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PHYSICS AND TECHNIQUE OF ACCELERATORS

Tune Measurement System of the SKIF Booster

O. V. Belikov[a], E. A. Bekhtenev[a], E. N. Dementev[a], and G. V. Karpov[a, *]

[a] *Budker Institute of Nuclear Physics, Novosibirsk, Russia*

**e-mail: karpov_gen@mail.ru*

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Abstract—Tune measurement system developed in Budker Institute of Nuclear Physics for the Booster of the SKIF project provides fast and accurate measurements of fractional part of betatron tunes during Booster acceleration cycle. Resonance excitation of betatron oscillations with help of radio frequency (RF) pulses feeding to the kiker electrodes is used in the system. The minimal tune measurement time is 1.3 ms, which allows having tunes measurement data for each phase of the Booster accelerating cycle. The system can perform up to 256 measurements during 400 ms time interval of Booster energy ramping. The tune measurement accuracy is better than $0.001f_0$, where f_0 is Booster revolution frequency.

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INTRODUCTION

Booster synchrotron for fours generation synchrotron light source SKIF is presently under construction in BINP, Russia [1]. The Booster main parameters are given in Table 1.

Requirements to Tune measurement system (TMS) for the Booster synchrotron are:

— Time of one measurement has to be less than 3 ms.

— Tune measurements accuracy has to be better than $10^{-3}f_0$.

TMS satisfied to these requirements has been developed and fabricated at BINP. The system includes stripline kicker, stripline BPM, power amplifier and Signal processing electronics (Fig. 1).

Resonance excitation of betatron oscillations with sinusoidal signal feeding to the kiker electrodes is used in the system. Betatron beam oscillations are excited by radio frequency (RF) pulse with the frequency f_e close to $f_B = (2 + \nu_{x,y})f_0$, where f_0 is the revolution frequency, $\nu_{x,y}$ – is the fractional part of the horizontal (vertical) tune (Fig. 2). Duration of the RF pulses t_e is 100–200 μs.

The measurements are possible when the difference between frequency f_e and frequency $(2 + \nu_{x,y})f_0$ does not exceed $(0.01–0.02)f_0$. In this case, the signal of the beam betatron oscillations appears in the stripline BPM electrodes after the end of the exciting RF pulse. Then the signal is transferred to the Signal processing electronics, where it is sampled by ADC and is processed by a Field Programmable Gate Array (FPGA). The result of signal processing are the values of the fractional parts of betatron tunes $\nu_{x,y}$.

SYSTEM DESCRIPTION

The functional diagram of the Tune measurement system is presented in Fig. 3.

The system consists of stripline BPM, stripline Kicker, Signal processing electronics and Beam oscillations Exciting Electronics. The Pickup and Kicker stripline electrodes are mounted at the angle of 45° relative to the horizontal plane. Both stripline ends are connected with BINP-made 50/450°C vacuum-tight feedthrough for SMA plug (Fig. 4). The length of striplines is 450 mm for the kicker and 210 mm for the BPM, which is about λ/4 (λ is the wavelength) at RF frequency of 356.98 MHz.

BPM signals come to Signal processing electronics, where they are processed and fractional parts of the betatron tunes are calculated. Signal processing electronics includes Direct Digital Synthesizer (DDS) where exciting frequency f_e codes are written. Beam Exciting Electronics consists of two 400 W Power Amplifiers, Bridge transformer and four 50 Ohm loads. RF pulses from DDS synthesizer come to one of the Power Amplifiers (PA) inputs. From PA outputs

Table 1. Main parameters of the SKIF Booster

Beam energy injection/extraction	200 MeV/3 GeV
Repetition rate	1 Hz
Revolution frequency f_0	1.888 MHz
RF frequency	356.98 MHz
Betatron tunes: ν_x/ν_y	9.6455/3.4105
Beam charge	0.5–15 nK
Energy ramping time	~400 ms

