324-MHz RF DEFLECTOR DESIGN AND TEST

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Abstract

In the design of JHF linac, the beam needs to be chopped for the injection into the following rapid-cycling ring. The chopper has been decided to locate in the 3-MeV medium-energy transport line between the RFQ and the DTL. A 324-MHz RF deflector (RFD) is adopted as a fast beam-chopper for its various merits, such as compactness and high deflecting field, which benefit for an efficient deflection of the beam within a short beam line. In the application of an RF deflector for an intense-beam linac, the beam loss in the transient time is a major concerned issue. The shunt impedance should be as large as possible to make the cavity to be powered by a commercially available solid RF source. An RFD cavity is designed by the HFSS code to have a very low loaded-Q value of about 10 by means of two large coupling loops, and meanwhile to keep the higher order modes sufficiently far away from the deflecting mode. An aluminum cold- model cavity was made for a test. In this paper, the design, simulation and the test results are described in detail.

1 INTRODUCTION

The JHF 200-MeV linac provides a H^- beam of 30 mA–60 mA peak current for injection into the following 3-GeV rapid-cycling ring[1]. A beam chopper must be used in the linac in order to produce a pulsed beam with a pulse length of 278 nsec and a pulse separation of 222 nsec. This chopper is located in the 3-MeV medium-energy beam-transport line (MEBT) between the 324-MHz RFQ and DTL[2]. As a high-current linac, beam-quality preservation and beam-loss control are of superior importance in the design. The MEBT should be short so as to avoid emittance growth, since the beam energy is low. An RF deflector (RFD)[3] was chosen as the chopper cavity owing to its compactness and high deflecting field. A fast rise/fall time is a fundamental requirement for the RFD to minimize the beam losses due to partial deflection to the beam during the transient time. This can be achieved in an RF cavity with a very low loaded Q value. On the other hand, a high transverse shunt impedance is pursued in the design in order to keep the RF power demand from a solid RF source within a reasonable range.

In this paper, a design study of the RF deflector cavity is presented. We first give the cavity simulations by MAFIA[4] and HFSS[5] codes in order to show the detailed design investigation in the geometry needed to meet the requirements mentioned above. Then the measurements of a cold model cavity are presented and shown to have a good agreement with the code simulation and a satisfactory result for our purpose.

2 CAVITY DESIGN STUDY

The RF deflector cavity is operated in a TE_{11}-like mode with two electrodes, as shown in Fig.1. A transverse electric field oscillating at 324 MHz between the two electrodes deflects the beam bunches away from the beam axis to a beam dump downstream during the beam-cutoff time of 222 nsec.

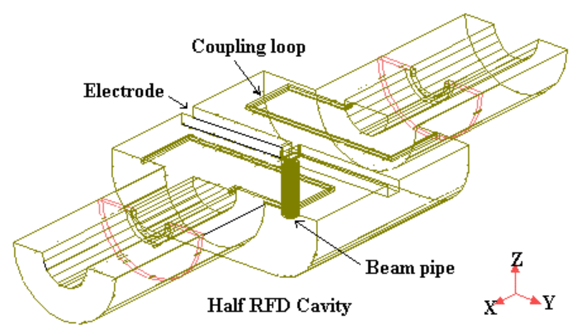

Fig.1 RF deflector cavity with large coupling loops.

One of the design target of the cavity is a high value of Z/Q_0, while keeping in mind the beam dynamics limitation. Here, Z is the transverse shunt impedance and Q_0 the unloaded Q value. In order to achieve a very short rise/fall time, the cavity will be heavily loaded by two coupling ports. In this case, the power demand from a solid RF source for operating the cavity becomes very high. To minimize the power demand P, a large value of Z/Q_0 should be pursued according to the approximate relation

$$P \cong \frac{V^2}{\omega_0 \tau (Z/Q_0)} \quad , \qquad (1)$$

where V is the deflecting voltage, ω_0 the oscillation frequency and τ the rise time.

2.1 Geometry of the electrode region

The ratio Z/Q_0 is determined by the equivalent capacitance C according to the relation

$$Z/Q_0 = \frac{1}{\omega_0 C} \quad . \qquad (2)$$

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The C for the mode is mainly dependent on the geometry of the electrode gap region. Therefore, the parameter choice around this region must be carefully made.

