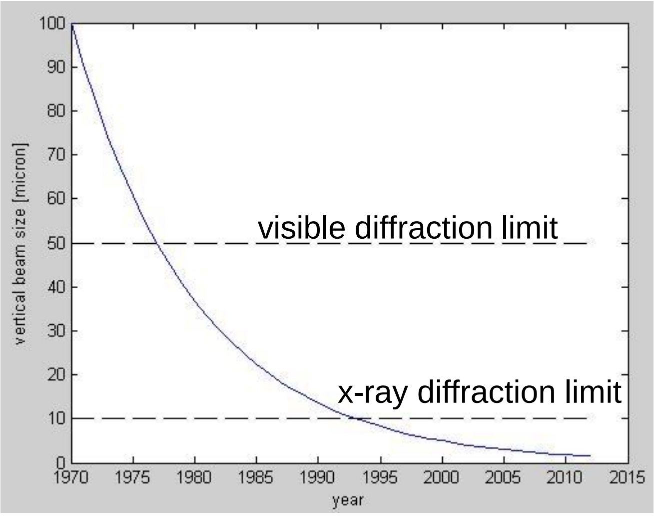
Stellar Interferometer - Theory and Practice

US Particle Accelerator School
January 18-22, 2010

- Motivation
- Two-slit Interference – Young's experiment
- Diffraction from a single slit - review
- Extended Source – Partial Coherence
- The Mutual Coherence function
- Van-Cittert/Ziernike theorem
- Stellar Interferometers for SR applications

Motivation for Interferometry

- Electron beam size can be very small



$$\sqrt{\varepsilon\beta} = \sqrt{(1)\left(1\times 10^{-9}/1000\right)} = 1\mu m!$$

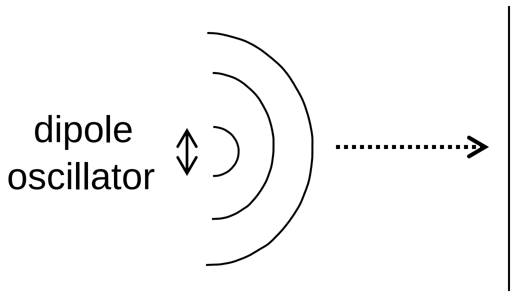
- Need to measure beam size for optics verification,
  machine monitoring and operation

- Conventional imaging diffraction limited
  σ_{res}~50 um visible
  σ_{res}~10 um x-ray pinhole

- What else can be used?

Motivation for Interferometry (cont'd)

- Take advantage of light *coherence* properties



$$e^{i(\vec{k}\cdot\vec{x}-\omega t)}$$

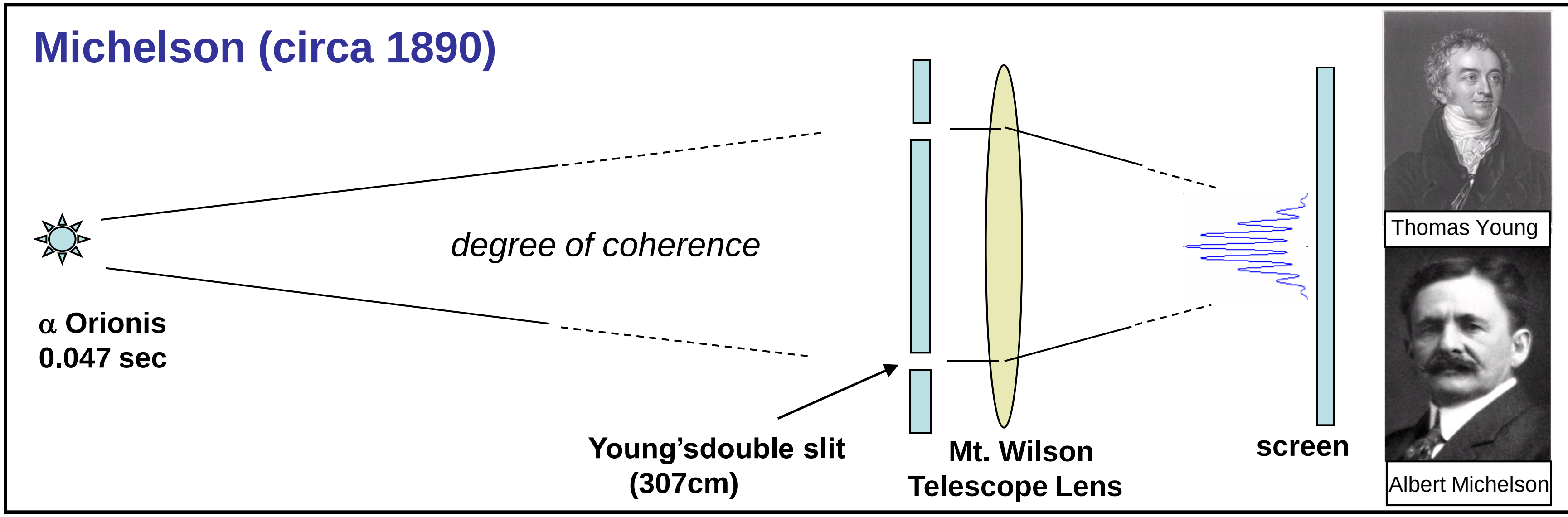
(plane waves at infinity)

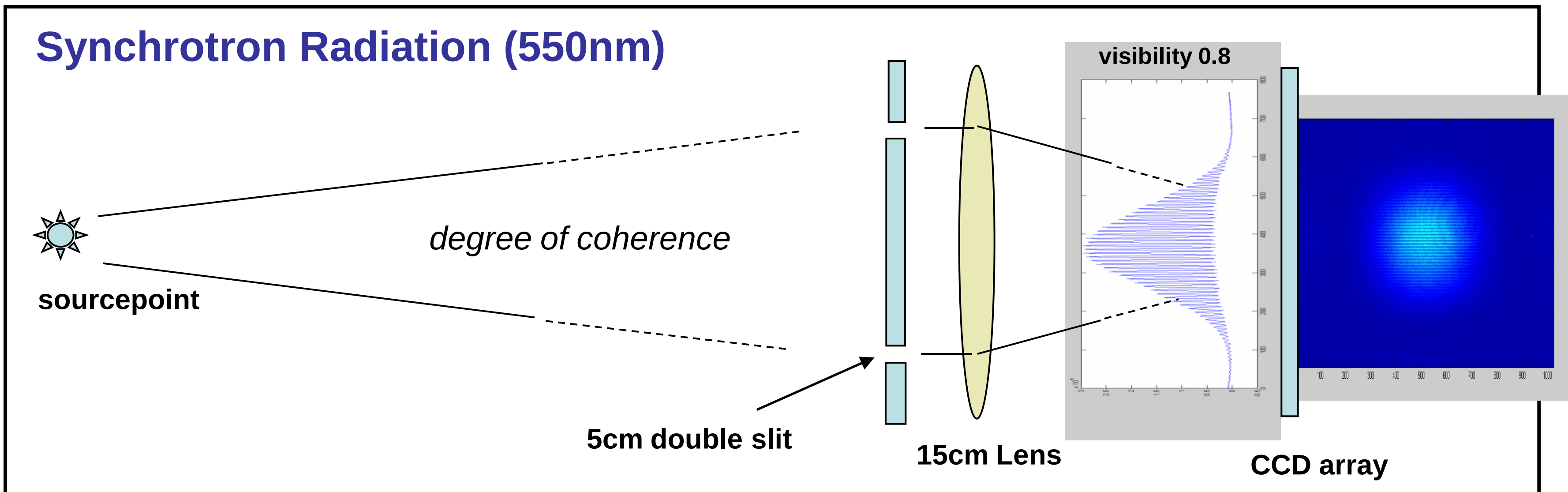
$$\vec{k} = k_x \hat{x} + k_z \hat{z}$$

- For a *distributed* source at finite distance the light is only *partially coherent*

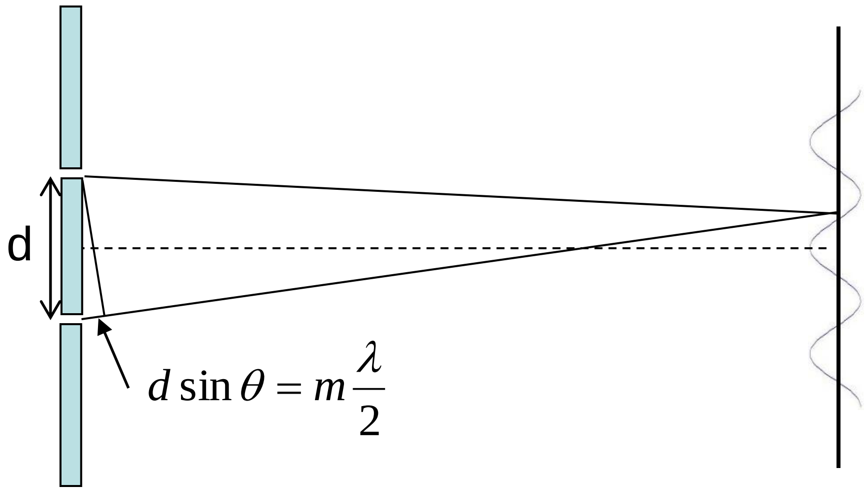
- Interferometry enters world of wavefront physics and statistical optics

Interferometric Beam Size Measurement





Two-Slit Interference: Young's Experiment



$$d \sin\theta = m\frac{\lambda}{2}$$

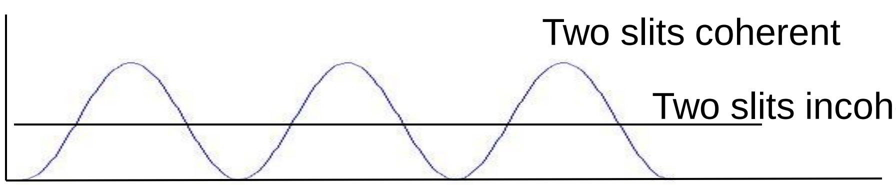
Field Pattern

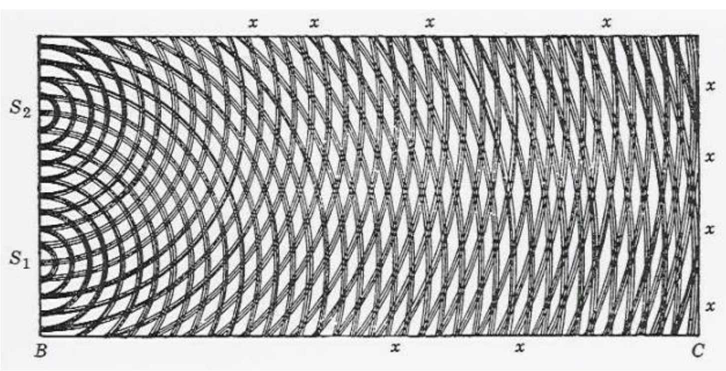
$$E = E_o e^{i(\Phi)} + E_o e^{i(-\Phi)} = 2E_o \cos(\Phi)$$

$$\int_{-\infty}^{\infty} (\delta(\Phi) + \delta(-\Phi)) e^{ikx} dx$$

monochromatic light!

