[2] J. P. Mondal, "An experimental verification of a simple distributed model of MIM capacitors for MMIC applications," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 403–408, Apr. 1987.

[3] M. Engels and R. H. Jansen, "Rigorous 3D simulation and an efficient approximate model of MMIC overlay capacitors with multiple feed-points," in *Proc. IEEE MTT-S Int. Microwave Symp. Dig.*, Atlanta, GA, 1993, pp. 757–760.

[4] G. Bartolucci, F. Giannini, E. Limiti, and S. P. Marsh, "MIM capacitor modeling: A planar approach," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 901–903, Apr. 1995.

[5] I. Wolff and N. Knoppik, "Rectangular and circular microstrip disk capacitors and resonators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 857–864, Oct. 1974.

[6] *IE3D Users's Manual*, Zeland Software Inc., Freemont, CA, 1998.

A Simple Procedure for Impedance Matching and Tuning of Microwave Couplers for an Electron Linear Accelerator

Marcos A. R. Franco, Valdir A. Serrão, Celso Fuhrmann, and Sílvio B. Herdade

***Abstract*—A simple experimental procedure to match and tune "doorknob"-type microwave couplers is presented in this paper. The procedure is suitable for accelerating structures with both input and output couplers and allows a fast convergence to the minimum reflection condition for a cavity coupler with fixed phase shift. The standing-wave ratio and the coupling cavity phase shift as functions of the coupler dimensions and frequency are also reported.**

***Index Terms*—Accelerator RF systems, electron linear accelerators, impedance matching, microwave measurements, waveguide couplers.**

I. Introduction

In an RF electron linear accelerator, the injected beam is accelerated by the longitudinal electric field of the pulsed electromagnetic wave, which propagates along the symmetry axis of an accelerating periodic structure. The microwave power is carried by rectangular waveguides in the fundamental propagation mode TE_{10}, while in the periodic structure, the fundamental mode is the TM_{01}. Therefore, to minimize reflections at the waveguide-to-accelerating structure junction, an impedance-matching and mode-transforming device is required. The device, called a "microwave coupler," must minimize the standing-wave ratio (SWR) between the waveguide and coupler cavity without changing the phase of the wave launched along the accelerating structure. For a safe high-power amplifier operation, only SWR values less than 1.1 are tolerated.

Two basic procedures to match and tune the coupling system are presented in the literature. First, the modified nodal-shift method (Gallagher's method) is used to match the coupler, while the phase between the cavities of the periodic structure is checked by the nodal-shift method [1]–[3]. A second approach is the time-domain reflectometry method [4], [5] in which the coupler is fed by a pulsed microwave signal, with width shorter than the structure filling time. The time difference between the reflected waves from the input and output couplers appears because of the time required for the microwave to travel through the structure. The matching adjustments are performed by varying the geometrical parameters of the couplers. After this step, the nodal-shift method is used to check the final tuning of the structure with the couplers.

In this paper, an experimental procedure to match and tune two doorknob-type couplers with a 1300-MHz $2\pi/3$-mode disk-loaded structure is presented [6]. This procedure, which includes the optimal characteristics of the two previously discussed methods, is a simple and fast way to improve the matching and tuning of the couplers.

Manuscript received October 4, 1999. This work was supported in part by the Fundação de Amparo à Pesquisa do Estado de São Paulo under Process 84/2869-0.

M. A. R. Franco, V. A. Serrão, and C. Fuhrmann are with the Division of Applied Physics, Centro Técnico Aeroespacial, CEP 12228-840 São Jose dos Campos, Brazil (e-mail: marcos@ieav.cta.br).

S. B. Herdade is with the Physics Institute, University of São Paulo, CEP 05315-970 São Paulo, Brazil.

Publisher Item Identifier S 0018-9480(01)01696-9.

