High intensity beam diagnostics system based on novel metal micro-detectors

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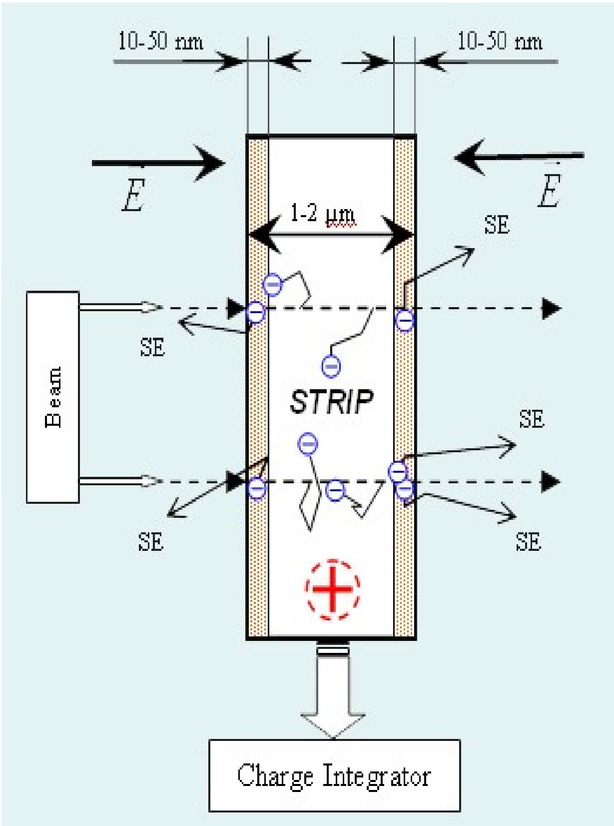
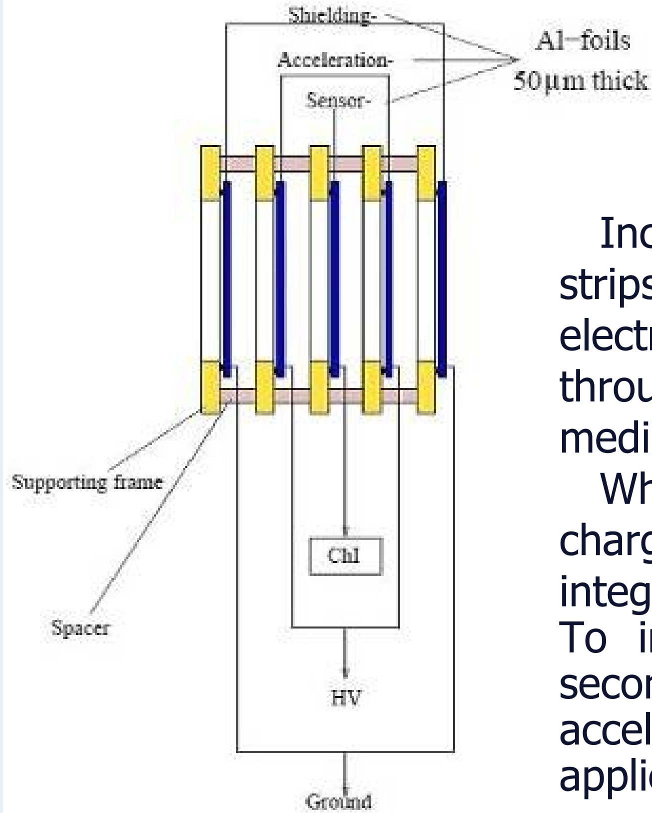
Content

- Physics and techniques of metal detector systems
- Applications for the beam profiling
  - Low energy ion beams
  - Intermediate ion energy
  - High energy particles (HERA-B, LHCb)
  - Synchrotron radiation beams (HASYLAB, ESRF)
  - Beam imaging (Metal Pixel Detector)
- R&D. Current status of metal micro-detectors

Metal Detector. Physics





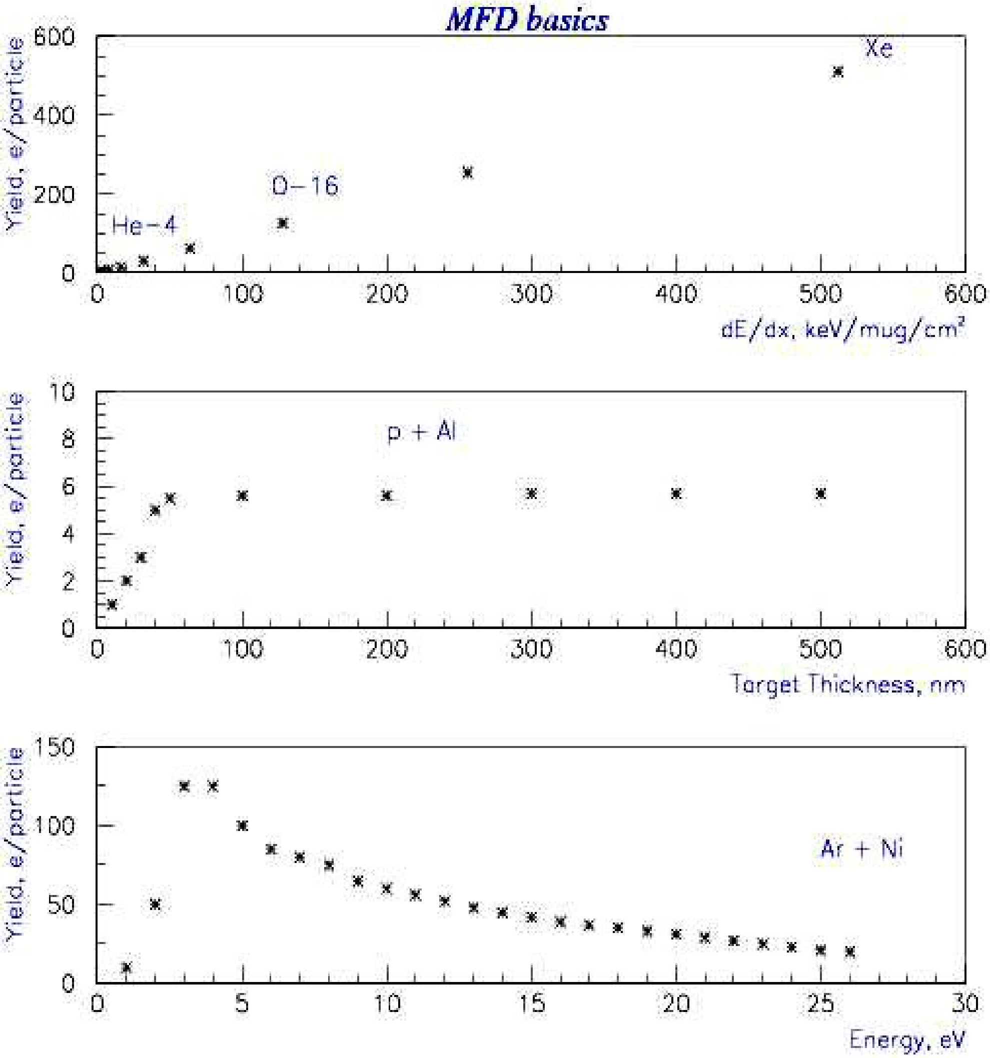
Incident particles on the strips initiate secondary electron emission as they pass through the nearly transparent medium.

When this happens, a positive charge appears at the integrator end is measured.

To improve the extraction of secondary electrons an accelerating electric field is applied around the strip.

This technology works with x-rays, protons and other ion beams. Additionally, the strips are nearly transparent to beams, significantly reducing degradation that is experienced by absorbing detectors.

Metal Detector. Physics

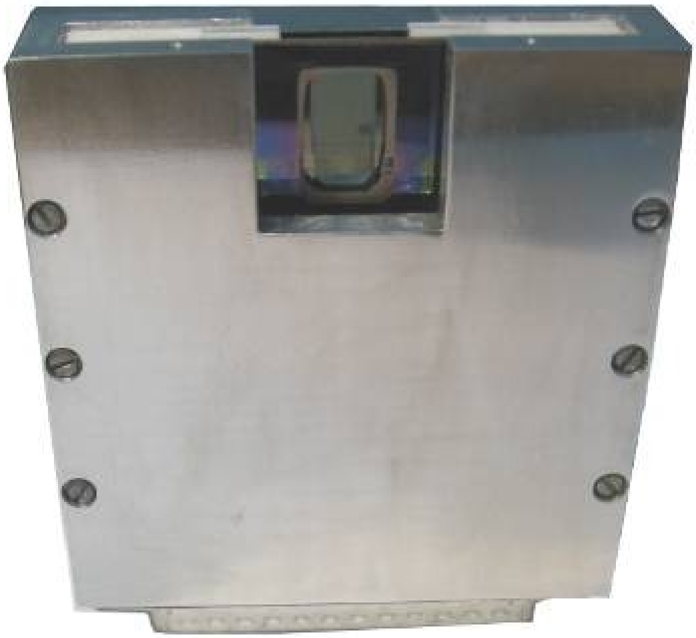


SEE yield as a function of dE/dx

SEE yield as a function of the foil thickness

Spectrum of 'zero'-energy electrons.
δ-electrons contribute at ~10 %, in total.

Micro-strip Metal Detector

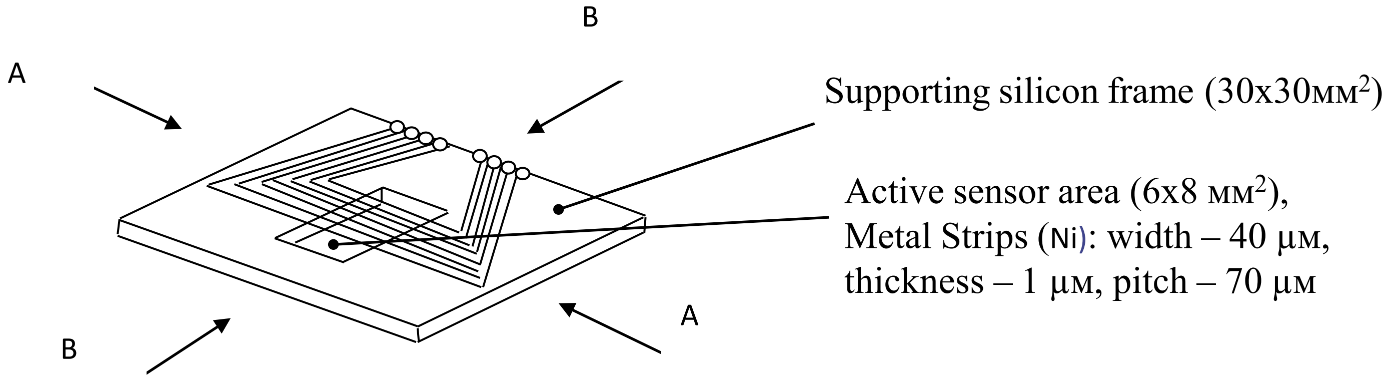


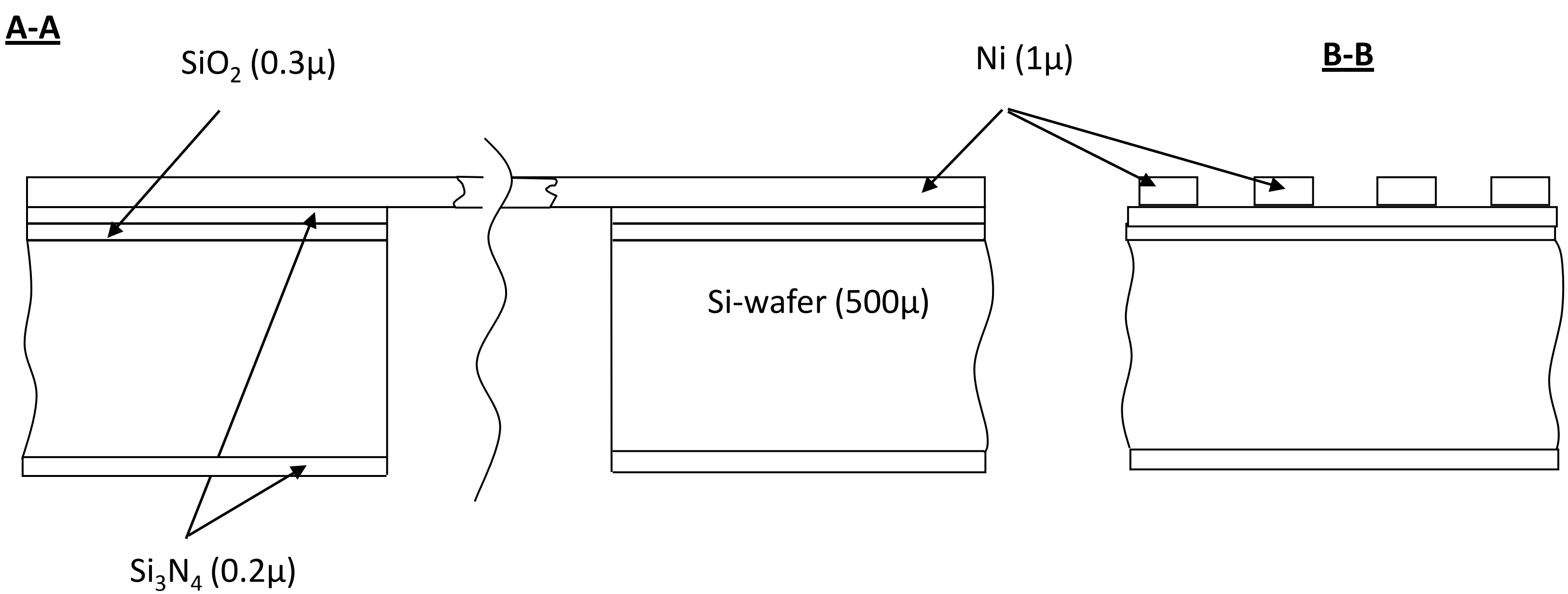
MMD has been developed at Kiev Institute of Nuclear Research (Kiev) in close collaboration with Institute of Micro-devices (Kiev), Max-Planck Institute of Nuclear Physics (Heidelberg) and DESY (Hamburg)

These detectors are 1 μm thick !

