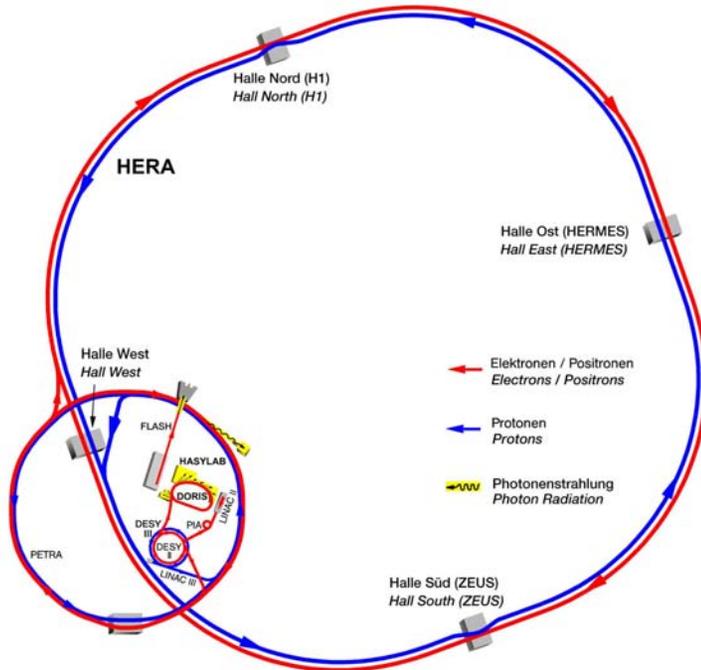


# Review of Synchrotron Radiation based Diagnostics for Transverse Profile Measurements

Gero Kube  
DESY / MDI  
[gero.kube@desy.de](mailto:gero.kube@desy.de)

- Introduction
- Small Emittance Measurements
- Non-standard Profile Measurements

# Deutsches Elektronen SYNchrotron



- one of the world's leading centres for the investigation of the structure of matter
- develops, runs and uses accelerators and detectors for photon science and particle physics
- carries out fundamental research in a range of scientific fields and focuses on three principal areas:

- **Accelerators**
- **Photon science**
- **Particle physics**

# DESY Accelerators

- Shut down of **ep** collider **HERA** in June 2007

- no high energy physics accelerator on-site
- no need for proton accelerator chain

- Remaining accelerators

- **e injector chain:**

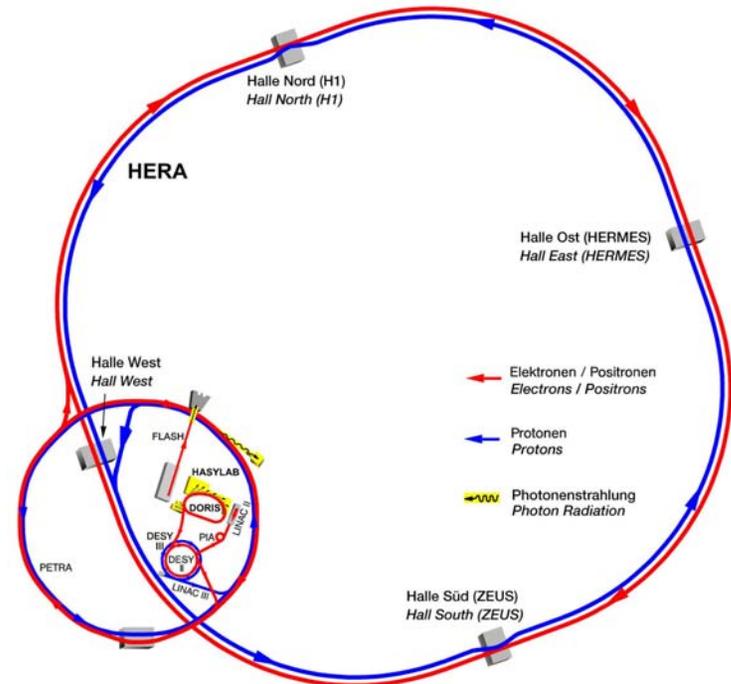
Linac II, PIA, DESY II, PETRA II

- **DORIS III**

1<sup>st</sup> generation synchrotron light source

- **FLASH**

VUV Free Electron Laser (4<sup>th</sup> generation synchrotron light source)



→ accelerator center for synchrotron radiation

- Future accelerator projects

- **European XFEL:** 4<sup>th</sup> generation **linac based** synchrotron light source

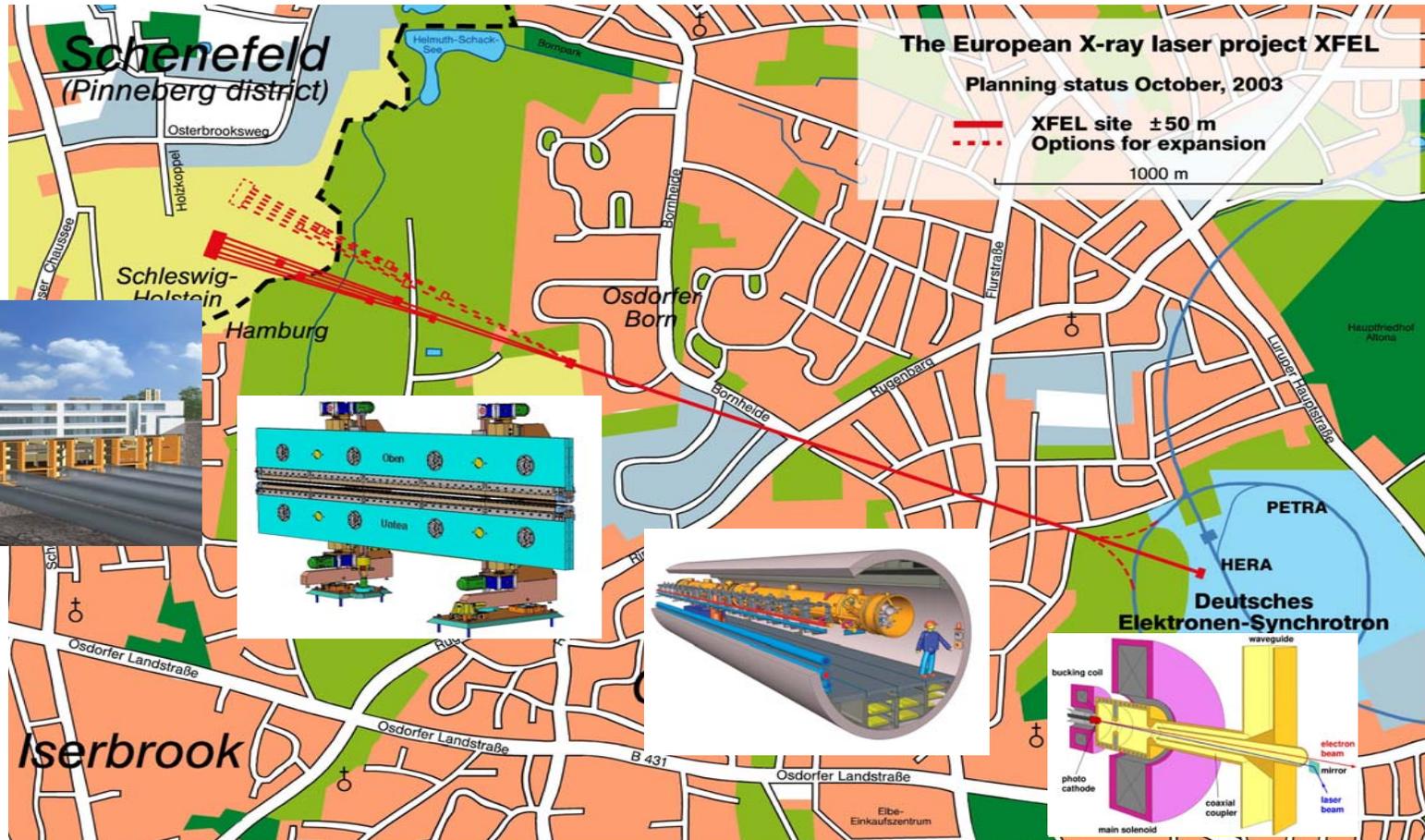
- **PETRA III:** 3<sup>rd</sup> generation **storage ring based** synchrotron light source

# Accelerator Projects @ DESY

**XFEL**  
X-Ray Free-Electron Laser

The European X-Ray Laser Project XFEL : 4<sup>th</sup> generation light source

← 3.4km →



# Accelerator Projects @ DESY

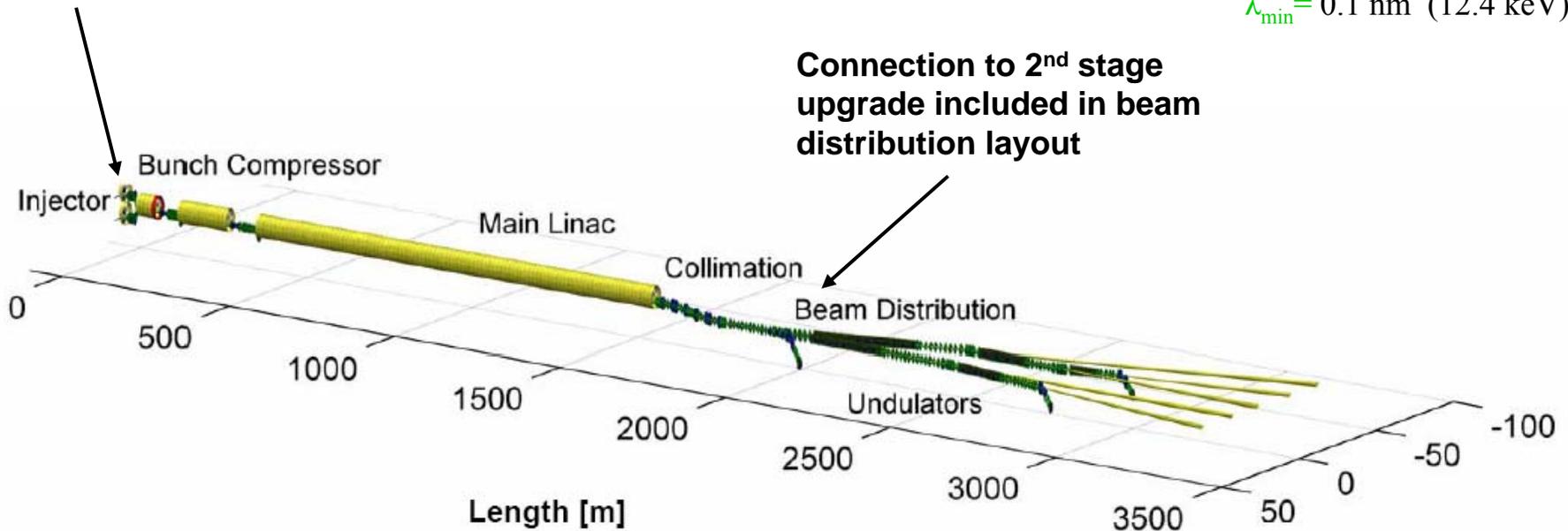
**XFEL**  
X-Ray Free-Electron Laser

The European X-Ray Laser Project XFEL

: 4<sup>th</sup> generation light source

Energy: 20 GeV  
Bunch Charge: 1 nCb  
Bunch Length: 80 fsec  
 $\lambda_{\min} = 0.1 \text{ nm}$  (12.4 keV)

One injector initially installed



# Accelerator Projects @ DESY



John Adams Institute  
Oxford

**The European XFEL Free Electron Laser  
at DESY**

Hans Weise / DESY  
for the TTF/FLASH and the XFEL Project Groups

(Free-Electron LASer in Hamburg)

Hans Weise, DESY  
Seminar at the John Adams Institute, Oxford, UK, November 29, 2007



**Thursday 29/11/2007:**

Hans Weise (DESY),

**The European XFEL project**

[http://www.adams-institute.ac.uk/lectures/XFEL\\_JAI.pdf](http://www.adams-institute.ac.uk/lectures/XFEL_JAI.pdf)

- Conversion of PETRA in a dedicated light source



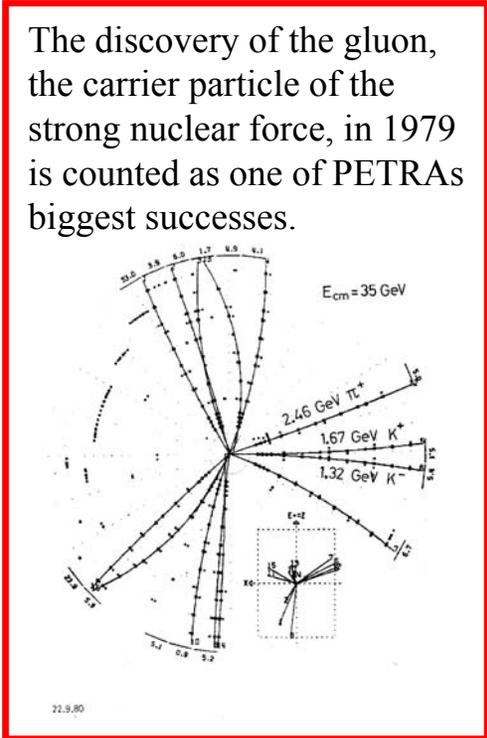
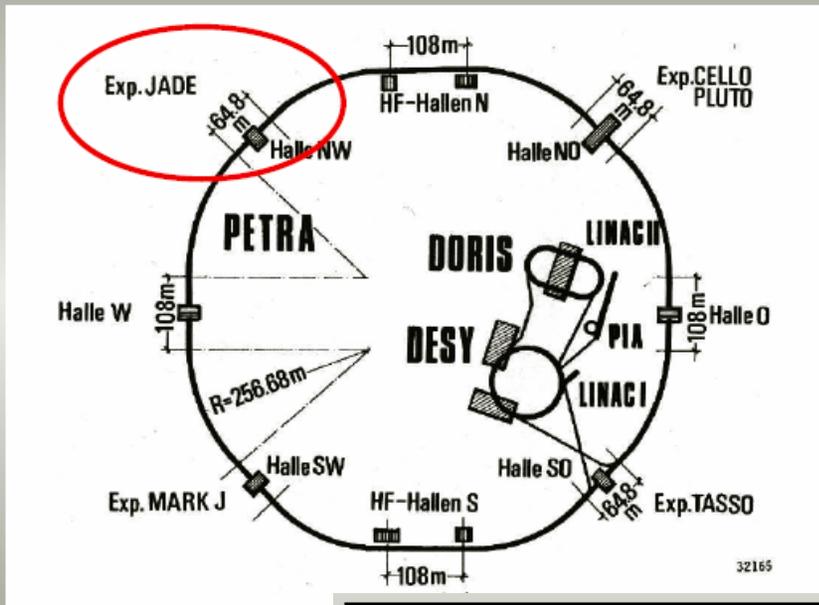
# PETRA History

## The PETRA $e^+e^-$ Storage Ring

Physics at  
PETRA  
from 1979-1986

- largest  $e^+e^-$  accelerator at that time
- luminosity  $\sim 24 \times 10^{30} / \text{cm}^2 \text{ s}^1$   
(= 26 hadronic events/hour)

(hadronic cross section  $\sim 0.3 \text{ nb}$ )



| CME range (GeV) | Data taking period | Luminosity ( $\text{pb}^{-1}$ ) | $\sqrt{s}$ (GeV) | MH events |
|-----------------|--------------------|---------------------------------|------------------|-----------|
| 14.0            | 07-08/1981         | 1.46                            | 14.0             | 1734      |
| 22.0            | 06-07/1981         | 2.41                            | 22.0             | 1390      |
| 33.8-36.0       | 02/1981-08/1982    | 61.7                            | 34.6             | 14372     |
| 35.0            | 02-06/1986         | 92.3                            | 35.0             | 20925     |
| 38.3            | 10-11/1981         | 8.28                            | 38.3             | 1587      |
| 43.4-46.6       | 06/1984-10/1985    | 28.8                            | 43.8             | 3940      |

23.3 GeV / beam !!!

## PETRA II

pre-accelerator for HERA (1988-2007)



12 GeV electrons  
(positrons);  
40 GeV protons,

Sync. Radiation  
Facility since 1995:  
equipped with one  
undulator to create  
synchrotron radiation  
especially in the X-  
ray part of the  
spectrum.

# PETRA III Upgrade Project

- Reconstruction of 1/8 of PETRA (288 m) in a new experimental hall
- 9 new straight sections in the new arc, canted undulators  
→ 14 separate undulator beamlines
- 100 m damping wiggler in the long straights
- Renewal of the **entire machine**
- Renewal of injection system  
(and removal of the blue)

Start commissioning: Middle/End of February 2009

## Parameters:

$E = 6 \text{ GeV}$

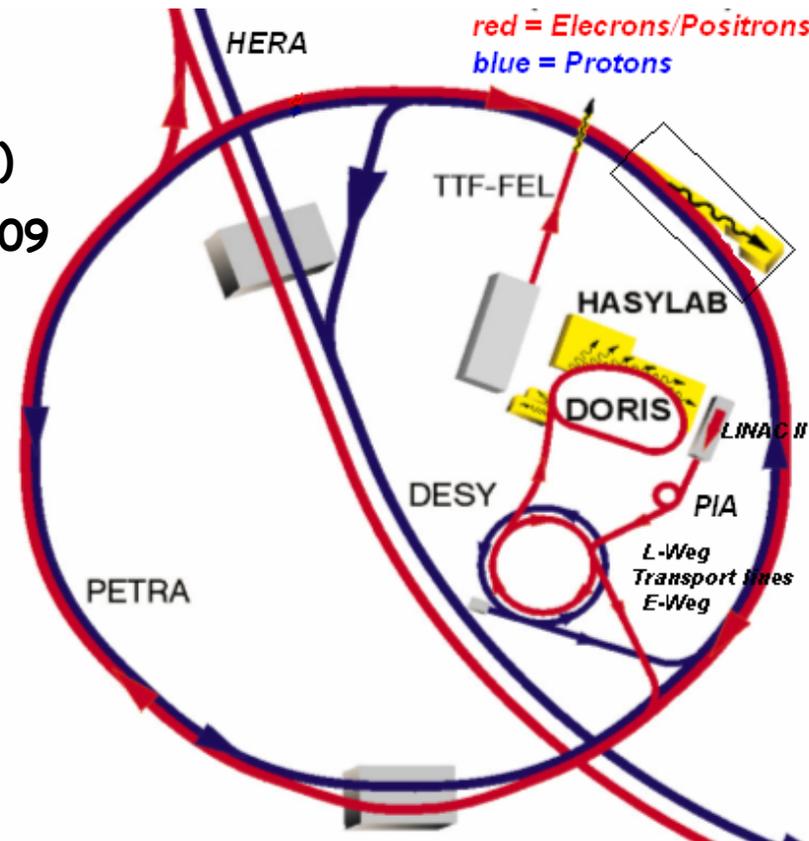
$I = 100 \text{ mA}$  (200 mA) – **top-up**

