

DEVELOPMENT OF TRANSVERSE BEAM POSITION AND SHAPE MONITOR FOR INTEGRABLE OPTICS TEST ACCELERATOR BASED ON PHOTOMULTIPLIER TUBE ARRAY

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Abstract: The report is dedicated to development and testing of a BPSM (Beam Position and Shape Monitor) for IOTA (Integrable Optics Test Accelerator) during summer internship at Fermi National Accelerator Laboratory (*Fermilab*). BPSM is based on 64-channel Photomultiplier tube (PMT) array *Hamamatsu H7546B*. Design with 8 of 64 channels is described in detail. Response, sensitivity and response speed test results are provided. Aspects of BPSM's signal digitization and future development and commissioning are discussed.

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OCIS codes: (040.0040) Detectors; (040.1240) Arrays; (040.5250) Photomultipliers; (120.4290) Nondestructive Testing; (320.7080) Ultrafast Devices; (340.6720) Synchrotron Radiation.

References and links

1. M. Gasior, R. Jones, T. Lefevre, H. Schmickler, K. Wittenburg, "Introduction to Beam Instrumentation and Diagnostics," CERN Yellow Report **CERN-2014-009**, 23–60 (2014).
2. M. Church, "Design of the Advanced Superconducting Test Accelerator", http://asta.fnal.gov/files/ASTA_technical_description.pdf.
3. A. Valishev, "IOTA – A Brief Parametric Profile," presented at the Focused Workshop on Scientific Opportunities in IOTA, Batavia, IL 60510, USA, 1 April. 2015.
4. A. H. Lumpkin, "Imaging Techniques for Transverse Beam-Profile/Size Monitors," Proceedings of BIW2012, Newport News, VA USA, 2012.
5. A. Hofmann, *Diagnostics with Synchrotron Radiation* (CERN, 2005).
6. I. N. Nesterenko, E. A. Perevedentsev, A. A. Valishev, "Coherent synchrotron beam-beam modes: Experiment and simulation," *Phys. Rev. E* **65**, 056502 (2002).
7. HAMAMATSU PHOTONICS K. K., *Photomultiplier tubes* (2007), Chap. 14.
8. Vertilon Company "Product sheet: SIB164B PMT Sensor Interface Board H12428 Series", <http://www.vertilon.com/pdf/PS2739.pdf>.
9. Hamamatsu Company "Multianode Photomultiplier Tube assembly H7546A, H7546B", https://www.hamamatsu.com/resources/pdf/etd/H7546A_H7546B_TPMH1240E.pdf.

1. Introduction

Beam instrumentation is an integral part of modern accelerators. These devices are specially designed for observation of a particle beam. They combine accelerator physics with optics, electronics, software engineering and several other related fields. Beam instrumentation technologies enable tuning, operating and improving beam lines in accelerators. Main types of beam instrumentation can be distinguished: beam position monitors (BPMs), beam intensity and current monitors, transverse beam diagnostics tools, longitudinal profile detectors and beam loss monitors [1]. Nowadays, advanced accelerator technologies extend beyond the limits of the fundamental research and reached more practical fields for applications in medicine, chemistry and biology. Modern world needs accelerators to save people's life and explore the nature. This leads to creation of new stable accelerators with unique parameters.

This report is dedicated to the development of transverse beam position and shape monitor