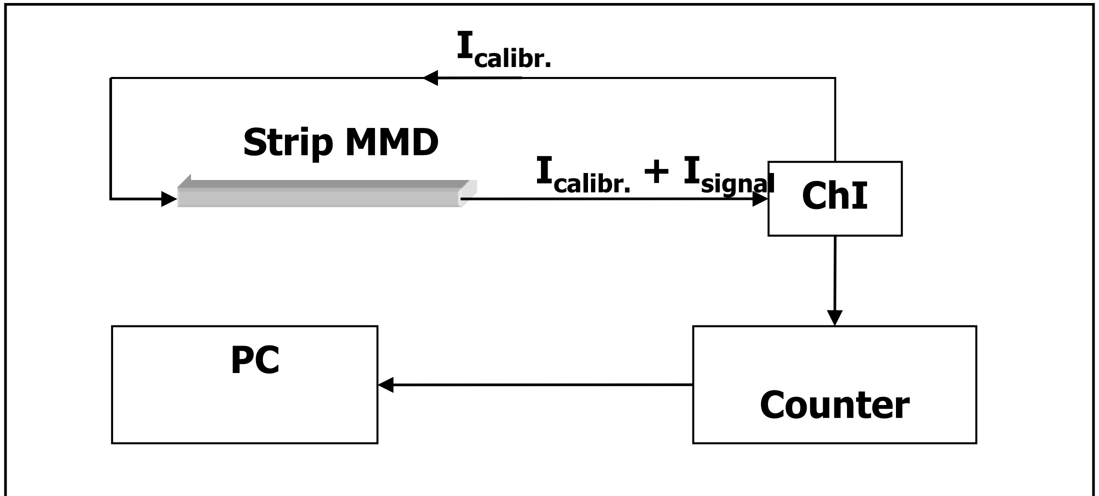
MMD initially were designed
for the beam profile monitoring
of charged particles and synchrotron radiation

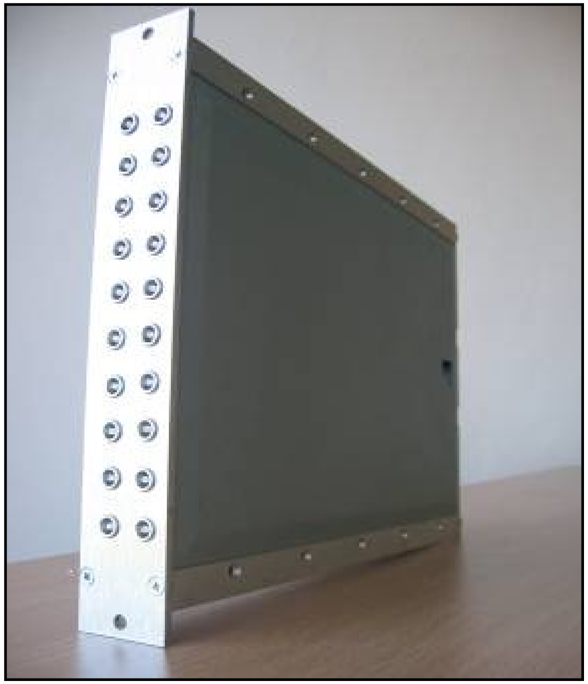
Micro-strip Metal Detector. Production technology





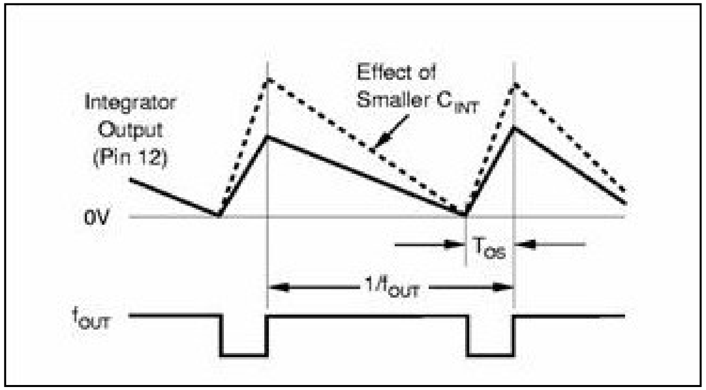
Charge Integrator for the MMD readout



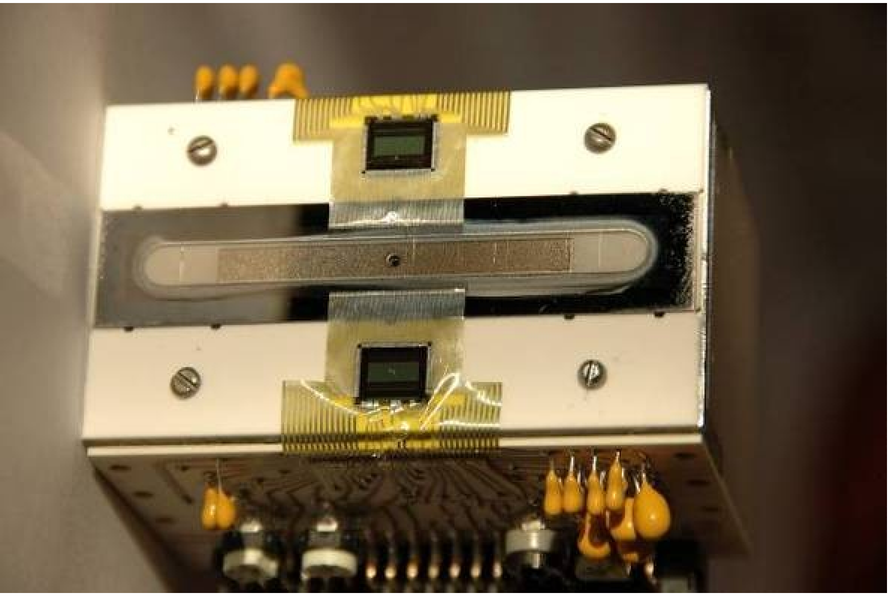


Charge Integrator (with VFC):

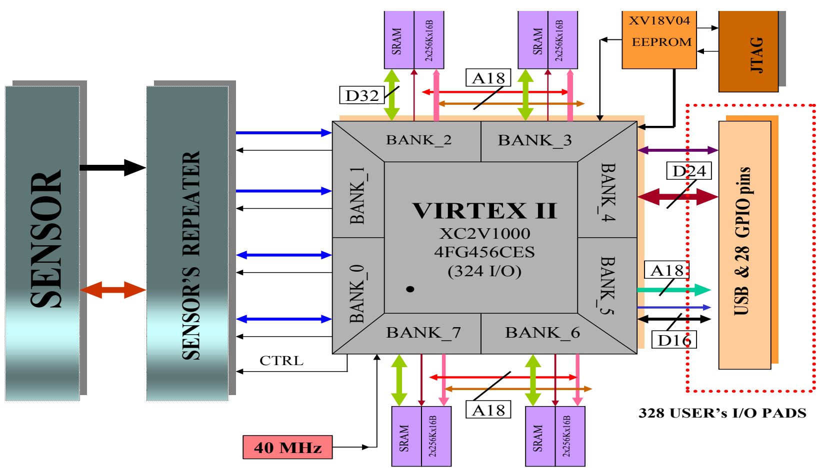
- 1 fA input charge – 1 Hz output frequency
- Dynamical range - 10 fA - 10 nA (~10 Hz – 10 MHz) **6 orders**
- Linearity: 0,02%
- Baseline drift: ±2.5 % / 24 h
- Temperature: < 0.3 % / 1 °C



MMD ReadOut



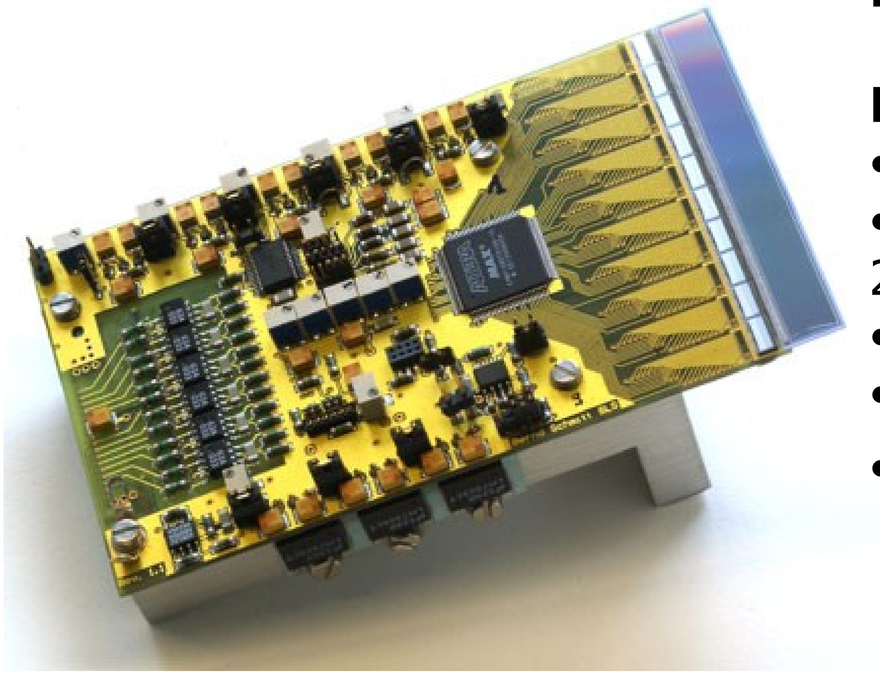
VA-SCM3 (Gamma-Medica, Oslo) – commercial 128 channel charge sensitive preamplifier. Mounted on the flexible micro-cable designed and built at the Institute of Micro-devices (Kiev)



Expected Performance of MMD are following:

- Spatial resolution: 20 μm
- Sensitivity: from 5000 ions/s
- Dynamic range: 10^4
- Integration time: from 100 μs

MMD ReadOut

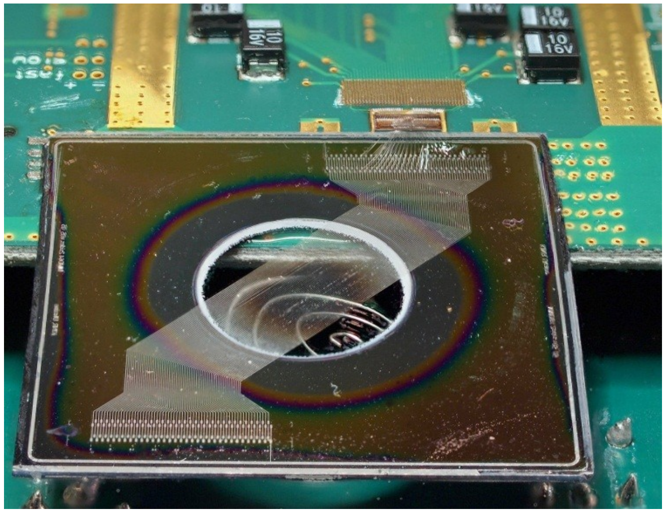


MYTHEN Detector Module

Read out chip:
- 128 channels
- low noise preamp (noise ≈ 230 e-)
- 18 bit counter
- Read-out time: 250 μs
- Count rate: 1 MHz per channel

GOTTHARD - Analogue readout system with single photon sensitivity and extended dynamic range

MMD64 connected to the GOTTHARD chip!



MMD advantages

- Metal strip sensor is the only object interacting with the ion 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.
- There is a good chance to build a metal pixel detector applying similar technology.

Metal Detectors. Applications

Metal Foil Detector technology allows for Building any size beam monitoring systems:

- **HERA-B Luminosity monitoring,**
- **LHCb Radiation Monitoring system**
- **BPM for 21 MeV proton beam (tandem MPIfK)**
- **BPM for the LHCb (ST) test beam studies**
- **21 keV Synchrotron BPM at HASYLAB**
- **5 MeV Electron beam BPM – KINR**
- **150 KeV Synchrotron BPM at ESRF**

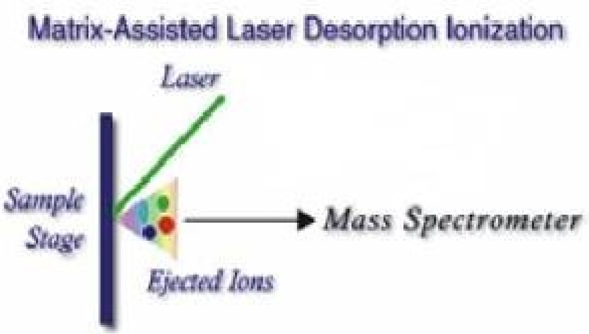
Metal detectors are suitable for measuring and imaging beams of charged particle in the energy range from keV to TeV as well as synchrotron radiation.

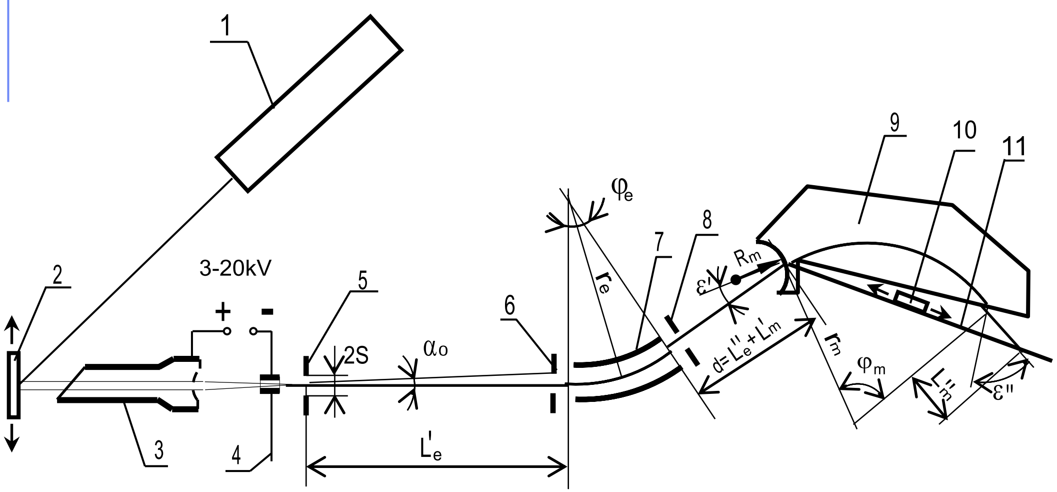
Low Energy Ion Beams

The TimePix chip was mounted in a vacuum chamber on a moveable platform at the focal plane of a laser double-focusing mass spectrometer.

