

# SIMULATION RESULTS OF RF COUPLER CONTROLLABLE BY DIELECTRIC FLUID\*

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*Abstract*

Tunable couplers for adjusting radiofrequency (RF) power coupling into accelerator cavities are useful devices for achieving optimal operation efficiency. Standard mechanical tuners currently used in large accelerator facilities are bulky and complicated. A novel tuner, based on the introduction of dielectric tubes or fluid-filled volumes adjacent to, but separated by window(s) from the coupler, is described. Simulations have shown that the tuner has a fairly large adjustment range and also demonstrated the viability of the tuning concept using fluid circuit.

## INTRODUCTION

High power couplers are among the critical components in microwave systems and are widely used in high-energy particle accelerators [1-5]. A correct coupling coefficient is critical to the efficient operation of an accelerator and the reliable performance of an RF source. However, the unloaded cavity Q-factor, and hence the coupling coefficient, for an as-built cavity is impacted by uncertainties such as temperature variations, machining errors, or installation deviations. A coupler with variable coupling properties is often needed to make the microwave power system work properly. Currently, there are tunable couplers utilized in both normal conducting (NC) and superconducting (SC) RF accelerators [1-2]. Dominantly, the tunable couplers are based on mechanic adjustments: movements of the couplers' conductors are necessary. Design of such couplers is complicated: for SC RF accelerators, cryomodules together with high vacuum parts need to be considered; while in NC RF accelerators, bellows for maintaining high vacuum in RF cavities will be employed. The coupler lifetime is of the order of a thousand cycles and is limited by bellow fatigue.

We proposed an alternative way of tuning the couplers using dielectric fluids. The method would provide in-situ adjustment of the external Q and a simple and flexible means of meeting the performance requirements of a large variety of vacuum electronics devices.

## DESCRIPTION OF SIMULATIONS

Couplers, together with devices such as RF sources, transmission lines and RF cavities, are integral parts of a large and correlated circuitry. The circuitry between an RF source and an accelerating structure is actually a combination of a transformer represented, e.g., by a mode transformer or a transition between two or more transmission lines, and a coupler itself as an input of the

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intermediate transmission line into the cavity. Overall coupling of the circuitry depends on the impedance matrix of the transformer that is represented by an equivalent four-pole device connected to a cavity. Thus one can vary the coupling by changing the characteristics of the transformer impedances while the internal coupling between the cavity and its direct or intermediate feeder remains fixed. One way to change the impedance is to change the effective dielectric constant of a part of the transformer (or coupler) volume. It can be accomplished, for instance, by varying the amount of a refractive liquid in an external volume connected electromagnetically to the cavity by controls of fluid circuits (e.g., the number of capillary tubes filled, or liquid type in a chamber or both), and/or by co-mixing liquids with different dielectric constants in a gas/fluid system or suspensions thereof.

### *Simulations of a 15.6 GHz Coupler*

Preliminary simulations were conducted on a HOM-suppressed coupler model, which was an original design (without fluids) in a previous DULY SBIR project. This coupler is essentially a rectangular waveguide (WR62) coupled to a circular waveguide at a normal intersection (see Fig. 1). The coupler used two rectangular stubs for matching (by changing the lengths of the stubs). The stubs have an angle of 120° with respect to the waveguide.

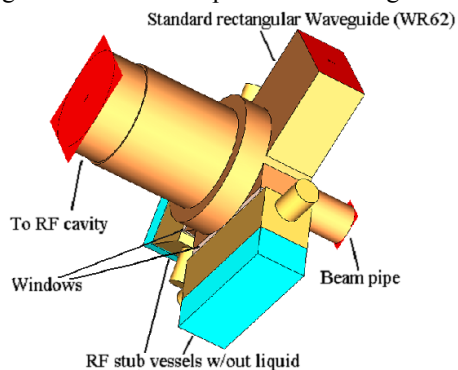


Figure 1: CST Microwave Studio model of the coupler

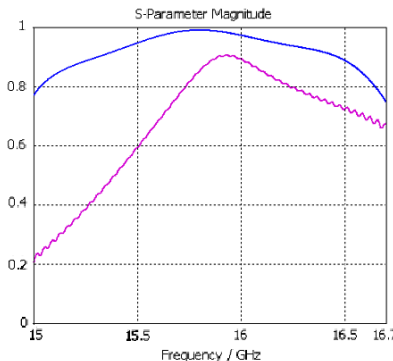


Figure 2: Curves before and after oil fills the stubs.

To demonstrate the adjustable coupling ability of the fluid-controlled coupler in this case, we first made a CST MWS model of the coupler with vacuum stubs that had unmatched transmission properties. Then we filled the stubs with transformer oil (permittivity=2.2), adjusted the level of oil in the stubs and calculated the transmission scattering parameter  $S_{21}$ . Simulation results in Fig. 2 indicate a large improvement of transmission properties. For the vacuum stubs without oil (pink curve),  $S_{21}$  is less than 0.7 at 15.6 GHz. After filling in an appropriate amount of oil into the stubs (blue curve),  $S_{21}$  is increased to 0.95 or above at 15.6 GHz. Meanwhile, transmission properties in the band from 15 GHz to 16.7 GHz have been also improved greatly, though the highest transmission frequency has shifted. The preliminary simulation results show the effectiveness of dielectric liquid exploited in a tunable coupler for an accelerator application.

