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Feasibility Study of 2D Machining of RDDS1 disks

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Abstract

The present note is to confirm the feasibility of the present machining technology of the RDDS1 disks. Diamond turned fifteen 2D-shaped disks were inspected both by mechanical dimension measurements and by the RF measurements with electrically shorted at both ends. The consistency among the precisely calculated frequencies, the RF measurements and the dimension measurements were studied.

Dimensions such as “OD”, "2a" and "2b" were found to agree with the design values within ±1 μm, while frequencies within ±0.5MHz to the calculated values.

Based on the studies described in the present note, we conclude that a process such as a moderate feed-forward process is enough to control the average frequency of the accelerating mode over a whole structure. Furthermore, we estimate that the higher-order mode frequencies are to be controlled within ±1 MHz or so. Then we conclude that the fabrication based on the present technology can produce disks, meeting the requirement of the RDDS1.

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Introduction

KEK has studied the precise fabrication of cells for the detuned structure (DS) and the damped detuned structure (DDS) based on the precise turning with a diamond tool in a precision lathe[1]. A precision of 1 MHz was established in the fabrication of the cell for the DS[1,2]. The basic shape of the cells for DS and DDS is formed by a thin flat disk with a beam hole which separates cells comprising of thicker cylinders with a bigger inner diameter than the beam hole.

Though such a fabrication technique for DS and DDS was established, we need to confirm that the technology is also suitable for the fabrication of the RDDS disks[3].

The reason is that the 2D contour shape of the rounded damped detuned structure (RDDS) is very different from DS and DDS in a sense that almost all of the inner surface in a cell is round, i.e. not flat nor cylindrical. This means the lathe which cuts those cells should move in X and Z directions at the same time. The present study is for us to confirm that the present fabrication technology can produce RDDS cells within a required tolerance.

In the present note, we call a unit part comprising of the structure as "disk" instead of "cell" because that of RDDS is symmetric with respect to the middle plane perpendicular to the passage of the beam and the middle plane forms a disk with a small hole. We named the unit from this appearance.

Design of disk

Design 2D contour shape is exactly the same as those of actual 3D test disks for RDDS1. All of the dimensions which determine the frequencies are listed in Table 1. The values are those at 20degC.

A cross sectional view of the disk is schematically shown in Fig. 1. The details are described in [4].

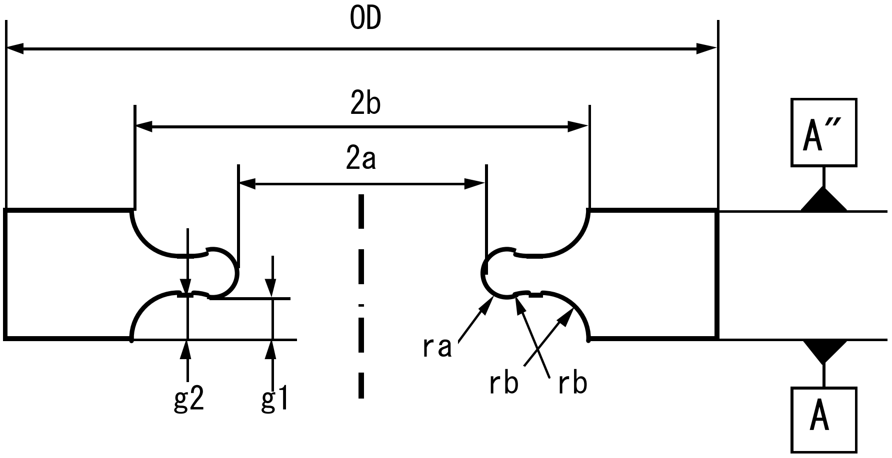


Fig. 1. Schematic of 2D disk showing the contour shape.

Table 1. Relevant dimensions of the disk.

OD	Outside diameter	61.0000 mm
2a	Iris diameter	9.41087 mm
2b	Cell diameter	22.98884 mm
ra	Iris nose radius	0.86146 mm
rb	Cell inner shape radius	3.81979 mm
p	Cell length	8.74377 mm

Criteria of frequency control

The tolerance on the random and systematic errors on frequencies will be discussed in detail in [5]. Here is presented a rough criteria to discuss the feasibility of the fabrication.