$\epsilon \approx 1.0 \text{ nm rad}$

$\kappa = 1\%$

960 bunches, 40 bunches, variable patterns

Additional options for long undulators

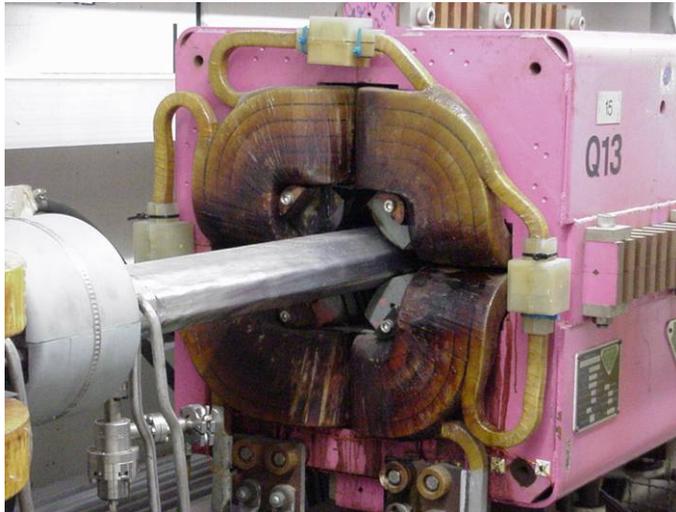


# Renewal of Entire Machine

- impressions from the accelerator tunnel



- renewal of individual components

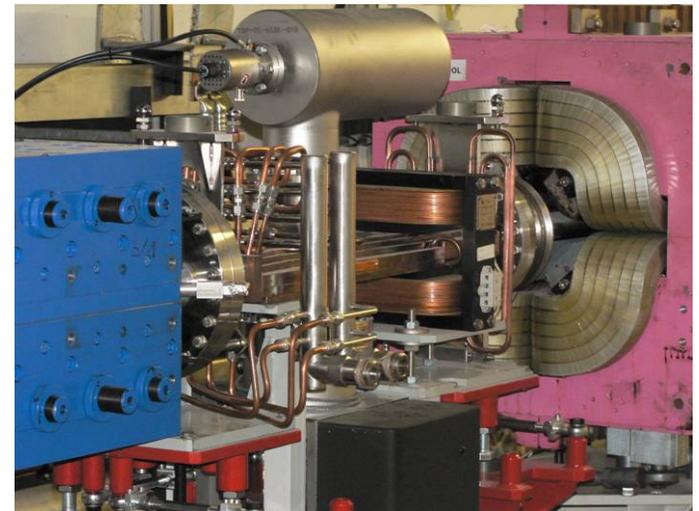
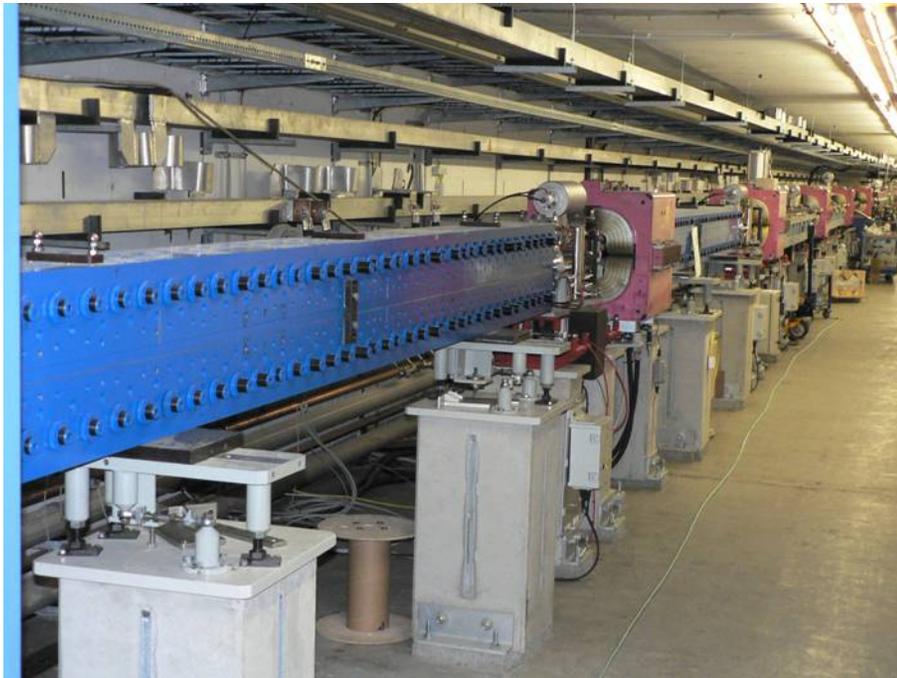


New Magnet Coils

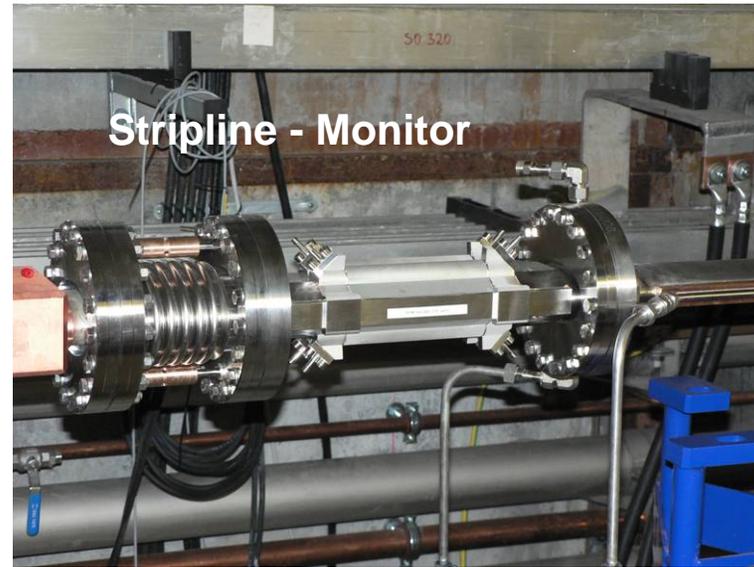
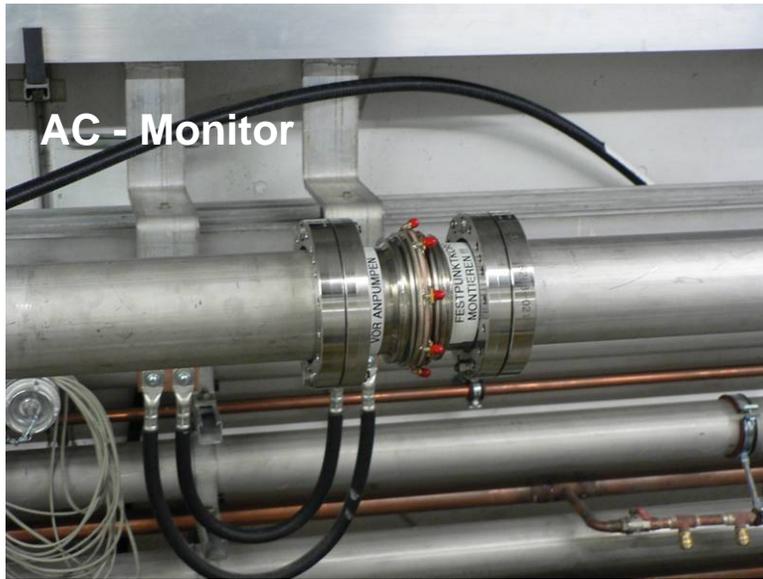


# Damping Wiggler Sections

- improvement of natural emittance: 4.5 nm rad  $\rightarrow$  1.0 nm rad
- 2 damping wiggler sections ( $\sim$  100m long)
- complicated vacuum system:  
 $\rightarrow$  absorption of up to 400 kW per section



# Diagnosics Elements



# Experimental Hall

Middle 2006 ...



Middle 2008 ...



# Experimental Hall



# Light Sources: Remarks

## ● key parameter: spectral brilliance

- measure for phase space density of photon flux
- user requirement: high brightness
  - lot of monochromatic photons on sample
- connection to machine parameters

$$B \propto \frac{N_\gamma}{\sigma_x \sigma_{x'} \sigma_y \sigma_{y'}} \propto \frac{I_{\text{beam}}}{\epsilon_x \epsilon_y}$$

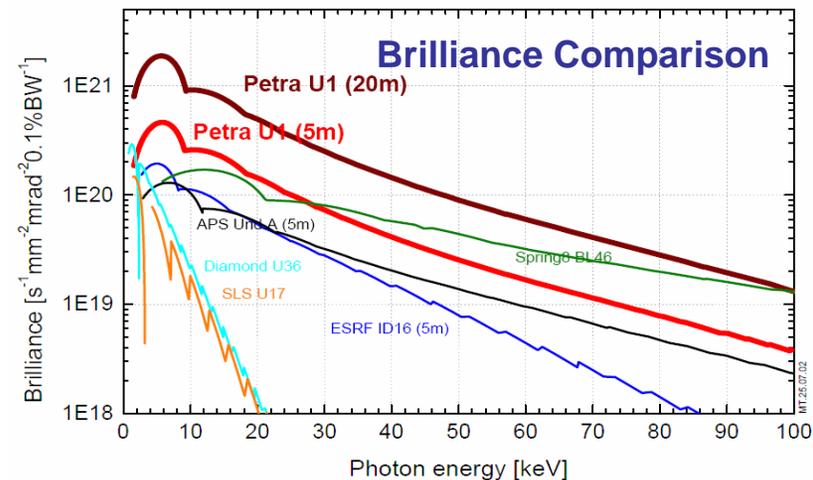
- requirements for storage ring and diagnostics

### i) high beam current

- achieve high currents
- cope with high heat load (stability)

⇒ diagnostics is important

$$B = \frac{\text{Number of photons}}{[\text{sec}][\text{mm}^2][\text{mrad}^2][0.1\% \text{ bandwidth}]}$$



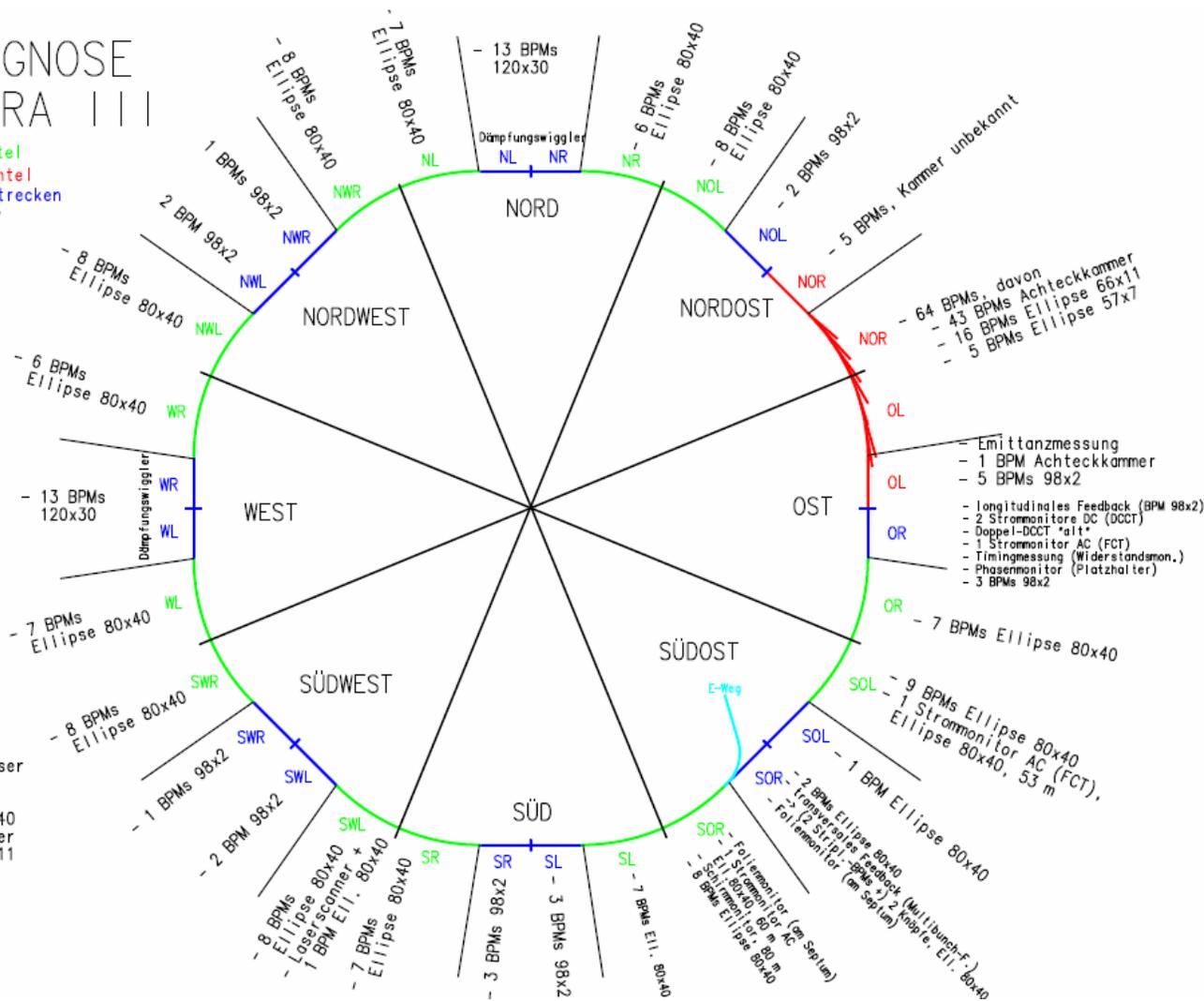
### ii) small beam emittance

- achieve small emittance (task of lattice designer)
- preserve emittance (stability)
- measure small emittance

# PETRA III Diagnostics

## DIAGNOSE PETRA III

alte Achtel  
neues Achtel  
gerade Strecken  
05.04.2007



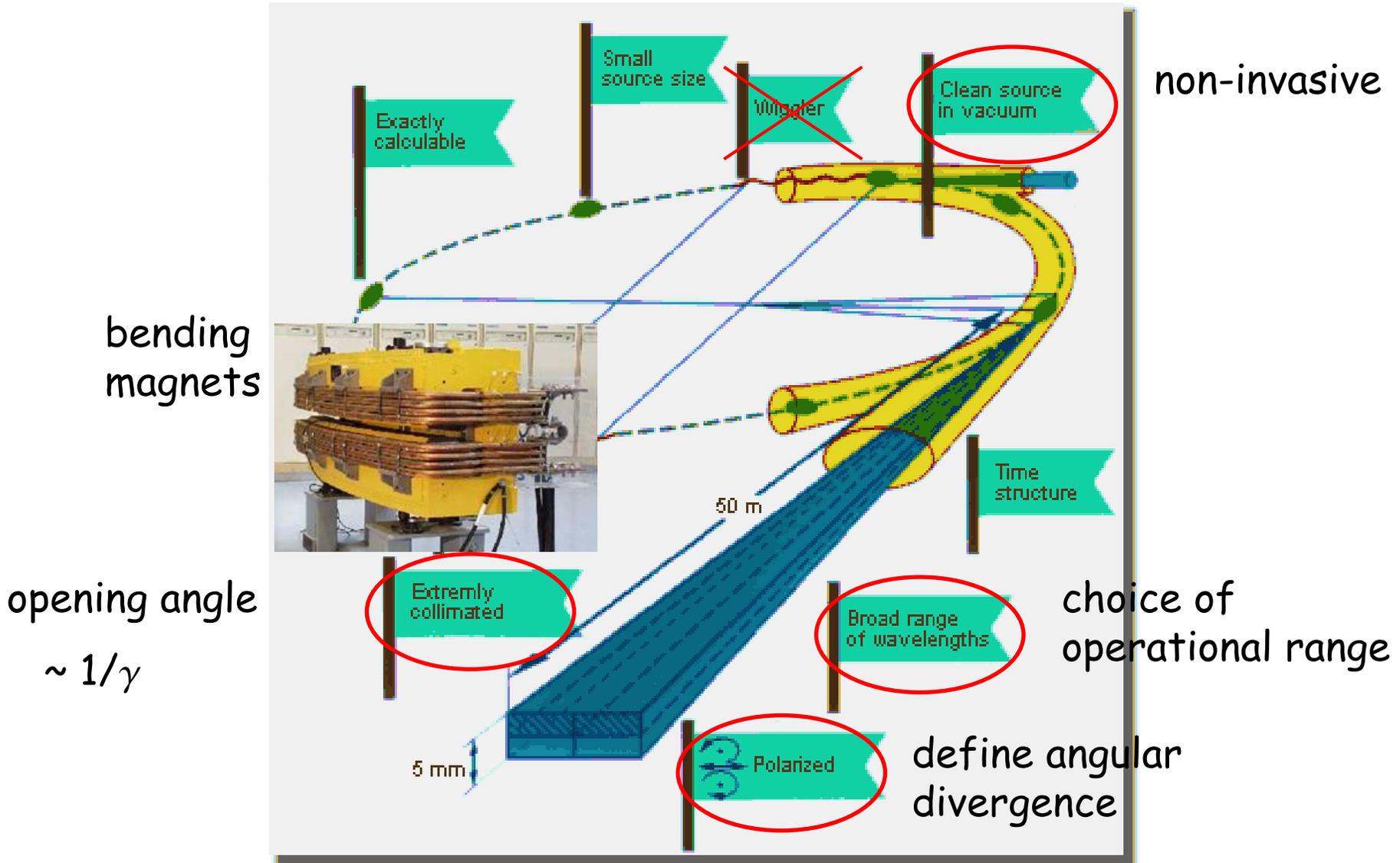
### PETRA III:

- 228 BPMs (Orbit)
- 6 Current Monitors
- 2 Stripline-BPMs and 2 Button-BPMs for Multibunch Feedback
- 1 Button-BPM for longitudinal Feedback
- 1 Wall Gap Monitor
- 1 Laser-Wirescanner
- 2 Beamlines for Emittance Diagnostics
- 3 Screens

### Transfer Lines:

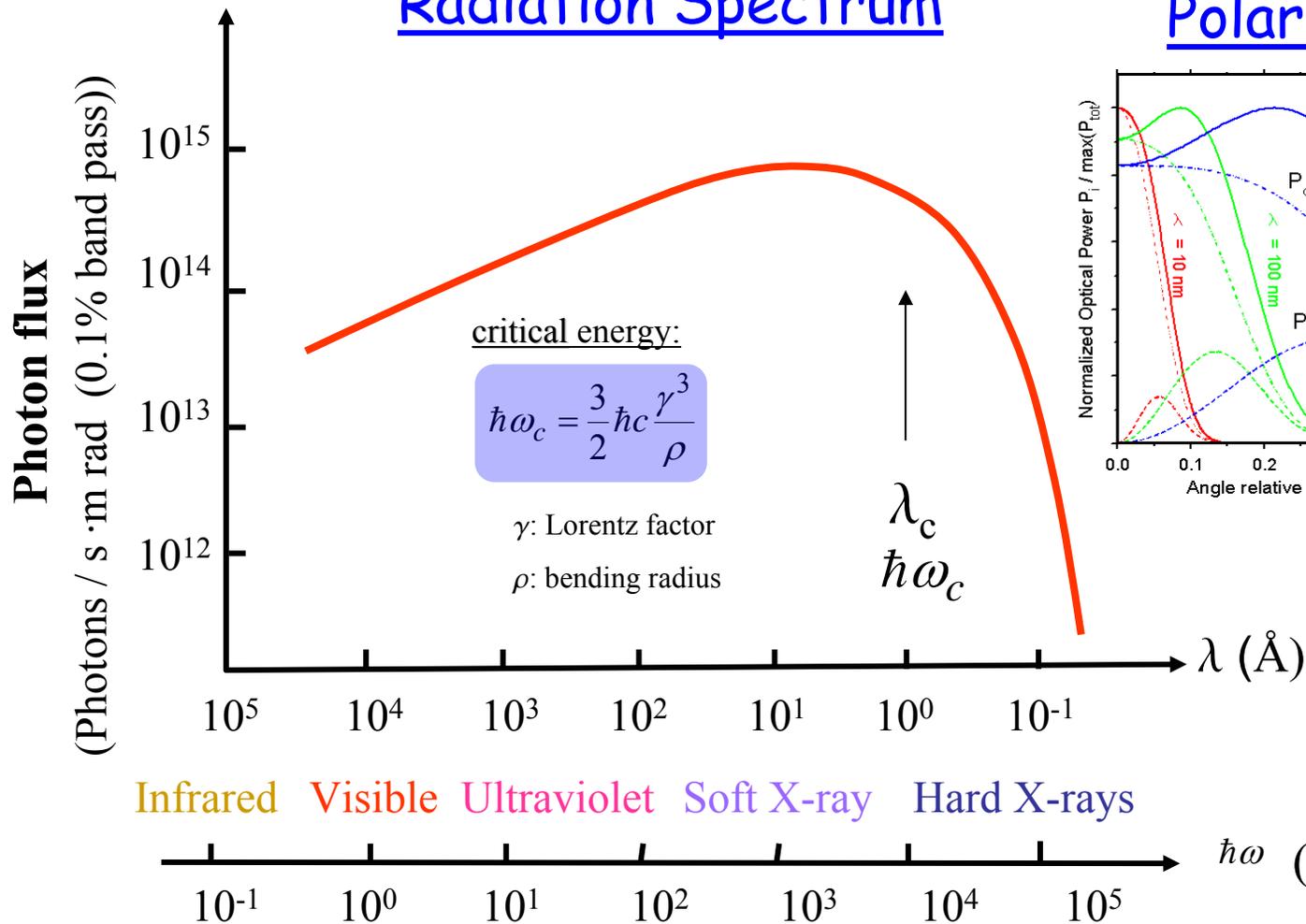
- 20 BPMs
- 10 Current Monitors
- 4 Wall Gap Monitors
- 11 Screens

