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BEAM DYNAMICS SIMULATIONS IN CYCLOTRON C230 CONSIDERING IMPERFECTIONS OF MAGNETIC FIELD RADIAL COMPONENT

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Abstract

We simulated axial motion of a beam in the IBA C230 cyclotron, which is a basic facility in several medical centers worldwide. Because of small axial focusing of the beam in the center of the cyclotron imperfections of the radial component of the magnetic field lead to additional proton losses. Measured maps of the axial and radial components of the magnetic field were used in the simulations. It was found that the radial component of 5-10 G in the center and approximately 2 G in the main region of acceleration leads to a decrease in the resulting beam intensity by about a factor of two and an increase in the beam axial width by 25% as well. Simulations define the requirements on the radial component shaping for the cyclotrons of this series in order to decrease the proton losses in axial direction.

INTRODUCTION

IBA has produced more than twenty C230 cyclotrons under contracts with the cancer therapy centers worldwide [1]. One cyclotron of this type (P116) was bought by Russia and successfully commissioned [2] in Dubna. The most difficult problem during commissioning was connected with too large axial losses of the beam in the center of the cyclotron. They were caused by (i) imperfections of radial component of the magnetic field and (ii) too small axial focusing in the center of the cyclotron.

The problem was overcome by shifting one central plug (decrease of radial component Br) and adding small steel plates on noses of sectors (increase of axial focusing).

The main purpose of the simulations was to determine the requirements on the radial component imperfections for the serial IBA C230cyclotron. Meeting those requirements with a new measuring technique [3] will provide faster cyclotron commissioning.

The calculations were performed using the final map of the axial component of the magnetic field in the PAP116, which was measured in Dubna.

The radial component of perturbations was used in several ways. In the central region of the cyclotron up to a radius of 35 cm the results of Br measurements [3] in the PAP125 were used. In the calculations of dynamics at radii greater than 35 cm the Br was evaluated using the experimental vertical shift of the beam in the PAP116 [2].

INITIAL CONDITIONS

Initial phase space volume of the bunch was formed from 2000 protons in the slit of the ion source 0.7x4.0 mm^2 in size. Emittances were $\varepsilon_r = 50\ \pi$ mm*mrad and $\varepsilon_z = 200\ \pi$ mm*mrad, and the range of initial RF phase was 30-70ºRF.

Radial distributions of Br are illustrated in the Figs. 1, 2. Since we did not have reliable measurements of the radial component in the center of the PAP116, we first used measurements (Fig. 1, curve 1) for the PAP125 [3]. Numerical change of the Br component (Fig. 1, curve 2) was done in order to minimize its value near the radius of 10 cm where Qz is too small. The radial component outside the center of the cyclotron (Fig. 2) was evaluated by the formula $B_r = \Delta z B_z Q_z^2 / r$ using the experimental axial position Δz of the beam in the PAP116, radial distributions of the average axial field B_z, and betatron tune Q_z. The initial and increased values of the axial tune are shown in Fig. 3.

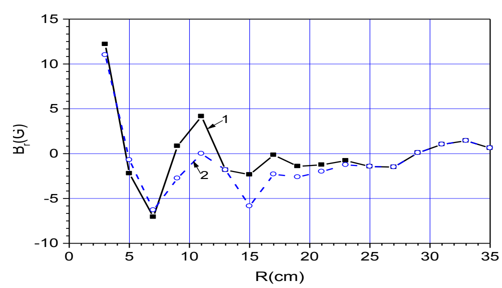

Figure 1: Radial distribution of Br field in the center of cyclotron.

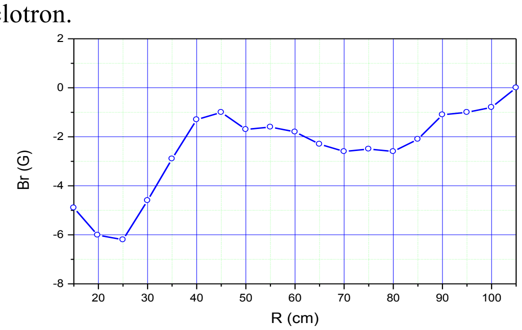

Figure 2: Radial distribution of Br field in main acceleration region.

