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Highly bright X-ray generator using heat of fusion with a specially designed rotating anticathode

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A new type of rotating anticathode X-ray generator has been developed, in which the electron beam irradiates the inner surface of a U-shaped anticathode (Cu). A high-flux electron beam is focused on the inner surface by optimizing the shape of the bending magnet. The power of the electron beam can be increased to the point at which the irradiated part of the inner surface is melted, because a strong centrifugal force fixes the melted part on the inner surface. When the irradiated part is melted, a large amount of energy is stored as the heat of fusion, resulting in emission of X-rays 4.3 times more brilliant than can be attained by a conventional rotating anticathode. Oscillating translation of the irradiated position on the inner surface during use is expected to be very advantageous for extending the target life. A carbon film coating on the inner surface is considered to suppress evaporation of the target metal and will be an important technique in further realization of highly bright X-ray generation.

Keywords: bright X-ray generators; U-shape anticathodes; heat of fusion; target life extension; low emittance; DC/pulse guns; focusing bending magnets.

1. Introduction

Since synchrotron radiation is very strong, very bright and ideally white radiation, it contributes to improvements in science and technology in many fields. Synchrotron radiation X-rays, however, cannot be used at an ordinary laboratory. A conventional X-ray generator is useful to set up in the home laboratory, but the intensity and/or brightness of the X-rays are sometimes not enough. In order to find the causes of the above limitation, we have analyzed the power limitations of a commercially available rotating-anticathode X-ray generator and studied the technology to break through these limitations by utilizing the heat of fusion of the target.

2. Design of a new X-ray generator

2.1. Causes of the power limitation of a conventional rotating-anticathode-type X-ray generator

In the conventional rotating-anticathode X-ray generator, an electron beam irradiates the outer surface of a rotating target. The power of the electron beam is severely limited for the following reasons: (i) the target should not be melted, otherwise melted material will be splashed and the target will be severely damaged; (ii) the surface roughness of the target caused by thermal stress should be kept small, otherwise the intensity of the X-rays, taken out at an angle that is normally 6°, will be weakened by absorption; and (iii) irregular electric discharge caused by the vapor of the target metal and the ion should be suppressed.

2.2. Advantages of the new X-ray generator

To overcome such limitations, we have developed a U-shaped rotating-anticathode (Sakabe, 1995) X-ray generator in which the target is irradiated by the electron beam such that the centrifugal force is in the same direction as the electron beam, as illustrated in Fig. 1. In this case, (i) the power of the electron beam can be increased to melt the irradiated part of the target, because the melted metal is strongly fixed to the target by the strong centrifugal force, which is at least ~2000 times stronger than the gravity on the earth when it is calculated by the parameters listed in Table 1; (ii) when the target surface is melted by the strong electron beam, the surface roughness caused by the thermal stress is reset and the surface is kept very smooth by the strong centrifugal force; (iii) the chances of an irregular electric discharge are extensively reduced, because a high electric field only exists between the cathode and the anode, whose temperature is not high, and the electron beam is bent 180° by the bending magnet (Ohsawa, 2004), while the metal atoms and/or ions from the target do not have a detrimental effect on the cathode because of the presence of the bending magnet. Therefore the particles do not get into the high electric field region.

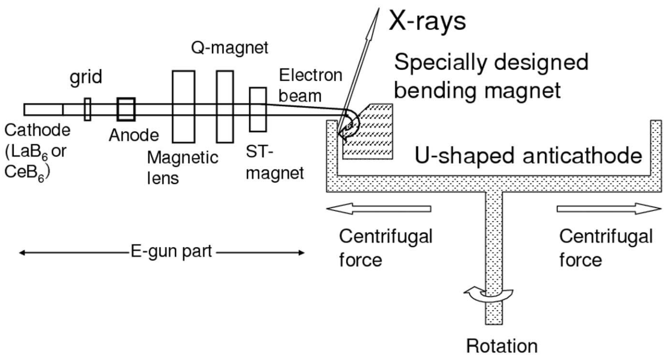

Figure 1
Design of the new X-ray generator, in which the direction of the electron beam used to irradiate the target is the same direction as the centrifugal force.

