DESIGN OF THE FAST TUNER LOOP FOR SUPERCONDUCTING RFQs AT INFN-LNL

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Abstract

The fast tuner system for the two superconducting RFQs of the LNL heavy ion high current injector PIAVE was studied. The fast tuners (FT) correct the frequency variations, caused mainly by mechanical vibrations. The design, which was proposed by ANL (Argonne, USA), uses the fast switching of two capacitances by means of PIN diodes to change the total impedance at the coupling loop.

The FT power dissipation depends on frequency tuning range, stored energy of the resonator and a coupling loop design. We estimated the power dissipation and the frequency variations using the MAFIA code, varying the position and the shape of the coupling loop. Analytical estimates are shown, that agree well with the results of the simulations. These results laid the groundwork of the fast tuner model measurements.

1 INTRODUCTION

Eigenfrequency excursions caused by vibrational mechanical modes which are excited by ambient acoustic noise is a typical problem for slow-wave superconducting (SC) resonators. First measurements of SC bulk Nb RFQ2 [1] showed Q of nearly 10^9, which corresponds to a bandwidth of approximately 0.1Hz for 80 MHz operating frequency. This means that eigenfrequency excursions are much larger than the bandwidth of the resonator. Overcoupling could permit extension of the effective bandwidth, however, it would results in an increase of the RF power dissipation at RF driver line and, hence, in liquid He consumption.

Slow eigenfrequency variations, mainly excited by liquid helium pressure perturbation will be corrected with a slow tuner, and fast ones with a fast tuner, operating in a 100 Hz window. A shift of the resonant frequency is equivalent to the insertion in the resonator of a parasitic reactance Z_p. In this case resonant conditions will be fulfilled when:

$$\omega_1 \cdot L_0 - \frac{1}{\omega_1 \cdot C_0} + \mathrm{Im}(Z_p) = 0 \qquad (1)$$

where: $\omega_1=\omega_0+\Delta\omega$; and ω_0 and ω_1 are resonant frequencies before and after a disturbance of the cavity; $\Delta\omega=2\pi\,\Delta f$

In order to compensate for $\Delta\omega$, a proper reactance $Z_i = -Z_p$ (Fig.1b).should be inserted into the cavity to keep the resonant frequency ω_0 constant :

$$\omega_0 \cdot L_0 - \frac{1}{\omega_0 \cdot C_0} + \mathrm{Im}(Z_p) - \mathrm{Im}(Z_i) = 0 \qquad (2)$$

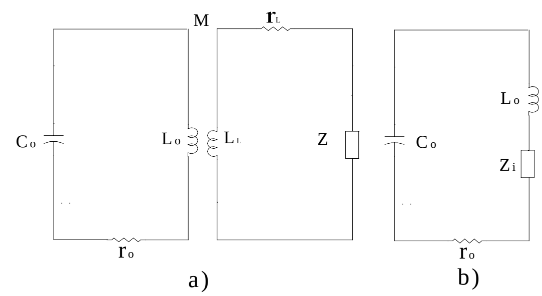

Fig.1: Equivalent circuit of the resonator coupled with reactance Z (a) and modified circuit (b) with actual reactance Z_i inserted in the resonator.

Here C_0, L_0, r_0 are the equivalent capacitance, inductance and resistance of the resonator; M is the mutual inductance of the resonator and FT loop; and L_L, r_L are the self-inductance and resistance of the FT loop;

$$Z_i = \frac{\omega^2 \cdot M^2}{Z_1}; \quad M = \frac{B \cdot S_L}{V_{el} \cdot \omega \cdot C_0}; \quad \omega = 2\cdot\pi\cdot f$$

$$Z_1 = r_L + i\cdot\omega\cdot L_L + Z \qquad (3)$$

S_L -is area of the loop, B-magnetic flux density in place of the loop, V_{el} =280 kV is RFQ inter-electrode voltage
Eigenfrequency shift is given by:

$$\Delta f = f_1 - f_0 = \pi \cdot M^2 \cdot \frac{f^2}{L_0} \cdot \mathrm{Im}\left(\frac{-1}{Z_1}\right) \qquad (4)$$

There are at least two ways to control the reactance. One way provides switching the SC resonator between two frequency states above and below the eigenfrequency with a switching rate of about 25kHz. Tuning the resonator eigenfrequency is achieved by a controllable switching time which can be varied, typically, from 5% to 95% of the switching cycle [2]. Another way provides switching one-by-one a set of uniform reactive elements, compensating the eigenfrequency excursions [3,4]. The first way has worked reliably at ANL for many years, and although it operates a quite high reactive switching power (10-30 kVA), it looks attractive.

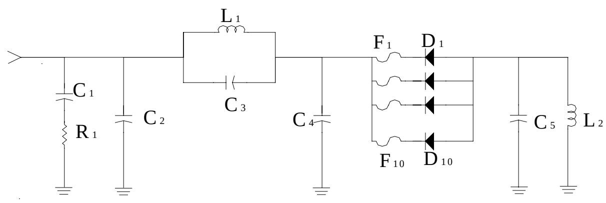

Fig.2: Schematic for the LN_2 part of the ANL fast tuner.

