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Beam Loss Monitor for AREAL electron beam based on PIN photodiodes

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We have developed and tested electron fluxes measurement system based on PIN-photodiodes for the 5 MeV electron beam of the AREAL. The system can be further upgrade to a Beam Loss Monitor (BLM) to measure beam losses from the vacuum chamber of the undulator SASE100.
The method of using PIN photodiodes as a BLM is based on the effect of electron-hole pair formation when particles pass through the matter. PIN photodiodes are distinguished by the fact that they contain a thick enough (up to several hundred micrometers) locking layer, on which there is a significant transfer of energy of a passing particle to this layer.
The electron-matter interaction processes were calculated using the PCLab program.
Preliminary calculations were done for various angles of electron flight.
The calculations showed that the system is capable of registering beam losses and monitoring them.

The AREAL accelerator upgrade program is based on increasing the energy of the electron beam to 20(50) MeV and includes the development of a terahertz radiation source based on the SASE100 undulator:
magnetic system period of 27.3 mm and a length of 4.4922 m, alternating magnetic field of 0.47 T in a gap of 12 mm in the vertical direction. Al vacuum chamber cross-section 15 mm x 20 mm, thickness 2 mm

Undulator SASE100. Space for detectors 1-2 mm.

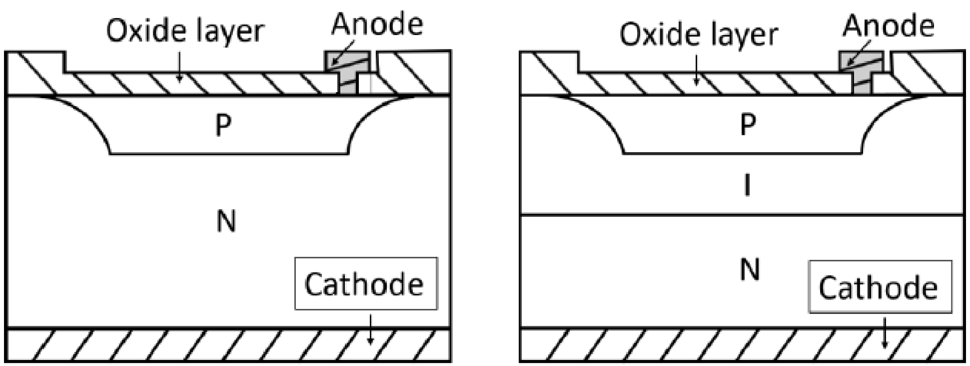
Beam loss monitors

Low space for detectors limits the choice of possible methods for beam loss monitoring practically to two methods: optical fibers, or compact PIN photodiodes.

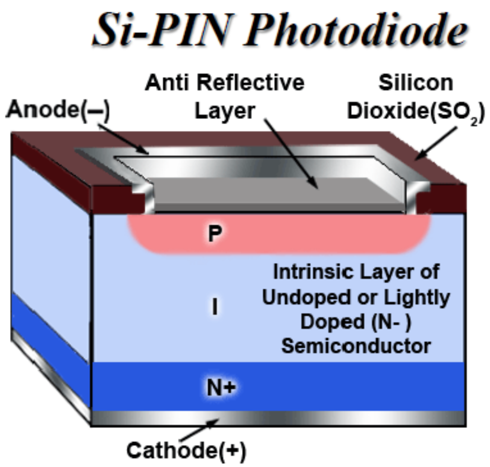
Optical fibers:
Radiation clouding of the fiber, or (at low irradiation intensities and high energies of detected particles) the measurement of Cherenkov photons generated when particles pass through the fiber.
Requires rapid measurements of rather small signals (spatial resolution of the order of 20 cm requires measurements in the region of 1 ns.
Sensitivity of the optical fiber decreases with prolonged irradiation of the fiber

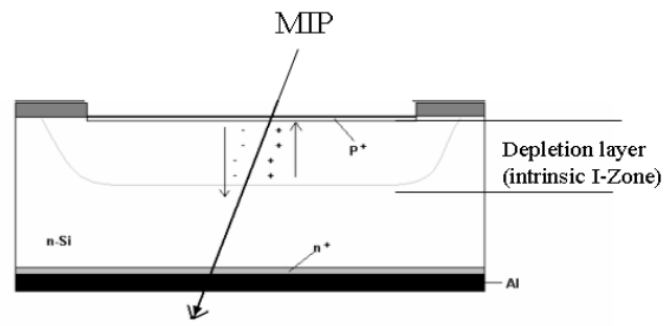
Photodiode as an ionization chamber

PN and PIN diodes difference



(a) PN Silicon photodiode (b) PIN Silicon photodiode

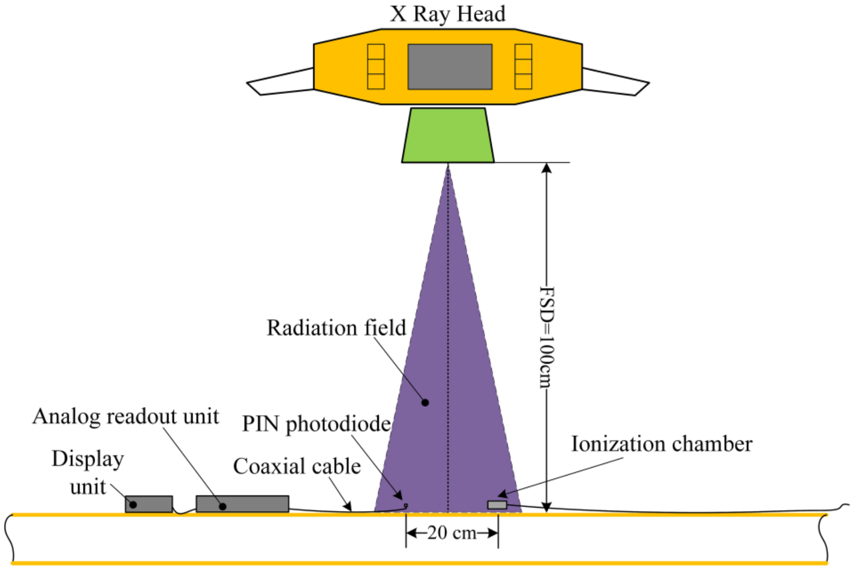




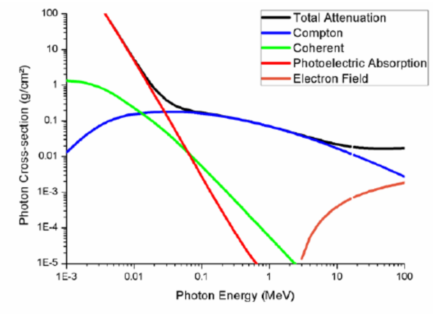
PIN photodiode as a solid-state ionization chamber: signal creation in a diode by a MIP (minimum ionizing particle).