### Simulations of a TTF Doorknob Coupler

In another feasibility demonstration of the tunable coupler concept, we modeled an L-band coupler that comprised a waveguide to a coax transition in which a doorknob coupling configuration was employed. The 1.3 GHz TTF coupler was adopted from DESY and used in our previous PWT project. The outer conductor radius of the coax is 50.74 mm and the characteristic impedance of the coax is  $50\Omega$ . RF power is coupled into the coax from a WR650 guide by a waveguide/doorknob transition. The original coupler has a fixed length vacuum stub to match the coupling properties in the transition.

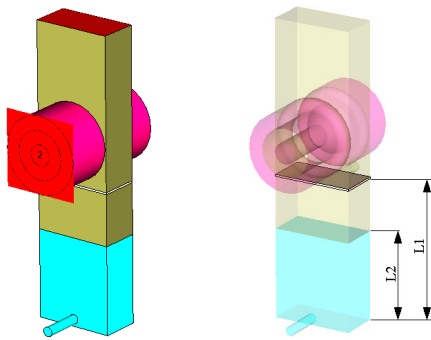


Figure 3: CST MW Model of an L-band Doorknob coupler.

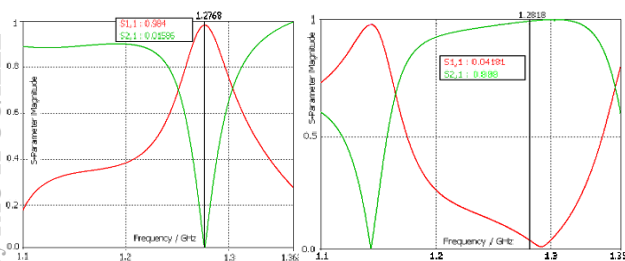


Figure 4: Simulation results of an L-band coupler. Left: stub is empty; Right: stub is full of Vaseline oil.

We added a ceramic window in the stub to separate the stub from the vacuum of the other part of the coupler. Vaseline oil (permittivity: 2.16, low loss) was put into the stub for varying the coupling properties. The stub length,  $L_1$ , is 385.2 mm. Oil level is indicated by  $L_2$  (mm). Variations of S-parameters vs oil level were studied.

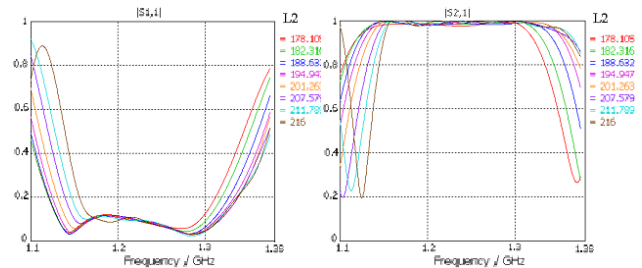


Figure 5: S-parameters for different Vaseline oil level.

First, the transmission through the couplers for two cases has been simulated: the vessels when empty and when filled with Vaseline oil. The results were plotted in Fig. 4 (excitation signal input from Port 1). VSWR for the second variant changed by more than two orders, from 124 to 1.13, in the vicinity of 1.28 GHz center frequency after the initially empty stubs are filled with oil. The variation range of the external  $Q$  in this approach is determined by how well the “operating” frequency, i.e. both transmission and its tuning range are maximum, of the tunable coupler is matched to the cavity frequency.

Beside these two simple cases, we studied the transmission property by varying  $L_2$  from the length of stub (oil full) to zero (empty) in fine steps. It is found that very large  $S_{21}$  ( $>0.97$ ) or pass-band has been obtained in a frequency range  $>150$  MHz while reflection is very small ( $S_{11} < 0.12$ ), when  $L_2$  is varied between 175.1 mm and 216 mm (see Fig. 5). Note that the pass-band will shift and it can cover 1.3 GHz if  $L_2$  is changed. These results can be further improved, using even finer steps, so that total transmission could be achieved with longer run time.

### Simulations of a Coupler with a Disk Matching Section

The Advanced Photon Source (APS) at Argonne National Laboratory (ANL) needs a 350 MHz tunable input coupler for an RF cavity. Cooperation between DULY and ANL is being carried out to study the feasibility of using the fluid-controlled tunable coupler to meet their need. APS’s original coupler uses a cylindrical coupling disk that couples the microwave power from a single-feed WR2300 rectangular waveguide with a half height to an RF cavity through a  $50\Omega$  short coax line.