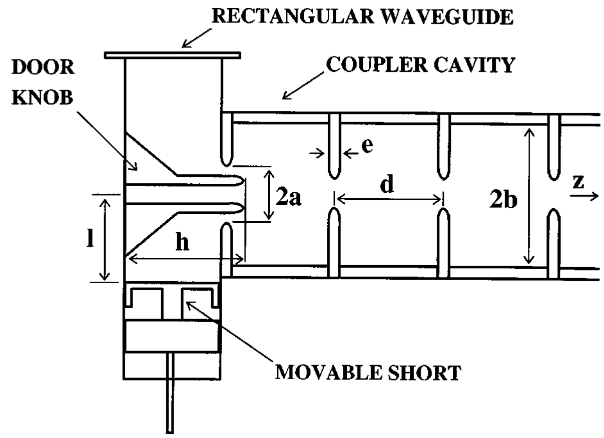

Fig. 1. Schematic view of the doorknob microwave coupler and disk-loaded waveguide structure, where **e** is the disk thickness, **d** is the cavity length, **2b** is the cylindrical cavity diameter, **2a** is the disk-hole diameter, **h** is the doorknob height, and **l** is the movable short position.

II. Doorknob Microwave Coupler

In the doorknob-type coupler, a cylindrical cone and movable short are used to match the impedance between the waveguide and accelerating structure (Fig. 1). The doorknob coupler permits a simple mechanical adjustment and, because of the cylindrical symmetry, it does not introduce transversal asymmetries in the axial electric field.

To match and tune a doorknob coupler, it is necessary to adjust three geometric parameters: the disk-hole diameter **(2a)** of the coupler cavity, the doorknob height **(h)**, and the movable short position **(l)**.

III. Experimental Methods and Procedure

Three complementary experimental methods were used to tune and match the couplers: the time-domain reflectometry method to determine approximate values of the geometric parameters (**h**, **l**, **2a**); the nodal-shift method to measure the phase shift between the cavities of the accelerating structure, and the Gallagher's method to obtain more accurate measurements of the SWR values.

In the reflectometry method, a microwave pulse is injected into the assembly composed by the doorknob couplers and the accelerating structure (Fig. 2). Although the reflections can be reduced (SWR values near 1.3) by varying the parameters **h**, **l**, and **2a**, the phase shift cannot be measured. The values of **h**, **l**, and **2a** determined by this method are the starting data to get more accurate measurements and to really minimize the SWR.

In Gallagher's method, the SWR is measured only for the coupler in which the microwave pulse is injected. These SWR measurements are

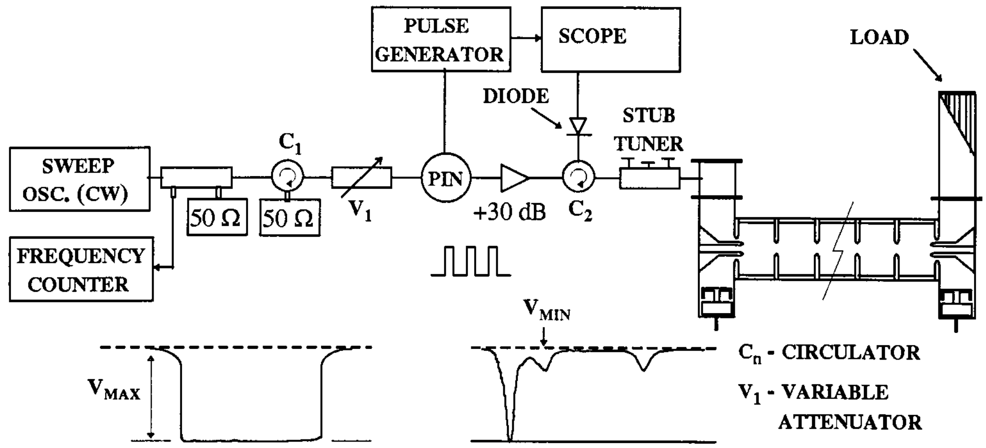

Fig. 2. Block diagram of the experimental arrangement used in the reflectometry method and the general shape of incident and reflected pulses.