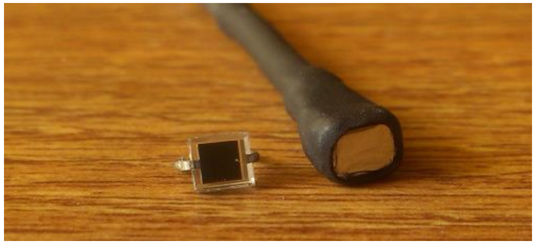
PIN Photodiode as a photon detector

[Sh. Taniguci, 2004] Si PIN photodiodes have been used as synchrotron radiation (SR) fluence monitor (KEK-PF and SPring-8, 10^{11} ph/sec and more, 15-20 keV



[M. Nazififard, RSI, 2016] low-cost pin photodiode dosimetry system for diagnostic radiology



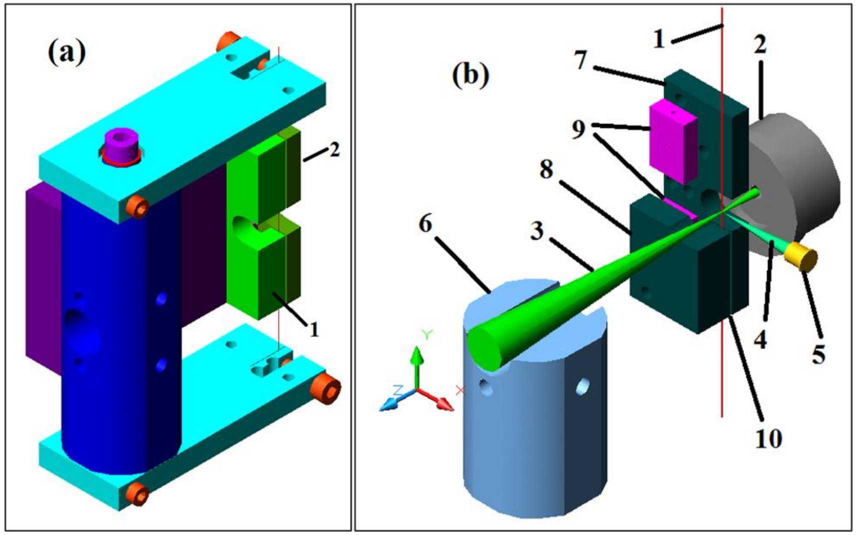


[F.J. Ramırez-Jimenez, NIMA, 2003] PIN diode-preamplifier set for the measurement of low-energy gamma- and X-rays

Beam loss monitors

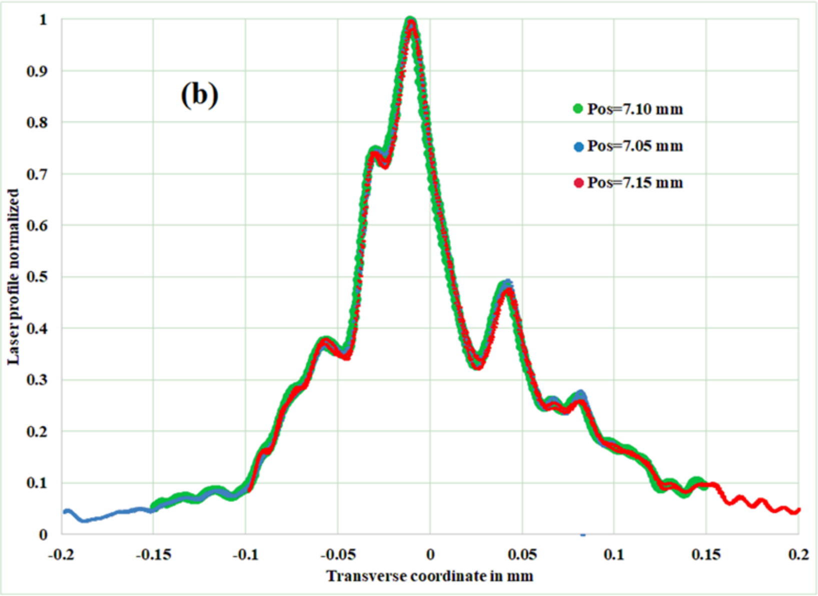
PIN photodiodes:
Method is based on the effect of electron-hole pair formation when particles/photons pass through matter. PIN photodiodes are distinguished by the fact that they contain a thick enough (up to several hundred micrometers) depletion layer, on which there is a significant deposition of energy of a passing particle.

PIN photodiodes usage experience



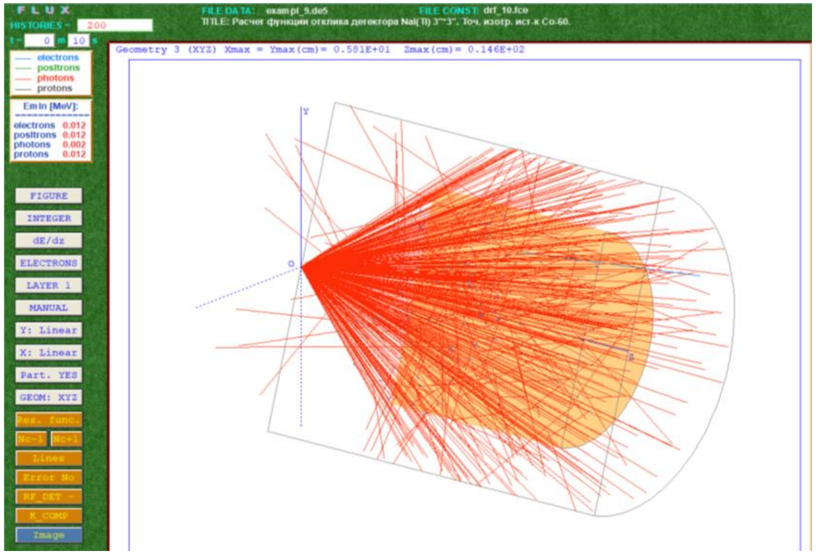
Vibrating wire (1), lens (2), focused laser beam
(3), reflected photons (4), Hamamatsu PIN-photodiode S1223-1 (5).
PIN photodiode advantage – small response time, ns and less

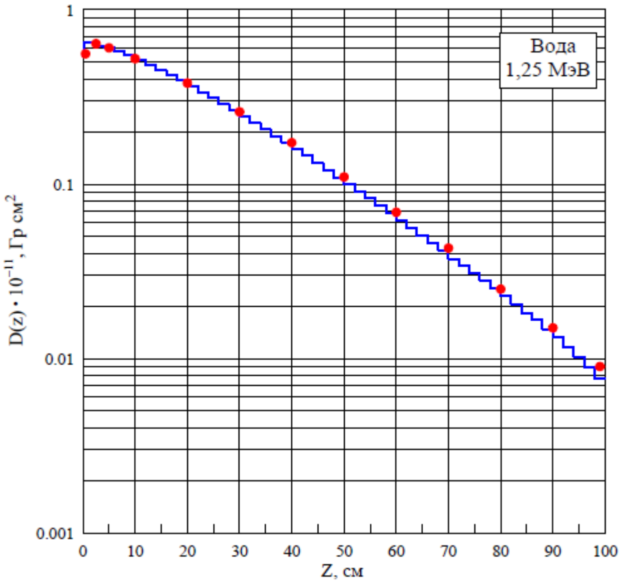
[S. Arutunian 2021, RSI]
Reconstructing the laser beam profile in absolute coordinates



Evaluation of PIN based method sensitivity

Calculations were performed on the basis of PCLAB program, developed in Tomsk polytechnic university (V.I. Bespalov). Program is created for students and has very simple interface





