DESIGN AND CONSTRUCTION OF CORONAGRAPH FOR OBSERVATION OF BEAM HALO

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Abstract

We developed the coronagraph for an observation of the beam halo or tail surrounding from the beam. An opaque disk is at the beam image plane to block the glare of the beam image. We succeeded to obtain the signal to background ratio better than 10^{-5}. As a test, we tried to observe a beam tail at the Photon Factory storage ring. We succeeded to observe the tail of the beam which has an intensity range of $1/10^4$ of the peak intensity.

INTRODUCTION

The beam tail and halo will be one of the significant problems in future Linac-based machines such as LC and ERL. To develop the apparatus to observe the beam tail or halo, we applied a concept of coronagraph. The coronagraph is a spatial telescope to observe the sun-corona by artificial eclipse [1]. The concept of this apparatus is to block the glare of central image and to observe a hidden image such as sun-corona. We applied this concept for the observation of the surrounding structure (halo, tail) of the beam. Since the background is mainly come from scattered light by the objective lens, the key point to realize the coronagraph is to reduce scattering light from objective lens. We used very well-polished lens for the objective lens, and succeeded to obtain the signal to background ratio better than 10^{-5}. As a test, we tried to observe the tail of beam by the coronagraph at Photon Factory storage ring. We succeeded to observe the tail of beam which has an intensity range of $1/10^4$ of the peak intensity.

CONCEPT OF THE OPTICAL SYSTEM OF THE CORONAGRAPH

The optical layout of the coronagraph is illustrated in Fig.1. The first lens (objective lens) makes a real image of the object (beam image) on to a blocking disk which makes artificial eclipse. Second lens (field lens) which is located just after the blocking disk makes a real image of the objective lens onto a mask (Lyot Stop). The diffraction fringes 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, and relay the hidden image by a third lens onto final observation plane [1]. The background light on the final observation plane is now mainly come from the scattering of the input light by the objective lens. To applying a very well polished lens as the objective, we can reduce the background light less than 10^{-6} to the main image. With this coronagraph, we can observe a hidden image surrounding from the bright main image.

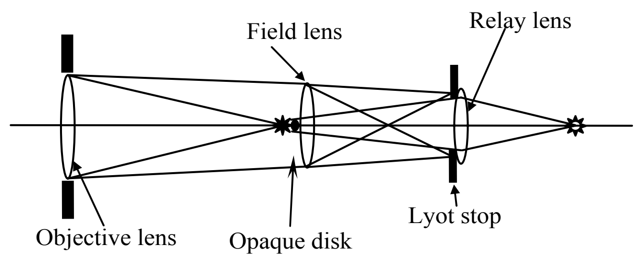

Figure 1: Layout of optical system of the coronagraph.

ELEMINATION OF DIFFRACTION LIGHT

The objective lens aperture makes a bright diffraction fringe surrounding from the beam image. The ratio of intensity between the diffraction fringe to the peak of Airy disc is approximately 10^{-2} at the first peak of the fringe. This intense diffraction fringes inhibits an observation of weak image surrounding from the central beam image. Lets consider the case of observation for beam tail at the Photon Factory. In this case, the second diffraction fringe has a same intensity of the geometrical image of the beam as shown in Fig. 2. The beam tail surrounding from second diffraction fringe has a weaker than diffraction fringe, and we cannot observe by normal imaging method.

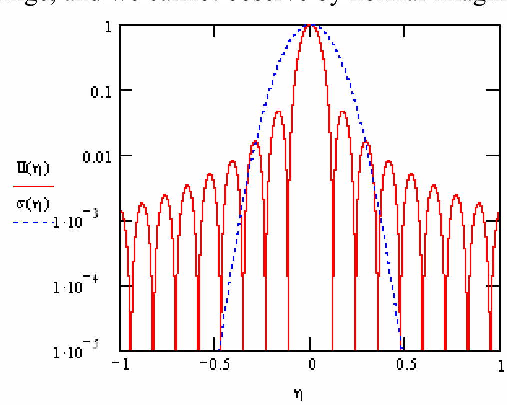

Fig 2. Comparison between beam profile and point spread function PSF. Solid line denotes PSF, and dotted line denotes horizontal beam profile at the Photon Factory.

To cut the intense diffraction fringe, we use the re-diffraction optics system in the coronagraph. The re-diffraction optics system is set after the blocking disk as shown in Fig 3.

