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Picosecond timing of high-energy heavy ions with semiconductor detectors

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ABSTRACT

Construction of new accelerating facilities to investigate reactions with heavy ions requires upgrading of the Time-of-Flight (TOF) systems for on-line ion identification. The requested time resolution of the TOF system developed for Super FRagment Separator in the frame of the FAIR program at GSI, Germany, is in the range of tens of picoseconds, which can be realized by using planar silicon detectors. Such resolution will allow characterization of relativistic ions from Lithium to Uranium. However, fast timing of heavy ions with semiconductor detectors is expected to be limited by the so-called plasma effect due to a high concentration of electron–hole pairs in tracks. Here the results of the experiment with relativistic ^{197}Au ions (the energy of 920 MeV per nucleon) obtained with Si detectors are described, which showed the TOF time resolution around 14 ps rms. The physical mechanism of charge collection from high-density penetrating tracks of relativistic heavy ions is considered and the analysis of timing characteristics is performed taking into account track polarization. Polarization is shown to have a strong influence on the formation of the leading edge of the detector current response generated by relativistic heavy ions, which allows us to explain the observed high time resolution.

1. Introduction

Construction of new heavy ion accelerators and the accompanying experimental facilities requires an advancement of the experimental tools for the beam monitoring and characterization of heavy ions. The project “Facility for Antiproton and Ion Research” (FAIR) being presently built at GSI, Darmstadt, Germany, is among the latest international projects aimed at creating innovative instrumentation. One of the goals of its first stage is building a new fragment-separator of heavy ions – Super FRagment Separator (Super-FRS) with enhanced beam intensity (up to 10^{11} s^{-1}) and the energy (up to 2 GeV/u) of ions from Lithium to Uranium. The Technical Design Report [1] for the Super-FRS beam monitoring includes the Time-of-Flight (TOF) system for ion beam diagnostics, whose specifications are presented in Table 1.

We describe here an approach to constructing a TOF system based on Si detectors and the experimental results of the time measurements of relativistic ^{197}Au ion beam using planar Si detectors. A physical model of current response generation and charge induction in Si detectors is considered, which proceeds from plasma effect in the tracks of short-range and relativistic heavy ions, i.e. in the case of High carrier Density inside Short-Range and Penetrating ion tracks (HDSR and HDP tracks, respectively).

2. Approach to high TOF resolution

The time resolution of the TOF system depends on the performance of the detectors and the readout electronics.

2.1. Materials and detectors

The TOF system for heavy ions is usually built on plastic scintillators and provides time resolution of several hundreds of picoseconds or more, i.e. worse than that required for Super-FRS. A severe limitation on using plastic scintillators for heavy ions also comes from the rapid degradation of their timing properties under high dose irradiation. Such issues motivate a search for an alternative approach based on the application of planar silicon detectors and/or diamond detectors [2–5]. The Si detectors have an appropriate sensitivity to the ions down to Lithium and Helium.

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Table 1
Parameters of TOF system for ion beam diagnostics in Super-FRS.

Parameter	Unit	Value
Quantity		4
Overall length	mm	200
Horizontal aperture	mm	400
Vertical aperture	mm	100
Time resolution	ps	<50
Rate	particles/spill	up to 10^7

In addition, well-developed technology of processing the detector units with a large sensitive area (up to 100 cm^2) provides high reproducibility of the parameters in mass-production. All this is advantageous for construction of the large-area detecting systems.

The radiation hardness of diamond detectors based on CVD-grown thick films, both monocrystalline and polycrystalline, is comparable and even higher than that of Si detectors, but the generated signals are, however, lower than in the Si devices. In single crystalline diamond detectors the charge collection time is shorter than in the Si ones, which along with a lower dielectric permittivity is advantageous for fast timing. The main drawback of the diamond detectors is the production technology, which restricts the detector unit area within a few cm^2 [6], fails to provide uniform sensitivity over the detector active area and, as a result, mismatches mass-production of detectors with predictable and identical characteristics. Therefore a TOF unit with uniform characteristics over the area up to 240 cm^2 using individual diamond sensors with 4–5 cm^2 active area is hardly achievable. One should not forget that a price of diamond material still remains very high.

