DEVICE FOR THE ELECTRON BUNCH LENGTH MEASUREMENT OF 1-5 MM RMS

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Abstract

Two variants of bunch length monitor (BLM) for the measurement of 1-5 mm rms bunch length (σ_z) are offered. The first one was designed for the measurement of a single bunch rms. It consists of two cavities, each of them operates at two modes, E_{010} and E_{110}. The second variant of BLM was designed for the measurement of a rms of the bunches with repetition period less then 16 ns (series of identical bunches). There are two cavities in the BLM too. Loop coupling is used for the cavities and cavity-filters.

1 INTRODUCTION

There are some methods of electron bunch length measurement with unknown charge distribution in the bunch. One of them is based on the measurement of the amplitudes of oscillations excited by the bunch in the two cavities with various frequencies [1]. The ratio of these amplitudes permit to determine σ_z.. This work is devoted to development of the BLM for the measurement of σ_z in a range from 0.5 to 1 mm. Additional work is devoted to development of BLM for the measurement of a single bunch length and of the identical bunches in the series in the range of σ_z from 1 to 5 mm.

2 THEORETICAL SUBSTANTIATION

Let us consider the bunch with the charge distribution, given by:

$$\xi(z_1) = qF(z_1) \qquad (1)$$

where q is bunch charge, $F_G(z_1)$ and $F_R(z_1)$ are Gaussian and rectangular charge distribution:

$$F_G(z_1) = \frac{1}{\sqrt{2\pi}\sigma_z}\exp\left(-\frac{z_1^2}{2\sigma_z^2}\right);\; F_R(z_1) = \begin{cases}\left[2\sqrt{3}\sigma\right]^{-1} & \text{if } |z_1| \le \sqrt{3}\sigma_z \\ 0 & \text{if } |z_1| > \sqrt{3}\sigma_z\end{cases} \qquad (2)$$

The electromagnetic field components of the bunch may be represented as

$$E_z(r,t) = -\frac{z_0 cq}{4\pi r^2}\int_{-Z_{11}}^{Z_{11}} F(z_1)\gamma\frac{z_1+\beta ct}{r}\left[1+\left(\gamma\frac{z_1+\beta ct}{r}\right)^2\right]^{-3/2} dz_1$$

$$E_r(r,t) = \frac{z_0 cq}{4\pi r^2}\gamma\int_{-Z_{11}}^{Z_{11}} F(z_1)\left[1+\left(\gamma\frac{z_1+\beta ct}{r}\right)^2\right]^{-3/2} dz_1 \qquad (3)$$

$$H_\varphi(r,t) = \frac{\beta}{z_0}E_r(r,t)$$

where γ is relativistic factor of the bunch, Z_0 is a free space impedance, Z_{11} can be equaled to $5\sigma_Z$ for the Gaussion distribution and $\sqrt{3}\,\sigma_Z$ for the rectangular distribution, $\beta=\gamma^{-1}(\gamma^2-1)^{1/2}$, r is a distance from the bunch axis.

Let's represent the cavity excited by the bunch as two port junction with own frequency f_{res}, loaded Q-factor Q_L, input coupling coefficient with free space χ_1 and output coupling coefficient with waveguide χ_2 (its wave impedance Z_{02}). The e.m.f. exciting the cavity has the same time dependence as $E_r(t)$ or $H_\varphi(t)$ in expressions (3). Using superposition principle one can get the expression for the output voltage $U_2(t)$ after excitation by N bunches as follows

$$\begin{aligned} U_2(t) \propto\; & 3\frac{\gamma^2 z_0 cq}{4\pi r^3}\sqrt{\frac{z_{02}}{z_0}}\,\frac{\sqrt{\chi_1\chi_2}}{1+\chi_1+\chi_2}\times \\ & \times\frac{\sqrt{A^2+B^2}}{Q_L\sqrt{1-(1/2Q_L)^2}}\times \\ & \times\left|\frac{\exp(-N\Delta Z_b/\beta c\tau_c)\exp(j\omega N\Delta Z_b/\beta c)-1}{\exp(-\Delta Z_b/\beta c\tau_c)\exp(j\omega\Delta Z_b/\beta c)-1}\right|\times \\ & \times\exp\left(-\frac{z-(N-1)\Delta Z_b+Z_{22}}{\beta c\tau_c}\right)\times \\ & \times\cos\left\{\frac{\omega}{\beta c}\left[z-(N-1)\Delta Z_b+Z_{22}\right]+\varphi+\alpha\right\} \end{aligned} \qquad (4)$$

