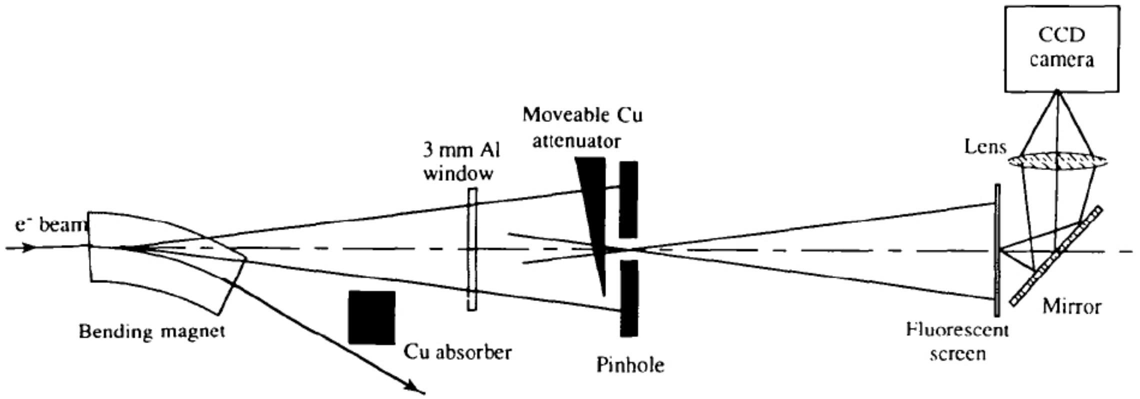
phase zone plate, Bragg Fresnel lense

Imaging: X-ray Pinhole Camera

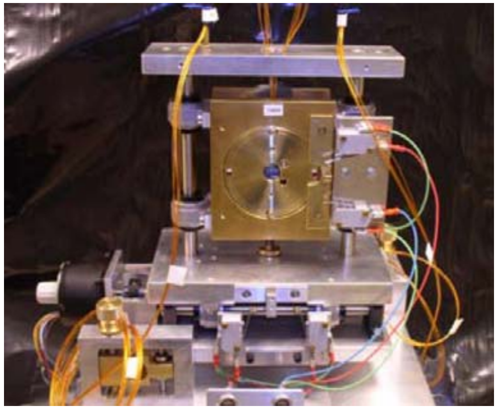
- „Camera Obscura"
  description of phenomenon already by Aristoteles (384-322 b.C.) in „Problemata"

- Setup (example: ESRF)

P.Elleaume, C.Fortgang, C.Penel and E.Tarazona, J.Synchrotron Rad. **2** (1995) , 209



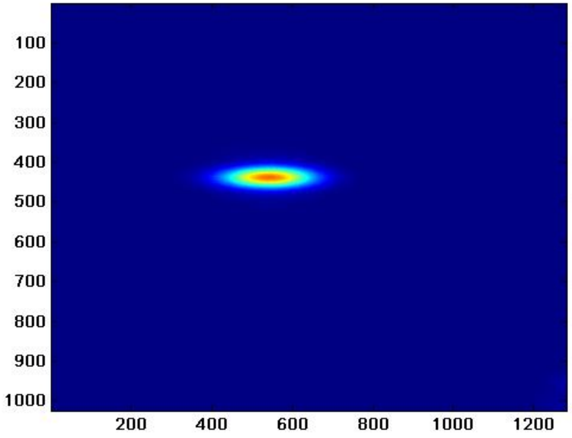
ID-25 X-ray pinhole camera:



pinhole setup @ DORIS

resolution:

$$\sigma_{res} \approx 20\,\mu m$$



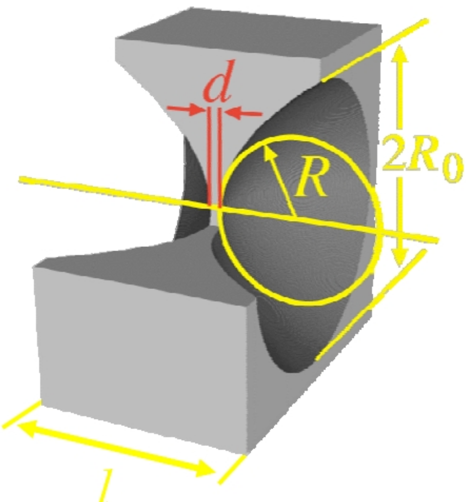
courtesy of K.Scheidt, ESRF

Imaging: Compound Refractive Lens

lens-maker formula: $1/f = 2(n-1) / R$

X-ray refraction index : $n = 1 - \delta + i\,\beta, \quad \delta \approx 10^{-6}$