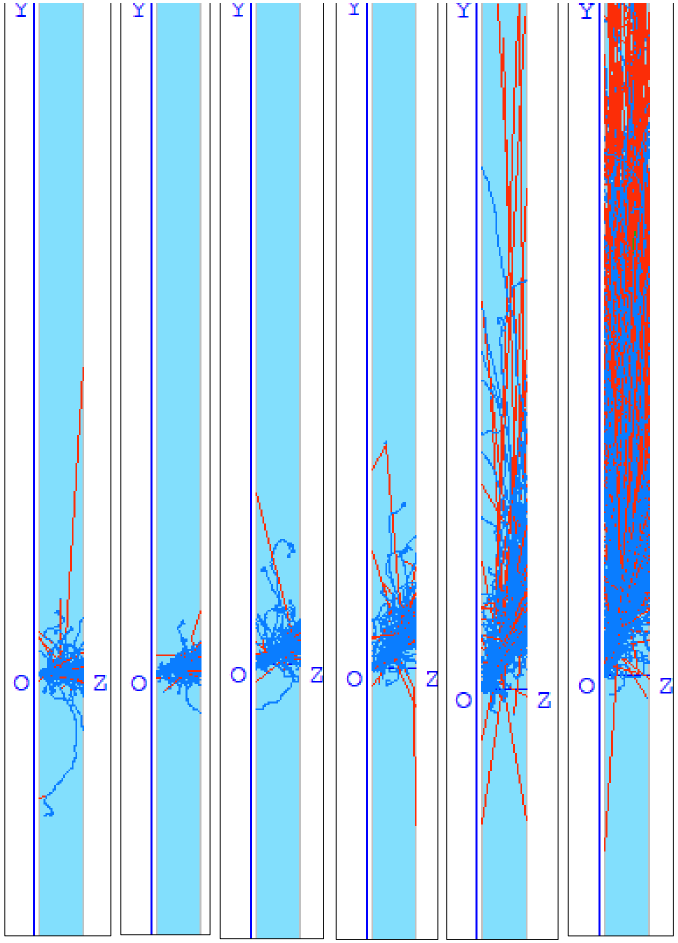
NaI detector response function calculation (includes electrons, positrons, photons and protons)

Red points – GEANT4, blue line – PCLab

The basic calculations are normalized to one fly-in electron. The following beam parameters were taken for the calculations:

Electron energy	20 MeV
Pulse repetition rate	20 Hz
Charge per pulse	250 pC
Average current	5 nA
Beam cross section	0.25 cm^2
Beam mean flux	1.25 E+11 $n_e/s/cm^2$

A modeling of electron passage through an aluminum layer of 2 mm thickness at different angles of incidence relative to the normal: 0^0, 15^0, 30^0, 45^0, 60^0, 75^0. Photon trajectories are shown in red and electron - in blue.



Calculations on the PS LAB program

Fluxes through a 2 mm aluminum wall at different angles, depletion layer = 100 μm : one electron with energies of 20 MeV passes for different angles of incidence relative to the normal (d_Al = 2 mm is the barrier thickness, d_Al_eff = d_Al/cos θ is the effective barrier thickness, e_Nf - number of electrons, e_Ef - average energy of electrons, p_Nf - number of positrons, p_Ef - average energy of positrons, ph_Nf - number of photons, ph_Ef - average energy of photons).

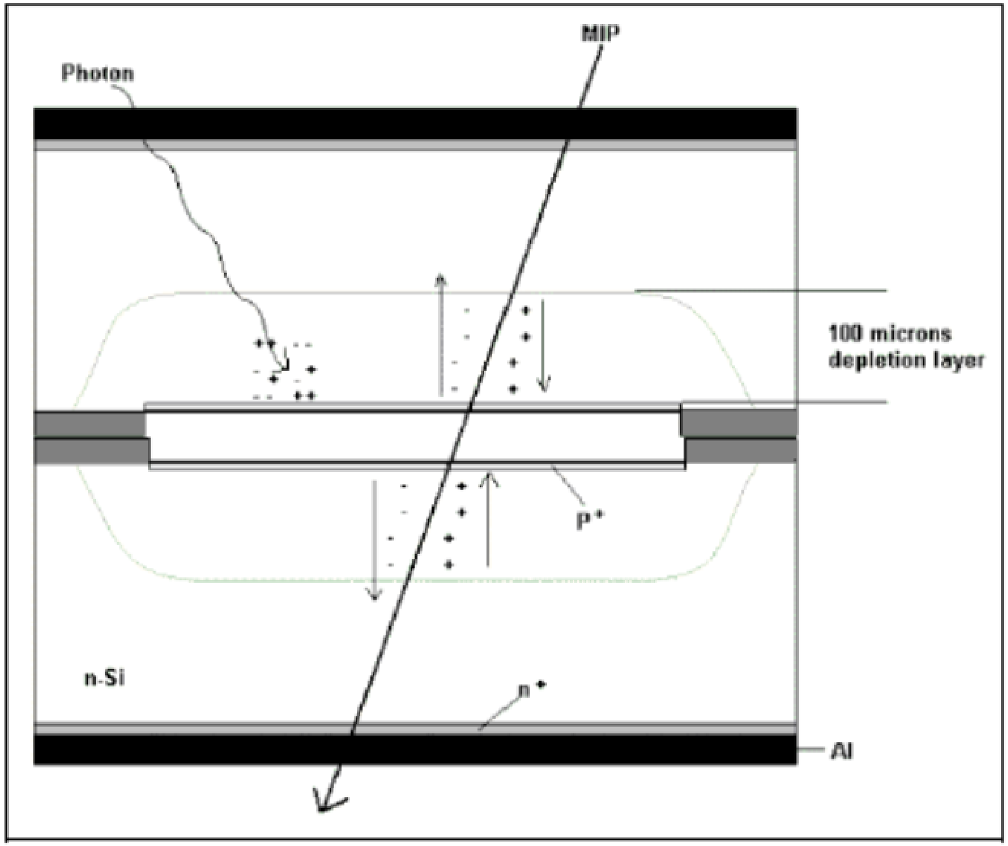
θ^0	d_Al_eff, cm	e_Nf	e_Ef, MeV	p_Nf	p_Ef, MeV	Ph_Nf	ph_Ef, MeV
0	2.00E-01	1.05E+00	1.88E+01	5.10E-05	2.33E-04	1.77E-01	3.30E-01
15	2.07E-01	1.05E+00	1.88E+01	6.00E-05	2.02E-04	1.82E-01	3.40E-01
30	2.31E-01	1.06E+00	1.86E+01	6.90E-05	2.82E-04	2.01E-01	3.75E-01
45	2.83E-01	1.07E+00	1.83E+01	8.50E-05	3.62E-04	2.45E-01	4.63E-01
60	4.00E-01	1.08E+00	1.75E+01	1.83E-04	6.78E-04	3.47E-01	6.53E-01
75	7.73E-01	9.94E-01	1.31E+01	6.12E-04	2.16E-03	5.91E-01	1.06E+00

Number of electron-hole pairs formed from one electron, the thickness of the Si depletion layer is 100 μm, the energy threshold of electron-hole formation 3.5 eV. (d_Si_eff is layer effective thickness; e_loss is energy of electrons; e_e-holes is quantity of electron-holes generated by electrons; p_loss is energy losses of positrons; p_e-holes is quantity of electron-holes generated by positrons; ph_loss is energy losses of photons; ph_e-holes is quantity of electron-holes generated by photons; F_e-holes is full number of generated e-holes

