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Calculation methods of RF power requirement on an RF dee cavity of cyclotron

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ABSTRACT

A calculation of the radio frequency radiofrequency (RF) power required to operate the RF dee cavity of cyclotron which of the two dee is in phase has been carried. In this calculation, the object is the RF dee cavity of the DECY-13 cyclotron which operates with an RF frequency of 77.77 MHz and a peak RF dee voltage of 40 kV. The power requirement was determined by calculating the dissipated power in the RF dee that was calculated by two methods. The first method using a relationship between the quality factor and lost power has resulted in the power requirement of 20.55 kW. The second method using a relationship between the electrical current and the lost power has resulted in the power requirement of 19.74 kW. The two results do not seem to have any significant difference. By these calculations, it can be determined the predicted power requirement for operating the RF dee of DECY-13 cyclotron was around 20 kW.

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1. INTRODUCTION

The radiofrequency (RF) system is one of the major components in cyclotron among other major components, i.e. an ion source, a magnet system and a vacuum tank [1], [2]. The RF system generates an electric field in the vacuum tank to accelerate ions cyclically that are produced by the ion source. The presence of a perpendicular magnetic field causes the ions move spirally towards maximum radius and maximum energy in the tank of the cyclotron [1], [3], [4]. There are also other components those are relatively small size such as a beam probe for beam current measurement [5], a beam stripper for extracting ion beam to beam port [6] and a target chamber for irradiating the target.

An RF system in a cyclotron consists of three main components, i.e., a RF dee cavity component, a RF generator component, and a low-level control unit [7]–[9]. The first component serves to accelerate particles or ions in the cyclotron tank and the second component is outside the cyclotron vacuum tank serves as an RF resource fed to the first component. The control unit picks the output up from the cavity to control the RF supply of RF generator. The power feed passes through a transmission line and the power transfer process through a coupler in a cavity located at the back end of the RF cavity [10].

The RF dee cavity (hereinafter referred to as RF dee) consists of two dee, two dee stems and two cavity tubes. The generated voltage in between of the two dee in the cyclotron can be operated in the opposite phases (push-pull mode) or in the in-phase (push-push mode) [11], [12]. Here it will be discussed in phase one as contained in the DECY-13 Cyclotron project in Indonesia. A project of a 13 MeV proton cyclotron accelerator to produce PET radioisotopes was started at the Research Organization for Nuclear Energy of Indonesia. The project is named by the Development of Experimental Cyclotron in Yogyakarta and abbreviated as DECY-13. This cyclotron is planned to be an experimental facility to produce radioisotopes that are used in PET imaging. This cyclotron is the only one of a homemade cyclotron in Indonesia even also in Southeast Asia.

For implementing the project, a homemade RF generator of the RF system has been constructed and will continue to be improved as needed, while the RF dee has designed and constructed. The RF generator itself has been tested by using a resistor 50-ohm dummy load, and the result showed that it can supply a power output of more than 10 kW. The problem that must be answered is whether the capability of the RF generator is sufficient to supply RF power to the RF dee. Next, in order to determine the need for RF power to be supplied to RF dee, a calculation on RF power requirement of RF dee will be calculated.

2. METHODS

2.1. RF system

The RF system in the DECY-13 Cyclotron can be divided into three parts, one part is a RF generator, the second part is a RF dee and another part is low level control unit. The RF dee consists of dee and cavity tube. The RF generator supplies power to RF dee cavity in the cyclotron chamber. Scheme of the RF system is shown in Figure 1.

In order to establish a suitable electric field in the RF dee, a noiseless RF signal must be generated and applied to the RF dee. The DDS exciter is a signal generating experimental device that has the functions of high resolution frequency adjustment and amplitude adjustment [13]. The exciter uses digital technology by utilizing a highly integrated circuit made by the analog devices manufacturer, namely the AD9851 IC, using a base frequency of 30 MHz generated from the crystal oscillator. The drive RF amplifier uses laterally diffused metal oxide semiconductor (LDMOS) transistor technology of the BLF188XRS type in the form of a module palette with a 48 V dc data supply. This module can output ~1000 watts of power. The final amplifier uses an electron tube made by the factory EIMAC type 3CX15000A7, this electron tube is of the triode type and is operated in grounded grid mode. With an anode voltage of ~7000 V dc, this electron tube is capable of producing ~12,000 watts of power.

