Study on the Resonant Cavity for Low-level RF System at the PBP-CMU Electron Linac Laboratory

W Foosang[1], N. Kangrang[1], S Pakluea[1], K Buakor[1], J Saisut[1,2,3], S Rimjaem[1,2,3,*]

[1]Plasma and Beam Physics Research Facility, Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand
[2]Thailand Center of Excellence in Physics, Commission on Higher Education, Bangkok 10400, Thailand
[3]Research Center in Physics and Astronomy, Chiang Mai University, Chiang Mai 50200, Thailand

*E-mail: sakhorn.rimjaem@cmu.ac.th, watanyu_f@cmu.ac.th

Abstract. This research aims to investigate characteristics of the resonant cavity, which is a part of the radio-frequency (RF) power system of the electron linear accelerator (linac) at the PBP-CMU Electron Linac Laboratory, Chiang Mai University. A resonant cavity is used to resonate the RF wave of the desired frequency by exploiting the relation between the cavity dimension and the resonant frequency. The resultant RF wave from the resonant cavity is later amplified in RF amplifier and klystron. Finally, it is used to accelerate electron beam in the linac that has a specific operating frequency. Simulations of the electric and magnetic field patterns inside the resonant cavity as well as the resonant frequency were performed by using the program SUPERFISH. Meanwhile, measurements of the resonant frequency for the real cavity were done with a spectrum analyzer. The relation between the cavity length and the resonant frequency was experimentally studied. The study results showed that our resonant cavity has TM_{012} mode and the resonant frequency has a negative linear correlation to the cavity length. This cavity has an inner radius of 6.892 cm. The resonant frequency of the cavity can be varied by adjusting its length. The optimal cavity length, which produces the RF waves of 2856 MHz, obtained from the measurement was 13.48 cm.

1. Introduction

At the PBP-CMU Electron Linac Laboratory, an upgrade facility to produce terahertz (THz) coherent radiation and mid-infrared (MIR) free-electron laser (FEL) is under construction. In order to obtain the MIR-FEL, it requires an electron beam with energy in a range of 15-30 MeV. The THz radiation requires a lower beam energy down to 10 MeV [1]. To fulfil that aim, the characteristics of the radio-frequency (RF) system for the accelerator needs to be diagnosed. The RF wave is generated in a low-level RF system with an RF oscillator and its desired frequency is obtained from a cylindrical cavity called a resonator. Combination of both devices generates the RF waves with small power in a range of watt, before being amplified by the amplifiers and the klystron, respectively. The klystron can increase the RF power up to more than million times of its initial value. Then, the high-power RF waves is transported to the linac for accelerating electron beam.

This research is concentrated on studying the resonant cavity, which is one of very important parts of the RF generator system. Although, the theory that describes the principle of a resonator is well

known, but there was no any complete study for our resonator that can tell the exact cavity mode. Thus, the characteristics of the resonant cavity was investigated in our study. Simulations of electric and magnetic field patterns inside the cavity and the resonant frequency were performed. Moreover, measurements of the resonant frequency for the real cavity were done with a spectrum analyzer. Furthermore, study on relation of the cavity length and the resonant frequency was conducted.

2. Simulation of the resonant cavity

The resonant cavity that is being used at our laboratory has a simple pillbox shape with a radius of 6.892 cm. It is designed to operate at the resonant frequency of 2856 MHz. That is, the output RF wave has the same frequency. The exterior and interior pictures as well as the drawing of the cavity's exterior view and dimensions are presented in figure 1. The cavity has two removable metallic end plates, one is for cavity length adjustment and another has antenna loops for RF wave transmission.

Figure 1. Pictures and drawing of the resonant cavity at the PBP-CMU Electron Linac Laboratory.