θ^0	d_Si_eff, cm	e_loss, MeV	e_e-holes	p_loss, MeV	p_e-holes	ph_loss, MeV	ph_e-holes	F_e-holes
0	1.00E-02	3.89E-02	1.11E+04	1.89E-06	5.39E-01	6.53E-03	1.87E+03	1.30E+04
15	1.04E-02	4.04E-02	1.15E+04	2.30E-06	6.57E-01	6.97E-03	1.99E+03	1.35E+04
30	1.15E-02	4.52E-02	1.29E+04	2.95E-06	8.42E-01	8.61E-03	2.46E+03	1.54E+04
45	1.41E-02	5.57E-02	1.59E+04	4.45E-06	1.27E+00	1.28E-02	3.67E+03	1.96E+04
60	2.00E-02	8.00E-02	2.29E+04	1.35E-05	3.87E+00	2.57E-02	7.33E+03	3.02E+04
75	3.86E-02	1.42E-01	4.06E+04	8.75E-05	2.50E+01	8.44E-02	2.41E+04	6.48E+04

Calculations of the resolution current density through the photodiode of order 0.1 pA/cm2 (S_eff is effective area of photodiode (Hamamatsu S1223 PIN photodiode with aperture area of 6.6 mm2), N_e - electron flux density through photodiode, which provides electron-hole current 0. 1 nA comparable with photodiode dark current (F_e is total electron flux through photodiode), P_e is electron-hole flux through photodiode (equal to value of F_e multiplied by conversion factor of electron-hole pairs on barrier (factor F_e-holes from Tab. 2). I_detect value of the resolution of the detected current density of incident electrons in the photodiode area)

S_eff, cm^2	N_e_e/s/cm^2	F_e, n_e/s	P_e, e-hole/s	I_detect, A/cm^2
6.60E-02	7.29E+05	4.81E+04	6.25E+08	1.17E-13
6.38E-02	7.25E+05	4.62E+04	6.25E+08	1.16E-13
5.72E-02	7.11E+05	4.07E+04	6.25E+08	1.14E-13
4.67E-02	6.83E+05	3.19E+04	6.25E+08	1.09E-13
3.30E-02	6.27E+05	2.07E+04	6.25E+08	1.00E-13
1.71E-02	5.65E+05	9.65E+03	6.25E+08	9.04E-14



K.Wittenburg measurement diagram

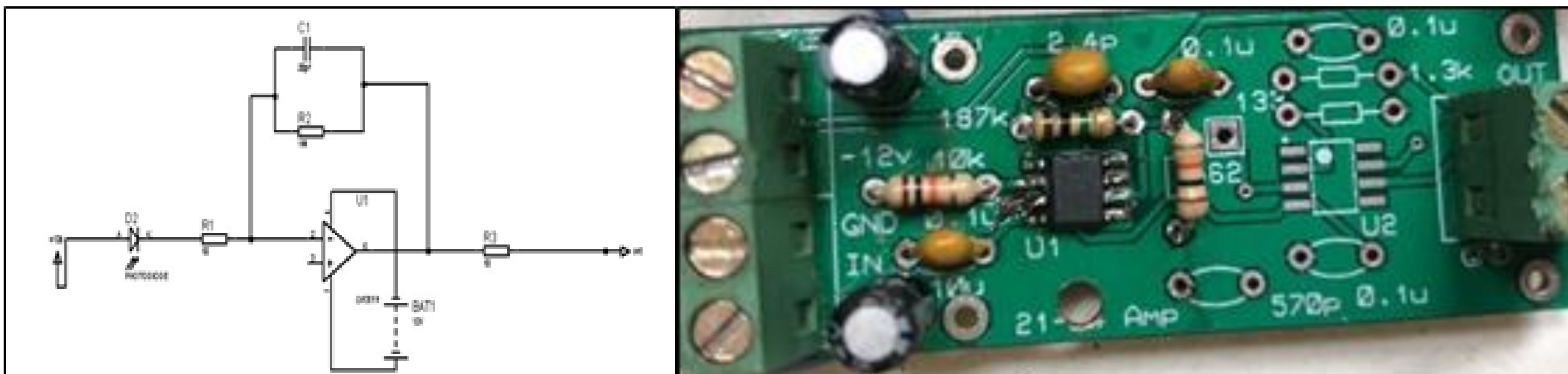
The BLM system based on PIN photodiodes (250 units) was installed in 1993 in HERAp and was running very reliably, as a very important part of the quench protection system for the superconducting magnets and as a useful diagnostic tool.

A second BLM system was installed in 1994 in HERAe to study a serious beam current limitation, characterized by very short lifetimes of the electron beam. A total of 214 PIN Diode BLMs were installed around the entire ring to locate the regions and diagnose the causes of the beam losses.

Electronic circuit

The purpose of the system is to registration electron losses of very short electron bunches (less than 1 ps). The passage of these electrons through the chamber walls gives rise to pulses of secondary electrons/positrons/photons with longer duration, which are to be measured. For this problem it is of interest to measure only the average values of these fluxes.

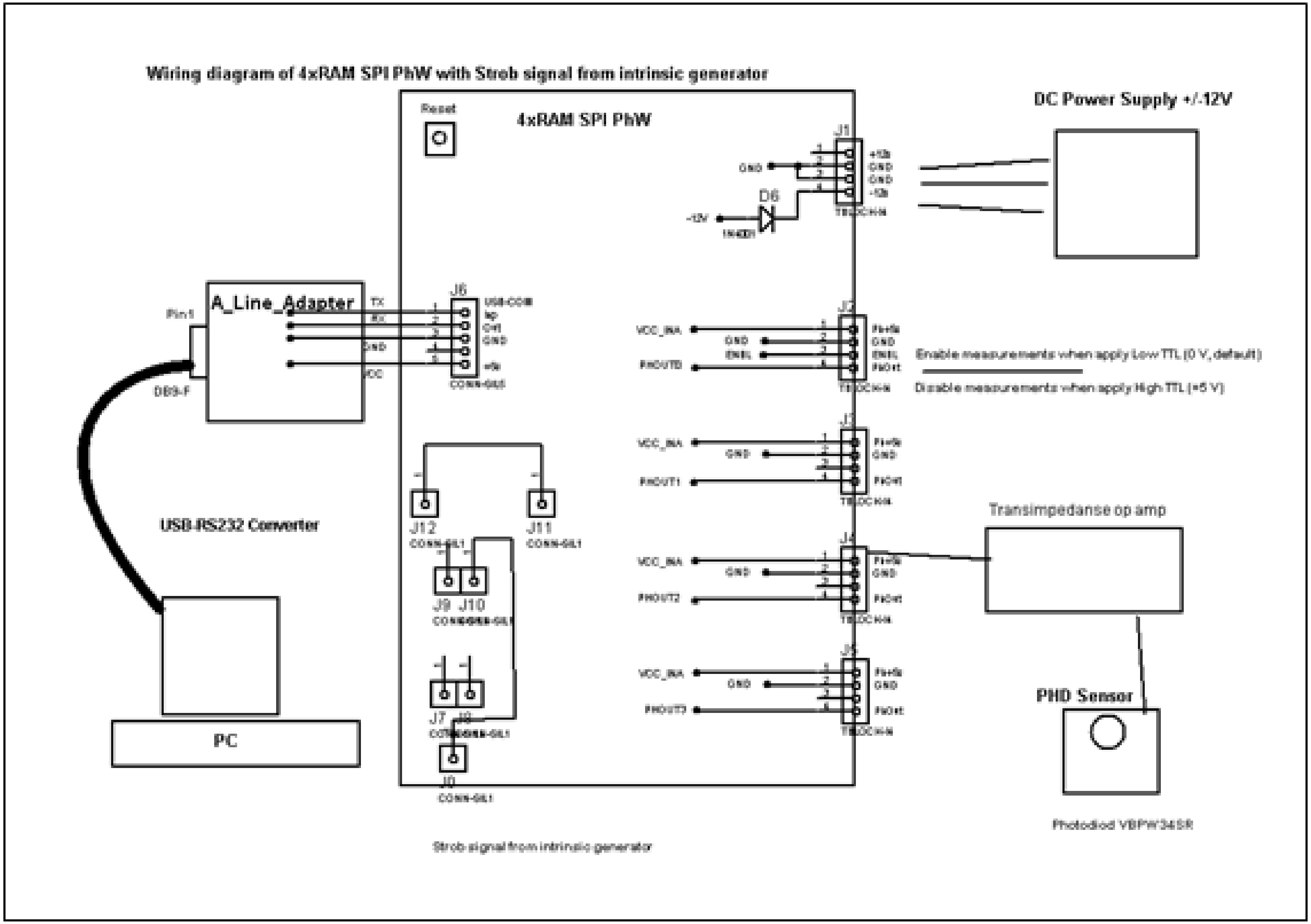
The measurement system consists of two boards: a pre-integration-amplification board and an amplification, digitization and data storage board



