Radiation hardness tests of Si detectors for Time of Flight measurements at the Super-FRS*

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The beam diagnostics of the Super-FRS consists of several stations of different kind at the defined positions along the pre- and main-separator [1]. Besides position and energy-loss, in case of measurements with slow extracted-beams, the Time of Flight (ToF) information is a key aspect for the beam identification. The main design parameters of the ToF detector are the time resolution ≤50 ps (rms), active area up to 380 x 50 mm^2 and the ability to stand the rates of the relativistic ions up to 10^7 per spill over the whole active area.

Few beam tests of Si detector prototypes have been performed. In 2012, several prototypes with different thickness (100, 300 and 600 μm) and small active area (~25 mm^2) have been tested at GSI using ^{197}Au at 750 MeV/u and ^{238}U at 370 MeV/u beams [2]. The detector signals were digitized directly by the fast digital oscilloscope. The time resolution, calculated using a method similar to the one implemented in a leading edge discriminators with amplitude corrections, was found to be ~20 ps (rms, averaged value). The measured energy resolution was close to few percent.

Another experiment with ^{40}Ar beam at 40.5 MeV/u was performed in February 2014 in JINR, Dubna, at the fragment separator ACCULINNA.

Figure 1: Si strip detectors inside the scattering chamber of ACCULINNA separator.

The performance of four silicon detectors, one of those large-area (41 cm^2), with different geometry, under heavy irradiation was investigated (Fig.1). The intensity of the beam was up to 10^9 ions/s and the diameter of the illuminated area varied from 10 to 40 mm. The irradiation was performed in several steps; before the first irradiation and after each irradiation, the performance of the detectors was measured at reduced beam rate. The total fluence reached $2.3 \cdot 10^{13}$ ions/cm^2, compatible to the one obtained by HADES collaboration with diamond detectors [3]. The changes of the silicon material were monitored using the special small Si detector and the TCT technique [4]. In addition to the fast oscilloscope, fast preamplifiers with discriminators PADI [5] and a VFTX2 FPGA TDC [6] have been used for the signal processing. The detectors were cooled to -20° C in order to prevent heating up due to the irradiation. The results showed that the performance of the detectors did not change much (amplitude decreased in 10%) after the irradiation to 10^{11} ions/cm^2 (equivalent of a year of Super-FRS operation). Thus, the time resolution of the full-size detector even after a year of Super-FRS operation can be down to 30-40 ps.

Another test experiment has been performed at GSI in August 2014 with ^{197}Au beam at 1 GeV/u. One full-size prototype and several small detectors were measured. In addition to the above mentioned readout methods, two types of Flash-ADCs were used – DT5742 (12 bit, 5 Gs/s) and DT5743 (12 bit, 3.2 Gs/s), both are from the company CAEN.

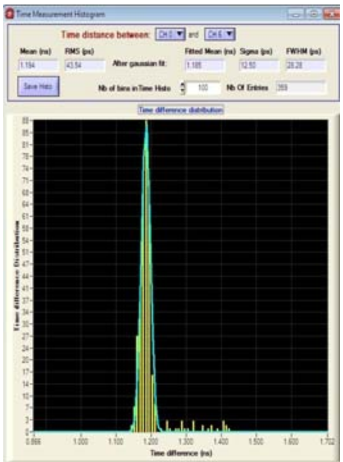

Figure 2: Time-of-flight resolution (measured by the waveform digitizer DT5743) of the small detector and one of the strips of the large Si strip detector.

Using the recorded waveforms, the time resolution between the small detectors and the single strips of the large detector were obtained using the Constant Fraction Discriminator (CFD) method. In order to avoid losses due to

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the lower than needed sampling frequency, the data points were interpolated by the 3-points splines. It has been demonstrated that the time resolution using fast digitizers can reach values down to 13 ps rms (Fig.2). Unfortunately, relatively large dead time of the waveform digitizers prevents to use them for the high-rate applications.

