

V.M. Pugatch

Institute for Nuclear Research NASU, Kiev

POSITION SENSITIVE MICRO-STRIP AND MICRO-PIXEL DETECTORS



Physics and techniques of the metal foil detectors measuring and imaging charged particles and synchrotron radiation beams are presented. An extremely low thickness (~1 micron) of the Metal Micro-strip Detector (MMD) combined with its high radiation tolerance (~100 MGy) introduces an opportunity to keep a device in the beam, permanently. 'In-situ' operation of the MMD provides non-destructive beam diagnostics in real time. The applications of the micro-strip as well as micro-pixel detectors are briefly described.

Key words: metal detectors of charged particles and synchrotron irradiation, monitoring of the synchrotron irradiation beams, micro-strip and micro-pixel detectors.

INTRODUCTION

Position sensitive micro-detectors are being intensively developed last two decades. Strip- as well as pixel-structured detectors were successfully applied primarily in high energy physics studies. There is a general tendency to integrate sensors and front-end electronics into a single device to fulfill the low-mass, low-noise, radiation hardness requirements. There are many types of such detectors like hybrid micro-pixel, Monolithic Active Pixels, Depleted Field Effect Transistor – DEPFET, Silicon-On-Insulator – SOI etc. In this paper we shall concentrate on recently developed metal foil detectors as well as metal micro-strip and micro-pixel detectors, applied, in particular for the beam profile monitoring of charged particles and X-rays.

PHYSICS AND TECHNIQUES OF THE METAL FOIL DETECTORS

The metal substance as a sensor for charged particles and photons is explored for quite some time in many devices (electroscopes, Faraday

cups, secondary electron multipliers, micro-channel plates, photo-diodes, photo-multiplier etc.). Physics and techniques principle of the Metal Foil Detector (MFD) have been developed at the Institute for Nuclear Research NASU (Kiev, KINR) [1]. Incident particles on a sensor initiate Secondary Electron Emission (SEE) as they pass through very thin (nearly transparent) metal medium. The electrons are mainly emitted from 10-50 nm surface layers of the metal sensor. The positive charge appearing at isolated sensor is measured by a sensitive Charge Integrator (ChI) connected to the sensor [2].

The current technology allows for production of the thin (~1 μm) Ni-strips with a pitch of about few micrometers, providing high position resolution. Micro-strip Metal Detector technology includes some stages: microstrip layout made by photo-lithography on silicon wafer, plasma-chemistry etching of the silicon wafer in the operating window, microcabling connection to the readout electronics and DAQ [3, 4].

The main technical features of the MMD: High Radiation tolerance (>100 MGy); Low thickness of sensors (~1 μm); Low operation voltage (20 V);

Perfect spatial resolution (5–25 μm). In comparison with the latest developments in beam profile monitoring based on the silicon micro-strip or micro-pixel detectors Metal Micro-strip Detectors have an advantage of being extremely thin and semi-transparent device. Those features provide: first, nearly non-destructive beam analysis; second, on-line measurement of the in-situ beam data; no danger of the charge accumulation leading otherwise to the high voltage breakdown resulting in a device loss. Below some applications of the detectors produced by the MFD technology are illustrated.

METAL FOIL DETECTORS APPLICATIONS

Interaction rate and radiation monitoring systems

A single layer MFD had been explored for the multi-target steering at the HERA-B experiment [5]. To provide unambiguous reconstruction of secondary vertices the interaction rate of 40 MHz had to be equally distributed over eight targets operated simultaneously in the halo of the 920 GeV proton beam. This has been realized by making targets as an MFD structure – thin metal strips connected to sensitive charge integrators. It has been proved that the SEE yield under the proton beam impact onto a single target was strictly proportional to that target partial contribution into the total interaction rate. The equal sharing (~12,5%) of the overall luminosity among eight operating metal targets-detectors has been demonstrated by means of the reconstructed primary vertices. Besides that the 12 sector MFD has been built and explored for the luminosity monitoring of the experiment HERA-B [5].

Based on the same MFD technology Radiation Monitoring System (RMS) [6] has been built at the Large Hadron Collider for the LHCb experiment and is currently under operation (Fig. 1).

