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INTRODUCTION

The performance parameters of a superconducting cavity, notably accelerating field and quality factor, are first obtained in a cryogenic vertical test Dewar, and again after the final assembly in its cryostat. The tests involve Network Analyzer (NA) measurements in which the cavity is excited through an input coupler and the properties are obtained from the reflected signal at the input and the transmitted signal from the output coupler. The interpretation of the scattering coefficients in terms of field strength requires the knowledge of the Fundamental Power Coupler (FPC} and Pick-Up (PU) coupler strength, as expressed by their "external" Q_{FPC} and Q_{PU}. The coupler strength is independent of the field level or cavity losses and thus can be determined at low levels with the scattering coefficients S_{11} and S_{21}, assuming standard 50 Ω terminations in the network analyzer. Also needed is the intrinsic cavity parameter, $R_a / Q_0 \equiv \{R/Q\}$, a quantity independent of field or losses which must be obtained from simulation programs, such as the Microwave Studio.

At resonance one finds the power into the cavity, representing the loaded cavity losses, as difference, $P_{in} = P_f - P_r$, directly from the directional coupler in the input waveguide where P_f and P_r is the forward and reflected power. Alternatively, the power into the cavity is given from the forward power alone as [1]

$$P_{in} = 4\frac{Q_{FPC} Q_0}{(Q_{FPC} + Q_0)^2} P_f \ .$$

The transmitted power at the PU, indicating the cavity voltage, is given as

$$P_{PU} = \left\{\frac{Q_0}{R_a}\right\}\frac{V_a^2}{Q_{PU}} \ .$$

A convenient method for finding the external Q's involves achieving critical coupling on the input side by arranging that the coefficient $S_{11} \to 0$, corresponding to $Q_0 = 2Q_L$, providing $Q_{FPC} = Q_0$ and together with S_{21},

$$Q_{PU} = Q_0 / S_{21}^2 \ .$$

This method is not practical for superconducting cavities at room temperature, and difficult to achieve during cool down. A general procedure, used in the March 11 cool down of the ERL cavity is the topic of this Technical Note.

THE FUNDAMENTAL POWER COUPLER

The measurements to determine the external Q of the FPC coupler involved the use of a network analyzer, Agilent E5071C, and the interpretation of the results via the equivalent circuit shown in Fig. 1. Note that the coupling to the PU probe is sufficiently weak to be ignored, $Q_{PU} \gg Q_0, Q_{FPC}$.

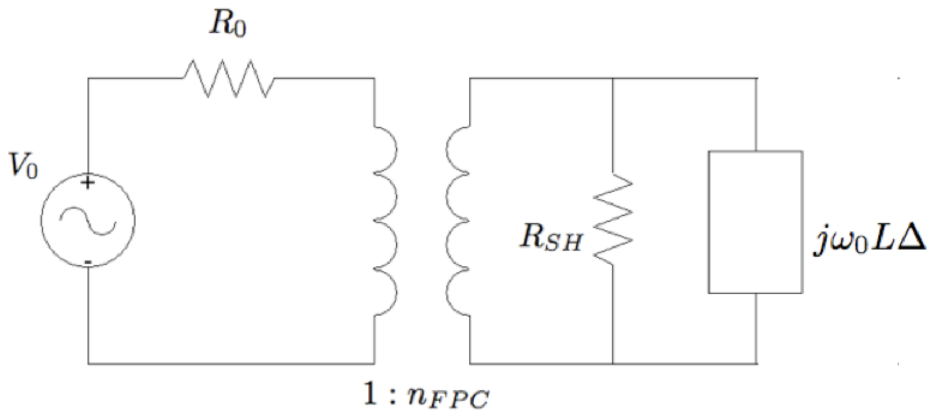


FIG. 1. Equivalent Circuit for the FPC modeled with a transformer

The circuit elements (in circuit definition) are related to the simulated cavity properties as follows:

$$L = \frac{1}{\omega_0}\left\{\frac{R_a}{2Q_0}\right\} = \frac{1}{\omega_0}\left\{\frac{R}{2Q}\right\},$$

