A BEAM DIAGNOSTIC SYSTEM FOR SIBERIA-2 SYNCHROTRON RADIATION SOURCE.

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Abstract.

For synchrotron radiation source SIBERIA-2, a beam diagnostic system based on electrostatic pickups, has been designed. The system includes turn-by-turn signal processing electronics, operates with computer control and data processing, and provides a wide range of beam diagnostic measurements. During commissioning the storage ring, the system had been used for closing the first turn, in circulating beam mode, injected beam parameters, betatron tune, closed orbit and dispersion function have been measured.. Other applications are beta function and phase advance measurements, observations of betatron phase space and low frequency beam vibrations. The system can be completely tested and calibrated by its own means.

INTRODUCTION.

The storage ring SIBERIA-2 is built with the purpose of producing SR beams. The SIBERIA complex includes 80 MeV Linac, the transfer line TL1, 450 MeV storage ring SIBERIA-1 used as a booster, the transfer line TL2 and the main 2.5 GeV storage ring SIBERIA-2.

SIBERIA-2 [1] has a six fold symmetry lattice with 12 three meter long straight sections to accommodate insertion devices, RF and injection equipment. A single-turn injection scheme with two kickers and one septum is used. SIBERIA-2 is designed for operating both in the 100 mA single-bunch mode and in the 300 mA multi-bunch mode (number of bunches is 10-30). Beam revolution frequency is 2.465 MHz, harmonic number is 75. The bunch length is approx. 6 cm

A set of various beam diagnostic instruments was used at SIBERIA-2 during commissioning in 1995: movable remote-controlled vertical probes, movable remote-controlled luminescent screens with TV-cameras, radiation monitors, SR photomultipliers, visible SR TV-monitor, electrostatic beam position monitors, DCT, SR beam image dissectors, resonance beam excitation.

The electrostatic monitors (24 monitors, 4 ones per the betatron wavelength) are united in a system (System) which is intended for closed orbit, dispersion function, beta-function and betatron phase advance measurements (with exciting betatron oscillations by a pulse kicker). System has a limited capability for observation of the first turn of beam. One more monitor (OMM) is meant for turn-by-turn current and position measurements of injected beam, for determining betatron and synchrotron frequencies, for observing of the phase space diagram of betatron oscillations, for low frequency beam vibration measurement.

At the stage of closing the first beam turn, where a rather complicate alignment of the injection devices and the magnet system was required, many instruments listed above, including the electrostatic monitors, were used together to get correct interpretation of results of the alignment. Beam signals of the electrostatic monitors were observed by a storage oscilloscope. Beam current did not exceeded few mA's (in units of booster beam current). The beam passing was accompanied by beam losses which produced secondary emission electrons causing parasitic signals on the electrostatic monitors. Under this condition, correct measurements of beam current and position were not possible, the signals were analyzed qualitatively only.

Beam losses took place for few turns next to the first one, and a circulating beam had a low current and could be observed by high sensitive SR photomultipliers and visible SR TV-monitor only. The last monitor was used for betatron tune measurement by resonance exciting the oscillations. Closed orbit and dispersion function measurements by System became possible when the current exceeded 100 μA (in units of SIBERIA-2 current). When the current exceeded 500 μA, turn-by-turn measurements by OMM of injected beam current and position and of betatron and synchrotron frequencies were carried out.

Beta-function and betatron phase advance measurements and observation of the phase space diagram by the monitors will be possible after coming installation of pulse kickers. The beam current more than 5 mA is necessary for these tasks and for beam vibration measurement too.

Thus, design performance of System and OMM tested to a certain extent by beam. These diagnostic instruments were used for aligning and studying SIBERIA-2. This is one of the results of the commissioning carried out till now.

ELECTROSTATIC PICKUP AND ZERO OFFSET ERROR.

Electrostatic pickups with button-type electrodes (BE's) are used. A single Button Electrode Unit (BEU) consists of two pairs of electrodes positioned in two parallel planes above and below the design-basic orbit. Horizontal (X) or vertical (Z) beam displacements in a BEU is calculated with expression :

$$Y = M_Y\,(k_1U_1 \mp k_2U_2 + k_3U_3 \pm k_4U_4)\,/\,\Sigma U_i - Y_0 - Y_G \qquad (1)$$

where Y is X or Z, M_Y is a scale coefficient of this BEU, U_i is the value of the output signal from BE of number 1,...,4, k_i is a levelling coefficient of the BE_i (see below), Y_0 is an electrical zero offset of this BEU and Y_G is the shift of the BEU center above the design-basic orbit.

