Development and Experimental Performance Evaluation of a Dose-Rate meter for Pulsed Beam

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Abstract

The detection of pulsed gamma radiation fields requires measurement devices characterized by high precision and fast response capabilities. El.Se. S.r.l., in collaboration with Sincrotrone Trieste, developed the front-end electronics for ionization chamber detector and the associated dose-rate digital meter.
The response of the new electrometer was tested inside the linac tunnel at different beam current intensities and repetition rates. The long-term stability was evaluated through environmental radiation measurements.
The design of the electronics, the performed measurements and the obtained results are presented and discussed here.

1. Introduction

During the construction of the new full energy booster injector at ELETTRA, preliminary studies have been performed to evaluate the response of the existing environmental Silena gamma radiation monitor, in the presence of short-time, high intensity pulsed radiation field.
Based on the experimental results obtained, a research project was defined with the aim of improving the performance of the front-end electronics and designing a new monitoring system able to satisfy the requirements of current legislation on radiation protection.
The first prototype of the new gamma radiation monitor was exposed to a high energy pulsed radiation fields by taking a PTW ionization chamber, connected to a Keithley electrometer, as a reference system.
The obtained results demonstrated that the new gamma monitor complies with the requirements for radiological surveillance monitoring system and is suitable for measurements of ambient dose equivalent and dose rates, taking into account the effects of the response functions of Centronic High-Pressure Ionization Chambers, especially those due to recombination and mixed field composition [1],[2],[3].

2. Electronics Design

The environmental Silena Gamma radiation monitor is composed by a Centronic Ion Chamber Detector mod. IGC5/A6.4 N9.6 and the associated modular electronics: high voltage power supply, 6 decades linear amplifier, auto-ranging & A/D converter, ratemeter and I/O relay board.
Basically the read-out electronic of the ionization chamber consists of a switched integrator connected to a programmable gain amplifier, an Analog to Digital converter (ADC) with a Sample & Hold input circuitry and a u-controller unit (see Fig.1).
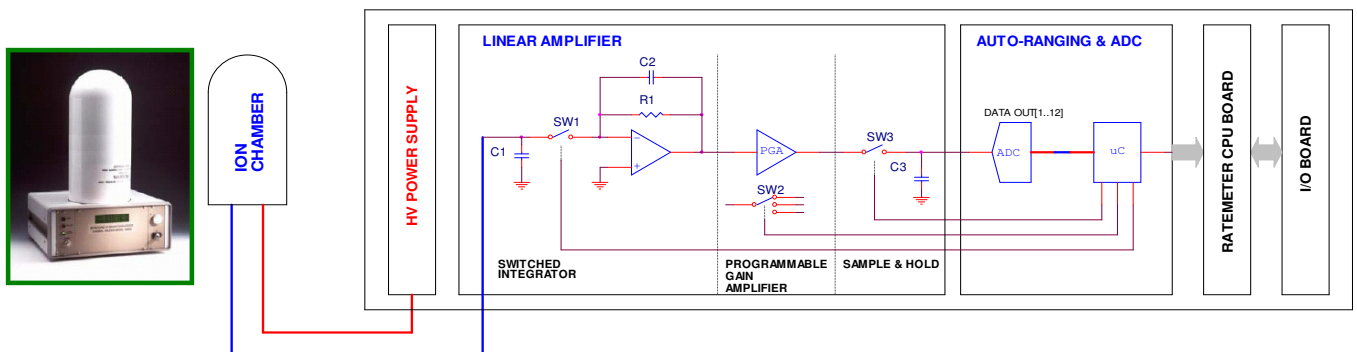

Fig.1 - Silena gamma radiation monitor (in the green box) and block diagram of its functioning.

Cyclically the u-controller unit acquires the data coming from the ADC and manages the different phases of measurement. Every second the charge stored in the input capacitor is transferred to the switched integrator while the gain of the programmable gain amplifier is properly selected, according to the previous processed data. The timing signals are also generated to convert the analog signal in numerical format.

