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Nuclear Instruments and Methods in Physics Research A 558 (2006) 210–213
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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Accuracy of the manufacture of electrodes for a 433 MHz RFQ

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Available online 21 November 2005

Abstract

Analysis of the dependence of the accuracy of the interelectrode distance on the accuracy of electrode surface machining for a 433 MHz four-segment radio-frequency quadrupole (RFQ) resonator is reported. The aim of the research was to determine the requirements for measurement methods and machining of the RFQ segments. Analysis of particle capture into acceleration as a function of the electrode modulation amplitude at the RFQ input is discussed.

Keywords: Accuracy; Electrodes; RFQ

1. Introduction

The accuracy of quadrupole symmetry of the electromagnetic field in a radio-frequency quadrupole (RFQ) structure is mainly determined by the accuracy of the manufacture of the segments. After manufacture and assembly of the four segments (Fig. 5), the electromagnetic field can be corrected using adjustment elements. The higher the manufacturing and assembly accuracy, the less is the necessity to use adjusting elements.

Fig. 1 shows the results of numerical calculations of the electric component of the electromagnetic field in a resonator with exact quadrupole symmetry.

Fig. 2 shows the result for similar calculations for a resonator with a displaced upper electrode; the top of the electrode is displaced to the right by 20 μm, which is $<1\%$ of the distance (2.899 mm) between the tops of neighbouring electrodes.

Analysis shows that realisation of tolerances for interelectrode distances of ~20 μm and less requires a high level of technology, and consequently, methods for measurement and electrode machining corresponding to this level.

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doi:10.1016/j.nima.2005.11.005

2. Analysis of tolerances

The accuracy requirements for the manufacture and assembly of RFQ resonators define the accuracy requirements for methods for measurement and machining of resonator segments. The analysis presented allows estimation of the accuracy requirements for these methods.

Fig. 3 shows the cross-section of the resonator. Fig. 6 displays the cross-section at the axes of the resonator. Dimension chains forming interelectrode distances $d = 7.000$ and $e = 2.899$ mm (shown in Fig. 4) were subjected to analysis for the conformity of both dimensions (d and e) to a tolerance of 20 μm. It was supposed that the electrode modulation was ideally manufactured using a diamond mill, i.e. the error due to this mill was not taken into account.

A dimension chain determining the dimension of interelectrode distance d is formed by the dimensions $a = 150.000$, $b = 126.500$ and $c = 16.500$ mm (Fig. 3).

Fig. 5 illustrates the dimension scheme for interelectrode distance $d = 7.000 \pm 0.025$ mm.

According to this scheme, the tolerance for dimension d of ± 25 μm is uniformly distributed among the dimensions a, b and c (assuming identical accuracy in machining of jointing planes) and hence the tolerance for dimensions a, b and c is $\pm 25/3\,\mu m = \pm 8\,\mu m$. Thus, the dimensions have values $a = 150.000 \pm 0.008$, $b = 126.500 \pm 0.008$ and

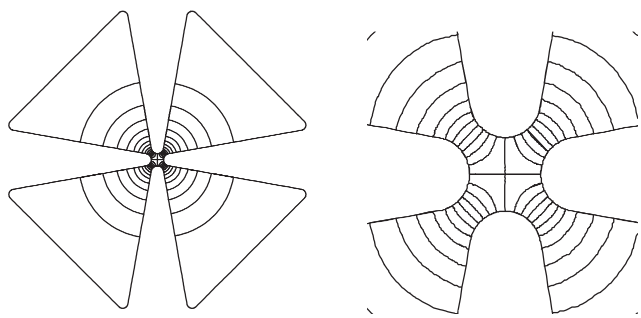

Fig. 1. Electric component of the electromagnetic field in a resonator with exact quadrupole symmetry.