The scale coefficients and the electrical zero offsets for the point (X=0, Z=0) were measured for each BEU with a charged wire and recorded in database to be used. The zero offset measurement accuracy is 100 μm. For each point of a coordinate grid, BE_i signals were measured too with the wire. These data can be used for linearization of BEU characteristics.

The signals U_i are equal GQ_i/C_i for measurement with scanning BE's by the same channel, and G_iQ_i/C_i for a four channel measurement, where Q_i is a charge induced on BE_i, C_i is a total capacitance of BE_i circuit and G or G_i are gains. Differences between C_i or G_i cause an zero offset which is eliminated by using levelling coefficients. To determine them, a calibration procedure is used when U_i, i=1,...,4, are produced by the same calibration current fed into each BE circuit, and the levelling coefficients are calculated with expression $k_iU_i = (\Sigma U_i)/4$ and recorded.

A built-in-system zero offset error elimination which results in a residual zero offset of the order of the accuracy being inherent in a system, is a merit of the system described, as opposite to systems using parameters premeasured or supposed to be equal [2,3].

SIGNAL PROCESSING.

Beam diagnostics by System and OMM is based on using the computer as their integral part which determines and displays beam parameters and controls the signal processing electronics.

Thanks of computer, maximum of information can be obtained from signals by using various data processing algorithms and many algorithms of the control can be used to carry out different measurements by the same processing electronics.

For entering the data in the computer, the final function of the electronics is to convert the pickup electrode signal into a signal, the form of which is suitable for measurement by ADC. The most informative measurement would be the turn-by-turn one. To achieve both the aims, Sample & Hold circuit (S&H) is used as the converter, the output signal of which is a quasi-DC, stepping voltage being equal to peak values of the turn-by-turn input pulses. Strobe pulses for the sampling are derived from revolution frequency signal which is taken from RF system. To lock the strobe pulses into step with the pulses of any bunch from BEU placed at any azimuth of the storage ring, the delay circuit is used.

To provide for S&H some optimal input voltage range independent of beam intensity varying in a wide range, two kinds of Amplifier Gain Control are used. In OMM, gain is set by computer according to the value of booster beam current before measurement of injected beam or to the value of beam current stored in SIBERIA-2 before other ones. In System, Automatic Gain Control is used. Before measuring the individual BE signals of one BEU, using the sum signal of them, gain is being varied (in steps) till a gain sought-for, is reached when the S&H output (i.e. input) signal has got a value within the range.

Short pulses induced by bunch on BE, are stretched by LP filters to obtain pulses, shape and duration of which are suitable for the sampling. As a consequence, amplitude decreases proportionally to the frequency band contraction degree. Noise voltage decreases as the square root of the degree, and generally, the stretching simplifying the tasks of design and fulfillment, results in a reduced sensitivity of the system.

For the turn-by-turn S&H output signal, resolution is determined by a noise voltage in a full band of the input signal. For the discrete Fourier transform (FT) of the output signal, resolution is $N^{1/2}$ times higher, where N is number of samples in the array. Discrete filters of other types or analog filters (for LP filter $N \sim T/T_0$ where T_0 is revolution period, $T=1/\Delta F$, ΔF is the transmission band) can be used for increasing resolution by the same factor.

Turn-by-turn arrays are used for a visual observation of some processes, for instance, injection. For betatron and synchrotron beam motions, the most suitable filter is the discrete FT. Low frequency beam vibrations and stationary orbits are measured with using LP filters. As LP filter with a varied band, a precise integrating ADC is used, the time of integration of which can be varied in a wide range.

ARRANGEMENT AND PARAMETERS.

In OMM, synchronous measurements of BE's signals of one BEU by four ADC's are carried out. In System, the procedure of scanning BE's of all 24 BEU's and serial measuring their signals by a single ADC, is used.

OMM has a four channel pickup station (FCPS) placed near BEU, and four channels of processing electronics placed in Control Room. System has 24 pickup stations (PS's) distributed along the storage ring, and a single channel of processing electronics placed in Control Room. PS's are connected with the channel one by one by a multiplexer. In a PS sampled, the BE's are scanned by switches of the PS.

Such arrangement seems to be an optimal one from the point of view of the measurement purposes and general cost and availability of electronic components.