This measurement technique assures high levels of linearity and accuracy, in the presence of stable radiation field, but could be inadequate for measuring the dose value of pulsed fields, because the long integration time required could result in saturation of the first stage and wrong selection of the amplifier programmable gain. Based upon these considerations an experimental acquisition system was designed, capable of overcoming the inadequacy (see Fig.2).
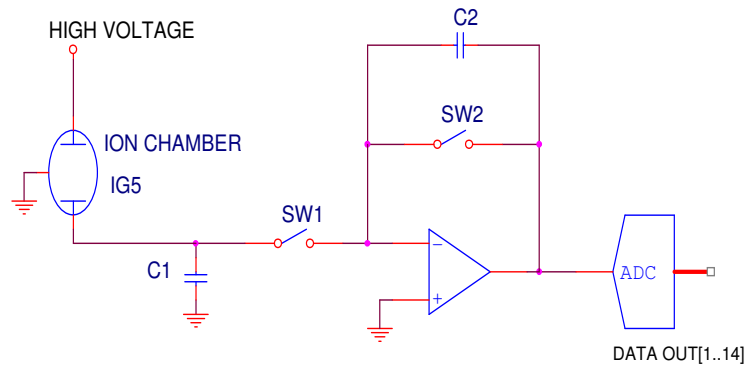

Fig.2 - Schematic of the experimental front-end electronics.

During the normal operation the capacitor C1 is charged by the ion chamber and the analog switches SW1 and SW2 are open. When the integration time is elapsed, the switch SW1 is closed and the charge is transferred to the capacitor C2. The switch SW1 is opened and the ADC starts the conversion. The output voltage signal of the operational amplifier is proportional to the charge accumulated during the integration time interval.

Assuming a constant input current (I_{INPUT}), during the integration time ($T_{INTEGRATION}$), the output voltage (V_{OPAMP_OUT}) of the ideal operation amplifier, when the switch SW1 is closed, is given by:

$$V_{OPAMP\_OUT} = -\frac{I_{INPUT} \cdot T_{INTEGRATION}}{C_2} \tag{1}$$

When the data acquisition is completed the switch SW2 is closed and the capacitor C2 is completely discharged. This operation mode allows no charge produced by the detector to be lost and the input signal to be continuously integrated.

The integration time is remotely selectable by software and different values are provided: 100 µsec, 1 ms, 10 ms, 100 ms and 1s.
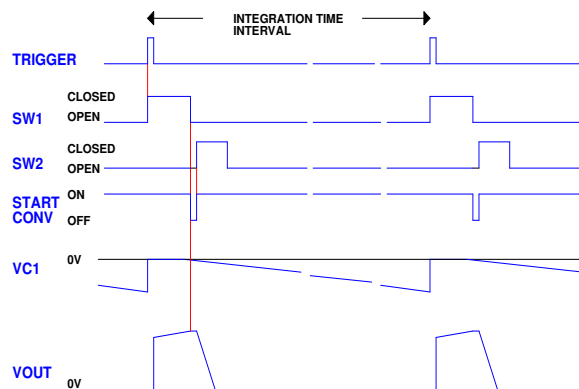

Fig.3 - Signals and timing of the experimental front-end electronics.

After the first tests inside the Elettra Linac tunnel, the experimental circuit was improved by adding two amplification stages and the fine gain in order to cover the desirable dynamic range (see Fig.4).
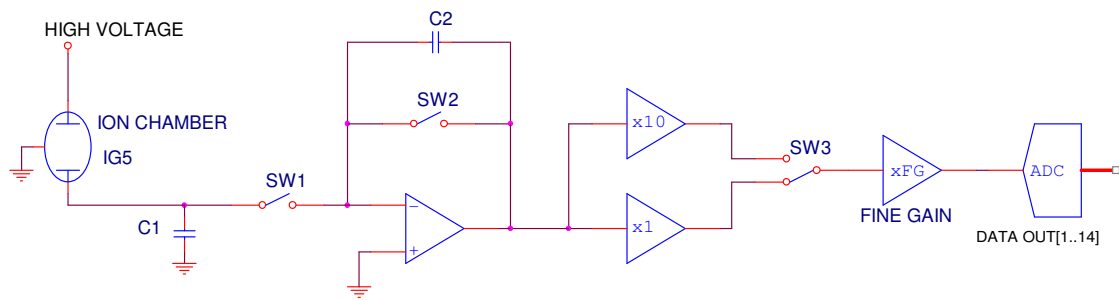

Fig.4 - Schematic of the new prototype front-end electronics.

