Application of Coronagraph for Beam halo observation In the SuperKEKB

T. Mitsuhashi, KEK
Everything was start with astronomer’s dream……

Eclipse is rare phenomena, and only few second is available for observation of sun corona, prominence etc.

Artificial eclipse was dream of astronomers, but……..
The eclipse
Inside umbra: total eclipse
Penumbra: partial eclipse

3.84 x 10^5 km

1.49 x 10^8 km
Why we can see the sun corona by eclipse without diffraction fringe?

Because no aperture between sun and moon. It means no strong diffraction source in eclipse.

The area of umbra is much larger than the diameter of the objective lens.
Why we can see the sun corona by eclipse without diffraction fringe?

Because no aperture between sun and moon. It means **no strong diffraction source in eclipse**.

The area of umbra $\gg\gg$ diameter of objective lens

**Question is can we make same system with artificial way?**
Compare two setup, eclipse and artificial eclipse.

The area of umbra>>diameter of aperture of objective lens

Diffraction source aperture is in here.

Diffraction source aperture is in here.
Diffraction source aperture is in here.

How to eliminate diffraction fringe from aperture.

A strong diffraction fringes are surrounding of the image.

The area of umbra >>> diameter of objective lens.
Convolution between diffraction fringes and object profile
Convolution between diffraction fringes and beam profile

Diffraction fringes

Gaussian profile

Blocked by opaque disk
The coronagraph to observe sun corona

Developed by B.F. Lyot in 1934 for a observation of sun corona by artificial eclipse.

Special telescope having a “re-diffraction system” to eliminate a diffraction fringe.
Optical system of Lyot’s corona graph

- Objective lens
- Field lens
- Baffle plate (Lyot stop)
- Relay lens
- Opaque disk
- Anti-reflection disk
- Baffle plates to reduce reflection
3 stages-optical system in the Lyot’s coronagraph

1st stage: Objective lens system
2nd stage: re-diffraction system
3rd stage: Relay lens
Re-diffraction optics system to eliminate the diffraction fringe

Detail of the diffraction theory of coronagraph, please see appendix 1
Function of the field lens: make an image of the objective lens aperture onto the Lyot stop.
Intensity distribution of diffraction fringes on focus plane of field lens

Geometrical image of the aperture of objective lens
Block the re-diffraction fringes
Relay of corona image to final focus point

Blocking diffraction fringe by Lyot stop
Background in classical coronagraph

This leakage of the diffraction fringe can make background level $10^{-6-8}$ (depends on Lyot stop condition).

Re-diffraction intensity on the Lyot stop
Diffraction background at 3rd stage
In Log scale \[2 \times 10^{-6} \text{ to } 10^{-7}\]
Background source in coronagraph

1. Scattering by defects on the lens surface (inside) such as scratches and digs.
2. Scattering from the optical components (mirrors) near by coronagraph.
3. Reflections in inside wall of the coronagraph.
4. Scattering from dust in air.
1. Scattering by defects on the lens surface (inside) such as scratches and digs.
2. Scattering from the optical components (mirrors) near by coronagraph.
3. Reflections in inside wall of the coronagraph. → Cover the inside wall with a flock paper (light trapping material).
4. Scattering from dust in air. → Use the coronagraph in clean room.
Scattering from the optical components (mirrors) in the coronagraph

Detail of this subject, please see appendix 2
Case 1. Noise source in the entrance pupil of objective lens

\[ P(x, y): \text{pupil function with assembly of diffraction noise sources on the lens} \]
Digs on glass surface of scratch & dig 60/40
The optical surface quality 60/40 guarantees no larger scratches than 6μm width, and no larger dig than 400μm.
Simulation result of Background produced by dig on objective surface
Comparison between normal optical polish and careful optical polish for coronagraph

S&D 60/40 surface of the lens  Surface of the coronagraph lens
Scattering from the optical components (mirrors) between source point and coronagraph.
Noise source to objective lens  Fresnel like diffraction

Then this input is re-diffracted by objective lens pupil

\( d_a \) is shorter  : out of focus image of noise source +Fresnel like diffraction
\( d_a \) is longer  : quasi-focused image of noise source +Fraunhofer like diffraction
Intentionally spread some dust on the mirror in 2m front of the coronagraph
Scattering background from mirrors near by coronagraph will not acceptable!

