BEAM OPTICS OF LARGE ACCEPTANCE MAGNETIC CHANNEL FOR SEPARATION OF RADIOACTIVE NUCLEI

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Abstract

Some problems concerning basic equipment configuration and optimization of first-order optical design of large acceptance magnetic channel for separation of radioactive nuclei COMBAS as well as calculation and correction of nonlinear beam distortions up to the third-order are discussed in the paper.

Introduction

High intensity beams produced in heavy ion reactions at medium energies offer unique possibilities for investigation of the states and structure of nuclei, Coulomb excitations and nuclear reactions. High-speed analyzing spectrometer magnetic channel COMBAS is designed to be used for experiments with heavy ions accelerated by the tandem of cyclotrons U-400 and U-400M at the Laboratory of Nuclear Reactions, JINR, Dubna. The main functions of the channel are collection, transport, analysis, and selection of products of nuclear reactions.

The program of experiments requires the following properties of COMBAS channel:

- The channel should accept ions with magnetic rigidity up to 4.5 Tm;

- The channel should be achromatic. In the middle of the channel dispersion of the particles with different magnetic rigidity should be provided with resolving power being greater than 4000. Installation of a thin degrader at this point should lead to separation of ions of equal magnetic rigidity, but different in mass (charge).

- Angular and momentum acceptances of the channel should be as large as possible taking into account technical and economical problems.

First-order channel design

Numerical optimization of linear optics of the channel was performed using computer program BETRAMF [1]. The layout of the lattice of the channel which mostly meets all experimental requirements is shown in Figure 1.

The magnetic structure of the channel possesses mirror symmetry with respect to the middle of the system. The first part of the channel is an analyzing section. It contains two main bending magnets M1 and M2 and two additional magnets M3 and M4. This part collects particles, bends the beam at the total angle of 50° and produces dispersion of ions with different magnetic rigidity at the first focal plane.

The linear optical properties of the system are mainly determined by the magnets M1 and M2. The effective focusing of the beam is produced by alternative gradient of magnetic field in these magnets. The field indices are $n_1 \cong 11$ and $n_2 \cong -7$. The envelopes of the beam as well as dispersion function are shown in Figure 1. The dispersion function in the middle of the system is parallel to the axis, so the channel is achromatic.

The correcting dipole magnets M3 and M4 form a system of parallel beam shift. In x-plane the total influence of these magnets on the beam is negligible. In y-plane there is additional focusing due to fringe fields of the magnets. That allows us to make the axial beam envelopes at the second part of the system symmetric to the first one.

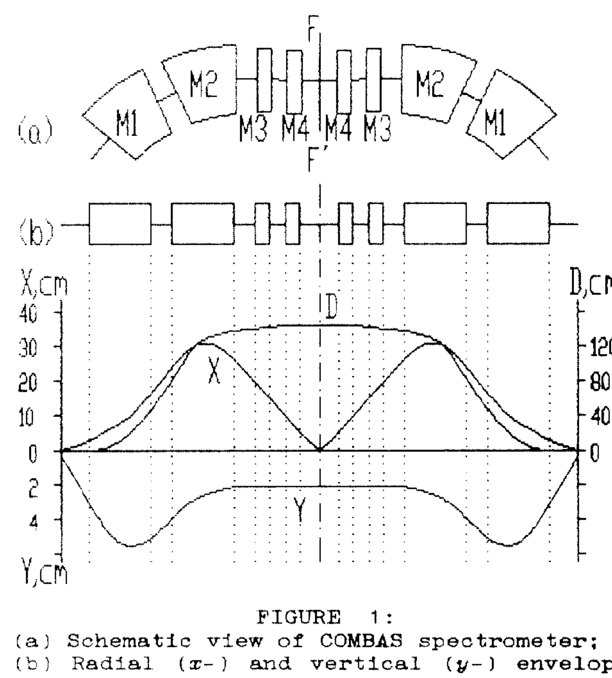

FIGURE 1:
(a) Schematic view of COMBAS spectrometer;
(b) Radial (x-) and vertical (y-) envelopes of the beam of ions with the nominal value of magnetic rigidity and dispersion function (D)

The resolving power of the channel is equal to

$$\Re = D/(M\cdot\Delta x) = 4360, \tag{1}$$

where D=157 cm is the maximum value of the dispersion function, M=0.36 is the coefficient of image enlargement by the first part of the channel, and Δx=1 mm is the input slot width.