(BPSM) for a new Integrable Optics Test Accelerator at FAST/IOTA facility at Fermi National Accelerator Laboratory (Fermilab) [2]. Currently, FAST 50 MeV electron photo injector, based on existing linear accelerator is working. The schematic of FAST/IOTA facility is shown on the fig. 1. It consists of the IOTA storage ring, electron and proton injectors and special equipment for advanced accelerator experiments. FAST/IOTA will be capable of generating electron beams up to 150 MeV and proton beams up to 2.5 MeV. IOTA is now under the construction and is planned to be commissioned in FY 2019. IOTA is a 40m circumference flexible low loss storage ring for accelerated particles. BPSM is planned to be installed on 8 bending magnets on the ring (fig. 2). IOTA has several unique features: the ability to operate with both electrons and photons, large aperture, significant flexibility of the lattice, precise control of optics quality and stability, and an optional set up for very high intensity operation (with protons). The main advantage of this ring is that it is based on conventional circular accelerator technology (RF cavities, magnets) and provides a cost-effective construction and operation solution [3]. FAST/IOTA will be capable of testing new accelerator technologies and carrying out transformative beam dynamics experiments, such as: optical stochastic cooling of particle beams and exploration of the quantum wave function of a single electron, integrable optics with a non-linear magnets and electron lenses, space-charge compensation with electron lenses and electron columns, crystal channel radiation and laser-beam interactions.

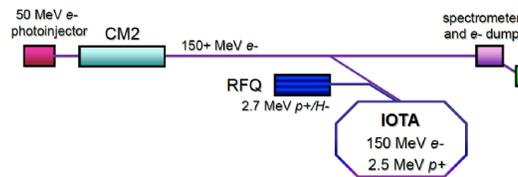


Fig. 1. Fast/IOTA facility at Fermilab

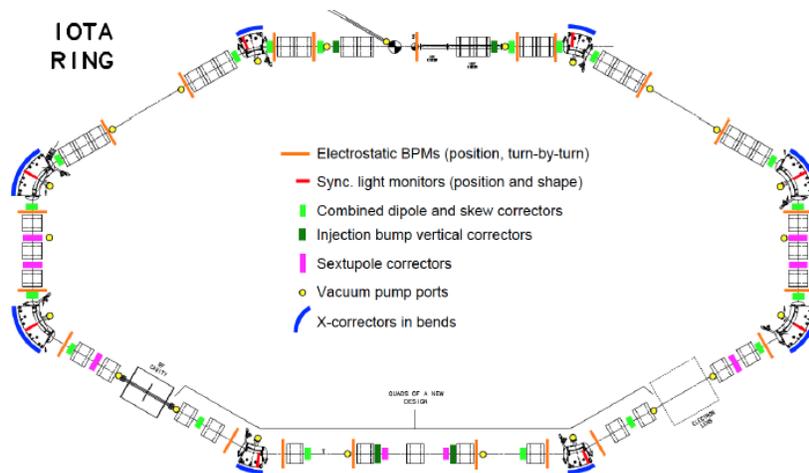


Fig. 2. IOTA storage ring. BPSM position corresponds to red stripes - synchrotron light monitors (position and shape).

Observation of the transverse beam motion is essential for the efficient operation of any circular accelerator. There are destructive and non-destructive techniques for performing such

measurements, such as: scintillators, optical transition radiation (OTR) screens, luminescence monitors, synchrotron radiation monitors, etc [1]. The first two techniques are currently used in the FAST photo injector: OTR screen for the longitudinal profile detection with a streak camera [4] and luminescence monitors with YAG:Ce crystals for the transverse beam shape imaging. The streak camera technique for the longitudinal profile detection is based on RF manipulation, where the longitudinal beam profile is encoded into the modulation of its transverse spatial profile. These all are the destructive kind of techniques, but they are acceptable for use in the photo injector, because there the losses can be controlled and taken into account during beam injection.

A synchrotron radiation detection is a totally non-destructive technique of measurement various beam properties [5]. This technique was chosen for development of BSPM in this project. The technology enables beam measurements without any disturbance of the beam, which is essential for the storage rings. Spectral characteristics, polarization and power of the synchrotron radiation are strongly dependent on the energy of particles, a bending radius of magnets and a lattice configuration. The synchrotron light is highly collimated in the tangent direction to the beam trajectory and has a broad frequency spectrum. Imaging of the synchrotron light with a conventional optics enables the transverse beam dimensions' measurements. Being a non-destructive measurement, this method of observation enables analysis of a long term beam evolution. The synchrotron radiation parameters were estimated in order to start BSPM design. In the calculations, the green wavelengths of the spectrum were considered to be acquired by detector, using a filter for $\lambda = 533 \pm 20nm$. The synchrotron radiation has optimal intensity and spectral bandwidth in this wavelength range. The main parameters of IOTA and results of estimation are the following:

- Time of one turn in IOTA ring = $\sim 133ns$ (7.5 MHz),
- Bunch length = 12 cm ($\sim 4ns$),
- Intensity of OSR for $2 \cdot 10^9$ 150 MeV $e^- \sim 10^5$ photons.