where $\omega=\omega_{res}[1-(1/2Q_L)^2]^{1/2}$, $\omega_{res}=2\pi f_{res}$, $\tau_c=2Q_L/\omega_{res}$, $\Delta Z_b=\beta c/f_b$, f_b is repetition frequency of the bunches, $z=\beta ct\geq(N-1)\Delta Z_b+Z_{11}$, Z_{22} can be equaled to $10r/\gamma$,

$$A+jB = \int_{-Z_{11}}^{Z_{11}}\int_{-Z_{22}-Z_{11}}^{Z_{22}+Z_{11}} F(z_1)\gamma\frac{z_1+z_2}{r}\left[1+\left(\gamma\frac{z_1+z_2}{r}\right)^2\right]^{-5/2}\times$$
$$\times\exp\left[\frac{z_2}{\beta c\tau_c}+j\left(\frac{\pi}{2}-\frac{\omega}{\beta c}z_2\right)\right]dz_1dz_2$$

$$\varphi = \arg(A+jB)$$

$$\alpha = \arg\left[\frac{\exp(-N\Delta Z_b/\beta c\tau_c)\exp(j\omega N\Delta Z_b/\beta c)-1}{\exp(-\Delta Z_b/\beta c\tau_c)\exp(j\omega\Delta Z_b/\beta c)-1}\right]$$

Spectra of H_φ (r is vary small) for rectangular and Gaussian distributions and bunch lengths of 1 and 5 mm are shown in Fig.1. For a measurement of σ_z it is necessary to choose frequencies of cavities in a such way that Gaussian and rectangular distributions are close to each other and steepness of characteristic is satisfactory.

3 SINGLE BUNCH σ_Z MEASUREMENT

BLM shown in Fig.2 includes two cylindrical cavities. Each cavity operates at frequencies of two modes E_{010} and E_{110} (frequencies of the first cavity are 4.5 and 7.2 GHz, frequencies of the second cavity are 11.3 and 18.0 GHz).

Each cavity (1 and 2) has input slot (3 and 4), two output slots for the coupling of E_{010} mode with waveguide (5 and 7) and one output slot for the coupling of E_{110} mode with waveguide (6 and 8).

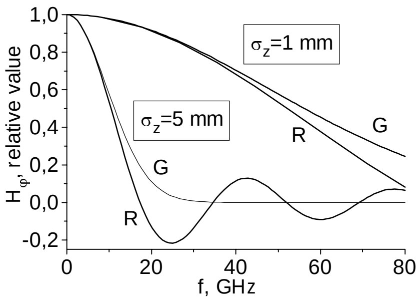

Figure: 1 The spectra of magnetic field H_φ at σ_z=1 and 5 mm for rectangular (R) and Gaussian (G) distributions.

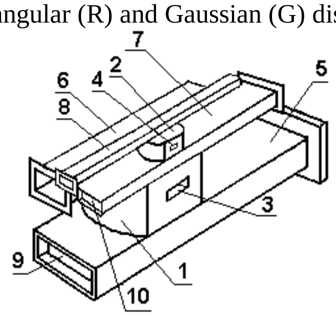

Figure: 2 Single bunch BLM.

One end of each waveguide is connected to a recording equipment. Movable plunger (9 and 10) is located in other end for regulation of output coupling coefficient χ_2.

The signal excited by bunch through input slot is extracted from the cavity through output slots, and comes through the waveguides to the recording equipment.

The time constants τ_c of cavities at these four frequencies should be equal each other and $\tau_c < T/3$, where T is bunch period (T=16 ns in this case). Let's assume τ_c = 5 ns. The values of own Q-factor Q_0, χ_1 and χ_2 are shown in Table 1.

