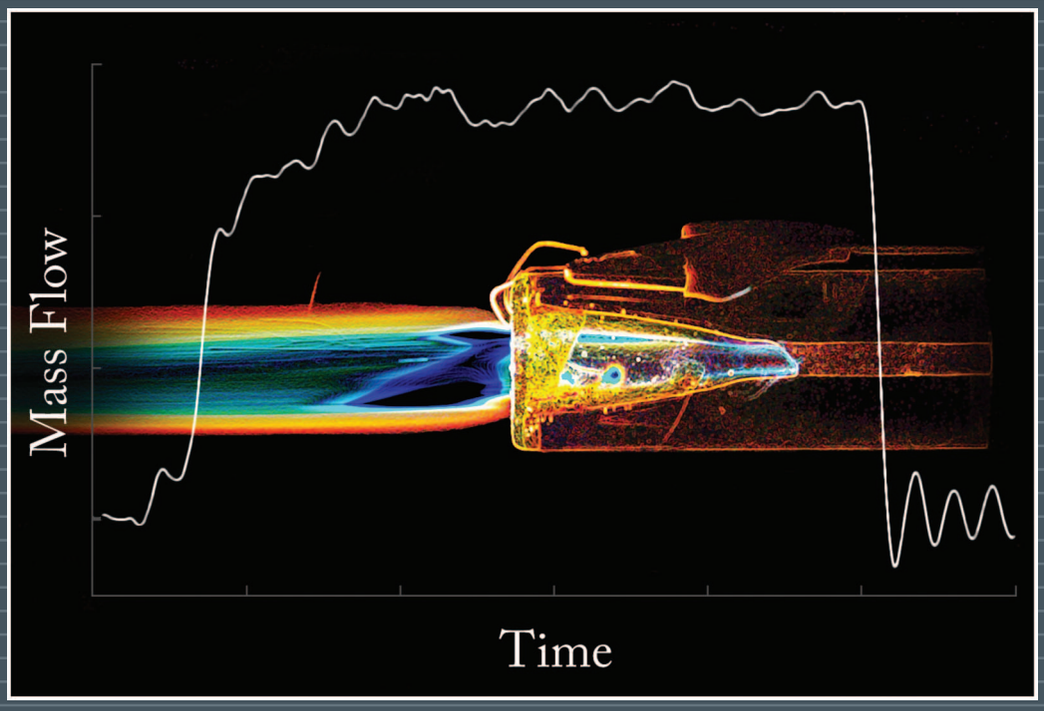
OCTOBER 2008
PART I

VOLUME 79 NUMBER 10

REVIEW OF SCIENTIFIC INSTRUMENTS



INVITED ARTICLE: Time accurate mass flow measurements of solid-fueled systems
by Jordan D. Olliges, Taylor C. Lilly, Thomas B. Joslyn, and Andrew D. Ketsdever

0034-6748(200810)79:10:1;1-4

AMERICAN INSTITUTE OF PHYSICS

REVIEW OF SCIENTIFIC INSTRUMENTS

Vol. 79, No. 10, Part I, October 2008

CODEN: RSINAK
ISSN: 0034-6748

► **Cover image** *from Jordan D. Olliges, Taylor C. Lilly, Thomas B. Joslyn, and Andrew D. Ketsdever, Rev. Sci. Instrum.* **79***, 101301 (2008). False color photograph of an acrylic (PMMA) hybrid motor fuel grain (black and blue correspond to regions of high spectral intensity). The region of high intensity inside the fuel grain is from the ignition system. Hybrid rocket firings were used to demonstrate time accurate mass flow measurements in solid-fueled systems.*

(Continued)

(Continued)

CONDENSED MATTER; MATERIALS

(Continued)

(Continued)

GENERAL INSTRUMENTS

NOTES

A publication of the American Institute of Physics, Suite 1NO1, 2 Huntington Quadrangle, Melville, NY 11747-4502

REVIEW OF SCIENTIFIC INSTRUMENTS

Vol. 79, No. 10, Part II, October 2008

CODEN: RSINAK
ISSN: 0034-6748

PROCEEDINGS OF THE 17TH TOPICAL CONFERENCE ON HIGH-TEMPERATURE PLASMA DIAGNOSTICS

(Continued)

(Continued)

(Continued)

(Continued)

(Continued)

(Continued)

(Continued)

(Continued)

(Continued)

X-RAY IMAGING, X-RAY DETECTORS, AND RADIOGRAPHY—ROBERT L. KAUFFMAN, SESSION CHAIRMAN

(Continued)

(Continued)

(Continued)

(Continued)

(Continued)