Table 1
Comparison of the parameters of a conventional X-ray generator and the new X-ray generator.

δ_1 is the electron beam focus size on the target, perpendicular to δ_2. δ_2 is the electron beam focus size on the target parallel to the rotation axis of the target.

Parameters	Conventional generator	New X-ray generator
Maximum power	60 kV, 100 mA	60 kV, 100 mA
Target metal	Cu	Cu
N, rotation speed	100 s^{-1}	100–150 s^{-1}
r, radius of target	50 mm	50 mm
δ_1	0.1 mm	< 0.1 mm
δ_2	1.0 mm	< 1.0 mm
d, thickness of target	2 mm	2 mm
Translation width	0 mm	3 mm
Electron gun	Only Wehnelt	Newly designed
Cathode	W filament	LaB_6/CeB_6
Aperture grid	–	DC +3 kV
Emittance	Not estimated	$\sim 3\pi$ mm mrad
Evacuation system	1 set	2 set

3. Experimental

3.1. Development of the new type of X-ray generator utilizing heat of fusion

The new type of X-ray generator shown in Figs. 1 and 2 is obtained by modifying a conventional rotating-anticathode X-ray generator whose maximum power is 60 kV $\times$ 100 mA. These parameters are listed in Table 1. The newly designed parts are an electron gun and a U-shaped rotating anticathode. Since the experimental details of the gun have been published by Sugimura *et al.* (2007*a*,*b*), the U-shaped rotating anticathode will be mainly described in the present paper. The X-ray takeout angle was 6°. Fig. 3 shows the modified main part of the X-ray generator for this experiment. The bending magnet (BM) was set outside of the cover of the vacuum chamber, as shown in Figs. 2–4. Thus a large area of the center of the cover is occupied by the bending magnet. The cover also has a window for a thermometer to observe the temperature, a Be window with a shutter and an Au pinhole for observing the X-rays, a movable beam catcher and two turns of a cooling pipe at the outer edge of the cover. The nearest gap between the target and the cover is only 1 mm, to achieve the small focus size of the electron beam on the target surface by the bending magnet. An electron beam travelling from the electron gun through a pipe, as shown in Fig. 5, is bent and focused by the bending magnet (see Fig. 4) and irradiates the U-shaped anticathode (Fig. 5).

3.2. Method of focus size measurement

The electron beam focus size on the U-shaped rotating anticathode was measured using a 10 µm-diameter Au pinhole and a chilled CCD camera with fluorescent film, as shown in Fig. 2.

The focus size of the electron beam is estimated by the X-ray image using the 10 µm Au pinhole, which is set at a distance of 75 mm from the irradiation point, as shown in Fig. 2. A fluorescent film was placed 750 mm from the pinhole and the image was observed by the CCD camera. The relation between the image on the fluorescent film and the stored image in the camera memory was obtained by mechanical movement perpendicular to the X-ray beam by a stage on which the fluorescent film and CCD camera were set.

3.3. Measurement of the temperature on the target surface near the irradiation point

The temperature near the irradiation area was observed by a two-color-type thermometer (Thermera–seen D414). The light for the measurement was taken out through a hole whose visible area on the target is 4.6 $\times$ 6.5 mm. The former length is limited by the gap of the bending magnet. The center of the visible area is the irradiation point

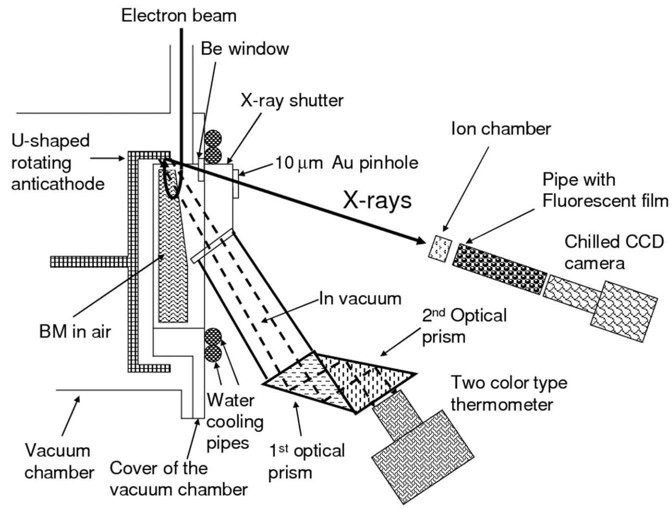

Figure 2
Schematic drawing of the measurement environment used to observe the X-ray beam size with a pinhole technique and the temperature around the irradiation point.

