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A microbeam irradiator without an accelerator

G. Garty *, G.J. Ross, A. Bigelow, G. Randers-Pehrson, D.J. Brenner

Radiological Research Accelerator Facility, Columbia University, 136 S. Broadway, Irvington, NY 10533, USA

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Abstract

The stand-alone microbeam, under development at RARAF, presents a novel approach to biological microbeam irradiation studies. Foregoing a conventional accelerator as a source of energetic ions, we propose to use a small, high-specific-activity, alpha emitter. Alpha particles emitted from this source are focused using a compound magnetic lens consisting of 24 permanent magnets arranged in two quadrupole triplets.

Using a "home made" 6.5 mCi Polonium source, a 1 alpha particle/s, 10 μm diameter microbeam can be realized. As the alpha source energy is constant, once the microbeam has been set up, no further adjustments are necessary apart from a periodic replacement of the source. The use of permanent magnets eliminates the need for bulky power supplies and cooling systems required by other types of ion lenses and greatly simplifies operation. It also makes the microbeam simple and cheap enough to be realized in any large lab.

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1. Introduction and overall design

Columbia University's Radiological Research Accelerator Facility (RARAF) currently offers its users access to a few-micron diameter single-cell/single-particle microbeam irradiator, based on a 4.2 MV Van de-Graaff particle accelerator and a compound electrostatic lens [1]. In order to further reduce the beam diameter and improve operational stability, the current accelerator will be replaced with a 5 MV Singletron from High Voltage Engineering, offering better stability and enabling better focusing. In order to continue providing this essential service to our users during the expected six-month down time in 2005, we have developed an isotopic source based microbeam irradiator. The so called "Stand Alone Microbeam" (SAM) consists of a ^{210}Po source, focussed by a compound magnetic lens on to the end station of the collimated microbeam beamline at RARAF,

* Corresponding author. Tel.: +1 914 591 9244; fax: +1 914 591 9405.
E-mail address: gyg2101@columbia.edu (G. Garty).

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which is no longer active. Using a 6.5 mCi ^{210}Po source, a beam flux of 1 particle/s onto a 10 μm diameter spot is achievable with this geometry.

We will keep the SAM active after the new accelerator is installed to increase experimental microbeam capacity, and to reduce the competing demands of facility development and biological experimentation. In addition, the design is simple and inexpensive enough that the SAM can become a routine tool in any radiation biology laboratory.

2. SAM layout

The layout of the SAM is shown in Fig. 1. At the base of the SAM is a 1 mm diameter ^{210}Po source which can be blocked or exposed, using a mechanical beam chopper. The first lens (see details below) is placed 2 m above the source, with a second (identical) lens placed 2 m above the focal plane of the first lens. At the focal plane of the first lens we place a movable silicone knife edge for measuring the beam profile. As each lens does not have identical demagnifications in the x and y axes, the two lenses are rotated by 90° in the xy plane so that a circular beam spot is obtained. A limiting aperture is placed inside the second lens to reject alpha particles which have very large aberrations.

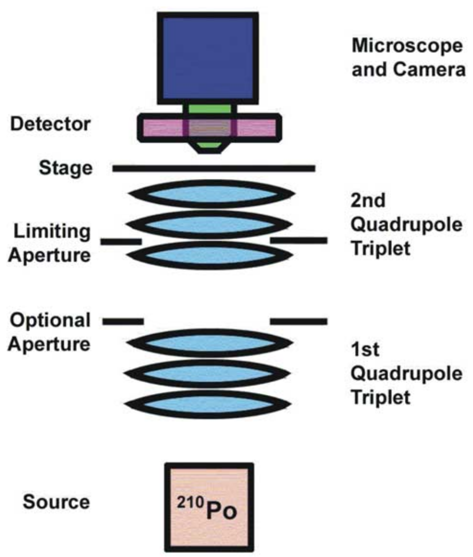

Fig. 1. Layout of the SAM, see text for details.

The cells to be irradiated are placed at the image plane. Details of the microbeam end-station are given below and in [2].

3. High specific-activity isotopic radiation source

The radioactive source at the base of the SAM must be a monochromatic alpha emitter; with a half-life short enough to provide sufficiently high specific activity, yet long enough to allow a few months of operation between source replacements. ^{210}Po is ideal for this purpose, as it has a half life of 138 days and decays via a single channel (a 5.407 MeV α-particle) into a stable daughter (^{206}Pb). The specific activity of pure ^{210}Po is 4.5×10^3 Ci/g (1.7×10^{14} DPS/g).

