Measurement of High Values of Q-factor of 1.3 GHz Superconducting Cavity of TESLA-type

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Abstract Presented the ideas and techniques underlying the measuring workbench created within the framework of a Dubna-Minsk research project to estimate, by measuring of S_{11} , of a high value (about 10^{11}) of Q-factor of a 1.3 GHz superconducting radio-frequency (SRF) niobium cavity of TESLA-type, which is a key element the superconducting accelerating system of the International Linear Collider (ILC) operating at 1.3 GHz and made of thousands of such cavities. In the paper, the results of measurements and Q-factor estimates are also presented and discussed.

Keywords Microwave, Niobium Resonator, Superconductivity, Quality Factor

1. Introduction

High quality and identity of thousands of superconducting radio-frequency (SRF) resonant cavities of the ILC accelerating system [1] are very important for gaining high energy efficiency of the ILC. These single-cell cavities made of niobium are not cheap (cost about US \$15,000 per unit) so that the problem of controlling of their quality before making 9-cell modules, namely of high identity of their central frequencies and Q-factors is very actual. To develop an efficient technique to resolve that problem we apply standard equipment that is presented in the market. Such a decision comes very

natural if you take into account that the manufacturing of a great number of single-cell cavities is pre-assumed to go in different locations. Even if it would be only in one place, time to time there should be some "stops" in production to control the technology and make tuning of production appliances and tools. After such tunings, measurement of RF-parameters of the fabricated cavities is a regular requirement.

For the purpose of our research, a single-cell 1.3 GHz SRF niobium cavity was kindly provided by Fermilab (USA) brokered by JINR (Russia) [2] for research in Belarus. The photo of this cavity is shown in the Fig.1. As it is seen in the Fig.1, the cavity has the (cylindrical) tubes of drift on both sides, and, as far as we know, Q-factor of such a construction has never been measured yet by a direct RF-method.

There were three main problems of measuring of both central frequency and Q-factor of such a cavity. First, the cavity came to us with no special device to excite microwave oscillations in it. Secondly, the analysis of the market of measuring equipment has shown that no standard RF-measuring instrument allows us to carry out such a measurement with the required accuracy because of the instability of the frequency of its frequency base; thus, to stabilize the frequency base one needs an extra equipment. And third, it was quite clear from the very beginning that the problem cannot be solved without applying processing of measurement data to filter out the noise that affects measurement accuracy of the amplitude-frequency response (AFR) of the cavity.

Figure 1. a) 1.3GHz SRF niobium resonant cavity – in the left; b) 1.3GHz SRF niobium resonant cavity with the end caps – in the right.

2. Measurement Technique

The measurement method relies on classical definition of Q-factor of a resonator [6], namely

$$Q = \frac{f_0}{\Delta f}$$

where f_0 is central (resonance) frequency, and Δf is the bandwidth (on – 3dB level) of the resonator.

As the cavity's Q-factor is expected to be very high, i.e. about 10^{11} , at 1.3 GHz, to calculate Q by the above formula one have to be able to sample AFR data with frequency resolution of about 0.01 Hz. There are few RF-measurement equipment that meet such a requirement, and the vector network analyzer (VNA) Agilent E5061B is among them. In our measurement scheme we apply it to direct measurement AFR of the reflection coefficient, S_{11} [3].

To excite the resonant cavity in a proper mode at 1.3 GHz, we developed a unique type of a tunable UHF matching device. This device allows us to feed the cavity

with a low-power UHF-source and, simultaneously, it is used as a measurement probe for the signal reflected out of the cavity. The device uses the principle of magnetic matching by current loop/coil set in the cavity. The mechanism of the device enables one to vary the length (area) of the loop and its setting at any angle position within 360 degrees around the vertical axis of the device. So that it allows us easy tuning the strength of coupling and reaching the best with the lowest standing wave reflection (SWR) value. The sketch-drawing of the coupling device is shown in Fig.2a. The device was purposely developed for setting on top of the end cap that closes the outlet opening of one of the two tubes of drift of the resonator, while the outlet opening of another tube of drift is closed by the dull end cap (see Fig. 2b). The initial height of the loop for 1.3GHz resonator of TESLA-type was set $H = 57.6$ mm, (equals $\lambda/4$, where λ is the wavelength at 1.3GHz). The coupling device is set in the cap so that the resonator runs in E010 oscillation mode - the (main) working mode in the ILC.

Figure 2. a) The rotating UHF matching device with the mechanics of tuning of length of the loop through a cylindrical hole in the lid; a) The scheme of the UHF matching device setting on the top end cap of the resonance cavity.

The coupling device provides excitation of the cavity with very low level of energy loss at the high symmetry of resonance curves that is very important for accurate measurement of Q-factor, and also gives high level of suppression of the unwanted modes oscillations. The device is as simple as handy in use. That was tested and proved In the series of "warm" and "cold" measurements of the resonance frequency and Q-factor of the sample resonant cavity. The device has been patented in 2014 [5].