Figure 2 shows the equivalent circuit of the fast tuner, which is directly immersed in coolant (LN_2) and loop-coupled (L_2) to the SC resonator. 10 PIN diodes, operating in parallel to provide redundancy, switch the SC resonator between two frequency states, which depend on inserted impedances. Each diode is accompanied by a fuse (F_1-F_{10}) , so in case of diode breakdown, it can be removed from the circuit by blowing the fuse with a reverse-bias current. The PIN diodes must switch a reactive power P = I (on-state) x V (off-state), which is proportional to the tuning range (Δf) and RF energy stored in the SC resonator (U_s).

$$P = 8 \cdot \pi \cdot \Delta f \cdot U_s \qquad (5)$$

where $U_s = \frac{1}{2} \cdot V_{el}^2 \cdot C_0$

U_s = 4 J for SC RFQ2 and U_s = 2 J for SC RFQ1.

2 DESIGN OF THE LOOP

2.1 Tuning range

The FT coupling loop should be designed to provide a proper tuning range (window) and to have an acceptable low power dissipation. As an initial step we used the ANL loop shape, trying to adapt it for real existing RFQs FT flanges.

The frequency range of the fast tuner is determined by formula (4), which can be easily transformed to:

$$\Delta f = \frac{V_{loop}^2}{8 \cdot \pi \cdot U_s} \cdot \mathrm{Im}\left(\frac{-1}{Z_{on}} - \frac{-1}{Z_{off}}\right) \qquad (6)$$

where Z_{on} and Z_{off} correspond to impedance Z_1 applied to the loop for "on" and "off" PIN diodes states.

The magnetic flux density (B) at the position of the FT loop is 10 mT for a nominal inter-electrode voltage (280 kV) of SC RFQ2 as calculated by M.A.F.I.A. The FT loop will be housed in a 48 mm ∅ RF port, which for H_{11} has cutoff wave length λ = 0.0819 m. The magnetic field varies as $B = B_{\max} \cdot \exp(-\gamma \cdot l)$; where propagation factor γ = 76.7 and l is the distance from the inner surface of the SC resonator to the loop.

Figure 3 shows the magnetic flux density distribution along the FT port, calculated both analytically and by M.A.F.I.A..

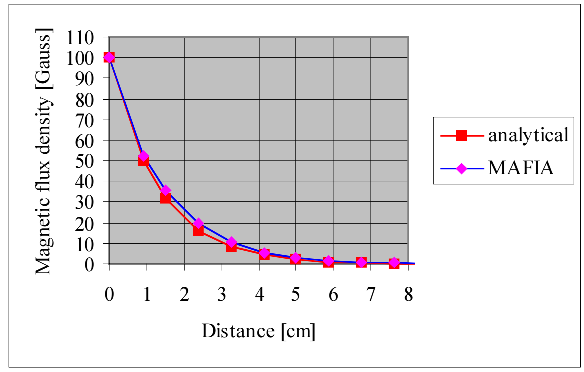

Fig.3 Magnetic flux density distribution inside the FT port

The loop voltage is: $V_{loop} = \omega \cdot B_{loop} \cdot S_L$.

Here S_L = 100 mm^2 - area of the loop, which is made out of a 25 x 3 mm copper strip, having 4.5 mm distance (d) between flat parts of the bent strip; whereas B_{loop}, average magnetic flux density passing through the loop is given by

$$B_{loop} = \frac{1}{d} \cdot \int_{l+t}^{l+t+d} B_{\max} \cdot \exp(-\gamma \cdot l) \cdot dl$$

where t =3 mm (loop thickness) and l is the distance from inner surface of the resonator to top of the loop.

For the chosen shape of the loop, the frequency range is determined by its position and inserted impedances Z_{on} and Z_{off}.

A lumped parameter model was used to calculate values for the capacitors, so as to provide the optimum diode-on rf current and diode-off rf voltage to the diode array. After tuning the assembly, the fast tuning window can be adjusted by changing the position of the loop.

Mesh point limitation does not allow calculation of the frequency shift for actual dimensions of the FT loop using M.A.F.I.A.. In order to evaluate the accuracy of the analytical calculations, Δf was calculated for a ANL like loop, having dimensions 5x20x20 mm (Fig.4) both analytically and M.A.F.I.A for two cases: when the loop has been shorted (gap=0) and disconnected (gap=2.5 mm).