The proposal is to make the BSPM based on Photomultiplier tube (PMT) array. A PMT is a common device in accelerator physics [6]. It is used to detect fast (in the range of ns) events in accelerator experiments. The working principle of PMT is the following: when a charge particle passes through a scintillator, a light flash is given off in accordance with a particle energy. Detection of this light makes possible measurement of the energy, speed and direction of charged particle. There are several particle detection methods, which uses PMTs: hodoscopes, Time of Flight (TOF) counters, calorimeters, Cherenkov counters, etc [7]. Such techniques using PMTs are absolutely essential in high-energy physics research.

2. BSPM design

PMT array, used in the project is *Hamamatsu H7546B* [9]. This device has required parameters needed for detection of synchrotron radiation: sensitivity in the visible range (300-650 nm), which covers most part of synchrotron radiation spectra, peak sensitivity of 80 mA/W, gain up to 3 million with high voltage (HV) supply of 1 kV and response time in a range of 1 ns and transit time of 12 ns, which is suitable for turn by turn beam detection in IOTA ring. In addition, the use of this array can give a reasonable resolution for beam shape measurements. PMT array has 64 2x2 mm high speed response and low cross-talk anodes. PMT requires a High Voltage (HV) supply and connectors for output channels. The detailed schematic of detector design is shown on the fig. 3. It consists of a *SIB164B H12428* series PMT interface board by Vertilon Company and connection board, which enables to have BNC outputs for oscilloscope. The interface board has separate HV output and two SIB ribbon cables, 32 channels each. The board has two trigger

outputs for a digitizing system and some other data acquisition opportunities, which could be useful for future implementations of the detector [8]. In order to be able to operate with usual BNC cables for oscilloscope readout, the connection board was used. It has connections for two SIB cables on one side and 64 places for soldering wires for any output needed. In the current design only 8 channels are connected. This relevant for tests of the PMT array.

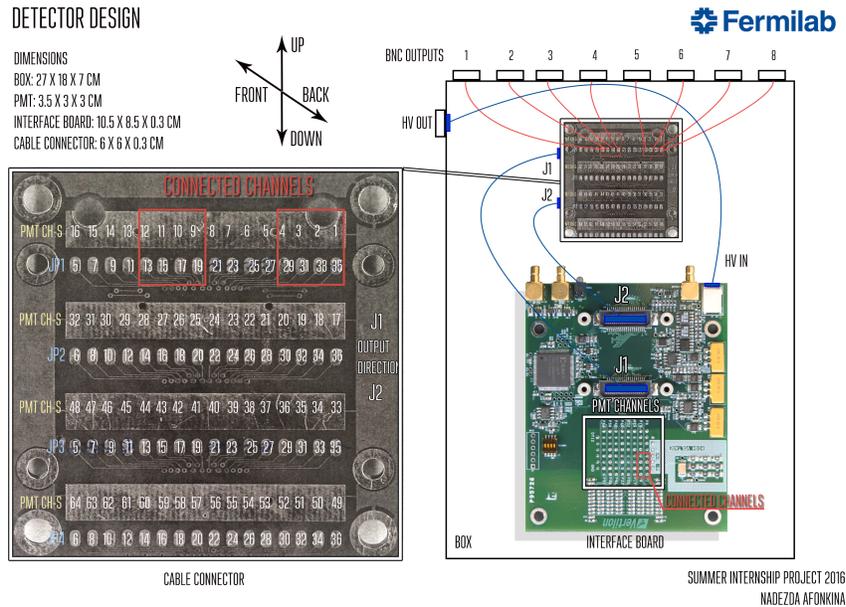


Fig. 3. BPSM design.

