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ФИЗИКА И ТЕХНИКА УСКОРИТЕЛЕЙ

RF CAVITY SIMULATIONS FOR SUPERCONDUCTING CYCLOTRON C400

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Compact superconducting isochronous cyclotron C400 [1] has been designed at IBA (Belgium) in collaboration with the JINR (Dubna). This cyclotron will be the first cyclotron in the world capable of delivering protons, carbon and helium ions for therapeutic use. $^{12}C^{6+}$ and $^{4}He^{2+}$ ions will be accelerated to 400 MeV/u energy and extracted by electrostatic deflector, H_2^+ ions will be accelerated to the energy of 265 MeV/u and extracted by stripping. It is planned to use two normal conducting RF cavities for ion beam acceleration in the cyclotron C400. Computer model of the double gap delta RF cavity with 4 stems was developed in the general-purpose simulation software CST STUDIO SUITE. Necessary resonant frequency and increase of the voltage along the gaps were achieved. Optimization of the RF cavity parameters leads us to the cavity with quality factor about 14000, RF power dissipation is equal to about 50 kW per cavity.

Бельгийская фирма IBA в сотрудничестве с ОИЯИ (Дубна) разрабатывает компактный сверхпроводящий изохронный циклотрон C400. Этот ускоритель будет первым в мире циклотроном, ускоряющим протоны, ионы углерода и гелия для лечения онкологических заболеваний. Ионы $^{12}C^{6+}$ и $^{4}He^{2+}$ будут ускорены до энергии 400 МэВ/нуклон и выведены при помощи электростатического дефлектора, ионы H_2^+ будут ускорены до энергии 265 МэВ/нуклон и выведены перезарядкой. Для ускорения ионов в циклотроне C400 планируется использовать два теплых резонатора. Компьютерная модель двухзазорного ВЧ-резонатора с четырьмя опорами была создана в программе CST STUDIO SUITE. Были получены необходимая частота и рост напряжения вдоль ускоряющего зазора. Оптимизация параметров ВЧ-резонатора привела к тому, что добротность его достигла 14000, а расчетная мощность потерь в резонаторе не превышает 50 кВт.

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INTRODUCTION

IBA, the world industrial leader in equipment of the proton therapy centres has designed a superconducting cyclotron C400 based on the design of the current Proton Therapy Cyclotron C235.

Most of the operating parameters of the cyclotron C400 are fixed. It is relatively small (6.6 m in diameter) and cost effective. It offers very good beam intensity control for ultrafast pencil beam scanning (PBS). But it requires an energy selection system (ESS) in order to vary the beam energy. The efficiency of the ESS for carbon is better than for protons due to less scattering and straggling of carbon ions in the degrader.

The key parameters of the 400MeV/u superconducting cyclotron are listed in the Table. View of the cyclotron is presented in Fig. 1.

Main parameters of the cyclotron C400

General properties	
Accelerated particles	H_2^+, $^4He^{2+}$, ($^6Li^{3+}$), ($^{10}B^{5+}$), $^{12}C^{6+}$
Injection energy, keV/Z	25
Final energy of ions, MeV/u protons, MeV/u	 400 265
Extraction efficiency, %	70 (by deflector)
Number of turns	$\sim$ 1700
Magnetic system	
Total weight, t	700
Outer diameter, m	6.6
Height, m	3.4
Pole radius, m	1.87
Valley depth, cm	60
Bending limit	$K = 1600$
Hill field, T	4.5
Valley field, T	2.45
RF system	
Number of cavities	2
Operating frequency, MHz	75 (4th harmonic)
Radial dimension, cm	187
Vertical dimension, cm	116
Dee voltage: centre, kV extraction, kV	 80 160

