PROBE FORMATION IN PROTON BEAM WRITING FACILITY AT IAP NASU

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The principles of a proton beam writing facility were described. Particular attention was paid to the problem of probe-forming system design. It was shown that using of separate systems and parts of the scanning nuclear microprobe is the most effective solution. Various probe-forming system configurations for proton beam writing facility have been investigated. The optimization problem of proton beam formation was solved. On the base of this solution the probe-forming system which has best corresponded to requirements for the lithographic process has been found.

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INTRODUCTION

The progress in nanotechnology relates to overcoming the difficulties of 3D structures fabrication with a high aspect ratio and characteristic dimensions less than 100 nm. This causes an interest in developing of alternative techniques for high-resolution lithography. Currently, the proton-beam writing (PBW) method of 3D micro- and nanostructure fabrication, based on the exposure of the material surface by a focused beam of protons with an energy of a several MeV, is well developed [1, 2]. Protons with a few MeV energy in contrast to electrons (e-beam lithography, EBL) [3] and slow heavy ions (Focusing Ion Beam, FIB) [4] have a number of characteristic features while moving in materials. These features are related to the fact that the probability of a proton interaction with atomic electrons is a few orders of magnitude larger than its scattering by atomic nuclei of the irradiated material. Since the effect of proton-electron interaction is small, the trajectory of protons on the first half of the path in material is close to a straight line. The low energy of secondary electrons is a result of the high mismatch in mass differences of the proton and the electron that gives a low proximity effect. Therefore, the advantage of this technology is a possibility to obtain structures with smooth and straight walls. The fact that the penetration depth of protons for the selected material depends on its energy enables to create complex three-dimensional multilayer structures.

Scanning nuclear microprobe (SNMP) [5, 6] is a hardware for proton beam writing, where a beam of protons accelerated by electrostatic accelerator to the energy of a few MeV is focused by the system of magnetic quadrupole lenses (MQL). The possibility of writing process is directly related to the characteristics of SNMP's probe-forming system (PFS). It should focus a proton beam into a spot with the minimum size and maximum current on the surface of irradiated material. This requires of the PFS with a high demagnification and large acceptance. In this paper, the principles to choose a PFS for proton beam writing facility of analytical accelerator-based facility (AABF) at the Institute of Applied Physics, National Academy of Sciences of Ukraine (IAP NASU) are reviewed.

1. BASIC PRINCIPLES OF FOCUSING SYSTEM CONFIGURATION

The SNMP is one of AABF's channels at the IAP NASU [7]. Its main applications are the study of structure and elemental composition of samples of different origin [8, 9]. The main methods of such studies are nuclear-physical techniques like μ-PIXE and μ-RBS. For these techniques, the magnitude of the beam current I ~ 100 pA is determined by small cross-sections of the processes of particle induced X-ray emission and backscattered ions respectively. To obtain the desired current the rectangular window of object collimator must be opened to 40 μm due to the low brightness of the beam. The size of the probe is provided at the level of 2 μm, because PFS at the conventional SNMP has low demagnification D = 23. To reduce the probe size requires decreasing the size of collimator windows. On the other hand, this reduces the beam current and leads to an increasing in the proportion of ions scattered on the collimators jaws. Due to the influence of aberrations, such ions are focused inadequately on the sample surface that results in deterioration of the microprobe resolution. Therefore, parameters of the current SNMP largely do not meet the requirements for proton beam writing facilities for the fabrication of small structures with typical dimensions of < 100 nm. It is necessary to use new PFS with demagnification D > 100 that can be implemented by using a multiplet of MQL with a fundamentally new focusing system configuration. A distinctive feature of this new PFS is the using of four independent power supplies of MQL. Currently PFS with two power supplies of MQL is used in SNMP of IAP NASU. This is necessary for stigmatic focusing of the beam, when Gaussian planes in two transverse directions are matched with the plane of irradiated sample. In this case, the definition of the currents of two power supplies, which are used to supply lens coils, is reduced to the solution of two transcendental equations

$$f_x(I_1, I_2) = 0,$$
$$f_y(I_1, I_2) = 0,$$

where I_1, I_2 are currents in coils of lenses from two power supplies.