# Synchrotron Radiation Properties

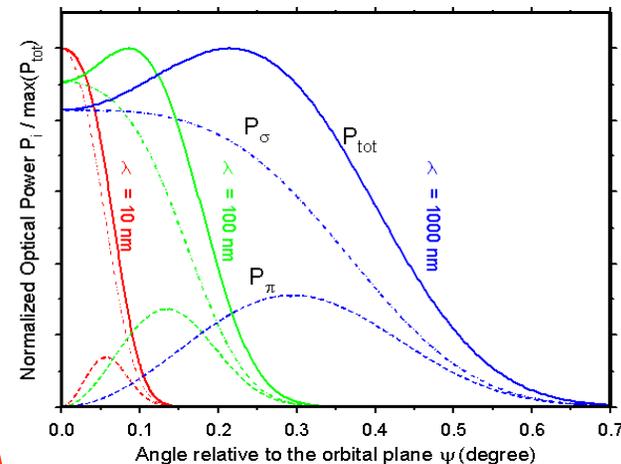


# Synchrotron Radiation Spectrum

## Radiation Spectrum

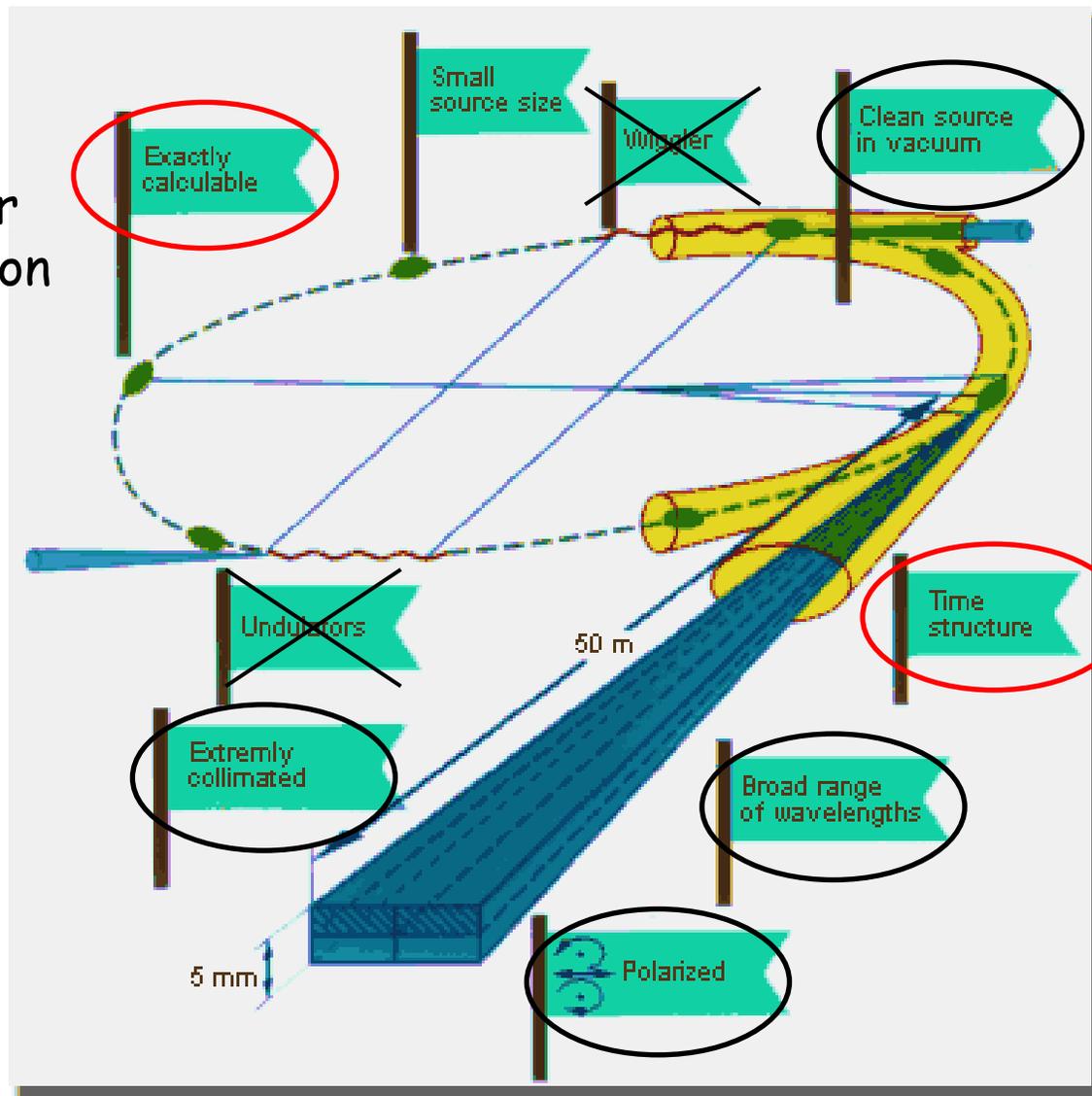


## Polarization



# Synchrotron Radiation Properties

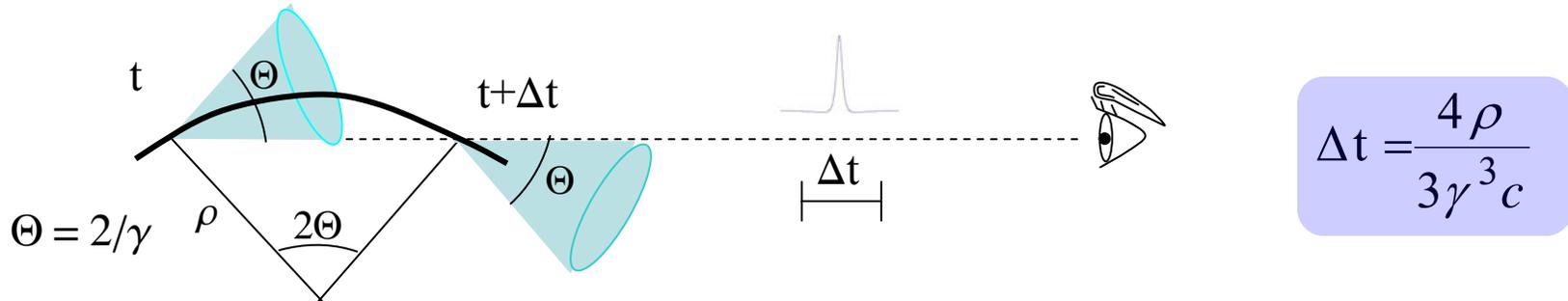
numerical near  
field calculation  
(SRW,  
SPECTRA,...)



influence  
single particle  
field

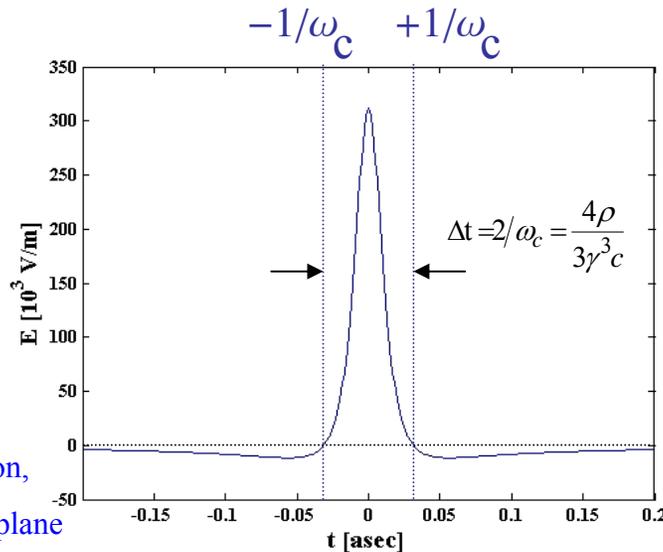
# Single Particle Time Structure

- geometrical interpretation



$\Delta t$ : distance in travel time between photon and particle

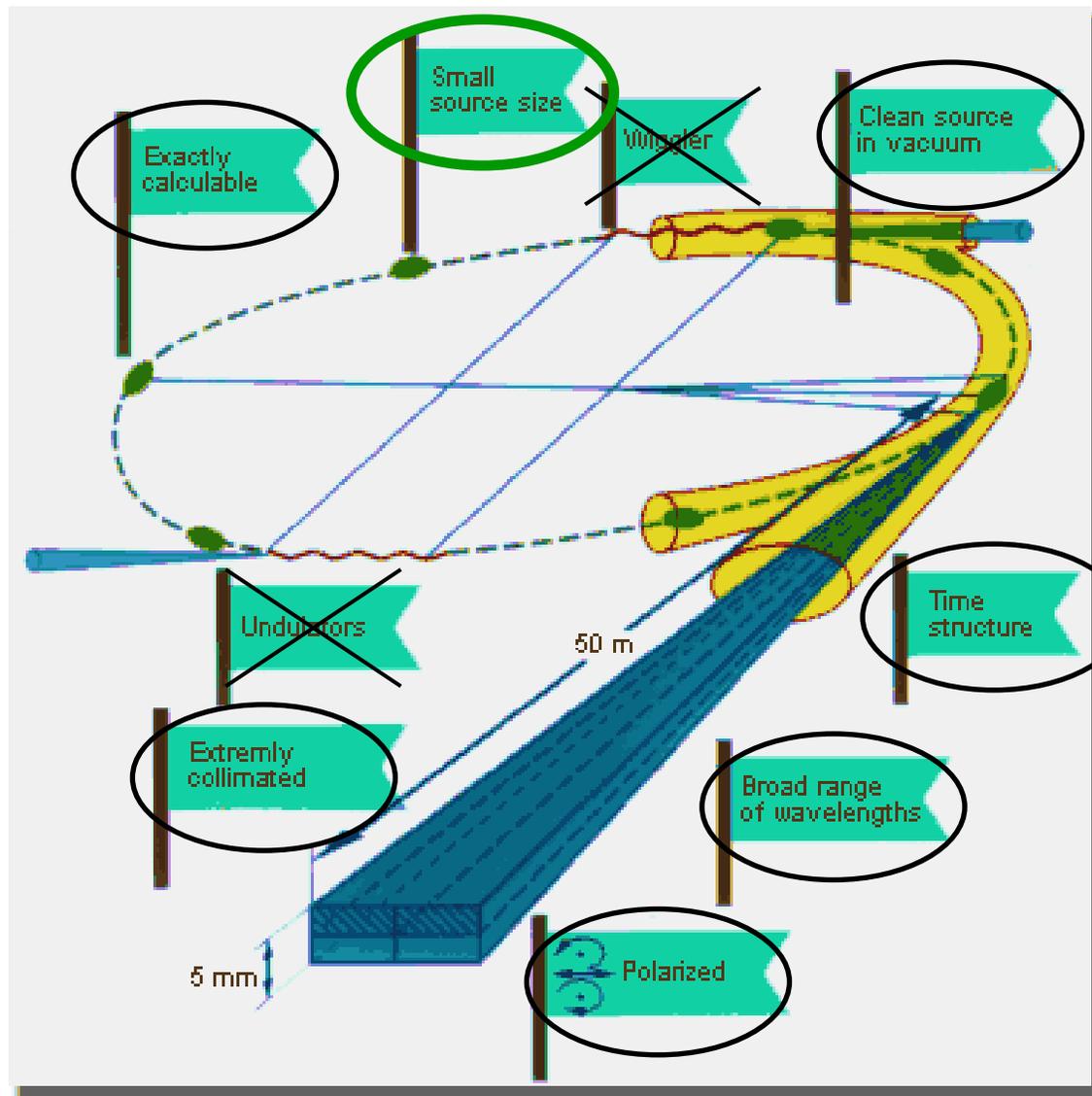
- radiation field in time domain



consequence:

time interval from maximum to zero crossing defines spectrum ( $\omega_c$ )

# Synchrotron Radiation Properties



- Exactly calculable
- Small source size
- Clean source in vacuum
- Wiggler
- Undulators
- Extremely collimated
- 5 mm
- 50 m
- Time structure
- Broad range of wavelengths
- Polarized

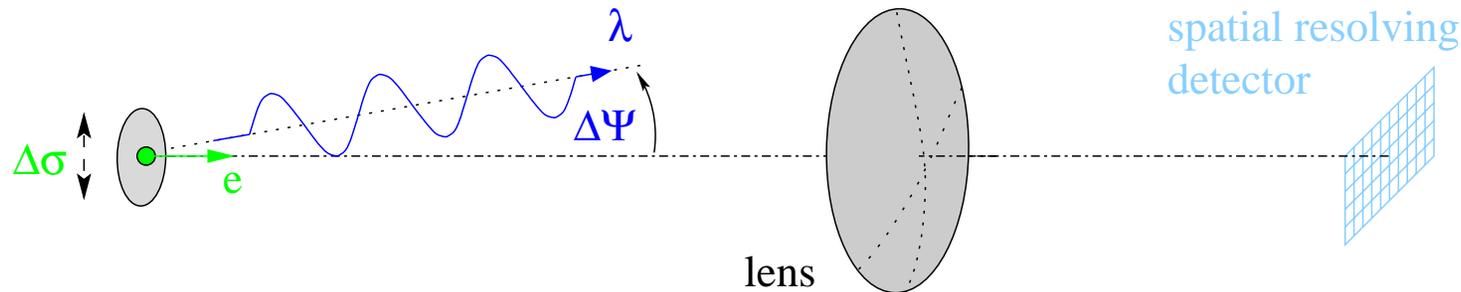
monitoring parameter



emittance

- size
- divergence





- resolution limit: uncertainty principle

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

- synchrotron radiation: small vertical emission angle  $\Delta\Psi$

typical half opening angle ( $\lambda \geq \lambda_c$ ) :  $\Delta\Psi = \frac{1}{\gamma} \left( \frac{\lambda}{\lambda_c} \right)^{1/3} \ll 1 \text{ mrad}$

⇒ resolution fully limited by uncertainty principle

- example:  $E = 6 \text{ GeV}$ ,  $\lambda_c = 0.35 \text{ nm}$  (ESRF)

$$\lambda = 500 \text{ nm} \Rightarrow \Delta\sigma_v = 260 \mu\text{m} \quad (\sigma_v = 30 \mu\text{m})$$

# Resolution Improvements

## 1.) decrease of wavelength

⇒ VUV, soft X-ray, hard X-ray, ...

$$\lambda = 0.124 \text{ nm} \quad (10 \text{ keV photons}) \quad \Rightarrow \quad \Delta\sigma_v = 1 \mu\text{m}$$

## 2.) interferometric approach

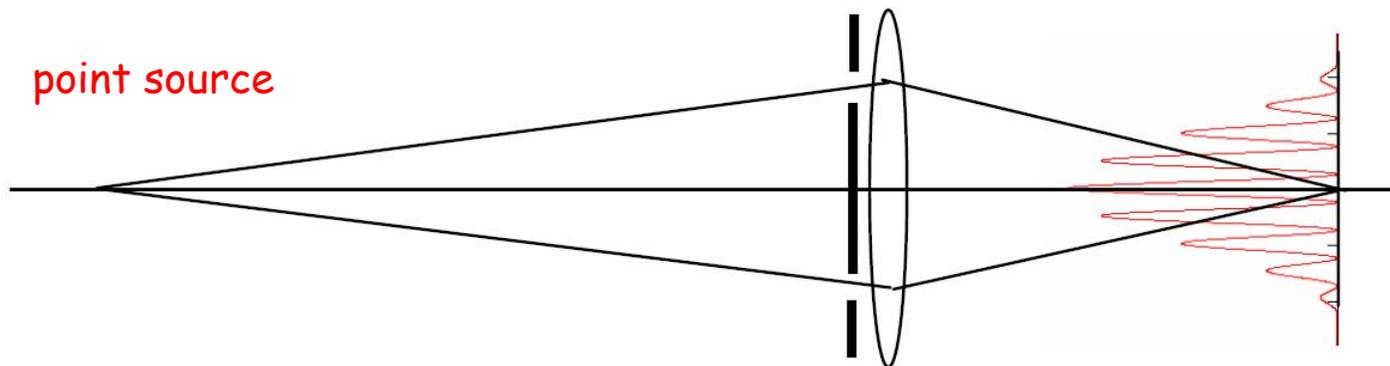
T. Mitsuhashi, Proc. Joint US-CERN-Japan-Russia School of Particle Accelerators, Montreux, 11-20 May 1998 (World Scientific), pp. 399-427.

⇒ probing spatial coherence of synchrotron radiation

visibility:

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

$$V = 1$$



T. Mitsuhashi, Proc. BIW04, AIP Conf. Proc. 732, pp. 3-18

• resolution limit: uncertainty principle

$$\Delta n \cdot \Delta\Phi \approx 1$$

$\Delta n$ : photon number

$\Delta\Phi$ : photon phase

# Resolution Improvements

## 1.) decrease of wavelength

⇒ VUV, soft X-ray, hard X-ray, ...

$$\lambda = 0.124 \text{ nm} \quad (10 \text{ keV photons}) \quad \Rightarrow \quad \Delta\sigma_v = 1 \mu\text{m}$$

## 2.) interferometric approach

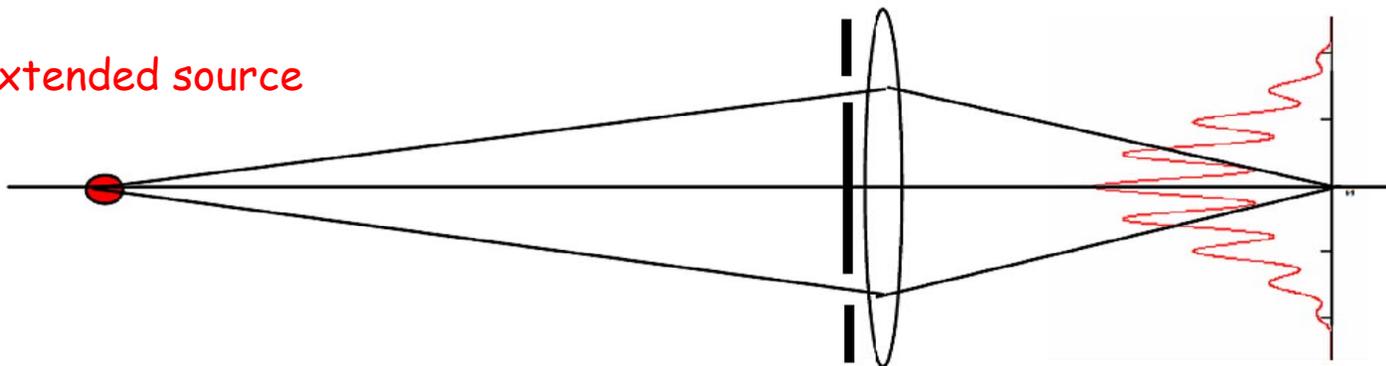
T. Mitsuhashi, Proc. Joint US-CERN-Japan-Russia School of Particle Accelerators, Montreux, 11-20 May 1998 (World Scientific), pp. 399-427.

