Improved detection resolution in single particle microbeam system

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ABSTRACT

A single particle microbeam (SPM) is uniquely capable of delivering precisely the predefined number of charged particles to determined individual cells or sub-cellular targets in vitro. It is a powerful tool to unveil mechanisms pertaining to the interactions between ionizing irradiation and living cells or tissues but it is necessary to achieve higher precision in cell irradiation. In order to obtain better energy and spatial resolution, it is imperative to improve the properties of the particle detection system. We propose the use of a scintillator deposited with a silver film instead of the conventional scintillator covered by an Al foil. The Ag film acts as a reflecting film and the performance of the scintillator is investigated.

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1. Introduction

Human cancer risks due to environmental and occupational exposure to low doses (and low dose rates) of ionizing irradiation have attracted attention. At low dose levels, very few cells in the human body experience more than one traversal by densely ionizing particles in their lifetime and the intervals between the tracks, if any, are typically months or years. A single particle microbeam (SPM) can deliver a predefined number of charged particles precisely to determined individual cells or sub-cellular targets in vitro. It is thus a powerful technique to elucidate biological responses and mechanisms such as reactions of cells, tissues, or organisms with the environment [1–7]. In the last 15 years, the use of microbeams in low-dose studies has generated much interest in the scientific community. As a result, many microbeam facilities have been established or are under development worldwide. Currently, at least 18 different laboratories are conducting research on the development of charged particle microbeams for radiation physics and radiobiology [8–28]. Ion implantation is characterized by not only energy absorption but also mass deposition, charge transfer, and atomic recoils. These factors act on the biological organisms and induce damage in concert [3]. In order to investigate the biological effects when the implanted ions stop in the target finally, the proton energy is reduced purposely to 1.4 MeV.

Targeting single cells and subsequent analysis of the induced damage on a cell-by-cell basis allow deterministic irradiation in terms of radiation quality, defined target, and defined dose. As a result, there is a high demand for high energy resolution and spatial resolution. A typical particle detection system is composed of a scintillator and Al foil acting as a reflecting film in conjunction with the incident particles.

Fig. 1. Reflectivities of the Ag and Al films in the UV and visible light regions.
with a photomultiplier (PM) tube [21,29–31]. However, when Al foils are used, energy loss and beam scattering become significant and the energy resolution and spatial resolution of the single particle beam will degrade.

The reflectivity of Ag is better than that of Al at the emission peak of the plastic scintillator used in this experiment. At a wavelength of 423 nm which is the emission peak of the scintillator, the reflectivity of the Al-coated sample is 63.47% whereas the reflectivity of the Ag-coated one is 91.28%. The thickness of the two films is about 500 nm. Furthermore, the reflectivity of the Ag coating is higher than that of the Al coating throughout the entire visible light region, although it is lower in the ultra-violet region (see Fig. 1). Hence, an Ag coating is more appropriate as a reflective film in the visible light region, but an Al coating is better in the UV region.

Here, we report the use of a plastic scintillator deposited with a thin Ag film instead of an Al foil. The energy spectra and the magnitude spectrum of the proton microbeam are investigated. In order to compare the result of the old design with that of the new design, two 5\(\times\)5 grids were fabricated on the CR39 detector. The influence of the coatings on ion stopping and scattering was theoretically investigated using Monte Carlo SRIM 2008. Our experimental results reveal that the Ag film deposited by magnetron sputtering can effectively improve the energy resolution and spatial resolution of the SPM system.

2. Particle detection system

2.1. Improvements of particle counting system

The design concept of the CAS-LIBB is shown in Fig. 2. The system is designed to deliver a defined number of hydrogen ions with an energy of 1.0–3.0 MeV, accelerated by a Van de Graaff accelerator, into an area smaller than that of the nucleus of an individual living cell. A fused silica capillary tube with an inner diameter of 1 or 5 \(\mu\)m, outer diameter of 210 \(\mu\)m, and length of 980 \(\mu\)m is used as the collimator exit. It is mounted at the center of the collimator and the position is adjustable in the center of the holder at the end of the beam line. A multilayered film is packaged at the collimator exit. Fig. 3 shows the schematic diagram of the collimator of: (a) the plastic scintillator with an Al foil and (b) plastic scintillator with an Ag film.

A commercially available plastic scintillator (BC400, Saint-Gobain) was used in our experiments. The thickness was 15 \(\mu\)m. The 500 nm Ag films were deposited on the BC400 by DC magnetron sputtering. A step was fabricated by partially covering the sample with a piece of silicon during magnetron sputtering and the thickness of the deposited film was determined from the
step. An atomic force microscope (AFM) made by Park Scientific Instruments/Auto Probe CP was used to determine the thickness of the Ag film. The AFM image (scanned area of 20 μm²) depicted in Fig. 4 was obtained by the contact mode.

The energy spectrum was measured using a gold–silicon surface barrier detector (GM-12, Beijing Nuclear Instrument Factory). The detector was calibrated by a radioactive source (²⁴¹Am) and the distance between the detector and the beam exit window was 2 mm.

