TECHNIQUE AND INSTRUMENTATION FOR BUNCH SHAPE MEASUREMENTS

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Abstract

Bunch shape is one of the most important, interesting but difficult to observe characteristics of a beam in ion linear accelerators. Different possibilities of bunch shape measurements are considered but the emphasis is put on the Bunch Shape Monitors (BSM) developed in INR RAS. The operation of BSM is based on coherent transformation of a longitudinal structure of a beam under study into a transverse distribution of a secondary electron beam through rf scanning. BSM characteristics found both by simulations and experimentally are presented. Modifications of BSM are described. Some experimental results of bunch observations are demonstrated.

INTRODUCTION

A longitudinal distribution of intensity in bunches $I(\varphi)$ or $I(z)$ as well as more complicated functions additionally dependent on transverse coordinates and time are meant by a bunch shape. The main requirement for bunch shape measurements is phase resolution. In ion linacs for typical bunch phase durations ranging from several degrees to several tens of degrees the resolution of 1° looks adequate. The corresponding temporal resolution, for example for 400 MHz, equals to 7 picoseconds. Small dimensions along the beam line, small beam distortion, wide range of measurements in beam intensity and sufficient one in phase, small power consumption and sufficient lifetime are of importance as well.

In ion beams, as opposite to electron ones, an attempt to extract information on bunch shape through beam electromagnetic field results in aggravation of phase resolution due to large longitudinal extent of the particle field to say nothing of the frequency response range of a beam monitor. The problem can be overcome if one localizes a longitudinal space passing through which the bunch transmits information on its shape. This approach can be implemented if a longitudinally small target is inserted into the beam and some kind of radiation due to interaction of the beam with this target is detected.

Different kinds of radiation are used or proposed to be used: Cherenkov radiation [1], detached electrons in case of H-, including photo-detachment by a laser beam [2-4], high energy electrons (δ-electrons) [5], X-rays [6]. Electrons obtained due to residual gas ionization are also used [7,8], the space of their generation being localized by electron collimation and separation in energy.

However low energy secondary electrons are used most extensively. The distinctive feature of these electrons is a weak dependence of their properties both on the type of primary particles and on their energy. Due to this features the detectors can be used for almost any ion beam. Among the characteristics of low energy secondary emission, influencing the parameters of the bunch shape monitor, one can mark out initial energy and angular distributions as well as time dispersion or delay of the emission. Time dispersion establishes a fundamental limitation on the resolution of the detector. The value of time dispersion for metals is estimated theoretically to be about $10^{-15}\div10^{-14}$ s [9], which is negligible from the point of view of bunch shape measurements. The experimental results of time dispersion measurements give not exact value but its upper limit. It was shown that the upper limit does not exceed $(4\pm2)\cdot10^{-12}$ s [10].

Operation of bunch shape monitors with low energy secondary electrons is based on coherent transformation of a time structure of the analyzed beam into a spatial distribution of secondary electrons through rf modulation. The first real detector is described in [11]. In this detector the electrons emitted from the thin strip target are accelerated by electrostatic field and simultaneously modulated in energy by rf electric field. Further energy analysis in a magnetic field enables to spatially separate the electrons with different energies, each point of the spatial distribution corresponding to a particular point of the longitudinal distribution of the analyzed beam. The detector described in [12] uses the same principle except for the feature that the processes of electrostatic acceleration and rf modulation are separated in space. Both the above detectors use rf modulation in energy or in other words a longitudinal modulation. Another possibility is using a transverse scanning. The electrons are modulated in transverse direction and deflected depending on their phase. Spatial separation is obtained after a drift space. In the first proposal of the bunch shape detector with transverse modulation of low energy secondary electrons, made in the early sixties [13], a circular scan with the help of two rf deflectors is foreseen. The circular scan provides a band of measurements equal to a full period of the rf deflecting field. However the bunches in linear accelerators are normally much shorter than the period and instead of a circular scan one can use a linear one thus twice loosing the phase range of measurements but essentially simplifying the detector.