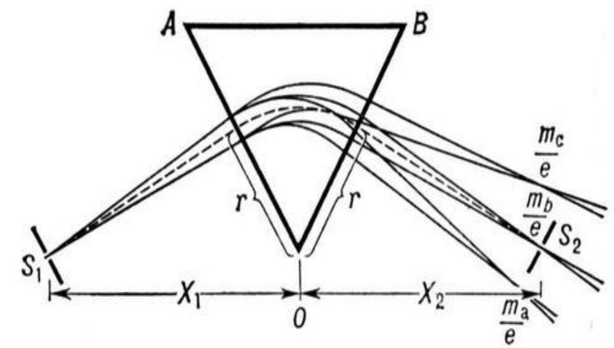
Schematics of the ion path in a laser mass-spectrometer
(Institute of Applied Physics NASU, Sumy, Ukraine.)

Ions: H – Pb, $1^+ <= Z <= 4^+$, 3 – 80 keV.



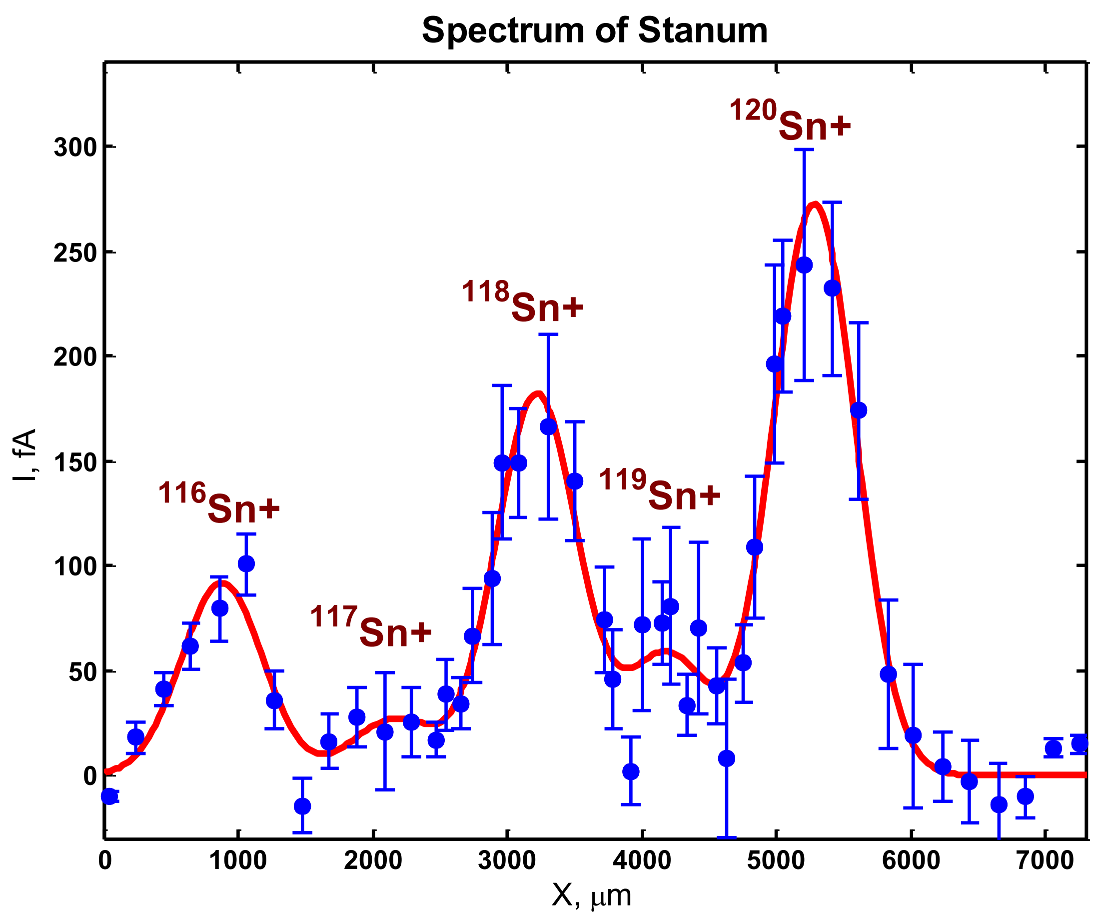


1 – Laser, 2 – Target, 3 – Accelerator, 7 – Energy analyzer, 9 – Magnet, 10 – Detector, 11 – Focal plane



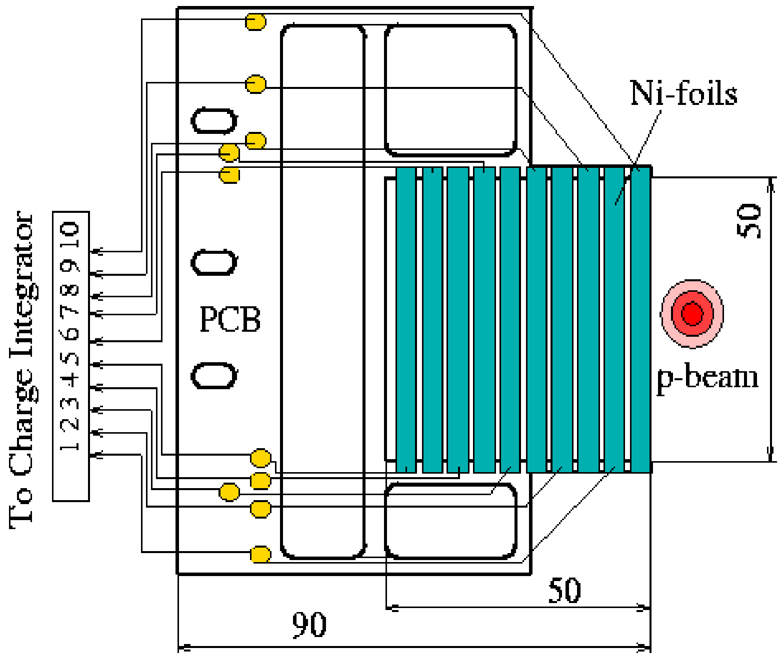
Low Energy Ion Beams

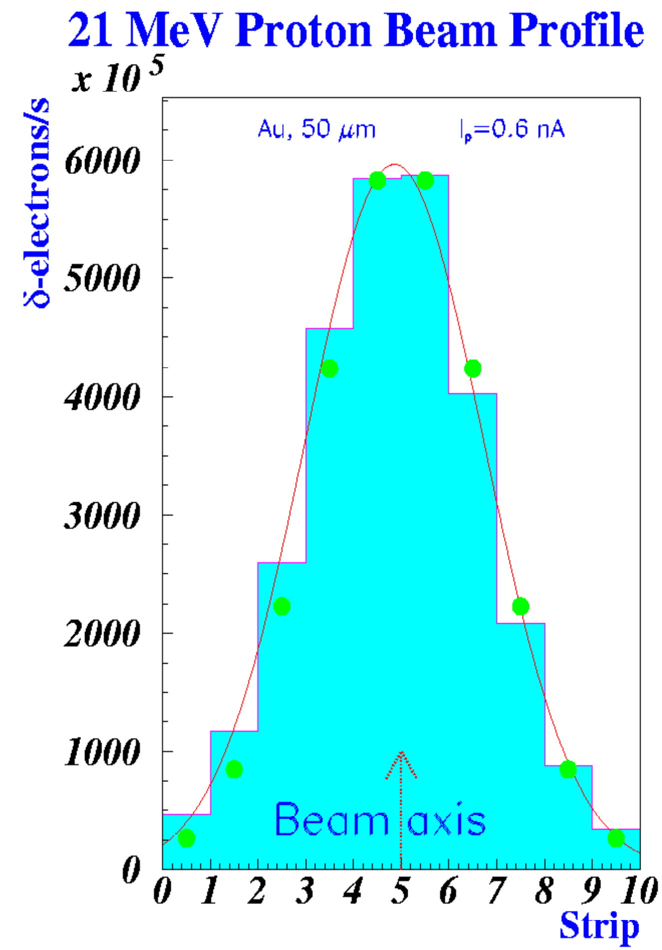
Mass-spectrum of Tin isotopes, measured by MMD in MS



Intermediate Energy Ion Beams

Proton beam profile monitoring. Tandem at MPIfK (Heidelberg)

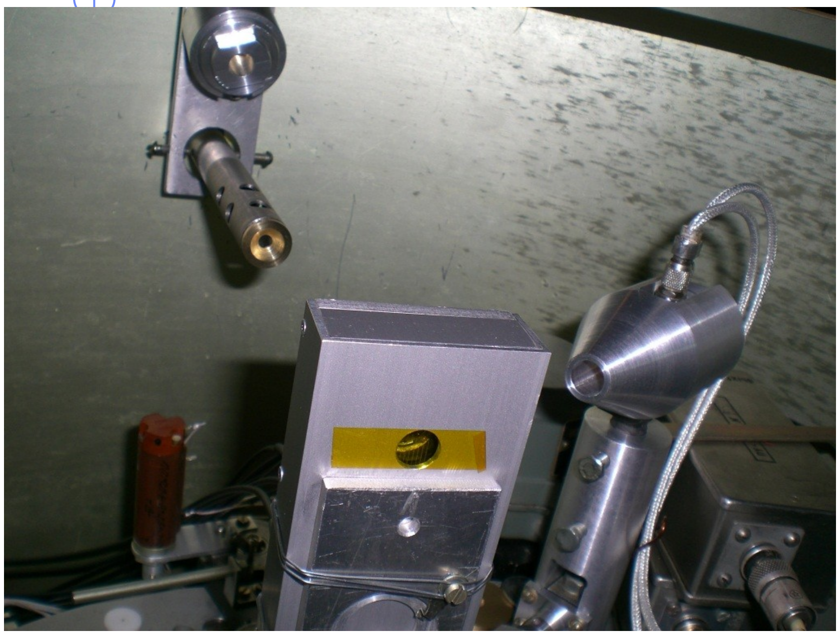


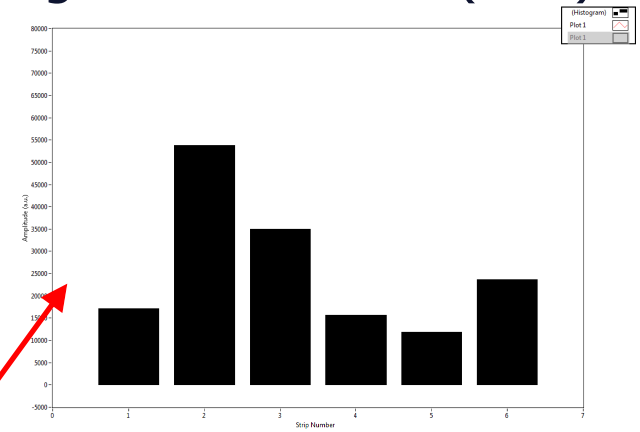


Left part: BPM (50 x 50 mm^2). Proton beam axis is perpendicular to the BPM plane. Right part: 21 MeV proton beam profile measured by the BPM.

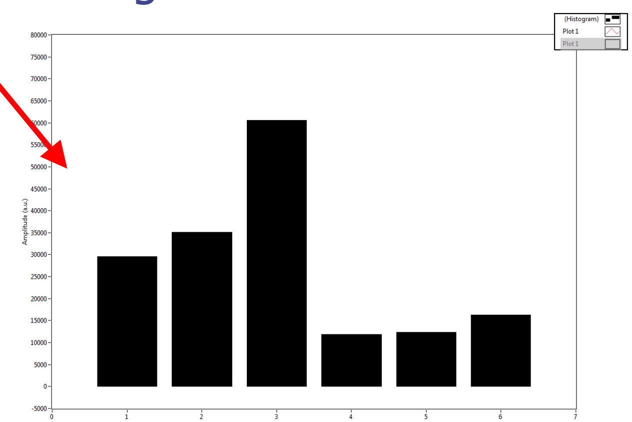
Intermediate Energy Ion Beams

6 MeV Proton beam profile monitoring. Tandem-generator at INR (Kiev)





Y-axis detector moving



High energy particles

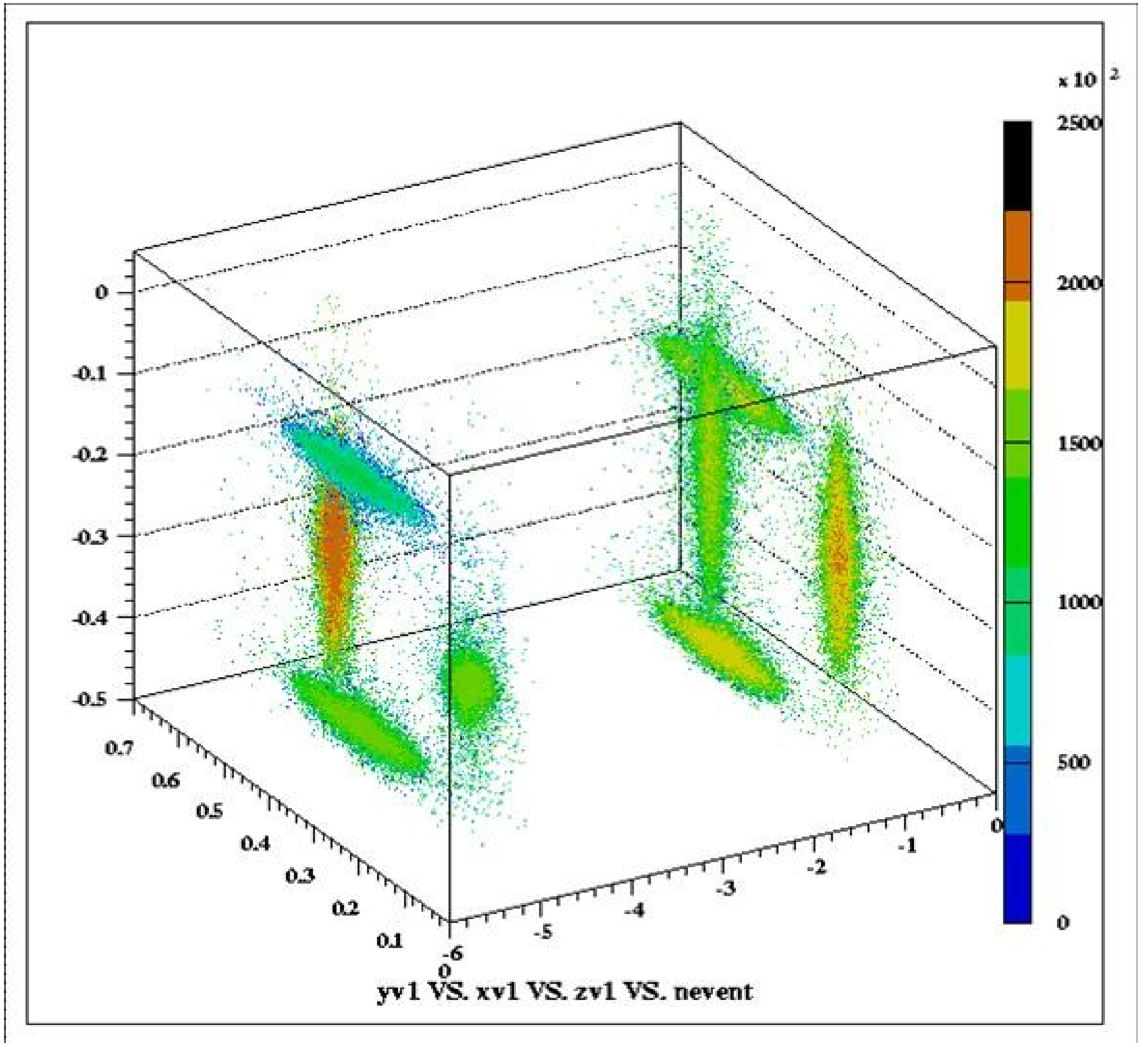
HEP experience - HERA-B (DESY, Hamburg) –

- 8 metal-target-detectors generating 8 Interaction Points (IP), simultaneously, at the 920 GeV proton beam halo.
- 12 –sector Metal-Foil-Detector (MFD) for the luminosity/background monitoring.

