RF CAVITY SIMULATIONS FOR SUPERCONDUCTING C400 CYCLOTRON

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Abstract

The compact superconducting isochronous cyclotron C400 [1] has been designed by IBA (Belgium) in collaboration with the JINR (Dubna). It 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 the energy of 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 cyclotron C400. Computer model of the double gap delta RF cavity with 4 stems was developed in is a 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.

RF CAVITY GEOMETRY

Magnetic field modeling and beam dynamics have determined orbital frequency of the ions equal to 18.75 MHz. As RF cavities will be operated in the 4th harmonic mode resonance frequency must be 75 MHz. It is planed to use two normal conducting RF cavities [1] for ion beam acceleration in the C400 cyclotron.

The geometric model of the double gap delta cavity housed inside the valley of the magnetic system of the C400 cyclotron was developed in the CST STUDIO SUITE. We studied a number of models that differ in the width of the accelerating gap, the height of the dee; the final variant of the model is presented in Figure 1. The depth of the valley permits using the cavity with the total height 116 cm. The vertical dee aperture was 2 cm. The accelerating gap width was 6mm at the center increasing to 8 cm at R = 75 cm, and remaining constant to extraction region as shown in Fig. 3.

Distance between dee and back side of the cavity was equal to 50 mm. Cavities have a spiral shape similar to the shape of the sectors. The sector geometry permits azimuth extension of the cavity (between the middles of the accelerating gaps) equal to 45 deg up to the radius of 150 cm, (see Fig. 2). We inserted four stems with different transversal dimensions in the model. We studied different positions of the stems to insure increasing voltage along the radius of the accelerating gap, which should range from 80 kV in the central area up to 160 kV in the extraction region. It is important to have a high value of voltage beginning approximately at R = 150 cm before crossing the 3Qr = 4 resonance.

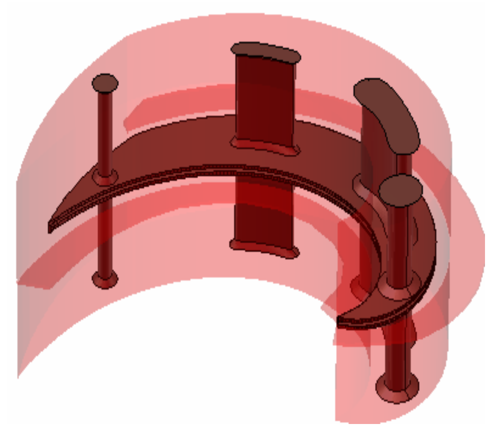

Figure 1. View of the cavity model.

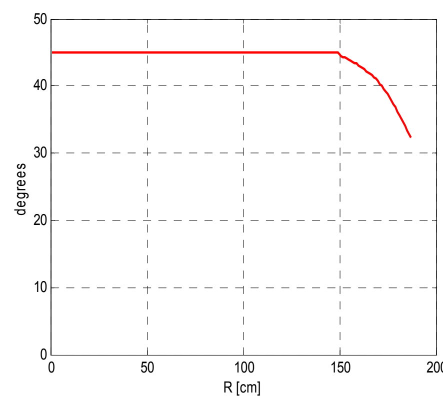

Figure 2. Azimuth extension of the cavities (between middles of the accelerating gaps).

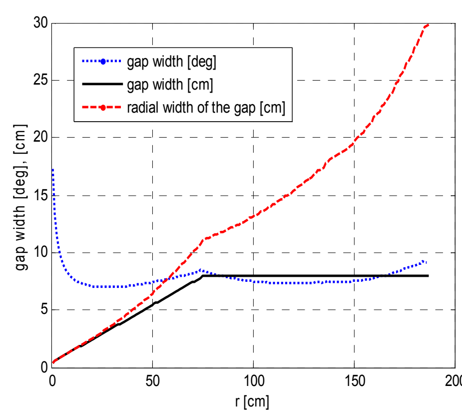

Figure 3. Gap width against radius. Dashed line- radial width in cm, dotted line-azimuth extension in deg, solid line-perpendicular in cm.

The thickness of the dee was 20 mm. The edges of the dees were 10mm thick and have a rounded form optimized from the 2D electric field simulations in order to minimize the electric field in the environment.

Each cavity will be excited with the RF generator through a coupling loop (which should be rotated azimuthally within small limits (+- 30 degrees). The active tuning system must be designed to bring the cavities to the frequency initially to compensate for detuning because of temperature variations due to RF heating and to provide frequency difference 450 kHz for C^{6+} and H_2^+ ions acceleration.

We analyzed effect from the tuner in the position R = 120 cm and at R = 70 cm with diameter 10 cm and 18 cm. One tuner with diameter 10 cm provides changing of frequency about 500 kHz. We found that the better position for the tuner is at radius R = 120 cm (see Fig. 4).