As the demagnification of the designed compound lens is 100×, the source size is limited to 1 mm diameter, and should be made as thick as possible, to obtain sufficiently high activity. On the other hand, in order to limit the chromatic aberrations, due to the varying degradation of alpha particles created within the source, the source must be extremely thin. Based on SRIM [3] as well as beam optics simulations, we have found that the optimal thickness of the source is 200 nm. Fig. 2 shows the expected energy spread of a 200 nm-thick source, with a FWHM of 40 keV. At this source thickness the spherical and chromatic aberrations are about the same.

The source will be prepared by electroplating ^{210}Po from a carrier free solution of $PoCl_2$ (Isotope Products, CA). The purity of the solution is important as any other metals present in it would contribute to the chromatic aberrations (by degrading the alpha particles) but not to the intensity. Therefore, if necessary, we will purify the polonium solution using an ion exchange column as described in [4]. The purification and plating processes will be done in a circulating glove box with an active charcoal filter, as ^{210}Po may become volatile and is extremely toxic. The source will then be sealed with a thin protective layer of gold.

By plating a 200 nm thick layer of pure ^{210}Po onto the tip of a 1 mm diameter rod, our

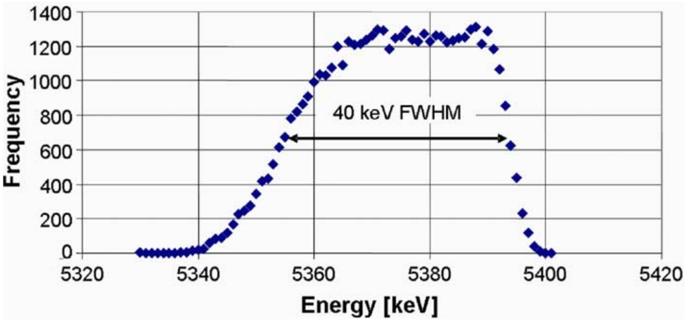

Fig. 2. SRIM simulation of the outgoing energy distribution of 5.407 MeV alpha particles formed at random depths in a 200 nm thick Polonium foil, and passing through a 15 nm thick gold foil.

calculations indicate we will obtain a 6.5 mCi (2.4×10^8 DPS) source with 40 keV energy spread. Assuming the alpha particles are emitted to 4π, beam optics simulations predict a beam flux of just over 1 alpha particle/s at the focal plane, which is sufficient for many applications of a single-particle microbeam.

4. Ion optics

The compound lens we will be using to focus the beam is based on the one used in the accelerator-based (electrostatic) microbeam [5]. However, in order to simplify the SAM operation, and making use of the fact that this is a fixed-energy beam that requires no daily tuning, we have elected to use permanent magnets to construct the lens. The lens can be initially tuned by extending or retracting the magnet poles (see Fig. 3), using micrometric screws and then no additional tuning is necessary.

The lack of large coils in the design allows for a smaller pole-face gap for the magnet, resulting in better focusing properties. The use of permanent magnets eliminates the need for costly power supplies and bulky cooling equipment while also significantly simplifying SAM operation. In addition, our simulations have shown that the spherical aberrations in a magnetic triplet are about three times lower than in an equivalent electrostatic quadrupole triplet [5].

The compound lens has been designed by Alexander Dymnikov, (who also designed the electrostatic lenses used in RARAF's accelerator-based microbeam) [5] to have a 100× demagnification resulting in a 10 μm spot size from the 1.0 mm diameter source. The optimized lens consists of two 4.25 cm long magnetic quadrupoles and an 8.5 cm long quadrupole with inter-magnet gaps of 1.67 cm and a bore of radius 6.35 mm. It should be noted that such a small bore radius is rather difficult to obtain with standard electromagnets. The design incorporates a strategically located circular aperture to reduce the spherical aberrations by catching particles on an unacceptable trajectory. Analytical calculations using the formalism of [6] have given the aberration coefficients: $C_p = 9.6 \times 10^5$ m; $C_s = D_s = 6.4 \times 10^6$ m; $D_p = 1.3 \times 10^7$ m. These coefficients were verified by Finite Element Analysis (FEA). FEA models enabled investigation into the cross section of the beam to determine characteristics of the individual ions such as their final position in the beam spot at the biological sample in correlation with their position in a cross-sectional plane at intermediate axial locations along the beam path (see [7]).