The transmission line has been set in the output of the RF generator for connecting to the RF dee resonator. The transmission line uses a rigid line connected with a coaxial cable. This is done because of the location of the RF generator and cyclotron, which are not possible to use a rigid line or coaxial cable as a whole. Such an installation requires several flange joints for bends and connecting flanges, and the disadvantage is that the bend connection is easily removed when there is movement or shock.

Some of supplied power to the RF dee will be reflected to the RF generator and the reflected power will cause to decrease signal amplitude in the dee. Apart from the impedance mismatch, the reflected power due to changing the cavity resonance frequency by thermal cavity deformation. The tasks of low level control unit are phase and frequency adjustment, stabilization and protection of the RF set from the reflected power [14]–[16].

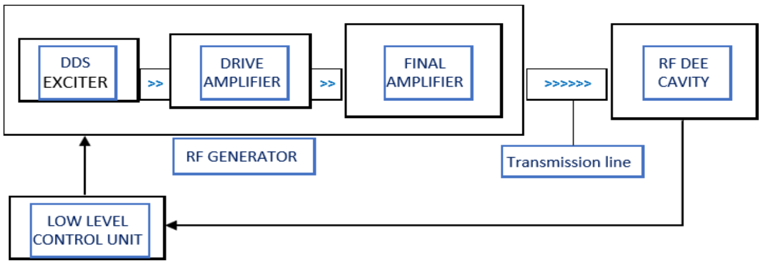

Figure 1. RF system of DECY-13 Cyclotron

2.2. The RF dee

The RF dee consists of two dee and cavity tube, the layout of the RF dee is shown in Figure 2. Two dee (right and left) facing the liners are capacitive components and the cavity tubes (right and left) consist of the cylindrical tube and dee stem forming inductive components, which means that the cavity is an L-C resonator. The RF power from the RF generator is supplied to the cavity by using a coupler type loop. The RF dee has low resistance of their conductive walls, has very high-quality factors; that is the frequency bandwidth is very narrow [17].

The equivalent electrical circuit is shown in Figure 3 [18]. The coupler is resented as an inductor Lc. The capacitive behavior of dee is presented in C1 and C2 while inductive behavior of cavity tube is presented in L1 and L2. The left dee and left dee stem have resistance of R1 while the right dee and right dee stem have resistance of R2. In order to simplify the analysis, the equivalent circuit is modified to a parallel R resonator circuit is shown in the Figure 4 [19], [20].

The RF dee has been designed with the following specifications:
- Dee angle: 36.50
- Dee radius: 520 mm
- Distance between dee and liner: 35.5 mm
- Diameter of stem: 70 mm
- Length of stem: 190 mm
- Resonant frequency: 77.7738 MHz