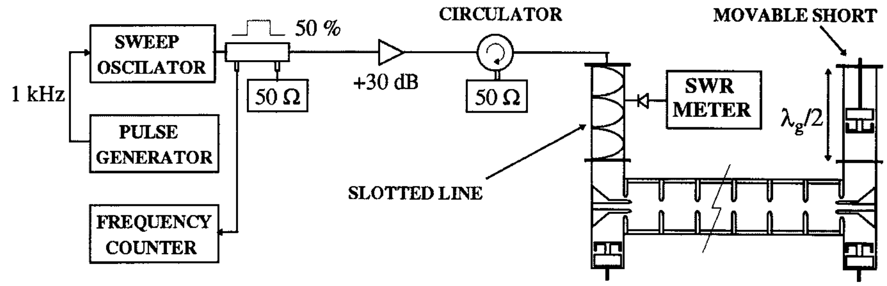

Fig. 3. Block diagram of the experimental arrangement used in Gallagher's method.

not influenced either by the accelerating structure or the other coupler, which is connected to a movable short (Fig. 3).

The phase shift between cavities, which should be maintained at 120°, is measured by the nodal-shift method as follows. A detuning plunger, acting as a short, is displaced between two cavities. The impedances (or admittances) are measured with a slotted line and the nodal point displacement of the standing wave in the slotted line supplies the phase shift of each cavity.

There are several groups of geometric parameters **h**, **l**, and **2a** that sometimes minimize the SWR and sometimes tune the coupler cavity. In order to improve the convergence process satisfying both conditions, the following procedure was adopted [6]: a disk-hole diameter (**2a**) of the coupler cavity is fixed, the parameters **h** and **l** are determined in an approximate way (reflectometry method), **h** and **l** are varied until a 120° phase shift (θ) in the coupler cavity (nodal-shift method) is obtained, the SWR of the coupler is measured and a set (**h**, **l**, SWR, $\theta = 120°$) is determined (Gallagher's method), new sets can be obtained by modifying **h** and **l** ($\theta = 120°$), and measuring the SWR. This procedure is fast and converges to the minimum SWR. However, if the condition $\mathrm{SWR} \leq 1.1$ is not satisfied, the procedure should be repeated changing the dimension of disk-hole diameter (**2a**).

IV. Experimental Results

The procedure presented in Section III was applied to tuning and matching two prototypes of doorknob couplers, using a traveling-wave constant-gradient structure with 12 cavities. The cavities of the accelerating structure have high quality factor ($Q \approx 19\,000$). Therefore, to avoid frequency detuning, the measurements were carried out in a carefully temperature-controlled dry room [6].

The doorknob coupler consists of two copper-machined pieces: a conical base and threaded tube, which screws on the base, thus providing the

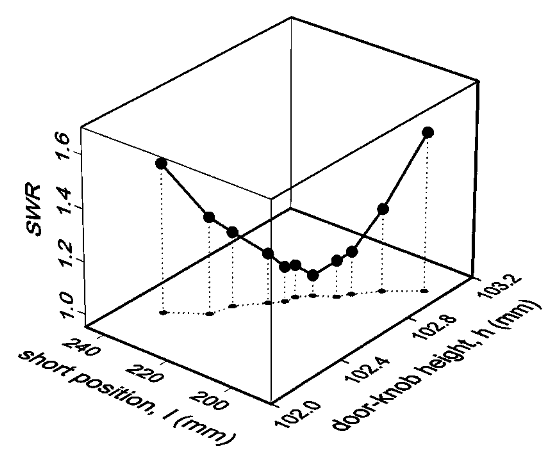

Fig. 4. SWR as a function of **h** and **l** for $\theta = 120°$ for the input coupler with **2a** $= 75$ mm.

adjustment of the doorknob height (**h**). The impedance matching (SWR) and phase of the first cavity both change very quickly with the doorknob height (**h**). Therefore, the prototypes were manufactured so as to allow this parameter to be varied in steps of 0.04 mm.

The data set (**h**, **l**, SWR, $\theta = 120°$) for the input coupler with **2a** $= 75$ mm, measured by the procedure proposed in this paper, is shown in the Fig. 4. The SWR values are obtained from the admittance circles in the Smith diagram, as described in Gallagher's method.

