A ROOM TEMPERATURE, LOW POWER FAST TUNER FOR SUPERCONDUCTING RESONATORS

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ABSTRACT

A fast tuner, capable to compensate for microphonic-induced frequency fluctuations in superconducting resonators was designed, constructed and tested. This device, to be connected to resonators with moderate frequency fluctuations (e.g. resonators equipped by mechanical dissipators), consists of a voltage-controlled reactance based on one-by-one switching PIN-diodes and RF capacitors, mounted outside the cryostat and connected to the cavity by means of a RF line and a RF coupler. Design and test results are discussed.

INTRODUCTION

Eigenfrequency stabilization is one of the most critical problems in superconducting resonators; typically, cavities working below 100MHz must be operated below their maximum field due to frequency fluctuations caused by mechanical instabilities. Microphonic effects from environmental noise can occasionally excite resonant mechanical vibrations in the LNL 80 MHz low ß superconducting quarter wave resonators (QWR); this can cause fluctuations of the rf eigenfrequency much larger than ±2 Hz, the bandwidth of the loaded resonator in our working conditions. The use of a mechanical dissipator inside the QWR [1] allows to damp considerably the vibration amplitude and, consequently, to reduce the maximum eigenfrequency excursion; however, it is not yet clear whether this device, which has already demonstrated to keep the resonator within about ±15 Hz, could be further optimized to guarantee a ±2 Hz bandwidth. Stronger coupling could increase the effective bandwidth but it would require power amplifiers delivering much more than the 150 W at our disposal.

The moderate tuning requirements of our resonators suggested us to develop a fast tuner with low power losses inside the cryostat and easy access to the electronics, located outside of it.

FT DESIGN AND CONSTRUCTION

The FT is based on a variable reactance connected to the QWR by means of a 50 Ohm RF line and a RF coupler. PIN-diodes are used in order to change the reactance value. There are at least three ways to control by means of PIN-diodes the reactance coupled to the resonator:

- switching between two different values of reactance at a rate which is much higher than the loaded resonator decay time: the resonator eigenfrequency depends on the average value, which can be controlled by varying the duty cycle between the two states [2];
-switching one-by-one a set of uniform reactive elements in parallel: the eigenfrequency will be determined only by the number of switched elements [3];
-switching between different configurations of non-uniform reactive elements; e.g., with a set of n elements with capacitance Co, 2×Co,... n×Co it is possible to build 2^n different configurations, uniformly spaced in capacitance, by switching the elements in binary code.

The first technique is characterized by high RF losses in the PIN-diodes, due to the fast switching rate, and a by a large phase noise in the resonator due to the big frequency step between the two states. The second technique produces lower noise and lower rf losses; the main disadvantage is in the higher number of lines needed to drive the PIN-diodes independently. The number of reactive elements depends on the required tuning step and bandwidth;

The third way could appear the best compromise but it would require a very accurate adjustment of the different elements in order to provide a homogeneous tuning; serious problems would arise in case of failure of one of the diodes.

According to our necessity, we developed and tested a $\approx 24Hz$ fast tuner (FT); due to the relatively small bandwidth we could choose the second technique described above, using an array of 12 RF capacitors and PIN-diodes.

The total switching reactive power on the PIN-diodes can be calculated according to a formula which is a consequence of Slater theorem [4]:

$$\Pr eact = 4 \cdot \pi \cdot W \cdot \Delta f_{window} , \qquad (1)$$

where $f = 80MHz$, $\Delta f_{window} = 20Hz$ is the frequency window produced by the FT and W is the energy stored in the QWR. In our case, at 4MV/m accelerating field, $W = 1.82J$ and a total switching reactive power $\Pr eact = 460VA$ (about $40VA$ for each PIN-diode) is required. The FT box, containing all the electronics, is located outside of the cryostat and connected with the resonator through a 50 Ohm line and an inductive coupler (fig.1). This approach offers several advantages:
- The RF power losses of the FT assembly are dissipated at room temperature;
- the access to the FT box is easy .

