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# BCalc —— A COMPUTER PROGRAM FOR PROCESSING THE CYCLOTRON MAGNETIC STRUCTURE MEASUREMENT DATA

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BCalc is an original computer program to process data from the measurements of cyclotron magnetic structures. It allows to analyze and visualize the measured data as well as to calculate some analytical quantities related to particle dynamics in isochronous cyclotrons. The program has been developed and written in the Flerov Laboratory of Nuclear Reactions (FLNR) of the Joint Institute for Nuclear Research in Dubna (JINR). The basic features of the program, its capabilities as well as examples of utilization are presented in the paper.

K e y w o r d s: cyclotron, isochronous cyclotron, cyclotron magnetic structure, magnetic field measurement, magnetic field forming

## 1 INTRODUCTION

Design of the magnetic structure is one of the crucial parts of the cyclotron design. Its goal is to provide the required magnetic field distribution in the active area of the cyclotron. In the case of isochronous cyclotrons, the relative inaccuracy of the real magnetic field distribution should be about $0.05\,\%$, inaccuracy of forming the average isochronous field as well as the required inaccuracy of the simulated field distribution is as low as $0.01\,\%$.

There are several methods of designing and forming the cyclotron magnetic structures, which may be combined complementarily. The first method is based on simulations of the magnetic field distribution with the aid of dedicated computer codes like POISSON [1], OPERA [2], KOMPOT [3] *etc*. However, even in this case, experimental work is necessary. Prior to simulations, the B-H-curve is measured on samples of materials used in the cyclotron magnetic circuit. The second method is based on measuring the magnetic field distribution on prototypes or downscaled models, evaluation and extrapolation of measured data and making corrections to the magnetic structure by shimming of sectors and a proper design of correction coils.

Measurements of the magnetic structure usually provide a large amount of data that should be processed effectively and repeatedly as part of the optimizing iteration procedure. A dedicated computer code BCalc developed for this particular purpose is described in the paper. BCalc allows to process and visualize the measured data as well as to calculate some quantities related to particle dynamics in cyclotrons.

## 2 DESCRIPTION OF THE BCalc CODE

### 2.1 Historical root, hardware and software requirements

The first version of a program developed to assist the field forming at the U400M JINR cyclotron was written in FORTRAN by E.L. Ivanov from Bulgaria [4, 5]. Later on, the code was essentially rewritten in PASCAL and compiled in DELPHI by I.A. Ivanenko [6, 7]. It was enriched by additional graphical and mathematical routines like 3D-plots and harmonic analysis reaching its current version described in this paper. It has successfully been applied to investigate magnetic structures of the cyclotrons that are presently being designed at JINR [8].

BCalc runs under MS-Windows operating system. The minimum required monitor resolution is $800 \times 600$. It is recommended to use at least a Pentium II processor and 64 MB operating memory in order to display the 3D-plots within a reasonable time. It is also necessary to install the OpenGL graphical library.

### 2.2 Data-processing tools

The input data to be processed by BCalc are provided in a specific MAP-file that contains values of the vertical component of the magnetic flux density, $B_z$, as a function of spatial co-ordinates. A cylindrical co-ordinate system is used. Radial axis $r$ coincides with the machine radius, vertical axis $z$ is perpendicular to the median plane of the cyclotron, and azimuthal axis $\theta$ is positive for the anticlockwise motion of particles in the machine. The centre of the co-ordinate system coincides with the centre

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of the cyclotron. The starting azimuthal position $\theta = 0$ can be chosen arbitrarily. It is, however, convenient to locate it either to the middle of a sector or to the middle of a valley, unless spiral sectors are used. The MAP-file contains always data in a single plane ($z =$ const). The input data may represent measured values as well as values generated by mathematical extrapolation. Measurements are usually done in the median plane of the cyclotron ($z = 0$).

The basic quantities calculated directly from the measured/simulated data are the flutter, the average magnetic field, the field index and the frequency of betatron oscillations. The frequency of betatron oscillations is defined as the number of betatron oscillations per one revolution.