The values of the parameters **2a**, **2b**, **h**, and **l** that match and tune the input and output couplers are presented in Table I.

During the high-power operation of the accelerating structure, a cooling-water system maintains the operating temperature of the cavities within a range of ± 1 °C. The rate of change of the cavity frequency

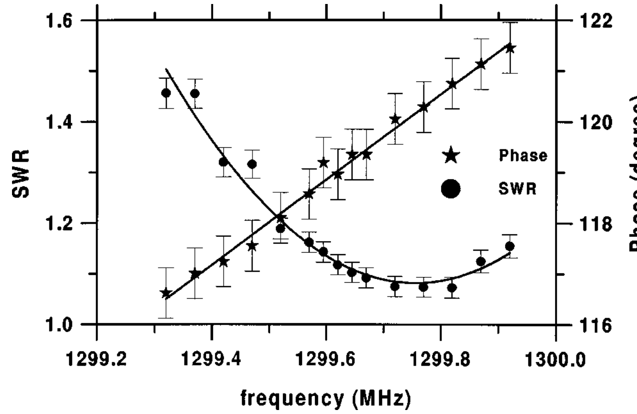

Fig. 5. SWR and phase shift (θ) of the coupler cavity versus frequency for the input coupler with **2a** $= 70$ mm.

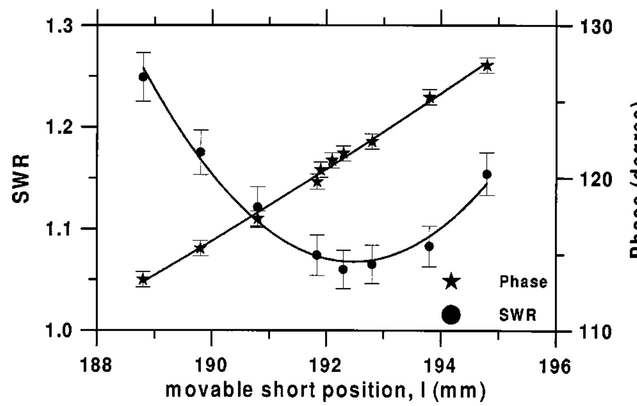

Fig. 6. SWR and phase shift (θ) of the coupler cavity versus movable short position (**l**) for the input coupler with **2a** $= 70$ mm.

TABLE I
RESULTS OF THE MATCHING AND TUNING OF THE MICROWAVE COUPLERS

Coupler	Coupler Cavity **2b** (mm)	Coupler Cavity **2a** (mm)	Door-Knob height **h** (mm)	Short position **l** (mm)	SWR
Input	180.161(5)	70.0(1)	101.15(4)	191.6(1)	1.080(20)
		75.0(1)	102.71(4)	212.9(1)	1.029(15)
Output	179.733(5)	66.0(1)	100.78(4)	191.6(1)	1.040(14)
		70.0(1)	101.83(4)	198.6(1)	1.012(17)

with the temperature is 21.7 kHz/°C. Thus, the maximum frequency variation is 43.4 kHz. Therefore, it is necessary to know how the matching and tuning of the couplers change with the resonant frequency.

The values of the SWR and θ as functions of the frequency, for the input microwave coupler with **2a** $= 70$ mm, are shown in Fig. 5. The measurements were accomplished starting from the matching and tuning conditions.

From the measurements performed both for the input and output couplers, it can be verified that the SWR is larger than 1.1 for frequency variations larger than 180 kHz. Therefore, the admitted bandwidth (43.4 kHz) satisfies the condition $\mathrm{SWR} \leq 1.1$ perfectly.

In order to determine the mechanical tolerances required for the microwave couplers design, it is necessary to know how the geometric parameters (**h** and **l**) affect the SWR values and the phase shift (θ) of the coupler cavity. The SWR and θ data as functions of **l** and **h**, for the input coupler with **2a** $= 70$ mm, are shown in Figs. 6 and 7, respectively. These measurements were also accomplished starting from the matching and tuning conditions.

