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PHYSICS AND TECHNIQUE OF ACCELERATORS

Characterization of Properties of 325-MHz Half-Wave Superconducting Resonators at Low Microwave Field Amplitudes

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Abstract—A prototype of the 325-MHz niobium half-wave coaxial resonator ($\beta = 0.21$) is developed, built, and tested at low microwave field amplitudes. Electromagnetic properties of the prototype in the superconducting state are investigated in the continuous wave regime and the damping regime using a highly stable radio-frequency (RF) generator and power detectors. The experimental data on the resonator's response in the superconducting state are used to calculate its most important characteristics—the intrinsic Q value and the accelerating field. The experimentally measured Q value of the prototype is $Q_0 = (3.5 \pm 0.1) \times 10^8$ at input powers of up to +20 dBm.

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INTRODUCTION

Half-wave coaxial resonators (HWRs) are widely used in superconducting sections of modern accelerators of heavy charged particles [1, 2]. This work reports the results of cooperation of the scientific teams from the Joint Institute for Nuclear Research (JINR), National Research Nuclear University MEPhI (NRNU MEPhI), Institute for Nuclear Problems Belarusian State University (INP BSU), and Physical-Technical Institute of the National Academy of Sciences of Belarus (PTI NASB) in designing, developing, constructing, and investigating properties of the 325-MHz HWR prototype. The HWR-325 prototype (Fig. 1a) was designed and built in the classical coaxial configuration [3]. Two pilot superconducting half-wave resonators ($\beta = 0.21$) with a working frequency of 325 MHz are now being made on its basis for the resonator acceleration sections of the proton and ion linear accelerator—a new injector of the Nuclotron–NICA collider complex.

Controlling electromagnetic properties at a low-power radio-frequency (RF) signal is an important intermediate stage in the manufacture of the cavity. In preliminary experiments on the measurement of RF characteristics of the HWR, vector network analyzers (VNAs) are commonly used. A VNA is a fast and convenient instrument for controlling the resonance frequency and estimating the Q value during preliminary "warm" tests of the cavities [3, 4]. Nevertheless, the use of VNAs is much limited for measurements of properties of high-Q systems. A typical Q value of HWRs in the superconducting state is over 10^8, and even modern network analyzers do not allow satisfactory measurements of their characteristics. In this case, another measurement scheme based on a highly stable RF generator and power meters is traditionally used to investigate HWR properties. The sections below deal with the main features of the method for RF measurements of the superconducting HWR-325 prototype in the continuous-wave (CW) and damping regimes.

1. EXPERIMENTAL SETUP FOR MEASURING PROPERTIES OF A SUPERCONDUCTING RESONATOR

To perform intermediate vacuum, temperature, and RF tests of the HWR, a test cryostat was designed and built [5]. A general view of the resonator with the connected power input and receiving antenna is shown in Fig. 1b.

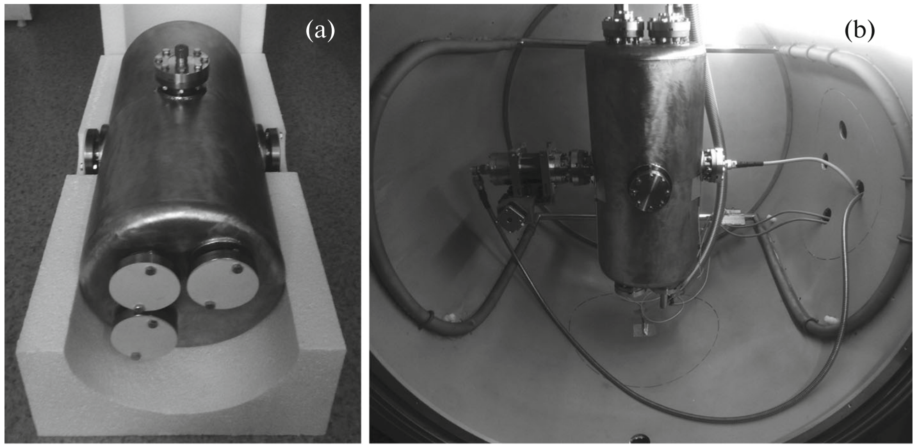

Fig. 1. (a) Half-wave coaxial resonator prototype; (b) cavity with connected power input and the receiving antenna before the experiment in the test cryostat.

