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ANALYSIS OF MIE SCATTERING NOISE OF OBJECTIVE LENS IN CORONAGRAPH FOR HALO MEASUREMENT

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Abstract

In beam halo measurements by means of a coronagraph viewing visible SR light, the theoretical image contrast is dominated by leakage of the diffracted fringe pattern from the Lyot stop. On other hand, the noise background in an actual coronagraph also contains light scattered from imperfections in the first objective lens. Most of this light is due to Mie-scattering from dig imperfections on the surface of objective which can reduce the image contrast to the 10-3 range for a lens with 60/40 scratch and dig figures. By introducing a high-quality objective lens into the system the theoretical value of 10-5-10-6 image contrast can be recovered for the Lyot coronagraph. In this paper, Mie-scattering due to dig imperfections is analyzed theoretically and results from measurements of the Mie scattering are presented.

INTRODUCTION

For high energy or high power accelerators such too much beam in the halo can lead to damage of accelerator components, either due to instantaneous beam loss or through long term irradiation. Beam halo control is essential and is best achieved by tuning the machine to avoid populating the tails of the bunch distribution. The beam diagnostic challenges here lie in developing non-invasive techniques with a high enough dynamic range to resolve a beam halo a factor 10^{-5} lower in intensity than that in the beam core. Synchrotron light sources, FELs and high energy hadron accelerators, such as the LHC, can all use synchrotron light to provide a non-invasive, transverse image of the beam distribution. To be able to measure the beam halo, however, requires an imaging system that eliminates the diffraction fringes created by the intense light from the beam core as is passes through the aperture of the first optical element. These fringes can have an intensity as high as 10^{-2} of the peak intensity and would hide any halo at the 10^{-5} level. To reduce this effect a coronagraph, developed by Lyot [1] in 1936 for solar astronomy, can be used. Such a technique has already been demonstrated by one of authors at the KEK Photon Factory to achieve a $6x10^{-7}$ ratio for background to peak intensity [2]. In this way, the coronagraph can escape from background due to diffraction fringe, but in other hand, strong illumination for objective lens can produce another background. The Mie scattering from digs on the surface of the objective lens. With typical commercial-available lens has scratch and dig 60/40 optical polishing quality, the Mie scattering background can make a background as like as intensity of diffraction fringe. In this paper, it is described analysis of Mie scattering from dig on the lens surface, and discuss the contribution to background in the coronagraph.

CORONAGRAPH

The optical layout of the coronagraph is illustrated in Fig. 1 [2]. The objective lens makes a real image of the object (beam image) on to a blocking mask which makes artificial eclipse. Second lens (field lens) which is located just after the blocking mask makes a real image of the objective lens onto a mask so-called Lyot Stop. The diffraction fringes on focal plane of the objective lens is re-diffracted by field lens aperture and making a diffraction ring onto the focal plane of field lens. The Lyot's genius idea of the coronagraph is to remove this diffraction rings by a mask, so-called Lyot stop in today and relay the hidden image such as Sun corona by a third lens onto final observation plane. The background light on the final observation plane is now mainly come from the leakage of diffraction fringe inside of Lyot stop and the scattering of the input bright light by the objective lens. Theoretically, diffraction fringe leakage to next stage can reduce greatly, and we can reduce the background light less than 10^{-6} to the peak intensity of blocked main image at final stage. With this coronagraph, we can observe a hidden image of beam halo in accelerator surrounding from the bright beam core image.

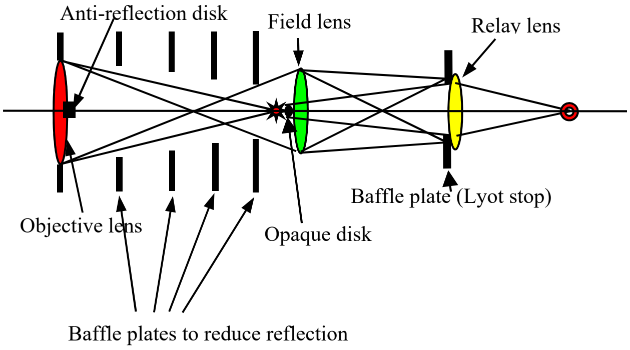

Figure 1: Layout of optical system of the coronagraph.

MIE SCATTERING SOURCE ON SURFACE OF OBJECIVE LENS

After blocking the central bright image and cutting the light from diffraction fringe, we have still scattered light (Mie scattering) from the defects in the objective lens such

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as scratches and digs on its surfaces. Figure 5 shows a surface of objective lens with the typical surface with optical polishing scratch & dig 60/40. The optical surface quality 60/40 guarantees no larger scratches than 6µm width, and no larger dig larger than 400µm. From this observation, we can find many digs (small spots in the photograph) with 10-100µm in diameter.

