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WIDE APERTURE MULTIPOLE MAGNETS OF THE KINEMATIC SEPARATOR **COMBAS**

Basic Principles of Magnets Design

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1. Introduction

At present two basic methods are used in nuclear physics laboratories for production of radioactive ion beams. In the first method radioactive beams are produced in the reactions of the projectile fragmentation in a target at intermediate and high energies. The target is followed by so-called fragment separator, in which ions are separated according to their magnetic rigidities and momentum losses in a degrader, a thin foil placed at the intermediate focus of the separator. This method has an advantage of in-flight separation of any kind, namely: very short-lived nuclei can be investigated immediately after their synthesis. Apart from this, the method is relatively not expensive. At the same time, the main problems of the fragment separation technique are those of contamination of secondary beams and, quite often, their rather low intensity. In the second technique, which is much more sophisticated, radioactive ions are produced in a target-ion source where the primary beam is stopped totally. Nuclear species born in the target are extracted and pass through several stages of separation and acceleration. Many stage separation combined with preacceleration between the stages allows one to achieve a very high level of purification for a wide variety of radioactive ions. Some most short-lived species, however, cannot be produced with such a technique.

In general, any fragment separator consists of three parts: two magnet sections containing bending magnets and an energy degrader in between. Nuclei produced in projectile fragmentation reactions are analyzed in the first section according to P/Q ratio, where P is ion momentum, Q ion charge state. Then, the ions pass through the degrader, which reduces the energy of ions. Such a reduction depends on nuclear charge Z and mass A of nuclei. Finally, the second section provides achromatic focusing at the exit of the separator, i.e. the radial focus position depends on the relative deviations of mass A, nuclear charge Z, ion charge state Q (but not the momentum) from those of the separated ion.

The kinematic separator COMBAS has been built for experiments with heavy ion beams at intermediate energies on the cyclotron U-400M in the FLNR JINR (fig.1) and can be used in the spectrometry mode. At the design stage the main requirements to the separator were as follows:

- the possibility of work at magnetic rigidities up to 4.5 T.m,
- maximum possible angular and momentum acceptances,
- high energy resolution at the intermediate focus,
- rather big, 5 mm, maximum size of the production target,
- quite short total length of the channel matching the available experimental aray in the U-400M hall in FLNR,
- minimization of power consumption and a small number of control elements.

To achieve the above requirements the following ideas have been implemented in the separator design:

- the use of only wide aperture bending magnets without (aperture reducing) quadrupoles let increase such important parameters as momentum and angular acceptances; as a result, combined function dipoles had to be used, i.e. dipoles containing quadrupole field components to provide radial an vertical beam focusing;
- the same idea has been used for multipole corrections: the 2nd and 3rd order multipole field components have been added to the main (bending and focusing) field of the dipoles; besides, special correcting magnets have been designed as dipoles containing higher order field components (hence, the separator has no special hexapole and octupole magnets reducing the aperture);
- the broad magnetic band of the main dipoles M1, M2 provided the required energy resolving power at the intermediate focus (for a given production target size);

- the requirement of quite high energy resolution and the use of the combined function magnets automatically provided necessarily short total length of the channel;
- the use of the low energy dispersion at the intermediate focus let keep the radial beam size relatively small for the required energy acceptance;
- the use of the symmetry of the magnetic structure and optical characteristics of the separator facilitated considerably optimization of its optics, reduced the price of the project and simplified tuning and exploitation procedures of the apparatus.

The main optical parameters of the separator one can find in table 1. The device is able to collect and separate nuclei in the range of magnetic rigidities from 0.5 to 4.5T*m within the solid angle of 6.4msr and energy acceptance of 40%. A wedge shaped degrader is used for isotope separation by A and Z. The identification of the separated particles can be performed by the TOF and dE-E methods. Short-lived exotic nuclei having time of life as small as 1μs can be separated with the device.

The separator COMBAS has been commissioned and is used at present in experiments to study mechanisms of nuclear reactions with heavy ions beams of N, O, S, Ar and Ca at energies 20-40 MeV/a.m.u..

