ULTRA-HIGH RESOLUTION OBSERVATION DEVICE FOR CARBON STRIPPER FOIL

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Abstract

During beam irradiation, the charge exchange foil is damaged by the heat and radiation, which causes structural changes, including the development of pinholes. Ultrahigh resolution observation devices of 10μm or less are necessary to the study the development of the damage and the growth of the pinholes in the charge exchange foils. However, no available device can be used in the high radiation and vacuum environment inside a proton accelerator. We devised an observation system that applied the principle of the telescope to observe at ultrahigh resolutions within a high radiation environment. Various optical systems were compared to find one that would provide high-resolution while being composed of materials that can be used in radiation environments. The best system resulted in an ultrahigh resolution observation device that could observe a subject approximately 8 m away at resolution of 8.33μm.

INTRODUCTION

At the Japan Proton Accelerator Research Complex (J-PARC), operated in Tokai Village, H^- beams are accelerated by a 180-MeV linear accelerator, and changed into H^+ beams by a carbon charge stripper foil of 200μg/cm^2 thickness installed at the injection area of a 3-GeV synchrotron. As it is exposed not only to injection beams but also to circulating beams, the charge stripper foil attains high temperatures (approximately 2000 K) locally owing to energy loss caused by the beams (Figure 1(a)) [1]. The temperature differences in the heated and non-heated areas cause the carbon foil to shrink and pinholes to form, resulting in damage to the carbon foil. As the foil must be replaced when damaged and exposure of the engineer to radiation during replacement is unavoidable, development of a foil that will last for hours without damage is underway. However, a satisfactory foil has not yet been developed.

In order to continue the research and development of a long-life carbon foil that has better resistance to thermal damage, the deformation mechanism leading to the foil being damaged must be studied in detail. It is necessary to be able to observe the surface of foil at a resolution of 10μm or less while the foil is in a vacuum environment in order to study in detail the processes of pinholes of approximately a few microns being generated and growing and the process of the foil shrinking. However, the foil is placed in a high radiation environment, which is a very severe environment; thus, there is a need for equipment that can endure exposure to radiation as well as can observe regularly to observe the process of pinhole growth.

We have developed a novel observation method applying the principle of the telescope. We succeeded in producing an ultra-high resolution observation device capable of observing a subject approximately 8 m away at a resolution of 8.33 μm comparing the capabilities of materials that can be used in radiation environments and considering how they combine with various optical systems enabling high resolution, then selecting the best combination. We are reporting the status of this development and the results of optical performance tests.

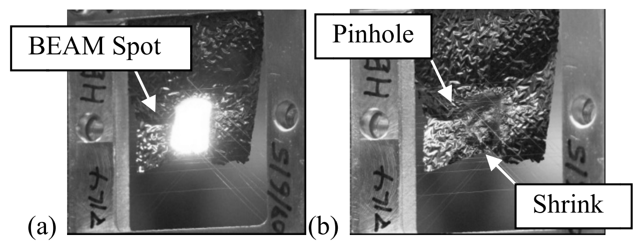

Figure 1: (a) Carbon foil being beam irradiated. b) Carbon foil deformed by beams with pinhole formation.

PURPOSE OF DEVELOPMENT

Foil used for charge exchange injection into synchrotron accelerators, beam monitoring, and nuclear experiments generally have high melting points, can endure high temperatures, and use carbon that causes little beam scattering. However, as carbon foil is significantly deformed, such as expansion and contraction due to heat and pinhole growth, it hinders the operation of accelerators and experimental designs (Figure 1(b)). Therefore, it is vital that we develop long-life carbon foil.

The most important task in the process of developing a long-life foil is to clarify the mechanism of the deformation of foil leading to damage. Regular observation of the change in the surface of the foil while it is being irradiated is a very effective method of clarifying this deformation mechanism. However, as image degradation due to radiation quickly occurs with commercial observation equipment, and observation equipment capable of observing the aforementioned minute damage does not exist, further research and development is not possible. Therefore, there is an urgent need for an observation device immediately that is highly durable and suffers from little image degradation in radiation environments.

Few pinholes are present in the foil before beam irradiation, and the number and size of pinholes increase with the level of beam irradiance. Pinholes in foil range in size from a few microns up to dozens of microns. In order to accurately measure the process of pinhole growth, it is necessary to install high resolution observation equipment with a resolution of 10μm or less.

