Improvement of the Tohoku Microbeam System

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Introduction

The microbeam system installed at Tohoku University for biological application has been operated for more than ten years[1)] and has been applied to simultaneous in-air/in-vacuum PIXE, RBS, SE, and STIM analyses[2-4)], and 3D PIXE-μ-CT[5-7)]. The Tohoku microbeam system comprises a quadrupole doublet and three slit systems. A beam spot of 0.4 × 0.4 μm^2 at a beam current of several tens of pA has been produced[8)]. In our set-up, μ-PIXE/RBS analyses demand beam currents of ca. 100 pA, which restricts the spatial resolution to around 1 × 1 μm^2. Recently, higher spatial resolution down to several hundred nm is required in e.g., aerosol studies. In *in-vivo* 3D imaging using 3D PIXE-μ-CT, the long measurement time of several hours weakened the specimen. Thus beam currents higher than ca. 1 nA with a several μm resolution are required in 3D PIXE-μ-CT applications.

To meet these requirements, update to a triplet lens system which has larger demagnification by adding a quadrupole lens was planned and designed. The triplet system can arrange both standard and separated triplet configuration. In the separate geometry, demagnification factors are more than 220 and 70 for horizontal and vertical planes, respectively, which are seven times higher than those of the previous doublet system.

Microbeam System

The Tohoku microbeam system was designed to achieve sub-micrometer beam sizes and was developed in collaboration with Tokin Machinery Corp.[1)]. Main components of the Tohoku microbeam system are mounted on the rigid support. Since the microbeam system was designed considering extensibility, introducing of triplet lens system could be done with minimum modification. The lens is almost the same deign as the previously used lenses except for the cancellation of excitation current[4,8]. While contamination fields of the previous lenses were less than 0.05%, the new lenses were designed to cancel the excitation current even in the upper part to reduce the contamination field as low as possible. The new lenses are mounted on the fine linear stage as shown in Fig. 1. The total length of the fine linear stage is ca. 1 m. Spacing between lenses can be adjusted between 700 mm to 50 mm. Once lens is aligned at one position, the lens can move without another alignment.

Beam properties were calculated using the raytracing software package "WinTRAX"[9]. In the triplet arrangement, the 1st quadrupole lens (Q1) and the 3rd lens (Q3) focus the beam on the same plane and the 2nd lens (Q2) focuses on the perpendicular plane (divergence-convergence-divergence; DCD or convergence- divergence-divergence; CDC). The demagnification factors are 25.4 and 65.7 for horizontal and vertical planes, respectively, with the 1st and 3rd lenses coupled in excitation. Calculated beam spot size is $0.7 \times 0.5\ \mu m^2$. Chromatic aberration coefficients are 846 and 422 μm/mrad/%ΔP/P. Spherical aberration coefficients of $\langle x|\theta^3\rangle$, $\langle x|\theta^2\phi\rangle$, $\langle y|\phi^3\rangle$ and $\langle x|\theta\phi^2\rangle$ calculated using the rectangular model are 362 126, 325 and 155 μm/ $mrad^3$, respectively. Due to larger spherical and chromatic coefficients than those of the doublet system, beam size will be $4 \times 1.9\ \mu m^2$ at beam divergence of ± 0.2mrad. Beam broadening calculated from chromatic aberration coefficients is estimated to be 0.8 and 0.4 μm with a beam divergence of 0.2 mrad and it is reported that intensity of the beam which has larger divergence and large energy spread was very low[9]. It is apparent that beam spot size is mainly restricted by the effect of spherical aberration. Since the actual spherical aberration cross terms is smaller than those by rectangular model[9], measured beam spot size will be smaller than that by the calculation. Actually, in our previous doublet system, a beam spot size of $0.4 \times 0.4\ \mu m^2$ was obtained at an object size of $30 \times 10\ \mu m^2$, beam divergence of ±0.2mrad and $\Delta E/E=10^{-4}$. Calculated beam spot size using the rectangular model is $0.5 \times 0.7\ \mu m^2$ and is large than the measured one. Therefore, better result will be obtained.

