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Reconstruction of the 3-dimensional magnetic fields of the strong focusing separator

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Abstract For unambiguous identification of products of nuclear reactions by the (TOF-ΔE) method, it is necessary to know exactly the magnetic field distributions, the 3D field map for the entire working area of separator. The possibility of the field reconstruction inside the total volume surrounded by the closed surface, on which the magnetic measurements are performed, is demonstrated in this paper. Distributions of the measured magnetic field components of the magnets, forming the magnetic structure of the separator, as well as the respective reconstructed fields together with the estimated reconstruction errors, are presented. Precise simulation of particle trajectories inside the separator becomes possible as a result of this work.

Key words magnetic separator • field reconstruction • KOMPOT code

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Introduction

A significant part of the magnetic systems (separators, beam transport channels etc.) is characterized by the presence of the working zone in which distribution of magnetic field should satisfy the given conditions. On the basis of this distribution, both processing of experimental data to determine characteristics of particles by means of investigations of their movement in a magnetic field and calculation of their trajectories are carried out.

Reconstruction of magnetic fields inside areas, on which boundaries 3D componental magnetic measurements were done, is demonstrated for the case of the separator with strong focussing. Conditions for the magnetic field reconstruction with required accuracy using magnetic field measurements along the boundaries of working areas have been formulated.

Reconstruction of magnetic fields using the data of magnetic measurements has been done using the modernized complex of the KOMPOT codes [5, 6] based on the finite element method. The applied reconstruction method has the following advantages. First of all, the number of necessary field measurements is considerably reduced. Secondly, the data interpolation provides more accurate estimates for the interior field, comparing with direct measurements, because the random measurement error tends to decay away from the boundary. Besides, calculation errors associated with integration, discretization or interpolation procedure can be eliminated from analysis of anticipated reconstruction errors by proper selection of a number and positions of the Hall probes as well as step of measurement in each direction.

In practice, for magnetic field measurements several modifications of measuring system are used, which are rigid constructions with Hall probes fixed to them. They move in such a way that working volume is included inside the

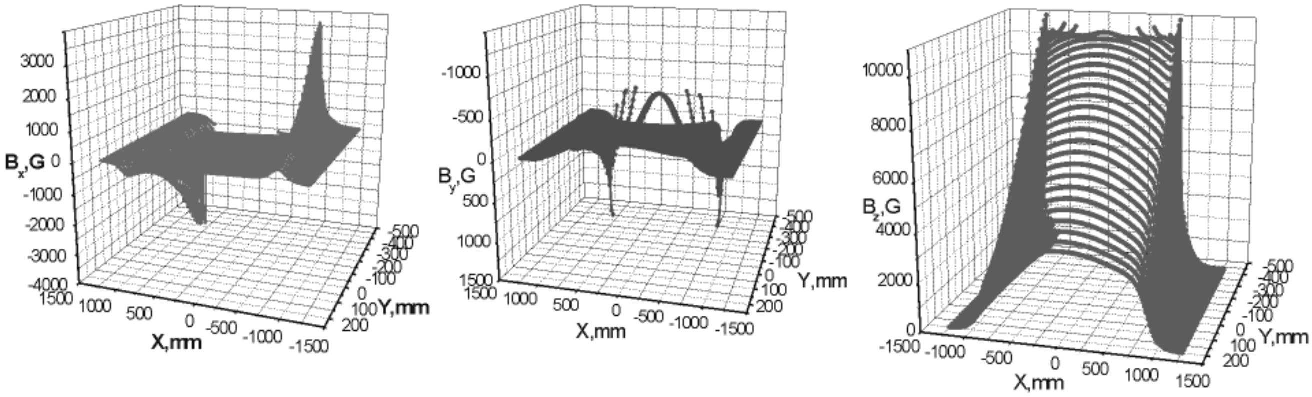

Fig. 1. The measured magnetic field distributions of the M_1 magnet at the field value $B_0 = 7050$ G. The B_x, B_y and B_z are the components of the magnetic field in the plane lying 30 mm below the median plane.