5. Endstation

The SAM will be mounted on an existing microbeam endstation consisting of a microscope with a particle detector mounted on the objective lens and a voice coil stage. The voice coil stage provides about 5 mm range in both x and y directions, submicron precision, better than 5 μm accuracy over 5 mm deflections and better than 0.5 μm

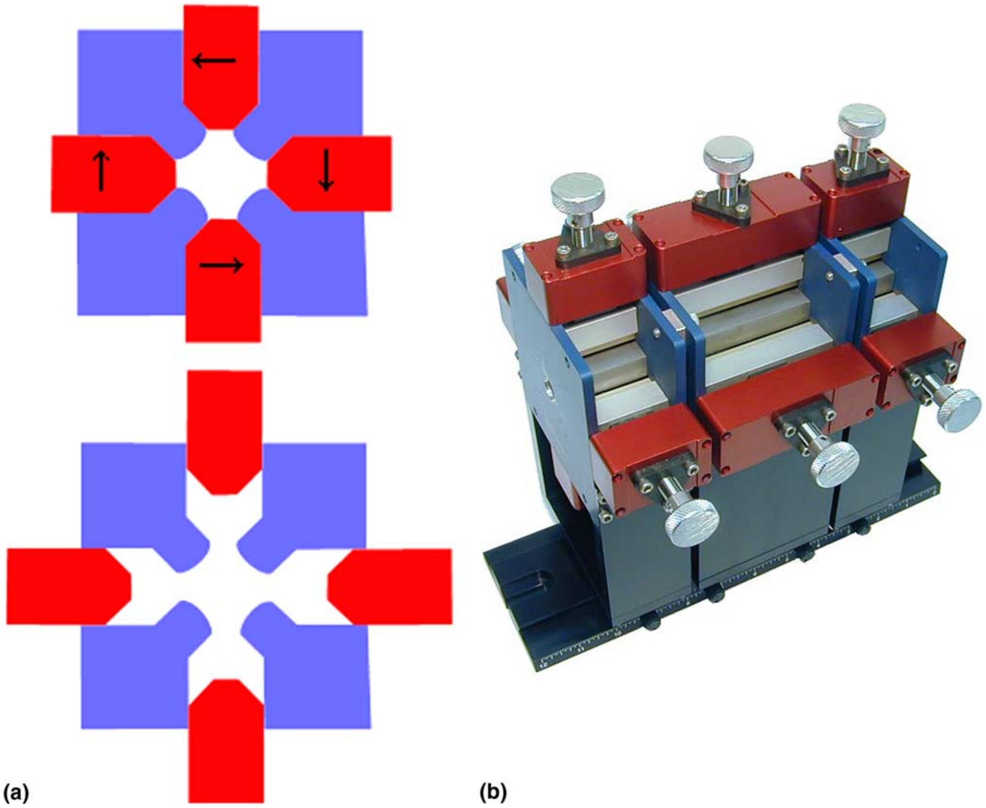

Fig. 3. (a) Cross-section of one permanent magnet quadrupole. The field intensity can be varied by extending or retracting the magnets. (b) A photo of one triplet.

accuracy over 200 μm deflections. The settling time is shorter than 200 ms. Key to the precision of a VCS is the closed-loop feedback and the response time of the overall system has been improved by using Model Predictive Control (MPC). More details are given elsewhere [2].

6. Tuning

In order to verify the focussing properties of the magnetostatic lens and to adjust the poleface retractions, we will first mount the SAM on the end of an accelerator beamline. This will allow us to use a high flux alpha particle beam, which will greatly facilitate tuning. The tuning will be performed in two stages.

The beam diameter will be first measured at the focal plane of the first triplet (see Fig. 1). This will be done using a thin silicone wafer cleaved along the crystal axis and scanned across the beam. The variation in the ratio of degraded and undegraded particles can be used to evaluate the beam width along the scan direction. As with the electrostatic lens, we will find the optimal lens setting using a multidimensional Nelder–Meade simplex search [8].

Once the first triplet is set to the optimal spot size (expected to be 50×150 μm), we will adjust the second triplet in a similar way to obtain a 10 μm diameter spot at its focal plane.

The SAM will then be dismounted from the (horizontal) beam line and, without changing the relative positions of the magnets, will be mounted vertically below the endstation. It will then be fitted with the isotopic source and the beam spot size will be verified.

Finally, a Secondary Electron Ion Microscope (SEIM) will be placed over the beam to visually confirm location and size [9].

7. Conclusions

The SAM has been designed and is under manufacture. FEA simulations indicate that the compound lens will provide a microbeam usable for single-particle single-cell irradiations. The isotopic ^{210}Po source will need to be replaced about once every few months. The system is designed using permanent magnets for focusing so that once settings are initially determined no further adjustment is necessary. The system uses off-the-shelf as well as custom endstation components for compact overall design.

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