DIAGNOSTIC SUITES, HARSH ENVIRONMENTS, NEUTRAL BEAMS, ION BEAMS, PELLET INJECTION, DATA ACQUISITION AND ANALYSIS, ENGINEERING, AND DUST MEASUREMENTS—*RÉJEAN L. BOIVIN, SESSION CHAIRMAN*

(Continued)

(Continued)

(Continued)

OPTICAL (IR, VISIBLE, UV, EUV), MOTIONAL STARK EFFECT, CHARGE EXCHANGE, RECOMBINATION, BEAM EMISSION SPECTROSCOPY, OPTICAL SPECTROSCOPY, AND SUPRATHERMAL ELECTRONS—*BRENTLEY STRATTON, SESSION CHAIRMAN*

(Continued)

(Continued)

(Continued)

(Continued)

A method to measure the frequencies of individual half cells in a dumbbell cavity

Sun An,[1,a)] Zhang Liping,[1,2] Tang Yazhe,[1] Ying-min Li,[1] and Yong-Sub Cho[1]
[1]*PEFP, Korea Atomic Energy Research Institute, Daejeon 305-353, Republic of Korea*
[2]*Construction Machinery School, Chang'an University, Xi'an 710064, People's Republic of China*

(Received 22 April 2008; accepted 31 August 2008; published online 7 October 2008)

Dumbbell fabrication is a midprocess for manufacturing an elliptical superconducting rf cavity. In order to understand how a welding shrinkage affects a dumbbell's frequencies and length, we need to measure the exact frequencies of each individual half cell of a dumbbell. To improve such a calculation precision and to simplify the calculation formulae, based on a two-coupled oscillator model and a cavity perturbation theory, a new formula to calculate the individual half-cell frequencies of a dumbbell or the individual cavity frequencies of a two-cavity coupling system has been developed, and its performance has been confirmed by using a dumbbell simulation. This formula can be applied to any kind of rf cavities with electric, magnetic, or electromagnetic coupling, if a coupling hole between two coupling cavities is small compared to the wavelength. Compared to other calculation formulae, this formula simplifies the calculation process of the individual resonator frequencies of a coupling system considerably, and it can also improve the calculation precision than that of a normal calculation method. Another advantage of this new method is that we do not need to consider a coupling factor between two resonators during a testing for an individual resonator frequency of an oscillator. The developed formula has been successfully used to tune the PEFP dumbbells. © *2008 American Institute of Physics.*
[DOI: 10.1063/1.2987686]

I. INTRODUCTION

At present, a superconducting rf (SRF) accelerator is part of the accelerating structure of new particle accelerators.[1–6] For a SRF elliptical cavity accelerator, a TM010 π mode electric field is used to accelerate a charged particle. Control of the cavity frequency and field flatness of the TM010 π mode is very important during a SRF cavity production.[7]

Based on the present technology, a dumbbell fabrication is a necessary midprocess for a SRF cavity manufacture. Normally, the two half cells are welded at their irises to become a primary dumbbell. After that, a stiffening ring (single or double) is welded between these two half cells, on their outer wall. Due to a stiffening-ring welding shrinkage, the frequencies and the lengths of the two individual half cells become different, and also, the electric fields become nonsymmetric in the two half cells.

A dumbbell with a right length and frequency is necessary to build up a desired cavity. PEFP low-beta dumbbell has a double stiffening-ring structure.[8–12] In order to know how a stiffening-ring welding shrinkage affects the frequencies and how difficult it will be to tune the length and frequency of the individual half cells of a PEFP dumbbell, we need to know the exact TM010 π mode frequency of the individual half cells.

In order to measure the TM010 π mode frequency of the individual half cells precisely, first we used a simulation result to confirm the existing calculation method, which can be used to calculate an individual half cell's frequency. After checking the existing methods described in Refs. 13 and 14 we found that the calculation method was too complicated, and the precision of the method could not meet our measurement requirements; with the same methods it is not easy to obtain a consistent result. Then based on a two-coupled oscillator model and a cavity perturbation theory, a new formula to calculate the individual half-cell frequencies of a dumbbell or the individual cavity frequencies of a two-cavity coupling system has been developed and its performance has been confirmed by using a dumbbell simulation. The new formula is much simplifier and easier to use than others. Finally, the new method is successfully used to tune the PEFP low-beta dumbbells.