Technical characteristics:

- Multi-beam production (8 IPs successfully tested).
- Precise beam-target positioning (10 nm) – 8 beam intensities equally distributed.
- Large dynamical range (10^8) for measuring beam intensity (from 10 fA).
- Imaging/separating IPs/background by asymmetry method with a precision of 0.1 mm using MFD.

Metal Detectors at HERA-B



920 GeV protons

Metal Detectors at HERA-B

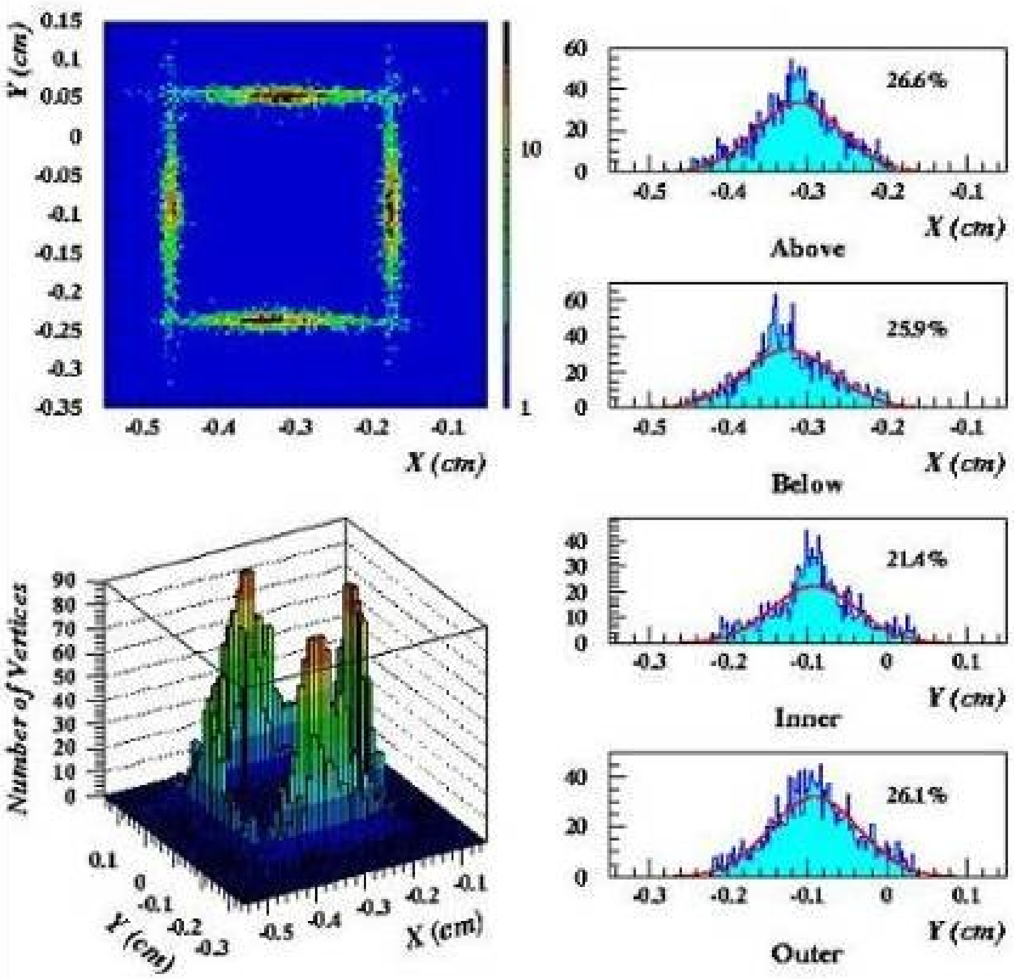


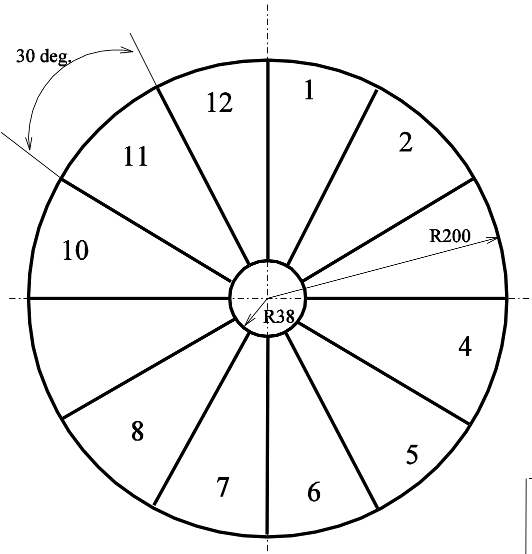
Illustration of the equalization of the Interaction rates among 4 IPs by means of the Metal Detectors-Targets. Shown are number of events reconstructed by Vertex Detector (~ 25 % pro target).

Metal Detectors at HERA-B

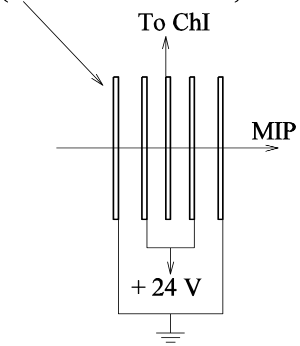
Luminosity Foil Monitor (LFM).

LFM is fixed at the VDS exit window
(downstream side of the SL-8 box).

There are 10 sectors of the Luminosity Foil Monitor.
Numbering is clockwise (looking into the beam).
No. 3 and No.9 do not exist.



Cross-section of the LFM sector.



Cable connections:

Foil sector	Cable	ChI-input	BNC cable
1	FM1	1 - 1	41
2	FM2	1 - 2	42
4	FM4	1 - 3	43
5	FM5	1 - 4	44
6	FM6	1 - 5	45
7	FM7	7 - 1	46
8	FM8	7 - 2	47
10	FM10	7 - 3	48
11	FM11	7 - 4	49
12	FM12	7 - 5	51

Remark: It is worthwhile to connect calibrating current at the ChI inputs (~ 20 kHz) in parallel to the FM cable (using T- BNC connector). There will be always control of the ChI baseline , which has to be updated.

Please, check ChI 7-3 (it didn't work)...

12 sectors Metal Foil Detector has been operated at the exit window of the Vertex Detector to monitor relative luminosity.

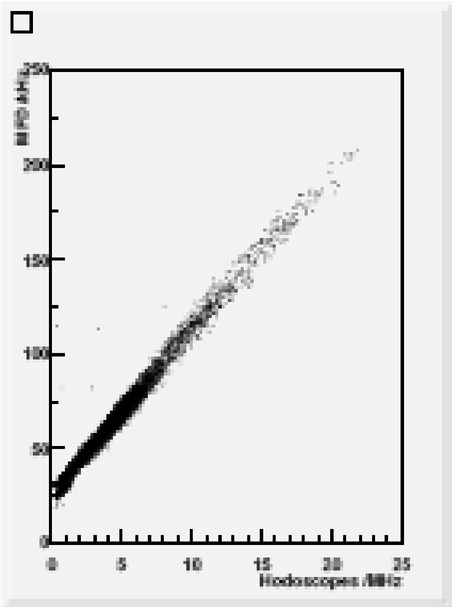
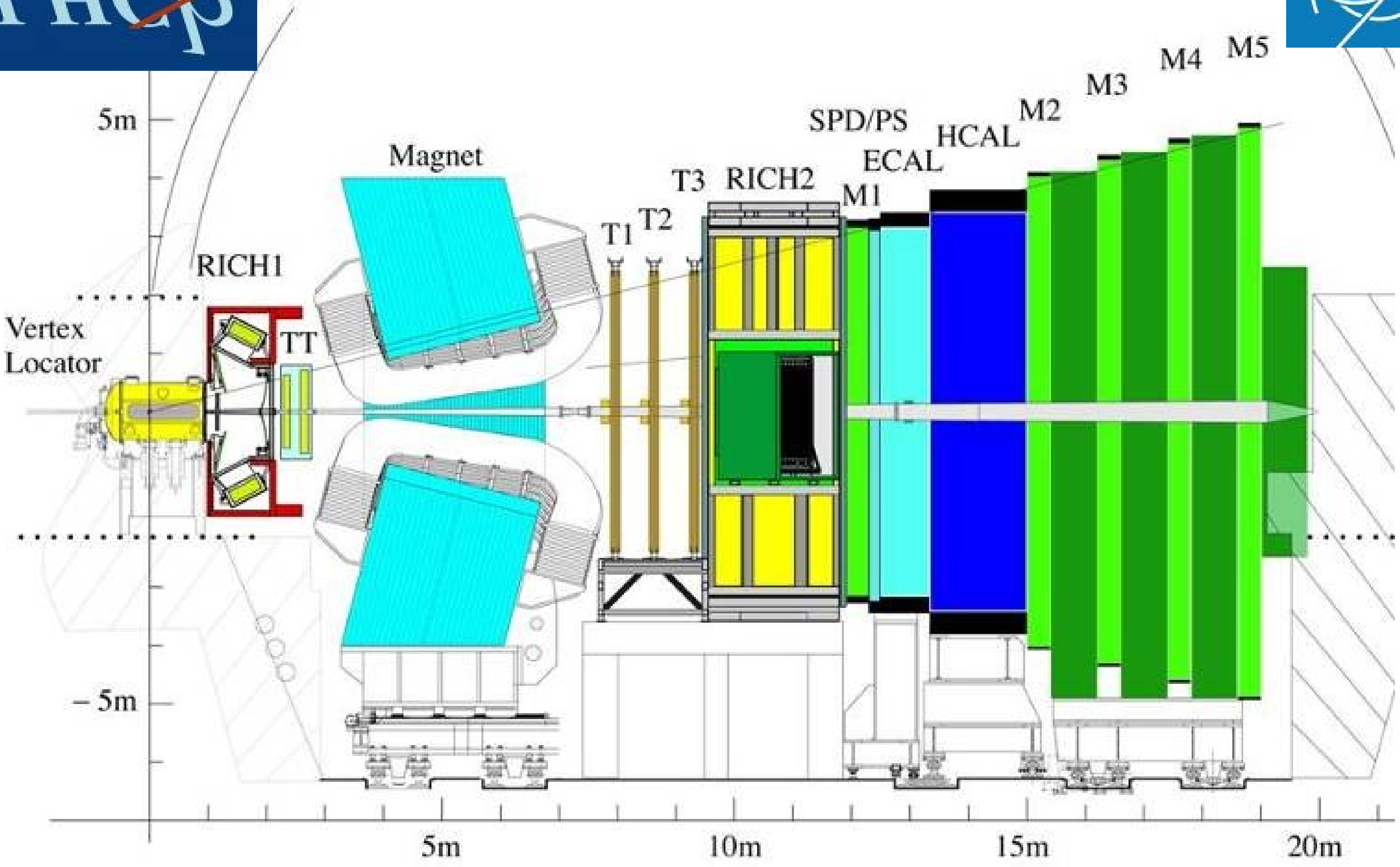


Figure 9: MFD luminosity monitor response to the HERA-B IR measured by hodoscopes.