The main goal of the RMS – monitoring of the radiation load on Silicon Tracker Sensors. The LHCb RMS comprises 4 boxes (left, right, top, bottom) fixed at the Inner Tracker IT-2 station. 7 MFD sensors (Al –foil, 50 μm thick, (110 × 75) mm^2 area) are built in each box.

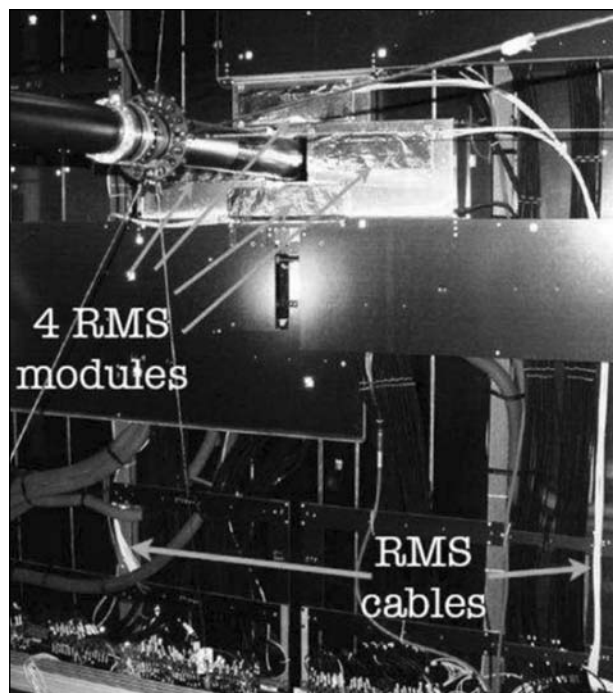


Fig. 1. Photo of the Radiation Monitoring System installed around the beryllium beampipe at the Large Hadron Collider (CERN, Geneva)

Applying calibration and Monte-Carlo simulation important characteristics of the LHC 3.5 TeV proton beams collisions at the IP-8 interaction point were evaluated. In particular, charged particles fluence as well as absorbed dose distribution (Fig. 2) over IT-2 silicon microstrip sensors has been measured for the 1.2/fb integrated luminosity delivered to the LHCb experiment in the year 2011. Evaluated from the RMS data leakage current increase in silicon sensors well agreed with direct current measurement confirming good performance of the RMS.

Metal micro detectors for the synchrotron radiation beam profile monitoring

A reliable performance of the Metal Foil detectors presented above as well growing demand for the low mass, radiation hard micro-detectors have evolved into the development of the Metal Micro-strip and Micro-pixel detectors (MMD). Such detectors have been successfully created at the