II. VERIFICATION OF THE EXISTING MEASUREMENT METHODS TO MEASURE THE INDIVIDUAL HALF CELLS' FREQUENCIES OF A DUMBBELL

Normally, a perturbation method is used to measure the frequencies of the individual half cells in a dumbbell. A dumbbell with shorted ends or two metal plates is a resonator.[15] We installed two small antennas on the plates and used a network analyzer to measure the dumbbell frequencies of the TM010 $\pi/2$ and π modes: $f_{\pi/2}$ and f_{π}, as shown in Fig. 1. A perturbation plate with an antenna and a short metal stick is used to measure the perturbed dumbbell frequencies of the TM010 $\pi/2$ and π modes (see Fig. 2).

[a)]Present address: Proton Engineering Frontier Project, Korea Atomic Energy Research Institute, Daejeon 305-353, Republic of Korea. Tel.: _82-42-868-2975. FAX: _82-42-861-6950. Electronic mail: sunan@kaeri.re.kr.

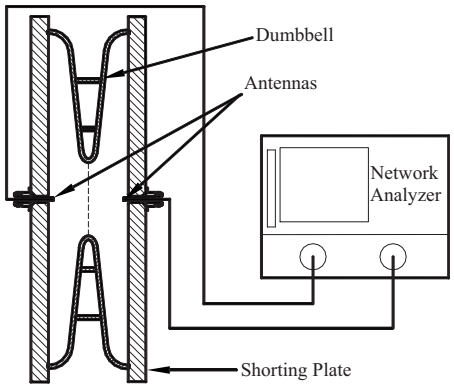


FIG. 1. A sketch of the frequency measurement setup for a PEFP low-beta dumbbell.

Alternating the positions between the plates with and without a tip, we obtain the frequency shifts of the TM010 $\pi/2$ and π modes of the individual half cells due to a perturbation. According to the tested frequencies of a dumbbell, the individual half-cell frequencies are obtained by using formulae, which can provide the individual half-cell frequencies. For a dumbbell cavity, here we use subscript "*l*" to indicate the physical parameters of the left half cell, and subscript *r* to indicate the physical parameters of the right half cell. The $f_{l,\pi}$ and $f_{r,\pi}$ describe the frequencies of the half cells simulated by POISSON SUPERFISH (Ref. 16) with such a boundary: the iris side is magnetic, and the equator side is electric. The simulated boundaries for frequencies $f_{l,\pi/2}$ and $f_{r,\pi/2}$ of the half cells are that both the iris side and the equator are electric. $f_{p,l,\pi}$ and $f_{p,l,\pi/2}$ are the TM010 passbands of the dumbbell with the tip on the left half-cell side; and $f_{p,r,\pi}$ and $f_{p,r,\pi/2}$ are the TM010 passbands of the dumbbell with the tip on the right half-cell side.

There are several formulae used to calculate the frequencies of individual half cells.[13,14] In order to confirm that these formulae can be used to calculate the half-cell frequencies precisely, we used CST MICROWAVE STUDIO (Ref. 17) to simulate an asymmetric dumbbell, as shown in Fig. 3. Here we used two PEFP low-beta half cells with different extra lengths at their equator to build a dumbbell: the extra length of the left half cell is 1.0 mm, and the extra length of the right half cell is 0.6 mm. The length and TM010 π mode frequency of a normal PEFP low-beta half cell are 45.0 mm and 700.095 MHz, respectively, simulated by CST MICROWAVE STUDIO. A metal cylinder with a diameter of 2.0 mm

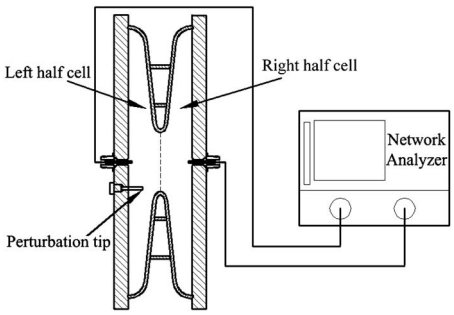


FIG. 2. A sketch of the perturbation measurement setup for a PEFP low-beta dumbbell.

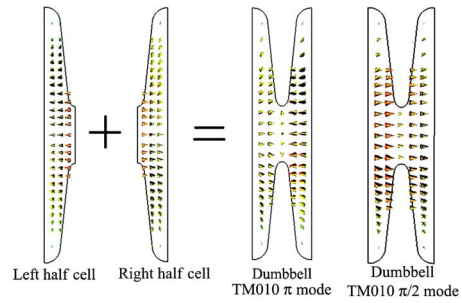


FIG. 3. (Color online) TM010 π mode field distributions of a left half cell, a right half cell; and the TM010 π and $\pi/2$ mode field distributions of a dumbbell combined by these two half-cells simulated by CST MICROWAVE STUDIO.

and a length of 5.0 mm as a perturbation tip is located either on a left half cell's wall [see Fig. 4(a)] or on a right half cell's wall [see Fig. 4(b)] near the dumbbell axis. Table I lists the simulation results by CST MICROWAVE STUDIO. In order to verify the accuracy of the simulation results, we confirmed the results by using POISSON SUPERFISH.