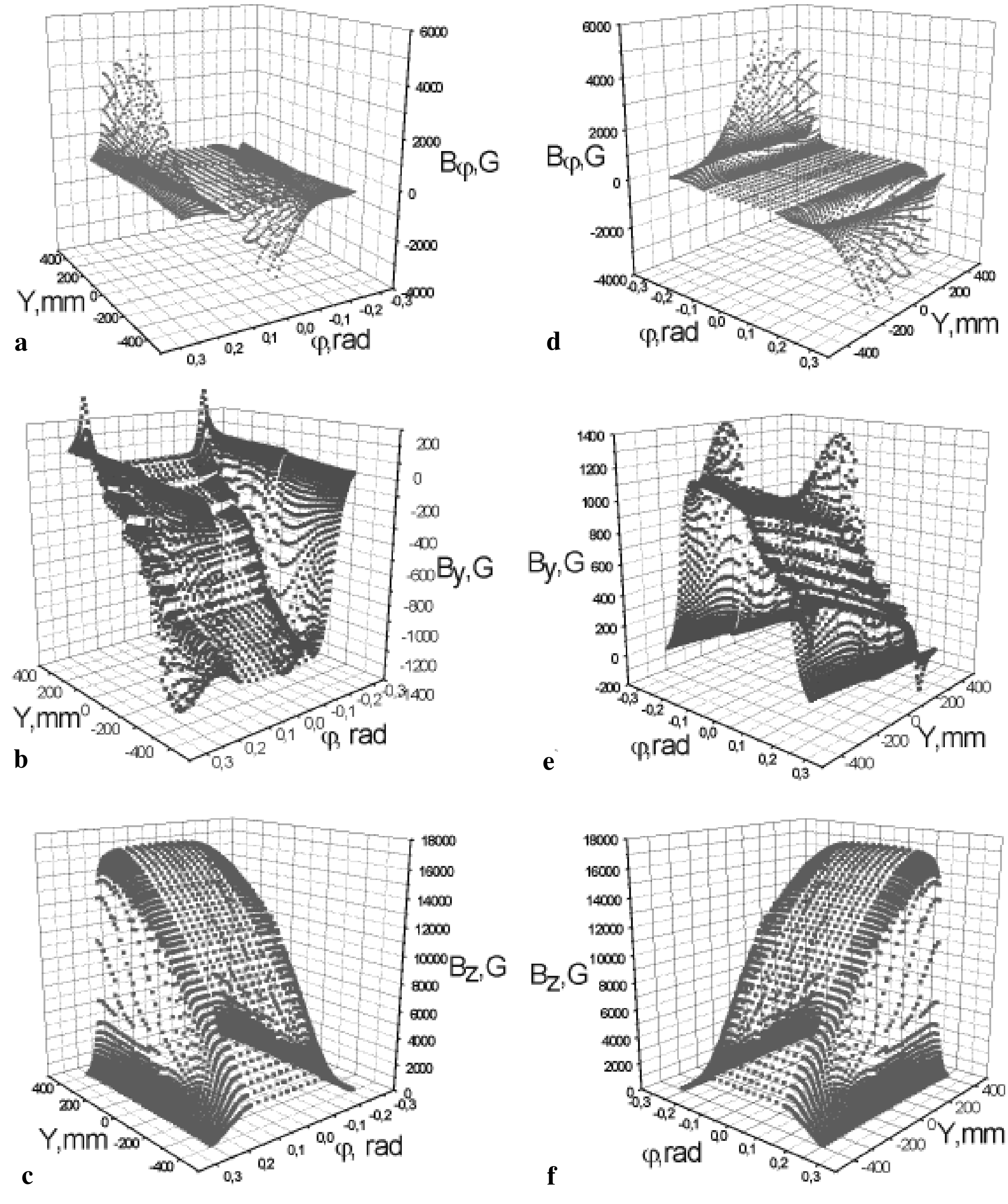

Fig. 2. The measured magnetic field distributions of the M_2 magnet at the field level B_0 = 11,610 G. The B_φ (a), B_y (b), and B_z (c) are the components of the magnetic field close to the upper pole of the magnet and the B_φ (d), B_y (e), and B_z (f) are the components of the magnetic field close to the lower pole of the magnet.

closed surface on which distributions of the magnetic field components are measured.