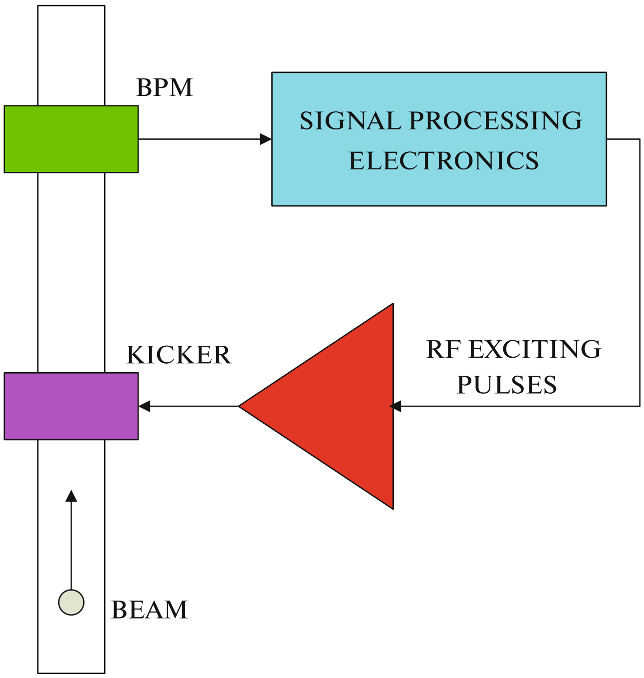

Fig. 1. Structure of the Tune measurement system.

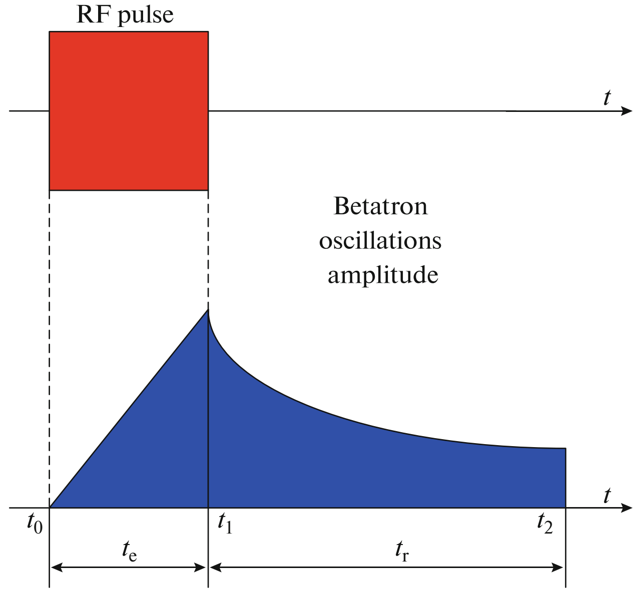

Fig. 2. Excitation of betatron oscillations.

RF pulses with amplitude up to 200 V are distributed to four kicker striplines by Bridge transformer. Such scheme provides selective excitation of horizontal or vertical betatron oscillations in dependence of switch S_1 position.

The Tune measurement system is shown in Fig. 5. The upper module is the Signal processing electronics. Lower of the Signal processing electronics module Power Amplifier is located. Then Power Supply for Power Amplifier is placed. The lower part is crate with transformer bridge and four 400 W 50 Ohm loads.

SIGNAL PROCESSING ELECTRONICS

A functional diagram of the Signal processing electronics is presented in Fig. 6.

The Signal processing electronics consists of 4 identical analog processing channels (A, B, C, D). For the measurements the first harmonics of RF frequency $189F_0$ (356.98 MHz) is used. It is extracted from the signal spectrum with help of SAW filters with bandwidth of 6 MHz. Each analog channel provides gain adjustment in the range 0–30 dB with step of 1 dB, which provides optimal operation in wide range of the beam current.