OPTICAL DESIGN

For the last several years, we have surveyed observation methods that can be used in high radiation environments. Thus far, no satisfactory technology has been established; radiation degradation occurs within a short period of time with any currently available system and the need to replace parts arises frequently. Therefore, a novel observation method with little radiation degradation must be developed. Our objective was to develop a novel observation system that can withstand an accumulated dose of 1 MGy or more with a resolution of 200 μm at a distance of 10 m from the subject. We quickly reached the conclusions that 1) glass materials such as lenses, which suffer from great radiation damage and discoloration, and 2) semiconductors, such as CCD elements causing polarity inversion, should not be placed in radiation environments. To avoid this issue, we decided to design a method that would not place any material likely to develop radiation damage within radiation environments. Namely, we devised a system with only mirrors made of metal resilient to radiation placed in the optical path and keeping the lenses, CCD cameras, etc., items easily impacted by radiation, outside the protective walls.

This novel system forms images outside radiation environments by applying the principle of the telescope. With our first experimental model, we confirmed the resolution through optical path computations and found a resolution of 200 μm from 10 m away. In addition, we succeeded in adding the ability to see a number of different subjects (5 subjects) from one observation area by switching mirrors and adjusting the focus and zooming.

Based on this design, we solved the issues necessary to observe at high resolutions under high radiation. First, we compared the decreases in reflectance of the optical components and the radiation degradation of the surface of the materials and selected the most appropriate material. Second, we designed the components so that the profile irregularity of the mirrors and lenses of the observation area would reach the Rayleigh limit, making improvements in the surface polishing method. Using the solutions to the aforementioned issues, we assembled a system to observe with a high resolution a square subject of 80 mm × 80 mm from 10 m away. We confirmed that there was virtually no chromatic aberration and the system achieved a resolution higher than designed, 125μm [2].

This time, we aimed to build a system with a higher resolution. We performed the optical path computation more minutely and designed a high resolution system with a resolution of 10 μm or less, revising the materials and performance of the optical components. As the optical components used for the current devices had reached the Rayleigh limit, there was virtually no room for improvement. To maintain the original performance, correct chromatic aberration, and obtain the maximum resolution, the method of magnifying the image created at the focal point of the observation area with a magnifying lens was used. This method provided a novel observation area with magnifying lenses attached to the focal point at the lower reach. The resulting image at the focal point was magnified to the max and the limit resolution of 10μm or less was obtained.

Because of the accuracy necessary in obtaining the ultrahigh resolution, we designed the system while aiming for the limit of optical design (the Rayleigh limit), using the optical calculation software Zemax. We specified the following: 1) the specifications of the precision of optical components shall be the Rayleigh limit or less; 2) the optimal materials for glass and reflection coating films shall be used; this mechanism is adopted to minimize the load for optical components; 3) in order to eliminate the impact of external heat, etc., on the images, the optical path shall be maintained at normal temperatures, pressures, and air tight; 4) adopt an optical design and a polishing method using cutting-edge technology; 5) use SUS, titanium resilient to residual radiation; 6) use automation where possible; 7) and design a structure that can deal flexibly with design changes.

Currently, the observation device installed on J-PARC/RCS receives the light of the square subject of 80 mm × 80 mm (charge stripper carbon foil) inside a vacuum chamber (radiation area) approximately 8 m away with the observation device (CCD camera) downstairs (sub-tunnel) through an optical path duct of φ200 mm. The diameter of the image is φ22.5 mm and the magnification is 1/5. The resolution of the image has been confirmed to be 125μm as it can completely resolve a grating of 100 pieces per inch installed on surface of the subject. As the size of a pixel for CCD cameras is approximately 5μm, this will be the limit of one resolution. The diffraction limit of light (airy disk) must be accounted for as well.

This value is $\varphi/2 = 1.22\lambda F$ (F is the F value of the main mirror being used). Thus, $1.22 \times 0.0006 \times 8 = 6$ μm

That is to say that, it is inferred from both the studies that approximately 6 μm is the limit resolution of the observation device.

We designed aiming for the Rayleigh limit and the three designs listed below were completed.

1) Expander lens method.
2) Expander lens + collimate magnification method.
3) Orthoscopic lens + collimate magnification method.

Each design has its advantages and disadvantages; we decided to select the best proposal by actually observing the images resulting from each method.

We developed Powermate (x4), a telecentric system of magnifying lenses, and a 4-ply orthoscopic lens, observed the actual images, and weighed them against each other. The orthoscopic lens was evaluated to be excellent in image resolution and we decided to adopt the orthoscopic lens + collimate magnification method. With this method, it is possible to design non-step magnifying optical systems by changing the distance from the lens to the observation area.