The magnitude spectra of the proton microbeam were obtained by a PM tube (R7400U-4, HAMAMATSU) and 5 × 5 grids of 100-hit 1.4 MeV protons were fabricated on CR39 (HARTZLAS TD-1, Fukuvi chemical industry).

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![Transverse View](image1.png)

**Fig. 5.** Transverse view comparison of simulations obtained from: (a) Mylar+Al foil+plastic scintillator+Mylar+air (incident depth of 28 μm) and (b) Mylar+plastic scintillator coated with 500-nm-thick Ag+Mylar+air (incident depth of 21.5 μm).

![Transverse View](image2.png)

**Fig. 6.** The 1.4 MeV protons beam magnitude spectra measured by PMT.

![Transverse View](image3.png)

**Fig. 7.** Typical energy spectrum of 1.4 MeV proton extracted from the 5 μm fused silica capillary at the sample position acquired in 20s: (a) old design and (b) new design.

<table>
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<th>Parameters and results of Monte Carlo simulation</th>
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2.2. Simulation and analysis

The Monte Carlo program SRIM is widely used to simulate ion stopping and ranges in solids and SRIM 2008 is used here to study the phenomena in the thin films [32,33]. The transverse views obtained by 1.4 MeV protons are shown in Fig. 5. Fig. 5(a) — depicts the simulation results of the Al foil plus plastic scintillator whereas Fig. 5(b) shows the results of a plastic scintillator with a 500 nm Ag coating. The images are analyzed using the ImageJ software available from NIH (http://rsb.info.nih.gov/ij/) and the simulation details and results are shown in Table 1. Comparing the 500 nm Ag film deposited on BC400 to the 7 µm reflecting foil, the beam diameter of 10000-hit decreases from 14.25 to 11.47 µm, the depth of high-energy particles increases from 6.04 to 17.2 mm, and the beam diameter decreases by 19.5%.

3. Results and discussion

In this work, we modify the structure of the particle detection system and study the properties of the new SPM system. The magnitude spectra are used to count the particles in the SPM cell irradiation experiments. It is composed of PMT and a 15 µm BC 400 plastic scintillator (see Fig. 2). Two samples are evaluated using 1.4 MeV protons under similar conditions. The first one is the plastic scintillator covered with a 7-µm-thick Al foil and the second one is a similar plastic scintillator deposited with a 500 nm Ag film (see Fig. 3). The spectra in Fig. 6 reveal peaks at about 896 and 595 channels, respectively. The peaks are observed to shift to the left because the reflectance from the 500 nm Ag film deposited on the plastic scintillator is not better than that of the 7 µm Al foil. Although the background noise observed from the plastic scintillator with Ag film is larger than that from the plastic scintillator covered with an Al foil, it can meet the requirements for setting the discrimination threshold.

Energy spectra are used to evaluate the divergence of the microbeam. Fig. 7 shows the monoenergetic peaks obtained from the two different designs (see Fig. 3). Fig. 7(a) shows the energy spectrum of the former design and Fig. 7(b) displays the energy spectrum of the new design. According to Fig. 7, the monoenergetic peak shifts from 1132.79 to 1228.27 keV and the full-width at half-maximum value changes from 118.33 to 103.11 keV. The shifts can be attributed to the replacement of the 7 µm Al foil by the 500 nm Ag coating. Our results indicate that energy scattering is reduced and the depth of incidence increases significantly.

The accuracy of the particle detection system and cell targeting system is evaluated using a CR39 detector (flaky form, 10 mm × 10 mm × 1 mm). In order to investigate the counting precision of the new design, a 5 × 5 grid of a pit cluster by single hit was etched on CR39. Two 5 × 5 grids of a pit cluster by 100-hit on the CR39 surface provide statistical assessment of the targeting accuracy of the different designs. The experimental details can be found elsewhere [29]. Fig. 8 shows the irradiated CR39 after etching in

![Fig. 8. A 5 × 5 grid by 1.4 MeV proton hitting on CR39 forming a 5 µm collimator, (a) with single proton per location and with a grid spacing of 25 µm, (b) old design, and (c) new design. The bar size is 50 µm.](image-url)
from 9.7 to 7.9

A typical set of results, the beam diameter of 100 hits decreases the minimum diameter ensures 95% hits within this diameter. As the data listed in Table 2 are the mean values. Determination of the beam diameter of all the 100 hits in the grid is evaluated, and protons of 1.4 MeV. These two images are analyzed using ImageJ. The improvement in the microbeam performance is spaced grid of the old and new designs, respectively by 100 protons of 1.4 MeV. These two images are analyzed systematically and the results are shown in Table 2. The experimental results are in good agreement with the calculated ones, especially with respect to the reduction in the microbeam diameter. The new design is unequivocally better than the old one. The improvement of microbeam performance, especially the decreased microbeam diameter, can effectively enhance the spatial resolution and accuracy in cell irradiation experiments.

4. Conclusion

We have modified the collimator structure of the SPM system. The plastic scintillator covered with a 7 μm Al foil is replaced by a plastic scintillator deposited with a 500 nm Ag film using magnetron sputtering. Our results indicate that the modified structure improves the spatial and energy resolution of the system as well as the depth of incidence.

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