

**CAVITY LONGITUDINAL LOSS FACTOR MEASUREMENTS BY MEANS OF A
BEAM TEST FACILITY**

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Abstract

A new method for the measurement of Loss Factor for a RF cavity is presented. The method consists of measuring the above quantity by means of the detection both of the RF voltage induced by an electron bunch in the device under test and the bunch charge. The device to be investigated is a copper reentrant T-shaped cavity. The experimental results and their comparison with analytical and numerical results are presented.

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1 INTRODUCTION

Improvement of beam cooling technique such as laser cooling allows the achievement of very cold ion beams inside storage rings. Moreover with the appropriate cooling force, ordered ion structures, the so-called Coulomb Crystals¹⁾, can be obtained. One of the most important requirements, that an ion ring devoted to such a purpose should fulfill, is to avoid every kind of coherent instabilities that may cause beam losses²⁾. One of these instabilities is related to beam-environment interaction by means of the Longitudinal Coupling Impedance (LCI) and of the Loss Factor (LF)³⁾. Therefore a precise knowledge of such a quantity allows a more accurate estimation of instability growth rate and, in turn, of the cooling rate needed.

Usually CI and LF measurements are performed in a laboratory using short current pulses propagating on a wire inside the accelerator element under test (*coaxial wire method*)⁴⁾, but this method is questionable for two reasons: a) the electromagnetic properties of an empty chamber differ from a chamber with a wire inside and b) coaxial wire method is not straightforward to use for velocities $\beta < 1$ as in the case of cooled ion beams.

The main feature of our experiment is the indirect measurement of LF with an electron beam whose energy varies in the range 18÷65 keV ($0.37 \leq \beta \leq 0.69$). The device under test is an RF reentrant T-shaped copper cavity.

In this article we will compare experimental results with those coming from a theoretical formulation. In fact, an analytical method for the LF calculation has been developed for any particle velocity and for some relevant accelerator structures⁵⁾.

2 THE EXPERIMENTAL METHOD: A DESCRIPTION.

Let us consider a resonant RF cavity inserted on a vacuum chamber and excited by a charged particle beam, passing through the cavity, whose current is supposed to be frequency modulated. The energy lost by the beam due to the field induced by the beam itself can be described in terms of the Loss Factor (LF) k :

$$k = \frac{1}{\pi} \int_0^{+\infty} Z_r(\omega) d\omega \quad (1)$$

with Z_r the real part of the longitudinal coupling impedance (see Appendix).

In the neighborhood a cavity resonant frequency ω_n , the interval of integration is reduced to a small region around the resonance, leading to the following formulation for k , as it is shown in Appendix:

$$k_n = \frac{\omega_n R_n}{2Q_n} \quad (2)$$

where R_n is the cavity shunt resistance and Q_n is the quality factor of the n-th mode.

It can be shown (see Appendix) that, for a bunch of charge q and spectral density $|F(\omega)|$, the LF is related to the energy stored in the n -th mode W_n after the bunch passage by means of the relation:

$$W_n = q^2 k_{in} |F(\omega_n)|^2 \quad (3)$$

For a Gaussian particle distribution we can write $|F(\omega_n)| = \exp(-\omega_n^2 \sigma^2 / 2)$ where σ is the rms temporal bunch width.

Let us consider now an external measurement line connected to the cavity. The energy balance for the n -th mode gives us the following relation, valid for a mode slowly decaying with respect to the beam transit time:

$$\frac{dW_n}{dt} = -\frac{W_n}{\tau_n} = -(P_{in} + P_{ext}) \quad (4)$$

where $\tau = Q_{Ln}/\omega_n$ is the decay time of the n -th mode, P_{in} the power dissipated inside the cavity, P_{ext} the power radiated in the measurement line. Q_{Ln} is the “loaded quality factor” which takes into account the power flowing towards the measurement line; it turns out to be:

$$Q_{Ln} = \omega_n \frac{W_n}{P_{in} + P_{ext}}$$

The peak voltage U_{RF} induced in the measurement line with impedance R is $U_{RF} = \sqrt{2RP_{ext}}$. Using now Eqs. (3) and (4) we get :

$$U_{RF}(q) = \sqrt{\frac{2Rk_{in}\alpha_n |F(\omega_n)|^2}{(1+\alpha_n)\tau_n}} q = r_n q \quad (5)$$

where we have introduced the coupling coefficient α_n defined as $\alpha_n = \frac{P_{ext}}{P_{in}}$

The expression (5) shows a linear dependence between the RF voltage and the beam charge.

It is very important to point out that this linear relationship holds as far as the time bunch length keeps constant. If it is not the case, the Eq. (5) must be modified in order to take into account bunch lengthening due to space charge forces and laser instability. If we assume that space charge effects are a first-order correction with respect to the “unperturbed” bunch duration σ_0 , we obtain:

$$\sigma = \sigma_0 + aq \quad (6)$$

where the angular coefficient a takes into account the way in which bunch duration is modified by the space charge.

