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Recent status of the Kiev nuclear probe

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ABSTRACT

The modified Van de Graaff accelerator with proton beam energy $W \leqslant 3$ MeV has been installed and put into operation at the TMM laboratory in Kiev. The laboratory incorporates the nuclear probe (NP) beam line, coupled to this accelerator. A short version of an optimized probe-forming system (PFS) has been developed for the Kiev NP. The system is based on divided triplet of the magnetic quadrupole lenses (MQLs). This PFS has two working regimes for the probe operations. The results of numerical calculations of the geometrical and ion-optical parameters of the PFS are presented. It is shown that this versatile PFS is a promising design for a modern nuclear nano-probe. A new precision adjustable MQL has been designed. Three lenses, the slit systems and target chamber are manufactured and installed at the Kiev probe beam line. Also a new data acquisition system for the Kiev NP is being developed.

1. Introduction

Recently an upgraded analytical unit has been installed and put into operation on the 3 MV Van de Graaff accelerator (HVEC, KN-3000) at the TMM Research laboratory “Spectra” in Kiev. The unit is equipped with a double-focusing 90° energy-analyzing dipole magnet, control slits and a precision voltage stabilizer system (High Voltage Engineering Europe and Projekt Elektronik GmbH). The system ensures an excellent energy stability of the ion beam $\Delta W/W \sim 0.01\%$ and user friendly accelerator control.

The short (~3.5 m) NP beam line is attached directly to this unit. As it has been shown [1,2], the short (total length $l = 3.25$ m) optimized PFS based on a divided triplet of the MQLs with the lens coupling: +C – A + B is promising for the high-current (50–100 pA beam spots) micro-/nano-probe applications (e.g. PIXE, RBS). This triplet system with one intermediate crossover has a moderate demagnification factor: $|D_x| \sim |D_y| \sim 14$. The extreme insensitivity to the dominant aberrations (spherical, parasitic and chromatic) is the main advantage of this PFS. This opens the way for the use of adjustable lenses as focusing elements for the NP [3], which can be manufactured cost effectively.

The goal of this paper is to demonstrate the potential of the developed two-regime (+C – A + B/+A – A + B) triplet PFS connected to the above mentioned unit to provide the Kiev probe with submicron spatial resolution in the high-current mode. Precision adjustable magnetic quadrupole lenses, a probe slit system and a target chamber were designed and manufactured for the NP. In the present paper the features of the probe under construction are described.

The computerized data acquisition system (DAS) is an important part of the presented NP. The main task of the newly developed DAS is to provide the easily configurable system for standard analytical techniques (PIXE/RBS/NRA/STIM). In the paper the merits of the system are discussed.

2. Calculated versatile two-regime NP

2.1. Formulation of the task

The parameters prescribed (Table 1, column 1) are dimensions of the PFS elements. The beam spot size and current can be determined from the following parameters: brightness b of the ion (protons in this paper) beam, beam emittance E at the PFS entrance, average ion energy W and momentum spread $\delta = \Delta p/p$ of the ions in the beam. In our non-relativistic case: $\delta = \Delta W/(2W)$.

The present paper describes the application of the first optimizing approach to PFS [3]. In order to optimize the PFS it is necessary to obtain the beam spot size d_x and d_y at the specimen surface (spatial probe resolution) at maximal micro beam current: $I_m = E_m bW$, where $E_m = (x_0 y_0 \theta_0 \varphi_0)_m$ is maximal phase-space of the ions that can be accepted by the PFS. On the other hand the value E_m can be determined by geometrical parameters of the PFS slits: $E_m = 4d_{1x} d_{1y} \theta_{0m} \varphi_{0m}$, where d_{1x} and d_{1y} are the aperture sizes of the object slit, the angles θ_{0m} and φ_{0m} are the maximal pre-lens beam divergence (half angle).

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Table 1
Comparison of ion-optical parameters of the Kiev PFS with four existing probe forming systems [3].

