INFLUENCE OF RF MAGNETIC FIELD ON ION DYNAMICS IN IBA C400 CYCLOTRON

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Abstract

Magnetic components of RF field in C400 [1] cyclotron, being under development by IBA, makes noticeable influence on ion dynamics.

In particular, increase in the dee voltage [2] along radius leads to essential phase compression of a bunch. At the same time RF magnetic field changes a central ion phase by only 2°RF.

Calculations have also shown that RF magnetic field makes visible but pretty small influence on the radial motion, while an impact of the RF magnetic field on the axial motion has not been detected.

The results are compared for the two RF magnetic field maps: (i) calculated numerically by Microwave Studio and, (ii) calculated analytically from RF electric field map by means of Maxwell' equations.

RF FIELDS COMPUTED BY MICROWAVE STUDIO

RF electric and magnetic field maps that were used in the computations corresponded to the last geometry of the dees in assumption that a dee voltage in the center is of about 80 kV. Three dimensional views of the components E_φ, E_r and B_z are shown in Fig. 1-4.

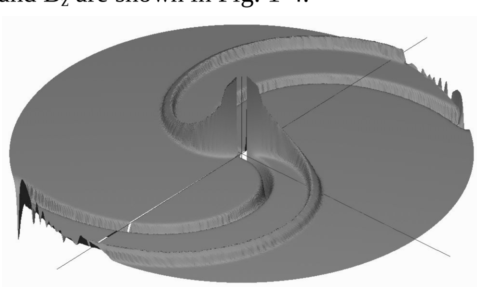

Figure 1: 3D view of E_φ component

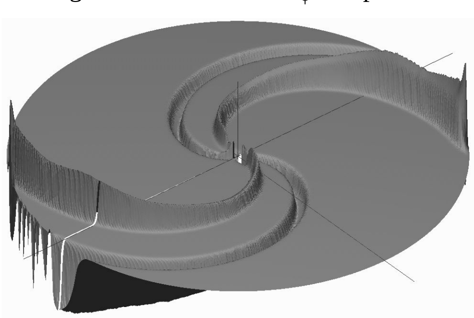

Figure 2: 3D view of E_r component.

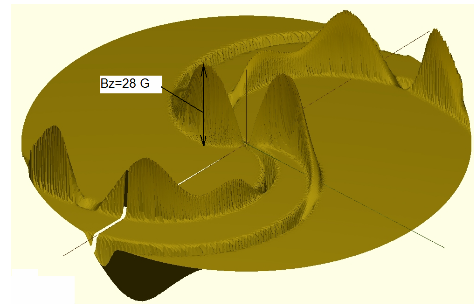

Figure 3: 3D view of the B_z(RF). Maximal positive value of B_z(RF)=28 G at radius 30 cm.

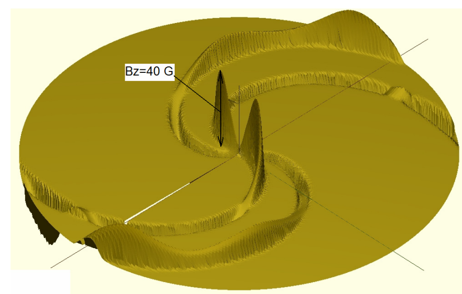

Figure 4: 3D view of the Bz(RF) through a half-period of the high-frequency oscillations in comparison with Figure 3. Maximal value of Bz(RF)=40 G at radius 22 cm.

Distribution of the maximal values of B_z(RF) along radius for two gaps of the dee is shown in Figure 5.

