DEVELOPMENT OF THE FOCUSING SYSTEM FOR A HIGHLY BRIGHT X-RAY GENERATOR

T. Sakai#, S. Ohsawa, T. Sugimura, M. Ikeda, KEK, 1-1 Oho, Tsukuba, Ibaraki, Japan
N. Sakabe, KEK-PF/FAIS, 1-1 Oho,Tsukuba, Ibaraki, Japan/586-9Akatsuka,Tsukuba, Ibaraki, Japan

Abstract

A new type of the rotating anticathode X-ray generator has achieved the beam brilliance of 130 kW/mm^2 (at 2.3 kW), in which the electron beam up to 60 keV irradiates the inner surface of a U-shaped Cu anticathode. Higher-flux electron beam is expected from simulation by optimizing the geometry of the combined function instead of flinging field of the bending magnet. In order to minimize the sizes of the X-ray source, the electron beam has been focused in a short distance by the new combined function bending magnet, of which geometrical shape was determined by simulation with the codes of Opera-3D, General Particle Tracer (GPT) and CST-STUDIO. The result of simulation clearly shows that the role of combined functions in both of the bending and the steering magnets is important to focus the beam in small sizes. FWHM sizes of the beam are predicted by simulation to be 0.45 mm (horizontal) and 0.05 mm (vertical) for a beam of 120 keV and 75 mA, of which effective brilliance is about 500 kW/mm^2 with the supposition of a two-dimensional Gaussian distribution. High power test has just been started by using the high-voltage power supply of 120 kV & 75 mA instead of 60 kV & 100 mA for the X-ray generator. The beam focus sizes on the target will be verified in the experiments.

INTRODUCTION

Beam power and the beam size are important for the high brightness X-ray generation. However, the conventional rotating anticathode X-ray generators have some severe limits in operation such as the beam power density not to exceed the melting point of the irradiated target as well as the electric discharge and the surface damage of the target caused by thermal stress. These factors are the obstacles for increasing the X-ray intensity, then the U-shaped rotating-anticathode has been developed for the X-ray generator to overcome such limitations [1],[2]. As for the electron gun for this generator, the thermionic electron gun was introduced with an aperture grid electrode instead of the conventional mesh grid. In addition, the beam focusing system was adopted with a magnetic lens, a quadrupole and a 180°-bending magnets [3],[4],[5]. The beam brilliance which has been achieved to date in experiment was 130 kW/mm^2 (at 2.3 kW) by the new X-ray generator with the U-shaped rotating-anticathode [4].

The system improvement is still under way. We raised the new target value of the beam brilliance up to 300 kW/mm^2. The increase of the beam brightness is expected from the beam simulation if we improve the system of the focusing and bending magnets [6].

#takeshi.sakai@kek.jp

NEW X-RAY GENERATOR

Fig.1 shows a schematic view of the X-ray generator with the U-shaped rotating-anticathode. The X-ray generator is comprised of three sections, which are the electron gun, the beam focus system and the 180°-bending magnet. The electron beam irradiates the inner surface of a U-shaped rotating-anticathode. The electron gun and the bending magnet are housed within the vacuum chamber. The X-ray take-off angle is at 6° with the surface of the anticathode so as to compress the elliptic shaped electron focus spot in the rotating-axis direction, and to make it a circle as being seen as an X-ray source.

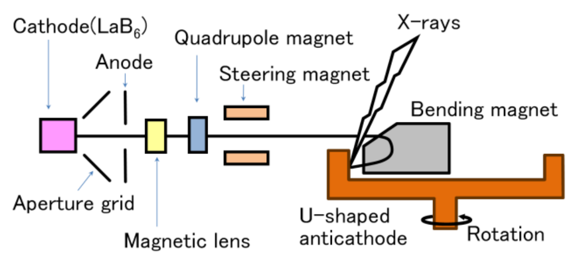

Figure 1: Schematic view of the new X-ray generator with the U-shaped rotating-anticathode. The X-ray generator is comprised of three sections, including the electron gun, the beam focus system and the 180°-bending magnet.

