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Magnetic field simulation in the central region of the VINCY Cyclotron

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Abstract The VINCY Cyclotron is under construction at the Vinča Institute of Nuclear Sciences, Laboratory of Physics, Belgrade, Serbia and Montenegro. One of the most difficult problems to solve is the magnetic field shaping in the central region of the machine in a wide range of field levels. The latest measurements showed a very large magnetic field depression in the central region. The following shimming elements are used for the field shaping in the central region: a central plug and a spacer ring between the sectors and the median pole plate. These elements should both release enough vertical space for the inflector and the RF electrodes and produce a field bump in the very center of the machine. Concerning this region, one has to mention the following facts: sectors are absent or very reduced, and the small gap between the sectors restricts remarkably the possibilities of producing a field bump. Therefore, the design of these elements is the most critical one. Optimization of the central plug gap affects both the vertical sparking probability and the beam dynamics at higher harmonic modes. The redesign of the magnetic structure of the central region relied solely on the detailed 3-dimensional calculations to speed up the experimental shimming procedure. The desired calculated magnetic field shapes, which include the influence of the plug, have been produced and confirmed by the particle tracing for the 3-field levels. The final tailoring of the field map will be performed by the measurements at the full-size magnet.

Key words cyclotron • central region • magnetic field • plug • beam dynamics

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Introduction

The VINCY Cyclotron is under construction at the Vinča Institute of Nuclear Sciences, Laboratory of Physics (Belgrade, Serbia and Montenegro) [5]. In the VINCY Cyclotron, as in any multipurpose isochronous machine, the magnetic field must be provided for all ion beams within the cyclotron operating range.

One of the most difficult problems to solve is the magnetic field shaping in the central region of the machine in a wide range of field levels. Concerning this region ($R <$ 10 cm), one has to mention the following facts: sectors are absent or very reduced, and the small gap between the sectors restricts remarkably the possibilities to produce a field bump. Therefore, the design of these elements is the most critical one. Optimization of the central plug gap affects both the vertical sparking probability and the beam dynamics.

The possibility of producing a required magnetic field in the region of the initial beam turns is considered in the present paper.

Formulation of the problem

The problem of the magnetic field shaping in the central region of the VINCY Cyclotron has been already considered on the basis of 2-dimensional magnetic field calculations and measurement with the magnet model [1].

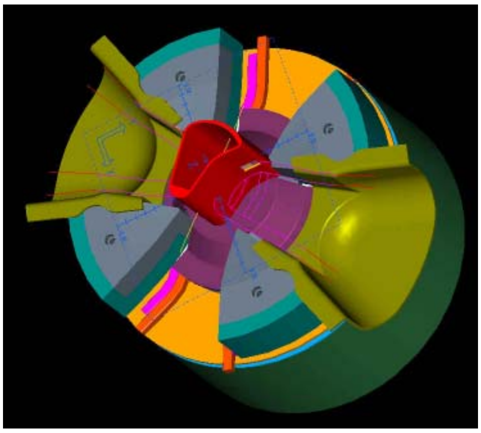

Fig. 1. Isometric view of the central region.

But the latest measurements with the full-size magnet for 3 basic main-coil currents 250, 600 and 1000 A have shown a large mean magnetic field depression in the radial range 0÷10 cm. The field distributions differ from the required values by ~170 mT, ~120 mT and ~100 mT for the 3 above-mentioned main-coil currents, respectively. Thus, there exists a problem of producing the desired magnetic field by the magnetic element structure of the central region. The following limiting conditions should be met [1]:

- sufficient space for placement of the inflector and central region electrode structure;
- requirements from the magnetic field measurement system;
- space limitations superimposed by the central harmonic and trim coils.

The redesign of the magnetic structure of the central region relied solely on the detailed three-dimensional (3D) calculations to speed up the experimental shimming procedure.