2. The structure of the separator COMBAS

The kinematic separator COMBAS (see fig.2.) is a complicated magnet system with advanced ion-optical characteristics hitting a record in the class of similar experimental devices. The setup and its different systems have been described in details in [1], [2]. It has the following magneto-optical scheme: F_o M1 M2 M3 M4 F_d M5 M6 M7 M8 F_a , where F_o is a production target, M1-M8 the magnets, F_d the intermediate dispersive focus, F_a the exit achromatic focus. The short description of the eight separator magnets is given in [3]. The first two multipole magnets, M1 and M2, are analyzing, while the next two, M3 and M4, correcting. Analyzing multipole magnets have the deflection angle of 25 deg each, and the correcting magnets 7.5deg. The induction sign of M4 is opposite to that of M1-M3. Due to this M3, M4 do not practically influence the 1^{st} order resolving power and other 1^{st} order optical parameters, they are performed the corrections of the 2^{nd} and 3^{rd} order aberrations. The first section of the apparatus is terminated at the dispersive focal plane, where the nuclear fragments are separated according to their magnetic rigidity (or the momentum over ion charge state ratio) transmitting through the 1^{st} momentum slit. Then a degrader follows, in which fragments lose energy in accordance with their masses and nuclear charges.

The second section of the separator is mirror symmetrical with respect to the first one, the intermediate focal plane being the plane of symmetry. It consists of the two pairs of magnets, M5, M6 (counterparts of M4, M3, respectively) and M7, M8 (counterparts of M2, M1). The second section of the separator compensates the momentum dispersion of the first section and collects fragments in the exit achromatic focus F_a. The radial position of the focus depends on the deviation of a fragment mass, nuclear charge and ion charge state from those of the central fragment to be separated. The 2^{nd} slit is located at F_a providing final separation of the desired fragments from other species.

3. Optimization of the optical parameters

Numerical optimization of the separator 1^{st} order optics has been done with a code BETRAMF [4]. The requirements of high angular and momentum acceptances in combination with a high momentum resolution at the intermediate focus made it absolutely necessary to optimize the system taking into account nonlinear distortions

of beam dynamics in the separator. The method of the aberrational decomposition [5], widely used for the design of broad range magnet spectrographs, has been used for the calculation and optimization of the beam optics in COMBAS. A computer program TOREX [6,7], calculating aberrational coefficients up to the 3^{rd} order by raytracing, has been used for practical calculations. The following form of the aberrational decomposition is used in the program:

$$x_i(1) = \sum_{q=1}^{\infty} \sum_{k_1 \ldots k_6 \geq 0}^{k_1+\ldots k_6=q} (x|x_1^{k_1}\ldots x_6^{k_6}) x_1^{k_1}(0)\ldots x_6^{k_6}(0) \quad , \qquad (1)$$

where vector $X = (x_1 \ldots x_6)^T \equiv (x, p_x, y, p_y, \sigma, \delta)^T$ consists of the pairs of canonically conjugate phase space coordinates: the radial coordinate and momentum x, p_x, the vertical coordinate and momentum y, p_y and the longitudinal displacement of a particle from the reference position with its canonically conjugate momentum σ and δ respectively. In the linear approximation p_x, p_y coincide with angular deviations of a particle from the reference trajectory in radial and vertical directions, and the variable δ to the relative deviation of the particle relativistic momentum from its reference value.

The system was optimized for the object (target) generating particles with coordinates uniformly distributed within the volume:

$$\begin{aligned} &x^2 + y^2 \leq r^2, r = 2.5mm, \\ &p_x^2 + p_y^2 \leq p^2, p = 0.04rad, \end{aligned} \qquad (2)$$

and having momenta deviations from -6 % to +6 %. The aberrations in the focal plane have been optimized so that the focal plane were normal to the beam direction (the condition of this is $(x|p_x\delta)$=0) and the images (for the object (2)) having difference in momentum as large as 0.12% were resolved in the all intermediate focal plane.

