Method to reduce microphonics in superconducting resonators

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The control of superconducting resonators requires a large amount of rf power due to their narrow bandwidth and the presence of microphonics in the ambience, although only a small part is dissipated inside the resonator to generate the accelerating field. A simple and innovative method has been devised to reduce the effect of microphonics on the quarter-wave resonators. Experiments have been conducted successfully at room temperature and at 4.2 K to demonstrate the effect of the new damping mechanism. A detailed report of the experiments with the superconducting resonators in a test cryostat and an on-line linac cryostat is presented in this paper.

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I. INTRODUCTION

The high value of the quality factor ($\sim 10^9$) of the superconducting resonators around 100 MHz is the cause for their narrow bandwidth (~ 0.1 Hz). This small bandwidth makes it difficult to stabilize the phase and amplitude of the rf fields of these resonators. To overcome this difficulty, the technique of dynamic phase control or that of voltage control reactance is employed for stable operation of the resonators. In the case of quarter-wave resonators (QWR) working around 100 MHz, the overall size of the resonators is usually large and the mechanical instabilities may cause frequency fluctuations up to hundreds of Hz in time scale of a few milliseconds. If the frequency jitter of a resonator operating at a frequency f is Δf, the forward power, P_f, required in feedback stabilization of the amplitude and phase is given by $P_f = 2\pi\Delta f U$, where U is the stored energy and given by $U = U_0 E_a{}^2$, U_0 is the stored energy at 1 MV/m field, and E_a is the accelerating field. A simple way to avoid operating the resonator at high forward power, P_f, is to control frequency fluctuations of the resonator by damping the mechanical vibrations.

A superconducting linear accelerator [1–3] based on niobium QWR is at the final stage of commissioning to boost the energy of the accelerated beam from the tandem accelerator [4] at Inter University Accelerator Center (IUAC). During recent off-line and on-line beam tests of the resonators, due to the presence of microphonics in the ambience of the linac, rf power of about a few hundred watts was required to lock the resonators in over-coupled mode even though only 5–6 W was dissipated into the resonator for generating the accelerating field. The constant usage of high rf power caused several operational problems. For resonators having a central conductor with uniform diameter, a mechanical damping mechanism had been tried out successfully elsewhere [5] to reduce the requirement of rf power. Since the central conductor of IUAC QWR has two different diameters with a smaller diameter tube followed by a bigger diameter tube (Fig. 1), the same damping mechanism cannot be implemented here. A novel technique of damping the mechanical mode of the resonator has been adopted to reduce the effect of microphonics. Measurements of the mechanical vibrations of QWR at the superconducting temperature have been performed with and without a damping mechanism with the help of a cavity resonance monitor (CRM) [6] in both a self-excited and a phase-locked loop. With the implementation of the new damping mechanism, a remarkable reduction of the input rf power was observed during repeated measurements with superconducting resonators.

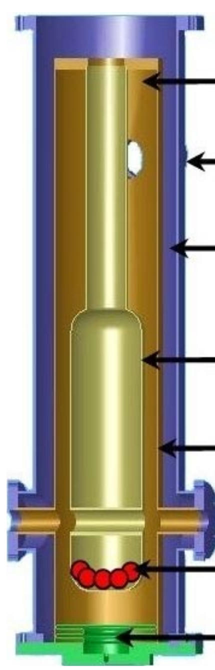

FIG. 1. (Color) Cross-sectional view of a resonator along with a few SS balls.

The method of damping is presented in this paper along with the results obtained.

II. DETUNING OF SUPERCONDUCTING RESONATORS AND ITS EFFECT

For low beta quarter-wave and half-wave resonators, the resonance frequency is primarily dependent on the length, inductance, and capacitance of the central conductor where the accelerating high voltage is developed. Any change of the geometry of the resonator can cause a change in the frequency. Deformations in the geometry can occur due to the following reasons: (i) Any change of pressure inside the helium bath will deform the bulk niobium resonator as they are made out of 2–3 mm thick sheets of niobium. (ii) Forces generated by a high electromagnetic field called ponderomotive forces would also deform the resonators at high fields.

