ELECTROMAGNETIC SIMULATIONS AND RF MEASUREMENTS RESULTS OF AN ULTRA-SHORT BUNCH LENGTH MONITOR

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Abstract

This paper summarizes the results of a study of a bunch length monitor based on the microwave spectroscopy. The monitor consists of a small coaxial cavity coupled to the beam pipe through four slots. The bunch length can be derived from the power spectrum of the electromagnetic field excited in the resonator by the beam and probed by a small antenna. We show the theoretical results, the e.m. simulations performed by HFSS and MAFIA and the RF measurements made on an aluminium prototype.

1 INTRODUCTION

Different methods to measure the bunch length have been proposed either in the time domain than in the frequency domain [1]. Monitors based on microwave spectroscopy seem to be quite promising for the measurement of very short bunch lengths [1,2]. In this paper we describe a bunch length monitor (b.l.m.) able to measure the bunch length through the power ratio of two different resonant modes excited by a bunch train in the resonant cavity. The coaxial cavity is coupled to the beam pipe through four identical slots (see Fig. 1). The slots have the longer side (l) in the beam direction in order to assure a small coupling impedance of the whole device [3]. The length L of the cavity is chosen as a fraction of the bunch spacing in order to excite efficiently (TEM) resonating modes. By probing the TEM field in the cavity with a small antenna, the amplitude of two beam power spectrum lines can be measured.

An aluminium prototype has been realised and its dimensions are optimised to measure bunch length in the 1-5 mm range. We will describe and compare three different methods to evaluate the signal in the cavity as a function of the beam power spectrum. The first one is an analytic approach based on the modified Bethe's theory [2]. The second one is based on HFSS [4] and MAFIA [5] simulations and the third one is based on the wire measurements method [6].

2 ANALYTICAL APPROACH RESULTS

A sketch of the bunch length monitor is shown in Fig.1 with the dimensions of the actual prototype shown in Table 1.

Considering a bunch train traveling at the center of the beam pipe, the intensity of the total current is given by

$$\tilde{I}(t) = \sum_{k=-\infty}^{+\infty} I(t - kT_0),$$

where $I(t)$ is the current distribution of the single bunch, T_0 is the bunch spacing and c is the velocity of light. The spectrum of the beam current is

$$\tilde{I}(t) = I_0 + 2\sum_{p=1}^{+\infty} I_p \cos(p\omega_0 t),$$

where $\omega_0=2\pi/T_0$, I_0 is the average beam current and I_p is the amplitude of the Fourier component at $p\omega_0$ [7]. For a Gaussian bunch we obtain

$$I(t) = \frac{I_0 T_0 c}{\sqrt{2\pi}\sigma_z}\exp\left[-\frac{1}{2}\left(\frac{c}{\sigma_z}t\right)^2\right] \Rightarrow I_p = I_0 \exp\left[-\frac{1}{2}\left(\frac{\sigma_z}{c}p\omega_0\right)^2\right],$$

where σ_z is the rms bunch length.

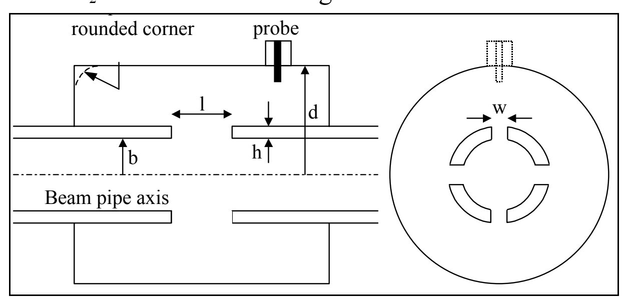

Figure 1: sketch of the bunch length monitor.