Metal Detectors at LHCb



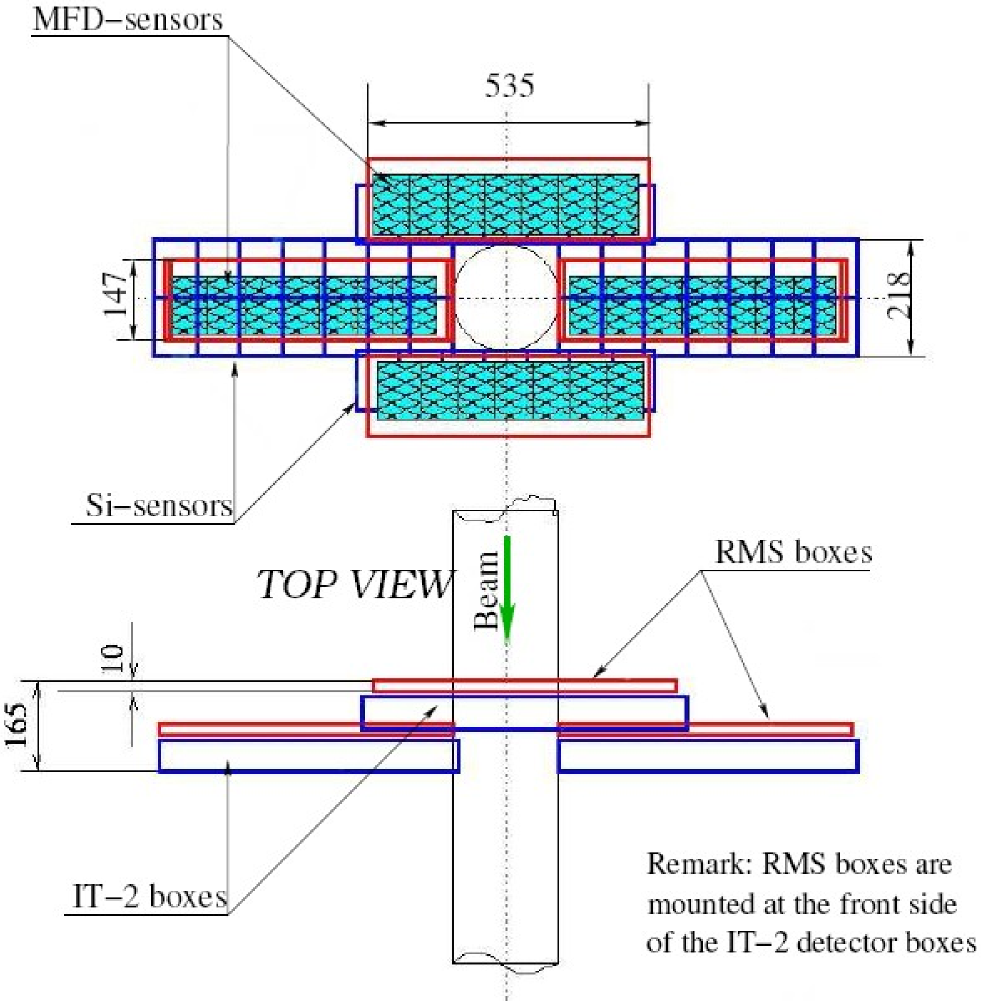
Metal Detectors at LHCb

Radiation Monitoring System (RMS) for the LHCb Silicon Tracker

- The RMS main goal – monitoring of the radiation load on Silicon Tracker Sensors
- Applying ASYMMETRY METHOD to the RMS data one can provide a monitoring for:

- charged particles induced background as well as relative luminosity of the LHCb experiment
- interaction point position (in XY-plane, only)

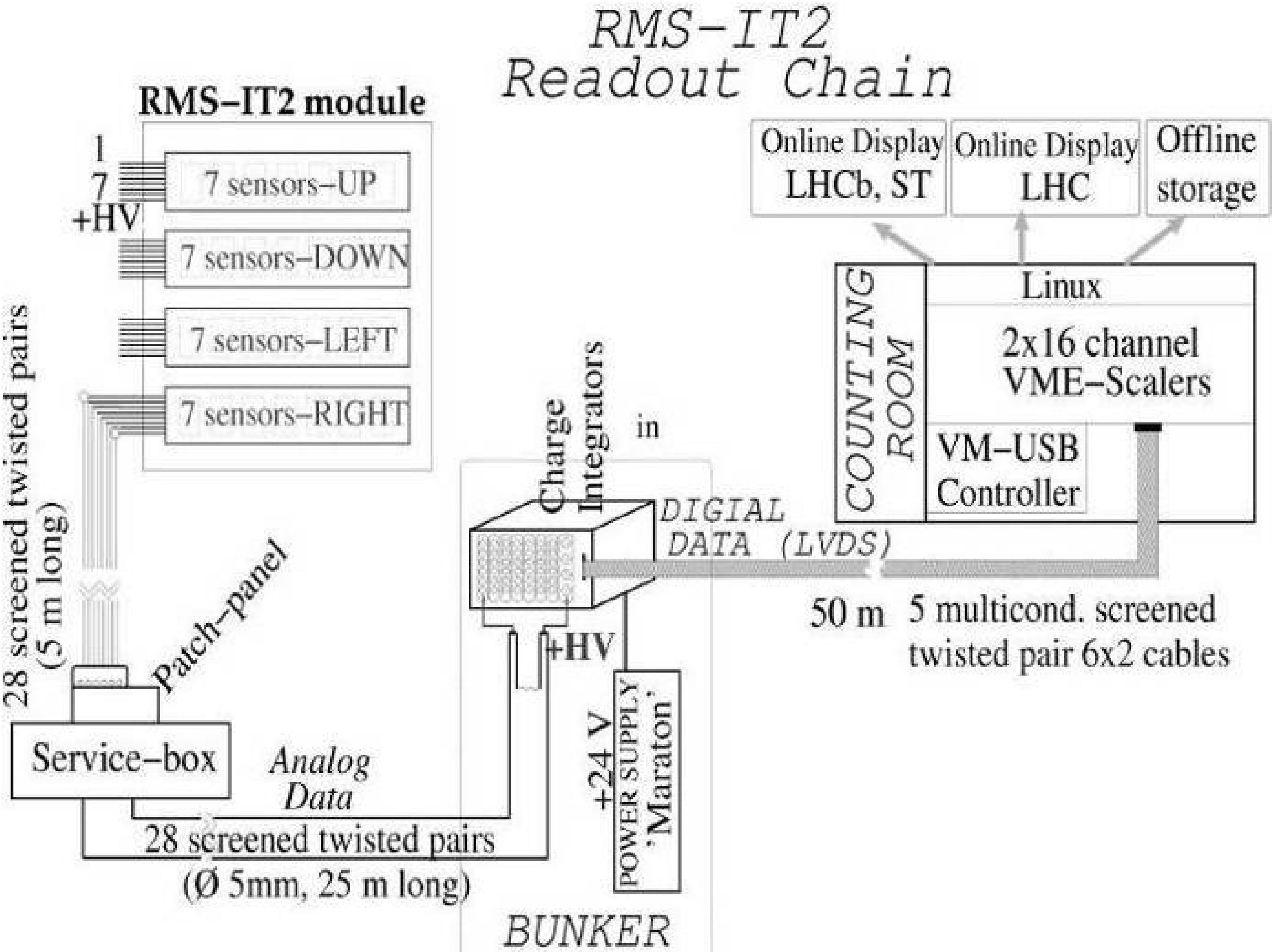
Metal Detectors at LHCb



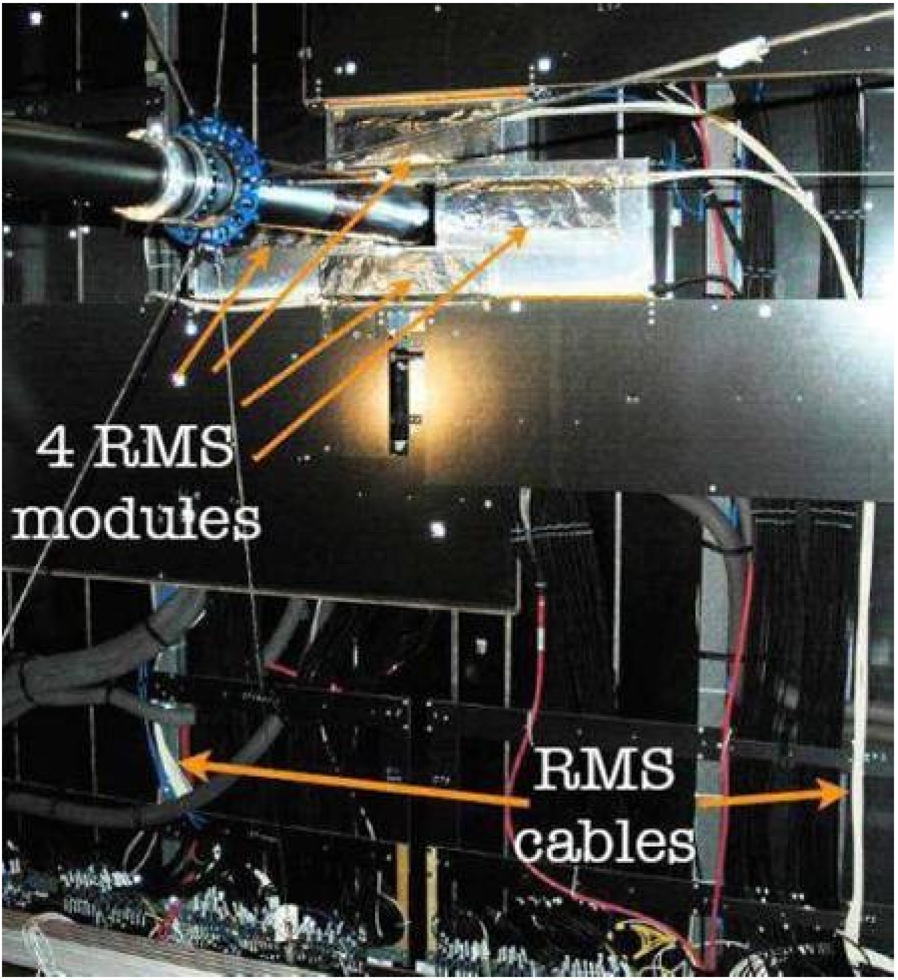
- The RMS (detection part) comprises 4 Boxes (left, right, top, bottom) fixed at the IT-2 station
- 7 MFD sensors (Al –foil 50 μm thick (110 x 75 mm^2) in each
- Dimensions are close to Inner Tracker modules

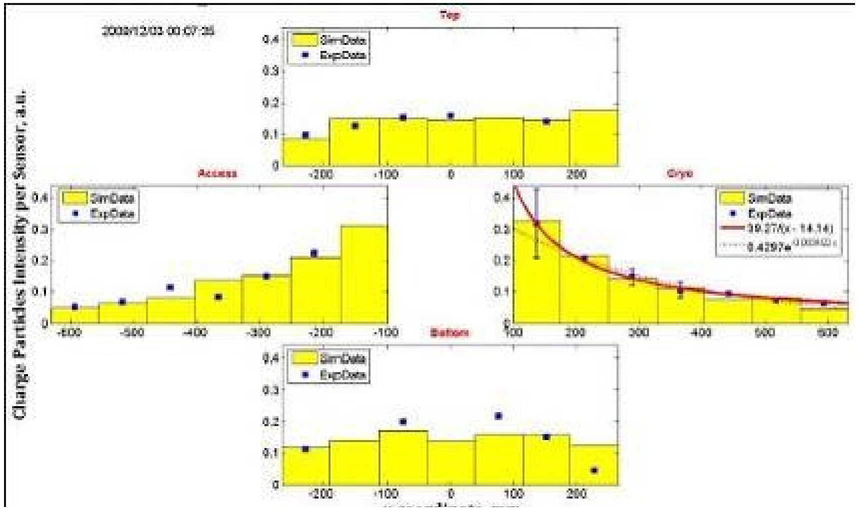
  (535 x 147 mm^2)

