Synchrotron Light Interferometer

Project at Jefferson Lab

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Properties of Light
Diffraction
Diffraction is the spreading of waves around obstacles.

Diffraction describes how light interacts with its physical environment.
\[ I(y) = I(0) \left( \frac{\sin(\alpha)}{\alpha} \right)^2 \]

\[ \alpha = \frac{Kay}{2L} \]

\[ k = \frac{2\pi}{\lambda} \]
Resolving power of image-forming systems

Diffraction of light limits the resolution of optical systems. The images of two objects, which are very close to each other, overlap.

How close two points can be brought together before they can no longer be distinguished as separate?
The Rayleigh criterion states that two similar diffraction patterns can just be resolved if the first zero of one pattern falls on the central peak of the other.

\[
\left( \frac{s}{R} \right)_{\text{min}} = \theta_{\text{min}} = \frac{\lambda}{a}
\]
Interference
Interference is the net effect of the combination of two or more wave trains.

Interference results from the superposition of electromagnetic waves. It is the mechanism by which light interacts with light.
The intensity pattern is given by:

\[ I(y) = I_0 \left[ \frac{\sin(\alpha)}{\alpha} \right]^2 \left[ 1 + \cos(\frac{kDy}{L}) \right] \]

\[ \alpha = \frac{ky}{2L} \]
If the light source is not “point-like”
\[
I(y) = I_0 \left[ \frac{\sin(\alpha)}{\alpha} \right]^2 \left[ 1 + V \cos(kDy/L + \phi) \right]
\]

\[\alpha = \frac{\text{Kay}}{2L}\]

\[V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]

visibility (fringe contrast)

And the visibility and the “phase shift” \(\phi\) are connected with the degree of coherence \(\Gamma\): 

\[V = |\Gamma|, \quad \phi = f(\text{arg } \Gamma)\]
Theorem of van Cittert – Zernike

The degree of coherence $\Gamma$ is given by the Fourier transform of the intensity distribution of the source object.

$$\Gamma(\theta) = \int I(\xi) \exp\{-i 2\pi \theta \xi\} \, d\xi$$

$$\Gamma = \frac{\Gamma(0)}{\Gamma(0)} \quad \theta = \frac{D}{\lambda R}$$

- the visibility of the interference fringe picture from a point source is equal to 1
- a small source object gives a good visibility (fringe contrast)
- a large source object gives a poor visibility (fringe contrast)
What is about the resolution of such a double slit assembly (interferometer)?

Following Rayleigh’s criterion, \( \left( \frac{s}{R} \right)_{\text{min}} = \theta_{\text{min}} = \frac{\lambda}{2D} \)

The resolution can be made very high …
... but only if
P₁ and P₂ remain correlated:

for all typical points S in the source

\[ |S P₁ - S P₂| << \frac{\lambda₀²}{\Delta \lambda} \]

\( \frac{\lambda₀²}{\Delta \lambda} \) is the coherence length for the bandwidth \( \Delta \lambda \)
Behavior of the function:

\[ I(y) = \left( \frac{\sin(\alpha)}{\alpha} \right)^2 \left[ 1 + V \cos(kDy/L + \varphi) \right] \]

\[ \alpha = k\lambda/(2L) \]
\[ \alpha = \frac{ka_y}{2L} \]

\[ I(y) = \left[ \frac{\sin(\alpha)}{\alpha} \right]^2 \left[ 1 + V \cos(kDy/L + \varphi) \right] \]
I(y) = \left( \frac{\sin(\alpha)}{\alpha} \right)^2 \left[ 1 + V \cos(kDy/L + \varphi) \right]

Env_{1,2}(y) = \left( \frac{\sin(\alpha)}{\alpha} \right)^2 \left[ 1 \pm V \right]
\[ I(y) = \left( \frac{\sin(\alpha)}{\alpha} \right)^2 \left[ 1 + V \cos(kDy/L + \phi) \right] \]
\[ I(y) = \left( \frac{\sin(\alpha)}{\alpha} \right)^2 \left[ 1 + V \cos(kDy/L + \varphi) \right] \]
Synchrotron Radiation
History - 1940th