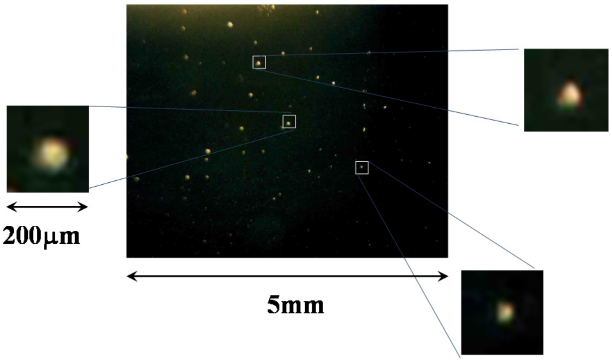

Figure 2: A microscope image of the digs on the surface of lens with normal optical polishing scratch & dig 60/40. This photo is taken by illuminating from the side.

MIE SCATTERING BY MEANS OF DIFFRACTION TREATMENT

Let us consider the Mie scattering by means of diffraction phenomena from dig on pupil.

Case 1, Consider the dig on the entrance pupil of the objective lens.

Let us introduce a generalized pupil function having the digs in the entrance aperture of the objective lens as shown in Fig. 3. In here, the dig is represented by a small opaque spot with a radius r_0 on the pupil.

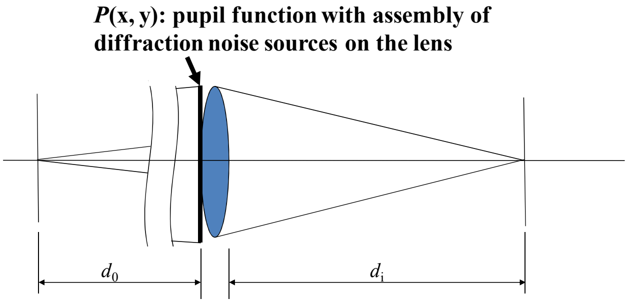

Figure 3: Case 1, the noise source in the entrance pupil of the objective lens

Using the Babinet's principle, we can replace such dig as opaque spot with a small hole having a same radius as shown in Fig. 4.

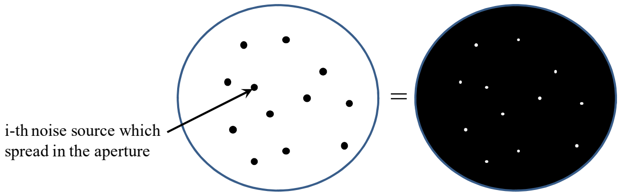

Figure 4: Babinet's principle for calculating diffraction from dig as the pupil having an opposite contrast.

Let us assume the shape of the dig is simple round shape, the pupil function of i-th hole is given by,

$$P_i(r_0, x, y) = circ(r_0, x_i, y_i) \qquad (1)$$

When the separations between the holes are smaller than coherent length of the illuminated light, the pupil function is given by,

$$P(\bar{r}, x, y) = \sum_i P_i(r_0, x, y) \cdot exp(-ik(x_i + y_i)) \qquad (2)$$

In other hand, the separations of the holes are enough lager than coherent length, the pupil function is give by incoherent summation.

$$P(\bar{r}, x, y) = \sum_i P_i(r_0, x, y) \qquad (3)$$

Using these pupil functions, the impulsive response on the image plane is given by,

$$h(x_i, y_i; x_0, y_0) = \frac{1}{\lambda d_0 d_i} \iint P(\bar{r}, x, y) \cdot exp\left\{-i\frac{2\pi}{\lambda d_i}\left[(x_i + Mx_0)x + (y_i + My_0)y\right]\right\} dxdy \qquad (4)$$

In here, $M = d_i / d_0$ denotes geometrical magnification.

In the case of separation between the holes are larger than coherent length of illuminating light, The diffraction intensity is given by incoherent summation of diffraction from holes.

Case 2, We consider Mie scattering source in front of Objective lens.

Let us consider the Mie Scattering source on the generalized pupil function at distance d_s in front of the objective lens as shown in Fig. 5. This case is corresponding to some optical component such as mirror in front of the objective lens.