Besides this, the other reasons for frequency jitter are the mechanical noise (microphonics) which is generated outside the cryostat and gets coupled to the resonator through its support structure. Mechanical movement of the drive coupler, tuner, etc. also contributes to the microphonic noise.

Deformation of the resonators due to the reasons mentioned above can be either resonant or nonresonant. In the case of resonant deformations, the cavity picks up a force whose frequency is very close or matches one of the resonant frequencies of the mechanical modes of the cavity as the Q-value of the mechanical mode varies only from a few hundreds to a few thousands. In our case, the dimension of the central conductor (Fig. 1) is such that the mechanical resonance frequency for the fundamental mode is 67 Hz. In the presence of this mode, the resonance frequency of the QWRs, mounted in the linac cryostat, has been observed to vary between $97\,000\,000 \pm 50$ Hz. The frequency jitter is the excursion of frequency around the electromagnetic resonance frequency of the resonator (97 MHz) due to the presence of microphonics. The microphonic jitter induced in the resonator would depend on the coupling of mechanical vibrations from the ambience through the lowest mechanical eigenmode of the resonator. In our case, it is very easy to excite the fundamental mode of the mechanical vibration of the resonator (67 Hz) as the line frequency is 50 Hz. As the time scale of the change in frequency is fast (approximately a few tens of μ sec to a few msec), it is essential to employ an electronic fast tuner responding in μ sec in the control of superconducting resonator. Nonresonant deformations mainly originate from the pressure fluctuation of the helium bath. Since this vibration is slower in nature (a few tens of milliseconds to a few seconds), it can be controlled by the mechanical tuner of the resonator.

During the operation of multiple cavities housed in linac cryostat No. 1, a typical Q-value of $\sim 2.0 \times 10^8$ corresponds to a field of ~ 4 MV/m at 6 W of rf power loss in the resonator. Dynamic feedback control of amplitude and phase [7] was adopted to achieve a stable operation of the superconducting resonators. A frequency window of ± 50 Hz (Δf) was found necessary for locking the resonators in the presence of microphonic noises. To obtain this large bandwidth, the resonators were strongly overcoupled corresponding to a reduced Q-value $\sim 1 \times 10^6$. The corresponding value of coupling coefficient β for this over-coupling level is ~ 200 and the maximum power required to lock the resonator is found to be ~ 300 W (max) as $P_{\text{amplifier}} = \frac{(1+\beta)^2}{4\beta} P_{\text{cavity}}$. During the first beam acceleration [3] through the linac resonators, the use of this large forward power for a prolonged duration of 24 hours or more resulted in several operational problems like melting of insulation of the rf power cable, excessive heating of the drive coupler leading to coating of the resonator surface by material from the coupler, and increased cryogenic loss. Thus, it was necessary to find a way to reduce the forward power for locking the resonator at the required field level. The quality factors, the accelerating fields at 6 W of input power dissipated into liquid helium and the forward powers required to lock the resonators (both amplitude and phase), are presented in Table II.

III. DAMPING OF THE MECHANICAL MODES OF VIBRATION OF THE RESONATOR

A. A novel way of damping of mechanical modes

The schematic of our quarter-wave resonator is shown in Fig. 1. Bellows are provided in the transition joints between the resonator body (Nb) and the outer SS jacket to prevent stress buildup on the Nb housing and the stub on cooling to liquid helium temperature. Because of the presence of microphonics, the central conductor of the resonator (Fig. 1) vibrates at its mechanical resonance frequency. The amplitude of this vibration is maximum at the tip of the central conductor. A very simple idea has been implemented to damp this mechanical vibration. A number of polished SS balls of diameter 4.0 mm were inserted into the central conductor of the resonator so that they could rest at the tip of the central conductor, which would be filled with liquid helium (LHe). The dynamic friction of the balls with the niobium surface helps in damping the amplitude of vibration of the central conductor. The experiment was also tried with 2.0 and 6.0 mm SS balls with some success. As the contact area and the mass of the balls play an important role in the whole process of vibration damping, the damping offered by 4 mm balls in the geometry of our resonator was found to be the largest compared to that offered by 2 and 6 mm balls. Hence, 4 mm balls were used as the damper. The obvious advantages of this technique are: (a) it does not require any additional fixtures and uses commercially available SS balls commonly used in bearings; (b) it does not create any hindrance in the path of liquid helium; (c) it provides high sensitivity to micron level vibration; (d) it provides no interaction with rf and causes no problem for the performance of the resonator; and (e) it has the potential to be implemented in other complicated structures of resonators.

