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# Dynamic focusing of microprobe lens system during scanning process

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ABSTRACT

Highly excited quadrupole lenses have significant spherical aberrations and they are very sensitive to the beam entrance angle, and microprobe size may vary considerably during scanning if the scanner is placed before or inside the focusing system. The effect of probe blurring while moving away from the optical axis can be partially compensated by adopting a dynamic focusing procedure to systems of magnetic quadrupole lenses like it is in electron beam devices. Dynamic focusing implies changing of quadrupole lens currents synchronously with the beam deflection on the certain rule such that probe size remains minimal in any raster point. A quadruplet of magnetic quadrupole lenses was considered.



## 1. Introduction

It is commonly known that an originally focused beam blurs while scanning over a sample surface because of deflection aberrations and because it leaves a focus of a lens system. These challenges are solved in electron-beam facilities by combined application of several optical elements correcting some aberrations and by a dynamic focusing. The dynamic focusing allows the focus depth of the optical system to be changed quickly and interactively; it permits to focus the beam on the target surface all the time, be it CRT screen or a specimen in SEM (TEM), even when measurements are performed on tilted objects. There is some information that the dynamic focusing could work in ion-beam lithography facilities (FIB) but for the $Ga^+$ beam energy of some tens of keV [1]. Microprobe forming systems (PFS), in comparison to the above-mentioned facilities, are less flexible; the theory of their optics is incomplete. Apart from some former systems of axial geometry, focusing is usually performed by a system of magnetic quadrupole lenses (MQL), a beam divergence is limited by a set of slits; system adjustment and current control in quadrupoles are mostly manual while beam yield profiles are analyzed. Neither aberration correctors nor lenses with time-variable field that are widely used in electron facilities have not been applied yet (see review [2]).

Meantime a time-variable field distribution may be realized in the principal focusing elements, i.e. in MQL. Modern power supplies allow lens excitations to be regulated during the experiment so the focus depth can be changed synchronously with the beam deflection. The following motivates a consideration of this possibility. As to [3], a space between the last lens and the target is the most suitable to install the scanner in order to minimize perturbations. The length $g$ of this space is called a working distance; it specifies a focal distance of the whole system. Recent trends lie in constant reduction of $g$, and in raised demands to process repeatability, scanning frequency and positional accuracy of submicron probes. An electrostatic scanner meets all these demands but it should be placed at the space in front of the whole PFS or between the lenses where the probe is formed. An additional element is therewith incorporated; the scanner becomes an additional source of perturbations, which involve unbalancing of the probe formation process.

Stigmatic focusing is preserved in the presence of deflection fields if the deflection is insufficient to violate the paraxial nature of the beam. Should the deflection field be strong enough paraxial approximation is not valid. Since strong quadrupoles are characterized by considerable spherical aberrations and sensitivity to the beam entrance angle, the probe size can change greatly during the scanning. Recently it was regarded as insignificant, e.g., in classical arrangement of the triplet with a pre-lens scanning [4] for a 1.25 mm deviation a beam spread was found to be 10 μm to a base size of the probe about 6–7 μm. But ignoring this factor is unacceptable with a view of submicron probe. This challenge will become relevant, primarily, for the latest PFS with considerable demagnifications (>100).

This work is aimed at the analysis of perturbations caused by the electrostatic scanner installed between the second and the

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third MQL of the quadruplet and at the study of how the dynamic focusing can be used to preserve probe size during the scanning. Here the dynamic focusing means synchronous change of the lens excitations and the voltage at the deflectors under some law in such a way that the spot remains the smallest in every raster point. Recently this task was not considered for the ion microprobes.

## 2. Dynamics of a beam at the PFS

The study is based on the evaluation of the beam spread in various raster points. The similar task was examined in [3], however, scanning in the x direction only was considered there and with the following simplifications: a mono-energetic beam, a deflection field assumed to be uniform inside the scanner and zero outside it (sharp cut-off fringe field or SCOFF model), the first-order trajectory equations in the scanner.

Here I used the trajectory equations along the $z$ axis, each particle of the beam was described through the $x$, $y$ coordinates counted off the optical $z$ axis, and the path inclinations $x'$, $y'$, where $x' = dx/dz$, $y' = dy/dz$. In contrast to [3], within the SCOFF model I have taken into account the third-order terms and chromatic phenomena caused by a discontinuous jump of the field derivative at the edge of the deflector using the $\delta = (p - p_0)/p_0$ term which is a relative divergence between the $p$ particle impulse and the $p_0$ average particle impulse at the moment of passing through the plane of the object collimator. The deflector was assumed to be two plates parallel to the $xz$ plane (similar equations would be for $yz$ plane if exchange $x$ and $y$) with the $r$ distance between them, with the $\Delta\varphi$ potential difference; the beginning of the plates was taken as 0 and their effective length was $L_c$. Limiting conditions for the boundary value problem before the deflector were $y|_{z=0} = y_i,\ y'|_{z=0} = y'_i$. The solution of this problem with the third-order terms was found as

$$y = y_i + L_c \cdot y'_i + L_c/2 \cdot \Delta y' \quad (1)$$

$$y' = y'_i + \Delta y' \quad (2)$$

$$\Delta y' = L_c\alpha \cdot ((1 - 2\delta)(1 + x'^2 + y'^2) + 3\delta^2 - 4\delta^3)$$

$$\alpha = -\frac{\Delta\varphi}{2Vr}$$

Eqs. (1) and (2) do not take into account the focusing effect that is proportional to the ratio of $r/L_c$, that may be determined by the method in [5]. At the same time Eqs. (1) and (2) account a change of a particle energy at the entrance and the exit of the deflector through the terms of the $\delta$ kind. More recent works [6,7] provide all aberration coefficients for quadrupoles and the rules for the calculation of the whole system coefficients using the coefficients of individual elements.

