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DESIGN OF THE FLAT-TOP RESONATOR FOR THE JAERI AVF CYCLOTRON

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Abstract

A flat-top acceleration resonator for the JAERI AVF cyclotron has been designed. The fifth harmonics of the fundamental frequency is used to make overall energy gain uniform. A cold model test was carried out to determine optimum parameters of the flat-top resonator. The design of the flat-top resonator has been modified using the MAFIA code to minimize a cavity length and to save output power of an amplifier. The optimum ratios of the fifth harmonic amplitude to the fundamental one for minimizing the energy spread were evaluated from a radial distribution of the dee voltage.

1 INTRODUCTION

The JAERI AVF cyclotron can accelerate a variety of ion species for the research in biotechnology and materials science. A flat-top (FT) acceleration system for the cyclotron has been designed to minimize the energy spread mainly for a microbeam production. The microbeam is extremely useful for elucidation of the dynamics of cellular repair and the intracellular process of functions such as apoptosis. The present microbeam [1] is produced by using a collimator with an aperture of about 10 μm in diameter. The size of the microbeam spot needs to be decreased to 1 μm to improve the precision of the biological experiment. The energy spread of the cyclotron beam is required to be reduced to $\Delta E/E = 2 \times 10^{-4}$ to produce the 1 μm diameter microbeam by focusing the beam with quadrupole magnets.

The cyclotron has a pair of quarter-wavelength (λ/4) coaxial type resonators with a movable-short [2]. A maximum acceleration voltage is 60 kV in a CW mode. The diameters of inner and outer tubes of the coaxial cavity are 300 mm and 1000 mm, respectively. The range of the fundamental frequency is 11 to 22 MHz. Harmonic modes of 1, 2 and 3 are used to cover a wide range of energy.

In general, the third- or fifth-harmonics of the fundamental frequency is used for the flat-top acceleration [3, 4]. The amplitude of the higher harmonics superimposed to the fundamental waveform is estimated to be $1/N^2$ times the fundamental voltage, where the N is the order of the harmonics. We have adopted the fifth-harmonics to save output power of an amplifier. The fifth-harmonic voltage in the frequency range of 55 to 110 MHz is required to cover the whole range of the fundamental frequency.

2 DESIGN OF THE FLAT-TOP RESONATOR

2.1 A Cold Model Test

To determine parameters of the FT resonator, a cold model test was carried out [5] using the model of an FT resonator preliminarily designed for the RIKEN AVF cyclotron [6]. Figure 1 shows the cross sectional view of the model of the FT resonator coupled to the main resonator with a capacitive coupler (C5) of 150 mm square. The diameters of inner and outer tubes are 40 mm and 200 mm, respectively. The gap of C5 was varied from 6 to 25 mm and the position of a movable-short (L5) from 29 to 388 mm. The induced FT waveforms were observed successfully at the dee voltage pick-up of the main resonator when the fundamental frequency were tuned to 11, 13, 15 and 20 MHz. Power dissipations for the fifth-harmonic frequencies were estimated from the amplitude levels of the signal generator and the pick-up signal. Assuming that the fundamental voltage was 30 kV, about 1 kW output power of an amplifier is required to achieve the FT acceleration. The power dissipations were corrected on the voltage distribution along the

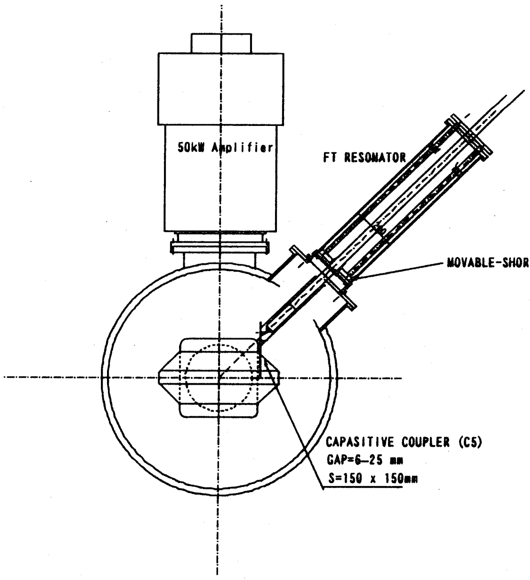

Figure 1: Cross sectional view of the main resonator and the model of the FT resonator. The FT resonator model is capacitively coupled to the main resonator with an electrode plate of 150 x 150 mm^2.

acceleration gap of the dee electrode and on frequency dependence of the pick-up capacitor.

