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PERMISSIBLE TECHNOLOGICAL LIMITATIONS OF QUADRUPOLE LENSES USED IN PARAMETER MULTIPLETS FOR ION MICROPROBE FORMING

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Parasitic components of lens field are ones of the main parameters that determine spatial resolution of the MeV energy ion microprobe based on parameter multiplet of the magnetic quadrupole lenses. The parameter set of probe-forming systems was examined, the maximum permissible parasitic components of the lens field were computed, technological limitations on pole tips positioning accuracy were determined such that aberrations caused by them did not result in substantial beam degradation. Influence of the field parasitic components on ion-optical properties of multiplets was estimated, and computation technique was presented.

INTRODUCTION

The magnetic quadrupole lenses are the main focusing elements to produce MeV energy ion microprobe. Taking into account of quadrupole lens physical features, a system of several lenses has to be used to provide stigmatic beam focusing on the target. Such a system is called a multiplet of magnetic quadrupole lenses [6].

Multiplet of lenses has a set of parameters that influence on system ion-optical properties such as demagnifications and aberrations. The set includes the following parameters [4]: number of multiplet lens *N*; total system length *l* (the distance between object collimator and the target); number of power supplies independent of each other *k*; distances a_i $(i=1\ldots N)$ between the lenses of multiplet; object distance $a=a_1$ (the distance between object collimator and the first lens of multiplet); working distance *g* (the distance between the last lens of multiplet and the target); effective length $L_{eff,i}$ and bore radius $r_{a,i}$ of lenses ($i=1\ldots N$); field parasitic sextupole $W_{3,i}$, $U_{3,i}$ and field parasitic octupole $W_{4,i}$, $U_{4,i}$ components of lenses ($i=1\ldots N$); beam momentum spread δ.

There is no necessity to form regular image at the target plane if the microbeam is used for technical purposes or substance analysis. In this case, probe-forming system (PFS) has to shape probe with maximum beam current at the spot on the target.

A parameter multiplet of magnetic quadrupole lens is defined as a multiplet with a set of parameters listed above.

A manufacture inaccuracy of lenses and an imperfection of lens adjustment system produce a distortion of quadrupole field symmetry. The distortion is the source of the field parasitic multipole components. These components result in the main parasitic aberrations that cause substantial beam degradation. Therefore, the problem of estimation of the influence of the quadrupole field parasitic components on PFS ion-optical characteristics is very important for practical purposes. The solution of the problem allows making recommendations about permissible lens manufacture accuracy.

FIELD PARASITIC COMPONENT COMPUTATION TECHNIQUE

The calculations of the parasitic sextupole and octupole components of magnetic quadrupole field involve the axial field model. It assumes that in the lens there is a straight-line optical axis along which the magnetic field $|\vec{B}|=0$. Naturally, this is an approximation corresponding to the averaged flight path of a particle that enters the lens at zero angles and retaining at the exit the position in the transverse plane and the direction of flight. The magnetic scalar potential $w(x,y,z)$ can represent the magnetic quadrupole lens field in the lens air gaps [1-3]. The potential satisfies the Laplace's equation $\Delta w=0$.

The entire lens adjustment may result in elimination of the dipole and the skew quadrupole field components. In this case, in the arbitrary Cartesian coordinates (*x*,*y*,*z*) where the *z*-axis is aligned with the optical lens axis, the magnetic scalar potential series expansion is represented as

$$\begin{aligned} w(x,y,z) &= 2W_2(z)xy + U_3(z)x^3 + 3W_3(z)x^2y - xy^2 - \\ &- 3U_3(z) - W_3(z)y^3 + U_4(z)x^4 + \\ &+ (4W_4(z) - W_2''(z)/6)x^3y - 6U_4(z)x^2y^2 - \\ &- (4W_4(z) + W_2''(z)/6)xy^3 + U_4(z)y^4 + \ldots \ , \end{aligned} \qquad (1)$$

where W_3, U_3 are desired sextupole and W_4, U_4 are desired octupole components and W_2 is the major quadrupole component of the field.