Because the tolerance on random frequency error is about 3 MHz in sigma, a criteria for the judgement on random error was set to 1 MHz. On the other hand, if the accelerating mode frequency in average is controlled within 1 MHz over a certain number of disks, such as 10-20 disks, the integrated phase slip can be suppressed within a tolerable level if we apply some feed-forward process in a series of disk fabrication. Therefore, the present judgement level was set to 1 MHz as a rule of thumb for both random and systematic error.

Numerical calculation of mode frequencies

The frequencies calculated by 2D codes should serve the references to judge the feasibility of the fabrication.

All of the relevant modes were calculated by a two-dimensional code, PISCES-II[6]. It uses linear or quadratic triangular elements to solve not only axisymmetric modes but also multipole modes. In the calculation, the mesh sizes were down to 0.01mm. Typical convergence of frequencies is better than 0.1MHz as shown in Fig. 2. The calculated values for various modes are listed in the row “Cal” of Table 4.

It should be noted that the frequency of F0-2π/3 mode was also calculated by Ω2[7], which gives 0.05 MHz lower value than PISCES-II. The Ω2 code also uses the quadratic elements and is estimated to give the value more precise than 0.1MHz. We conclude that the frequencies calculated by these two codes agree within 0.1 MHz.

Considering the above results, we estimate that the present precision of 2D calculation of frequencies is better than 0.1MHz.

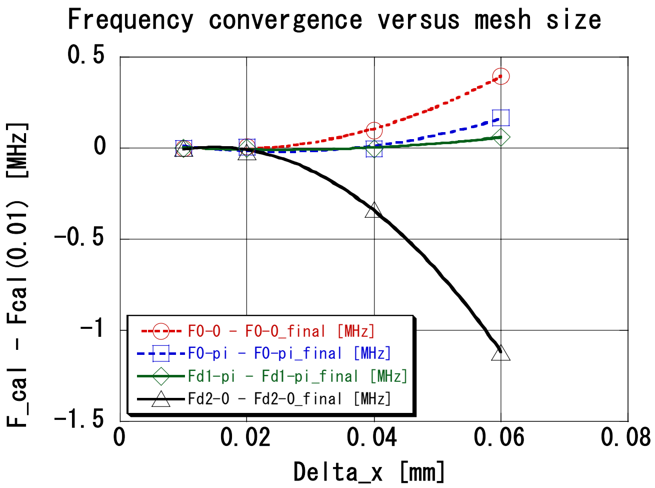


Fig. 2 Frequency convergence of PISCES-II for the four modes, F0-0, F0-π, Fd1-π and Fd2-0, as functions of mesh size.

Fabrication of disks

Typical fabrication process of disks is the following.

1. Rough cutting with 40 μm undercut.
2. Cut the outer cylinder of a dummy disk.
3. Measure the outside diameter and calibrate the position of the tool in the radial direction.
4. Set a disk on vacuum chuck and cut a half of the disk.
5. Set the disk on vacuum chuck after flipping.
6. Cut another half of the disk.
7. Measure the outside diameter.
8. If necessary, the tool radial positioning is re-adjusted for the following fabrications based on the data taken in stage 7.

Fifteen disks were made in the present study. The record of the fabrication is shown in the table below. Since the fabrication was performed in two days separating three weeks in between, it became a good example to glimpse at the reproducibility of machining disks over a long term.

Disk #	#1,2,3,4,5,6,7	#10,11,12,13,14,15,16,17
Date of fabrication	Mar. 18, 1999	Apr. 9, 1999

Profile and dimension measurement

Contour measurement

The contour line of one of the disks, #2, was measured at SLAC by a CMM, 3D coordinate measuring machine, type 12106 of LEITZ. We believe that the precision of the measurement was better than ±1 μm level. In Fig. 3 is shown the measurement of the contour. This example shows that the machined surface agreed within ±1 μm to the design. Random staggering of the order of a micron happened to appear in this case which was not usually seen. The general trend of the contour is still seen from this measured curve, which can be used for comparison between mechanical measurement and electrical one.

Typical dimension measurement

Relevant dimensions of the disks were measured at KEK using another CMM machine, CARAT 850 of ZEISS. The disks were set on a flat vacuum chuck in a horizontal situation. A 3mm probe was used as the sensing probe with a probing pressure of 0.2N. The probe was calibrated with a calibration sphere before measurement. Firstly, reference copper cylinders with an outside diameter of 61mm and an inner diameter of 22mm were measured using the same setup. The measured values agree within 0.5 μm with those measured independently by Mitsutoyo co., one of the Japanese companies which produce precise measurement tools.