The most important 2^{nd} order aberrations deteriorating momentum resolution were $(x|p_x^2), (x|p_y^2), (x|p_x\delta), (x|xp_x), (x|x\delta)$. These aberrations, and also the nonlinear dispersion $(x|\delta^2)$, have been minimized by introducing sextupole components in the radial field distributions of M1-M4 and curving field boundaries of the correcting magnets M3, M4. The other 2nd order aberrations were also taken into account in the minimization procedure to keep their values reasonably low. One should note the untypical importance of the aberrations $(x\,|\,xp_x), (x\,|\,x\delta)$, connected with the object size. This is due to the rather big dimension of the source(2). In the 3rd order the most important aberrations to be corrected were $(x|p_x^3), (x|p_x^2\delta), (x|p_x\delta^2)$ and $(x|p_x p_y^2)$, which were compensated by introducing octupole components in the radial field distributions of M1-M4.

Monte Carlo trajectory simulations, performed after the optimization, showed that the corrections considerably improved momentum resolution at the focus F_d. Namely, peaks having the momentum difference as small as 0.15% were resolved (at FWHM) in the center of the focal plane, while at both the focal plane borders the resolution was approximately 0.2-0.3 %. These results have been considered acceptable.

The compensation for the aberrations at the achromatic focus F_a have been done similarly, by introducing sextupole and octupole components in the field of M5-M8. The 1st order mirror symmetry of the device with respect to the intermediate focal plane facilitated such a compensation, as some aberrations were zero at F_a due to the symmetry.

Apart from the introduction of the sextupole and octupole components in the fields of the magnets, special correcting coils mounted at the poles of M4, M5 have been foreseen to compensate for small deviations (within a few percents) of the 2nd and 3rd order field components from the design values, which are probable due to manufacturing errors in all the magnets.

4. Realization of the quadrupole, sextupole and octupole components in the magnets

As it is known higher order corrections in dipoles can be realized in two ways: creating radially variable field (by profiling the magnet pole pieces, shimming and special positioning of the main magnet coils) and profiling entrance and exit pole faces. The 1st method was used to introduce sextupole and octupole components in the fields of all the magnets and quadrupole components in the fields of M1, M2, M7, M8, and the 2nd method - to create extra sextupole components in the correcting magnets M3-M6.

Table 2. presents the M1-M8 field parameters found as a result of the COMBAS optics optimization up to the 3rd order (see previous section). In case of the radial field variation, the field decomposition can be written as

$$B_0(\Delta R) = B_0(1 - n\frac{\Delta R}{R} + (\beta_2 R)\Delta R^2 + (\beta_3 R)\Delta R^3), \quad (3)$$

where $B_0 = B_0(0)$ is the value of the field in the magnet center, n - the 1st order field index, β_2 and β_3 sextupole and octupole field components:

$$n = -\frac{R}{B_0}\partial B/\partial\Delta R,\ \ \beta_2 = \frac{1}{2!\,B_0 R}\partial^2 B/\partial\Delta R^2,\ \ \beta_3 = \frac{1}{3!\,B_0 R}\partial^3 B/\partial\Delta R^3. \quad (4)$$

The parameters n, β_2, β_3 are directly proportional to the respective quadrupole, sextupole and octupole forces. In case of an entrance (exit) pole face curvature, having radius R_c, the respective sextupole strength is defined as $B_0/(2R_c)$. R_{in} (R_{out}) in the table 2. refer to the entrance (exit) radii of the pole face curvatures in the correcting magnets M3-M6.

In order to determine profiles of the M1-M8 pole pieces, which create the required field distributions in the median planes, a special mathematical procedure has been developed and used in calculations. Namely, by the use of the analytical continuation method the field scalar potentials, defined in the median planes, were reconstructed in volumes around the median planes. Pole profiles were calculated supposing their equipotentiality and the absence of the saturation. The method has been realized in the program POLUS [8] for the MCAD package. The found pole profiles were used as input to the program SCALAR [9], which calculated the profiles more precisely, taking into account the saturation in the pole pieces. 2D-aproximation is used in the program.