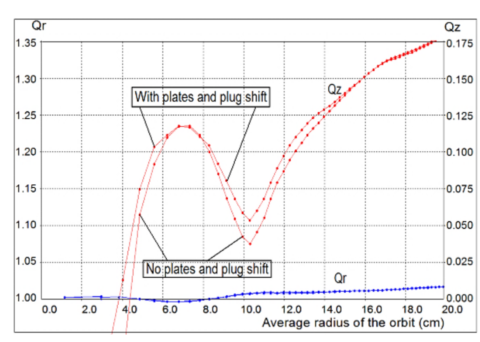

Figure 3: Influence of the plates and plug shift on the axial tune.

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RESULTS OF SIMULATIONS

Center of Cyclotron

Computations were carried out for 30 turns to a radius of about 20 cm, i.e. to the end of the resulting bunch formation. The focus was done to allow for the protons losses, which were divided into the radial and axial ones. A proton was considered lost radially if its radius was smaller than 1 cm (initial radius of the proton is ~ 1.6 cm). The losses in the axial direction were calculated with allowance for the increase in the dee aperture from 1.0 cm (radius 1.5 cm) to 2.0 cm (radius 10 cm and more).

Figure 4 shows trajectories of protons in the (r, z) plane for the first 30 turns. Up to a radius of 12 cm the beam almost completely fills the apertures of the dees. If Br corresponds to curve 1 of Fig. 1, then the axial coherent oscillations reach the amplitude of 5 mm near the radius of 14 cm. Br of (Fig. 1, curve 2) leads to essential reduction of the coherent amplitude.

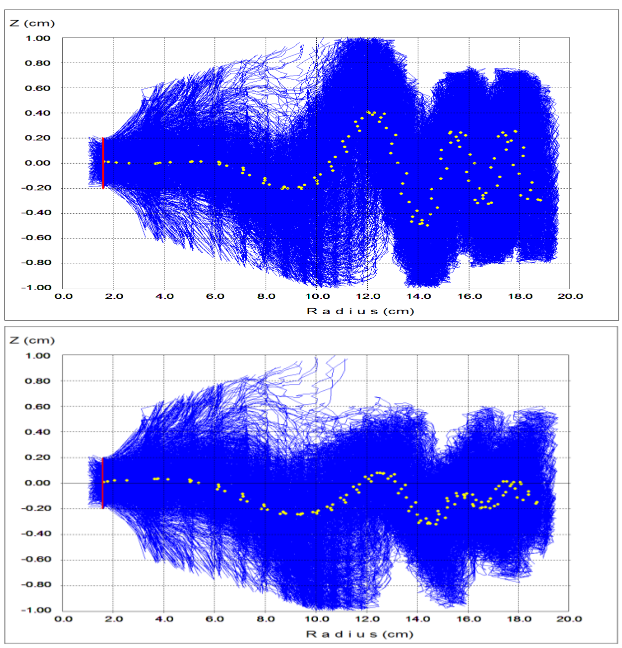

Figure 4: Axial-radial motion of protons during the first 30 turns. Large points correspond to the position of the center of gravity of the bunch. Top: Br=Fig. 1, curve 1, below: Br=Fig. 1, curve 2.

The results of counting for the proton losses are summarized in Table 1. It can be seen that Br leads to a factor of 2 increase in axial losses. The resulting intensity decreases by a factor 1.5.

Table 1: Results of Proton Loss Analysis in the Center

Radial losses(%)	Axial losses(%)	Captured in acceleration(%)	Radial component
18	21	61	absent
18	42	40	Fig. 1, curves 1, 2

One can compare the radial distributions of the axial losses in Figs 5 and 6. Both Br dependences in Fig. 1 give identical axial losses with an accuracy of 1% in the center of the cyclotron. But in the main acceleration region (60-100 cm) Br in Fig. 1, curve 2, allows avoiding additional axial losses as will be seen below.

