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

Correcting Pair of Multipole Magnets M3M4 (M5M6) with Compensation for Higher Order Aberrations

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Широкоапертурные мультипольные магниты кинематического сепаратора КОМБАС.
Корректирующая пара мультипольных магнитов М3М4 (М5М6) с компенсацией аберраций высоких порядков

Создан и введен в эксплуатацию высокоразрешающий широкоапертурный сепаратор КОМБАС, магнитная структура которого выполнена на принципе жесткой фокусировки. В состав сепаратора входят восемь широкоапертурных мультипольных магнитов. В корректирующую секцию сепаратора вошли стирерные магниты М3—М6 с введенными в распределение поля секступольной и октупольной компонентами. Наличие данных компонентов позволило отказаться от квадрупольных линз, а также добиться минимизации сферических аберраций и компенсации хроматических эффектов. Для пар М3М6 (М4М5) проведены измерения магнитного поля в медианной плоскости, позволившие проанализировать качество изготовления магнитов. По данным измерений было решено провести коррекцию распределений магнитных полей магнитов. Для пары магнитов М3М6 выполнено шиммирование, а для пары магнитов М4М5 были рассчитаны, изготовлены и установлены корректирующие обмотки. Проведен анализ качества полей после коррекции. Данные магнитных измерений будут использованы для проведения траекторных расчетов по трассировке частиц через сепаратор.

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Wide Aperture Multipole Magnets of the Kinematic Separator COMBAS.
Correcting Pair of Multipole Magnets M3M4 (M5M6) with Compensation for Higher Order Aberrations

The high-resolving large aperture separator COMBAS has been created and commissioned. The magneto-optical structure of the separator is based on the strong focusing principle. The separator consists of eight wide aperture multipole magnets M1—M8. The magnets M1, M2, M7, M8 forming the 1st order optics together with some higher order optical corrections and M3-M6 being dedicated to higher order corrections of the chromatic and spherical aberrations at the intermediate and exit foci of the separator. The multipole correctors M3-M6 contain the dipolar, sextupole and octupole components in their magnetic field distributions. It was the use of the rectangular dipoles M3-M6 as carriers of sextupole and octupole field components that let achieve high values of the separator angular and momentum acceptances. Measurements of the magnetic field distributions in the median planes of the pairs of magnets M3M6 (M4M5) have been performed. These measurements allowed one to analyze the magnets manufacturing quality. Based on the analysis, shimming of pole pieces of the pair of magnets M3M6 have been done. Pole surface correcting coils for the magnets M4M5 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 M1-M8. The measured magnetic field distributions are supposed to be use for particle trajectory simulations throughout the entire separator.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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1. Introduction

According to the concept of the use of only pair bending magnets [1] in the magnet structure of the separator COMBAS two pairs of the correcting multipoles M3M4 and M5M6 have been calculated and produced (see Fig.1). These multipoles are the rectangular dipole magnets with small deflection angles of 7.5 deg. each having sextupole and octupole components in their field distributions to perform 2nd and 3rd order corrections of aberrations at the intermediate and exit focii of the separator. The use of the dipoles as carriers of higher order field components (instead of standard sextupole and octupole magnets) let considerably increase the momentum acceptance of the separator.

In the 1st order magnets M3 and M4 is a parallel-to-parallel (steering pair) beam transfer system having, due to fringe fields, vertical focusing properties. The influence of M3, M4 on the momentum resolving power at the intermediate focus is negligible, as their dipole components have opposite signs (that is the deflection angles of M4, M5 are opposite to those of M1-M3, M6-M8).

2. Main technical characteristics of the magnets

Main technical parameters of M3-M6 are presented in Table 1. The 3D shapes of the M3-M6 pole pieces have been calculated by the use of the procedures described in brief in [1]. The vertical gaps of the magnets vary with bending radius forming necessary sextupole and octupole field components. To introduce eight additional sextupole corrections the entrance and exit pole faces are curved with the radii of curvature -50 cm (convex surfaces) in M3, M6 and +50 cm (convex surfaces) in M4, M6. All the magnets have zero quadrupole components.