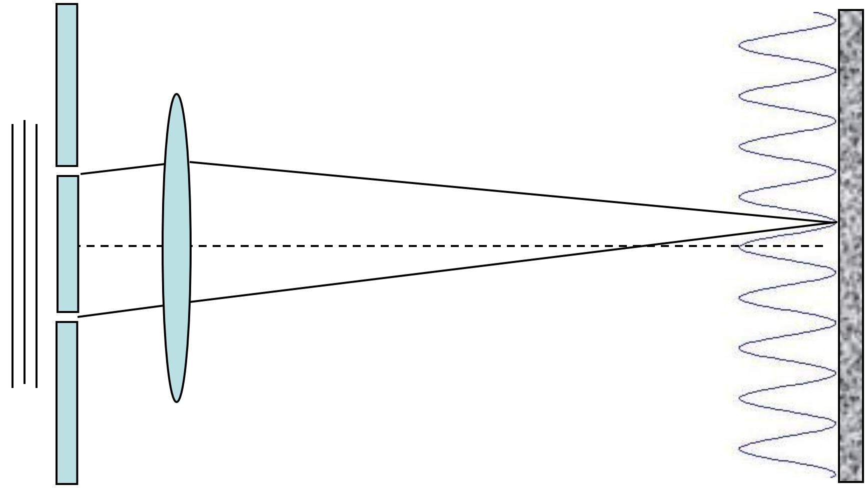
Intensity Pattern: $\cos^2(\Phi)$





Two-Slit Interference (cont'd)

Use a lens to concentrate image on screen



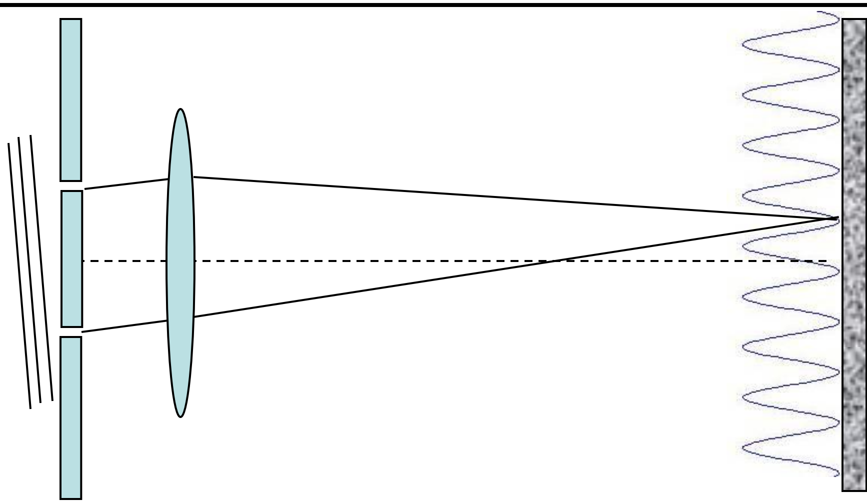
Intensity Pattern

Note Contrast/Visibility

$$V = \frac{I_{Max} - I_{Min}}{I_{Max} + I_{Min}} = 1.0$$

fully coherent!

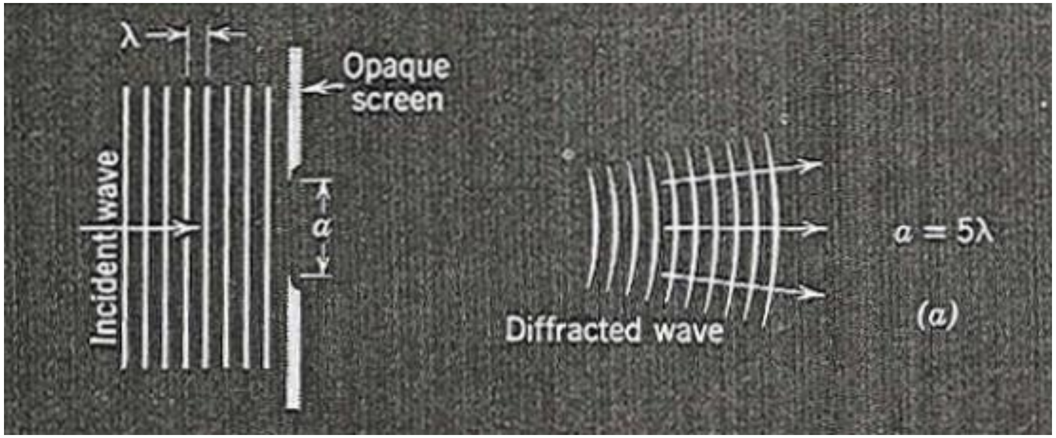
Change phase/incidence angle, shift pattern phase



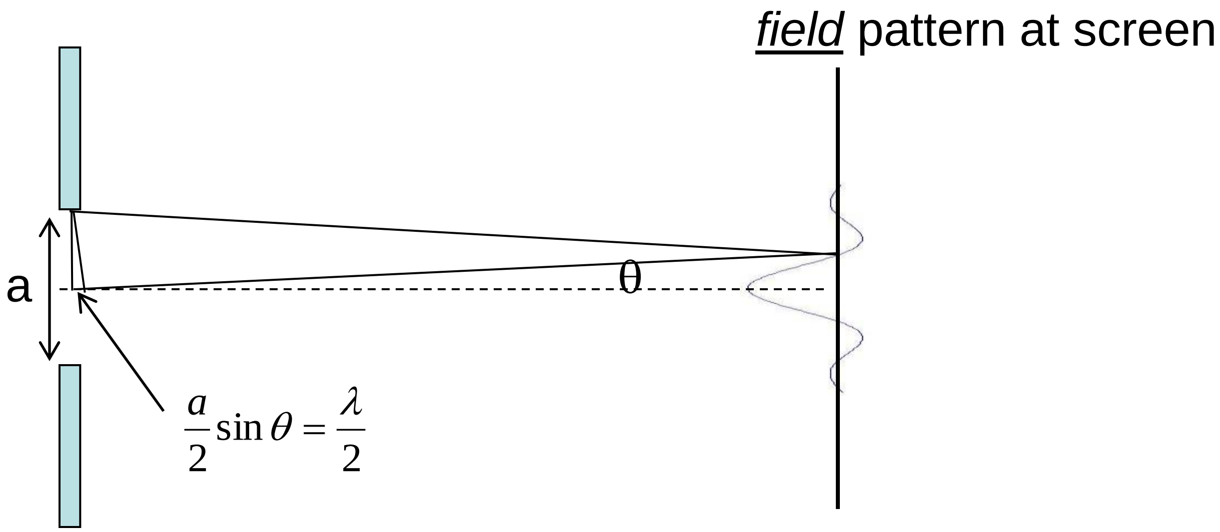
V=1.0 (no change)

Single-Slit Diffraction - Review

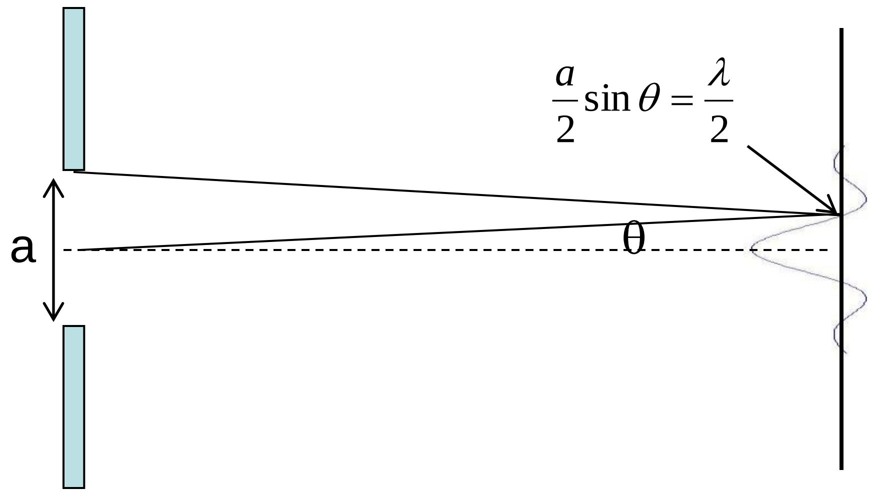
Plane wave incident on aperture - diffraction



Condition for first diffraction minima



Single-Slit: Electric Field Pattern

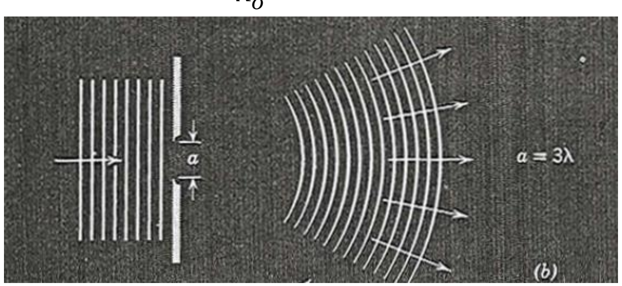


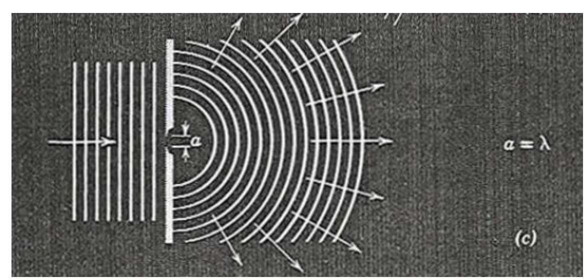
Field pattern

$$E_\theta = E_o \frac{\sin(x)}{x}$$

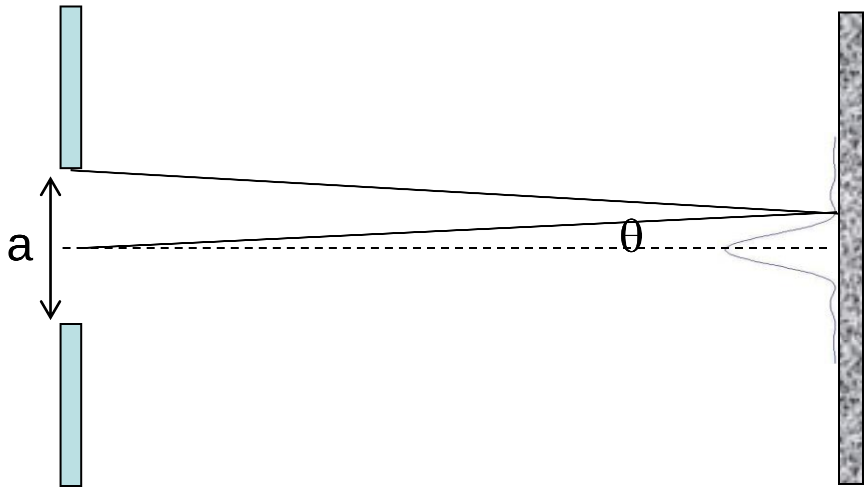
Field pattern is the *Fourier Transform* of the Aperture

$$\int_{-x_o}^{x_o} e^{ikx} dx = \frac{e^{ikx_o} - e^{ikx_o}}{ikx_o} = \frac{\sin(kx_o)}{kx_o}$$





