COMPUTER MODELS OF THE VINCY CYCLOTRON MAGNET

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This paper presents the computer models that have been used to compute the VINCY Cyclotron magnet. The program package POISCR is used as a routine solver for 2D calculations. Both the r-z and x-y geometry are considered in order to get the radial distribution and to simulate the azimuthal variation, respectively. In addition, a particular x-y geometry model is used to compute the force density in the yoke. To check the validity of 2D approach, a simplified 3D model is formulated and a series of calculations had been carried out by the FEM code TOSCA. Comparing the 2D and 3D results, a remarkable difference is detected in the radial field distribution, while the higher order harmonics are in a good agreement. To improve the 2D model a variable stacking factor is used for the sector region.

1. Introduction

The VINCY Cyclotron is a compact isochronous cyclotron with four straight sectors per pole. Detailed description of the cyclotron can be found elsewhere.[1,2,3] This paper presents the computing methods and the geometric models that have been used for magnetic field simulation. A selected set of the most appropriate parameters for computer modeling of the magnet is given in Table 1. Figure 1 presents a schematic view of the magnet.

Table 1: Selected parameters of the VINCY magnet

Diameter of the pole	2000 mm
Yoke length	5600 mm
Yoke width	1998 mm
Yoke height	3470 mm
Number of sectors	4
Spiral angle of the sector	0^0
Angular span of the sector	42^0
Distance between the valleys	190 mm
Minimum magnetic gap	31 mm
Maximum extraction radius	860 mm
Number of main coils	2
Number of the main coil turns/pole	256
Maximum main coil current	1000 A
Main coil current at field B(r=0) = 1.84 T	650 A
Number of trim coils per pole	10
Maximum current of trim coils	200 A
Number of harmonic coils per pole	8
Maximum current of harmonic coils	200 A

The ferromagnetic elements of the VINCY Cyclotron are made from the ferromagnetic elements of the CEVIL Cyclotron, which had been operating until eleven years ago in the Institute of Nuclear Physics, in Orsay, France. To determine the magnetic characteristic of that material, several measurements have been carried out in the Laboratory of Nuclear Problems, JINR, Dubna. A number of toroidal iron samples from various ferromagnetic elements has been considered. Figure 2 compares the measured results with the B(H) curves for two types of iron from the literature,[4] Armco and ST-08. The measured curve is closer to the ST-08. But except Armco all the other magnetization curves are incomplete. Therefore, the computations here presented rely only on the Armco data for the moment until new measurement data, covering all the range of interest, is available.

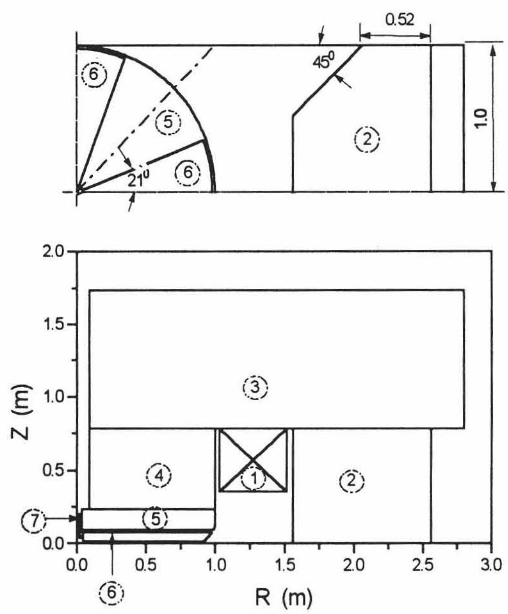

Figure 1: VINCY Cyclotron Magnet Configuration.
1- main coil, 2 - vertical yoke, 3 - horizontal yoke, 4 - pole, 5 - median pole plate, 6 - sector, 7 - central plug