The results of measurements of coupling coefficients χ_1 of the E_{010} and E_{110} cavity modes with free space are shown in Fig.3 (l_{s1} is slot length, cavity diameter D=82.9 mm, cavity length L=29.4 mm, slot width h_{s1}=4 mm).

The possibility of output coupling coefficient regulation by plungers displacement is shown on Fig.4 (D=51 mm, L=16 mm; E_{010} - 4,5 GHz, two slots, l_{s2}=23 mm, h_{s2}=3 mm; E_{110} - 7.2 GHz, one slot, l_{s2}=8 mm, h_{s2}=2 mm. Λ - wave length in the waveguide).

Parameters of BLM got on the basis of calculations and measurements are summarized in Tab.1.

Calculations executed with use of the above-mentioned method allow to get the form of the signal in output waveguide (see Fig.5).

Table 1

D, mm	51		20	
L, mm	8.0		6.8	
l_{s1}, mm	16.0		5.4	
h_{s1}, mm	2.4		1.0	
f_{res}, GHz	4.5	7.2	11.3	18.0
l_{s2}, mm	23	8	5	2.5
h_{s2}, mm	3	2	2	1
a, mm	35	23	16	11
b, mm	15	10	8	5.3
Q_0	7860	10240	4960	6460
χ_1	5	85	1	18
χ_2	105	5	28	4
σ_Z, mm	-	5-4	4-2.5	2.5-1
$\Delta\sigma_z/\sigma_z$, %	-	15-21	6-16	6-29

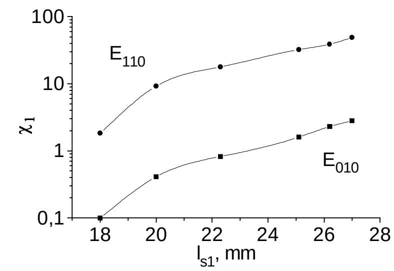

Figure: 3 Input coupling coefficients as function of coupling slot length.

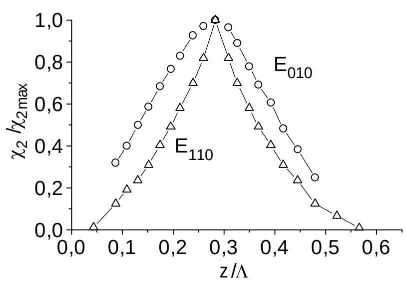

Figure: 4 The output coupling coefficients χ_2 as function of plunger position.

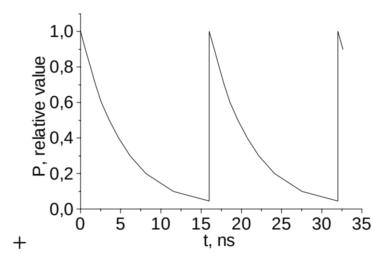

Fig.5. Time dependence of RF power in the output waveguide (T=16 ns).

The calibration diagram is shown in Fig.6, where P_i (i=1, 2, 3, 4) are peak power in waveguides (see Fig.5) with sides a and b at frequencies 4.5, 7.2, 11.3 and 18.0 GHz correspondingly.

The error of σ_z measurement is determined by recording equipment error (3%), errors of χ_1, χ_2, Q_0 measurements (3%), and by steepness of calibration diagram $\sigma_z(P_i/P_1)$ in the point of interest.

4 σ_Z MEASUREMENT WITH A SERIES OF BUNCHES

Series of bunches have following parameters: the bunch length σ_z=1-5 mm, the frequency of an accelerating field f_0=2998 MHz, the bunch repetition rate $f_b=f_0/48$-$f_0/18$ (bunch spacing T=6-16 ns), the current pulse length τ_p=2 μs. The BLM must satisfy the following conditions.

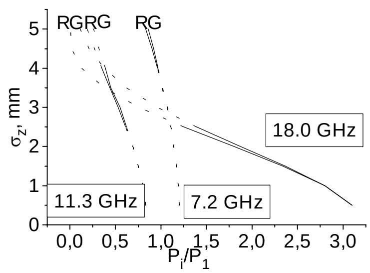

Figure: 6 Calibration diagram.