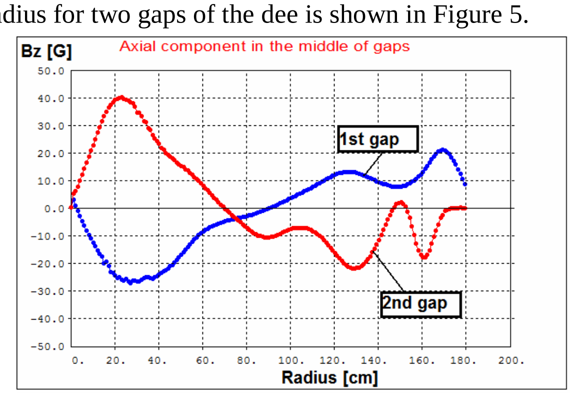

Figure 5: Maximal values of component B_z(RF) in the middle of gaps versus radius

In the case when obtaining of B_z(RF) is provided by Microwave Studio the three RF magnetic field components during acceleration are calculated by the following formulas of first approximation with respect to (z/r):

$$B_r(t) = z \frac{dB_z}{dr} \sin \psi \quad (1)$$

$$B_\varphi(t) = \frac{z}{r}\frac{dB_z}{d\varphi}\sin\psi \qquad (2)$$

$$B_z(t) = B_z \sin\psi \qquad (3)$$

where $\psi = 2\pi h f_{rev} t + \psi_0$ is time dependent RF phase of the ion.

Another way of RF magnetic field calculations was implemented using direct connection between electric and magnetic RF fields which is described by the Maxwell' equations. It is enough to have E_φ and E_r components in the median plane in order to compute RF magnetic field components in the vicinity of the median plane. We have derived the following formulas of first approximation with respect to (z/r):

$$B_r(t) = \left[\left(-\frac{1}{r}\frac{\partial E_r}{\partial\varphi} + \frac{\partial^2 E_r}{\partial r\,\partial\varphi} + \frac{1}{r}E_\varphi - \frac{\partial E_\varphi}{\partial r} - \frac{r\partial^2 E_\varphi}{\partial r^2}\right)\sin\psi\frac{1}{\dot\psi}\right]\frac{z}{r} \qquad (4)$$

$$B_\varphi(t) = \left[\left(\frac{1}{r}\frac{\partial^2 E_r}{\partial\varphi^2} - \frac{1}{r}\frac{\partial E_\varphi}{\partial\varphi} - \frac{\partial^2 E_\varphi}{\partial\varphi\,\partial r}\right)\sin\psi\frac{1}{\dot\psi}\right]\frac{z}{r} \qquad (5)$$

$$B_z(t) = \left[\frac{1}{r}\frac{\partial E_r}{\partial\varphi} - \frac{1}{r}E_\varphi - \frac{\partial E_\varphi}{\partial r}\right]\sin\psi\frac{1}{\dot\psi} \qquad (6)$$

where $\dot\psi = \frac{d\psi}{dt} = 2\pi h f_{rev}$. Parameters of RF electric field maps that were used in (4)-(6) are illustrated in the Figures 6-8.

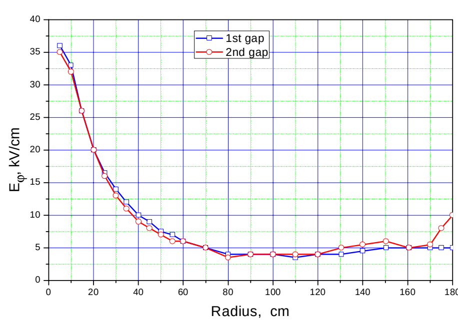

Figure 6: Maximal absolute values of component E_φ (RF) in the middle of gaps versus radius

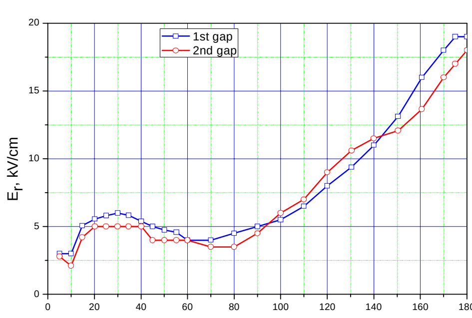

Figure 7: Maximal absolute values of component E_r (RF) in the middle of gaps versus radius

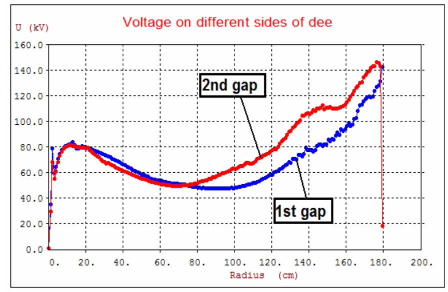

Figure 8: Radial distribution of the dee voltage along two accelerating gaps

To study influence of RF magnetic field on the ions dynamics a bunch of 200 ions was specified at radius ~4 cm, one turn after inflector. The bunch had 35°RF phase width, maximal initial value of radial oscillations was ~ 0.2 cm, initial axial amplitudes were defined by the dees axial aperture ±1 cm.

