A vertical test system for China-ADS project injector Ⅱ superconducting cavities*

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Abstract: To test superconducting cavities, a vertical test system has been designed and set up at the Institute of Modern Physics (IMP). The system design is based on VCO-PLL hardware and the NI Labview software. The test of the HWR010#2 superconducting cavity shows that the function of this test system is satisfactory for testing the low frequency cavity.

Key words: vertical test, superconducting cavity, labview

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1 Introduction

A prototype of a half-wave resonator (HWR) superconducting cavity HWR010#2 has been developed at the Institute of Modern Physics (IMP). This type of cavity is used for the China-ADS project injector-Ⅱ superconducting linac. Some parameters of the prototype cavity are listed in Table 1. The Q_0 of this cavity is very high, but the frequency is just 162.5 MHz. Consequently, the bandwidth of the cavity is very narrow (BW<0.25 Hz).

Table 1. HWR010 cavity parameters.

parameter	value
frequency/MHz	162.5
$\beta_{\rm opt}$	0.095
Q_0	6.7E+8
$E_{\rm pk}$/(MV/m)	25
$B_{\rm pk}$/mT	50
$V_{\rm acc}$/MV	0.78
$(R/Q)/\Omega$	148
G	28.5

For this low frequency cavity test, a suitable vertical test system needs to be built. The system should be different from the elliptical cavity test system which has a higher frequency and unnecessarily uses broadband frequency sweeping conditioning.

The frequency measured by this vertical test system is in accordance with the HWR cavity. Because of the very high Q_0 of the superconducting cavity, the test system should be based on VCO-PLL hardware [1] in order to lock the frequency of the cavity. To facilitate the test, NI Labview (which provides a friendly user interface and higher efficiency data acquisition and processing) is used as the software system.

2 The vertical test system design

The vertical test system at IMP consists of the hardware based on VCO-PLL and the software is based on NI Labview. Each part of this system is introduced as follows.

2.1 The hardware design

The hardware system consists of VCO, two power amplifiers, PLL loop, power meters and environmental monitors. The testing system hardware design block diagram is shown in Fig. 1.

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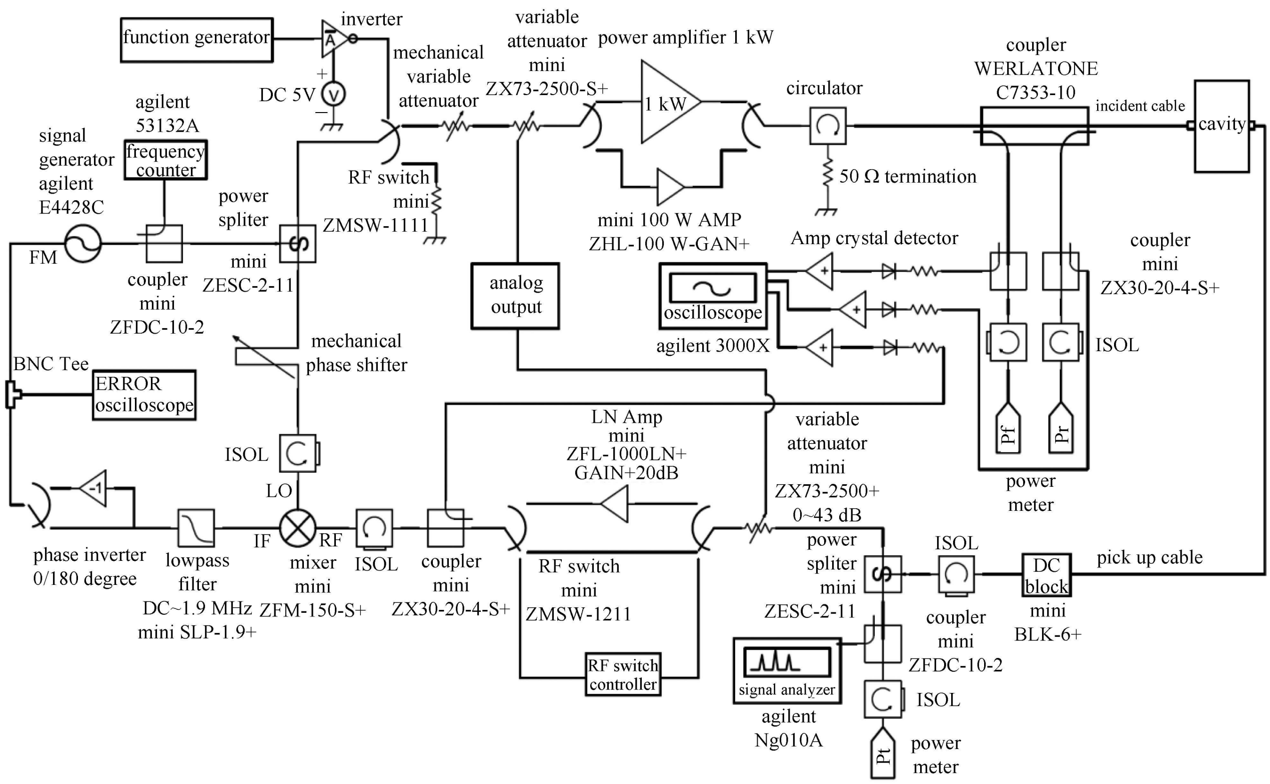

Fig. 1. (color online) Block diagram of the hardware design.