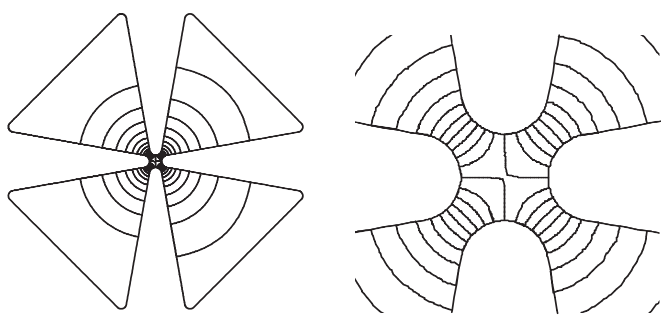

Fig. 2. Electric component of the electromagnetic field in a resonator with a displaced upper electrode.

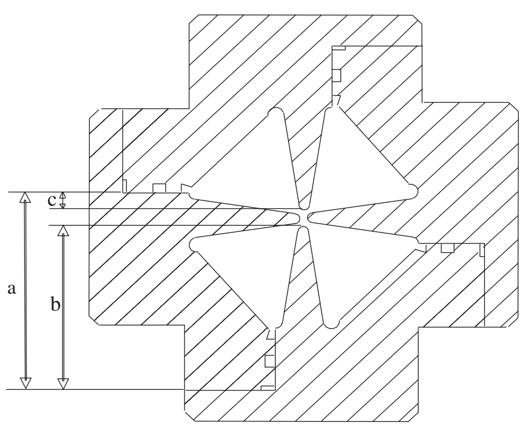

Fig. 3. Resonator cross-section.

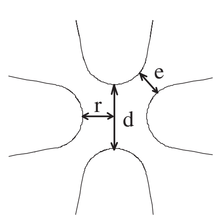

Fig. 4. Interelectrode distances d and e at the tops of the electrodes.

$c = 16.500 \pm 0.008$ mm. The maximum deviation of dimension d takes place when dimension a deflects in antiphase in relation to dimensions b and c. For example, $d = a–b–c =$

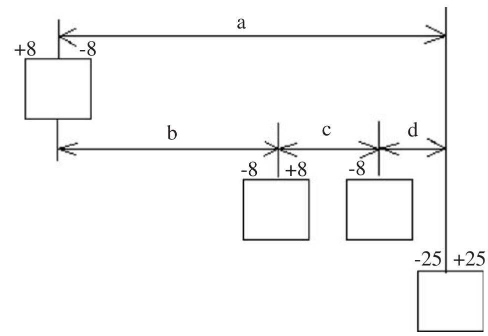

Fig. 5. Dimension scheme for interelectrode distance d.

149.992–126.508–16.5086.976 mm, i.e., $d = 7.000–0.024$ mm, or $d = a–b–c = 150.008–126.492–16.492 = 7.024$ mm.

Furthermore, it is necessary to choose a tolerance level for non-flatness of the jointing planes corresponding to the dimension chain considered. The most reliable value for tolerance of non-flatness for jointing planes is one-tenth of the tolerance for the dimensions, i.e. for the case given, $16\,\mu m \times 0.1 = 1.6\,\mu m$, but achievement of such accuracy involves significant costs. A more optimum solution from the point of view of both costs and reliability is a factor of 0.2 of the dimension tolerance, i.e., $16\,\mu m \times 0.2 = 3.2\,\mu m$. Similar arguments are applicable to the measurement error for non-flatness—it is more reliable to have one-tenth of the tolerance value for non-flatness, i.e. $3.2\,\mu m \times 0.1 = 0.32\,\mu m$, but a more realistic variation is $3.2\,\mu m \times 0.2 = 0.64\,\mu m$.

Thus, for the nominal dimension $d = 7.000$ mm and tolerance $\pm 25\,\mu m$, we have tolerance for dimensions a, b and c of $16\,\mu m$, non-flatness tolerance of $3.2\,\mu m$, and measurement error for non-flatness of $0.64\,\mu m$.

Fig. 6 shows the cross-section of the RFQ resonator; the dimensions specified form the dimension chain determining the interelectrode distance e in Fig. 4.