All types of computations have been done using 3 different conditions:

(1) B_z(RF) is off;
(2) B_z(RF) is on (Maxwell' formulas (4-6));
(3) B_z(RF) is on (map of B_z and formulas (1-3)).

RADIAL MOTION

Results of calculations presented in Figure 9 show that B_z(RF) field slightly improves quality of the radial motion. This is observed in the middle radii and after the structural resonance $3Q_r=4$ as well.

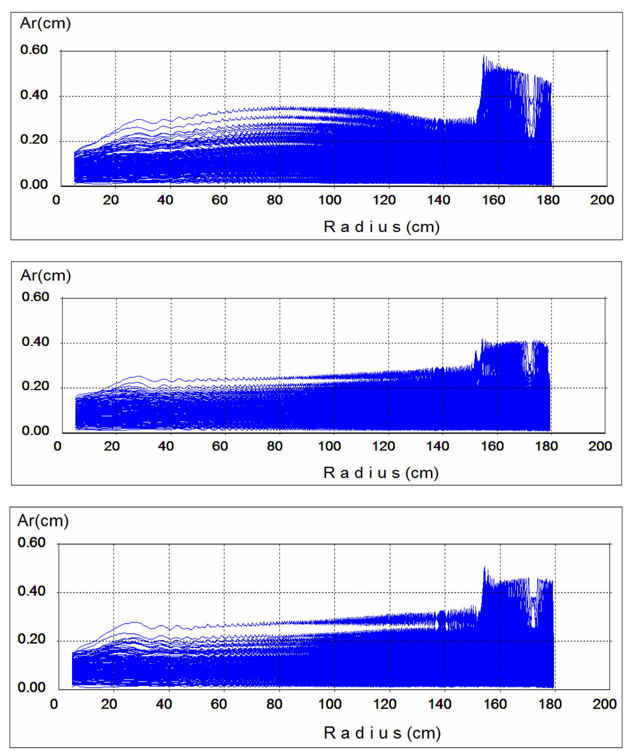

Figure 9: Radial distribution of free radial oscillations. Above - B_z(RF) is off, middle - B_z(RF) is on (Maxwell' formulas (4-6)), below - B_z(RF) is on (map of B_z and formulas (1-3)).

AXIAL MOTION

Results of calculations presented in Figure 10 show that B_z(RF) field does not give noticeable effect on the axial motion.

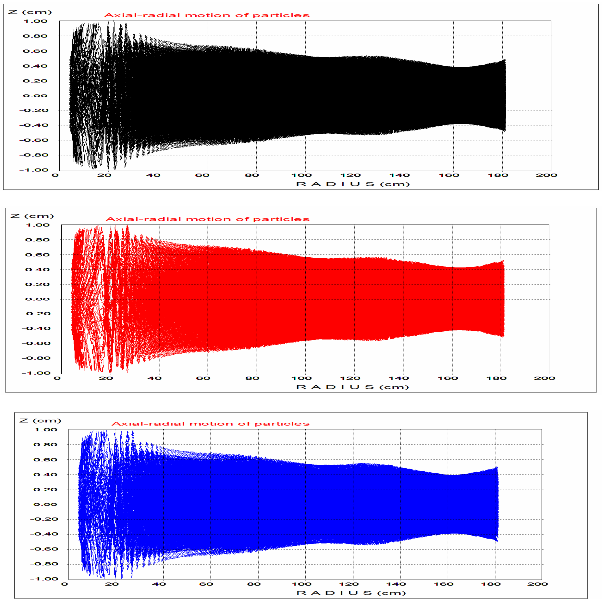

Figure 10: Axial-radial profile of the beam. Above - Bz(RF) is off, middle - Bz(RF) is on (Maxwell' formulas (4-6)), below - Bz(RF) is on (map of Bz and formulas (1-3)).