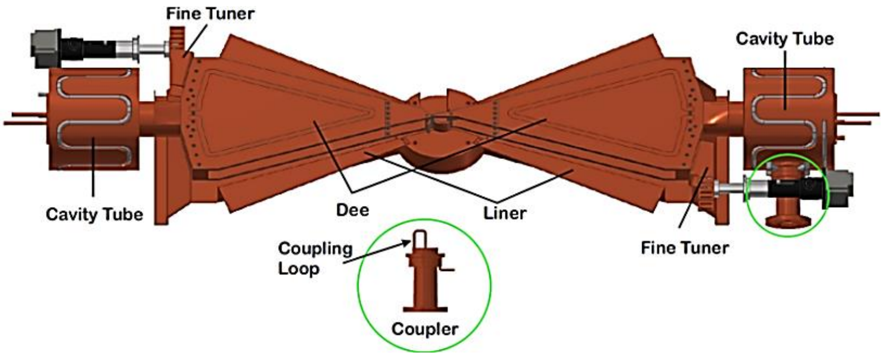

Figure 2. The layout of RF dee

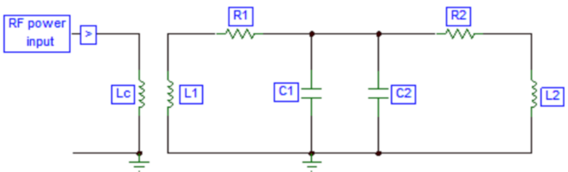

Figure 3. Equivalent circuit of RF dee cavity

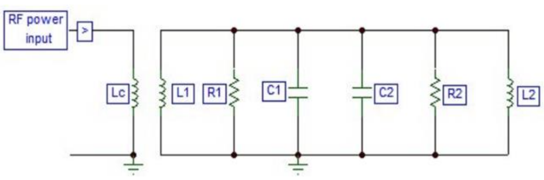

Figure 4. Modified equivalent circuit of RF dee cavity

2.3. Calculation method

The RF power which is supplied (P_{sup}) to the RF dee components will be stored in the RF dee (P_{std}) and will be lost (P_{los}) by changing into power dissipated in the RF dee walls (P_{cav}) and is also will be reflected through the coupler into the matched load of the RF generator (P_{ref}) [21]. It means that the relation of the power is as (1) and (2).

$$P_{sup} = P_{std} + P_{los} \quad (1)$$

$$P_{los} = P_{cav} + P_{ref} \quad (2)$$

The supplied power requirement is needed to compensate for the lost power and that is required from the RF generator [22], it means that the supplied power requirement will be determined by calculation result of the lost power. The calculation of RF lost power in the RF dee will be carried out by two methods and then the two results will be compared and be concluded. The detail of two methods is described as follows:

2.3.1. The first method: using a relationship between the quality factor and the lost power

The lost power can be calculated using a quantity of quality factor of the cavity (in this case is the RF dee). The quality factor, which is commonly defined as 2π times the ratio of the cycle mean stored energy and the lost energy [23]–[25], and in according with this definition the quality factor will be formulated by (3),

$$Q = 2\pi f \frac{W_{std}}{P_{los}} \tag{3}$$

where f is resonance frequency, W_{std} is stored energy in the dee cavity and P_{los} is lost power. If the lost power is not only dissipated power in the cavity (P_{cav}) but also consists the reflected power to the source, the Q will be as (4),

$$Q_L = 2\pi f \frac{W_{std}}{P_{los}} \tag{4}$$

or

$$P_{los} = 2\pi f \frac{W_{std}}{Q_L} \tag{5}$$

where $P_{los}= P_{cav} + P_{ref}$. The stored energy in the dee with the capacitance of C and peak voltage of V_{dee} that it is well be known is (6).

$$W_{std} = \frac{1}{4} C V_{dee}^2 \tag{6}$$

The loaded quality factor Q_L is calculated by a simulation program of CST Studio Suite. This simulation program has been widely used for calculating RF dee parameters [26]–[29]. First step, basic parameters are formulated in this case the items as mentioned in the section 2.2 above, for modelling of RF cavity using "modelling" menu that attached in the program. The modelling results then are used for simulation step that for simulating electric and magnetic field and creating the parameters of distribution of electric field and magnetic field, impedance and S parameters. The modelling and simulation processes could be iterated to be obtained a resonance frequency to be reached. The final step is "post-processing" when the dissipated power, dee voltage and quality factor are calculated.

The value of the capacitance of one dee (C_1 or C_2 in the Figure 3 or Figure 4) for the upper and lower surfaces is (7).

$$C_{dee} = 2 \frac{\varepsilon_0 S_{dee}}{d} \tag{7}$$

Where ε_0 is permittivity of vacuum, S_{dee} is the surface area of dee and d is the distance from dee to ground (liner).

2.3.2. The second method: using a relationship between the electrical current and the lost power

In this method the power will be calculated with the fact that there is an electric current flowing from dee to ground through the dee stem, and along there is an electrical resistance resulting heat as a dissipated RF power. The amount of power is obtained from the multiplication of the square of the current multiplied by the resistance. Before calculating the power, firstly it is calculated the electrical skin depth of copper.

The power loss that is reflected to the RF generator is designed in the normal operation is 10%, so that the dissipated power in the RF dee components is 90%. This design accordance with the normal operation of RF dee cavity that the allowed reflected power is more-less 10% [25], [30]. By this design, the total lost power will be 100÷90 × dissipated power in the components.