- ➢ concave lens shape
- ➢ strong surface bending R

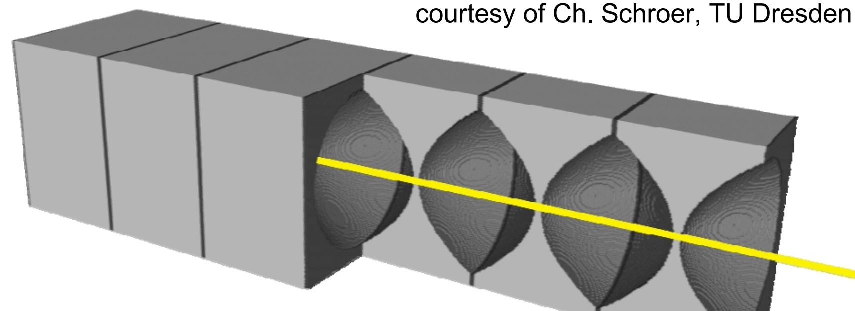


- ➢ small Z (Be, Al, …)
- ➢ small d

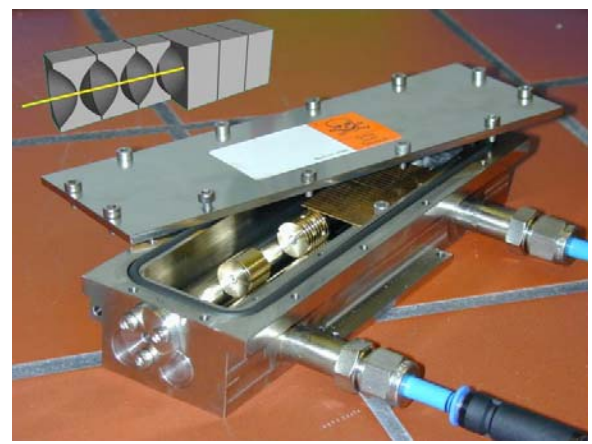
$$f = \frac{R}{2\delta N}$$

÷ many lenses

courtesy of Ch. Schroer, TU Dresden



Number of lenses: N = 10...300



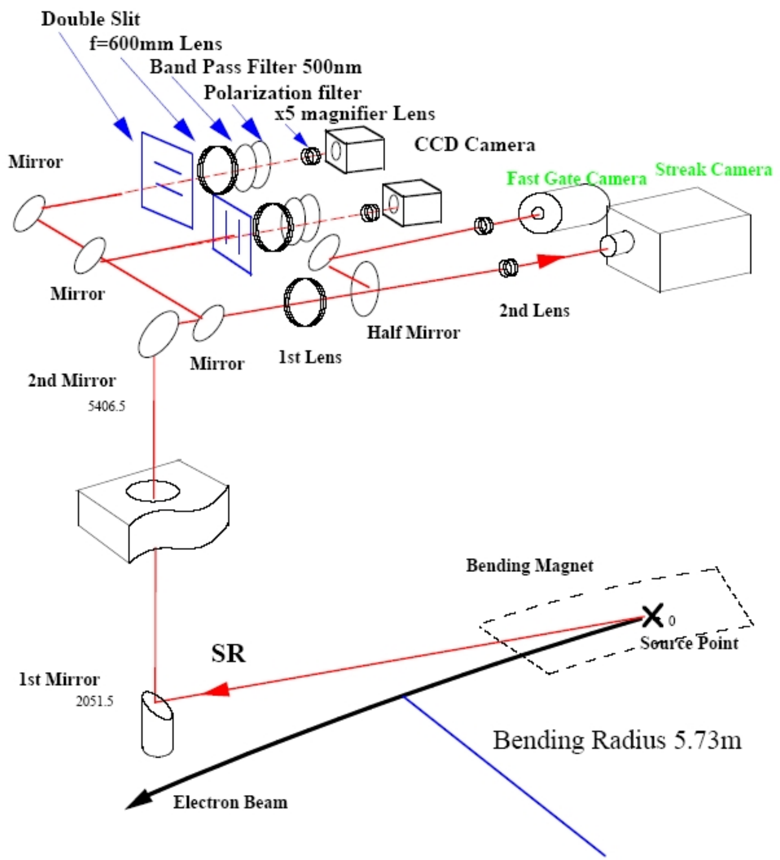
