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Study on the Function of Dipole Stabilizer Rods in an RFQ Accelerator *

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Abstract Dipole field in an RFQ accelerator exerts beam a bending force and thus results in beam losses on the machine. Measures must be taken to diminish the influence of the dipole field. Dipole stabilizer rod was proposed to shift the dipole modes far from the working quadrupole mode. In our recent measurements on a cold model RFQ, we observed some new phenomena associated with the function of dipole stabilizer rods. In this paper we report our results and give an analysis on these results. A new idea of imbalance insertion of the dipole stabilizer rods is proposed for both shifting dipole mode and reducing the dipole components in an asymmetrical RFQ.

Key words RFQ accelerator, dipole mode, dipole stabilizer rod

1 Introduction

Radio Frequency Quadrupole (RFQ) accelerator is widely used to accelerate high-current and low-energy ion beam, owing to its special capability of simultaneously providing an ion beam with transverse focusing, longitudinal bunching, as well as acceleration. All these advantages are essential to keep a good quality for a beam from an ion source with an intensive space-charge effect. In an RFQ cavity, the cutoff quadrupole mode is used to achieve these functions. However, a dipole mode in a symmetrical RFQ cavity can also be excited if the dipole frequency is very close to that of the working quadrupole mode, as the usual case in a four vane RFQ with a small coupling among the quadrants. And, if the cavity geometry is not symmetrical among the four quadrants, there are some dipole field components mixed in the quadrupole field. Symmetry requirement, in fact, is a great technique challenge to the fabrication and assembly of the vanes. Therefore, how to diminish the dipole mode effect is always a basic task in RFQ study and manufacture. Several tricks were proposed to fight against the dipole effect. For example, the Vane Coupling Ring (VCR) invented in the 80's last century generates an additional coupling among quadrants for a larger mode separation[1]. It effectively shifts the dipole mode far away from the working mode and is applied in some real RFQs. But unfortunately, the rings inside an RFQ cavity are difficult to be cooled and therefore VCR is not suitable for a high power machine. PISL stabilizer invented at KEK, Japan can overcome this drawback[2], and it is recently utilized in the J-PARC RFQ, Japan and the SNS RFQ, USA. It shifts the dipole mode obviously and also the working mode slightly. So a cold model cavity is necessary to clarify the shift amount of the working mode for the cavity design on the right resonant frequency. Dipole stabilizer rod proposed in the end of the 80's last century shifts the dipole mode while keeping the working mode unchanged[3]. Moreover it is easy to be cooled and thus it is a good candidate for a high power machine. The LEDA RFQ at LANL, the highest power RFQ in the world, used this device and operated well[4]. Some other high-power RFQs under construction will also adopt this

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option. In this method, four rods are inserted into the corresponding quadrants with an equal insertion length.

A high power RFQ is under construction at IHEP, China for the purpose of basic study on the Accelerator-Driven Subcritical System (ADS)[5]. We intend to take the advantage of dipole stabilizer rod in this RFQ. Before the manufacture of the RFQ, a section of cold model was made jointly with IHIP, Peking University[6]. With this model we conducted some measurement studies on the effect of the dipole stabilizer rod. In this paper, we will briefly introduce our RFQ design and measurement method. Then the experimental results with some new phenomena are presented and analyzed with code simulations. Finally, we suggest an imbalance insertion of dipole stabilizer rod to suppress the dipole component in the asymmetrical RFQ cavity, with an experimental demonstration of the new idea.

2 A brief description of the IHEP-RFQ

The IHEP-RFQ has a length of about 5 times the wavelength and it is separated into two segments and then resonantly coupled together by a coupling cell. Each segment consists of two technological modules of about 1.2m long. The dipole stabilizer rods on the both end plates and the coupling plate are applied to move the dipole mode far away from the operating mode[7]. As a high-duty machine, water cooling on both the vane and the wall is necessary to keep the thermal stability. There are 20 cooling channels on the cavity body in each section. Four vane-wall pieces are brazed together to form a cavity for both RF and vacuum seals. On each module there are 16 tuners distributed on the 4 quadrants. There are 8 vacuum ports on both the first and fourth modules, respectively. Eight RF feed ports are located on the second and third sections and the RF-power is coupled into 4 quadrants evenly to keep the field balance among them. Table 1 lists the major parameters of the RFQ.