Schematic of the photodiode with integration function and photo.

Electronic circuit

Left – photodiode signal integration circuit (preamplifier)
Center – fast 4 channel circuit (INA 128 Opamp amplification - ADC MCP3301 - data storage (512 kb))
Right – USB interface with PC (used chaanels #1, #2, #4)
Down – three PIN photodiode (BPW34)



4-channel signal measurement system of the preamplifier board.

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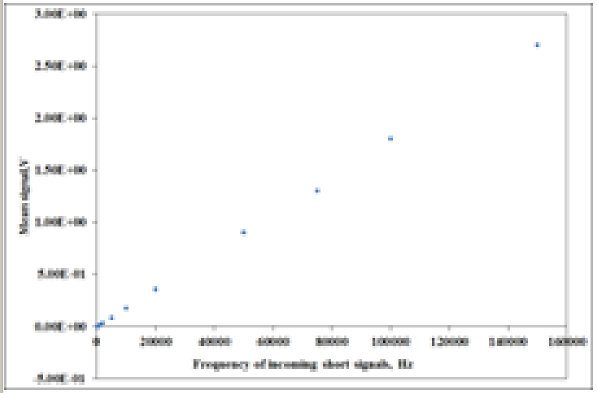
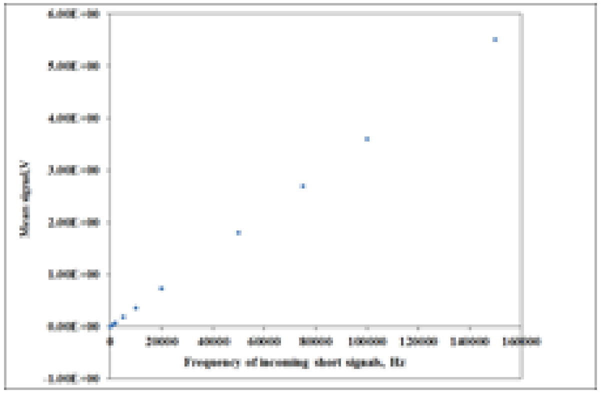
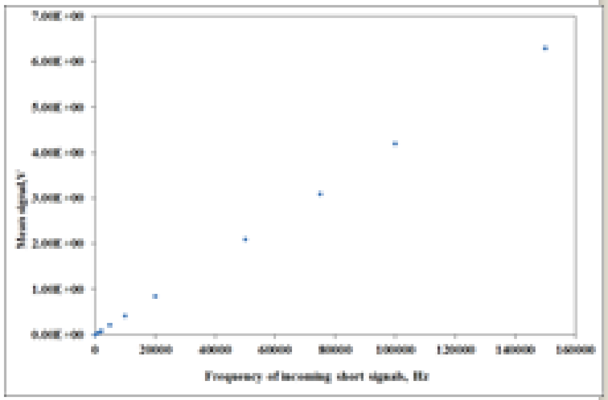
Preliminary experiments – integrability

Lighting system using LEDs powered by short pulses (on the order of 40 ns) with different repetition rate.



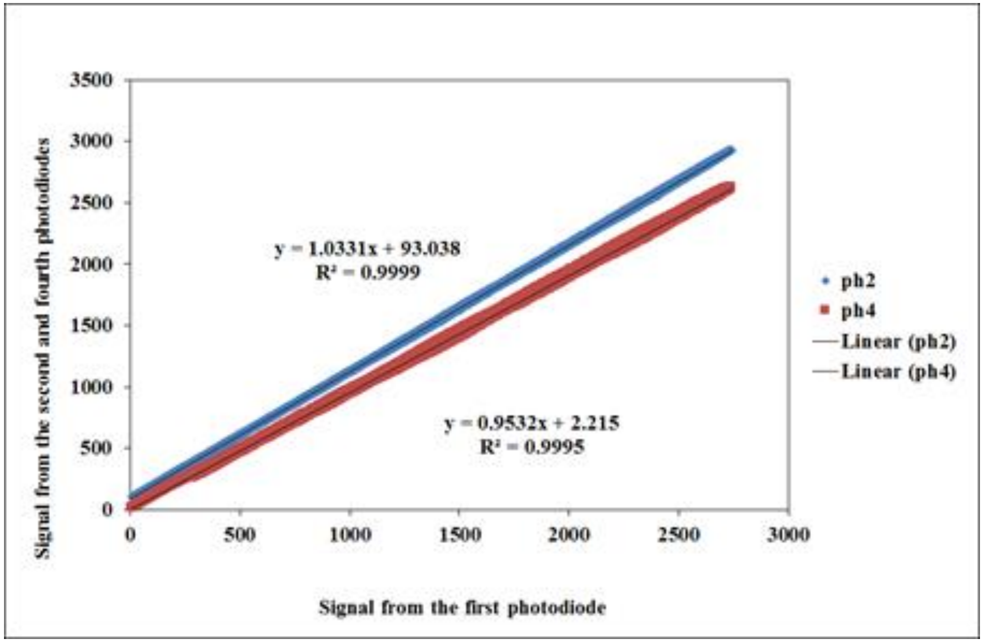




Lighting the photodiode by LEDs powered by short pulses with different repetition rates

Preliminary experiments - mutual calibration

Illuminating system with incandescent lamp powered with different voltages



Comparison of the characteristics of the measurement circuit of photodiodes 2 and 4 in relation to photodiode 1. Irradiation of the photodiode system by regulated light emission. Comparison of the characteristics of the measurement circuit of photodiodes 2 and 4 with respect to photodiode 1

Experiment on electron beams

Experiments on the AREAL electron accelerator were carried out in the following modes:

- The RF system of the accelerator was switched off

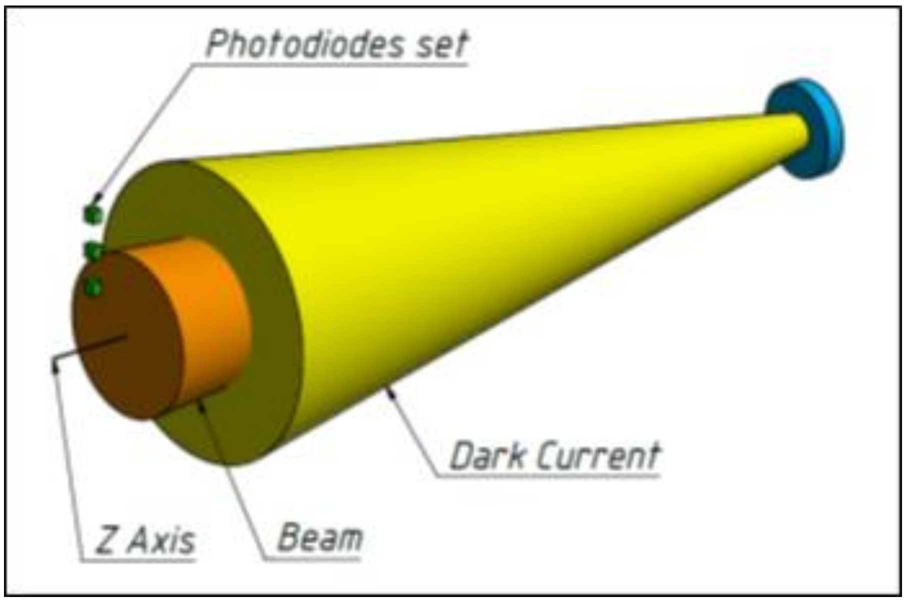
- The accelerator RF system is switched on, the accelerator photocathode is not illuminated by the powerful UV laser. In this mode the accelerator generates a dark electron current, which consists of random electrons. The duration of this current pulse is equal to the duration of the RF pulse.

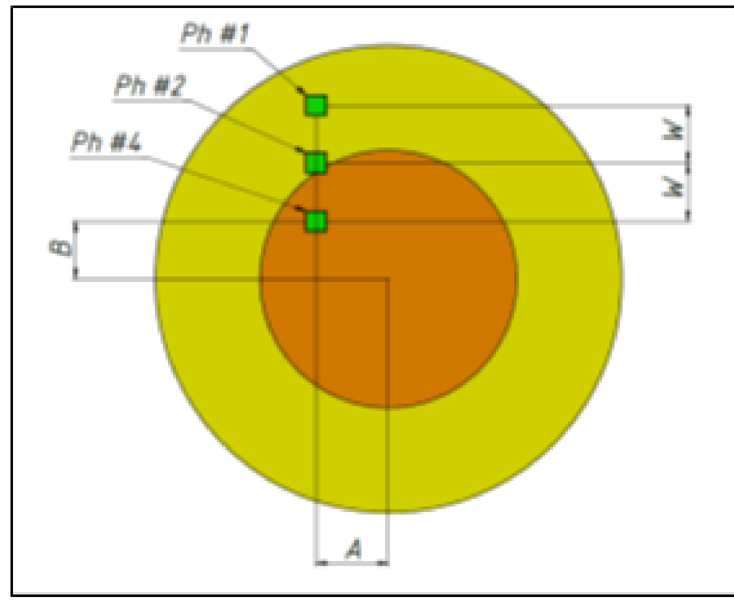
- The accelerator RF system is switched on, illumination of the photocathode by the powerful UV laser is switched on. Short bunches of electrons with varying amounts of charge are formed at the accelerator output. The duration of the bunch is less than 1 ps. In this mode it is possible to regulate the energy of electrons by changing the amplitude of the accelerating RF field.

The experiments were performed at a RF pulse repetition rate of 20 Hz.

The first experiment - detection of the electrons by PIN photodiodes

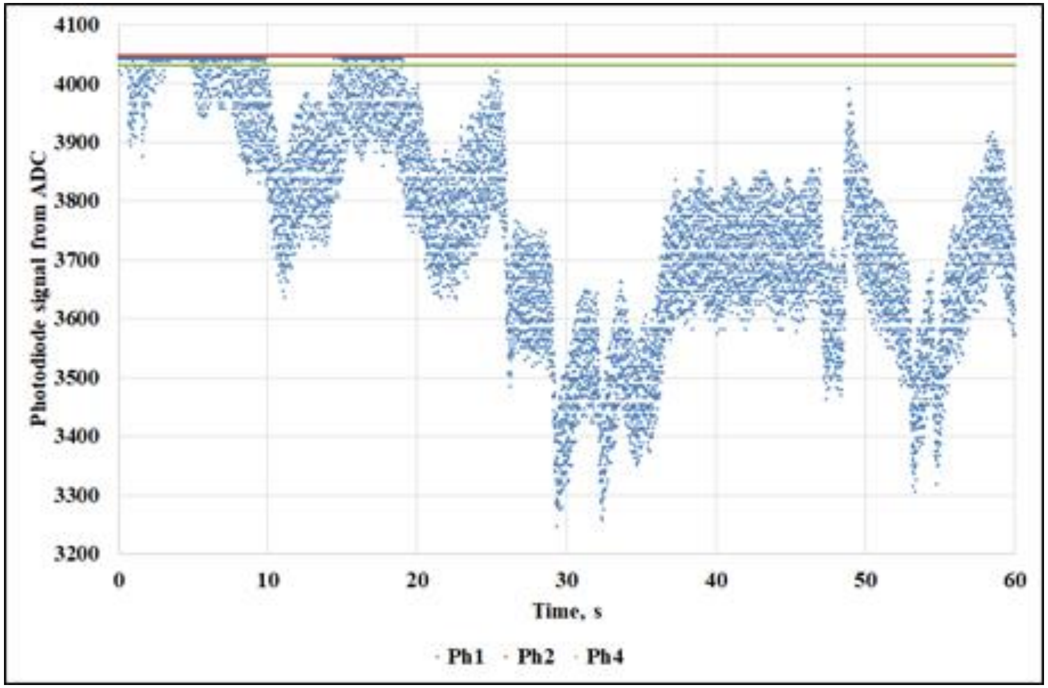
Photodiodes were placed in plane Z = 400 mm from the output flange, electron energy 3.6 MeV, bunch repetition rate 20 Hz. Only dark current. The photodiodes are mounted with vertical offset of 30 mm.





Location of photodiodes in the plane orthogonal to the accelerator axis Z: A and B the distances of photodiode 4 from accelerator axis (in horizontal and vertical), W - distance between photodiodes.