3. Tests

3.1. LED test

The BPSM test with LED was performed in order to verify the operational performance of the device with an easy and safe in operation light source, which characteristics were close to the synchrotron radiation in IOTA ring in terms of wavelength range and frequency. The goal of this test was to have the first idea of BPSM response, using possible gains and beam shapes.

3.1.1. Experimental Setup

In order to test the BPSM's response, pulsed green LED light was used. The light source had the following properties: $f = 6$ MHz, pulse length = $5 \mu s$, $\lambda = 520$ nm, peak intensity = 3.1 V. The experimental setup is shown on the fig. 4. The setup consists of 2 mirrors for aligning the optical axis, 2 diaphragms for limiting the aperture and enabling handy control of the intensity or the beam size, and 2 lenses: L1 – collimation lens and L2 – focusing lens ($f = 10$ mm). The area in front of BPSM is covered with an enclosure box to limit the influence of a background light on the measurements. Two levels of the Optical density (OD) filters are used to decrease the light intensity from the LED as well as the background light: one OD filter is placed just right after PMT array sensitive surface (OD1.1) and another one – at the output of enclosure box (OD 1). Total attenuation is then $10^{-2.1}$. Apart usage of the attenuation filters to decrease light intensity on the detector, the experiment was performed in a dark room to prevent saturation of PMT array, which is sensitive to light.

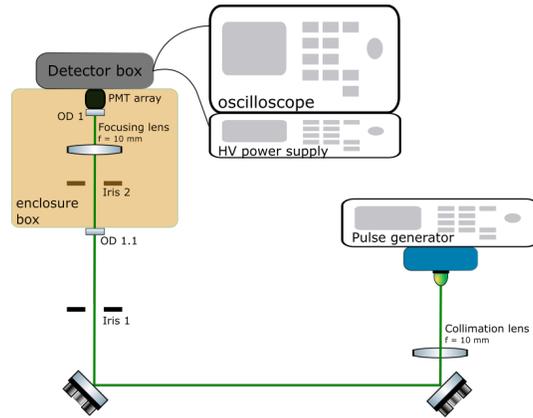


Fig. 4. LED test, experimental setup.

3.1.2. LED test results

As a preliminary step before the test, the numerical estimation of the experimental results was performed. Final result of the estimation was the voltage on PMT channel from the LED light source, propagated through the optical setup. The most important in the estimation were definitions of uncertainties. Thus, 20% possible uncertainties on the LED efficiency and current were considered, due to the absence of precise information about it, 10% uncertainty in spectral response of BPSM due to absence of precise information about the LED wavelength and as a consequence, BPSM sensitivity to its wavelength, and 20% of uncertainty in definition of the optical loss due to propagation of light through the optical system. The expected voltage was $V = 1.1 - 2.6V$.

The set of measurements with varying gain voltage and three different beam shape were done. The beam shapes are shown on the fig. 5. The variation of intensity was achieved by changing the beam size with irises. These beam shapes are relevant to draw conclusion on BPSM performance.

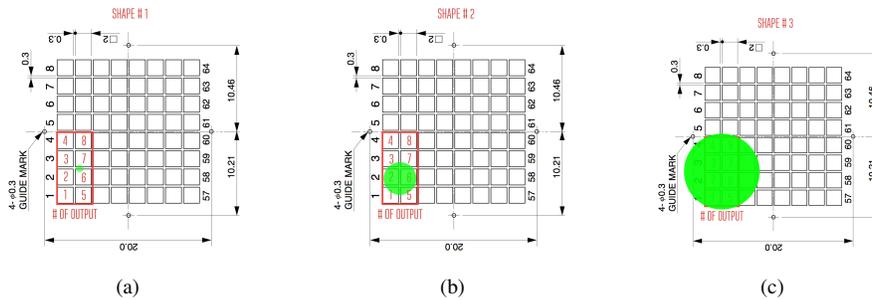


Fig. 5. Three shapes for LED test: (a) – low intensity, $d = 1-2$ mm; (b) – medium intensity, $d = 4$ mm; (c) – high intensity, $d = 8$ mm.