A 1.2m long cold model was fabricated before the manufacture of the accelerator cavity. There are vane undercuts of about 46mm long at each end of the module. These undercuts are tuned for the working quadruple mode TE_{210} in order to get a flat field distribution for this mode. Four dipole stabilizer rods with variable insertion length are mounted on one end plate of the cavity, as shown in Fig. 1.

Table 1. IHEP-RFQ major parameters.

input energy	75keV
output energy	3.5MeV
peak current	50mA
structure type	4 vane
duty factor	6%
RF frequency	352.2MHz
maximum E_s	33MV/m
beam power	210kW
structure power	420kW
total power	630kW
total length	4.75 m
segments	2
modules	4

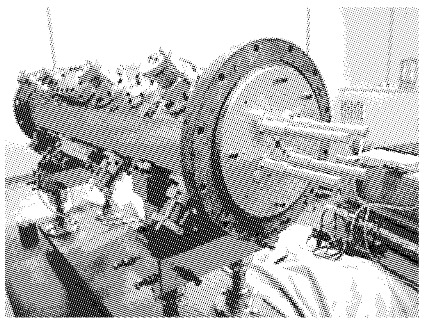

Fig.1. The cold model RFQ with four dipole stabilizer rods on one end-plate.

RF cold measurements were conducted on this module with a vector network analyzer (VNA). The field distribution along the cavity is measured by bead pulling method. The scattering parameter S_{21} was swiped when quadrants 1 and 2 were coupled with the VNA. In the spectrum shown in Fig.2,

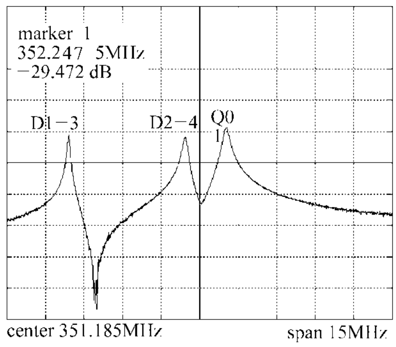

Fig.2. The S_{21} spectrum of the model RFQ with the working quadrupole(Q0) and the nearby dipole modes (D1—3 and D2—4).

we can see the quadrupole mode $f_{Q0} = 352.247$MHz, and two dipole modes f_{D1-3} and f_{D2-4}, resulting from the asymmetry of the cavity. To distinguish these two dipole modes, quadrants 1 and 3 were excited, so only 1—3 dipole mode presented S_{21} peak at f_{D1-3} without the peak of 2—4 dipole mode at all because quadrants 2 and 4 have no dipole field.

3 Effects of dipole stabilizer rod on frequency shift

A series of measurements were conducted to study the effect of dipole stabilizer rod on the frequency shift of the quadrupole and dipole modes. From Fig.2 we observed that the 2—4 dipole mode is close to the working quadrupole mode and thus we inserted the four rods into the quadrants. As a result, the dipole rods have almost no perturbation to the frequency of the operating quadrupole mode ($\delta f_{Q0} = -0.216$MHz when the rod insertion length = 15cm), and the tuning effect on the dipole mode is obvious when the rods length is longer than 10cm. Fig.3 plots the shift of the two dipole modes and the quadrupole mode. It is noticed that the dipole modes keep almost no shift when the rods insertion length is less than 5cm. This indicates that the dipole mode shift is not singly resulted from the rod perturbation to the undercut region.

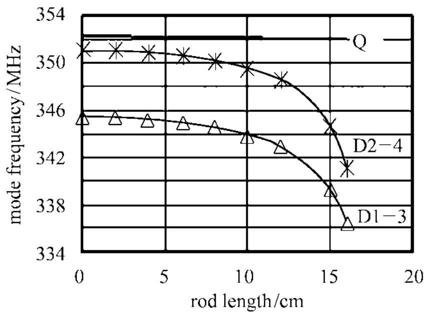

Fig.3. The measured dipole stabilizer rod effect on the operating quadrupole mode and the two dipole modes.

Now that the mode shifts quickly only when the rods are inserted deeply inside the quadrants, should we think that the dipole mode shift comes from the long rod perturbation to the inside part of the dipole field? To clarify it, a simulation with 2-D code SUPERFISH[8] was conducted, as shown in Fig.4. It is found that the rod introduces a perturbation to the quadrupole mode $\delta f_{Q0} =$ 0.36MHz, and to the dipole mode $\delta f_{D} = 0.293$MHz. They are both small and almost the same. They are nearly the same because their field distributions, in fact, are almost the same, as shown in Fig.5. From these results we know that the rod effect on the dipole mode shift does not singly come from the rod perturbation of the inside dipole field. In fact, the 2D simulation shows the rod has almost no influence over the dipole mode. Then, what is responsible for the dipole mode shift? Before we reply this question, let us look at another experimental result.

