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# TESTING THE STAND-ALONE MICROBEAM AT COLUMBIA UNIVERSITY

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**The stand-alone microbeam at Columbia University presents a novel approach to biological microbeam irradiation studies. Foregoing a conventional accelerator as a source of energetic ions, a small, high-specific-activity, alpha emitter is used. 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$^{-1}$, 10 μm diameter microbeam can, in principle, be realised. 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 realised in any large lab. The Microbeam design as well as first tests of its performance, using an accelerator-based beam are presented here.**

## 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 (proton/Helium) microbeam irradiator, based on a recently installed 6 MV Singletron particle accelerator and an electrostatic quadrupole triplet. In order to further reduce the beam diameter and increase the range of radiation fields available, intensive development work is being performed on a new, six-element lens(1) for focusing the microbeam down to submicron sizes, on a heavy ion source(2) for generating higher LET beams and on a proton induced soft X ray microbeam(3). During this development work we foresee long periods where the electrostatic particle microbeam will be unavailable for biology. In order to continue providing this essential service to our users during the down time, a second microbeam irradiator, which can be operated either directly from the accelerator or using an isotopic source, is being developed.

The 'so-called' stand alone microbeam (SAM) consists of a $^{210}$Po source, focused by a compound magnetic lens on to the end-station of the decommissioned collimated microbeam beamline at RARAF. Simulations indicate that, using a 6.5 mCi $^{210}$Po source, a beam flux of 1 particle s$^{-1}$ onto a 10 μm diam. spot is achievable with this geometry(4,5). Alternatively, a higher beam flux and potentially smaller spot size is achievable when the source is removed and beam from the accelerator is let into the lenses. In addition to providing a secondary user facility at RARAF, the design is simple and inexpensive enough that the SAM can be reproduced in any large radiation biology laboratory.

## SAM LAYOUT

The layout of the SAM is shown in Figure 1. At the base of the SAM is a 1 mm aperture defining the accelerator-based beam. This aperture can be easily replaced with a holder containing an isotopic alpha particle source ($^{210}$Po) and a mechanical beam chopper.

The first lens, a magnetostatic quadrupole triplet (MQT 1) is placed 2 m above the source, with a second (identical) lens placed 2 m above the focal plane of the first lens (MQT 2). 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(4).

Limiting apertures are placed just before the first lens as well as between the first and second elements of the second lens to reject alpha particles which have been scattered on the beam line or which possess large aberrations.

The cells to be irradiated are placed at the image plane of the second lens. Details of the microbeam end-station are given elsewhere(6).

For beam diagnostics, a retractable ion-implanted silicon detector (SSD) and a CCD chip (Kodak model KAF-402E) are placed respectively before and after the first triplet. The former enables monitoring particle energy and tuning it to the lens setting. The latter allows checking the focusing in the

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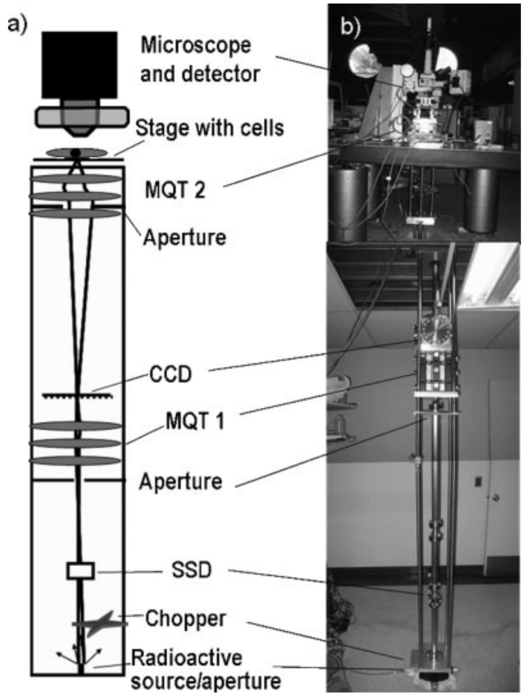