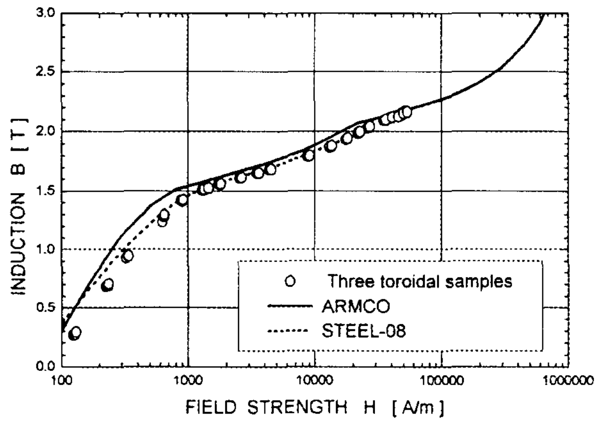

Figure 2: B(H) curve of the VINCY iron compared both to ARMCO and ST-08 iron

2. Computing methods

The magnet of a compact cyclotron is a large and rather complicated 3D structure where various details of very small dimensions have to be taken into account. Most of the todays 3D solvers can cope easily with such kind of problems. However, owing to large computing time it is inconvenient to apply a 3D solver repeatedly in some iterative procedure as is the case with the computation[5] of isochronous sector profile. Moreover, due to highly irregular mesh, unexpected numerical effects might arise in some cases. On the other hand, due to high computing speed, a 2D solver can be efficiently used for large series of calculations. Also, it is easy to refine the mesh locally in order to consider various details, such as the sector shimming. However, the validity of 2D approach may generally be questioned.

To resolve this problem, the following strategy has been adopted in the design of the VINCY Cyclotron magnet.

- The program package POISCR[6] is used as a routine 2D solver for problems where a large series of repeated calculations is necessary, for instance:
  - Computation of isochronous sector profile
  - Determination of the operating range
  - Optimization of the trim coil currents

- The 3D code TOSCA[7] is used as a reference solution technique in order to study particular problems such as:
  - Cross check of the 2D models
  - Computation of the stray field in extraction region
  - Computation of the second harmonic that is due to the rectangular yoke

- Measurements on a model magnet are being performed in the Laboratory of Nuclear Reactions, JINR, Dubna, in order to check the computing methods.

3. Geometric models

Since we are applying a 2D solver on a typical 3D problem, particular attention has to be paid to the proper choice of geometric model. Therefore, a simplified 3D model and three types of 2D models were suggested as follows.

3.1 A simplified 3D model of the VINCY Cyclotron

At first step two main goals of 3D simulation were: (*i*) to perform a cross check of 2D calculations in order to find out some possible limitations, and (*ii*) to study the peculiarities of the 3D structure, if any, due both to the sectors and the rectangular yoke contrary to the axial symmetry of the poles. To get a quick result with minimum efforts, one should start with as simple as possible configuration. Hence, the following simplifications have been made:

- No central hole (axial channel) for the ion source
- No gap between the sectors and the pole
- The magnetic plug is removed and combined with the other elements
- The gap between the sectors is taken to be constant and equal to 4 cm
- The sectors are extended both to the very center and the end of the pole

The corresponding computer model is constructed by the VF OPERA-3D - TOSCA package. Only 1/8 of the magnet iron was taken into consideration due to the symmetry. The starting configuration consisted of 1872 finite elements with 2227 and 8522 nodes for the 1-st and the 2-nd order approximation, respectively. Afterwards the mesh is refined to 6300 FEs with 27407 nodes for the second order approximation. Figures 3 to 7 present the TOSCA results compared to the corresponding 2D calculations.

3.2 Cylindrical model for radial field calculation

Those parts of the magnet which differ from cylindrical symmetry are modified in order to model the problem in r-z geometry. The rectangular yoke is cylindrized so that the cross-section of the model is equal to the cross-section of the actual magnet along the flux lines. Contrary to that, the cylindrical model of the sector has the same cross-section shape like the actual one, but a reduced iron density is assumed. According to the angular span of the sector, the stacking factor is equal to 0.46667. This type of model is largely used when the radial distribution of azimuthally averaged field is considered.

A convergence study is carried out in order to determine the standard finite element mesh as a compromise between the computing time and the accuracy. The results are presented in Table 2.

Table 2: A convergence study of 2D solution

Mesh type	Δr (cm)	Δz (cm)	Meshes	Magnetic induction B_z (T)				
				R = 0	R = 10	R = 50	R = 90	R = 100
Uniform	5	5	66 x 58	1.7809	1.8891	1.9037	1.8406	0.2626
	2	2	161 x 137	1.8613	1.9203	1.9102	1.8160	0.2663
	1	1	321 x 281	1.9058	1.9202	1.9088	1.8073	0.2660
Locally refined	1	0.50, z < 2 ; 1, z > 2	321 x 283	1.9077	1.9203	1.9089	1.8073	
	1	0.33, z < 2 ; 1, z > 2	322 x 285	1.9107	1.9203	1.9089	1.8074	
	1	0.25, z < 2 ; 1, z > 2	322 x 287	1.9095	1.9205	1.9090	1.8073	0.2660
Locally refined	0.25, r < 2 0.50, r < 5 1.00, r > 5	0.25, z < 2 ; 1, z > 2	330 x 287	1.9205	1.9205	1.9090	1.8074	0.2661
Irregular			200 x 172	1.9180	1.9180	1.9068	1.8073	0.2650

Figure 3 presents the radial field distribution for the case without sectors. A very good agreement between 2D and 3D results is evident. However, the situation is quite different when the sectors are in place, as shown in Figure 4. It is easy to see that the r-z model leads to a very unrealistic solution. Compared to the 3D results, the average field differs for 0.2 T.