Systems	Classic RQ (MARC)	Long DRQ (Leipzig)	Short DRQ (Cracow)	Classic triplet (Oxford)	Short divided triplet (Kiev) regime 1	Short divided triplet (Kiev) regime 2
Coupling	+A − B + B − A	+A−B + B − A	+A − B + B − A	+A − A + B	+C − A + B	+A − A + B
Overall system length (m)	8.3	9.27	2.3	7.4	3.25	3.25
S_{12} (m)[a]	0.03	0.033	0.033	0.05	1.68	1.68
S_{23} (m)[a]	0.03	2.45	0.64	0.05	0.033	0.033
Working distance (mm)	155	300	150	152	140	140
Effective quadrupole length (mm)	27.7	64	64	108	73	73
Lens bore diameter (mm)	12	12.7	12.7	15	12.7	12.7
Maximum pole-tip field, 3 MeV protons (T)	−0.227	0.2	0.323	0.218	0.25	0.25
Demagnification						
D_x	−25	110	17.6	92	14	127
Dy	−25	110	17.6	−26	−14	−39
Rotation aberration (μm/mrad^2)						
$\langle x/\varphi\rho_1\rangle$, $\langle y/\Theta\rho_1\rangle$	−26	6	2	7; −29	0.4; −0.4	0.2; −0.6
$\langle x/\varphi\rho_2\rangle$, $\langle y/\Theta\rho_2\rangle$	63	−3	0.1	14; −61	10; −10	28; −92
$\langle x/\varphi\rho_3\rangle$, $\langle y/\Theta\rho_3\rangle$	−51	188	13	−20; 90	−10; 10	−28; 92
$\langle x/\varphi\rho_4\rangle$, $\langle y/\Theta\rho_4\rangle$	14	−191	−15	–	–	–
Chromatic aberration (μm/mrad/%)						
$\langle x/\Theta\delta\rangle$	130	−1861	−281	−343	−31	−260
$\langle y/\varphi\delta\rangle$	173	−542	−68	873	173	485
Spherical aberration (μm/mrad^3)						
$\langle x/\Theta^3\rangle$	−112	64,270	161	426	1.3	990
$\langle x/\Theta\varphi^2\rangle$	−370	30,530	26	207	9	660
$\langle y/\Theta^2\varphi\rangle$	−370	30,530	26	−743	−9	−2157
$\langle y/\varphi^3\rangle$	−262	4900	6	−2197	−47	−1014
Figure of merit Q_s	20	18	33	24	50	50
Figure of merit Q_c	0.028	0.012	0.016	0.008	0.036	0.039
Parasitic aberration sensitivity						
Largest sextupole term (μm/mrad^2/%)	$\langle y/\Theta\varphi s\rangle$	$\langle x/\Theta^2 s\rangle$	$\langle x/\Theta^2 s\rangle$	$\langle y/\Theta\varphi s\rangle$	$\langle y/\Theta\varphi s\rangle$	$\langle y//\Theta\varphi s\rangle$
	−827	−41,350	−665	1733	113	2968
Largest octupole term (μm/mrad^3/%)	$\langle y/\varphi^3 o\rangle$	$\langle x/\Theta^3 o\rangle$	$\langle x/\Theta^3 o\rangle$	$\langle y/\Theta^3 o\rangle$	$\langle y/\Theta^3 o\rangle$	$\langle y/\Theta^3 o\rangle$
	−1530	410,000	−821	18,986	−304	8857

[a] S_{12} and S_{23} are the separation between the first and the second, the second and the third lenses, respectively.

The optimal acceptances of the PFS can be calculated by formulas [4]: $A_c \cong d^4/16D_xD_y/\delta^2/\langle x/\theta\delta\rangle/\langle y/\varphi\delta\rangle$ or $A_s \cong \frac{9}{16}d^{5/3}(D_x^4D_y^4/4/\langle x/\theta^3\rangle/\langle y/\phi^3\rangle)^{1/3}$, respectively depending whether chromatic or spherical lens aberrations are dominating. Therefore the value $Q_c = D_xD_y/(\langle x/\Theta\delta\rangle\langle y\varphi\delta\rangle)$ or $Q_s = D_xD_y/(\langle x/\Theta^3\rangle\langle y\varphi^3\rangle)^{1/3}$ can be used as a figure of merit for the PFS [5].