Z = 400 mm, A = 70 mm, B = 0 mm



	A	B	R
#4	70	0	92.2
#2	70	30	114.0
#1	70	60	138.9

RF turned on (dark current), no beam. The physical effect is detected. Photodiodes 2 and 4 register going beyond the upper limit of the measurement range. The photodiode #1 furthest from the axis shows a strong signal near this limit

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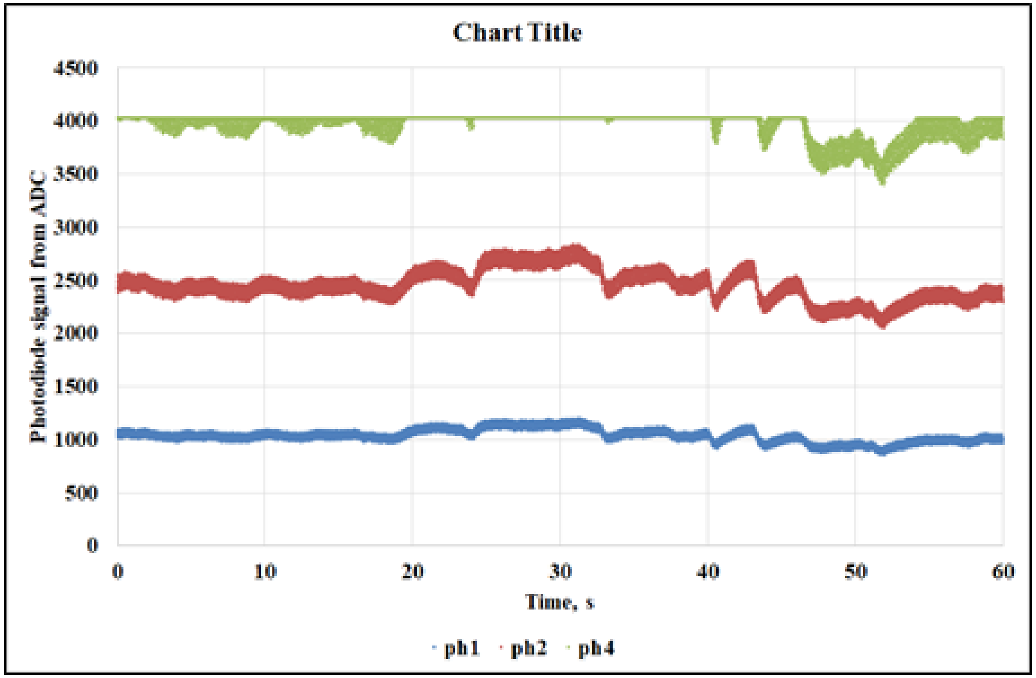
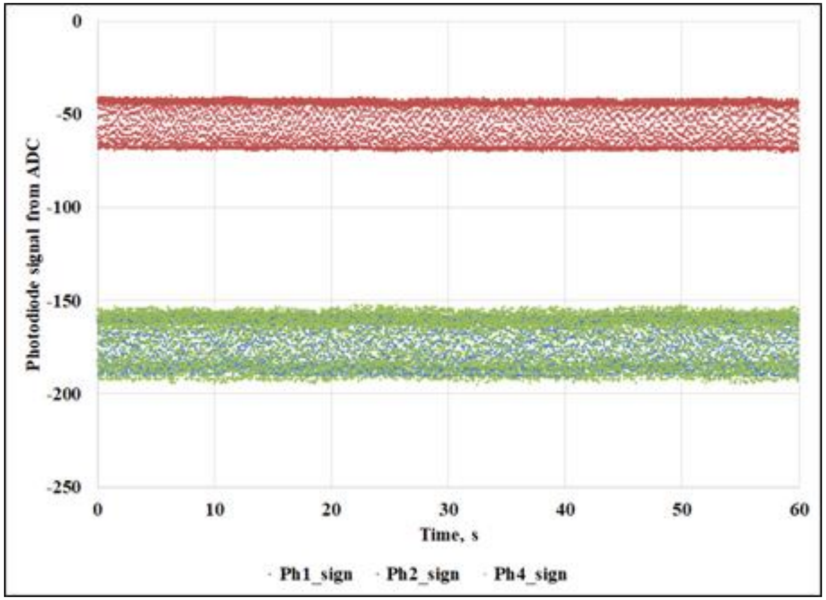
Z = 400 mm, A = 70 mm, B = 60 mm

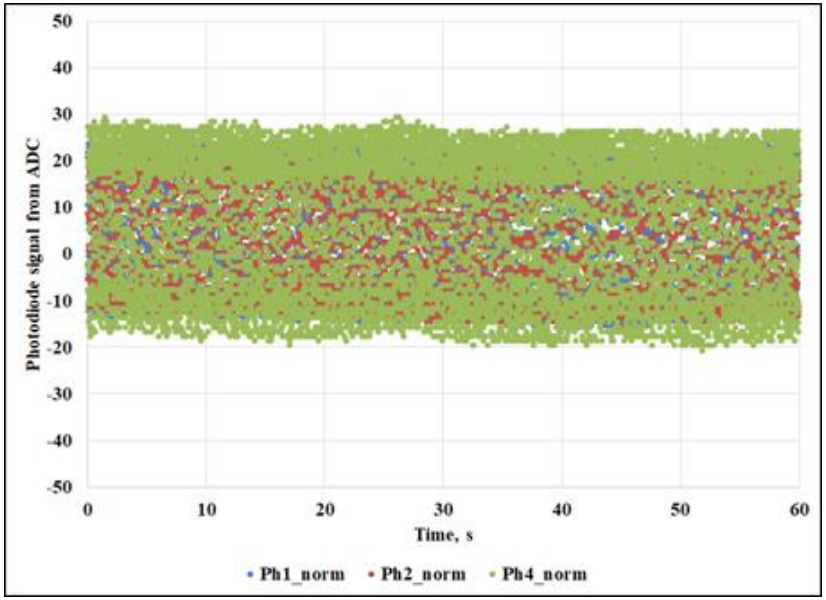


	A	B	R
#4	70	0	70
#2	70	30	76.2
#1	70	60	92.2

The beam was switched on 20 sec, off on 40 sec



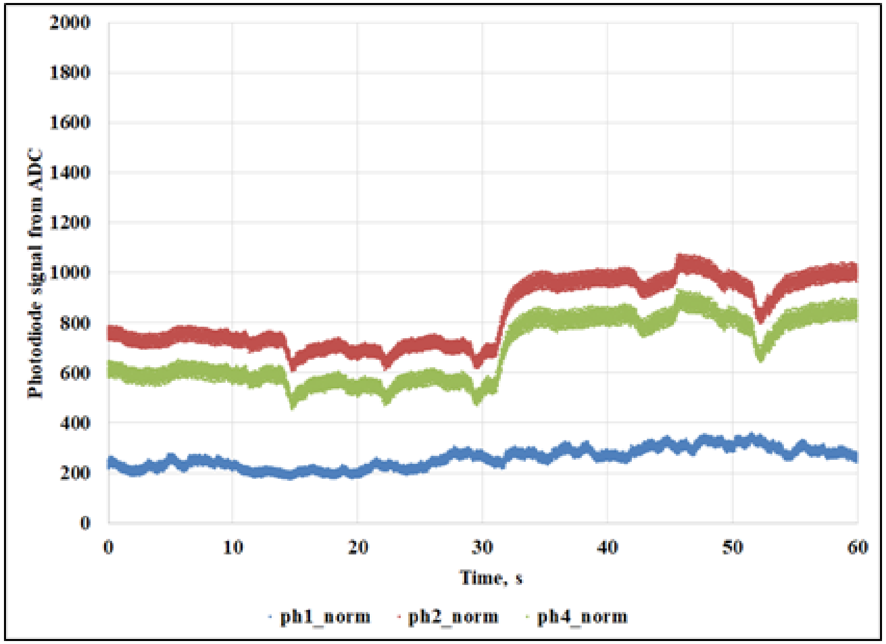
Photodiode measurement system readings when the photodiodes are in absolute darkness (black box), the accelarator RF system is off, the electron source laser system is off (absolute background).

