

Radiation Monitoring System for the LHCb Inner Tracker

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Abstract

The performance requirements and the design of the Radiation Monitoring System (RMS) for the LHCb Inner Tracker are presented. Details of the Metal Foil Detector technology employed for the RMS are described, along with results from tests of RMS prototypes.

1 Introduction

Particle fluences expected at the LHCb [1, 2] are high enough to make a significant impact onto the performance of the LHCb Inner Tracker (IT) [3] sensors. For instance, the level of the radiation load in the region of the IT-2 station after 10 years of operation will reach up to 60 kGy. The radiation load on silicon micro-strip sensors of the Inner Tracker should be monitored to measure an absorbed radiation dose on-line and archive the measured data for adequate evaluation and tuning of the silicon sensor biasing voltage [4]. This is the task for the Radiation Monitoring System (RMS). The data measured by the RMS have to be transferred to the LHC and LHCb shift crews for permanent monitoring.

2 Metal Foil Detectors for the Radiation Monitoring

There are numerous approaches to monitor the radiation load, including monitoring of sensor leakage currents, using p-mosfet dosimetry, induced radioactivity in Al-foils etc. [5]. The Metal Foil Detector (MFD) technology was chosen for the IT RMS [6] in the Inner Tracker TDR [7] as it provides a set of advantages as discussed below. The MFD principle is illustrated in Fig. 1. A fast charged particle hitting a metal foil initiates electron emission from the surface layers ($10 \div 50$ nm). This is known as Secondary Electron Emission (SEE) [8, 9, 10].

The electron emission makes the electrically isolated foil positively charged. This charge is integrated by a sensitive charge integrator connected to the metal foil (Fig.1). The first SEE monitor was built and tested by Tautfest and Fechter in 1955 [11].

SEE properties essential for the MFD performance can be summarized as follows:

- The SEE yield for a given material is proportional to the rate of the energy loss of the incident particles. The number of SEE electrons per single incoming particle varies between 0.5 and few hundred as measured for a wide range of incident particles and emitting metals.
- The width of the emitting metal zone corresponds to few atomic layers. The SEE yield does not depend on the emitter thickness, if it is larger than a few microns. For instance, for copper the SEE yield saturates already at a thickness of 5 nm reaching 4 e^- per α -particle of 3 MeV energy [12].
- The observed energy distribution of the SEE peaks at a few electron-volts. There is a high energy tail related to δ -electrons, directly kicked out of the electron shells by the incident particle. The relative yield of SEE and δ -electrons is 10:1.
- For clean metals, the SEE yield does not change significantly with the temperature of the emitter.
- A detector based on SEE is radiation hard. It was shown that the SEE yield remains constant up to a proton-fluence of 10^{20} protons/cm². A stable operation of the SEE monitor was observed up to an average beam density of $150 \mu\text{A}/\text{cm}^2$ corresponding to $10^{15} \text{ cm}^{-2}\text{s}^{-1}$ charged particles [13].

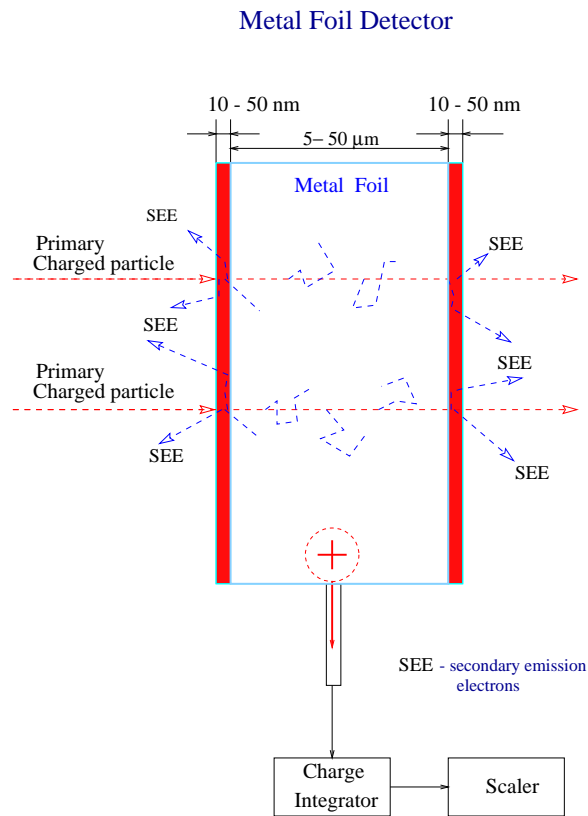
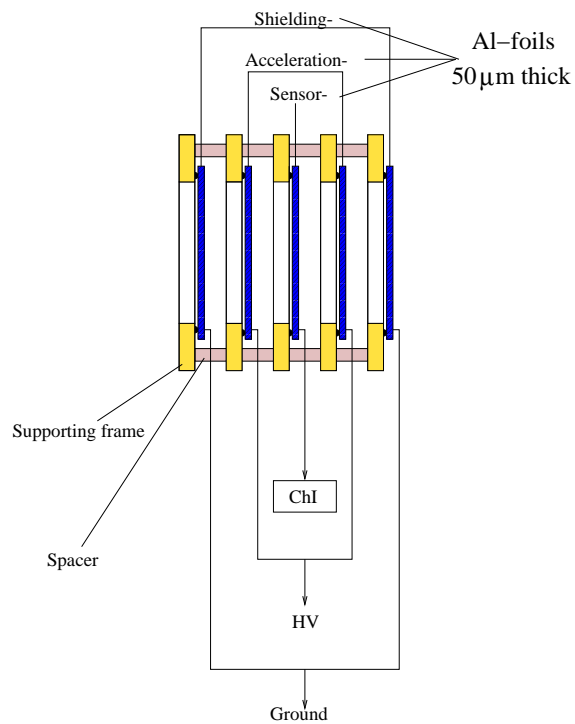
In combination with the micro-strip technology MFD may become the thinnest detector ever built for the monitoring of the high energy particle fluxes [14]. As a practical device, the MFD comprises a 5-layer structure as is shown in Fig. 2. Thin metal foils, usually $5 \div 50 \mu\text{m}$ thick, are glued to isolating and supporting frames (e.g. 0.5 mm thick epoxy plates). The auxiliary foils (i.e. two accelerating foils and two shielding foils) cover the sensor from both sides and thus stabilize the SEE yield. The charge generated in the sensor is measured by a sensitive Charge Integrator (ChI) [15]. The accelerating voltage needed to saturate the MFD response is in the range of $10 \div 20 \text{ V}^1$. This is due to prevailing contribution of low-energy electrons in SEE [8]. The MFD response increases by a factor of 5 in comparison with a non-biased detector [16].