The signals are sampled by 16-bit ADC with sampling frequency $f_{ADC} = 58f_0 \approx 109.55$ MHz. The sampling frequency for ADCs is generated by the PLL generator with jitter less than 0.5 ps. The digitized signals come to FPGA Cyclon-V 5CSTFD6D5F31I7. where they are processed. Due to frequency folding the signal frequency at the FPGA input is $15f_0$. Digital processing performed by the FPGA includes:

(1) synchronous detecting;

(2) filtering;

(3) calculation of the turn-by-turn data array;

(4) subtraction of the average value (signal of orbit displacement) from the turn-by-turn data array;

(5) multiplication of the array by Hann window;

(6) 2048-points Fast Fourier Transformation (FFT);

(7) calculation of the spectrum center of gravity.

This center of gravity corresponds to the desired fractional part of betatron tune $\nu_{x,y}$. The time required for calculation of one $\nu_{x,y}$ value is ~0.8 ms.

Besides of FPGA the 5CSTFD6D5F31I7 contains ARM processor, where Linux operational system works. In this processor EPICS IOC operates. It controls the BPM electronics and provides link with SKIF control system via 1 Gb Ethernet interface.

Besides of tune measurements Signal processing electronics allows making an usual beam position measurements. BPM electronics occupy one 1U 19" chassis (Fig. 5, up).

MEASUREMENT CYCLE DESCRIPTION

Time diagram of the measurement cycle is represented in Fig. 7.