The fringe fields of the electrode along the beam axis should be taken into account in the beam dynamics to calculate the effective deflection. To avoid an inverse deflecting effect of the high fringe field, the length of the electrode along the beam axis should not be equal to, but less than $\beta\lambda/2$, with β being the relative speed of a particle (v/c) and λ the free-space RF wavelength. To determine the length, MAFIA runs were conducted and the electromagnetic field distribution from MAFIA was used in a modified TRACE3-D[6] for beam-deflection tracking. The result showed that the length of the electrode should be slightly less than $\beta\lambda/2$. In this way, Z/Q_0 is larger (due to smaller C) and the high fringe field beside the electrodes can work in phase with the field in the central part of the electrodes, while keeping the effective deflecting length long. It was concluded that the electrode length along the beam axis should be 29 mm. Furthermore, the fringe field between the electrodes and the cavity wall needs to be sheltered so as to minimize its inverse effect. A beam-deflection simulation of a cavity without beam pipes showed that the net deflection is less than half that in a cavity with beam pipes. Therefore, two beam pipes are added beside the electrodes with 5.5 mm gaps between the pipes and the electrodes.

Of course, the two electrodes should be as close as possible to generate high deflecting field between them. This gap is, however, limited by the full beam size. The beam envelope from TRACE3-D suggests that the gap should be around 10 mm in order to guarantee no particle losses on the electrodes.

Also, the size of the electrode in non-deflection direction should be small in order to obtain a large Z/Q_0 value. Again, the beam envelope sets the minimum limit. The necessary size is 20 mm according to TRACE3-D simulation on beam size and the MAFIA result concerning the field distribution.

2.2 Cavity shape optimization

After the electrode size has been decided, the other dimensions of the cavity is then further optimized for the value of Z/Q_0 to be as high as possible. Since two RFD cavities will be cascaded in the beam line, the cavity should not be too long along the beam axis, due to a lack of focusing to the beam in this space, which may result in a beam emittance increase. Taking all of these factors into account, MAFIA runs suggested a cavity of 324 MHz with Z/Q_0= 437 Ω. It can be estimated from Eq.(1) that the demanded power from an RF source is reasonably about 27 kW (more accurately, HFSS gives the power of 22 kW in the next subsection) to generate a necessary deflecting field of 1.6 MV/m if a rise time of 10 nsec is assumed. Such a fast rise time indicates that the loaded Q of the cavity should be decreased down to about 10.

2.3 Cavity design with a very low loaded Q

The use of two large input/output loops is an easy option to realize a low loaded Q. A loop-coupled cavity was redesigned using the HFSS code on the basis of the previous design by MAFIA, provided that the electrode region maintains the same geometry. A modification to the cavity shape is necessary because of the introduction of large loops into the cavity, which shift the cavity resonant frequency due to the additional inductive reactance.

Two large loops with the same size are inserted into the cavity. The loops are connected to a coaxial transmission line of 50 Ω. To reach such a low loaded Q value, the size of the loop is 75×218 mm in the surface with the maximum flux. An HFSS simulation gives the S parameters, S_{21} and S_{11}, versus the frequency, as shown in Fig.2. From the figure, it can be found that the resulting Q_L is about 10, assuming it is given by the whole frequency width, Δf (31 MHz), at 70% maximum value.

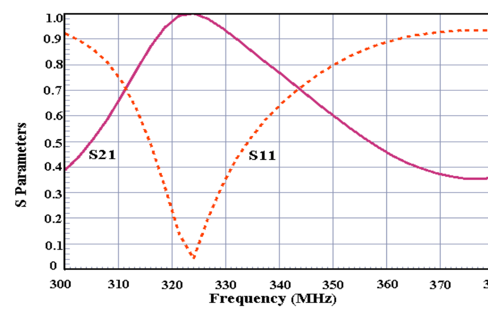

Fig.2 S-parameters from the HFSS for the cavity with Q_L=10.

The two loops of the same size are placed asymmetrically with respect to the middle plane. This induces a spectrum asymmetric with respect to the central frequency: the high-frequency side is wider than the other side, as depicted in Fig.2. It thus helps to reach a larger Δf. On the other hand, it also makes the fundamental mode to be close to and mix with the higher mode. To avoid such a problem, the loop should not be too deeply inserted into the cavity. It must keep a sufficient distance between the loop and the electrode in order to insure that the electric field between them remains extremely low. We thus increase the other dimension of the loop to a very large value (i.e. 218 mm) so as to guarantee a sufficient coupling as well as a wide mode separation.

HFSS simulations also showed the dependence of the large coupling on the diameter of the coaxial transmission line. A large coaxial line of WX-152D was adopted for the input/output of the cavity, resulting in a loaded Q of 10. However, the loaded Q became 17 if a coaxial line of WX-77D was used.

The variation of the deflecting field (Ey) in three directions calculated with HFSS is plotted in Fig.3. The original point corresponds to the center of the cavity. The beam radii in x and y directions are both less than 5 mm according to the TRACE3-D result. It can be observed from the figure that the field has no obvious variation within the beam-size region, and hence that the beam can be deflected by a field having the same magnitude. HFSS gives Ey=1.6 MV/m in the deflecting gap when the input power is 22 kW.