To prevent saturation of the input stage, due to fast input pulses, the integration time is dynamically adjusted according to the previous acquired value. This method is applicable if the maximum expected input signal, corresponding to the maximum dose rate, within the selected integration period, generates an output signal lower than 50% of the total dynamic range. To satisfy this constraint the u-controller unit collects the data every 1 ms and the charge transferred to the capacitor C2 can be hold or reset, depending on the value acquired.

During the reset period, when the capacitor C2 is completed discharged, the output offset voltage is also measured and digitally subtracted to eliminate the offset errors.

Undesired charge injections are produced during SW1 and SW2 aperture and closure; a precise charge injection circuitry was implemented to compensate this effect, by adding equal and opposite charges.

The temperature compensation technique was also adopted to reduce the thermal drift effects and to guarantee an adequate performance when very low current are measured.

Every second all the acquired data are elaborated by the u-controller unit and the dose-rate value is periodically sent to the digital rate meter. A remote computer control of the Fine Gain stage allows a fine-tune of the calibration factor (A/(uSv/h)) during the calibration procedure.

4. Measurements and results

4.1. Linearity of the read-out electronics

The linearity of the read-out electronics was preliminary tested with an input current range between $3 \cdot 10^{-13}$A up to 10^{-7}A, using a current generator to simulate the equivalent dose rate values. At lower currents the linearity was not verified because the specifications of the current generator, used for these measurements, was not compliant with the required electronic noise level and impedance value.
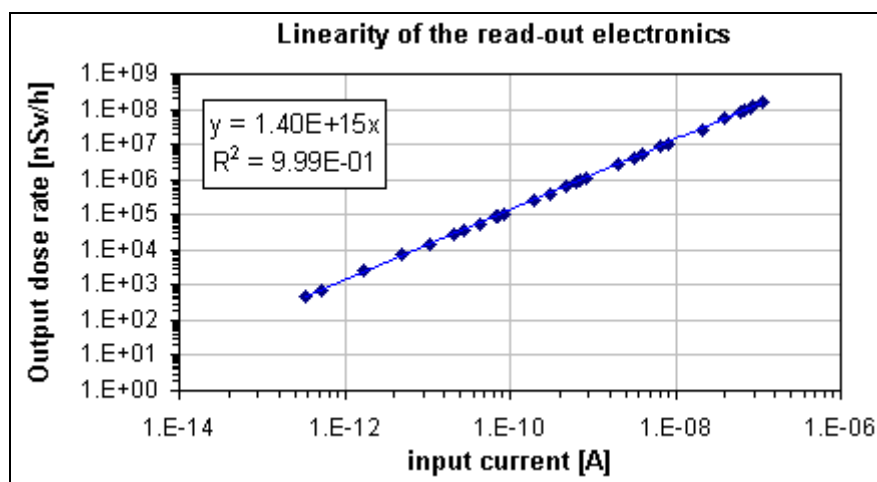

Fig 5 - Linearity of the read-out electronics.

4.2. Radiation measurements inside Elettra Linac tunnel

The upgraded El.Se. prototype, the old-type Silena gamma ionization chamber and a PTW ion chamber model 32003 connected with a Keithley electrometer model 6517 were exposed to gamma pulsed radiation fields inside Elettra Linac tunnel, using the experimental layout shown in Fig.6.