Table 1: prototype dimensions.

d	30 mm
b	10 mm
L	52 mm
w	2 mm
l	5 mm
h	1 mm

In an ideal cavity, according to the modified Bethe's theory [2], the first two resonant modes ($TEM_{1,2}$) dissipate a normalized average power given by

$$\underline{P}_1 = \frac{P_1}{I_1^2} = \frac{8\alpha_E^2 Q_1 \pi \ln(d/b) / \left\{\varepsilon\omega_1 L\left[4\alpha_E - b^2\pi L \ln(d/b)\right]^2\right\}}{1 + \left\{\dfrac{\pi^3 b^2 Q_1 \ln(d/b)}{\mu\varepsilon\omega_1^2 L\left[4\alpha_E - b^2\pi L \ln(d/b)\right]} + 1 + Q_1\right\}^2}$$

$$\underline{P}_2 = \frac{P_2}{I_2^2} = \frac{8\alpha_M Q_2 / \left(\pi^2 L^2 \varepsilon\omega_2 b^4\right)}{\left[\dfrac{4Q_2\pi^2}{L^2\mu\varepsilon\omega_2^2} + \dfrac{(1 + Q_2(1 + 4\alpha_M))}{\pi L b^2 \ln(d/b)}\right]^2 + 1},$$

where $\omega_{1,2}$ and $Q_{1,2}$ are the resonant angular frequencies and the quality factors of the two TEM modes. $I_{1,2}$ are the amplitudes of the Fourier components at the resonant

frequencies $\omega_{1,2}$, $P_{1,2}$ the dissipated average power for each mode and α_E, α_M are the electrical and magnetic polarizabilities of the single slot.
The bunch length σ_z as a function of the ratio P_2/P_1 is given by

$$\sigma_z = c\sqrt{\frac{1}{\omega_1^2-\omega_2^2}\ln\left(\frac{\underline{P}_1}{\underline{P}_2}\frac{P_2}{P_1}\right)}\,. \qquad (1)$$

Being ε the relative uncertainty of the measured power ratio P_2/P_1, the corresponding uncertainty of σ_z is given by

$$\frac{\Delta\sigma_z}{\sigma_z} = \frac{c^2}{2\sigma_z^2\left(\omega_2^2-\omega_1^2\right)}\varepsilon\,.$$

Therefore, measurement of very short bunch lengths requires precise measurement of P_2/P_1, preferably at high frequencies.

3 SIMULATION RESULTS

To compare the analytical results with the numerical simulations, we have studied the coupling impedance of the cavity. In other words, we have calculated the values of the R/Q of the two resonant TEM modes, using the eigenmode solver of HFSS and MAFIA (R being the shunt impedance of the mode).

The HFSS model is shown in Fig. 1. It is only 1/8 of the structure with magnetic boundary conditions on the symmetry planes. Table 2 compares the values for R/Q, for the resonant frequencies and the Q factors obtained with HFSS and with MAFIA.

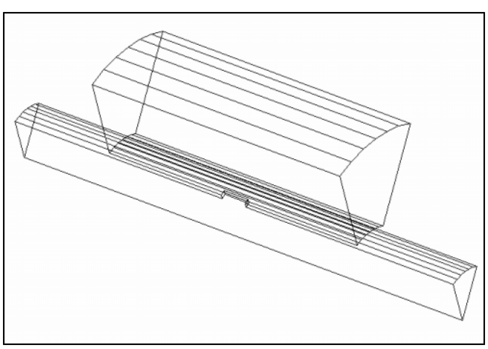

Figure 2: HFSS model.

The normalized average power dissipated in the cavity for the two TEM modes is (j=1,2)

$$\underline{P}_j = \frac{P_j}{I_j^2} = 2\frac{R}{Q}\bigg|_j Q_j \qquad (2)$$

If the cavity is coupled through a probe to an external load, then the normalized average power dissipated in the system is still given from eq. (2) but with Q_j replaced by Q_j loaded. Therefore, the average power dissipated eventually in the load is given by (j=1,2)

$$P_j^* = \underline{P}_j\beta_j/\left(1+\beta_j\right) \qquad (3)$$

where β_j is the coupling coefficient between the probe and the cavity mode TEM$_j$. The coupling coefficients can be obtained from reflection coefficient measured at the probe port.