B. Descriptions of damping experiments and results

When the tip of the central conductor of the resonator, a coaxial transmission line, is shifted by a finite amount, the capacitance of the equivalent LC circuit changes, causing a change in its resonance frequency. The total capacitance between two coaxial cylinders of radii a and b, can be written (in Gaussian units) as

$$C = \frac{q}{\Delta V} \approx \frac{1}{2\ln\frac{b}{a}}, \qquad (1)$$

where the dielectric constant (ε) is unity in the present case.

When the center of the inner cylinder is shifted by a small amount δ from their previous concentric axis, the calculated value of the new capacitance, using the image method for two-dimensional cylindrical geometry, is given by (in Gaussian units)

$$C = \frac{q}{\Delta V} \approx \frac{1}{2\ln(\frac{b}{a} - \frac{\delta^2}{b^2-a^2})}. \qquad (2)$$

It is assumed here, for simplicity, that the displacement of the first half of the central conductor (the tube with lesser diameter) is negligible and the frequency change originates from the displacement of the end portion (the tube with bigger diameter) of the central conductor.

1. Damping of transient vibration at room temperature

A set of experiments was carried out with the resonator at room temperature and atmospheric pressure with the region inside the central conductor evacuated. In these experiments, the decay of the amplitude of the displacement (δ) of the central conductor was measured when vibrations were induced from a single strike on the outer body of the resonator. The resonator was powered by a self-excited loop with the help of a resonator controller module implementing dynamic feedback control of amplitude and phase. The variable resonance frequency of the resonator was compared by the resonator controller with its mean frequency supplied by a stable signal generator (Agilent E4400B). The frequency difference was then converted into a dc voltage by the CRM of the controller. The voltage signal from CRM was amplified with the help of an audio frequency (DC) amplifier before it was fed to a computer via a picoscope (model No. 2202, made by Pico-technology Ltd.). The dc voltage signal from CRM was then converted into the frequency jitter (Δf) of the resonator. From the frequency variations, the change of capacitance of the resonator was calculated, which ultimately

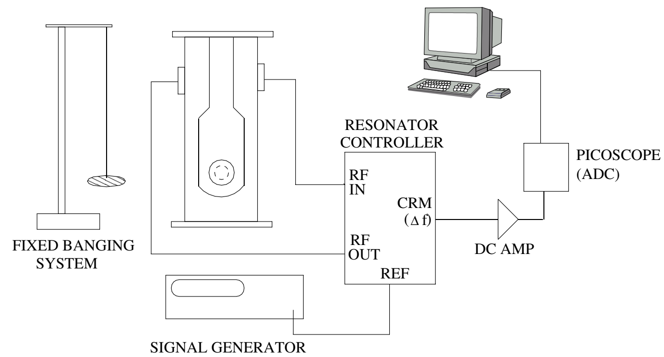

FIG. 2. Block diagram to measure frequency excursion of a resonator with the help of the cavity resonance monitor.

generated the displacement data δ of the central conductor from its mean position using Eq. (2). The block diagram of the experiment is shown in Fig. 2. The vibration from the single hit induced a sinusoidal displacement, at the free end of the central conductor, which decayed over a period of time. The decay time of the amplitude of vibration of the central conductor was measured with 0 to 170 balls inside the central conductor in steps of ten balls. The whole experiment was then repeated with the inside portion of the central conductor filled with air and alcohol. Alcohol was chosen to study the effect of viscous damping in the presence of a liquid, as would be the case with liquid helium although the values of their specific gravity and viscosity differ considerably. Variations of the decay times of the vibration amplitude of the resonator in three different conditions against number of balls are shown in Figs. 3–5. We find that the nature of decay of amplitude of vibration with time is exponential (shown in the smaller