Using the results from measurements of PMT response from the shape # 3 (fig.5(c)), the preliminary numerical estimations can be compared to the experimental values. Intensity distribution over BPSM channels is shown on the fig. 6. The example of PMT response from the shape #3, obtained with the oscilloscope is shown on the fig. 6(b). It was easy to define an optimal gain for measurements. If the gain was insufficient – oscilloscope did not trigger the signal, if over gain occur – the signal amplitude was not increasing along with the gain anymore, as it had been predicted in PMT array characteristics [9], but the noise has been increasing. For

the shape #3, the optimal gain voltage is 600 V. The calculations of the signal from the LED with values of the channels' responses were done. In these calculations the uncertainties on the spot diameter measurement and voltage measurement were considered. The calculations using experimental results (0.8 – 1.4V) agreed with estimations obtained before the experiment, with some divergence. Uncertainty intervals of experiment and estimation crosses at $V = 1.1 - 1.4V$.

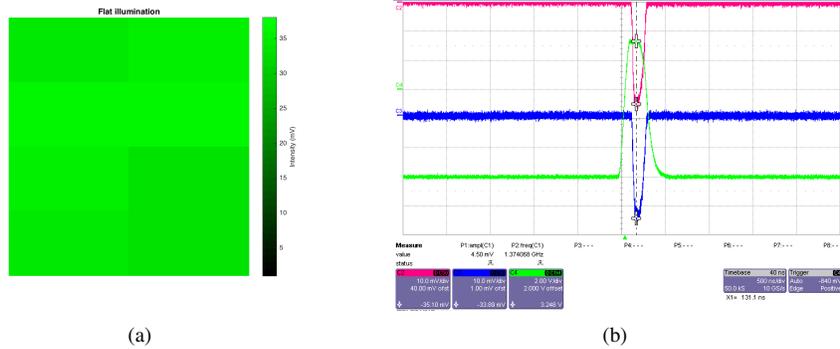


Fig. 6. (a) – flat illumination response from 8 channels of BPSM; (b) – oscilloscope response: signals from channels #2 (pink) and #6 (blue) with gain voltage 600 V are shown as well as the LED signal (green).

Measurements of the shape #2 (fig. 5(b)) showed how signal varies with the gain. The intensity distributions were measured with the gain voltages 700 and 800 V. The results are shown on the fig.7. The expected gain $\times 3$ was observed. In addition, this experiment proved, that it is possible to observe the beam shape with BPSM. The results were satisfactory even with 8 channels, so when operating with 64 channels, the reasonable resolution (2 mm) can be achieved for the future beam shape measurements on IOTA. The measurements of the shape #1 (fig. 5(a)) with lowest intensity showed expected response from only 1 channel with the gain 900 V.

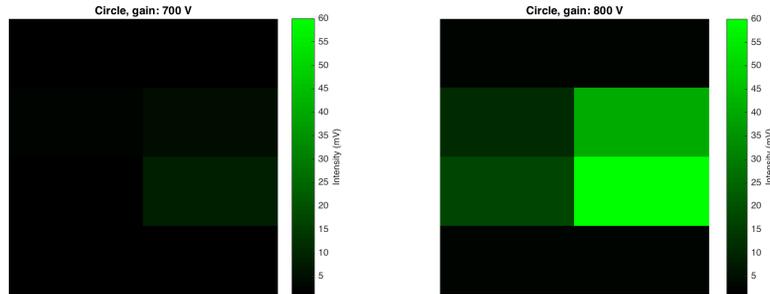


Fig. 7. Intensity distribution from the shape #2 (fig. 5(b)) with 2 different gain voltages.

3.2. OTR test

Next tests of BPSM were performed with a real radiation from accelerated electron beam at the FAST photo injector. The aim of this experiment is to measure the response time of BPSM on a picosecond pulse, which is a Dirac pulse for the device and deduce requirements for digitization of its signals.