In the case of four power supplies, there are infinitely set of solutions of choosing lens excitations. Therefore, the currents of two additional power supplies are determined by solving of the optimization problem, where a figure of merit is the acceptance of PFS. The acceptance is defined as a maximum quantity of the trajectory phase volume of the beam formed by rectangular object and angular collimators, which can be focused into a probe of specified size *d*. Optimization problem in this case is a nonlinear programming problem in the form

$$\Omega^*(d) = \max_{r_x, r_y, R_x, R_y, \boldsymbol{\tau}} [\Omega(\boldsymbol{\tau}, d)],$$

$$\Omega(\boldsymbol{\tau}, d) = vol(\Theta(\boldsymbol{\tau}, d)),$$

$$|B_i| \le B_{i\max},$$

$$f_x(I_1,I_2,I_3,I_4)=0, \quad f_y(I_1,I_2,I_3,I_4)=0,$$

$$\Theta = \{(x_0, y_0, x_0', y_0', \delta_0) \,|\, |x_0| < r_x, |x_0| < r_y,$$

$$\frac{-R_x - x_0}{a_0} \le x_0' \le \frac{R_x - x_0}{a_0}, \quad \frac{-R_y - y_0}{a_0} \le y_0' \le \frac{R_y - y_0}{a_0},$$

$$|F_x(z_t)| \le d/2, \ |F_y(z_t)| \le d/2,$$

$$|\delta_0| \le \delta_{\max}/2\},$$

where $\boldsymbol{\tau} = \{I_1, I_2, I_3, I_4, a_1,\ldots,a_N, a_g, L_{1,eff},\ldots, L_{N,eff}\}$ is a vector of parameters that affects the beam formation in the quadrupole PFS, N is a quantity of MQL in the system, a_i is a drift gap before lens with the number I, a_g is a working distance, B_i, $L_{i,eff}$ are a magnetic induction at the pole and the effective length of the lens with the number I;

$\Theta(\boldsymbol{\tau},d)$ is a phase volume of the beam ions formed by using of object and angular collimators;

r_x, r_y, R_x, R_y are dimensions of the rectangular object and angular collimators;

$F_x(z_t)$, $F_y(z_t)$ are nonlinear transformation of phase coordinates of ions from the object collimator plane into the plane of the irradiated sample, due to the influence of aberrations;

δ_{max} is a maximum momentum spread of the ions in the beam.

In works [10 - 12] it was shown that the probe-forming systems with additional power supplies of lenses have a set of advantages in compare to systems with two power supplies. Such PFS have a higher acceptance and possibility to change the demagnification in a wide range.

The most efficient solution in designing of PBW facility is to use separate elements and systems of existed microprobe (Fig. 1, positions 1-6), while the microprobe channel still can be used for its original objectives. This allows to reduce costs and space occupied in the experimental hall. General scheme of PBW facility at IAPis shown in Fig. 1. Collimators of PFS uses an object (position 1) and angular (position 2) collimators of microprobe.

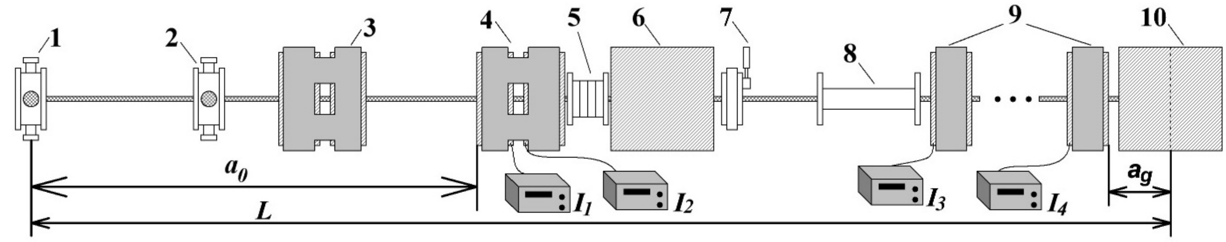

Fig. 1. Scheme of the PBW's probe-forming system at IAP NASU: 1 – object collimator; 2 – angular collimator; 3, 4 – integrated doublet of MQL; 5 – magnetic scanning system; 6 – microprobe target chamber; 7 – vacuum valve; 8 – electrostatic scanning system; 9 – final multiplet of MQL; 10 – PBW chamber

The PBW lens system consists of the second integrated doublet of MQL of SNMP (position 4) and the final multiplet (position 9). Design feature of integrated doublet is that the yoke and poles are made from a single piece of soft iron (Fig. 2,a) using the electrical discharge machining.

