NON-DESTRUCTIVE SINGLEPASS MONITOR OF LONGITUDINAL CHARGE DISTRIBUTION IN AN ULTRARELATIVISTIC ELECTRON BUNCH

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We present here the first experimental test of a singlepass non-destructive method of monitoring of longitudinal charge distribution in an intensive relativistic electron bunch. This method is based on the scanning of a thin electron beam within the energy range 20-100 keV in the electromagnetic field of an intensive relativistic bunch.

The probe beam was injected across the path of primary relativistic bunch. This type of an electron beam probe is suitable for both circular or linear accelerators. The prototype results obtained at VEPP-3 storage ring are in good agreement with the calculations and give us a very high degree of confidence that this single bunch diagnostic tool can be very useful not only for accelerator tuning, but also for precise measurements.

1 THEORY

The thin probe beam moves along X axis, is orthogonal to the direction of the relativistic bunch motion (Z axis) with the offset parameter ρ (Fig.1).

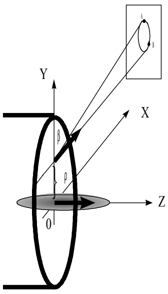

Fig. 1.

The results of scanning are monitored on the screen parallel to the Y-Z plane and positioned at the distance L from Z axis. Let the center of the relativistic bunch is located at the origin at time t=0 whereas the testing beam has the uniform density along X and the diameter d<<ρ . Here, we assume ρ exceeds the typical transverse size of the relativistic bunch. At the time t=0 every testing beam particle is corresponded to the certain x -coordinate. The total deflecting angle in Y direction for every particle under the influence of the electric field of the relativistic bunch can be expressed as:

$$\theta_y(x) = \frac{2\rho r_e}{\beta}\int\limits_{-\infty}^{+\infty}\frac{n(z)dz}{\rho^2+(x+\beta z)^2} \qquad (1)$$

where r_e is the classical electron radius, β =v_t/c – is a relative velocity of the testing beam, c – is a velocity of light, x - is a coordinate of testing beam particle at t=0, $n(z)$ - is a relativistic bunch linear density along Z axis. The expression for the deflecting angle of the particle in Z direction due to magnetic field can be written as:

$$\theta_z(x) = 2r_e\int\limits_{-\infty}^{+\infty}\frac{(x+\beta z)n(z)dz}{\rho^2+(x+\beta z)^2} \qquad (2)$$

As a result, the testing beam traces the closed curve on the screen. In assumption of the constant current I of the testing beam one can derive the simple correlation between the x -coordinate and the charge distribution $q(l)$ along the indicated curve on the screen from point A to point B (Fig. 1):

$$x = \frac{\beta c}{I}\int\limits_{A}^{B} q(l)dl \qquad (3)$$

Integrating the charge along the curve from point A up to point B (Fig.1) one can find the x -coordinate (3) and correspond to it the certain angles $\theta_z(x)$ and $\theta_y(x)$ at point B. Since the dependencies $\theta_y(x)$ and $\theta_z(x)$ are determined, it is possible using any of this functions to restore the dependence $n(z)$:

$$n(z) = \frac{\beta^2}{4\pi^2 r_e}\int\limits_{-\infty}^{+\infty}\theta_{\mathrm{y}}(k)e^{(ikz\beta+|k|\cdot\rho)}dk \qquad (4)$$

where $\theta_{\mathrm{y}}(k) = \int\limits_{-\infty}^{+\infty}\theta_{\mathrm{y}}(x)e^{-ikx}dx$.

It is necessary to emphasize that dependencies (1), (2) and (4) are valid only for ultra relativistic bunch with γ>>1 and for $\theta_Y^{MAX} << 1$ (5). The last condition gives a small perturbation of probe beam longitudinal motion by the electric field of relativistic bunch.

2 EXPERIMENTAL SETUP

The test of the electron beam probe was held at VEPP-3 storage ring at the bunch energy 350, 1200 and 2000 MeV. We placed the device in the straight section of the ring between two RF cavities. The probe system was evacuated to a typical storage ring vacuum level of 10^{-9} Torr. The schematic diagram of the layout is shown in Fig. 2. The probe electron gun had a flat diode geometry with 0.2 mm diameter anode diaphragm. We used 4 mm dispenser cathode with emission ability 3 A/cm^2. The maximum pulse current of the probe electron beam was 1 mA at the energy of 60 keV. Axial magnetic focusing lens formed a minimal transverse probe beam size as at the interaction region as on the screen. Transverse correction coils was installed to adjust the position of the probe beam on the screen. We used to direct the probe beam to the thing strip placed just before the Micro Channel Plate (MCP) of 20 mm diameter. It allowed to avoid the MCP saturation by 5 μs, 1mA probe beam and to measure its pulse current. We also measured probe beam energy. These two parameters gave us a possibility to restore the x value (3) or time from the charge distribution on the MCP entrance. The relativistic bunch duration was in the range of one nanosecond, so all voltages on MCP, screen and gun could be considered as constant during this time period. The shortest pulse on the MCP served as a gate pulse. It helped to make a single bunch picture on the phosphor screen (the revolution frequency of the bunch in the ring is 4.03 MHz). To digitise the screen image we used the conventional black and white CCD video camera and special ADC grabber of standard video signal with external start. Synchronous start of the camera is absolutely necessary to the brightness stability of the screen image from pulse by pulse for brightness to charge conversion.