BSM WITH TRANSVERSE SCANNING

Principle of Operation

The BSM operation principle has been described in detail earlier [14÷16]. Briefly it can be repeated with the reference to fig. 1. The series of bunches of the beam under study crosses the wire target 1 which is at a high negative potential ($U_{t\arg}$ about -10 kV). The target represents a tungsten wire of 0.1 mm diameter. Interaction of the beam with the target results in emission of low energy secondary electrons. The electrons are

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accelerated by electrostatic field and move almost radially away from the target. A fraction of the electrons passes through input collimator 2 and enters rf deflector 3 operating at a frequency equal to or multiple of the linac accelerating field frequency. Deflection of the electrons at the exit of the rf deflector depends on their phase with respect to deflecting field. Downstream of the drift distance the electrons are spatially separated and their coordinates are dependent on phase of the deflecting field. Temporal structure of the analyzed ion beam is initially transformed into that of secondary electrons and then into spatial distribution of the electrons. The intensity of the electrons at a fixed coordinate is proportional to the intensity of the primary beam at a fixed point along the bunch. These electrons are separated by output collimator 4 and their intensity is measured with electron detector 5. Adjusting the deflecting field phase with respect to accelerator rf reference, one can obtain a longitudinal distribution of charge in the bunches of the analyzed beam.

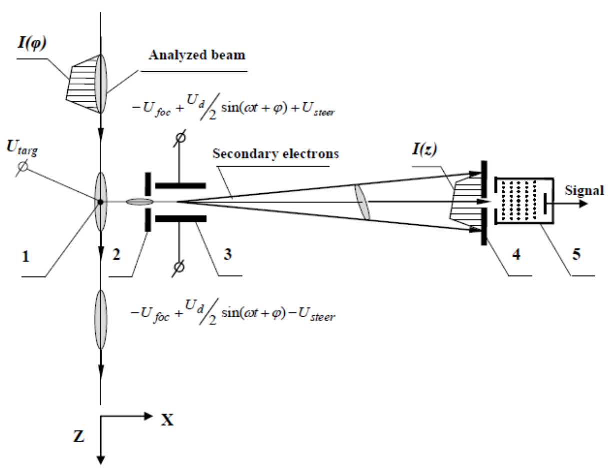

Figure 1: Principle of operation of Bunch Shape Monitor (1 - target, 2 - input collimator, 3 - rf deflector combined with electrostatic lens, 4 - output collimator, 5 – electron collector).

Main Parameters

The most important characteristic of BSM is its phase resolution. We define phase resolution by a simple relation $\Delta\varphi = \Delta Z / nZ_{\max}$, where $Z_{\max}$ is the amplitude of electron displacement at collimator 4 plane, n is a harmonic number of the deflecting field with respect to the fundamental bunch array frequency and ΔZ is a full width at a half maximum of the electron beam at the collimator 4 for zero phase duration bunches of the analyzed beam. To decrease ΔZ and hence to improve the resolution the electron beam must be focused. In the first BSM [14] a separate electrostatic lens located between the input collimator and the rf deflector was used. Later rf deflector was combined with electrostatic lens [17] by additionally applying focusing potential U_{foc} to the deflector electrodes (fig.1). This solution enabled to bring the deflector nearer to the input collimator thus decreasing temporal structure distortions and to improve deflector stability by reliably suppressing multipactoring. To steer the electron beam additional potential difference U_{steer} is also applied between the deflector electrodes. Evidently the size of the collimator should not exceed ΔZ. Otherwise the size of the collimator is to be used in the above formula instead of electron beam size ΔZ.

The value of maximum displacement $Z_{\max}$ can be both calculated and found experimentally [15]. As for the ΔZ value, its finding is not a trivial task. To find the value of ΔZ for the purpose of phase resolution evaluation both theoretical and experimental data are used. Initially focusing properties of the detector can be found experimentally using thermal electrons. Heating the wire target made of tungsten, it is possible to visually observe the thermal electron beam on the phosphor covering the front surface of the plates of collimator 4 through the viewing port. The size of the focused beam of secondary electrons can be measured by adjusting the steering voltage U_{steer} for the turned off rf deflecting field. After that computer simulations can be done to find the value of ΔZ for real parameters of the low energy secondary electrons taking into account a real spatial distribution of the deflecting field. Sometimes instead of full width at a half maximum a double rms size is used.