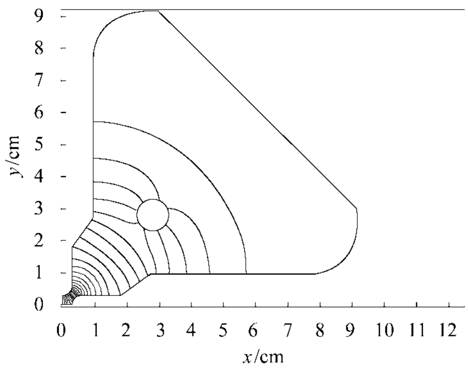

Fig.4. Dipole E field with stabilizer rod in one quadrant.

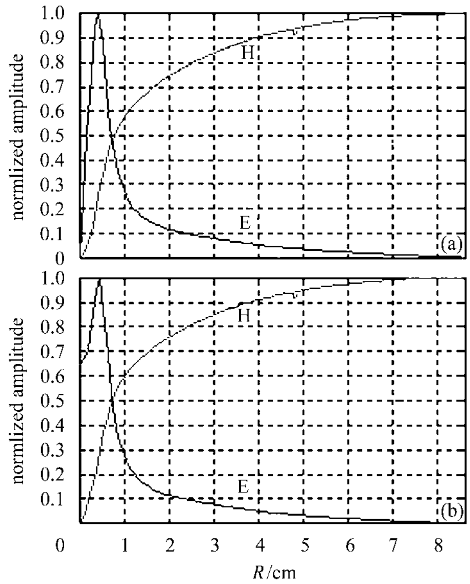

Fig.5. E & H field distribution along the middle line between two vanes (45° line in Fig.4) for quadrupole (a) and dipole (b) modes without rod insertion.

When we inserted rods into 1 and 3 quadrants only, the 1—3 dipole mode has no response to the rod insertion. Instead, 2—4 dipole mode shifts, as shown in Fig. 6. This result agrees with the above 2D simulation. The rod in a quadrant will not give an obvious perturbation to this quadrant, but to their neighborhood quadrants.

To illustrate these phenomena in the measurements and

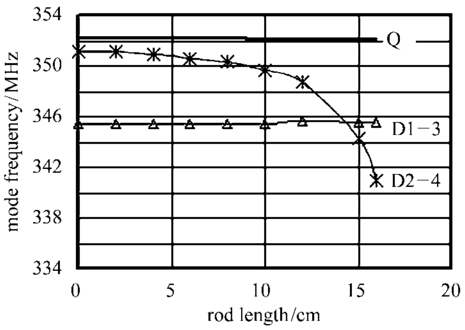

Fig.6. Two rods are inserted into 1 and 3 quadrants, resulting in the frequency of dipole 2—4 shifts, but no effect on 1—3 dipole.

2D simulations, we need a 3D view to understand the rod function. For the 1—3 dipole mode, let's suppose the H field comes out from quadrant 1, and then go through the undercut regions of 2 and 4 quadrants separately, and finally goes into quadrant 3, as plotted in Fig. 7. When the field goes across the quadrant 2 and 4, a circle field is generated on the rods in clockwise direction in quadrant 4 and anti-clockwise direction in quadrant 2. This means that a current along the rod exists, and just for this reason the rod needs cooling in high power operation. At this moment, the two vanes of quadrant 4 are positively charged, while the other two vanes are negatively charged. For the rod in quadrant 4, the inside end of the rod is negatively charged according to the current direction. So there is a capacitance between the rod and the two vanes. The case is the same for the rod in quadrant 2. This additional capacitance decreases the frequency of the mode. Moreover, the electric field between vanes and rod increases along the rod from the undercut to the inside of the cavity, as shown in Fig.8. As the rods are inserted more deeply the capacitance becomes larger, and consequently, the mode frequency drops. When the rods are just inserted in the depth of the undercut, the additional capacitance is rather small, and thus the mode frequency just shifts slightly. This explanation is supported by the measurement results in Fig.3.