3. Magnet measurements

3.1. Organization of the magnet measurements

Measurements of the magnetization curve and median plane field distributions together with subsequent analysis of the results have been done at the Efremov Scientific Research Institute of Electrophysical Apparatus (ESRIEA), Saint-Petersburg, where designed and manufactured the magnets. A rectangular coordinate system was used in the measurements, originating in a magnet center with the axis **0X** tangential to the optical axis and pointing in the beam direction, **0Y** coinciding with the direction of the bending radius and **0Z** pointing downwards for M3, M6 and upwards for M4, M5. The measurement system consisted of a bar made of a nonmagnetic material, which had special gadgets fixing to the bar a head of Hall probes, and guides, which had marks for precise positioning of the bar and the head. Before measurements the initial mutual positioning of the measurement system and the magnet was done with a theodolite. The measuring head was always situated in the median plane of a magnet with the accuracy of 0.1 mm. Along the **0X** and **0Y** axes the head positioning accuracy was approximately 0.2 mm. Before measurements the probes were calibrated on the special test bench in order to have the measurement accuracy of 2 Gauss (0.02% of the nominal magnetic field in the magnet center). To reduce measurement errors the field was measured 5 times at each point. The r.m.s. field measurement error due to the head positioning errors and the error of measuring the Hall probe voltage was estimated as being less than 3 Gauss (0.03% of the nominal field level). This correspond to the required field forming accuracy.

3.2. The magnetization curves

The measured magnetization curves of the magnets M3 and M4 are shown in Fig. 4 and 5 respectively in comparison with the calculated points. As one can see at currents less than I=800A in M3 the calculated points lie below the measured curve, while at I>800A the calculations give higher induction values. For the magnet M4 the calculations underestimate the induction values in all the range of the current variation.

3.3. Analysis of the field distributions in the central sections

Analysis of the induction distributions in the median planes of the magnets has been performed according to the procedure described in [1]. The measured field maps shown the identity of the magnet pairs M3, M6 and M4, M5. For each pair the differences between the induction values at the same map points were less than 0.2%. On the other hand, the measured radial field variations were found to be different from those required by the design. The measured radial field distributions in the centers of the median planes of M3, M6 and M4, M5 are shown in Fig.6 and 7, respectively, for the field level $\mathbf{B_0}$=4600 Gauss in comparison with the required distributions. The field deviations from the design values do not exeed 3% for M3, M6 and 2% for M4, M5. At the field levels $\mathbf{B_0}$=11600 and 15000 Gauss in M3, M6 they are less than 2.5 % (for both the levels), and in M4, M5 - 2.0% (for $\mathbf{B_0}$=11600 Gs) and 1.5% (for $\mathbf{B_0}$=15000 Gs).

The analysis deviations is performed an extra raytracing simulations using the programs TOREX [2] and COSY INFINITY [3] to check their influence on the beam quality at the intermediate and exit focii. The simulations showed, in part, that the beam trajectories concentrate within the radial range of ± 200 mm in the magnets M3, M6 and ± 150 mm in M4, M5 (the radial extent of the pole pieces being as large as ±

300 mm). So we performed our analysis and corrections only within these working regions.

Based on the calculations, shimming of the pole pieces of M3, M6 have been made, and the pole surface correcting coils of M4, M5 have been used to compensate for the deviations. The shims, mounted at the radii –250, -200, -150, 0 and +250 mm in M3, M6, compensated the lack of the field in the range of the interest and, according to the newly performed magnetic measurements, reduced the field deviations to the level of 1% for all three the field levels. These corrections have been done in ESRIEA, St.Petersburg. The field deviations in M4, M5 were compensated with the pole surface correcting coils. The measurements of the corrected fields in such a way have been done in FLNR JINR Dubna and showed the reduction of the deviations till the value of less than 1% for all the field levels.

At the end of the section one should comment the radial field dependences in Fig. 6 and 7. As it is seen from the figures, the dominating field component in M4, M5 is the sextupole one (excluding the dipole component). Small asymmetry of the curve is due to the presence of the octupole. In the magnets M3, M6 the sextupole and octupole components are comparable. At positive $\Delta\mathbf{R}$ they almost compensate for each other, resulting in the field close to uniform.

3.4. Analysis of the field distributions in the mediane plane

A study of the induction distribution in the median planes of the magnets M3(M6) and M4(M5) has been done, according to the procedure in the [1] described.