⇒ probing spatial coherence of synchrotron radiation

visibility:

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

extended source



$$V < 1$$

T. Mitsuhashi, Proc. BIW04, AIP Conf. Proc. 732, pp. 3-18

• resolution limit: uncertainty principle

$$\Delta n \cdot \Delta\Phi \approx 1$$

$\Delta n$ : photon number

$\Delta\Phi$ : photon phase

# Classification

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

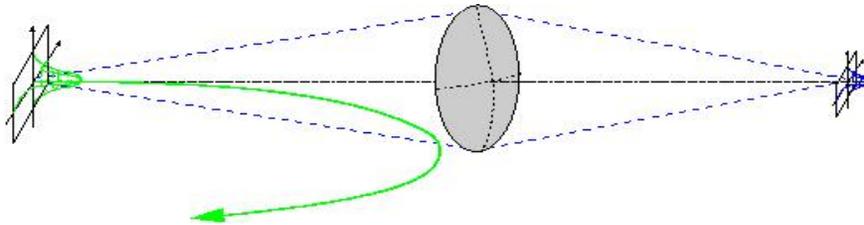
beam spot

wavefront manipulation

spatial resolving detector (CCD)

⇒ signal :

imaging :

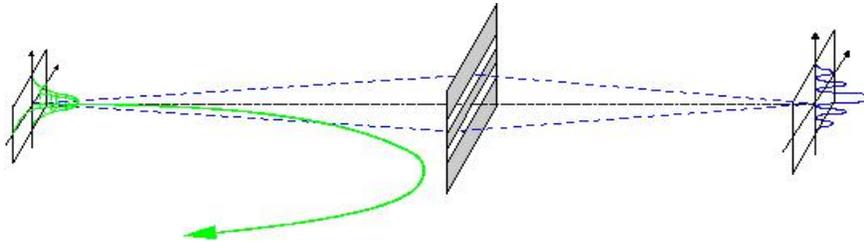


size of beam image

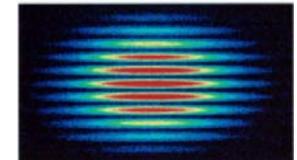


DORIS

interference :

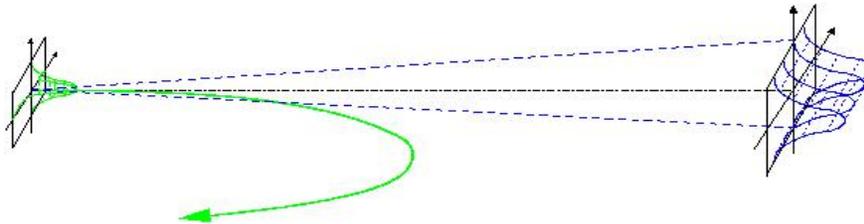


interference pattern (visibility)

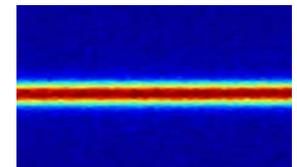


AURORA (courtesy T. Mitsuhashi)

projection :



angular distribution



ESRF (courtesy K. Scheidt)

# Imaging: X-Ray (Focusing) Optics

- focusing of X-rays: interaction with matter
- characteristic value: complex index of refraction
- parametrization:

$$n = 1 - \delta + i\beta$$

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

⇒ small deviation from air ( $n=1$ )

- principles:
  - reflective optics
  - diffractive optics
  - refractive optics

# Grazing Incidence Reflective Optics

• condition for reflection:  $\theta \leq \sqrt{2\delta}$

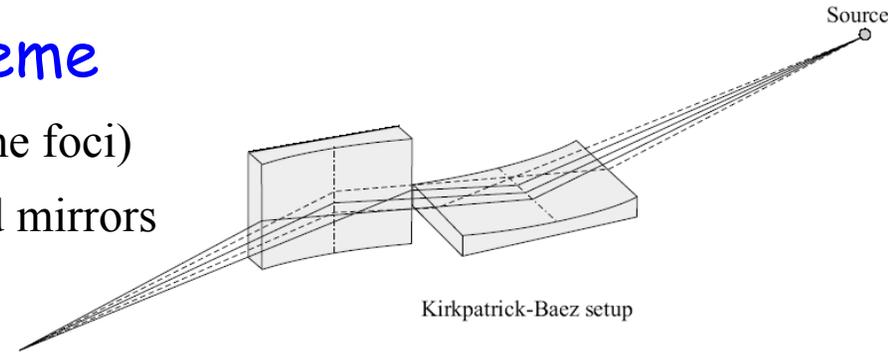
typically:  $\theta < 0.5^\circ$

• Kirkpatrick-Baez mirror scheme

concave spherical mirror: astigmatism (2 line foci)

⇒ pair of ellipsoidal / cylindrical curved mirrors

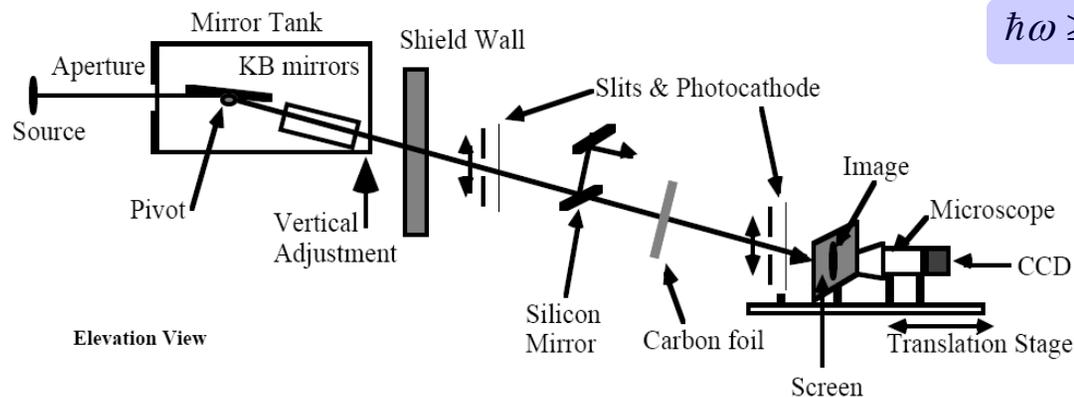
⇒ point focus



Kirkpatrick-Baez setup

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

• Advanced Light Source: Diagnostics Beamline



$$\hbar\omega \geq 250 \text{ eV}$$



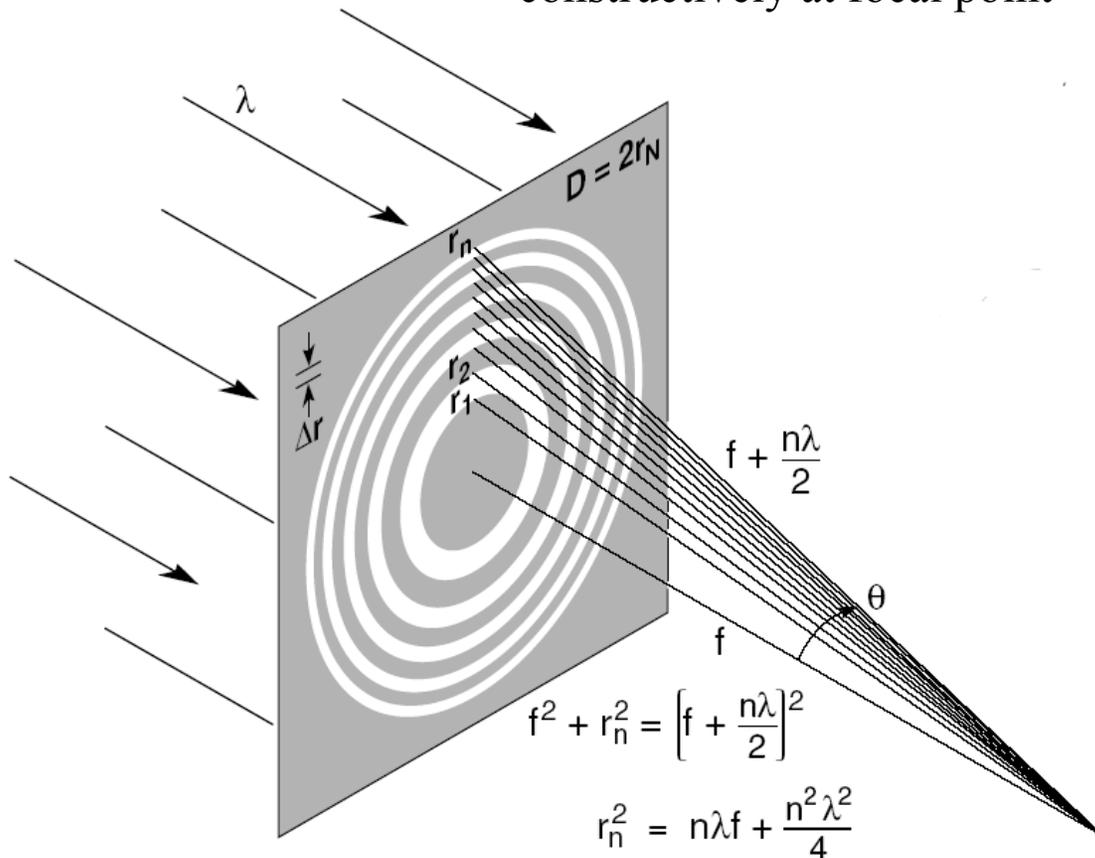
T.R. Renner, H.A. Padmore, R. Keller, Rev.Sci.Instrum. 67 (1996) 3368

⇒ additional diagnostics beamline using pinhole array

F. Sannibale et al., Proc. EPAC04, Lucerne, Switzerland (2004) 2783

# Fresnel Zone Plates

**diffractive optics:** spacing of rings such that penetrating light waves interfere constructively at focal point



E. Anderson, LBNL

D.T. Attwood, „Soft X-rays and extreme ultraviolet radiation principles and applications“, Cambr. Univ. Press 2000  
<http://www.coe.berkeley.edu/AST/sxreuv/>

$$\delta \approx 1.22 \cdot \Delta r$$

resolution

$$f = \frac{4N(\Delta r)^2}{\lambda}$$

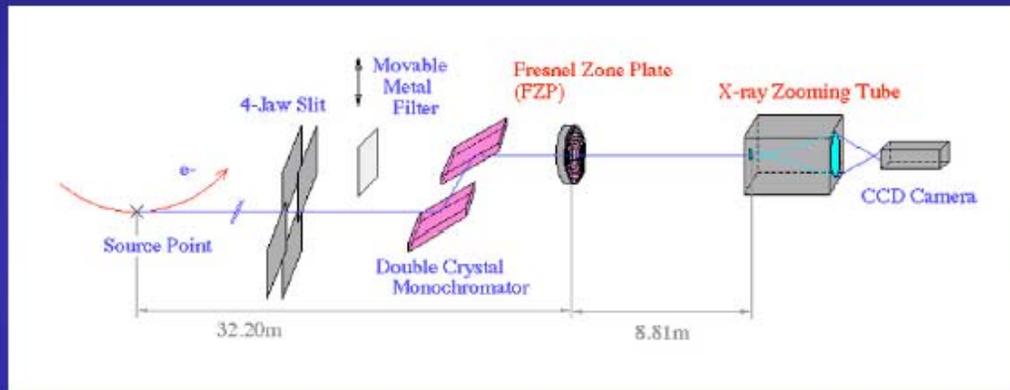
focal length

further types: phase zone plate, Bragg Fresnel lense, ...

⇒ monochromator required

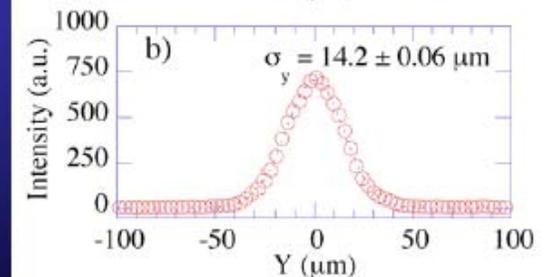
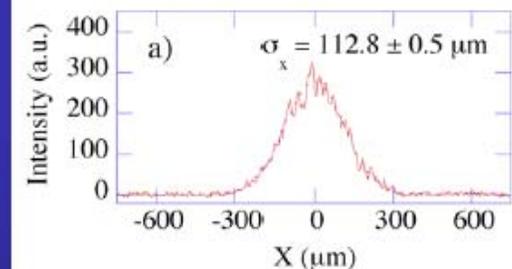
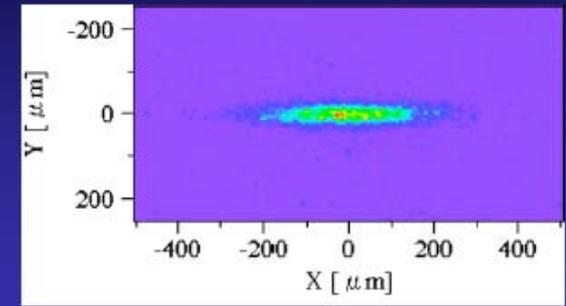
# X-Ray Beam Imager @ Spring-8

## Single FZP + X-ray Zooming Tube



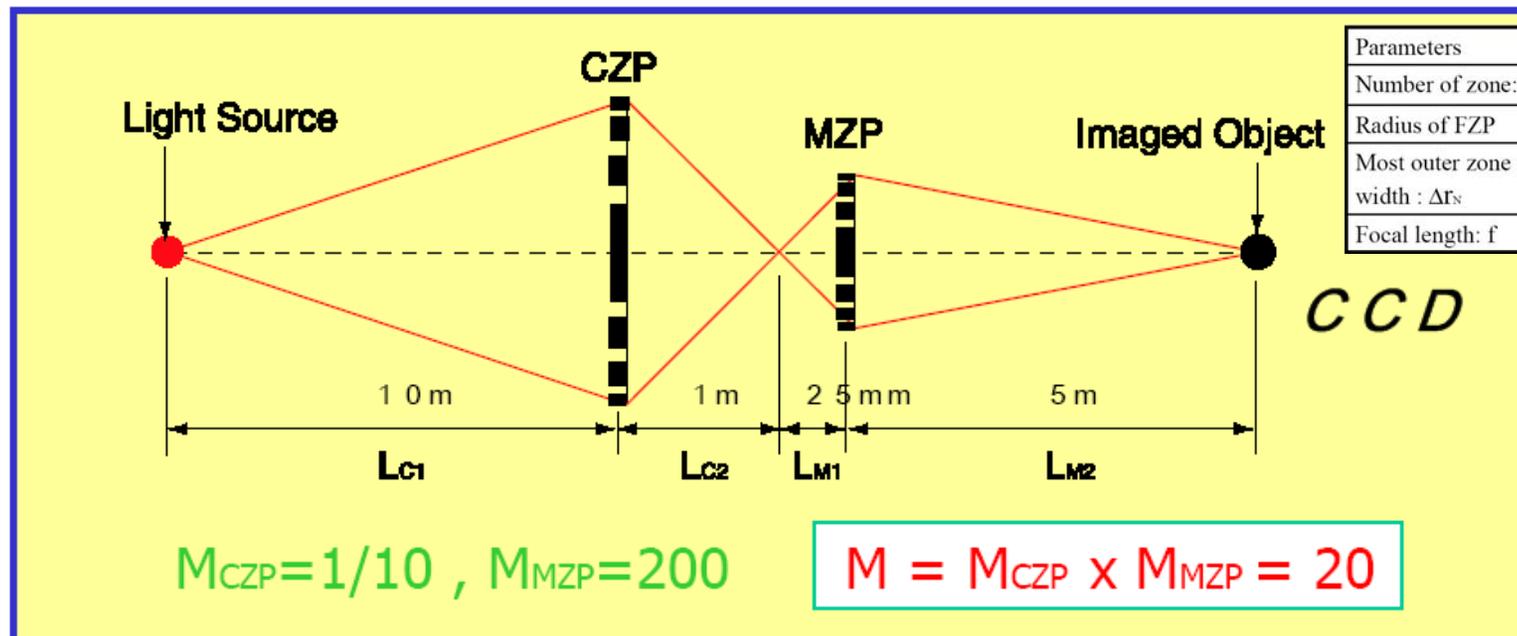
|                         |                                      |
|-------------------------|--------------------------------------|
| Spatial Resolution      | 4.1 $\mu\text{m}$ ( $1\sigma$ )      |
| Time Resolution         | 1 ms                                 |
| Field of View           | $\geq \phi$ 1.5 mm (vignetting-free) |
| Magnification Factor    | 13.7 (FZP & XZT)                     |
| Observing Photon Energy | 8.2 keV ( $\lambda = 0.15$ nm)       |

courtesy of S.Takano, Spring-8



*S. Takano*  
*Accelerator Division, Spring-8*

# FZP Monitor @ ATF (KEK)



- Monochromated **X-ray SR(3.235keV)** from bending magnet is used.

→ Reduce the diffraction limit from SR-light.