www.xray-lens.de

PETRA III @ 15 keV:

- R = 201.8 pm, R_0 = 447 pm, d = 10 pm
- N = 20
- material: beryllium

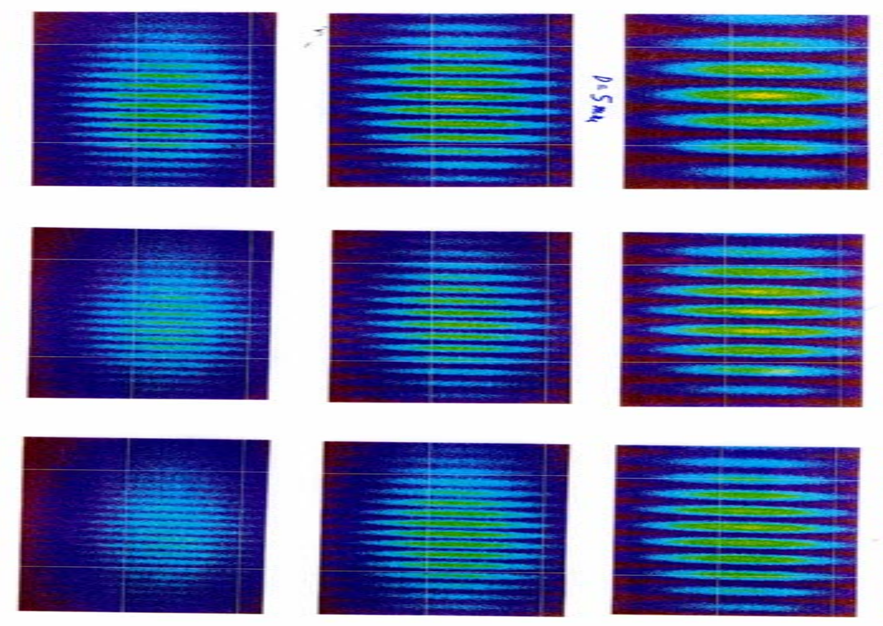
$$f = 3.33\,\text{m}$$
$$\sigma_{res} \approx 1\,\mu\text{m}$$

Interference: ATF (KEK)



H.Hanyo et al., Proc. of PAC99 (1999), 2143

vertical beam size:

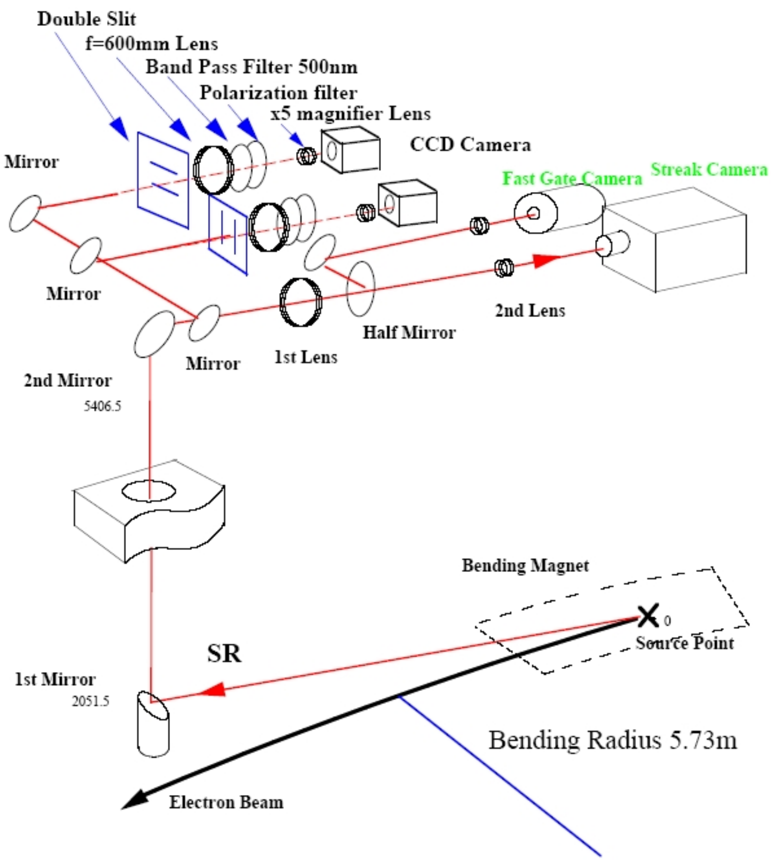


courtesy of T.Mitsuhashi, KEK

- smallest result: 4.7 pm with 400nm @ ATF, KEK

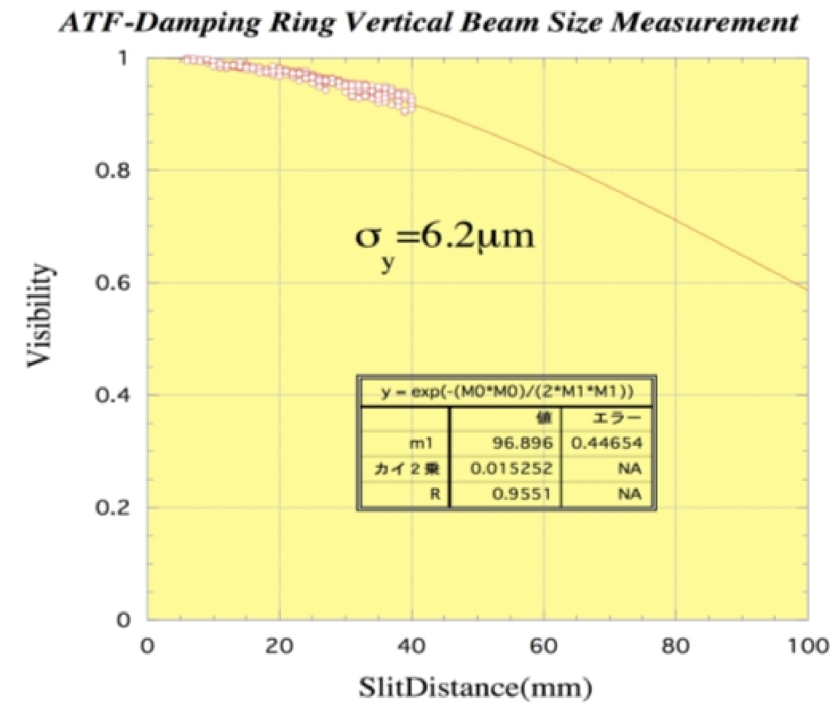
  accuracy ~ 1 pm

Interference: ATF (KEK)



H.Hanyo et al., Proc. of PAC99 (1999), 2143

vertical beam size:



courtesy of T.Mitsuhashi, KEK

- smallest result: 4.7 μm with 400nm @ ATF, KEK

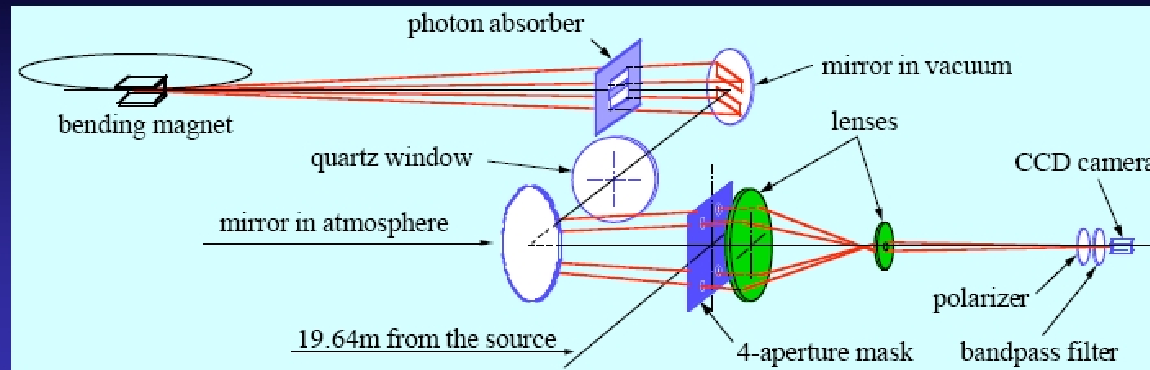
  accuracy ~ 1 μm

Interference: 2D Interferometer

SPring-8 2D Synchrotron Light Interferometer

M. Masaki & S. Takano,

J. Sync. Rad. (2003). **10**, p295



Resolution

$\sigma_{inter,X}$ =121μm , $\sigma_{inter,Y}$ = 52μm

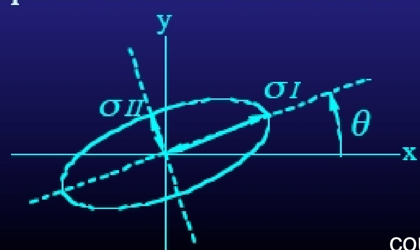
2D Beam Profiling

model function: $\tilde{I}(x,y) = \int_{-\infty}^{\infty} I(x,y;x_e,y_e)\rho(x_e,y_e)dx_e dy_e$

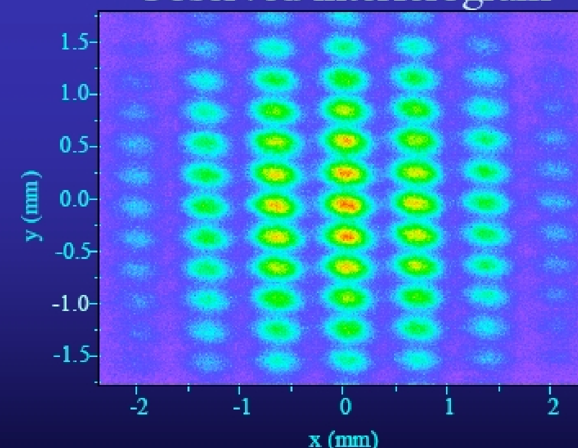
point-spread function: $I(x,y;x_e,y_e)$

electron beam : $\rho(x_e,y_e)$

elliptical Gaussian distribution



Observed interferogram



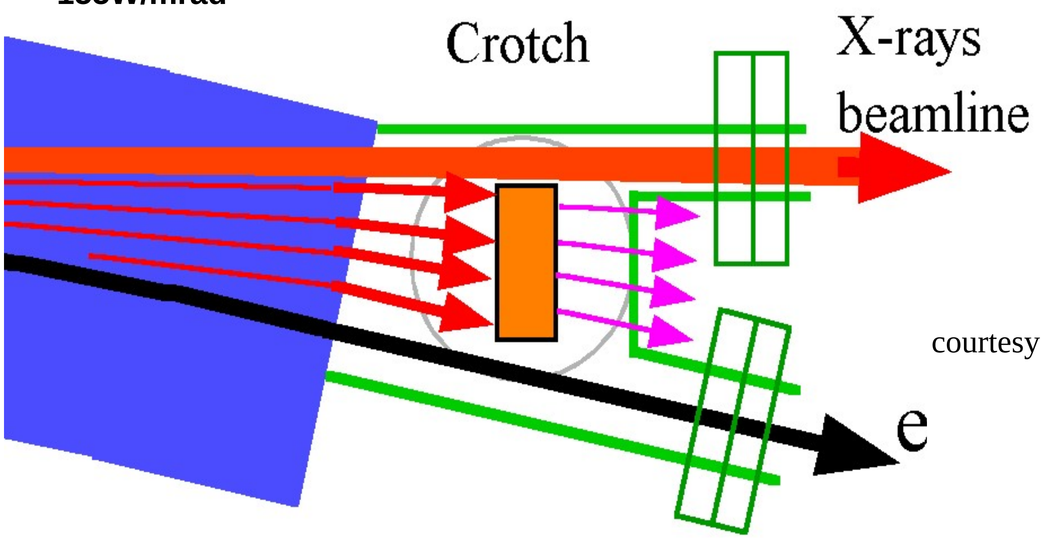
σ_I = 116(μm), σ_{II} = 64(μm), θ = -18(deg.)