Distance e changes to the greatest degree when both adjacent electrodes are simultaneously displaced towards or apart from each other. Thus, the value Δ (change in interelectrode distance e) is connected to Λ (displacement of electrodes on the x and y axes; Fig. 6) by $\Delta = \sqrt{2\Lambda}$, i.e., if dimension $e = 2.899$ mm has tolerance $\Delta = \pm 25\,\mu m$, the displacement of each electrode on the x or y axis for the centre of quadrupole symmetry should not exceed $\Lambda = \pm 25\,\mu m/\sqrt{2} \cong \pm 18\,\mu m$; thus, we have $r = 3.5 \pm 0.018$ mm (Fig. 4).

The dimension chain dictating the interelectrode dimension e is shown in Fig. 7. Here r is the distance from the top of the electrode to the centre of quadrupole symmetry (Fig. 4). As the deviation of the electrode from the nominal position is defined by two dimensions, f and g, the tolerance for these dimensions will be $\Lambda/2 = \pm 18\,\mu m/2 = \pm 9\,\mu m$, i.e., $f = 130.000 \pm 0.009$ mm and $g = 126.000 \pm 0.009$ mm. Assuming a tolerance for non-flatness of the jointing planes of $18\,\mu m \times 0.2 = 3.6\,\mu m$, we obtain a value for allowable measurement error for non-flatness of $3.6\,\mu m \times 0.2 = 0.72\,\mu m$. A summary of the results is shown in Table 1.

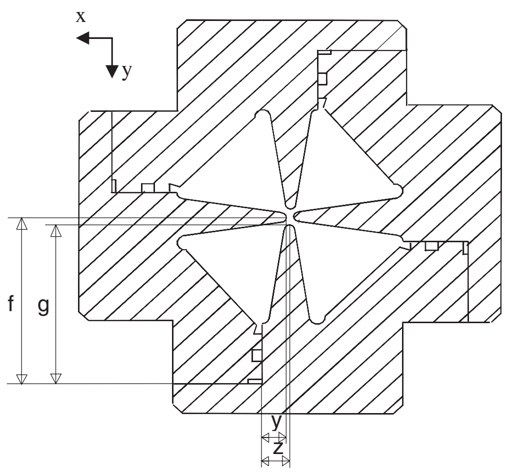

Fig. 6. Resonator cross-section.

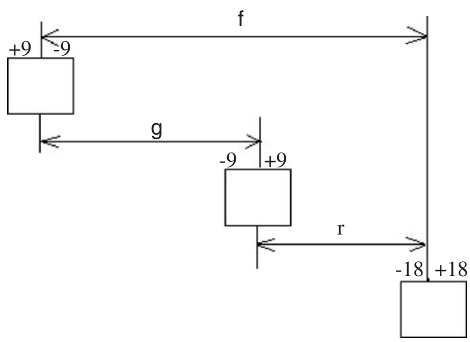

Fig. 7. Dimension chain for interelectrode distance *e*.

Table 1
Summary of calculated results

	Dimension	
	d	*e*
Dimension tolerance (μm)	±25	±25
Tolerance for non-flatness of jointing planes (μm)	3.2	3.6
Non-flatness measurement accuracy for jointing planes (μm)	0.64	0.72

Practice has shown that such requirements assume temperature monitoring in the room and machine tool capability (elements and detail) to within 1/10 and even 1/100 of 1°. In particular, achieving a measurement error of 1 μm for the NPK LUTS used in the HS328 machine tool required both modification of the machine tool software and improvement of its cooling system to maintain the coolant temperature and elements of the machine tool within a narrower temperature range.

Figs. 8 and 9 show diagrams reflecting the dependence of the tolerance for non-flatness of the jointing planes ε and the required measurement accuracy ζ on tolerance δ for interelectrode distance *d*.