2.2 Design of the FT Resonator Using the MAFIA Code

In order to improve the design of the FT resonator, optimum parameters to downsize the FT resonator itself and to decrease power dissipation were investigated using the MAFIA code [7]. The compactness of the resonator is indispensable condition due to the limited space for mounting the FT resonator.

The resonance frequencies of the λ/4 and 3λ/4 modes were evaluated to determine the reliability of a mesh used for the calculation with the MAFIA code. Dependence of the resonance frequencies on the position of the movable-short is shown in Fig. 2. The calculated frequencies were consistent with the measured ones. The power dissipation at the fundamental frequency of 15 MHz was found to be minimized using the FT resonator consisting of a 70 mm diameter inner- and a 300 mm diameter outer-tubes. The power consumption was estimated to be 80 % of the result in the cold model test. Figure 3 shows a correlation between the gap of C5 and the position of L5 to obtain the fifth-harmonic frequencies. The maximum length of L5 was limited to 400 mm for the compactness, and the minimum length to 100 mm to mount a power feeder and a frequency compensation tuner.

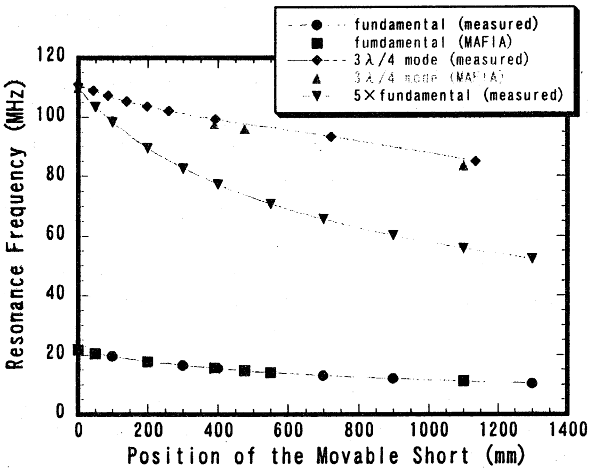

Figure 2: Comparison of the resonance frequencies between the calculation and the measurement.

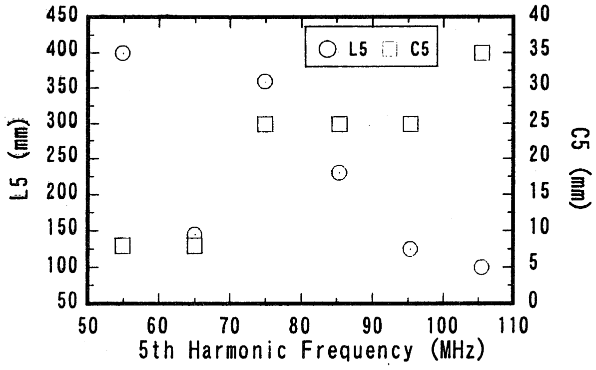

Figure 3: Parameters of the FT resonator calculated with the MAFIA. C5 is the gap of the capacitive coupler. L5 is the position of the movable-short.

In principle, the amplitude of the fifth-harmonic voltage should be 1/25 of the fundamental one to acquire a uniform energy gain when the voltage distribution along the acceleration gap is uniform. However, the resonator actually has position dependence of the voltage distribution, which varies with the resonance frequency. Variations of the fundamental and fifth-harmonic voltages are shown in Fig. 4. The calculated fifth-harmonic voltage along the acceleration gap of the dee at the fundamental frequency of 21 MHz decreases to 30 % of the muximum voltage at an extraction radius of 92.3 cm. On the other hand, the fundamental voltage has a little decrease. Therefore, the fifth-harmonic amplitude needs to be optimized for each frequency to uniform the overall energy gain just before extraction.

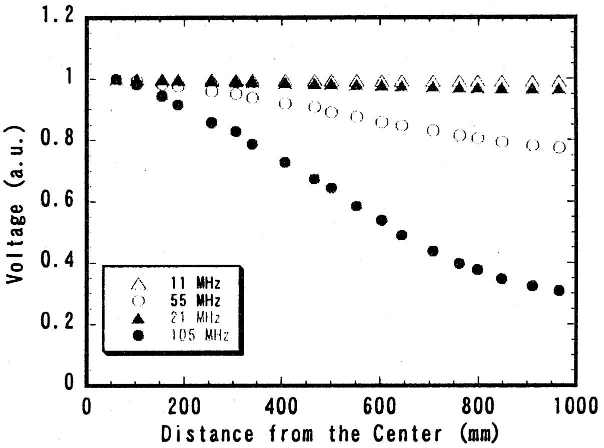

Figure 4: Distribution of the fundamental and the fifth-harmonic voltage along the acceleration gap at the fundamental frequencies of 11 and 21 MHz.