Separator, measurements and reconstruction of the magnetic fields of the M_1 and M_2 magnets

A separator with a large entrance solid angle and high momentum acceptance has been specially designed for collecting efficiently extremely short-lived nuclei, which are produced in intermediate energy massive transfer reactions [1–3]. The separator has been constructed in accordance with the scheme $F_0M_1M_2M_3M_4F_dM_5M_6M_7M_8F_a$, where F_0 is the production target (object), F_d is the intermediate low dispersive focus, F_a is the final achromatic focus, M_1, M_2, M_7, M_8 are the main analysing and focusing magnets and M_3, M_4, M_5, M_6 are the correcting magnets. The second half of the separator (from F_d to F_a) is a mirror, the symmetrical counterpart of the first one (from F_0 to F_d) and the intermediate focal plane at F_d is the plane of the symmetry. Multipole M_3, M_4, M_5, M_6 magnets with special profiled poles are used to correct higher order aberrations.

Distributions of the magnetic fields of the M_1 and M_2 magnets were measured using Hall probe systems, which allowed measuring the magnetic field components both inside the working areas and on their borders [4]. These data were used for numerical reconstruction of the fields and for direct calculation of the $((B^{(l)\mathrm{cal}} - B^{(l)\mathrm{mes}}), l = \varphi, y, z)$ difference in all volumes of the working areas. This difference characterizes the quality of the magnetic field reconstruction as well as the magnetic measurements.

The measured magnetic field distributions of the M_1 magnet at the field value $B_0 = 7050$ G and the B_φ, B_y and B_z components of the magnetic field in the plane lying 30 mm below the median plane are presented in Fig. 1. The magnetic field distributions in the planes close to the upper and lower poles of the M_2 magnet are shown in Fig. 2, while the magnetic field distributions in the inner (the minimal radius) and outer (the maximal radius) planes of the volume of the M_2 magnet are shown in Fig. 3.