$$R_{SH} = \left\{\frac{R}{2Q}\right\}Q_0,$$

$$\Delta = \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega},$$

with the numerical values $R_0 = 50\ \Omega$ and $\{R/2Q\} = 200\ \Omega$ for the ERL cavity. The cavity viewed through the transformer, when under-coupled, has a port impedance,

$$R_{port} = R_0 \frac{1-S_{11}}{1+S_{11}}$$

that defines the transformer ratio,

$$n_{FPC}^2 = R_{SH} / R_{port}.$$

The Q-external due to the R_0 termination is now found from

$$Q_{FPC} = n_{FPC}^2 R_0 \left\{\frac{2Q}{R}\right\} = Q_0 \frac{1+S_{11}}{1-S_{11}}.$$

The contribution from the extremely weak PU coupler, Q_{PU}, can be considered by replacing $Q_0 \to Q_0 \dfrac{Q_{PU}}{Q_{PU} - Q_0}$.

If Q_0 is not yet known, then the unknown *Q*-values, Q_0 and Q_{FPC}, are obtained from the measurement of S_{11} and Q_L via the S_{21} 3 dB points, as the solution of a system of two coupled equations,

$$Q_{FPC} - Q_0 \frac{1+S_{11}}{1-S_{11}} = 0 \text{ and } Q_0 Q_{FPC} - (Q_0 + Q_{FPC}) Q_L = 0.$$

The system is nonlinear and can be solved numerically with the MATHEMATICA program, or by iteration in view of $Q_{FPC} \gg Q_0$ before going superconducting.

THE PICK-UP PROBE COUPLER

The external *Q* of the PU probe, Q_{PU} is obtained together with the loaded Q_L, from the interpretation of the forward transmission coefficient based on Fig. 2. [2]

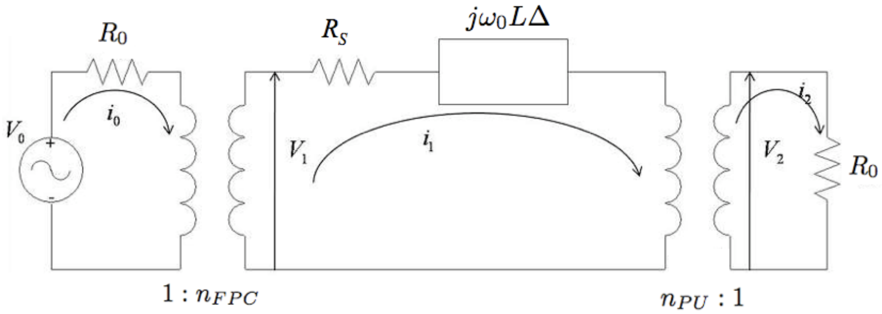


FIG. 2. Transformer equivalent circuit for the transmission coefficient

Based on the circuit, and after some rearrangements, one finds the expression for the transmitted signal

$$S_{21} = \frac{2V_2}{V_0} = \frac{2n_{FPC} n_{PU} R_0}{R_S + n_{FPC}^2 R_0 + n_{PU}^2 R_0 + j\omega_0 L\Delta}$$

$$= \frac{2Q_L}{\sqrt{Q_{FPC} Q_{PU}}\,(1 + Q_L \Delta)}$$

The external Q_{FPC} was defined above in terms of the reflection coefficient, and taking the applicable simplification, $Q_{PU} \gg Q_0$, one finds the loaded quality factor,

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{FPC}} + \frac{1}{Q_{PU}} \approx \frac{Q_0 + Q_{FPC}}{Q_0 Q_{FPC}}$$

A convenient method to find the Q_{PU} would involve adjusting the input to critical coupling yielding at resonance

$$Q_{PU} \to Q_0 / S_{21}^2.$$

In the ERL cavity with its fixed coupler geometry, critical coupling occurs only during cool down (or warm up) and is replaced by the general expression

$$Q_{PU} = \left(\frac{2Q_L}{S_{21}}\right)^2 / Q_{FPC}.$$

MEASUREMENTS AND RESULTS

A series of network analyzer measurements were made during the March 11 cool down that produced essentially simultaneous frequency scans of the S_{11} and S_{21} coefficients. The S_{11} was taken in linear and the S_{21} in dB units providing directly the 3-db loaded Q_L. Two examples, one taken at the beginning and the other close but below critical coupling are shown in Figs. 4 and 5. The temperature changed extremely rapidly thus prevented a result at critical coupling. Measurements taken during warm-up following future cool downs may provide a better opportunity for recording at this value.