The pulsed radiation fields were produced by the electron beam accelerated up to 900 MeV, impinging on a cylindrical beam stopper with a diameter of 8 cm. The electron beam was operated at 10 Hz producing single and multi-bunch trains of electron pulses (1, 5 and 10 bunches) at different pulse amplitude (1, 2, 5, 10 and 15 mA). The difference in the expected gamma dose rate reaching the three instruments was calculated to be within 15%.
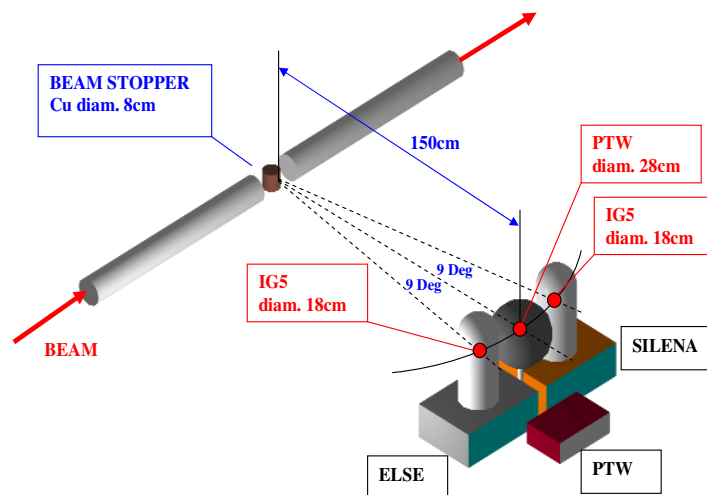

Fig.6 - Experimental layout with the position of the radiation monitors and the PTW ion chamber.

The only data valid for the old-type Silena gamma ionization chamber were the ones with train of single electron bunches of 1 mA amplitude. When the number of bunches or the pulse amplitude was increased, the detector showed overflow values due to the electronics input stage saturation.

The response of the El.Se. prototype to single and multi-bunch trains of electron pulses with 5 mA amplitude are shown in Fig.7. Measurements were taken second by second.