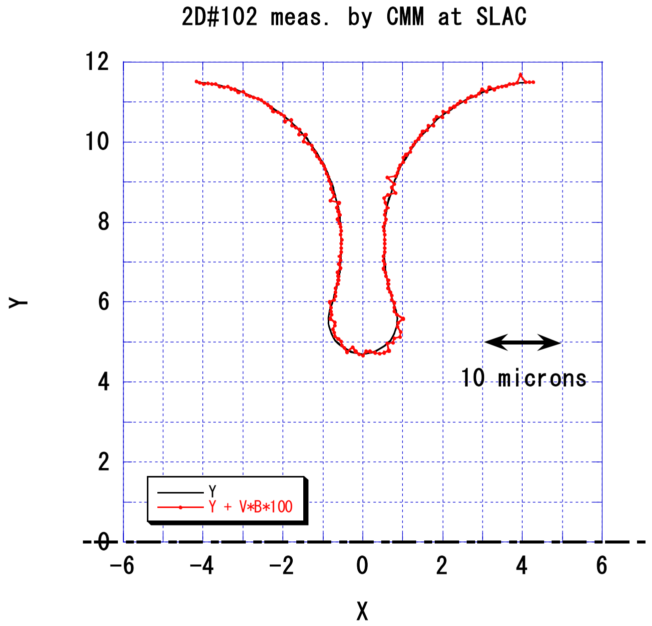
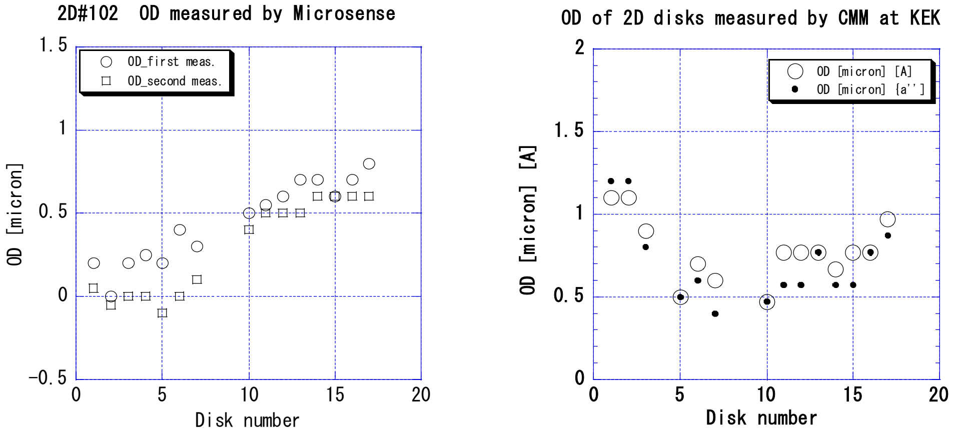


Fig. 3. Contour line of disk #2 measured by CMM at SLAC. Solid line shows the design shape. Dashed line shows the measured shape but the deviation from the nominal position to the actually measured one is expanded by 200 times, i.e., 5 µm / mm.

The "OD" are routinely measured just after fabrication by using two Microsenses (capacitive gap sensor supplied by ADE Technologies Ltd.) which sandwich the disk. This method to measure "OD" is a relative measurement with respect to a reference but serves data with an error, ±0.2 µm.

