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Rearranging a nanoprobe: Line foci, grid shadow patterns and performance tests

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ABSTRACT

After a major modification of the target chamber at the Leipzig high energy ion nanoprobe the probe forming lens system, consisting of two separated quadrupole doublets, had been carefully realigned. This was done by adjusting the line foci position of each individual quadrupole on the centre position defined by the unfocused beam. Using a high magnification microscope the alignment process is very effective and precise. The lens system could be precisely realigned except an intrinsic rotational misalignment which is essentially reduced by a correction lens.

Grid shadow patterns have been taken and analysed in order to assess the characteristics of the system. The dominant aberrations are spherical with an additional parasitic octupole.

The grid shadow method is also very useful to determine the best position of the aperture diaphragms which minimizes the influence of the aberrations onto the beam spot size.

The rearrangement allowed larger aperture diaphragms for higher beam currents at a moderate increase in beam spot sizes. Performance tests yielded proton microbeam currents and half-widths of 4.5 nA at 1.5 μm, 8.3 nA at 1.5 μm and 17.2 nA at 2 μm. For high resolution work the expected beam spots around 0.3 μm at 100 pA were not achieved. The reason is very likely interference on the beam scanner, correlated in *x*- and *y*-direction, which results from the insufficiently rectified power supply voltage of the transconductance amplifier.

1. Introduction

Nuclear microprobe analysis of minor and trace elemental distribution with a spatial resolution in the micrometer or submicrometer range commonly involves data acquisition times for a single scan in the order of an hour even though the detector geometry is already optimized for efficiency. For broadly based studies with a great number of samples the required beam time can easily exceed weeks [1]. This is however hardly incorporable into a usually tightly packed beam schedule. The compromise made is often the reduction of the number of samples selected for a measurement. Another compromise is to accept a reduction of spatial resolution which allows an increase in beam current and therefore shortening the acquisition time without losing sensitivity. The increased beam current also allows measurements with higher sensitivity when the acquisition time is not reduced [2].

The applications of nuclear microprobes for elemental analysis would benefit from higher beam currents. Therefore, high performance systems have been constructed [3] or are currently under development [4–6]. The performance of the Leipzig nuclear microprobe system, in particular the beam current, has also significantly improved since its commissioning in 1998 [7]. These improvements based mainly on a careful alignment of the object and aperture diaphragms, which allowed greater aperture settings with marginal broadening of the beam diameter but ample increase in beam current. In order to further improve the performance of LIPSION, the whole probe forming system has been recently rearranged utilizing single lens line foci and the grid shadow method.

Although the alignment process is commonly known and elucidated in the nuclear microprobe handbook [8] the experiences and improvements during the rearrangement of the Leipzig nanoprobe are described here.

2. The Leipzig separated Russian quadruplet

The whole probe forming system is mounted on a single steel girder, similar to an optical bench, to ensure as much rigidity as possible [9]. The main part of the system is a split Russian quadruplet of magnetic quadrupole lenses. In other words it consists of two pairs of magnetic quadrupoles that are separated from each other. The arrangement provides a large orthomorphic demagnification of more than 100 in both directions, i.e. the beam through a circular 100 μm object diaphragm is focused to a spot of less than 1 μm. Table 1 shows the specification of the system and Fig. 1

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Table 1
Specifications of the Leipzig separated Russian quadruplet and resultant parameters of PRAM calculations.

Coupling	+A−B+B−A
Overall system length (m)	8.53
Object to aperture (m)	4.90
Aperture to Q1 (m)	0.54
Q2–Q3 (m)	2.49
Working distance (mm)	330
Quadrupole length (mm)	57
Spacing Q1–Q2 and Q3–Q4	40
Lens bore diameter (mm)	12.7
Maximum pole-tip field, 2.25 MeV p (T)	0.192
Demagnification $D_x = D_y$	104
Spherical aberration (µm/mrad^3)	
(x/θ^3)	53,475
(y/φ^3)	4088
$(x/\theta\varphi^2) = (y/\theta^2\varphi)$	25,195
Figure of Merit Q	18
Chromatic aberration (µm/mrad/%)	
$(x/\theta\delta)$	−1688
$(y/\varphi\delta)$	−490
Parasitic aberration sensitivity	
Largest sextupole term $(x/\theta^2 s)$	
Value (µm/mrad^2/%)	−33,000
Largest octupole term $(x/\theta\varphi^2 o) = (y/\theta^2\varphi o)$	
Value (µm/mrad^3/%)	90,000