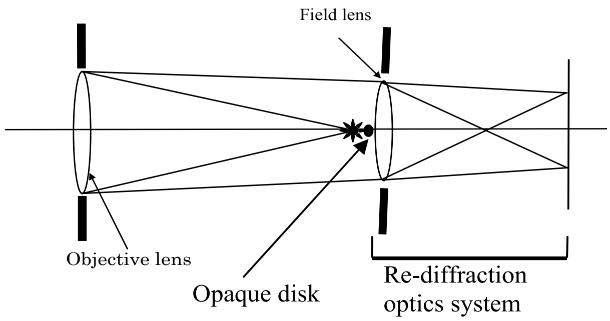

Fig. 3 Re-diffraction optics system set after the blocking disk.

The re-diffraction system consists of a field lens, and the diffraction fringe surrounding from the central image is re-diffracted by this system and making a diffraction image onto the imaging plane of the field lens. Let F(ξ) denotes disturbance of the light on the imaging plane of the objective lens. The disturbance of re-diffracted light u(x) on the imaging plane of the field lens is given by,

$$u(x) = \frac{1}{i \cdot \lambda \cdot f} \int_{\xi 1}^{\xi 2} F(\xi) \exp\left\{ -\frac{i \cdot 2 \cdot \pi \cdot x \cdot \xi}{\lambda \cdot f} \right\} d\xi \quad .$$

Where λ denotes wavelength of input light, ξ1 denotes radius of blocking disk, ξ 2 denotes radius of aperture at the blocking disk, and f denotes distance between field lens and its imaging plane, respectively. An example of simulation of intensity distribution $u^2(x)$ using a input squire-aperture at the objective lens is shown in Fig. 4.

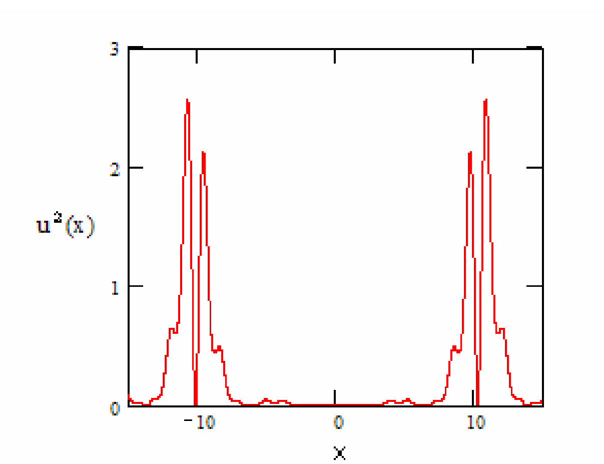

Fig. 4 An example of simulation of intensity distribution $u^2(x)$ using a squire input aperture on the objective lens. Valley between the diffraction peaks corresponds to the position of geometrical image of objective lens edge.

From this figure, we can see two diffraction rings locate in the inner and outer of the geometrical image of objective lens edge. To hide this diffraction ring with a mask (Lyot Stop), the light from diffraction fringe will not come to the later stage of the coronagraph.

OPTICAL POLISHING OF OBJECIVE LENS

After blocking the central bright image and cutting the light from diffraction fringe, we have still scattered light from the defects in the objective lens such as scratches and digs on its surfaces. Since this scattered light intensity easily reached to the order of 10^{-3}, we mast polish carefully to remove such scratches and digs on the lens surfaces. Figure 5 shows a surface with the optical polishing for the object lens compare with the typical surface with optical polishing scratch & dig 60/40. The surface with optical polishing scratch & dig 60/40 still has many digs (small spots in the photograph). The surface of the objective lens with careful polishing has almost no digs.

(a) (b)

Fig. 5 A microscope image of the digs on the surface of lens illuminated from the side. (a) Surface with normal optical polishing scratch & dig 60/40. (b) Surface of objective lens for coronagraph. The side of this picture is 5mm.

MEASURE THE BEAM TAIL AT THE PHOTON FACTORY

To investigate the performance of the coronagraph, we measured a beam tail at the Photon Factory.

The Coronagraph

A well-polished singlet lens made of BK7 having a diameter of 150mm is used as an objective lens. The focal length of objective lens is chosen to 2000mm to obtain an enough size of the beam image onto the blocking disc. A squire aperture is set just in front of the objective lens to define the entrance pupil. An opaque disk is set in front of field lens to block the glare of central beam image. An ED achromatic lens having a focal length of 500mm with a diameter of 50mm is used as the field lens. A quadratic slit is set in the imaging plane of the field lens as the Lyot stop. A band-pass filter of 550nmwith a bandwidth of 10nm is inserted before the Lyot stop. We used a couple of ED achromatic lens for the final image relay system. A high-speed gated camera (Hamamatsu photonics C2925-01) is used to observe the final image. The diameter of opaque disk is carefully chosen to block 4σ of the beam size.

Observation of beam tail

At first, we observed an image of stored beam profile without the opaque disk and Lyot stop. The result is shown in Fig. 6. The exposure time to catch this image was 10μsec.