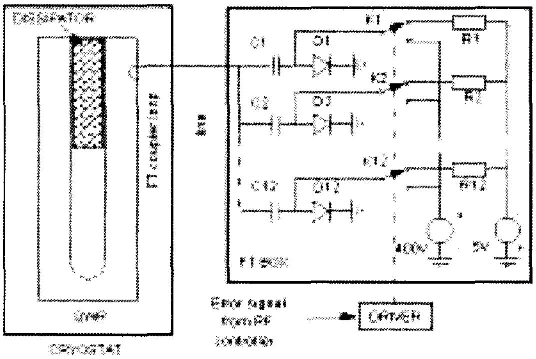


Fig.1 The room temperature FT scheme

We have used 1500V LORAL PIN-diodes GC 4600-172. According to our calculations and measurements, the maximum RF voltage in the FT box at 4MV/m accelerating field is 250V (Fig.2). We have set the PIN-diodes lock voltage at 400V. The value of the C1-C12 RF capacitors must be chosen according the PIN-diodes characteristics: for 80MHz, $V_{breakdown}/2=750V$ and $I_{rfmax}=1A$ we took C=3.3pF. The measured quality factor of the RF board is about 100. The K1-K12 switchers are based on Siemens BUZ 50 B MOSFET; the R1-R12 resistors are providing a PIN-diodes bias current of 100mA. The PIN-diodes minority carrier lifetime is $\tau = 5\mu s$; since our rf frequency is $f > 10/\tau$, the maximum safe value of rf current for the PIN-diode is $Irf_{\max} \approx 10 \cdot Ibias = 1A$. According to our calculations, at 4MV/m $Irf_{\max} \leq 0.5A$.

The frequency shift induced by the FT can be calculated by means of the following formula, valid for $\Delta f << f$:

$$\Delta f \cong 2 \cdot \pi^2 \cdot f^3 \cdot \frac{M^2}{\sqrt{L_R / C_R}} \cdot \mathrm{Im}\left(-Z^{-1}\right), \qquad (2)$$

where M is mutual inductance between QWR and FT coupler loop, L_R, C_R are the equivalent parameters of the resonator and Z is the FT total impedance at the coupler loop plane (see equivalent scheme of the QWR with the FT on fig.2).

The FT line, which is completely enclosed in the cryostat, is terminated by means of an inductive coupler loop in the resonator. The FT line phase length is 170deg, optimised in order to obtain the maximum frequency window with uniform frequency steps at a given dissipated power. The FT impedance has an inductive effect in the QWR, thus $\Delta f < 0$. The resonant frequency of the QWR, f_o, is adjusted so to obtain the central position when 6 capacitors are switched on:

$$f_o + \Delta f_6 = 80MHz. \qquad (3)$$

The resonant Q – curves calculated for the QWR equipped with the FT are shown in fig.3. $\Delta f'$ is the frequency shift from the central position:

$$\Delta f' = \Delta f - \Delta f_{m=6}. \qquad (4)$$

According to our calculations and measurements, the quality factor of the FT coupled to the QWR for the required tuning window at 4 MV/m is $Q_{ft} \approx 7 \cdot 10^7$. We have chosen a FT window of 20 Hz and a step equal to half the loaded resonator bandwidth (about 4 Hz), resulting in a total loaded quality factor $Q \approx 2 \cdot 10^7$ and a total tuning range of $\approx 24Hz$ (equal to the FT window plus the QWR bandwidth). To obtain the same bandwidth without FT we would need an RF amplifier 6 times more powerful than we have. Since

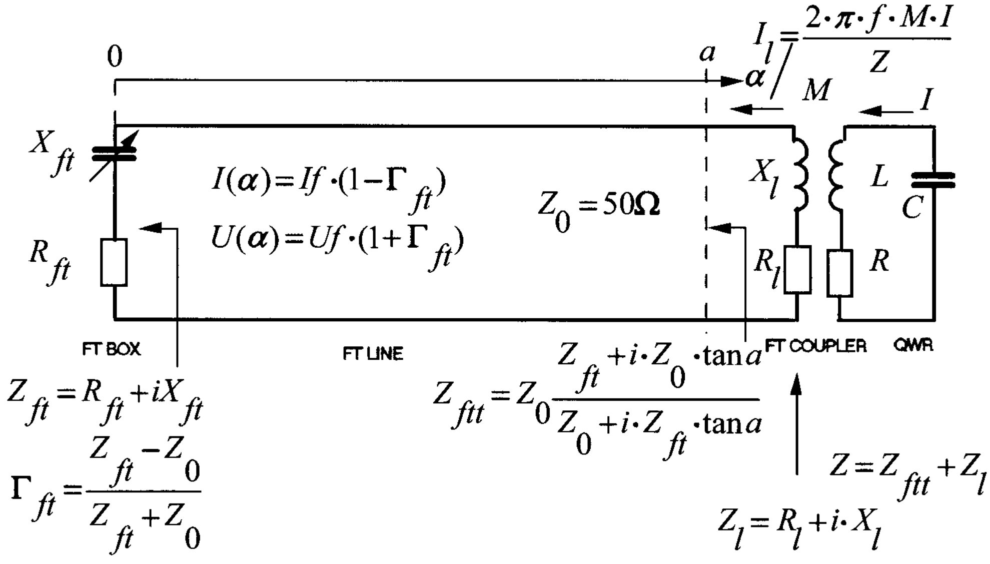
$$\frac{\Delta f_{window}}{P_{for}} \leq \frac{1}{2\pi W}\left(\frac{m}{2}+1\right) \qquad (5)$$

where m is the total number of FT steps (capacitors), the needed rf forward power is roughly inversely proportional to the maximum number of steps.