Based on this design, we produced the actual device, adding focus adjustment and zooming mechanisms with a motor (Figure 2).

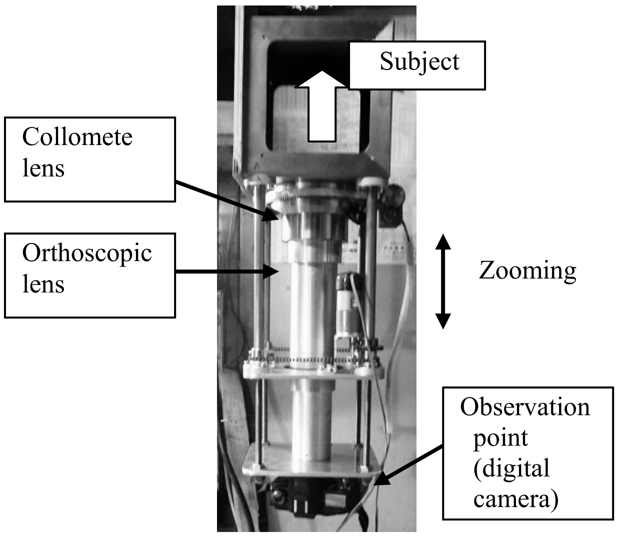

Figure 2: The ultra high resolution observation device we produced.

OPTICAL CHARACTERIZATION TEST

We sought to confirm resolution, chromatic aberration, and magnification in the optical performance test. Testing with an observation optical path similar to that of the RCS observation device was desirable for evaluation. Therefore, we produced a mock optical path for the optical system similar to that of the RCS observation device and conducted an optical performance test.

The specifications of the mock optical path were as follows:

- L-shaped optical path
  (a mirror is installed in the L area).
  Optical path length: approximately 8 m.
  Optical path diameter: φ150 mm.
  Settle by installing APO lenses.

We installed a digital camera (Nikon D5000 12.6 M pixels) in the observation area and made measurements by watching the images on the monitor.

Resolution Test:

We installed grating on the subject and confirmed the resolution by observing its image. Specifically, if the grating lines were successfully resolved then the resolution of the line spacing could be obtained. We prepared several kinds of grating ranging from 20 lines/mm to 60 lines/mm (resolution 8.33μm). We used fluorescent light for lighting and conducted the test at various light levels.

As a result, as shown in Figure 3, we confirmed that lines at 8.33μm intervals could completely be resolved.

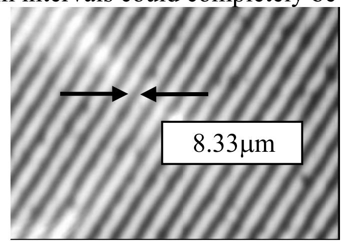

Figure 3: It can be confirmed that the lines of 8.33μm grating (60 lines/mm) have completely been resolved.

Chromatic Aberration Test:

Chromatic aberration is checked by observing the change in the white part of the image. If there is chromatic aberration, the original white part changes color.

As shown in Figure 3, the white part seen between the black lines had not changed color. There was no chromatic aberration at all as far as could be seen with eyes.

Magnification Test:

The grating line spacing was measured on the monitor and the magnification was identified by converting it into the CCD magnification.

We confirmed that the optical magnification was 5 times when the magnification of the zooming feature was the smallest and 7.9 times when the magnification of the zooming feature was the largest. There was also no problem magnifying the image from 11.6 times to 18.5 times on the monitor.

CONCLUSION

The observation device we produced was proved by the optical performance test to be very high performance optical equipment with a high resolution of 8.33μm and little chromatic aberration.

This resolution was sufficient to achieved the high resolution (10μm or less) needed to observe the process of pinholes forming in carbon foil.

It is expected that in the future the mechanism leading to damage in charge stripper carbon foil will be identified by carefully observing the deformation of charge stripper carbon foil and the process of pinholes growing due to beam irradiation with the use of the ultrahigh resolution observation device we produced.

REFERENCES

[1] I.Sugai et.al. “Development of Hybrid Type Carbon Stripper Foils with High Durability at >1800K for RCS of J-PARC” Proc. Particle Accelerator Conference PAC 2007

[2] Y.Takeda et.al. “Exchange and observation system for charge stripper foils at the J-PARC 3GeV-RCS” Nucl. Instr. and Meth.A590 p.213-220