PECULIARITIES OF THE BUNCH SHAPE MONITOR OPERATION FOR HIGH- INTENSITY ELECTRON BEAMS

V.A. Moiseev, A.V. Feschenko
Institute for Nuclear Research, Russian Academy of Sciences
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Moscow, 117312, Russia, e-mail: moiseev@al20.inr.troitsk.ru

The simulation results of the Bunch Shape Monitor operation using coherent transformation of a time structure of an analyzed high-intensity electron beam into a spatial one of low-energy electrons emitted from a wire target will be presented. The electromagnetic field of an analyzed bunch disturbs the trajectories of secondary electrons, thus resulting in a degradation of phase resolution and in errors of phase position reading. Moreover there is a perturbation of the target potential due to the current compensating emission of the secondary electrons. The accuracy analysis has been carried out. The confident result to achieve the phase resolution less then one degree was obtained.

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1 INTRODUCTION

There is a long-term experience of INR Accelerator Division in development of Bunch Shape Monitors (BSM), Bunch Length and Velocity Detectors (BLVD) and Three-Dimensional Bunch Shape Monitor (3D-BSM) [1]÷[5]. Operation of all these detectors is based on the same principle: the longitudinal structure of a beam under study is coherently transformed into a spatial one of the low energy secondary electrons through transverse RF modulation. The properties of low- energy secondary electrons are almost independent on the type and the energy of primary particles and hence the detectors look to be applicable for a large variety of accelerated beams.

Typically the phase resolution of the detectors is about 1° at the frequencies of hundreds MHz. The resolution is determined by a number of parameters. The most complicated effects are due to the influence of electromagnetic field of the analyzed beam. The fields disturb the trajectories of the electrons thus resulting in degradation of the accuracy of measurements. Another effect is the perturbation of the potential of the target due to the current in the wire induced by a bunch as well as to the current compensating emission of the secondary electrons.

In this paper the simulation results are presented for studies of a possibility to create a detector of three-dimensional distribution for the DESY photo-injector (PI). Below the parameters of the DESY photo-injector beam are presented:

– type of particles:	electrons;
– beam energy:	20 Mev;
– bunch charge:	~1nC;
– bunch dimensions:	$\sigma_x \approx 1$mm, $\sigma_y \approx 1$mm, $\sigma_z \approx 1$mm;
– accelerating frequency:	1.3 GHz;
– period of bunch sequence:	80 ns;
– beam pulse duration:	800 μs;
– beam pulse repetition rate:	up to 10 Hz.

From point of view of detector operation the following parameters are extreme: high density of a charge in bunches, small longitudinal dimensions, large pulse duration and relatively large beam current.

The typical BSM geometry is presented in Fig. 1. The electron motion is analyzed from target 1 to the plane of electron collector 4.

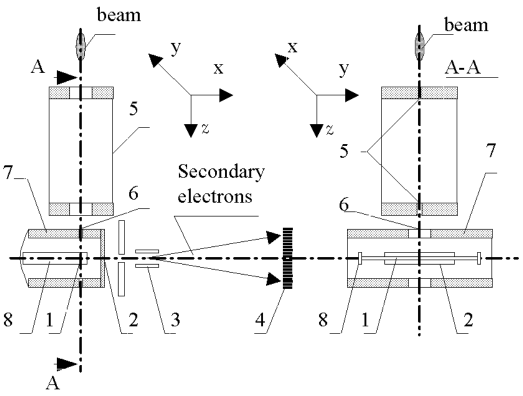

Fig. 1. General configuration of the BSM for DESY Photo-Injector (1 - target, 2 - collimator of secondary electrons, 3 - RF deflector, 4 - multi-channel collector, 5 - horisontal collimators, 6 - vertical collimator, 7 - screen, 8 - target holders).

2 PECULIARITIES OF THE PROBLEM

Compared with the assumptions for ion beam simulations [6] there are the specific features of the measured electron beam and its self fields:

- As a rule, the bunch charge is essentially higher for electron beam. It follows the self bunch electric and magnetic fields are greater, that can lead to the higher measurement errors.
- A bunch velocity is higher for electron beams. As a rule the electron bunch relativistic factor is tens whereas it is in unit order for ion beams.
- From above remark the electron bunch self field has transverse polarization, its longitudinal component is negligible and concentrates close to the bunch ends. The longitudinal region of the electron bunch self fields is approximately equal to the bunch length.
- The longitudinal bunch length is essentially smaller for electron beams.
- Due to the above remarks the time interval of interaction of the secondary electrons with bunch self

field is drastically less for electron beams. For ion beams the secondary electrons are under the action of a self bunch fields over the full transport distance target-collimator 2, whereas for electron beams the interaction takes place approximately up to the moment when bunch has traversed the target wire. In latter case the interaction travel distance for electrons is less then 0.5 mm.