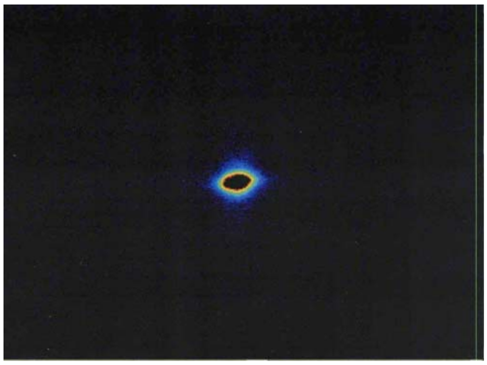

Fig. 6 Image beam profile without the opaque disk. Exposure time of CCD camera is 10μsec.

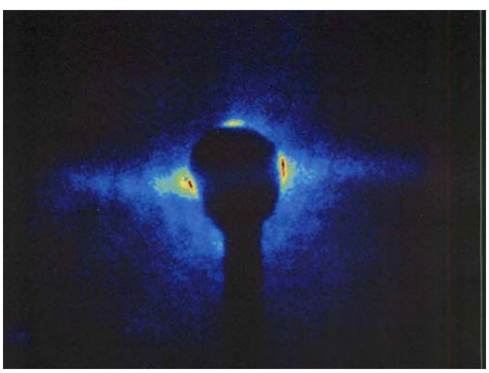

Fig.7 Image of beam tail with the opaque disk. Transverse magnification is same as in Fig.6. Exposure time of CCD camera is 10msec.

In the next, we observed an image of beam tail by applying the opaque disk to blocking the central beam image and Lyot stop. Since the image of beam tail is very weak, we increased the exposure time of CCD camera. A result of beam tail image is shown in Fig. 7. The exposure time was 10msec. Consider the difference in the exposure time, the intensity scale in figure 7 is 1000 times smaller than the intensity scale in figure 6. A comparison of beam tails measured with and without opaque disk and Lyot stop are shown in Fig.8. The both intensities are normalized by peak intensity of the central beam image. As discussed in section 3, beam tail image with diffraction taken without opaque disk and Lyot stop is range of 10^{-2} of the peak. With opaque disk and Lyot stop, we succeeded to observe the tail of the beam which has an intensity range of $1/10^4$ of the peak intensity.

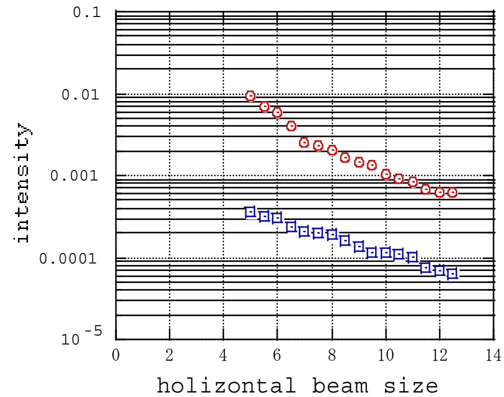

Fig. 8 Comparison of beam tails; circles denote beam tail without opaque disk, ;squires denote beam tail measured with opaque disk and Lyot stop. The horizontal axis is normalized by 1σ of the beam size.

On trial, we observe a tail image with opaque disk and without Lyot stop. A result is shown in Fig.9. In this figure, we turn entrance squire aperture by 30deg for the easy distinction of diffraction image. We can see inclined diffraction image in this figure.

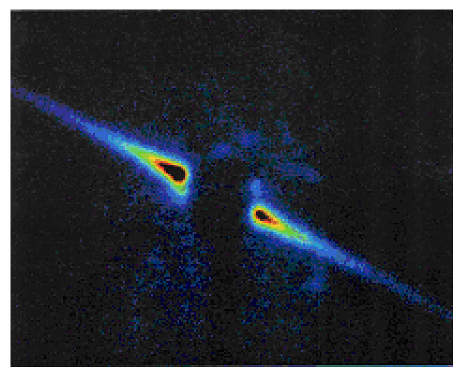

Fig. 9. Tail image with opaque disk and without Lyot stop.

CONCLUSION

We developed and constructed the coronagraph for an observation of the beam halo or tail surrounding from the beam. We succeeded to obtain the signal to background ratio better than 10^{-5}. To investigate the performance of the coronagraph, we measured a beam tail at the Photon Factory. We succeeded to observe the tail of the beam which has an intensity range of $1/10^4$ of the peak intensity. The coronagraph is applicable not only to observe the beam tail or halo but also having a many possibilities such as observation of injected beam under the presence of stored beam by its high S/N ratio.

REFERENCES

[1] B.F.Lyot Month. Notice Roy. Ast. Soc, p580, **99** (1939.)