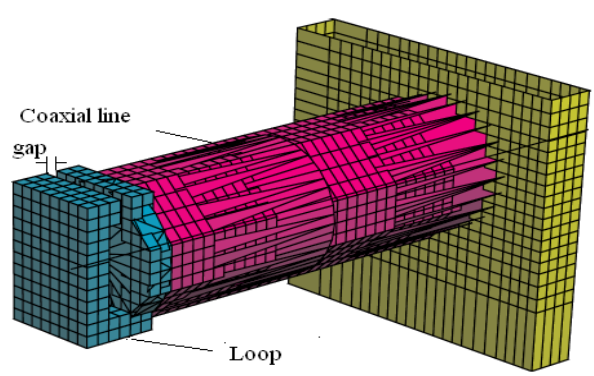

Fig.4: M.A.F.I.A. plot of the FT loop with coaxial line

For the analytical calculation we used L_L = 4.2 nH;

Z_{on}, according to the equation (3), corresponds to Z_1 when Z = 0 and Z_{off} is equal to Z_1 when Z= -5620i. (a reactance of 2.5 mm gap)

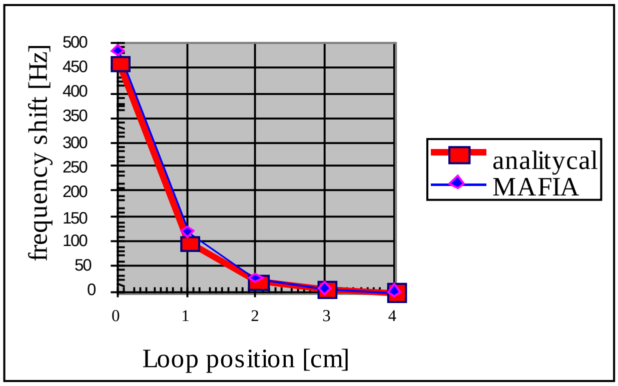

Fig.5: Dependence of frequency shift from loop position

The agreement between the analytical calculation and MAFIA simulation allows easy correction of the position of the loop for actual values of Z_{on} and Z_{off} .

It should be noted that according to the equation (3) impedance Z_1, and hence also Z_{on} and Z_{off}, includes the reactance $X_L = i \cdot \omega \cdot L_L$. In order not to insert an active impedance component into resonator, which would result in reducing the resonator Q, the case when $Z = -i \cdot \omega \cdot L_L$ should be strongly avoided. The ANL approach completely prevents such situation, since both Z_{on} and Z_{off}. are fixed.

2.2 Power dissipations in the FT loop

Power dissipation in the FT loop, which determines the LN_2 consumption, depends on both the switching reactive power and loop position. Since the switching reactive power is fixed by chosen Δf (5), it means that power dissipation in the loop is practically determined by Z_{on} and Z_{off} . There is a freedom of choice between "on" and "off" impedance to minimise active power component. This can be done by lumped parameter circuit analysis software (e.g. "SUPER NOVA"). We have calculated several combinations for Z_{on} and Z_{off}, following ANL recommendations, and have obtained a active power losses in the FT of about 250 W. for a 200 Hz window We hope that a 100 Hz window will cover the possible excursions of the cavity eigenfrequency and, hence, actual power dissipation caused by switched reactances will be about 125 W.

The additional power dissipation (P_{mf}) will be produced by the magnetic field in the loop location. In our case:

$$P_{mf} = \frac{1}{2} \cdot |H_\tau|^2 \cdot R_s \cdot A ,$$

where R_s is the copper surface resistance for 77K, A is the total surface loop area, which includes both coaxial and loop itself (Fig.4).

Fig. 6 shows the dependence of the power dissipation on the loop position as it was simulated by M.A.F.I.A for a disconnected loop with dimensions 5x20x20 mm (Fig.4).

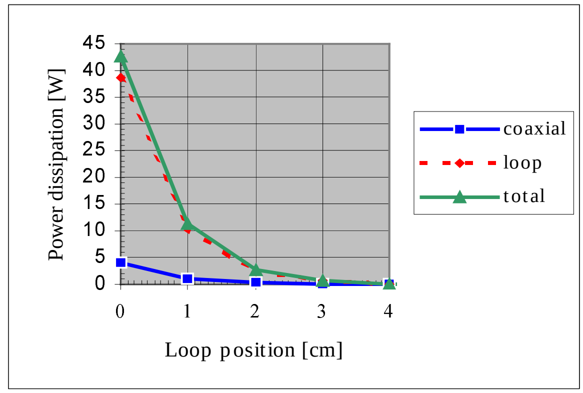

Fig.6: Loop power dissipation vs loop position

As can be seen from Fig.6, P_{mf} is mainly determined by the part of the loop, which "looks" at resonator. The loop voltage should be 201V, for a 200 Hz window. This can be achieved by a loop position equal to 8 mm from inner part of the resonator. P_{mf} in this case will be about 20 W i.e. 10% of what was created by switching reactive power. Thus, there is no need to reduce the width of the loop, because a gain due to reducing P_{mf} can result in increasing the active component of the switched impedance.

3 CONCLUSION

Our simulations allowed us to determine the FT loop dimensions and to fix the loop design. In the future we plan to optimize the values of switched reactances in order to get the proper voltage current ratio of the PIN diodes and hence reliable operation of the fast tuner.

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