STUDY OF THE SILICON DETECTORS FOR TIME-OF-FLIGHT MEASUREMENTS AT THE SUPER-FRS FACILITY AND EXPERT EXPERIMENTS AT FAIR*

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An important part of the beam diagnostics of the future superconducting Super-FRS fragment separator at FAIR will be the time-of-flight measurement. The tests of radiation-hard silicon detectors for such measurements at the Super-FRS and the EXPERT project within the Super-FRS Experiment Collaboration are presented. The main part of the current work is devoted to an investigation of the time characteristics of silicon detectors under the irradiation caused by intermediate energy Xe and C beams. The time resolution, obtained for the detector prototypes irradiated with Xe, reaches down to 20 ps, for C ions to 100 ps. These results are presented and discussed.

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1. Introduction

One of the main scientific instruments of the future FAIR facility is the superconducting fragment-separator Super-FRS [1, 2], a scheme of which is

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shown in Fig. 1. This high-resolution magnetic spectrometer, coupled to the heavy-ion synchrotron complex, will be the central device for the research with exotic nuclei. The in-flight separator will provide a broad range of exotic nuclei beams from hydrogen up to uranium. In order to obtain information on the specific desired isotope, one needs to perform an identification of the particles. The conventional method of the particle identification is in simultaneous measurements of the energy deposition, time-of-flight (TOF) and the magnetic rigidity. The reliability of such particle identification depends, in particular, on the accuracy of the time measurements, *i.e.* the determination of the moment when the particle passes trough the detector. For example, for unambiguous identification of the light ions with mass number around 10, the time resolution can be about 300 ps (σ), and for the heavy isotopes like uranium, the time resolution of TOF detectors is more demanding and should be of about 30 ps. Such a value brings up a challenge to the properties of the detector and the corresponding electronics. Thus, fast radiation-hard silicon strip detectors (SSDs) for the TOF beam diagnostics at Super-FRS have been suggested.

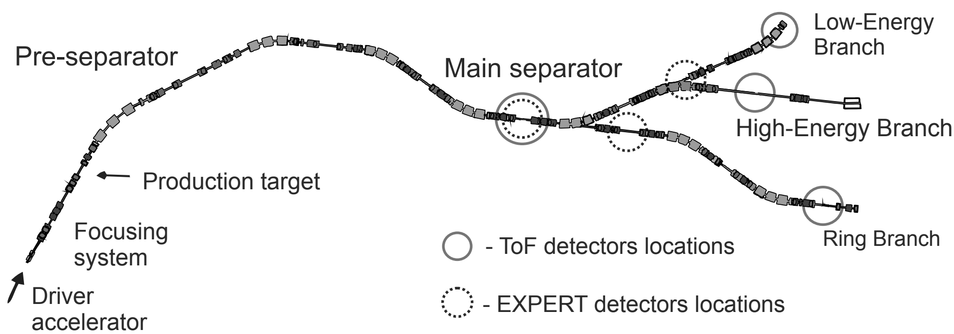

Fig. 1. Scheme of the Super-FRS fragment-separator at future FAIR. The locations of TOF detectors are shown by solid circles and the EXPERT-project one by dashed circles.

Up to now, several tests concerning the radiation hardness and time properties of Si detectors were performed. In particular, a test with ^{40}Ar beam at 40.5 MeV/u at the ACCULINNA fragment separator in JINR, Dubna, showed that the performance of silicon detectors did not undergo a significant change (*e.g.* signal amplitudes decreased by only 10%) after the irradiation of 10^{11} ions/cm^2 [3]. A similar fluence is expected after one year of Super-FRS operation. Another test at GSI with ^{197}Au beam at 1 GeV/u showed that SSDs provide time measurements with a resolution of $\sigma \approx 20$ ps [4]. This work is devoted to an investigation of the time characteristics of silicon detectors under the irradiation caused by the intermediate energy ^{124}Xe and ^{12}C beams.

Similar detectors are planned for the experiments within the EXotic Particle Emission and Radioactivity by Tracking (EXPERT) project, which is a part of the physics program of the Super-FRS Experiment Collaboration [2]. The EXPERT experiments aim at studies of exotic nuclear systems in the most remote parts of the nuclear landscape, which are located near the borders between bound and unbound nuclides (*i.e.* near the proton and neutron drip-lines). These experiments will use the first half of the Super-FRS main separator as a radioactive beam separator and its second half as a high-resolution spectrometer. The exotic nuclei of interest will be produced in the middle focal plane of the Super-FRS. They are expected to decay in flight, and the outgoing fragments (*i.e.* the precursor-like decay products) will be tracked and identified by the spectrometer part. Silicon strip detectors will be used for triggering, time and energy-deposition measurements, and double-side silicon micro-strip detectors for tracking trajectories of the decay products. The EXPERT locations are shown in Fig. 1 as well.