One channel of FCPS consists of a series of LP filters loaded on a buffer circuit, the output stage of which is a cable driver with DC isolation. Into the input of the last filter, a calibration current can be fed by using a switch. In PS, the BE circuit concludes a part of same series and a switch for scanning. The outputs of four switches are united and connected with the input of the last filter. The calibration signal is fed into the same input by the fifth switch. The buffer circuit is same one as in FCPS.

A series of LC-filters and RC-circuits is used for a step-by-step stretching. BE is loaded on the series input (the HF input resistance is approx. 50Ω), the last stage is a matched filter of Gaussian type. Within the transmission band of this filter, the equivalent diagram of the BE circuit is a total capacitance C and a resistance R in parallel where R is a load resistance of the filter. The resistance is chosen as high as practically possible to compensate reducing sensitivity caused by rising the total capacitance by the combined capacitance of the series.

The total capacitance of BE circuit is approx. equal to 200pF, the load resistance R=400Ω. For a single bunch, the output pulse of FCPS or PS is like on a sine-shaped pulse with duration 40 nsec on half-height, followed by an exponential undershot with decay time approx. 200nsec (Fig.1).

The processing electronics is made under CAMAC-standard. One channel consists of a wide band amplifier with gain (0-60)dB varied in steps 10dB, and S&H (sampling gate is 10nsec). Besides, there are digital delay circuits (step is 4nsec, 7 bits) and some auxiliary modules for controlling PS's and FCPS, for triggering fast ADC's, etc.

ADC's of two sorts are used: a fast ADC (8 bits, 100 nsec, 1K memory) and a slow one ((13+n) bits and time of integration $1.25*2^n$ msec where n=0,1,...,7 can be set, 1K memory).

For measurements in betatron frequency band turn-by-turn beam signals are measured by four fast ADCs. It is possible to use FCPS for measurements in the frequency band from zero up to some hundreds Hz. Four slow ADCs connected to LPF output of every S&H are used. An integrating time of ADC determines frequency bandwidth.

DATA PROCESSING.

A basic algorithm for test and calibration of both the beam diagnostic instruments, System and OMM, is as following. The S&H output signal is measured in a stroboscope mode for strobe pulse delay values scanned within the period of one turn. A plot of the values measured, represents an informative picture of the input signal. The delay value of the pulse peak is registered. With the FCPS or PS switched off, the S&H output offset is measured, and its value at the moment of the pulse peak is registered too. The S&H offset will be subtracted from any output signal of this S&H. This provides as eliminating the S&H DC offset as an effective suppressing of a turn-by-turn parasitic signal which may be in the processing channel.

Spectral data analysis is carried out using digital Fourier transformation. Frequency can be determine using FFT algorithm with 1/N accuracy (N is array size). Amplitude and phase can be measured with rather worse accuracy. To increase measurement accuracy making more precise algorithm is used [5]. The idea of this algorithm is digital Fourier transformation of N elements long coordinate array with step 1/kN (k=1,2,...) in the narrow region near peak found roughly by standard FFT. This algorithm provides to measure amplitude and phase of oscillations, that is important to measure beta function and betatron phase advance.

For spectral analysis of beam vibrations or electronics noise, a power spectrum and a spectrum integral are used. The power spectrum is calculated as array of harmonic's amplitude squares, the spectrum integral is a sum of harmonic's amplitudes from zero up to current frequency.

Statistical analysis is used also. A histogram is obtained from sequence of coordinates calculated with formula (1) from beam or calibration signals, measured on one pickup with some period. R.m.s. coordinate deviation is half-width of the histogram. These r.m.s. deviations for all pickups are calculated, when averaged closed orbit is measured.

Phase space diagram of betatron oscillations can be observed. For this aim two pickups with $\pi/2$ betatron phase advance are usually applied. Beam coordinate on the second pickup is proportional to beam angle on the first one. At SIBERIA-2 only one pickup can be used. Necessary $\pi/2$ phase advance is obtained by passing some number of turns k, found from condition: $kQ=n+\pi/2$, where Q is betatron frequency, n *is* integer value. Thus, coordinate on the same pickup measured after k turns, is proportional to the angle. In strict consideration this is not an accurate proportionality, because of sextupoles influence. But it is possible to use this method to approximate evaluate of dynamic aperture and to observe high order resonances.

SOFTWARE.