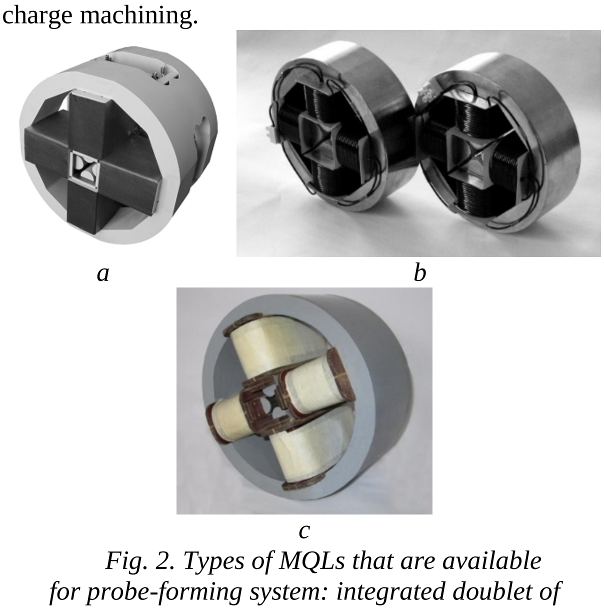

Fig. 2. Types of MQLs that are available for probe-forming system: integrated doublet of MQL (a); OM50m lens (b); IAP lens (c)

The design ensures the identity of the magnetic fluxes in all four poles of each doublet's lens and the precision positioning of the poles to provide quadrupole symmetry [13]. This design also allows accurate alignment of the doublet axes with the beam axis, which is necessary in separated PFS to reduce lens positioning aberrations. The outside diameter of the yoke is 235 mm, aperture radius is 6.5 mm, lens lengths are 65 and 44 mm, and the distance between the lenses is 46 mm. The maximum value of the magnetic field on the pole is 0.45 T.

Two modernized MQLs – OM50m and IAP MQL – are available for the final multiplet of MQL (position 9).

The pole form of IAP lens (see Fig. 2,c) is similar to integrated doublet and differs only in increased length [14]. The yoke of IAP lens has cylindrical shape with a diameter of 235 mm, length is 110 mm and an aperture radius is 6.5 mm, the maximum value of the magnetic field on the poles is no more than 0.4 T. Two OM50 type MQLs (Oxford Microbeams Ltd [15]) (see Fig. 2,b) have been modified. The modification was in replacing the current-carrying coils to allow using power supplies with a maximum current of 10 A In this case, the maximum achievable value of magnetic field on the poles is 0.2 T, length of the lens is 60 mm, aperture radius is 7.5 mm, and yoke outside diameter is 200 mm.

Thus, seven configurations of final multiplet have been identified employing between 2 and 3 lenses, as shown in Fig. 3. The notations of configurations are: *C* means that lens focuses in the plane xOz and defocuses in the plane *yOz*, *D* means that lens defocuses in the plane *xOz* and focuses in the plane *yOz*, number indicates the power supply connected to the lens. The spacing between lenses of all configurations is fixed and equal 32.5 mm.