Theory of radiation from relativistic particles
Pomeranchuk, Ivanenko, Sokolov, Ternov (USSR)
Schwinger (USA)

Synchrotron ideas - 1945
Veksler (USSR), McMillan (USA)
The first visual observation of synchrotron radiation was in 1947 from the General Electric synchrotron in the USA.
Synchrotron radiation (SR) is emitted from relativistic charged particles when their paths are changed.

By the magnetic field, for example.

Everywhere further we will consider only the synchrotron radiation from electrons generated in the bending magnets.
Because of the relativistic effect, the synchrotron radiation is emitted in a narrow cone in the forward direction, at a tangent to the orbit.

\[ \psi \sim \frac{1}{\gamma} \quad (5 \text{ GeV electrons} \rightarrow 10^{-4}) \]
\( \psi \sim 1/\gamma \)  

(5 GeV electrons -> \( 10^{-4} \))

?  

\(~ 2 \text{ cm} \)

\(~ 100 \text{ m} !\)
Synchrotron radiation

- extremely intense and highly collimated
- highly polarized ($E_\sigma$ and $E_\pi$)
- has a wide energy spectrum (from infrared to $\gamma$-rays)
A typical energy spectrum of synchrotron radiation

The critical wavelength $\lambda'$ (or $\lambda_c$) divides the radiated power into two equal parts: one-half of the power is radiated above this wavelength and one-half below.
The critical wavelength [A. Hofmann]

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

Example: 5 GeV electrons, \( \rho = 40 \text{ m} \)

\[ \lambda_c = 0.16 \text{ nm} \]
At low frequencies the properties of synchrotron radiation are independent of the particle energy and depend only on the radius $\rho$ of the curvature.

The rms opening angle for $\lambda >> \lambda_c$

$$\psi_{\sigma\text{-rms}} = 0.41 \left(\frac{\lambda}{\rho}\right)^{1/3}$$

$$\psi_{\pi\text{-rms}} = 0.55 \left(\frac{\lambda}{\rho}\right)^{1/3}$$

Example: $\lambda = 630 \text{ nm}, \ \rho = 40 \text{ m}$

$$\psi_{\sigma\text{-rms}} = 10^{-3}$$
Synchrotron Radiation Beam Diagnostics
Imaging of the beam cross section with synchrotron radiation - SLM
The natural opening angle of the emitted light sets a limit to the resolution of the SLM
The diffraction limited resolution of synchrotron light imaging systems in the visible part of the spectrum [A.Hofmann]:

\[ \sigma_s \approx 0.3 (\lambda^2 \rho)^{1/3} \]

Example: \( \lambda = 630 \text{ nm}, \quad \rho = 40 \text{ m} \)

\[ \sigma_s \approx 0.1 \text{ mm} \]
Can we build a synchrotron light interferometer and use its data to measure smaller beam sizes?
T. Mitsuhashi, Photon Factory, KEK, Japan
Problems
Synchrotron radiation is like a moving narrow searchlight in horizontal direction.
We observe photons coming from different positions when the electron moves from point A to point B. We must sum these photons.
When an electron is moving from point A to point B, the light is sweeping from slit $S_1$ to slit $S_2$.

- The intensities of two modes of light illuminating the slits are different.
T. Mitsuhashi has modified the van Cittert-Zernike theorem and developed the method to calculate the beam size on the basis of the interference picture for the synchrotron light emitted by the beam.

“Beam Profile and Size Measurement by the Use of the Synchrotron Light Interferometer”
OK. Now we build our interferometer.
Synchrotron Radiation Interferometer

Synchrotron Light Source

Double slit assembly

Lens

CCD

Image

S

R

L

D

a
Two polarized components of the synchrotron light (p and s) are “in anti-phase”. Their superposition will not give us the interference fringes at all.