Table 2: values of R/Q, resonant frequencies and Q factors obtained with HFSS and MAFIA.

		HFSS	MAFIA
TEM1	**R/Q**	11.70e-7 Ω	8.67e-7 Ω
	Q	6300	6300
	f	2.883 GHz	2.883 GHz
TEM2	**R/Q**	6.94e-6 Ω	4.71-6 Ω
	Q	8790	8950
	f	5.762 GHz	5.762 GHz

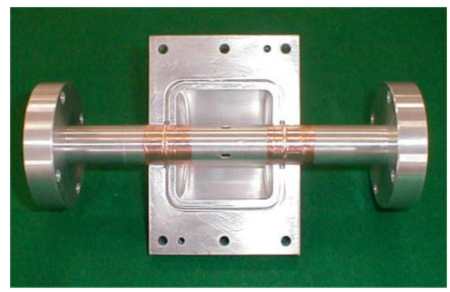

Figure 3: bunch length monitor prototype.

4 PROTOTYPE MEASUREMENTS

Wire measurements have been performed on the aluminum prototype shown on Fig. 3. Two tuners can be inserted in the cavity in order to properly tune the frequencies of the two TEM modes. An antenna (small compared to the wavelength) probes the signal in the cavity.

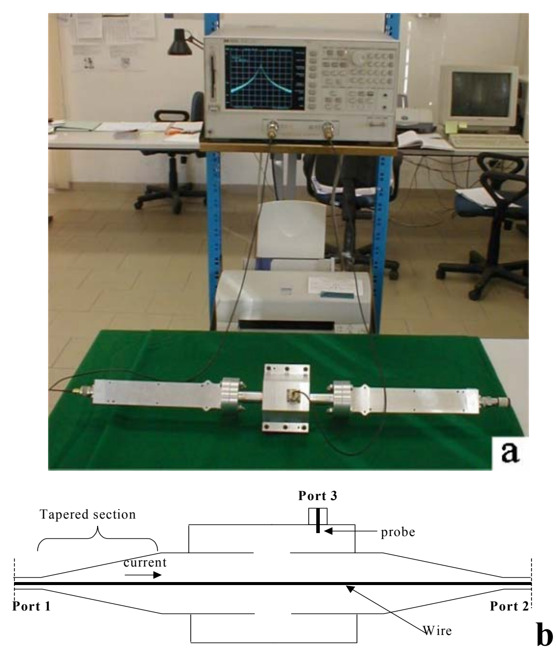

Figure 3: measurement setup.

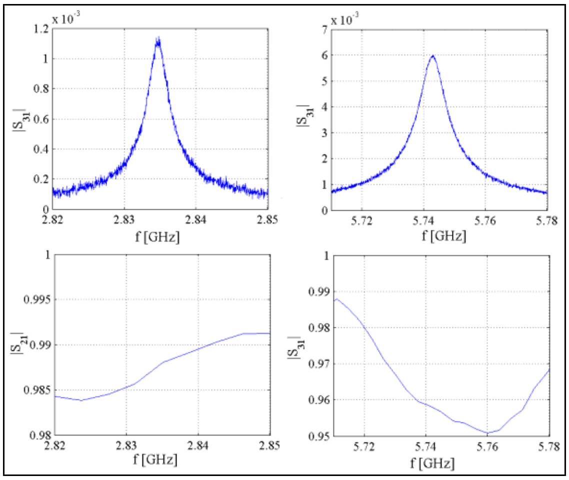

Figure 4: measured transmission coefficients (S_{21}, S_{31}).