Use same quality of optical polishing for mirrors!
Clean optical elements are necessary for optical beam transport line.
Observation of beam halo at the Photon Factory, KEK
Beam profile
Beam halo
Observation in PF, KEK 2005
Beam core (superimposed) + halo
Observation with better than 6 order of magnitude
Beam tail images in the single bunch operation at the KEK PF measured at different current

65.8mA 61.4mA 54.3mA

45.5mA 35.5mA 396.8mA

Multi-bunch bunch current 1.42mA
Single bunch
65.8mA
Exposure time of CCD : 3msec

Intensiy in here : 2.05x10^{-4}
of peak intensity

Halo in deep outside
Exposure time of CCD : 100msec

Background level : about 6x10^{-7}
Coronagraph for SuperKEKB

1. Optical design
Optical configuration of SR monitor line in SuperKEKB  total optical path=60m

Polycrystal Diamond extraction mirror 20mm x 30mm

MIRRORS D=150mm

Coronagraph objective
Optical configuration of SR monitor line in SuperKEKB

- Polycrystal Diamond extraction mirror 20mm x 30mm
- Mirrors D=150mm
- High quality Mirrors D=150mm will replace in future
- Coronagraph objective
Design of the objective

1. Due to diffraction theory of the coronagraph, leakage background in 3ed stage is roughly proportional to transverse magnification of the objective system.

Large transverse magnification will necessary → long focal length

2. Diamond mirror aperture must set at the front principal point of Objective

Use the telephoto system
Detail of optical design of telephoto-objective system, Please see appendix 3.
Optical design of Gregorian system for SuperKEKB

- $M_1 = 240\,\text{mm}$
- $R_2 = -410\,\text{mm}$
- $C.P. = -0.502$
- $R_1 = 2400\,\text{mm}$
- $C.P. = -1$
- $M_2 = 1440\,\text{mm}$
- $B_f = -34.3\,\text{mm}$

Gregorian extension ratio $= \frac{R_1}{2M} = 5.857$

$f = M \frac{R_1}{2} = 7028\,\text{mm}$
Relation of conjugation points (between source point and beam image)

Magnification = 0.574
Distance between H and H' is 24608mm
Relation between source point and beam image

Set diamond mirror aperture at here
Designed magnification  0.574
Measurement           0.606

Error is about 5%

Majority source should be Focal length error (2% each) and distance error.

Wonderful agreement!
Observed beam image and diffraction fringes

Higher order fringes are clearly observed.
Big problem is long distance between aperture and field lens
Big problem is long distance between aperture and field lens. Difficult to obtain enough size of aperture image on Lyot stop!
Use Kepler system for obtain enough magnification

Expected problem
Focusing system has all +, +, + power
Enhancing the aberration
Especially for field flatness
Observation Graphical indication of double peaked diffraction pattern

Diffraction image on Lyot stop
Adding 3rd stage, Relay optics
Results of observation from last operation
Stored beam with total optics
5mm opaque disk is applied

2 x 10^{-2}
Close horizontal Lyot stop

vertical Lyot stop is slightly closed

$6.6 \times 10^{-6}$

$2.8 \times 10^{-4}$
Scattering noise or something beam origin??

Stored beam (superimposed)
Conclusions

1. We design Gregorian objective having a diffraction limited quality for SuperKEKB.

2. A Kepler type re-diffraction system is applied.

3. With third relay system, we got beam image and we established basic function of coronagraph with Lyot stop (elimination of diffraction fringe).
Problems

Kepler style re-diffraction system enhanced the field distortion. Difficult to reach more large transverse magnification in total system. Difficult to further elimination of diffraction fringe.

To solve these problems, Galileo type re-diffraction system will test in next operation.
Galileo type re-diffraction system

Focusing system has all +, +, - power

Lyot stop
1. High quality (low noise) Optical beam line is necessary to coronagraph.

2. New polycrystal Diamiond mirror can establish perfect wavefront transfer without significant distortion.

3. Using Gregorian objective, we can optimize coronagraph design for long optical beam line (60m in the Super KEKB).
Application of coronagraph objective for turn by turn observation of injected beam profile
Gregorian objective for observation of injected beam \( f=7028\text{mm} \)