The flutter at a given constant radius $r$ is calculated in BCalc as:

$$F(r) = \frac{\frac{1}{2\pi}\int_0^{2\pi} B_z^2(r,\theta)\mathrm{d}\theta - \left(\frac{1}{2\pi}\int_0^{2\pi} B_z(r,\theta)\mathrm{d}\theta\right)^2}{\left(\frac{1}{2\pi}\int_0^{2\pi} B_z(r,\theta)\mathrm{d}\theta\right)^2} = \frac{\overline{B^2} - \bar{B}^2}{\bar{B}^2}\,. \quad (1)$$

BCalc approximates the average isochronous magnetic field $\bar{B}_{iso}$ by the average magnetic field at a constant radius:

$$\bar{B}_{iso} \cong \bar{B}(r) = \frac{1}{2\pi}\int_0^{2\pi} B_z(r,\theta)\mathrm{d}\theta\,. \quad (2)$$

The field in isochronous cyclotrons is a periodical function of the azimuthal co-ordinate $\theta$. In such a case, the integration is performed merely over one period:

$$\bar{B}(r) = \frac{1}{2\Lambda}\int_0^{2\Lambda} B_z(r,\theta)\mathrm{d}\theta\,, \quad (3)$$

where $\Lambda$ is the half-period.

The present version of BCalc can handle the periods of $\pi/2$, $\pi$ and $2\pi$, which is suitable for isochronous cyclotrons with four sectors. The evaluation of the integral is performed by numerical integration according to the Simpson method [9].

The field index, $k$, is expressed as [10]:

$$k = \frac{r}{\bar{B}}\frac{\mathrm{d}\bar{B}}{\mathrm{d}r}\,. \quad (4)$$

Finally, the frequency of betatron oscillations $\nu_r$ and $\nu_z$ in the radial and vertical plane, respectively, are calculated by BCalc according to [10]:

$$\nu_r^2 = 1 + k + F\frac{3N^2(1+\tan^2\psi)}{(N^2-1)(N^2-4)}\,, \quad (5)$$

$$\nu_z^2 = -k + F\frac{N^2(1+\tan^2\psi)}{N^2-1} \quad (6)$$

where $N$ is the number of sectors and $\psi$ is the sector spiral-angle.

### 2.3 Harmonic analysis

Harmonic analysis of the magnetic field provides information about the stability of particle motion. It is important especially in the vertical (axial) direction because an appreciable focusing effect can only be achieved with the aid of azimuthal field variation. It can be seen from equation (6) that for radially increasing magnetic field ($k > 0$) the flutter term must overbalance the field index term $-k$ in order to get a real value of the betatron oscillation frequency. The flutter is related to the Fourier coefficients of the $B_z(\theta)$-expansion. BCalc expands the magnetic field into the Furrier series [11]:

$$B_z(\theta) = \frac{a_0}{2} + \sum_{h=1}^{\infty}\left[a_h\cos(h\omega\theta) + b_h\sin(h\omega\theta)\right] = \bar{B}\left\{1 + \frac{1}{\bar{B}}\sum_{h=1}^{\infty}\left[A_h\cos(h\omega\theta+\varphi_h)\right]\right\}, \quad (7)$$

where $\omega = \frac{\pi}{\Lambda}$, $\Lambda$ is the half-period, $a_h$ and $b_h$ are the Euler-Furrier coefficients [11], $A_h = \sqrt{a_h^2 + b_h^2}$ is the amplitude, and $\varphi_h = -\arctan\left(\frac{b_h}{a_h}\right)$ is the initial phase of the given harmonic component.

BCalc calculates the amplitude and phase of the harmonic components up to the $5^{\mathrm{th}}$ one. Interpretation of the harmonic number in BCalc needs a special care. When expressing the harmonic number, $H$, with respect to the full revolution ($2\pi$), the output harmonic number $h$ obtained by the BCalc harmonic analysis must be converted:

$$H = \frac{\pi}{\Lambda}h\,. \quad (8)$$

### 2.4 Graphical tools

All measured data and calculated quantities can be written to a text file that can be imported to any suitable software for further processing. The BCalc is, however, equipped with its own plotting routines that can be used directly. The following plots can be produced:

- $B_z = f(\theta)$, $r =$ const; 2D-plot,
- $B_z = f(r)$, $\theta =$ const; 2D-plot,
- $\bar{B}$, $F$, $k$, $\nu_r$, $\nu_z$, $A_h$, $\varphi_h$ as a function of the radius; 2D-plot,
- $B_z = f(r,\theta)$; 3D-plot.