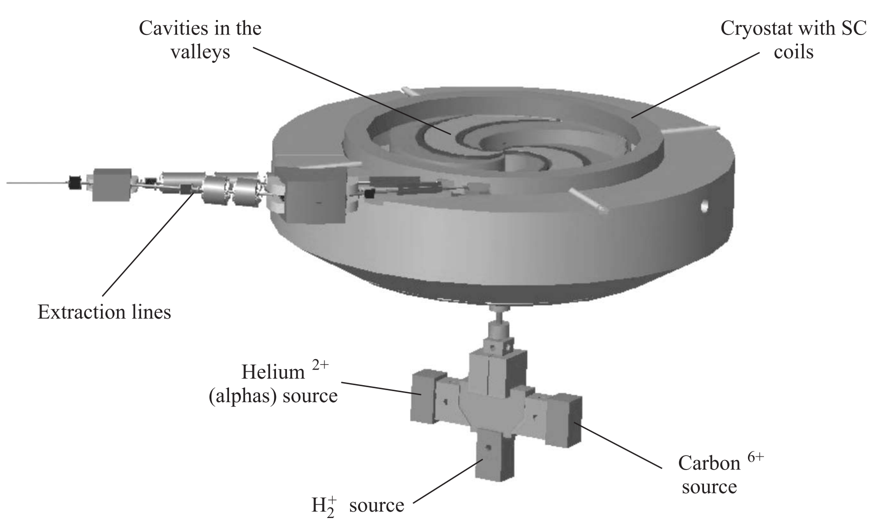

Fig. 1. Artist's view of the median plane in the carbon/proton superconducting cyclotron

1. RF CAVITY GEOMETRY

Magnetic field modeling and beam dynamics have determined the orbital frequency of the ions equal to 18.75 MHz. As RF cavities will be operated in the 4th harmonic mode, the resonance frequency must be 75 MHz. It is planned to use two normal conducting RF cavities [2] for ion beam acceleration in the C400 cyclotron.

Geometric model of the double gap delta cavity housed inside the valley of the magnetic system of the cyclotron C400 was developed in the CST STUDIO SUITE. We have studied a number of models differing in width of accelerating gap and in height of dee; view of the final variant of the model is presented in Figs. 2, 3. Depth of the valley permits one to set the cavity with total height of 116 cm. Vertical dee aperture was equal to 2 cm. Accelerating gap width was equal to 6 mm in the centre then increased to 8 cm in $R = 75$ cm remaining constant to extraction region as shown in Fig. 4.

Distance between dee and back side of the cavity was equal to 50 mm. Cavities have spiral shape similar to the shape of the sectors. Sectors geometry permits azimuth extension of the cavity (between the middles of the accelerating gaps) equal to $45°$ upto radius 150 cm (see Fig. 5). We have inserted four stems with different transversal dimensions in the model.

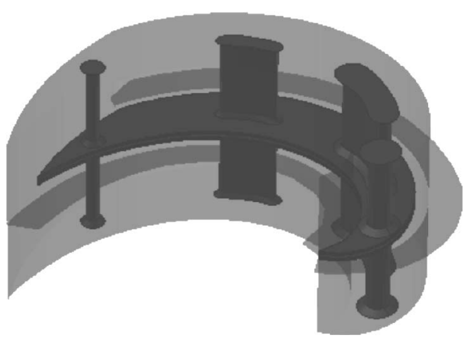

Fig. 2. View of the cavity model

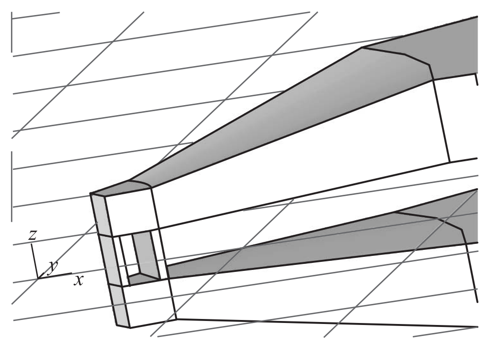

Fig. 3. View of the dee tip

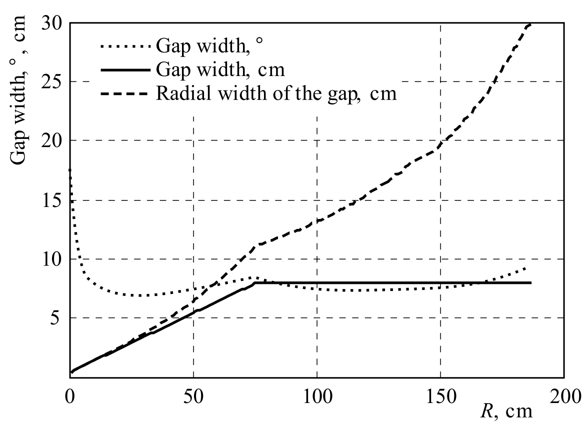

Fig. 4. Gap width against radius. Dashed line — radial width in cm, dotted line — azimuth extension in °, solid line — perpendicular in cm