Submitting the simulated frequencies of the dumbbell with and without a perturbation body into the calculation method described by Ref. 13, we obtained the TM010 π mode frequencies of the individual half cells: 697.510 MHz for the left half cell, and 698.129 MHz for the right half cell. The errors are 0.789 and 0.089 MHz for the left and right half cells, respectively. We think this calculation method is too complicated and the precision of the calculation formula cannot meet our measurement requirements. Another formula described in Ref. 15 is more complicated than this one, and it is not easy to obtain similar results. In order to improve the precision for a calculation and to simplify the calculation formulae, we decided to develop a new formula.

III. DEVELOPMENT OF A NEW FORMULA TO CALCULATE THE FREQUENCIES OF THE INDIVIDUAL HALF CELLS OF A DUMBBELL

Because we only consider the half-cell frequencies, here the cavity wall loss can be neglected. According to the theory for a diffraction by a small hole (the coupling hole is small compared to the wavelength), if the difference of the TM010 π mode frequencies of the two individual half cells is not too

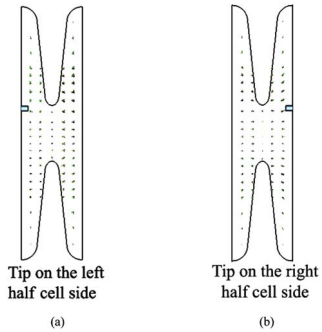


FIG. 4. (Color online) TM010 π mode field distributions of a dumbbell for different tip positions simulated by CST MICROWAVE STUDIO.

TABLE I. A simulated dumbbell based on the PEFP low-beta middle half cells.

Resonator type	Length (mm)	Frequencies of TM010 mode (MHz)	
Normal half cell	45.00	f_π	700.095
Left half cell	46.0	$f_{l,\pi}$	696.721
Right half cell	45.6	$f_{r,\pi}$	698.041
Dumbbell	91.6	f_π	697.422
		$f_{\pi/2}$	687.463
Dumbbell with tip on the left half-cell side	91.6	$f_{p,l,\pi}$	697.341
		$f_{p,l,\pi/2}$	687.277
Dumbbell with tip on the right half-cell side	91.6	$f_{p,r,\pi}$	697.312
		$f_{p,r,\pi/2}$	687.306

large, namely, $f_{l,\pi}\approx f_{r,\pi}\approx f_{0,\pi}$, the frequencies and fields of the two half cells can be described by two-coupled oscillators without a energy loss[18]

$$\frac{d^2E_l}{dt^2}+(2\pi f_{l,\pi})^2E_l=(2\pi f_{0,\pi})^2k(E_l-E_r),$$

$$\frac{d^2E_r}{dt^2}+(2\pi f_{r,\pi})^2E_r=(2\pi f_{0,\pi})^2k(E_r-E_l). \quad (1)$$

Here k is a coupling factor between the half cells, and can be electric, magnetic, or both. E_l and E_r are the electrical fields of the TM010 modes in the left half cell and in the right half cell, respectively. At a stable resonant state E_l and E_r can be expressed as

$$E_l=E_{0l}\exp(-i2\pi ft),$$

$$E_r=E_{0r}\exp(-i2\pi ft). \quad (2)$$

Here f is either the frequency of the TM010 π or the $\pi/2$ mode. E_{0l} and E_{0r} are the electrical field amplitudes of E_l and E_r, respectively. Submitting Eq. (2) into Eq. (1), Eq. (1) becomes

$$(f^2+f_{0,\pi}^2k-f_{l,\pi}^2)E_{0l}=f_{0,\pi}^2kE_{0r},$$

$$(f^2+f_{0,\pi}^2k-f_{r,\pi}^2)E_{0r}=f_{0,\pi}^2kE_{0l}. \quad (3)$$

From Eq. (3), we obtain

$$\frac{f^2+f_{0,\pi}^2k-f_{l,\pi}^2}{f_{0,\pi}^2k}=\frac{f_{0,\pi}^2k}{f^2+f_{0,\pi}^2k-f_{r,\pi}^2}. \quad (4)$$