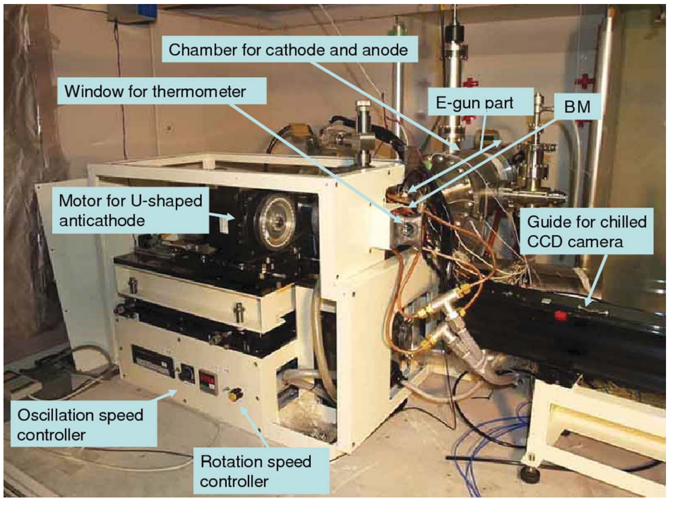

Figure 3
Modified main parts of the new X-ray generator.

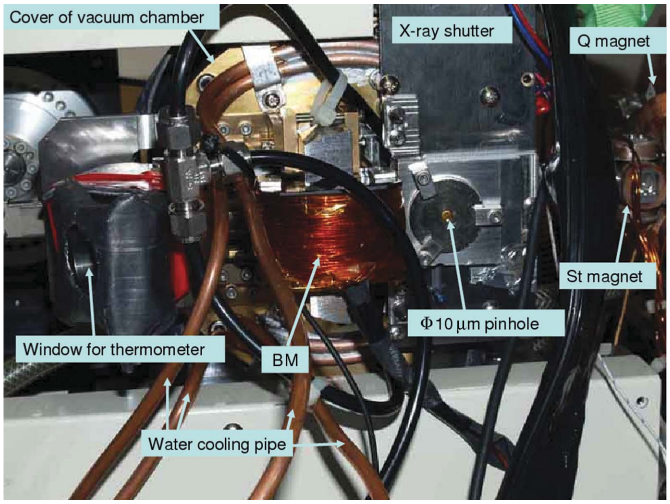

Figure 4
Cover of the vacuum chamber for the U-shaped rotating anticathode.

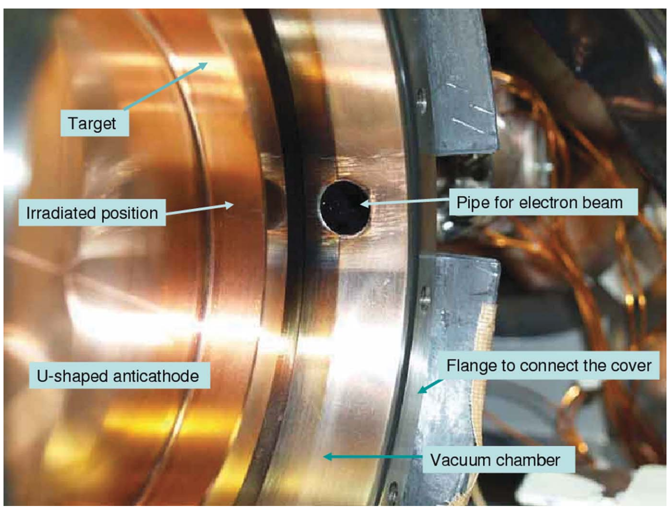

Figure 5
U-shaped anticathode.