Single-Slit: Intensity Pattern



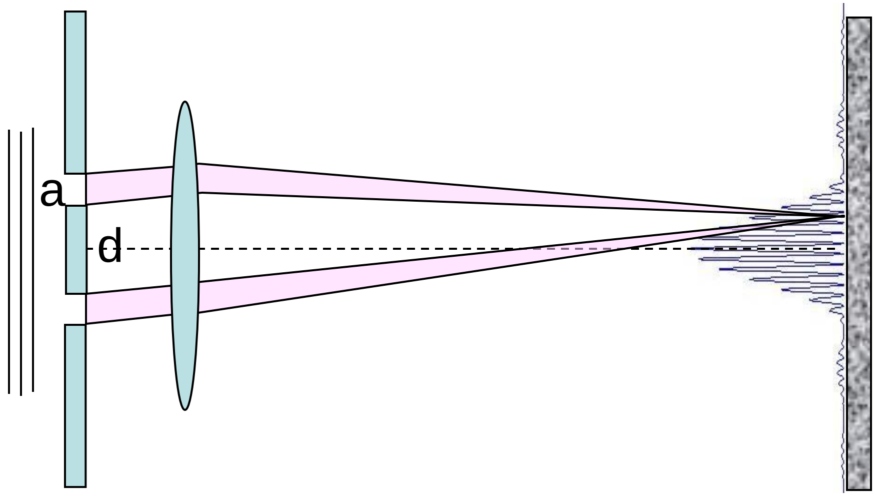
Intensity

$$I_\theta = E^* E = I_o \left(\frac{\sin(x)}{x} \right)^2$$

(measure laser diffraction through pinhole in afternoon)

Two-Slit Interference (cont'd)

Consider 2-slit interference with finite slit size:



Intensity Pattern

$$I_\theta = I_o \left(\frac{\sin(a\theta)}{a\theta} \right)^2 \times \cos^2(d\theta)$$

V=1.0 (no change)

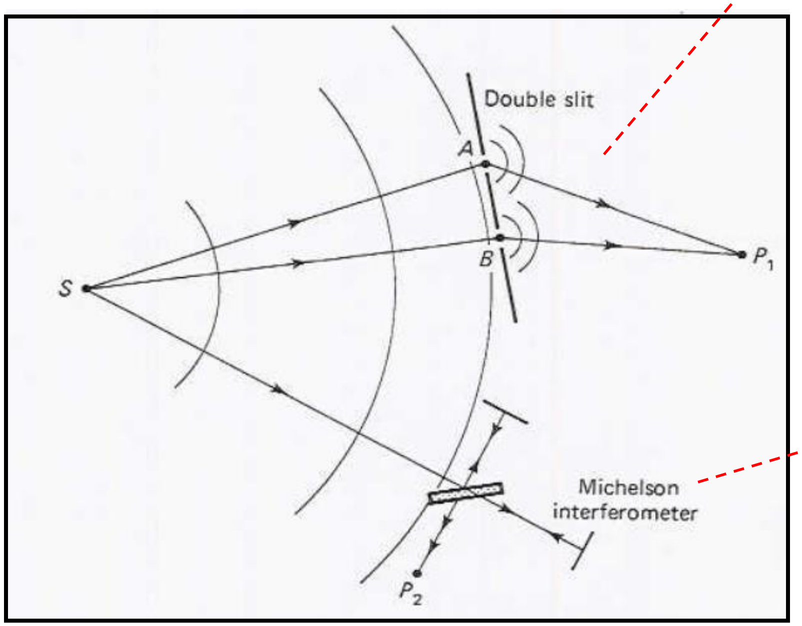
Important mathematical point: $1 + \cos(\theta) = 2\cos^2(\frac{\theta}{2})$

Intensity pattern can be written: $$I_\theta = I_o \underbrace{\left(\frac{\sin(a\theta)}{a\theta} \right)^2}_{\text{Single-Slit}} \times \underbrace{\left(1 + \cos(d\theta)\right)}_{\text{Two-Slit}}$$

This is *approximately* the form we will work with (but visibility 1.0)

From Interference to Interferometry

Interferometry is used to measure *coherence* properties of light



Spatial Coherence

coherence length is inversely proportional to size

a star emits plane-waves randomly in direction
-emission is not coherent at close distance

a point source emits sphereical-waves in all directions
-emission is coherent at long distances

Temporal Coherence

coherence time is inversely proportional to line-width

thermal source emits wavepackets randomly in time
-emission is not coherent

laser source emits continuous wavetrain in time
-emission is coherent

Degree of Coherence

Light can be totally coherent, partially coherent or incoherent

The *degree of coherence* is found from a correlation function

Temporal Degree of Coherence

Consider two colinear light waves $E_1(t)$ and $E_2(t)$

the correlation function is $\Gamma_{12}(\tau) = \left\langle E_1(t) E_2^*(t+\tau) \right\rangle$

Γ_{12} *is the degree of self-coherence*

if $\tau < \tau_o$ (correlation time), then waves are coherent and light interferes

if $\tau > \tau_o$ then coherence is lost and light waves do not interfere

Spatial Degree of Coherence

Consider two waves $E_1(\vec{k})$ and $E_2(\vec{k})$ from two sources

the correlation function is now $\Gamma_{12}(r) = \left\langle E_1(P_1) E_2^*(P_2) \right\rangle$

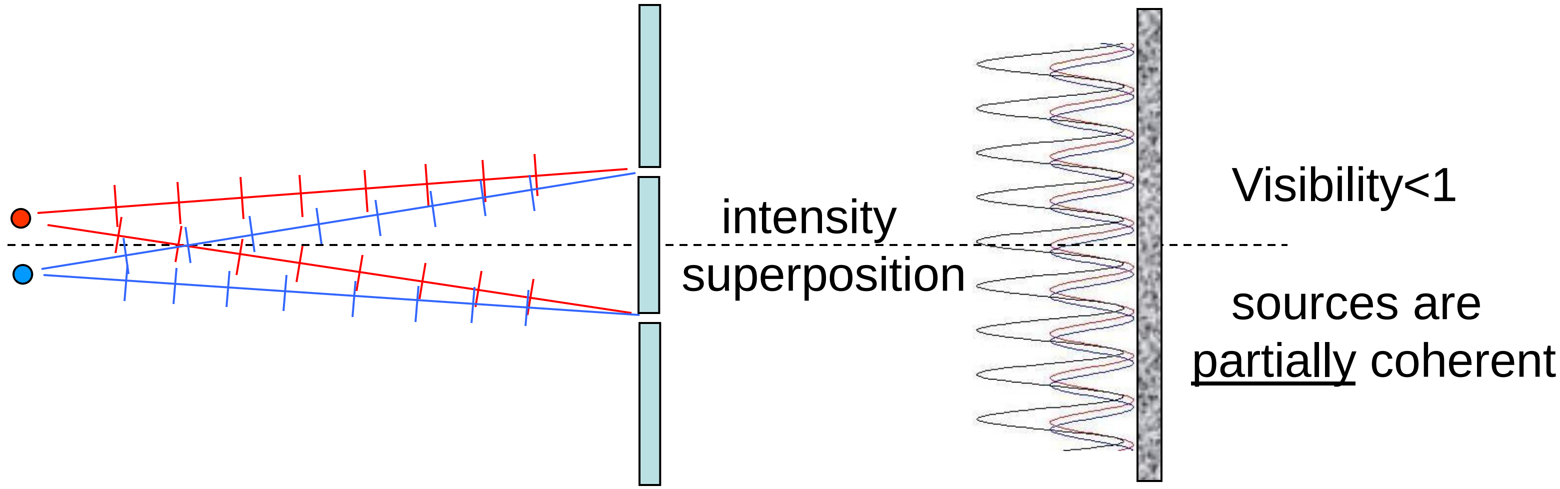
P_1 and P_2 are two points in space and $r = P_1 - P_2$

Γ_{12} *is the degree of mutual-coherence*

if $r < r_o$ (correlation length), then waves are coherent and light interferes

if $r > r_o$ then coherence is lost and light waves do not interfere

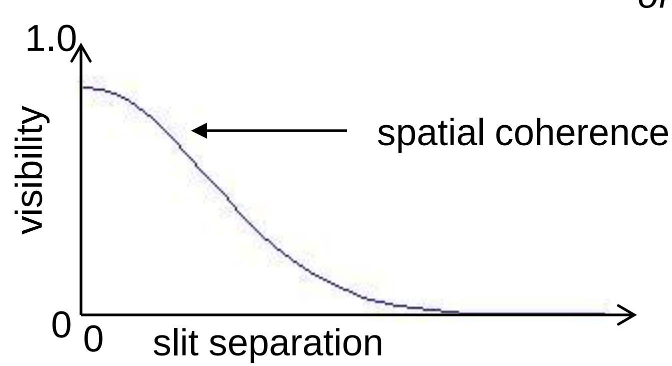
Spatial Coherence - Two Sources



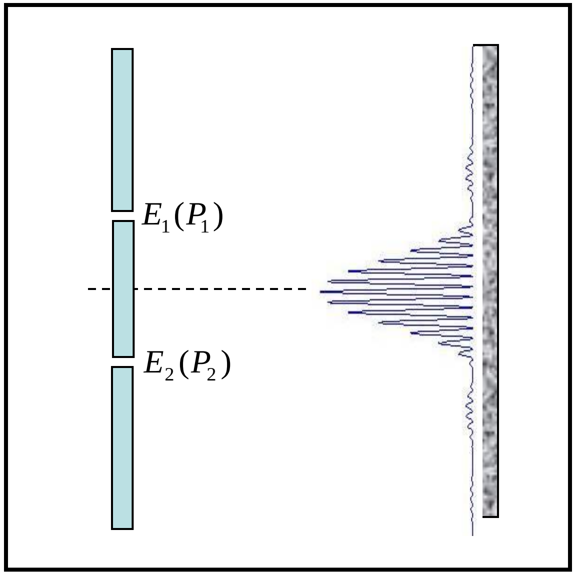
preview: visibility is Fourier Transform of source intensity