The instruments control and data processing are carried out in framework of SIBERIA multi-program control system [4]. A single computer included into the network of this system, is used. A set of program is designed to test and calibrate both the beam diagnostic instruments and to determine beam parameters. Initiating or stopping the programs' operation is carried out by external interrupts generated by a peripheral hardware using CAMAC-interface. Control and data processing algorithms are designed as a set of segments so that a new program can be easily compiled [5]. A database is there for BEU's' and electronics' parameters including that ones which were determined by a built-in-system calibration. A database manager and other auxiliary programs are designed too.

All the programs can operate with both the beam signal and the calibration one imitated beam, that is useful for full system testing and calibration without beam.

EXPERIMENTAL RESULTS.

Calibration signals and S&H zero offset on one PS are shown on Fig.1. An analysis of the shape and amplitude of the signals provides to test the instrument workability. The vertical line marks the delay value of the pulse peak.

To check the resolution and stability, the "orbit" from calibration signals is measured with averaging. R.m.s "orbit" deviation is appear due to noise of electronics and determines the PS resolution. Non-zero average values are caused by a long time drift of electronics characteristics. Because of this drift, the system periodically needs calibration to keep the measurement accuracy without changing to the worse. On Fig.2. one can see such the "orbit" averaged by 5 measurements, with

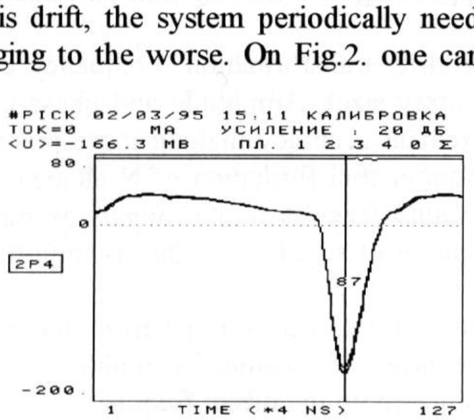

Fig.1. Calibration signals of one PS.

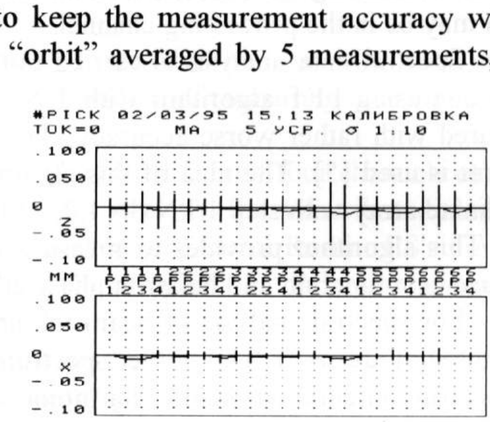

Fig.2. "Orbit" measured with calibration signal.

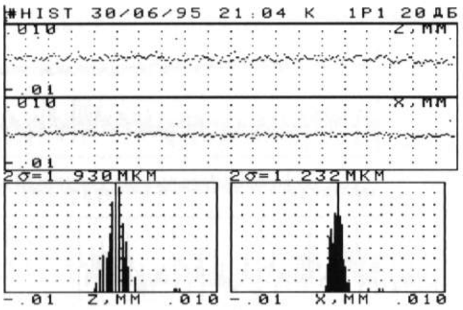

Fig.3. PS resolution.

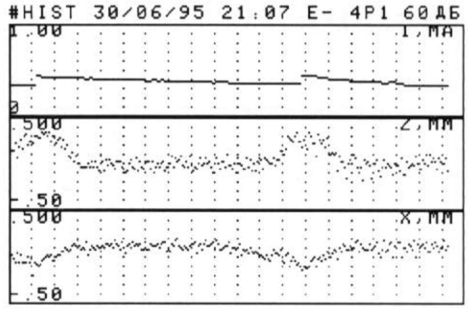

Fig.4. Slow beam position deviation.

lewelling coefficients written 6 weeks ago. The r.m.s deviation values are shown multiplied by 10. Vertical resolution is less than 5 μm (typically 2 μm), horizontal one is less than 1 μm. Long time drift is less than 10 μm.

Statistic analysis of coordinates calculated from calibration signal, is used to determine instrument's resolution. On Fig.3. one can see graphs of 256 calibration "beam positions" measured with 100ms period, and statistic distributions. The histogram widths is the average PS resolution due to electronic noise. It is less than 2 μm.