- **Two Fresnel zone plates (FZPs)** are used

→ The 20 times magnified beam image is obtained at X-CCD.

direct incidence  
back-thinned illuminated

⇒ total estimated spatial resolution: 0.7  $\mu\text{m}$  (rms)

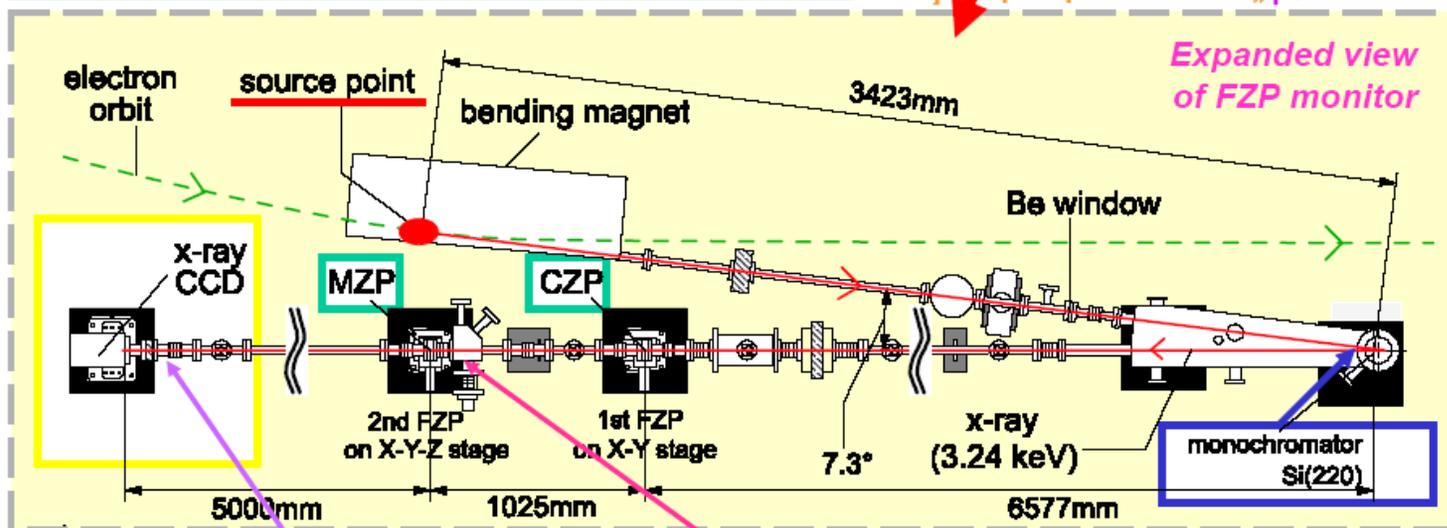
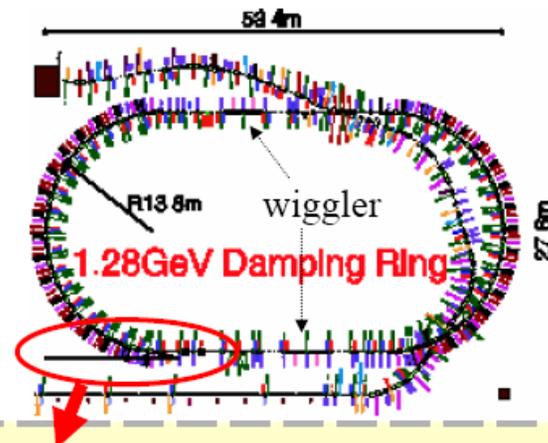
# FZP Monitor @ ATF (KEK)

## Setup of FZP monitor

FZP monitor was installed at KEK-ATF damping ring.

Expected beam sizes are

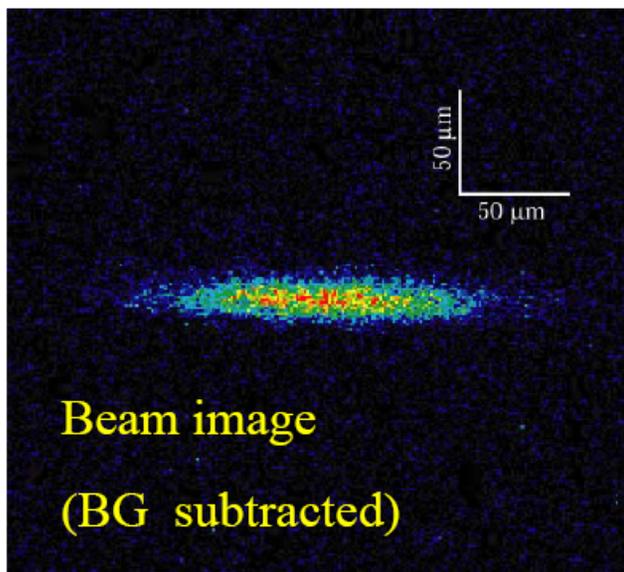
**Horizontal:  $50\mu\text{m}$ , Vertical:  $<10\mu\text{m}$**



Previous shutter was set in front of CCD camera [shutter time  $>20\text{ms}$ ]

New mechanical shutter installed on April 2005 (opening shutter time  $<1\text{ms}$ )

# FZP Monitor @ ATF (KEK)



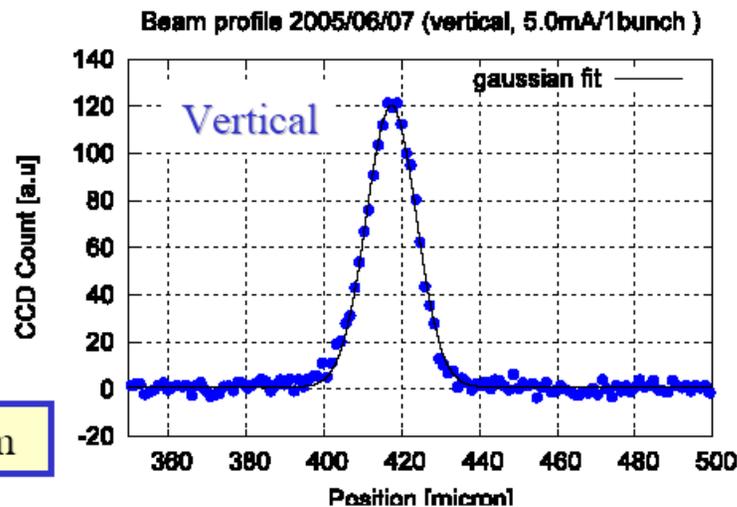
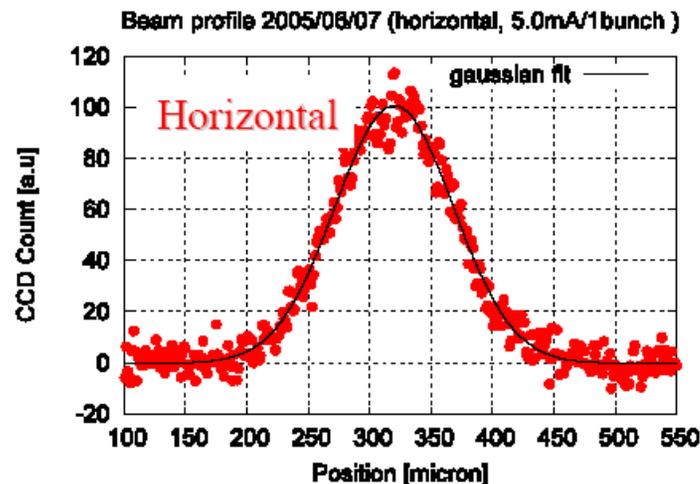
I=5.0mA, Shutter time = 1ms  
(2005/06/07)

$$\sigma_x = 48.2 \pm 0.5 \text{ } [\mu\text{m}]$$

$$\sigma_y = 6.4 \pm 0.1 \text{ } [\mu\text{m}]$$

Reduce vertical beam size : 9.2 $\mu\text{m}$   $\rightarrow$  6.4 $\mu\text{m}$

remove effect of unknown  
100 Hz oscillation



H. Sakai et al., Proc. EPAC 2006 Edinburgh, Scotland p.2784

H. Sakai et al., Phys. Rev. ST Accel. Beams 10 (2007) 042801

[http://accelconf.web.cern.ch/Accelconf/e06/TALKS/THOBF102\\_TALK.PDF](http://accelconf.web.cern.ch/Accelconf/e06/TALKS/THOBF102_TALK.PDF)

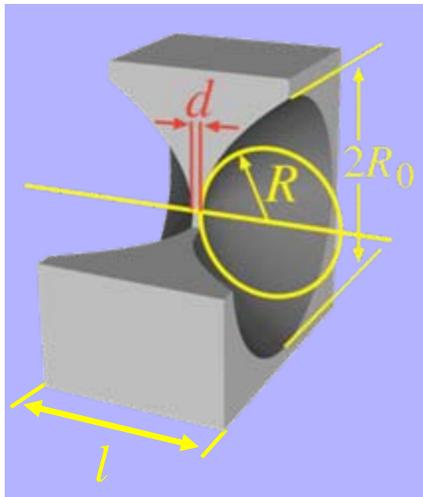
# Compound Refractive Lens

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

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

➤ concave lens shape

➤ strong surface bending  $R$

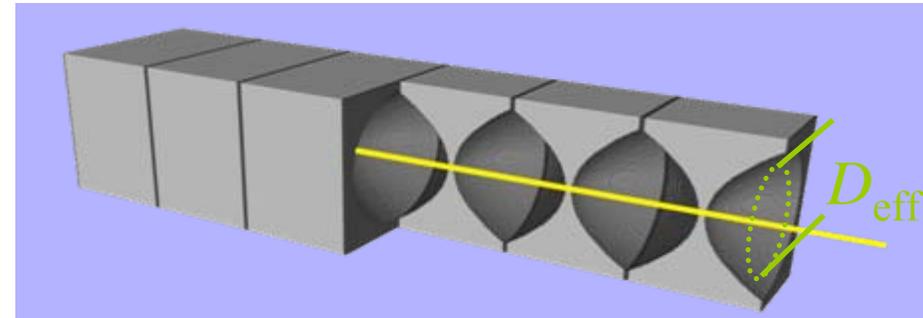


➤ small Z (Be, Al, ...)

➤ small d

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

⇒ many lenses (N=10...300)



## PETRA III @ 20 keV:

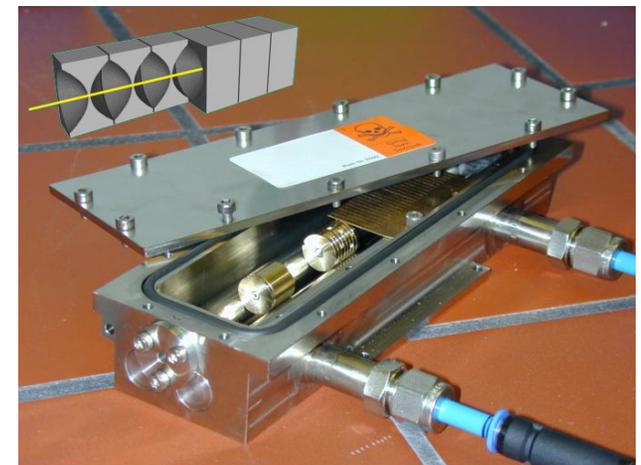
- $R = 200 \mu\text{m}$ ,  $R_0 = 500 \mu\text{m}$ ,  $d = 10 \mu\text{m}$ ,  $l = 1\text{mm}$

- $N = 31$

- material: beryllium

$$f = 3.8\text{m}$$

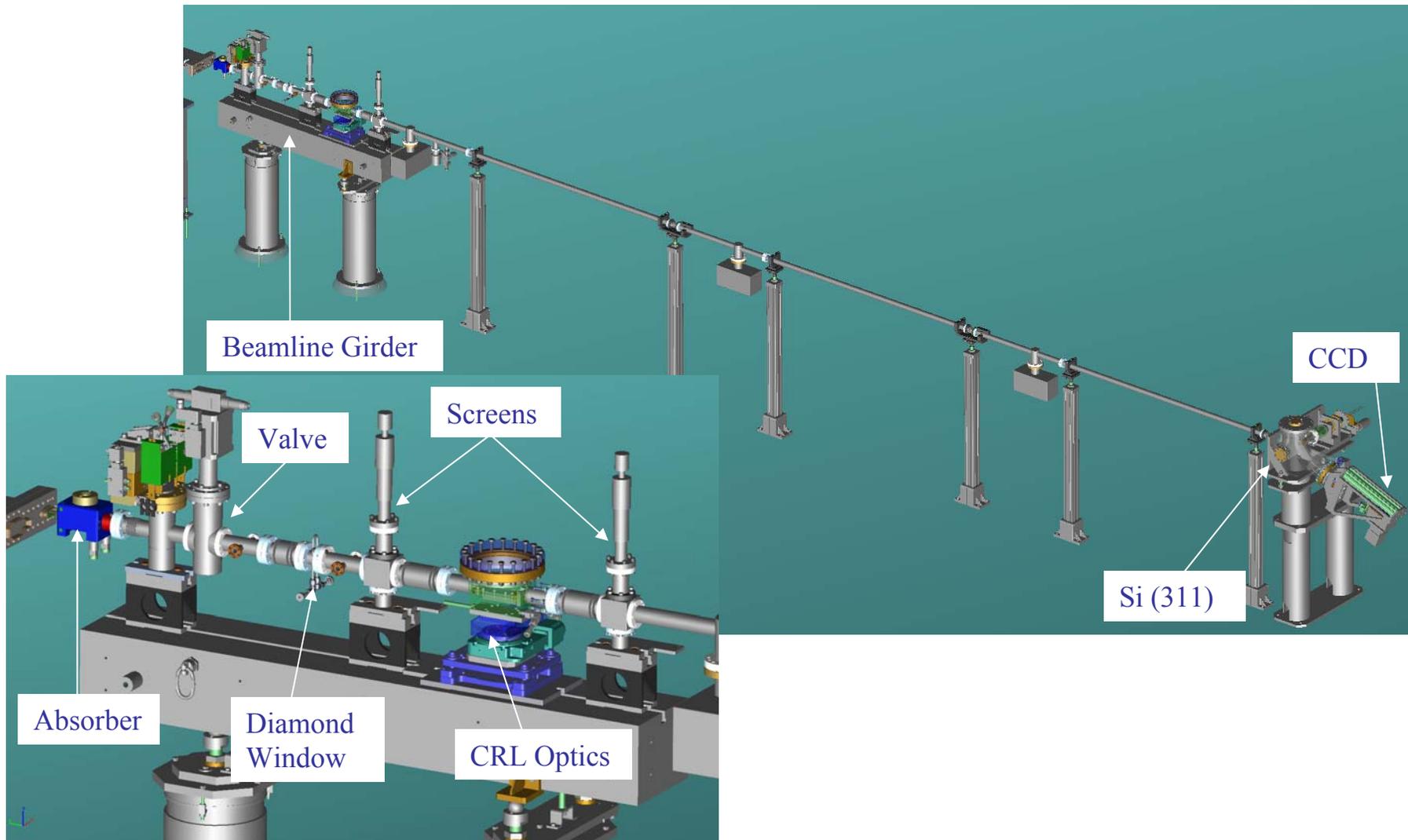
$$\sigma_{res} \approx 0.6 \mu\text{m}$$



courtesy of Ch. Schroer (TU Dresden)

# Compound Refractive Lens

## PETRA III diagnostics beamline



# X-ray Pinhole Camera

- „camera obscura“

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

- most common emittance monitor

simple setup

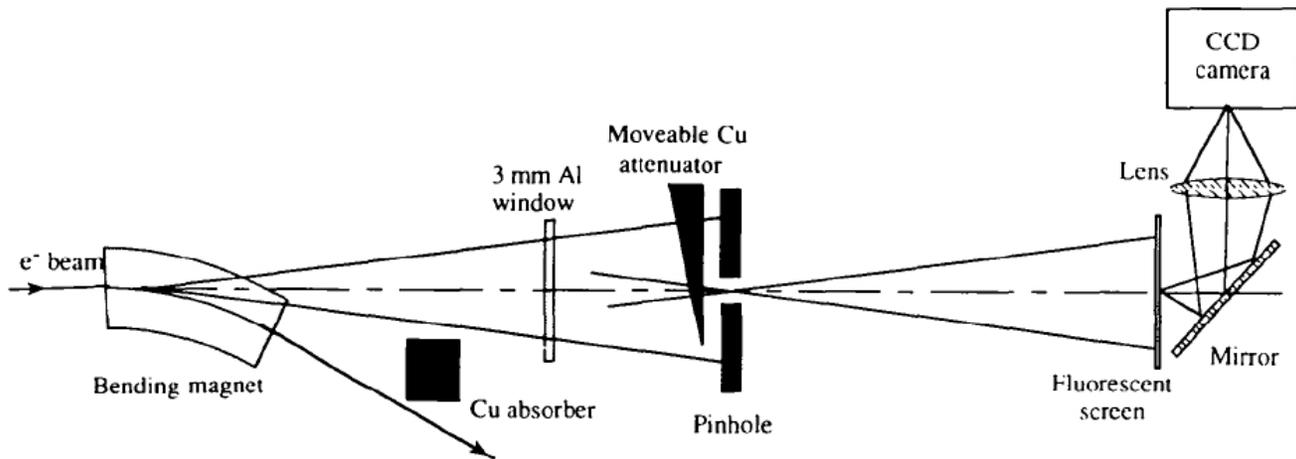


limited resolution

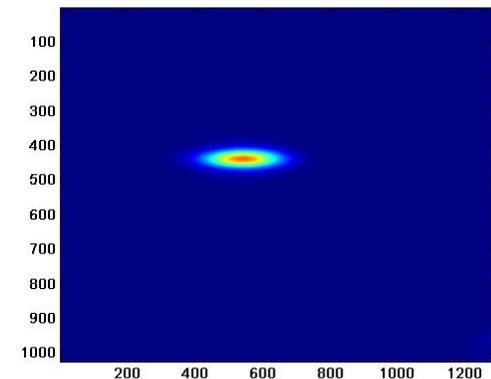
$$\sigma_{res} \geq 10 \mu m$$

example: ESRF

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



ID-25 X-ray  
pinhole camera:



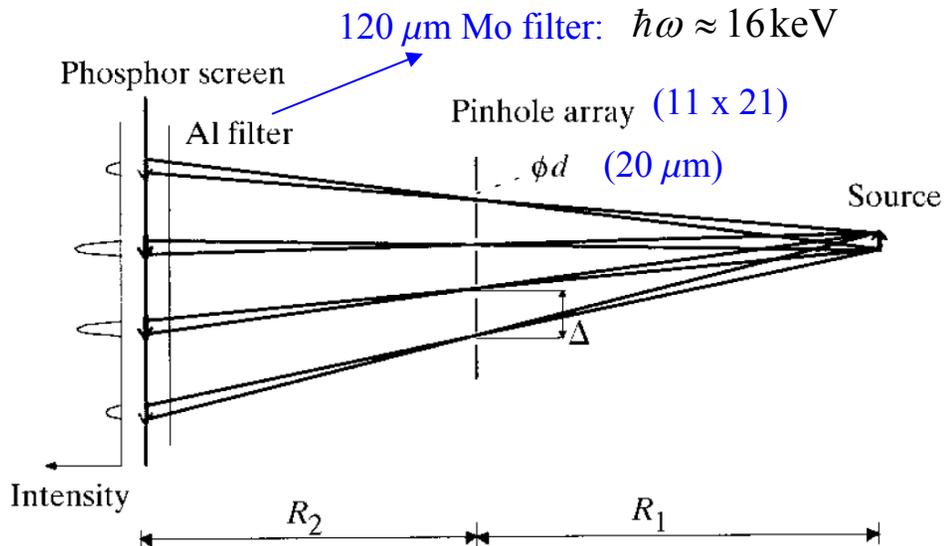
courtesy of K.Scheidt, ESRF

# Pinhole Array @ BESSY

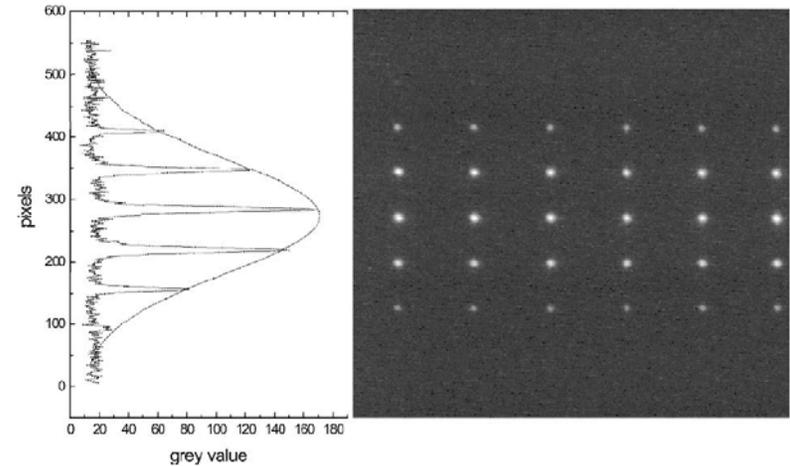
- simultaneous measurement of beam size and divergence

beam size: single pinhole image

beam divergence: envelope



K. Holldack et al. | Nuclear Instruments and Methods in Physics Research A 467-468 (2001) 235-238



W.B. Peatman, K. Holldack, J.Synchrotron Rad. (1998) 5, 639-641

⇒ diff. limited resolution 11  $\mu\text{m}$  (rms)