2. Experiment

The test of a few SSD prototypes has been performed using ^{124}Xe and ^{12}C primary beams at the energies of 600 MeV/u at GSI, Darmstadt in summer 2016. The beam intensity was varied between 10^3 and 10^5 pps. Several types of silicon detectors were used: a prototype SSD B with an active area of 64×64 mm^2 and a strip pitch of 1 mm, and a prototype SSD A with the same strip length but a different topology (it was divided into 3 groups of strips with pitch widths of 1, 1.5 and 2 mm). In addition, a non-segmented silicon quadrant detector was used as a start detector. It consisted out of four 3×3 mm^2 pads. Each of the detectors had a thickness of 300 μm.

In order to perform fast time measurements, dedicated fast readout electronics were used: a PADI preamplifier/discriminator with ASIC chip [5] and a VME-based high-resolution Time-to-Digital Converter implemented in a Field Programmable Gate Array (VFTX2) [6]. Both devices are designed and developed at the GSI Experiment Electronic Department.

The ions of ^{124}Xe produce signals in SSD prototypes with amplitudes of about 40 mV, and for ^{12}C of about 15 mV. The signals had rise times of about 1.2 ns. The amplifiers of PADI increased the signal amplitude by a factor of approximately 100 times. The thresholds for the PADI discriminator have been set to a value just above the noise level. The PADI provided timing signals in the LVDS standard to the VFTX2 device. The FPGA component inside VFTX2 is running on a 200 MHz clock, which corresponds to 5 ns time cycle. In order to perform the precise timing, the measurement is split into the coarse (clock cycle of 5 ns) and fine (channel) times, see Fig. 2 (a). The channel-to-channel time resolution of VFTX2 is around 7 ps.

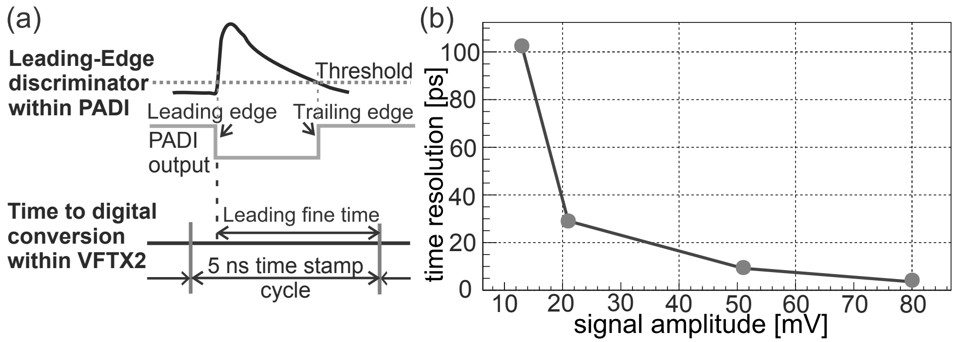

Fig. 2. (a) The scheme of signal processing within the PADI-VFTX2 electronics. The top panel shows a signal treatment by PADI, the bottom panel by VFTX2. For leading/trailing edges of the input signal from PADI, two values are recorded by VFTX2: the corresponding time stamp and fine time. (b) Dependence of the intrinsic time resolution σ (channel-to-channel) of PADI-VFTX2 electronics on the amplitude of the input signal, generated by pulser.

3. Data analysis and results

The most important parameter for accurate time measurements is the slope of the rising (leading) edge of the signal. A very steep and fast (order of ns) leading edge helps to decrease such effects as time jitter. Also the noise level must be kept as small as possible. Another phenomenon which influences the accurate time marking is the time-amplitude dependence. The PADI board has only Leading-Edge discriminator, but the output signal length depends on the amplitude (see Fig. 2 (a)). Due to this and the fact that the VFTX2 performs time measurements of both, leading and trailing edges, a parameter like Time-over-Threshold (ToT) can be used for a signal selection and correction of the time-amplitude dependence. The ToT value is the time period during which the signal amplitude exceeds the threshold value, *i.e.* the difference between trailing and leading time stamps of the signal. The ToT is proportional to the amplitude of the signal. One can improve the time resolution by applying the correction of the time difference *versus* ToT value. For our case, this dependence is rather small, and the correction does not improve the results.

In Fig. 3 (a), the ToT two-dimensional distribution derived from the SSD B and SSD A channels measured in coincidence is presented. The histogram in Fig. 3 (b) shows the ToT spectrum for one of the detectors. By applying the selection gate shown in Fig. 3 (a), we take into account only the events with similar ToTs and the highest number of coincidences. The applied gate helps to improve the time resolution by the factor of 2, which is illustrated below.

