Beam Diagnostics
with Synchrotron Radiation
in Light Sources

S. Takano
JASRI / SPring-8
Outline

- Transverse Beam Profiling
- Bunch Length Measurement
- Single Bunch Purity Measurement
- Diagnostics with a Dedicated Insertion Device
Transverse Beam Profiling

Key Instrumentation for Emittance Diagnostics.

\[ \varepsilon_i = \frac{\sigma_i^2 - (\sigma_E/E)^2}{\beta_i} \eta_i^2 \quad i = x, y \]

Light Sources are Competing to Achieve Lower Emittance and Emittance Coupling Ratio.

Vertical Emittance \( \varepsilon_y \) Approaching to 1 pm rad

\[ \varepsilon_y = 1 \text{ pm} \cdot \text{rad}, \quad \beta_y \sim 10 \text{m} \quad \Rightarrow \quad \sigma_y = \sqrt{\varepsilon_y \beta_y} \sim 3 \mu \text{m} \]

High Resolution is Demanded for Beam Profiling.
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<th>Energy (GeV)</th>
<th>$\epsilon_x$ (nm rad)</th>
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<th>$\sigma_y$ (µm)</th>
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Trends in Modern Light Sources

X-ray pinhole cameras and visible SR interferometers are widely used.

Developments of imaging systems based on the X-ray focusing optics are pursued to further improve the spatial resolution.

Other Methods are also performing such as π-polarization method and in-air X-ray monitors.
X-ray Pinhole Camera

System Resolution

\[ \Delta \sigma_y^2 = S_{\text{Pinhole}}^2 + S_{\text{Camera}}^2 \]

Pinhole Optimization

Simplistic Model

\[ S_{\text{Pinhole}}^2 = S_{\text{Diffraction}}^2 + S_{\text{Aperture}}^2 \]

\[ S_{\text{Diffraction}} = \frac{0.36 \lambda d}{w}, \quad S_{\text{Aperture}} = \frac{w(1 + 1/m)}{\sqrt{12}} \]

**Given** \( d \), \( m \), and \( \lambda \)

\[ S_{\text{Pinhole}_{\text{opt}}} = 0.46 \sqrt{\lambda d \left(1 + \frac{1}{m}\right)} \]

with \( w_{\text{opt}} = 1.12 \sqrt{\frac{\lambda d}{1 + 1/m}} \)

For better resolution...

closer distance \( d \), larger magnification \( m \),
and shorter observing wavelength \( \lambda \).
Quantitative optimization needs **PSF calculation** based on **wave optics** taking account of the **SR bandwidth**.

The most performing X-ray pinhole cameras are elaborately designed to achieve resolution in the $\mu$m range.
Pinhole design from ESRF
- The resolution analysis is a SOLEIL work
- Beam-based pinhole aperture measurements in progress to control if the theoretical pinhole size is really set.

 sistem Resolution
\[ \Delta \sigma_y = 4.1 \mu m \]

Minmum Coupling
\[ K < 0.1\% \]
\[ \epsilon y \approx 3.5 \text{ pm} \]

Visible Optics
\[ \sigma_{\text{Camera}} = 2 \mu m \]

Courtesy of M.-A. Tordeux and J.-C. Denard, SOLEIL
Pioneering Works with X-ray Imaging Optics

Kirkpatrick-Baez Mirror (K-B mirror)
ALS, PLS
Bragg-Fresnel Lens (BFL)
ESRF, BESSY II
Fresnel Zone Plate (FZP)
APS
Compound Refractive Lens (CRL)
ESRF

Transverse Beam Profiling

26 May 2010 S. Takano JASRI/SPring-8 IPAC10
Beam Profiling with X-ray Imaging Optics

Developments of imaging systems based on the X-ray focusing optics are pursued to further improve the spatial resolution.