The measurement setup is shown Fig. 3a and schematically represented in Fig. 3b. The wire has a radius of 1.5 mm. In order to minimize reflections at ports 1 and 2, we have inserted two tapered sections that match the 50Ω impedance of the network analyzer with the 114Ω impedance of the wire in the beam pipe. The measured transmission coefficients S_{21} and S_{31} are shown in Fig. 4 for frequencies around the first two cavity resonances.

The normalized average power dissipated in the cavity is given for each mode by (j=1,2)

$$\underline{P}_j = P_j^* \frac{(1+\beta_j)}{\beta_j} \cong 2Z_c \frac{|S_{31}(\omega_j)|^2}{|S_{21}(\omega_j)|} \frac{(1+\beta_j)}{\beta_j} \tag{4}$$

where P^*_j is the normalized average power measured at port 3. When the b.l.m. is inserted in the accelerator the bunch length is simply given by eq. (1) where P_j is the power measured at port 3 for the mode TEM$_j$ and $\underline{P}_1/\underline{P}_2$ must be substituted with P^*_1/P^*_2 (see eq.(3)) to account for the coupling coefficients.

In order to compare the measurement results with the theoretical ones, the normalized power given by eq. (4) must be properly scaled. In fact, since in the prototype there are additional losses (mainly due to RF contact in the cavity final assembly), the Q factors (also the unloaded ones) are much lower than the theoretical expectations (Q_1≈1400, Q_2≈1600 instead of the ones in Table 2). Therefore the normalized power, obtained by eq.(4), has to be scaled accordingly, i.e.

$$\underline{P}'_j = \underline{P}_j \frac{Q_j}{Q_{Mj}} \quad \text{with } j=1,2.$$

Eventually, $\underline{P}'_j$ and $\underline{P}'_1/\underline{P}'_2$ can be meaningfully compared to theoretical and numerical expectations (see Table 3).

Since the matching with the tapered section is not perfect, the reflected wave at port 2 introduces a perturbation in the cavity field and, consequently, an error in the evaluation of the transfer function between the beam current and the cavity field. This perturbation is related in a complicated way to the scattering matrix of each element included in the measurement setup. Considering the equivalent circuit of the setup, it is possible to estimate the error introduced in the evaluation of the transfer function and, therefore, in the $\underline{P}_{1,2}$ calculations. In our case we obtain an error of ~±0.2% for $\underline{P}_1$ and ~±1% for $\underline{P}_2$.

The results obtained by wire measurements must be considered as calibration coefficients that allow to calculate the normalized average power dissipated in the cavity, and, therefore, the σ_z when the b.l.m. is inserted in the accelerator (eq. (1)).

The results of Table 3 show a fairly good agreement between simulation and measurement results, especially considering the mechanical differences between the prototype and the simulated structure (tuners, probe antenna, rounded corners as schematically shown in Fig. 1) and the losses in the prototype due to the non perfect RF contacts.

Table 3: Compare between the norm. dissipated powers

	THEORY	HFSS	MAFIA	MEAS.
$\underline{P}_1$ (W/A^2)	4.02e-3	1.47e-2	1.10e-2	4.10e-2
$\underline{P}_2$ (W/A^2)	1.46e-2	1.22e-1	0.84e-1	1.83e-1
$\underline{P}_1/\underline{P}_2$	2.76e-1	1.20e-1	1.31e-1	2.26e-1

5 CONCLUSIONS

A novel bunch length monitor has been described. Measurements on an aluminium prototype have been compared to theoretical and numerical expectations for the power dissipated by two modes of the external coaxial cavity. The absolute values seem to be under-estimated by the theory, although power ratios are in fairly good agreement. Improvements in the measurement setup are still possible, for instance by substituting the RF contact between cavity and pipe with weldings or by improving the impedance matching between the network analyser and coaxial line. These results confirm the potential application of this device as a bunch length monitor. The very low coupling impedance of the device and the possibility of a calibration by simple wire measurements make the device hopefully usable in the accelerators machines.

6 REFERENCES

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