PARAMETRIC STUDY ON THE IMPROVEMENT OF THE BEAM ENERGY GAIN OF THE FANTRON-I CAVITY

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Abstract

The industrial electron accelerator named FANTRON-I whose merits are its low fabrication cost, high reliability and easy maintainability is under development at Physico - technology laboratory, KAPRA (Korea Accelerator and Plasma Research Association). To make the simplified machine, it is required to optimise the beam energy gain and beam transport efficiency. The beam energy gain is dependent on the several factors, such as geometry (loop area, coupler diameter, shape, direction of the coupler area, etc.) of RF power input antenna. In addition, RF cavity also should be tuned to match the impedance between cavity and RF generator. As a result, various parameters which have effects on the machine performance should be surveyed for the optimisation through computations and experiments. In this paper, parametric study results on the optimisation of the beam energy gain of FANTRON-I cavity are presented.

1 INTRODUCTION

An X-ray source using electron accelerator to sterilize the agricultural, forest and aquatic products has been developed by KAPRA [1][2]. The electron accelerator named FANTRON-I is one type of the so-called recirculating accelerators. It consists of coaxial cavities that accelerate the electron beam around the electric field maximum plane and bending magnets that redirect the electron beam into the cavity.

For low fabrication cost and easy maintainability, the nonagon shape was chosen as a cavity geometry which had equivalent electrical properties to those of circular shape coaxial cavity [3]. The cold test of the real size nonagon shape cavity confirmed the TM_{010} like mode which could be used to accelerate the beam in the cavity. The optimum coupling beta could be obtained by rotating the loop antenna. The magnetic flux density of the bending magnet and the length of the straight section were determined by using PARMELA code. The error analysis of the beam transport element showed that the system was sensitive to the amplitude and phase errors of accelerating field in the cavity.

To improve the beam energy gain and reduce the sensitivity of the beam transport efficiency to the accelerating field errors, a modified nonagon cavity into which metallic pipes intruded was considered. Additional advantage of the modified nonagon cavity was its operating frequency (which can use various commercially available RF amplifier) with reasonable cavity size.

To improve the beam transport efficiency in real system, various methods including adjusting the magnetic flux density of the bending magnet using signals from BPM have been considered.

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2 FANTRON-I CAVITY

2.1 Selection Guideline of the Cavity

As is well known, the number of pair of solutions of the inner and outer conductor radius of the coaxial cavity which satisfies a given resonant frequency is infinite. To select the cavity parameters, guidelines which considered i) cavity size (inner conductor diameter ≥ 0.2 m, outer conductor diameter ≤ 2.5 m), ii) required RF power (≤ 250 kW), iii) required magnetomotive force of the bending magnet (≤ 10,000 AT) were setup. The cavities which satisfied the size limitations should also satisfy the below equations,

$$\frac{10^7}{\sqrt{R_a P_{rf}}} \le \frac{r_{max}}{r_g}\pi$$

where R_a is a shunt impedance of the cavity, r_{max} is the cavity radius where the electric field is maximum, both of which were determined from the cavity geometry limited by condition i), P_{rf} is the required RF power which is limited by condition ii) and r_g is the gyroradius of the 10 MeV electron limited by condition iii).

The selected cavity size was such that its inner conductor diameter was 0.6 m, outer conductor diameter 2.4 m and resonant frequency 160 MHz.

2.2 Cold Test of the Cavity

For low fabrication cost and easy maintainability, the nonagon shape was chosen as a cavity geometry. The calculation results of the cavity parameters such as resonant frequency, quality factor and shunt impedance using SUPERFISH and OPERA3D code showed that there were no differences of electrical properties between circular and nonagon shape coaxial cavities. To validate the above calculation results, the nonagon shape coaxial cavity was fabricated and tested [4]. The measured resonant frequency was within +500 kHz of the design value without tuning process, which could be adjusted by external tuners, and the measured shunt impedance was 78 % of that of the calculated one. The results of the cold test confirmed the TM_{010} like mode in the nonagon shape coaxial cavity which could be used to accelerate the beam in the cavity.

To match the cavity to the RF system, the coupling beta should be adjusted by controlling the coupling loop area. The differences between calculated and measured coupling betas for various loop shapes such as half circle, triangle and rectangle were within 10 %, and the design value could be obtained by rotating the loop.

