THE JYVÄSKYLÄ K130 CYCLOTRON MAGNET

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ABSTRACT

The present small MC–20 cyclotron of the Department of Physics (JYFL) will be replaced by a K130 heavy ion cyclotron[1)] in the early 90's. The national budget for 1987 included a small initial funding for a new cyclotron and the main funding was allocated for the years 1988–91. The magnet and the RF system will be transported to Jyväskylä in 1990. The magnet has been manufactured by Scanditronix AB, Uppsala, Sweden, and the design has been done in collaboration between Scanditronix and JYFL. The design was done using computer calculations without a model magnet.

The new K130 cyclotron has a conventional magnet with a pole diameter of 2.37 m and a total weight of 311 tons. A maximum field of 1.76 T together with an average extraction radius of 94.5 cm give a bending limit K_B = 130 MeV. The focusing limit has been adjusted to be a little above 90 MeV which is above the 85 MeV maximum proton energy guaranteed in the contract.

The field calculation method will be described and the comparison of calculated and measured fields will be given.

1. FIELD CALCULATION METHOD

The median plane field is divided into two parts:

$$B(r,\theta) = B_0(r) + \sum_i B_i(r)\cdot\cos\Big(i(\theta-\phi_i(r))\Big), \qquad (1)$$

where $B_0(r)$ is the average field over the azimuth and the $B_i(r)$ are the Fourier coefficients of the field. The average field and the azimuthally varying field are calculated separately and then added together to obtain the total field.

1.1 The Azimuthally Averaged Field $B_0(r)$

The azimuthally averaged median plane field is calculated using the code POISSON. Since POISSON is a two-dimensional code, a cylinder symmetric model for the rectangular yoke must be generated.

The pole pieces are cylinder symmetric and can be taken as such in the model. Those parts in the return yoke which differ from cylinder symmetry are modified so that the cross section through which the magnetic flux flows corresponds to the actual cross section (see figure 1), i.e. the flux density B in the iron is the same in the model and in the magnet.

Closest to the median plane are the sectors that are not cylinder symmetric. The angular width of the sectors is a function of radius, and thus the use of stacking factors in POISSON does not give good results. The effect of the sectors (or hills) is determined by taking a weighted average of the field without hills and the field with the fields and also the valleys filled with iron:

$$\begin{aligned} B_0(r) =& w^{\text{hill}}(r)\cdot B_0^{\text{hill}}(r) + w^{\text{valley}}(r)\cdot B_0^{\text{valley}}(r), \\ & w^{\text{hill}}(r) + w^{\text{valley}}(r) = 1, \end{aligned} \qquad (2)$$

where w^{hill} and w^{valley} are the relative widths of the hills and valleys at radius r, respectively, or, more precisely, the relative area cut by a cylinder of radius r. This method works well when the magnetization in the hills is (almost) axial, which is true for fields higher than $\approx$ 1.5 T. The method was tested[2)] with the Scanditronix cyclotrons MC40 and MC50, and the fields were found to differ from the measured fields some parts of 1 % for $B \geq$ 1.5 T and about 2 % for $B \approx$ 1 T.

Another constraint for the cylinder symmetrical model is to keep the total Fe–volume constant. This condition, however, is not very critical and has only minor effects on the field value in the median plane.

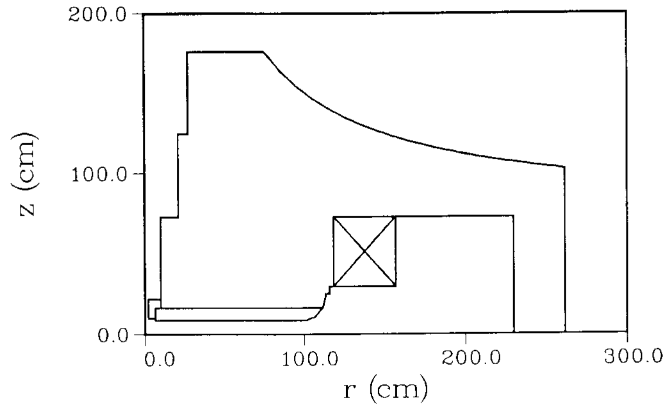

Figure 1

$r - z$ cut of the cylinder symmetrical model of the K130 magnet.

