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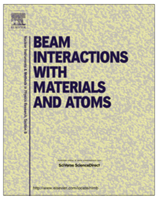

Experimental results of microprobe focusing by quadruplet with four independent lens power supplies

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ABSTRACT

Earlier we have proposed the idea in optics of one-stage quadrupole probe-forming systems that consisted in using independent power supplies for all lenses [1]. The new arrangement, in comparison to Oxford triplets and Russian quadruplets, theoretically allows operating in regimes with considerably higher density of ion current. The probe-forming system of the Sumy microprobe has been arranged as a quadruplet with four independent lens power supplies. Current density growth was experimentally verified and sub-micron probe size was obtained, despite the large working distance of 23.5 cm, the moderate beam brightness of 7 A/(m^2 rad^2 eV) and the energy spread of 10^{-3}. This upgrade did not require changes in the beam-line design.

1. Introduction

Probe-forming systems (PFS) in most microprobes are either Oxford triplets or Russian quadruplets that are the most effective in practice today. These one-stage systems are well studied, but there are still some possibilities to improve them. As two-staged systems [2] have not gained the expected resolution we proposed to rearrange a one-stage system equipping it with two more power supplies. We have published the investigation results in optics of one-stage quadruplets with four independent lens power supplies in [1]; this work is an experimental extension of that research.

2. QIPS (quadruplet with individual power supplies) systems

In Oxford triplets (number of magnetic quadrupole lenses $N = 3$) or in Russian quadruplets ($N = 4$) only two lens power supplies ($n = 2$) are used [3]. At least two power supplies are required for the two last lenses along the beam. These two lenses (the final doublet) are the most important as they provide final focusing and cannot be connected to the same supply due to peculiarities of quadrupole optics. As the number of quadrupole lenses in PFS is $N > 2$ (excluding a doublet where $N = 2$), the other $N - 2$ lenses do not have their own power supplies and are in fact electrically coupled with one of the lens of the final doublet. Such an arrangement provides stable and straightforward focusing procedure but at the same time limits the system influence on the transmission and focusing beam parameters.

The QIPS system (acronym of quadruplet with individual power supplies) that is used for the calculations presented in [1], is considered to be a one-stage PFS that instead of having two excitation sources as usual in the well-known Russian quadruplet and systems earlier presented [4], has four excitation sources ($n = 4$) for the magnetic quadrupoles. In other respects, the QIPS geometry coincides with the geometry of the Russian quadruplet [5]. Design of this one-stage system is shown in Fig. 1. Initial phase volume of the beam is specified by two collimators (an object one with $2r_x \times 2r_y$ dimensions and an angular one with $2R_x \times 2R_y$ dimensions); then this volume is focused by the lens system on a spot on a target $d \times d$ in size.

There are two parameters ($N - 2$ when $N = 4$, excitations of lenses of the first doublet) that can be varied freely in the QIPS. For all their acceptable values, we calculated excitations of the final doublet from a stigmatic condition and found a system acceptance [1]. In the obtained two-parameter set, we searched for the maximal value of acceptance A_d reduced to probe-size d that corresponded to the maximal current density. The most important optical parameters such as demagnifications, chromatic and geometric aberrations of the third order were taken into account when calculating the reduced acceptance. The calculations predicted that it is possible to obtain a considerably higher current density than that in Russian quadruplets configuration, and to develop systems with higher demagnifications and acceptable aberrations. Acceptance grows in the QIPS comparatively with Russian quadruplets due to the optimal relation between demagnifications and aberrations can be found when there are no strict dependencies between the lens excitations.

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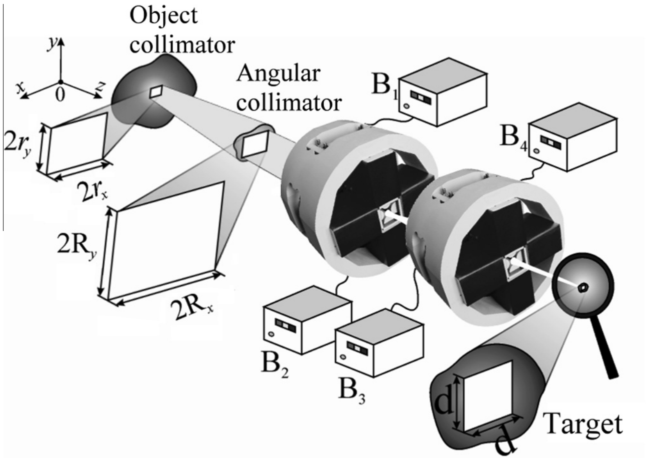

Fig. 1. General diagram of QIPS for the Sumy microprobe.

It was shown in [1] that considerably large variation of magnetic inductions B_1 and B_2 for the first two lenses resulted in relatively small deviations of acceptance. Flat maximum in the optimization problem allows QIPS to be implemented in practice. Because of this, it is not necessary to include the excitations of the first two lenses into the adjustment procedure. Their excitations were set to the calculated values after lens degaussing in the experiment. The optimal focus was determined by a standard procedure of excitation variation of the third and the fourth lenses while observing a beam spot on a scintillation screen or secondary electrons mapping from the edges of a fine grid.