3 DESCIPTION OF THE MODELS

The motion of the electrons from the target to input collimator 2 (Fig. 1) was analyzed for the real 3D geometry. Downstream of input collimator a 2D model was used. The field in the target-collimator region satisfies the Poisson equation:

$$divE\,(r,t) = \rho\,(r,t)/\varepsilon_0\ , \quad \phi_\Gamma = f\,(\Gamma,t) \qquad (1)$$

where $\rho\,(r,t)$ is a charge density in the bunch of the analyzed beam at the moment of time t, ϕ_Γ is a boundary potential. One can split the problem (17) into two independent problems to find the fields E_1 and E_2 ($\vec{E} = \vec{E}_1 + \vec{E}_2$) with the boundary conditions $\phi_{\Gamma 1}$ and $\phi_{\Gamma 2}$ ($\phi_\Gamma = \phi_{\Gamma 1} + \phi_{\Gamma 2}$).

Problem 1: $$div\vec{E}_1(\vec{r}) = 0\ , \quad \phi_{\Gamma 1} = f_1(\vec{\Gamma}) \qquad (2)$$

The field E_1 can be found from a solution of the Laplace equation for the potential $\phi_1(\vec{r})$ without a beam: $\vec{E}_1(\vec{r}) = -grad\phi_1(\vec{r})$.

Problem2: In this problem the electromagnetic field of a moving bunch for zero boundary condition is calculated. Generally the bunch generates both electric and magnetic fields and a complete system of Maxwell equations must be solved. To simplify the problem we consider the field to be electrostatic in the reference frame moving with the bunch. In this frame we assume all the particles of the bunch to be at rest and the geometry of the boundaries to be defined according to Lorenz transformations. The field in a beam frame is defined by charge distribution in bunches and by zero boundary conditions and can be found as a solution of Poisson equation:

$$divE_{02}(r_0,t_0) = \rho\,(r_0,t_0)/\varepsilon_0\ , \quad \phi_{\Gamma 02} = f_{02}(\Gamma_0,t_0) = 0 \qquad (3)$$

The subscript “0” indicates that the beam frame is considered. After solving the equation (3) the electric and the magnetic fields in the laboratory frame can be found with the help of Lorenz transformations for electromagnetic fields. The equations (2) and (3) were solved numerically for a 3D uniform mesh.

The boundary condition (3) means that the boundary charge distribution is exactly tracking a charge distribution of the bunch as it passes through the detector. However this assumption is valid for relatively slow processes. The criterion of slowness of the process can be formulated as $D_z/V_z > L_0/c$, where D_z and V_z are typical longitudinal dimension of the bunch and its velocity correspondingly and L_0 - typical dimension of the boundary elements. In our case $V_z=c$ and the longitudinal rms bunch size σ_z can be used in the capacity of D_z. One half of the target length can be treated as L_0. For σ_z =1 mm and a target wire length of 45 mm the above condition is not satisfied. Nevertheless in this case Problem 2 can be used for an extreme estimation.

Another extreme estimation can be done by assuming that the distribution of the charge in the target does not change at all. In this case the bunch “does not see” the target and the boundary conditions for Problem 2 should be modified: the target should be excluded from the geometry.

One can expect that in reality the effects are confined within the limits of the above two extremities. Hence we did the simulations for the two extreme cases. We will refer to the extremities as to Model #1 and Model #2.

Influence of the effects of space charge in Bunch Shape Monitor comes through in two ways: degrading of phase resolution and arising of phase errors.

For Model #1 changing of the charge distribution along the target $q(y,t)$ is related with the current along the wire. In its turn, the current results in some extra voltage on the target. This voltage can be estimated if the target is considered as a transmission line [6]. In this case the current in the wire and the voltage satisfy the equations:

$$\frac{\partial q(y,t)}{\partial t} = \frac{\partial i(y,t)}{\partial y}\ ; \quad \frac{\partial U(y,t)}{\partial y} = L\frac{\partial i(y,t)}{\partial t} + Ri(y,t) \qquad (4)$$

Here L, C and R are inductance, capacitance and resistance of the transmission line per unit length. These parameters have been considered to be the same as those for a coaxial transmission line with the outer and inner diameters of 50 mm and 0.1 mm, respectively, and a frequency of 300 GHz. One can show that a reasonable variation of the parameters does not strongly influence the final results. The line was assumed to be grounded at the ends of the target because the dimensions of the target holders are much larger than the transverse dimension of the target.

The model of a transmission line can also be used to calculate a voltage on the target because of the currents due to emission of secondary electrons. In this case the voltage can be described by the equation:

$$\frac{\partial^2 U}{\partial y^2} - LC\frac{\partial^2 U}{\partial t^2} - RC\frac{\partial U}{\partial t} = RI + L\frac{\partial I}{\partial t}\ , \qquad (5)$$

Here $I(y,t)$ is a distributed current generator due to secondary emission. It can be written as

$$I(y,t) = \frac{I_0 T}{2\pi\sigma_y\sigma_t} e^{-\frac{\left(t-\frac{T}{2}\right)^2}{2\sigma_t} - \frac{(y-y_0)^2}{2\sigma_y}} \qquad (6)$$

The value of the average electron current I_0 was estimated to be about 120 μA [7].