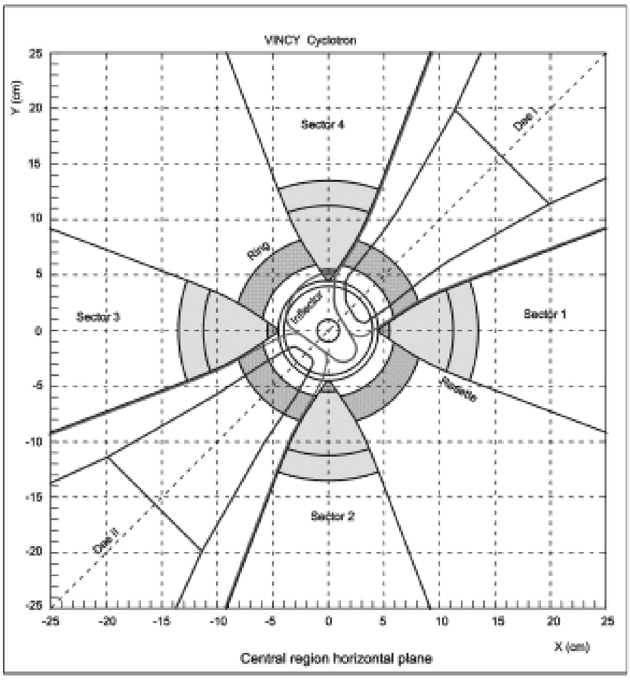

Fig. 2. Central region structure, XOY plane.

Central shims

The general 3D view of the central region with the original structure of the plug (Figs. 1 and 2) schematically presents the median-plane layout of the central region. The proposed geometry modifications are marked in colour in Fig. 2: darker grey colour – addition of magnetic material, lighter grey – cutting in the original structure. The contour of the inflector case at potential and the acceleration system (dee, anti-dee) are also shown in the Figure.

Figure 3 shows the axial cross section of the magnetic system "valley". The colour definitions in the figure are analogous to those in Fig. 2. The zoomed cross section of the structure is shown in Fig. 4.

The shimming elements used for the field shaping in the central region are a central plug and a spacer ring between the sectors and the median pole plate. These elements should both release enough vertical space for the inflector and the RF electrodes, and produce a field bump in the very center of the machine. The plug consists of 2 cylinder shims and one 4-fold sector shim ("rosette"), which provide a rather smooth transition from the cylinder form of the plug to the 4-sector structure of the magnetic system. Assessment of the effect of the "valley" shims, installed in every 2nd "valley" of the magnetic structure at the axial position of the "rosette" was also performed.

Method

Magnetic field simulation of the facility was performed with the help of the well-known computer code "Mermaid" [3]. Detailed description of the central region structure and the magnetic properties of its elements are given in [6]. In the report, the description of the spatial (3D) computer model of the whole magnetic system and its central zone is also given.

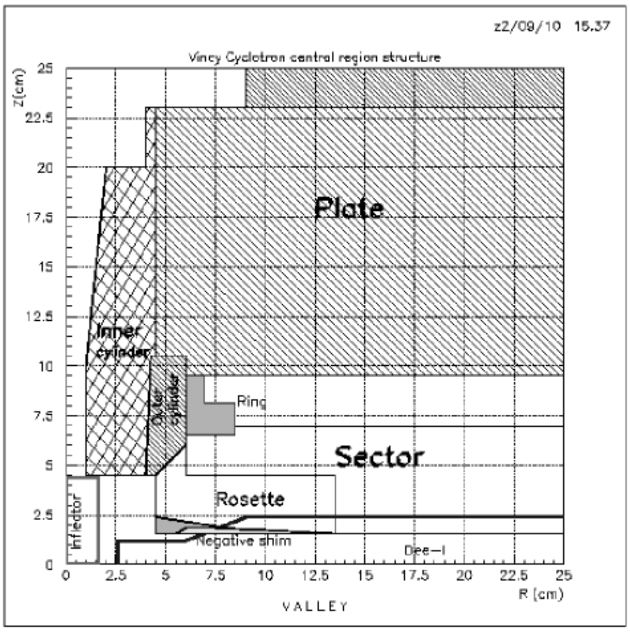

Fig. 3. Central region structure, valley cross section.