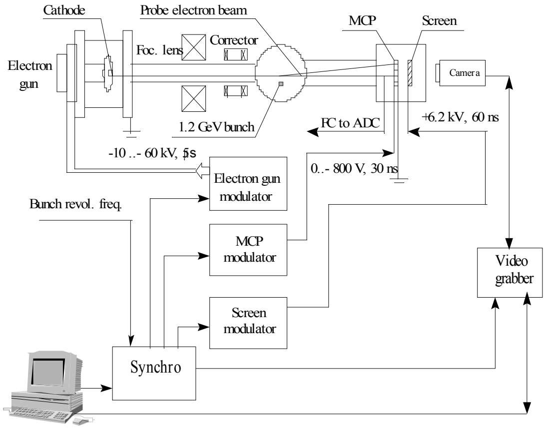

Fig. 2 The scheme of installation.

Since built-in brightness to charge calibration system was not ready at the first set of experiments we used for that purpose longitudinal charge distribution data obtained by dissector [2]. This stroboscopic device works properly for operation with a stable bunch at the time resolution level of 100 ps.

The maximum repetition rate for our system was limited by the screen luminescence time (5 ms) and video data acquisition time (500 ms). So all presented measurements was made on 0.5 pps.

Probe beam focusing system, all modulators, video and synchronous start system was controlled by computer from the main control room.

3 EXPERIMENTAL REZULTS

At first we adjusted the synchronous start system and modulators to reach a reliable operation with good time stability (a maximum long time jitter was less then 1 ns). The pulse to pulse voltage stability at the moment of relativistic bunch passing was better then 2% for each modulator. Then we checked the surface uniformity of MCP-Screen-Camera conversion system. The nonuniformity less then 3% was detected. All presented measurements was made with 60 keV, 1 mA probe electron beam. The probe beam size was 0.5 mm at the interaction point and 1 mm on the screen. To restore the bunch shape according to (4) we need the ρ value. It was measured directly by moving the probe beam up to the crossing with relativistic bunch trajectory. One can recognise the crossing picture very clearly.

After that we fulfilled the calibration measurements with stable bunch in the ring in order to have a real longitudinal charge distribution in the bunch from the dissector (the longitudinal bunch shape is very close to the Gaussian). Using this data one can calculate the brightness to charge conversion coefficient, pentium-133 can process the image for the time period less then 1 second. Since the range of brightness changing was not so big in comparison with dynamic range of video signal (less then 10%) and MCP-Screen system can be considered as linear within our range of parameters it was possible to use that conversion coefficient for the most of our measurements. Fig. 3 shows an example of calibration measurement with a stable bunch state at the energy of 1200 MeV.

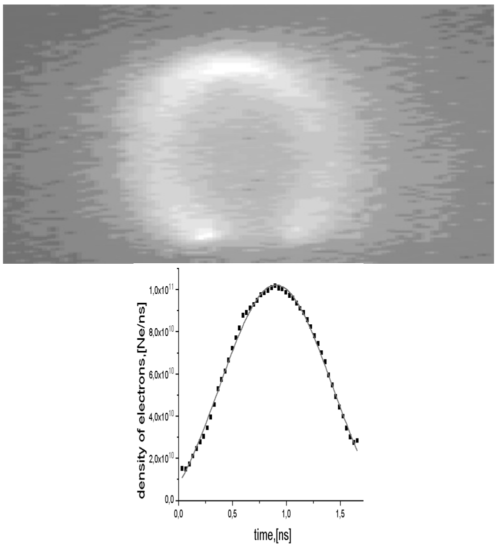

Fig.3. The calibration measurement with dissector at a stable bunch state. The solid line is a result of the best Gaussian fitting to the dissector data. Dots correspond to our device measurement.

After calibration procedure we used our device to monitor the longitudinal bunch instability. In this case the signal from dissector was very wide and unstable and it had two pikes with flashing amplitudes. Fig.4 shows typical single bunch pictures for that instability at the energy of 1200 MeV.