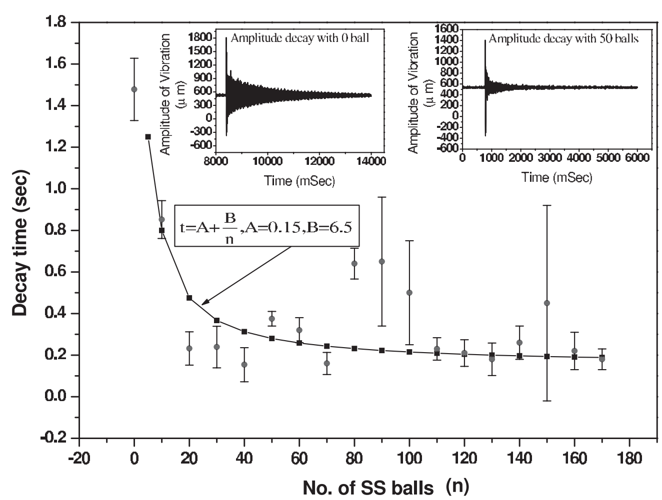

FIG. 3. Decay time of the displacement amplitude of the central conductor with the number of balls. The inside portion of the central conductor is in a vacuum. The resonator is at room temperature and atmospheric pressure. Two inset figures show how the vibration amplitude decays with time for 0 and 50 balls.

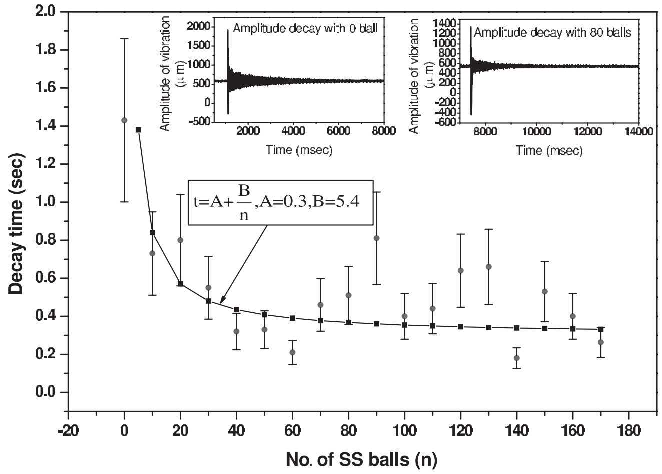

FIG. 4. Decay time of the displacement amplitude of the central conductor with the number of balls. The inside portion of the central conductor is in air. The resonator is at room temperature and atmospheric pressure. Two inset figures show how the vibration amplitude decays with time for 0 and 80 balls.

graphs inside Figs. 3–5). This suggests that the friction between the SS balls and the niobium surface is not purely sliding, as the decay of the vibration with time would be perfectly linear [8] for the case of sliding friction between solids. Similar behavior was also observed when the measurements were done in the presence of air and alcohol (Figs. 4 and 5).

The frictional damping is expected to be proportional to the total contact area of the balls with the niobium surface and hence linearly proportional to the number of balls. Therefore the decay time (t) of the vibration amplitude

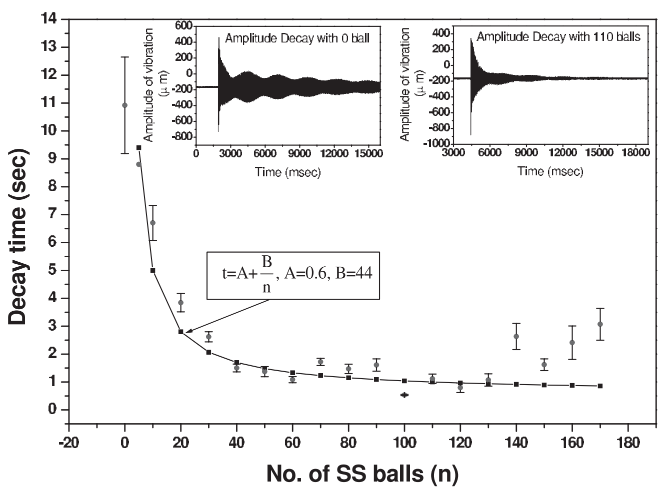

FIG. 5. Decay time of the displacement amplitude of the central conductor with the number of balls. The inside portion of the central conductor is filled with alcohol. The resonator is at room temperature and atmospheric pressure. Two inset figures show how the vibration amplitude decays with time for 0 and 110 balls.