Intermediate experiments with the HWR-325 prototype showed that measurements in the frequency region using modern VNAs allowed satisfactory characterization of resonators the Q value up to 10^7. To measure higher Q systems, another experimental setup is used (see block diagram in Fig. 2). It is based on a high-stable RF generator, power detectors, and a phase-locked loop (PLL).

In this scheme, the signal from the generator arrives at the power input of the resonator. Using a bidirectional coupler and power detectors, one can directly measure forward power P_f, reflected power P_r, and power that passes through the cavity P_t. In the CW regime, these quantities are used to calculate the coupling coefficient β of the power input.

2. MODEL FOR CALCULATING THE Q VALUE

In the scheme of Fig. 2, the experimentally measured quantities are the forward, reflected, and passed-through powers P_f, P_r, and P_t, respectively. General relations connecting P_f, P_r, P_t, and characteristics of superconducting resonators can be found in [6, 7]. For the HWR-325 (β = 0.21), expressions for the calculation of the Q value Q_0 take the form

$$Q_0 = Q_L\left[1 + \beta\left(1 + \frac{P_t}{P_{diss}}\right) + \frac{P_t}{P_{diss}}\right], \quad (1)$$

where β is the coupling coefficient of the power input, P_{diss} is the resonator wall loss power, and Q_L is the loaded Q value

$$\beta = \frac{1 - \sqrt{P_r/P_f}}{1 + \sqrt{P_r/P_f}}, \quad (2)$$

$$P_{diss} = P_f - P_r - P_t. \quad (3)$$

For experiments in the time region, Q_L can be calculated based on measurements of the damping constant τ. After the RF generator is switched off in the CW regime, the system goes into the damping regime, in which the energy stored in the generator is gradually released from the ports of the power input and the measuring antenna. The power detectors register variations in the time of signals at the antenna and the power input. This process is well described by the exponential law, with its damping constant τ being easily estimated. In this case, $Q_L = 2\pi f\tau$, where f is the working frequency of the cavity. Note also that for experiments in the frequency region, Q_L can be calculated from S_{21} spectra measured by the VNA, $Q_L = f/\Delta f$, where Δf is the half-width of the passage peak.

Finally, the relation between the Q value and the accelerating field in the resonator is defined by the expression

$$E_{acc} = \frac{\sqrt{Q_0 P_{diss}(r/Q)}}{L}, \quad (4)$$

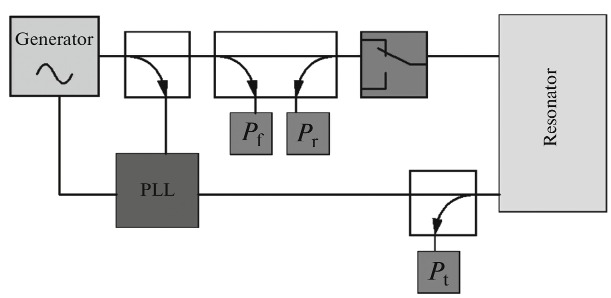

Fig. 2. Block diagram of the setup for measuring the Q value of the superconducting HWR.

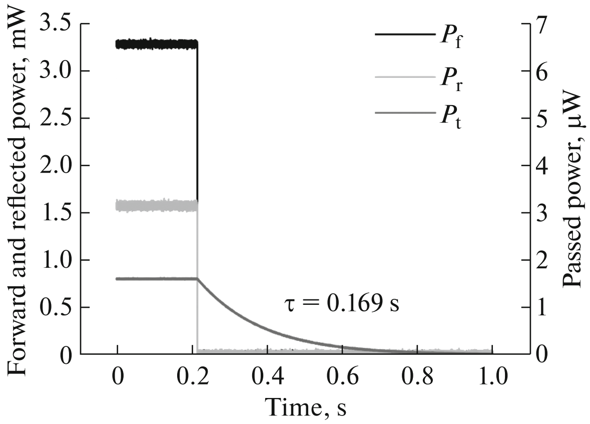

Fig. 3. Time dependences of powers P_f, P_r, and P_t in the CW and damping regimes.