As slits separate

1) 'cosine' frequency goes up
2) superposition decoheres
3) visibility decreases



Mutual Coherence of field at two points



Solve for intensity on the screen

$$I(\theta) = E_T^* E_T = \left(E_1 + E_2 e^{+i\theta}\right)^* \left(E_1 + E_2 e^{-i\theta}\right)$$

$$I(\theta) = E_1^2 + E_2^2 + E_1^* E_2 e^{-i\theta} + E_1 E_2^* e^{+i\theta}$$

Now take the time average

$$I(\theta) = E_{01}^2 + E_{02}^2 + E_{01}E_{02}\left(|\gamma| e^{-i\gamma} e^{-i\theta} + |\gamma| e^{+i\gamma} e^{+i\theta}\right.$$

$$\boxed{I(\theta) = E_{01}^2 + E_{02}^2 + E_{01}E_{02}|\gamma|\cos(\gamma + \theta)}$$

$$Visibility = \frac{I_{Max} - I_{Min}}{I_{Max} - I_{Min}} = \frac{2E_{01}E_{02}|\gamma(P_1, P_2)|}{E_{01}^2 + E_{02}^2}$$

For E_{01}=E_{02}, $$Visibility = \frac{I_{Max} - I_{Min}}{I_{Max} - I_{Min}} = |\gamma(P_1, P_2)|$$

Mutual Coherence (cont'd)

For the case when $I_1 = I_2$, we have

$$Visibility = \frac{I_{Max} - I_{Min}}{I_{Max} - I_{Min}} = \left|\gamma(P_1, P_2)\right|$$

Where $\gamma = \left|\gamma(P_1, P_2)\right| e^{i\gamma} = < E_1 * E_2 >$

has various descriptive labels

"mutual intensity"
"mutual coherence function"
"complex degree of coherence"
"correlation function"
"fringe parameter"

...fringe parameter measurement is central to all problems involving coherence

Putting it all together…

$$I(\theta) = E_{01}^2 + E_{02}^2 + E_{01}E_{02}|\gamma|\cos(\gamma+\theta)$$

$$I(y) = I_0\left[\sin c\left(\frac{2\pi a}{\lambda R}y\right)\right]^2 \cdot \left[1 + |\gamma|\cos\left(\frac{2\pi d}{\lambda R}y + \Phi\right)\right]$$

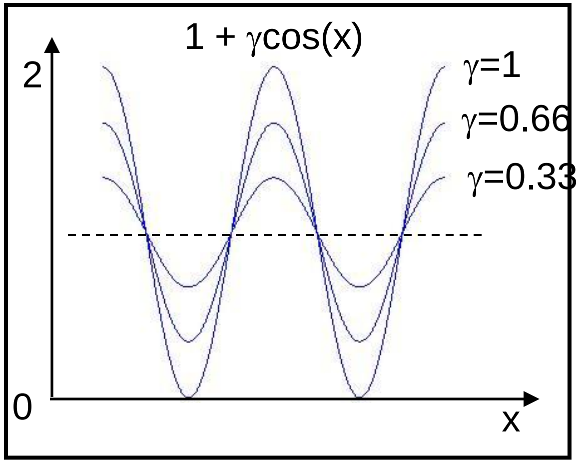
Single-Slit

Two-Slit

beam intensity
(equal both slits)

visibility factor (mutual coherence)

$$Visibility = \frac{I_{Max} - I_{Min}}{I_{Max} - I_{Min}} = |\gamma|$$



Alan will derive in-depth with chromatic effects

Van-Cittert/Zernike Theorem

"Visibility is the Fourier transform of source intensity"

$$\gamma(\nu) = \int I(y) e^{i2\pi\nu y} dy$$

I(y)=intensity distribution

$$\nu = \frac{d}{\lambda L} = spatial - frequency$$

d=slit width
λ=wavelength
L=source to slits

In two dimensions: $\gamma(\nu_x, \nu_y) = \iint I(x,y) e^{i2\pi(\nu_x x + \nu_y y)} dxdy$

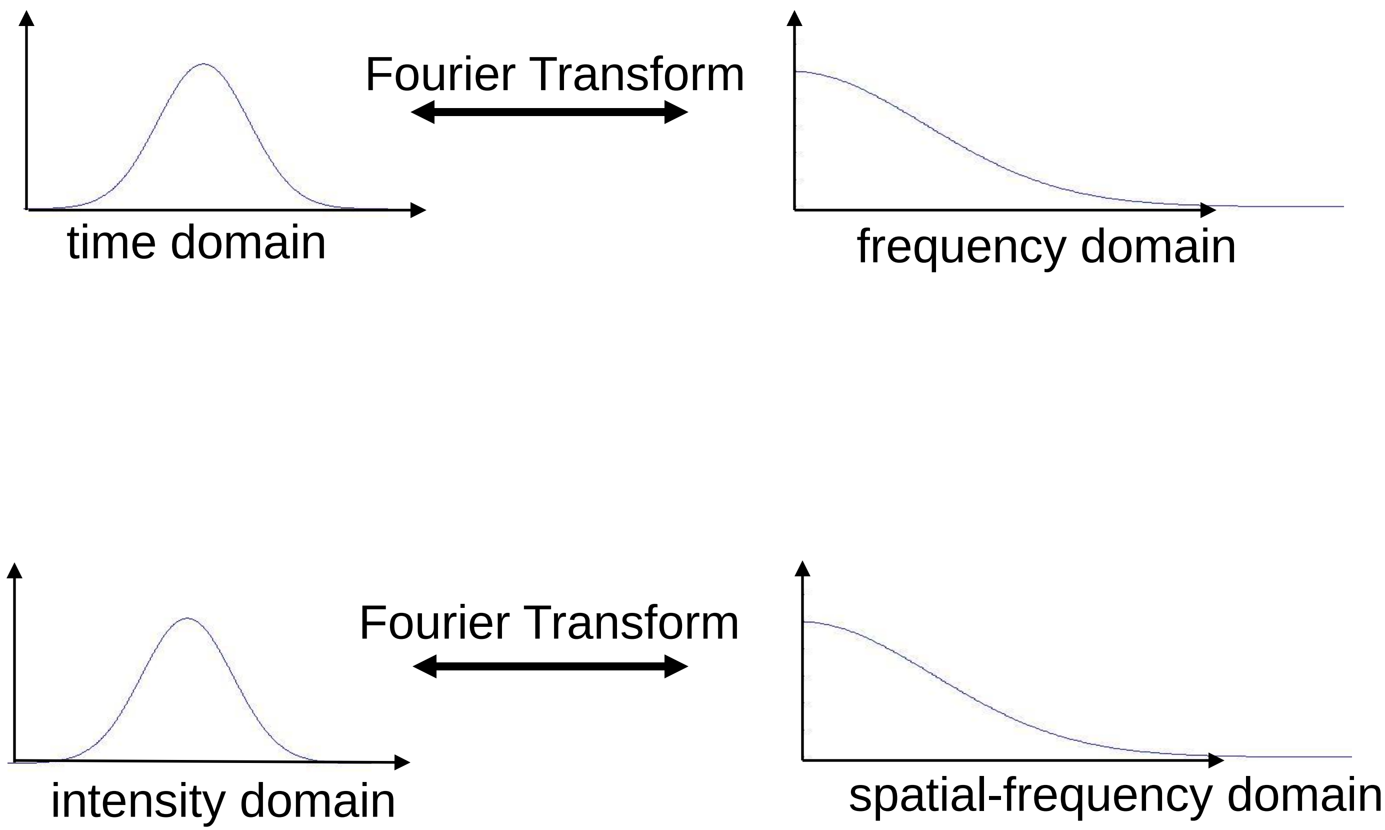
For a Gaussian, thermal-light source distribution

$$\gamma(d) = e^{\frac{-d^2}{2\sigma_d^2}}$$

(one dimension)

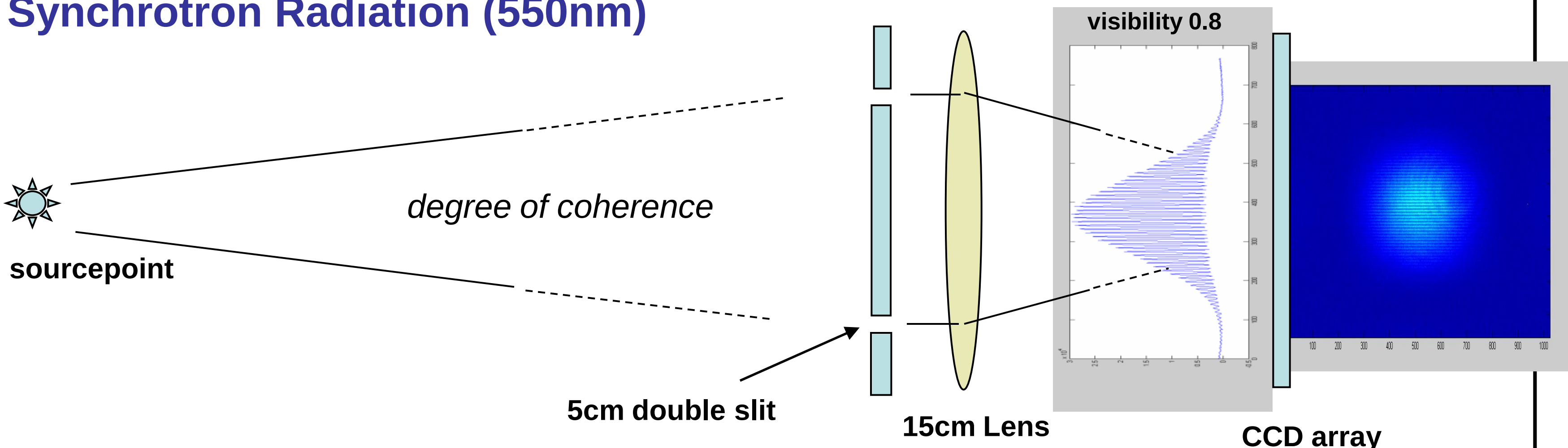
where $\sigma_d = \frac{2\pi\sigma_y}{\lambda L}$ = spatial frequency characteristic