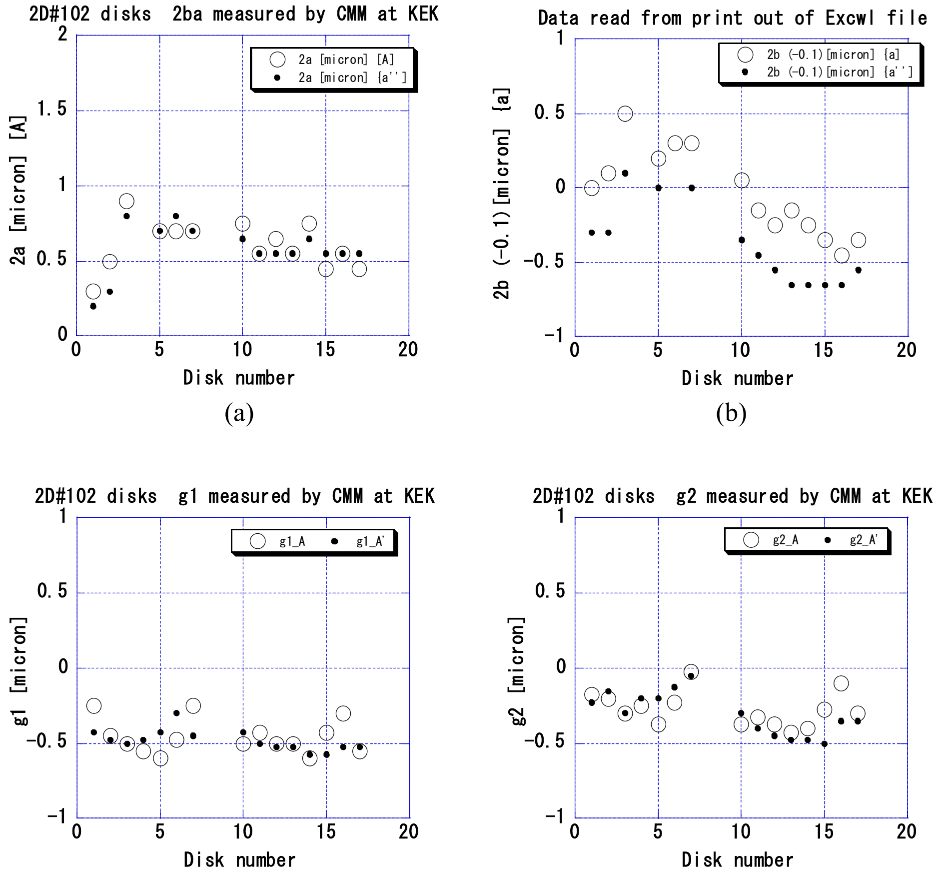
The results of "OD" measurement by two Microsenses are shown in Fig. 4(a). We found a change of 0.5µm from the first batch to the second. The values obtained by CMM are shown in Fig. 4(b) and they are consistent to those by Microsenses within ±0.5 µm.

The dimensions such as "2a", "2b", "g1" and "g2" measured by CMM are plotted in Fig. 5. It is to be noted that the measurement from A-side was in a separate run from that of the other side, A" side. It can be seen from these figures that these dimensions were well controlled within ±0.5 µm among these disks.



(a) (b)

Fig. 4. (a): Outside diameters of all of the disks measured by two microsenses. Relative values with respect to a reference are measured. (b): Outside diameter measured by CMM. Deviation from 61.000mm are shown. In both cases, the measurement were made twice, which are shown with two different symbols.



(a) (b)

(g1) (g2)

Fig. 5. Dimensions measured by CMM at KEK. (a): "2a" measured at the middle of the disk thickness, (b): "2b" measured 0.1mm off from the end plane, (g1): "g1" and (g2): g2, measured from each end surface.

RF measurement

The disks were stacked on a V-block and sandwiched by two flat plates at both ends to make the stack to be electrically shorted. In each plate was inserted an antenna through which the transmission characteristics, S21, was measured to obtain the resonant frequencies of the standing waves in the stacked disks. The detailed description on the measurement will be presented elsewhere[8].

Single-disk QC

Although the single-disk stack measurement was adopted as the main method for the RDDS1 case to check the characteristics of each disk, a floating setup [9] with a choke circuit equipped in each end plate was used here to check the characteristics of all of the disks. Here each disk under test was kept floated by five dielectric thin posts. This set up did not work for all of the RDDS1 disks but it gave us reasonable characteristics of the present disks. The result for the F0-0 and F0-π mode are shown in Fig. 6.

It was found that the frequencies of the two batches of fabrication were bunched into two groups. The frequencies of F0-0 were separated by 0.4 MHz while all of the F0- π were the same in two batches.

