

# DEVELOPMENT OF THE FLAT-TOP ACCELERATION SYSTEM FOR THE JAERI AVF CYCLOTRON

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## Abstract

A flat-top acceleration system with a fifth-harmonic frequency of a fundamental acceleration voltage has been developed to achieve energy spread of  $\Delta E/E = 0.02\%$  in the JAERI AVF cyclotron. A configuration of a flat-top cavity was designed by the MAFIA code. The flat-top acceleration system, consisting of the flat-top cavity, a power amplifier and an rf control system, has been installed in the main rf resonator. A flat-top waveform was successfully observed at the dee voltage pick-up in a power test at the fundamental frequency of 17.475 MHz. We have succeeded in accelerating 260 MeV  $^{20}\text{Ne}^{7+}$  ions by superimposing the fifth-harmonic voltage on the fundamental one.

## INTRODUCTION

The JAERI AVF cyclotron with a K number of 110 can accelerate a variety of ion species for the research in biotechnology and materials science. A flat-top acceleration system for the cyclotron has been designed to minimize energy spread mainly for a microbeam production [1]. The size of the microbeam spot needs to reduce to 1  $\mu\text{m}$  for a precise biological experiment. A beam focusing system using a set of quadrupole magnets, in combination with a series of slits, is being developed to improve the resolution of the microbeam [2]. The energy

spread of the cyclotron beam is required to be reduced to  $\Delta E/E = 0.02\%$  (FWHM) to avoid the effect of chromatic aberration in the quadrupole lenses.

In order to achieve the energy spread of  $\Delta E/E \leq 0.02\%$ , precise control of beam phase, high stabilization of the magnetic field [3] and the acceleration voltage are required in addition to the flat-top acceleration system. The tolerable stability of the acceleration voltage,  $\Delta V/V \leq 0.02\%$ , and the magnetic field,  $\Delta B/B \leq 0.002\%$ , have been already achieved. A newly designed center region, equipped with an rf shield cover for inflector electrode, a puller electrode and two sets of a phase slit, has been improved in August, 2003.

The cyclotron has a pair of quarter-wavelength ( $\lambda/4$ ) coaxial type resonators with a movable-short which can move 1300 mm at the maximum. An outline of the cyclotron resonator is shown in Fig. 1. The diameters of inner- and outer-tubes of the main resonator are 300 mm and 1000 mm, respectively. The range of the fundamental frequency is 11 to 22 MHz. A maximum acceleration voltage is 60 kV in a CW mode.

The third- or fifth-harmonic of the fundamental frequency is generally used for the flat-top acceleration. The harmonic voltage can be obtained by installing an additional resonator to the existing main resonator of the AVF cyclotron [4] in which there is no space for installing an independent resonator like a ring cyclotron. We have adopted the fifth harmonics to save output power of an amplifier. The fifth-harmonic frequency of

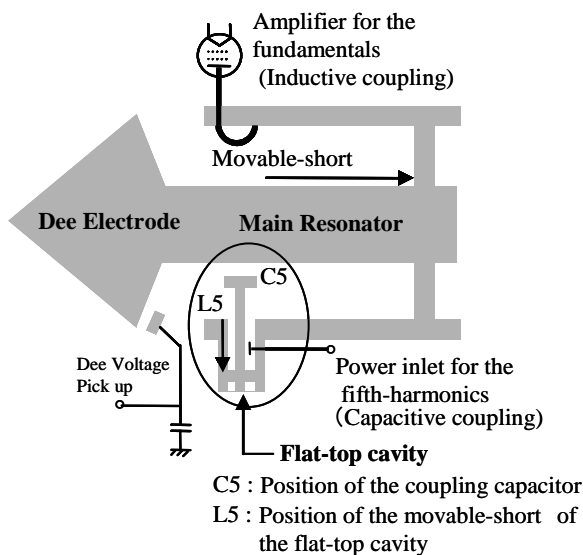


Figure 1: Outline of the cyclotron resonator (including the flat-top cavity). A span angle of the dee electrode is  $86^\circ$ .

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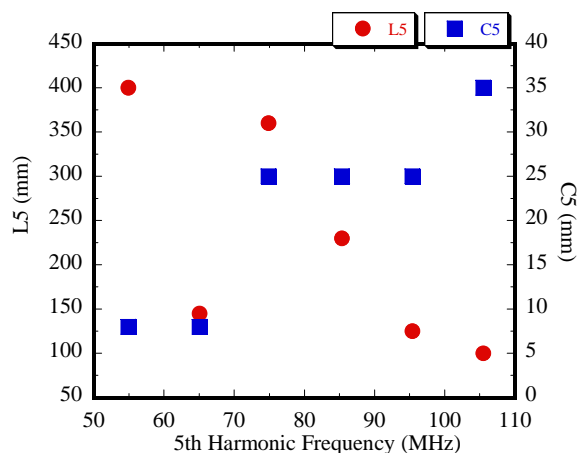


Figure 2: Parameters of the flat-top cavity calculated with the MAFIA code. C5 is the gap of the coupling capacitor, and L5 is the position of the movable-short indicated in Fig. 1.

