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DESIGN AND CALCULATION OF THE RF SYSTEM OF DC140 CYCLOTRON

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Abstract

Flerov Laboratory of Nuclear Reaction of Joint Institute for Nuclear Research carries out the works under creating of FLNR JINR Irradiation Facility based on the cyclotron DC140. The facility is intended for Single Event Effect testing of microchip, for production of track membranes and for solving of applied physics problems. The main systems of DC140 are based on the DC72 cyclotron ones that now are under reconstruction. The DC140 cyclotron is intended for acceleration of heavy ions with mass-to-charge ratio A/Z within interval from 5 to 5.5 up to two fixed energies 2.124 and 4.8 MeV per unit mass. The intensity of the accelerated ions will be about 1 pμA for light ions (A<86) and about 0.1 pμA for heavier ions (A>132). The designed radio frequency (RF) system of the DC-72 cyclotron with a half-wave cavity is not suitable due to the big vertical size. For this reason, a new quarter-wave RF system was developed for the DC140 cyclotron project. The results of calculating the parameters of the new RF-system are given in this work.

INTRODUCTION

The RF system of the DC140 cyclotron works as a resonator, which creates the necessary voltage in the accelerating gaps for acceleration of beam. The quarter-wavelength coaxial resonant cavity has been adopted in DC140. The RF system consists of dee, stem, cavity, adapter sleeve, outer barrel, short-circuiter, coupling loop, tunable shorted terminal.

According to the technical documentation of the DC140 cyclotron the main parameters of RF system are presented in the Table 1 [1].

Table 1: Technical Parameters of DC140 RF System

Parameter	Value
Frequency	8.632 MHz (2 or 3 harmonic)
Resonant number	2
Resonant type	λ/4 coaxial
Dee azimuthal extension	40 º
RF voltage	60 kV

CALCULATION OF THE RESONANT

The first step of the designing a RF system is choosing its geometry. The geometry of the RF system is limited by the layout of the cyclotron magnet and magnetic channel MC2. It is installed inside the dee. The widest part of the dee was lengthened to protect the magnetic channel from the RF electromagnetic field. A sketch of the design model is shown in Fig. 1.

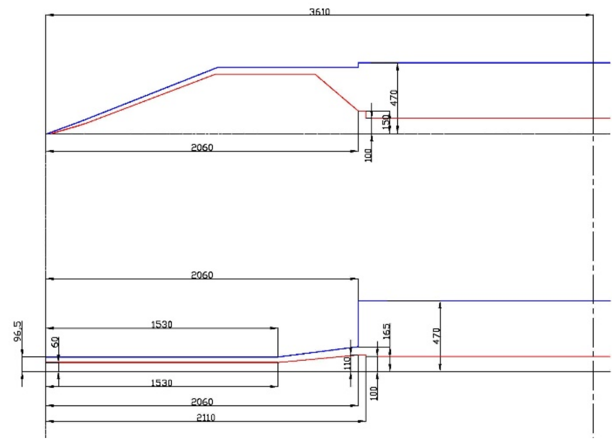

Figure 1: Sketch of the RF system of DC140 cyclotron.

The height of the dee gradually increases from a distance of 1530 mm from the centre of the cyclotron. This ensures its structural strength and fastening to the stem. The dee enters the coaxial part of the RF system by 50 mm to avoid electrical breakdown between the electrodes at the attaching point of the adapter sleeve with the outer barrel.

The results preliminary calculation and 3D simulation has been calculated, as shown in Table 2 [2].

Table 2: Results Preliminary Calculation and 3D Simulation

Parameter	Preliminary	3D-simulation
Frequency	8.632 MHz	8.632 MHz
Resonator length	3610 mm	3606 mm
Power dissipation (P)	7.57 kW	8.12 kW
Quality factor (Q)	8452	8054

The RF cavity created for to generate the high-frequency electric field in the gap between the dee and the ground. Accelerating voltage was obtained according to the integral of tangential component of the electric field in the accelerating gap on a fixed radius. The voltage distribution along the radius was shown in Fig. 2. The dee voltage practically does not change with increasing radius.