FPC calibration.

The interpretation of the measurement data is done with a correction of the S_{11} offset, assuming that it is caused by a calibration error. The data and the results for the FPC are collected in Table I. The network analyzer data for the loaded quality factor and the reflection coefficient are shown in the Q_L and S_{11} columns. The "full" reflection value at the resonance frequency is listed as $S_{\wedge 11}$ and is used for the corrected $S'_{11} = S_{11} / S_{\wedge 11}$. The external Q_{FPC} is obtained with the Q_L data and the corrected S'_{11}. The averaged $Q'_{FPC} = \langle Q_{FPC} \rangle = 2.90 \times 10^7$ is then used to find the unloaded Q_0 column. The quasi independence of the Q_{FPC} over a wide range of Q_L is worth noting. The last measurement was done at a rapidly changing cavity temperature and must be excluded. The cavity temperature during cool down and measured Q_L versus temperature is shown in Fig. 3.

TABLE I. Cavity Q_0 and FPC external Q_{FPC}.

Q_L	$S_{\wedge 11}$	S_{11}	S'_{11}	Q_{FPC}	Q_0
5.00E+04	0.980	0.9770	0.9966	2.93E+07	5.01E+04
6.80E+04	0.978	0.9736	0.9953	2.87E+07	6.82E+04
7.80E+04	0.978	0.9725	0.9945	2.82E+07	7.82E+04
1.46E+05	0.979	0.9688	0.9900	2.93E+07	1.47E+05
9.40E+05	0.977	0.9155	0.9367	2.97E+07	9.71E+05
9.90E+05	0.977	0.9118	0.9328	2.95E+07	1.02E+06
2.93E+06	0.976	0.7742	0.7935	2.83E+07	3.26E+06
				2.90E+07	
1.257E+07	0.971	0.1927	0.1984	3.32E+07	2.22E+07

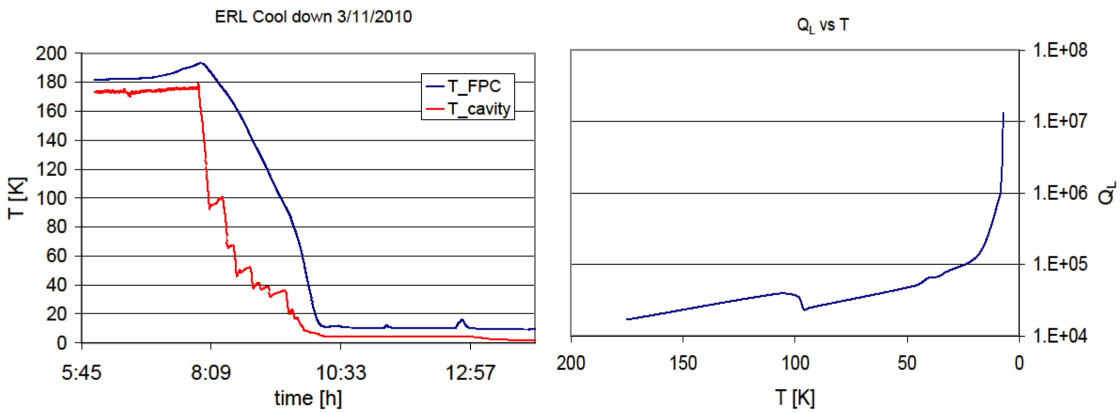


FIG. 3: ERL Cool down showing temperature at cavity and FPC and Q_L versus T. Ragged curves are result of non-uniform cool down.

Determination of the PU external Q

The Q_{PU} is found according to

$$Q_{PU} = \left(\frac{2Q_L}{S_{21}}\right)^2 / Q_{FPC}$$

and can now be obtained based on the above data, with results listed in the Table II. Taking the average of reliable data yields the external pick-up $\langle Q_{PU} \rangle = 3.03\times10^{11}$. A more plausible result is obtained by ignoring the low-Q values and considering the highest credible Q-values pointing to $Q_{PU} \approx 2.93\times10^{11}$.