Several MFD advantages determined our choice for the IT RMS:

- Possibility to provide extremely low mass of the detecting material;
- Simple structure at any shape and size;
- Low operating voltage;
- Simple readout electronics (charge integrators and scalers);
- High radiation tolerance;
- Long term performance with minimal maintenance;
- Low cost.

MFDs have been shown to be a reliable tool for charged particle radiation monitoring in a wide range of applications [16].

¹For a distance between the foils of less than 3 mm.

Figure 1: *Metal Foil Detector operation principle.*Figure 2: *The schematic view of the MFD-components.*

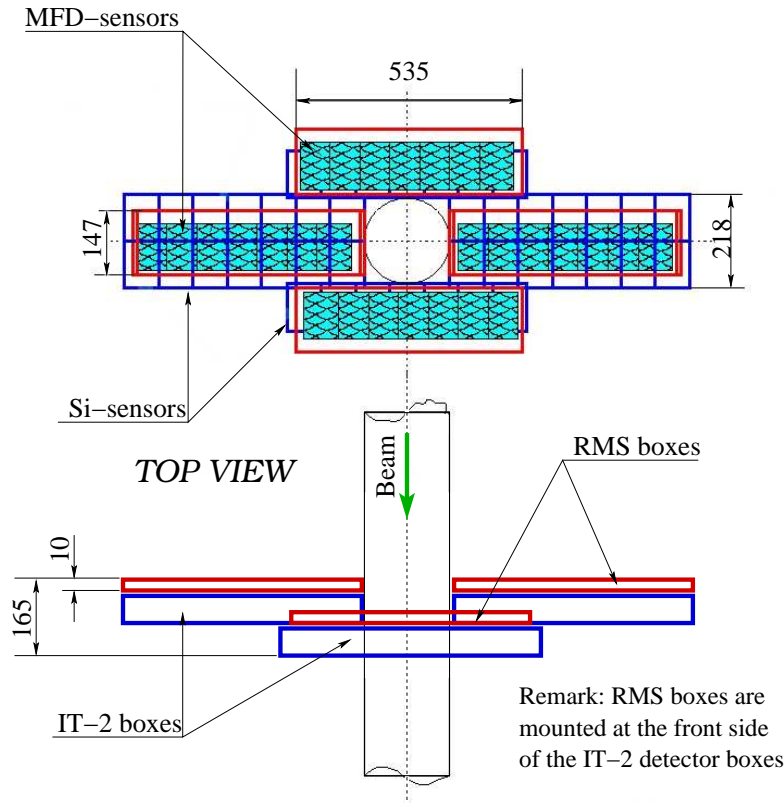


Figure 3: Schematic front (above) and top (below) view of the RMS for the LHCb Inner Tracker housed at IT-2 station.

3 Performance Requirements for the Radiation Monitoring System

The requirements for the Inner Tracker Radiation Monitoring System are as follows:

- Permanent measurement of the distribution of charged particle rates over the silicon sensors of the Inner Tracker IT-2 station with an accuracy better than 10 % during a period up to 10 years.
- On-line information including warning and alarm messages for the LHCb and LHC shift crews.
- On-line display as well as off-line data storage.

The level of charged hadron fluxes [1, 2] at the location of the silicon sensors of the IT-2 station varies from about $10^4 \text{ cm}^{-2}\text{s}^{-1}$ to $10^5 \text{ cm}^{-2}\text{s}^{-1}$ at nominal LHCb luminosity². Under these conditions the rate integrated over the area of a single silicon sensor ($11 \times 7.8 \text{ cm}^2$) will range from $8 \times 10^4 \text{ s}^{-1}$ to $2 \times 10^7 \text{ s}^{-1}$. This level of hadron rates is inside the dynamical range ($5 \times 10^3 \div 5 \times 10^8 \text{ s}^{-1}$) of the designed IT RMS (see Section 6 for details). The MFD technology provides a stable response over a long-term operation with fluctuations within a few percent [16, 17]. Assuming 1 s readout, the most distant from the beam pipe sensors of

²Luminosity of $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ corresponding to 16 MHz pp-interaction rate

the RMS will be able to measure charged particle rates with 6 % precision. The precision for the innermost sensors is expected to be better than 1 %.

