NON-DESTRUCTIV SINGLE PASS MONITOR OF LONGITUDINAL CHARGE DISTRIBUTION

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Abstract

This paper contains the present development of a non-destructive method for intensive relativistic bunch diagnostic. The method is based on the scanning of the thin electron beam within the energy range 20-100 kV in the electromagnetic field of an intensive relativistic bunch. We used to inject the probe beam across the path of relativistic bunch. This type of an electron beam probe is suitable for both circular and linear accelerators. The prototype results obtained on the VEPP-3 storage ring and on the electron linac of VEPP-5 injector complex at BINP have found out some new features of this non-destructive single bunch diagnostic tool. It is able to investigate not only the longitudinal charge distribution in the bunch [1,2], but also the transverse one. It is also sensitive to the transverse motion inside the bunch [3] and, it can even feel wake-fields after the bunch.

1 THEORY

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

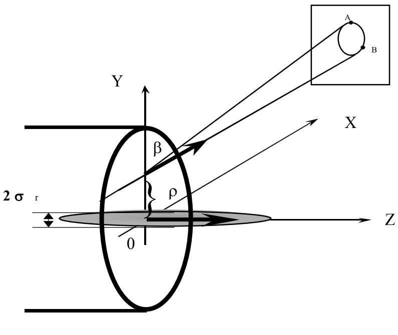

Fig. 1: Simple scheme of the experiment.

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 be located at the origin at time t=0 whereas the probe beam has the uniform density along X and the diameter d<<ρ. Here we assume that σ_r is the transverse sigma of the round Gaussian relativistic bunch. At the time t=0 every x -coordinate is assigned to the certain probe beam particle. Then 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:

$$\theta_y(x) = \frac{2\rho r_e}{\beta\gamma} \int_{-\infty}^{+\infty} \frac{n(z)[1 - e^{-\frac{\rho^2 + (x+\beta z)^2}{2\sigma^2_r}}]dz}{\rho^2 + (x+\beta z)^2} \quad (1),$$

where r_e is the classical electron radius, $\beta = v/c$ and $\gamma = 1/\sqrt{1-\beta^2}$ corresponds to the probe beam, c - the velocity of light, x - the coordinate of testing beam particle at t=0, $n(z)$ is the relativistic bunch linear density along Z-axis in the lab. system. The expression for the deflecting angle of the particle in Z direction due to magnetic field can be written in a similar way:

$$\theta_z(x) = \frac{2r_e}{\gamma} \int_{-\infty}^{+\infty} \frac{(x+\beta z)n(z)[1 - e^{-\frac{\rho^2 + (x+\beta z)^2}{2\sigma^2_r}}]dz}{\rho^2 + (x+\beta z)^2} \quad (2)$$

2 RESULTS

As a result, thin probe beam traces the closed curve on the screen. The dependence $\theta_y(x)$ can be measured in experiment [3] and $n(z)$ can be found as a solution of the integral equation (1).

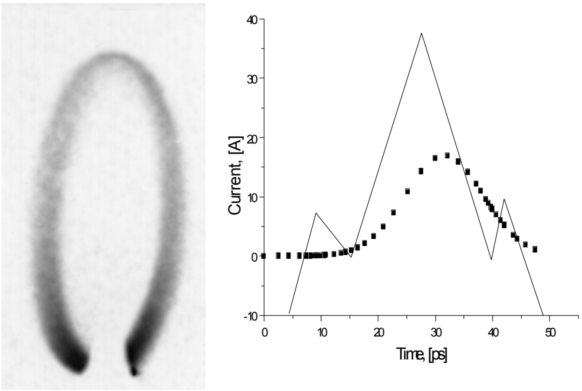

Fig. 2: Probe beam image on the screen and result of its processing. Solid curve represents the solution of linear system with 7x7 matrix sizes (error is about 20%). Dots are a result of Gaussian curve fitting by special procedure.

Fig.2 shows the result of longitudinal charge distribution measurement in the bunch of VEPP-5 injector linac. This measurement is done at 35 keV of the probe beam energy, with 3 mm offset parameter and 1.5 mm of relativistic bunch transverse sigma. Unfortunately this approach has a natural limitation for accuracy of the solution $n(z)$. For 5% deviation in $\theta_y(x)$ one can find less than 10% deviation in $n(z)$ only if $\sigma_l \beta > 3\rho$, where σ_l - longitudinal size of the relativistic bunch. This limitation comes from the mathematical properties of integral equation (1) and corresponding system of linear equations. Actually this integral equation is an approximation, since it can not take the longitudinal modulation of the probe beam velocity in the interaction region into account.

Fig. 3 represents dependencies of the solution $n(z)$ deviation upon the parameter $\alpha = \sigma_l \beta / \sigma_t$ for different value of $\theta_y(x)$ deviation (A and B) and number of equations in corresponding linear system – the matrix size nxn. In order to improve resolution one can reduce offset parameter ρ up to transverse relativistic bunch size σ_t. Since the useful value of parameter α depends on the error in $\theta_y(x)$ measurement, and this error strongly connected to the quality of the probe beam, the temporal resolution in this approach is limited by the probe beam spot size on the screen [4] and by the relativistic bunch shape. If transverse relativistic bunch size is close to the longitudinal one, the temporal resolution becomes very poor.