The simulations are done with the following assumptions. Bunches of the primary beam are considered to have a δ-function type longitudinal distribution. The target is an ideal cylinder with no surface roughness. Deceleration of primary electrons in target material is not taken into account. Initial energy of secondary electrons is distributed within the range of 0÷30 eV according to a typical for secondary emission distribution function [9]. Initial angles with respect to the emitting surface are randomly distributed within the hemisphere. The delay of emission is randomly distributed within the range of $(0\div6)\cdot10^{-12}$ s.

To simulate electron motion from target 1 to input collimator 2 three models have been examined: coaxial line model, wire and plane model and a model with a real 3D geometry. Due to concentration of the electric field in the vicinity of the target the influence of the outer boundaries in not essential and all the three models give approximately the same results. The fields in the deflector are calculated in a quasi-static approximation.

The example of typical behaviour of phase resolution versus deflecting voltage for different input collimator sizes is presented in fig. 2. The calculations are done for the frequency of 352.2 MHz. Because of displacement of the trajectories of those electrons, which pass through the output collimator, off the deflector axis due to rf deflecting field the electrons are defocused and the value of ΔZ increases with increasing of the deflecting voltage. As a result the resolution changes rather slowly within a wide range of the deflecting voltages. The effect depends on electron beam size in the deflector which depends on the input collimator size.

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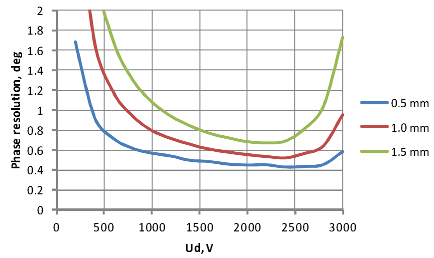

Figure 2: Dependence of phase resolution on deflecting voltage for different input collimators.

Another important characteristic is an ability of measuring small intensities. This feature is especially important for longitudinal halo measurements. Using a secondary electron multiplier as an electron beam detector 5 (fig.1) enables the measurements to be done within 5 orders of intensity magnitude.

The limitation of BSM use for high intensities is due to two reasons. The first one is target heating. In case of tungsten target before its destruction the overheating is manifested as arising of thermal electron current. A bunch substrate increasing within the beam pulse is observed when bunch behaviour within the beam pulse is measured [16].

The second limitation is effect of space charge of the analysed beam.

Influence of Analyzed Beam Space Charge

Influence of electromagnetic field of the analyzed beam on bunch shape measurement accuracy has been estimated and analyzed elsewhere by several authors including the author of this report [18-23].

The influence of the electromagnetic field of the analyzed beam results in two effects: deterioration of phase resolution and appearance of a specific error which we call phase reading error. Deterioration of phase resolution results in a loss of a fine longitudinal structure and phase reading error distorts the shape of the measured function. Both effects depend on many parameters and vary along the bunch. As opposite to the phase resolution which is influenced by many factors the phase reading error is due only to electromagnetic field of the analyzed beam.

We use two models for the analysis of bunch field influence for two utmost cases. The first model is suitable for relatively long bunches. Boundary conditions are supposed to be kept constant while the bunch passes the BSM chamber. The fields are found by multiple solving of Poisson equation in the beam frame for fixed bunch positions as the bunch passes the chamber. Electrostatic fields found in the beam frame produce both electric and magnetic components in the lab frame. The field effecting secondary electrons is represented as a superposition of electromagnetic field of the bunch and an unperturbed electrostatic field due to target HV potential. In case of short bunches the charge distribution providing invariability of target potential has no time to be formed. Electrostatic fields of the bunch in the beam frame are found by Poison equation multiple solving for boundary conditions with the target absence. The field effecting secondary electrons is found similarly to the first model as a superposition of electromagnetic field of the bunch and an unperturbed electrostatic field due to HV potential applied to the target. The considerations on applicability of the models are given in [22].