The own frequencies of BLM cavities should be divisible by f_0. The values of operational frequencies of the BLM are f_0, $3f_0$, $5f_0$ (see Tab.2). The time constants of cavities should be equal to each other and should satisfy to following condition $T<\tau_c<\tau_p/3$. χ_1 and χ_2 decrease with increasing of τ_c, with results in a decrease of the transmission factor of the BLM. At low τ_c the envelope of the RF oscillations becomes more sawtooth, but simultaneously the cavity frequency tuning tolerance increases. We take τ_c =50 ns.

Table 2.

Cavity	1	2	
D, mm	76	25	
L, mm	4	9	
l_{s1}, mm	17.5	5	
h_{s1}, mm	4	2	
f, MHz	2998	8994	14990
Q_0	2400	5560	7240
χ_1	2.5	0.1	2
χ_2	1.6	2.8	0.1
σ_Z, mm	-	5-2.5	2.5-1
$\Delta\sigma_z/\sigma_z$, %	-	6-22	10-40

BLM includes two cavities. The first cavity has an operational mode E_{010} and resonant frequency $f_{res1}=f_0$, the second one has two operational modes E_{010} and E_{110} with frequencies $f_{res2}=3f_0$ and $f_{res3}=5f_0$.

The second cavity represented in Fig.7 includes input slot 1, output E_{010} mode pin coupler 2 with the RF connector 4, output E_{110} mode loop coupler 5 with the RF connector 3, tuning elements 6, 7, 8. The ring ledges 9 near the cavity axis allow to ensure $f_{res2}/f_{res3}=3/5$. The first cavity includes an input slot, output pin coupler and axial tuning element. The parameters of BLM are summarized in Table 2. The calculated voltage pulses in output line for T=6 ns and T=16 ns are shown in Fig.8. The calibration diagram calculated with expression (3) is shown in Fig.9.

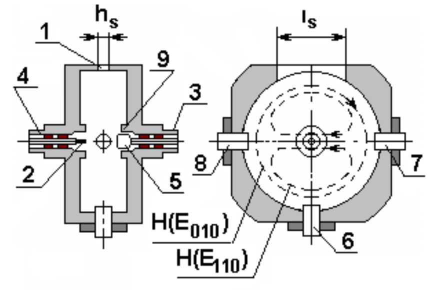

Figure: 7 The cavity with frequencies $3f_0$ and $5f_0$.

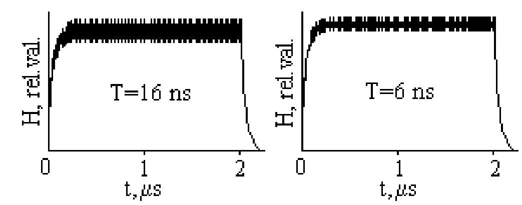

Figure: 8 The voltage pulses in output line.

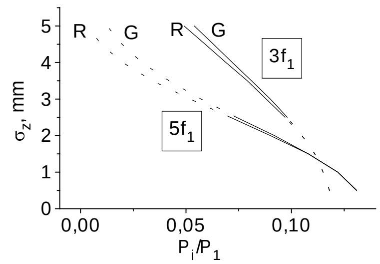

Figure: 9 The calibration diagram.

5 HIGH FREQUENCY FILTERS

Fig.1 shows the bunches generate frequencies up to tens GHz. RF signal at frequencies of higher non-operational modes of BLM cavities can pass through BLM to the recording equipment and produce an additional error of the measurement. The cavity-filters are used to eliminate this influence. The lowest own frequency of the cavity-filter is equal to operational frequency f_0.

These cavity-filters are necessary for both BLM modifications.

REFERENCES

1. E.Babenko, R.K.Jobe at. all. Length Monitor for 1 mm SLC Buncher, Proc. of the 1993 Particle Accelerator Conference, 1993, V.3, p.2423-2426.