**Compound Refractive Lens (CRL)**
- PETRA III
- NSLS-II (planned)

**Fresnel Zone Plate (FZP)**
- SPring-8
Compound Refractive Lens

lens-maker formula: \( \frac{1}{f} = \frac{2(n-1)}{R} \) → concave lens shape

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

- \( R = 200 \mu m, \ R_0 = 500 \mu m, \ d = 10 \mu m, \ l = 1 \text{mm} \)
- \( N = 31 \)
- material: beryllium

\( f = 3.72 \text{ m} \)

Courtesy of G. Kube, PETRA III
Transverse Beam Profiling

Diagnostics Beamline with CRL System @ PETRA III

CRL $f = 3.72 \text{ m} @ 20 \text{ keV}$
magnification $\sim 1.55$

$\sigma_{\text{CRL}} \sim 0.2 \mu\text{m}$

X-ray Detector System

$\sigma_{\text{Camera}} \sim 6 \mu\text{m}$ currently

$\sigma_{\text{Camera}} = 1~2 \mu\text{m}$
in preparation

Courtesy of G. Kube, PETRA III

Details given in IPAC’10 Poster MOPD089 “PETRA III Diagnostics Beamline for Emittance Measurements”
Fresnel Zone Plate (FZP) Optics

Between rays passing adjacent transparent zones, the difference of optical paths to a focal spot is equal to one wavelength.

The rays passing all the transparent zones contribute in phase at a focal spot to the amplitude.

In the hard X-ray region, absorbing zones are not completely opaque. If the phase shift originating from absorbing zone material corresponds to the half wavelength, the rays passing absorbing zones also contribute in phase at a focal point.
Transverse Beam Profiling

X-ray Beam Imager (XBI) @ SPring-8

Single FZP + X-ray Zooming Tube

System Resolution 4.1 μm
Time Resolution 1 ms
Field of View ≥ φ 1.5 mm
Magnification 13.7

Focal length \( f \) 6.92 m
Magnification factor 0.274
Resolution \( \sigma_{FZP} \) 1.5 μm
Efficiency 32%
Number of Zones 468
Minimum Zone Width 0.75 μm

Low-emittance User Optics (Regular)
\( \epsilon = 3.4 \text{ nm rad} \)

\( \sigma_x = 111.7 \pm 1.1 \text{ μm} \quad \sigma_y = 14.1 \pm 0.14 \text{ μm} \)

FZP

SiN Membrane
Si Frame
Ta Absorber
Zone Structure

Focal length \( f \) 6.92 m
Magnification factor 0.274
Resolution \( \sigma_{FZP} \) 1.5 μm
Efficiency 32%
Number of Zones 468
Minimum Zone Width 0.75 μm

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Synchrotron Radiation (SR) Interferometer

T. Mitsuhashi noted the application of the method to transverse beam profiling.
proc. of PAC'97 (1997) p.766

Interference Pattern

\[
I = I_0 \left\{ \text{sinc} \left( \pi \frac{y_c}{y_0} \right) \right\}^2 \left[ 1 + V \cos \left( 2\pi \frac{D}{w} \cdot \frac{y_c}{y_0} \right) \right], \quad y_0 = \frac{d_1 \lambda}{w}
\]

Extended source smears out the interference fringe.

Visibility

\[
V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \exp \left( -2 \frac{\pi^2 D^2 \sigma_y^2}{\lambda^2 d_0^2} \right)
\]

\[
\sigma_y = \frac{\lambda d_0}{\pi D} \sqrt{\frac{1}{2} \ln \left( \frac{1}{V} \right)}
\]
SR interferometer @ SSRF

First Mirror
Be
Parabolic back surface
two cooling tubes

Interferogram
Patten for different current

Beam size measurement for transverse feedback

Courtesy of K.R. Ye & Y.B. Leng, SSRF
2-D SR Interferometer @ SPring-8

1-D Analysis

\[ \sigma_{x,y} = \frac{\lambda}{\pi \eta_{x,y}} \sqrt{\frac{1}{2} \ln V_{x,y}} \]

- \( V \): visibility
- \( \lambda \): observing wavelength
- \( \eta \): angular separation of the 4-aperture mask
- \( \sigma \): projected rms beam size at the source point

2-D Analysis

Point spread function: \( I(x,y;x_e,y_e) \)

Ellipsoidal electron beam distribution:

\[ \rho(x_e,y_e) \propto \exp \left[ -\frac{1}{2} \left( a x_e^2 + b y_e^2 + c x_e y_e \right) \right] \]

\[ a = \left( \frac{\cos \theta}{\sigma_I} \right)^2 + \left( \frac{\sin \theta}{\sigma_{II}} \right)^2, \quad b = \left( \frac{\sin \theta}{\sigma_I} \right)^2 + \left( \frac{\cos \theta}{\sigma_{II}} \right)^2, \quad c = \left( \frac{1}{\sigma_I^2} - \frac{1}{\sigma_{II}^2} \right) \sin 2\theta \]

We can obtain the parameters \( \sigma_I, \sigma_{II}, \theta \) by fitting procedure.