The design of the Radiation Monitoring System (RMS) has to minimize the amount of construction materials while keeping the assembly mechanically stable as well as shielded against pick-up and/or cross-talk.

4 The design of the IT RMS

The IT RMS will be located at the Inner Tracker Station IT-2, where a z-space of about 10 mm has been reserved (Fig. 3). Four identical boxes, each containing 7 MFD sensors and auxiliary layers made of 50 μm thick Al foil, will be fixed on the upstream surfaces of the four IT-2 detector boxes.

The MFD sensors inside the top and bottom RMS boxes are 75 mm wide and 110 mm high and therefore have approximately the same size as the IT silicon sensors. Due to space constraints they will be vertically displaced by 14 mm (away from the beam pipe) with respect to the corresponding silicon sensors. The MFD sensors inside the RMS boxes on the left and right sides (75 mm wide and 110 mm high) will cover only a half the height of the sensitive area of the silicon ladders (see Fig. 3).

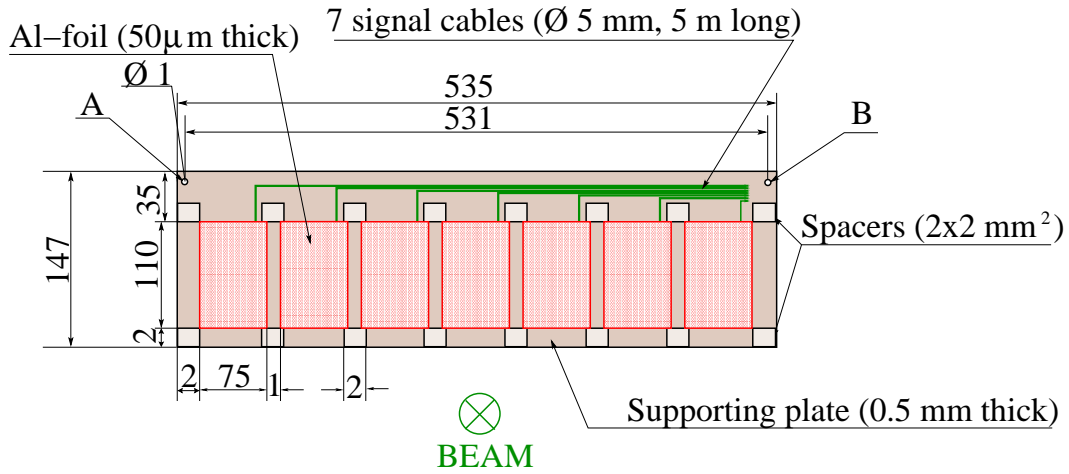
The scheme of a single MFD-Ladder of the RMS for the IT-2 station is shown in Fig.4. The RMS support plate ($535 \times 147 \text{ mm}^2$) is made of 0.5 mm thick G10 material³. The holes in the support plate will be used for the alignment and fixation of the RMS boxes to the surface of IT-2 detector boxes. Seven sensors are glued to a thin frame made of 0.5 mm thick G10 material with 2 ÷ 3 mm wide borders and windows of the size of the MFD sensors ($75 \times 110 \text{ mm}^2$). The accelerating and shielding foils are glued onto similar frames (Fig. 4). The supporting plate and the frames provide necessary profiles to keep the 5-layer MFD structure mechanically stable.

A 100 μm thick insulating mesh is inserted in between each pair of auxiliary Al layers. This mesh is made of polypropylene threads with widths of 1 mm and 0.25 mm. The threads are knotted together at 4 mm intervals along the 0.25 mm threads and at 3 mm intervals along the 1 mm threads. 16 epoxy spacers ($2 \times 2 \text{ mm}^2$ and 3 mm thick) are inserted between the sensors and the accelerating layers in order to ensure uniform spacing. They cover less than 0.1 % of the ladder area.

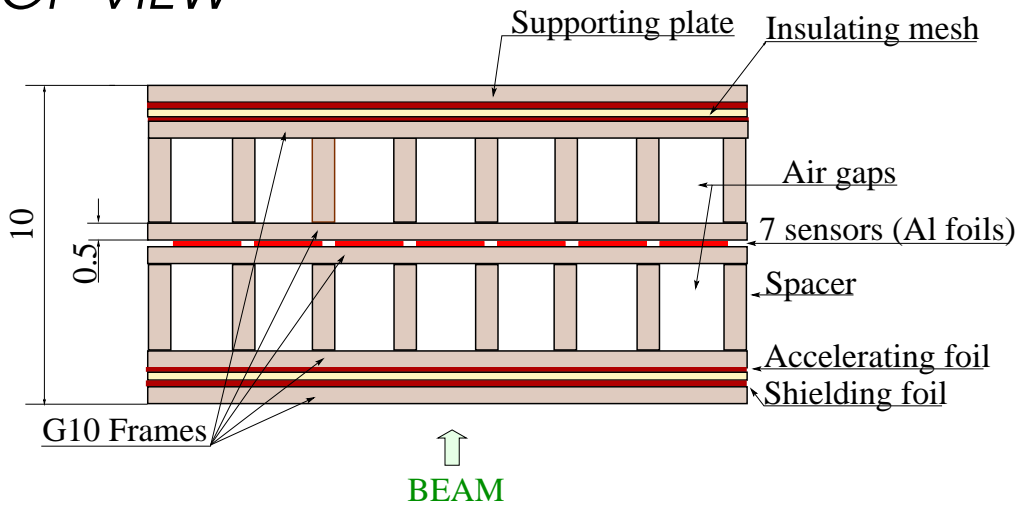
The grounding scheme is shown in Fig. 5. The shielding layers are connected to the IT Outer Shield. The grounding of the cables for bias voltage and sensor readout will be incorporated in the patch panels that are located at a distance of about 5 m from the detectors, close to the Inner Tracker Service Boxes. Fig. 6 together with Table 1 provide an estimate for the material budget for the RMS ladders and the signal cables in terms of the radiation length (X_0). The largest part of the RMS ladder ($\sim 72 \%$) introduces no more than 1 % X_0 . In the "hottest" points of the ladder, the material thickness amounts to 5 % X_0 . This hot-spots add up to no more than 5 % of the total area of the ladder. The signal cables will introduce additional material equivalent to 2 % X_0 .