TABLE I. Minimum decay time in three different mediums

Medium inside the central conductor	Decay time without ball (sec)	Minimum value of decay time for 80 balls (sec)
Vacuum	1.47	0.23
Air	1.43	0.36
Alcohol	10.85	1.15

should be inversely proportional to the number of balls. The curves in Figs. 3–5 are fitted with the equation

$$t = A + \frac{B}{n},$$

where A and B are two coefficients that depend on the geometry, medium and effective coefficient of friction, and n represents the number of balls.

The fall of decay times is sharp at the beginning and approaches a saturation value as the number of balls is increased in all three cases of vacuum, air, and alcohol. The explanation for the saturation value lies in the finite size of the flat niobium surface at the bottom of the central conductor where the SS balls rest. Beyond a certain number, all the balls will no longer be in direct contact with the niobium surface. From the size of the central conductor and the ball diameter, this number is close to 80. The decay times found from the fitted curves of Figs. 3–5 are given in Table I for a typical value of 80 balls.

It is interesting to note (Table I) that, for a given number of balls, the decay time is minimum when no fluid medium is present inside the central conductor to put any hindrance against the free movement of SS balls and/or to provide lubrication between niobium surface and SS balls. When the central conductor oscillates with some fluid inside it, the fluid also moves but with a time lag. Because of this out of phase motion between the fluid, the balls, and the niobium surface, and also due to the lubrication provided by the liquid between SS balls and niobium surface, the vibration takes a longer time to decay.

In Figs. 3–5, the error bars are different and the measured values are scattered, as the actual placement of the SS balls inside the central conductor is not uniform due to the somewhat irregular shape of the bottom part of the central conductor. When the balls are added in groups inside the central conductor, the irregular shape causes variable damping in successive measurements. However, the falling trend of the decay time as shown in Figs. 3–5 is observed repetitively in a large number of experiments.

2. Damping of vibration induced by repetitive disturbances at room temperature

After demonstration of vibration damping from the experiment of a single strike on the resonators, the effect of damping on the frequency excursion of a resonator coupled

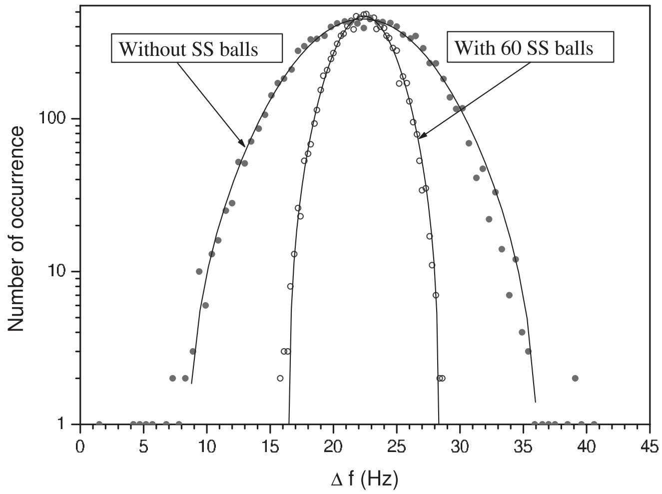

FIG. 6. Frequency excursion (Δf) of a niobium resonator at room temperature without SS ball and with 60 SS balls.

with a source of constant artificial vibration was measured. This experiment was done to simulate the condition of a superconducting resonator installed in a cryostat picking up microphonic vibration from the surroundings. The experimental setup was similar to Fig. 2, the only difference being that a mechanical vibrator attached at the top of the resonator replaced the fixed banging system. This experiment was also done on a resonator outside the cryostat at room temperature and at atmospheric pressure with air medium inside the central conductor. When a continuous vibration with a frequency spectrum of few tens of Hz to few tens of kHz, was coupled to the resonator operating in a self-excited loop shown in Fig. 2, its frequency fluctuated around the mean frequency. The error voltage from the CRM output of the resonator controller module was recorded by the same setup mentioned earlier and the frequency jitter data were recorded after calibrating the error voltage data with and without SS balls as a vibration damper. The number of SS balls was then increased from 0 to 160 in steps of ten. The reduction of frequency excursion around its mean value began to saturate at around 60–80 SS balls and after that no significant reduction was observed up to 160 balls. A comparison of the frequency excursion (Δf) with 0 and 60 balls are shown in Fig. 6. The value of Δf recorded was 25 and 11 Hz, respectively, for the case of undamped and SS ball induced damping. Thus, there is a substantial reduction on the frequency excursion due to damping by SS balls.