The Agilent E4428C signal generator with FM function, which can convert maximum 1 V error voltage to maximum 1 MHz frequency shift, has been selected for the VCO part. The RF power source part contains two amplifiers. The small one is 100 W but has wide frequency bandwidth, which is used for broadband frequency sweeping conditioning. The big one is 1 kW but has narrow frequency bandwidth, which is used for testing and high power conditioning.

The PLL loop is based on an analog mixer. The mini-circuits ZFM-150-S+ mixer has been selected. The power level of the mixer's LO port is set to 10 dBm and the RF port power level range can be set from −26 dBm to 5 dBm to make the PLL loop work. The mechanical phase shifter is used for the PLL loop adjusting error signal, which can help the system lock the frequency. Lots of ISOLs are used in the system to decrease the VSWR of each cable. The Mini-circuits BLK-6+ DC block is used to protect the system from being damaged by an unexpected DC voltage. The power sensors, which have high dynamic range in this system, are used for measuring forward, reflected and pick-up power of the superconducting cavity. Environmental monitors contain cavity temperature sensors, LHe level sensors, helium gas pressure sensors, cavity vacuum gauges and X-ray radiation detectors. Each sensor is connected to its own equipment, which communicates with the computer by GPIB or RS232.

2.2 The software design

The software system is based on NI Labview. The main code structure is mixed the state machine structure and the event structure (Fig. 2). Data acquisition and data analysis are separated, and each subroutine can run fast and independently but synchronously. The data acquisition contains two separated parts, which are quick acquisition and slow acquisition. The quick acquisition records data from power meters and the frequency counter, and the running period is 1 ms/cycle; the slow

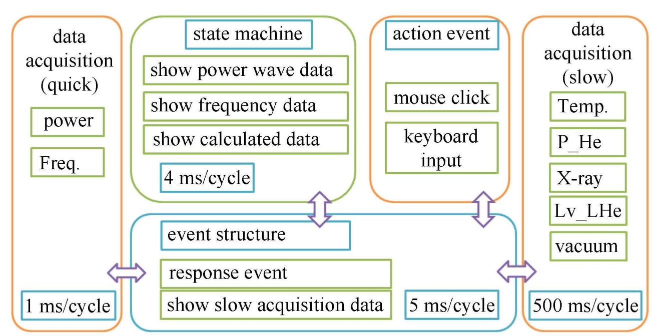

Fig. 2. (color online) Software system architecture.

acquisition records data from temperature meters, helium gas pressure meters, X-ray meters, liquid helium level meters, and vacuum meters, and the running period is 500 ms/cycle. The state machine subroutine collects the quick acquisition data to calculate and show real-time measurement result; the event structure subroutines responds to the action event from input devices and show the slow acquisition data. The software system user interface is shown in Fig. 3.

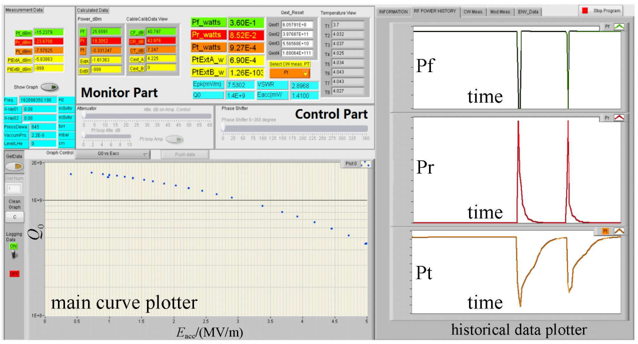

Fig. 3. (color online) User Interface.

3 Test result of the HWR010#2 cavity

The HWR010#2 cavity developed by IMP is a kind of superconducting half-wave resonator. Three procedures are used for this superconducting cavity test. Firstly, the external Q measurement, which is used to confirm forward coupler and pick-up the antennas' length, has been done at room-temperature. Secondly, RF conditioning, which is for the cavity conditioning during 4.2 K temperature, helped the cavity to overcome the multipacting and improve performance. Thirdly, the decay time measurement, which measures the Q-load, is used to calibrate the external Q of the pick-up antenna for CW measurement.