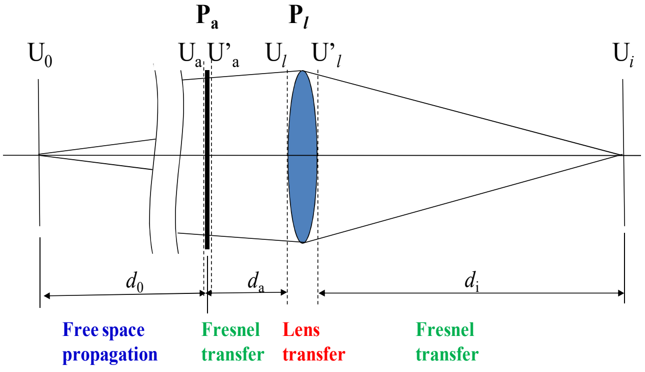

Figure 5: Case 2, Noise source in front of the lens.

In this case, impulsive response on the image plane is calculated by 3 stages, stage one; Fresnel transform of pupil function U'$_a$ onto lens pupil U$_l$, stage 2; paraxial lens transform U$_l$ to U'$_l$, stage 3, Fresnel transform of U'$_l$ onto image plane U$_i$. The result of impulsive response on the image plane is given by,

$$U_i(x_i,y_i)=\iint\left[\iint P_a(x_a,y_a)\,exp\left\{i\frac{k}{2}\left(\frac{1}{d_0-d_a}-\frac{1}{d_a}\right)\left(x_a{}^2+y_a{}^2\right)\right\}\right.$$
$$\left.\cdot\,exp\left\{-ik\left(\left(\frac{x_0}{d_0-d_a}+\frac{x_l}{d_a}\right)x_a+\left(\frac{y_0}{d_0-d_a}+\frac{y_l}{d_a}\right)y_a\right)\right\}dx_a dy_a\right]$$
$$\cdot\,P_l(x_l,y_l)\,exp\left\{i\frac{k}{2}\left(\frac{1}{d_l}+\frac{1}{d_i}-\frac{1}{f}\right)\left(x_l{}^2+y_l{}^2\right)\right\}$$
$$\cdot\,exp\left\{-i\frac{k}{d_i}\left(x_i\,x_l+y_i\,y_l\right)\right\}dx_l dy_l \tag{5}$$

The first integral in this equation represents the Fresnel diffraction by Mie scattering source, and the second integral represents the Fresnel diffraction of the lens pupil.

This result indicates when d_a is shorter, out of focus image of noise source with Fresnel like diffraction, and when d_a is longer, quasi-focused image of noise source with Fraunhofer like diffraction.

SIMULATION OF MIE SCATTERING BACKGROUND FOR CASE 1

The Mie scattering background for case 1 using impulsive response equation 4 is simulated for several diameters of digs. In this simulation, the density of digs is estimated from Fig. 2.

Simulation results for dig diameter of 50,100,200 and 400µm are shown in Fig.6 with diffraction pattern of objective lens aperture. The vertical scale for each diffraction pattern is normalized by peak intensity of diffraction of the lens aperture.

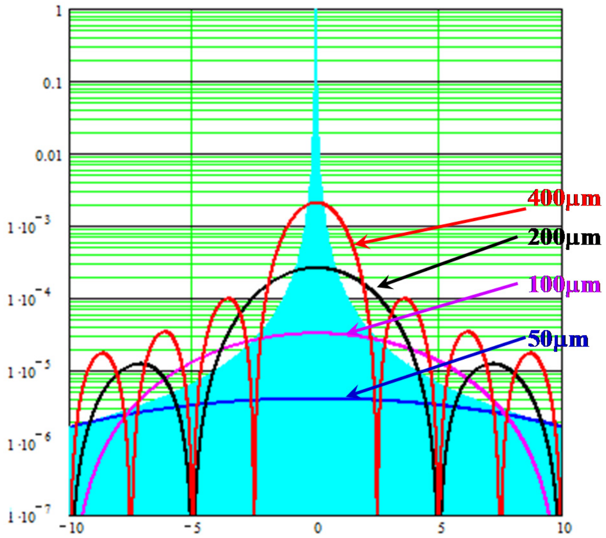

Figure 6: Simulation results for dig diameter of 50,100,200 and 400µm with diffraction pattern of lens aperture.

A close-up of Fig. 6 in horizontal axis is shown in Fig. 7. From these results, Mie scattering background from smaller dig such as 50µm is widely spread, and having contrast level of 10^{-5} to 10^{-6} of the peak intensity of the diffraction from lens aperture. More lager digs has lager noise. For example, dig larger than 100µm can make almost same noise intensity level as like as the intensity of diffraction fringes by lens aperture.