3 EVALUATION OF THE FIFTH-HARMONIC VOLTAGE

In order to evaluate the fifth-harmonic voltage required to minimize the energy spread of a beam, we have calculated particle energy using the voltage distribution obtained by the MAFIA code. Assuming that isochronism was ideally guaranteed and particles traveled on equilibrium orbits, energy gains of the particles were summed up until reaching to the extraction radius. Energies of the particles with different initial beam phases were averaged simply. The fifth-harmonic voltage providing the minimum energy spread was estimated by a least-squares method. We have calculated the optimum fifth-harmonic voltage for each harmonic mode. The χ^2 values of the least-squares fitting for 70 MeV H^+ are shown in Fig. 5. The ratio of the fundamental voltage to the fifth-harmonic one, V_f/V_5, giving the minimum χ^2

value, shifts toward the smaller side when the initial beam phase acceptance $|\phi_0|$ increases.

The permissible range of the fifth-harmonic voltage to reduce the energy spread to $\Delta E/E = 2\ \mathrm{X}\ 10^{-4}$ becomes wider for smaller initial phase acceptance. The optimum voltage ratio is 11.86 for the beam phase acceptance of $|\phi_0| \leq 6°$ RF, 11.68 for $|\phi_0| \leq 8°$ RF, 11.45 for $|\phi_0| \leq 10°$ RF. The calculated voltage ratio is about a half of the predicted value of 25. The energy spread within $\Delta E/E = 2\ \mathrm{X}\ 10^{-4}$ can be achieved for the initial beam phase acceptance of $|\phi_0| \leq 10°$ RF. Figure 6 shows the dependence of the V_f/V_5 on the fundamental frequencies for each harmonic mode. The voltage ratios for the harmonic mode 2 and 3 are larger than the harmonic mode 1. The turn number of the harmonic mode 1 is 550, which is more than twice of the turn number of the harmonic mode 2 and 3. The energy gains in the larger radius region decrease due to the noticeable drop in the fifth-harmonic voltage distribution as shown in Fig. 4. The harmonic mode 1 is more sensitive to the effect because of the large turn number. In the higher frequency region, the effect is clearly identified, since the voltage drop becomes steeper.

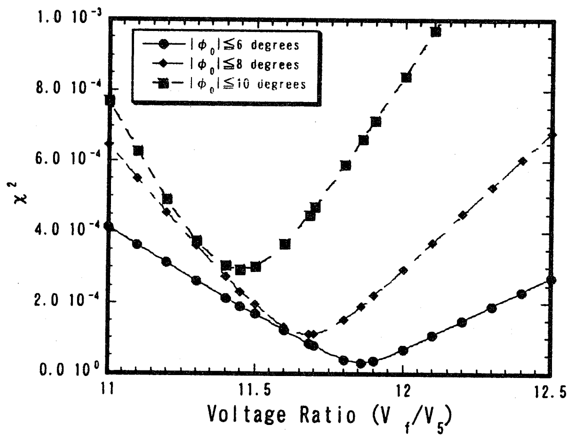

Figure 5: The χ^2 of the least-squares method obtained for 70 MeV H^+. The optimum voltage ratio V_f/V_5 was calculated for the initial beam phase acceptance of $|\phi_0| \leq 6°$ RF, $|\phi_0| \leq 8°$ RF and $|\phi_0| \leq 10°$ RF.

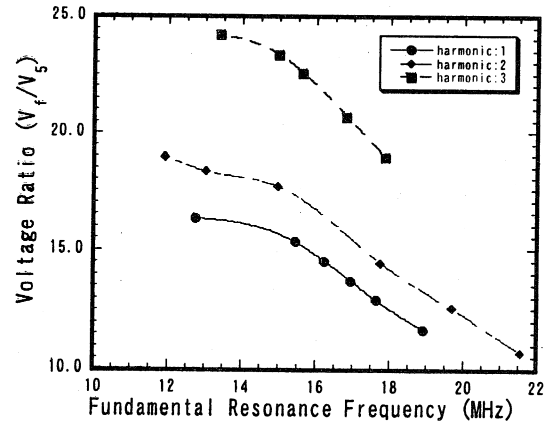

Figure 6: Dependence of the optimum voltage ratio on the fundamental frequencies. The optimum voltage ratios were calculated for each harmonic mode. The initial beam phase acceptance was $|\phi_0| \leq 8°$ RF.

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