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ION OPTIC DESIGN OF THE MICROPROBE SYSTEM AT SICHUAN UNIVERISTY*

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Abstract

At the end of 2016, the first beam was extracted from the 3.0 MV Tandetron accelerator system at Sichuan University, China. The accelerator is imported from HVEE (High Voltage Engineering Europa B.V.) as base of a multi-purpose research platform. For one of the main applications, the system will be connected to a micro-beam line to achieve submicron resolution (less than 1 um beam spot size on the target), so the accelerator is designed with energy stability as high as 0.01% and high brightness. The measured brightness for 3.0 MeV proton beam is 5.06 pA/um^{2}mrad^{2}MeV, and the energy stability is also reached the goal of design. The heart of the probe is a focusing system based on magnetic quadrupole lenses provided by Oxford Microbeams Ltd. The ion optic design of the microprobe system will be presented in this paper.

INTRODUCTION

The Institute of Nuclear Science and Technology of Sichuan University was founded in 1972 and mainly focuses on researches educations about the nuclear science and its applications. In order to enhance the research capability, a state-of-the-art dynamitron type 3MV tandetron accelerator was imported from HVEE (High Voltage Engineering Europa B.V.) as the key facility of the proposed new multipurposes research platform related with the nuclear science and technology. The accelerator was designed to have the capability of providing almost all ions in the periodic table with the help of the equipped two ion sources, and the energy stability after the analyser magnet is better than 10^{-5}. At 2016 the first beam was accelerated successfully just after the installation of the whole system. Up to now, more than 10 kinds of ions were accelerated and the heaviest ion even accelerated is Au. The beam current of proton is about 60uA at the exit of the accelerator, the brightness of the proton beam after the analyser is 5.06pA/μm^2/mrad^2/MeV. At present there are three end stations opening for applications by users, they are ion beam analysis end station, ion implantation end station and nuclear physics experiment end station, and the details about the status of the platform can be can be found in [1].

Besides these three end stations, there are 6 beam ports with energy stability of 10^{-4} available at the exit of the switch magnet (SW2) just behind the exit of the accelerator and 4 beam ports with energy stability of 10^{-5} available at the exit of the switch magnet (SW3) downstream of the analyser magnet and stabilizer slits as shown in figure 1. As part of the platform upgrading program, a nuclear microprobe system will be connected at the 0-degree beam port of the SW3 and be constructed in the following two years. The microprobe will have a spatial resolution better than 1mm with beam current more than 50 pA. It can used in applications such as high-resolution RBS and PIXE analysis in high current mode, at the same time it also has the ability to do STIM analysis and micro manufacture (PBW-proton beam writing) at low current mode with even higher resolution better than 100 nm. The system also has the ability to allow the beam to be extracted into air at the back of the target chamber to analyse large objects such as artefact of cultural heritage which cannot be placed inside the vacuum. The main parameters of the microbeam line are listed in table 1.

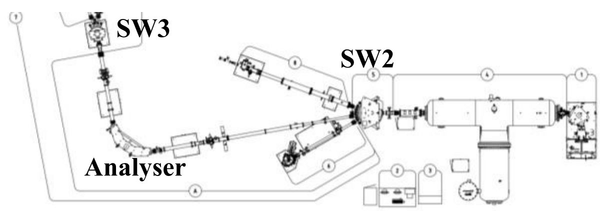

Figure 1: Layout the 3MV tandetron accelerator.

Table 1: Main Parameters of the Microbeam Line

Parameters	Values
Beam size at target	<1×1 μm^2
Beam current	>50 pA
Applications	PIXE, RBS, STIM, PBW

GENERAL CONSIDERATIONS AND LAYOUT

Although the first nuclear microprobe system constructed at Harwell around 1970 already attained a spatial resolution of 2.2μm with a beam current of 250 pA [2], it is still not easy to construct a microprobe system with a spatial resolution less than 1 μm for high current applications now. The reason is that there are too many factors that may deteriorate the spatial resolution of the system, such as the intrinsic and parasitic aberrations, stray magnetic fields, environment vibrations and so on. So how to avoid such unfavoured factors becomes most important for the success in nuclear microprobe construction.

