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Progress of the 473 MHz Four-Rod RFQ

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Abstract

We have constructed a new four-rod type Radio Frequency Quadrupole to operate at 473 MHz. Four-rod type structures have not been used for such a high frequency before. The RFQ is designed to accelerate 10 mA of H^- ions from 30 keV to 0.5 MeV. Low rf power and high rf power measurements of the RFQ have been performed successfully. In this paper we will present our design of the RFQ and the results of tests related to low and high rf power operations such as Q and power measurements, multipactoring problems, sparking problems, vacuum performance, and cooling.

I. INTRODUCTION

The four-rod RFQ structure invented at Frankfurt [1] not only has been a viable alternative to the four-vane structure, but also offers several advantages such as simplicity of structure and elimination of the dipole mode. However, the four-rod design has not been studied extensively for frequencies much above 200 MHz. Higher frequencies (400 to 500 MHz) are desirable for pre-injectors of proton machines. We have developed a four-rod type design for these higher frequencies by introducing a small variation to the Frankfurt geometry [2,3]. After designing several simple test models, checking them using computer codes such as MAFIA [4], and obtaining desirable results from cold model measurements, we set out to make a test RFQ at 473 MHz and to accelerate a 10mA of H^- ion beam from 30 keV to 500 keV. (The reason for 473 MHz is the rf power source.) A cold model was built and tested with results which matched our theoretical calculations very well [5]. Next, we made a full beam dynamics design for a short low power RFQ. Pieces were machined and assembled and a cold test of the RFQ was done. This paper will discuss the design of the structure, the beam dynamics design, and the results of the cold and high power rf tests of the final RFQ.

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II. THE STRUCTURE

The structure is made of a series of modules. Figure 1 shows two modules next to each other. Each basic module of length ℓ consists of two square plates of thickness T and width W supporting the four rods. Each supporting plate is connected to two opposing rods. Four rectangular plates cover the sides of the structure with the corners of the structure being left open to give better vacuum quality. The corners can be left open for the following reasons: First, the diagonal planes going through the opposing corners are the symmetry planes of the structure. Therefore, there should be no currents crossing these planes. In other words, the $\vec{B}$ field is perpendicular to these planes. Second, the fields are weak at the corners, so leaving the corners open should not appreciably change the resonant frequency or the Q. Figure 2 shows the magnetic field for a cross section at the middle of a module ($z = \ell/2$), showing that $\vec{B}$ is negligible at the corners.

Since the two opposing rods are attached to the same plates at many points through the structure, the dipole mode, which appears when the two opposing rods oscillate at different voltages, is not a problem. In other words, there is no mixing of unwanted dipole modes with the desired quadrupole mode. This is an advantage that all the four-rod type structures share over the four-vane types in which the mode mixing can be a serious problem.

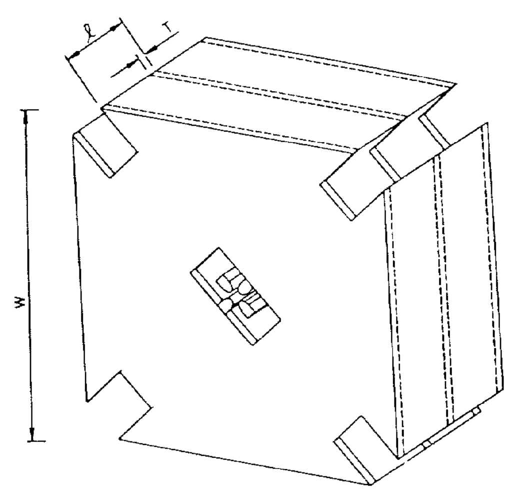

Figure 1. Two modules of the 473 MHz structure.

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All parts of the structure are bolted together and can be fully disassembled. To make it possible for the vanes to be positioned exactly in place and attached to the square plates, each plate is split diagonally into two halves. The rods are then held in place between these two halves and positioned using dowel pins. To make good rf contacts at the joints, thin annealed copper wires are squeezed in at the contact points between the plates and the sidewalls, and the rods and the plates. However, we need not worry about the quality of the joints between the two halves of the square plates; since they fall on one of the two diagonal symmetry planes which have no currents crossing them.

To design such a structure at a specific frequency, we only need to design a module using the MAFIA code. Since the structure is made of a series of identical modules it will have the same frequency, quality factor, power per unit length, etc., as a single module. Our RFQ structure is made of 10 modules. Table 1 lists the dimensions of a module for the 473 MHz structure. It also lists the frequency and Q factor predicted by MAFIA and capacitance per unit length of the vanes calculated by the CAP program, a modification of POSSION for calculating capacitance. Note that the quality factor predicted by MAFIA is not a good prediction since the Q factor also depends on other factors such as small geometrical details and surface quality, which are not taken into account by the code.

III. THE BEAM DYNAMICS DESIGN

The beam dynamics of the RFQ has been studied using the PARMTEQ program. In this design an effort has been made to keep the length of the RFQ short and the intervane voltage low, so that the total power required is below 100 kW. The input to the RFQ is 10 mA and 0.7 π mm·mrad (normalized 90%) emittance. The output beam should be about 9 mA with less than 10% emittance growth. Table 2 and Figure 3 give the parameters of the RFQ.