The electrodes geometry of the electron gun was optimized, being based on the EGUN [7] simulation results [5]. Instead of a conventional mesh grid electrode, the aperture grid electrode was adopted in consideration of emittance and grid heating. The material of the cathode is LaB_6, and the dimension of the cathode is ϕ2 mm. An operating grid voltage of the electron gun has been optimized to be 3 kV against the cathode.

The beam focusing section is composed of a magnetic lens, a quadruple magnet, and a steering magnet. The magnetic lens and Q-magnet are introduced for getting smaller the beam sizes on the target in both directions horizontally and vertically. In addition, the steering magnet is used to optimize the horizontal incidence angle into the bending magnet as being shown in Fig. 2a, in which the horizontal direction is shown vertically.

The electron beam is focused strongly in a short distance by the bending magnet as well as being bended. This was due to the effect of a fringing field at the incidence plane of the 180°-bending magnet (See Fig. 1).

Table 1 summarizes the specifications for the new X-ray generator. The specification of the maximum power is 120 kV & 75 mA. However, since high-power test has just started, the tested power ranges are covered up to 60 kV & 100 mA and 120 kV & 10 mA.

Table 1: Specifications of the new X-ray generator

Component	Specifications
Maximum power	120 kV, 75 mA
Rotation frequency	100 s^{-1}
Cathode material	LaB_6
Cathode diameter	ϕ2 mm
Cathode grid type	Aperture grid
Cathode grid voltage	3 kV

SIMULATION AND VERIFICATION BY EXPERIMENT WITH BEAM

Beam Simulation for Flinging Field Focusing

Bending magnet field was firstly calculated by use of the code Opera-3D (Vector Fields) [8]. Then the beam trajectories were simulated from the electron gun to the anticathode target with the code GPT (Pulsar Physics) [9] by using the magnetic field data previously obtained with the code Opera-3D. Fig. 2 shows a typical simulation result. The beam trajectories (Figs. 2a & 2b) and the beam spot shape on the target (Fig. 2c) were calculated with the space charge effect for the beam of 60 kV and 38 mA. The simulation result is consistent with the experiment performed under the same beam condition (Fig. 3).

In this case as noted above, the flinging magnetic field was used at the cut corner for focusing of the beam in the 180°-bending magnet, of which pole pieces were parallel each other. Therefore, as being seen in Fig. 2b, the beam does not receive focusing forces inside the bending magnet. Furthermore, the beam spot on the target has the part out of focus as shown in Fig. 2c. It is obvious that the aberration of the magnet is not negligible to obtain finer focusing.

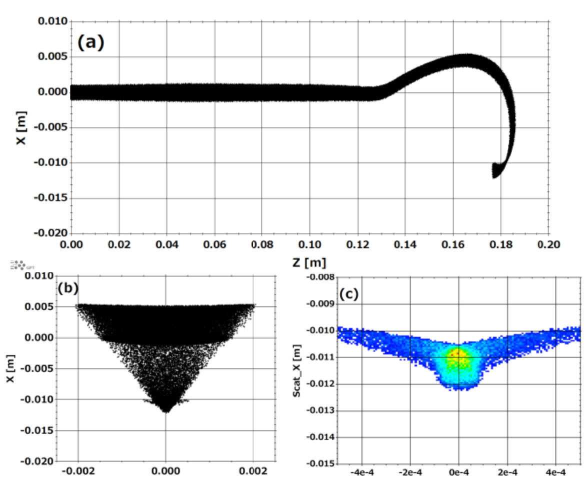

Figure 2: The beam trajectories were simulated from the electron gun to the anticathode target with the code GPT for the beam of 60 keV & 38 mA. (a) Beam trajectory of the side view. (b) Beam trajectory of the front view. (c) Beam profile on the target.