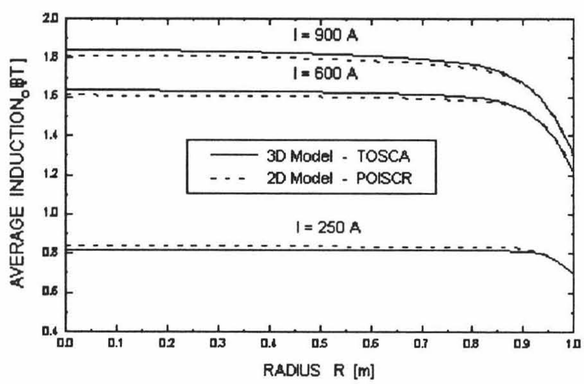

Figure 3: Radial field for the case without sectors

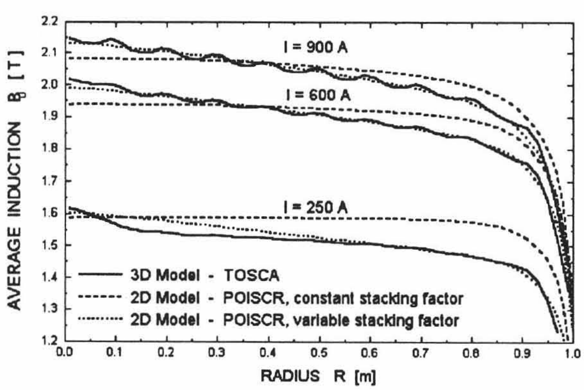

Figure 4: Radial field distribution when the sectors are in place

To avoid this problem, a variable stacking factor is introduced. The sector region is subdivided into a number of subregions in which the stacking factor decreases linearly with the radius. In a general case, the stacking factor depends not only on the radius, but on the sector thickness and the main coil current as well. Thus, a number of 3D calcultaions is necessary in order to establish a proper variation of the stacking factor for a given configuration.

It is worth to mention here that the 3D solution exhibits an oscillatory behavior for the higher level field. To remove this, one might either use a finer mesh (larger computing time) or apply some smoothening technique (post-processing).

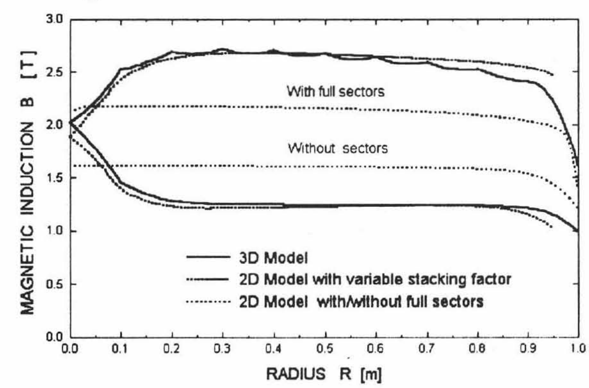

Figure 5: Magnetic field along two directions $\theta = 0^0$ and $\theta = 90^0$

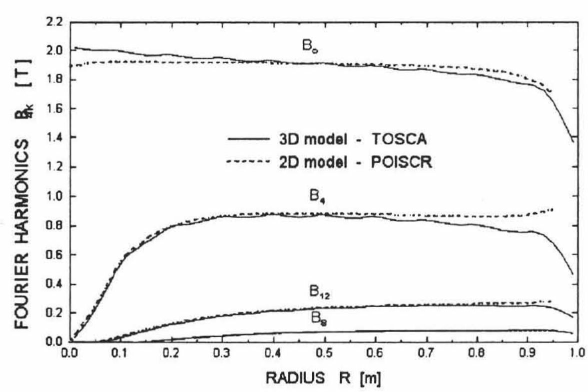

Figure 6: Fourier analysis of the median plane field

3.3 An x-y geometry model for azimuthal field simulation

This model is designed to simulate the azimuthal field variation. Repeating the calculation for a set of radii and using the radial distribution from the r-z model, one can synthesize the field map in the median plane. It is for this reason that the magnet is modeled in x-y geometry, assuming that the problem is invariant in z-direction.

For the sake of simplicity, a 2m pole is assumed. The yoke shape is chosen such that the ratio of the yoke/pole cross-section is the same as in the real magnet. A number of sectors is uniformly distributed over the pole according to the radius for which the azimuthal computation is simulated. Also, depending on the radius, the main coil current is adjusted in an iterative procedure to get the same average field as in the r-z model.