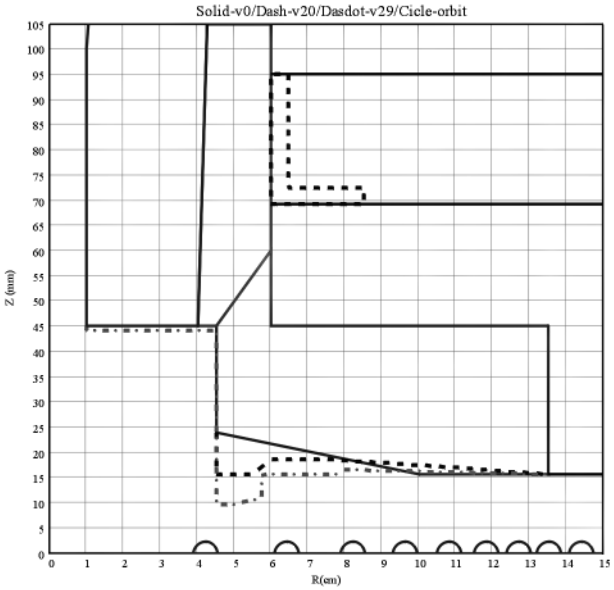

Fig. 4. Central region cross section in the sector symmetry plane. Solid curve – measured profile; dashed curve – calculated profile version 20; dash-dotted curve – calculated profile version 29; semicircles – radial positions of the D-beam orbits at the dee edge.

Based on those models, the results shown in Figs. 5 and 6 were obtained. The simulation curves are close to the measurements with enough accuracy for the given study. This fact allows conducting calculation to reliably shape the magnetic field in the center of the cyclotron.

Nevertheless, when selecting the new central region structure to minimize the field "dip" in the radial range $R < 10$ cm, one should take into account the systematic error in calculations (the difference between calculation and measurement of the order of 10÷30 mT). The maximal deviation of the calculation from the measurement takes place at the main-coil current of 250 A.

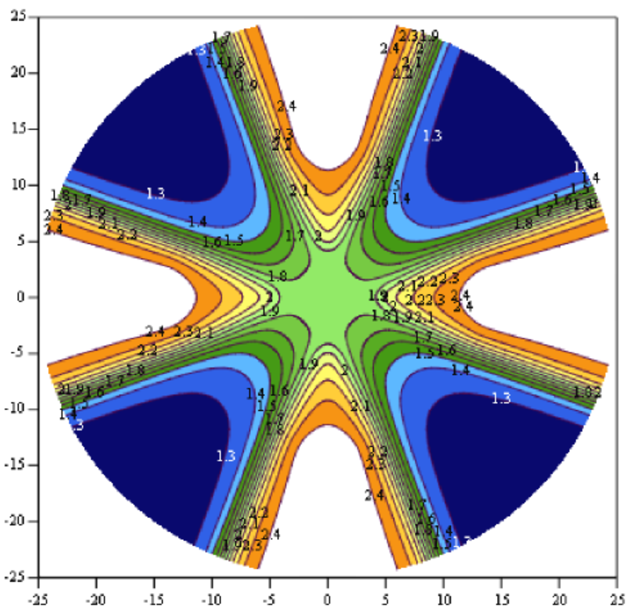

Fig. 5. Contour plot of the calculated magnetic field distribution. Main-coil current 600 A; X, Y – coordinates in cm; constant *B*-field curves in T.

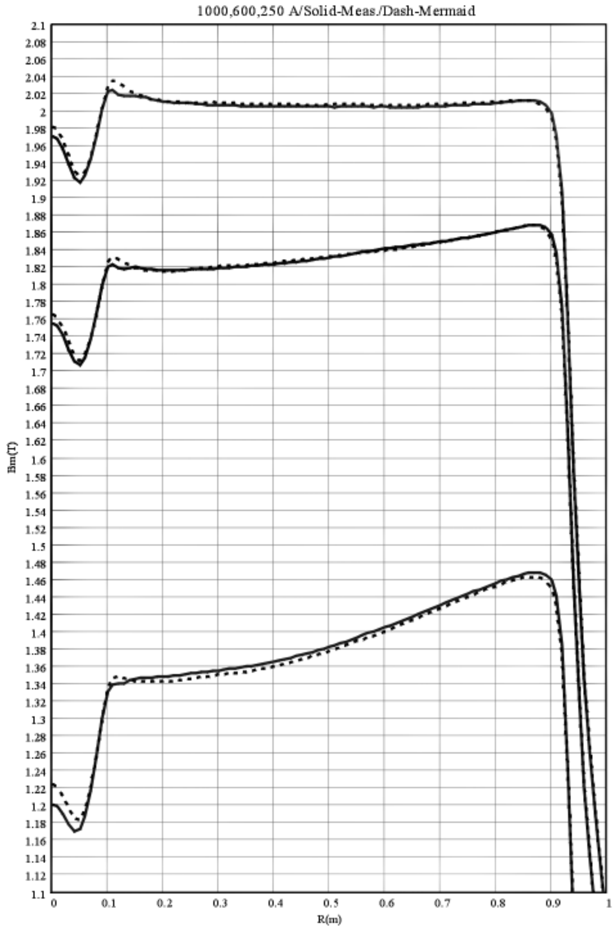

Fig. 6. Measured (solid curve) and calculated (dashed curve) mean magnetic field. Main-coil currents 1000 A (upper curves), 600 A (middle curves) and 250 A (lower curves).