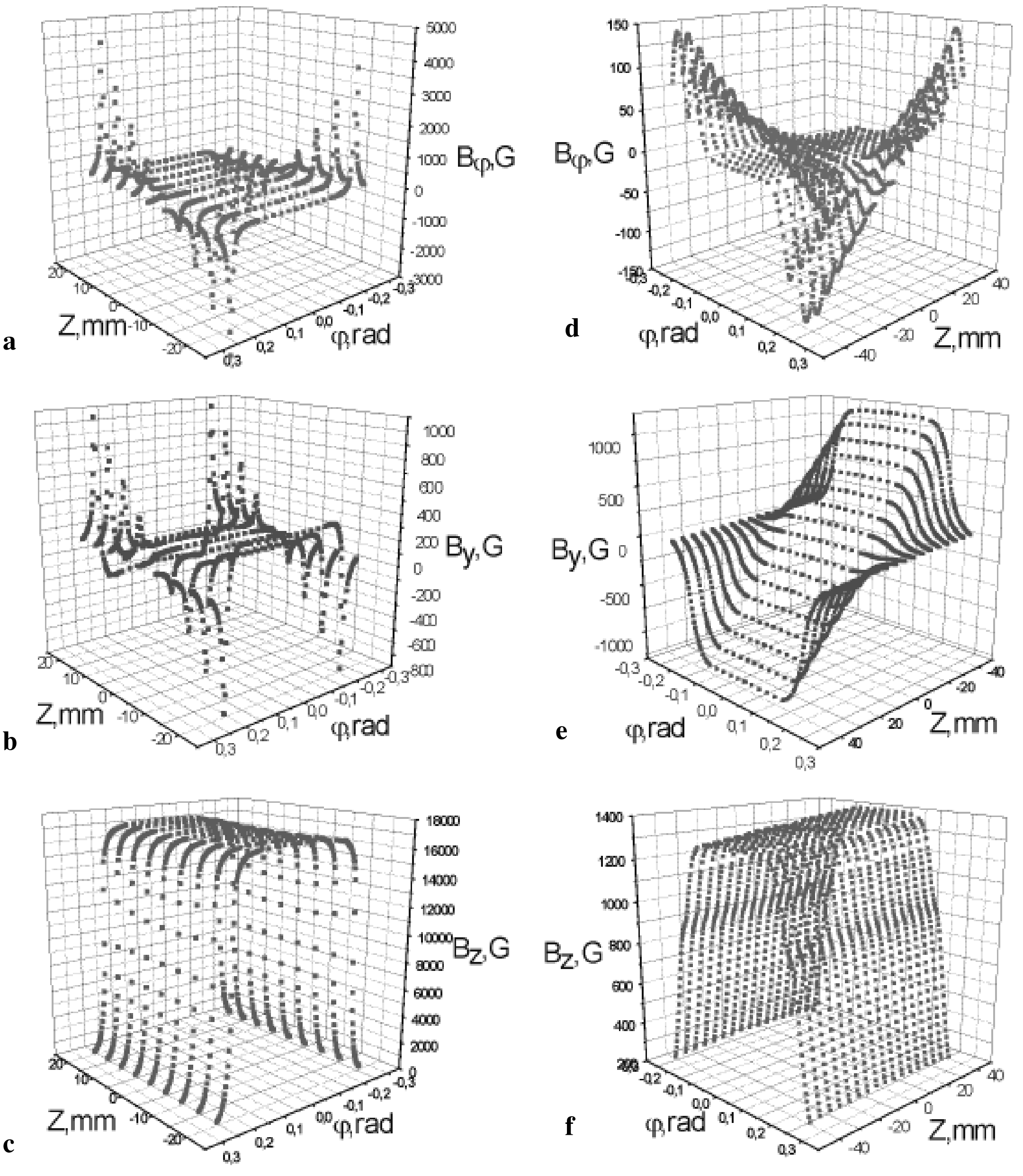

Fig. 3. The measured magnetic field distributions of the M_2 magnet at the field value B_0 = 11,610 G. The B_φ (a), B_y (b), and B_z (c) are the components of the magnetic field along the border of the maximum radius of the working region and the B_φ (d), B_y (e), and B_z (f) are the components of the magnetic field along the border of the minimum radius of the working region.

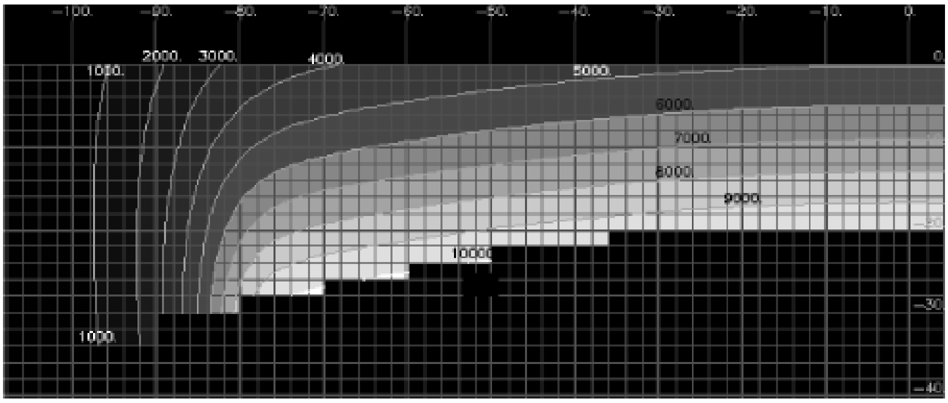

Fig. 4. Reconstructed field distribution of the B_z component in the median plane of the measured on field boundaries M_1 magnet. Reconstruction was based on the experimental data from planes lying at distances ±30 mm from the median plane.