3 BEAM TRANSPORT SYSTEM

The beam transport system consisted of two nonagon shape cavities, straight sections like drift tubes and bending sections. The beam pass length of the cavity outside were 0.5λ for intermediate cavity straight sections and 1.5βλ for bending sections. The magnetic flux density of the individual bending magnet and length of the straight section were calculated which gave the beam transport efficiency of the value more than 95 %. The pass number of the electron beam through the cavity to reach 10 MeV energy was 17. The electron beams were focused by the geometric and edge focusing effects of the bending magnet which consisted of supplementary and main bending magnet.

The error analysis of the beam transport elements such as beam line length, bending magnet pole face rotation angles, amplitude and phase of the accelerating field in the cavity were carried out [5]. The results showed that the beam transport efficiency was very sensitive to the amplitude and phase errors of the accelerating field. Detailed analysis showed that energy spread due to accelerating field errors had a larger value than those due to the other two cases, and almost the particle losses occurred in the low energy bending region. The above two facts showed that the designed beam transport system was more sensitive to the longitudinal beam dynamics rather than the transverse one, and this was partly due to the relatively long accelerating section and several passes through the cavity were required to reach the relativistic velocity.

4 IMPROVEMENT OF THE BEAM ENERGY GAIN OF THE CAVITY

Several methods to improve the performance of the cavity were proposed. One of those was to install hollow metallic pipes along the parts of the beam pass zone of the cavity to increase the shunt impedance. The calculation results of the cavity parameters using OPERA3D code are shown in Table 1. In the Table 1, Case I is a nonagon cavity without any perturbations and Case II is a nonagon cavity with metal pipe (inner diameter : 30 mm, outer diameter : 40 mm) insertion with 100 mm accelerating gap.

Despite the uncorrected shunt impedance of the Case II which does not consider the transit time effect is lower than that of Case I, the corrected shunt impedance which takes into account the transit time effect is higher than that of the Case I by about 150 %. From the parametric study, the required pass number of the electron beam through the cavity to reach 10 MeV reduced from 17 in Case I to 7 in Case II. The reduction of the pass number means that the number of beam transport elements can be reduced, and the system much more simplified. Moreover, possibly the sensitivity of the beam transport efficiency to the amplitude and phase errors of the accelerating field of the cavity can be mitigated, because of the shorter accelerating gap which results in smaller energy spread of the electron beam. Another advantage of Case II modified cavity is its lower operating frequency with reasonable cavity size, because that frequency is popularly used in broadcasting, which means there are more chances for selecting commercially available RF amplifiers. In spite of its several advantages, Case II cavity should be considered carefully in view of the cavity cooling especially beam pipe section and beam instability due to the higher order mode which seems to be more complex compared with Case I cavity.

Table 1. Calculation results of the modified cavity

Cavity Type	Resonant frequency	Quality Factor	Shunt impedance
Case I	159.4 MHz	9820.4	468431 Ω
Case II	108.4 MHz	8095.4	727296 Ω

In addition to the improvement of the beam energy gain of the cavity, several methods to improve the beam transport efficiency in real system were proposed. One of them was to install a BPM near the bending magnet. By adjusting the magnetic flux density of the bending magnet using signals from BPM, it is expected to improve the beam transport efficiency in real system.

5 CONCULSIONS AND FUTURE WORKS

The selection of the coaxial cavity parameters was reviewed for parametric study. The advantages of the nonagon cavity were its low fabrication cost and easy maintainability. On the basis of the selected cavity parameters, real size cavity was designed, fabricated and tested. The cold test result confirmed the TM_{010} like mode in the nonagon shape coaxial cavity which could be used to accelerate the beam in the cavity.

Beam transport elements were designed using nonagon shape coaxial cavity which had more than 95 % beam transport efficiency. An error analysis of the beam transport system has been carried out. The results showed that the beam transport efficiency was very sensitive to the amplitude and phase errors of the accelerating field. This was because the accelerating sections were relatively long and several passes through the cavity were necessary to reach the relativistic velocity.

Several methods to improve the cavity performances were proposed. One of them was related with the acceleration efficiency of the cavity by installing metallic pipes along the parts of the beam pass zone of the cavity inside. The results of cavity analysis using OPERA-3D code showed that the operating frequency of the cavity with metal pipe was 108.4 MHz and corrected shunt impedance was 1.5 times that of the unperturbed nonagon cavity. This fact tells that the beam pass number through the cavity to reach 10 MeV can be reduced from 17 to 7 and the RF amplifier can be purchased easily because the frequency is within commonly used range. In addition to the above merits, another merits may be that the effects of the field amplitude and phase errors on the beam transport efficiency may be reduced because of the shorter accelerating gap and smaller pass number to reach the relativistic velocity. But to accept that cavity modifications, additional analysis should be done such as cavity cooling, higher order mode effects.

6 REFERENCES

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