The theoretical maximum FT window vs. accelerating field is shown in table 1. The window can be adjusted to the required value by choosing the proper coupling strength.

Table 1. Theoretical maximum FT window vs. accelerating field.

Ea, MV/m	3	4	5	6	7
$\Delta f \max_{window}$, Hz	320	180	115	80	58



RF voltage and current distribution along the FT line at 0, 6 and 12 switched capacitors, window=20 Hz and Ea=4 MV/m.

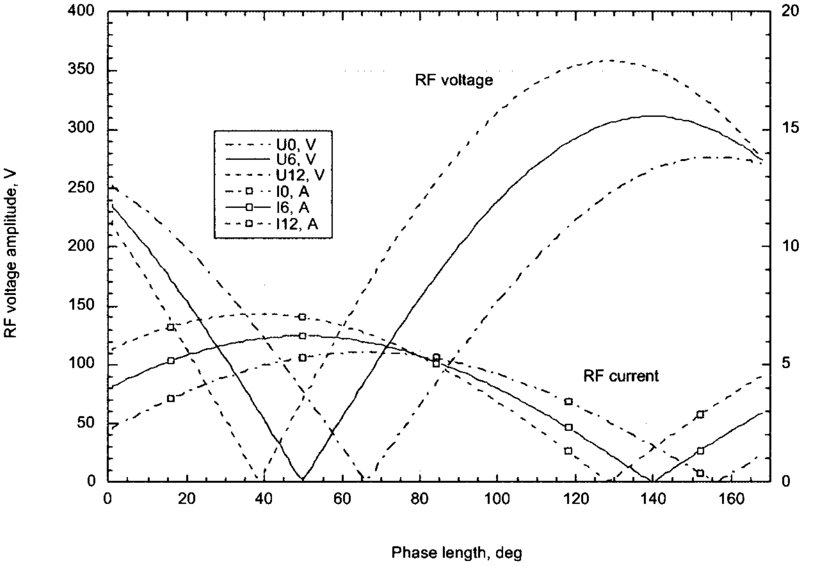


Fig.2. Equivalent scheme of a QWR equipped by the FT, with RF voltage and current distribution along the FT line.

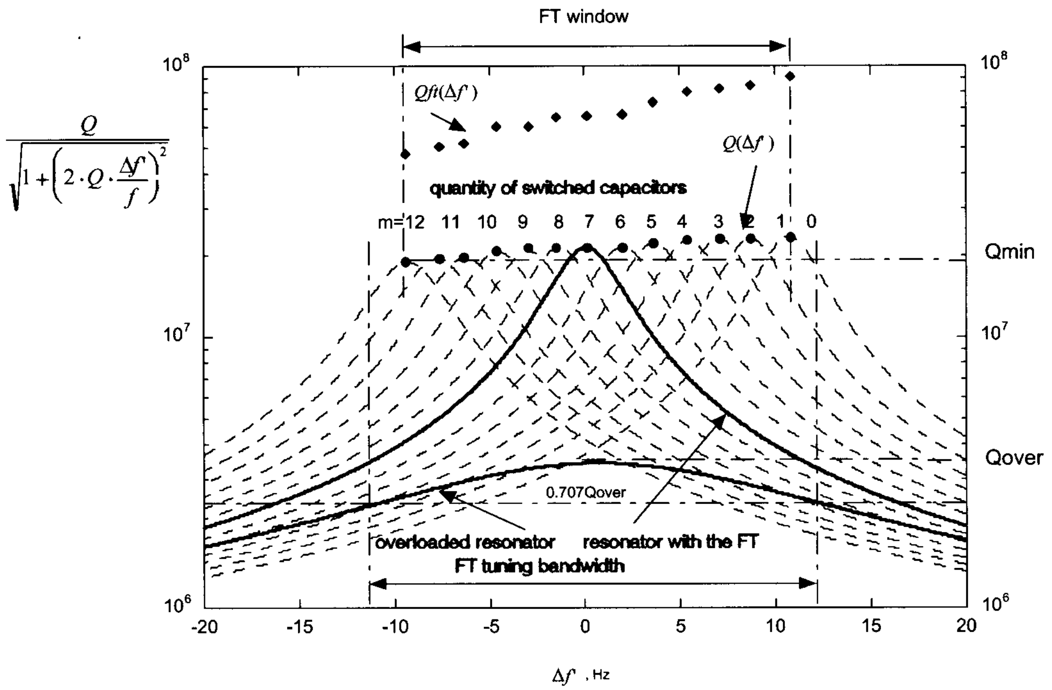


Fig.3. Q-curves of the QWR with the FT.