Additionally, a set of Si samples was irradiated to get quantitative information on Si detectors degradation rate under heavy ion irradiation. From the physical point of view, degradation of silicon under irradiation is a result of the crystalline lattice damage by impinging radiation. Two groups of the radiation defects are distinguished: extended disordered regions or clusters produced via direct interaction of the high energy particle with the Si atoms, and point defects generated in a separate crystalline cell via ion interaction with the electrons in the crystal.

The electronic properties of clusters cannot not be explained in terms of simple microscopic parameters like activation concentration, activation energy and trapping cross-section well describing the physical properties of point defects. Therefore their effect on the detector parameters is evaluated via changing certain detector characteristic, in particular, the current of reverse biased detector operated at full depletion mode as a most predictable and simple parameter. This current I is generated by clusters and point defects and is proportional to the irradiation fluence F. The slope of I-F characteristic α proportional to dI/dF is a specific parameter depending on the ratio between introduction rates of clusters and point defect. Therefore the current-related damage rate α normalized to the unit volume is a unique characteristic for scaling other radiation effects [7] like degradation of the free carriers trapping time, changes of the effective concentration in the detector sensitive region and, finally, for modeling the detector long-term operational scenario [8] for planning the experiments.

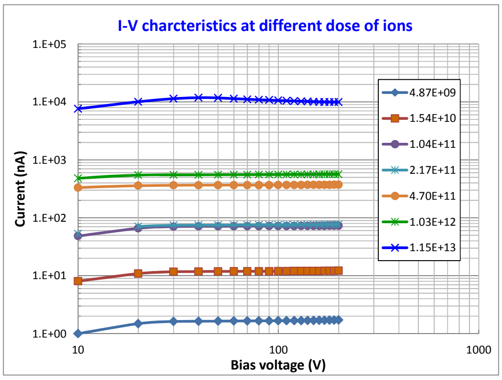

Fig. 3 I-V characteristics of irradiated detectors. The irradiation fluence is in the legend.

The damage rate α was measured for the run of multi-fluence irradiation of 120 Si test detectors. The detector set included pad detectors with a sensitive area 5 x 5 mm^2 and a thickness of 300 μm processed from high resistivity Si (10 kΩcm). The detectors were installed on the plates from Al foil which then were placed in the frames combined together in a solid block for irradiation. The installed detectors had nearly identical I-V characteristics with the reverse current less than 1 nA per detector. The ions passed through 7 detector layers, whose total thickness was less than the range of ^{40}Ar ions in silicon.
The fluence was controlled by the time of irradiation, and as soon as the certain fluence was reached the layer was taken out from the irradiation area, while the rest were left for future irradiation. Just after irradiation the detectors were placed in the fridge (T = -20 C°) till their evaluation.

The I-V characteristics of the irradiated detectors measured at room temperature are presented in Fig 3. All of them were measured with the activated guard ring for cleaning-up the bulk generated current from the surface leakage. Up to the fluence $1{\cdot}10^{11}$ ions/cm^2 the characteristics exhibit the current saturation. A linear fit of the saturated current vs F curve (Fig. 4) gives $\alpha = 7.8{\cdot}10^{-17}$ A/cm.

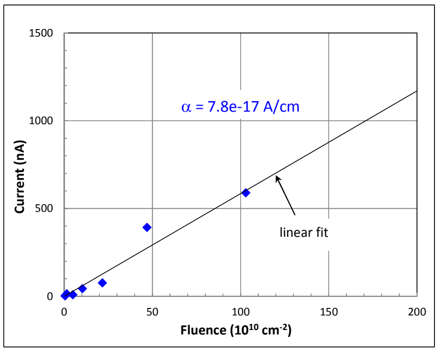

Fig. 4 Measured values of the saturated current vs fluence and their linear fit.

Table 1 Summarizes current-related damage rates for relativistic protons, ^{40}Ar ions and the 1 MeV neutrons as a reference type of irradiation.

Table 1

Radiation	Damage rate, A/cm	Scaling factor
Protons	$2.5{\cdot}10^{-17}$	0.62
^{40}Ar ions	$7.8{\cdot}10^{-17}$	1.95
Neutrons	$4{\cdot}10^{-17}$	1

The analysis of the samples is still going on. Once done, it will be unique data never measured systematically with heavy ions.

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