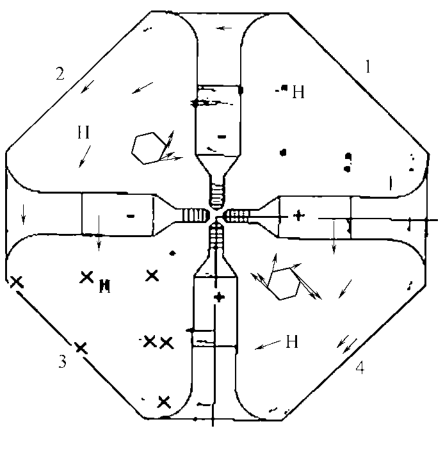

Fig.7. The H field of 1—3 dipole mode in the undercut region from a 3D simulation. There are two rods in the quadrant 2 and 4.

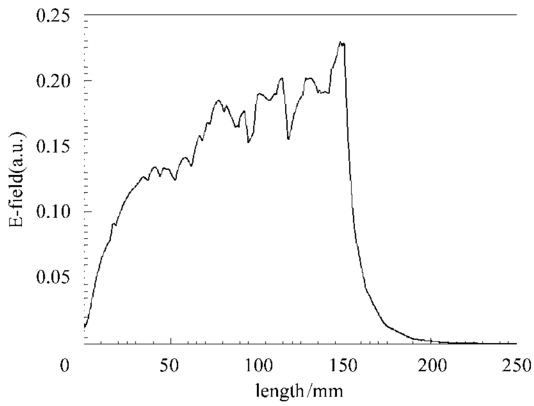

Fig.8. The E-field long the rod increases.
(the peaks are resulted from the simulation error)

With this understanding, it becomes easy to illustrate the reason that the rods in quadrant 1 and 3 make almost no effect on 1—3 dipole mode. In such a case the H field goes in parallel with the rods and thus no current goes along the rod, no matter how deeply the rods are inserted into these two quadrants.

4 Effect of stabilizer rod on dipole field component

The stabilizer rods have effects not only on the frequency of the dipole mode, but also on the dipole field component. In this section we will give some measurement results of the dipole field tuned with the imbalance insertion of the stabilizer rods.

The dipole field components mixed in the quadrupole field of the RFQ at the tuning status corresponding to Fig.2 is shown in Fig.9, in which the curves noted with D1—3 and D2—4 stand for dipole mode 1—3 and dipole mode 2—4, respectively. These fields are normalized to the quadrupole field. The mono mode is not a real cavity mode and it comes from errors in measurement and data processing. It is observed that the 1—3 dipole component is in a range from -5% to 5%, but the 2—4 dipole component has a rather large span: -35% to 0. Apparently the field was not well tuned and the cavity is largely asymmetrical.

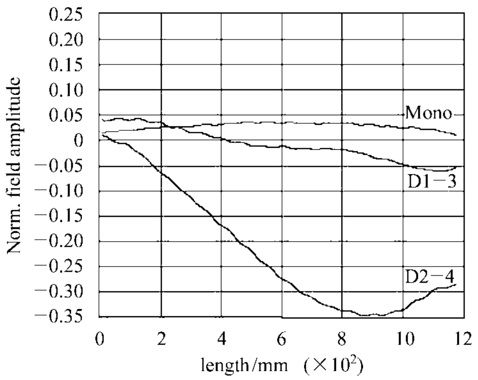

Fig.9. Dipole field components distribution along the RFQ without stabilizer rod insertion.

Inserting the 1—3 stabilizer rods 7cm into the cavity without moving the tuners, we got a result as shown in Fig. 10. It can be seen from Fig. 10 that the 1—3 dipole field distribution has almost no change, while the field of 2—4 dipole mode obviously rises up and distributes from −14% to 20%. The 2—4 dipole frequency is low shifted and the frequency separation between 2—4 and 1—3 dipole modes is reduced to 1.96MHz. When the rods were further inserted into the cavity we found the curve of 2—4 dipole mode shifted up further, as shown in Fig.11, in which the rods were inserted so that the 1—3 dipole mode and 2—4 dipole mode became almost overlapped($\delta f = 0.425$MHz). This result indicates that the rods did not alleviate the 2—4 dipole component even though the two dipole modes are very close to each other and both far from the quadrupole mode. It can also be observed that the field tilt of the dipole 2—4 is not reduced by the rods insertion.

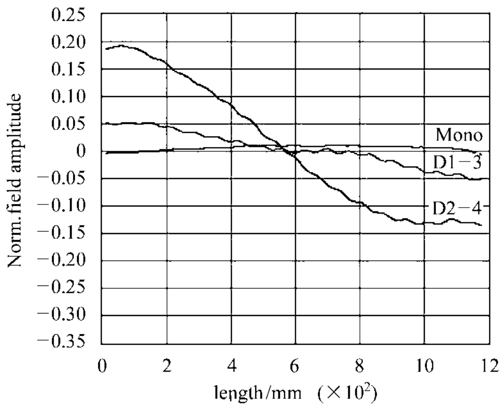

Fig.10. Dipole field components distribution along the RFQ with 1—3 stabilizer rod insertion of 7cm.