The study was performed within the project on construction of proton beam writing channel in the institute. The PFS of this channel is developed as a quadruplet with four independent power supplies [8], with demagnifications 133.2 × 164.1 (horizontally and vertically), the length $L$ is 6.681 m, $g$ is 70 mm. Geometric parameters are planned to be: the distance from the object to the first lens is 358.2 cm; the distances between lenses in doublets are as follows: 3.94 cm between the first and the second and 3.18 cm between the third and the fourth lenses; the distance between doublets (between the second and the third lenses) is 270.2 cm; the working distance is 70 mm; the effective lens lengths are $L_{1,eff}$ = 5.068 cm, $L_{2,eff}$ = 7.141 cm, $L_{3,eff} = L_{4,eff}$ = 6.825 cm; the lens bore radii are $r_{a1} = r_{a2}$ = 6.5 mm, $r_{a3} = r_{a4}$ = 7.5 mm; the distance between the object and the angular collimators is 195 cm, the deflector on $x$ is the first after the second lens and is of 70 mm length with 5 mm distance between the plates, then the deflector on $y$ that is of 280 mm length with 4 mm distance between the plates is placed in the distance 5 mm, and then in 344 mm distance the third lens is placed. Arrangement of excitations is $C1D2C3D4$, where $Cn$ or $Dn$ denotes connection to a supply with number $n$ ($n = 1\ldots4$) thus the lens focuses the beam on x or $y$ direction, correspondingly. Energy of the beam assumed to be 1.5 MeV, $\delta_{max}$ is $5 \times 10^{-4}$.

Basic probe size $d_0$ is 512 × 518 nm$^2$ (0.27 μm$^2$), object aperture is of size 36 × 80 μm$^2$ and angular aperture is 48 × 130 μm$^2$. The aperture sizes remain the same during calculations because there is not any way to change them quickly and precisely during the experiment. For the practical tasks at this channel the scanning raster should be about 1 mm$^2$. Distribution of beam current density at the system entrance was taken from [9].

The electrostatic scanner for the separated quadruplet is incorporated between two lens doublets. Such an arrangement is said in [3] to provide smaller broadening of the probe in comparison to that in case of the scanner placed in front of the whole system and it should give an opportunity to scan without considerable blurring up to 1 mm$^2$ for the systems where $g$ = 180 mm.

Focus depth is shifted by the third and the fourth lenses that are not coupled by power to the first doublet [8], otherwise the dynamic focusing is meaningless to speak of because it is not possible to re-adjust the whole lens system considering the hysteresis loops of four lenses in an instant.

## 3. Dynamic focusing in a quadruplet

Fig. 1 shows the effect from the dynamic focusing usage. Because of the task symmetry, only one fourth of the raster was considered. The $G$ focus depth was varied about $g_0$ = 70 mm, the current in the first two lenses remained constant, the current in the third and the fourth lenses was changed to provide the focusing in the $G$ plane. If $G$ is optimally chosen (Fig. 1d), the FWHM probe size is reduced (compare Fig. 1a and b) from $d_{Nx} * d_{Ny}$ to $d_x * d_y$. In Fig. 1c the ratio $(d_x * d_y)/(d_{Nx} * d_{Ny})$ is shown.

For deflections on $y$ < 100 μm the dynamic focusing is not required, but its significance stably increases further. Compensation of blurring is mainly effected on the $y$ direction; the optimal focus depth neatly correlates with the deflection on $y$. It is from Fig. 1a that the conclusion of [3] that the quadruplets without considerable spreading may perform scanning within 2–3 mm is wrong when more accurate model is used and both principal directions $x$ and $y$ are considered. The paraxial approximation is no longer valid at the raster of 500 × 200 μm$^2$.

The process in the selected point with (0.25;0.25) mm coordinates away from the optical axis is shown in details in Fig. 2. Initial probe 512 × 518 nm$^2$ deflected by (0.238;0.203) mm grew to 33.9 × 24.1 μm$^2$ (FWHM) for $G = g_0$. The necessary deflection (0.25;0.25) mm therewith could not be attained, the spherical aberrations limited the deflection with (0.238; 0.203) mm, on further increase of $\Delta\varphi$ the beam deflection on the target even reduced but the probe size still enlarged. On focusing at $G$ = 72.2 mm the probe size in the plane $g_0$ = 70 mm reduced to 1.4 × 9.0 μm$^2$ (FWHM), the deflection on the target could be made the specified (0.25;0.25) mm. The probe area was 65 times decreased.

Fig. 3 explains the correlation between the beam characteristics and the deflection on $y$. Asymmetry of the optics of the quadrupole system causes the beam to stay close to the optical axis in the $x$ plane; but the beam is deflected by $y$ to a great extent where the beam gets to the zone of spherical aberration influence. The similar data were published for the triplet [4, fig. 6] too but there the beam suffers from a greater degradation in the $x$ direction.

The focus depth increasing by 3.1% of the 1.5 MeV ion beam was provided by the change of the magnetic induction in the third lens