The actual configuration of the photo injector is shown on the fig.8. FAST photo injector consists of: RF gun – photo cathode for the electron generation with the photo effect, high energy

laser system to heat the cathode, Faraday cup (FC) – absorber for measuring the beam shape and dark current right after the injection, two capture cavities CC1 and CC2, controlled by the low level RF (LLRF) – set of programmed feedback loops, modulators (MOD) at 1.3 GHz and klystrons (KLY) – vacuum tube amplifiers, that accelerate electrons at the modulator frequency and send power to the cavities. Apart this, there are sets of FODO (focusing-defocusing magnets) to control the shape of the beam during the accelerator's path.

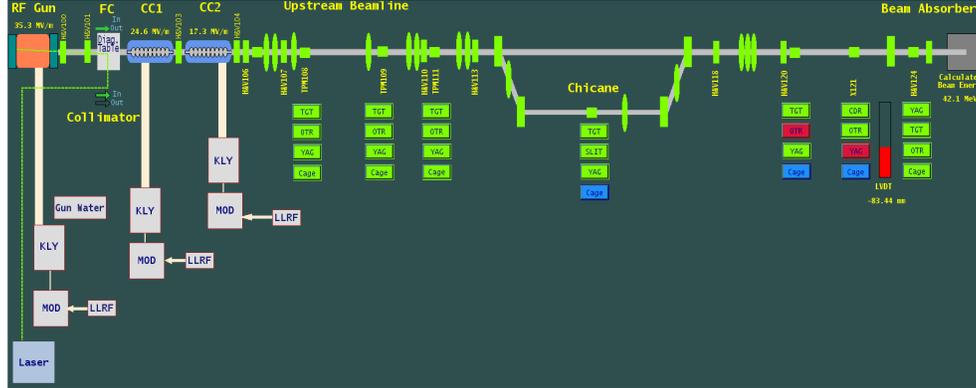


Fig. 8. FAST photo injector schematic. FC – Faraday cup, CC – capture cavity, KLY – klystron, LLRF – low level radio frequency, MOD – modulator. TGT, OTR, YAG, Cage, SLIT, CDR – different screens to monitor and control the beam. Ellipses – quadrupoles, rectangles – dipoles, squares – BPMs

3.2.1. Experimental setup

X121 station on FAST is designed to support the transverse and longitudinal beam profiling. There is an actuator with a stepper motor control for selecting between YAG:Ce screen $100 \mu\text{m}$ and Al-coated $3 \cdot 10^3 \text{ Si}$ screen, that generates optical transition radiation (OTR), coherent transition radiation (CTR) and coherent diffraction radiation (CDR). The YAG:Ce is used to obtain the transverse beam profile and is viewed by a standard Prosilica CCD camera. The scintillation process is slow compared to OTR ($\sim 80\text{ns}$). The YAG:Ce screen is very useful for the alignment - it gives the transverse beam size and position any time it is needed during experiments. An all-mirror optical transport is used to bring OTR to the "streaky hut" - a tight optical enclosure outside the tunnel of accelerator. In this enclosure, the streak camera for the longitudinal beam profile measurements is located. The BPSM was placed in the same box to acquire the OTR, using the flipping mirror in front of the streak camera (fig. 9).

OTR radiation is generated when a charged-particle beam transits the interface between two different media. In our case, the interface is between vacuum and thin Al foil. OTR generation is a femtosecond process (10 fs) and has conversion efficiency of approximately 10^7 photons/nC or 1 photon/1000 incident electrons in the visible range (400-700 nm) [4]. The OTR properties are similar to OSR in some aspects. Both type of radiation is broadband in the visible range and prompt conversion mechanism for beam characterization. From the schematic of experiment, it can be seen, that cameras are acquiring backward OTR radiation, which is emitted at 90° to the beam direction because the mirror is located at 45° .