In these magnets the bending radius is **R**=3m, the bending angle is $\varphi=7.5^0$. The radiuses of curvature of the effective magnetic lengths in the lateral faces are $\mathbf{R_c}$=-50cm for the magnets M3(M6) and $\mathbf{R_c}$=50cm for the magnets M4(M5). We used the

(5), (6) and (7) equations from the [1] for analysis. In the Fig.8, the measured distribution $\mathbf{B_z}$ of the magnetic field induction in the median plane, depending on the radial deviation in the magnet M3, is shown ($\mathbf{B_o}$=4600Gs).

The $\mathbf{B_x}$- and $\mathbf{B_y}$-components in the median plane are equal to zero. That's why our measurements can presented as $\mathbf{B} = \mathbf{B_z}$. One can see that the distribution in the magnet axis (**0Y**-axis) corresponds to the distribution in the Fig.6. In the figure the decrease of the effective magnet length in the region of the optical axis is shown. The decrease reflects the influence of the concave shape of the pole lateral faces.

The measured data showed that the errors in the values of effective magnet lengths at $\mathbf{B_o}$=4600 Gs, were less than 10%. For the field level at $\mathbf{B_o}$=11600 Gs they were less than 7%. For field level at $\mathbf{B_o}$=15000 Gs they were less than 5%.

After the shimming, the maximum deviation in effective magnetic lengths for the $\mathbf{B_o}$=11600 Gs magnetic field level compiled less than 1%.

The similar measurements were performed for the magnets M4(M5). In the Fig.9 the magnetic field distribution in the median plane of the magnet M4 ($\mathbf{B_o}$=4600Gs) is shown. One can see that the distribution in the magnet axis (**0Y**-axis) corresponds to the distribution in the Fig.7. One can notices the strong narrowing of the working area from the central trajectory to the borders, which corresponds to the convex shapes of the pole lateral faces.

At the result of calculations of the effective magnetic lengths based on the primary measurements, it was determinated that the errors in values of effective magnetic lengths compiled less than 5% ($\mathbf{B_o}$=4600 Gs). For the field level $\mathbf{B_o}$=11600Gs the errors compiled less than 6% and for the field level $\mathbf{B_o}$=15000 Gs the errors compiled less than 9%.

After the using of the correcting coils the deviation in the effective magnetic lengths compiled less than 1% at the **B**$_o$=11600 Gs field level.

The error in the border field of magnets influences the dispersion focus and the achromatic focus positions along the beam-line.

Before the shimming in the magnets M3(M6), the error in the slope of entrance and the exit angles of the border field was 1.5° for the field level at **B**$_o$=4600Gs, 1° for the field level at **B**$_o$=11600 Gs and 0.2° for the field level at **B**$_o$=15000 Gs. Such errors lead to the shifts of dispersion focus at 30mm (**B**$_o$=4600Gs), 20mm (**B**$_o$=11600 Gs) and 5mm (**B**$_o$=15000 Gs) along the beam-line.

The magnetic measurements showed, that before setting up of the correcting coils the error in the slope angle of the effective magnetic borders in magnets M4(M5) compiled less than 1° for all field levels. This gives the shift of the dispersion focus less than 5mm.

After the magnets M3(M6) shimming, the errors in the slope angle of the effective magnetic borders compiled less than 0.5°, 0.2° and 0.1° for the field levels **B**$_o$=4600, **B**$_o$=11600 and **B**$_o$=15000 Gs accordingly. The setting of the correcting coils on the magnets M4(M5) lead to the decrease of the error in angles up to 0.2° for all field values.

Such errors lead to the shifts of dispersion focus after the pair of magnets M3M4 at 11mm, 5mm and 2mm for the field levels **B**$_o$=4600, **B**$_o$=11600 and **B**$_o$=15000 Gs accordingly.

4. Beam characteristics in the intermediate focal plane

In the Fig.10. one can see the real image of the ^{18}O ion beam with an energy 35MeV*A transported to the intermediate focal plane through COMBAS setup. The beam parameters on the target were **x**=3mm, **x'**=20mrad, **y**=3mm, **y'**=20mrad and energy dispersion 1% [4]. According to the [4] in a linear approach the magnification coefficient of the first part of the separator in the horizontal plane is –0.36. The magnification coefficient in the vertical plane is –6.05. Simulations showed that the beam image should be of the half-size at 1.1mm in the horizontal plane and of 18.15mm in the vertical plane. According to the Fig.10., the real half-sizes of the beam were estimated in the horizontal plane at ≈1-1.5mm and in the vertical plane at ≈18-20mm, with taking in account the quality of luminophore shining. In a linear approach, we can tell about quite full accordance of the real image to the calculated one.