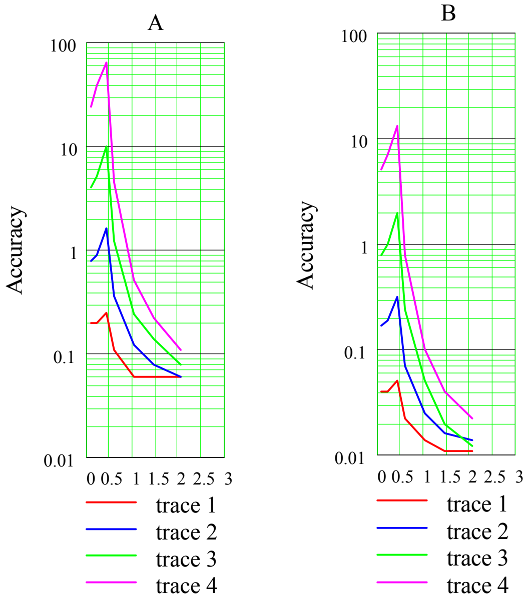

Fig. 3: Accuracy of the solution $n(z)$ versus the parameter α for different accuracy of $\theta_y(x)$ measurement: A-0.05, B- 0.01. Different traces correspond to the different matrix sizes: 1-5x5, 2-7x7, 3-9x9, 4-11x11.

But there is another way to evaluate the longitudinal bunch size at low α values. It comes from the idea to use head on collision with zero offset parameter for probe beam. Equations (1), (2) can be used for investigation of the image on the screen. Actually the image is formed by three factors: the transverse distribution in the probe beam at interaction point, transverse and longitudinal distribution in relativistic bunch, the probe beam offset parameter. If transverse probe beam size at the interaction point grater, than transverse relativistic bunch size, the image on the screen will have a sharp border of elliptical shape for zero offset parameter. Thus it is possible to measure the vertical and horizontal size of the image. Both of these sizes are proportional to the number of particles in the bunch. So the ratio of the vertical size to horizontal one is independent upon the bunch intensity and sensitive to the transverse and longitudinal bunch density distribution (see Fig. 4).

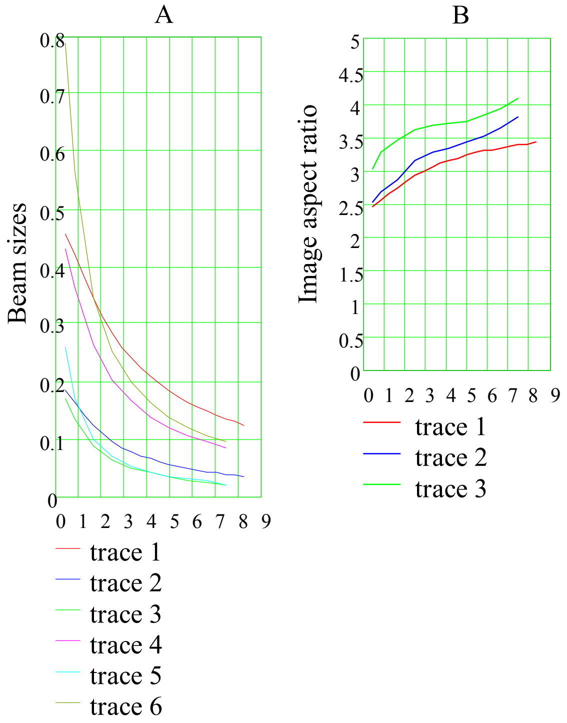

Fig. 4: Horizontal and vertical image sizes and image aspect ratio versus parameter α.

There are the dependencies (see Fig.4) of vertical size (traces 1,4,6) and horizontal one (traces 2,3,5) on parameter α for three cases: 1) Using equations (1),(2) – traces 1,2; 2) Simulation for round Gaussian bunch in transverse plane – traces 3,4; 3) Simulation for the round uniformly charged bunch – traces 5,6. Part B gives the dependencies of image aspect ratio upon the α value for three mentioned above cases: 1) trace 1; 2) trace 2; 3) trace 3. Simulation (cases 2 and 3) gives the result of 3d motion in relativistic bunch fields. A significant difference in aspect ratio is obvious for different transverse charge distributions. These calculations were done for 50 keV probe beam energy, transverse relativistic bunch sigma or radius 0.5 mm and number of electrons in a bunch $1.2 \cdot 10^9$.

The picture on the screen is very sensitive to transverse displacement of the transverse distribution center along the bunch. If the transverse displacement of bunch center and transverse bunch size are smaller then probe beam size in the interaction point, it is possible to evaluate the bunch shifting by comparing the brightness balance upper and bellow the probe beam axis (see Fig.5). Fig. 5 shows the result of the probe beam interaction with the bunch train of VEPP-5 injector linac at practically zero offset parameter.