Increasing the number of nodes from ~ 4 million to ~ 9 million with higher density of nodes in the region of interest did not remove the systematic error, which is an indication of the good quality of the calculations.

The difference between the calculated and measured field curves could be substantially decreased by increasing the axial gap between central cylinders by ~ 2 mm (~2%) and introducing a facet with radius ~ 0.4 mm at the median-plane surface corner of the "rosette" ($r = 100$ mm, $z = 15.5$ mm). This dummy shimming of the "rosette's" axial profile could be used in subsequent calculations to exclude the above-mentioned systematic error.

Shimming

The tentative shimming of the magnetic field for the main-coil current 600 A (nominal regime) shows that the only change of the plug shape did not produce the desired field distribution.

To obtain the desired level and shape of the field in the central region a number of different combinations of shimming elements were considered. The shimming elements considered were: the plug cylinders, the "rosette", the spacer ring, and the "valley" shims.

Table 1. New geometry of the central region structure.

"Rosette"	*R* (mm)	45	45	55	60	75	100	135	135	60	60
	Z (mm)	45	15.5	15.5	18.5	18.5	17.5	15.5	45	45	60
Ring-"valley"	*R* (mm)	60	85	85	69.5	69.5	60				
	Z (mm)	65	65	81	81	95	95				
Ring-"hill"	*R* (mm)	60	85	85	64.5	64.5	60				
	Z (mm)	69.3	69.3	72.5	72.5	95	95				

Table 2. Accelerating regimes.

Ion	Final energy (A MeV)	Rotation frequency (MHz)	RF harmonic (kV)	Dee voltage	Magnetic field in the center (T)	Magnet current (A)
H^-	65	19.71	1	100	1.293	~250
D^-	30	13.75	2	80	1.801	~600
$^{40}Ar^{6+}$	3.1	4.52	4	80	2.010	~1000

But the "valley" shims, installed in every 2nd "valley" of the system, introduce the 2nd harmonic of the axial component of the field. The beam dynamics calculations showed that the presence of too large amplitude of the harmonic deteriorated the beam considerably [2]. So, "valley" shims were rejected.

The magnetic field shaping was performed at the main-coil current 600 A with the help of an additional ring and variation of the axial profile of the "rosette" from the median-plane side. The resulting modifications of the structure elements in the central region (*R*-radius, *Z*-deviation from the median-plane) are given in Table 1 and Fig. 4. The azimuthal dimensions of the elements were not changed, i.e. only axial shimming was used.

Magnetic field distribution inside the structure elements can be seen in Fig. 7 (sector symmetry plane *ROZ*). Concentration of the magnetic flux in the direction of the machine center due to the cutting in the "rosette" profile is clearly visible there.

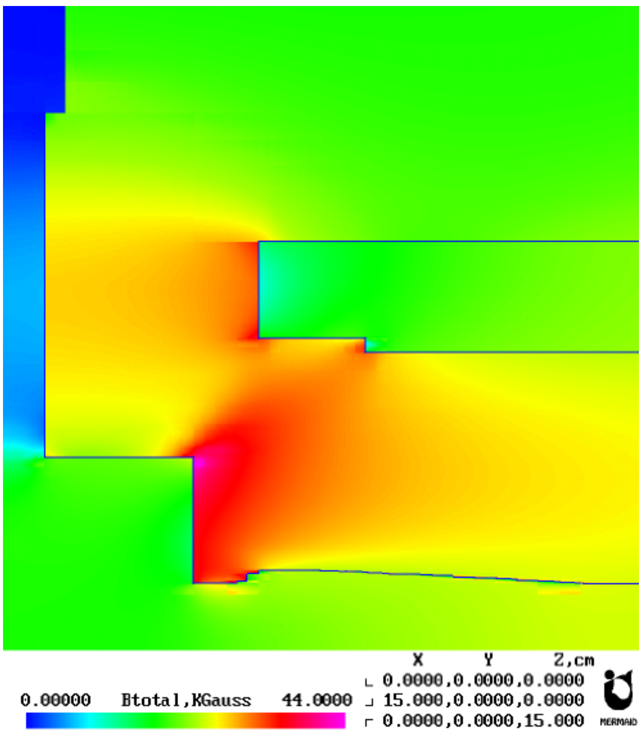

Fig. 7. Magnetic field map in the sector symmetry plane. Main-coil current 600 A; 0 < *R* < 15 cm, 0 < *Z* < 15 cm.