The same program is used to study low frequency beam vibrations. The graphs of beam position deviation are shown on Fig.4. This motion is produced by booster magnet system influence on SIBERIA-2 during booster cycle.

Fig.5 illustrates spectral resolution of the FCPS in the frequency band 0-60Hz. These spectra are obtained from array of 1024 horizontal coordinate samples. The coordinate is calculated from calibration signals measured with 15ms period by four ADSs with 10ms integrating time. There are (from up to down) graphs of the coordinate (μm) and its amplitude spectrum (μm) both in linear scale, the power spectrum (μm^2/Hz) and the spectrum integral both in logarithmic scale. Frequency step in spectra is 0.13Hz, amplitude resolution is 0.15μm (resolution of 16-bit ADC). The spectrum integral in the full band is the OMM resolution. It is about 2 μm, that corresponds to the System resolution (see Fig.3.). This is to have been, because System and OMM have same processing electronics.

Spectral analysis can be used to study low frequency beam vibrations. The graphs on Fig.6 obtained by processing of beam signal from FCPS measured by the same way. This picture illustrates spectral distribution of low frequency beam vibrations. Because of small current, the noise of electronics is comparable with beam signal and the picture is not so informative. But it is possible to assert, that no any spectral peak is there in beam vibrations.

Closed orbit program was used to measure both the orbit and the storage ring dispersion function. Dispersion function is proportional to a difference between two closed orbits measured with different revolution frequencies.

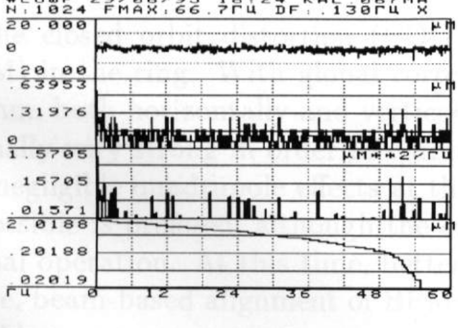

Fig.5. FCPS horizontal spectral resolution .

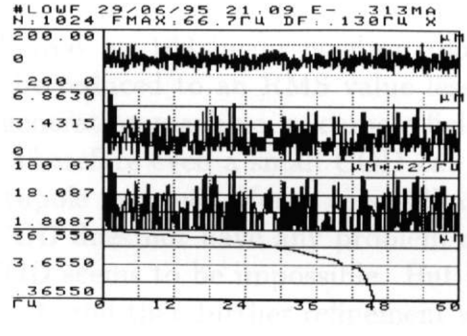

Fig.6. Horizontal beam vibrations.

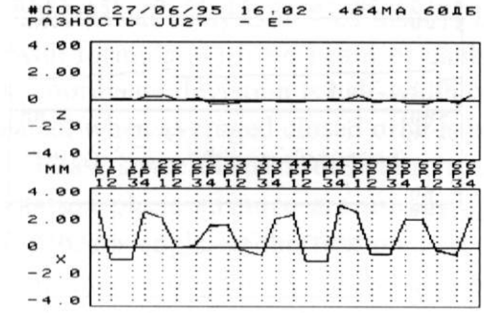

Fig.7. Dispersion function.

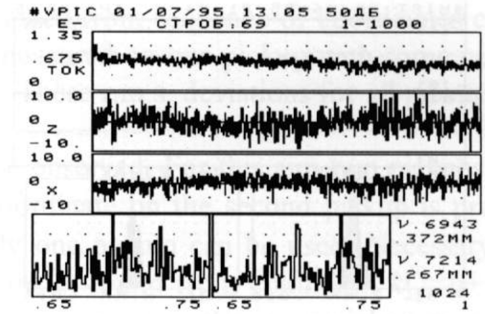

Fig.8. Diagnostics of injected beam.

On Fig.7. such the difference with 0.004% revolution frequency shift, is shown. Orbit values on the lower graph are proportional to dispersion function on the pickups.

An example of injected beam diagnostics is shown on Fig.8. There are (from up to down) injected beam current, vertical and horizontal coordinates during 1000 turn after injection and betatron spectra. Vertical betatron frequency is about 0.69, horizontal one is about 0.72. Betatron spectra are calculated by Fourier analysis of arrays of 1024 turn-by-turn beam position samples, measured by four fast ADCs. Betatron frequencies and amplitudes are calculated using the precise algorithm, described above.

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