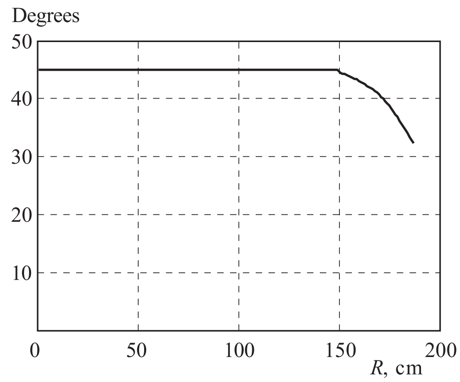

Fig. 5. Azimuth extension of the cavities (between the middles of the accelerating gaps)

We have studied different positions of the stems to insure increasing voltage along radius of accelerating gap, which should range from $\sim$ 80 kV at the centre area to 160 kV at the extraction region. It is important to have high value of voltage beginning from about $R = 150$ cm before resonance $3Q_r = 4$ crossing.

Thickness of the dee was equal to 20 mm. Edges of the dees have thickness equal to 10 mm and rounded form optimized from the 2D electric field simulations (Fig. 6) in order to minimize electric field value in the environment.

Each cavity will be excited with the RF generator through a coupling loop (which should rotate azimuthally within small limits ($\pm 30°$). The active tuning system must be designed to bring the cavities on the frequency initially to compensate detuning for temperature variations

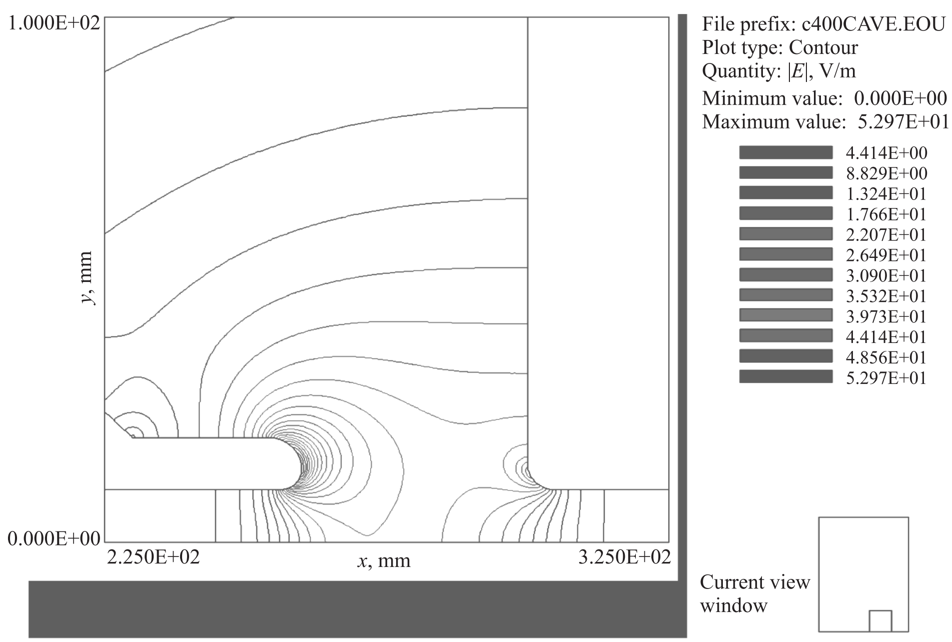

Fig. 6. View of the edge of the dee

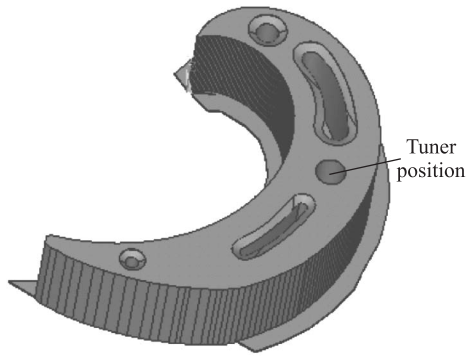

Fig. 7. View of the ANSYS model with tuner

due to RF heating and to provide frequency difference 450 kHz for C^{6+} and H_2^+ ions acceleration.