and the takeout angle of the light is 65° from the rotation surface. Two optical prisms are set to seal the vacuum and to protect the thermometer from strong X-rays, as shown in Fig. 2. Color centers were formed on the vacuum side of prism 1 by the strong X-ray irradiation. The prism surface was slightly colored yellow as a result. Therefore, temperature calibration was made for the Thermera-seen D414 combined with the colored prism 1 against a reliable pyrometer (model IR-U, CHINO) in the range 1200–1900 K

4. Results and discussion

4.1. Observation of the irradiated area by an optical microscope

On the surface of the irradiated area of the target, many tiny grains of less than 80 μm are observed, as shown in Fig. 6. Such a texture must be caused by a very rapid repeated change between the melted and solidified states. It has not yet been confirmed experimentally whether this rugged surface preferentially absorbs emitted X-rays in the direction nearly along the surface. However, these grains will be melted to form a smooth liquid surface with a sufficiently high density beam, and the output X-ray will not be obstructed.

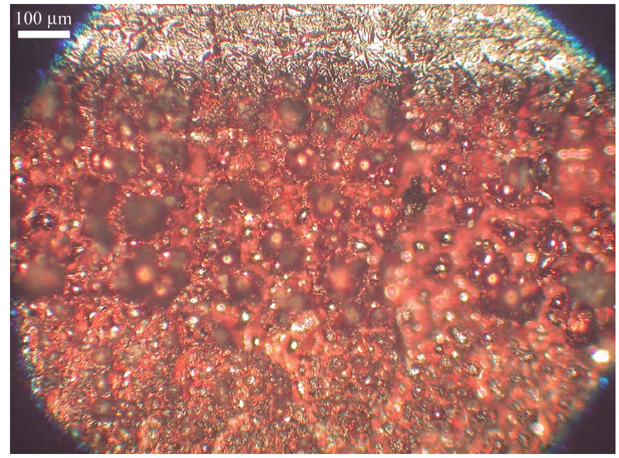

Figure 6
Irradiated area of the target observed by optical microscopy.

4.2. Focus size and brilliance

The full width at half-maximum focus size of the electron beam on the target was determined as $\delta_1 = 0.08$ mm and $\delta_2 = 0.65$ mm when a load of 60 kV × 45 mA was supplied. Thus the brilliance was 52 kW mm^{-2}, which is about 4.3 times brighter than that of a conventional rotating-anode X-ray generator.

4.3. Target temperature and melted area on the target

The temperature on the target surface was observed near the irradiation point where the brilliance of the X-rays was 52 kW mm^{-2}. However, stronger transition white light than the light for the temperature measurement was observed. Thus the temperature of the irradiated area could not be observed by the perturbation of the transition light.

Since the 50 mm-radius rotor was rotated at 100 cycles s^{-1}, which corresponds to 10 ms per turn, the velocity of the target surface is 31416 mm s^{-1}. An inner surface point of the anticathode can be observed through optical prisms (Fig. 2) only for 0.146 ms per rotation, which is the time for a point to pass through the visible region of 4.6 mm. Fig. 7 shows the relation between the temperature of the target and the corresponding time since the point at which the

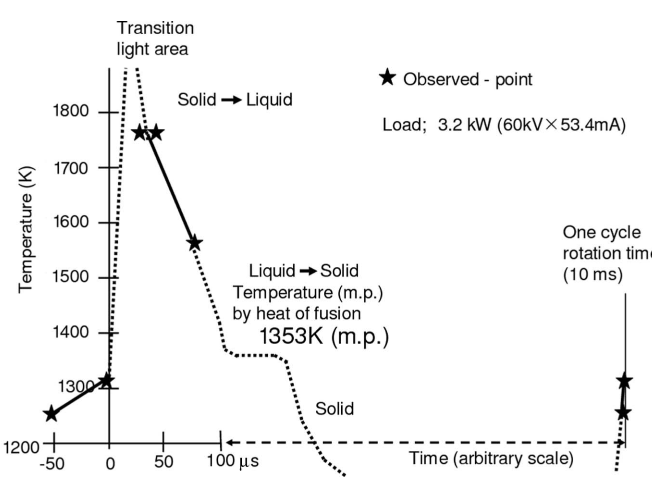

Figure 7
Relation between the time from the irradiation point and the corrected temperature of the corresponding point.