A QIPS-11 system with intermediate crossovers both in horizontal x and vertical y planes was selected for an experiment. The positions of the crossovers were different, inside the second lens in x plane and 294 mm after it in y plane. This is the main difference from the two-stage systems where both crossovers should be in the plane of intermediate focus [6].

Parameters of our integrated doublets of lenses were evaluated in experiments [7]. It was found that current in the lenses with each coil having 90 windings should not exceed 8 A, otherwise considerable overheating is observed and the lens diameter would increase then implying a shift up of the doublet axis. Thus operating current cannot reach 12 A, as it should have been from [1], therefore parameters of the QIPS-11 system were recalculated for currents limited to 8 A for a maximum beam energy of 1.5 MeV. Comparable ion-optical characteristics of two quadruplets are shown in Table 1.

Geometric parameters match the real PFS [8]: the distance from the object to the first lens is 250.4 cm; the distances between lenses in doublets (between the first and the second lenses and the third and the fourth lenses) are 3.94 cm; the distance between doublets (between the second and the third lenses) is 78.75 cm; the working distance is 23.5 cm; the effective lens lengths are $L_{1,eff} = L_{4,eff} = 7.141$ cm, $L_{2,eff} = L_{3,eff} = 5.067$ cm; the lens bore radii are 6.5 mm; the distance between the object and the angular collimators is 194.5 cm. The energy spread is $\Delta E/E = 10^{-3}$. Arrangement of excitations in the QIPS is $C1D2C3D4$, where Cn or Dn marks a connection to a power supply with number n ($n = 1\ldots4$) thus the lens focuses the beam in xz or yz plane, respectively.

Focusing effect of the QIPS ($D_x \times D_y \approx 5 \times 10^3$) is more than an order of magnitude greater than the analogous parameter of the Sumy SRQ ($D_x \times D_y = 620$). Though QIPS aberration coefficients are considerably higher than that of the Sumy SRQ, value of the acceptance $A_{1.0}$ reduced to a probe size $1.0 \times 1.0\ \mu m^2$ in the target plane is $A_{1.0} = 1.81\ \mu m^2\ mrad^2$ in the QIPS as compared to $A_{1.0} = 0.67\ \mu m^2\ mrad^2$ in the Sumy SRQ. Current density was expected to increase by a factor of three.

3. Experimental results

In our experiments, we scanned a 1000 mesh copper grid and analyzed secondary electron emission. The Agar Scientific commercial standard grid was placed in a hollow cylinder (2 mm in diameter and 15 mm in depth) thus there was no yield of secondary electrons in paths between the grid bars. The analysis of the observed secondary electrons yield while beam scans along the standard template is the most effective method for probe size determination [10] since secondary electrons yield is higher than that of other interaction products. Size of the grid bar of is between 6.8 and 7.1 μm, as can be seen in Fig. 2a obtained with a scanning electron microscope.

Images of the grid obtained with the microprobe are shown in Fig. 2b and c. All the experiments were performed with 1.5 MeV proton beam. Unfortunately, there is an alternating magnetic field with frequency of 50 Hz in the system. Though the beam line is equipped with a magnetic shield of 4 mm permalloy (10 layers of 0.4 mm), we failed to shield some parts of irregular shape (collimators, systems of beam diagnostics, lenses, etc.) Therefore, an alternating current distributed in space generates a parasitic oscillation of the beam in the horizontal plane with amplitude about 1 μm at the target. This can be clearly seen at vertical grid bars in Fig. 2b. Due to the parasitic beam oscillation, the beam size of the non-oscillating beam could not be determined. Thus, only the beam size of the beam in y-direction is evaluated in the following paragraphs.

Secondary electron yields (averages of 10 profiles) along a line intersecting the horizontal bar (in y-direction) are shown in Fig. 3a for different sizes of collimators. As currents in the

Table 1
Ion-optical characteristics of PFSs based on separated Russian quadruplet (Sumy SRQ) and QIPS.

PFS	Sumy SRQ [8,9]		QIPS-11	
Demagnifications $D_x \times D_y$	24.9×24.9		52.1×96.4	
Length of the system, L, m	3.85		3.85	
Working distance, g, cm	23.5		23.5	
Acceptance, $\mu m^2\ mrad^2$, $A_{1.0}$	0.67		1.81	
Dimensionless excitations	0.8530; −0.6275		1.029; −0.730	
κ1; κ2; κ3; κ4	0.6275; −0.8530		0.614; −0.827	
Field on poles, T	0.1897; −0.2039		0.239; −0.239	
(E = 1.5 MeV) B1; B2; B3; B4	0.2039; −0.1897		0.169; −0.155	
Currents in lenses, A				
(E = 1.5 MeV) I1; I2; I3; I4	5.93; 5.42; 5.42; 5.93		7.96; 7.96; 5.80; 5.20	
Aberrations, μm, mrad, %				
$\langle x/x'\delta\rangle\langle y/y'\delta\rangle$	−524	−152	−1006	−411
$\langle x/x'^3\rangle\langle x/x'y'^2\rangle$	1000	288	8137	8658
$\langle y/y'^3\rangle\langle y/y'x'^2\rangle$	38	289	1509	4681