In the separated triplet configuration, the demagnification factors are further improved to 74.4 and 228 for horizontal and vertical planes, respectively. Chromatic aberration coefficients are 1381 and 856 μm/mrad/%ΔP/P. The spherical aberration coefficients of $\langle x|\theta^3\rangle$, $\langle x|\theta^2\phi\rangle$, $\langle y|\phi^3\rangle$ and $\langle x|\theta\phi^2\rangle$ are 2772, 945, 2946 and 2148 μm/ $mrad^3$, respectively. These values are ten times larger than those of standard triplet system. Calculated beam spot size was $4.2 \times 2.5\ \mu m^2$ at an object size of $120 \times 30\ \mu m^2$, beam divergence of ±0.1 mrad and $\Delta E/E=10^{-4}$, due to larger spherical aberration. To get better resolution, beam divergence into the quadrupole should be reduced. By reducing the divergence to ±0.05 mrad, beam spot size could be reduced down to 0.7 × 0.5 μm^2.

Preliminary Result of the Microbeam System

The beam spot size was measured by beam scanning across mesh samples, and measuring X-rays. Figure 2 (a) shows elemental maps of Ni mesh (2000lines / inch) using standard triplet configuration. This image was obtained with an object size of 15 × 30 μm^2 and divergence of ±0.2 mrad. Estimated beam size was ca. 4 × 2 μm^2 and was consistent with calculated one. The images was getting better by reducing with the beam divergence of ±0.1 mrad as shown in Fig. 2 (b). Estimated beam size was ca. 2 x 1 μm^2, which is worse than calculated one and than that obtained by the doublet system. While effect of spherical aberration is the largest component of beam broadening by the calculation, effect on chromatic aberration is also affects beam size. Both aberration of the triplet system are larger than those of the doublet system. We are now readjusting the whole system including the energy stability of the Dynamitron accelerator. After adjustment of the standard triplet configuration, separated configuration will be tested.

Conclusion

The microbeam analysis system installed at Tohoku University has applied to simultaneous in-air/in-vacuum PIXE, RBS, SE, and STIM analyses, and 3D PIXE-μ-CT for ten years. Update to a triplet lens system which has larger demagnification by adding a quadrupole lens was carried out to get higher spatial resolution down to several hundred nm and higher beam current with a several μm resolution. The system can arrange both standard and separate triplet configurations. The new triplet system did not achieve design goal. We are now readjusting the whole system including the energy stability of the Dynamitron accelerator.

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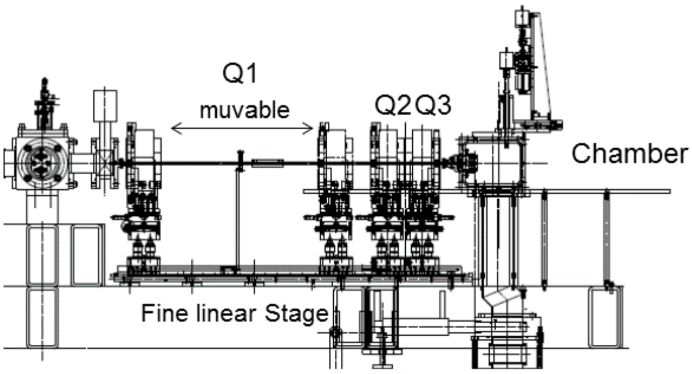

Figure 1. Layout of the triplet lens system.

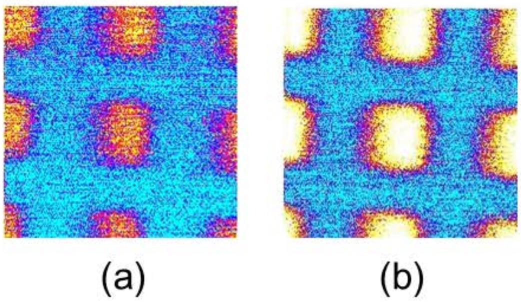

Figure 2. Elemental map of fine mesh grid (2000 lines/inch). (a) Ni mesh using standard triplet system for beam divergence of 0.2 mrad, and (b) Ni mesh using triplet system for beam divergence of 0.1 mrad.