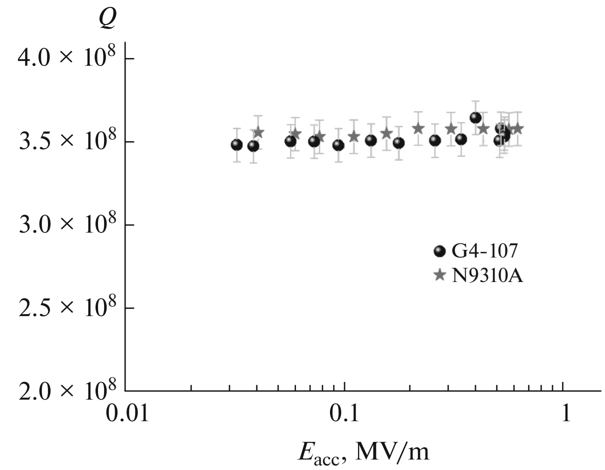

Fig. 4. Dependence of prototype Q on the accelerating field with two different types of generator used, G4-107 and N9310A.

where (r/Q) is the shunt impedance, and L is the accelerating gap length. The quantity (r/Q) is usually calculated numerically, e.g., using CST simulation. For the HWR-325 prototype considered in this work, we have $(r/Q) = 306\ \Omega$ and $L = 2 \times 0.043$ m.

3. EXPERIMENTAL CHARACTERISTICS OF THE NIOBIUM PROTOTYPE

Measurements in the CW regime allow obtaining information on the HWR energy balance. Based on the CW-measured P_f, P_r, and P_t, the coupling coefficient β can be estimated, and the term in the square brackets in (1) can be calculated. To obtain the missing factor Q_L, the generator is switched off, and the rate of oscillation damping with time in the cavity is measured. During the experiments, in addition to switching off the generator, channels P_f and P_r were switched to the mismatched load. Thus, only the power output through the measuring antenna was measured in the damping regime, while the energy variation in the cavity was mainly determined by the loss on the niobium surface. The Q value of the antenna was about 10^{10}.

A typical result of power measurements in the CW regime and the damping regime for the investigated HWR-325 prototype is shown in Fig. 3 (left and right sides of the plot respectively).

The experimental data in Fig. 3 allow the intrinsic Q value of the prototype to be estimated. The input power variation within the range from −18 to +20 dBm made it possible to construct the dependence of the prototype Q value on the accelerating field. Figure 4 presents the dependences of the HWR-325 Q value on the accelerating field with two different types of generators used: the analog G4-107 and digital N9310A ones.

In two different generators, the experimental Q values of the prototype in the investigated range of accelerating gradients from 0.03 to 0.6 MV/m remained almost constant, $Q_0 = (3.5 \pm 0.1) \times 10^8$. Note that the value that is obtained is about three times lower than the theoretically expected $Q_0 \sim 10^9$ at 4.2 K. This may be due to the small amplitudes of the microwave field used in the experiment (input power up to +20 dBm). According to [8], this effect is well known for elliptic superconducting cavities operating at the frequency of 1.3 GHz. In the literature, it is often called the LFQS (low field Q-slope).

It is important to note that, unlike the case of elliptic resonators, which typically feature a considerable increase in Q [8] in the accelerating gradient range from 0.1 to 1 MV/m, no significant increase in Q of the HWR-325 prototype was observed in the above range. Further experiments with a higher level of incident power will allow more information on the LFQS for niobium HWR-325.

4. CONCLUSIONS

The results reported above demonstrate the possibility of superconducting resonators for acceleration technologies. The concerted effort of the scientific teams from JINR, NRNU MEPhI, INP BSU, and PTI NASB has resulted in the creation of a superconducting HWR-325 prototype with characteristics close to the design specification. The experimentally measured Q value of the HWR-325 at low microwave amplitudes was $Q_0 = (3.5 \pm 0.1) \times 10^8$ at input powers up to +20 dBm. The results will be used for the further development and manufacture of HWR-325 niobium cavities for the NICA project.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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