During the experiment, the electron beam was running at 42 MeV. Three pulses at 3 MHz were set. The beam charge was 320 pC/pulse. Although there was a possibility to align OSR from a chicane dipole to BPSM to test its final purpose for IOTA usage, the decision was made to acquire OTR for the following reasons: a) OTR was already aligned for the streak camera experiment; b) it has brighter intensity compared to OSR at the beam energies, available at the photo injector; c)

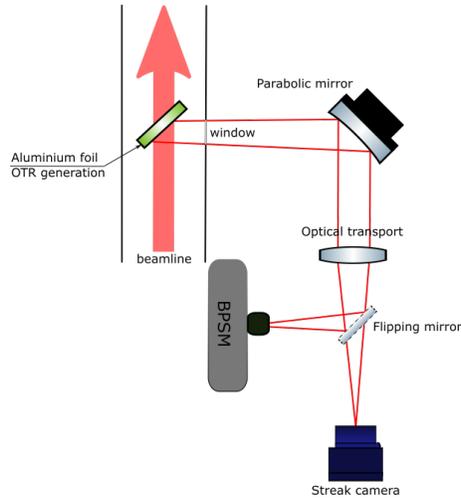


Fig. 9. Experimental setup for OTR test in "streaky hut".

streak camera measures a pulse length, which is also useful information for the experiment.

3.2.2. OTR test results

This test was a the qualitative analysis of BPSM. The quantitative analysis was impossible in this case, because the amount of light that was reaching the surface of detector, could not be estimated. The longitudinal length of the pulses, that were observed by BPSM, was measured with the streak camera: $t = 4.8ps$. The BPSM response from 3^{rd} and 7^{th} channels with the gain 900 V is shown on the fig. 10. Expected $\sim 330ns$ (3MHz) spacing between pulses was observed. This is the evidence, that this was a signal from the beam. The next step was to define the length of BPSM response from each pulse. The value, obtained with the oscilloscope is $t = 7.25ns$. The main result of this experiment is a proof, that an integrator is needed to digitize signals from the detector.

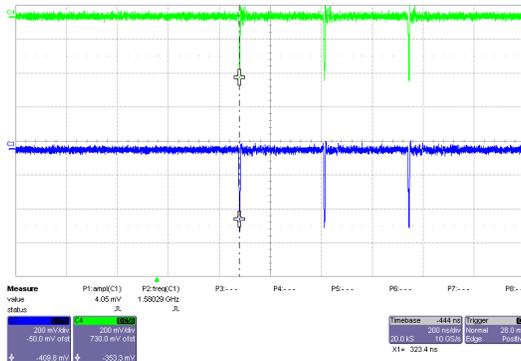


Fig. 10. The BPSM response from 3^{rd} and 7^{th} channels with the gain 900 V.

3.3. Green laser test

The new setup with a green laser was supposed to simulate a short OTR pulse to prepare the digitizing system for a further utilization of BPSM and test the device in new conditions.

3.3.1. Experimental setup

The experimental setup was built in the laser lab, where the drive laser for the photo injection is operating. The schematic of the system is shown on the fig. 8. The class IV laser for the photo injector is IR Nd:YLF (1054nm). The IR light is doubled with BBO nonlinear crystal to 527 nm (green). Both IR and green pulses are 4 ps long and have pulse energy 50 μJ and 25 μJ respectively, because BBO crystal's efficiency is 50%. The goal of the setup is to acquire 527 nm green light from the mirror without any disturbance of the laser operation. BPSM signals were digitized with 125 MHz digitizer, available in the laboratory.

30 pulses at 3 MHz were sent to the surface of the detector. OD 4 filter was limiting the intensity of the incoming light. The averaged intensities over 30 pulses from 8 digitized BPSM signals from the laser spot of 500 μm , placed on 7th channel, with the gains 600 V and 700 V, are shown on the fig. 11. The example of the digitized signals from 7th channel, shown separately (fig.12) shows, that 4 picosecond pulse can be digitized with 125 MHz digitizer in an under-sampling condition. In order to digitize signals properly, Shannon condition of sampling should be satisfied ($f_{\text{digitizer}} > 2f_{\text{signal}}$). In our case, Shannon condition is violated, because $f_{\text{digitizer}} \approx f_{\text{signal}}$.