PHASE MOTION

Phase motion of the bunch of ions is shown in Figure 11.

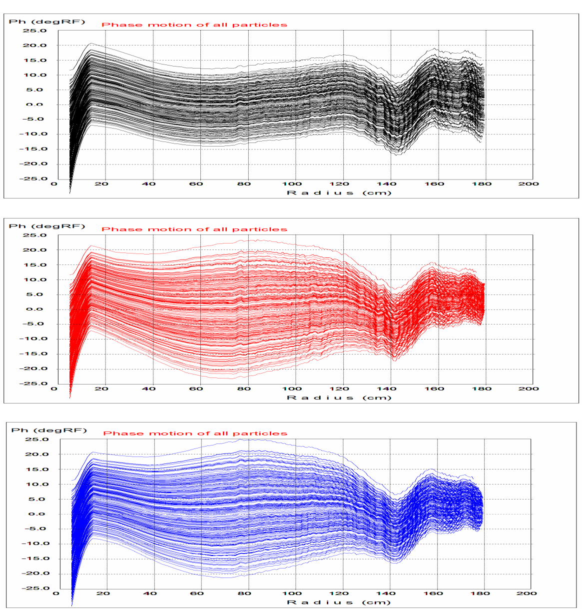

Figure 11: Phase motion of the bunch. Above - Bz(RF) is off, middle - Bz(RF) is on (Maxwell' formulas (4-6)), below - Bz(RF) is on (map of Bz and formulas (1-3)).

One can see almost full coincidence of the bunch phase motion obtained by the help of different ways of RF magnetic field calculations. Both approaches to RF magnetic field show the bunch phase width inversely proportional to the dee voltage that is predicted theoretically [3].

As it is seen in Figure 12, impact of RF magnetic field on the phase motion of central ion (having RF phase deviation inside ±5°RF during acceleration) leads to shift of the phase by not more than 2°RF. This shift is much less than one (20°RF) that has been obtained in the ACCEL cyclotron [4]. A reason of this is explained by another distribution of B_z(RF) field in C400 cyclotron, which is provided by 4 stems instead of 1 stem in ACCEL cyclotron dee.

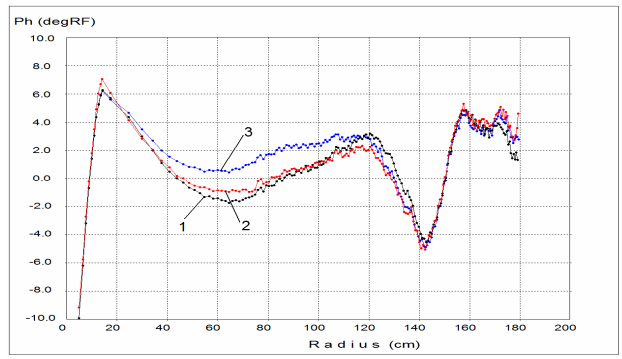

Figure 12: Phase of central ion versus average radius of orbit. 1 - no B_z(RF), 2 – B_z(RF) from Maxwell' formula (6), 3 – B_z(RF) from the map (formula (3)).

CONCLUSIONS

Bunch phase width in C400 increases and decreases inversely proportional to the dee voltage along radius.

Phase deviation of the central ion due to action of RF magnetic field is not more than 2°RF.

RF magnetic field ensures small decrease in the radial amplitudes.

No visible impact of the RF magnetic field on the axial motion has been detected.

REFERENCES

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[4] J.M.Schippers, D.C.George, V.Vrancovic, "Results of 3D beam dynamic studies in distorted fields of a 250 MeV superconducting cyclotron", 17th Int. Conf. on Cyclotrons and Their Applications, Tokyo, 2004.