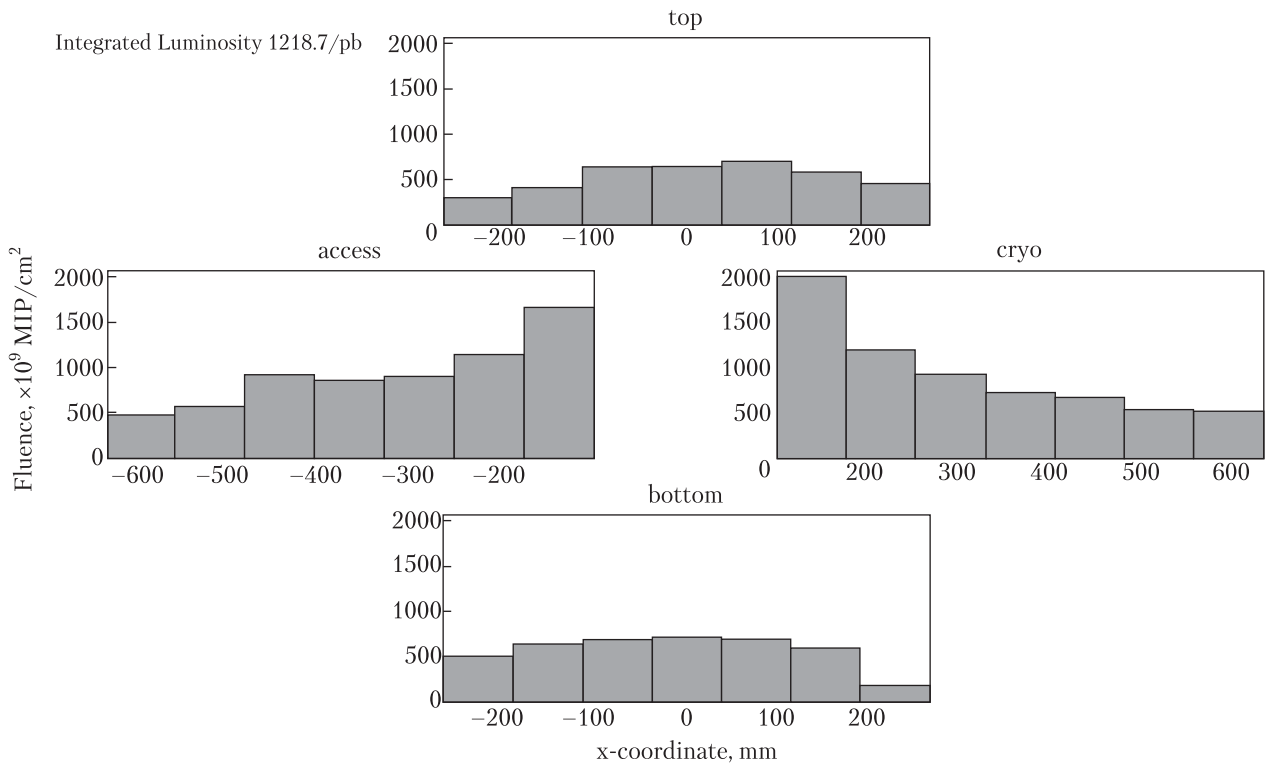


Fig. 2. Fluence distribution of relativistic charged particles measured by the RMS at the Inner Tracker location (LHCb experiment) for integrated luminosity of 1.2 inverse femtobarn in 2011 year

Kiev Institute for Nuclear Research NASU (KINR) [3] in close collaboration with MPIfK (Heidelberg), DESY (Hamburg), Institute of Micro-devices NASU (Kiev) and CERN.

MMD current technical data are as follows:

- ✦ Signal – positive charge created by the electron emission under the impinging particles. Conversion factor (electrons/particle) ranges from 0,1 (for MIP) to few hundreds (for the fast heavy ions).
- ✦ Noise – (thermoelectric emission, r/f pickup, fluctuation of the leakage current, etc.) depends also on the connecting cables and read-out electronics: ENC = 500–1000 electrons.
- ✦ Thickness – 1–2 μm (transparent, non-destructive device for the measured beam).
- ✦ Position resolution – 10 μm .
- ✦ Radiation hardness – more than 10 G Gy.

To achieve the micrometer level position resolution and low thickness (few μm) the silicon mic-

ro-strip detector technology combined with plasma-chemistry etching has been developed and used for the MMD design and production [4]. The sensors were prepared by means of microelectronics technology and plasma-chemistry etching. To isolate a metal film from the wafer the dielectric layers were grown up on both sides of a wafer. At first, the silicon oxide (0,1–0,3 μm thick) was grown up covered later by 0,2 μm thick silicon nitride. A thin (0,1 μm) titanium layer was deposited onto dielectric layers. Afterwards, nickel (0,5 μm) layers covered finally by silver layers (0,6 μm) served as films for the photo-lithography shaping of the strip pattern as well as contacting lines and pads. A window from the back side has been created for the plasma-chemistry etching. The KINR plasma-chemical reactor with variable ion energy has been used. The current technology allows for production of the the strip width at the level of few micrometers, thus, pro-

viding 1–2 μm position resolution for 1–2 micrometer thick sensors.

Photo of some metal micro detectors are shown in Fig. 3.