The type of the plot can be selected from a menu. The parameters of the plot (for example the range of variables) can be specified in interactive windows or can be changed by a scroll-bar located on the bottom margin of the plot. If, for example, the plot of $B_z = f(r)$, $\theta =$ const is displayed, then the scroll-bar allows stepping the value of $\theta$ to follow changes of the radial field distribution as

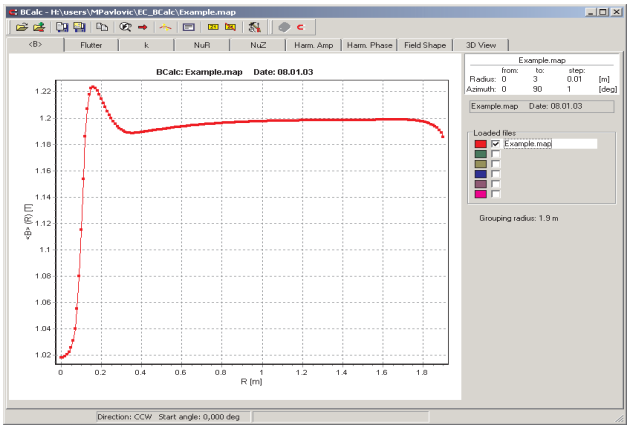


**Fig. 1.** The interactive BCalc window containing a current plot, the plot-selection menu, the tool-bars, the file-header and the plot-control windows.

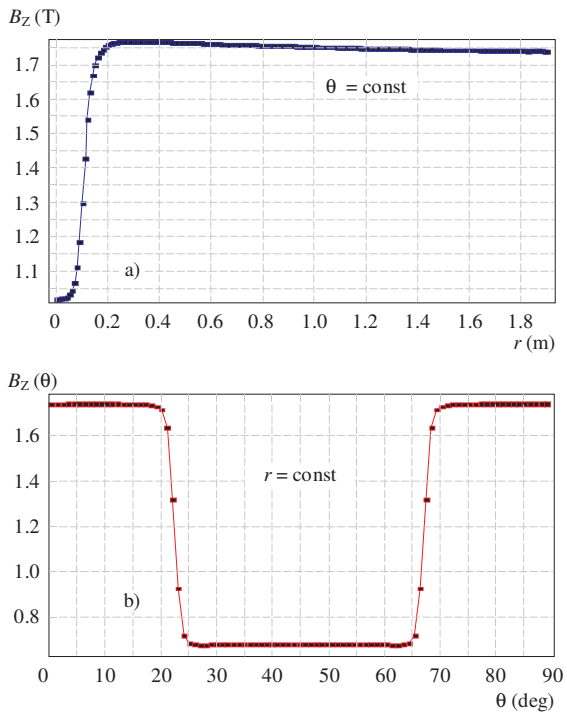


**Fig. 2.** The magnetic field as a function of the spatial co-ordinates. Upper plot: $B_z = f(r)$ in the middle of a U400 sector; lower plot: $B_z = f(\theta)$ at the extraction radius of the U400 cyclotron.

a function of the azimuth. Figure 1 shows a typical window of the BCalc containing a $\bar{B} = f(r)$ plot. The upper tool-bar contains the standard file management, data management and setting tools. Below this tool-bar, a desired type of plot can be selected. The lower scroll-bar enables stepping of the plot parameter. The right margin contains the file header as well as other plot parameters and options that can be controlled interactively. The scaling and zooming tools are available with the aid of the mouse.

The 3D-plots have some additional options like displaying or hiding the measurement mesh, choosing the colours, shading controls, displaying the gradient of the current data, shifting and rotating the plot, scale-control, *etc.*

## 3 EXAMPLES OF UTILIZATION

Since the input MAP-file is basically a standard ASCII-text file, BCalc can, in principle, handle any data containing numerical values in the cylindrical co-ordinate system if they are conformed to the MAP-file internal structure. The data may be produced by measurement or by simulation and they need not necessarily represent the magnetic field of a cyclotron magnetic structure. This is fully true for the BCalc graphical tools, in particular the 2D and 3D-plots of the input data. From this point of view, the graphical environment of BCalc, like its scaling, zooming tools and 3D-plot manipulations, is universal and can be useful also for users outside the cyclotron community. Some of the mathematical tools are universal, too, for example the calculation of the average value and the harmonic analysis, whereas the others are dedicated to particle dynamics in cyclotrons, like the calculation of the field index and the frequency of betatron oscillations. Processing of the cyclotron magnetic structure measurement data has, however, always been a typical application of BCalc and was also the original and primary purpose of its development.

BCalc has successfully been applied to analyze the magnetic structure of several cyclotrons operated or designed at the Joint Institute for Nuclear Research in Dubna [8, 12]. The data measured on the U400 and U400M cyclotrons are presented in this section to illustrate the BCalc built-in features. U400 is a 4-sector cyclotron with straight sectors whereas U400M is based on a magnetic structure with spiral sectors. The extraction radius of the U400 cyclotron is 1.72 m.

Figure 2 shows the magnetic field as a function of the radius in the middle of the sector and the magnetic field as a function of the azimuth at the extraction radius, respectively. Data correspond to the U400 cyclotron with straight sectors.