3.1 The external Q measurement

Before the cold test, the external Q should be tested first in order to ensure the forward coupler coupling situation at the cavity Q_0 and to guarantee that the pick-up power is not too strong and able to damage the test system at 4.2 K temperature. To determine the external Q, each length of antennas, which are fixed on the forward coupler and the RF pick-up probe, need to be verified. We can use a series of different length of antennas to set up the coupling port of the cavity, and then measure "S" parameters of each antenna with the vector network analyzer. Therefore, the external Q of each antenna can be calculated [2].

The antenna length versus the Q_{ext} test result curve of the HWR010#2 cavity at room-temperature is shown in Fig. 4. The antenna relative length "0" position represents that the antenna ends just reach the coupling port flange plane, and the positive direction toward inside of the cavity.

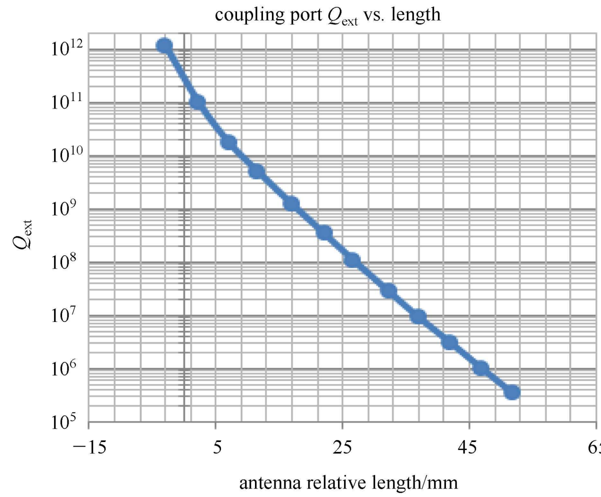

Fig. 4. (color online) Q_{ext} versus antenna relative length.

In the vertical test, the forward coupler is a dynamic adjustable coupler and the external Q can be selected from 4.5E+10 to 9.1E+6. The pick-up probe is a fixed length antenna and the external Q can be selected to 4E+11.

3.2 RF conditioning

During the vertical test, RF conditioning can help the cavity to overcome the multipacting and improve performance.

In the very low field range, if the multipacting is very strong, the sweeping frequency conditioning can be chosen. With the sweeping frequency signal, the wideband amplifier Mini-ZHL-100W-GAN+ can output sweeping frequency power into the cavity to help the cavity to get the established electromagnetic fields.

Between the low field and the high field, the pulse way should be chosen (Fig. 5), which can help the cavity to overcome the multipacting or increase the quench limitation.

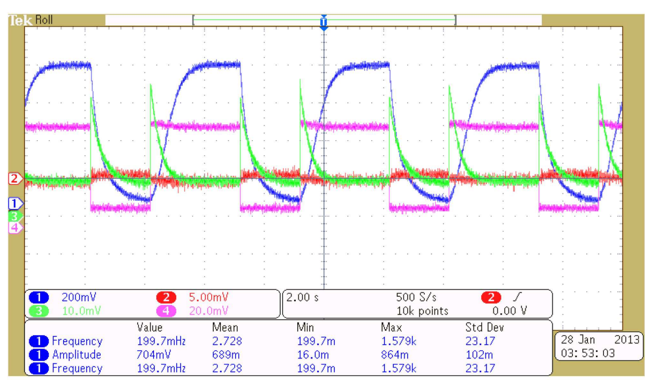

Fig. 5. (color online) Pulse conditioning.

3.3 Decay time measurement

The load Q should be measured by the decay time measurement method because of the very high Q_0 of the cavity and approximate critical coupling of the forward coupler. After the VCO-PLL locks the frequency of the cavity, if the forward power has been turned off then the decay time of the cavity could be measured by the signal analyzer or the oscilloscope with a cryostat detector. However, the decay time of the cavity is related to the forward coupler external Q; in other words, it is related to the forward coupler antenna ends position inside the cavity. So, if the decay time measurement needs to be tested, the adjustable forward coupler should be in a fixed position. When the decay time has been measured, the load Q can be calculated according to the following formula (1):

$$Q_{\rm L}=2\pi f(-\Delta t)/\left[\ln\left(10^{\frac{-\Delta a}{10}}\right)\right], \quad (1)$$

$Q_{\rm L}$ is the load Q, f is the frequency of the cavity, Δt is the decay time and Δa is the attenuation corresponding to the decay time (unit: dB) [2]. In the HWR010#2 cavity test, the decay time measurement is done in the low field range. The frequency of the cavity is 162.898730 MHz, Δa and Δt are −3 dB and 0.442 s. So the load Q is 6.5E+8 (Fig. 6).