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The power loss of the RF cavity is surface loss of the conductors. The surface loss of the conductors [(Eq. 1)] can be written as:

$$P = \frac{1}{2} \cdot \sqrt{\frac{\pi \cdot \mu \cdot f}{\sigma}} \cdot \int \left|\overline{H}_\tau\right|^2 \cdot dS, \quad (1)$$

where μ is the copper permeability, $\mu = 4\pi \times 10^{-7}$ H/m, f is the working frequency, $f = 8.632\times10^6$ Hz, σ is conductivity of the cavity materials, $\sigma = 5\times10^7$ S/m (commercial copper); H is the magnetic intensity vector [3].

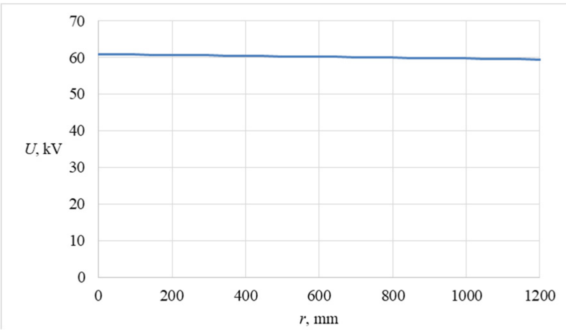

Figure 2: The voltage distribution along the radius.

The RF system was split into several parts to consider the loss of each part. The magnetic intensity vector H of the corresponding position has been integrated on the surface of each part. Then total power loss of the RF system is 8.12 kW (excluding the tunable shorted terminal and coupling loop). The distribution of power loss of each part has been calculated, as shown in Table 3.

Table 3: The Distribution of Power Loss of Each Part

Part	Cavity Length (mm)	Power Loss (W)
Dee	0 – 2110	973.9
Stem	2110 – 3606	4714.4
Cavity	0 – 1530	208
Adapter sleeve	1530 – 2060	672.7
Outer barrel	2060 – 3606	1045.7
Short-circuiter	3606	508.2
ALL	-	8122.9

COUPLING LOOP

The coupling loop is designed to transmit RF power into the RF system. The coupling loop is located on top of the outer barrel at a distance $l = 2715$ mm from the centre of the cyclotron, as shown on Fig. 3.

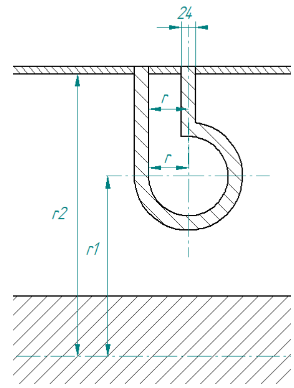

Figure 3: The conditional layout of the coupling loop.

The geometric dimensions of the coupling loop are related to the power loss [(Eq. 2)] according to the formula:

$$2\pi \cdot \left(r_1 - \sqrt{r_1^2 - r^2}\right) + (r - r_{\text{cut}}) \cdot ln\left(\frac{r_1}{r_2}\right) = \frac{\sqrt{2 \cdot W \cdot P}}{\mu_0 \cdot f_0 \cdot I_{\text{stem}}}, \quad (2)$$

where r is the radius of the circle of the coupling loop, r_1 is distance from the stem centre to the centre of the coupling loop, r_2 is inner radius of the outer barrel, W is feeder impedance, I_{stem} is stem current at the location of the coupling loop, r_{cut} is cutting radius of conductor.

The optimal value of the mutual inductance between the coupling loop and the resonator was calculated using an equivalent electrical circuit ($M_{\text{opt}} = 7.62$ nH).

The results of calculating the coupling loop are shown in Table 4.

Table 4: The Results of Calculating the Coupling Loop

r_1 (mm)	r_2 (mm)	r (mm)	M (nH)	P (W)
400	470	83	10.55	65

TUNING

Because of the RF power loss, increasing temperature must influence the resonance frequency of cavity. The tunable shorted terminal is used compensate for this frequency shift. The tunable shorted terminal is decided to be located on the top of the outer barrel at a distance $l = 3300$ mm from the center of the cyclotron, as shown in Fig. 4.

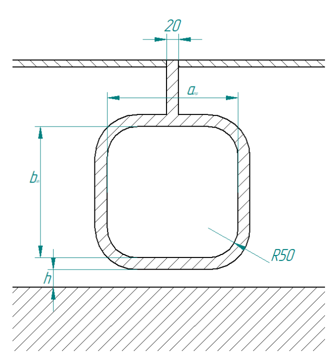

Figure 4: The conditional layout of the tunable shorted terminal.