55 to 110 MHz is required to cover the whole rf region to apply the flat-top acceleration to a wide range of energy.

## DESIGN OF THE FLAT-TOP CAVITY

To determine parameters of the flat-top cavity, a cold model test was carried out [5] using the model of a flat-top cavity preliminarily designed for the RIKEN AVF cyclotron [6]. The flat-top cavity was capacitively coupled to the main resonator as shown in Figure 1. The fifth-harmonic frequency was shifted by changing the gap of the coupling capacitor or the position of the movable-short. The induced flat-top waveforms were observed successfully at the dee voltage pick-up of the main resonator when the fundamental frequency was tuned to 11, 13, 15 and 20 MHz.

In order to improve the design of the flat-top cavity, optimum parameters for downsizing the flat-top cavity itself and for decreasing 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 flat-top cavity.

The power dissipation at the fundamental frequency of 15 MHz was decreased clearly using the flat-top cavity consisting of a 70 mm diameter inner- and a 300 mm diameter outer-tubes. The power consumption was estimated to be 80 % as compared with the configuration used in the cold model test. Based on that design, the higher mode resonant frequency was calculated to find the frequency 5 times as high as the fundamental one. Figure 2 shows a correlation between the gap of C5 (coupling capacitor) and the position of L5 (movable-short) to obtain the fifth-harmonic frequencies. The maximum length of L5 was limited to 400 mm for the compactness, and the minimum length was fixed at 100 mm to keep enough space for mounting a power feeder and a frequency compensation tuner. A specification of the flat-top acceleration system, consisting of a set of the

Table 1: Specification of the flat-top acceleration system.

<b>Resonant frequency</b>	<b>55 - 110 MHz</b>
<b>Movable gap range of the coupling capacitor (C5)</b>	<b>6 - 50 mm</b>
<b>Size of the electrode of the coupling capacitor</b>	<b>130 mm x 130 mm</b>
<b>Movable range of the shorting plate (L5)</b>	<b>250 mm</b>
<b>Inner tube diameter</b>	<b>70 mm</b>
<b>Inside diameter of outer tube</b>	<b>300 mm</b>
<b>Relative frequency change <math>\Delta f/f</math></b>	<b>Maximum of 2 %</b>
<b>Power feeder</b>	<b>Capacitive coupling</b>
<b>Maximum output power of amplifier</b>	<b>3 kW (50 ohm)</b>
<b>Voltage stability</b>	<b><math>\pm 5 \times 10^{-4}</math></b>
<b>Phase stability</b>	<b><math>\pm 0.1</math> deg.</b>

flat-top cavity, a set of power amplifier, low-level devices and an overall control system, is shown in Table 1.

## MANUFACTURING AND PERFORMANCE TEST

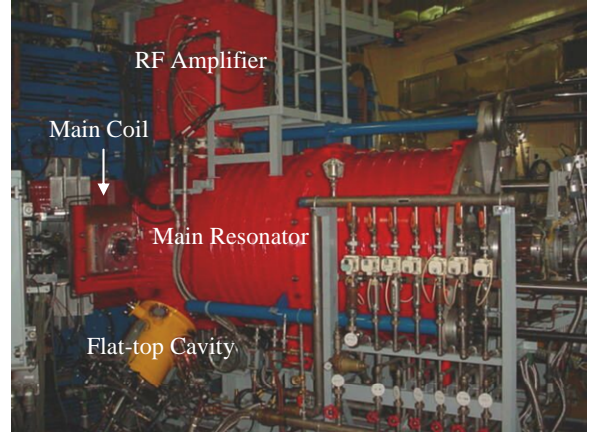


Figure 3: Photograph of the flat-top cavity mounted on the main resonator.