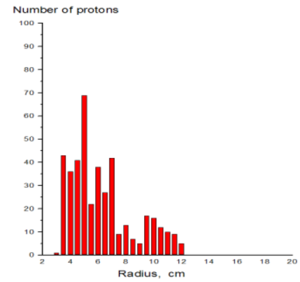

Figure 5: Histograms of the proton losses in the center of the cyclotron without imperfections of the Br component.

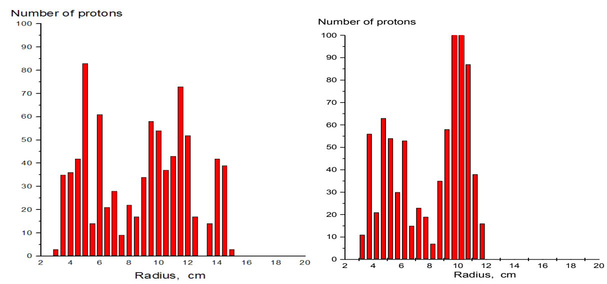

Figure 6: Histograms of the proton losses in the center of the cyclotron. Left: Br=Fig. 1, curve 1; right: Br=Fig. 1, curve 2.

Whole Region of Acceleration

The following three radial dependences of Br imperfection were implemented in the calculations of beam dynamics in the whole region of acceleration:

- (Br_1) →Br is zero at all radii;
- (Br_2) → Br corresponds to the measured one in the PAP125 at radii 0-35 cm (Fig. 1, curve 1), and Br equal to the calculated values for the axial beam position in the PAP116 at radii larger than 35 cm (Fig. 2);
- (Br_3) → Br corresponds to calculated curve 2 of Fig. 1 at radii 0-35 cm and is the same as for Br_2 at radii larger than 35 cm.

Figure 7 compares the axial rms size of the beam in the whole range of acceleration at three dependencies of Br.

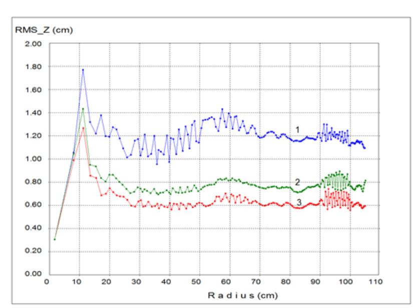

Figure 7: Beam axial rms size (±2σ) for different radial component dependencies. (1) Br_2; (2) Br_3, (3) Br_1.

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In absence of Br the beam size is 0.6 cm beginning from the radius of 30 cm. The radial component in the form of Br_2 leads to doubling of the beam size, i.e. it is 1.2 cm up to the edge region. Dependence Br_3 essentially decreases the beam size down to 0.8 cm. The results depicted in the Figs. 4 and 7 show that the radial component leads to two effects. The first effect is due to the coherent displacement of the beam from the Z=0 plane, and the second is associated with increase in the amplitude of incoherent oscillations, appearing after the passage of the Br perturbation near the minimum betatron tune. Optimization of the Br distribution near the radius of 10 cm permits the axial beam size to be decreased by a factor of 1.5 at radii larger than 30 cm.

Note that a noticeable number of protons were lost beginning from 50 cm in the case of Br_2 dependence (Fig. 8). These losses comprise ~8% of the protons from 2000 started ones or ~20% of the protons accelerated to the radius of 50 cm. One can conclude that quite a small change of the Br distribution in the form of Fig. 1, curve2, increases the beam transmission by ~20%.

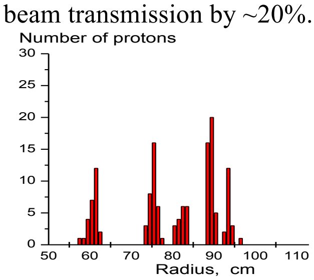

Figure 8: Histogram of proton losses at radii larger than 50 cm for option Br_2.