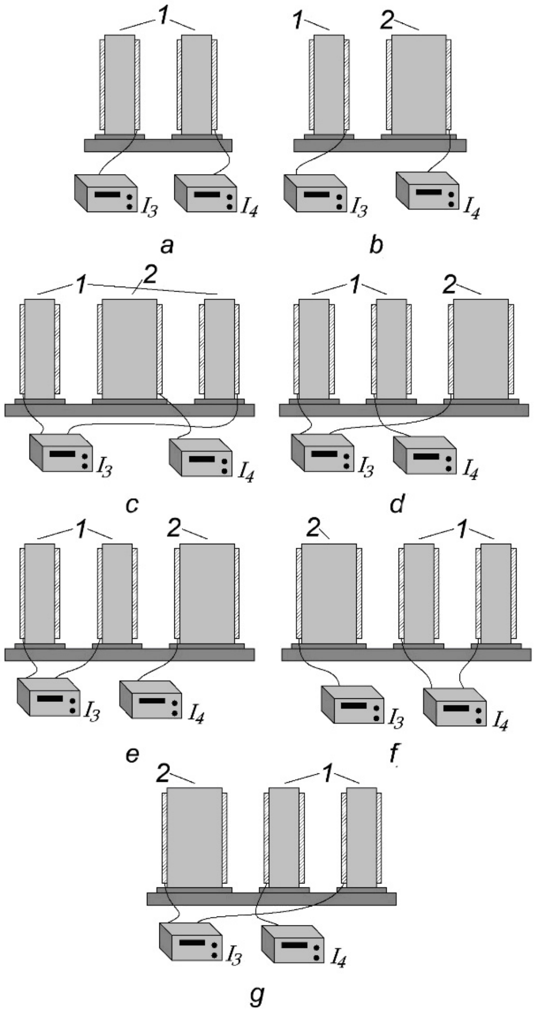

Fig. 3. Configurations of the final multiplet of MQL. In consideration of the integrated doublet of MQL, PBW lens systems are: quadruplet 1 (a); quadruplet 2 (b); quintuplet 1 (c); quintuplet 2 excitation mode (C3D4C3) (d); quintuplet 2 excitation mode (C3C3D4) (e); quintuplet 3 excitation mode (C3D4D4) (f); quintuplet 3 excitation mode (C3D4C3) (g). Types of lenses: 1 – OM50m; 2 – IAP

2. SIMULATION

Simulation was performed for 1.5 MeV proton beam with $5{\cdot}10^{-5}$ energy spread. The system length (from object collimator to target) was L = 661.1 cm. Object-lens distance for all configuration was a_0 = 345.3 cm. Linear properties of the focusing system were determined using a numerical code PROBFORM [16] based on the matrizant method [17]. The working distance a_g was varied by moving the final multiplet along the beam axis in the range 4…25 cm. For each position the optimal system parameters were obtained with the criterion of maximum acceptance. The criterion was limited by the condition of the maximum current density, when the maximum possible ion current had to be focused into a spot size *d* in the image plane. Optimization process was described in [18, 19] and realized in the numerical code MaxBEmit.

The quadruplet 1 and quintuplet 2 with the excitation mode of the final multiplet (*C*3*C*3*D*4) (Fig. 4) showed the best performances for 4…9 cm and 10…25 cm working distance range respectively.

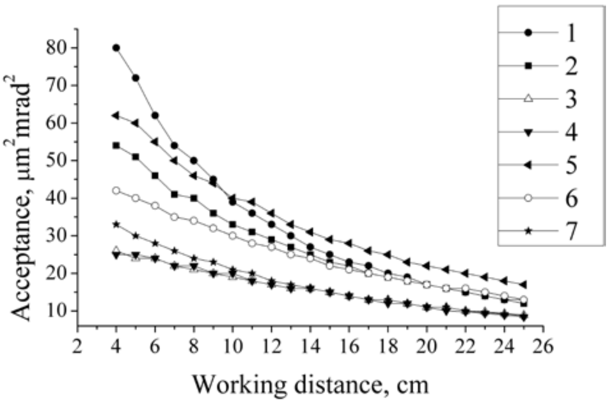

Fig. 4. Acceptance: 1 – quadruplet 1; 2 – quadruplet 2; 3 – quintuplet 1; 4 – quintuplet 2 excitation mode (C3D4C3); 5 – quintuplet 2 excitation mode (C3C3D4); 6 – quintuplet 3 excitation mode (C3D4D4); 7 – quintuplet 3 excitation mode (C3D4C3)

These two configurations are of the greatest interest. It should be mentioned that the working distance reduction is limited by the physical parameters of the lens. However, as seen in Fig. 5 the magnetic field required for the second lens of the quadruplet 1 at the range of 4…18 cm working distance exceeds the value of the saturation of magnetic field of 0.2 T for that type of lens. At the same time, the obtained magnetic field of all lenses of the quintuplet 2 (see Figs. 5, 6) does not exceed the maximum value.

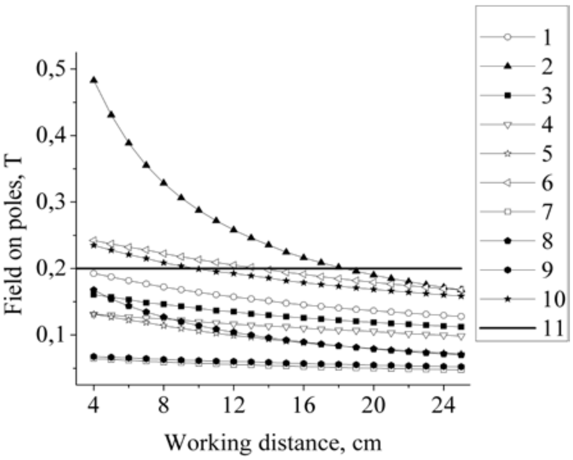

Fig. 5. Required field on poles of lenses OM50m: 1 – lens 1 quadruplet 1; 2 – lens 2 quadruplet 1; 3 – quadruplet 2; 4 – quintuplet 1; 5 – lens 1 quintuplet 2 excitation mode (C3D4C3); 6 – lens 2 quintuplet 2 excitation mode (C3D4C3); 7 – quintuplet 2 excitation mode (C3C3D4); 8 – quintuplet 3 excitation mode (C3D4D4); 9 – lens 1 quintuplet 3 excitation mode (C3D4C3); 10 – lens 2 quintuplet 3 excitation mode (C3D4C3); 11 – maximal field on poles