The present calculations were performed for a short ($l = 3.25$ m) divided triplet PFS [2] that can additionally produce a stigmatic point of beam focusing at a second working regime with the lens coupling +A − A + B. This made it possible to develop a versatile two-regime PFS in which the first regime (+C − A + B) is ideally suited for the routine specimen analysis by PIXE/RBS techniques at the NP facilities with user friendly adjustment, while the second working regime is optimized for a wide range of applications (PIXE/RBS/STIM) at the novel nano-probe beam line.

2.2. Results of the calculations and discussion

The values for the probe-forming systems (Table 1) and probe resolutions (Tables 2 and 3) are results of simulations using programs PRAM and OXTRACE, respectively [6]. The simulations are based on tracing 10,000 protons spread randomly over the entrance phase-space. It is assumed that the proton beam had uniform brightness and the slits (object and angular) had rectangular apertures.

The results of the optimized calculations for the Kiev PFS are given in Table 1, columns 6 and 7.

As it can been seen (Table 1, columns 4 and 6) the short PFSs demonstrate remarkable insensitivity to parasitic and intrinsic lens aberrations providing compromised demagnification. Therefore the short systems have higher coefficients Q_s and Q_c compared to those of conventional long PFSs (Table 1, columns 2, 3 and 5). In this respect the Kiev PFS with $Q_s = 50\ \mu\mathrm{m}^{-2/3}\ \mathrm{mrad}^2$ and $Q_c > 0.035\ \mu\mathrm{m}^{-2}\ \mathrm{mrad}^2(\%)^2$ seems to be the most attractive.

Table 2 shows that the Kiev system at the first working regime (+ C - A + B) is promising for a nano-probe operation in the high-current mode (100 pA beam spot) even with rather large parasitic components (0.3%) included in all lenses.

It is significant to note that the ion beam brightness is one of the key factors that determine the beam spot size in the high-current techniques. At present, our HVEC accelerator based on a standard radio-frequency ion source (*SO-173* HVEE) can generate the proton beam with $b = 20\mathrm{A/m^2/rad^2/eV}$ (Table 2).

As known [7], a high-brightness ($b = 74\ \mathrm{A/m^2/rad^2/eV}$) HVEE 3.5 MV ultra-stable ($\Delta W/W \leqslant 0.001\%$) Singletron accelerator of the Research Centre for Nuclear Microscopy (National University

Table 2
Calculated beam spot size for the Kiev probe at the first working regime of the PFS in the high-current mode at $W = 2.5$ MeV, $\Delta W/W = 0.02\%$ with 0.3% parasitic aberrations included in all lenses.

Beam brightness: b (A/m^2/rad^2/eV)	20
Object aperture: $d_{1x} \times d_{1y}$ (μm^2)	10 × 10
Pre-lens beam divergence: $\theta_{0m} \times \varphi_{0m}$ (mrad^2)	0.20 × 0.025
Beam spot size: $d_x \times d_y$ (μm^2)	0.95 × 0.95

Table 3
Calculated beam spot size for the Kiev probe at the second working regime of the PFS in the high-current mode (50 pA beam spots) at $W = 2.5$ MeV, $\Delta W/W = 0.02\%$ and with perfect MQLs.

Beam brightness: b (A/m^2/rad^2/eV)	70
Object aperture: $d_{1x} \times d_{1y}$ (μm^2)	32 × 10
Pre-lens beam divergence:$\theta_{0m} \times \varphi_{0m}$ (mrad^2)	0.012 × 0.005
Beam spot size: $d_x \times d_y$ (μm^2)	0.3 × 0.3