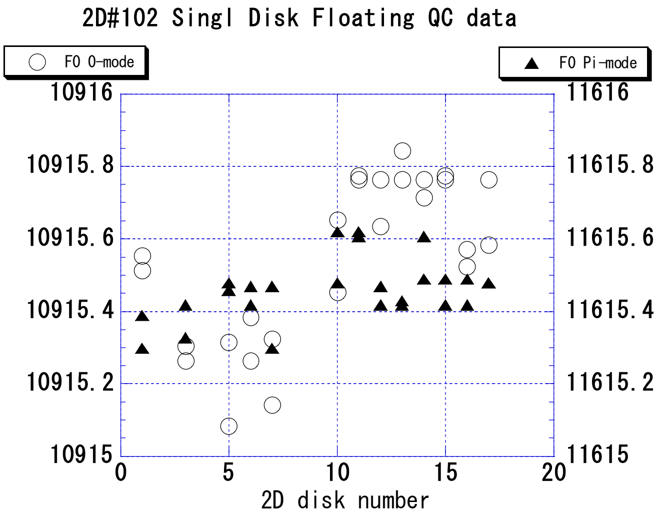


Fig. 6. F0-0 and F0-π frequencies measured by a floating single-disk setup.

This relation between two batches was confirmed in the stack measurement as shown in Fig. 7. Two dipole mode frequencies were also measured and shown in Fig. 8. In this case, both 0-mode and π-mode showed the difference in two batches. The frequency changes stated above are summarized in the Table 2.

Table 2. Difference of the average frequencies between two batches.

Mode	Difference of frequency
F0-0	0.5 MHz
F0-π	0.0 MHz
Fd1-π	0.6 MHz
Fd2-0	0.4 MHz

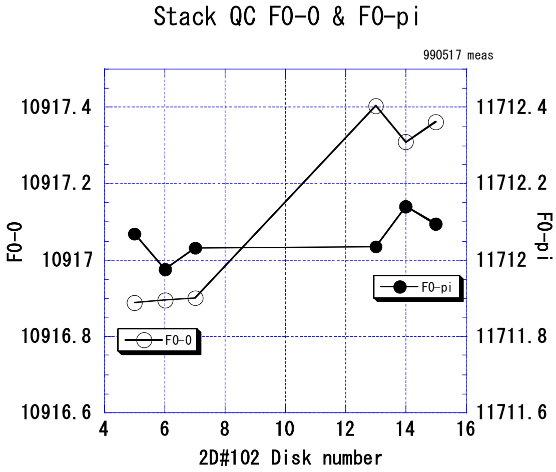


Fig. 7. Frequencies of F0-0 and F0-π mode in a single-disk stack QC setup for disks #5,6,7 and disks #13,14,15.

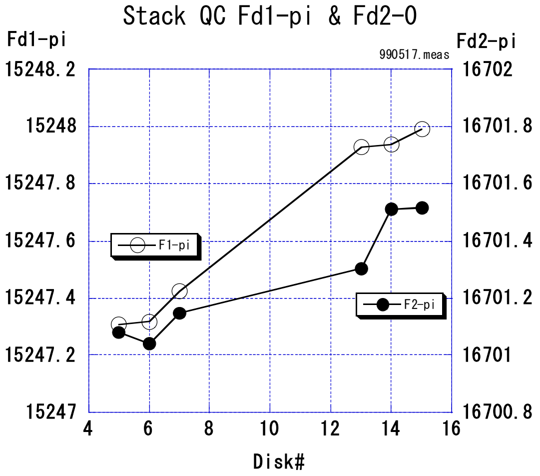


Fig. 8. Frequencies of Fd-1st-π and Fd-2nd-0 mode in a single-disk stack QC setup for disks #5,6,7 and disks #13,14,15.

Estimation of dimensional change from frequency change

In order to estimate the related dimension differences, those frequency difference listed in Table 2 were analyzed by using the sensitivity coefficients of frequencies on dimensional change. The sensitivities of those for 3D shaped disks were adopted which are listed in Table 3.

If we use these sensitivity coefficients and measured frequency differences, we can estimate the dimensional change between the two batches if the parametrization by taking the four parameters, a, b, rb and ra is a reasonable choice to represent the change. The obtained dimensional changes are listed in the same table. The changes of dimensions thus obtained are not consistent to those measured by CMM shown in Fig. 5. It should be concluded that the errors of less than 1 MHz should be analysed in a more sophisticated treatment.

Table 3. Sensitivity of frequencies on dimensional changes and obtained dimensional change. Units are MHz/μm and μm for sensitivity and dimension, respectively.