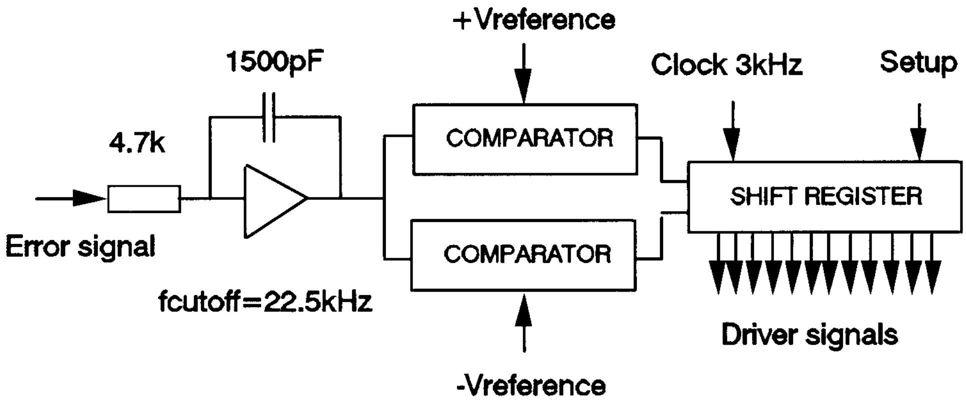


Fig.4. Block diagram of the FT driver.

Our FT driver (fig.4) consists of an operational amplifier, 2 comparators and a counter; a bi-directional shift register changes the number of switched PIN-diodes. The driving signal is the residual phase error signal coming from the resonator RF controller; the switching clock frequency is 3 kHz.

EXPERIMENTAL RESULTS

The FT was tested with a superconducting QWR equipped by a mechanical dissipator; the rf coupler was adjusted for a bandwidth of 3.6Hz at Ea=3MV/m accelerating field. A mechanical vibrator was applied to the cryostat and operated at 48.7 Hz, the strongest mechanical resonance of the cavity. The mechanical damper alone (an early model) was limiting considerably the maximum frequency excursion, but the rf amplifier could not stabilise the phase error within our requirements; however, the FT could control rf frequency fluctuations in the range of about 24 Hz, according to the design expectations, and perform phase stabilization satisfactorily (fig.5). During the test, we measured power losses much larger than expected in the FT line, caused by field emission in the FT coupler due to a poor design of such component. This prevented us to complete the measurements at 4MV/m; at this field the FT was working properly, but the helium consumption due to field emission forced us to stop the operation.

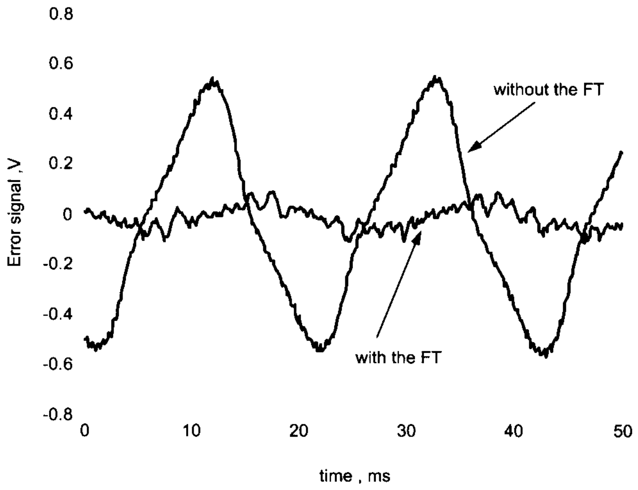


Fig.5. Phase error signal of the superconductive QWR measured with and without the FT, in the presence of an artificially induced mechanical vibration.

CONCLUSIONS

A FT was designed, constructed and tested at LNL with a 80 MHz, low β quarter wave resonator in superconductive regime. The 24 Hz bandwidth, required by our resonators equipped with mechanical dissipators, was reached; the fast tuner box and the control system were working satisfactorily. Strong power losses due to field emission in the fast tuner coupler were observed; the aim of the developments foreseen in the next future will be the solution of this problem.

REFERENCES

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