Stability test of ion microbeams produced by tapered glass capillary optics for biological use

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Ion beam irradiation to cell nucleus has played an important role in the induction of artificial damage in DNA. The extent or type of DNA damage depends on the stopping power of the ion, which is a function of ion mass and velocity. For example, heavy ion cancer therapy employs carbon ions. Ion beam breeding to produce mutants of plants uses C, Ar, and Fe ions and so on. Both cases use fast heavy-ions in the order of 10 to 100 MeV/nucleon to obtain a range varying between a few mm and a few tens of cm and maintain a stopping power large enough to induce double-strand breaks (DSB) in DNA. To investigate a similar effect in single cells, slow light-ions (H or He) with energy of a few MeV are available. A He^{2+} ion with 4 MeV energy has the range of approximately 20 μm in water, which is larger than the thickness of cells, and a stopping power greater than 200 keV/μm, which is strong enough to create DSB.

Employing such H or He ions with energies of a few MeV provided by the Pelletron tandem accelerator (1.7 MV max.) in Nishina R&D Building, we developed a microbeam irradiation system based on single tapered glass capillary optics with a plastic end-window at the thin outlet. Figure 1 (a) shows an image of an approximately 7-cm-long glass capillary mounted at the beam port of BL-W30. The capillary inlet/outlet diameters were 1.8 mm/10 μm, respectively, and the thickness of the end-window at the outlet was 9 μm. The cylindrical object just downstream of the capillary was a PIN photodiode assembly to count the ions.

Because we plan to perform single-ion irradiation to a cell nucleus, the stopping power of the ions and the dose (number of ions in the target area) are critical factors. A cell irradiation system, in particular, requires accurate irradiation time and highly stable microbeam intensity. However, the stability of Pelletron terminal (acceleration) voltage is not better than 0.5% and consequently, the microbeam intensity was really unstable until the beginning of 2018. The accelerated ions go through a series of quadrupole magnets (QM), a vertical steerer, and a switching magnet (SM), and enter the capillary optics after travelling 5–6 m. The unstable terminal voltage results in the fluctuation of the spot position. To stabilize the number of ions entering the capillary, the beam was defocused by QM. The beam profile was monitored by an Al_2O_3 fluorescent plate with a 5 mm interval grid connected to a pico-ammeter shown in Fig. 1 (b). The profile monitor was installed at BL-W15, which is a beam line next to BL-W30. The monitor and the capillary optics were at a similar distance from SM. Figure 1 (c) shows a round shaped beam spot. Because the position fluctuation was mainly in the horizontal direction, the beam was defocused horizontally but focused vertically as shown in Fig. 1 (d).

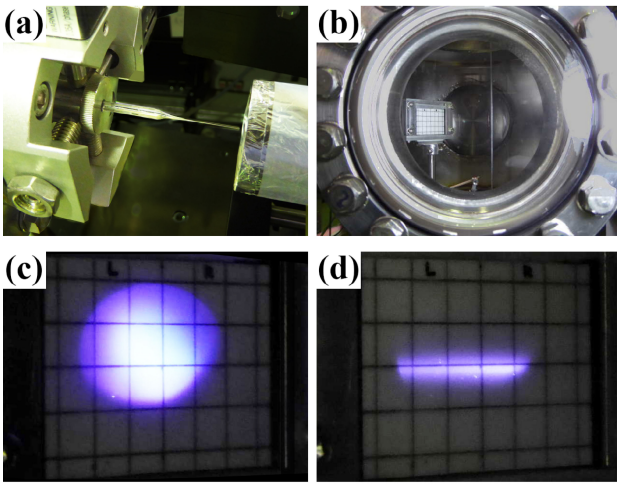

Fig. 1. (a) Tapered glass capillary optics mounted at a beam port of BL-W30. (b) Al_2O_3 fluorescent plate with 5-mm interval grid in BL-W15. (c) Round-shaped beam spot. (d) A spot defocused horizontally but focused vertically.

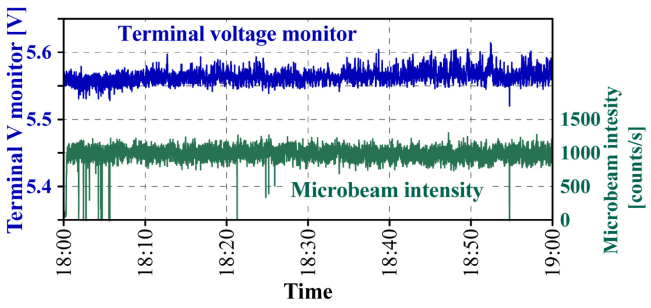

Fig. 2. Pelletron terminal voltage monitor (blue) and microbeam intensity (green) as a function of time.

After profile tuning, the beam was switched to BL-W30. The upper curve in Fig. 2 shows the time evolution of the Pelletron terminal voltage monitor ($\sim$ 5.56 V) proportional to the terminal voltage setting to 1.400 MV. The standard deviation (σ) was 2.372 kV (0.169%), which corresponds to $\sim$ 5 mm fluctuation at the capillary entrance. However, the modified shape as shown in Fig. 1 (d) realized the stable rate of the microbeam around 1000 ions per second even when the terminal voltage became more unstable within 0.9% peak-to-peak. The fluctuation σ of ion-count rate (microbeam intensity) in Fig. 2 was 8.10%, which became successfully stable. Before this method, the ion-count rate had fluctuated between 0 and 1000 counts/s randomly.

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