The pole profiles of the correcting magnets M3-M6 have been calculated even in a more precise way. The large apertures and short effective lengths of these magnets made it necessary to use for the profiles calculations refined 3D-field models, which takes into account saturation effects. The calculations have been done with the complex of programs COMPOT [10] for 3D magnetic fields calculations. The profiles preliminary found in the 2D calculations described above were used as initial approximations.

5. Main criteria of analysis of the magnet field quality

Measured magnetic field distributions are very important from different points of view. At the magnets manufacturing stage they allow one to control the quality of the real magnetic fields and, if necessary, introduce corrections during the magnets manufacturing process. Thus, the shimming of the pole surfaces of the correcting magnets M3-M6 (having rather complicated 3D forms) has been done on the base of the measured median plane field distributions. At the stage of the exploitation of the apparatus the comprehensive data of the magnetic fields distributions (field maps) at

different induction levels is a base for the construction of its realistic optical model. Such a model is a skeleton for the interpretation of the measured beam parameters, which facilitates the device operation. In particular, confident particles identification with TOF method requires precise particle trajectories reconstruction along the separator.

The experimental magnetic field distributions were analyzed in different ways. To localize possible domains and shells in the pole pieces, having anomalous magnetisation, the symmetry of field distributions and the behaviour of the field in the vicinity of the pole pieces were checked. Then, radial fields dependences were inspected to control their agreement with the design parameters (see table 2). Longitudinal behaviour of the fields has been controlled through the calculation (from the measured data) of the effective lengths and the comparison of these lengths with the design values, which were used in the ion optical optimization of the total system.

The effective lenght is defined as

$$L_{eff}(\Delta R) = \int B(\Delta R, X)dX / B_0(\Delta R) , \qquad (5)$$

where $B(\Delta R, X)$ is the vertical component of the magnetic field measured in the median plane at the radial and longitudinal coordinates ΔR and X, respectively. The design lengths of the sector magnets M1, M2, M7, M8 are calculated as follows

$$L(\Delta R) = (R + \Delta R)\varphi , \qquad (6)$$

where R, ΔR and φ are the bending radius of the central trajectory, the radial deviation from the central trajectory and the magnet deflection angle, respectively.

For the rectangular correcting magnets M3,M4,M5,M6, having the entrance and exit pole face curvatures, the design lengths are defined as

$$L(\Delta R) = 2R\sin(\varphi/2) - 2R_c(1 - \sqrt{1 - (\Delta R / R_c)^2}) , \qquad (7)$$

where R_c is a pole face curvature radius, positive sign of R_c corresponding to a convex surface. One should note that the lengths were calculated at different radii that let also investigate the radial dependencies of the effective field boundaries at the entrance and exit of each magnet.

At the stage of the ion-optical optimization of the separator it was found that the error of 0.2% in the effective field lengths and the main fields distributions is acceptable and will not cause noticeable deterioration of the main parameters of the separator.

6. Conclusion

Magnetic field measurements of the separator COMBAS magnets showed the satisfactory quality of their production. The errors of the field distributions in the central sections of all the magnets exceed designed errors, depending on the magnets working regimes. At high magnetic field values in the narrow gap regions the saturation effects are noticeable. This makes some magnet optical parameters closer to their design values (for the pairs M1(M8), M2(M7) and M3(M6)), but, on the other hand, narrows working pole widths (in M1(M8) and M2(M7)). At the design stage the possibility of the additional treatment of the magnet pairs has been foreseen. After the field distribution analysis we decided not to treat additionally the pole pieces of the magnets M1(M8) and M2(M7). For the magnets M3(M6) and M4(M5) the field distribution analysis and the relevant trajectory simulations, made on the results of the measurements, specified their real working pole widths. Based on this, shimming of the magnets M3(M6) has been performed, and, for the magnets M4(M5), the pole surface correcting coils have been calculated, produced and mounted on the pole pieces. We expect the distribution errors less than 1% for the magnets M1(M8), M3(M6) and M4(M5) and 2% for the magnets M2(M7) would not cause essential

Fig.1. Separator COMBAS in the cyclotron U-400M hall (FLNR JINR).