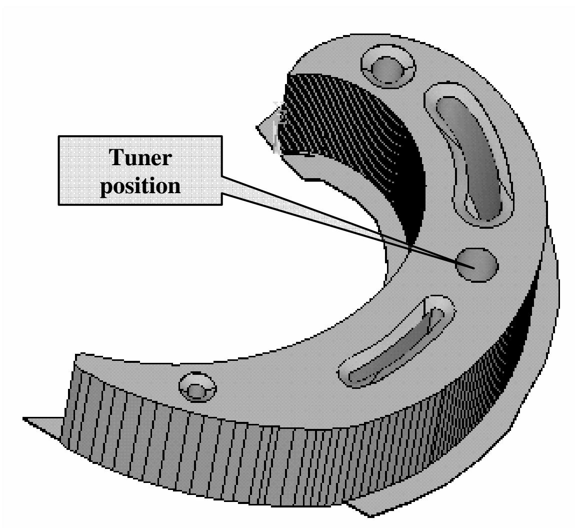

Figure 4. View of the ANSYS model with tuner.

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. [2]. ANSYS is an engineering simulation software which mainly rely 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 electro-magnetic problems. [3]. Calculations of the created model were performed using the eigenmode JD lossfree solver (Jacobi Division Method) in the CST Microwave Studio and the 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. 4).

In order to shape the radial voltage distribution we moved stems. In addition, we needed to change the transversal dimensions of the stems. The voltage value was obtained by integrating 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 found that variation of the horizontal dimensions of all stems by one percent changes the frequency by about 300 kHz and the value of the voltage along the radius does not change noticeably while the frequency is fitted by less than 1 MHz.

Simulations show that the frequencies from both programs are about the same beginning with the number of meshcells 7 million for CST and 3 million for ANSYS:

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

F_{rf} = 74.80 MHz, ANSYS.

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

From Fig. 5 one can see the difference between the acceleration gap voltage profiles in two programs is negligible. For these simulations we needed a powerful computer with the 8 GB RAM. Less meshcells number gives substantially bigger difference not only in frequency value but in voltage distribution.

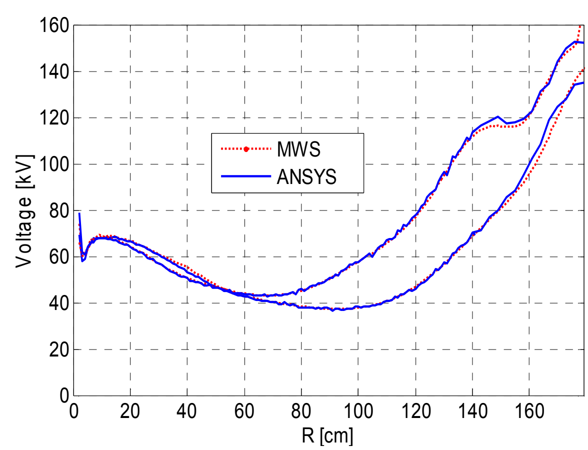

Figure 5. Voltage distribution along the radius.

Radial and azimuth electric field components and magnetic field maps in median plane were created for the beam dynamics simulation. This model simulation technique can be used to study central region of the accelerator.

Power dissipation in the model was calculated on the assumption that the wall material is copper with conductivity $\sigma = 5.8*10^7$ 1/(Ωm). The quality factor was about 14000 and power losses of the model were as follows:

For the storage energy 1 J the voltage at the center is 65 kV, and average losses are 35 kW

For the storage energy 1.5 J the voltage at the center is 80 kV, and average losses are 50 kW

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

FITTING OF THE FREQUENCY OF THE CAVITY

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

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

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

Then in the model with frequency 75.8 MHz we changed diameter of the fourth stem. Initially diameter of the fourth stem was D_0 = 8 cm. We decreased diameter step by step in order to achieve frequency 75 MHz. The frequency difference per diameter difference is about 115 kHz/mm_{pillar} for the fourth pillar. Influence on voltage value in the center region was much smaller for the fourth stem diameter decreasing than for the first stem's. Practically, it is possible to decrease cavity's resonant frequency by 300 kHz, decreasing diameter of the fourth stem by 2.5 mm.

CONCLUSIONS

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

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

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

REFERENCES

[1] Yves Jongen et al, "IBA C400 Cyclotron Project for Hadron Therapy", The 18th International Conference on Cyclotrons and their Applications Cyclotrons 2007, Laboratori Nazionali del Sud, Giardini Naxos, Italy 2007.

[2] Yves Jongen et al, "Radio Frequency System of the Cyclotron C400 for Hadron Therapy", The 18th International Conference on Cyclotrons and their Applications Cyclotrons 2007, Laboratori Nazionali del Sud, Giardini Naxos, Italy 2007. http://felino.elettra.trieste.it/cyc07/papers/TUPPRA05.pdf

[3] CST STUDIO SUITE http://www.cst.com

[4] ANSYS http://www.ansys.com