Therefore, by substituting into Eq. (5), we get:

$$\begin{aligned} U_{RF}(q) &= \sqrt{\frac{2k_{in} \alpha_n \exp(-\omega_n^2 \sigma_0^2) R}{(1 + \alpha_n) \tau_n}} q \exp\left[-\frac{\omega_n^2}{2} aq(2\sigma_0 + aq)\right] = \\ &= r_n q \exp\left[-\frac{\omega_n^2}{2} aq(2\sigma_0 + aq)\right] \end{aligned} \quad (7)$$

This equation tells us that the dependence of the induced RF voltage on the charge q can be described by means of two parts: a first one, linear, containing in the coefficient r_n the loss factor and so the “interaction” beam – cavity; a second one, exponential, due to the effect of space charge on the bunch length and on the time spent in the cavity.

The LF can be extracted from r_n as follows:

$$k_{in} = r_n^2 \frac{(1 + \alpha_n) \tau_n}{2R\alpha_n |F(\omega_n)|^2} \quad (8)$$

The relations (7) and (8) gives us the base for the setting up of the experimental measurement method.

The induced RF voltage in the cavity can be measured as function of the incoming beam charge by varying its value. At the same time and separately the beam charge has to be measured. In this way, an experimental relation between the two quantities can be then found. By means of Eq.(7), the data (q, U_{RF}) are interpolated varying the two parameters, r_n and a ; the LF can be then calculated from the coefficient r_n , (see Eq.(8)), once α_n , and τ_n have been measured. Therefore we get the loss factor for a given resonant mode frequency and for a fixed beam energy.

Changing the beam energy, the couple of data (q, U_{RF}) are measured again as before and a new value of LF can be found. The same has to be done to study the behavior of k_n as function of the frequency.

3 EXPERIMENTAL APPARATUS AND TECHNIQUE

From the above discussion it is clear that, as far as Eq. (7) holds, by measuring several times, independently, the induced RF voltage in the cavity and the amount of beam charge passing through the cavity, it is possible to interpolate the data and to extract the required LF from the coefficient r_n .

The experimental setup is shown in Fig.1:

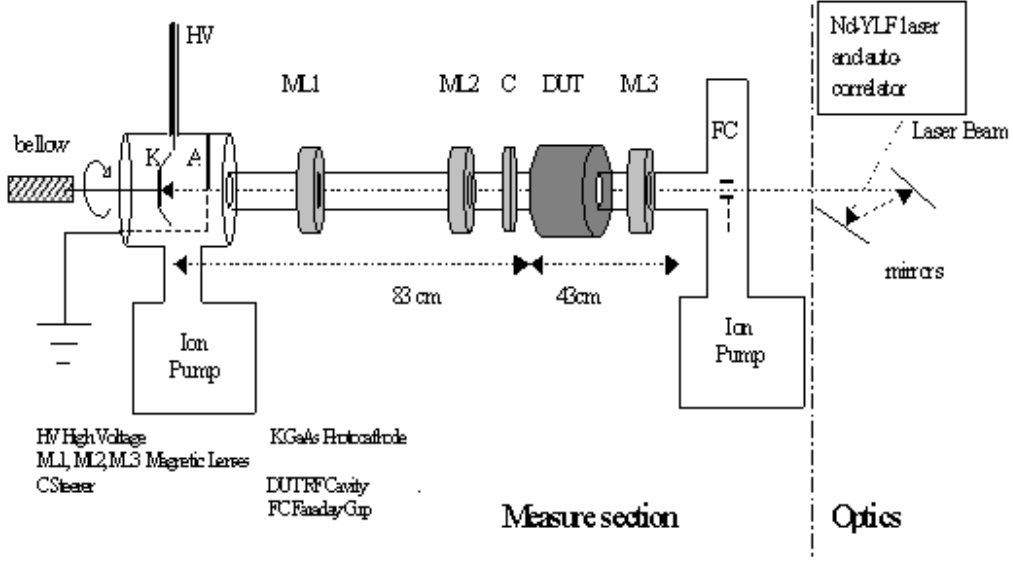


FIG. 1:The experimental setup for the longitudinal Loss Factor measurement.

A bunched electron beam is emitted by a GaAs photocathode excited by a frequency doubled Nd:YLF laser. The measured rms pulse duration of photon bunch is $\sigma_{\text{photon}} = (70 \pm 10)$ ps. The photocathode is installed in a Pierce type electron gun. A voltage applied between anode and cathode accelerates the bunch. By varying the anode-cathode voltage it is possible to perform measurements for different values of the particle energy and therefore of the velocity, β .

A Faraday Cup (FC), put at the end of the measurement line, is used to collect and measure the bunch charge q passing through the cavity.

The beam transport to the device under test, DUT (RF cavity in our case) and then to the FC is accomplished by using a magnetic lens system.

Varying the laser intensity by means of polaroid filters the photoemitted current changes; in correspondence of this, beam charge intensity varies from $(1.2 \pm 0.06) \cdot 10^7$ electrons (minimum photoemitted current) to $(4.2 \pm 0.21) \cdot 10^8$ electrons (maximum photoemitted current). Following our assumption (Eq. 6), the rms “unperturbed” electron bunch duration σ_0 is equal to σ_{photon}

Since the proposed experimental technique is valid only around cavity resonances, as a first step we must measure the cavity resonance frequencies and relative loaded quality factors without beam flowing. For our experiment we chose two TM resonant frequencies, whose measured values, corresponding loaded quality factors and relative decay time are shown in Table 1.

TAB. 1: Loaded Q's, coupling factors and decay times for the two resonant frequencies

n	f_n [GHz]	$Q_{L,n}$	α_n	τ_n [ns]
1	0.8567	1178	0.2	438
2	2.361	595	0.5	80