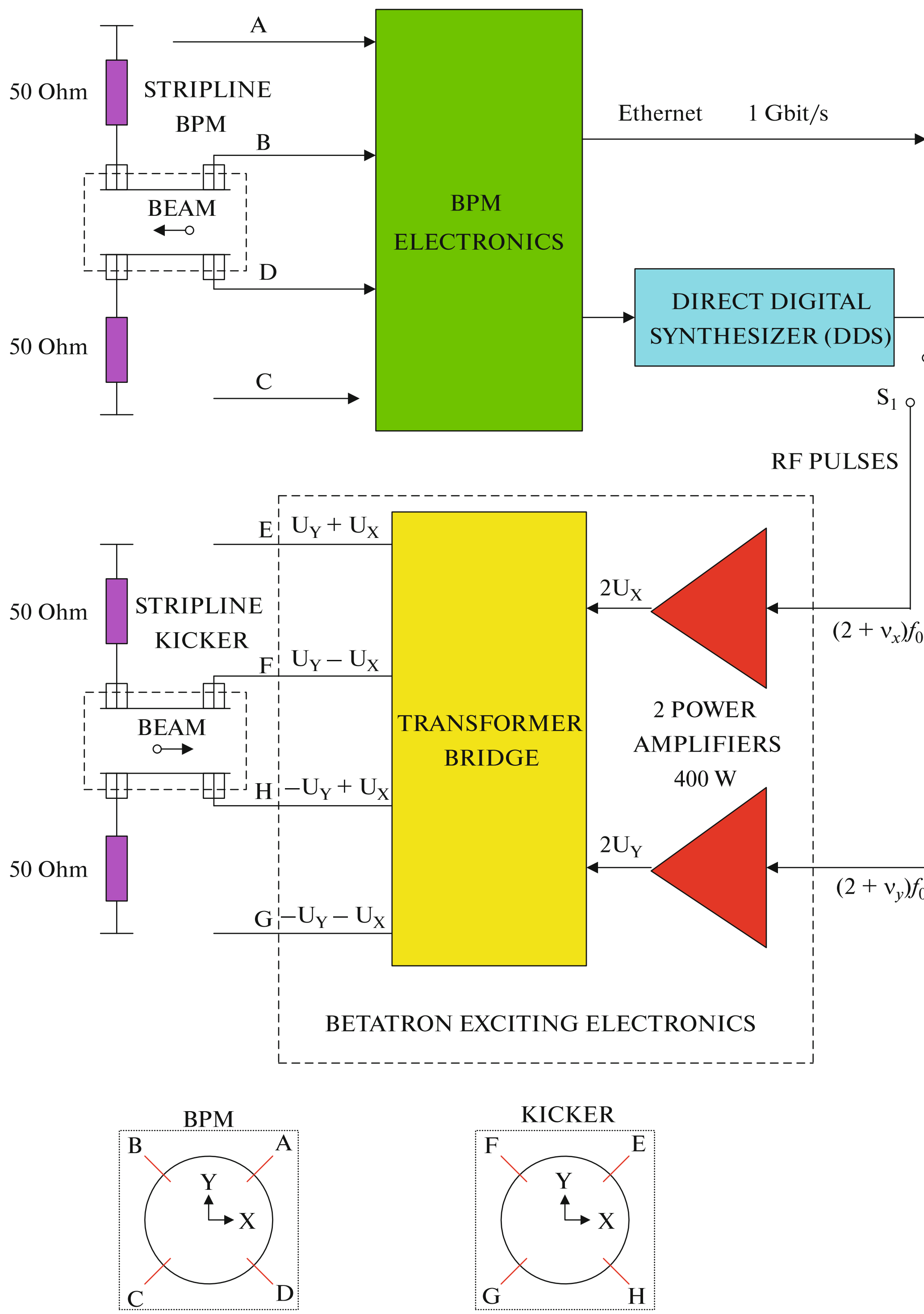

Fig. 3. The functional diagram of the Tune measurement system.

The whole measurement cycle starts from the beam injection to the Booster and consists of N elementary cycles. Each elementary cycle includes 4 stages:

— beam oscillations excitation;

— signal registration;

— signal processing and calculation of $\nu_{x,y}$;

— setting of the new DDS frequency.

The total time of one elementary cycle T_{ec} is less than 1.3 ms. Measurements of ν_x and ν_y are altered from one elementary cycle to another elementary

Fig. 4. The kicker (upper) and BPM (lower).

Fig. 5. Tune measurement system electronics.

cycle. In odd elementary cycles numbers (1, 3, 5, ...) a horizontal betatron tune ν_x is measured, in even elementary cycles numbers (2, 4, 6, ...) a vertical betatron tune ν_y is measured.

The tune measurement is possible when the difference between DDS frequency and frequency $(2 + \nu_{x,y})f_0$ does not exceed $(0.01–0.02)f_0$. In this case, the signal of the beam betatron oscillations appears at the end of the exciting RF pulse. To provide this condition a tracking of the DDS frequency to measured betatron tune is made in the electronics. Before an odd elementary cycle m the DDS frequency F_m equaled to $(2 + \nu_x)f_0$ is set, where ν_x is horizontal betatron tune measured during elementary cycle m-2. Before an even elementary cycle n the DDS frequency F_n equaled to $(2 + \nu_y)f_0$ is set, where ν_y is vertical betatron tune measured during elementary cycle $n - 2$. It is important to set correct DDS frequency values for two first elementary cycles with nos. 1, 2. Residual beam oscillations right after beam injection to the Booster are used for this purpose. Signal spectrum of these oscillations gives as horizontal as vertical betatron tune values.

ELECTRONICS TESTING RESULTS

Made at BINP TMS electronics had been tested at Lab test stand. Scheme of Lab test of the Signal processing electronics is presented in Fig. 8. Two sinusoidal signal generators and one pulse generator are used in this test. One of generators (Rohde&Schwarz SMB 100A signal generator) generates sinusoidal signal of RF frequency ~356.98 MHz with amplitude modulation. The second generator (Tetronix AFG3102) generates amplitude modulation frequency F_{MOD}, which comes to modulation input of the first generator. This frequency is changing linearly in the range 50–