-> We get just a sort of a “SLM”.

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**Figure:**

- a) interferogram by s-polarized components.
- b) interferogram by p-polarized components.
The synchrotron light is not monochromatic.

\( \lambda \) range is the whole visible spectrum!
Synchrotron Radiation Interferometer

- Synchrotron Light Source
- Polarization filter
- Double slit assembly
- Band pass filter ($\lambda_0 \pm \Delta\lambda$)
- Lens
- CCD
- Image

$S$

$R$

$L$
Beam Size Calculation
In case of a gaussian beam shape it is easy:

$$\Gamma(\theta) = \int I(\xi) \exp\{ -i 2\pi \theta \xi \} \, d\xi$$

$$\Gamma = \frac{\Gamma(\theta)}{\Gamma(0)}$$

$$I(y) = I_0 \left[ \frac{\sin(\alpha)}{\alpha} \right]^2 \left[ 1 + V \cos(kDy/L + \varphi) \right] \quad \alpha = kay/2L$$

$$V = \exp\left(-\frac{2\pi^2 D^2 \sigma^2_{\text{beam}}}{\lambda^2 R^2}\right) = V(D)$$
Methods to calculate the beam size
1. We measure (experimentally) the contrast of the interferogram as a function of the slit separation $D$. Then we define the RMS of the visibility curve $\sigma_v$.

$$\sigma_{\text{beam}} = \frac{\lambda R}{2 \pi \sigma_v}$$
2. We can also measure the RMS beam size from one data of visibility which is measured at a fixed separation of a double slit assembly

\[ \sigma_{\text{beam}} = \frac{\lambda R}{\pi D} \sqrt{0.5 \ln(1/V)} \]
\[ V = 0.8 \quad \sigma_s = 0.12 \text{ mm} \]
Synchrotron Light Interferometer at Jefferson Lab

Main Components
Synchrotron Radiation Interferometer at Jefferson Lab

Synchrotron Light Source

Polarization filter

Double slit assembly

Band pass filter ($\lambda_0 \pm \Delta\lambda$)

Lens

Synchrotron Light Interference Picture

R = 9.18 m  \hspace{1cm} L = 1.12 m  \hspace{1cm} \lambda_0 = 630 \text{ nm}  \hspace{1cm} \rho = 40 \text{ m}
Resolution of our synchrotron light interferometer
Our Synchrotron Light Interferometer

Main Control Components
Control Software Structure

Stepper-motor Control Software

Video Camera Control Software

Multiplexed Maxvideo Library

Common Serial Driver

EPICS Distributed Database
STV CCD CAMERA
CONTROL PANEL

Acquire
- focus
- image
- monitor

Guide
- calibrate
- track
- fileops

Process
- display

Control
- IMAGE
  - Norm, Exp = 2.0s
  - Bright
  - Contrast
- parameter
- value
- left
- right

Setup
- setup

Interrupt
- Interrupt
Very First Experimental Results
(exposure time = 2 sec)
V = 0.8 \quad \sigma_S = 0.12 \text{ mm}
SLI Data After 2002 Summer Shutdown
(exposure time = 50 sec)
(exposure time = 10 sec)
Shift began with beam delivery to both halls. At 10:00 we terminated beam delivery to the halls to do a spot move, repair Fast Feedback, and send CW G0 beam to the BSY dump. All of these things were achieved :)
Spot move increased A current to ~24uA.
PPB restored by returning missing trim cards.
Steered ~12uA CW G0 beam to BSY dump. G0 beam delivery continued in parallel with delivery to halls A and B.
Recent Data
(exposure time = 15 sec)
Very Last Data
Summary

- Jefferson Lab has a modern beam diagnostic device based on non-invasive technology

- Jefferson Lab has a great experience in design and installation of such a device

- The resolution of this device can be made less than 10 μm

- The device’s operational current range:
  a few microamps → milliamps
SLI team:

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