³Epoxy-impregnated fiberglass laminate.

FRONT VIEW



TOP VIEW



SIDE VIEW

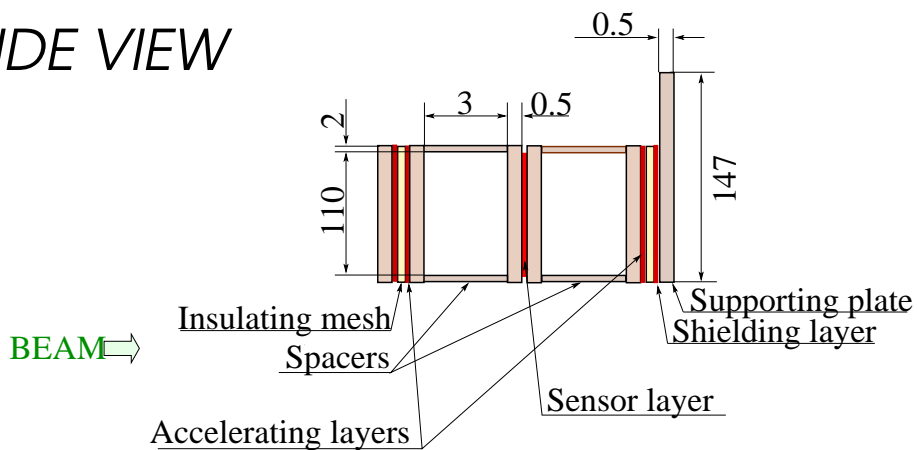


Figure 4: Scheme of a single MFD-Ladder (not to scale). All sizes are in mm if not otherwise specified.

Table 1: *Material budget of the RMS ladder (Fig. 6).*

Track's direction	Material	Area Fraction, %	Thickness, g/cm ²	Fraction of X_0 , %
S1	G10: plate	22.5	0.085	0.26
S2	G10: plate, frames		1.53	4.63
	spacers			
	PP*		< 0.001	$\sim 10^{-3}$
	Al: 4 layers		0.054	0.22
	In total	~ 0.1		4.85
S3	G10: plate, frames		0.51	1.55
	PP		< 0.001	$\sim 10^{-3}$
	Al: 4 layers		0.054	0.22
	In total	~ 5		1.77
S4	G10: plate		0.085	0.26
	Al: 5 layers		0.0675	0.28
	PP		< 0.001	$\sim 10^{-3}$
	In total	72.5		0.54
Cable	C-50-1-1			2

* PP denotes polypropylene, i.e. insulating mesh material.

5 RMS Readout electronics and software

Long-term performance and reliability of operation of the RMS make it necessary to provide a simple and fast data acquisition as well as continuous calibration. The schematic view of the RMS readout chain is shown in Fig. 7. The analog signals from the 28 sensors are read out by charge integrators. 28 signal cables (2x0.22 mm, 5 m long and 5 mm in diameter) are electrically connected to the MFD sensors by a silver glue and mechanically fixed to the supporting frame by a standard epoxy glue (see also Fig. 4). They transmit the signals to a patch panel that is located at the lower end of the IT-2 support frame, close to the Inner Tracker Service Boxes. From here, 25 m long cables of the same type transmit the signals further to the charge integrators that are located in the bunker below the IT stations. The accelerating voltage (+24 V) is delivered by additional 4 cables of the same types.ed in the bunker.

A non-switchable charge-to-frequency converter was first developed at KINR [15, 18] and then modified at MPIfK (Heidelberg). It was used as part of a luminosity monitor for the HERA-B experiment [17] (see Section 6.2), where it survived an irradiation dose of 2 to 3 krad. The expected dose in the LHCb bunker does not exceed a few hundred rad after ten years of operation.