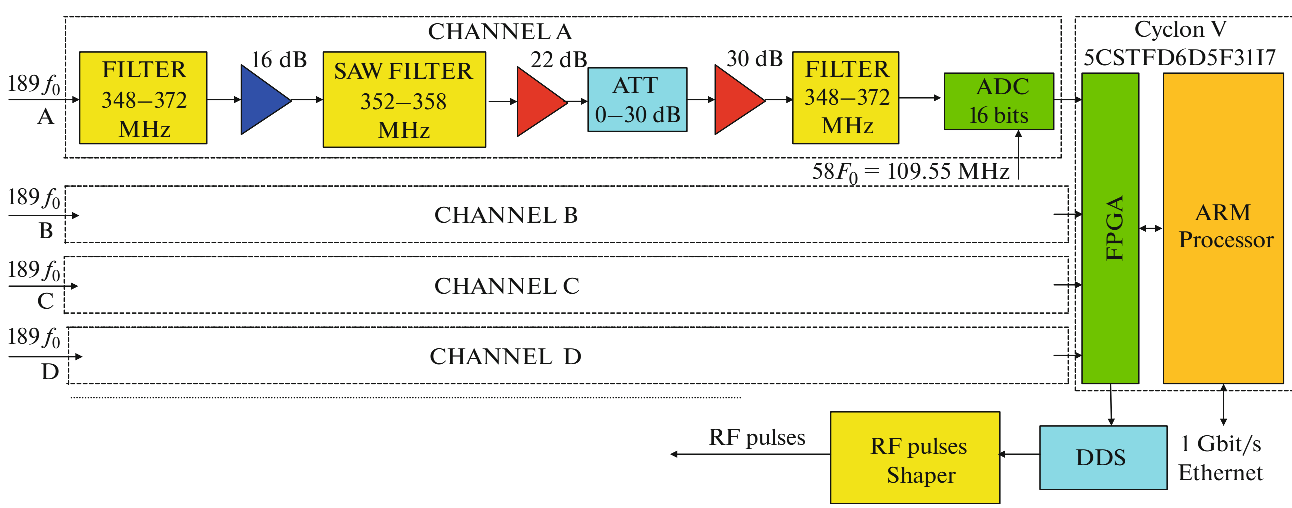

Fig. 6. Functional diagram of the Signal processing electronics.

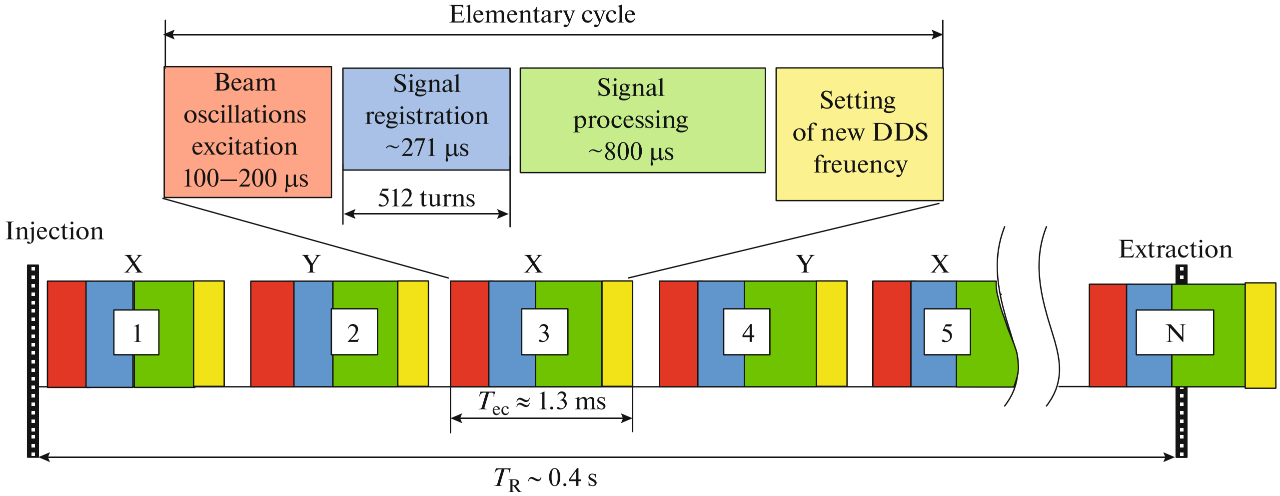

Fig. 7. Time diagram of the whole measurement cycle.