Moreover the frequencies of the TM010 modes

$$f_\pi^2=\tfrac{1}{2}(f_{l,\pi}^2+f_{r,\pi}^2)-f_{0,\pi}^2k+\tfrac{1}{2}\sqrt{(f_{l,\pi}^2-f_{r,\pi}^2)^2+4f_{0,\pi}^4k^2},$$

$$f_{\pi/2}^2=\tfrac{1}{2}(f_{l,\pi}^2+f_{r,\pi}^2)-f_{0,\pi}^2k-\tfrac{1}{2}\sqrt{(f_{l,\pi}^2-f_{r,\pi}^2)^2+4f_{0,\pi}^4k^2}. \quad (5)$$

Combining Eqs. (3) and (5), we found

$$\frac{E_{0r,\pi}}{E_{0l,\pi}}=\frac{f_\pi^2+f_{0,\pi}^2k-f_{l,\pi}^2}{f_{0,\pi}^2k}=\frac{f_{r,\pi}^2-f_{l,\pi}^2}{2f_{0,\pi}^2k}+\sqrt{\frac{(f_{l,\pi}^2-f_{r,\pi}^2)^2}{4f_{0,\pi}^2k}+1},$$

$$\frac{E_{0r,\pi/2}}{E_{0l,\pi/2}}=\frac{f_{\pi/2}^2+f_0^2k-f_{l,\pi}^2}{f_{0,\pi}^2k}=\frac{f_{r,\pi}^2-f_{l,\pi}^2}{2f_{0,\pi}^2k}-\sqrt{\frac{(f_{l,\pi}^2-f_{r,\pi}^2)^2}{4f_{0,\pi}^2k}+1}. \quad (6)$$

From Eq. (6) we found that $E_{0r,\pi}/E_{0l,\pi}>0$ and $E_{0r,\pi/2}/E_{0l,\pi/2}<0$. This means that the electric field direction is out of the normal plane or into the normal plane of the shorting plates at the same time for the TM010 π mode; but for the TM010 $\pi/2$ mode, the electric field direction is that one is out of the normal plane and another is into the normal plane of the shorting plates at the same time.

Because the tip is located very near to a cell's axis, where mainly an electric field exists, for the TM010 modes, according to the Slater perturbation theorem, the frequency changes of a dumbbell are given by[19] $(f_0^2-f^2)/f_0^2=1.5\ E_0^2\varepsilon_0V/U$, in which V is the volume of the tip. f_0 and E_0 are the dumbbell frequency (TM010 π or $\pi/2$ mode) and the electric field at the tip position before a tip perturbation, respectively. f is the dumbbell frequency after the tip perturbs. U is the stored energy in the dumbbell. Noting that $E_{0r,\pi}/E_{0l,\pi}>0$ and $E_{0r,\pi/2}/E_{0l,\pi/2}<0$, we obtained

$$\frac{E_{0r,\pi}}{E_{0l,\pi}}=\sqrt{\frac{f_\pi^2-f_{p,r,\pi}^2}{f_\pi^2-f_{p,l,\pi}^2}},$$

$$\frac{E_{0r,\pi/2}}{E_{0l,\pi/2}}=-\sqrt{\frac{f_{\pi/2}^2-f_{p,r,\pi/2}^2}{f_{\pi/2}^2-f_{p,l,\pi/2}^2}}. \quad (7)$$

Combining this with Eqs. (5) and (6), we obtained the frequency calculation formulae for the individual half cells of a dumbbell

$$f_{l,\pi}=\sqrt{\frac{f_\pi^2+f_{\pi/2}^2}{2}+\frac{(f_\pi^2-f_{\pi/2}^2)(2-R)}{2\sqrt{R+4}}},$$

$$f_{r,\pi}=\sqrt{\frac{f_\pi^2+f_{\pi/2}^2}{2}+\frac{(f_\pi^2-f_{\pi/2}^2)(2+R)}{2\sqrt{R+4}}},$$

$$\text{here } R=\sqrt{\frac{f_\pi^2-f_{p,r,\pi}^2}{f_\pi^2-f_{p,l,\pi}^2}}-\sqrt{\frac{f_{\pi/2}^2-f_{p,r,\pi/2}^2}{f_{\pi/2}^2-f_{p,l,\pi/2}^2}}. \quad (8)$$

Submitting the data in Table I into Eq. (8), we found that the TM010 π mode frequency of the left half cell is 696.684

MHz, and the one for the right half cell is 697.868 MHz. Compared to the simulated $f_{l,\pi}$ and $f_{r,\pi}$, the errors are 0.037 and 0.173 MHz. By neglecting the errors introduced by the CST MICROWAVE STUDIO simulation, we assume that this calculation formula is simpler, and can improve the precision of a result by four times that calculated in Sec. II by using the calculation method in Ref. 13.