The main component of the converter is a recycling charge integrator with an automatic start and restoring circuit. It converts the input charge into a sequence of output pulses with a frequency F_{out} that is proportional to the input current $+I_{in}$ and inversely proportional to the value of the integrating capacitance C_i and the difference of the low and high thresholds ($U = U_H - U_L$) of the differential discriminator (DD).

$$F_{out} = \frac{I_{in}}{UC_i} \quad (1)$$

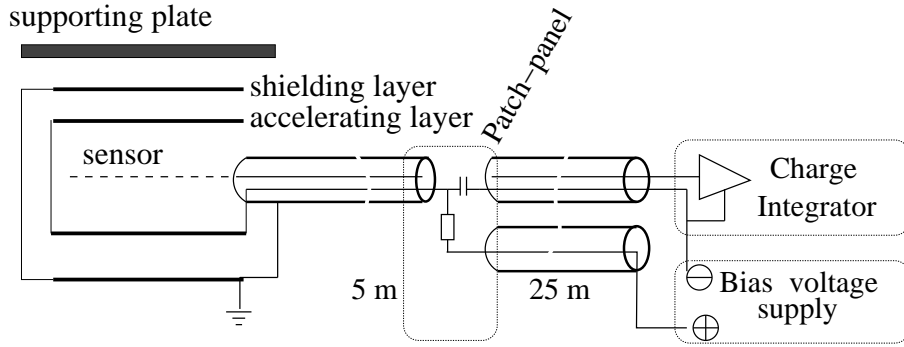


Figure 5: *Grounding scheme of MFD-Ladder. ($R=1\text{ MOhm}$, $C = 5\ \mu\text{F}$)*

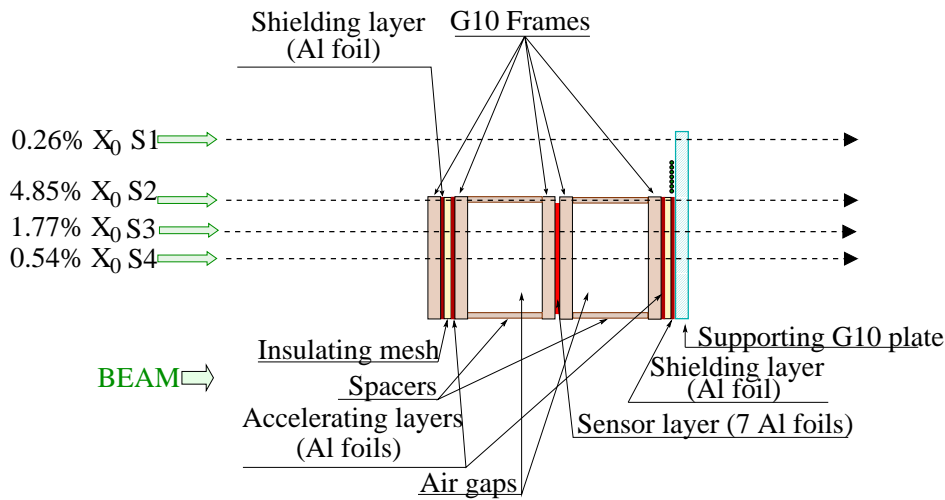


Figure 6: *Material budget of MFD-Ladder in terms of radiation length X_0 shown for track's direction $S1, S2, S3, S4$*

A positive input current is integrated until the output voltage U_{out} of the integrator drops to the level of the low threshold U_L of the discriminator. The discharging current is switched on at that moment and the U_{out} starts to increase. When U_{out} reaches the high threshold U_H of the DD, the discharging current is switched off and a new cycle of the charge integration is started. An output shaper produces output pulses in NIM and TTL standards. Fig. 8 shows the scheme of the modified charge integrator designed and built at MPIfK (Heidelberg).

The sensor signal is amplified by a wide bandwidth FET operational amplifier (IC19, OPA602) and then integrated using an operational amplifier (IC20, OPA37). The next stage (IC24, VFC110) converts the voltage to a frequency in the manner described above. The output stages (IC21, MC01024, 74HC08) are used to provide NIM/TTL output signals. The baseline measurements are realized by connecting a reference voltage V_{ref} to the charge integrator input. This reference voltage is currently set to 25 pA providing 25 kHz output frequency. The conversion factor of the charge integrator is 1 kHz per 1 pA input current (output fluctuations do not exceed a few Hz). Its linearity is better than 0.02 % for input currents in the range $1 \div 1000$ pA. The long term stability is ± 0.05 % per 24 hours and the temperature instability amounts to less than 0.1 % per 1 degree C. Five charge integrators are housed in a single PCB (NIM unit size). In total, there will be seven PCBs (35 charge integrators) inside the designated crate. The crate is powered by ± 24 V (1 A) and ± 6 V (1.5 A) by a dedicated MARATON based power supply placed in the bunker. This power

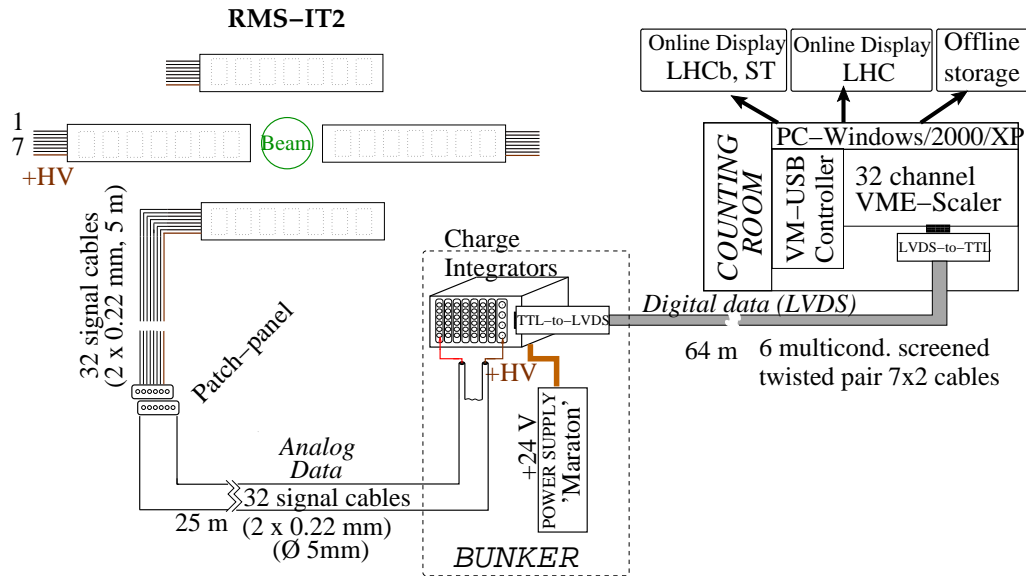


Figure 7: Schematic view of the RMS readout.