What is interesting to observe is that when a single bunch was extracted from the linac and impinged on the beam stopper, the charges produced inside the chamber were collected and the related signal was elaborated by the electronics within 1 second, producing single peaks with the same amplitude (about 1.2 nC, as shown in Fig.7a). When the number of bunches per train increased up to 5, in some cases the total charge produced inside the chamber was splitted in two ouput peaks (see Fig.7b): the total charge of the two peaks (indicated in red in Fig.7b) was comparable with the charge integrated in the same set of measurements producing single peak outputs, which means that no charge was lost. As the number of pulses or the pulse amplitude was increased up to 10 bunches/train, the probability of splitting the signal in two peaks grew (see Fig.7c), but the total charge/train remained the same (about 11.3 nC). The results obtained at 1, 2, 10 and 15 mA are similar.
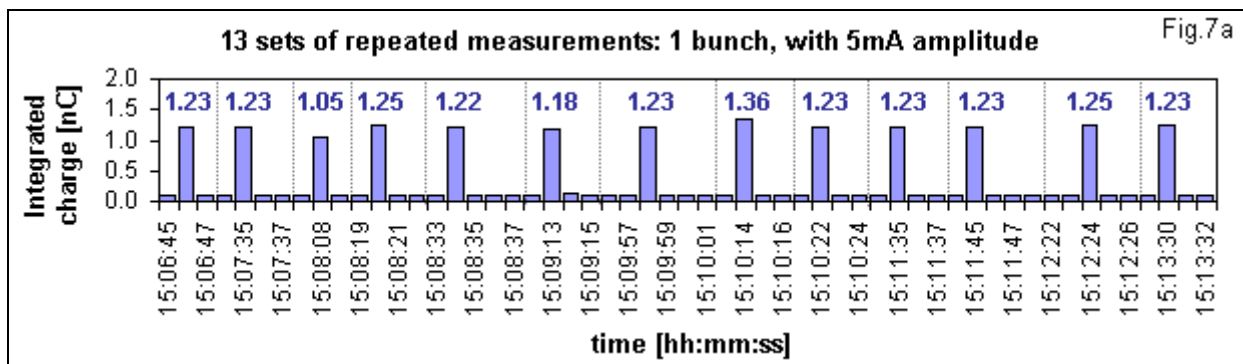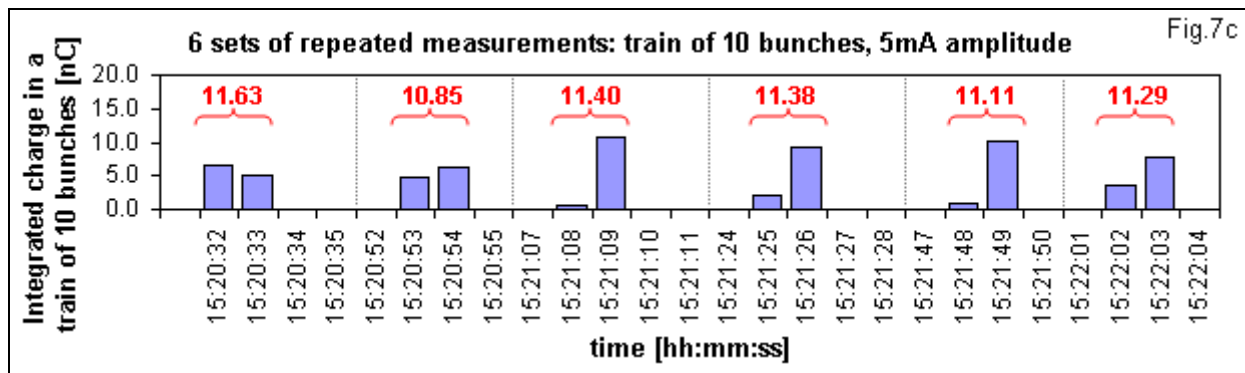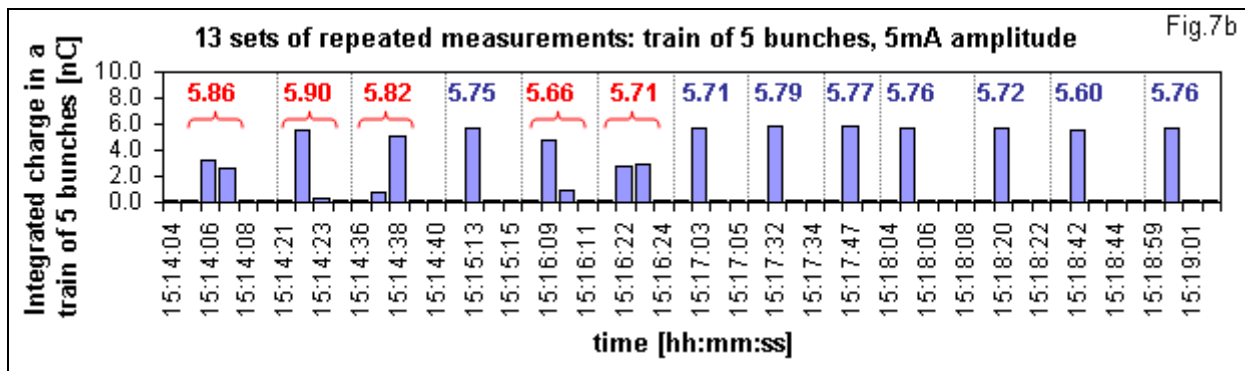
Fig.7 - Response of the EL.SE. prototype to single and multi-bunch trains of electron pulses with 5 mA amplitude.

The response of the El.Se. prototype gamma ionization chamber was also plotted versus the dose per train of pulses integrated by PTW ionization chamber, chosen as reference and already tested in a previous experiment [4].