3. Measurement Equipment, Settings, and Experimental Results

Our measurement scheme was realized in two modifications (see. Fig.3a,b) – the first one for the "warm" measurements, i.e. at the room temperature (about 300K), where the VNA was used with the Option 1E5 (frequency stability of time base of about 10^{-8}), and the second scheme – for the "cold" measurements at the temperature about 6.4K, when the resonator was placed into a cryogenic

camera with liquid helium and, in this case, the VNA's time base was stabilized by the frequency standard on rubidium vapor, LPFRS-01 (LLC "Vremya CH", Russia). The last measurement scheme has a short-term frequency stability about 10^{-11} , that, along with the VNA's frequency resolution of 0.01 Hz, gives us the potential ability to organize measurement of Q-factor with the values 10^9 and more.

The adjustment for getting an optimal matching is done at room temperature by several operations as follows. At first, turning the device's disc with the loop on it, one should find a position that gives the highest value of loaded Q-factor. In our case, it was found that such maximal value corresponds approximately $|S_{11}| = -42.648$ dB at the resonant frequency of about 1.2729987 GHz. At this point, standing wave ratio (SWR) is of value of 1.03. Then, one should get the maximum value of the loaded Q-factor by setting the height of the loop. In our case, after such tuning, we got value of $|S_{11}| = -56.873$ dB at the resonance frequency 1.2750953 GHz. Measured SWR in this final state is about 1.01.

Figure 3. a) The RF-measuring workbench for “warm” measurements based on the VNA Agilent E5061B, Opt. 1E5 (in the left); a) The RF-measuring workbench for “cold” measurements based on the VNA Agilent E5061B and LPFRS-01 (in the right)

The difficulties of direct measurement of f_0 and evaluation of Q-factor of 1.3 GHz SRF resonant cavities in the state of superconductivity are caused mainly by their extremely narrow bandwidth in such the state - the bandwidth might be about 1 Hz or less, while dynamic range of the amplitude-frequency response of $|S_{11}|$ might be more than -120 dB. Thus, in such a measurement, one is faced the problem of extraction of measurement signal out of the noise of different nature. Signal processing is the only effective method to resolve such a problem, and therefore we use a method of accumulation/storage and statistical processing of the data on $|S_{11}|$ along with an automation of the measurement process.

The automation of measurement of AFR was made so to meet measurement conditions in the resonator. They were as follows. First, the resonant cavity was not closed and evacuated for doing "cold" measurements – this makes the measurement process considerably cheaper. So that, the cavity in the process of measurements was partly or fully filled with liquid helium from cryogenic chamber. Liquid helium is not a polar liquid, its permittivity is close to the vacuum's, so that such liquid does not make any substantial effect on the value of Q-factor. On the other hand, taking no special measures for stopping the liquid helium's flows going back and forth, and for damping mechanical oscillations (of any nature) of the resonator in the cryogenic chamber, we allow the cavity's AFR moving slowly in tact of such fluctuations. This gives a chance to have such samples of AFR when one point out of the set of measurement points is about at the peak while its two neighboring points lie at the peak's slopes on the right and left. It should be noted that such the states can be registered only by chance, so one needs to collect many samples of AFR to discover then these states among many.

Having many such digital data with the peaks, one can approximate the AFR's shape within the peak by using of a procedure of fitting to a bell-shaped curve and then calculate Q-factor. Usage of Lorenz formula as a math model for such a fitting can be considered a good choice,

as Lorenz law represents itself standard mathematical model for narrow bandwidth resonant curves and therefore it widely used in spectral analysis.

Right choice and setting of an optimal measurement mode are very important for getting reliable results also. The measurement mode should be set so that to avoid the effect of distortion of the AFR with a very narrow bandwidth [7]. Indeed, the bandwidth is expected would be about 1 Hz. This means simply that the effective time of analysis of such an AFR should not be less than 1 s. We also need to have at least 3 measurement points at the peak of the resonant curve to calculate f_0 and Q on the basis at least of parabolic approximation. This condition also can be satisfied if the resonance curve be measured many times. In this case, the efficient measurement time is simply the sum of time intervals of separate measurements.

Having multiple measurements allows one to apply some effective statistical procedures, e.g. the arithmetic averaging, for gaining higher signal-to-noise ratio and thus for getting a more reliable evaluation of the position and width of the resonance peak resulting from absorption of UHF signal power in a superconducting resonant cavity of more than -120 dB.

When setting up a hardware smoothing of digital measurement data on a profile of a narrow bandwidth AFR, e.g. by applying moving average, one should take into account that there is a risk that the sought peak in the frequency response might be skipped by such a smoothing. Therefore, if there is a need in a smoothing of sampling data, then it is better to do this on the external PC using specific software.

Data transfer from the VNA to the PC that is used to control the VNA, is a principled decision in our method of measurement. It makes our method more flexible, because measurement and processing of the data can be separate and independent processes.