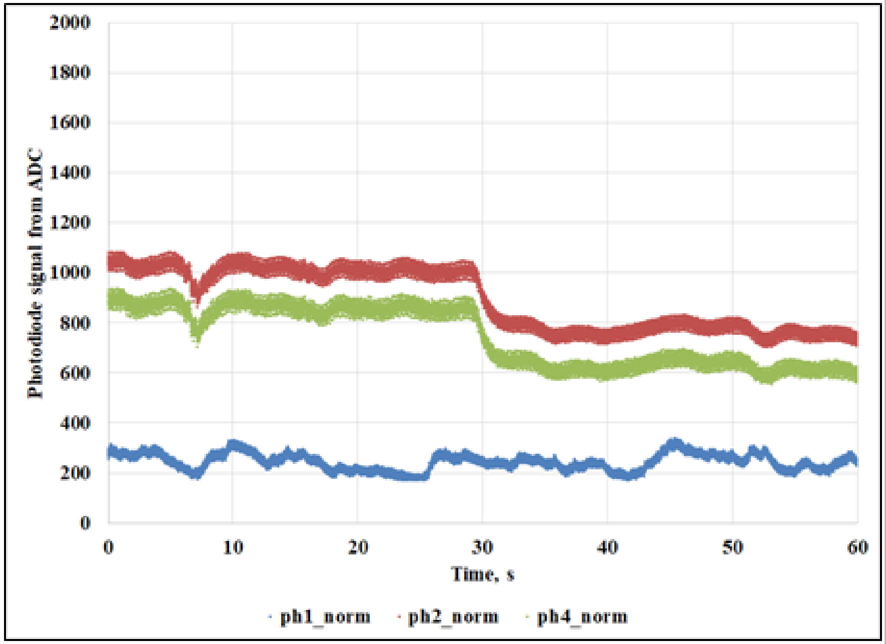


The light background in the AREAL accelerator tunnel. The corresponding measurement results normalized to the absolute background

Photodiode	**#1**	**#2**	**#4**
mean value	7.47	6.27	7.46
standard deviation	11.8	11.6	13.8

Experimental plane 1400 mm, energy 3.6 MeV





Up to 30 s only dark current was present, from 30 s the electron current was included

Up to 30 s both beam and dark current were present, from 30 s only dark current was present.

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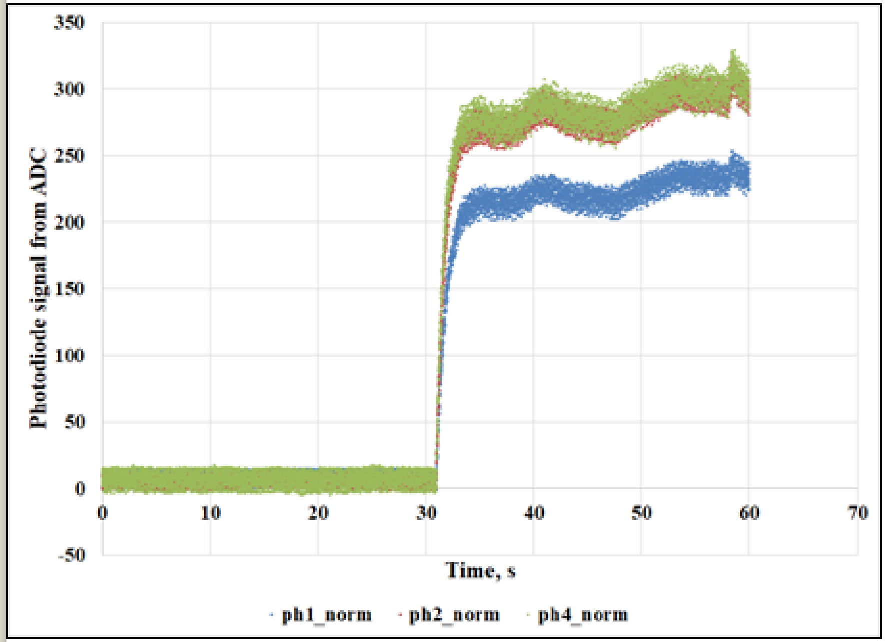
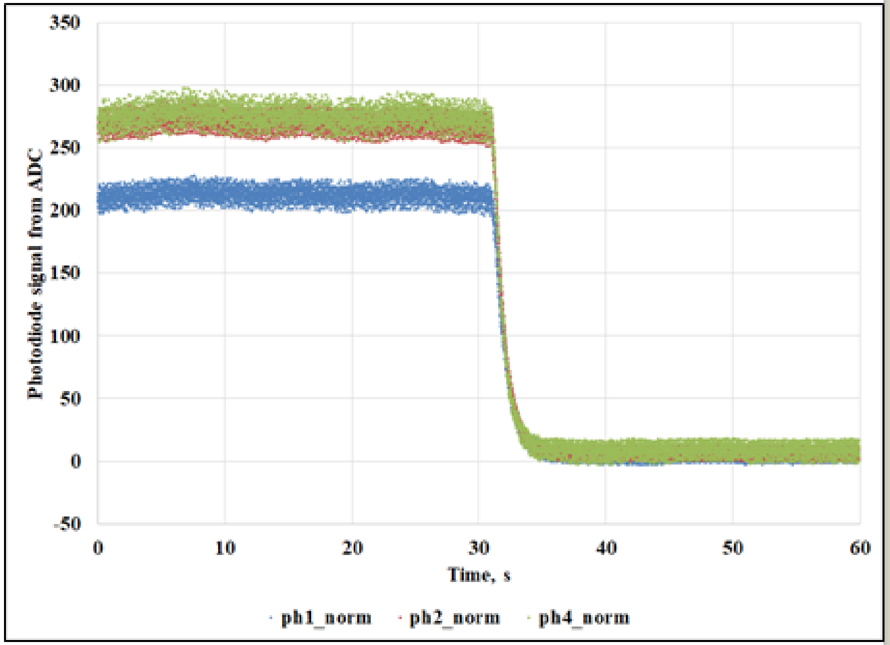
Experimental plane 1000 mm, energy 2 MeV





Approximate position of photodiode 4 - along the accelerator axis

Conclusion

1. Preliminary experiments have shown that the measurement system does integrate short light pulses, as well as pulses of ionizing radiation (primary electrons of the dark beam current and accelerated electron beam, as well as possible secondary electrons/positrons and photons.

2. Unfortunately, in the experiments it was not possible to obtain the absolute characteristics of the electron measuring system, because the measuring range of used Faraday cup did not match with our system (the resolution of the Faraday cup was in the region of electron fluxes, which saturate the PIN-photodiodes).

Conclusion

Next steps:

3. Calibration of PIN photodiodes with electron beams (preferably taking into account the energy spectrum of electrons). Development of electronics for signal registration from a large number of PIN photodiodes (based on our developed primary transimpedance board for integration and preamplification of photodiode signal)
4. The developed system can be used to map electron beams in experiments in air (our developed system exceeds by sensitivity the Faraday cylinder used in this experiment).

Thank you for attention