Figure 1. (a) A scheme and (b) photo of the SAM. See text for details. The two lines in a) are theoretical predictions of the beam profile in the *x* and *y* directions.

first triplet. The final beam size is measured at the image plane using the knife edge technique(7)

The SAM superstructure was designed to provide mechanical rigidity and fix the relative positions of the source, magnets and biological endstation. The SAM is rigidly connected to an optical table and coupled to the accelerator using a floppy bellows. Any mechanical vibrations will pivot the SAM as one unit around the biological endstation rather than distorting it. The stability of the SAM to thermal fluctuations still needs to be studied systematically although no significant fluctuations were seen on a day to day basis.

## ION OPTICS

The compound magnetic lens used in the SAM is based on the electrostatic quadrupole sextuplet designed for the electrostatic microbeam(1). 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, the lens was constructed using permanent magnets. 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 also eliminates the need for costly power supplies and bulky cooling equipment while also significantly simplifying SAM operation. In addition, simulations have shown that the spherical aberrations in a magnetic triplet are about three times lower than in an equivalent electrostatic quadrupole triplet(1,5).

Prior to ordering the lens as well as during its tuning, extensive use has been made of both finite element analysis and analytical calculations(8) to characterise the spot size dependence on pole tip strength, misalignment of the lenses and residual higher order fields (hexapole and octapole). The lens itself consists of two quadrupole-triplets; each triplet consisting of two 4.25 mm long magnetostatic quadrupoles, surrounding an 8.5 mm long quadrupole, rotated at 90° to the other two. The two triplets are also rotated 90° to each other giving Russian symmetry. Each quadrupole strength can be tuned by extending or retracting four NdFeB magnets inside a shaped yoke, using micrometric screws(9).

## TUNING THE MAGNETS

The RARAF accelerator was used to generate a 1 mm collimated beam, mimicking the alpha particles generated by an isotopic source. The accelerator beam was scattered on a 2 μm thick aluminium foil to obtain a large solid angle spread coming into the lens resulting in a 100 particle $s^{-1}$ beam at the image plane. Using this foil the energy spectrum of the beam matches that of the required $^{210}Po$ source (as verified using a solid state detector). This beam was used to tune the lenses, in two stages. At first a commercial CCD chip was placed at the expected focal plane of the first triplet. Alpha particles impinging on the CCD chip deposit electrons directly in the CCD well, resulting in a light spot in the obtained image. However, the well depth in the CCD chip used was not sufficiently deep and as a result typically 4–9 pixels were illuminated by each alpha particle. Furthermore, at high rates (hundreds of particles $s^{-1}$) ghosting, i.e. false light spots generated by alpha particles hitting the CCD shift register during the readout phase, was apparent. Both problems were overcome by tuning the beam to a low rate and locating, in each frame, the centre of gravity of each light spot. The resulting 2-D histogram is shown in Figure 2.

After the first lens was tuned to its optimal focusing, the CCD was removed. The second lens was brought to the same settings and the beam spot at the image plane was optimised. During this optimisation Russian symmetry of the lenses(1) was maintained. In particular quadrupoles 1, 3, 4 and 6 were kept at the same setting (A) and quadrupoles 2 and 5 at the same setting (B).The beam spot size was measured using the knife edge technique(7), namely, a thin foil was scanned across the beam and the fraction of degraded particles reaching a solid state