C. Measurement of frequency jitter (Δf) and forward power required to phase and amplitude lock a niobium resonator at LHe temperature

During these experiments, resonators were mounted in the test cryostat and the same measurement technique as mentioned earlier was used. The superconducting resonator was phase and amplitude locked in a self-excited loop at a value close to maximum achievable field at 6 W of absorbed power with a minimum forward rf power for an optimum value of coupling coefficient β. The frequency jitter (Δf) of the resonator was measured with the CRM output of the resonator controller. SS balls in steps of ten were then inserted inside the central conductor. The forward power and Δf to achieve the best stable lock were measured in each step. No external strike was introduced onto the resonator and all the measurements were performed with the vibrations picked up by the resonator from the supporting structure of the cryostat. The actual frequency of the resonator was recorded at intervals of a few milliseconds over a period of 10–15 secs. In a typical experiment, the total excursion of the resonance frequency (Δf) of a resonator without any SS ball as a damper was measured to be ~80 Hz (Fig. 7) and the resonator could be phase and amplitude locked for its maximum achievable field with a forward power of around 60 W (Table II). With 80 SS balls, inside the central conductor, a reduction of ≥ 50% in Δf was recorded (shown in Fig. 7) and it was possible to obtain a stable phase and amplitude lock of the resonator for the same accelerating field with a forward power of ~28 W. The experiment was repeated on this resonator and another resonator for a number of times and, in each case, 50% or more reduction in Δf and forward power had been measured with 80 SS balls inside the central conductor. It is important to note that the test cryostat is located in a much quieter environment than the linac cryostat, which is a part of the beam line. The operation of the cryogenic plant and the continuous liquid helium filling system in the linac cryostat also increases the

TABLE II. A comparison of the power requirement to obtain the phase and amplitude lock of the resonators without and with damping mechanism in test and linac cryostat.

Cryostat	QWR	Q_0 at 6 W	E_{acc} (MV/m) at 6 W	E_{acc} (MV/m) during phase lock	Required power (W) without damping	Required power (W) with damping
Test	1	1.6×10^8	3.5	3.5	60	28
	2	4.7×10^8	6.0	5.0	80	35
Linac	3	2.1×10^8	4.0	3.1	218	90
	4	2.1×10^8	4.0	2.5	280	100

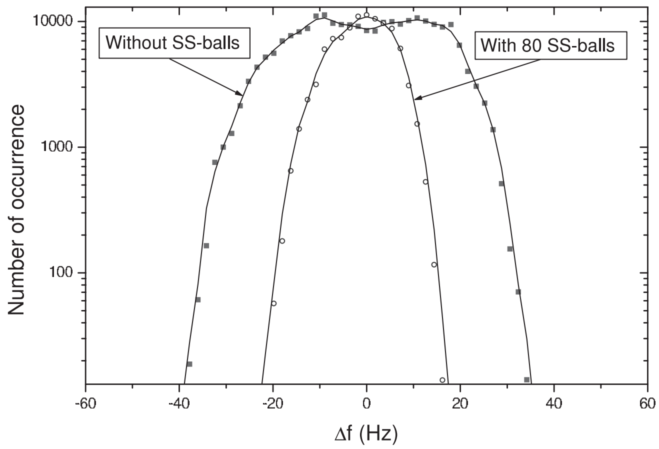

FIG. 7. Frequency excursion (Δf) of a superconducting resonator at 4.2 K with and without the vibration damper.

amount of microphonics in comparison to the test cryostat. The main cause is the opening and closing of the control valves in the helium distribution system, which introduces large amplitude vibrations. The pressure fluctuation of the helium also plays a significant role in introducing frequency shifts of the resonators but this happens at a much slower rate and is corrected by the mechanical tuner. Since the test cryostat does not have all these mechanical noises, it is possible to lock a resonator with ~60–80 W of forward power without using a damper whereas, for the linac cryostat, a factor of 3–4 higher power was required.