- increasing number of users

ALS (Berkeley):

F.Sannibale et al., Proc.EPAC 2004, Lucerne, Switzerland, p.2783

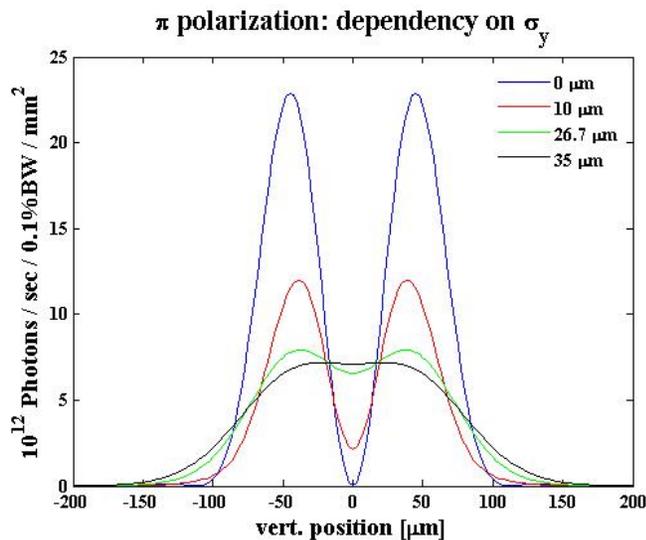
Australian Synchrotron:

M.J. Boland et al., Proc.EPAC 2006, Edinburgh, Scotland, p.3263

# Optical Imaging @ SLS (PSI)

imaging with vertically polarized optical radiation

⇒ smearing out of minimum with increasing vert. beam size  $\sigma_y$



SRW calculation, parameters similar to SLS monitor:

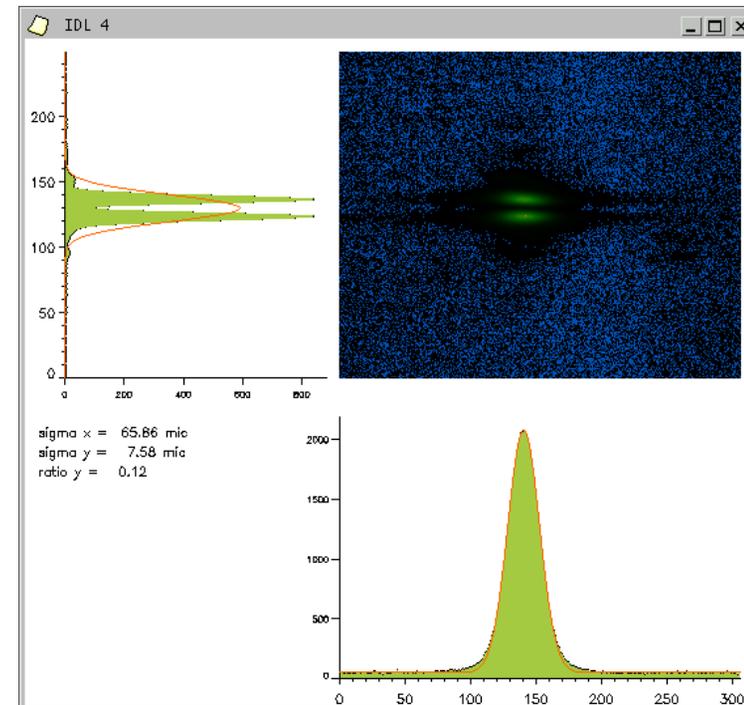
$E = 2.4 \text{ GeV}$

$\lambda = 365 \text{ nm}$

1:1 imaging

[monitor screenshot:](#)

courtesy of Å. Andersson, SLS



⇒  $\sigma_y$  from peak/valley ratio  
 $\sigma_x$  from fit

good agreement with independent  
pinhole measurements

Å. Andersson et al., Proc. EPAC 2006, Edinburgh, Scotland, p.1223

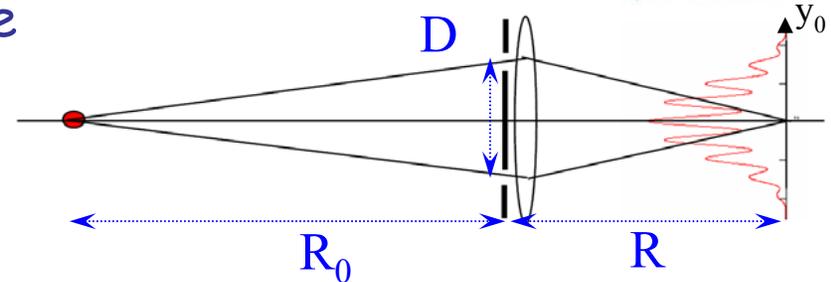
⇒ Å. Andersson, DIPAC 2007

# Interferometry

- quantification of (spatial) coherence

$$\gamma(D) = \frac{\langle \vec{E}_1 \cdot \vec{E}_2^* \rangle}{\sqrt{|\vec{E}_1|^2 \cdot |\vec{E}_2|^2}}$$

first order degree of mutual coherence



- intensity of partial (spatial) coherent source

$$I(y_0) = I_{inc} \left[ \text{sinc} \left( \frac{2\pi a}{\lambda R} y_0 \right) \right]^2 \left[ 1 + |\gamma| \cdot \cos \left( \frac{2\pi D}{\lambda R} y_0 + \varphi \right) \right]$$

- van Cittert-Zernike theorem (far field limit)

relation between coherence  $\gamma(D)$  and profile  $f(y)$  by Fourier transform

$$\gamma(D) = \int dy f(y) \cdot \exp\{-i2\pi \nu_y \cdot y\}$$

spatial frequency:  $\nu_y = \frac{D}{\lambda R_0}$

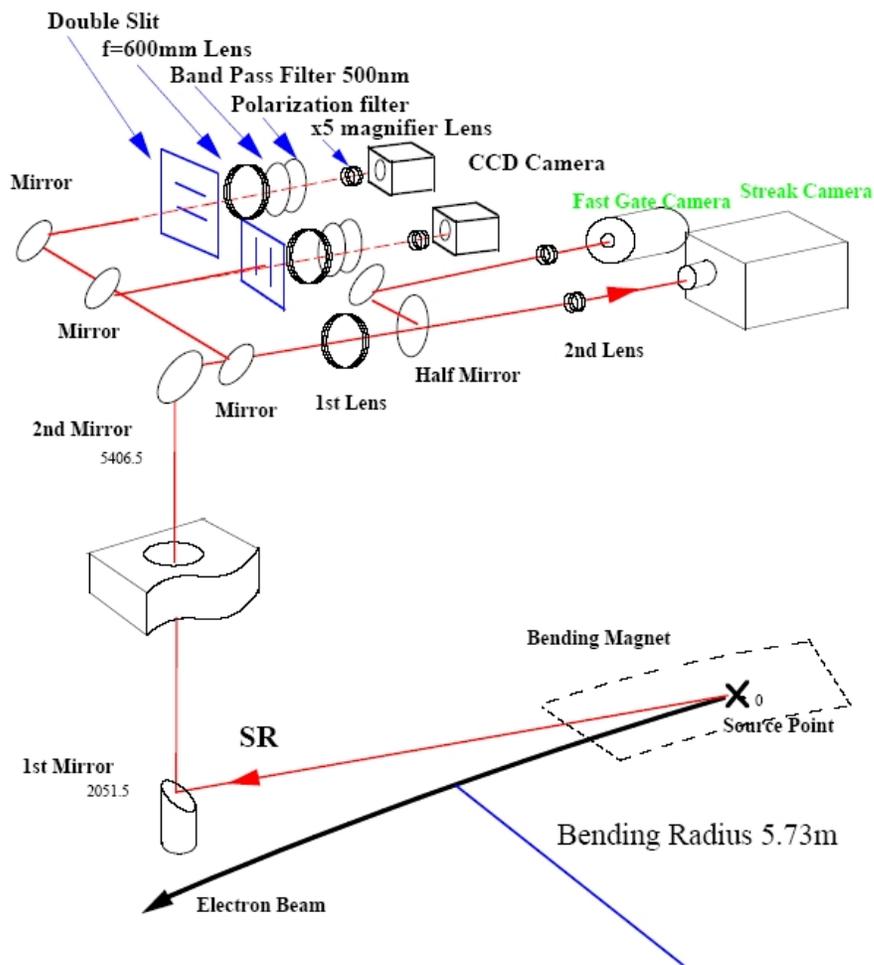
- two modes of operation

scanning  $D$ : shape reconstruction

fixed  $D_0$ : beam size measurement

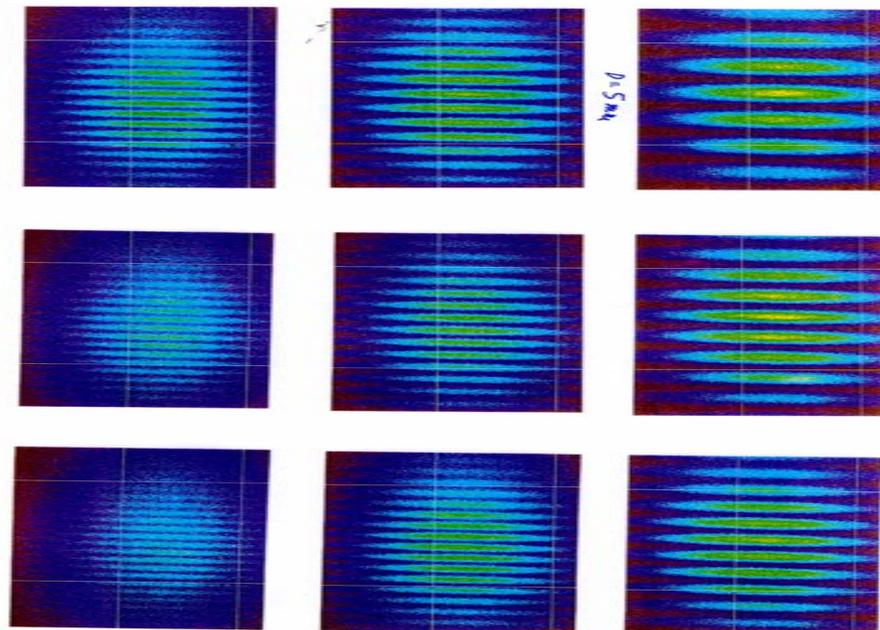
$$\Rightarrow \sigma_y = \frac{\lambda R}{\pi D_0} \sqrt{\frac{1}{2} \ln \left( \frac{1}{\gamma} \right)} \quad \text{Gaussian distributed}$$

# Interferometer @ ATF (KEK)



vertical beam size:

courtesy of T. Mitsuhashi, KEK

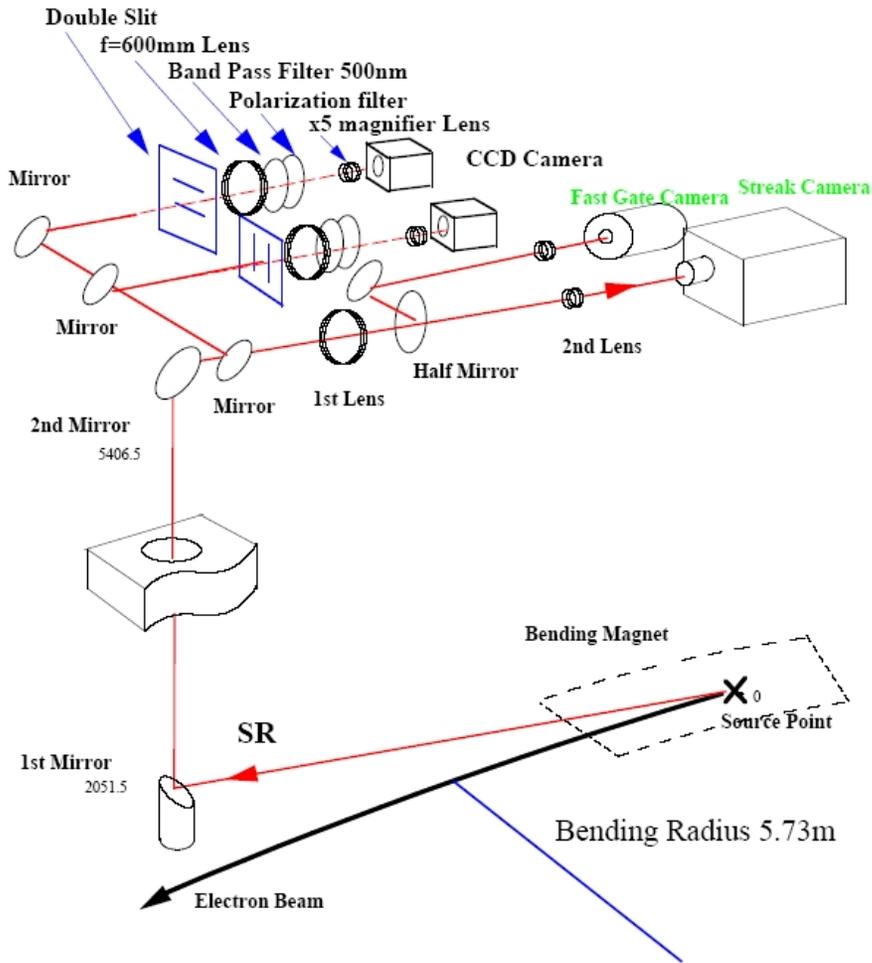


1.) fit of intensity pattern

⇒  $\gamma(D)$

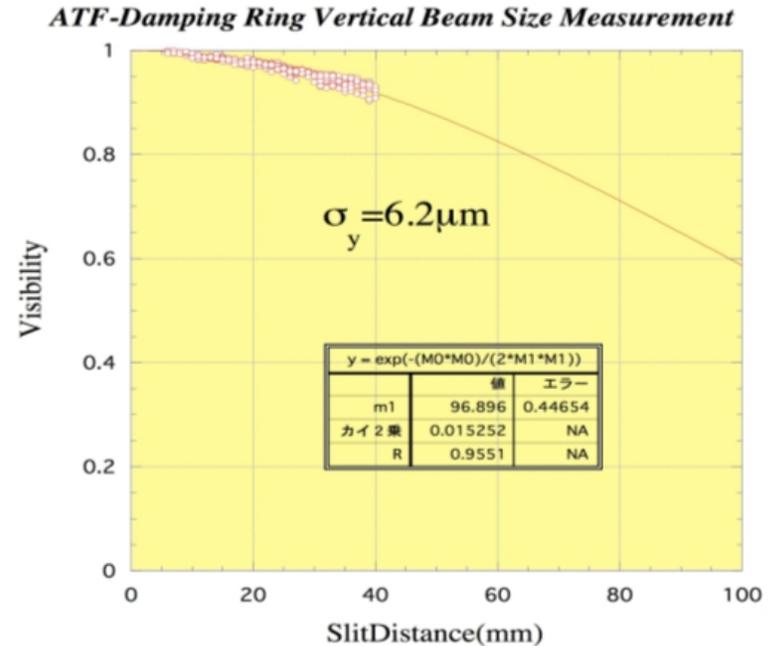
H.Hanyo et al., Proc. of PAC99 (1999), 2143

# Interferometer @ ATF (KEK)



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

vertical beam size:



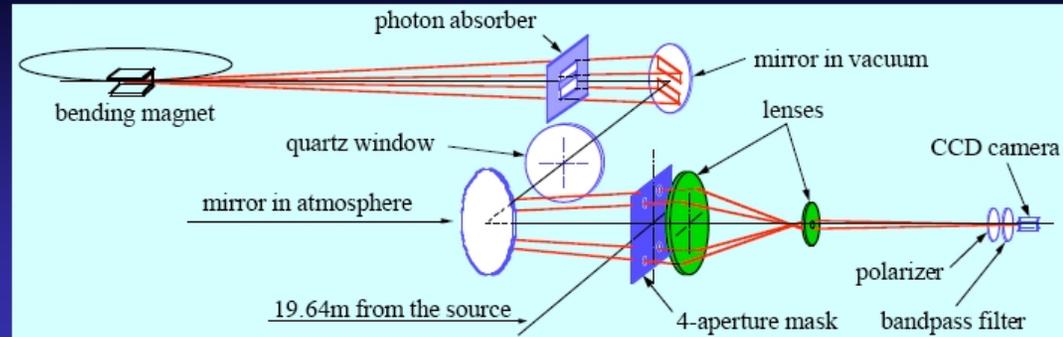
- 1.) fit of intensity pattern  $\Rightarrow \gamma(D)$
- 2.) Fourier-back transformation  $\Rightarrow \sigma_y$

$$\sigma_y = 6.2 \mu\text{m} \quad \text{accuracy} < 1 \mu\text{m}$$

# 2D Interferometer @ Spring-8

## SPring-8 2D Synchrotron Light Interferometer

M. Masaki & S. Takano,  
J. Sync. Rad. (2003). 10, p295



### Resolution

$$\sigma_{inter,X} = 121\mu\text{m}, \quad \sigma_{inter,Y} = 52\mu\text{m}$$

### 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:  $I(x,y;x_e,y_e)$

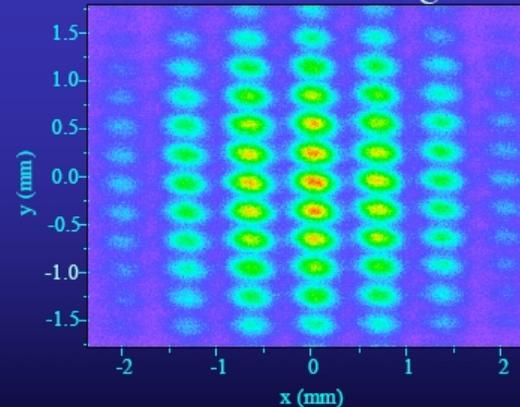
electron beam:  $\rho(x_e,y_e)$

elliptical Gaussian distribution



courtesy of S.Takano, Spring-8

### Observed interferogram

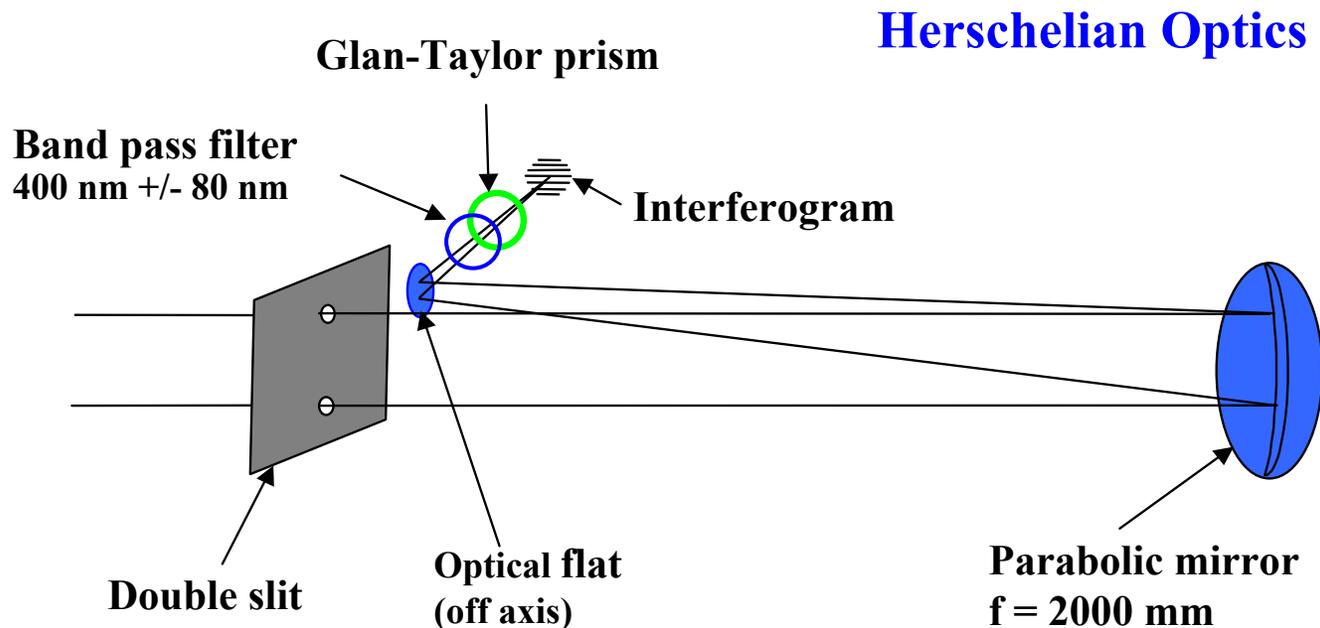


$$\sigma_I = 116(\mu\text{m}), \quad \sigma_{II} = 64(\mu\text{m}), \quad \theta = -18(\text{deg.})$$