1.2 Azimuthally Varying Field

The azimuthally varying component of the median plane field in superconducting cyclotrons is calculated assuming magnetization current $\nabla \times \mathbf{M}$ flowing on the vertical surfaces of the sectors and using the Biot–Savart law[3]. This method gives good results as long as the iron can be assumed to be homogenously magnetized (saturated). The azimuthally averaged part of the sector field is extracted and the remaining Fourier components are added to the averaged field calculated separately as explained above.

In conventional cyclotrons the same procedure can be used with the exception that the magnetization current flows also inside the pole pieces. To determine the current distribution in the poles an infinitely long cartesian model is created with the actual hill and valley gaps.

The field is first calculated with POISSON and the average field is extracted. We call the remaining field $B_{\mathrm{AC}}^{\mathrm{POISSON}}$. The corresponding magnetization current is assumed to flow on hill surfaces and inside the pole on surfaces that follow the edge of the hills. The magnetization in the hills is assumed to be (piecewise) homogenous and thus

$$\mathbf{j}_M = \mathbf{n} \times \mathbf{M}, \tag{3}$$

where $\mathbf{n}$ is the normal unit vector. The field from the current flowing on axial hill surfaces is called B^{hill}. Inside the poles $\nabla \times \mathbf{M}$ is not known. The magnetization current density can be assumed to drop linearly from j_0 to zero when z goes from z_{valley} to approximately $2z_{\mathrm{valley}}$. The upper limit of z should be adjusted so that j_0 does not exceed the corresponding current density on vertical sector surfaces. The choise of the upper limit has only a minor effect on the higher harmonics of the field and is not very critical. Now j_0 is the only unknown and it comes from the condition

$$B_{\mathrm{AC}}^{\mathrm{hill}}(M) + B_{\mathrm{AC}}^{\mathrm{pole}}(j_0) = B_{\mathrm{AC}}^{\mathrm{POISSON}}. \tag{4}$$

The AC field of the real sectors can now be calculated using the actual M in the hills and j_0 from the cartesian model, i.e. the current flowing along surfaces that follow sector edges.

2. RESULTS

The field mapping started in Uppsala in the beginning of March 1989. The measured field at 1000 A was about 1.5 % higher than the calculated one. One reason for this is the hysteresis of the magnet which is not taken into account in POISSON (each field level was set through saturation). Another reason is that the magnetic properties of the sectors were better than those used in the calculations. The sectors have been manufactured from an ARMCO–steel which has less than 0.01 % C. The measured azimuthally averaged field at 1000 A and the corresponding calculated field (current adjusted to give the same extraction field) are seen in figure 2.

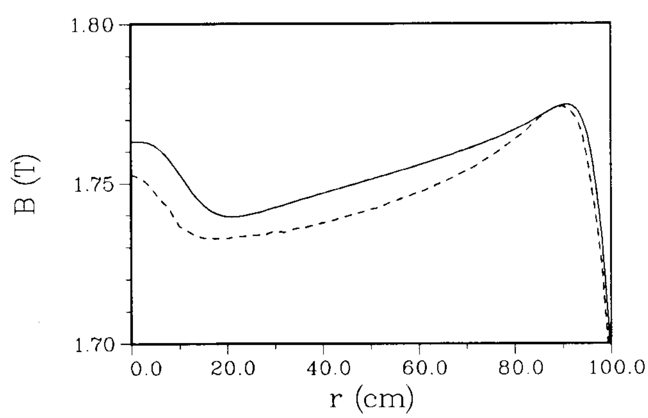

Figure 2

Azimuthally averaged measured (dashed) and calculated (solid) field at 1000 A.

As can be seen from the figure, the calculated field differs from the measured only 0.6 % when the extraction fields have been adjusted to be the same. A small shift of $\nu_r = 1$ inwards was seen at large fields due to saturation effects. This effect can be handled with trim coils and by moving the extraction elements radially.

The azimuthally varying part of the fields can be compared by looking at the Fourier components of the field (cf. eq. 1). The first five components are seen in figure 3. The corresponding flutter is seen in figure 4. Flutter is defined as

$$F = \frac{< B^2 > - < B >^2}{< B >^2}, \tag{5}$$

where $< ... >$ denotes the average over the azimuth.