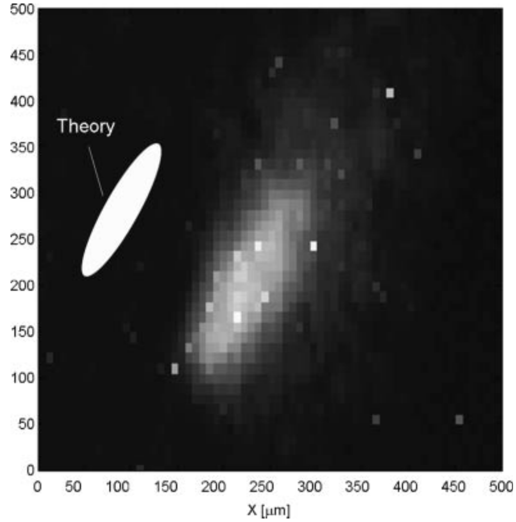


Figure 2. Beam profile at the waist of the beam just above the first magnetic quadrupole triplet, as measured on the CCD. The white elipse represents the theoretical prediction of $50 \times 150$ μm . The tilt is due to rotation of the CCD with respect to the quadrupoles.

detector was measured as a function of the foil edge position. Figure 3a shows an example of the integrated beam profile obtained with this method. Numerically, the FWHM of the beam is obtained as the reciprocal slope at the transition region.

Figure 3 also shows theoretical and measured spot shapes at various settings in AB space. The theoretical values (Figure 3b) were obtained by a fifth order matrix calculation using GIOS2000[8] and reach an optimal beam spot of 10 μm diam. Experimentally, a 20 μm spot was reproducibly obtained, as demonstrated in Figure 3a and c. During the magnet tuning elliptical spots, with either axis (but not both) 10 μm long, were measured. This implies that a 10 μm round beam is attainable. The apparent discrepancy between the obtained spot size and the theoretically predicted one is probably due to residual high order moments (mostly octapoles) which were not yet completely eliminated from the lenses. GIOS calculations show that 1% octapole moment in the quadrupoles may double the spot size. In addition the spot size was seen to be extremely sensitive to the alignment of the lenses with respect to each other. It is possible that this alignment is not yet good enough.

## HIGH SPECIFIC-ACTIVITY ISOTOPIC RADIATION SOURCE

When operated in an offline mode, a radioactive source is placed instead of the SAM entrance aperture. The radioactive source must be a monochromatic alpha emitter with a half-life short enough

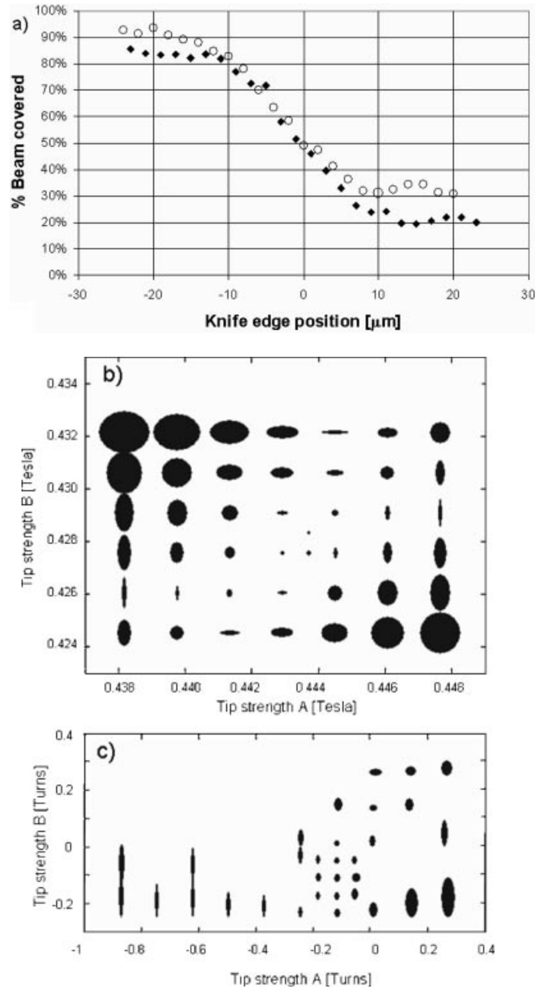


Figure 3. (a) Raw data from the knife edge scan of the optimal beam. The open and closed symbols represent two orthogonal scans of the same beam. (b) Theoretical and (c) measured aspect ratio and relative size of the beam at the image plane of the SAM. The axes of (c) are in turns of the micrometric screw with each turn representing a 5% change in magnetic field.