courtesy of S.Takano, Spring-8

Projection: In Air X-Ray Detectors

= 155W/mrad

40mm Cu & 5mm Fe

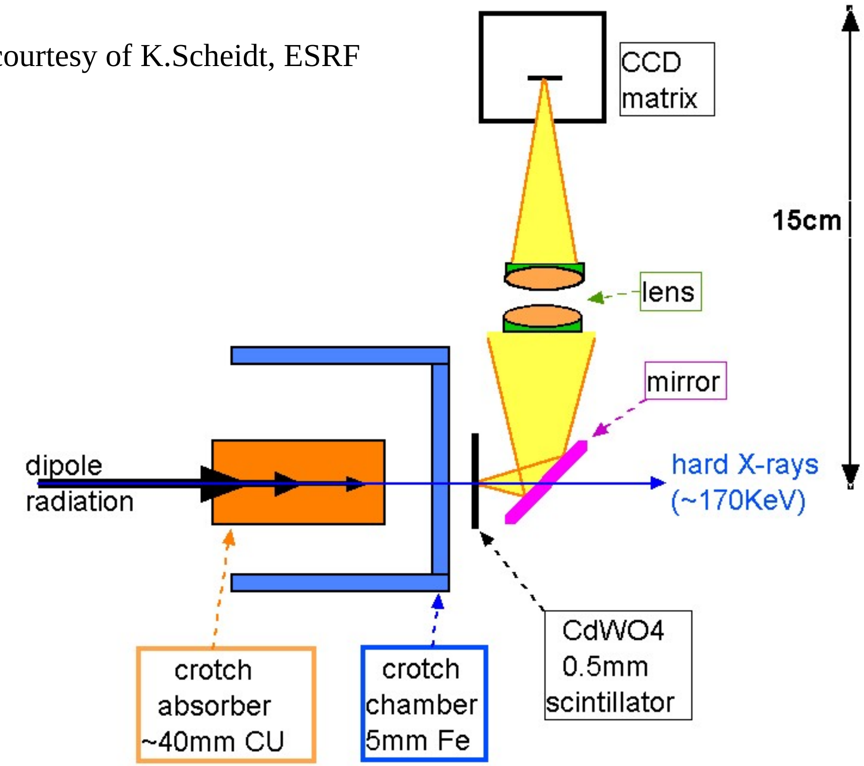


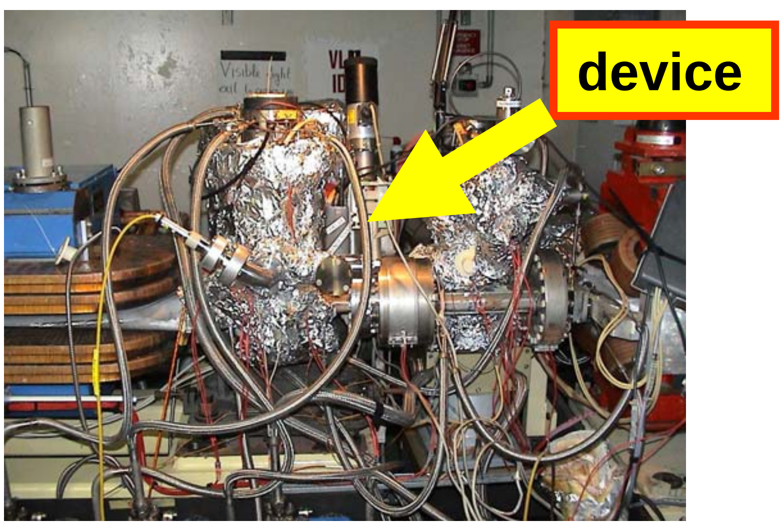