Figures 3 and 4 demonstrate a behavior of phase resolution and phase reading error along the bunch of H^- beam for the two models. In both cases the target position is at the beam center.

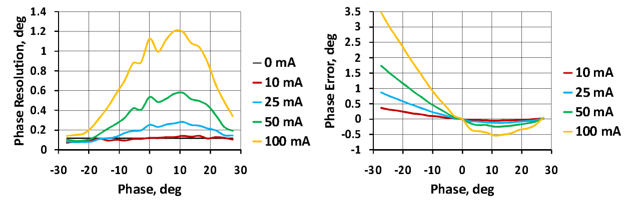

Figure 3: Resolution and phase reading error for the following beam parameters: W=3 MeV, σ_x=2.6 mm, σ_y=2.6 mm σ_φ=13° (Model 1).

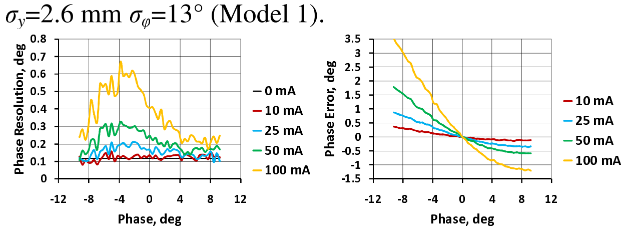

Figure 4: Resolution and phase reading error for the following beam parameters: W=200 MeV, σ_x=1.2 mm, σ_y=1.2 mm σ_φ=2.1° (Model 2).

Experimental data available [22] demonstrate applicability of BSM for the measurements at high peak currents, but do not reveal the measurement errors and are not straightforward ones. The only directs experiment confirming negligibility of the errors was done with the 20 mA beam [15]. The measurements were done for the full beam and for the beam collimated at the BSM entrance. No difference in the measured distributions was observed.

MODIFICATIONS OF BUNCH SHAPE MONITOR

Additionally to the basic detector above described there are three BSM modifications: BSM for H^- beams, Bunch Length and Velocity Detector (BLVD) and Three Dimensional Bunch Shape Monitor (3D-BSM).

BSM for H- minus Beams

In case of H^- beam a fraction of the detached electrons after interaction with the BSM target gets into the secondary electron channel of BSM and the detected signal represents a superposition of signals due to low energy secondary electrons and the detached electrons [24]. The effect has been analyzed in [25]. The energy of the detached electrons differs from that of low energy secondary electrons so the two groups of the electrons can be effectively separated. BSM for H^- beam includes

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additional element – bending magnet located between the output collimator and the electron detector.

Bunch Length and Velocity Detector

BLVD is a BSM, which can be mechanically translated along the beam line [26-29]. In this detector a time of flight method of energy measurements is implemented. The translation results in a shift in phase of the observed distribution. Measuring the value of the translation and the value of the shift one can find an average velocity of the beam. The accuracy of bunch shape measurements for this detector is the same as for normal BSM. Special procedure of velocity measurement enables to decrease systematic error to ±0.1%. Total error of velocity measurements is typically within ±(0.3÷0.4)%.

Three Dimensional Bunch Shape Monitor

3D-BSM is aimed to measure a three dimensional distribution of charge in bunches [30,31]. Due to high strength and concentration of electric field near the wire target the electrons move almost perpendicular to its axis with very small displacement along the wire in the area between the target and the input collimator. Additional slit perpendicular to the target installed outside the beam enables to separate the secondary electrons emitted from a fixed coordinate along the wire. For fixed position of the wire and fixe position of the additional slit the intensity of the electrons passed through the slit is proportional to beam intensity at the fixed transverse coordinate. The phase distribution of the separated electrons is measured in the same manner as in basic BSM. Moving the target and the slit and each time measuring longitudinal distribution one can obtain a three dimensional distribution of charge in bunches.