An accelerating mode's field flatness is an important parameter for a multicell cavity. For a dumbbell cavity, according to the definition of the field flatness,[7] its field flatness can be expressed as

$$\eta_{ff} = \frac{|E_{0r,\pi} - E_{0l,\pi}|}{0.5(E_{0r,\pi} + E_{0l,\pi})} 100\%. \tag{9}$$

Combining this with Eq. (7), the dumbbell cavity's field flatness is

$$\eta_{ff} = \frac{|\sqrt{|f_\pi^2 - f_{p,r,\pi}^2|} - \sqrt{|f_\pi^2 - f_{p,l,\pi}^2|}|}{\sqrt{|f_\pi^2 - f_{p,r,\pi}^2|} + \sqrt{|f_\pi^2 - f_{p,l,\pi}^2|}} 200\%. \tag{10}$$

The dumbbell cavity's coupling coefficient[13] can be obtained by

$$K = \frac{0.5(f_\pi^2 - f_{\pi/2}^2)}{2f_{\pi/2}^2 - f_\pi^2}. \tag{11}$$

The above formulae have shown that we can calculate an individual half cell's frequencies, and its field flatness by directly using a perturbation technique.

IV. PEFP DUMBBELL TUNING BY USING THE NEW FORMULA AND THE EXPERIMENTAL RESULTS

Before a PEFP low-beta dumbbell fabrication, each half-cell equator is 1.0 mm longer than the length determined by a SUPERFISH calculation for a dumbbell tuning and trimming, and each iris is trimmed to a suitable length by considering a welding shrinkage, then the two half cells are welded at their irises to become a primary dumbbell. After a single or double stiffening ring has been welded between two half cells, the primary dumbbell becomes a dumbbell for a SRF cavity fabrication. In order to measure and tune the PEFP low-beta dumbbells, a frequency measurement set and tuning set have been designed and fabricated. The PEFP dumbbell tuning set can stretch or press an individual half cell of a dumbbell. A spacer is used to press a half cell at its iris. A tuning ring can stretch or press a half cell at or around its equator, as shown in Fig. 5.

During the tuning of a dumbbell, the following procedure[20] is used. (1) Measure dumbbell's TM010 passbands f_π and $f_{\pi/2}$ by using a frequency testing set and a network analyzer (see Fig. 6). (2) Measure a dumbbell's length by a vernier caliper. (3) Test its perturbation frequencies $f_{p,l,\pi}$, $f_{p,l,\pi/2}$, $f_{p,r,\pi}$, and $f_{p,r,\pi/2}$ by using an asymmetrical frequency testing set and a network analyzer. (4) According to Eq. (8) obtain its individual half cells' frequencies; compare the target frequency and length with the measured frequency and length; and obtain the tuning frequencies or the trimming length: Δf_l and Δf_r. The trimming frequency sensitivity S_{trim} at an equator in a dumbbell's axial direction is obtained by a testing or by a simulation. The trimming lengths are $\Delta L_l = \Delta f_l / S_{\text{trim}}$ and $\Delta L_r = \Delta f_r / S_{\text{trim}}$. (5) If the trimming length is too large or minus, use a tuning set with a digital vernier caliper to tune the half-cell frequencies, as shown in Fig. 5. (6) Remeasure the individual half cells' frequencies of the tuned dumbbell; if their TM010 π frequencies and lengths meet the requirements, the final trimming lengths are determined, if not, redo the above steps.

In order to ensure the accuracy of the frequency measurements, maintaining a good electric contact between a