The difference between magnetic or corresponding electrostatic potential computations in gaps of magnetic circuit is non-essential if the circuit is made of ferromagnetic material that has a high value of magnetic permeability μ_r [1]. In this case, magnetic potential may be considered invariable on a surface area. Inaccuracy of this approximation is proportional to $1/\mu_r$. Two additional conditions have to be satisfied as well. The material of magnetic circuit has to be unsaturated and any external current influence may be negligible.

The scalar magnetic potential $w(x,y,z)$ in the lens working area was found using the charge-density method [2]. It is an integral method. It is known to be very accurate and ideally suited to determination of the field structure in ion-optic elements. It is permitting higher derivatives of the scalar potential to be calculated analytically by differentiating the integral operator nucleus. Potential and its higher derivatives may be found out in any point of definitional region. Non-closed boundary surface using is allowed as well.

The value of potential $w(x, y, z)$ in any point of definitional region $p = (x_p, y_p, z_p)$ and on the boundary area G as well can be represented as

$$w(p) = \int_G \sigma(q) / R_{pq} dS_G \ , \qquad (2)$$

where $p = (x_p, y_p, z_p)$ is the point where value of the potential is evaluated,

$q = (x_q, y_q, z_q)$ is a point on G area,

$R_{pq} = \sqrt{(x_p - x_q)^2 + (y_p - y_q)^2 + (z_p - z_q)^2}$,

dS_G – infinitesimal part of G area,

$\sigma(q)$ – virtual 'magnetic charge' surface density.

Unknown distribution of 'magnetic charge' surface density $\sigma(q)$ on G area is found out of suitable boundary condition

$$w(p)\big|_G = \int_G \sigma(q) / R_{pq} dS_G, \quad p, q \in G . \qquad (3)$$

Derivatives of w are calculated analytically by differentiating the integral equation (2) nucleus

$$\frac{\partial^{(i+j+k)} w(p)}{\partial x_p^i \partial y_p^j \partial z_p^k} = \int_G \sigma(q) \frac{\partial^{(i+j+k)}}{\partial x_p^i \partial y_p^j \partial z_p^k} \left(\frac{1}{R_{pq}} \right) dS_G, \qquad (4)$$

$$i,j,k = 0,1,2,\ldots$$

Multipole components of the magnetic field are evaluated by analysis of the magnetic scalar potential. Its derivatives are found out as a result of boundary-value problem (2-3) solution. Multipole components of the field at arbitrary point (x_l, y_l, z_l) can be represented as

$$W_2(z_l) = \frac{1}{2} \frac{\partial^2 w(x_l, y_l, z_l)}{\partial x_l \partial y_l} \bigg|_{x_l = y_l = 0} = \frac{1}{2} \int_G \sigma(q) \frac{\partial^2}{\partial x_l \partial y_l} \left(\frac{1}{R} \right)_{x_l, y_l = 0} dS_G,$$

$$W_3(z_l) = \frac{1}{6} \frac{\partial^3 w(x_l, y_l, z_l)}{\partial x_l^2 \partial y_l} \bigg|_{x_l = y_l = 0} = \frac{1}{6} \frac{\partial^3 w(x_l, y_l, z_l)}{\partial y_l^3} \bigg|_{x_l = y_l = 0}, \qquad (5)$$

$$U_3(z_l) = -\frac{1}{6} \frac{\partial^3 w(x_l, y_l, z_l)}{\partial x_l \partial y_l^2} \bigg|_{x_l = y_l = 0} = \frac{1}{6} \frac{\partial^3 w(x_l, y_l, z_l)}{\partial x_l^3} \bigg|_{x_l = y_l = 0}.$$

Algorithm of computation of the charge surface density, the potential, its derivatives, and the multipole components of the field is implemented in LAPLAS computer programme.

FIELD PARASITIC COMPONENTS EVALUATED

The calculations of the field parasitic sextupole and octupole components relative to the major quadrupole component versus the pole shifts and the excitation error were performed. These calculations were completed for real pole tip shapes.