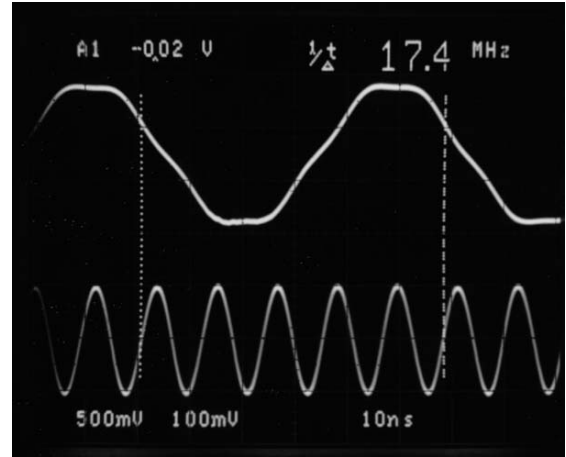


Figure 4: Waveforms observed at the dee voltage pick-up when the fundamental frequency and voltage are 17.4 MHz and 25 kV, respectively. The upper waveform is the combined waveform of the fundamental and the fifth-harmonic frequencies, and the lower is the fifth-harmonic waveform separated with a high-pass filter. Output power of the amplifier was 1.2 kW.

The flat-top acceleration system has been installed in March, 2002. Figure 3 shows the flat-top cavity mounted on the main resonator. The flat-top cavity was attached to the port which was formerly used for a cryogenic pump. The cryogenic pump was removed. Though the port has low slanting axis, there is a little space to move the shorting-plate which strokes 250 mm at the maximum. The required range of the fifth-harmonic frequency, 55 to 110 MHz, is fully covered by the flat-top cavity in a cold test. A power test at the fundamental frequency of 17.4

MHz has been carried out, and the flat-top waveform was successfully observed at the dee voltage pick-up as shown in Fig. 4. The power test indicated that power dissipation in the flat-top cavity was dependent on the position of the coupling capacitor although the resonant frequencies were the same. When the coupling capacitor was placed closer to the main resonator, the power dissipation decreased. So, we have to find out the optimum condition for each frequency before feeding high power of rf to the cavity.

## PREREMINARY BEAM DEVELOPMENT

After conditioning of the flat-top cavity we have started to accelerate 260 MeV  $^{20}\text{Ne}^{7+}$  ion beam, which is used for biological experiments, at a fundamental frequency of 17.475 MHz by superimposing the fifth-harmonic voltage on the fundamental one. In this preliminary beam development, operation parameters of the cyclotron, such as the ratio of fundamental and fifth-harmonic voltages, magnetic field, beam pulse width, were optimized to achieve single-turn extraction that is an indispensable condition to obtain the energy spread of  $\Delta E/E = 0.02\%$ .

In an ideal condition, the amplitude of the fifth-harmonic voltage should be 1/25 of the fundamental one. However, the resonator actually has position dependence of the voltage distribution, which varies with the resonant frequency. The voltage distributions of the fifth-harmonic frequency along the acceleration gap of the dee electrode are shown in Fig. 5. We cannot ignore the variation of the distribution particularly in the higher frequency region. 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.

An ion beam extracted from an ion source was pulsed by a beam chopper using a rectangular voltage wave form. The pulse width of the beam was modulated to around

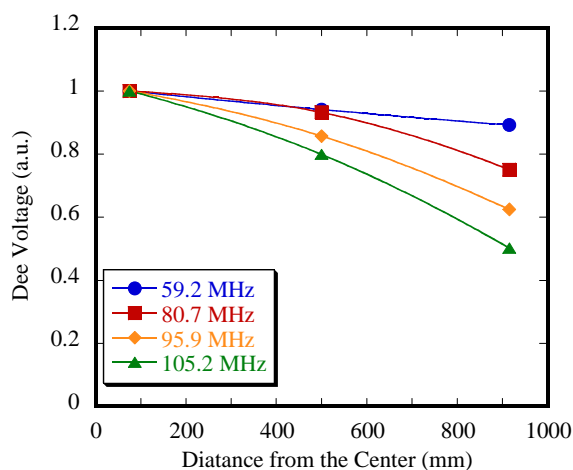


Figure 5: Voltage distributions of the fifth-harmonic frequency along the acceleration gap of the dee electrode measured by vector volt meters.

100 ns. After the beam was injected into the cyclotron, two or three beam bunches with a period of 57.2 ns (17.475 MHz) were produced by periodic acceleration. The single-turn extraction was proved by the fact that the number of the beam bunches extracted from the cyclotron corresponded to the initial bunch number. A beam bunch distribution for the acceleration using the fifth-harmonic voltage of 1.6 kV was obtained by measuring beam phases with a plastic scintillator placed on a beam transport line. Only two significant peaks were observed in the distribution, which indicated that the number of the beam bunches was invariable after the extraction. In ordinary acceleration using a sinusoidal voltage waveform, the number of beam bunches enormously increases due to multiturn extraction. Although the energy spread of the extracted beam was not measured precisely, it was obvious that the energy spread of the flat-top accelerated beam was smaller than the ordinary acceleration.

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