⇒ changed to X-Ray Beam Imager

# Improvement of ATF Monitor

- high accuracy in phase  $\Leftrightarrow$  sufficient intensity  
 $\Rightarrow$  large bandpass filter (400 nm  $\pm$  80 nm)
- dominant error: dispersion in refractive optics (lenses)  
 $\Rightarrow$  smearing out of interferogram
- reflective optics

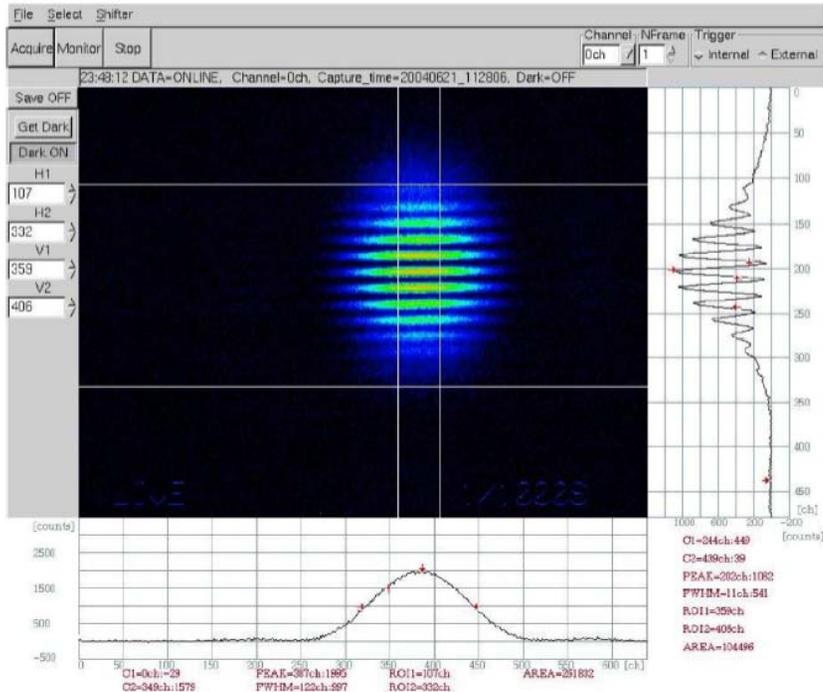


courtesy of T. Mitsuhashi, KEK

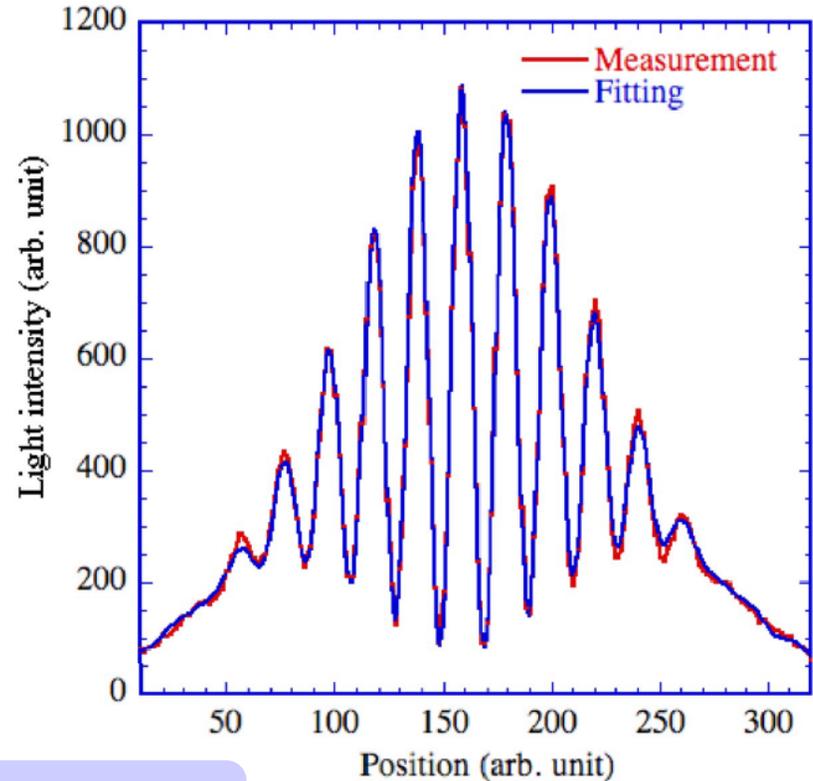
# Improvement of ATF Monitor

T. Naito and T. Mitsuhashi, Phys. Rev. ST Accel. Beams 9 (2006) 122802

interferogram



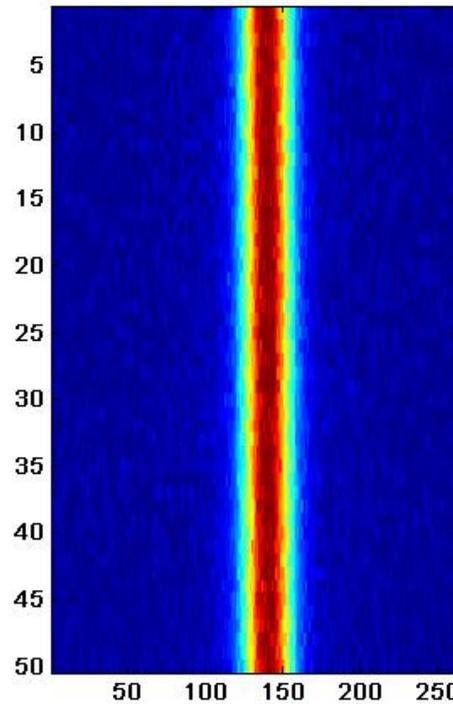
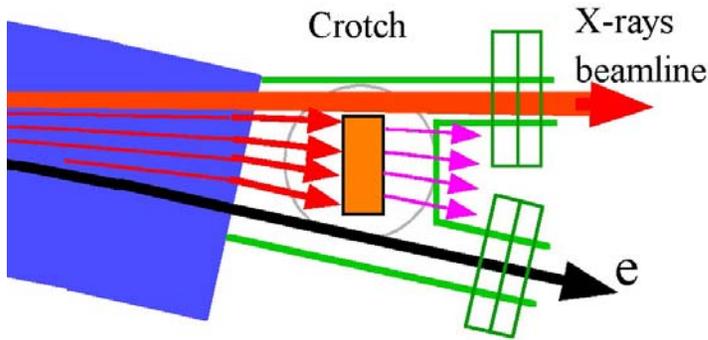
measurement / fit



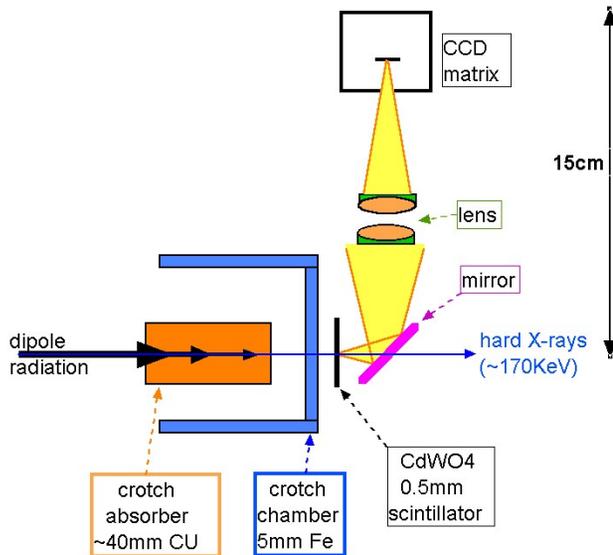
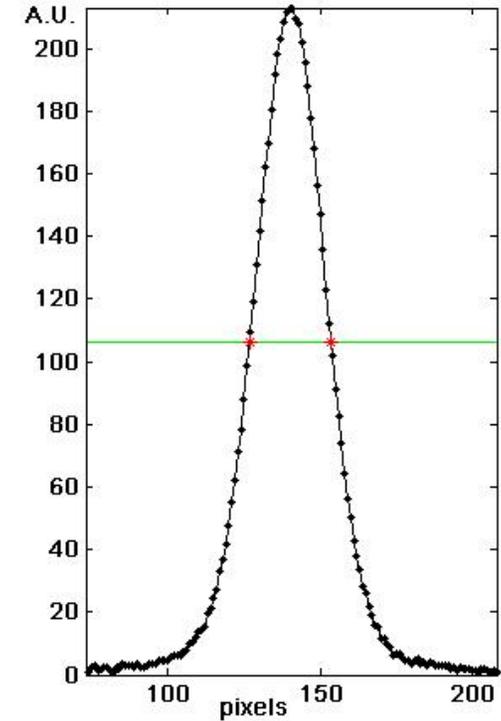
$$\Rightarrow \sigma_y = (4.73 \pm 0.55) \mu\text{m}$$

$$\sigma_y = (7.2 \pm 0.8) \mu\text{m} \quad (\text{refractive optics})$$

# In-Air X-Ray Detectors @ ESRF



size [fwhm um] = 118.85



$$\varepsilon_y = \frac{\sigma_{\gamma,y}^2 - \langle g_\gamma^2 \rangle L^2}{\beta_y + 2\alpha_y L + \gamma_y L^2}$$

K.Scheidt, Proc. of BIW06 (2006), Batavia, Illinois, p.208

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

⇒ K. Scheidt, DIPAC 2007

based on formalism developed in

P.Elleume et al., J.Synchrotron Rad. 2 (1995), 209

# Overview: Emittance Monitors

|           | Energy [GeV] | $\epsilon_x / \epsilon_y$ [ $\pi$ nm rad] | $\sigma_x / \sigma_y$ [ $\mu\text{m}$ ] | $\Delta(\sigma_x / \sigma_y)$ [ $\mu\text{m}$ ] | Type                                      | Reference   |
|-----------|--------------|---|---|---|---|---|
| Spring-8  | 8            | 3.4 / 0.01                                | 114 / 14                                | 121 / 52<br>~ 4                                 | 2-dim interferometry<br>single zone plate | DIPAC 01/J.Sync.Rad (03)<br>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<br>- / 35                      | 60 / 40   | pinhole camera<br>in air X-ray detector   | J.Sync.Rad (95)<br>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            | 4.3 / 0.043                               | 62 / 30                                 | ~ 15  | pinhole camera                            | EPAC 06   |
| ELETTRA   | 2            | 7 / 0.07                                  |   |   | opt. imaging +                            | EPAC 00   |
|           | 2.4          | 9.7 / 0.1                                 | 146 / 25                                | 30 / 30   | interferometry                            |   |
| SLS       | 2.4          | 5.5 / 0.019                               | 61 / 19<br>56 / 20                      |   | opt. imaging +<br>pinhole                 | EPAC 06   |
| ATF(KEK)  | 1.28         | 1.1 / 0.011                               | 48.2 / 6.4<br>26 / 4.7                  | < 0.7<br>- / < 1                                | zone plate microscope<br>interferometry   | Phys.Rev ST 10 (2007)<br>Phys.Rev ST 9 (2006)     |
| ALS       | 1.9          | 6 / 0.03                                  | 88 / 45<br>~100 / ~ 10                  | 10 / 10<br>~ 30                                 | Kirkpatrick-Baez +<br>pinhole array       | BIW 96<br>EPAC 04                                 |
| PETRA-III | 6            | 1 / 0.01                                  | 44 / 18                                 | ~1  | comp. refractive lens                     |   |
| BESSY-II  | 1.9          | 6 / < 0.02                                | 50-60 / 40-50                           | 11 / 11<br>3 / 3                                | pinhole array +<br>Bragg-Fresnel lens     | NIM A467/468 (2001)                               |

# Proton Synchrotron Radiation

- spectrum characterized by  $\lambda_c$ :

$$\lambda_c = \frac{4\pi}{3} \frac{\rho}{\gamma^3}$$

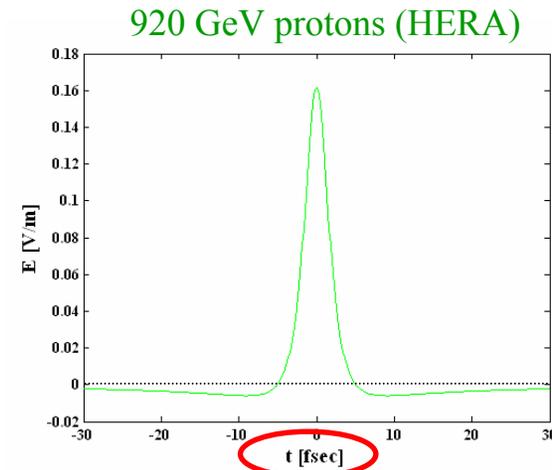
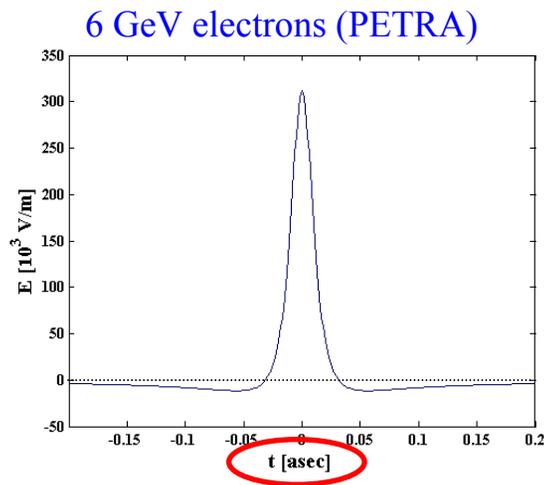
$\gamma$ : Lorentz factor  
 $\rho$ : bending radius

- large p mass  $\Rightarrow$  small  $\gamma = E/m_p c^2$

HERA-p:  $E = 40 \dots 920 \text{ GeV} \Rightarrow \lambda_c = 55 \text{ mm} \dots 4.5 \mu\text{m}$

$\Rightarrow$  large diffraction broadening, expensive optical elements, ...

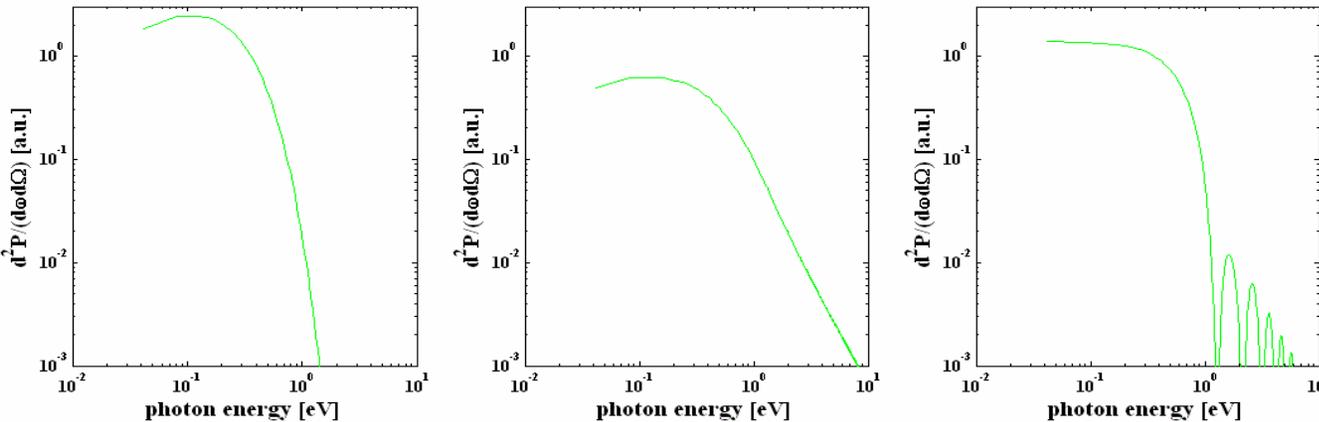
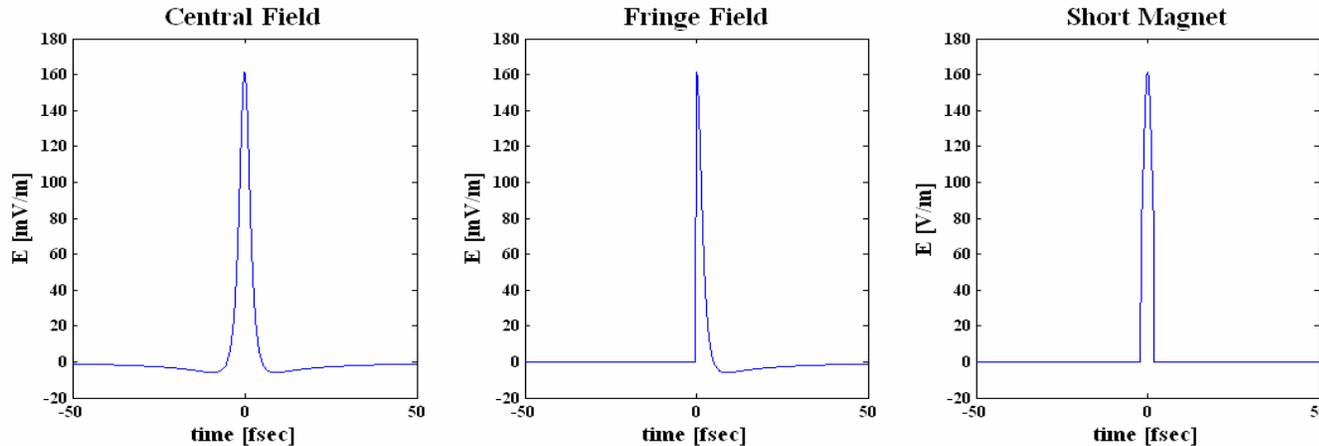
- radiation in time domain



$\Rightarrow$  „frequency boost“ required

# Generation of Frequency Boost

sharp cut-off of wavetrain in time domain



⇓

$$\frac{d^2N}{d\Omega d\omega/\omega} \propto |\vec{E}_\omega|^2$$

with

$$\vec{E}_\omega = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} dt \vec{E}(t) e^{i\omega t}$$

⇒ still requires high beam energies (CERN, Tevatron, HERA)

# p SyLi Monitors @ CERN

- first monitor realized at SPS ( $> 350$  GeV)