The transfer matrix of the total channel is equal to

$$R(1) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 1e-2 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -6e-2 & -6.09 & 0 & 0 \\ 0 & 0 & 0.16 & -6e-2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -114 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

The angular acceptance of the COMBAS magnetic channel is determined by configuration of the poles of the magnets and vacuum chamber shape. The horizontal angular acceptance is about ±50 mrad and the vertical one equals to ±35 mrad. Momentum acceptance of the channel is ±10%.

Nonlinear corrections

COMBAS magnetic channel is a unique spectrometer considering its linear optics parameters. To achieve these parameters it is necessary to study nonlinear effects in ion dynamics and to provide compensation of the beam nonlinear distortions.

In the study of nonlinear distortions of the beams the most efficient method is a method based on aberration theory [2-4]. In this method canonical transformation of particle phase space variables is expressed as a six-fold Taylor expansion using their initial boundary values:

$$x_i(1) = \sum_{q=1}^{\infty} \sum_{k_1 \ldots k_6 \geq 0}^{k_1+\ldots+k_6=q} (x_i | x_1^{k_1} \ldots x_6^{k_6}) \times x_1^{k_1}(0) \ldots x_6^{k_6}(0). \tag{3}$$

The 6-vector $X=(x_1 \ldots x_6)^T \equiv (x, p_x, y, p_y, \sigma, \delta)^T$ is a vector describing the location of a particle in phase space, x, y, and σ are radial, axial, and longitudinal displacements of a test particle from the equilibrium particle, p_x, p_y, and δ are the canonical momenta. In linear approximation p_x and p_y are equal to the slope of the test trajectory with respect to the axis of the channel, δ is equal to the fractional error in magnetic rigidity of the particle.

When studying nonlinear beam distortions we assumed, that the particles were uniformly distributed in the volume, which was defined by the following inequalities

$$\begin{aligned} x^2+y^2 &\leq R^2, \qquad R=0.25\text{cm}; \\ p_x^2 + p_y^2 &\leq P^2 \qquad P = 0.04. \end{aligned} \tag{4}$$

These inequalities correspond to the conditions of beam collimation. The distribution on δ was also assumed to be uniform within the limits of ±6%.

The most dangerous for resolving power of the channel are effects driven by chromatic nonlinear terms and spherical aberrations proportional to p_x and p_y. In linear approximation and initial phase space volume given by (4) the channel can separate ions with the 0.12% difference in momentum (magnetic rigidity). Nonlinear effects substantially reduce the resolving power. That is why the most important problem was correction of nonlinear beam distortions at the chromatic focal plane F-F' in the middle of the channel (see Figure 1).

The aberration coefficients of the second- and the third-order were calculated using the computer program TOREX [6]. Figure 2 shows the intensity of ion distribution along x-axis at the focal plane F-F' without any correction. All nonlinear effects are taken into account. The magnetic rigidity of ions corresponds to momentum errors δ=0 and ±0.3%. It is well seen that aberrations smear the distribution away in the direction of less values of x, so that the ions with different δ overlap within large interval. That leads to substantial reduce in resolving power. Thorough analysis shows that the main influence in beam distortions is given by the following second-order aberrations: $(x|xp_x)$, $(x|p_x^2)$, $(x|x\delta)$, $(x|p_x\delta)$, $(x|\delta^2)$ and $(x|p_y^2)$. It is necessary to compensate these aberrations not exciting another second- and third-order aberrations.

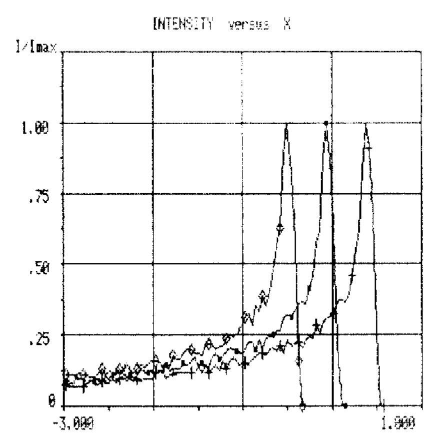

FIGURE 2:
x-Axis ion distribution at the F-F' focal plane without correction of nonlinear effects. The magnetic rigidity of ions corresponds to momentum errors δ=0 and ±0.3%.

Correction of second-order aberrations can be achieved by means of sextupole component being introduced in the bending magnetic field. That can be done by magnetic poles shaping and shimming (distributed sextupole component) as well as by curving of effective field boundaries which affects the beam as a thin sextupole lens. It was decided to introduce the sextupole component in all the magnets and to curve field boundaries of dipoles M3 and M4.