supply is a 3U power box with 385 VDC input. It includes four $2\div 8$ V and four $23\div 25$ V DC output channels with nominal output power 90 W and peak output 11.5 A. The accelerating voltage (+24 V) needed for the MFD operation will be provided by the same power supply. It will be filtered by an RC circuit on the detector frame.

The output signals of the charge integrators will be converted from TTL to LVDS and then transmitted via 64 m long round twisted-pair cables to 32 channel VME-830 scaler that is located in the counting room. Here, the signals will be converted back to TTL logic⁴. Programming as well as readout of the VME scalers will be provided by means of a VME controller WIENER VM-USB with USB-2 interface at 8 MByte/s. Using a PC to PVSS interface, the data will be stored in the PVSS archive while summary information will go to the conditions database. The RMS data are planned to be displayed on-line in the LHCb and possibly LHC control rooms.

A hardware trigger will be used to start multiple counters simultaneously. A gate-and-delay generator will be used to generate time windows to measure sensor loads during 'beam-on' and 'beam-off' data taking periods. These data will be stored in separate buffers for the off-line analysis, while 'pure' luminosity data are permanently (every $1\div 10$ s) sent to the on-line displays at the LHCb and LHC control rooms. In total, 5 kbit/s have to be transferred.

A Graphical User Interface will permit to select a 'Nominal Radiation Load' corresponding to the nominal pp-interaction rate, 'Warning' and 'Alarm' levels. The RMS online software will allow for:

- Monitoring of the particle rates for each of the RMS sensors (with appropriate calibration, this information can be used to monitor the pp interaction rate);
- Monitoring of left/right and up/down rate asymmetries (with appropriate calibration, this information could be used to monitor the transverse position of the pp interaction point);

⁴LVDS quad CMOS differential line drivers/receivers (DS90C031/DS90C032) will be used for the TTL to LVDS and the LVDS to TTL conversions.