The sensitivity of the MMD to the radiation flux is determined by the physics conversion factor as well as by the readout electronics (charge fluctuations at the ChI input due to the leakage currents, temperature/humidity impact, r/f pick-up etc.). Currently, for relativistic particles the reliably detectable flux is in the range of 10^4 particles/s per MMD sensor. The MMD was applied successfully for the X-rays beam profile monitoring at HASYLAB (DESY, Hamburg) [3]. To prevent microwave heating of the metal strips five-layer MMD (32 Al strips, 70 μm pitch, 3 μm thickness) has been introduced into the 15 keV X-ray beam ($4,5 \times 10^{14}$ photons/second/ mm^2). The conversion factor has been evaluated as $1,5 \times 10^4$ photons/e.

Characterization studies of the Metal Micro-detectors measuring in real time high level dose distribution of the synchrotron radiation at the Mini-beam Radiation Therapy (MBRT) setup (ESRF, ID17) have been performed. The biomedical features of that therapy requires rather high doses up to several kGy/sec [7]. High radiation load factor makes unable to apply any conventional detectors for measuring dose distribution in real time. The distribution of dose is currently measured by using special X-ray films processing of which takes 1–2 days.

For monitoring in real time the distribution of dose from individual beams of synchrotron radiation we have proposed and tested detector system based on metal mode micro-pixel detector TimePix [8]. 'In-situ' operation of the TimePix provides measurement of the dose distribution in real time. The results obtained illustrate an excellent performance of the metal TimePix micro-detector providing 2D image of the dose distribution over many beams in $(14 \times 14) \text{mm}^2$ area (Fig. 6). Peak-Valley-Dose-Ratios measured by the TimePix and gafchromic films agree well.

Data obtained for various modifications of mini- as well as micro- beam configurations will be used

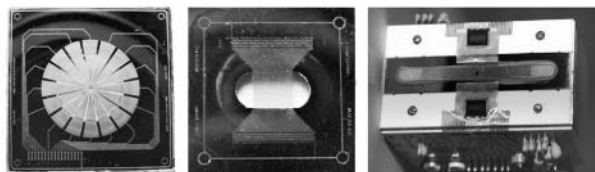


Fig. 3. Metal Micro-detectors: a) 16 – sector MMD (tested at the DIAMOND Light Source (UK, Oxfordshire), b) 128-channels MMD, c) 1024-channels MMD, connected by micro-cables to the readout micro-electronics

for creating a novel MMD-based radiation hard monitoring system for radiation therapy applications.

Metal Micro-pixel detectors for measuring low energy ion beams at the focal plane of the mass-spectrometer

Recent years indicated significant achievements in miniaturization of mass spectrometers. Many areas of science and technology need such devices providing simultaneous measurement of wide mass-spectra in real time. This progress occurred, in particular, due to micro-detectors and readout electronics developed for High Energy Physics experiments.

In a conventional mass-spectrometry few steps are usually made to convert the intensity of the ions with a definite mass at the focal plane into a digital data for presentation. In most of cases Micro Channel Plates (MCP) are used to transform the ions into electron streams (gained up to 10^8 times) collected then by different detector arrays.

Below some test results are presented for testing TimePix micro-pixel readout chip [8] as a (256×256) metal micro-detectors at the focal plane of the laser mass-spectrometer. It is a bare read-out chip with its input contact pads used as metal sensors with an external metal grid positively biased to improve a charge collection. TimePix chip was readout by the PIXELMAN hardware/software via USB-connection to PC. In the TimePix readout chip each pixel was programmed to record Time-Over-Threshold (TOT) data getting in this way analog information.

Fig. 5 shows two dimensional plot of data measured by a Metal TimePix detector at the focal