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Beam Brightness and Energy Stability

The brightness and the energy stability of the beam provided by the accelerator is one of the most important factors that will determine the spatial resolution of the nuclear microprobe can obtain. The final beam size is determined by linear demagnification factors and higher order intrinsic aberrations. Theoretically the particle position at the image plane is decided by the position divergence at the object plane and energy difference as the following equations,

$x_i = (x|x)x_0 + (x|\ _0 + (x|\ )_0\delta_0 + (x|^3)_0^3 + (x|\ ^2)_0\varphi_0^2$,

$y_i = (y|y)y_0 + (y|\varphi)\varphi_0 + (y|\varphi\delta)\varphi_0\delta_0 + (y|\varphi^3)\varphi_0^3 + (y|^2\varphi)_0^2\varphi_0$.

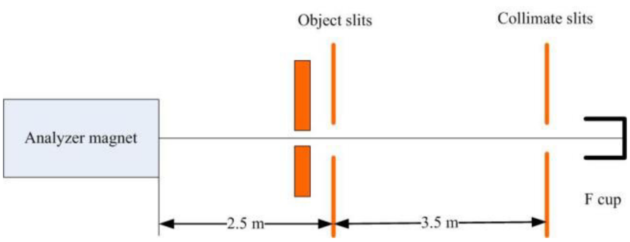

Figure 2: Schematic layout of the brightness measurement setup.

For the nuclear microprobe system, the astigmatism coefficients $(x|$ and$(y|\varphi)$ are equal zero. The aberration coefficients together with the particle's initial positions, the initial divergence angle and the energy difference determines particle's final position. In our case the energy stability is 10^{-5}, which is already the best record for the same kind of machine. Because the beam intensity distribution in phase space is highly non-uniform. It is clear that only a small proportion of the beam particles passing through the object collimators has both a large divergence and a large energy error. If we have a very intense beam, then we can just select a small phase volume, then the aberrations will have little effect on the final beam size. We have measured the proton brightness after the analyser magnet, the setup is shown in figure 2.

During measurement, the size of the object and collimate slits are set to 0.2 mm and 2 mm respectively, the corresponding maximum divergence is about 0.57mrad, both sizes and divergences are much larger than the values in operation. Since there is no cooling in the slits, as silt sizes further decrease, the heat deposited on the slits make the system unstable. For 3 MeV proton beam, the measured brightness is 5.06 pA/μm²/mrad²/MeV. Compared with the brightness record in microprobe systems, it is a lit bit small, but for a two-ended machine, it is already quite promising. Because the flux in phase space is not uniform, it can be expected that even more bright beam can be get for smaller phase volume.

Focusing Structures

In order to get the required spatial resolution with required beam current, a focusing system must be applied to focusing a large spot size on object plane to a small spot on image plane. We suppose the average demagnification fac-tor as D, and the divergence is 0.1 mrad to make sure that the aberration is not significant, for safety we asked the 100pA beam current on target, twice as that required by the system, then we can get the beam current on the target for 3 MeV protons,

$$I = B \times D^2 \times 0.1^2 \times 3 \geq 100$$

Then it is easy to get the required magnification D should greater than

$$\mathrm{D} \geq 26.$$

For a high performance nuclear microprobe, the focusing quadrupoles are most important elements, they should be manufactured precisely so that the higher order field component can be as small as possible. The OM series magnet produced by Oxford Microbeam Ltd has very good reputa-tion in the microprobe community, so we choose the MO50 quadrupole as the focusing elements. The configuration of the focusing is the high excitation triplet. With the help of numerical simulations, the working distance, that the dis-tance between the edge of last quadrupole and the image is 126 mm, the distance between object slit and collimator slit is 6500 mm, the length of the quadrupoles is 100 and the distance between quadrupole is 40 mm. the first two quad-rupole are excited equally but in opposite sign. By properly setting the excitation level of first two lenses and the third lens, we can find the right solution that make sure that the beam can be imaged at the image plane. The layout the of the system is shown in figure 3.

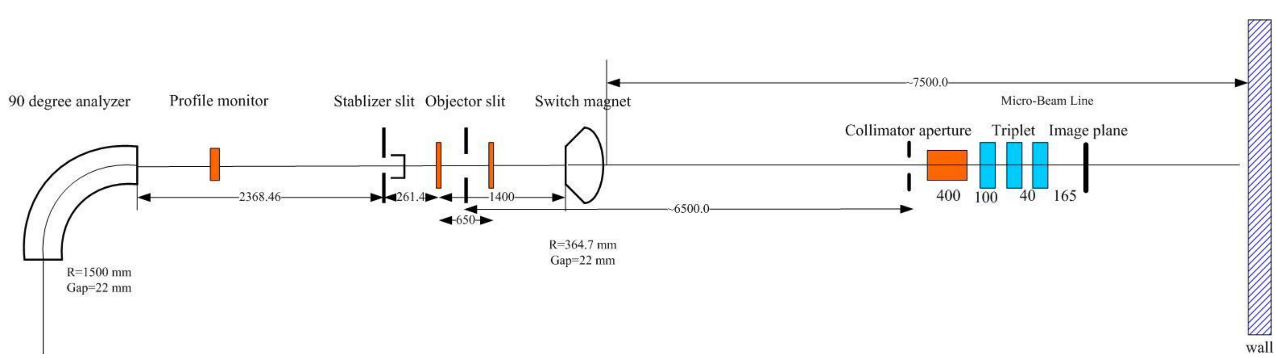

Figure 3: The general layout the microbeam line in Sichuan University.