	F00	F0p	F1p	F20		Dimension	Change
df/da	+0.1	+0.7	-0.3	+0.1		δa	-0.2
df/db	-1.05	-1.25	-1.2	-1.5		δb	-1.0
df /drb	-0.15	-0.15	-0.1	-0.05		δrb	0.0
df /dra	-0.4	-0.8	-0.5	-0.8		δra	+1.5

Multi-disk stack-QC

The single-disk QC is subjected to the frequency perturbation due to the probes themselves and the surrounding holes etc. Being free from these perturbations, the absolute frequencies for the infinitely periodic structure can be obtained from the linear extrapolation of the measurements with different numbers of disks.

In order to measure the accelerating mode frequency, multiples of three disks were stacked where the internal order of the disks in each three-disk stack was kept. This process makes the field pattern of the mode in any disk the same in any setup even with a different number of disks. Through this process, the averaging process of measured frequencies with the same number of disks is certified. The frequency was thus obtained as shown in Fig. 9. Solid circles show the average frequency of the measurements with the same number of disks. As four data are needed to make the averaging for N=9 case, the averaging could not be performed from the existing two data.

When we want to obtain the frequencies of 0-mode and π-mode, any setup with any number of disks can be used for the points to be extrapolated. The measurement of those modes are shown in Fig. 10, where number of disks are 1, 3 and 6.

The measured values obtained as stated above are listed in Table 4. The values were corrected to those at 45 degC in vacuum. The effect of skin depth on frequencies measurement was included based on δf/f=1/2Q formula to obtain a loss-less frequencies as listed in the row "Meas.+Q.corr", where the Q values were obtained from the theoretical calculation. It was found that all of the measured frequencies agree with those calculated within 0.5 MHz.

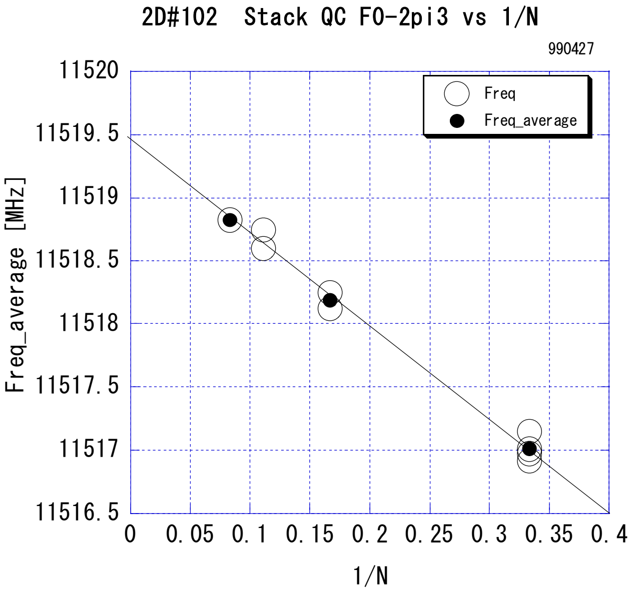
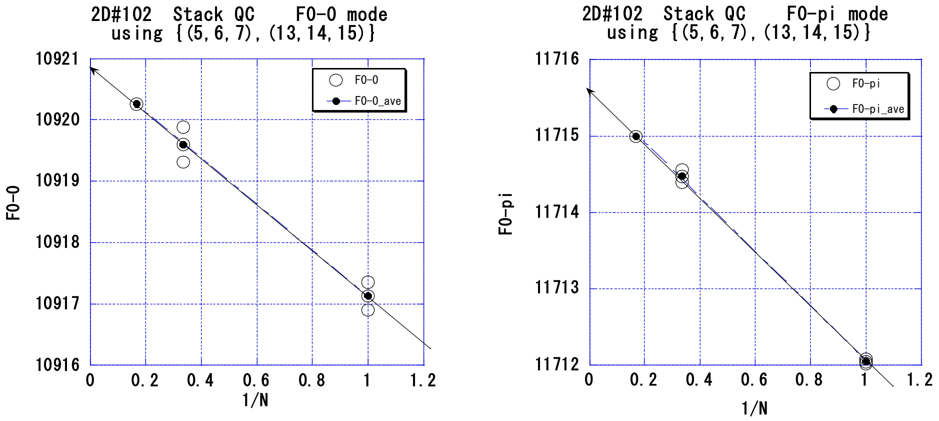
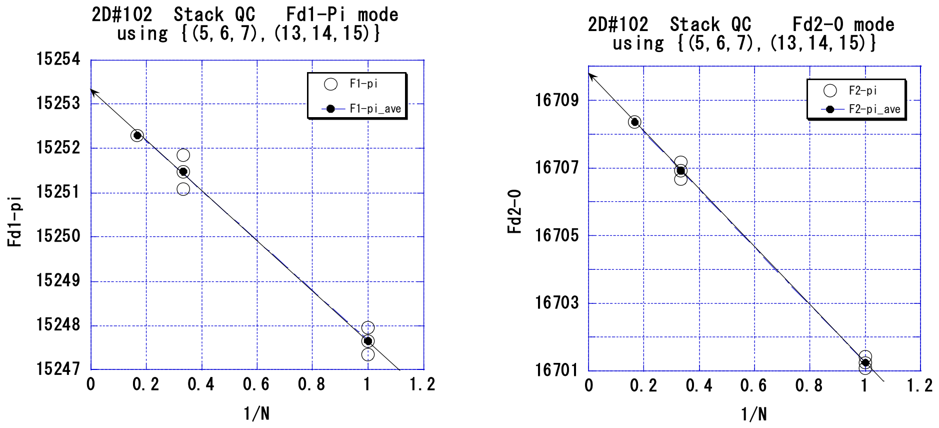