In order to study the resonant-cavity mode, computer simulations with program SUPERFISH [2], which can solve 2-D or cylindrical symmetric electromagnetic (EM) problems, were performed. A simple pillbox cavity with an initial mesh size of 0.25 cm was used to investigate the field pattern in the resonant cavity. Figure 2 (left) presents the simulated EM field patterns inside the pillbox cavity. The pink lines indicate electric equipotential lines and the arrows represent the electric field vectors. The red circles and the directional symbols (crosses and dots) indicate the magnetic field vectors. As seen in the figure, the RF field pattern inside the cavity is not a simple TM_{010} mode. Since the longitudinal distribution has two electric field variations, the longitudinal index p of the TM_{mnp} cavity mode has to be 2. Whereas, m and n need some calculation before being answered accurately.
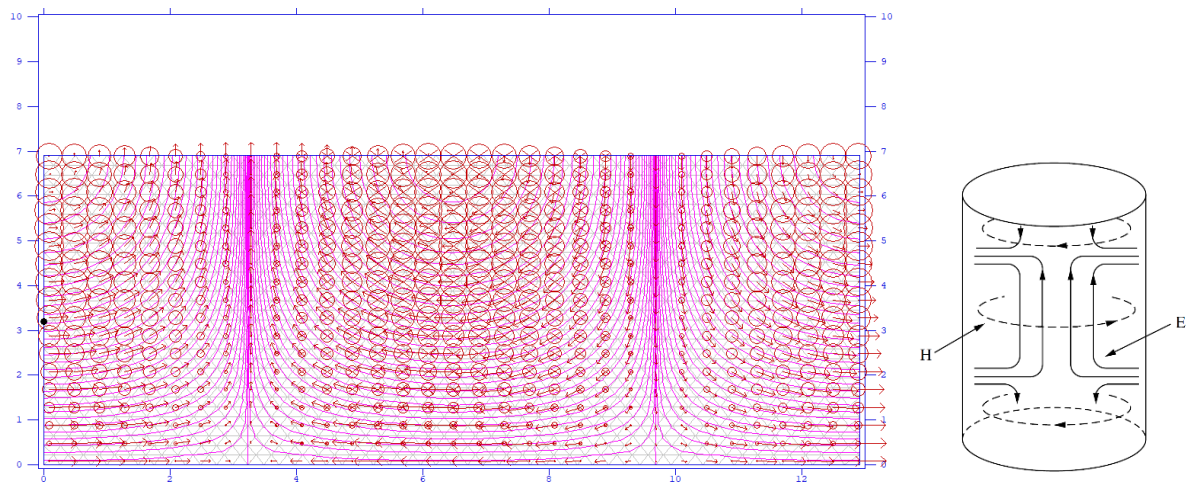
Figure 2. (left) SUPERFISH output graphic showing the cavity's side view with upper part of the symmetry plane. (right) Schematic patterns of electric and magnetic field inside the TM_{012} resonant cavity. The solid lines represent electric fields and the dashed lines represent magnetic fields [3].

The study on relation of the cavity length and the resonant frequency was conducted. The cavity length was adjusted from 12.85 cm to 13.50 cm. The mesh size was kept at 0.25 cm. The results show that the resonant frequency decreases as the cavity length increases. The length that produced the resonant frequency closes to 2856 MHz was 12.91 cm. Thus, the n-th zero point of the m-th order Bessel function was calculated from [4]

$$r_{mn} = a\sqrt{\left(\frac{2\pi f}{c}\right)^2 - \left(\frac{p\pi}{L}\right)^2} = 6.892 \times 10^{-2}\,\mathrm{m} \times \sqrt{\left(\frac{2\pi \times \left(2.856 \times 10^9\,\mathrm{Hz}\right)}{c}\right)^2 - \left(\frac{2\pi}{12.91 \times 10^{-2}\,\mathrm{m}}\right)^2} = 2.404\ \mathrm{cm}.$$

The calculated radius of 2.404 cm corresponds to the first zero of the zeroth order Bessel function (r_{01}). Therefore, this resonant cavity is a TM_{012} mode (m = 0, n = 1 and p = 2). Schematic patterns of the electric and magnetic field in the TM_{012} resonant cavity are presented in figure 2 (right).

As a mesh size is one of important parameters for the simulation with SUPERFISH, it is necessary to be optimized for obtaining the reliable simulation results. The mesh size in the input file of program SUPERFISH was varied from 0.01 to 0.25 cm. As a result, different mesh sizes significantly yield different resonant frequencies. The optimal mesh size for this study was 0.02 cm, which resulted in the simulated resonant frequency of 2856.1927 MHz.

3. RF measurements of the resonant cavity

RF measurements to investigate the relation between resonant frequency and cavity length were performed. The RF wave used in the experiments was generated from the USB-TG44A tracking generator. The measuring device was the USB-SA44B spectrum analyzer with the capabilities of measuring wave harmonics and modulation. Both devices are commercially available from the company Signal Hound®. During the experiments, they were powered by a PC via two USB ports. These ports were also used for data transmission between the PC and the devices. The tracking generator was connected to the transmitter antenna inside the cavity via a coaxial cable. Then, the RF wave from the generator was guided into the cavity. The spectrum analyser was linked to the cavity's receiver antenna and an attenuator via other coaxial cables for picking up the RF wave from the cavity. The data from the spectrum analyzer were then sent back to the PC. Figure 3 shows a diagram and a picture of the measurement setup.
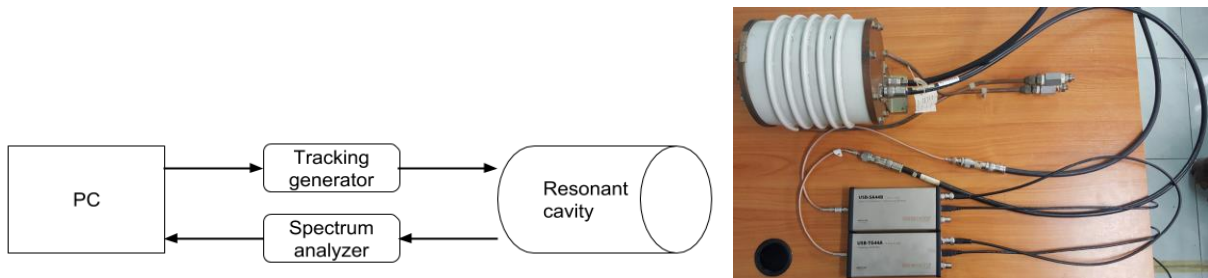

Figure 3. A diagram (left) and a picture (right) showing the RF spectrum measurement setup.