- Fast gate II camera
- Band-pass filter: 550nm/80nm

SR
Appendix 1

Diffraction theory for the Coronagraph
Instantaneous diffraction pattern at focus point of Objective lens is given by,

\[
F(x_{obj}, y_{obj}, \theta) = \frac{1}{i \cdot \lambda \cdot f_{obj}} \int \int F_0(x \ + R \theta, y) \exp \left\{ -\frac{i \cdot 2 \cdot \pi \cdot (x \cdot x + y \cdot y)}{\lambda \cdot f_{obj}} \right\} dx \ dy
\]

\[
F_0(x, y) = \left\{ \frac{e^2}{3\pi^2 c} \left( \frac{\omega \rho}{c} \right)^2 \left( \frac{1}{\gamma^2} + \left( \frac{x}{R} \right)^2 + \left( \frac{y}{R} \right)^2 \right)^2 \left[ K_{2/3}^2 (\zeta) + \frac{\psi^2}{\left( \frac{x}{R} \right)^2 + \left( \frac{y}{R} \right)^2} K_{1/3}^2 (\zeta) \right] \right\}^{1/2}
\]

\[
\zeta = \frac{\omega \rho}{3c} \left( \frac{1}{\gamma^2} + \left( \frac{x}{R} \right)^2 + \left( \frac{y}{R} \right)^2 \right)^{3/2}
\]

Apparent diffraction pattern on focus point is given by integrating instantaneous diffraction pattern in incoherent manner,

\[
I_{obj}(x_{obj}, y_{obj}) = \int \left| F^2(x_{obj}, y_{obj}, \theta) \right| d\theta
\]
Function of the field lens: make a image of objective lens aperture onto Lyot stop.
Field lens diffraction

The integration performs $\xi_1$ and $\xi_1$

$\xi_1$: radius of field lens

$\xi_2$: radius of opaque disk
Disturbance of light on Lyot’s stop by re-diffraction system is given by;

\[
u(x) = \frac{1}{i \cdot \lambda \cdot f_{\text{field}}} \left[ \int_{0}^{\xi_2} F(\xi) \exp \left\{ - \frac{i \cdot 2 \cdot \pi \cdot x \cdot \xi}{\lambda \cdot f_{\text{field}}} \right\} d\xi - \int_{0}^{\xi_1} F(\xi) \exp \left\{ - \frac{i \cdot 2 \cdot \pi \cdot x \cdot \xi}{\lambda \cdot f_{\text{field}}} \right\} d\xi \right]
\]

\[
= \frac{1}{i \cdot \lambda \cdot f_{\text{field}}} \left[ \int_{0}^{\xi_2} F(\xi) \exp \left\{ - \frac{i \cdot 2 \cdot \pi \cdot x \cdot \xi}{\lambda \cdot f_{\text{field}}} \right\} d\xi + \int_{\xi_1}^{0} F(\xi) \exp \left\{ - \frac{i \cdot 2 \cdot \pi \cdot x \cdot \xi}{\lambda \cdot f_{\text{field}}} \right\} d\xi \right]
\]

\[
= \frac{1}{i \cdot \lambda \cdot f_{\text{field}}} \left[ \int_{\xi_1}^{\xi_2} F(\xi) \exp \left\{ - \frac{i \cdot 2 \cdot \pi \cdot x \cdot \xi}{\lambda \cdot f_{\text{field}}} \right\} d\xi \right]
\]
Intensity distribution of diffraction fringes on focus plane of field lens
Corse period correspond to inner aperture diameter

Fine period correspond to outer aperture diameter
dependence of diffraction width for different diameter of oparque disk

- 0.162mm
- 0.6mm
- 1.0mm
diffraction fringe on Lyot stop

0.162mm

0.6mm

1.0mm

Larger opaque disk has small diffraction width

Easy to eliminate
Block the rediffraction fringes
Lyot stop

Blocking diffraction fringe by Relay of corona Lyot stop

image to final focus point
Relay lens diffraction
The integration performs $\eta_1$

$\eta_1$: radius of Lyot stop
Disturbance of light on final focus point \( V(x) \) is given by:

\[
V(\phi) = \frac{1}{i \cdot \lambda \cdot f_{\text{relay}}} \int_0^{\phi_1} u(x) \exp\left\{ -\frac{i \cdot 2 \cdot \pi \cdot \phi \cdot x}{\lambda \cdot f_{\text{relay}}} \right\} dx
\]

\( U(x) \) is still not 0 inside of relay lens pupil!
Background in classical coronagraph

Re-diffraction intensity on the Lyot stop

This leakage of the diffraction fringe can make background level 10^{-8} (depends on Lyot stop condition).
Diffraction background at 3rd stage
In Log scale \(2 \times 10^{-6}\) to \(10^{-7}\)
Appendix 2

Mie scattering,

it’s diffraction treatment
Case 1. Noise source in the entrance pupil of objective lens

