Formation of uniform heavy-ion beam for industrial utilization

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RIKEN provides 70 MeV/A Kr and 95 MeV/A Ar beams from RIKEN Ring Cyclotron (RRC) to private companies under fee-based utilization. The customers irradiate their samples in atmosphere with a beam of uniform flux distribution and specified LET. In order to address their requirements, we installed a dedicated irradiation setup at the E5A beam line with a pair of wobbler magnets, scatterer foil, and variable energy degrader.[1)] The principle is the same as that for biological irradiation at RRC.[2)] Here, we report the formation and characterization of the uniform beam-intensity distribution.

The ion beam experiences multiple scattering at the scatterer foil and its angular distribution has a Gaussian form. Accordingly, the lateral beam-intensity distribution at downstream has a Gaussian form $\exp(-d^2/\sigma^2)$, where d is the distance from the spot center, and the spot width σ is proportional to the distance from the foil. In addition, the wobbler magnets deflect the beam so that the beam center traces a circle, whose radius is denoted as R. Combining these effects, we can obtain a uniform dose distribution for the irradiation. According to the customers' requests, we aim at a uniform beam flux within 50-mm diameter at the irradiation position, approximately 4 m downstream from the scatterer. The dose at a distance r from the center of the circle is proportional to:

$$F(r) = \exp\left[-(r^2+R^2)/\sigma^2\right] \sum_{n=0}^{\infty} \frac{1}{(n!)^2} \left(\frac{Rr}{\sigma^2}\right)^{2n}. \quad (1)$$

The shape of $F(r)$ is determined by a parameter R/σ, and the intensity distribution is nearly uniform within radius R when $R/\sigma \gtrsim 1$.

We evaluated the effects of the scatterer and the wobbler magnets by measuring the lateral beam-flux distribution at the irradiation position. As the scatterer, we used a gold foil with a thickness of 73 μm for the Ar beam and 46 μm for the Kr beam. The beam-flux distribution was measured with a Si detector that moved across the beam in 5-mm steps on a motor-driven linear slider. The count rate of the Si detector at each position was normalized by the total flux counted by a plastic scintillator upstream. With the wobbler OFF, we obtained the width σ of the beam-spot distribution and with the wobbler ON, we evaluated the beam uniformity and compared it with Eq. 1.

Figure 1 shows the results for the Ar beam and Fig. 2 for the Kr beam. The dots denote the normalized count rate of the Si detector. The open dots are not included in the following analyses because they are out of the aperture at the beam extraction window that was 60 mm ϕ for Ar and 50 mmϕ for Kr. The best-fit Gaussian functions to the measurements with the wobbler OFF, shown by lines in the left-hand side figures, give the beam-spot widths σ of 28.25 mm for the Ar beam and 26.5 mm for the Kr beam. With the wobbler ON, the beam-spot center drew a circle with a radius $R = 28.8$ mm for Ar ($R/\sigma = 1.02$) and 29 mm for Kr ($R/\sigma = 1.09$). The beam uniformity is within ± 10 % for Ar and ± 5 % for Kr within the aperture. The lines in the figures on the right-hand side show the calculation results using Eq. 1, which well reproduces the measurements.

The Bethe-Molière formula[3)] of multiple scattering well reproduced the angular width of multiple scattering deduced from the measured σ, and it can be a useful guideline for heavier ions.

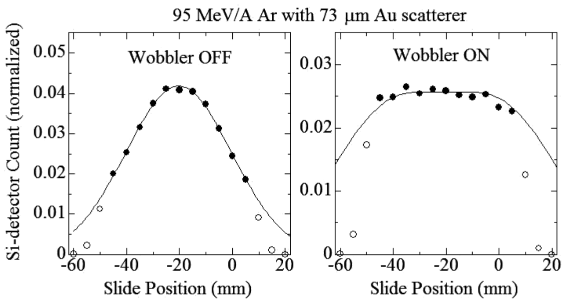

Fig. 1. Flux distribution of Ar beam without (left) and with (right) wobbler. The line in the graph on the left is the best-fit Gaussian function for the data of black dots, the line on the right is calculated using Eq. 1.

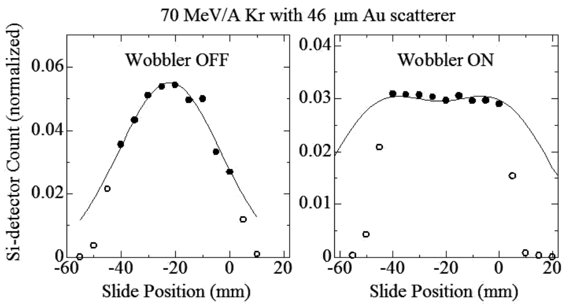

Fig. 2. Same as Fig. 1 for Kr beam.

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References

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3) H. A. Bethe, Phys. Rev. **89**, 1256 (1953).