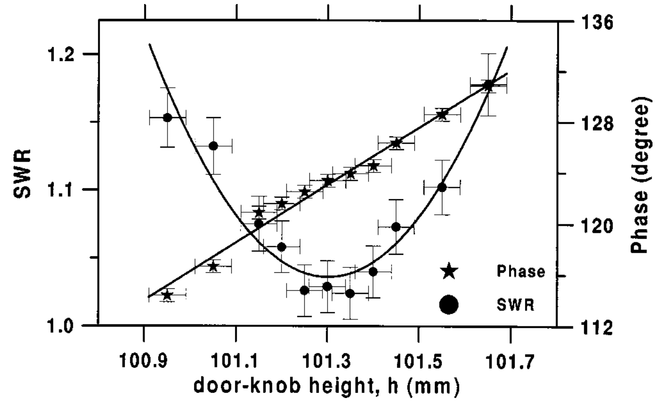

Fig. 7. SWR and phase shift (θ) of the coupler cavity versus doorknob height (**h**) for the input coupler with **2a** $= 70$ mm.

TABLE II
TOLERANCES AND VARIATION RATE OF THE COUPLER PARAMETERS FOR THE CONDITION $\mathrm{SWR} \leq 1.1$

Coupler	**2a** (mm)	**Δh** (mm)	**Δl** (mm)	**Δθ/Δh** (degree/mm)	**Δθ/Δl** (degree/mm)
Input	70.0	0.42	2.8	22.6(7)	2.40(9)
	75.0	0.36	12.0	28.7(6)	0.61(2)
Output	66.0	0.29	2.2	33.2(8)	5.76(11)
	70.0	0.31	6.2	36.7(8)	1.70(4)

Table II presents both the maximum permitted ranges Δ**h** and Δ**l** that satisfy the condition $\mathrm{SWR} \leq 1.1$ and the rates of the coupler cavity phase shift change ($\Delta\theta$) with respect to **h** and **l** variations. The SWR and phase shift of the coupler cavity are both more sensitive to changes in the parameter **h** than in the parameter **l**.

V. CONCLUSION

A simple procedure for impedance matching and tuning of microwave couplers, which feed an accelerating periodic structure, has been presented in this paper. The procedure was developed by taking into account experimental techniques usually applied in an independent way.

Curves for both the SWR and phase shift (θ) were obtained as functions of the microwave frequency, doorknob height (**h**), and movable short position (**l**). The mechanical tolerances of the design parameters and frequency bandwidth of the doorknob couplers were determined. The experimental results are compatible with the linear accelerator RF system project requirements.

REFERENCES

[1] W. J. Gallagher, "Measurement techniques for periodic structures," Microwave Lab., Stanford Univ., Stanford, CA, Rep. 767, 1960.
[2] R. B. Neal, Ed., *The Stanford Two-Mile Accelerator*. New York: W. A. Benjamin, 1968, pp. 136–142.
[3] P. M. Lapostolle and A. L. Septier, Eds., *Linear Accelerators*. Amsterdam, The Netherlands: North-Holland, 1970, pp. 96–105.
[4] H. Matsumoto, J. Tanaka, S. Arai, Y. Iino, N. Yamaguchi, and S. Kato, "Phase characteristics of accelerator guide with the couplers," in *Proc. 2nd Accelerator Sci. Technol. Symp. Dig.*, Tokyo, Japan, 1978, pp. 47–48.
[5] H. Matsumoto, J. Tanaka, I. Sato, S. Arai, N. Yamaguchi, Y. Iino, and S. Kato, "Characteristics of the door-knob type coupler for an electron linear accelerator," (in Japanese), Nat. Lab. High Energy Phys., Ohomachi, Japan, KEK-Accelerator-79-5, 1980.
[6] M. A. R. Franco, "Contribution to the study of electron accelerating structures and microwave couplers," Masters thesis (in Portuguese), Inst. Física, Univ. São Paulo, São Paulo, Brazil, 1991.