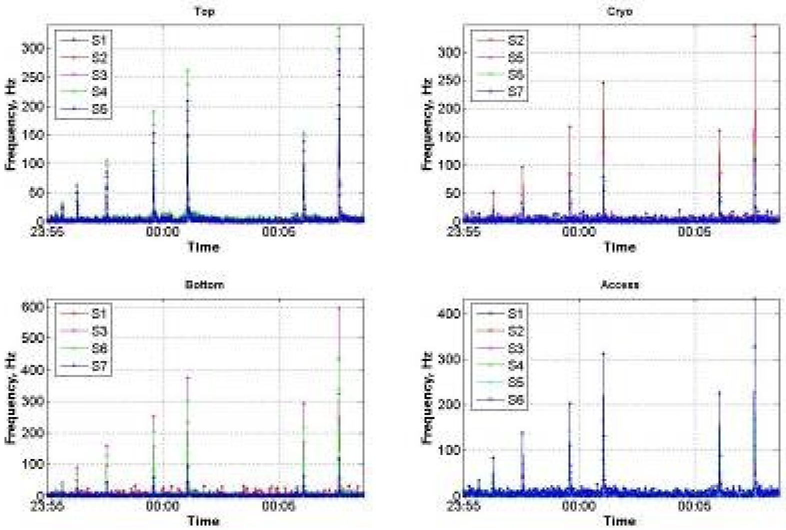
Metal Detectors at LHCb



Metal Detectors at LHCb



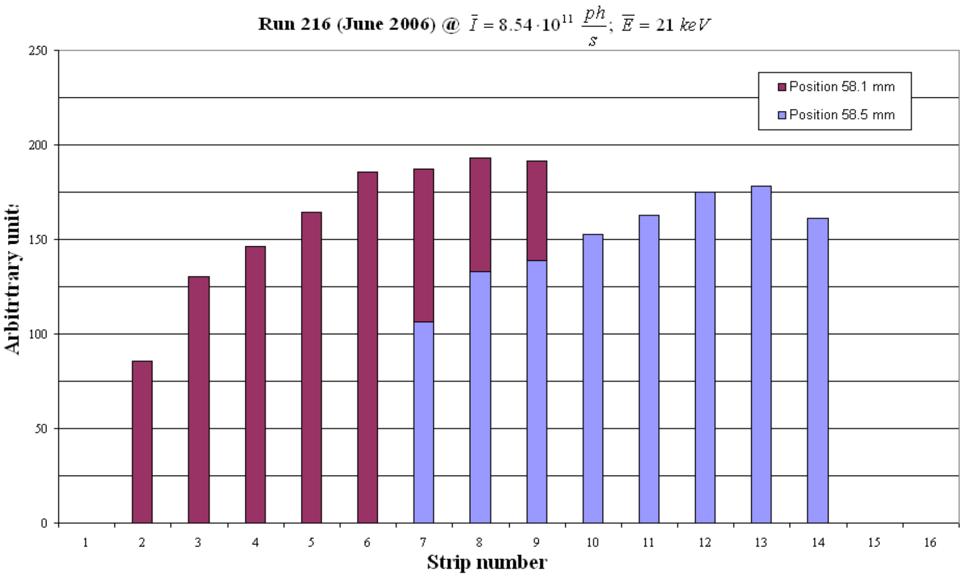


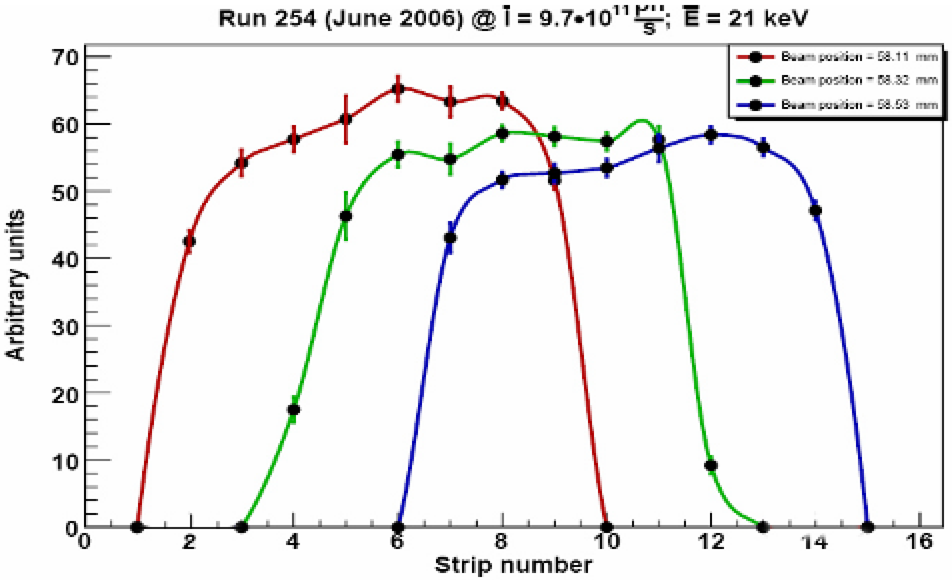


Synchrotron Radiation Profiling

21 keV synchrotron radiation

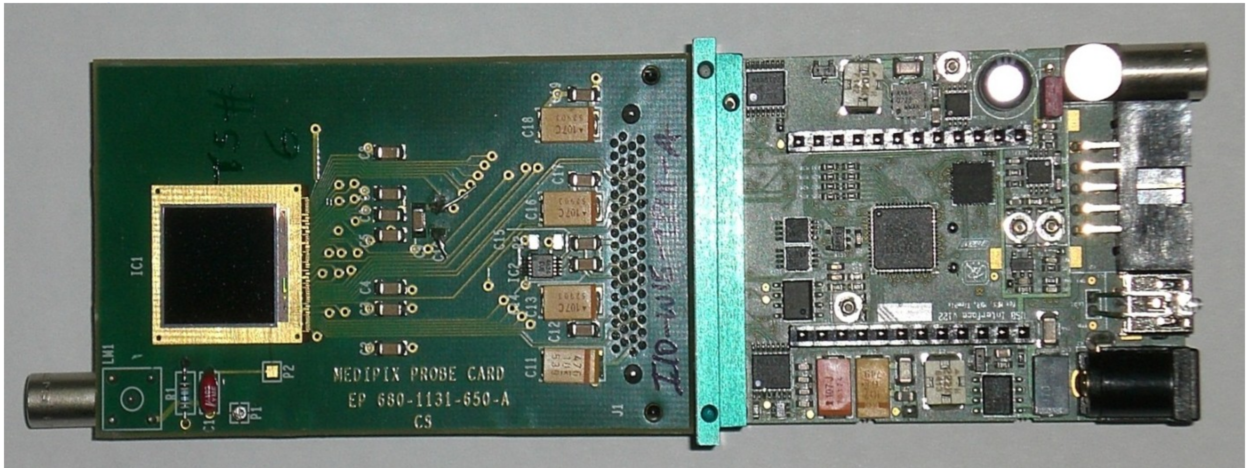
MMD test at the HASYLAB (DESY, Hamburg).

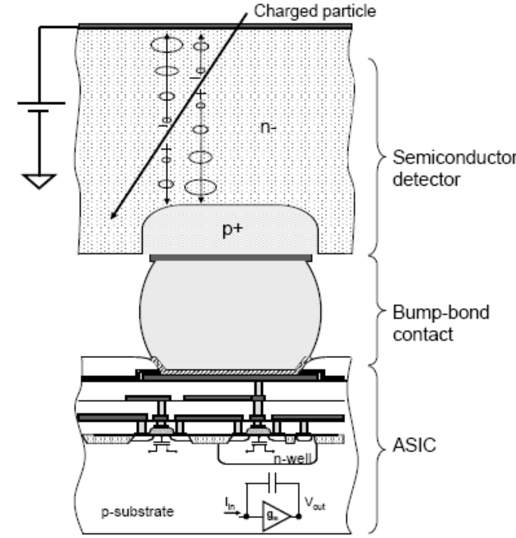




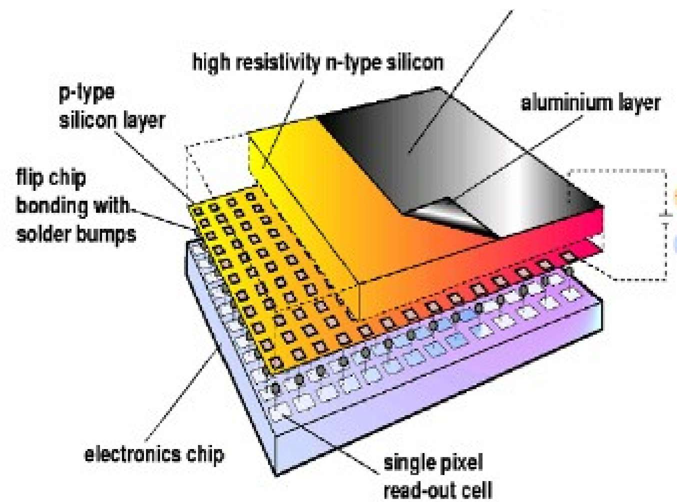
Beam Imaging. TimePix Detector

Hybrid pixel detector with the n-Silicon sensor chip and the TimePix electronics chip connected via bump bonds.





- 256 x 256 pixels
- 55 µm side length
- Direct X-ray conversion
- positive or negative charge input
- single energy threshold.
- 3 modes: Single particle counting, Time over Threshold or Arrival time mode.
- 13-bit counter per pixel.
- Parallel and serial read-out are realised.



TimePix Detector. Metal mode

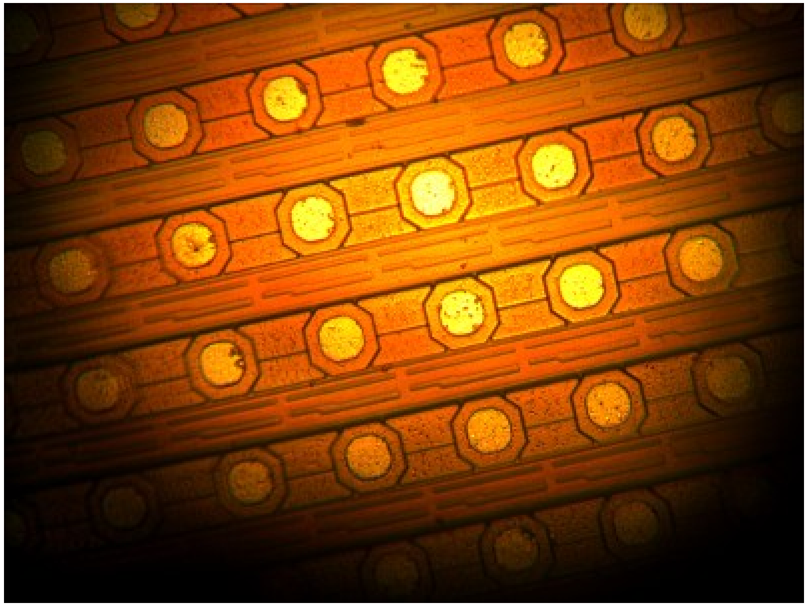
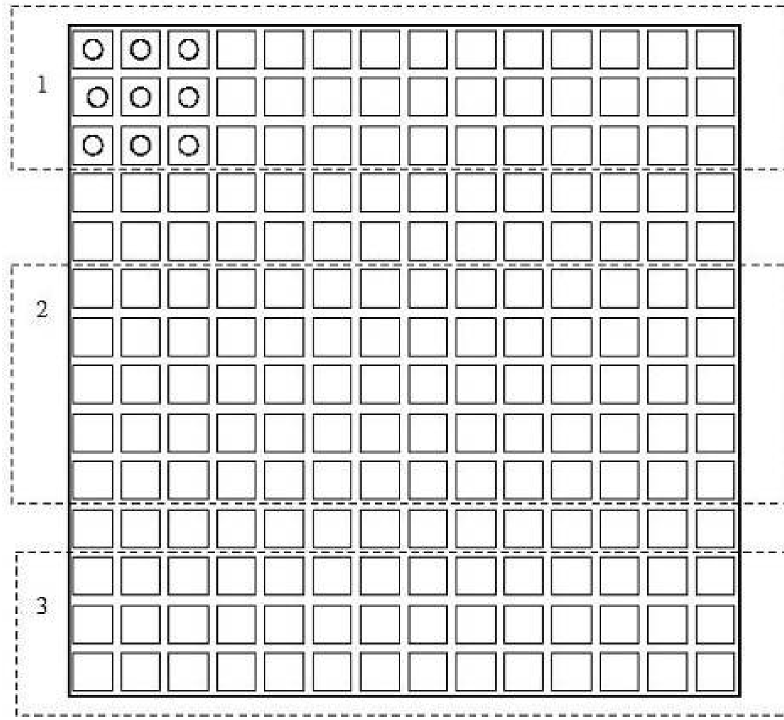


Photo of the individual pixels
of the MEDIPIX-2 chip (55 x 55 μm^2,
256 x 256 pixels)
(CERN, MEDIPIX Collaboration).

FOUR–Zone–test–TimePix (TpX, 256 x 256 pixels, 55 x 55 mu^2)



ZONE–1 – 256 pixels will be bonded to 256 strips of the MMD by two flexible microcables (128 + 128) lines , pitch 110 mu, width 40 mu, 5 cm long – to the 1st and 3d raw of the TPX
Bonding pads – (40 x 40) mu^2

ZONE–2 – (256 x 128) pixels will be bump bonded to the METAL Pixels on Poliimide
Poliimide – 40 mu thick, Metal pixels – 20 mu thick (50 x 50) mu^2

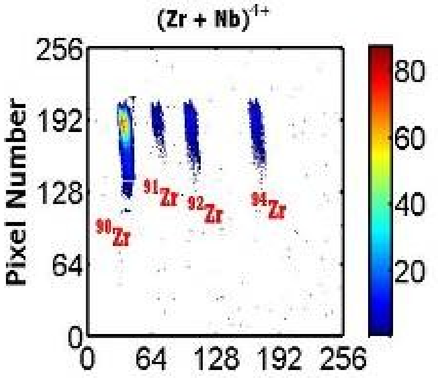
ZONE–3 – (256 x 100) pixels – virgin TPX.

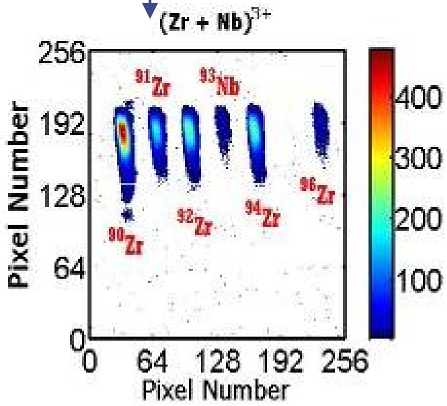
TimePix measuring low energy ion beams

- Ions beam has been generated at the sample-target by the infrared (1064 nm) laser (15 ns, 50 Hz).
- Passing through the magnetic sector ions were focused accordingly to their mass over charge ratio in a focal plane (210 mm long) of the mass-spectrometer.
- For each bunch of ions detected by a pixel a triangular pulse is formed with a height proportional to a number of ions in a bunch. Whenever the new bunch of ions arrives at the pixel its counter content is increased accordingly to the number of ions in the bunch.
- TimePix chip was readout by the PIXELMAN hardware/software (IEAP, Prague) via USB-connection to PC.
- Real-time digital information, high speed communication and data transfer are essential features of TimePix chips for a mass-spectrometry.

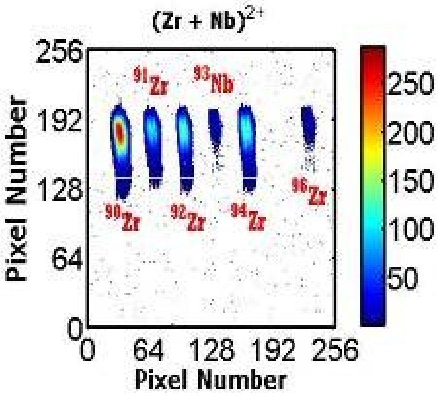
TimePix measuring low energy ion beams

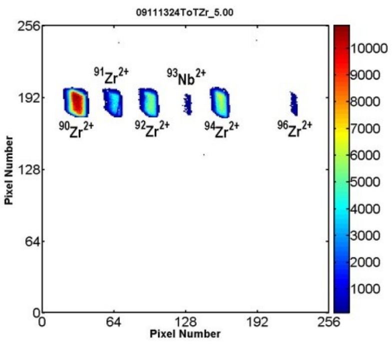
Zr (Nb) isotopes (May 2009).





Metal mode of MEDIPIX-2 is operational for low energy ions !

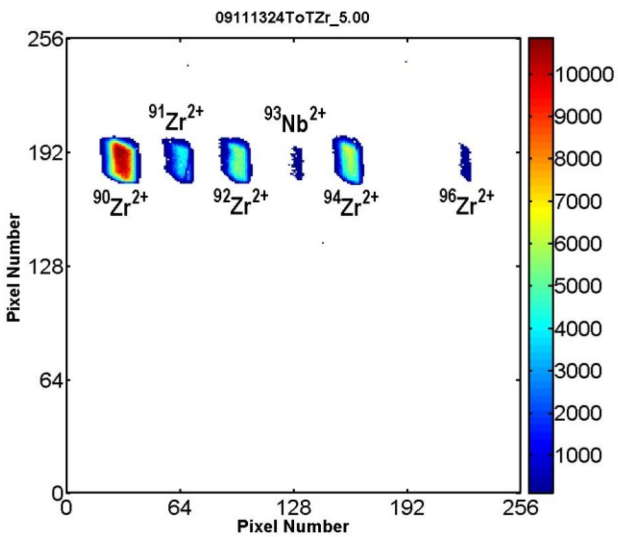




Data 14th Nov. 2009

Compare new data (Nov. 2009) and (May 2009): The TimePix data were used to improve focusing: the vertical size is ~ 3 times less, now!

TimePix measuring low energy ion beams



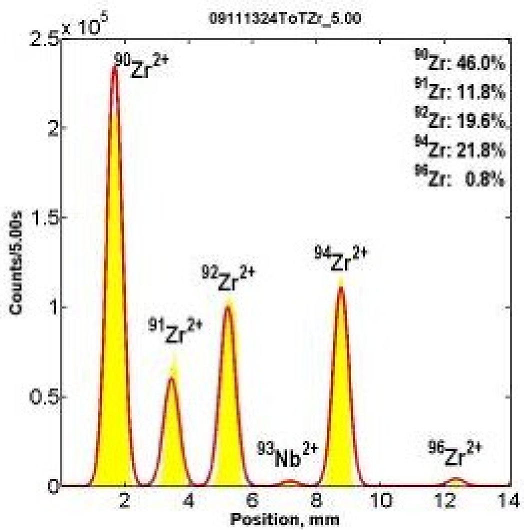
X – axis –
along the focal plane
(mass-spectrum)

Y – axis –
along the image
of the laser beam spot
at the target

Z – axis –
intensity of the
analyzed ions

2D mass spectra of sample with Zr^{2+} – isotopes .