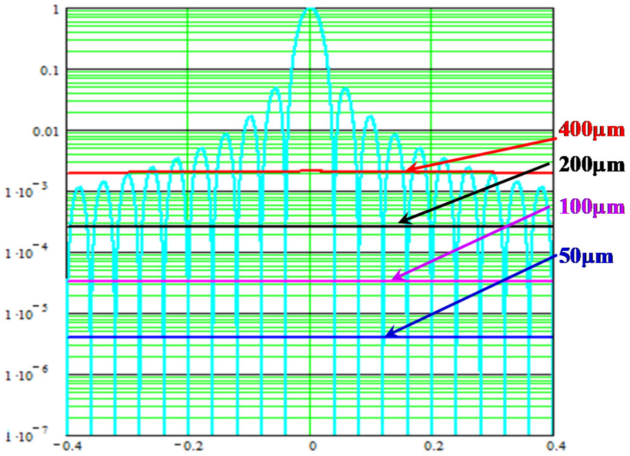

Figure 7: A close-up of Figure 6.

OBSERVATION OF MIE SCATTERING BACKGROUND FOR CASE 2

The Mie scattering background for case 2 is observed by spraying dust on the mirror which is located 2m in front of the objective lens. A result of this observation is shown in Fig.8. The white frame indicates aria on the mirror which is illuminated by input light.

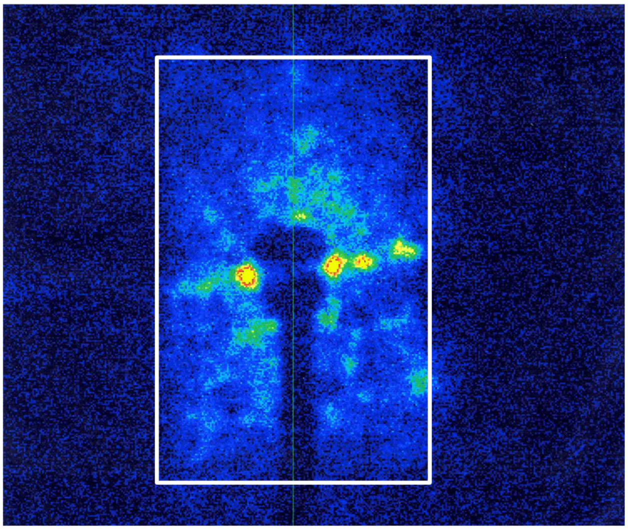

Figure 8: Result of observation for Mie scattering background from the dust on the mirror. The mirror is located 2m in front of the objective lens.

The dark circle in the centre is corresponding to opaque disc with supporting load for artificial eclipse. This observation is corresponding to shorter d_a . The out of focus image of noise source (dust) with Fresnel like diffraction is observed.

Without such Mie scattering background, we can observe beam halo with high contrast as shown in Fig. 9 [2].

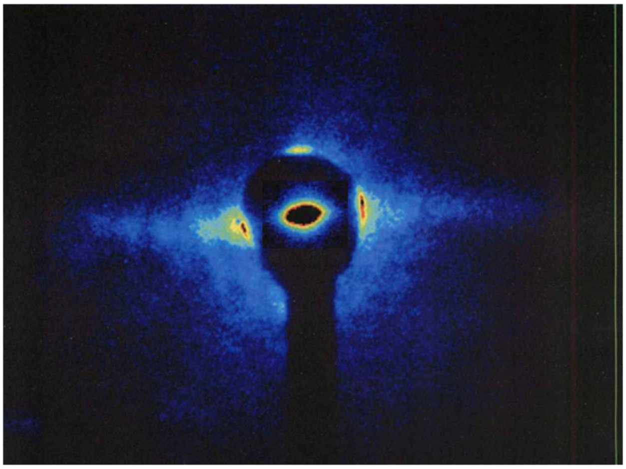

Figure 9: A result of beam halo observation with coronagraph at Photon Factory in the KEK. The profile of beam core image is super imposed in inside of opaque disk image.

CONCLUSIONS

The theoretical analysis for Mie scattering from dig by using a diffraction treatment is discussed for two cases. The case 1, dig is located on the lens surface, and Case 2 Mie scattering source is located in front of the objective lens. In the case 1, the Mie scattering background from smaller dig such as 50μm is widely spread, and having contrast level of 10^{-5} to 10^{-6} of the peak intensity of the diffraction from lens aperture. More lager digs has lager noise. For example, dig larger than 100μm can make almost same noise intensity level as like as the intensity of diffraction fringes by lens aperture. For the case 2, the result indicates when d_a is shorter, out of focus image of noise source with Fresnel like diffraction, and when d_a is longer, quasi-focused image of noise source with Fraunhofer like diffraction. From these results, we can conclude we need Mie-scattering background free objective lens for the First stage of the coronagraph and optical components such as mirrors in near front of objective lens.

REFERENCES

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