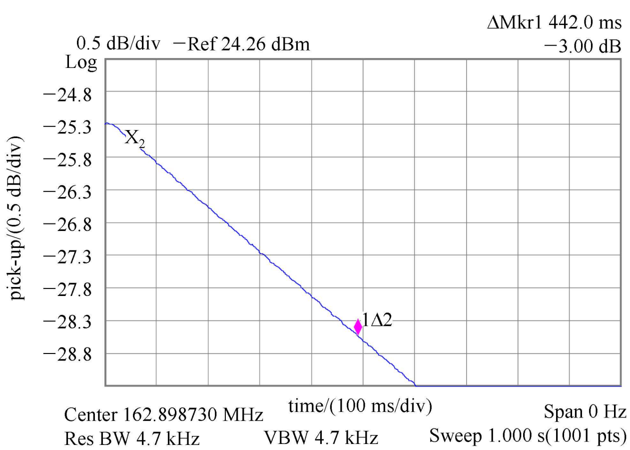

Fig. 6. (color online) Decay time measurement of HWR010#2.

After the load-Q is calculated, the pick-up probe external Q can be measured and calculated [2]. So, during the CW measurement, the pick-up probe external Q can be used for the Q_0 vs. $E_{\rm pk}$ curve measurement [2]. Q_0 and $E_{\rm pk}$ are as follows:

$$Q_0 = (Q_{\rm ext,pickup})\frac{P_{\rm t}}{P_{\rm diss}}, \quad (2)$$

$$E_{\rm pk} = \kappa\sqrt{P_{\rm t}\times Q_{\rm ext,pickup}/(2\pi f)}, \quad (3)$$

where, $Q_{\rm ext,pickup}$ is the pick-up probe external Q, $P_{\rm t}$ is the pick-up power, $P_{\rm diss}$ is the loss power, κ is a constant depending on the CST Microwave Studio software simulating result, which is identically equal to $E_{\rm pk}/\sqrt{U}$, U is cavity stored energy.

3.4 HWR010#2 cavity 4.2 K test result

The HWR010#2 cavity has been tested twice under this vertical test system.

For the first test, the cavity was shown multipacting (Fig. 7) at very low fields. After several hours of RF conditioning, the multipacting barrier was still insurmountable, so the test had to be stopped. Before the second test, surface processing (including long time high pressure rinsing and three days 120 ℃ vacuum baking) has been done. After this processing, the multipacting barrier was disappeared during the test.

Finally, the HWR010#2 cavity performance reached Q_0=5.2E+8 at $E_{\rm pk}$=25.2 MV/m. The test result of the Q_0 vs. $E_{\rm pk}$ curve is shown in Fig. 8.

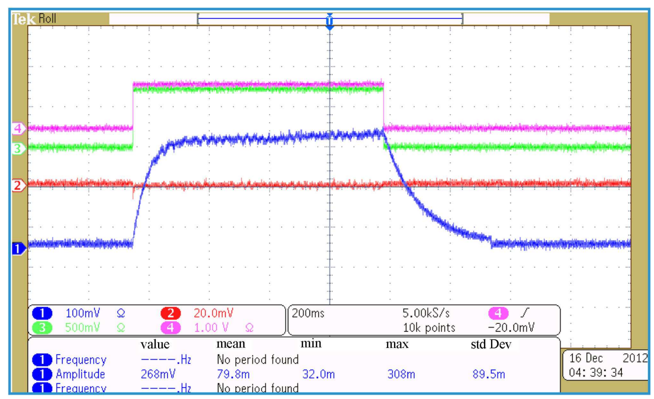

Fig. 7. (color online) Multipacting.

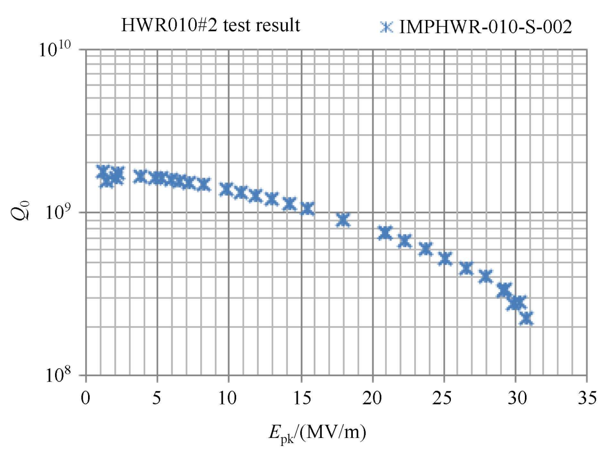

Fig. 8. (color online) HWR010#2 cavity.

4 Conclusions

The vertical test system for the China-ADS project injector II superconducting cavities was designed and set up. All of 162.5 MHz cavities are ready to be performed on this system. The system based on the VCO-PLL hardware and the NI Labview software is not only used for testing cavities but is also used for cavity conditioning. After the HWR010#2 cavity was tested, the function of this test system was shown to be satisfactory for testing low frequency cavities.

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