Energy of ions 12,3 keV



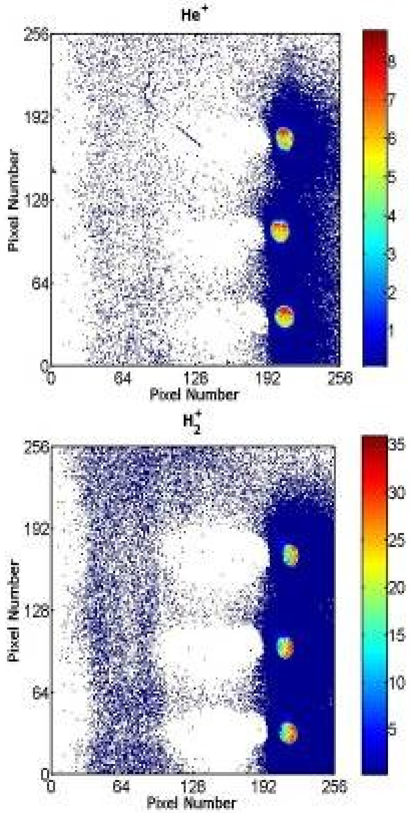
Two dimensional data on-line – 'electronic photo-plate' –
for alignment, focusing, testing stability of electric and magnetic fields etc.,)
A powerful tool in a feedback system for fine tuning of a mass-spectrometer and similar devices.

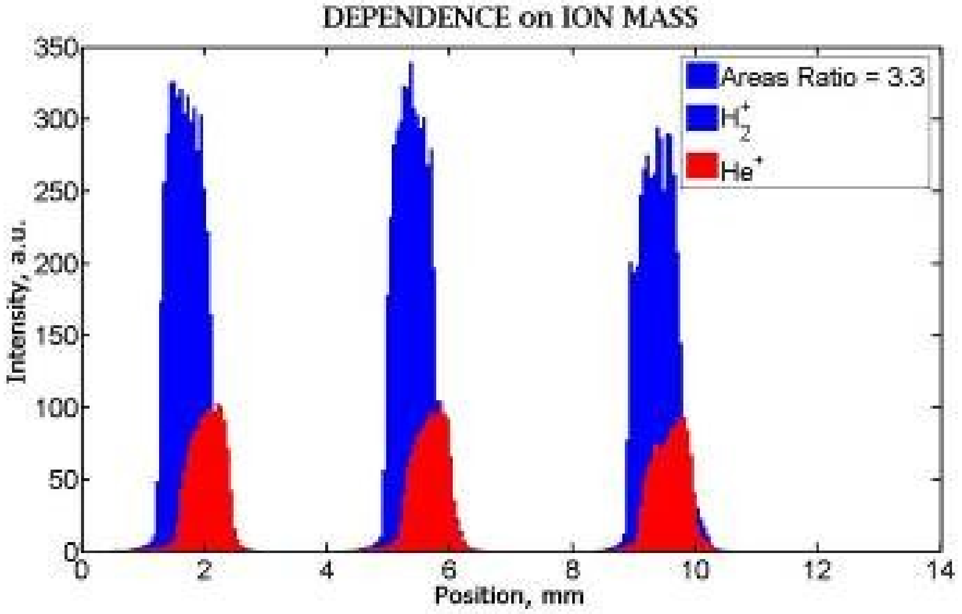
TimePix measuring low energy ion beams

Ion source at the INR (Kiev) isochronous cyclotron U-240.

Energy of ions – 30 keV.

Aperture: 3 holes, 1mm diameter separated by 4 mm



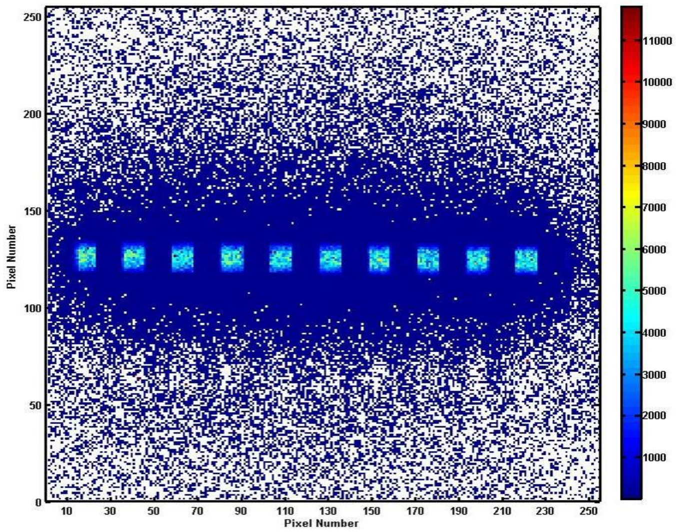


Factor of 3 difference in the response of Timepix to He and H_2 ions.

TimePix measuring High intensity X-Ray beams

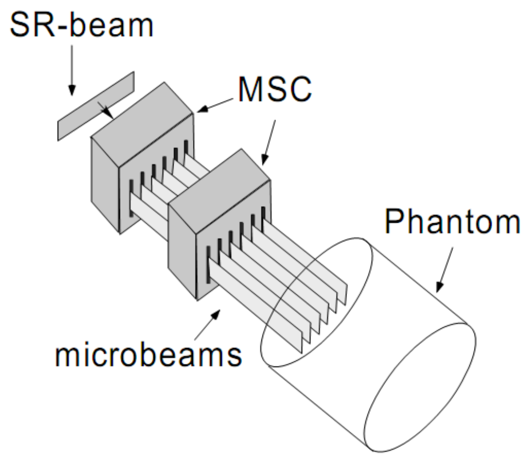
Measurements at the beamline ID17 ESRF (Grenoble)

The experiment (ESRF, MI1056) was carried out at the beamline ID17 with closed wiggler gap (24.8 mm) in the 16-bunches mode and with 200 mA electron beam current in the storage ring with the electrons energy of 6 GeV. X-rays with peak energy of 150 keV (ranging from 20 to 500 keV) were produced with intensity of 2,7×109 photons/(c×mm2×mA).



2D image of the 10 X-ray beams measured by the TimePix (Metal) detector.

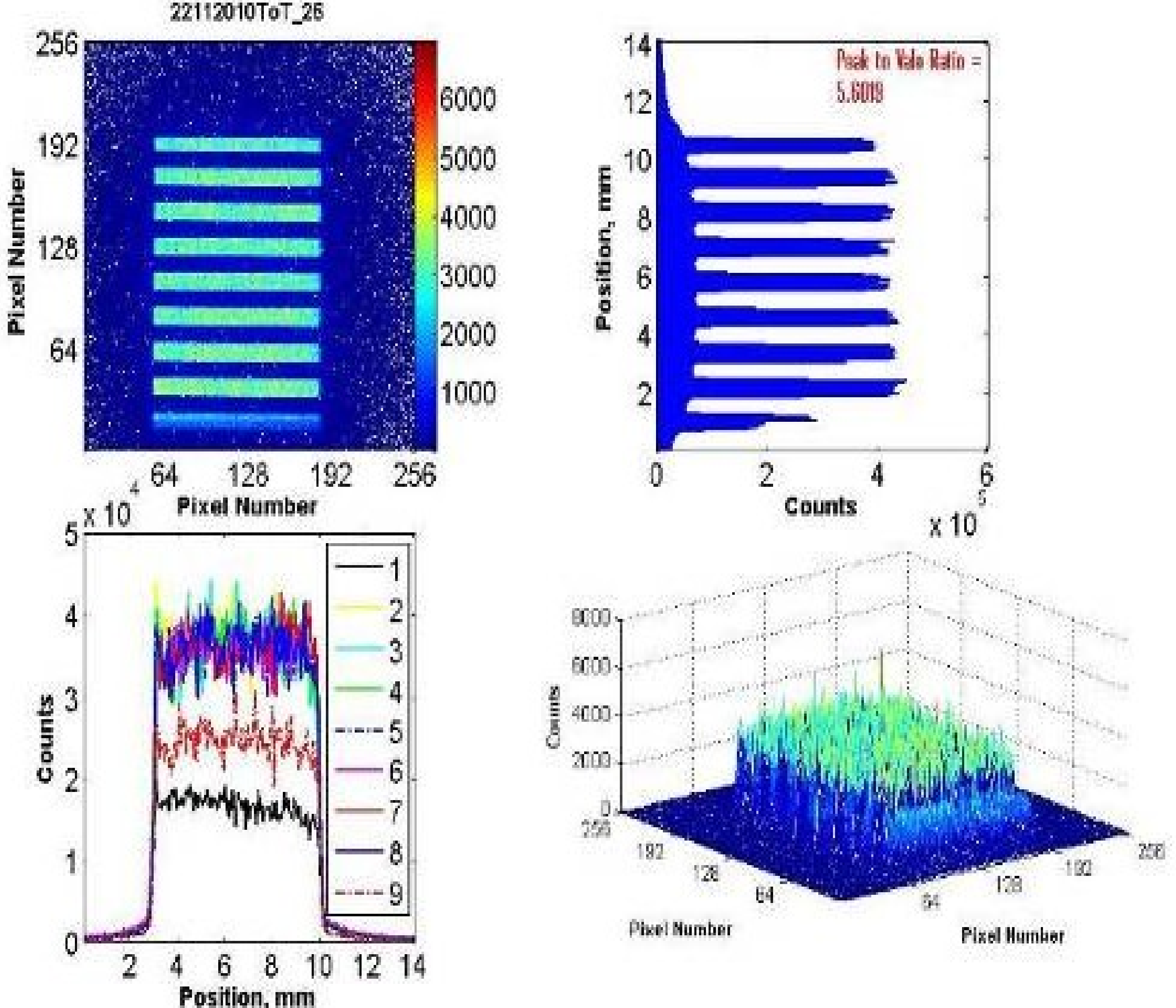
The spatially fractionated mini-beam



Energy: 150 keV
Intensity: $2{,}7 \cdot 10^{11}$ photons/(c·mm^2)

Metal TimePix detector imaging the X-ray beam.
Color grade indicates the relative beam intensity.

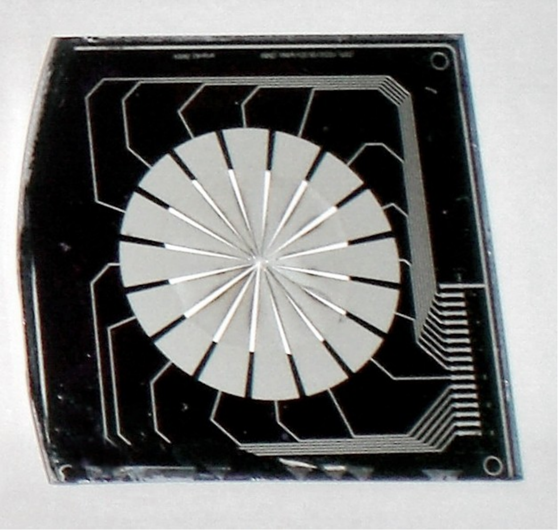
TimePix measuring High intensity X-Ray beams



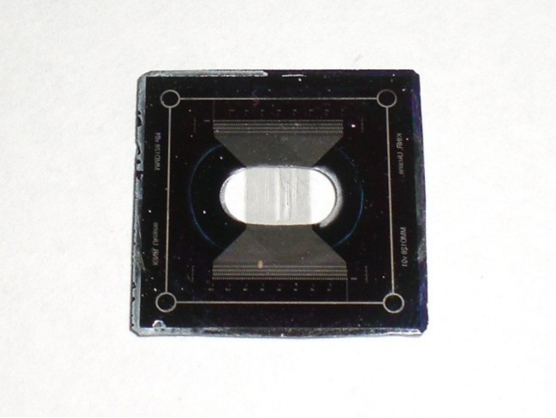
Micro-strip Metal Detectors. Current Status

MMD: 64 strips, 100 µm pitch, 40 µm width, 1 µm thick

MMD: 16 sectors, 1 µm thick

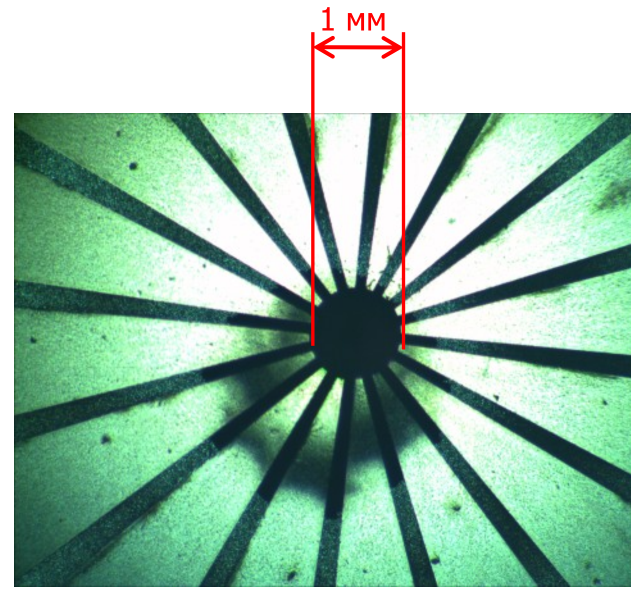


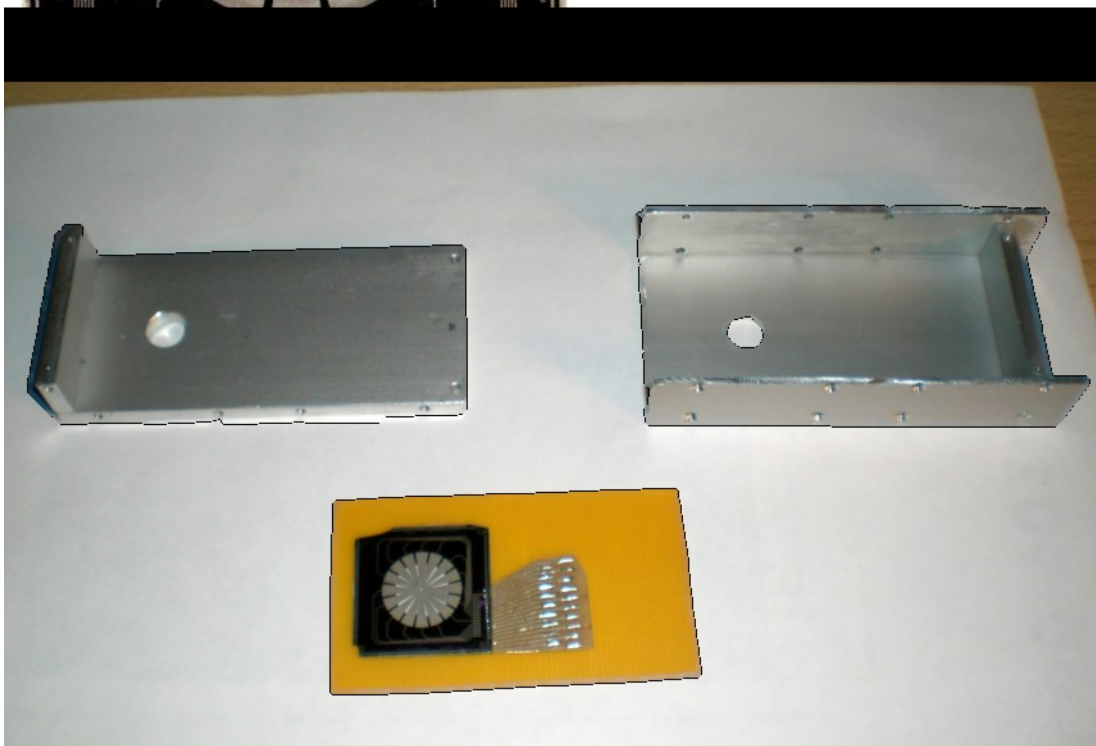
MMD: 128 strips, 30 µm pitch, 10 µm width, 1 µm thick