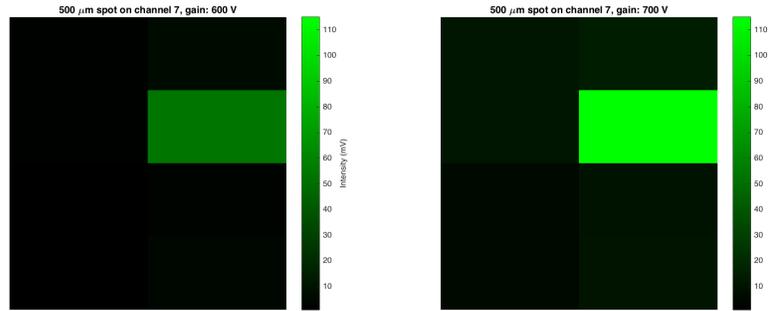


Fig. 11. 8 digitized BPSM signals from a laser spot of 500 μm , focused on 7th channel, with the gains 600 V and 700 V

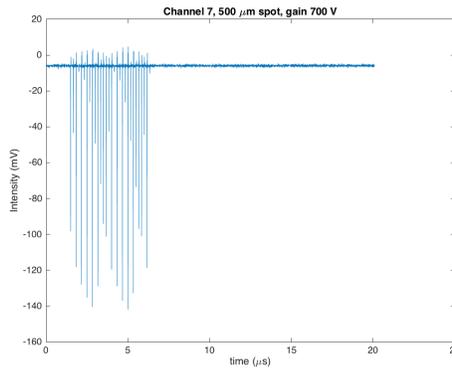


Fig. 12. Example of undersampling. Digitized signal from 7th channel

The experience in performing measurements with BPSM, leads to the set of requirements, that should be satisfied while operating the device. These requirements considered to be the main

results of the green laser experiment.

Requirements for future utilization of BPSM:

1. Device should be isolated from the background noise in order to avoid the saturation of BPSM and loss of useful signal.
2. Before the start of BPSM operation, optimal combination of optical density filters and gain voltage should be chosen. For this purpose, the intensity of the light source should be estimated in advance.
3. Depending on the properties of the light source, proper sampling rate should be used. The sampling rate should satisfy Shannon condition, mentioned above. The integrator should be built and utilized if needed.
4. Optical imaging system should be designed and used when utilizing BPSM on IOTA ring. In order to have information about the shape of the beam, light spot should cover 4-8 channels.
5. In order to operate with all 64 channel of PMT array of BPSM, the new device box should be designed considering a large amount of wires.

3.4. Conclusion

During the summer internship in Fermilab, a new device was designed and built. The device has a function to measure transverse position and shape of the accelerated electron beam in the developing IOTA storage ring at FAST/IOTA facility. The principle of such measurements is acquiring synchrotron radiation to characterize the beam. The device was named BPSM – Beam Position and Shape Monitor. Due to the fact, that IOTA will be commissioned only in 2019, the device was tested using 3 different light sources with the properties, closest to future experiments on IOTA. The following results were obtained in accordance with the objectives of the research:

- all possible operating settings of the BPSM were tested,
- the performance capability of the device was proved,
- the requirements for future utilization of BPSM were formulated.

The results of the project can be used to finalize the design of BPSM and digitizing system for future commissioning of the device. The BPSM usage is not limited by high energy physics experiment. Development of the devices, based on PMT arrays is promising in various experiments, connected to measurements of fast events in experimental physics. The device can be also used for optical laboratory purposes. The potential applications include:

- optical alignment of the setup with a pulsed light sources
- intensity measurements of any short light pulses in the BPSM sensitivity range
- distortion and shift detection of the beam along propagation through the optical setup
- measurement of the light pulses up to 140 MHz in time domain