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SIMULATIONS

Wintrax [3] is used to calculate the image properties of the nuclear microprobe system. Wintrax is a ray tracing program, it solves the equation of motion numerically for a representative set of particles in the beam and to derive the properties of the image from the trajectories of the particles leaving the system. The design and simulation procedure as follows,

- Creating the beam line by defining the elements position and parameters;
- Setting the parameters that can be changed in finding the right solution;
- Setting the optimization goals, in our case, it is the astigmatism;
- Simulation with multi-ray to say the image properties on the image plane, if the aberration is too serious, change the beam size and the divergence;
- Using GenFit to get the aberration coefficients in to the order you want.

After optimization, the final setting is like this: the object sizes are 65 µm and 16 µm in x and y direction respectively, and the collimator slit sizes are 500mm and 250 mm in x and y respectively, the corresponding maximum divergence in x and y is 0.077 mrad and 0.038 mrad respectively, the beam current on the target is 54.04 pA calculated with the measured brightness. The demagnification factor is 83.58 in x direction and is 24.18 in y plane. The image on the target plane is shown in figure4 and the intrinsic aberration coefficients up to third order are listed in table 2. The last column are the corresponding values calculated with the maximum size and divergence, and the energy difference of 10^{-5}.

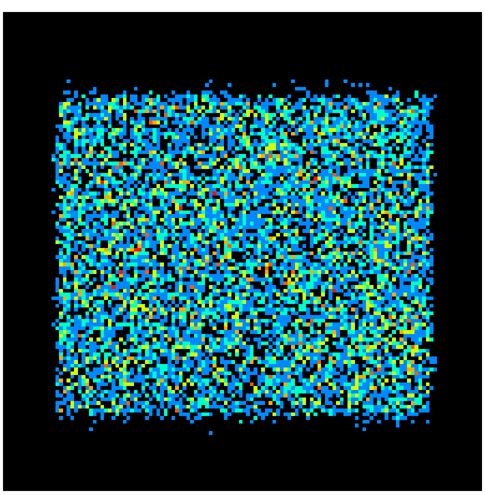

Figure 4: the image on the target plane, the size of the black box is 1 µm in each side.

If we further decrease the object size to 20 and 6 mm in x and y direction respectively, and the divergence to 0.06 and 0.003mrad in x and y direct respectively, the image size in x and y is less than 300nm, the corresponding beam current is about 4 pA and it is sufficient for the low current beam applications.

Table 2: The aberration Coefficients

Coefficients	Value	
$\langle x \vert x \rangle$	0.012	
$\langle y \vert y \rangle$	-0.041	
$\langle x \vert \theta \rangle$	-0.184	0.015
$\langle y \vert \phi \rangle$	0.132	0.005
$\langle x \vert \theta^2 \rangle$	0.256	0.002
$\langle x \vert \theta\delta \rangle$	-347.220	0.138
$\langle y \vert \phi^2 \rangle$	-1.356	0.002
$\langle y \vert \phi\delta \rangle$	872.680	0.174
$\langle x \vert \theta^3 \rangle$	327.230	0.168
$\langle x \vert \theta\phi^2 \rangle$	438.030	0.056
$\langle y \vert \phi 3 \rangle$	-1735.000	0.111
$\langle y \vert \theta^2\phi \rangle$	-1586.100	0.406

CONCLUSION AND OUTLOOK

A nuclear microprobe system based on Oxford Microbeams Ltd. OM-2000 endstage will be added at the Sichuan university, the expected spatial resolution is 1µm with beam current more than 50 pA, it can be used for high precision RBS and PIXE analysis in high current mode both in vacuum and in air. The system also can be used in micro-manufacture study with focused proton beams with spatial resolution better than 300 µm in low current mode. With the help of Wintrax code, the beam optic properties of the microbeam system is studied, and the simulation results show that the expected parameters can be reached.

ACKNOWLEDGEMENTS

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