Fourier Transform Pairs



Interferometeric Beam Size Measurement

Synchrotron Radiation (550nm)

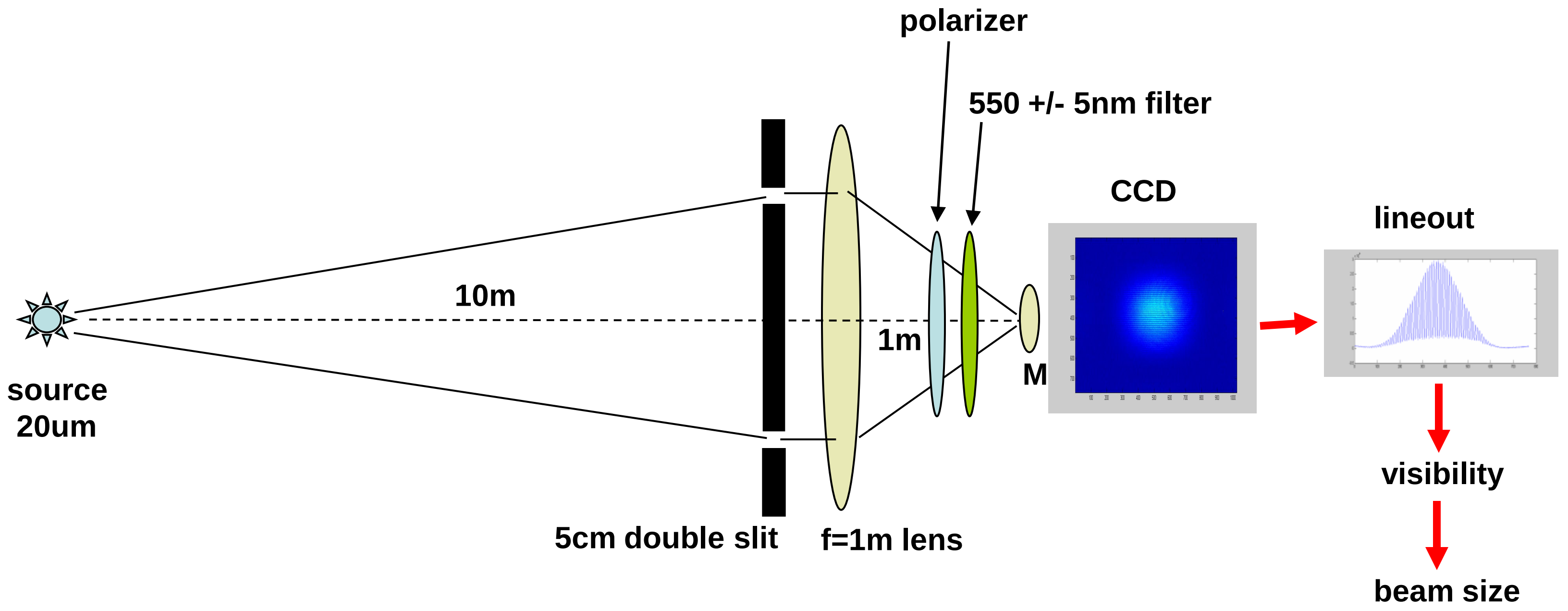


For a Gaussian source

$$\gamma(d) = e^{\frac{-d^2}{2\sigma_d^2}} \qquad \sigma_d = \frac{\lambda L}{2\pi\sigma_y}$$ = spatial frequency characteristic

1) Measure γ(d) [visibility as a function of slit separation]
2) Solve for characteristic width σ_d
3) Infer beam size from: $\sigma_y = \lambda L / 2\pi\sigma_d$

Typical Stellar Interferometer for SR Measurements



Typical System Parameters

Source size: σ_y=20um

Source-slit: L=10m

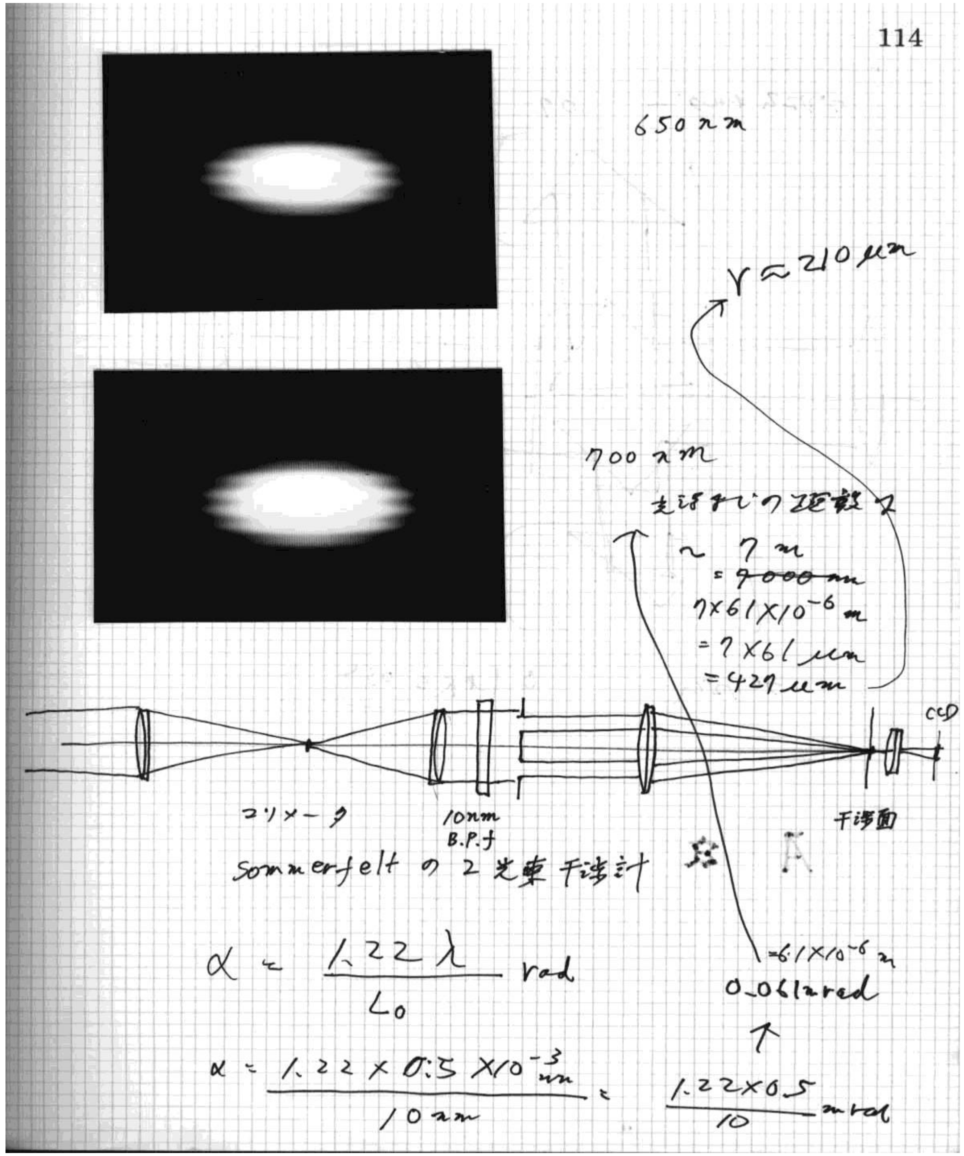
wavelength: λ=550nm

Visibility $$\gamma(d) = e^{\frac{-d^2}{2\sigma_d^2}}$$

$$\sigma_d = \frac{\lambda L}{2\pi\sigma_y} = \frac{550\times10^{-9}\cdot 10}{2\pi\cdot 20\times10^{-6}} = 44mm$$