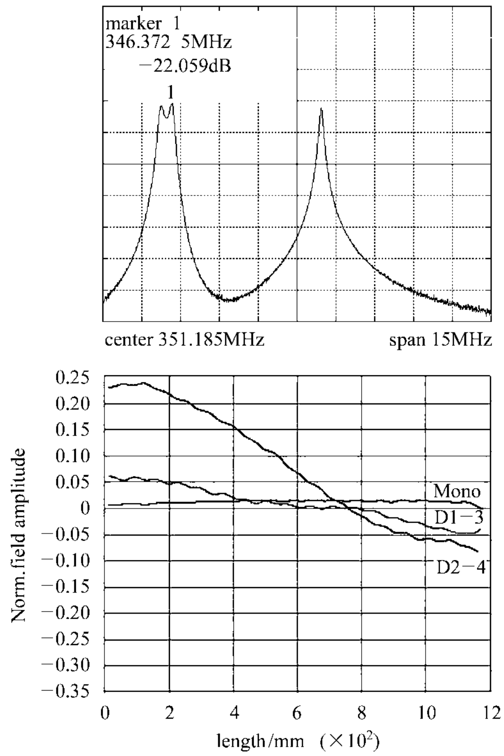

Fig.11. When the rods are further inserted so that the 2—4 mode is almost overlapped with the 1—3 mode (a), the field of 2—4 dipole mode rises further (b), without any reduction of the dipole component in comparison with that in Fig.10.

5 Conclusions

This paper studies the function of dipole stabilizer rod. It is found by the experiments that the rods inserted in 1—3 quadrants of an RFQ will disturb the frequency and field of 2—4 dipole mode, instead of 1—3 dipole mode, and vice versa. The field analysis with 3D simulations illustrates this phenomenon. The imbalance insertion of the rods can be used to reduce the dipole field component in an asymmetrical cavity, but it cannot decrease the tilt of the dipole field. It is also found that the closest two dipole modes produced by the rod insertion do not directly mean a smallest dipole field component.

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References

1 Howard P, Lancaster H. Technique for Stabilizing a Four-Vane Radio Frequency Quadruple Structure. In: Proc. 7th Conf. on Application of Accelerators in Research and Industry. North Holland, 1982

2 Ueno A et al. First Operation of a 432-MHz 3MeV RFQ Stabilized with PISLs. In: Proc. of 1994 LINAC Conference. 1994. 166—168

3 Schrage D et al. A Flight-Qualified RFQ for the BEAR Project. In: Proc. of the 1988 Linear Accelerator Conference. CEBAF-Report-89-001, 54

4 Young L M, Rybarcyk L. Tuning the LEDA RFQ 6.7MeV Accelerator. In: Proc. of LINAC'98. 1998. 270—272

5 FU Shi-Nian, GUAN Xia-Ling et al. R&D Status of a 3.5MeV RFQ Accelerator for ADS Study in China. In: Proc. of LINAC'2002. 2002, 154—156

6 GUO Zhi-Yu, FANG Jia-Xun et al. HEP & NP, 2004, **28**(7): 762 (in Chinese)
(郭之虞,方家驯等. 高能物理与核物理,2004,**28**(7):762)

7 OUYANG H F, FU S N et al. HEP & NP, 2004, **28**(7): 753 (in Chinese)
(欧阳华甫,傅世年等. 高能物理与核物理,2004,**28**(7):753)

8 Billen J, Young L. Poisson Superfish, LA-UR-96-1834

RFQ加速器中二极模稳定杆作用机理的研究*

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摘要 RFQ加速器中的二极模场给束流施加一个偏转力,导致束流损失在机器上. 因此,必须采取降低二极模场的措施. 人们提出采用二极模稳定杆使二极模频率远离四极工作模. 在一台RFQ冷模上开展的实验研究中,发现了一些与二极模稳定杆作用机理相关的新现象,本文报告这些实验结果,并对其进行分析解释. 根据这些结果,提出,利用非对称性地插入二极模稳定杆,可以降低非对称RFQ腔体中的二极模场分量.

关键词 RFQ加速器 二极模 二极模稳定杆

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