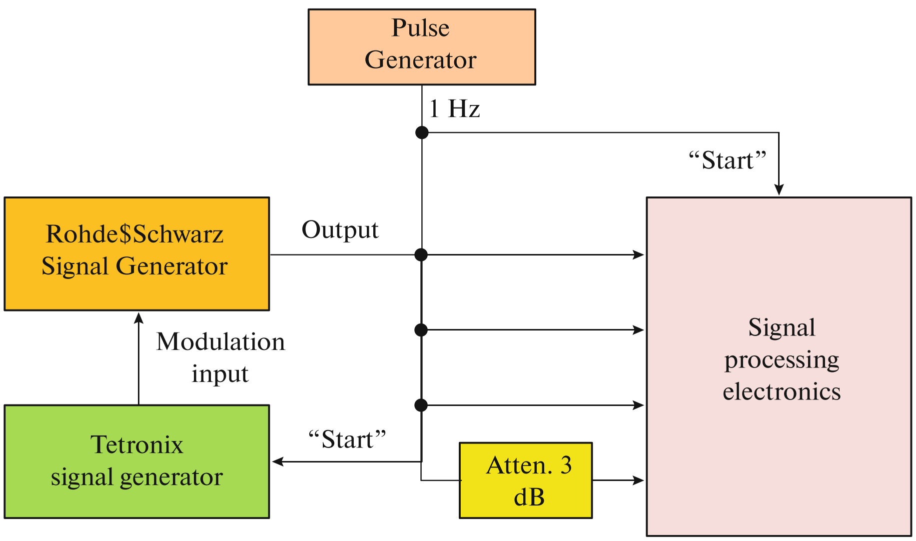

Fig. 8. Scheme of Lab test of Signal processing electronics.

220 kHz (0.026–0.116)f_0 during the time 400 ms after "Start" pulse coming from Pulse generator. The same pulse comes to the Signal processing electronics starting the measurement cycle. Signal processing electronics measure modulation frequency F_{MEAS}. The results of the measurements are represented in Fig. 9.

Difference between two frequencies: F_{MOD} and F_{MEAS} gives the measurement error. This test gives tune measurement error does not exceed $10^{-3}f_0$.

TUNE MEASUREMENT WITH BOOSTER BPM SYSTEM

Booster BPM system consists of 37 BPMs with electronics. Developed in BINP BPM electronics allows performing turn-by-turn measurements during the whole cycle of the beam energy ramping. After each Booster operation cycle beam position values for each turn in the time between beam injection and extraction are contained in the BPM electronics memory. Measurement elementary cycles are tied in

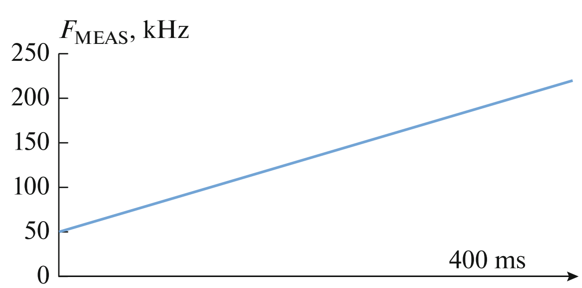

Fig. 9. Measurements results during sweeping of the modulation frequency F_{MOD} in the range 50–220 kHz.

the time to the synchronization signals "10 kHz". This signal is inside the every BPM electronics module. Therefore, an each BPM electronics module has an information about the time of each elementary cycle. Reading of defined arrays from turn-by-turn beam position memory we can get tune measurement array for whole time interval between injection and extraction for each of 37 BPM electronics modules. It gives a possibility to measure not only betatron tunes but Booster beta-function too.

SUMMARY

Developed and fabricated at BINP Tune Measurement System satisfies all requirements of SKIF Booster. It allows performing of the tune measurements in each acceleration cycle phase with accuracy better than $10^{-3}f_0$. It is especially important for the Booster commissioning. At present all TMS components have been manufactured and tested. It is planned, in 2024 yr the system will be commissioned at Booster.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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