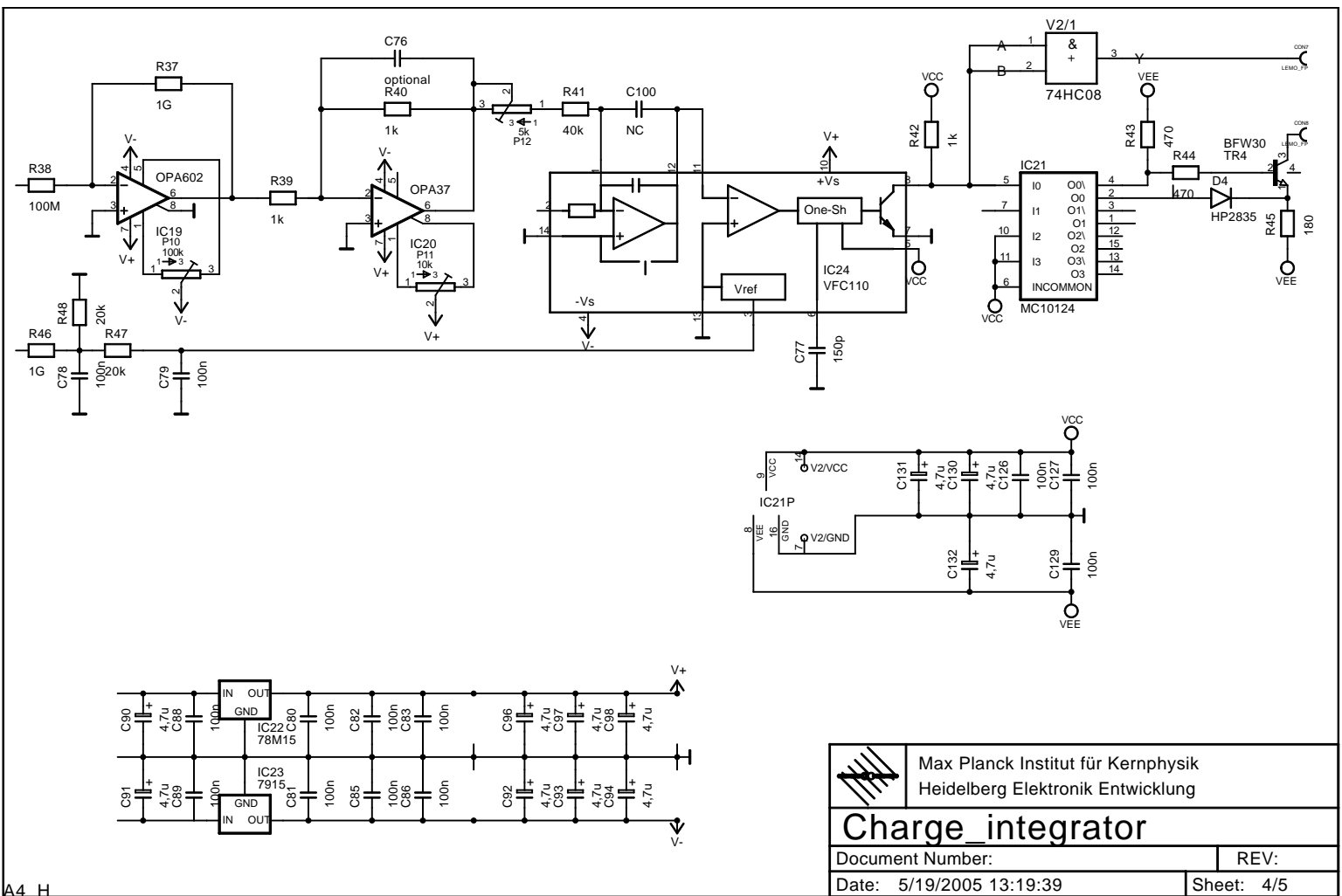


Figure 8: The scheme of the charge integrator.

- Generation of warning and alarm messages;
- Monitoring/correction of the ChI baseline and/or background contribution;
- Background subtraction;
- On-line data presentation;
- Off-line data storage.

6 RMS Prototype Results

MFD prototypes and real devices have been built and tested at accelerators of KINR (Kyiv), DESY, MPIfK (Heidelberg) and CERN [16].

The employed charge integrators have a conversion rate of 1 kHz/pA. Output frequency fluctuations of the charge integrators themselves are at the level of $1 \div 2$ Hz. However, connected to a sensor via long cables, these output fluctuations increase to a level of about 100 Hz, due to shot noise, RF pickup and various other backgrounds. Yet, it was demonstrated that a correction for those factors is possible by measuring the MFD response during the time of a particles spill and between spills. This permits the measurement of charged particle rates above $5 \times 10^3 \text{ s}^{-1}$ per MFD sensor. At nominal LHCb luminosity, the expected lowest rate at the location of the silicon sensors of the IT-2 station is by an order of magnitude higher.

6.1 Beam Profile Monitor (BPM) for the LHCb ST X7-test-beam at CERN

As a test of the MFD technology, a Beam Profile Monitor (BPM) for the LHCb ST X7-test-beam at CERN was built and used in test measurements in May 2001 and November 2001 [20]. The MFD BPM data was in agreement (within 10 %) with the beam profile⁵ measured by multi-wire proportional chambers, the regular BPM devices at CERN.

6.2 Luminosity monitor at HERA-B

The MFD technology was also employed for a luminosity monitor at HERA-B⁶ [16]. A twelve sector MFD luminosity monitor was installed around the beam pipe at the exit window of the Vertex Detector System. Fig. 9 shows the measured MFD output frequency as a function of the proton-nucleus (pA) interaction rate, as determined from a set of scintillator hodoscopes. The linearity of the MFD response was better than 5 % for pA interaction rates up to 25 MHz. This corresponds to charged particle rates to $5 \times 10^8 \text{ s}^{-1}$ per MFD sensor. Using charge integrators with a lower conversion factor, a linear response could be obtained for pA interaction rates of up to a few GHz, corresponding to a charged particle rate of 10^{10} s^{-1} per MFD sensor.

The NIM crate containing the charge integrators was operated for more than three years in close vicinity of the HERA-B interaction region. No radiation-induced failures and no deterioration of performance were observed. The accumulated dose at this location was estimated to be about $2 \div 3$ krad.

Also the long term stability of the MFD performance was studied at HERA-B. The upper plot in Fig. 10 shows the ratio of the charge integrator output frequency to the proton-nucleus interaction rate measured by the scintillator hodoscopes. The lower plot in Fig. 10 shows its

⁵120 GeV π -meson beam with 5.2×10^5 particle per 2.4 s spill

⁶920 GeV proton beam energy

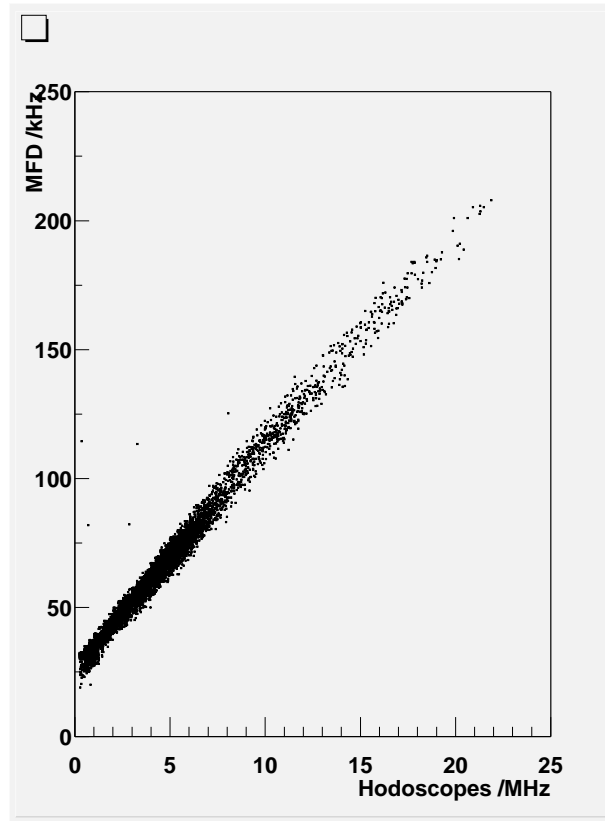


Figure 9: *MFD luminosity monitor response to the HERA-B IR measured by hodoscopes.*

projection onto the y-axis. During 2000 hours of permanent operation, the MFD response was stable within 6 %. The stability of the baseline of the charge integrator (Fig. 10, middle plot) was 0.8 %.