We analyzed effect of the tuner in the position $R = 120$ cm and at $R = 70$ cm with diameter 10 and 18 cm. One tuner with diameter 10 cm provides changing of the frequency about 500 kHz. We revealed that better position for tuner is on the radius $R = 120$ cm (Fig. 7).

2. SIMULATIONS IN CST MICROWAVE STUDIO AND ANSYS (MODAL)

CST STUDIO SUITE is a general-purpose simulator based on the Finite Integration Technique (FIT). This numerical method provides a universal spatial discretization scheme applicable to various electromagnetic problems ranging from static field calculations to high frequency applications in time or frequency domain [3]. ANSYS is an engineering simulation software which mainly relies on the Finite Element Method (FEM). These are general-purpose finite element modeling packages for numerically solving mechanical problems, heat transfer and fluid problems, as well as acoustic and electromagnetic problems [4]. Calculations of the created model were performed by means of eigenmode JD loss-free solver (Jacobi Division Method) in CST Microwave Studio and Block LANCZOS solver in ANSYS. For simulations in ANSYS we imported in ***.sat*** format the model created in CST Microwave Studio. The half-structure model of the cavity was used where the vertical symmetry could be utilized and the accuracy of the solution was important (see Fig. 7).

In order to shape the radial voltage distribution we were moving stems. We needed to change transversal dimensions of stems in addition. Voltage value was obtained by integrating of the electric field in the median plane of the resonant cavity. To fit the frequency of the cavity to the project value after rearranging stems positions, we had to change horizontal dimensions of all stems by the same value. We revealed that variation of the horizontal dimensions of all stems by one per cent changes frequency by about 300 kHz, and the value of the voltage along radius does not change noticeably while fitting by less than 1 MHz.

Simulations show that the frequency from both programmes is about the same beginning from meshcells number 7 mill for CST and 3 mill for ANSYS:

$F_{\rm rf} = 75.02$ MHz, CST Microwave Studio.

$F_{\rm rf} = 74.80$ MHz, from ANSYS.

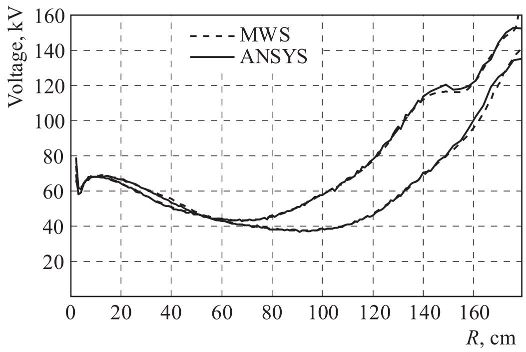

Fig. 8. Voltage distribution along radius

Now we can conclude that accuracy of calculations of the frequency of the cavity in our simulations is better than 0.3%.

From Fig. 8 one can see that the difference between acceleration gap voltage profiles in two programmes is negligible. We needed for this simulations powerful computer with memory 8 Gb. Less meshcells number gives substantially bigger difference not only in the frequency value but in the voltage distribution.

For beam dynamics simulation radial and azimuth electric field components and magnetic field maps in median plane (see Figs. 9, 10) were created. This model simulation technique can be used to study the centre region of the accelerator.

Power dissipation in the model was calculated assuming the wall material is copper with a conductivity $\sigma = 5.8 \cdot 10^7$ $1/(\Omega\mathrm{m})$. The quality factor was about 14000 and power losses of the model were:

for storage energy 1 joule voltage in the centre — 65 kV, average losses 35 kW,

for storage energy 1.5 joule voltage in the centre — 80 kV, average losses about 50 kW.

Each cavity will be powered by a 75 MHz, 100 kW tetrode-based amplifier (as used in the current C235).