From the point of the spherical aberrations minimization, we received enough correction of these aberrations. In the Fig.10 the long vertical form of the beam is clearly expressed. In other words, we did not find the influence of aberrations for the beam particles deviated above and below the median plane.

5. Conclusion

After the correction had been introduced, the repeated magnetic measurements showed a satisfied quality of the steering magnets production. The errors in the field distributions in the central sections composed less than 1%. The admitted errors received at the result of simulations should be less than 0.2%. The shimming of magnets M3(M6) poles and setting the correcting coils on the magnet's M4(M5) poles could not compensate these deviations enough. The process preparation of magnet poles have helped us to improve integral characteristics of the fields for both magnet types. It decreased errors in the effective magnet lengths up to the level of 1% and quite compensated errors in the border fields forming.

The test beam transmissions through the separator and the first physical experiments showed that these errors don't influence much the main parameters of separating channel. The beam parameters received in the intermediate plane (Fig.10.) showed a good quality of the separator in common. We suppose to use the magnetic field distributions to use for carrying out of particle trajectory simulations. As the steering magnet's gaps are small and the trajectories of particles in the magnets vertical plane are practically parallel, we suppose to use the median plane cards for the whole working volume of vacuum chamber of magnets.

The following improvement of set up parameters we find in more accurate choice of the correcting coils currents at the beam going.

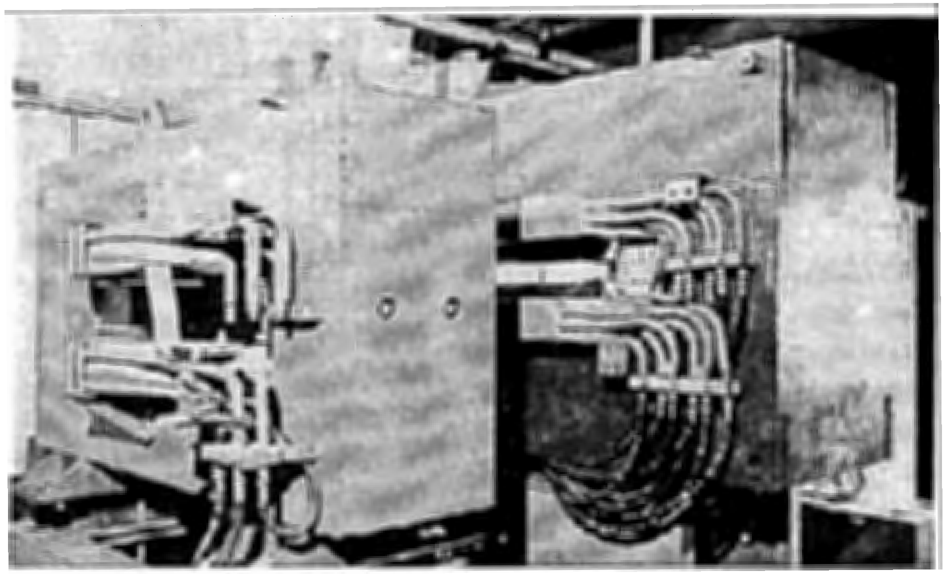

Fig.1. Multipole magnets M4(6X60EF32-1.5)(left) and M3(6X70EF32-1.5)(right).

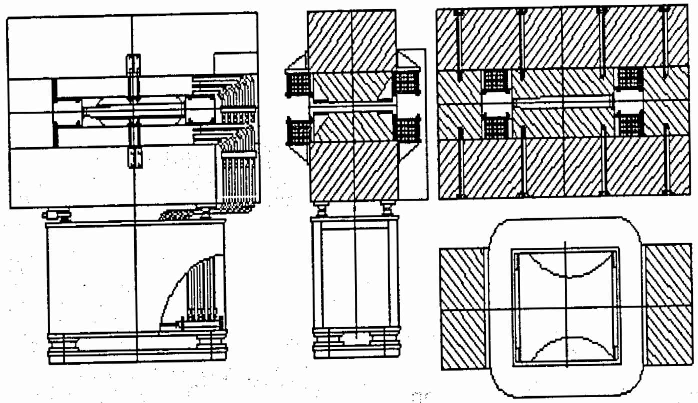

Fig.2. The drawing and sections of magnets M3, M6.