Figures 1 to 3 represent sample computation results. Lens bore radius was 6 mm. All the shifts were performed to move away pole tips from the optical axis. If a pole tip shifted along y-axis, the pattern was similar to one retrieved in the pole tip shift along x-axis case if only $U_3 \leftrightarrow W_3$ and W_4 sign was inverted.

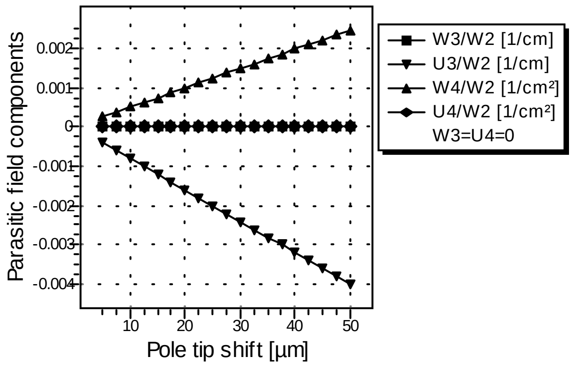

Fig.1 Parasitic field components as function of pole tip shifts. Two neighbouring pole tips were shifted along x-axis in the opposite direction

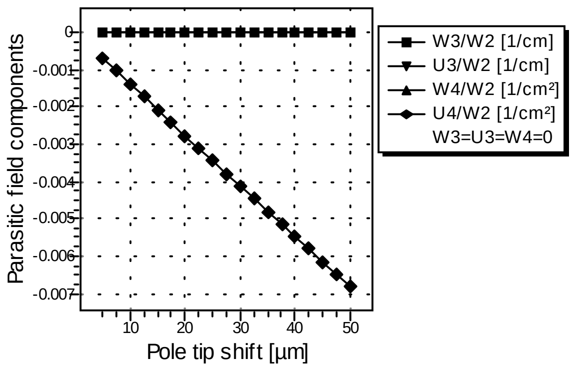

Fig.2 Parasitic field components as function of pole tip shifts. The opposite pole tips were shifted along x-axis and y-axis

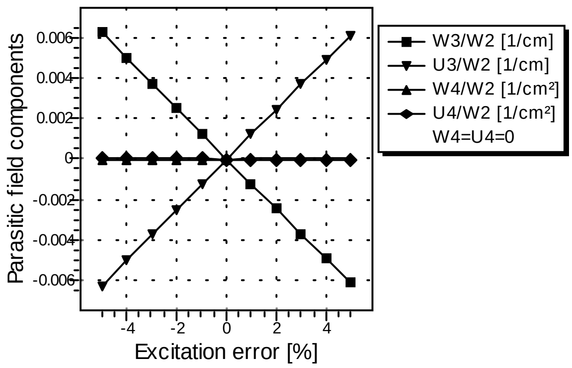

Fig.3 Parasitic field components as function of excitation error of single pole tip

It turned out, that the most serious cases of distortions of quadrupole symmetry took place when two neighbouring pole tips were shifted along *x*-axis in the opposite direction, and two opposite pole tips were shifted along *x*-axis and *y*-axis. The fastest growth of sextupole components took place in the first case (see Fig.1). The fastest growth of octupole component took place in the second case (see Fig.2). These dependencies were nearly linear.

Excitation error of a single pole tip resulted in the highest relative sextupole component value (see Fig.3) while excitation error influence was studied. The dependency was nearly linear. Octupole components were nearly independent of excitation errors.

Field parasitic components were found to be dependent of lens bore radius r_a. The dependency is represented on Fig.4.

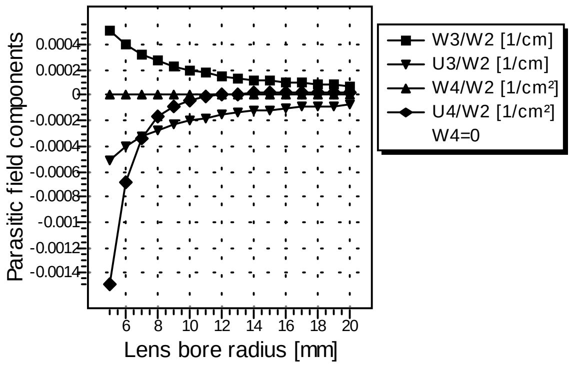

Fig.4 Parasitic field components as function of lens bore radius. Single pole tip was shifted along x-axis and y-axis for 10 µm

According to data represented on Fig.4, field parasitic components caused by quadrupole field distortions may result in negligible negative effects if the lenses are of large bore radius. On the other hand, these lenses are significantly weaker.