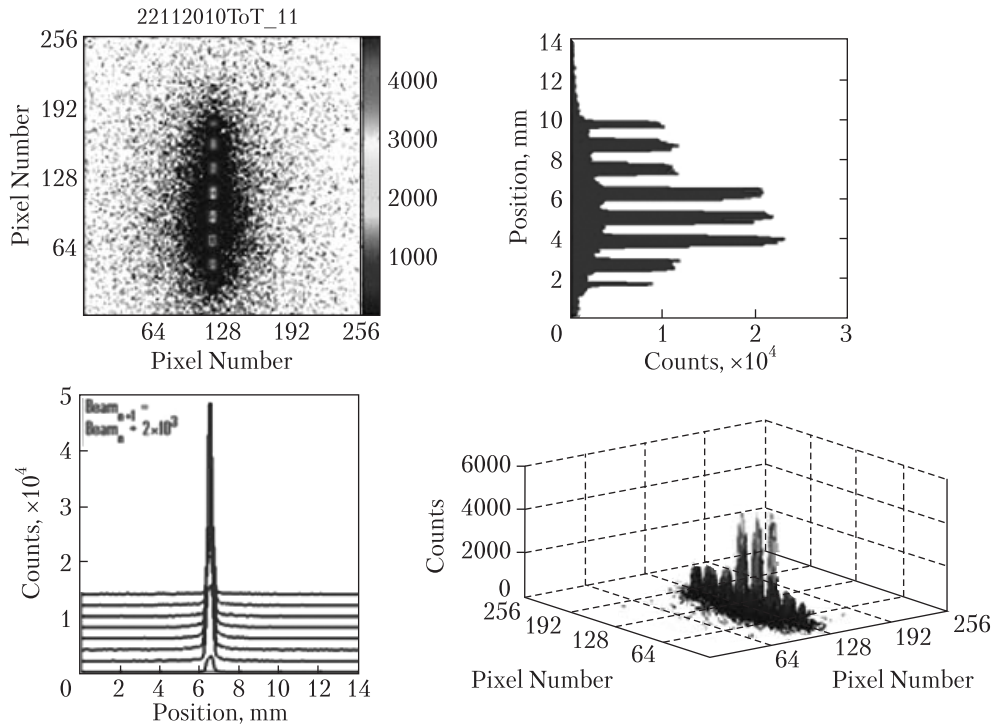


Fig. 4. Image of the radiation dose distribution measured by the metal TimePix detector at the ID17 beamline of the European Synchrotron Radiation Facility (Grenoble, France). Left (top) – 2 D image, Right (top) and Left (bottom) – projections on X- and Y-axis, Right (bottom) – isometric image

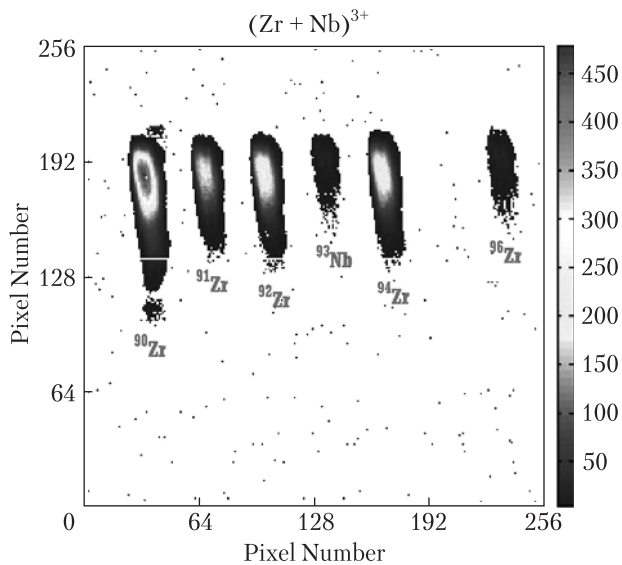


Fig. 5. Two-dimensional distributions of Zr and Nb isotopes measured by the TimePix in a metal mode of operation at the focal plane of the mass-spectrometer

plane of a laser mass-spectrometer [9]. Position of the detector, accelerating voltage and magnetic field were adjusted to observe 21 keV double charged ions of the Zr isotopes detected approximately at the middle part of the sensor. A horizontal pixel number (Fig. 5) corresponds to a mass of detected ions while vertical one shows an ion beam shape defined by aperture slits. Z-axis (color, Fig. 5) reflects a number of measured counts, proportional to a number of ions detected by pixels. It is a dynamically varying picture measured in real time (fixed in former times by photographic plate positioned in a focal plane of mass spectrometer).