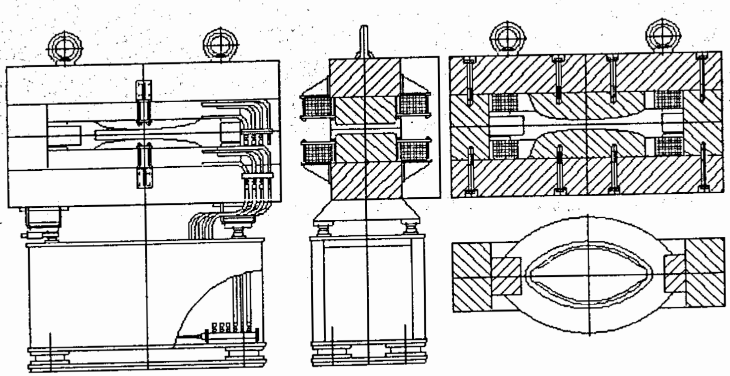

Fig.3. The drawing and sections of magnets M4, M5.

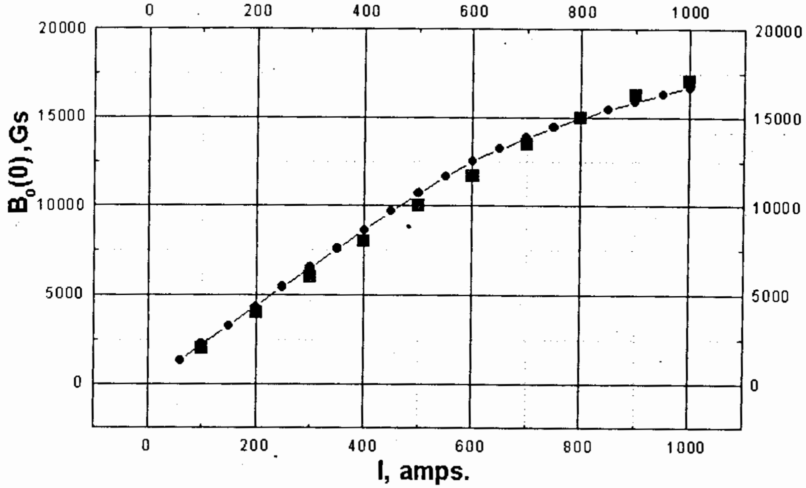

Fig.4. The magnification curve of the magnet M3: the squares represent theoretical calculations, circles are experimental data.

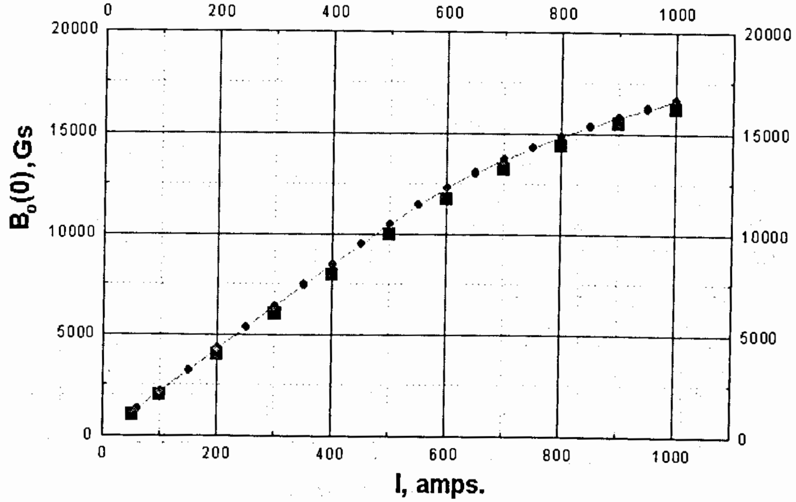

Fig.5. The magnification curve of the magnet M4: the squares represent theoretical calculations, circles are experimental data.