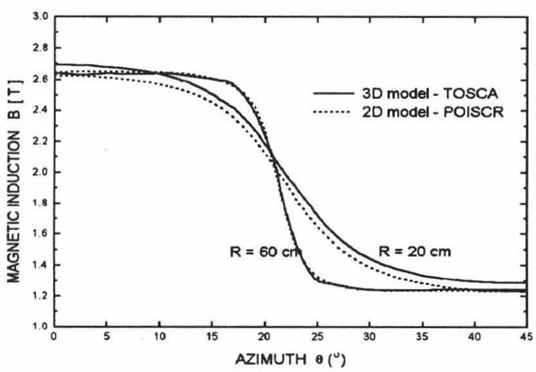

Figure 7: Azimuthal field distribution

Figures 5 to 7 compare the synthesized solution with the 3D calculations. Generally, one may say that the results agree well when the median plane is considered.

3.4 An x-y geometry model for force density computation

In the magnet assembling process it is crucial to know the ponderomotive forces that act on particular ferromagnetic elements. The cylindrical model, as formulated in section 3.2, can yield satisfactory results for the elements of cylindrical shape. However, it is inapplicable when the yoke is considered. Therefore, the following x-y geometry model has been formulated.

Each cylindrical element is approximated by a number of equivalent rectangular regions of 2 m length as shown in Figure 8. The stacking factor of each of them is determined as the ratio of the considered part of the actual region versus the corresponding 2m slab. Similarly, the main coil is represented by a number of current carrying regions. The effective currents are computed in the same manner as the above stacking factors. By increasing the number of regions one would get a better approximation of the real situation. Figure 9 shows the force distribution in the horizontal yoke that is obtained by the following subdivision:

- 20 subregions in the pole domain,
- 10 subregions of the main coil region, and
- 5 subregions in trapezoidal part of the vertical yoke.

To check the validity of this approach the median plane field is compared to the radial solution of the r-z model averaged on the square 2x2 m^2. The relative error is equal to 0.15 %.

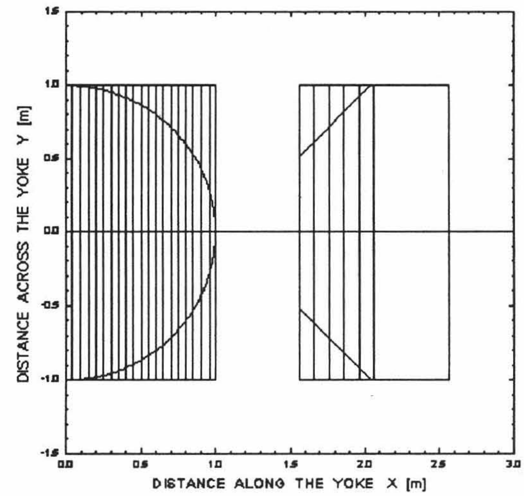

Figure 8: Equivalent rectangular regions

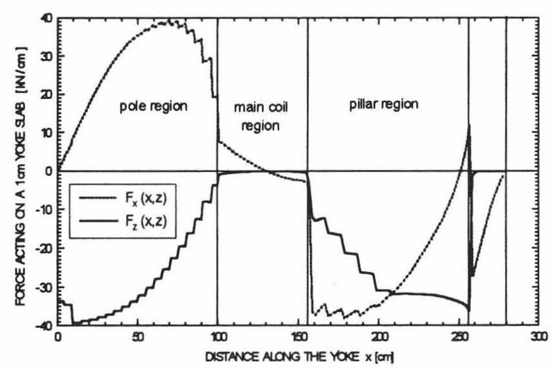

Figure 9: Force distribution in the horizontal yoke

References

1. N. Nešković et al., TESLA Accelerator Installation, TESLA Report 1/93, Vinca Institute of Nuclear Sciences, Belgrade, 1993.
2. N. Nešković et al., TESLA Accelerator Installation, EPAC-Berlin, 24-28th March, 1992, p.415.
3. N. Nešković, Status Report oN the VINCY Cyclotron, this conference, P1-10.
4. S.B. Vorozhtsov et al., Permeability Measurements with the Systematic Error Correction by Calculation of Stand Magnets, April 3, 1993, SDC-93-486.
5. D.V. Altiparmakov et al., Computer Modeling of Isochronous Field in the VINCY Cyclotron, This conference, P1-26.
6. F. Rohner, User Guide of the CERN-POISSON Program Package, CERN, 1991.
7. TOSCA User Guide, Version 6.3, 1993.