For these reasons, the bending magnet has been improved to the combined function type, of which magnetic pole faces have a slope so that the beam always receives the focusing force from the magnetic field as well as the bending force. In addition, it has turned out to be effective for fine focusing to optimize the pole shape of the steering magnet which is in front of the bending magnet. On the other hand, we have other possibilities for improvement: The simulation predicts the more suitable distances of each magnet. We have not yet adjusted the distance.

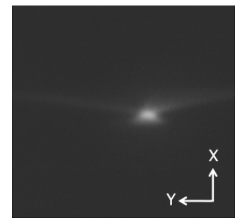

Figure 3: Experimental example of a beam profiles on the anticathode target.

(Beam of 60keV and 38mA)

Beam Simulation for Combined Function Focusing

For the new magnet system, the beam trajectory were simulated with the code Opera-3D and the GPT. Fig. 4 shows the simulation results for the beam of 120 keV and 75 mA. It can be seen from the simulation results in Fig. 4b that the beam is receiving the focusing force until just before the anticathode target. FWHM sizes of the beam are predicted in Fig. 4c to be 0.45 mm (x: horizontal) and 0.05 mm (y: vertical) of which effective brilliance is about 500 kW/mm^2 with the supposition of a two-dimensional Gaussian distribution.

After modifying the bending magnet to the combined type, we have made beam tests in the region from 60 kV to 120 kV, but the current was limited up to 10 mA. As is seen in the beam profile for the beam of 120 keV, 10 mA and grid voltage of 1.6 kV shown in Fig. 5, the beam

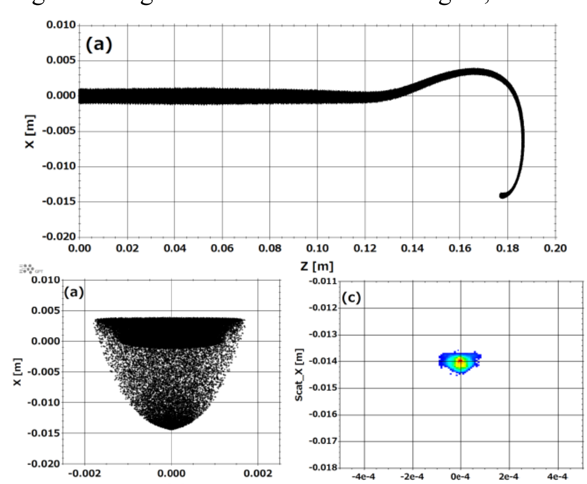

Figure 4: Simulation results of the new magnet system, for the beam of 120 keV & 75 mA. (a) Beam trajectory of the side view. (b) Front view. (c) Beam profile on the target. FWHM sizes of the beam are predicted to be 0.45 mm (x: horizontal) and 0.05 mm (y: vertical).

aberration became obviously smaller than before observed at 60 kV. In the experiment, we can see in Fig. 5 that the bending-magnet has the expected function for the horizontal beam focusing. However, the vertical size is large. We optimized the system at 120 keV & 75 mA. Therefore, it is necessary to make a test in the high power region to confirm the performance. We have recently obtained a 120 kV power supply, and just started beam tests at the higher beam current region.

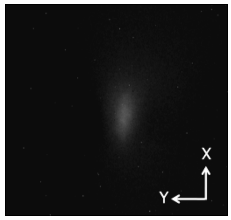

Figure 5: A typical example of experimental beam profiles on the anticathode target. (Beam of 120 keV and 10 mA.)

Remaining Issues and Challenges for the Future

The simulations and experiments revealed some issues about the focusing and bending magnets. The positions and the geometric field shapes have not yet been optimized for all of the magnets. In particular, the present steering magnet has a complicated shape due to the limited installation space, as is seen in Figs. 6 and 7. The distance from the Q-magnet to the bending magnet is relatively long. Therefore, if the flinging field is not negligibly small on the beam line, the electron beam will be easily influenced by the field.

More realistic simulation is required for detail studies.