Fig. 9. Stack-QC measurement on $2\pi/3$ mode. Open circles are those measured. Solid circles are the average values of the same number of disks.



F0-0 F0-π



Fd1-π Fd2-0

Fig. 10. Evaluation of frequencies for an infinately periodic structure. Open circles are those measured in 1-disk, 3-disk and 6-disk setups. Solid circles are the average values for the measurements with the same number of disks, N.

Table 4. Frequencies calculated and measured. The values in the row "Meas.-Cal." are the difference between measurement and calculation with the finite conductivity correction included. Units are in MHz.

	F0-0	F0-2π/3	F0-π	Fd1-π	Fd2-0
Measurement	10920.80 ±0.1	11519.40 ±0.1	11715.60 ±0.1	15253.30 ±0.2	16709.7 ±0.3
Meas.+Q.corr	10921.49	11520.13	11716.35	15254.48	16710.47
PISCES-II Q	7960	7870	7840	6490	10840
Cal.	10921.20	11519.66	11716.19	15254.12	16710.08
Meas. – Cal.	**0.29**	**0.47**	**0.16**	**0.36**	**0.39**

Discussions and conclusion

The CMM measurement of the 2D contour agreed to the design within ±1 μm. One micron results in 3 MHz frequency error even if the worst pattern of the error distribution is assumed. But 3 MHz is still within the tolerance. On the other hand, one-micron dimensional error of a certain dimension results in at most 1 MHz frequency error. This value probably is within the tolerance because only a few relevant dimensions are to be coherently added to make the frequency error of some modes larger than 1MHz by a few times. Actually we estimate a practical error of 1 MHz as described below.

The disk-to-disk scattering of the frequencies representing the accelerating mode was within ±0.5 MHz, much smaller than the requirement of 3MHz. It shows that the random machining error is small enough.

The single-disk RF QC showed a sensible difference between two batches of disks but only by a half of MHz in all of four relevant modes, zero and π mode of accelerating-mode pass band and the π and zero mode of the first and second dipole pass band, respectively. This result indicates that the machining is stable in a level better than 1 MHz.

By measuring in a few configurations with different numbers of stacked disks, the frequency equivalent to that of the periodic structure was obtained by extrapolation. The obtained values agree within 0.5MHz with those calculated by precise 2D codes. Since we believe the 2D calculation is much precise than 1 MHz, we understand that the above agreement confirmed the precision of the machining to be within 1 MHz.

From the above considerations, we estimate that the random error of the accelerating-mode frequency of each disk is within its tolerance but simple application of the present fabrication technology does not meet the systematic error tolerance. However, the present technique is stable enough to apply some moderate feed-forward process in a continuous fabrication stage to control the integrated phase advance much less than the level equivalent to the average frequency error of 1 MHz. On the other hand, higher-order mode frequencies will be controlled better than 1 MHz level in smoothness from disk to disk. If we know the exact dimensions to realize the higher-mode frequencies, the present fabrication will produce the disks with higher-mode frequency error within 1 MHz to the ideal distribution.

Thus we conclude that the fabrication based on the present technology can produce disks which meets the basic frequency requirement of the RDDS1.

Acknowledgments

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