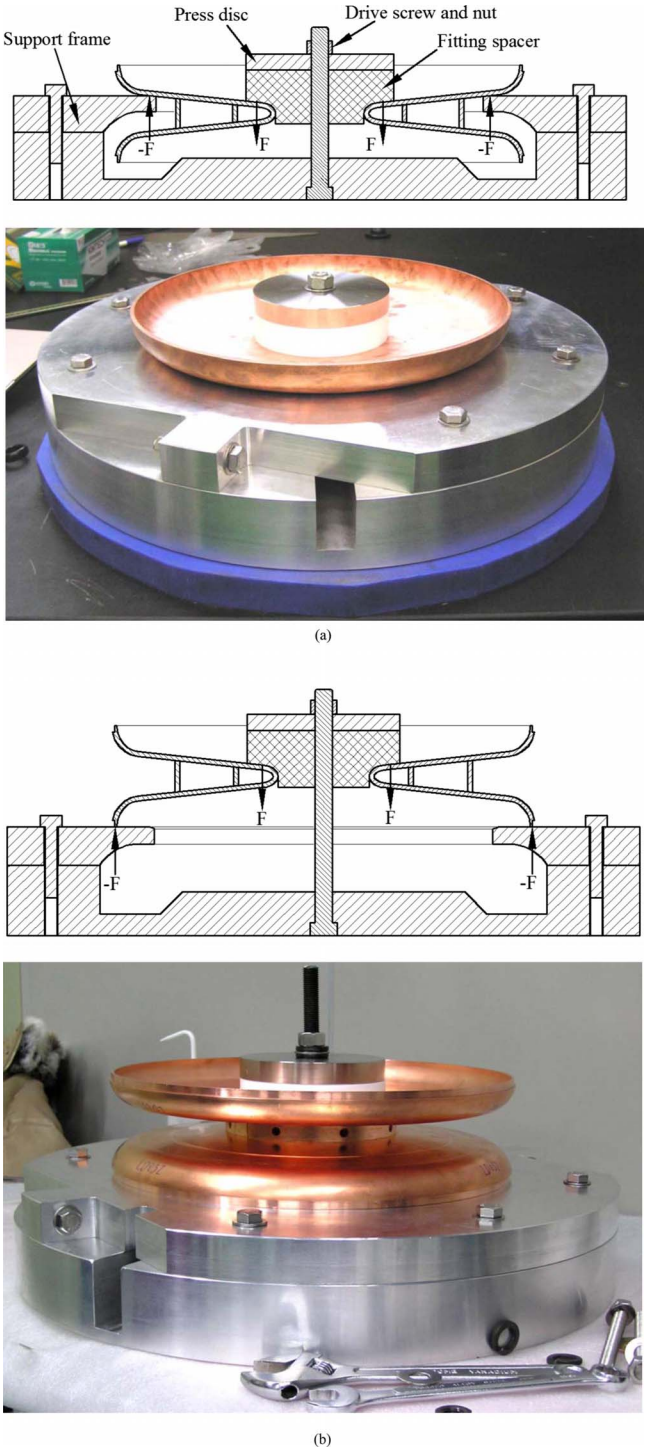


FIG. 5. (Color online) The sketches to tune the individual half cells and the PEFP tuning set. (a) Stretch a half cell and increase its TM010 π mode frequency; (b) press a half cell and decrease its TM010 π mode frequency.

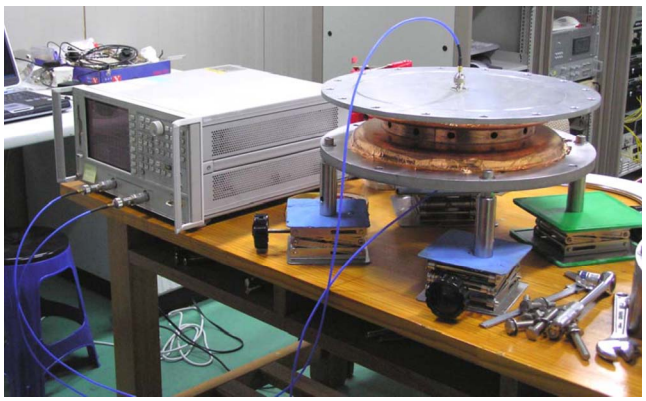


FIG. 6. (Color online) The setup to measure the PEFP dumbbell frequencies.

dumbbell and the used plates is very important, a loaded quality factor Q_L for the PEFP low-beta dumbbell measurements should be more than 200 during such frequency measurements. In order to avoid any effects by a room temperature change and the pressure of the fixtures, the testing was carried out at a constant temperature room. An aluminum tape was used to seal the dumbbell and the plates, but screw bolts and torque wrench were not used to adjust the pressure between the dumbbell and the plates during the testing.

According to this procedure, four PEFP low-beta dumbbells have been tuned successfully. Table II lists the data for a PEFP low-beta dumbbell before and after a tuning. Here we need to consider the shrinkage due to an electron beam welding at the equator, and because the tolerance control of a cavity length during a production and the dumbbell tuning are difficult tasks, the target length of a PEFP low-beta dumbbell cavity is specified as 91.280 ± 0.50. During the tuning of the PEFP low-beta cavity listed in Table II, by using our tuning calculation and tuning method, one or two times can complete a dumbbell tuning.