a~2 mm

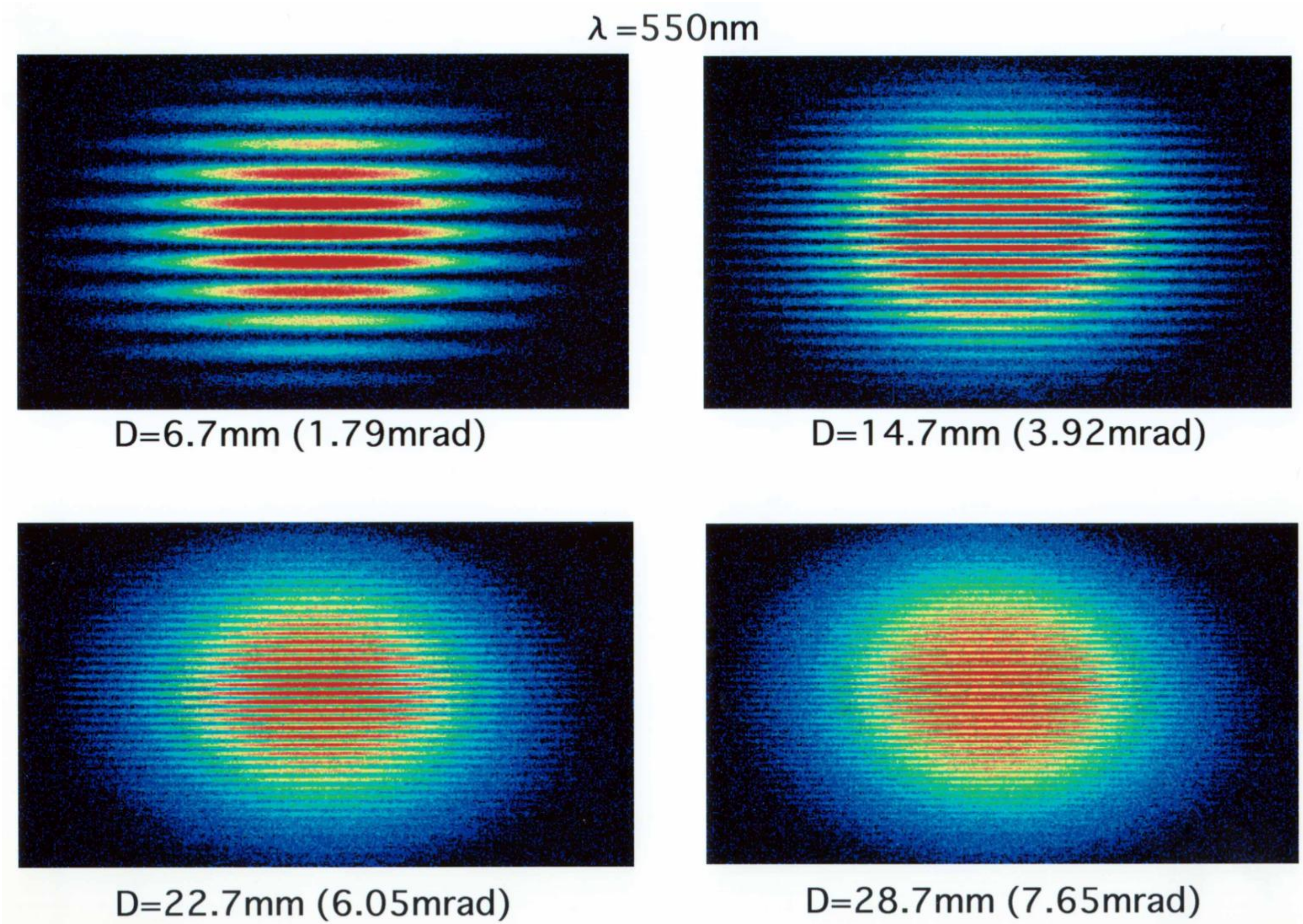
d~40 mm



Result of beam size is 210μm

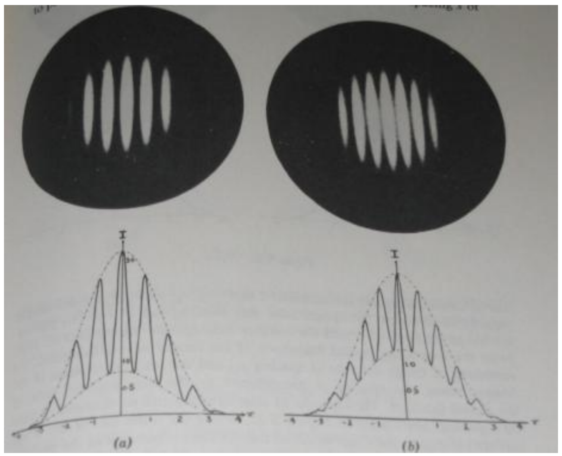
compliments: T. Mitsuhashi

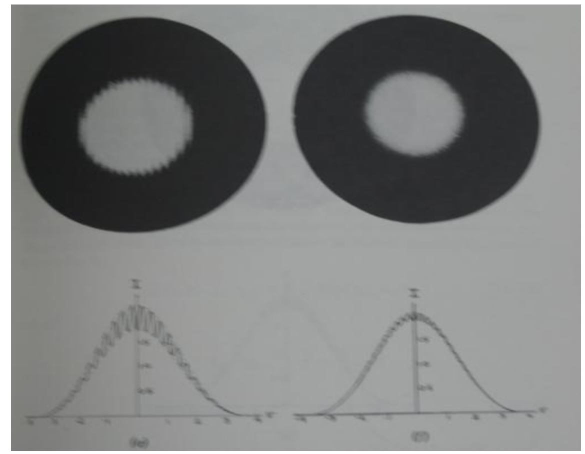
Vertical beam size at the SR center of Ritsumeikan university AURORA.



compliments: T. Mitsuhashi

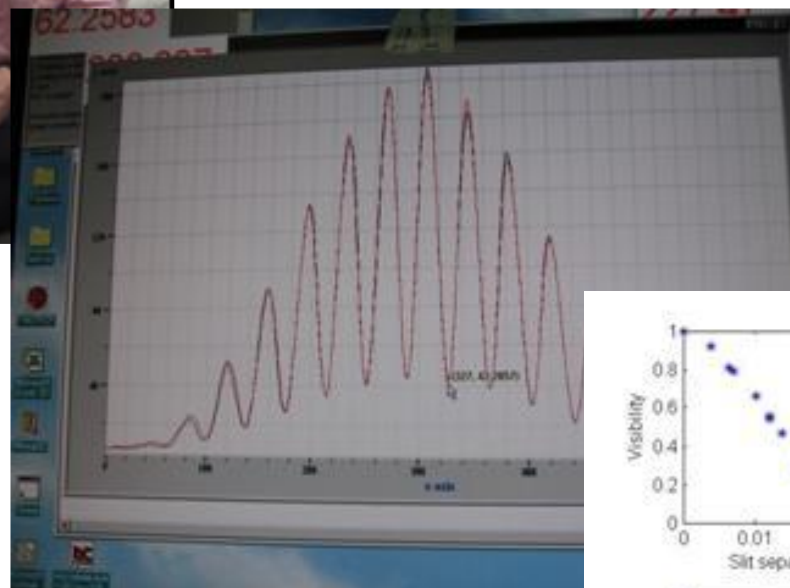
Example from Goodman/Statistical Optics

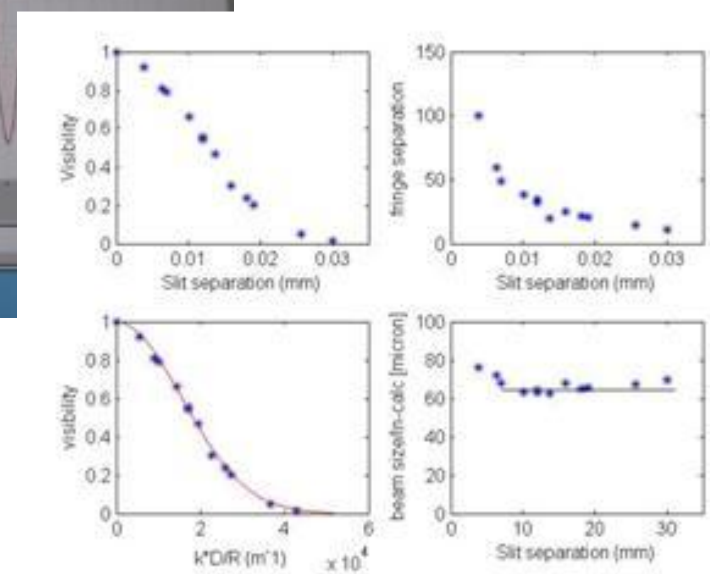




Note effect of vibration!

Photon Factory Laboratory





Beam Size Measurement (cont'd)

From a single measurement at slit separation d_o

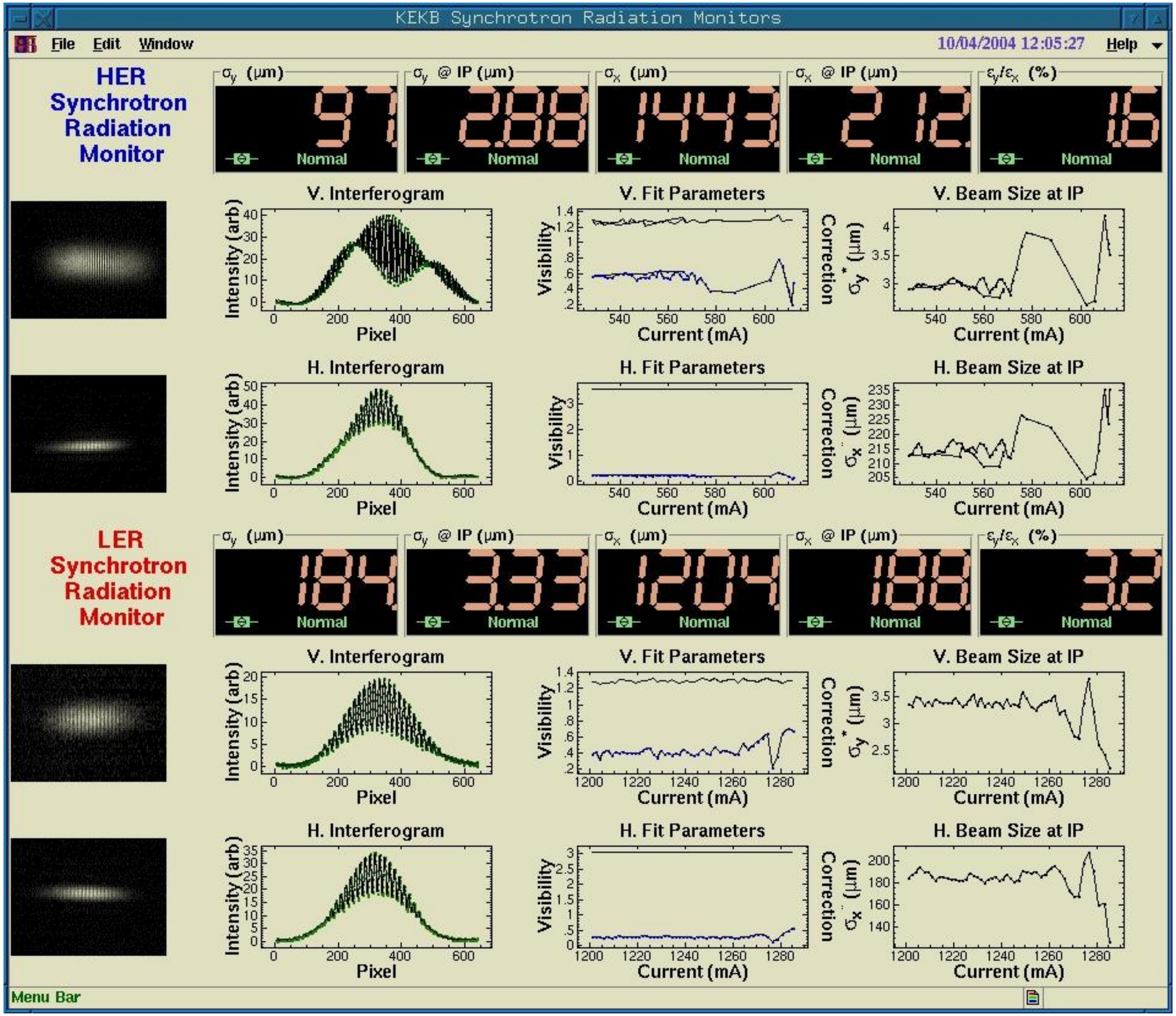
$$\gamma(d_o) = e^{\frac{-d_0^2}{2\sigma_d^2}}$$ solve for $$\sigma_d = \sqrt{\frac{d_o}{\ln(\frac{1}{\gamma})}}$$