The tracking generator was controlled by a software from Signal Hound® named SPIKE. The main frequency that is of interest, called the center frequency, was set to 2856 MHz with the frequency span of 50 MHz. Thus, the RF waves were generated in the range of 2.856 GHz±50 MHz. The data processing was also done by SPIKE after receiving data from the spectrum analyzer. It created a spectrum of the RF wave and displayed the most dominant frequency, which is the resonant frequency. The cavity length was varied from 129.88 mm to 138.78 mm. The step of the measurement was taken at two turns of the adjustment knob, which is approximately equivalent to 1 mm. An example of the RF spectrum in frequency domain obtained by the spectrum analyzer measurement is illustrated in figure 4 (left).

The result of the cavity length variation is presented in figure 4 (right). The resonant frequency has a negative linear correlation to the cavity length. The rate of change in resonant frequency with respect

to the cavity length (df/dz) was -2.913 MHz/mm. To obtain the resonant frequency of 2856 MHz, the cavity length needed to be 134.8 mm for the real cavity while the result from SUPERFISH simulation suggested that the cavity length should be 129.1 mm for this resonant frequency. Thus, the simulated optimal length was 3.9% shorter that the measured value. This difference was expected to be an effect of antenna couplings, which was unable to avoid in the experimental setup and is difficult to be simulated.
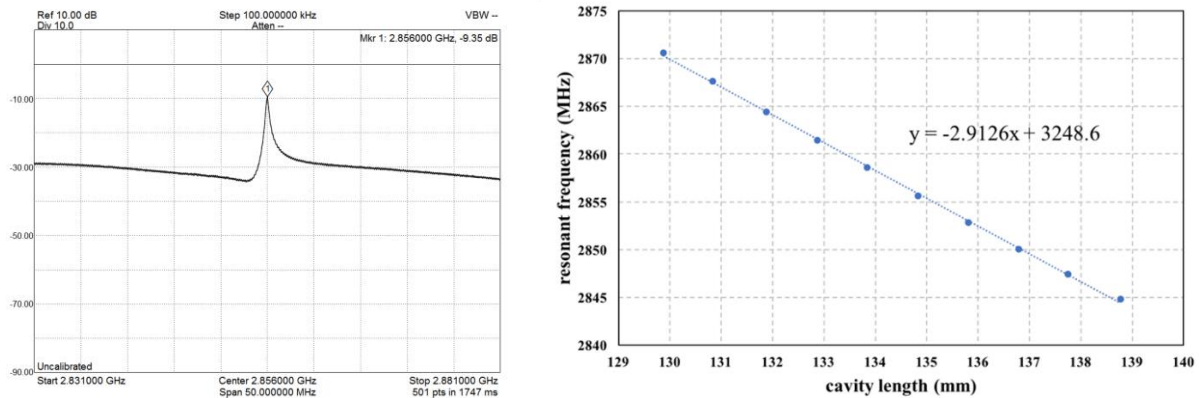
Figure 4. (left) An example of the RF spectrum in frequency domain obtained by the spectrum analyzer measurement. (right) The measured resonant frequencies for different cavity lengths.

4. Conclusion

The resonant cavity of the low-level RF system at the PBP-CMU Electron Linac Laboratory has a simple cylindrical pillbox shape. Its desired operating frequency is 2856 MHz. The cavity mode was investigated by using a 2-D electromagnetic problem solver, SUPERFISH. The simulation results revealed that its cavity mode is TM_{012}, which has longitudinal length dependent. The measurement of the resonant frequency as a function of cavity length was also performed by using a tracking generator and a spectrum analyzer from Signal Hound®. To obtain the resonant frequency of 2856 MHz, the cavity length needed to be 134.8 mm for the real cavity while the simulation suggested that the cavity length should be 129.1 mm. This difference could be reduced by including the effect of environment temperature and the cavity-filled material inside the cavity. However, the simulated optimal length is still 3.9% shorter that the measured length. Another factor that could give a better measurement result was an exclusion of the RF antenna couplings, which may be done by using the reflection method instead of transmission method to measure the resonant frequency.

5. Acknowledgements

References

[1]   Buakor K *et al* 2017 *Proc of IPAC2017 (Copenhagen:Denmark)* pp 2763-66
[2]   SUPERFISH Ref. Manual La-ur-87-126 LANL.
[3]   Chen L F *et al* 2004 *Microwave Electronics: Measurement and Materials Characterization* John Wiley & Sons, Ltd.
[4]   Wangler T P 2008 *RF Linear Accelerators* vol 2 Wiley-VCH Verlag p 26