The damping mechanism was then tried on the resonators mounted in the linac cryostat. As there was no provision to insert SS balls from outside after mounting the resonators in the cryostat, an optimum number of SS balls (80) were inserted at the time of mounting the resonators in linac cryostat. Without the damping mechanism, the resonators used to require a few hundred watts of forward power for amplitude and phase locking. As the supply of forward power is limited by the rf amplifier and our system is not equipped to handle this large amount of rf power for more than few hours, locking was done at lower fields. When the damping mechanism was applied, it was possible to operate the resonators at higher fields even with ≤ 100 W of forward power. We compare in Table II the forward power required to lock the resonators at the same field value, with and without damping. It may be noted that the resonators could be locked at higher fields than these values with the damping in place. During the past one year operation of the resonators in the linac cryostat, most of the QWRs were locked at fields ~3 to 5 MV/m with ≤ 100 W of forward power. We observe a large variation in the forward power (60–100 W) required to lock different resonators mounted in the linac cryostat at comparable field values. This is due to the different amount of microphonics picked up by individual resonators mounted at different positions in the linac cryostat.

IV. CONCLUSIONS

Because of the presence of microphonics in the ambience of the linac cryostat, high forward power of a few hundred watts was required to operate the resonators in the past. Implementation of an innovative and simple damping mechanism has brought down the required power level below 100 W. The new damping mechanism will also be used for the resonators in the forthcoming linac cryostats No. 2 and No. 3. This simple technique of damping has the potential to remove or to reduce the usage of complicated fast tuner devices during the operation of superconducting niobium resonators. This method will be extremely fruitful especially for bigger structures of low frequency superconducting accelerators, whose stability still poses a challenge to the accelerator community.

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[1] K. W. Shepard, A. Roy, and P. N. Potukuchi, Proceedings of the 1997 Particle Accelerator Conference, Vancouver, BC, Canada, 1997, p. 3072.

[2] S. Ghosh, R. Mehta, P. N. Prakash, A. Mandal, G. K. Chaudhari, S. S. K. Sonti, D. S. Mathuria, K. K. Mistry, A. Rai, S. Rao, P. Barua, A. Pandey, B. K. Sahu, A. Sarkar, G. Joshi, S. K. Datta, R. K. Bhowmik, and A. Roy, in the 9th International Conference on Heavy Ion Accelerator Technology, New Delhi, India, 2002 [Pramana J. Phys. 59, 881 (2002)].

[3] S. Ghosh, R. Mehta, G. K. Chowdhury, A. Rai, B. K. Sahu, A. Pandey, D. S. Mathuria, S. S. K. Sonti, K. K. Mistry, P. Patra, S. Ojha, A. Sarkar, R. Joshi, P. N. Prakash, A. Mandal, D. Kanjilal, and A. Roy, Proceedings of the Indian Particle Accelerator Conference, Kolkata, India, 2005, p. 48.

[4] D. Kanjilal, S. Chopra, M. M. Narayanan, I. S. Iyer, V. Jha, R. Joshi, and S. K. Datta, Nucl. Instrum. Methods Phys. Res., Sect. A **328**, 97 (1993).

[5] A. Facco, V. Zviagintsev, and B. Cheremushkinskaya, in Proceedings of the Particle Accelerator Conference, Vancouver, BC, Canada, 1997, p. 3084.

[6] M. P. Kelly, J. D. Fuerst, M. Kedzie, S. I. Sharamentov, K. W. Shepard, and J. Delayen, in Proceedings of the Particle Accelerator Conference, Portland, Oregon, 2003, p. 1291; Dr. M. P. Kelly (private communication).

[7] G. Joshi, C. I. Sujo, B. K. Sahu, A. Pandey, A. Kumar B.P., and J. Karande, presented in the 9th International Conference on Heavy Ion Accelerator Technology, New Delhi, India, 2002 [Pramana J. Phys. 59, 1035 (2002)].

[8] X. Wang, C. Schmitt, and M. Payne, Eur. J. Phys. **23**, 155 (2002).