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The tuning system is designed to cover the resonant frequency of the 8.632 MHz with bandwidth of ±13 kHz (~0.3%). The results of calculating the tuning system are shown in Table 5.

Table 5: The Results of Calculation the Tuning System

a **(mm)**	***b*** **(mm)**	***h*** **(mm)**	***Δf*** **(kHz)**	***P*** **(W)**
210	210	20	29.22 (0.34 %)	400.2

Figure 5 shows the simulation result of tuning system, the x-coordinate represents the angle the plane of the tunable shorted terminal and vector H, the y-coordinate represents the resonance frequency of the RF system.

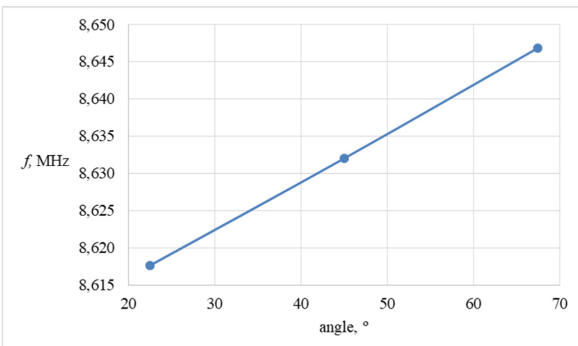

Figure 5: Resonance frequency as a function of angle.

COOLING SYSTEM

Water is a coolant for the resonant system cooling system. The cooling system consists of cooling ducts, which are soldered to the surfaces of the parts of RF system. The volumetric water discharge Q_v for each part of RF system is calculated [(Eq. 3)] by the formula:

$$Q_V = \frac{P_{+30\%}}{c_{H2O} \cdot \rho_{H2O} \cdot \Delta T_{H2O}}, \quad (3)$$

where ΔT_{H2O} is temperature difference inlet and outlet, $\Delta T_{H2O} = 5$ ºC, c_{H2O} is specific heat of water, ρ_{H2O} is density of water, $P_{+30\%}$ is the dissipated power with a margin of 30%.

The minimum diameter d_{min} of the cooling ducts for each part RF system is determined from the Eq. (4).

$$d_{min} = \sqrt{\frac{4 \cdot Q_V}{\pi \cdot \upsilon}}, \quad (4)$$

where v is the speed of movement of water in the cooling ducts, $v = 0.8$ m/s.

The system is designed taking into account the maximum temperature difference on the surface ΔT_{Cu} of the parts no more than 10 ºC. The maximum limit of the distance ΔL between the cooling ducts is calculated by the Eq. (5).

$$\Delta L = \sqrt{\frac{8 \cdot \Delta T_{Cu} \cdot \lambda \cdot \delta \cdot S}{P_{+30\%}}}, \quad (5)$$

where λ is the specific thermal conductivity of the material, δ is the material thickness of part RF system, S is surface area of part of RF system. The calculation results are shown in Table 6.

The total water consumption for the RF system is 63.7 l/min.

Table 6: The Results of Calculation the Cooling System

Part	$P_{+30\%}$ **(W)**	Q_V **(l/min)**	d_{min} **(mm)**	δ **(mm)**	ΔL **(mm)**
Half of dee	633.1	1.81	6.9	2	254
Stem	6128.8	17.53	21.6	3	86
Half of cavity	135.2	0.39	3.2	2	499
Adapter sleeve	874.5	2.5	8.1	15	151
Outer barrel	1359.4	3.9	10.2	15	201
Shorting-circuiter	660.6	1.9	7.1	5	283
Coupling loop	84.5	0.12	1.8	-	-
Tunable shorted terminal	455.9	1.5	6.3	-	-

SUMMARY

The geometry of the resonator system of the DC140 cyclotron was chosen. This geometry provides an almost constant dee voltage with increasing radius. The characteristic parameters of RF system are calculated using simulation. Total power loss of the cavity is 8.59 kW. The coupling design has been completed through inductive coupling. It was decided that the design of the coupling loop will be identical to the U400M project. The tuning system is designed to the resonant frequency of 8.632 MHz with bandwidth of ± 14.5 kHz.

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