In our measurements, the VNA operates under control of external PC via USB-port using proprietary software Agilent IO Libraries Software Suite 15.5 [8]. The cycle of

measurement starts and stops on the VNA under control of PC with software application named ENA_Data_transfer_macro_0105, this software is also recommended by Agilent. The application has been modified a little to allow users to run/stop the repeating cycles of measurements by simply pressing any key on the PC and to get data transfer from the VNA to the PC in

14-digit format with the resolution of 0.01Hz.

Below we present a graph of the AFR (of absorption) of the resonant cavity from Fermilab. The measurements were made at the temperature nearby 6.4K, and the graph was built on the external PC by the modified ENA_Data_transfer_macro_0105. The AFR data in the peak's region, in this case are presented in Table 1.

Figure 4. Resonant energy absorption in the sample of 1.3 GHz superconducting resonant (SRF) cavity of TESLA-type from Fermilab at $T \approx 6.4$ K; $f_0 \approx 1,274,983,421.896$ Hz, $\text{loss} f_0 \approx -128.71$ dB

Table 1. The data on $|S_{11}|$ (7 points around the resonance peak) of 1.3 GHz SRF niobium TESLA type resonance cavity from Fermilab at $T \approx 6.4$ K

Frequency, Hz	Log Amplitude, dB
1,274,983,363.245	-100.7759788
1,274,983,382.796	-102.3960799
1,274,983,402.346	-104.1038561
1,274,983,421.896	-128.7089532
1,274,983,441.447	-102.4467944
1,274,983,460.997	-101.7109461
1,274,983,480.547	-102.5946921

We also have got the refined value of Q-factor of the resonant cavity with the usage of the procedure of non-linear fitting of these tabulated data with a Lorentzian curve with software application Fityk [9]. The approximating procedure is performed with the inverted data taken in a linear scale, and only for 3 central points on the peak. The resulting plot is

shown in the Fig.5.

Figure 5. Approximation by Lorentzian curve of the AFR of 1.3 GHz niobium SRF resonant cavity from Fermilab. $T=6.4\text{K}$, $f_0 = 1,274,983\,403.346\text{ Hz}$, $\Delta f = 0.9\text{ Hz}$, $Q=1.41665 \times 10^9$

The found parameters of the approximating Lorentzian curve have the following values: $f_0 = 1,274,983\,403.346\text{ Hz}$, $\Delta f = 0.9\text{ Hz}$, so that we get $Q = f_0 / \Delta f = 1.41665 \times 10^9$ for an estimate for Q-factor of 1.3GHz niobium SRF cavity in the state of superconductivity, and this value is well consistent with the well-known theoretical estimates.

Presented measurement technique was applied also to 1.3 GHz niobium SRF cavity of a TESLA-type, which was made in Belarus using the unique technology of deep drawing by the high pressure of the liquid.

The measurements of AFR of the Belarus' sample were done with the same equipment and using the same measurement technique, but as an improved measurement condition - certain measures had been taken to lower mechanical vibrations in the cryogenic lab that allowed us to lower step of sampling of the AFR up to 5 Hz. To fitting the measurement data of AFR with Lorentzian curve, we also applied the software application Fityk. The inverted data on the AFR in the region of its peak are presented in the Table.2, while the image on the Fityk's main screen with the curve of fitting one can see in the following figure, Fig.6.

Table 2. The sampled in the peak's region and inverted data on $|S_{11}|$ (in linear scale) of the 1.3 GHz niobium SRF cavity manufactured in Belarus

Frequency, Hz	Lin Amplitude
1,290,180,377.81	660
1,290,180,382.70	2,734
1,290,180,387.59	3,894
1,290,180,392.47	10,000,000
1,290,180,397.36	739
1,290,180,402.25	934
1,290,180,407.14	1,489

Figure 6. Approximation of the Lorentzian curve of the AFR of 1.3 GHz niobium SRF cavity manufactured in Belarus. $T=6.4\text{K}$, $f_0=1,290,180,392.47\text{ Hz}$, $\Delta f=0.11828054\text{ Hz}$, $Q=1.09 \times 10^{10}$ (Note: the frequency marks in x-axis (frequency) are numbered with the increment of 1 Hz so that the frequency ticks is 0.2 Hz.)

4. Conclusion

The automated measurement system and technique described here might be found useful in production control of single-cell resonant cavities of TESLA-type (with drift tubes on both sides) for the ILC. The proposed technique uses a direct method of measurements of Q-factor and makes use standard RF-measurement equipment for that. The method does not require evacuating and sealing the cavity and thus the technique can be considered both effective and practical for quality control of the cavities directly at the production site. In the series of 'cold' experiments there have been registered the values of Q about 10^{10} which are well-consistent with the theoretical estimates for such a type of resonant cavities. The measurement equipment and the extra UHF parts are relatively cheap, so that the presented technical solution could be considered an alternative to more expensive special and unique tools and measurement methods that are used for measuring Q-factor of such resonance cavities. Further improvements of measurement accuracy with the automated measurement system can be made when applying the same measurement techniques but for the transmission coefficient S_{12} . That will improve the signal to noise ratio in the neighborhood of the peak of AFR, and also the isolation level of measurement UHF channels of the VNA. Applying a VNA with a wider dynamical range is also preferable.

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