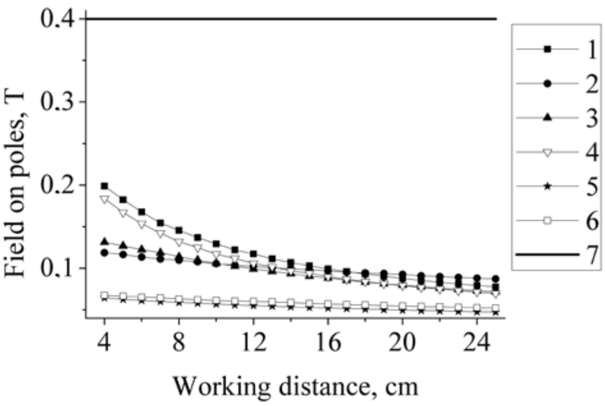

Fig. 6. Required field on poles of lens IAP:
1 – quadruplet 2; 2 – quintuplet 1; 3 – quintuplet 2 excitation mode (C3D4C3); 4 – quintuplet 2 excitation mode (C3C3D4); 5 – quintuplet 3 excitation mode (C3D4D4); 6 – quintuplet 3 excitation mode (C3D4C3); 7 – maximal field on poles

These results indicate that an optimum PFS is quintuplet 2 with the excitation mode of final multiplet (*C*3*C*3*D*4), because such configuration in practice can ensure maximum acceptance for small working distances. Table shows parameters of the optimum probe-forming system.

Working distance, cm	11
Field on poles, T	
B_1;B_2	-0.1254000;0.1648000
B_3;B_4	0.0567160;0.1119512
Demagnifications $D_x \times D_y$	102×(-127.5)
Chromatic aberrations, µm/mrad/%	
$< x / x'\delta >$	-175990.5
$< y / y'\delta >$	21053.8
Spherical aberrations, µm/mrad/%	
$< x / x'^3 >$	16301.5
$< x / x'y'^2 >$	3661.2
$< y / y'^3 >$	-332.1
$< y / y'x'^2 >$	-2929.6
Acceptance, µm^{2}mrad^2	39

CONCLUSIONS

Seven configurations of PFS for proton beam writing facility was determined basing on available magnetic quadrupole lenses and considering their different excitation by four independent power supplies. For each configuration, the ion-optical characteristics were calculated and the optimal parameters based on the value of maximum acceptance were determined. Comparison of simulation results showed that the quintuplet 2 with the excitation mode (*C*3*C*3*D*4) is the optimum probe-forming system for PBW facility, because it has the highest achievable acceptance on entire range of the considered working distances as well as can provide the demagnification D > 100.

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ФОРМИРОВАНИЕ ПУЧКА В КАНАЛЕ ПРОТОННО-ЛУЧЕВОЙ ЛИТОГРАФИИ ИПФ НАНУ

А.С. Лапин, А.Г. Пономарев

Дано описание принципов построения канала протонно-лучевой литографии. Особое внимание уделено задаче по созданию зондоформирующей системы. Показано, что наиболее эффективным решением является использование отдельных систем и устройств канала ядерного сканирующего микрозонда. Рассмотрены различные конфигурации зондоформирующей системы канала протонно-лучевой литографии. На основании решения оптимизационной задачи по формированию пучка протонов найдена зондоформирующая система, которая наилучшим образом отвечает требованиям для проведения литографического процесса.

ФОРМУВАННЯ ПУЧКА В КАНАЛІ ПРОТОННО-ПРОМЕНЕВОЇ ЛІТОГРАФІЇ ІПФ НАНУ

О.С. Лапін, О.Г. Пономарьов

Надано опис принципів побудови каналу протонно-променевої літографії. Особливу увагу приділено завданню щодо створення зондоформуючої системи. Показано, що найбільш ефективним є рішення з використання окремих систем і пристроїв каналу ядерного скануючого мікрозонда. Розглянуто різні конфігурації зондоформуючої системи каналу протонно-променевої літографії. На підставі рішення оптимізаційної задачі з формування пучка протонів знайдена зондоформуюча система, яка найкраще відповідає вимогам для проведення літографічного процесу.