Table 1
Dimensions of a 473 MHz module

Length of the module(ℓ)	5.48	cm
Width of square plates (W)	18.8	cm
Thickness of the plates (T)	1.27	cm
Intervane capacitance (C_T)	107	pf/m
MAFIA Results:		
Frequency	473	MHz
Q	8500	

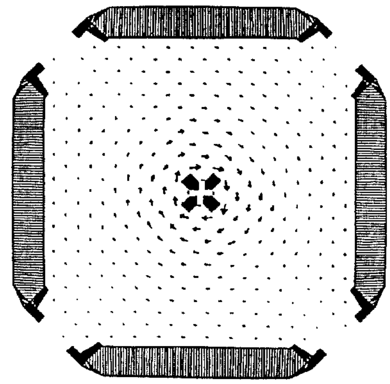

Figure 2. Plot of the magnetic field in the middle of a module. (MAFIA output)

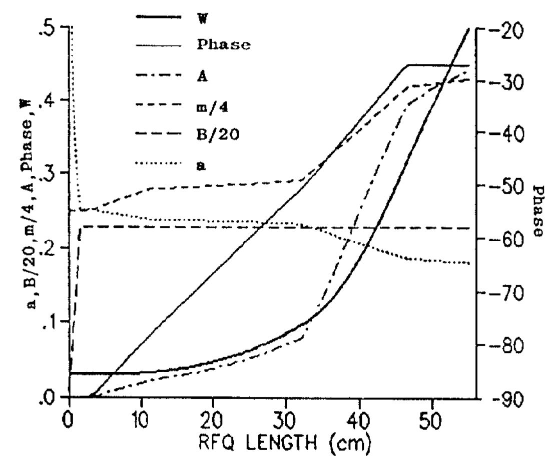

Figure 3. The RFQ parameters vs. RFQ length.

Table 2
RFQ Parameters

Ions	H^-	
Target frequency	473	MHz
Initial energy	30	keV
Final energy	500	keV
Nominal Current	10	mA
ϵ_t (norm,90%)	0.7	π mm.mrad
Transmission	95%	
Vane length	56.25	cm
Intervane voltage	67	kV
Aperture (r_0)	0.25	cm
The Cold Model:		
Frequency	473.1	MHz
Q	4400	
The RFQ:		
Frequency	470.3	MHz
Q	5000	
Power	90	kW

IV. THE RFQ

The RFQ consists of 10 modules described above. At the low energy end of the RFQ, a small single gap cavity has been added to eliminate any axial electric field at the beginning of the RFQ. The two opposite corners of the wall between this extra cavity and the first module of the RFQ have been opened wider to let the magnetic field couple the cavity to the first module of the RFQ. The resonant frequency is kept constant by decreasing the length of the first module in the RFQ from 5.48 cm to 4.1 cm.

The coordinates for machining the RFQ vane tips were calculated based on the PARMTEQ results. The transverse radius of the vane tip is 0.188 cm ($0.75 \cdot r_0$) and is kept constant through the RFQ's length. The machining of the vanes was done on a MAZAK computer controlled milling machine. A high speed cobalt tool was used to machine the modulation on the vanes which are made of tellurium copper.

V. THE TEST RESULTS

A. The low RF Power Measurements

A resonant frequency of 470.3 MHz was measured for the RFQ. This is lower than the design frequency of 473 MHz by about half a percent and can be corrected by tuning. The measured unloaded Q value is 5000, requiring a structure power of about 90 kW which is within the reach of our 100 kW rf source. Figure 4 shows the reflection coefficient versus the frequency for the RFQ. No neighboring modes are seen within 100 MHz span of the desired mode, which confirms our prediction that there should be no mode mixing.

B. The High RF Power Measurements

The RFQ was put in a vacuum chamber and pumped to less than 10^{-7} torr. The rf power is provided by an EIMAC 2KDW60LA klystrode which is capable of providing pulsed power ($\leq 100 \mu s$) up to about 115 kW [6]. The RF power is delivered via a 50Ω, $1\frac{5}{8}''$ diameter coaxial line. At the klystrode with the aid of a four port directional coupler and HP 408A power meter, the amounts of power transmitted to and reflected from the RFQ are measured.

A small pickup loop in the RFQ cavity gives a sample of the RF power inside the RFQ. Knowing the attenuation factor between this pickup loop and the input transmission line gives the measurement of the RF power inside the RFQ. (The attenuation factor was measured by a HP 8753B network analyzer.) The reflected power and power inside the RFQ are monitored by a fast digital scope (Tektronix 602A.)

The RFQ was conditioned by ramping up the RF power gradually. We have seen indications of multipactoring between the RFQ vanes at power levels from $\sim$ 200 mW to few kilowatts. However once getting to higher power levels, we did not see any indications of serious multipactoring anywhere in the cavity. The RFQ was conditioned successfully up to 112 kW with $20 \mu s$ pulses and 0.1% duty factor. This is well above our 90 kW target. The RFQ is water cooled on three sides and the temperature is monitored and kept constant within one degree celsius.

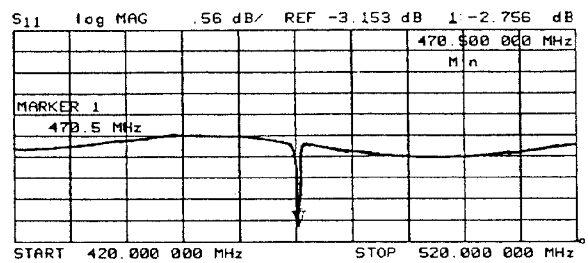

Figure 4. The reflection coefficient vs. frequency for the RFQ.

VI. CONCLUSION

The cold tests and high rf power measurements of the RFQ have been accomplished, and the results are in good agreement with the calculations. The RFQ has been conditioned to 110% of the operating voltage. We are now in the process of attaching the RFQ to the ion source [7] and arranging a beam test.

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