The time difference distribution is obtained using the following equation:

$$dt = (\text{lts1} - \text{lts2}) * 5000 - (\text{ft1} - \text{ft2}) \,,$$

where dt is the time difference in ps, lts1, lts2 are the coarse time stamps of the channels 1 and 2, ft1, ft2 are the corresponding fine times. The fine time values were calibrated.

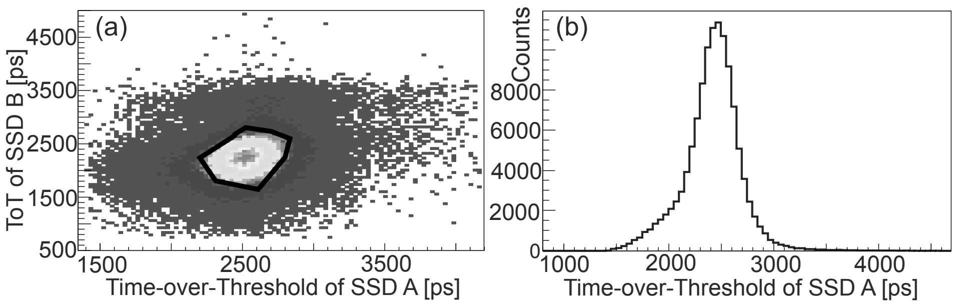

Fig. 3. (a) The Time-over-Threshold coincidence distribution. The solid black line shows the area with the highest number of coinciding events with similar ToT values. (b) ToT spectrum of the SSD A channel.

The resulting time difference spectrum is presented in Fig. 4. Its shape is a narrow symmetric peak which can be approximated by a Gaussian distribution. For the case of ^{124}Xe, the standard deviation of time difference is $\sigma \approx 20$ ps, which is, in fact, the total time resolution for the detector pair, see Fig. 4 (b). For one detector in this case, the time resolution is $\sigma \approx 14$ ps [3].

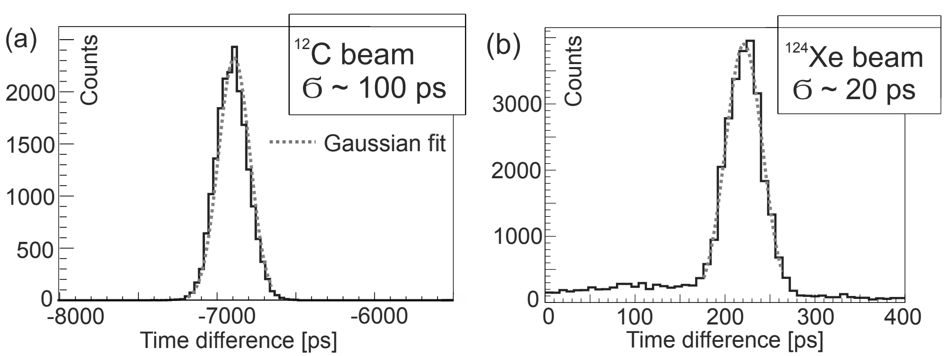

Fig. 4. (a) Time difference spectra obtained with ^{12}C beam at 600 MeV/u. (b) Time difference spectra obtained with ^{124}Xe beam at 600 MeV/u.

As it was mentioned in the previous section, the signals from ^{12}C were significantly lower in amplitude than the ones from ^{124}Xe. The time resolution obtained for the SSD pair in the case of ^{12}C is about 100 ps, see Fig. 4 (a), which corresponds to individual detector resolution $\sigma \approx 70$ ps. We have found that the different resolution is mainly due to the properties of the electronics itself. A recent laboratory test with a pulser has shown that the intrinsic time resolution of PADI deteriorates with the decrease of the input signal amplitude, see Fig. 2 (b). Nevertheless, for the Super-FRS beam diagnostics and application for the EXPERT experiments, the obtained time resolution is sufficient. As low-mass ions have much larger relative separation, the respective requirements for the TOF system are moderate, see introduction section.

4. Conclusions

The measured time resolution of the full-size Si detector prototype with ^{124}Xe beam is $\sigma \approx 20$ ps (including the resolution of 3×3 non-segmented quadrant detector). This fully matches the requirements to the TOF system of the beam diagnostics of the future Super-FRS fragment-separator of the FAIR project. Signals from ^{12}C beam have much lower signal-to-noise ratio. The corresponding time resolution reaches $\sigma \approx 100$ ps. This value is mainly determined by the PADI front-end electronics. For light isotopes, this value is sufficient for the particle identification.

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