The effect of the new ring shim inserted in the gap between the sector and the plate for increasing the field level in the center region is obvious from the figure. Substantial flux redistribution inside the structure elements takes place for the main-coil current 250 A as compared with 600 A and 1000 A, which leads to quite different performance of the mean field at this regime compared with other field levels.

Optimization of the form and position of the cutting in the axial profile of the "rosette", which is indicated as "negative shim" in Fig. 3 [10], reduces the deviation of the calculated mean field from the desired one down to (–5 mT)÷(+20 mT) for the main-coil current 600 A (Fig. 8, middle frame, solid curve). The difference in the field level between the required and obtained distributions in the acceleration range (r = 0÷87 cm) could be reduced to minimum by selecting a proper current of the main-coil. Additional variation of the field level in the central region (r = 0÷25 cm) could be obtained with the help of the 1st trim coil [9] (dash curve in the Figure) to let the beam pass through the central region.

Simulation results for the other basic main-coil currents are also given in Fig. 8 (deviation from the required curves, [11]). The 1000 A case is similar to the 600 A simulation but with the field level being somewhat higher (~20 mT) than the required one. The 250 A maximal field deviation is ~ 70 mT lower than the desired one in the region.

Parameters of the acceleration regimes ([7, 8]) for the basic main-coil currents are given in Table 2.

Beam dynamics

Simplified beam dynamics analysis of the calculated magnetic field in the central region was performed with the parameters from Tables 2 and 3.

Varying the beam injection angle, the central RF phase and the emittance correlation coefficients provided optimal matching of the beam to the acceptance of the initial cyclotron orbits. Modified distributions (dashed curves in Fig. 8) were used for particle tracing.

Table 3. Injected beam parameters.

Ion	Energy (A keV)	Radial emittance (π mm·mrad)	Axial emittance (π mm·mrad)	Energy spread (%)	RF phase range
H^-	29.1	124	160	~0.5	~5°
D^-	13.2	124	160	~0.5	~5°
$^{40}Ar^{6+}$	3.9	124	160	~0.5	~5°

A computer model of the classical differential probe was used to simulate the measurement of the radial beam density in Fig. 9. The beam position electrode of the probe has a finger jutting 0.5 mm out of the main interceptive target. The virtual radial probe is at $\theta = 69°$ downstream of the magnetic structure "valley" and near the dee edge azimuth.