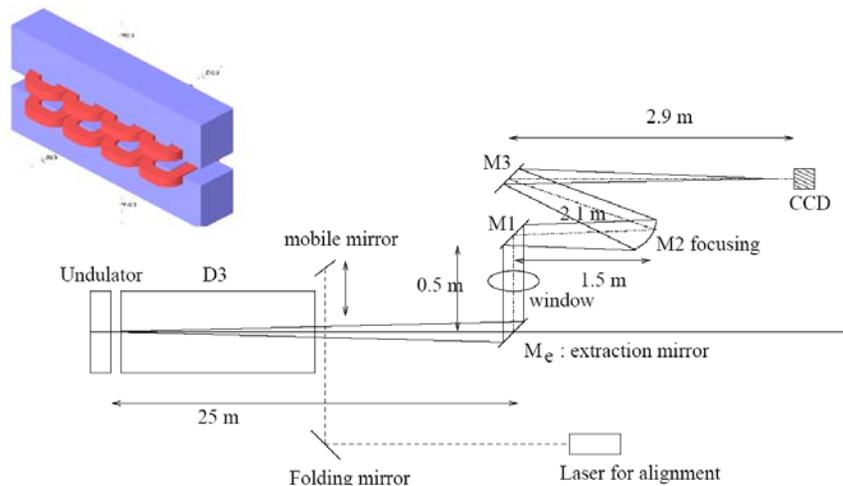
R. Bossart et al., Nucl. Instr. and Meth. 164 (1979) 375, R. Bossart et al., Nucl. Instr. and Meth. 184 (1981) 349

- use of undulator to extend energy range

J. Bossert et al., CERN-SPS/83-5 (1983)

- LHC: superconducting undulator & separation dipole

- whole energy range: undulator and D3 edge



undulator parameters

|  |   |
|--|---|
| Period   | 280 mm                                    |
| Period number                                    | 2   |
| Iron yoke length                                 | 710 mm                                    |
| Gap  | 60 mm                                     |
| Beam tube size                                   | 50 mm inside / 53 mm outside              |
| Maximum magnetic field in the gap                | 5 T                                       |
| Maximum field error within $\pm 10$ mm from axis | 0.25%                                     |
| Supply current                                   | 250 A                                     |
| Total energy stored at 250 A                     | 150 kJ                                    |
| Magnet inductance                                | 4.8 H                                     |
| Coil cross-section                               | $36.5 \times 42.5 \text{ mm}^2$           |
| Cable size                                       | $1.25 \times 0.73 \text{ mm}^2$           |
| Overall coil size                                | $140 \times 220 \times 36.5 \text{ mm}^3$ |
| Operating temperature                            | 4.2 K                                     |
| Margin to quench on load line                    | 20%                                       |

- from 2 TeV to 7 TeV: D2 dipole

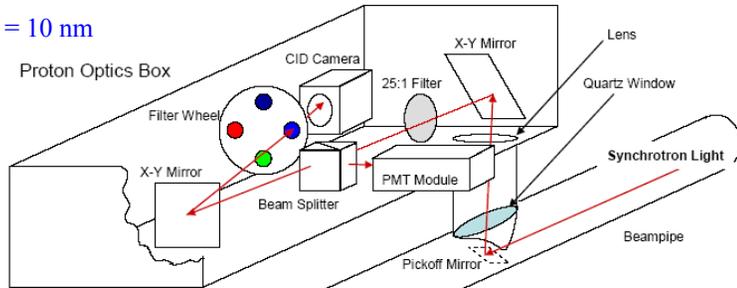
L. Ponce, R. Jung, F. Méot, CERN-2004-007 (2004)

# Synclite Monitor @ Tevatron (FNAL)

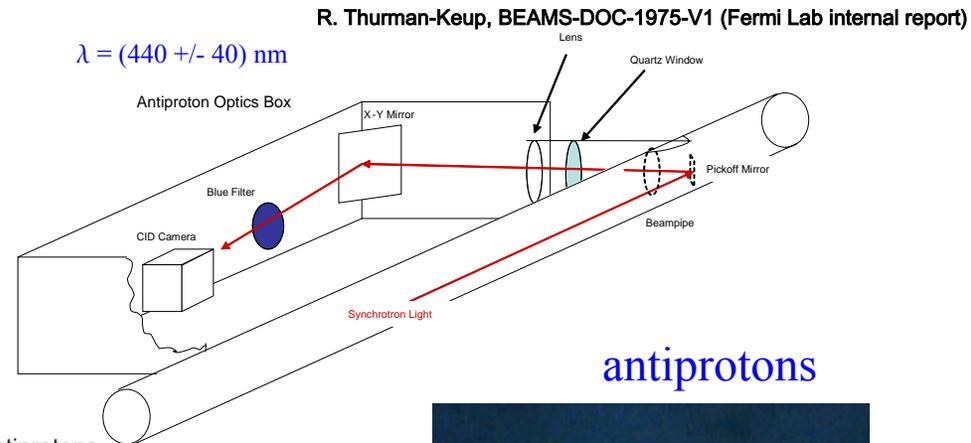
- individual monitors for p and pbar
- p monitor combined with abort gap monitor

$\lambda = 360 \text{ nm}, 440 \text{ nm}, 530 \text{ nm}, 620 \text{ nm}$

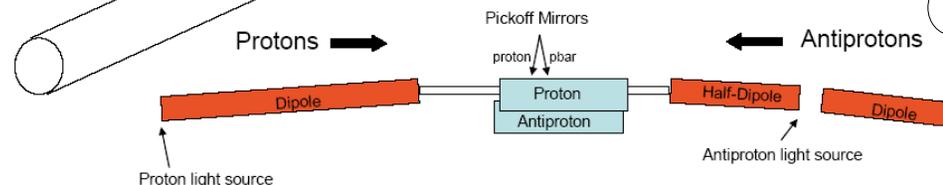
$\Delta\lambda = 10 \text{ nm}$



$\lambda = (440 \pm 40) \text{ nm}$

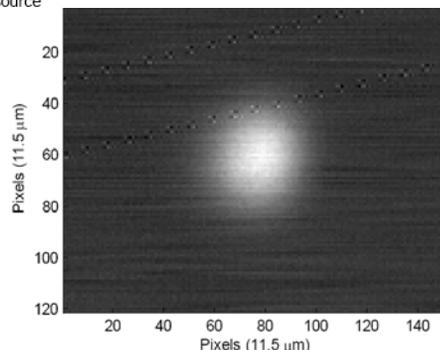


antiprotons



Proton light source

Antiproton light source



protons



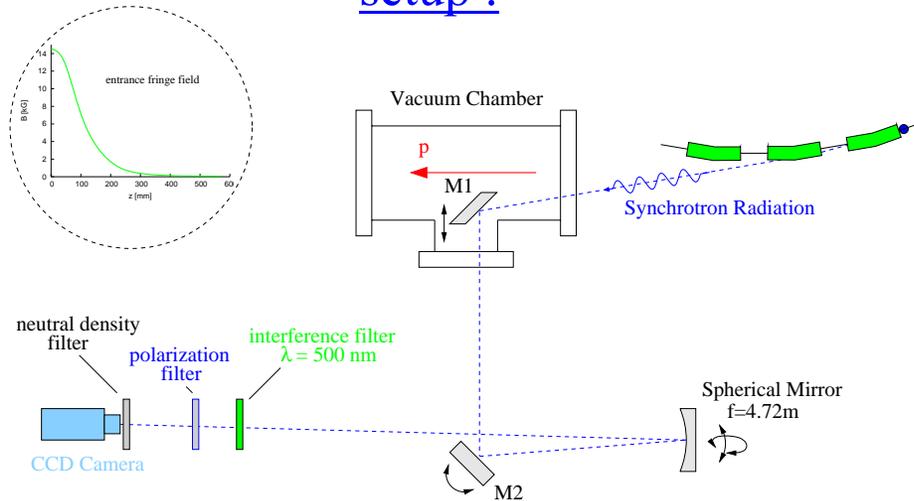
A.A. Hahn and P. Hurr, in 1992 IEEE Part. Accel. Conf. 1991, p.1177

R. Thurman-Keup, Proc. of BIW06 (2006), Batavia, Illinois, p.364

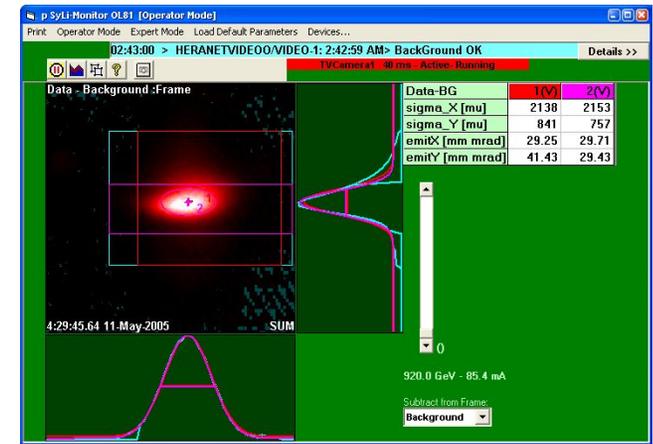
# p SyLi Monitor @ HERA (DESY)

fringe field of vertical deflecting dipole

setup :



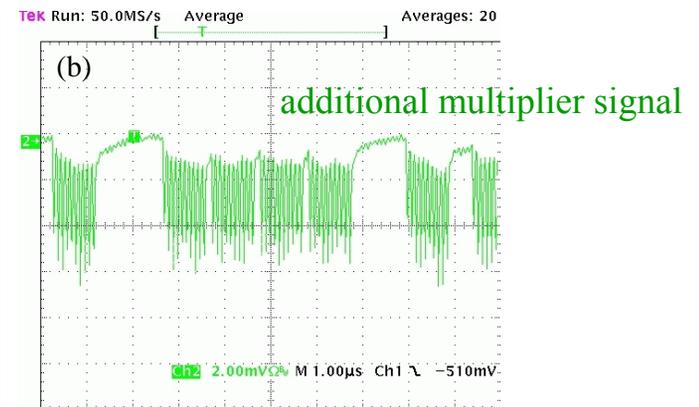
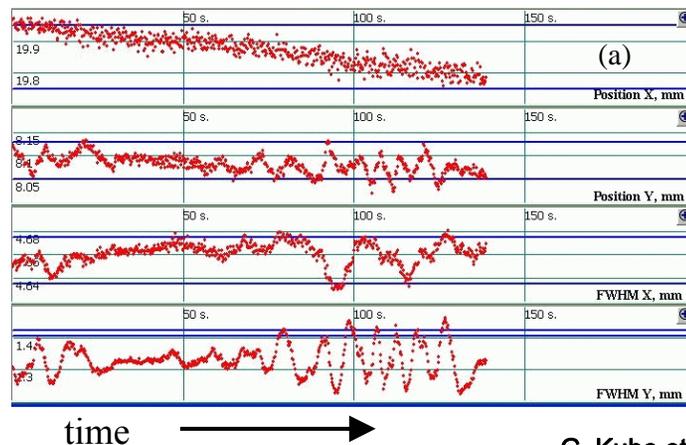
screen shot :



visible light spot for E > 600 GeV

dynamics study:

moving collimators  
towards the beam

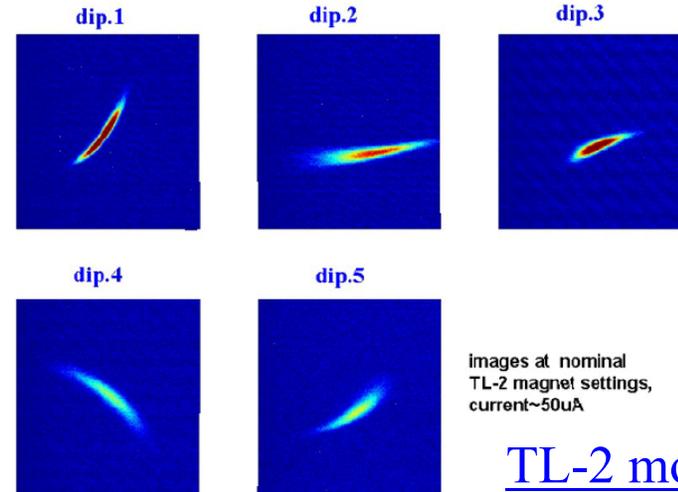
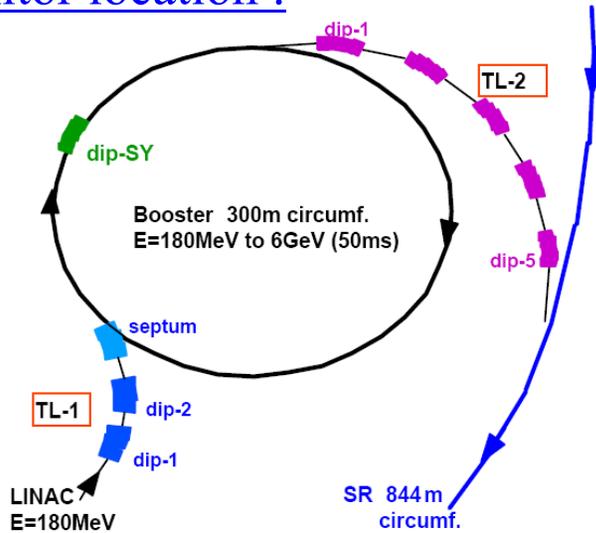


G. Kube et al., Proc. of BIW06 (2006), Batavia, Illinois, p.374

# Injector Monitor System @ ESRF

application in transfer lines

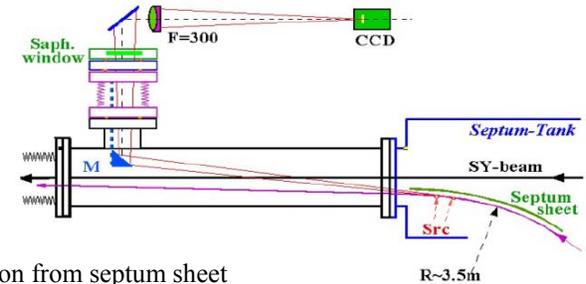
monitor location :



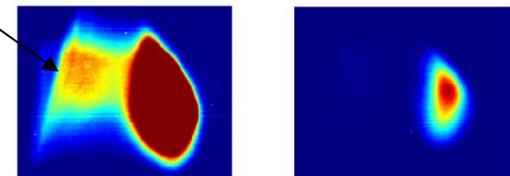
images at nominal TL-2 magnet settings, current~50uA

TL-2 monitors

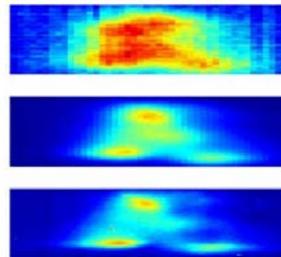
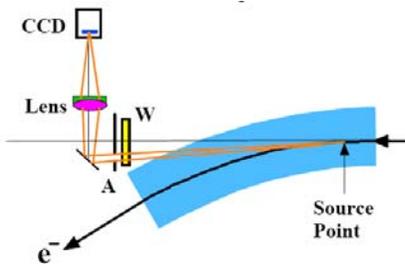
booster septum :



reflection from septum sheet



TL-1 extraction :



comparison :

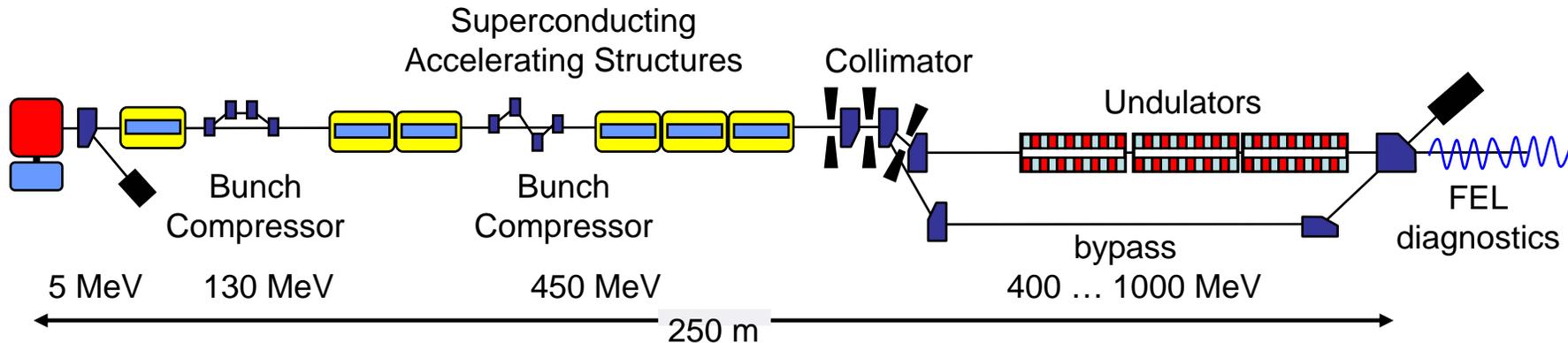
screen

screen

SyLi monitor

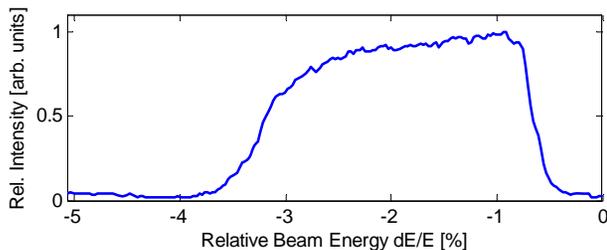
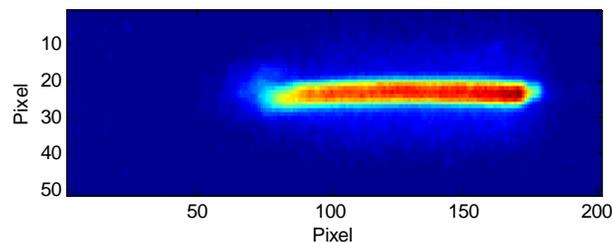
# Energy Monitor @ FLASH (DESY)

## SR based profile diagnostics in bunch compressor

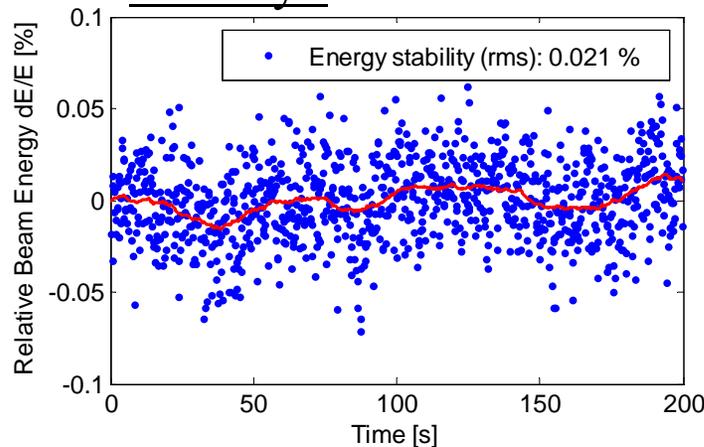


dispersive section  $\Rightarrow$  information about energy distribution (and more...)

single  
bunch



stability :



Ch. Gerth, DIPAC 2007

- injection mismatch

M.G. Minty et al., Proc. Accelerator Instrumentation Workshop, Berkeley AIP Conf. Proc. 281 (1992) , p.158

M.G. Minty, W.L. Spence, Proc. of 1995 IEEE PAC, Dallas (1995), p.536

- turn-by-turn imaging

instabilities, injection, ...

A.S. Fisher et al., Proc. of BIW06, Batavia, Illinois, AIP Conf.Proc. 868 (2006), p.303

O.I. Meshkov et al., Proc. of DIPAC05, Lyon (France) 2005, p.42

- beam halo measurements

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⇒ END