Thus, the TimePix detector providing two-dimensional picture surveys as an ‘electronic plate’ imaging ion beams and their charge/mass distribution. Such images could be used for tuning mass spectrometer ‘on-line’ (focusing, alignment, testing stability of electric and magnetic field, quality

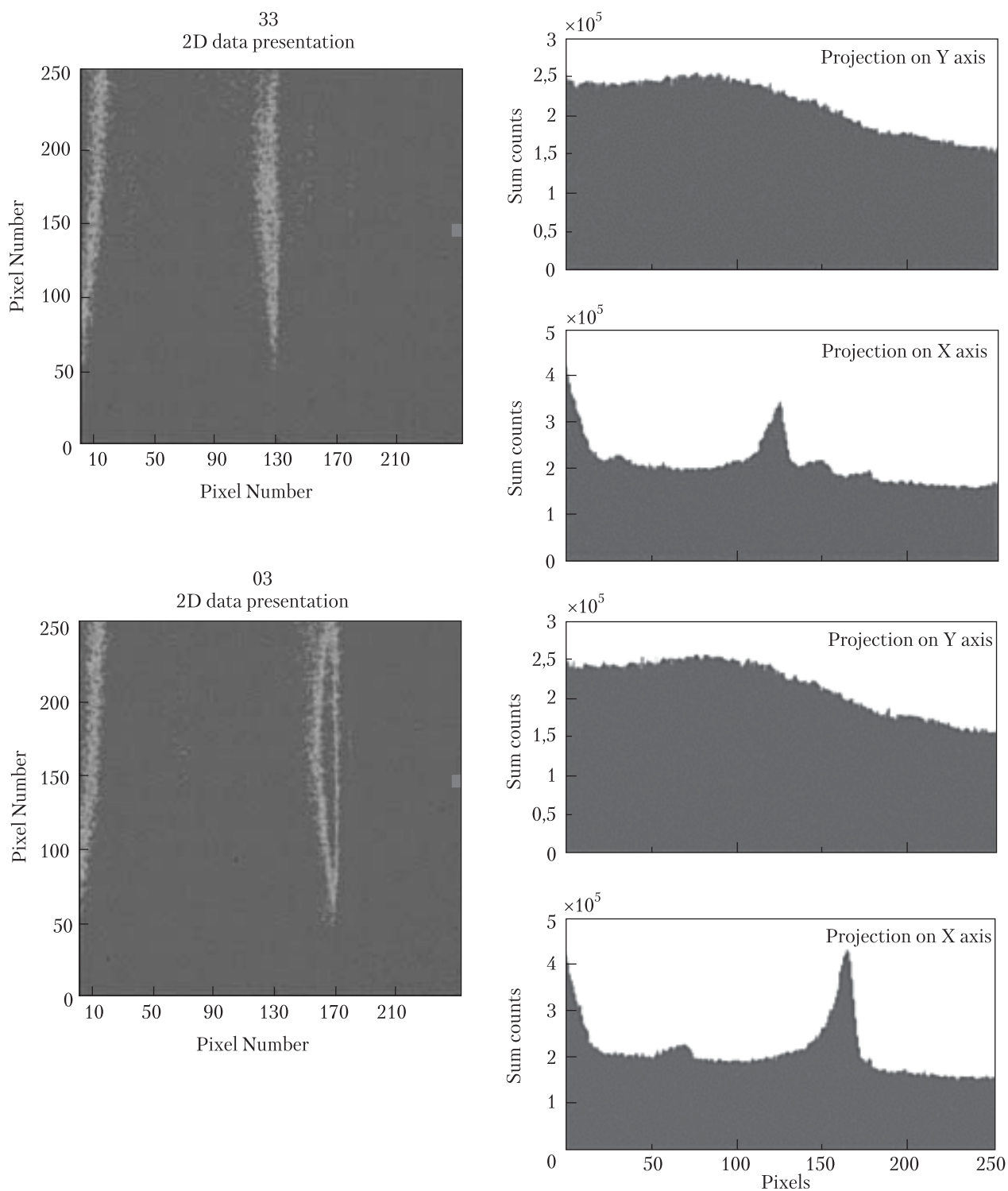


Fig. 6. Shift of the diffraction maxima during the phase transition observed by micro-pixel detector TimePix under the heating of the metal sample

of the magnetic field uniformity etc.) or for 'off-line' data analysis taking into account the shape of the chosen ion line ('locus') to improve mass resolution by projecting mass-data from that locus rather than simply onto the horizontal axis.