A stub was added in the CST MWS models for tuning the waveguide to the coax coupling. In Fig.6,  $l$  is the inner conductor length and  $t$  is the thickness of the coupling disk.  $L_1$ ,  $L_2$ , and  $L_3$  are the stub length, the waveguide length, and the transformer oil height in the stub respectively.  $D_1$ ,  $D_2$ , and  $D_3$  are diameters of the

coupling disk, the outer conductor and inner conductor of the transmission line in sequence. Six representative cases of the coupler have been simulated and their results are summarized in Table 1. From the table, it is viewed that mismatch can be greatly improved when the level of the transformer oil is adjusted.

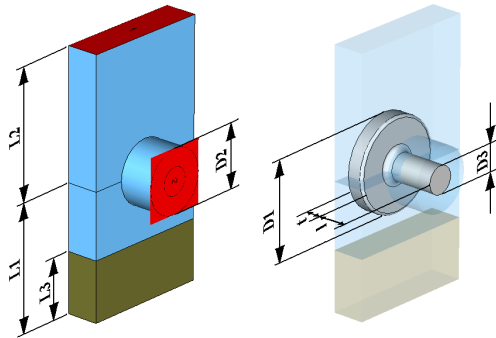


Figure 6: Model of the ANL coupler at the transition from the half-height WR2300 to the coax, incorporating fluid for coupling adjustment.

Table 1: Simulation Results Summarized from the Six Cases

Case No.	D1 (mm)	D2 (mm)	D3 (mm)	t (mm)	L1 (mm)	L3 (mm)	S11 at 350 MHz	S21 at 350 MHz
1	409.32	102.01	44.30	65.19	646.14	0	0.996	0.025
2	409.32	102.01	44.30	65.19	646.14	203.66	0.042	0.9998
3	409.32	102.01	44.30	65.19	731.47	0	0.633	0.774
4	409.32	102.01	44.30	65.19	731.47	167.33	0.061	0.993
5	420.6	286.03	124.22	72.08	565.00	0	0.981	0.165
6	420.6	286.03	124.22	72.08	565.00	340.00	0.065	0.9996

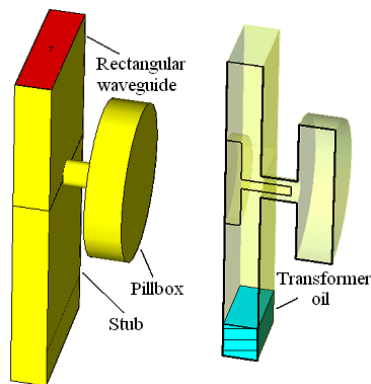


Figure 7: CST MWS Model of the ANL coupler including a coaxial coupling into a pillbox. Left: coupler with the pillbox; Right: cross section of the model.

To simulate a simplified variant of the ANL coupler that is coupled with an RF cavity, we combined a pillbox with the disk matching coupler above and set up a CST

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MWS model to include the couplings both at the rectangular waveguide/coaxial line transition and at the coaxial line/RF cavity transition. The model is shown in Fig. 7. The length of the stub (L1) is 870 mm.

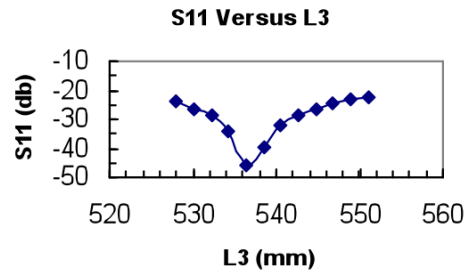


Figure 8: S11 tuned by the transformer oil level in the stub with  $l_{in}$  fixed at 285.8 mm

With the stub being empty, we obtained the relation between S11 and  $l_{in}$ , the length of the inner conductor of the coaxial transmission line, by varying  $l_{in}$  in the above model. From this relation, we found that the inner conductor length for inducing critical coupling to the pillbox lies between 280.1 mm and 280.2 mm. To simulate the correcting function of the transformer oil-filled stub to the coupling change due to, for example, beam loading, we chose two mismatched points on either side of the critical coupling point and found the levels of fluid needed to make the corrections. The two inner conductor's positions we chose for the simulations were at  $l_{in}=274.5$  mm and 285.8 mm respectively. And we also found that both of the mismatches caused by the changes of  $l_{in}$  have been corrected perfectly by the oil level changes in the stub: S11 can be changed by oil level more than 20db. Further simulations confirmed that mismatches due to over-coupling, as well as under-coupling (not shown in this article), can also be corrected by the transformer oil (see Fig.8) and the correction amplitude is as high as 36 db when oil level is at 536.5 mm.

SUMMARY

We have demonstrated the feasibility of fluid-controlled couplers through calculations and simulations in our Phase I work. These simulations show that the fluid-controlled couplers have the advantages of large tuning ranges, good sensitivity and ease of tuning. The liquid can be exploited to correct mismatching when the coupler is in either under-coupling state or over-coupling state, thus extending the usefulness of this method beyond accelerator applications, potentially to other applications such as microwave wireless communications.

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