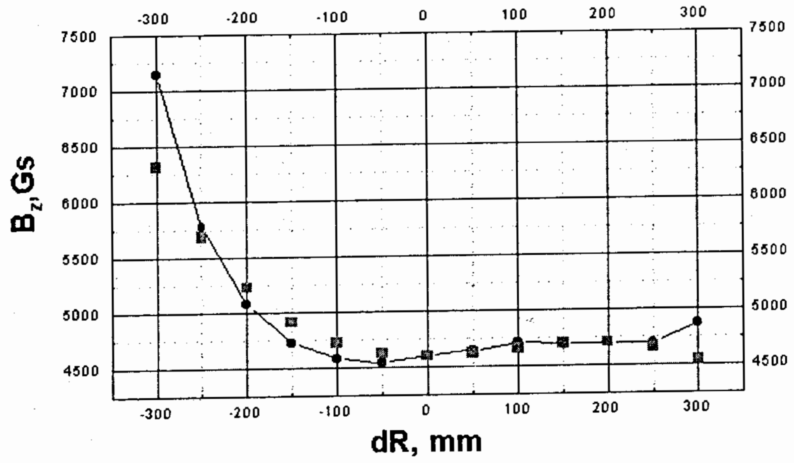

Fig.6. Magnetic field distribution in the central section of the magnet M3 at B_0=4600 Gauss before shimming. Squares represent the design distribution [1], circles are experimental points.

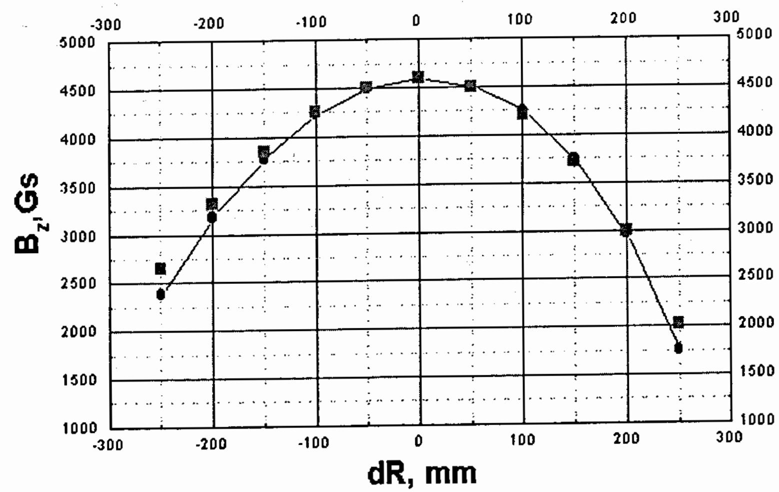

Fig.7. Magnetic field distribution in the central section of the magnet M4 at B_0=4600 Gs before using the correcting coils. Squares represent theoretical calculations, circles are experimental data.

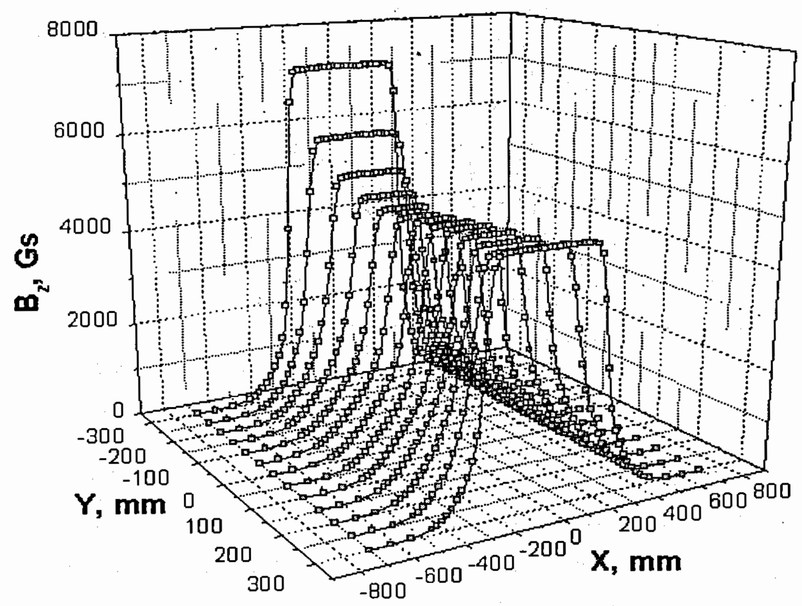

Fig.8. The measured distribution of the B_z-component of the magnetic field (B_0=4600Gs) in the median plane of the magnet M3. The rectangular system of coordinate was used (**OX, OY, OZ**). The center of the measuring system coincided with the magnet center. The **OX**-axis was directed along the magnet axis in the direction of the beam motion. The **OY**-axis was laid in the central section of the magnet. The **OZ**-axis was directed vertical down. The steps of measurements were: **dX** = 20 mm, **dY** = 50 mm. The number of measured points was more than 700.