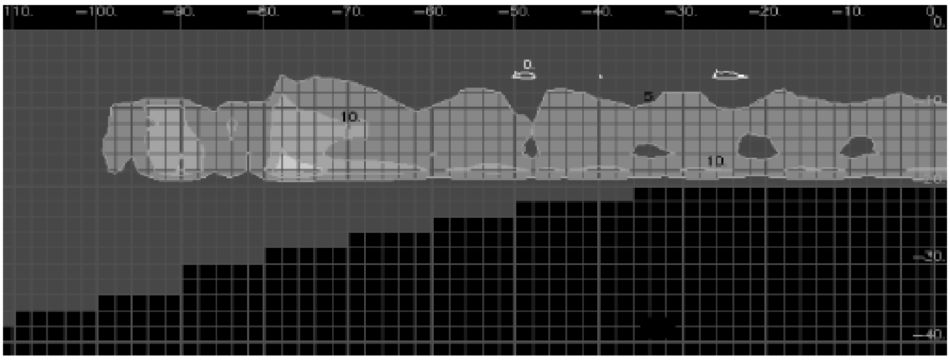

Fig. 5. The absolute error distribution of the B_z ($\Delta B_z = B_z^{\text{exp}} - B_z^{\text{rec}}$) component in the median plane of the M_1 magnet.

Reconstruction of the magnetic fields has been based on the model which uses discretization of differential equations via finite elements, simultaneous consideration of different nonlinear effects associated with materials, modelling of current carriers with realistic geometry, modelling of combination of conductors and permanent magnets, the iterative solving of large systems of nonlinear algebraic equations, and comprehensive pre- and post-processing. We have used the KOMPOT code to create the 3D magnetic system model using as the input the data of our magnetic measurements [5, 6]. The output is available as an exact field map generated from boundary measurements only or as a global model constructed according to the field measured at the given sub-regions and points.

In the process of the reconstruction of magnetic field, we have dealt with two kinds of computing errors. The first one is connected with both the number of measured points and with the form of the function approximating distribution of the magnetic field. Another kind of computing errors is connected with the interpolation of the magnetic measurements aimed at obtaining the normal field component, B_n, at borders of the working area.

Apart from the computing errors, there are errors connected with the accuracy of the magnetic measurements, namely the error of the field measurement ($\approx 5 \times 10^{-4}$–10^{-5}) and the error of the determination of the Hall probe positions.

Comparison of the results of the magnetic field reconstruction with the data of the magnetic measurements

The measured values of the magnetic fields of the M_1 and M_2 magnets were used to check the reconstruction procedure. As the entrance data, the measured values of the

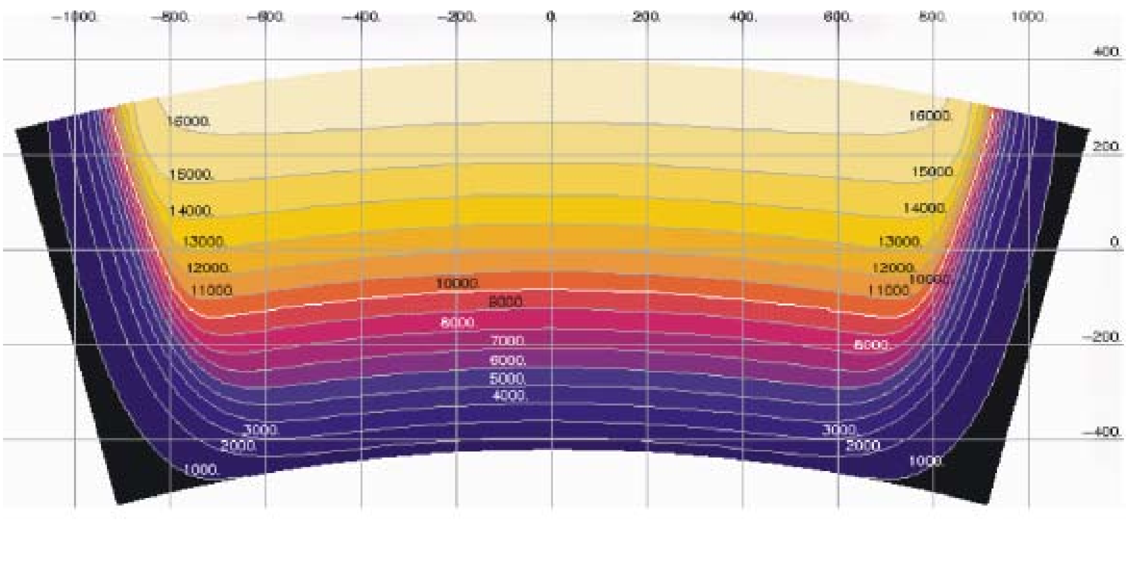

Fig. 6. The reconstracted magnetic field distribution in the median plane of the M_2 magnet.