Table II. The external Q_{PU} from the S_{21} transmission coefficient

Q_L	S_{21} [dB]	S_{21} [u]	Q_{PU}
5.00E+04	-89.754	3.25E-05	3.26E+11
6.80E+04	-86.930	4.50E-05	3.15E+11
7.80E+04	-85.701	5.19E-05	3.12E+11
1.46E+05	-79.979	1.00E-04	2.93E+11
9.40E+05	-63.748	6.50E-04	2.89E+11
9.90E+05	-63.352	6.80E-04	2.93E+11
2.93E+06	-53.934	2.01E-03	2.93E+11
			3.03E+11
1.257E+07	-40.130	9.85E-03	2.25E+11

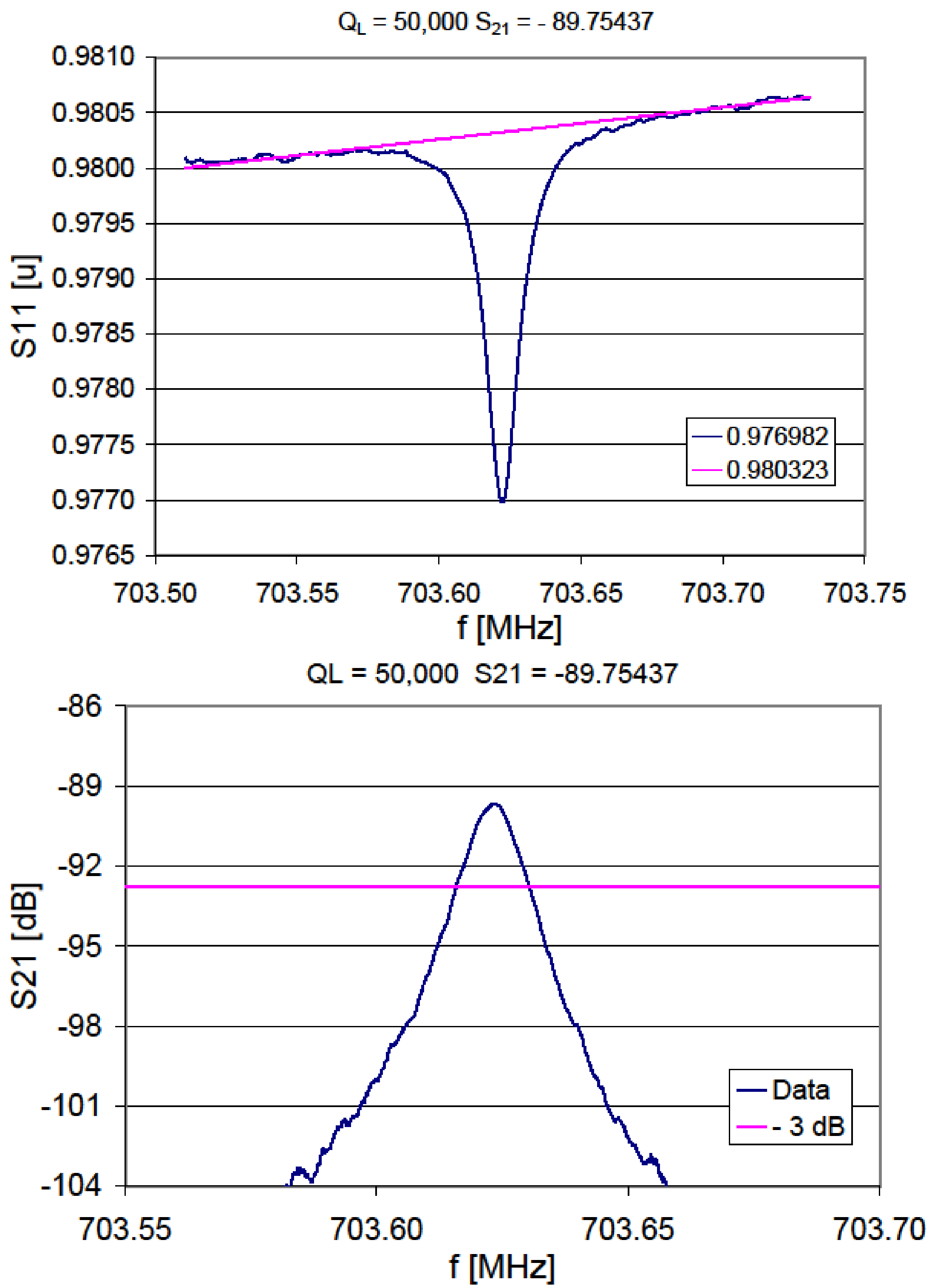
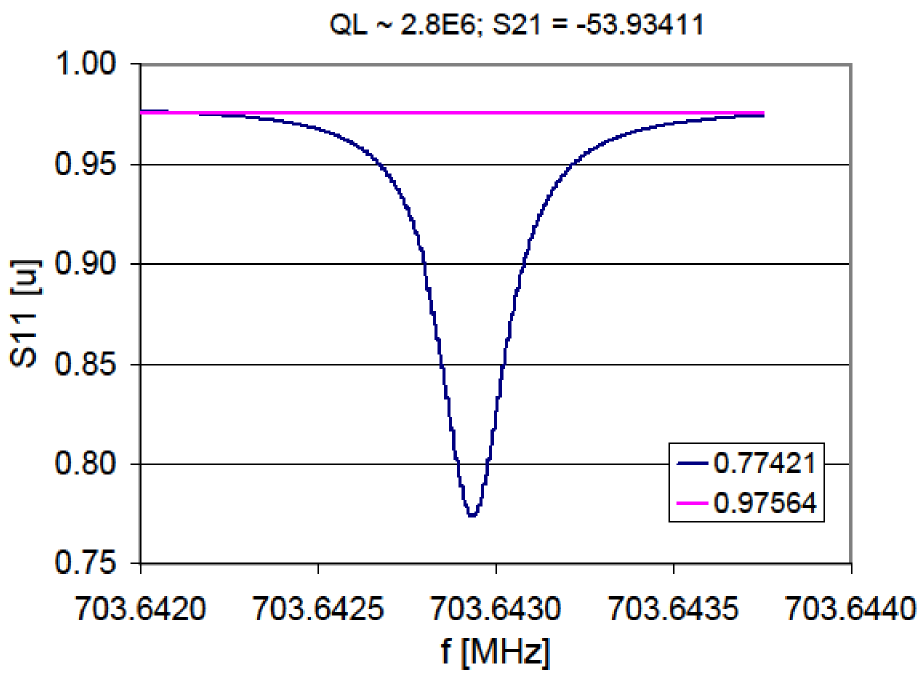