\( P(x, y) \): pupil function with assembly of diffraction noise sources on the lens
Digs on glass surface of scratch & dig 60/40
The optical surface quality 60/40 guarantees no larger scratches than 6μm width, and no larger dig than 400μm.
Let us approximate $i$-th noise source in the pupil as a opaque disk having a diameter of $r_0$. Using the Babinet's principle,

\[ P_i(r_0, x, y) = circ(r_0, x_i, y_i) \]

Then pupil function having many noise source is given by,

\[ P(r, x, y) = \sum_i P_i(r_0, x, y) \cdot \exp(-ik(x_i + y_i)) \]
When the mean distance of noise source is longer than 1st order transverse coherent length, pupil function with noise sources is simply given by,

\[ P(\bar{r}, x, y) = \sum_i P_i(r_0, x, y) \]

Then the impulsive response \( h(x_i, y_i; x_0, y_0) \) on the image plane is given by,

\[ h(x_i, y_i; x_0, y_0) = \frac{1}{\lambda d_0 d_i} \iint P(\bar{r}, x, y) \exp \left\{ -i \frac{2\pi}{\lambda d_i} [(x_i + Mx_0)x + (y_i + My_0)y] \right\} dx dy \]

in here, \( M = d_i / d_0 \) denotes geometrical magnification.
The intensity of diffraction from noise sources is inverse-proportional to extinction rate,

Extinction rate = entrance pupil aperture area / total area of noise source

To escape from noise produced by the objective lens is most important issue in the coronagraph!!
Simulation result of Background produced by dig on objective surface

Diffraction by objective lens aperture
Diffraction by objective lens aperture
How to eliminate Mie scattering?

1. A careful optical polishing for the objective lens.

2. Reduce number of glass surface. Use a singlet lens for the objective lens.

3. No coating (Anti-reflection, Neutral density etc.) for objective lens.
A careful optical polishing for the objective lens
Comparison between normal optical polish and careful optical polish for coronagraph

S&D 60/40 surface of the lens  Surface of the coronagraph lens
Case 2. Noise source in front of the objective lens
Noise source in front of the lens

\[ U_0 \quad U'_a \quad U_l \quad U'_l \quad U_i \]

Free space propagation

Fresnel transfer

Lens transfer

Fresnel transfer

\[ d_0 \quad d_a \quad d_i \]
After tired calculations,

\[
U_i(x_i, y_i) = \iiint P_a(x_a, y_a) \exp \left\{ i \frac{k}{2} \left( \frac{1}{d_0 - d_a} - \frac{1}{d_a} \right) (x_a^2 + y_a^2) \right\} \\
\cdot \exp \left\{ -ik \left( \frac{x_0}{d_0 - d_a} + \frac{x_l}{d_a} \right)x_a + \left( \frac{y_0}{d_0 - d_a} + \frac{y_l}{d_a} \right)y_a \right\} \, dx_a \, dy_a \\
\cdot P_l(x_l, y_l) \exp \left\{ i \frac{k}{2} \left( \frac{1}{d_l} + \frac{1}{d_i} - \frac{1}{f} \right) (x_l^2 + y_l^2) \right\} \\
\cdot \exp \left\{ -i \frac{k}{d_i} (x_i \, x_l + y_i \, y_l) \right\} \, dx_l \, dy_l
\]

in here, \( d_l = d_a + d_0 \)
After tired calculations,

**Diffraction by noise source**

\[ U_i(x_i, y_i) = \iiint \left[ \iint P_a(x_a, y_a) \exp \left\{ i \frac{k}{2} \left( \frac{1}{d_0 - d_a} - \frac{1}{d_a} \right) \left( x_a^2 + y_a^2 \right) \right\} \right. \]
\[
\cdot \exp \left\{ -ik \left( \left( \frac{x_0}{d_0 - d_a} + \frac{x_l}{d_a} \right) x_a + \left( \frac{y_0}{d_0 - d_a} + \frac{y_l}{d_a} \right) y_a \right) \right\} \left. \right] \, dx_a \, dy_a \]

\[
\cdot P_l(x_l, y_l) \exp \left\{ i \frac{k}{2} \left( \frac{1}{d_l} + \frac{1}{d_i} - \frac{1}{f} \right) \left( x_l^2 + y_l^2 \right) \right\} \]
\[
\cdot \exp \left\{ -i \frac{k}{d_i} (x_i \, x_l + y_i \, y_l) \right\} \, dx_l \, dy_l
\]

**Diffraction by lens pupil**
Noise source in front of the lens

Noise source $\rightarrow$ Fresnel diffraction

Then re-diffracted by lens pupil
Noise source to objective lens $\rightarrow$ Fresnel like diffraction

Then this input is re-diffracted by objective lens pupil

$d_a$ is shorter : out of focus image of noise source +Fresnel like diffraction

$d_a$ is longer : quasi-focused image of noise source +Fraunhofer like diffraction
Intentionally spread some dust on the mirror in 2m front of the coronagraph
Appendix 3

Telephoto system
No. 1

No. 2
What is the meaning of the diagram?