temperature was suddenly increased (assumed to be an irradiation point), where the time is calculated according to the distance from the irradiation point. The star marks are the observed points and these are connected by solid lines, whereas the dotted line is an estimation. According to Fig. 7, the time at which a point on the target passes through an electron beam of 0.08 mm is 2.5 ns. In such a short time of irradiation, the temperature is suddenly increased to the point where it exceeds the melting point of the target and the metal melts. The temperature may quickly fall to the melting point by the effect of 'heat of fusion'. The temperature of the melting point may be maintained until almost all of the liquid metal changes to the solid state. After solidification, the temperature falls by the effect of thermal conductivity, as shown in Fig. 7. One of the most important points is that the time at the temperature higher than the melting point is very short. Thus, the deterioration of the target is suppressed by the heat of fusion. No Cu atoms were detected on the vacuum side of the surface of prism 1 (Fig. 2) by X-ray fluorescence after a high electric loading for 20 h.

The maximum load, when the percentage of the liquid phase is 100%, is calculated from the thermal conductivity, where the liquid area S is supposed to be $S = 2\pi r\delta_2$ (see Table 1). Thus, the maximum load of the U-shaped rotating anticathode is expected to be 40 kW and the brilliance is expected to be 816 kW mm^{-2}, when the focus size is supposed to be 0.07×0.7 mm. In such a high load condition, the evaporation speed of the target metal is calculated to be larger than 4.0×10^{-8} g mm^{-2} s^{-1}.

4.4. Coating method to suppress the evaporation speed of the target metal

The speed of target deterioration as a result of the evaporation of the target metal can be extensively reduced by coating the target with a film. The film must have the following characteristics.

(i) The vapor pressure of the film must be lower than that of the target metal.

(ii) The density of the film must be smaller than that of the target metal.

(iii) The film must not be made of a material that reacts with or dissolves in the target metal.

(iv) The absorption of the electron beam must be small.

(v) The vapor of the target metal should not penetrate the coating film.

(vi) It would be preferable if the film had some electrical conductivity to prevent charging up.

One of the best materials for the Cu target is a carbon film in the graphite phase, whose vapor pressure is 1.33×10^{-9} Pa at 1700 K. This pressure is obviously much lower than the vapor pressure of Cu, about 16 Pa, at the same temperature. Thus, evaporation of Cu should be effectively suppressed by the coating carbon film, even at a temperature more than 344 K higher than its melting point, if the carbon film does not penetrate Cu atoms. Carbon films possess all the other characteristics mentioned above. The technical problem is how the film can be fixed onto the melting target. The answer is the centrifugal force. The centrifugal force R of the present target is 19738 m s^2, 2014 times larger than that on the Earth's surface.

The pressure (P_f) produced by an h = 1 μm-thickness film against the target surface is calculated using the density of carbon ($\rho_c = 2.25 \times 10^3$ kg m^{-3}). Thus

$$P_f = R\rho_c\, h\, \text{Pa} = 19738 \times 2.25 \times 10^3 \times 10^{-6} = 44.4\, \text{Pa}.$$

When P_f is larger than the vapor pressure of the Cu target, the film can be fixed onto the target. The temperature of the irradiation point of the target is higher than the melting point, namely vapor pressure must be higher than that at the melting point. Assuming that the vapor pressure of Cu is 16 Pa at the temperature (1700 K) of the irradiation point, 344 K higher than the melting point of Cu, a ~1 μm-thick film can exert a pressure about three times stronger than the vapor pressure of Cu.

5. Conclusion

A U-shaped rotating anticathode has been developed. We have also developed a high-brilliance electron gun with a new type of bending magnet, which can focus the electron beam to a very small area on the target, yielding 4.3 times brighter X-ray beams than can be obtained from a conventional generator as already observed by these preliminary experiments. Irregular discharge between the cathode and the U-shaped rotating anticathode was not observed. The irradiation area melted with no adverse effects.

Coating the U-shaped target will prolong the target life extensively, and translational oscillation of the target will also prolong the life. We are aiming to obtain an X-ray source that is 50 times brighter than a conventional X-ray generator by these methods; details will be published elsewhere.

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