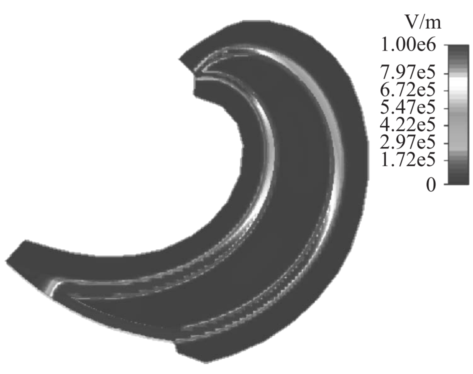

Fig. 9. Electric field distribution

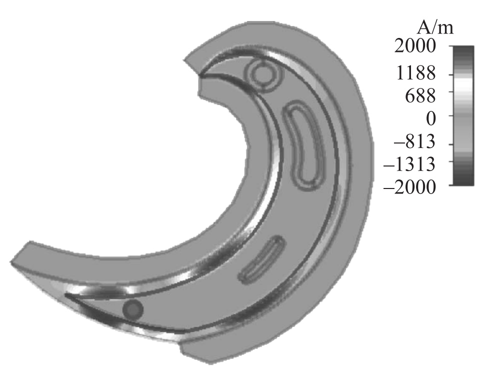

Fig. 10. Magnetic field in the median plane

3. FITTING OF THE FREQUENCY OF THE CAVITY

As the accuracy of calculations of the frequency of the cavity in our simulations is about 200 kHz (0.3%), we needed to think about possible fitting of the frequency of the cavity by about 300 kHz.

We analyzed methods of fitting the frequency of the cavity. In order to decrease the resonant frequency it is possible to change the pillar diameter. It was shown earlier that simultaneous variation of the transversal dimensions of stems changes the frequency without changing the voltage behavior along the radius. But machining of so many stems of the real cavity is not a simple task. In addition, the second and third stems have rather complicate transversal shape. That is why, we test the influence of machining of the round stems on the resonant frequency and voltage variation along radius.

First of all, we created the model with resonant frequency 75.8 MHz and examined the possibility of decreasing the resonant frequency of this model by modulation of the diameter of the first stem. Diameter of the first pillar was decreased by 1.9 cm. As a result, the resonant frequency decreased from 75.8 to 75.45 MHz, i.e., the magnitude of frequency difference per diameter difference is about 19 kHz/mm for the first pillar. It is a too small value. In addition, the voltage in the centre was changed too much — more than 10 kV.

Then in the model with the frequency 75.8 MHz we changed the diameter of the fourth stem. Initially diameter of the fourth stem was equal to $D_0 = 8$ cm. We decreased diameter step by step in order to receive the frequency 75 MHz. Results are presented in Fig. 10.

From Fig. 11 one can see that frequency depends linearly on the diameter. The magnitude of frequency difference per diameter difference is about 115 kHz/mm for the fourth pillar. Influence on voltage value in the centre region was much smaller for the fourth stem diameter decreasing than for the first stem's. Practically, it is possible to decrease the resonant frequency of the cavity by 300 kHz, decreasing the diameter of the fourth stem by about 2.5 mm.

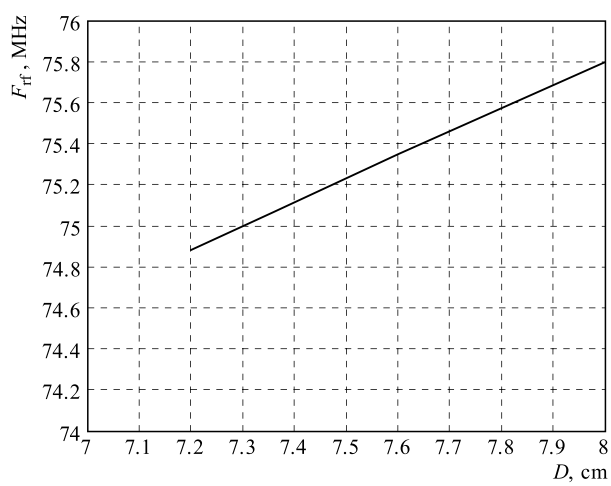

Fig. 11. Frequency of the cavity against diameter of the fourth stem

CONCLUSIONS

Computer model of the double gap delta RF cavity with 4 stems was developed, simulated and analyzed in CST Microwave Studio and ANSYS. Model had the frequency 75 MHz, necessary voltage distribution — from 80 kV in the centre to 160 kV (average) in the extraction region. It was shown that the voltage behavior along radius depends substantially on the positions and diameters of the stems. The frequency value can be changed by scaling of transversal dimensions of all stems without essential modification of voltage profile.

It was demonstrated that it is possible to change resonant frequency of the cavity by variation of diameter of the fourth stem. The magnitude of frequency difference per diameter difference is about 115 kHz/mm. Capacitance tuners in the position $R = 120$ cm will provide necessary frequency tuning.

Optimization of the RF cavity parameters leads us to the cavity with quality factor about 14000, RF power dissipation being about 50 kW per cavity.

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