4 RESULTS OF SIMULATIONS

Some results of simulations are presented in Fig. 2, 3. One should note that the electrons corresponding to the head of the bunch (left part of the curves) are influenced by the bunch fields much stronger than those corresponding to the tail. Fig. 2 shows deviation of energy of secondary electrons passing through the input collimator 2. The behaviour of the curves is rather complicated and is different for different parameters and models. For Model #2 (empty signs) the secondary electrons are always decelerated, the biggest energy deviation corresponding to the head of the bunch. For the Model #1 (dark signs) the behaviour of the curves is more complicated. Due to the charge located close to the target the decelerating effect is prevailing.

The behaviour of a phase error generally follows the behaviour of energy deviation. To decrease the phase error one should collimate the beam, increase the target potential and locate the deflector 3 as close as possible to the beam axis.

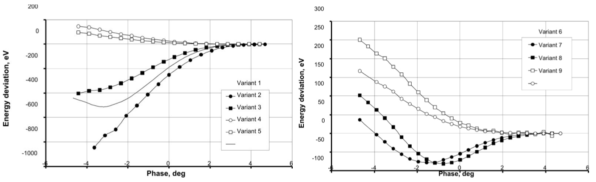

Fig.2. Deviation of energy of electrons at the input collimator.

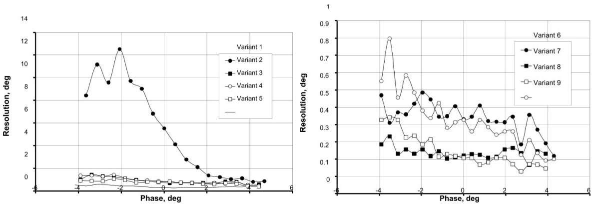

Fig. 3. Behaviour of phase resolutions along the bunch.

Small influence of the space charge on the phase resolution and on the contrary strong influence on the phase error is due to relativistic shrinking of the fields in the laboratory frame: for the secondary electrons the field is practically longitudinal.

Perturbation of the target voltage $U(y,t)$ (4) due to the current induced by the bunch is shown in Fig. 4. The solution of equation (4) gives a bipolar shape of perturbation. Evidently the changing of the voltage within the range –58 kV….+25 kV is impossible: even the potential inside the bunch is equal to –3.4 kV. This result confirms that the Model #1 gives only extreme estimation of the errors.

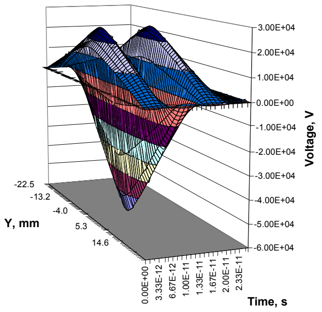

Fig. 4. Voltage on the target due to the charge induced by the electron bunch.

The solution of the equation (5) is shown in Fig. 5. The bunch produces the waves, propagating from the target center. The waves are reflected from target holders (grounded ends of the transmission line) and propagate in opposite directions. At the center of the target the waves interfere producing a spike and continue propagating towards the target holders etc. The magnitude of the waves in our case is negligible. The above considerations should be taken into account when selecting the dimensions and especially the material of the target. Thus the improper choice of the target length can result in a resonant interaction of the waves induced by a series of bunches. Using the targets with bad conductivity, for example carbon wires, also can result in undesirable effects.

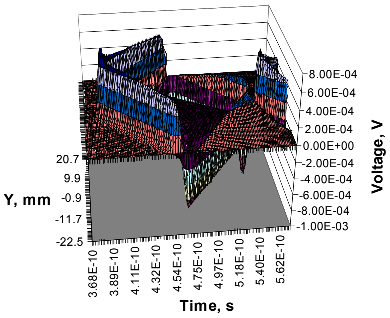

Fig. 5. Voltage on the target due to emission of secondary electrons.

5 CONCLUSIONS

The possibility to create the 3D-BSM with transverse RF scanning of low energy secondary electrons for the DESY Photo-Injector has been investigated. The detector can provide an accuracy of longitudinal measurements of 0.5°÷1°. For the vertical coordinate the accuracy is defined by the size of the horizontal collimator and is about 0.4 mm. For the horizontal coordinate the accuracy is extremely high as the only electrons emitted from a very small portion of the target surface are used as an information-carrying medium. Though the problems of space charge and high density of the beam are of extreme importance nevertheless they can be overcome by collimating the analyzed beam. The increasing of the target wire potential evidently decreases all the space charge effects. The longitudinal distribution can be measured per one beam pulse. The accuracy of both longitudinal and vertical measurements can be improved by decreasing the size of the collimating slits for both primary and secondary electrons.

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