INR ACTIVITY IN DEVELOPMENT AND FABRICATION OF BUNCH SHAPE MONITORS

The first BSM with transverse scanning of low energy secondary electrons has been developed and built in INR in the eighties and the first measurements has been done in 1988 during commissioning of INR linac. Since that time BSMs of various modifications have been developed and built for several accelerators including SSC Linac (four BSMs), CERN Linac-3 (one BLVD), CERN Linac-2 (two BSMs, one 3D-BSM), DESY Linac-3 (two BSMs, one BLVD), JHP-RFQ (one BLVD), SNS Linac (eight BSMs), CERN Linac-4 (one BSM), J-PARC Linac (three BSMs).

It should be noted that the detectors of this type have also been developed in other laboratories [32-34].

MAIN BSM SYSTEMS

The main BSM systems are rf system, HV system, electron detection system and control system.

RF System

The system includes rf deflector, rf amplifier and phase shifter. Depending on bunch lengths and BSM design features both fundamental bunch array frequency and higher harmonics are used. There is a variety of deflector types used in BSMs. For the deflector combined with the electrostatic lens the most suitable are the cavities based on coaxial or parallel wire lines. HV potentials are applied to the deflector electrodes at zero points of rf electric field. Typical value of rf power required for deflector excitation is near 10 W. Phase of the deflecting field is normally adjusted from pulse to pulse and the most suitable are voltage controlled electronic phase shifters.

HV System

The system is intended to supply HV potentials to the target and electrostatic lens as well as to secondary electron multiplier. Typical value of target potential is −10 kV. To provide BSM tuning with thermal electrons a filament source is foreseen at HV target potential. To provide steering of the electrons an adjustable voltage difference of several hundred volts must be superimposed on focusing potential.

Electron Detection System

Secondary electron multipliers are most widely used. In this single channel system only one phase point is detected for a fixed phase setting hence multiple beam pulses are required for bunch shape measurement. The detection system of 3D-BSM [31] uses 30-channel electron collector thus enabling the measurement of the whole longitudinal distribution to be done per single beam pulse. This possibility also exists in BSM described in [33, 34] where the electrons are detected with micro channel plate, phosphor screen and CCD camera.

Control System

In principle any type of control system can be used. However the most recent our developments are based on LabView platform with the use of National Instruments control modules.

DEMONSTRATION OF MEASUREMENT RESULTS

Here just for demonstration we confine ourselves with basic BSM or its modification for H^- beam with a single channel for electron signal detection. Normally different phase points are measured for different beam pulses and the signal is digitized within the beam pulse. It is implied that bunches are reproducible from pulse to pulse though can vary within the beam pulses. Bunch shape measurements can be used for restoration of longitudinal emittance, setting of accelerating field parameters, longitudinal beam matching etc. However the data directly obtained from BSM represent no more than a two dimensional function of phase and time. If the measurements are done with increased gains of secondary

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electron multiplier a longitudinal halo and bunch tails can be observed after stitching together the pieces of the measured functions. The examples of such a data reported in [35] are shown in fig. 5, 6.

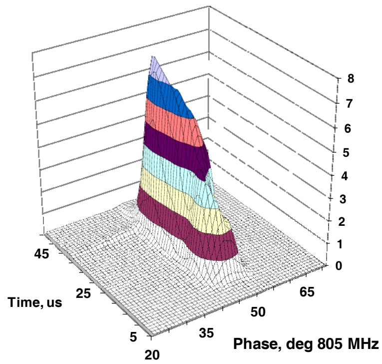

Figure 5: Typical BSM experimental data.

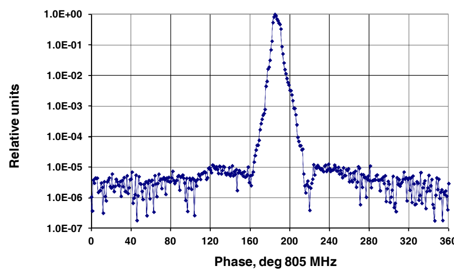

Figure 6: Longitudinal profile combined from several measurements with gains ranging within 3500.

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