A full axial beam profile in the (r, z) plane is shown in Fig. 9 for different radial dependences of the components.

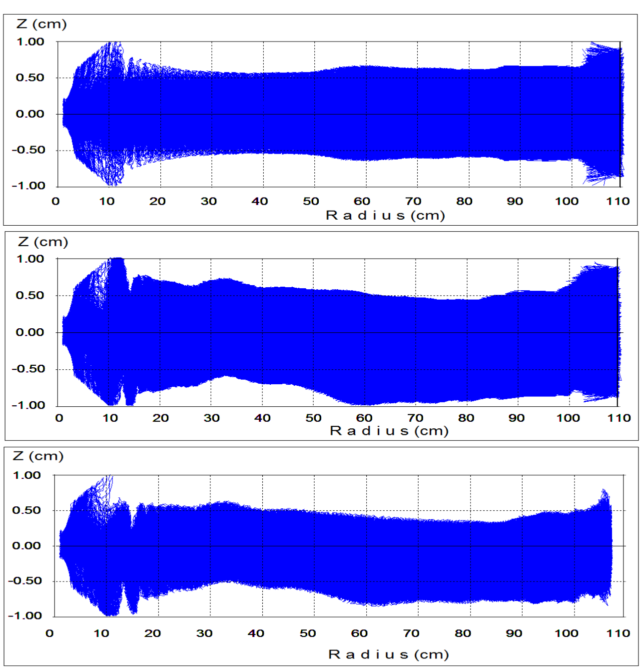

Figure 9: Axial beam profile in the (r, z) plane. Top: Br_1; middle: Br_2; bottom: Br_3.

EXPERIMENTAL RESULTS

During C235 commissioning in Dubna, the axial rms beam size at radii of 15-20 cm in the first experiments with the beam was ~17-18 mm (Fig. 10 , curve 1) , which is comparable to the vertical dee aperture of 20 mm. Then the structure of the magnetic system was optimized in the central region by (1) positioning shimming correctors on sectors, which increases value of Qz near radius 10 cm, and (2) selecting a special asymmetric arrangement of the upper and lower plugs, which decreases the radial component.

Due to this optimization the axial dimension of the beam at a radius of 30 cm was reduced to ~7-8 mm (Fig. 10 , curve 2). This increased the efficiency of acceleration in the C235-V3 cyclotron by 72 % without using a diaphragm that is usually installed in the center to limit the vertical aperture in this type of cyclotron.

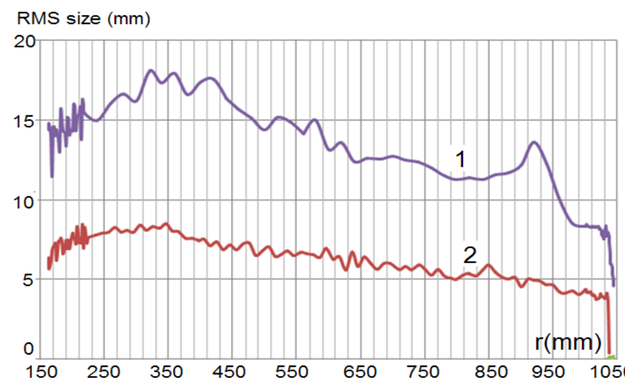

Figure 10: Experimental results. 1, 2 are the beam axial rms sizes before and after optimization.

CONCLUSION

Beam dynamics simulation has shown that the optimization of the radial component near the position of the minimum axial focusing reduces the axial dimension of the beam by a factor of 1.5 and increases its transmission by 20% in the radial range 15-105 cm.

Experimental optimization of the magnetic system in the central region of cyclotron provided an increase in acceleration efficiency by 72% without installation of the limiting vertical diaphragm. This allowed an approximately 1.5 times increase in the current of accelerated protons at entrance of the C235-V3 deflector as compared with a serial C235 cyclotron.

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