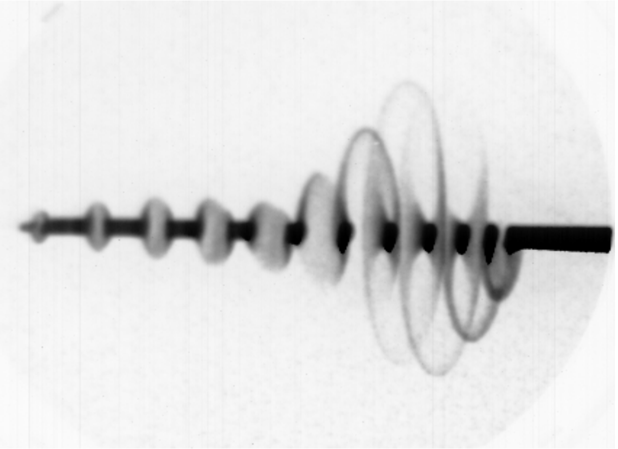

Fig. 5: Probe beam interaction with the bunch train of VEPP-5 injector linac for zero offset parameter.

A linear scanning was applied to separate images from different bunches. The time interval between bunches is equal to 350 ps. This picture demonstrates transverse oscillations in the bunch train. It is also possible to measure the maximum electric field value in each bunch, if longitudinal and transverse bunch sizes are known. The maximum vertical size of the bunch image is proportional to the maximum electric field inside the bunch. Together with other diagnostics this measurement can be useful.

Another interesting application of the linear scanning of the probe beam is the wake fields observation in accelerator vacuum chamber. Wake fields propagating through the vacuum chamber modulate the motion of probe beam in horizontal direction. It can be seen as the brightness modulation of beam image on the screen (see Fig.6). Upper line demonstrates the picture produced by bunch train, which excites several high order modes of accelerating structure. This picture was done at big offset parameter (about 10 mm) in order to put the time scale on the scanning line (350 ps per bin). Down picture shows the wake fields influence on the probe beam scanning line. This picture can be seen just after the bunch train up to the several tens of nanoseconds after the train. Then the brightness amplitude and its spectrum are presented. These wake fields come from the accelerating structure and correspond to the longitudinal mode at the frequency of 8714 MHz.

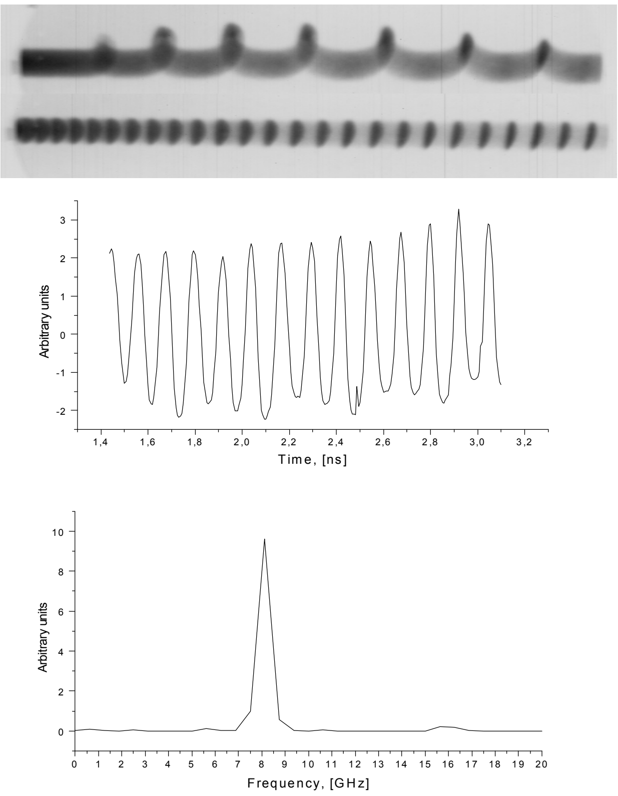

Fig. 6: Observation of the wake fields.

3 CONCLUSION

The experiments on VEPP-5 injector linac demonstrated at least two new applications for electron beam probe with linear scanning:

1. Head on collision multi bunch tomography.
2. Wake fields observation.

4 REFERENCES

1.John A. Pasour and Mai T. Ngo “Nonperturbing Electron Beam Probe To Diagnose Charged-Particle Beams”, Rev. Sci. Instrum. 63 (5), May 1992.

2. P.V. Logatchov at al. “Nondestructiv Diagnostic Tool For A Monitoring Of Longitudinal Charge Distribution In A Single Ultrarelativistic Electron Bunch”, PAC-99, New York, 29 March -2 April 1999.

3. A.A. Starostenko, P.A. Bak, Ye.A. Gusev, N.S. Dikansky, P.V. Logatchov, A.R. Frolov, “Non-destructive singlepass bunch length monitor: experiments at VEPP-5 preinjector electron linac”,EPAC-2000, Viena, 30 June – 4 July 2000.

4. P. V. Logatchov, “The tutorial No 3”JAS 2000, JOINT CERN-JAPAN-JINR-RUSSIA-USA ACCELERATOR SCHOOL, July 1 - 14 2000.