Micropixel detector TimePix for imaging dynamics of phase transitions in metals

The MEDIPIX Collaboration (CERN) has developed a pixel readout chip TimePix used for a variety of applications [8]. In particular, it has been successfully tested as a prototype of the electronic focal plane for measuring mass-spectra of low energy ions at the mass-spectrometer [9]. Its metal mode of operation has proved to be a reliable tool for imaging in real time intense X-ray beams at the bio-medical beam-line (ESRF, Grenoble). The TimePix hybrid pixel device consists of a silicon (300 μm thick) semiconductor chip with a common n-side electrode and a (256 \times 256) matrix of p-side (55 \times 55) μm^2 pixels bump-bonded to a readout chip with the same pixel structure. TimePix charge sensitive preamplifiers can operate input signals of both polarities providing leakage current compensation per pixel. There are two discriminators with globally adjustable threshold and a possibility of 3 bit threshold adjustment per pixel. 13 bit pseudo-random counter is activated via external shutter signal. For testing and masking purposes there are 1 test-bit and 1-mask bit per pixel.

We report here on the results of the first test of a TimePix as a tool for studies in real time of a dynamics of phase transitions in metal alloys under heating or cooling. Experiments were performed at the setup for the X-rays diffraction studies at the IPMS NASU. As metal is heated it may transform through different crystal structures before melting (α -, β -, γ - phases). Physical properties like density and thermal expansion vary significantly from phase to phase, inducing change of the corresponding diffraction maximum position. This phenomena is explored in for characterization studies of metal structure applying usually scintillator detector and mechanical

scanning of the slit ahead of the detector. It is a time consuming procedure while TimePix allowed us to get precise data in real time. Each pixel was programmed to record Time-Over-Threshold (TOT) data getting in this way analog information. The fast framing rate of up to 100 Hz is achievable with a new USB interface called FitPix [10]. This is a key feature for dynamical phase transition studies.

As an example the phase transition process was observed using the X-Ray diffraction. The sample was heated up to 700 $^{\circ}\text{C}$ and alpha- gamma-phases were observed in heating/cooling stages (Fig. 7). The TimePix can cover about 10° \times 2θ with angular resolution of $0,017^{\circ}$ at the distance of 220 mm from the specimen. Thus, the TimePix detector providing two-dimensional picture surveys as an 'electronic plate' imaging in real time a dynamics of phase transitions in metals.

CONCLUSIONS

Metal micro-detectors are on the way to become a powerful instrument for High Energy Physics and other applications. They have successfully demonstrated their reliable performance for measuring and imaging in real time ion as well as synchrotron radiation beams with energies ranging over nine orders of magnitude. Metal strip sensor is the only object interacting with the beam in the working area. This is achieved due to the developed original technology combining photo-lithography and plasma-chemistry etching. Besides creation in this way ideal conditions for the charge production/collection in a sensor its metal nature provides the highest possible radiation hardness of a device. MMD (currently available in Ukraine, only) are the thinnest (1 μm) sensors ever existed for measuring particles fluxes.

ACKNOWLEDGEMENTS

The author would like to thank colleagues from the HERA-B, LHCb and MEDIPIX Collaborations for the fruitful studies and discussions. The results presented were obtained in a pleasant collaboration with co-authors from:

CERN @ Geneva (M. Campbell, L. Tlustos, X. Llopart), IEAP @ Prague (S. Pospisil), ESRF @ Grenoble (Y. Prezado, M. Renier), IAP NASU @ Sumy (V. Storizhko, V. Eremenko, S. Homenko, A. Shelekhov), IPMS NASU @ Kiev (V. Burdin, S. Firstov, Yu. Podrezov, V. Minakov), INR NAS @ Kiev (O. Fedorovich, A. Chaus, O. Kovalchuk, O. Okhrimenko, D. Storozhik et al.), IMP NASU @ Kiev (V. Perevertailo et al.).