V. CONCLUSION

Based on a two-coupled oscillator model and a cavity perturbation theory, a new formula to calculate the individual half-cell frequencies of a dumbbell or the individual cavity frequencies of a two-cavity coupling system has been developed and its performance has been confirmed by using a dumbbell simulation. This formula can be applied to any kind of rf cavities with electric, magnetic, or electromagnetic coupling, if a coupling hole between two coupling cavities is small compared to the wavelength. Compared to other calculation formulae, this formula simplifies the calculation process of the individual resonator frequencies of a coupling system considerably, and it can also improve the calculation precision than that of a normal calculation method. Another advantage of this new method is that we do not need to consider a coupling factor between two resonators during a testing for an individual resonator frequency of an oscillator. This measurement method can achieve a measurement of a dumbbell's individual half cells' frequencies, length, and field flatness at the same time. The developed formula has been successfully used to tune the PEFP dumbbells.

TABLE II. The individual half-cell frequencies of a PEFP low-beta dumbbell before a tuning and after a tuning, and the trimming length at the equators of a tuned dumbbell.

Dumbbell state and trimming length	TM010 mode (MHz)	
Target frequency	f_π	697.907
Target length (mm)	91.280 ± 0.50	
Before tuning	$f_{l,\pi}$	695.540
	$f_{r,\pi}$	698.171
	K	1.76%
	η_{ff}	100.5%
After tuning	$f_{l,\pi}$	697.075
	$f_{r,\pi}$	697.719
	K	1.57%
	η_{ff}	12.3%
Trimming length (mm)	Left half cell	0.229
	Right half cell	0.040
Length after trimming (mm)	91.731	

ACKNOWLEDGMENTS

The authors would like to thank P. Kneisel from JLab for the essential assistance in designing the frequency measurement and tuning sets. This work is supported by the 21C Frontier R&D program in Ministry of Science and Technology of the Korean Government.

[1] J. R. Alonso, Rev. Sci. Instrum. **67**, 1308 (1996).
[2] M. Sawamura, R. Nagai, N. Kikuzawa, M. Sugimoto, N. Nishimori, and E. J. Minehara, Rev. Sci. Instrum. **70**, 3865 (1999).
[3] R. Gebel, O. Felden, and P. von Rossen, Rev. Sci. Instrum. **75**, 1860 (2004).
[4] J.-W. Kim, A. Goto, and Y. Yano, Rev. Sci. Instrum. **70**, 2293 (1999).
[5] S. H. Kim, M. Doleans, D. O. Jeon, and R. Sunlelin, Nucl. Instrum. Methods Phys. Res. A **492**, 1 (2002).
[6] R. Benaroya and K. W. Shepard, Rev. Sci. Instrum. **59**, 2100 (1988).
[7] S. An, H. Wang, and G. Wu, Proceedings of the LINAC 2004, Lübeck, Germany, August 2004, p. 815.
[8] S. An, Y. S. Cho, B. H. Choi, and J. H. Jang, J. Korean Phys. Soc. **50**, 1421 (2007).
[9] S. An, H. S. Kim, Y. S. Cho, and B. H. Choi, J. Korean Phys. Soc. **52**, 793 (2008).
[10] S. An, Y. S. Cho, and B. H. Choi, Proceedings of the APAC'07, Indore, January 2007, p. 564.
[11] S. An, C. Gao, Y. S. Cho, and B. H. Choi, Proceedings of the PAC'07, Albuquerque, NM, June 2007, p. 2164.
[12] S. An, Y. S. Cho, and B. H. Choi, Proceedings of the APAC'07, Indore, January 2007, p. 506.
[13] H. Padamsee, J. Knobloch, and T. Hays, *RF Superconductivity for Accelerators* (Wiley, New York, 1998), p. 140.
[14] C. Yinghua, J. Sekutowicz, and W. Yixiang, *Proceedings of the Fourth Workshop on RF Superconductivity*, Tsukuba, Japan, 1990/DESY-M-89-11, August 1989.
[15] S. An, T. Yazhe, Z. Liping, Y.-m. Li, G. Changyi, and Y. S. Cho, Proceedings of the EPAC'08, Genoa, Italy, June 2008, p. 823.
[16] Los Alamos Accelerator Code Group, *Poisson/Superfish Reference Manual* (Los Alamos National Laboratory, Los Alamos, NM, 1987), p. LA-UR-87-126.
[17] CST MICROWAVE STUDIO, Version 5, Getting Started, *CST-Computer Simulation Technology*, 2003.
[18] H. A. Bethe, Phys. Rev. **66**, 163 (1944).
[19] E. L. Ginzton, *Microwave Measurements* (McGraw-Hill, New York, 1957), p. 448.
[20] G. Ciovati, P. Kneisel, and J. Sekutowicz, *Method to adjust frequency and length of dumbbells to nominal values* (TJNAF, Newport News, VA, 2002), Paper No. JLab-TN-02-005-1.