K.Scheidt, Proc. of DIPAC05 (2005), 238

K.Scheidt, Proc. of BIW06 (2006), to be published

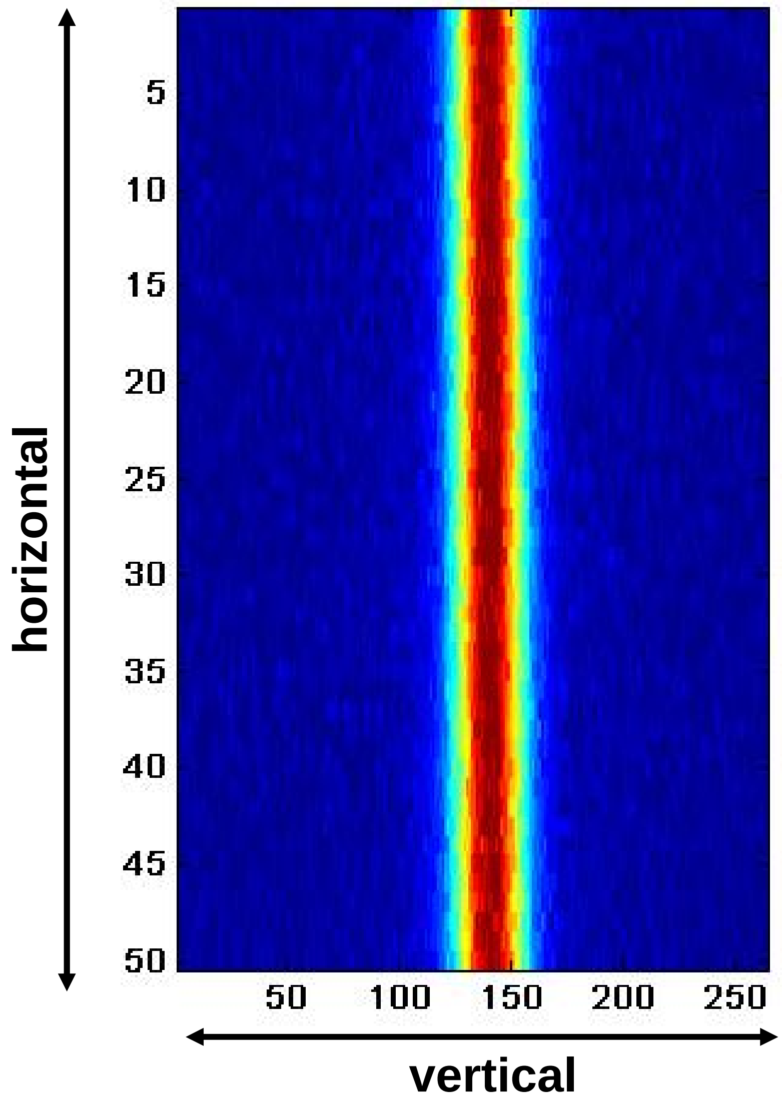
side-view i.e. in the vertical plane of the beam:

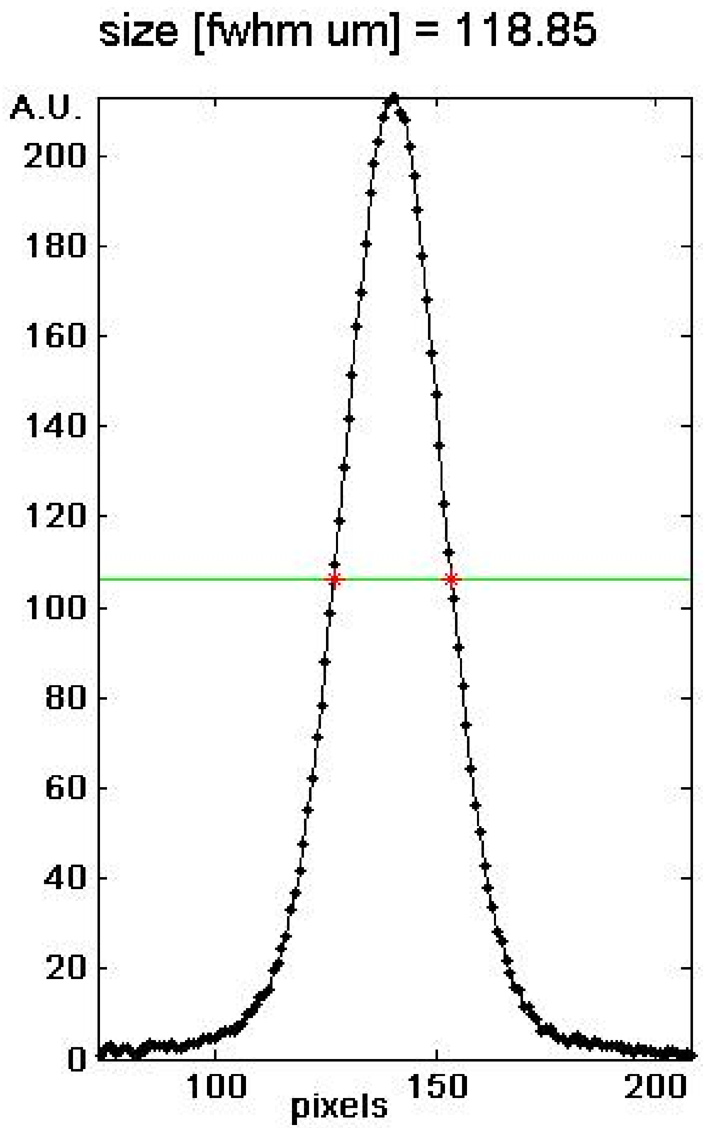
courtesy of K.Scheidt, ESRF





Projection: In Air X-ray Detectors





courtesy of K.Scheidt, ESRF

Summary

	Energy [GeV]	h_x 2h_y ˆs nm rad ˈ	v_x 2v_y ˆpm ˈ	G∓v_x 2v_y) ˆpm ˈ	Type	Reference
Spring-8	8	3.4 / 0.01	114 / 14	121 / 52 ~ 4	2-dim interferometry zone plate + monochr.	DIPAC 01/J.Sync.Rad (03) DIPAC 01+05/ NIM A556
APS	7	2.5 / 0.03	140 / 55	35 / 35	pinhole camera	EPAC 98
ESRF	6	3.9 / 0.03 (0.01)	104 / 33 - / 35	60 / 40	pinhole camera in air X-ray detector	J.Sync.Rad (95) DIPAC 05/BIW (06)
DIAMOND	3	2.7 / 0.03	50 / 25	25 / 25	pinhole camera	BIW 04/DIPAC 05
SOLEIL	2.75	3.75 / 0.04	114 / 14	121 / 52	pinhole camera	DIPAC 03
ALBA	3	4 / 0.04	45 / 35	20 / 20	pinhole camera	private communication
ELETTRA	2 2.4	7 / 0.07 9.7 / 0.1	 146 / 25	 30 / 30	opt. imaging + interferometry	EPAC 00
SLS	2.4	4.8 / 0.05	45 / 40	2 / 2	imaging (zone plate) (pinhole array ?)	DIPAC 01
NSLS	2.58	90 / 0.1		16 / 16	pinhole camera	EPAC 96
PF KEK	2.5	37 / 0.37	262 / 87	~ 1	interferometry	PAC 99
ALS	1.9	6 / 0.03	88 / 45	10 / 10	Kirkpatrick-Baez	BIW 96
MAX-II	1.5	9 / 0.09	~100 /~ 20	2 / 2	opt. imaging + interferometry	EPAC 04
BESSY-II	1.9	6 / < 0.02	50-60 / 40-50	11 / 11 3 / 3	pinhole array + Bragg-Fresnel lens	NIM A467/468 (2001)