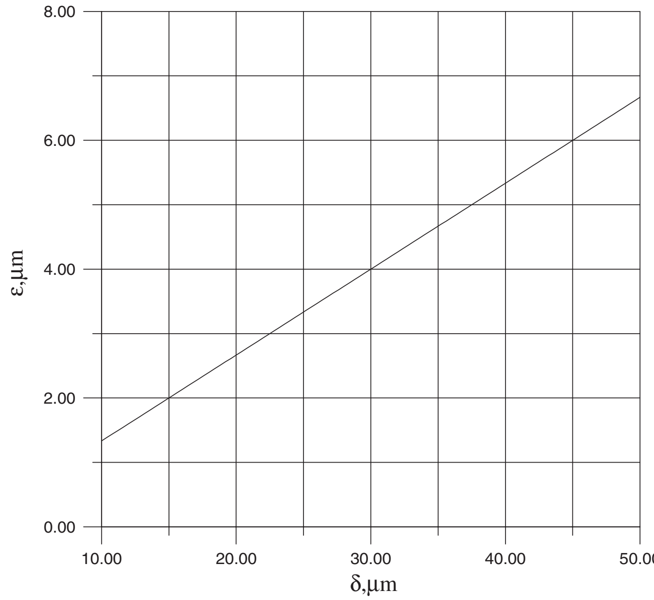

Fig. 8. Dependence of the non-flatness tolerance for jointing planes ε on tolerance δ for interelectrode distance *d*.

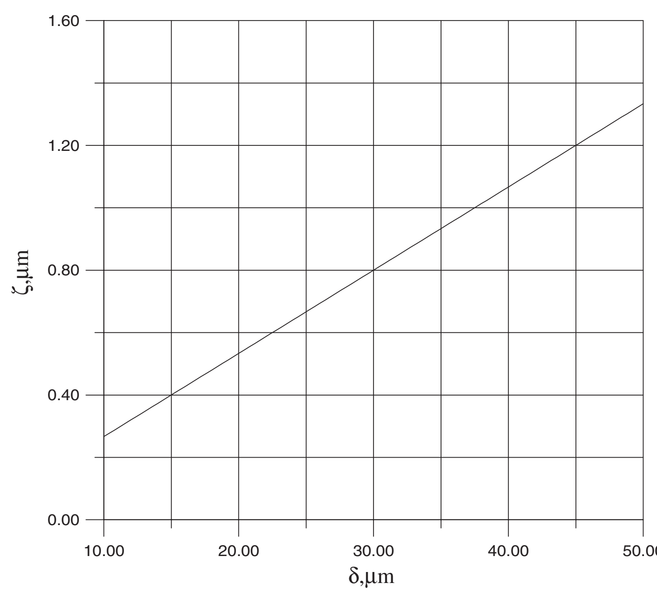

Fig. 9. Dependence of the required measurement accuracy ζ on tolerance δ for interelectrode distance *d*.

3. Results of particle dynamics optimisation

A number of measures to improve the HS328 machine tool are now planned to realise an accuracy of 2–3 μm for machining of the jointing planes and electrode modulation.

As stated earlier, numerical calculations for optimisation of the particle dynamics for a 1 MeV deuteron 433 MHz RFQ structure have been carried out. The calculations take into account the opportunity to downsize the electrode modulation amplitude at an accelerating–focusing channel input from 40 to 10 μm. The purpose of this optimisation

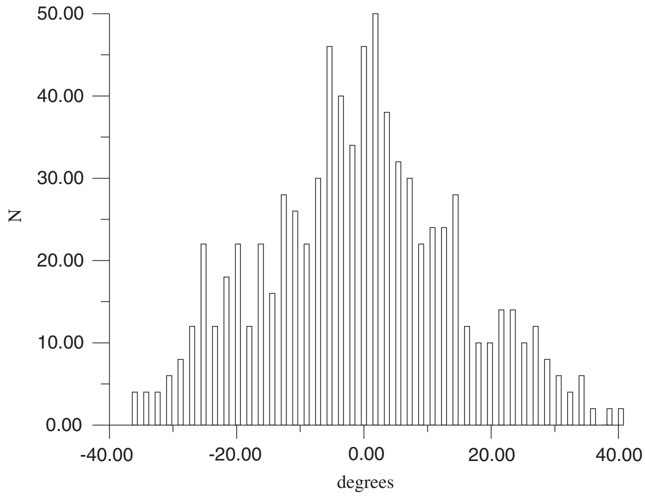

Fig. 10. Phase spectrum of the output beam in the structure before optimisation.