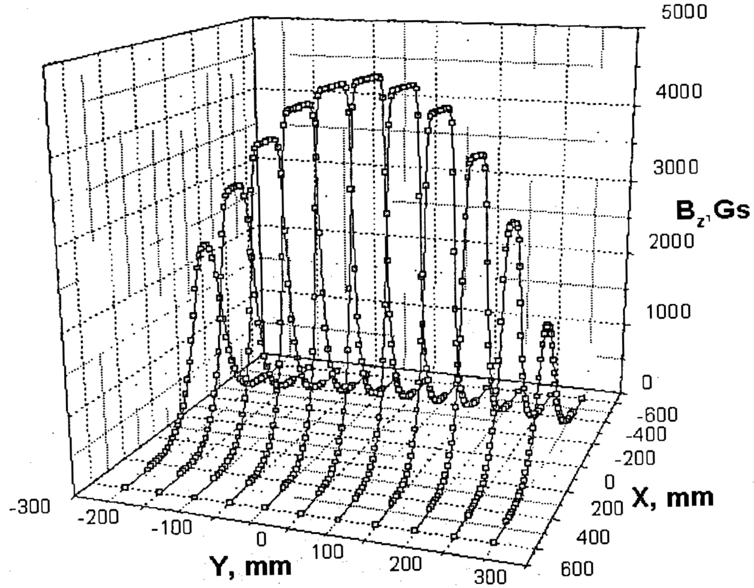

Fig.9. The measured distribution of the $\mathbf{B_z}$-component of the magnetic field (B_0=4600Gs) in the median plane of the magnet M4. The rectangular system of coordinate was used (**OX, OY, OZ**). The center of the measuring system coincided with the magnet center. The **OX**-axis was directed along the magnet axis in the direction of the beam motion. The **OY**-axis was laid in the central section of the magnet. The **OZ**-axis was directed vertical up. The steps of measurements were: **dX** = 20 mm, **dY** = 50 mm. The number of measured points was more than 550.

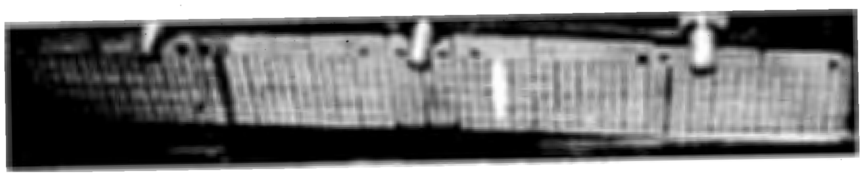

Fig.10. The image of the beam vertical light strip in the intermediate focus plane of the separator COMBAS. The solid thick vertical lines on the luminophore are drawn in an interval at 10mm.

Table 1. The main parameters of magnets M3-M6 and M4-M5.

Parameters	Magnets M3,M6	Magnets M4,M5
Maximum induction on the central trajectory (T)	1.5	1.5
Nominal induction on the central trajectory (T)	1.167	1.167
Radius of the central trajectory (m)	3	3
Working pole width (mm)	600(±300)	500(±250)
Gap along the central trajrctory (mm)	60	60
Effective length (mm)	393	393
Bending angle (deg)	7.5	7.5
Resistance of main coils (Ω)	0.03	0.034
Maximum current (A)	900	900
Rated current (A)	610	610
Maximum Voltage (v)	30	20
Rated Voltage (v)	20	13
Maximum Power (kW)	27	13.5
Rated Power (kW)	12	8
Inductance of main coils (H)	0.08	0.04
Water discharge (liter per minute)	22	9
Water overheating (C)	18	30
Mass of copper (tns)	0.5	0.33
Mass of steel (tns)	6.6	2.3
Total magnet mass (tns)	7.5	3

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7. References

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