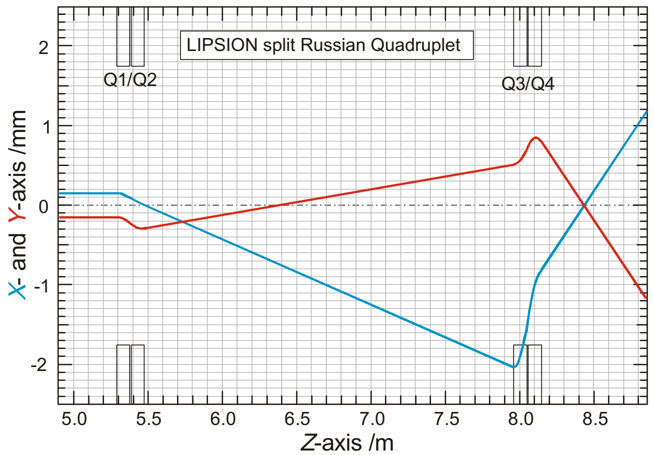

Fig. 1. Ion optics ray tracing of the LIPSION system. The initial settings were 100 µm diameter for the object and 300 µm diameter for the aperture collimator.

shows the corresponding ion optics ray tracing of the beam envelope (100 µm object and 300 µm aperture diaphragm).

Having a large demagnification is almost unavoidably connected with large intrinsic spherical aberrations of the ion optical system which introduce image distortions. Beam trajectories of increasing distances to the optical axis cause a growing beam halo. The degrading influences of these third order contributions on the final beam spot size can be kept reasonably low by limiting the beam divergence, in practice by using smaller aperture diaphragms. The gain in beam intensity due to the larger object diaphragms has to be paid by smaller aperture diaphragms than usually used in systems with less spherical aberrations. However, a careful alignment of the lens system including the object and aperture diaphragms can bring out an improved performance.

3. The quadrupole alignment

In the course of replacing the old by a newly designed target chamber the split Russian quadrupole lens system had to be realigned due to a modification of the casing in which the quadrupoles Q3 and Q4 are contained. The initial rough alignment of the quadrupoles was done optically along to the axis of the object and aperture diaphragms which were previously fixed at the position of maximum beam current before any modification of the system. The positions of the object and aperture diaphragms matched the straight optical line from the 90°-magnet to the final focus position on the sample. This was verified utilising an intense cold light source fed into an extension flange of the 90°-magnet via a centered diaphragm. The light through the three diaphragms, the entrance diaphragm of 1 mm diameter, the object diaphragm of 100 µm diameter, and the aperture diaphragm of 300 µm diameter was still recognizable downstream by an aligned theodolite. The two quadrupole doublets, equipped with alignment diaphragms on both sides, were than aligned on the axis seen by the theodolite.

The optical alignment of an ion microprobe forming system is controversially discussed. Due to external magnetic fields (from earth, currents and components) the ion beam trajectory does not take the optical path, however, the shielding of the beam tube with mu-metal significantly reduces these influences. A discussion of the influences from external magnetic fields on the beam spot position is given by Jamieson [10] and for the described Leipzig system discussed in detail by Spemann [11]. Both references give an influence in the order of 1 µm/µT. This deterioration of the beam path should be inferior to the uncertainty of the theodolite.

A major inaccuracy arose from the uncertainty of the position of the quadrupole centre. The centre was not taken from the pole tips but from the outer bezels which presumably are not adjusted to the field centre. The resulting misalignment of the quadrupoles was easily seen when the line focus procedure was carried out.

As it is described in [8] the line focus adjustment starts with an unfocused beam observed with the sample chamber microscope on a luminescent screen at the sample position. The centre of the unfocused beam defines the position where the line foci of both directions of each individual quadrupole will intersect at right angle when carefully aligned. It was very helpful to have a microscope with low and high magnification. The unfocused beam as well as the line foci are best seen in the low magnification; however, to verify that the line focus position is in the center of the unfocused beam, the high magnification is recommended.

As the two doublets of our system are made as a single piece, the alignment cannot be done for each individual quadrupole separately. Therefore, we started the alignment process with the quadrupole doublet Q3/Q4. This is the second doublet which finally focuses the beam onto the sample. Due to its short distance to the focus (330 mm) the alignment is straightforward. The alignment of the first doublet Q1/Q2 was much more time-consuming. The large distance to the focus point (ca. 3 m) cause a high sensitivity to the tilt angle. A careful adjustment then runs into regions where even elastic properties of the lens support and presumably of the quadrupole itself become apparent.

Another effect is the magnetic hysteresis. It influences the position of the line foci when reversing the magnetic field. We decided to align the line foci according to the field which will be applied under normal focusing conditions.

It turned out, that there is a rotational misalignment which could not be corrected. It is assumed to be mechanically inherent in one of the doublets. The usually applied correction field adjusted by an anti-skew lens [7] did not change significantly after the rearrangement.

4. Grid shadow patterns

The grid shadow technique is described in detail in [8]. It is commonly used during testing and installation of microprobe com-