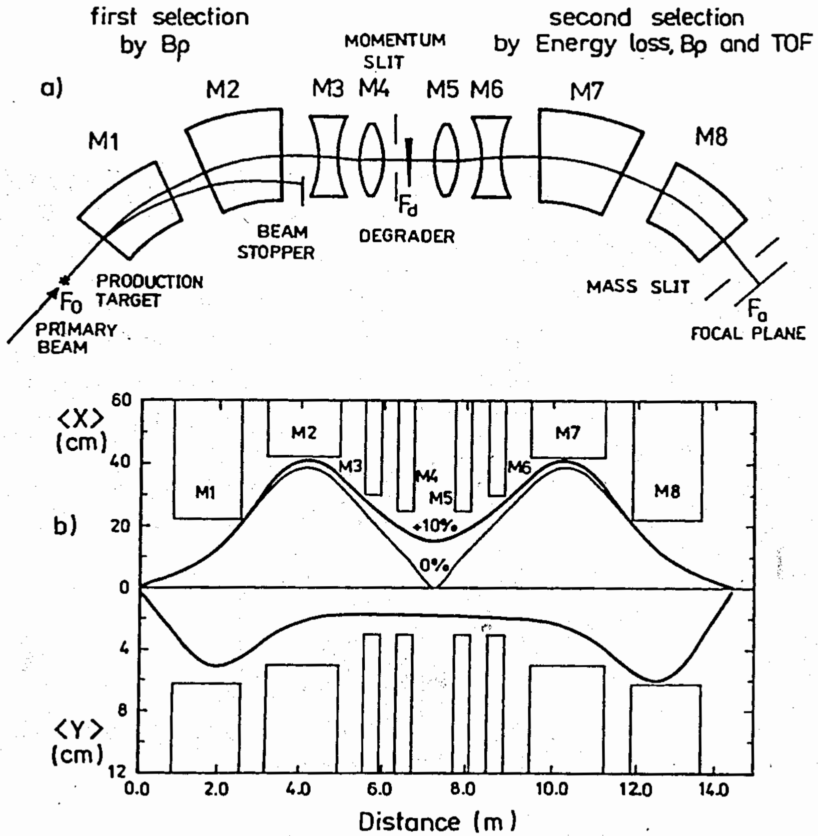

Fig.2. (a) Magneto-optical sketch of the fragment-separator COMBAS; (b) The horizontal X and vertical Y beam envelopes of the magnetic channel. The solid thick line is the contour of the δ = ± 10 % momentum acceptance; the thin line corresponds to δ = 0 %.

Table 1.

Main parameters of the separator COMBAS.

$B\rho_{max}$	T*m	4.5
Solid angle (maximum)	msr	6.4
Momentum acceptance (maximum)	%	20
Momentum resolution Main object slit width = 1mm.	[FWHM]	4360
Momentum dispersion in the linear approximation At dispersion focus F_d normal to the optical axis	cm/%	1.53
Length of the channel	m	14.5

Table 2.

The designed quadrupole, sextupole and octupole component parameters of the magnets.

Magnets	R_{in} (cm)	R_{out} (cm)	n	β_2 (cm^{-2})	β_3 (cm^{-3})
M1(M8)	-	-	11.0024	0	$1.67*10^{-8}$
M2(M7)	-	-	-6.75	$-2.77*10^{-7}$	$-4.02*10^{-10}$
M3(M6)	-50	-50	0	$6.69*10^{-7}$	$-2.38*10^{-8}$
M4(M5)	50	50	0	$-2.62*10^{-6}$	$-1.46*10^{-8}$

distortions of the separator designed optical properties. Raytracing simulations and the first experiments on spectra measurements for energetic heavy ion products showed that the main separator characteristics match, in general, with those of the design.

The measured magnetic field distributions are supposed to be used for trajectory simulations. Further improvement of the separator parameters will be achieved by the use of the pole surface correcting coils of M4(M5).

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