Explanation diagram.
Corresponding reflective system is Cassegrain system

First mirror is parabolic

Second mirror is hyperbolic
Corresponding reflective system Gregory system

First mirror is parabolic

Second mirror is elliptic
Difference between Cassegrain and Gregory

First mirror is parabolic

Second mirror is hyperbolic

First mirror is parabolic

Second mirror is elliptic
Optical design of Cassegrain objective in Supper B factory
Existing Cassegrain system $f=5000\text{mm}$ for streak camera
Put an aperture at certain height $h$

\[ M = \frac{m_2 + bf}{m_1} \quad \text{Cf} = M \cdot \frac{R_1}{2} \quad R_2 = \frac{2 \cdot m_1 \cdot m_2}{m_2 - m_1} \]

$R_1 = 2000\text{mm}, \quad M = 4, \quad \text{Cf} = 5000\text{mm}, \quad R_2 = 500\text{mm}$
Corresponding conjugation points

Front focus point: \( F_f = 5000 \text{mm} \)

\( H_f \)

11000mm

\( H_b \)

Back focus point: \( F_b = 5000 \text{mm} \)

21000mm
Front focus point

| HF | 11000mm | HB |

Back focus point

| FF = 5000mm | 21000mm | FB = 5000mm |
With geometrical optics

\[ \frac{f'}{x} = - \frac{x'}{f} \]
Using the Newton’s equation,

\[
\frac{f}{x} = -\frac{x'}{f}
\]

\[f = 5000\text{mm}\]

\[x = 9018\text{mm}\]

\[x' = 2772\]

Transverse magnification = 0.554
Optical design of Cassegrren objective in Super B factory

Cassegrain focal length = 8038 mm
Cassegrain extension ratio = 4.018

R₂ = 1065 mm
C.P. = -2.680

M₁ = 400 mm
M₂ = 1600 mm
Bₓ = 7.5 mm

R₁ = 4000 mm
C.P. = -1.0
レイアウト
多色回折 φφφ

図の解説

多色回折のデータです。

回折角：φφφ

カセグレン φφφ
コンフィグレーション φφφ
スルーフォーカス スポットダイアグラム

<table>
<thead>
<tr>
<th>面</th>
<th>像</th>
<th>デフォーカス（単位）</th>
</tr>
</thead>
</table>

単位は \( \mu \) です。

<table>
<thead>
<tr>
<th>視野</th>
<th>半径</th>
<th>半径</th>
<th>スケールバー</th>
<th>基準</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>主光線</td>
</tr>
</tbody>
</table>

カセグレン

コンフィグレーション
Relation between source point and beam image

Magnification = 0.414
Distance between H and H' is 16113mm
Optical design of Gregory system for SuperKEKB

- $M_1 = 240 \text{mm}$
- $R_2 = -410 \text{mm}$
- C.P. = -0.502
- $M_2 = 1440 \text{mm}$
- $R_1 = 2400 \text{mm}$
- C.P. = -1
- $B_f = -34.3 \text{mm}$

Gregorian extension ratio = 5.857

$$f = M \frac{R_1}{2} = 7028 \text{mm}$$
Corresponding conjugation points

Front focus point  \( H_f \)  Back focus point

\[ F_f = 7028\text{mm} \quad 24608\text{mm} \quad F_b = 7028\text{mm} \]
スルーフォーカス スポットダイアグラム

<table>
<thead>
<tr>
<th>面</th>
<th>像</th>
<th>デフォーカス（単位）</th>
</tr>
</thead>
</table>

**単位:** ディップする度
**視野:** 未定
**スケールバー:** 未定
**基準:** 主光軸

**コンフィグレーション:** 未定
多色回折

面：像面

コンフィグレーション
Relation between source point and beam image

Magnification=0.574
Distance between H and H’ is 24608mm