We would like to thank MEDIPIX-2 Collaboration. This work was partially supported by the CNCP (UK) project «Microstrip Metal Detectors».

REFERENCES

1. *Pugatch V. et al.* Metal foil detectors and their applications. Nucl. Instr. and Meth. A 535 (2004) 566–569.
2. *Pugatch V. et al.* Beam profile imaging target. Nuclear Physics. A701 (2002) 204–208.
3. *Pugatch V. et al.* Micro-strip metal detector for the beam profile monitoring // Nucl. Instr. and Meth. — 2007. — Vol. A581. — P. 531–534.
4. *Pugatch V. et al.* Plasma technologies for manufacturing of micro-strip metal detectors. Voprosi atomnoi nauki i tehniki (in Russian). № 1 (2007) 173–175.
5. *Pugatch V.M.* Quark processes at the nuclear multi-target setup of the HERA-B. Summer School And Conference On New Trends In High-Energy Physics: Experiment, Phenomenology, Theory. 16-23 Sep 2006, Yalta, Crimea, Ukraine. PROCEEDINGS. Edited by P.N. Bogolyubov, L. Jankovszky, V.K. Magas, Z.I. Vakhnenko. Kiev, Bogolyubov Inst. Theor. Phys., 2006. 287 p.
6. *Пузач В.М. та ін.* Система радіаційного моніторингу внутрішнього трека експерименту LHCb // Український фізичний журнал. — 2009. — Vol. 54, N 4. — С. 337–342.
7. *Llopart X. et al.* Timepix, a 65k programmable pixel readout chip. Nucl. Instr. and Meth. A 581 (2007) p. 485–489.
8. *Pugatch V. et al.* Metal and Hybrid TimePix Detectors Imaging Beams of Particles. Nucl. Instr. and Meth. A 650 (2011) 194–197.
9. *Prezado Y., Renier M., Bravin A.* A new method of creating minibeam patterns for synchrotron radiation therapy. J. Sync. Rad. 16 (2009) 582–586.
10. *Kraus V. et al.* FITPix — fast interface for Timepix pixel detectors. Journal Of Instrumentation (2011) Volume: 6, Issue: 01, Pages: C01079-C01079.

В.М. Пузач

ПОЗИЦІЙНО ЧУТЛИВІ МІКРО-СТРІПОВІ
ТА МІКРО-ПІКСЕЛЬНІ ДЕТЕКТОРИ

Наведені фізичні та технічні характеристики металевих детекторів для вимірювання та візуалізації профілю пучків заряджених частинок і синхротронного випромінювання. Надзвичайно мала товщина (~1 мкм) детекторного матеріалу мікросріпового металевго детектора (ММД) у поєднанні з високою радіаційною стійкістю (~100 МГр) дозволяє проводити визначення пучків на постійній основі. *In-situ* робота ММД забезпечує неруйнівну променеву діагностику в реальному часі. Коротко описано застосування мікро-стріпових та мікро-пиксельних детекторів.

Ключові слова: металеві детектори заряджених частинок і синхротронного випромінювання, моніторинг пучків синхротронного випромінювання, мікро-стріпові та мікро-пиксельні детектори.

В.М. Пузач

ПОЗИЦИОННО ЧУВСТВИТЕЛЬНЫЕ
МИКРО-СТРИПОВЫЕ
И МИКРО-ПИКСЕЛЬНЫЕ ДЕТЕКТОРЫ

Приведены физические и технические характеристики металлических детекторов для измерения и визуализации профиля пучков заряженных частиц и синхротронного излучения. Чрезвычайно малая толщина (~1 мкм) детекторного материала микро-стрипового металлического детектора (ММД) в сочетании с высокой радиационной стойкостью (~100 МГр) позволяет проводить определение пучков на постоянной основе. *In-situ* работа ММД обеспечивает неразрушающую лучевую диагностику в реальном времени. Кратко описано применение микро-стриповых и микро-пиксельных детекторов.

Ключевые слова: металлические детекторы заряженных частиц и синхротронного излучения, мониторинг пучков синхротронного излучения, микро-стриповые и микро-пиксельные детекторы.

Стаття надійшла до редакції 04.01.12