FIG. 4: Scattering coefficients S11 (top) and S21 (bottom) in the ERL cavity at ~ 47 K. The off-resonance S11 values are either calibration error or the indication of a FPC impedance.



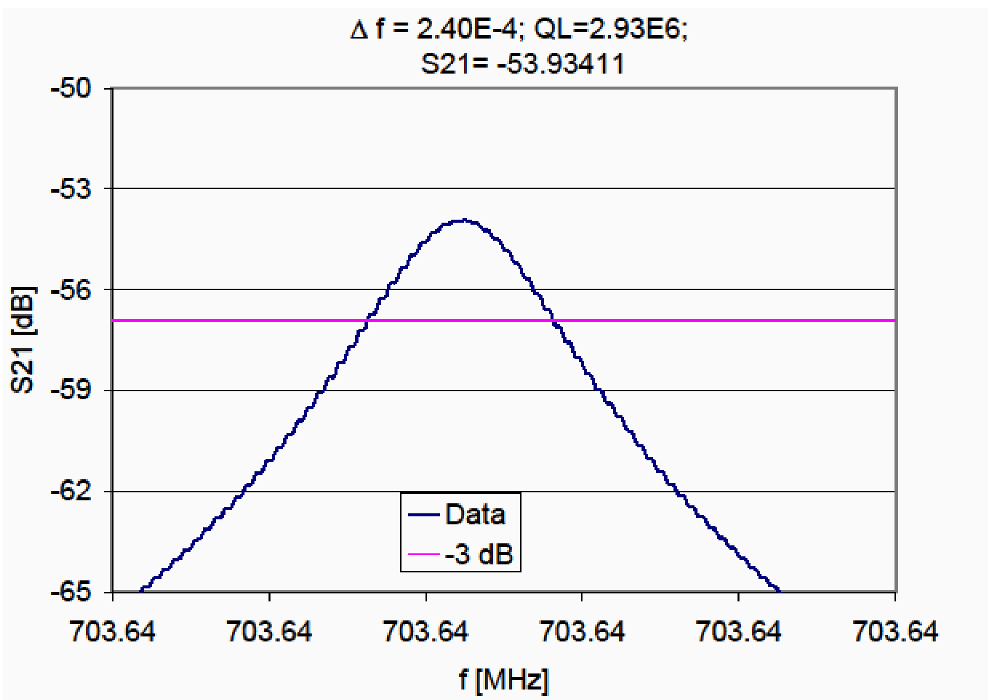


FIG. 5. Scattering coefficients S11 (top) and S21 (bottom) in the ERL cavity during cool down close to the superconducting transition. The off-resonance S11 values are either calibration error or the indication of a FPC impedance.

Extraneous Losses

The foregoing numerical analysis assumes that the off-resonance $S_{11} < 1$ is caused by calibration errors and can be corrected by an appropriate division. Losses extraneous to the superconducting cavity such as a FPC loss should be treated directly. The suspected heating of the FPC at higher currents points to transmission line losses that is represented as a resistor on the circuit diagram in Fig. 6. This resistor R_{TL} must be placed ahead of the transformer, is unchanged when Q_0 changes, and follows directly from the off-resonance $S_{11}(\omega \neq \omega_0)$.

$$R_{TL} = R_0 \frac{1 - S_{11}(\omega \neq \omega_0)}{1 + S_{11}(\omega \neq \omega_0)}.$$

Assuming zero calibration errors, the on-resonance $S_{11}(\omega = \omega_0)$ provides R_{port} as the sum

$$R_{port} = R_0 \frac{1 - S_{11}(\omega = \omega_0)}{1 + S_{11}(\omega = \omega_0)} = n'^2_{FPC} R_s + R_{TL}.$$

The overall impact on the Q_{PU} value is best handled by redefining the transformer ratio as

$$n'^2_{FPC} = \frac{R_{SH}}{R_{port} - R_{TL}}$$

and leading to the external

$$Q_{FPC} = n'^2_{FPC} (R_0 - R_{TL}) \left\{ \frac{2Q}{R} \right\}.$$

Again, assuming zero calibration errors in the ERL cavity data, listed in Table I, one can attribute the off-resonance $S_{11}(\omega \neq \omega_0) \approx 0.980$ to transmission losses with $R_{TL} \approx 0.5\ \Omega$

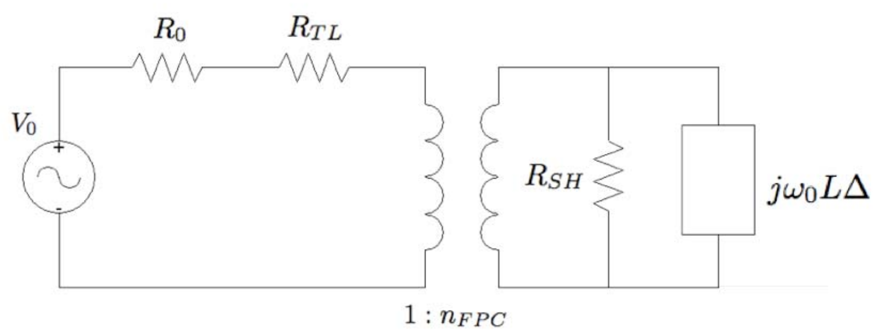


FIG. 6: Circuit diagram with extraneous losses

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[1] H. Padamsee, J. Knobloch, T. Hayes, *RF Superconductivity for Accelerators,* p. 151.
[2] H.Hahn and E. Choi, *56 MHz Cavity Prototype Measurements*, Report C-A/AP/342 (BNL 2009)