Calculation of optimum compensation mode was performed using LEASQ computer code which implement regularized least square method on the base of partitive influence of each of the sextupole components on the total second-order beam distortion. Sextupole compensation excites third-order effects, so that octupole component was also introduced in the magnetic field.

Figure 3 presents x- ion distribution at the F-F' focal plane when second- and third-order effects are compensated. The magnetic rigidity of separated ions correspond to the value of momentum deviation $\delta=0$ and $\pm0.15\%$. It is well seen that x-distribution became more compact. If initial distribution satisfies inequalities (4) the magnetic channel COMBAS resolves ions with magnetic rigidity difference of 0.15% at the central part of momentum spectrum and 0.2–0.3% at both ends.

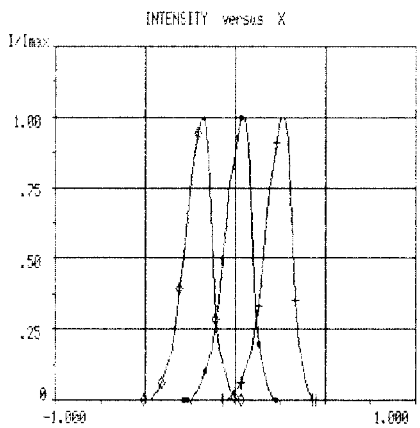

FIGURE 3:
x-Axis ion distribution at the F-F' focal plane when second- and third-order nonlinear effects are compensated. The magnetic rigidity of ions corresponds to momentum errors $\delta=0$ and $\pm0.15\%$.

Figure 4 shows x-distribution of ions at the exit point of the channel at the achromatic focus. Magnetic rigidity of ions is within the range $\pm6\%$. Sextupole and octupole components of magnetic field are similar at the both parts of the channel.

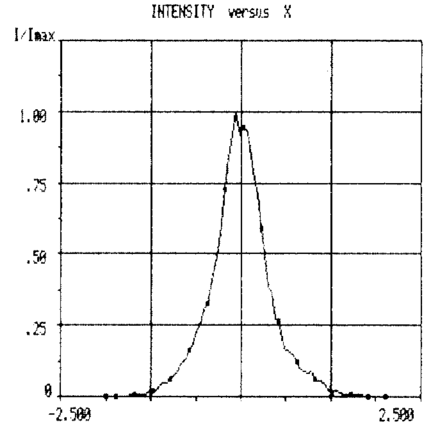

FIGURE 4:
x-Axis ion distribution at the point of achromatic focus. The magnetic rigidity errors of ions are within the range $\pm6\%$.

Conclusion

Let us summarize the main parameters of COMBAS channel: solid angle acceptance ~ $6.4\cdot10^{-3}$ steradian; maximum momentum acceptance ~ $\pm10\%$; maximum magnetic rigidity $B\rho$ = 4.5 Tm; resolving power $\Re$=4360. The total length of the channel is about 10 m. The design project of the channel is completed. Computation of 3D-magnetic field and full-scale beam dynamics simulation are underway. The first results show good agreement with aberration theory predictions.

There are different ways of further development of the COMBAS channel. Mirror symmetry of magnetic structure of the channel and beam optics makes it possible to use another such a channel after the first one. No matching quadrupoles are needed. So a double spectrometer channel COMBAS-2 may be constructed like double spectrometer DUO [6]. The resolving power of COMBAS-2 will be 2.5 times greater than that of DUO. That will produce more thorough mass separation of ions up to uranium with the help of degraders. Another way is to turn over the second part of COMBAS with respect to longitudinal axis. Such optical scheme doubles resolving power of the channel ($\Re$=8700 if Δx=1 mm). Compared to spectrometer SPEG+α [8], it can be seen, that the channel will provide almost the same resolving power, angular and momentum acceptances, but the upper limit of momentum rigidity of particles will be 1.5 times greater.

References

[1] M.G.Nagaenko, Preprint NIIEFA B-0614. Leningrad, 1983.
[2] K.Brown *et al.*, CERN 80-04.-Geneva, 1980.
[3] K.Steffen, High Energy Beam Optics. New York: Interscience publishers, 1965.
[4] M.G.Nagaenko and Yu.P.Severgin, Preprint NIIEFA B-0379. Leningrad, 1978.
[5] M.G.Nagaenko, Preprint NIIEFA P-E-0665. Moscow: CNIIatominform, 1984.
[6] Grunberg G. *et al.*, Nouvelle optique pour DUO, CG/MLM 380/88.
[7] Birien R., Valero S. CEA-N-2215, 1981.