This is just an example to show the ability of the method. But for detail instability analysis one need at least few pictures: for example after 10th, 20th, 30th turn and so on. Unfortunately at existing device we can not make this shot. It need some changes in modulators, additional horizontal scanning system and bigger MCP with screen. We plan all this changes this year as a next step.

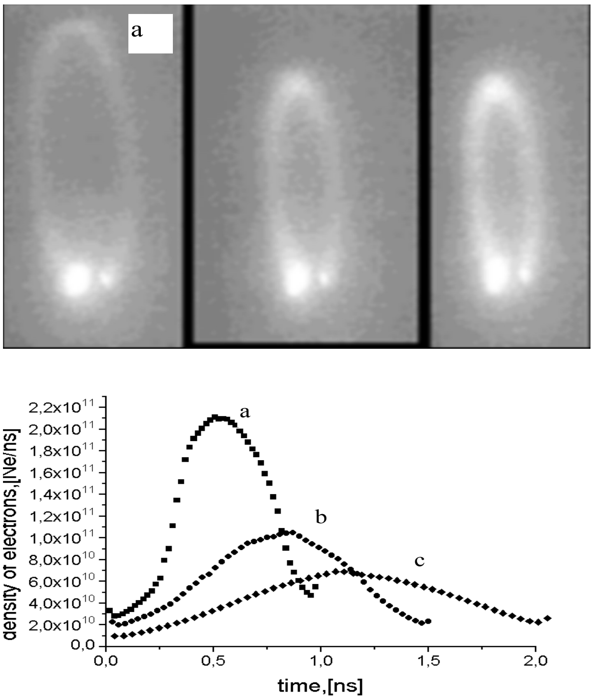

Fig. 4. Typical single bunch pictures for longitudinal instability: (a) - minimum bunch length, (c) - maximum, (b) - intermediate state.

4 DISCUSSION

The basic idea of this diagnostic looks simple, but one should be very careful evaluating the time resolution of this method. At first we have a finite angle resolution $\Delta\theta_Y$ due to a probe beam size on the screen or spatial resolution of electron detecting system. An angle resolution can be recalculated to a time resolution as follows:

$$\Delta t_1 = \frac{\Delta\theta_y}{\left[d\theta_y(x)/dx\right]_{MAX}} \cdot \frac{1}{\beta c} \qquad (6)$$

From the other side the modulation of longitudinal probe beam velocity due to x component of bunch electric field increases the time error value. Total time resolution is given by both effects. Assuming that

$$n(z) = \frac{Ne}{\sigma\sqrt{2\pi}} e^{-\frac{z^2}{2\sigma^2}},$$

we can evaluate time resolution τ in two occurrence:

for $\frac{\sigma\cdot\beta}{\rho} \rangle\rangle 1$, $\tau \approx \frac{r_e\cdot Ne\cdot\rho}{c\cdot\sigma\cdot\beta^3} + \frac{\Delta\theta_y\sigma^2\beta^2}{c\cdot r_e\cdot Ne}$ (6); and

for $\frac{\sigma\cdot\beta}{\rho} \langle\langle 1$, $\tau \approx \frac{\Delta\theta_y\rho^2}{c\cdot r_e\cdot Ne} + \frac{2r_e\cdot Ne}{c\beta^2} e^{-\sqrt{\frac{\rho}{\beta\cdot\sigma\cdot\sqrt{2}}}}$ (7)

Our experiment fits the first case, the expression (7) is suitable to linear accelerators. Taking into account the final size of the screen, one can evaluate (6) the time resolution value for our experiment (50 ps). To improve time resolution significantly we plan to rearrange optic and decrease the beam size on the screen. The maximum vertical size of the loop on the screen can be calculated for Gaussian bunch as follows:

$$h_{\max} = \frac{Lr_eN_e\sqrt{2\pi}}{\beta^2\sigma} e^{\frac{\rho^2}{2\beta^2\cdot\sigma^2}} \left(1 - erf\left(\frac{\rho}{\beta\sigma\sqrt{2}}\right)\right) \qquad (8)$$

where L is the distance between the interaction point and the screen. So you can not decrease probe beam energy to much in order to feet the image to the screen.

5 CONCLUSION

The design of the monitor essentially depends on the relativistic beam parameters. We just note the general useful qualities of the method:

1. Ability of simultaneous measurement not only longitudinal distribution of beam density, but the transverse position of its center of mass also [1] (two testing beams - above and below the relativistic beam).
2. Testing beam has practically no influence on the relativistic bunch, so its parameters don't get worse.
3. Small slots for testing beam transit in main vacuum chamber don't change its impedance.

In this year the monitor will be installed either in the (VEPP-4) storage ring and in the linear accelerator (VEPP-5 injector).

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