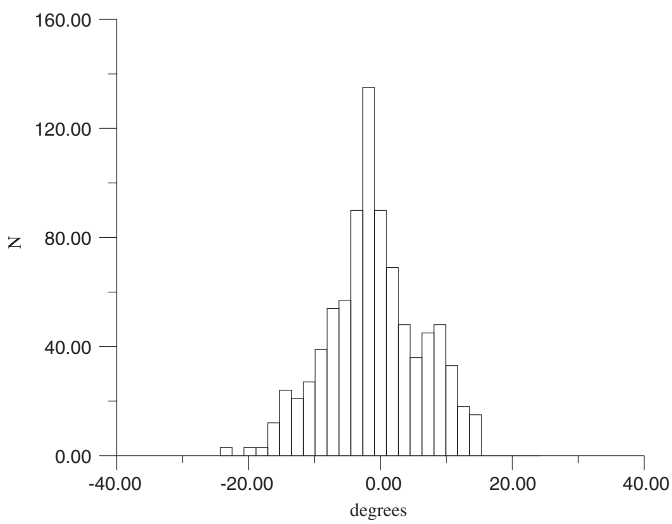

Fig. 11. Phase spectrum of the output beam in a structure with smaller electrode modulation amplitude.

was to increase particle capture into acceleration for a 15 mA input beam (while preserving the length of the structure at 2300 mm) with input modulation amplitude of approximately 10 μm.

By optimising the particle dynamics, particle capture into acceleration was increased from 80% to 91% and the phase length of output bunches decreased from 72° to 36°. Fig. 10 shows the phase spectrum for the output beam in the structure before optimisation. Fig. 11 illustrates the phase spectrum in the structure for a smaller electrode modulation amplitude. Figs. 12 and 13 illustrate power spectra for the output beam for these two variations.

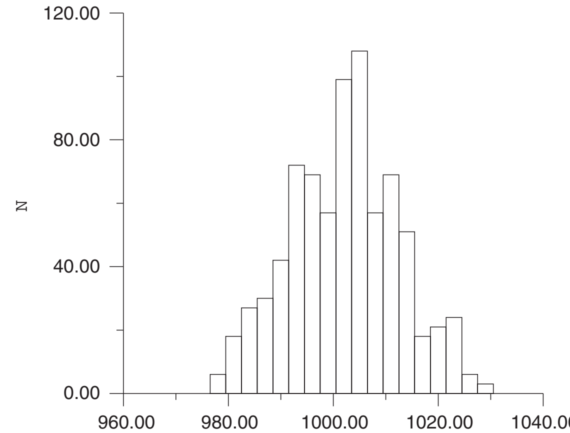

Fig. 12. Power spectrum for the output beam in the structure before optimisation.

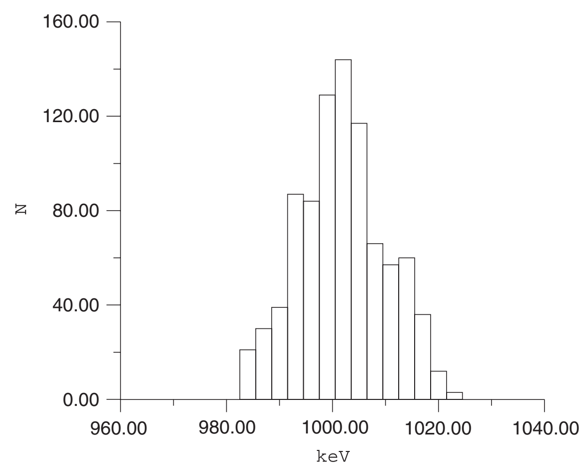

Fig. 13. Power spectrum of the output beam in a structure with smaller electrode modulation amplitude.

4. Conclusion

Analysis of the tolerances for a 433 MHz RFQ shows that for tolerance of ±25 μm for the interelectrode distances, the error in measurements of the machining of jointing planes must be approximately 1 μm. Correspondingly, the tolerance for the non-flatness of jointing planes must be approximately 3 μm. At present, using the HS328 machine tool it was possible to achieve measurement error of 1 μm, while the realisation of 3 μm for non-flatness of the jointing planes will require additional efforts. Resolution of these problems will essentially allow simplification of the procedure for RF tuning.