Courtesy of M. Masaki, SPring-8
**π-Polarization Method**

Imaging with Vertically Polarized Visible-to-UV SR


Vertical source size $\sigma_y$ smears out the zero minimum at the center of the $\pi$-component PSF.
$\pi$-Polarization Method @ SLS


SLS Diagnostic Beamline

Vertical Profiles

$\sigma_y = 6.4 \pm 0.5 \mu m$

Acquired Image

$\lambda = 364$ nm
$\Delta \lambda = 1.5$ nm (FWHM)

Horizontal Profiles

$\sigma_x = 60 \mu m$
$\sigma_x = 57 \mu m$
$\sigma_x = 54 \mu m$

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In-Air X-ray (IAX) Monitors @ ESRF

Dipole: $= 155\text{W/mrad}$

Crotch

X-rays beamline

IAX

a tiny fraction ($\sim 2 \cdot 10^{-6} = 300\text{uW/mrad}$) traverses the crotch: Xrays $> 150\text{KeV}$

IAX monitors on 11 dipoles (behind crotch absorbers)

IAX Side-View

Generated by 0.86T dipole (60GeV, 20mA)

detected in scintillator

trace the absorber

crotch absorber: ~40mm Cu

crotch chamber: 5mm Fe

Prelude™ 0.5 mm scintillator

Courtesy of K. Schedt, ESRF
The projected beam size $h$ is measured by the IAX.

The source size $\sigma_v$ can be obtained by subtracting contribution of photon beam divergence $\alpha_v$.

The advantage of IAX monitors include:
- easy, simple, cheap, compact
- can have many of them
- useful for local emittance coupling correction

The drawbacks are:
- limited resolution & absolute precision for small emittance values (for $\epsilon < 40 \text{ pm}$)
- NO info in horizontal plane

IAX monitors are also used at ANKA.


Courtesy of K. Schedt, ESRF
Bunch Length Measurement

Topics from Recent Developments ...

Fluctuation Analysis

ALS

SR/Laser Cross Correlation

ALS, SPEAR3
Incoherent Radiation Fluctuation Analysis

Based on the method described in Zolotorev, Stupakov, SLAC-PUB 7132 (1996)

In real beams, due to the random modulation in the bunch longitudinal distribution, and to the passage to passage variation of this modulation, incoherent radiation is emitted with intensity and spectrum fluctuating passage to passage.

It has been shown that by measuring the variance of the radiation in intensity in a part of the spectrum where the emission is incoherent, the bunch length can be measured.

Proof-of-Principle Experiment
@ The ATF at BNL

Single-shot spectra of spontaneous undulator emission showing fluctuational characteristics measured.
Length of a 1-5 ps long bunch successfully extracted.

Example: synchrotron radiation from a bending magnet

Courtesy of F. Sannibale, ALS
Incoherent Radiation Fluctuation Analysis @ ALS

A simpler scheme with a band-pass filter

Radiation intensity within a fixed bandwidth $\Delta \lambda$ measured turn-by-turn

Courtesy of F. Sannibale, ALS PRST-AB 12, 032801 (2009).

$S_{AB}$: photon signal including electronic noise
$S_{CD}$: measure of noise contribution

A complete 5k sample measurement required ~ 1 minute

$$\delta_M^2 = \frac{\sigma_{S_{AB}}^2 - \sigma_{S_{CD}}^2}{\left(\langle S_{AB} \rangle - \langle S_{CD} \rangle\right)^2}$$
Incoherent Radiation Fluctuation @ ALS (cont')

Analysis

\[ \delta^2 = \delta_M^2 - \frac{s^2}{\langle N_p \rangle} \]

\[ = \frac{1}{\sqrt{1 + 4\sigma_\omega^2 \sigma_t^2}} \cdot \frac{1}{\sqrt{1 + \sigma_x^2 / \sigma_{xc}^2}} \cdot \frac{1}{\sqrt{1 + \sigma_y^2 / \sigma_{yc}^2}} \]

Photon Shot Noise Contribution

evaluated by performing 2 or more measurements of \( \delta_M^2 \)
for the same bunch length
for different number of photons

Results

\( \sigma_t \): r.m.s. bunch length
\( \sigma_\omega \): r.m.s. band-width of the filter
\( \sigma_{xc}, \sigma_{yc} \): transverse coherence lengths
\( \sigma_x, \sigma_y \): transverse beam sizes