PFS PERFORMANCE CRITERION

Parameter multiplet allows the search for optimal systems by varying some of its parameters. The search can be fulfilled for different performance criterion.

Maximum beam current allowed by PFS while the beam spot size on the target is fixed was used as PFS performance criterion [5].

This criterion is taken place logically because of the requirements of analytical techniques used to substance analysis and investigation of the beam ion to target atom interaction phenomena. It is evident that the interaction count has a direct relation to total amount of incident particles in unit time. The spot size has to be the smallest simultaneously. It is necessary to allow determination of element distribution through sample.

Search has to be made for the systems that their relation of demagnifications to aberrations allows to shape the spot on the target with maximum current density. Thus, current density value in the spot on the target has to be accepted as PFS performance criterion. The systems that provide higher beam current while the spot size is fixed are preferred among PFS set.

It is known that beam current is evaluated as $I \approx b \cdot \varepsilon$ where *b* is beam brightness and ε is beam emittance. Brightness is the characteristic of ion source and beam transport system simultaneously. It is different for various accelerators. Thus, it is necessary for a general purpose PFS to have functional dependency $d = \partial^*(\varepsilon)$ where *d* is minimal beam spot size for the specified emittance ε. Function $\partial^*(\varepsilon)$ is monotone increasing for physical reasons (ε growth results in *d* increasing). Inverse dependency $\varepsilon = \varepsilon^*(d)$ can be constructed if the search procedure is looking up for the maximum beam emittance while beam spot size is fixed.

Maximum beam emittance method is implemented in MaxBEmit computer programme. It allows determining of the maximum beam emittance provided by the arbitrary PFS that is focusing beam to the spot of specified size on the target.

FIELD PARASITIC COMPONENTS INFLUENCE ON PFS ION-OPTIC PROPERTIES

The effect of lens field parasitic components on microprobe spatial resolution was simulated for the set of conventional magnetic quadrupole probe-forming systems. While varying the parameters of multiplet, some of them were fixed. These parameters were selected as to cover most microprobe available [4]:

lens count $N = (3;\ 4)$ (the Oxford high excitation triplet and the separated Russian Quadruplet);

effective lens lengths $L_{eff,\,i} = L = 6.4\,\text{cm}$;

lens power supply for the triplet $k_1 = k_2$ and for the Russian Quadruplet $k_1 = k_4$, $k_2 = k_3$, each even-number lens being rotated about basic position through 90°;

working distance $g = 10$ cm;

fixed distance in paired doublets $s = 3.3$ cm (for the triplet $a_3 = s$ and for the quadruplet $a_2 = a_4 = s$);

beam momentum spread $\delta = 10^{-4}$;

$a_1 = a$;

140.5 cm < l < 830.5 cm;

30 cm < $a < l - g - (N-2)*s - N*L$.

System length l and object distance a were varied to construct parametric multiplet set.

Maximum beam emittance allowed by PFS while the spot size if fixed was used as PFS performance criterion.

The calculations of the field structure in the lenses gave the dependence of maximum beam emittance on the field parasitic components. The increasing of relative sextupole $S = U_3/W_2 = W_3/W_2$ or octupole $O = W_4/W_2 = U_4/W_2$ components resulted in substantial emittance degradation.

The maximum permissible values of field parasitic components were found to be $S = 0.000375$ [1/cm] (sextupole) and $O = 0.000538$ [1/cm^2] (octupole) for the set of PFS been analyzed. These imposed limits upon the lens manufacture requirements (see Fig.5).