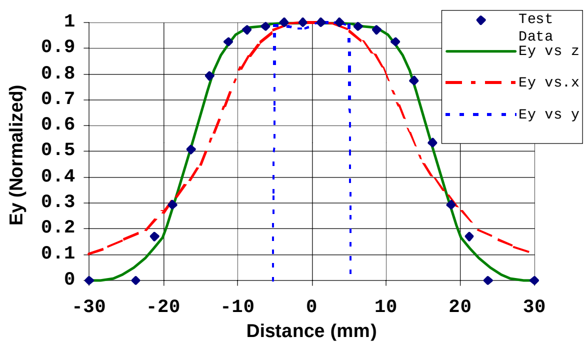

Fig. 3 Ey field distribution in three directions (test data is in the z-direction).

3 COLD MODEL TEST

An aluminum cold-model cavity was manufactured according to the design by HFSS. A series of measurements were conducted to check the applicability of the design.

A direct measurement of the rise time was performed by means of a digitizing oscilloscope with the result shown in Fig.4. It indicates that the rise time (Delta T) is 18.3 nsec, which includes about a 9 nsec contribution from the pulsed RF signal source. The effect of the transient time on the beam dynamics is discussed in Ref. [2], in which an improved method is proposed for the cavity, and the unstable particles are estimated.

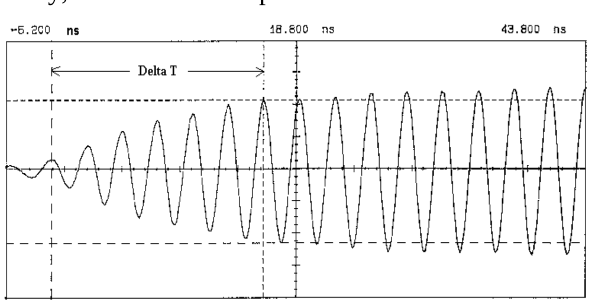

Fig.4 Measured rise time (Delta T) of the RFD cavity.

Network Analyzer depicted the scattering parameter S_{21} versus frequency in Fig.5. It gave a loaded Q of 9.7 and a resonance frequency of 324 MHz. The results are well concordant with the HFSS simulation. Some small coupling loops were prepared for a test of the dependence of the loaded Q on the size of the loops. For example, when the loops size became 65×218 mm, the loaded Q increased to 23. With two very small coupling loops, the loaded Q equaled 1463 and S_{21} was –2.18 dB. The unloaded Q was deduced to be 6580.

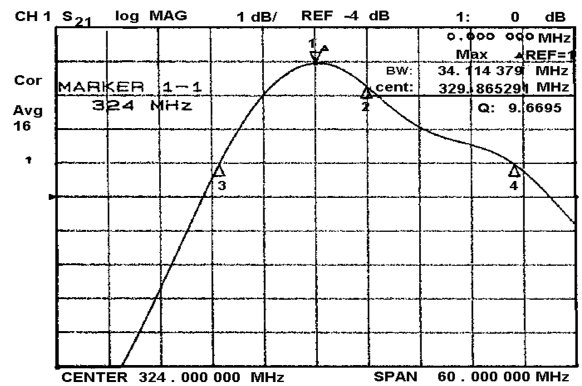

Fig.5 Spectrum of S_{21} showing the Q_L=9.7.

The field pattern in the deflecting gap was measured with a pulling bead of 5 mm in diameter. In Fig.3 the measured deflecting field (Ey) along the beam axis (z direction) is dotted. It shows a good agreement with the calculation result from HFSS.

Since the cavity is heavily loaded with a very wide spectrum, it is possible to operate it without a tuning device. To verify the temperature dependence of the resonance frequency, the cavity was heated. It was found that the cavity has a frequency shift of 60 KHz when the temperature rises up to 10^{o}C.

CONCLUSIONS

A 324-MHz RF deflection cavity used for JHF linac was designed and a cold model was tested with satisfactory results. The measurement gives a loaded Q of about 10, which is necessary for a fast rise/fall time. The test results are in good agreement with the design calculations with MAFIA and HFSS. To meet the deflection requirement, the cavity with a loaded Q of 10 requires an input power of 22 kW according to HFSS.

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REFERENCES

[1] JHF Project Office, JHF Accelerator Design Study Report, KEK Report 97-16, March,1998.
[2] T. Kato, S. Fu, “MEBT Design for the JHF 200-MeV Proton Linac,” in these Proceedings.
[3] T. Kato, “New Design of an RF Beam Chopper,” Proc. of 7th Symp. On Acc. Sci.& Tech. (1989) 288.
[4] T.Weiland, Part. Accl. , Vol.17 (1995)227.
[5] HFSS Ver. A.04.01, Ansoft Corp, HP Co..
[6] K.R.Crandall, D.P.Rusthoi, TRACE3-D Documentation, LA-UR-97-886, May,1997.