The electrical charge generated by the dee with the frequency of f, the capacitance of C and the voltage of V_{dee} is in amount of:

$$I_{rf} = \frac{dQ_{dee}}{dt} = C \frac{dV_{dee}}{dt} = 2\pi f C V_{dee}$$

and the valid value of I_{rf} can be expressed as (8).

$$I_{rf}(rms) = \sqrt{2}\pi f C V_{dee} \quad (8)$$

Where Q_{dee} is an electrical charge in the dee. The calculation of the capacitance of dee, C, is the same as mentioned in (6). The dissipated power in the RF dee components with resistance of R will be as (9).

$$P_{rf} = {I_{rf}}^2 R \quad (9)$$

The resistance R of RF dee components consist of the resistances of the dee plate and the dee stem in the cavity tube. In the calculation of dee resistance, the dee is considered to have a shape like pizza and the dee stem is considered to have a cylindrical tube.

According to (2), the total lost power is calculated from the summation of the dissipated power in the dee component as expressed in (9) and the reflected power. The reflected power is determined by measurement of return loss quantity (S11) using a network analyzer. Relation between reflection coefficient [Γ] and return loss (S11) is S11 = 10 logΓ.

3. RESULTS AND DISCUSSION

3.1. The first method

The supplied power or lost power P_{los} in (5) is determined by calculating the loaded quality factor, Q_L, and capacitance, C, and setting the voltage V = 40 kV. The load quality factor Q_L was calculated by using a simulation code of CST Studio Suite with the input is the geometric dimensions of the RF cavity as mentioned in section 2 above, and the result is Q_L = 829. Furthermore, for dee angle of 36.5° and radius r = 0.52 m, it is easily obtained that the surface area of one dee is $S_{dee} = \pi r^2 \frac{36.5^0}{360^0}$ = 0.0861 m². If the value of ε_0= 8.861 ×10^{-12} F.m^{-1} [31], [32] and the distance between dee plate to liner is 0.035 m, then the value of capacitance of one dee is (10).

$$C_{dee} = 2 \times \frac{8.861\times10^{-12}\times0{,}0861}{0{,}035} = 43.596 \times 10^{-12} \text{ F} \quad (10)$$

If the RF dee operates in frequency of $\omega_0 = 2\pi \times 77.77 \times 106\ Hz$ and the dee peak voltage to be obtained is $V_{dee} = 40 \times 103\ V$, the lost power accordance with (5) will be as (11).

$$P_{los} = 2 \times \pi \times 77.77 \times 10^6 \times \frac{0.25\times43.596\times10^{-12}\times1600\times10^6}{829} = 10{,}273 \text{ watt}$$

It means the total lost power of two dee is 20,545 watt or ≅ 20.55 kW.

3.2. The second method

If dee voltage is V_{dee}, it will be collected electrical charge in the dee, $Q_{dee} = C_{deed}V_{ee} = 43.51 \times 10 - 12 \times V_{dee}$. If operating frequency f = *77.77* MHz and the maximum voltage of dee is 40 kV, the electrical charge will flow to the dee stem (coaxial part) according to (8) in the amount of (12):

$$I_{rf} = \sqrt{2}\pi f C V_{dee} = 4.44 \times 77.77 \times 10^6 \times 43.51 \times 10^{-12} \times 40 \times 10^3 \approx 601A \quad (11)$$

This current flows only on the surface of the stem in the electrical skin depth (δ) of copper [33]–[35] where the δ is:

$$\delta = \sqrt{\frac{2\rho}{2\pi f_{rf}\mu_0}} \quad (12)$$

with $\boldsymbol{\rho}$ resistivity of copper is 1.68 × 10^{-8} ohm-m, μ_0 magnetic permeability of vacuum is 12.57×10^{-7} H/m [36], [37]. If the values of those constants are used and the frequency of the RF is 77.77 MHz, then it is obtained that:

$$\delta = \sqrt{\frac{2\times1.68\times10^{-8}}{2\times3.14\times77.77\times10^6\times12.57\times10^{-7}}} = 7.40 \times 10^{-6} \text{ m}$$

The resistance calculation in the dee and the stem. The resistance of stem with length (l) of 0.19 m and radius (r) of 0.035 m is (13).

$$R_{stem} = \boldsymbol{\rho}\frac{\boldsymbol{l}}{\boldsymbol{s}} = \frac{l}{\delta \times 2\pi r} = 1.68 \times 10^{-8} \times \frac{0.19}{7.40 \times 10^{-6} \times 2 \times 3.14 \times 0.035} = 0.196 \times 10^{-2}\ ohm \quad (13)$$

The resistance of dee plate was calculated in the following way.