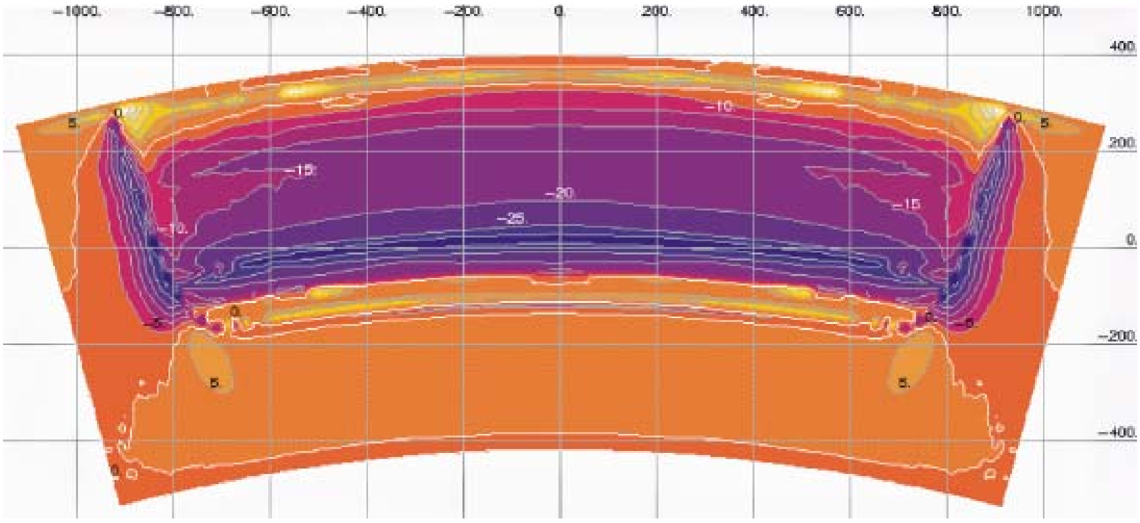

Fig. 7. The absolute error distribution of the B_z ($\Delta B = B_z^{\mathrm{exp}} - B_z^{\mathrm{rec}}$) component in the median plane of the M_2 magnet.

magnetic field components on borders of the working areas were used [1]. Values of the magnetic field in the internal volume were used for both the comparison with the result of the field reconstruction and for the calculation of the $((B^{(l)\mathrm{cal}} - B^{(l)\mathrm{mes}}),\ l = \varphi, y, z)$ difference in all volume of the working area.

The magnetic field of each magnet was measured in several planes at thousand positions on each of them. All points of the measurements formed 3D grid with more than 20,000 units.

In Figs. 4 and 6, the results of reconstructed values of the magnetic field of the $B^{(z)\mathrm{cal}}$ components done in the central plane of the M_1 and M_2 magnets are shown. In Figs. 5 and 7, the differences $((B^{(l)\mathrm{cal}} - B^{(l)\mathrm{mes}}),\ l = \varphi, y, z)$ between reconstructed values of the field components $B^{(l)\mathrm{cal}}$ and the measured ones $B^{(l)\mathrm{mes}}$ are shown. The respective volume-averaged relative error was found to be below 10^{-3}.

Conclusion

The dedicated software package KOMPOT-MAP has been developed to numerically reconstruct magnetic field in a closed volume using boundary measurements of normal field or three-field components. The output is available as a precise 3D field map. The reconstruction accuracy depends on the accuracy of boundary measurements. It is estimated as the difference between the measured and reconstructed field values. In the future, it is planned to use the reconstructed fields in beam dynamics simulations in the framework of implementation of the (TOF-ΔE) method.

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