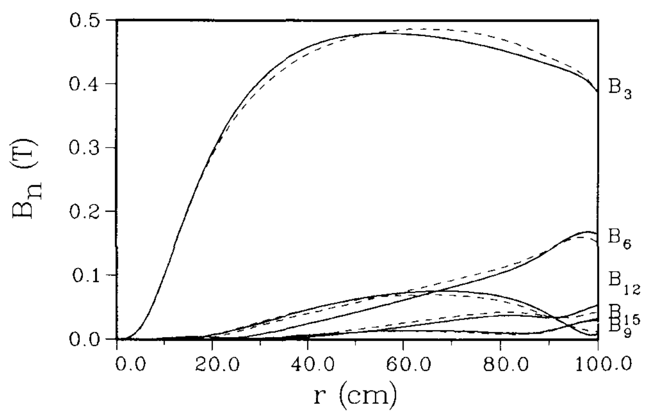

Figure 3

Measured (dashed) and calculated (solid) Fourier coefficients of the field at 1000 A.

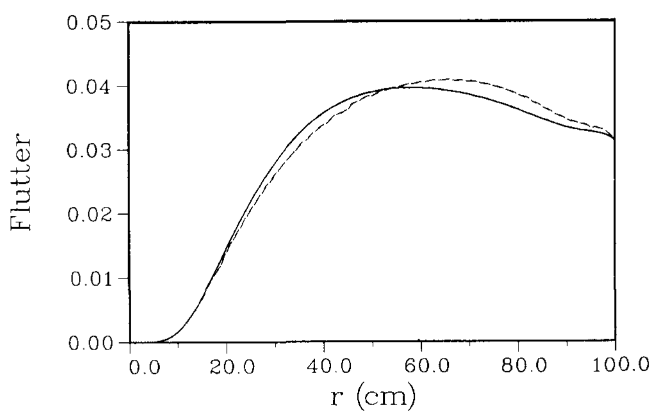

Figure 4

Measured (dashed) and calculated (solid) flutter of the field at 1000 A.

The measured Fourier coefficients are slightly larger at the extraction area than the calculated ones. One reason for this is the good quality of the sector material. Since the flutter near extraction is a little larger than the calculated one the field can focus at least those ions that could be focused with the calculated fields. Nevertheless, the difference in flutter at $r = 90$ cm is less than 5 %, which is satisfactory and confirms our choise not to use any model magnets. A similar agreement was seen when testing the calculation method with the Scanditronix cyclotrons MC40 and MC50.

The field was also measured with the two passive focusing channels installed and the first harmonic perturbation was shimmed to below 1 gauss at the $\nu_r = 1$ region at maximum field. The final first harmonic perturbation is seen in figure 5.

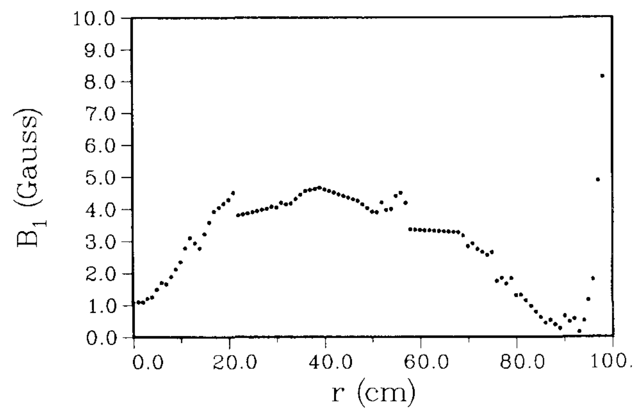

Figure 5

Measured first harmonic perturbation at 1000 A after shimming with focusing channels installed.

3. DISCUSSION

The field calculation method described above has been found to give results sufficiently good to obviate the need for a model magnet. The most critical point in the field design is axial focusing at high energies (high field where the method gives better results). For lower fields the field shape changes somewhat, but the final shaping can be easily done with trim coils.

The field shape for low B can be approximated using the fact that the relative permeability for good iron is very high at low fields (≥ 4000) and can be assumed to be infinity as compared to 1. This together with the boundary conditions on magnetic fields leads to a situation where the boundary of pole tips with sectors is a constant scalar potential surface. Then the field can be calculated by solving a three-dimensional Laplace equation, for example with the code[4)] RELAX3D. This has been done and the results are in agreement with other calculations.

References

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4) H. Houtman and C.J. Cost, A Fortran program (RELAX3D) to solve the 3 dimensional Poisson (Laplace) equation, Computing in accelerator design and operation, Europhysics Conference Abstracts 1983 Vol.74, Berlin.