The dee has a shape like pizza with outer radius l_2, inner radius l_1, the thickness is δ, and the angle is θ, is illustrated in the Figure 5. An element of the "pizza" with a radial length of *dr* will has resistance:

$$dR = \rho\frac{dr}{a(r)}$$

where $\boldsymbol{\rho}$ is specific resistance and $a(r) = r\delta\theta$ is the vertical cross section of the pizza. The resistance of the element of the pizza is:

$$dR = \frac{\rho\, dR}{r\delta\theta}$$

total resistance of pizza over l_1 to l_2 is:

$$R_{dee} = \int_0^R dR = \int_{l_2}^{l_1}\frac{\rho}{h\theta}\frac{dr}{r} = \frac{\rho}{\delta\theta} ln\left(\frac{l_1}{l_2}\right)$$

In this case δ=7.40×10^{-6} m, l_1=0.1 cm and l_2=51 cm, ρ=1.68×10^{-8} ohm-m (for copper) [38], θ=36.50=0.64 rad, then:

$$R_{dee} = \frac{1.68 \times 10^{-8}}{7.40 \times 10^{-6} \times 0.64}\ln\left(\frac{51}{2.9}\right) = 1.020\ \times 10^{-2}\ \text{ohm} \quad (14)$$

The total resistance of RF dee for stem and dee is summation of resistances in (13) and (14), that is in (15).

$$R_{RF\ dee} = 0.196 \times 10^{-2}\ \text{ohm} +\ 2.216 \times\ 10^{-2}\ \text{ohm} = 2.41\ \times 10^{-2}\ \text{ohm} \quad (15)$$

The resistance of $R_{RF\ dee}$ accordance with R_1 or R_2 in the Figure 4.

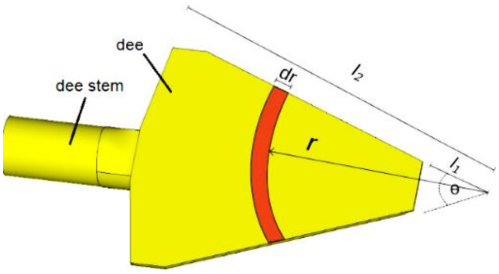

Figure 5. The illustration of pizza like of dee

3.2.1. The dissipated power calculation in the cavity

The dissipated power in one stem and one dee that accordance with (9) using the value of I_{rf} in the (11) and R value in the (15) is:

$$P_{one\ RF\ dee} = I_{rf}{}^2R =\ (601)^2 \times 2.41 \times 10^{-2}\ W \cong 8.705\ \text{kW}$$

it means the total dissipated power for two stems and two dee is:

$$P_{RF\ dee} = 17.41\ \text{kW}$$

3.2.2. The total lost power

According to (2) that the total lost power consists of the lost power in the cavity and the reflected power, so in the calculation of total lost power, it must be considering how much the power reflects back to the RF generator through the coupler. The result of measurement of the return loss of RF dee cavity using a network analyzer is being -14.77 dB, this is accordance with value of 3.3% of the reflected power compared to supplied power, so that the forward power to be dissipated power in the RF dee cavity is 96.7%. By using this calculation and if the dissipated power in the RF dee cavity is 17.57 kW, the total lost power (equal to supplied power) is $100 \div 96.7 \times 17.41\ kW\ =\ 18\ kW$.

3.3. The comparison of two methods

The result of dissipated power total which is calculated in the first method is within limits that still can be compared with the result of the second method, namely 20.55 kW in the first method and 18 kW in the second method, it means that the difference between two results is in around 10%. From those results it can be taken an average value of the power requirement is 20 kW. The result in the second method also gets a real understanding that the dee plate it must be considered in the calculation of the power dissipation even more playing a role compared with the dee stem or coaxial part.

4. CONCLUSION

The RF power requirement that is supplied to the RF dee of the two dee of in phase has been predicted by calculating using two methods. The calculation of the power has been carried out for the dee voltage in the peak value that is 40 kV. The differences result of two methods is in around 10%, it means that the two methods can be used without any doubt, it means the methods used in the calculations seem to be reasonable. Particularly in the DECY-13 cyclotron, it can be determined that the RF power requirement for the RF dee is in around 20 kW. It means that the 10 kW power of the existing RF generator is not sufficient for supplying power to the DECY-13 Cyclotron. Further development must be carried out to increase power to 20 kW or even more.

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