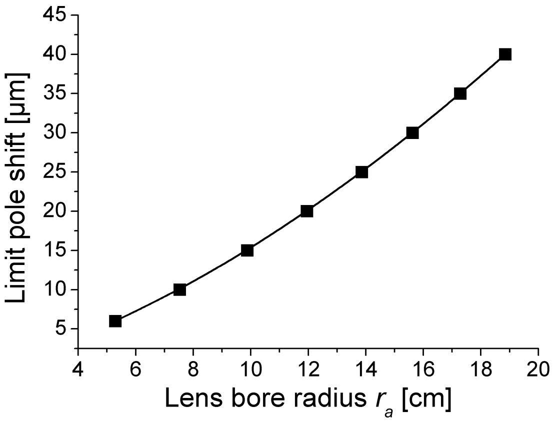

Fig.5 Permissible pole tip positioning inaccuracy as function of lens bore radius

Fig.6 represents the maximum beam emittance dependency on the required beam spot size and the level of parasitic field components of the magnetic quadrupole lenses. The Oxford high excitation triplet and the separated Russian Quadruplet were examined.

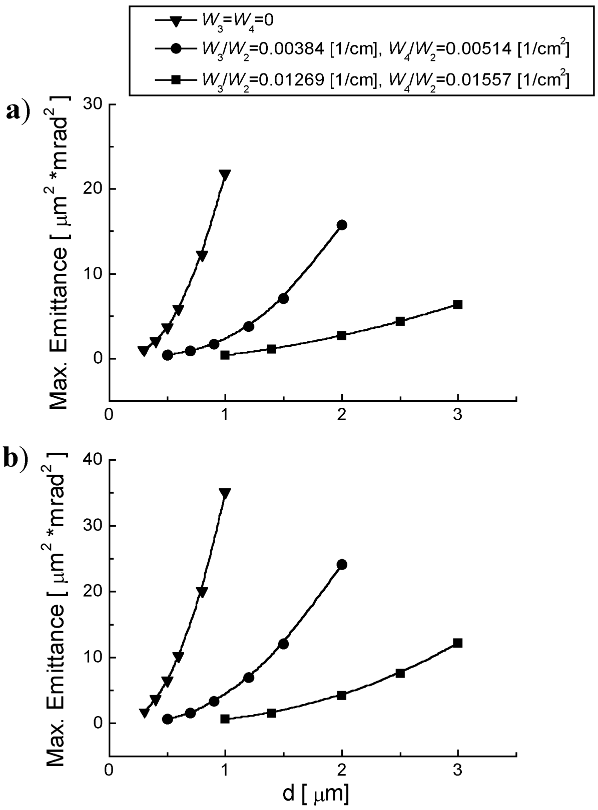

Fig.6 Maximum emittance as function of the beam spot size d on the target for some levels of parasitic components of the magnetic quadrupole lenses field. a) Oxford high excitation triplet; b) Separated Russian Quadruplet

Thus, it is possible to determine minimum beam spot size *d* on the target if the level of parasitic components of the magnetic quadrupole lenses field is known.

Comparing Fig.6a with Fig.6b, it is evident that the triplet has worse characteristics than the Russian Quadruplet. Maximum beam emittance is 30 % higher in the Russian Quadruplet than in the triplet if the conditions are equal. Thus, the separated Russian Quadruplet has to be the preferred system.

CONCLUSIONS

Some conclusions may be performed on the calculation result basis.

Evaluation of field parasitic components caused by lens manufacture inaccuracy and determination of its influence on beam degradation allowed to find out the maximum permissible field parasitic components for parameter multiplets of magnetic quadrupole lenses. Maximum permissible sextupole component was found to be $W_3 / W_2 = 0.000375$ [1/cm] and octupole component was found to be $W_4 / W_2 = 0.000538$ [1/cm^2] for the examined PFS set.

Permissible pole tip positioning inaccuracy is dependent of lens bore radius. The lens bore radius has to be as small as manufacture equipment may provide. In this case, field gradient has maximum value while the magnetic induction on the pole tip surface is the same. This allows minimization of lens effective length for specified lens strength. Ion-optical properties of PFS will be improved as a result. According to Fig.5 data, it is possible to specify the technological limitations for lens manufacture process.

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