Courtesy of F. Sannibale, ALS PRST-AB 12, 032801 (2009).
SR/Laser 'Cross-Correlation' Method

proof of principle experiment on ALS (M. Zolotorev et al, PAC'03)

Mixing of SR and Laser in a non-linear crystal
Up-Converted Radiation
Good Time Resolution
Short Laser Pulse Length

Mode Locked TiS Laser Oscillator
repetition 71 MHz (14 ns)
pulse length 50 fs
wavelength 800 nm
power 100-200 mW
phase locked to the ring RF
SR/Laser ‘Cross-Correlation’ Measurement

Experimental Schematic April 2010

lock-in amplifier
photodiode
544nm
800/400nm
BBO crystal (sum generation)

1.28MHz
Labview, scope

delay line
1ps
800/1700nm
SR beam
800nm
70:30
Timing (indirect), overlap, BBO orientation

Signal Detection
APD
Lock-in Amplifier
1.28MHz ring frequency

Mode Locked TiS Laser Oscillator
repetition 5MHz
pulse length 50 fs
wavelength 800 nm

April 6, 2010 scan : 15mA single bunch

Courtesy of J. Corbett, SPEAR3
Details given in IPAC’10 Contributed Oral WEOCMH03
“Bunch Length Measurements by SR/Laser Cross-Correlation”
Single Bunch Purity Measurement

Time Correlated Single Photon Counting (TCSPC)

Visible Photons  MCP-PMT
X-ray Photons   APD
Bunch Clock

Time to Digital Converter

Dynamic Range: $10^{-6} \sim 10^{-7}$

Time Spectrum

Counts

http://www.picoquant.com
Gated TCSPC @ SPring-8

Fast Light Shutter

HV Pulser

Measured Time Profile

Repetition Rate: 209 kHz ($= f_{re}$)
Rise/Fall Time: < 2 ns (bunch spacing)
Voltage: 1.5 kV

When HV is applied, the polarization is rotated and the shutter is opened.

Gated TCSPC System

Two shutters in tandem
Gate opened to the parasitic bunches

Dynamic Range ~ $10^{-10}$

History of the Bunch Purity in FY2009 @ SPring-8

Courtesy of K. Tamura, SPring-8
Diagnostics with a Dedicated Insertion Device (ID)

**APS Diagnostic Undulator Line**
- Simultaneous measurement of beam divergence and source size
- Horizontal emittance obtained independent of lattice functions

**ESRF ASD Beamline (ID30)**

Horizontal emittance is calculated from the measured photon beam size $\sigma_m$ with knowledge of the lattice parameters.

- Based on the previous experiment at ID6 beamline


Courtesy of K. Schedt, ESRF

26 May 2010
S. Takano JASRI/SPring-8 IPAC10
The SPring-8 Diagnostics Beamline II (BL05SS)

Insertion Device (ID)

Planar Halbach type made of the Ne-Fe-B alloy (NEOMAX-44H)
- Period length: 76mm
- Period number: 51
- Maximum peak field: 0.82T
- Maximum deflection parameter K: 5.8

Energy Spectrum measured at K=5.8
- Rectangular slit aperture on the optical axis: $4.2\mu\text{rad}(H) \times 4.2\mu\text{rad}(V)$
- Stored beam energy: 8GeV
- Emittance: 3.4nm rad
- Relative energy spread: 0.11%

Elaborate tuning of the magnetic field has led to the rms phase error < 2 degrees, which allows us to observe many clear peaks of the higher harmonics.

The measured spectrum is well reproduced by the theoretical calculation assuming the rms phase error of 1.8 degree.

Courtesy of M. Masaki, SPring-8
Simultaneous Energy Spread & Emittance Measurement

Vertical angular divergence of the photon beam is dominated by the beam energy spread, because of small horizontal-vertical emittance coupling.

Higher harmonics with large $K$ are sensitive to the beam energy spread.

Experimental study of the sensitivity by modulating RF phase at the synchrotron frequency (~2.2kHz).

A fast turn-by-turn system under development

The X slit makes a 1-D pinhole image of the beam in the horizontal

 Courtesy of M. Masaki, SPring-8
Summary

A brief overview of the transverse beam profiling instrumentation is given.

Bunch length measurements based on the statistical analysis of the intensity fluctuations and on the cross-correlation of the SR and the external laser pulse are described as well as the bunch purity measurement by using a fast light shutter.

Finally, an example of beam diagnostics based on observation of x-rays from a dedicated ID is presented.
Acknowledgements

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And Thank You for Your Attention!