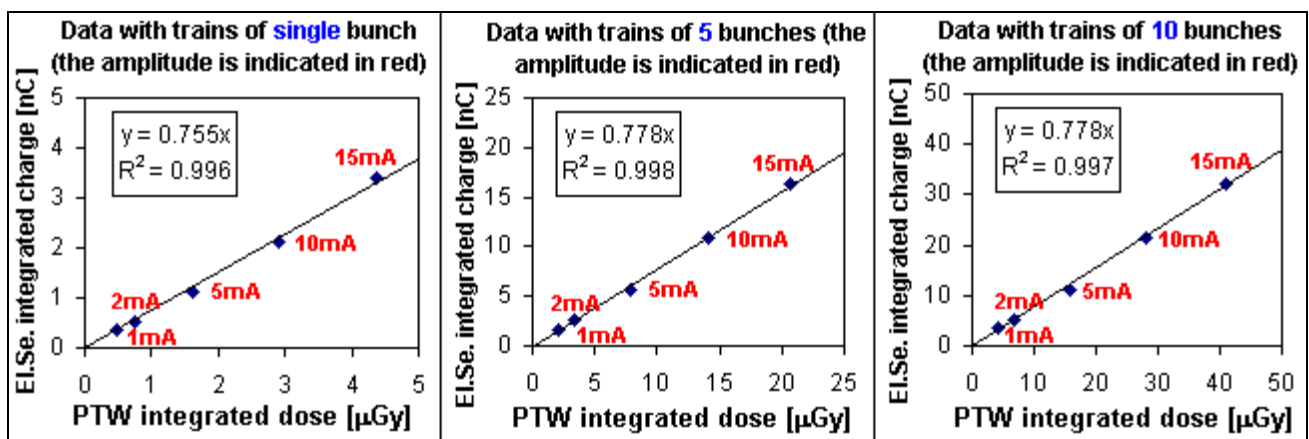The obtained trends are shown in Fig.8 and appear linear.

Fig.8 - Response of the EL.SE. prototype gamma ionization chamber plotted vs. the PTW integrated dose.

4.3. Environmental radiation background measurements

The long-term stability of the two El.Se prototypes were evaluated through environmental radiation measurements in comparison with an old-type Silena gamma ionization chamber.

Results are shown in Fig.9: all the detectors proved to be very stable (within 1.5% for all the monitors).

The difference in the mean values of the radiation background is due to the fact that the two El.Se. prototypes readings were plotted before final adjustment of the offset correction factor.
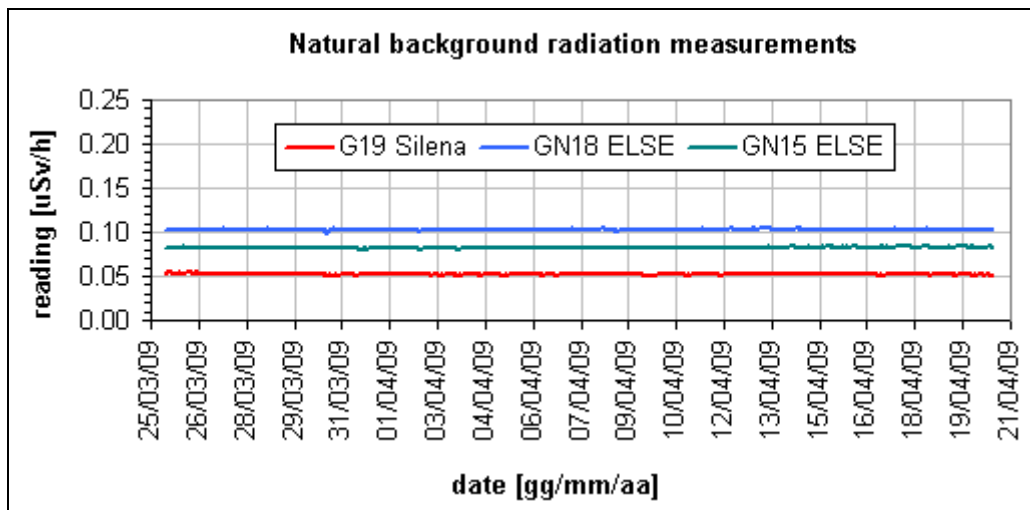
Fig.9 - Stability test of two El.Se. prototypes in comparison with an old-type Silena gamma ionization chamber.

5. Summary

The evaluation of the performances demonstrates that the new El.Se. gamma monitor meets all the expected requirements in terms of accuracy, linearity within 7 decades dynamic range (up to 10^{-7}A - high radiation dose rate), fast time response (<2ms) and long-term stability. The new monitor is able to process high number of charges within a very short time interval and a single shot radiation (e.g. storage ring beam dump). The response to single shot pulse was tested up to 3.5 nC/pulse (corresponding to ~ 4.3 uGy/pulse) and showed a linear trend.
At natural background radiation level, corresponding to a low input current (10^{-14}A), the new monitor proves to be very stable.
The system is completely remotely controlled and the calibration of the electrometer is performed by setting digital offset and gain parameters.

6. References

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