7 RMS prototypes for the LHCb Inner Tracker

Several RMS designs have been worked out at KINR (Kyiv). In the following we present the results of the characterization of a 7-sensor MFD prototype ladder produced in 2004. 25 μm thick Al sensor-foils were glued to an epoxy support frame with overall dimensions of $550 \times 200 \times 0.1 \text{ mm}^3$ and windows of $75 \text{ mm} \times 110 \text{ mm}$. The sensor layer was placed between two accelerating foils and the whole structure was shielded from both sides by foils connected to ground. The auxiliary Al foils were 25 μm thick and were also supported by epoxy frames similar in size to the sensor frame. The distance between all Al-foil layers was 3 mm. Five meter long coaxial cables (RG 178) were used to connect the sensors to the input of charge integrators and to deliver the voltage to the accelerating foils. The CAMAC based DAQ included the following units:

- Accelerating voltage;
- Charge integrators;
- Clock generator 730-B;
- Quad scalers;

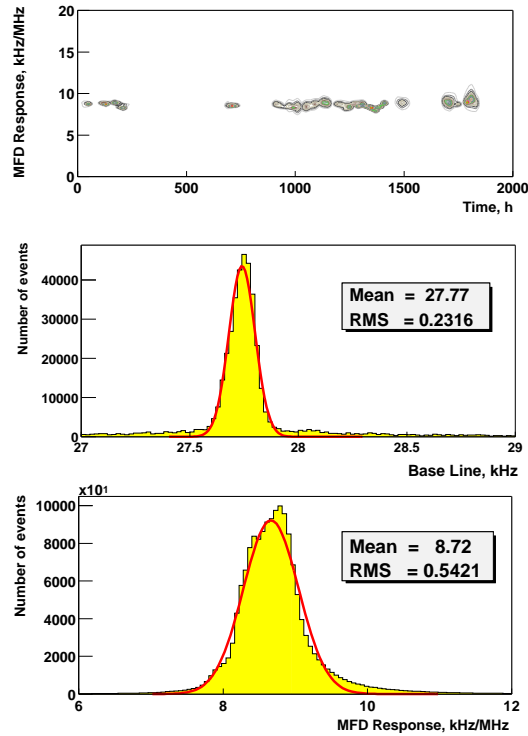


Figure 10: 2000 hours MFD prototype performance.

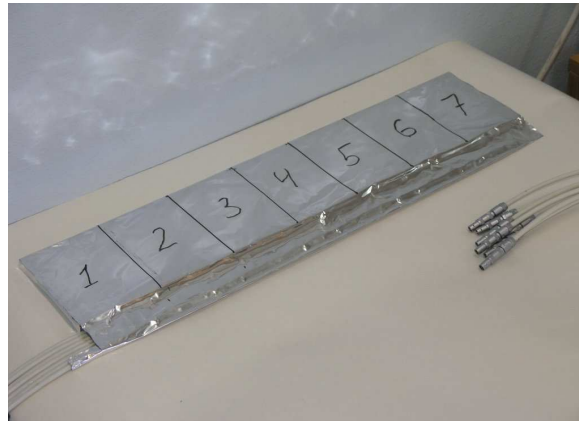
- Voltage converter +/- 12V;
- Crate controller FK4410.

The data were interfaced to an IBM-386 PC and transferred further to a Linux PC for offline data analysis. The scalers were read out once per second. To ensure a correct calibration over the entire data taking period, the baselines of each channel from a stable current source were measured permanently.

The performance of this RMS prototype was analyzed using a ^{90}Sr β -source. The β -particle rate at the sensor surface was about 10^6 s^{-1} . The individual sensor response varied from 4.1 kHz to 8.8 kHz with a signal width of about 55 Hz. The response was different due to the absorption of soft β -particles in the volume of the support frame which thickness was not uniform over the area of different sensors for that prototype. Comparing the 8.8 kHz signal, corresponding to 10^6 s^{-1} electrons, and the 55 Hz fluctuation one obtains the minimum detectable β -particle rate of $6 \times 10^3 \text{ s}^{-1}$ per sensor. The results obtained with the latest RMS prototype confirm the above figures.

A photograph of the latest prototype of the RMS ladder built, according to the design presented in this note (see Section 4), is depicted in Fig. 11. The ladder comprises five Al foil layers and seven sensors. The accessories (i.e. supporting plate, frames, spacers) are made of epoxy-impregnated fiberglass laminate.

Figure 11: *Photograph of the latest seven-sensor five-layer prototype, built according to the design specification described in Section 4.*



8 Conclusions and Outlook

The Metal Foil Detector technology has been adopted for the Radiation Monitoring at the LHCb Inner Tracker. Four ladders of the RMS containing twenty eight aluminum sensors, in total, are proposed to be installed at the IT-2 station. Several prototypes were built and have been shown to deliver the requested performance.

Once being calibrated, we believe that the RMS could also serve as a luminosity monitor for LHCb. Radiation monitoring at LHCb could be expanded by installing a second MFD system close to the TT station, where it could cover a significantly larger fraction of the solid angle. A proposal for such a system will be described in a separate LHCb note.

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