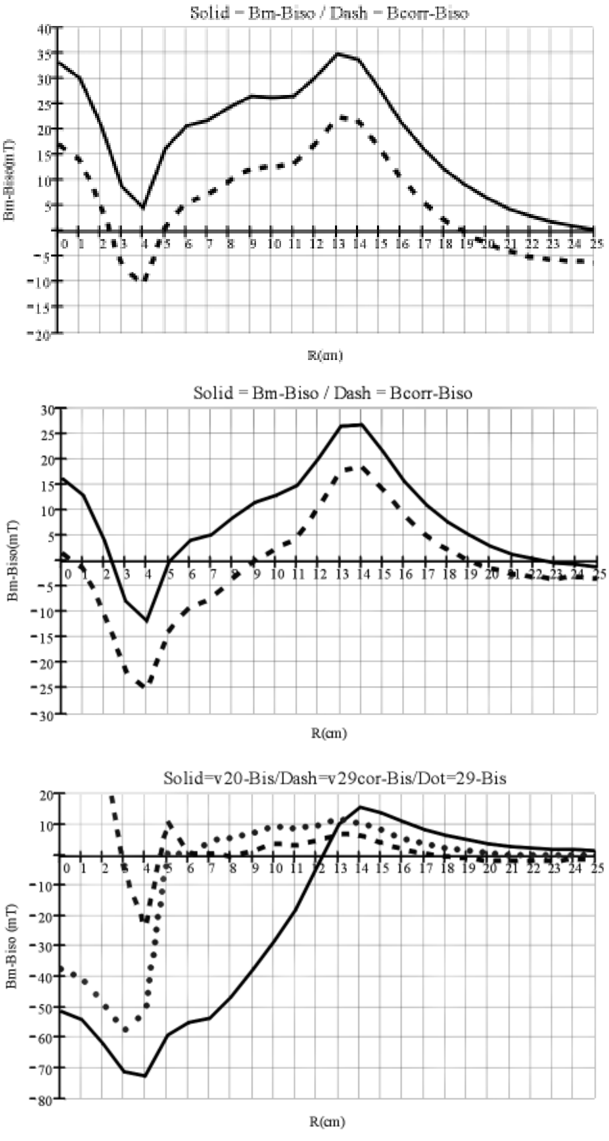

Fig. 8. Deviations of the mean magnetic fields from the isochronous radial distributions. Main-coil currents 1000 A (upper frame), 600 A (middle frame) and 250 A (lower frame); solid curves are calculated fields for the new plug (+57 mT for 1000 A, +20.5 mT for 600 A and +64 mT for 250 A); dashed curves are proposed corrected fields used for the beam dynamics analyses; dotted curve is corrected field for the plug version 29.

The simulation showed that there is no problem for the longitudinal and transverse D^- ion motion (Figs. 9 and 10). This conclusion is in compliance with the previous estimations [4].

An analogous beam dynamics simulation confirmed that the field at the main-coil current 1000 A was good enough for acceleration of $^{40}Ar^{6+}$ ions.

The situation is more complicated in the case of the main-coil current 250 A (H^- acceleration). The field produced by the central region structure (Fig. 8, lower frame, solid curve) does not allow accelerating H^- beam. Ability of the trim coils to shape the field is not sufficient to cope with the problem. So, the concept of a separate plug was tried for this case. As an example of this development, version 29 profile in Fig. 4 is given. The results of the field simulation for this profile are shown in Fig. 8 (lower frame, dotted curve). After additional correction of the obtained field distribution (Fig. 8, lower frame, dash curve) the H^- beam passed through the central region without any problem, showing what type of distribution is acceptable in this case. This result should be reconsidered again at the

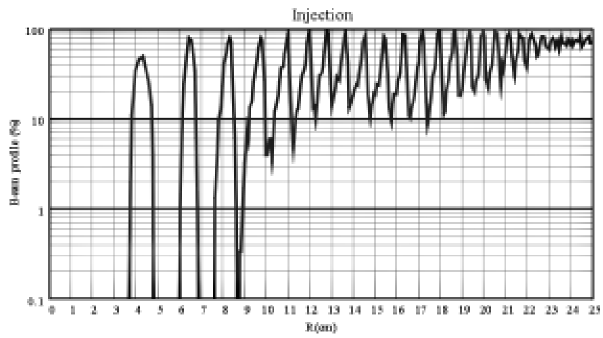

Fig. 9. D-beam radial pattern at the dee edge azimuth.

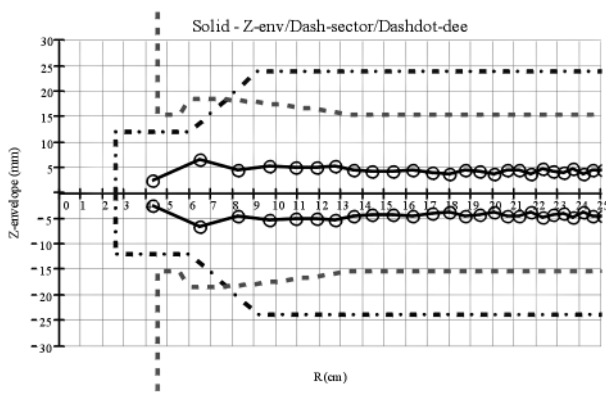

Fig. 10. D-beam axial envelope (4 standard deviations). Solid curve is the beam; dashed curve is the magnetic structure contour; dash-dotted curve is the RF system contour.

stage of the magnetic field measurements with allowance made for the given simulations.

Conclusions

The calculated magnetic field generated by the selected shim structure is close to the required distribution.

Preliminary beam dynamics simulations for the magnetic field maps, corresponding to the main-coil currents of 600 and 1000 A, confirmed the suitability of the maps for acceleration of the corresponding ions.

At the main-coil current 250 A an acceptable field shape has been defined. The concept of a separate plug can be considered as an alternative solution in this case.

The final tailoring of the field map will be performed by the measurements with the full-size magnet accompanied by the detailed beam dynamics analysis of the field distributions.

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