Micro-strip Metal Detectors

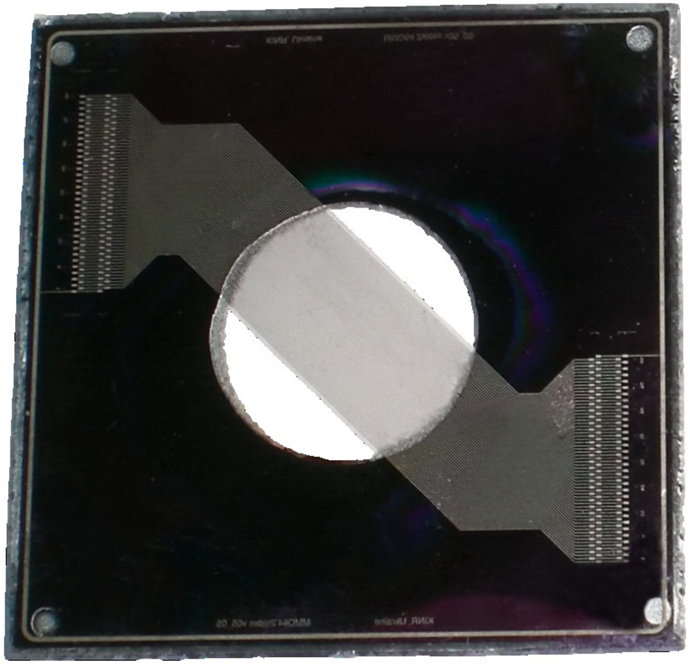
MMD: 16 sectors, 1 μm thick for micro-beam positioning (Diamond Light Source, UK).

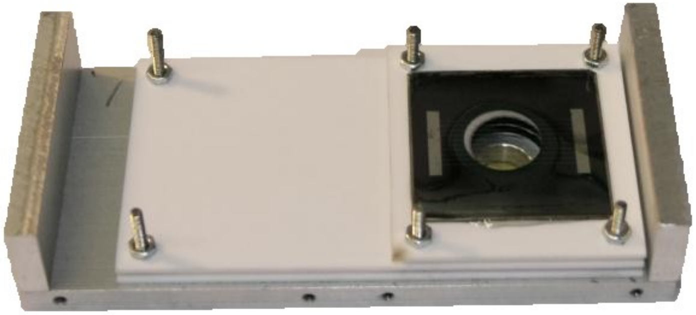




Micro-strip Metal Detectors

MMD: 64 strips, 100 μm pitch,
40 μm width, 1 μm thick
for 2D beam profile monitoring

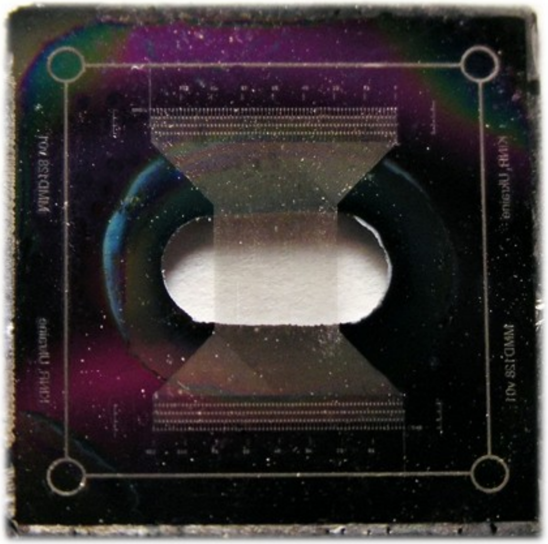


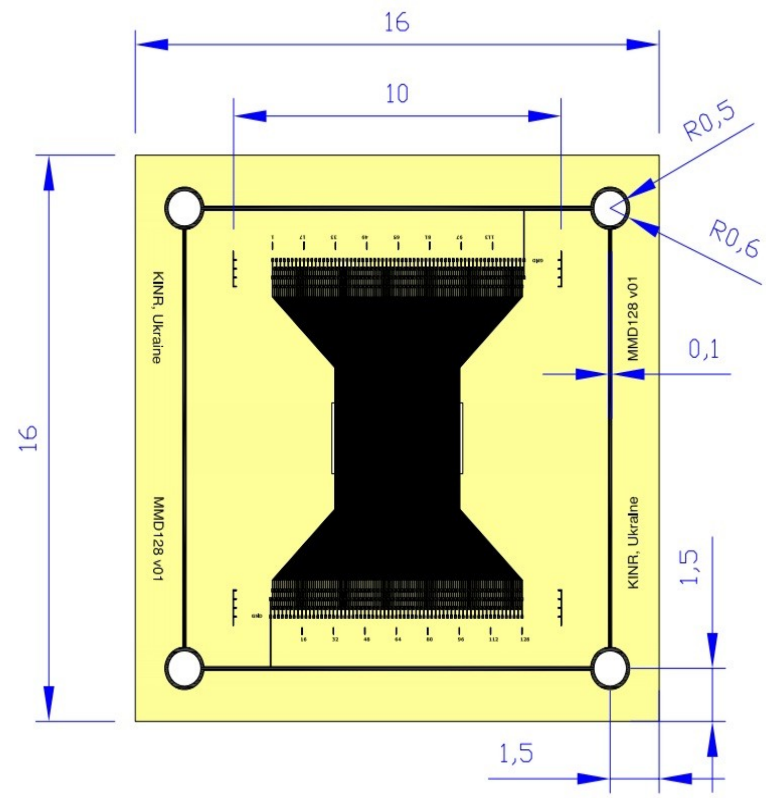


The same mask is used for production X-, Y- sensors.

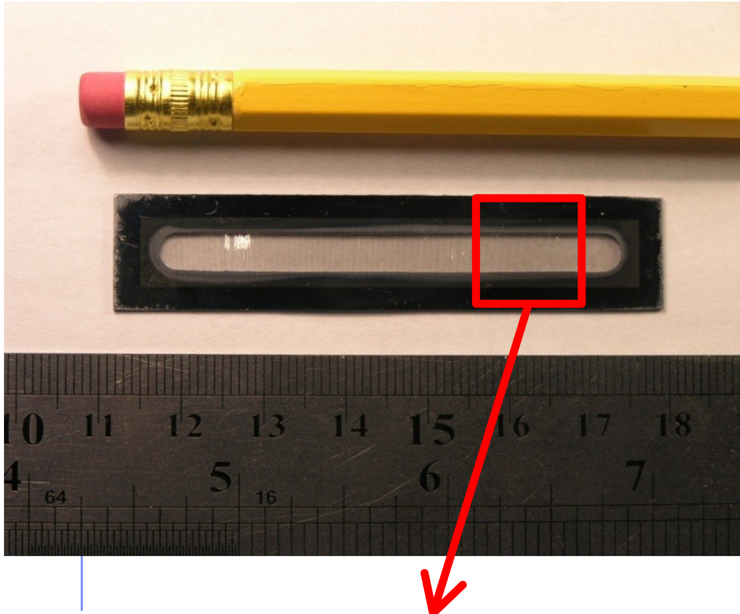
Micro-strip Metal Detectors

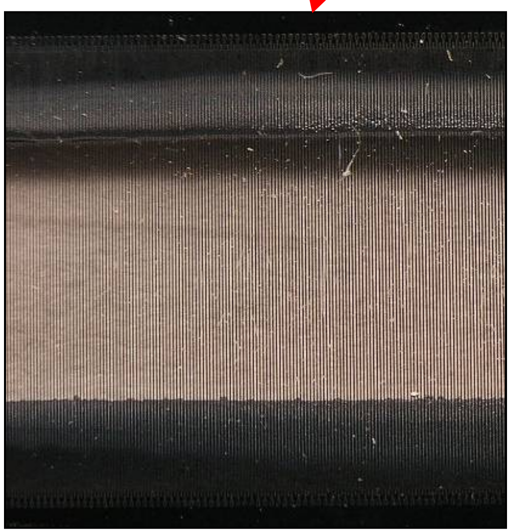
MMD: 128 strips, 30 μm pitch, 10 μm width, 1 μm thick for micro-beam profile monitoring (ESRF, Grenoble)





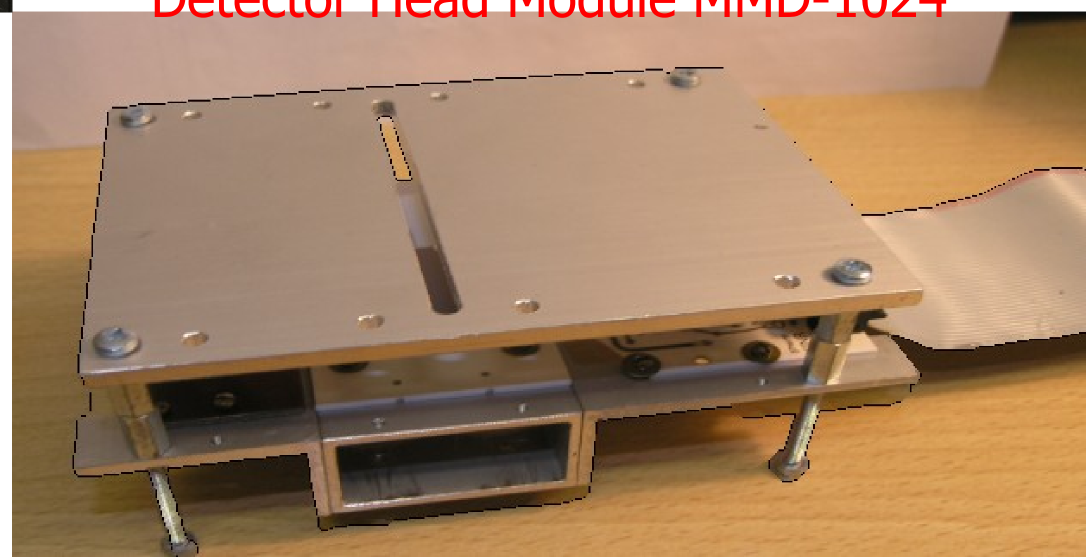
Micro-strip Metal Detectors





MMD: 1024 strips, 40 µm width, 60 µm pitch, 1 µm thick for mass-spectrometry

Detector Head Module MMD-1024



Micro-strip Metal Detector

Current Technical data

- 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 Ion)
- Noise – thermoelectric emission, r/f pickup, fluctuation of the leakage current, …
  - Determined by the connecting cable and readout electronics: ENC: (100 – 500) electrons
- Thickness – 1 μm (transparent, non-destructive device for the measured beam)
- Position resolution – 10 μm

Micro-strip Metal Detector

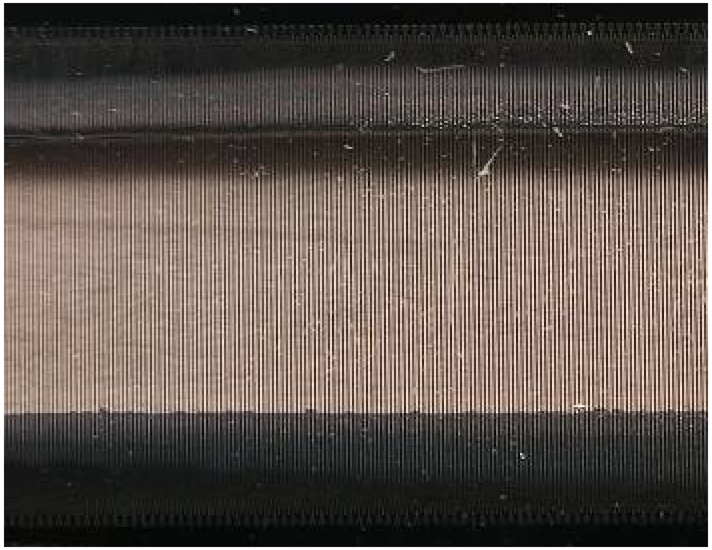
Current Technical data

Radiation hardness - more than 100 MGy

Stable operation at X-ray intensity
- up to 10^{16} photons·s^{-1}·mm^{-2}

Stable operation at proton beam intensity
- up to 10^{10} protons·s^{-1}·mm^{-2}

Conclusion



Advantages:

- High Radiation tolerance (more than 100 MGy)
- Nearly transparent sensor – 1 μm thickness
  the thinnest detector ever made
  for the particle detection
- Low operation voltage (20 V)
- Perfect spatial resolution (10 μm)
- Unique, well advanced production technology
- Commercially available readout hardware
  and software.

MMD potential applications

- **Micro-beam Profile Monitoring for Charged Particles and Synchrotron Radiation**
- **Detectors at the focal plane of mass-spectrometers and electron microscopes**
- **Imaging sensors for X-ray and charged particle applications**
- **Precise dose distribution measurements for micro-biology, hadron-therapy etc.**
- **Industrial applications: micro-metallurgy, micro-electronics, etc.**