From $$\sigma_y = \frac{2\pi}{\lambda L \sigma_d}$$

$$\sigma_y = \frac{\lambda L}{\pi d_o} \sqrt{\frac{\ln(\frac{1}{\gamma})}{2}}$$

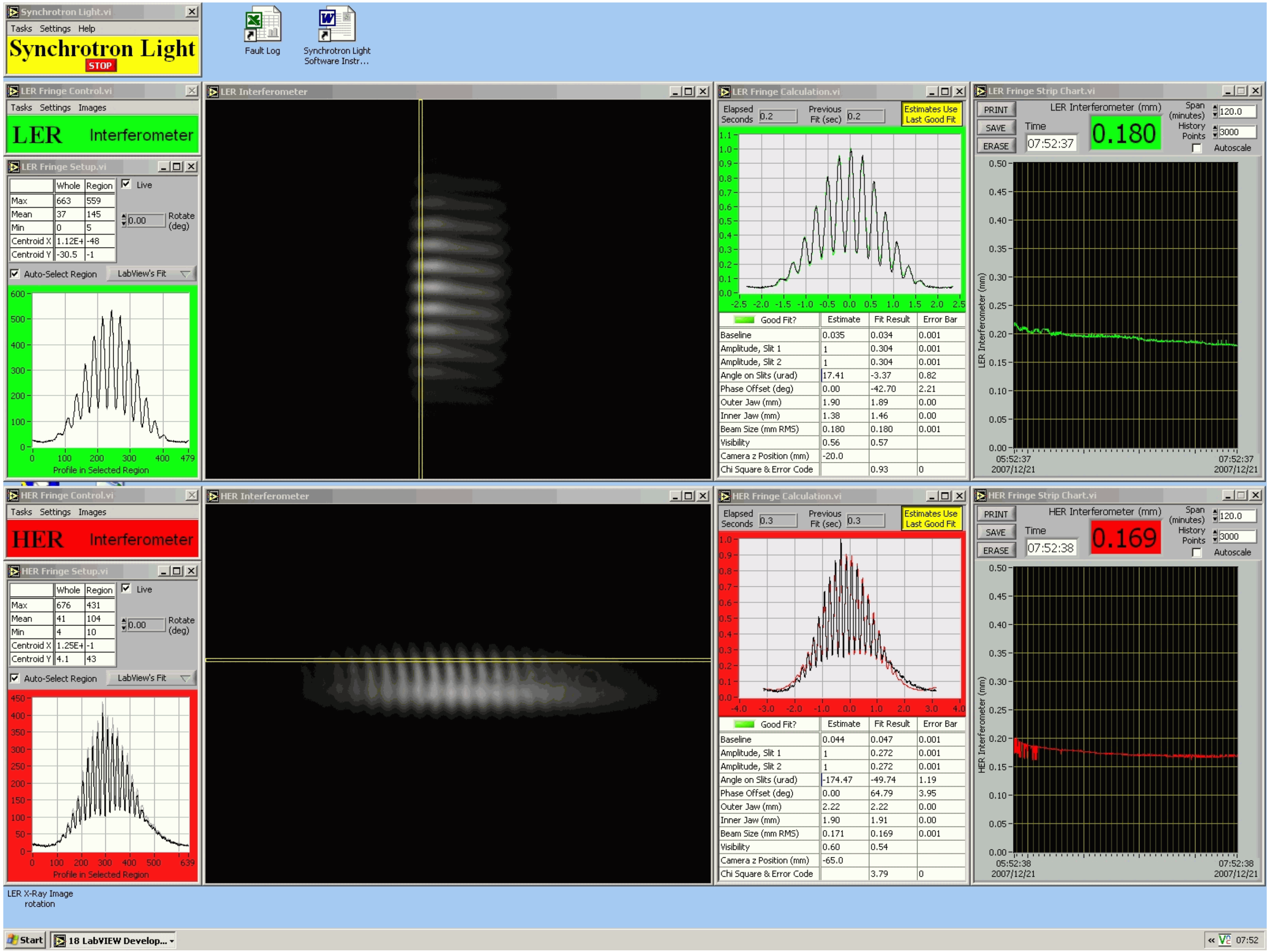
on-line diagnostic for slit separation d_o

KEK-B system

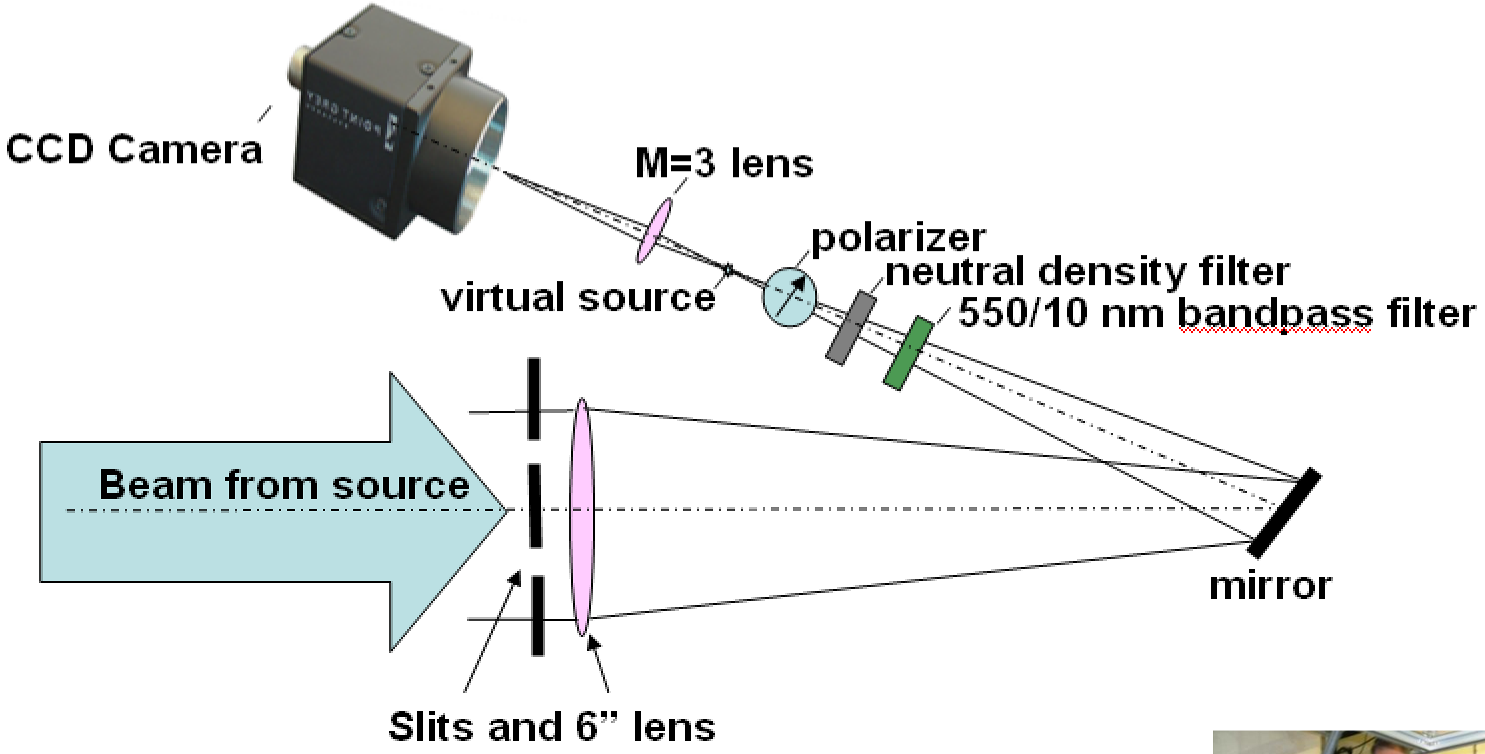


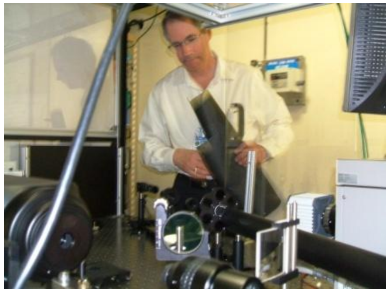
KEKB Synchrotron Radiation Monitors
File Edit Window
10/04/2004 12:05:27
Help
HER Synchrotron Radiation Monitor
σy (μm) 97 Normal
σy @ IP (μm) 2.88 Normal
σx (μm) 1443 Normal
σx @ IP (μm) 212 Normal
εy/εx (%) 1.6 Normal
V. Interferogram
V. Fit Parameters
V. Beam Size at IP
H. Interferogram
H. Fit Parameters
H. Beam Size at IP
Intensity (arb)
Pixel
Visibility
Correction
Current (mA)
LER Synchrotron Radiation Monitor
σy (μm) 184 Normal
σy @ IP (μm) 3.33 Normal
σx (μm) 1204 Normal
σx @ IP (μm) 188 Normal
εy/εx (%) 3.2 Normal
Menu Bar