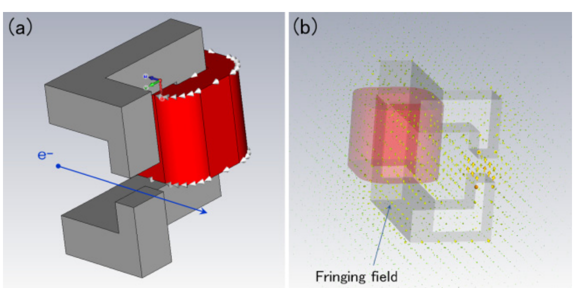

Figure 6: (a) Schematic view of steering magnet. The present steering magnet has a complicated shape due to the limited installation space. (b) Calculated example by CST-STUDIO shows it clear that the fringing field is not negligibly small.

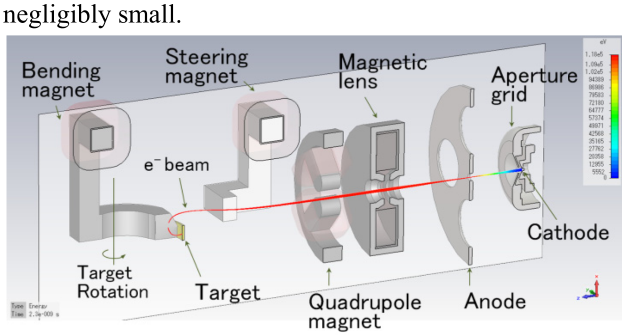

Figure 7: It shows vertical cross sections of the computation model in CST-STUDIO. The entire realistic beam trajectory is shown by red colour from the gun to the target for the beam of 120 keV, 75 mA and grid voltage of 3 kV.

The code CST-STUDIO (CST) [10] makes it easy to simulate the more realistic beam trajectory including these causes. Fig. 7 shows the computation model in CST-STUDIO. The new simulation made it clear that the fringing field of the steering magnet was not negligibly small, and it should be decreased by putting the magnetic shielding or changing its shape to simple (for instance, C-type). It is expected that the new code will be more useful for improving the beam focusing by simulating the entire beam trajectories from the gun to the target. Optimization will be necessary in detail.

SUMMARY

The results of the simulations and the experiments clearly show that the beam brightness is expected to increase with the decrease of aberration owing to the improvement of the pole faces of the bending and the steering magnets. Simulation shows that the beam brightness will reach about 500 kW/mm^2 at the condition of the beam 120 keV and 75 mA. However, optimization in real system is still insufficient, and further realistic simulations will be necessary for improving further the beam focusing by simulating the entire beam trajectories. It is expected that the beam brightness increases further by optimizing the entire beam line.

ACKNOWLEDGMENT

The author would like to thank Dr. M. Tawada, Dr. M. Yoshida and Mr. A. Kataoka for their many helpful suggestions and support. We would like to thank Rigaku Corp. for providing the high power supply of 120 kV.

REFERENCES

[1] N. Sakabe, (1995). US Patent No. 6 229 871 B1.
[2] N. Sakabe et al., "Highly bright X-ray generator using heat of fusion with a specially designed rotating anticathode", J. Synchrotron Rad. (2008), 15, pp.231-234
[3] S. Ohsawa, (2004), JP Application No. 2004-241301; US Patent Application No. 11/204967; EP Application No. 05018063.7
[4] S. Ohsawa et al., "Development of a New Highly Bright X-ray Generator", Proceedings of LINAC08, Victoria, BC, Canada, (2008), pp.539-541
[5] T. Sugimura, et al., "Performance of an electron gun for a high-brightness X-ray generator", J. Synchrotron Rad. (2008), 15, pp.258-261
[6] T. Sakai et al., "Optimization of the Bending Magnet for a Highly Bright X-ray Generator", (2009) Proceedings of Particle Accelerator Society Meeting 2009, JAEA, Tokai, Naka-gun, Ibaraki, Japan, pp.900-902. (In Japanese)
[7] Herrmansfeldt, W. B. (1988). SLAC Report 331. SLAC, CA, USA.
[8] http://www.vectorfields.com/
[9] http://www.pulsar.nl/
[10] http://www.cst.com/