Figure 3 shows the average magnetic field and the flutter as a function of the radius. The data are taken from the U400 cyclotron. The average magnetic field increases with the radius in order to satisfy the isochronous condition for particle motion.

Figure 4 shows the results of the harmonic analysis, namely the amplitudes of the $4^{\text{th}}$, the $8^{\text{th}}$, the $12^{\text{th}}$, the $16^{\text{th}}$ and the $20^{\text{th}}$ component. In this case, the data were taken in one quadrant ($2\Lambda = \pi/2$), hence the harmonic analysis gives the $1^{\text{st}}$, the $2^{\text{nd}}$, the $3^{\text{rd}}$, the $4^{\text{th}}$ and the $5^{\text{th}}$ harmonic components with respect to period $\pi/2$. These harmonic numbers are multiplied by factor 4 according to relation (8). As the field distribution is close to a rectangular one (see Fig. 2), the odd cosine-like components dominate the Furrier series.

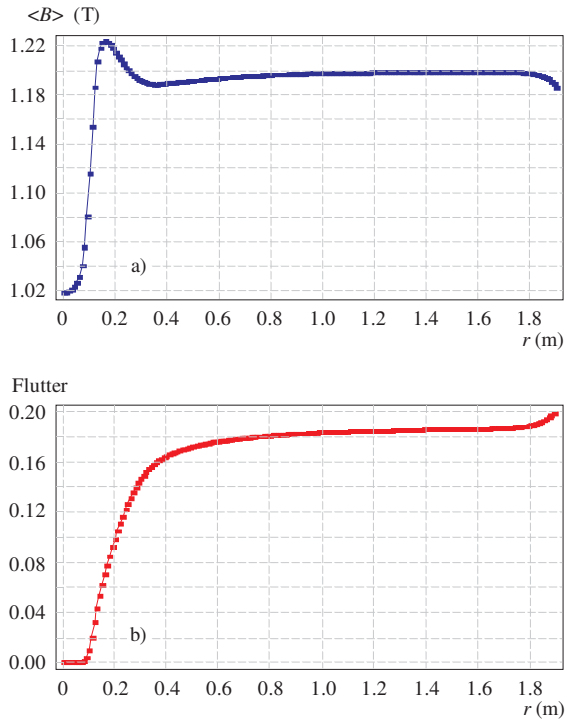


**Fig. 3.** A plot of calculated quantities. Upper plot: the average magnetic field as function of the machine radius; lower plot: the flutter as a function of the machine radius.

Figure 5 demonstrates a 3D-view of the magnetic field distribution in the median plane of the U400M cyclotron. The spiral sectors are clearly visible.

## 4 RESULTS, DISCUSSION AND CONCLUSIONS

BCalc has successfully been used in measurements and design of several cyclotrons operated in JINR Dubna. It is also applied to investigate magnetic structures of new cyclotrons that are currently being designed. The user-friendly environment makes it easy to learn and use. It has become a standard cyclotron magnetic structure design tool. Except for routine data processing of the cyclotron magnetic structure measurement, it is also suitable for investigating different methods of the field-forming (*eg* shimming [8]), influence of construction details like fixation elements or holes in the yoke on the final field distribution, *etc*.

BCalc is open to further development. The graphical environment is subject to continuous maintenance and up-grade. The physical (particle dynamics) part is going to be completed with calculation of the equilibrium orbit and the average magnetic field along the equilibrium orbit.

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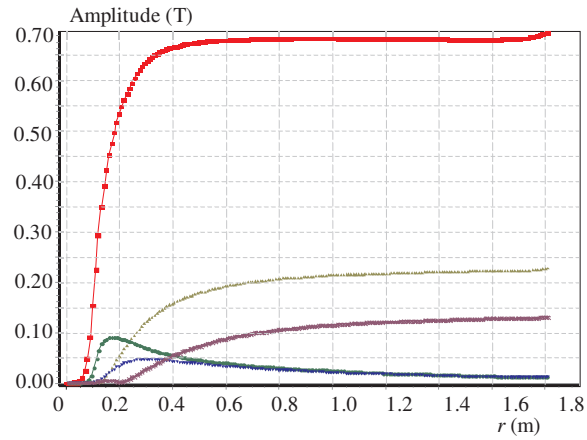


**Fig. 4.** An example of the harmonic analysis. The amplitudes of the first 5 harmonic components of the azimuthal field distribution are shown as a function of the machine radius. The data correspond to the U400 cyclotron.


**Fig. 5.** A 3D-view of the magnetic field distribution in the median plane of the U400M cyclotron. The spiral sectors are clearly visible.

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