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 d and decays via a single channel (a 5.305 MeV alpha particle) into a stable daughter ($^{206}$Pb). The specific activity of pure $^{210}$Po is 4.5 $10^3$ Ci g$^{-1}$ (1.7 $10^{14}$ DPS g$^{-1}$).

The source diameter should be made as small as possible, to minimise spot size for given demagnification, and its thickness should be made as large 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

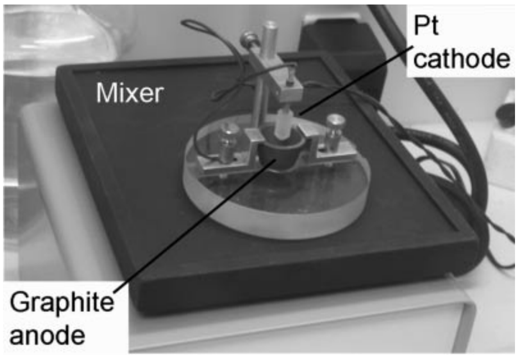


Figure 4. A photo of the plating setup. See text for details.

created within the source, the source must be extremely thin. Based on SRIM[10] as well as beam optics simulations, the optimal thickness of the source is 200 nm, yielding an energy spread of 40 keV and an activity of 6.5 mCi ($2.4 \times 10^8$ DPS)[5]. Assuming the alpha particles are emitted to $4\pi$, beam optics simulations predict a beam flux of just over 1 alpha particle $s^{-1}$ at the focal plane, which is sufficient for many applications of a single-particle microbeam. At this source thickness the spherical and chromatic aberrations are about the same[5]. As such a source is not commercially available, a setup for electroplating $^{210}$Po on the tip of a platinum wire was designed and assembled (Figure 4). As an anode, a 1.5 ml Fabmate (graphite) crucible is used. It is loaded with 1 ml of polonium solution (Isotope Product Laboratories , CA) containing the required activity. Approximately 2 V are placed between the platinum wire and the crucible, using a voltage regulated power supply. The plating set-up is placed on an orbital mixer (Thermolyne RotoMix) as mixing the solution assists in preventing depletion of the polonium from the vicinity of the cathode. The plating processes is done in a vented glove box with an active charcoal filter, as $^{210}$Po may become volatile and is extremely toxic. So far several small sources (0.1–100 μCi) have been made. The rate of plating was seen to be proportional to the concentration of polonium in solution. This means that the time required to plate a certain fraction of the polonium present in the solution is independent of the actual amount plated. It is therefore expected that a source of any size can be made within 24 h of plating. A 6.5 mCi source has not yet been produced, as our radioactive source license amendment is pending.

## CONCLUSIONS

A microbeam irradiator based on a compound magnetostatic lens was designed and built at Columbia University's RARAF. The focusing properties agree well with those predicted by GIOS 2000. As seen from these calculations the lens is extremely sensitive to its self alignment as well as to high order moments resulting in a factor of 2 degradation of spot size over the theoretically predicted one. These problems will be overcome shortly with better alignment of the magnets and finer tuning of their strength and symmetry.

So far the SAM has only been tested with an accelerator-based beam although it has been designed around operation with a custom made 6.5 mCi $^{210}$Po alpha emitter. Such a source is currently under development.

Once fully optimised the SAM will provide a useful secondary microbeam facility at RARAF and will enable biology to be performed in parallel with developments on the electrostatic microbeam. Based on our experience, a similar facility can be reproduced in any large radiobiology lab, although the tuning and alignment procedures are faster when an accelerator is available.

## ACKNOWLEDGEMENTS

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