PEP-II system

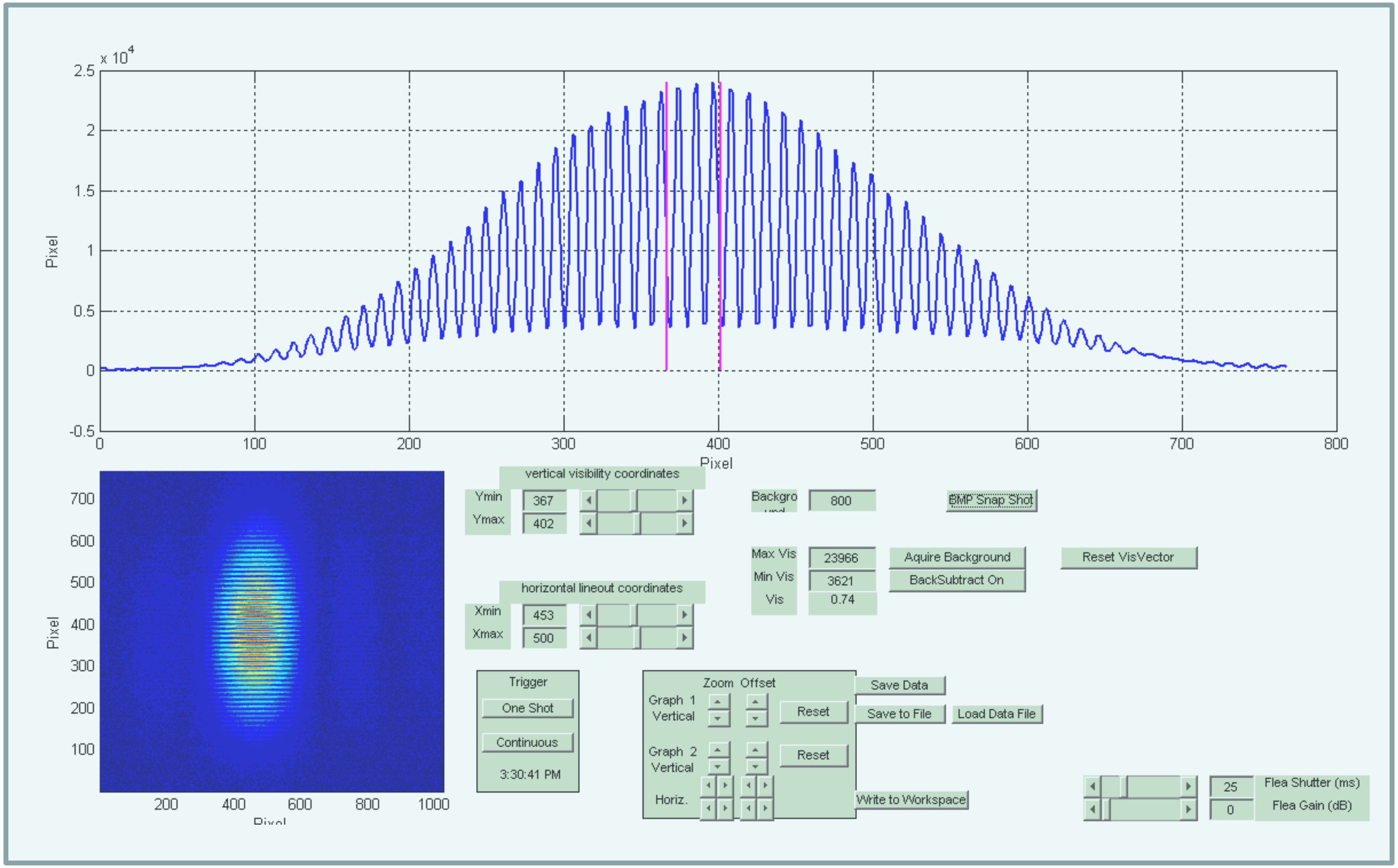


SPEAR3 system

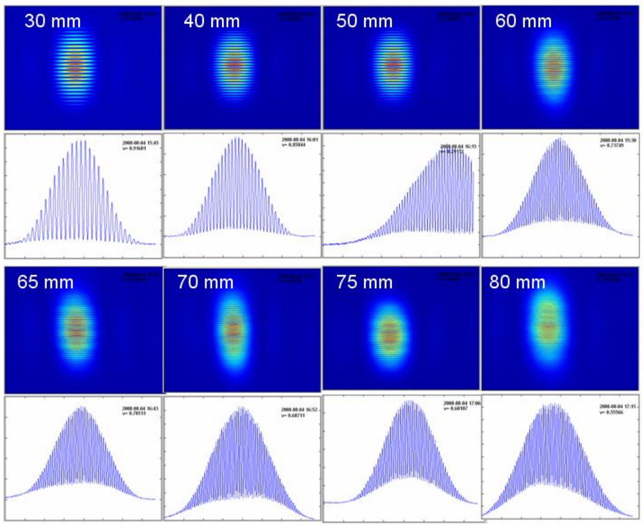




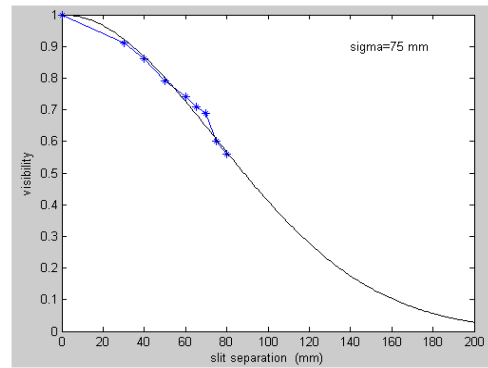
SPEAR3 system (cont'd)

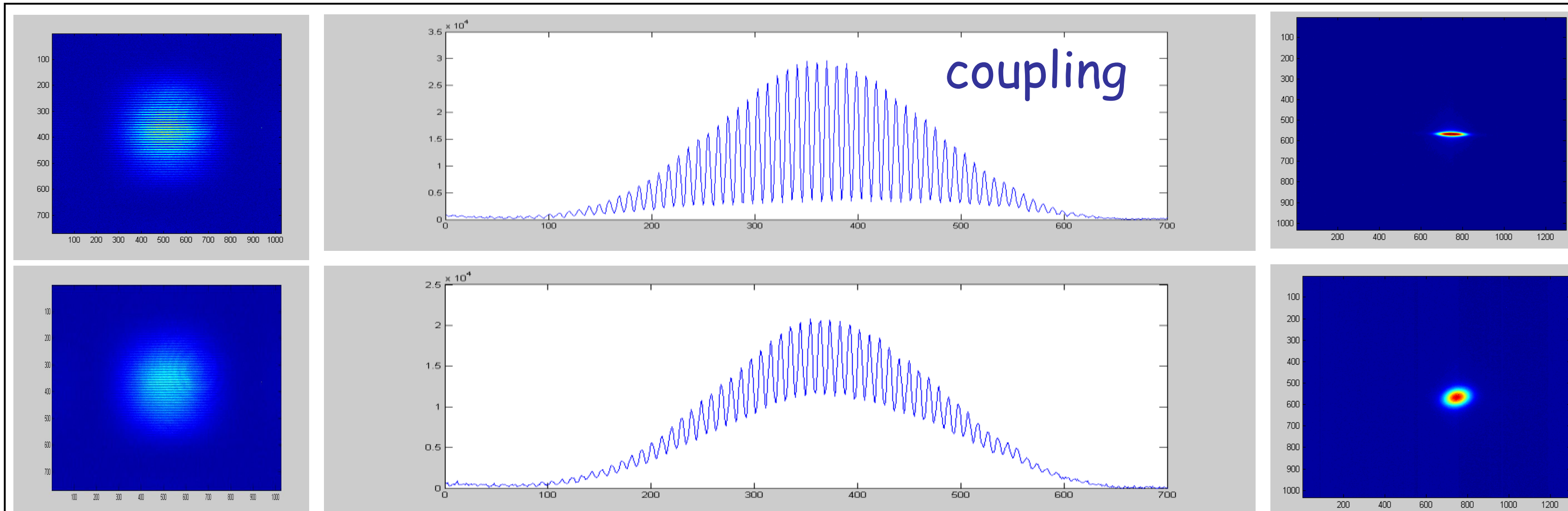


SPEAR-3 measurements

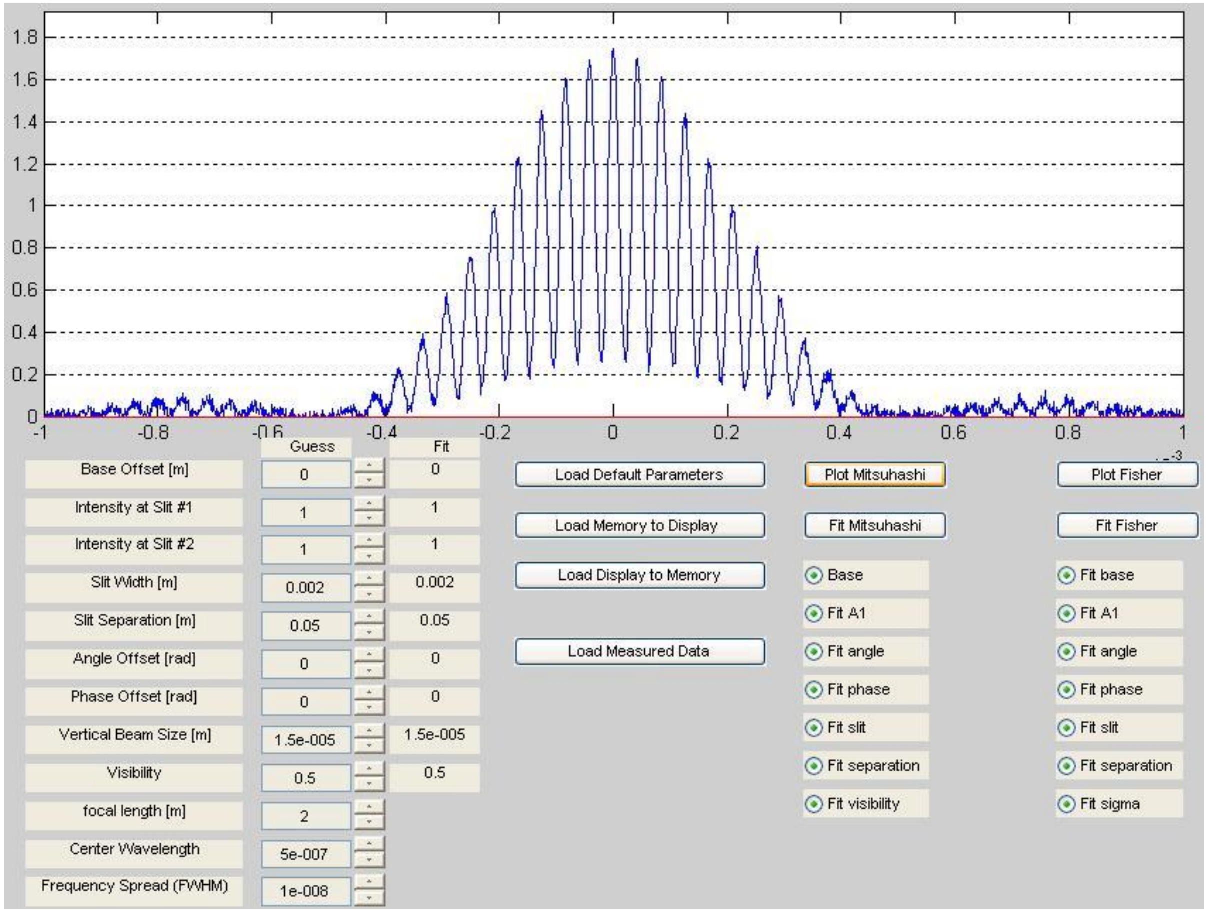


Slit separation





USPAS Simulator



Practical Issues

- Thermal distortion of mirrors – wavefront distortion
- Precision control of slit width (l_1 and l_2)
- Depth of field effects
- CCD camera linearity
- Table vibrations
- Readout noise
- Beam stability
- Numerical fitting

Michelson's Interferometer - Summary

- Interferometers useful below the diffraction limit
- Two-slit Interference – Young's experiment
- Diffraction from a single slit
- Extended Source – Partial Coherence
- Visibility and the Mutual Coherence function
- Van-Cittert/Ziernike theorem: Fourier XFRM
- Stellar Interferometers for SR applications