2.2. Readout electronics

It is also important to choose an appropriate type of front-end electronics to be applied in TOF systems. Standard charge sensitive readout electronics consists of a charge-sensitive (integrating) preamplifier, a voltage amplifier/shaper and a fast constant fraction discriminator (CFD). A minimal rise time t_r of the output signal is the charge collection time of the electrons and holes in the detector sensitive region, which is well predictable for detectors with negligible carrier trapping. In this case a rise time is determined by the distribution of the generated electron–hole (e–h) pairs and of the electric field. For the fastest semiconductor detectors (based on Si and diamond) with a standard thickness of 300 μm and a uniform electric field, the collection time is 3–10 ns or 3–30 ns, depending on whether the electrons or the holes, respectively, are dominating in charge collection. The values depend on the operational bias voltage V_b and the carrier mobility μ. However, even for a semiconductor with high carrier mobility, like the single crystalline diamond (μ_e and μ_h are close, each about 2000 cm^2/sV [5]), the minimal rise time ($\sim$3 ns) is limited by the carrier saturated drift velocity v_s being of the order of 10^7 cm/s for electrons and holes in both silicon and diamond detectors. For the so-called low-gain silicon detectors (Low Gain Avalanche Diodes, LGAD [7]) intensively developed in the frame of the CERN-RD50 collaboration program, the collection time is up to two times longer due to the additional phase of the collection of holes generated via avalanche multiplication near the detector n^+ side. The rise time of the charge pulse is consequently enlarged, approaching 10 ns. Meanwhile, minimization of detector thickness reducing the collection time increases the capacitance, which is critical for the detectors with the area of several cm^2. As a result, the time parameters of the detector signals become worse.

For a detector signal with a linear leading edge the time resolution component related to the signal-to-noise ratio S/N and denoted as jitter (σ_j) is as follows:

$$\sigma_j = t_r (S/N)^{-1} \tag{1}$$

Thus, to achieve time resolution of 30 ps in the 300 μm semiconductor detectors with t_r equal to the collection time of 3 ns the S/N ratio around 100 is required. This rather high value forces optimization of the front-end electronics bandwidth (BW) by shaping the output pulse of the preamplifier. A negative impact of the optimization is a linear increase of the pulse rise time. In this case σ_j can be expressed by replacing t_r in Eq. (1) with the shaping time τ_{sh} which is longer than the collection time. Since in a first order approximation, the rise time will increase as τ_{sh} and the S/N ratio is proportional to $\sqrt{\tau_{sh}}$, the net effect will be negative, and the time resolution will become worse.

An alternative approach to obtain high time resolution is to operate using the current pulse generated by the detector. Its rise is much faster compared with that of the charge pulse. A circuit of the current pulse readout contains the current/voltage convertor providing either attenuation or amplification of the detector current response, and a CFD. Thus, the charge sensitive preamplifier and the shaper are replaced by a fast current amplifier with the 50 Ω input impedance, which allows the amplifier to be connected with the detector via a wide-band RF cable to receive a signal with a minimal distortion of the original detector response. In the case of mounting the preamplifiers directly on the detector, the input impedance is less critical. Then the jitter-related component of the time resolution can be evaluated according to Eq. (1), with t_r being now the rise time of the current pulse. The fact that the rise time of the current pulse is usually shorter than that of the charge pulse makes the current readout electronics advantageous for measuring time with the best possible resolution.

3. Experimental setup

The experiment was performed with a beam of ^{197}Au ions with the energy of 920 MeV/u produced by synchrotron SIS 100 at GSI. The beam spot was approximately 1 cm in diameter and had the intensity up to 10^6 ion/s. The experiment was aimed at reproducing typical operational conditions for the TOF detectors of the future Super-FRS. All detectors were placed on the metallized PCBs mounted on the cooled plate (Fig. 1) installed inside a vacuum chamber. The temperature of the detectors was around −13 °C.

The set of installed detectors included a full-size 64 × 64 mm^2 strip detector with a pitch of 1 mm, small microstrip detectors with the area of 13 × 13 mm^2 and a pitch of 100 μm, and small pad detectors with the area of 5 × 5 mm^2 and 1 × 1 mm^2. The latter had very low capacitance which allowed minimizing the detector pulse distortion and its time constant RC. The thickness d of all detectors was 300 μm.

The shapes of the current pulse response were recorded using a digital oscilloscope Tektronix TDS 5204 (2 GHz analog bandwidth and 10 GHz sampling frequency). The time resolution was measured by the two 5 × 5 mm^2 pad detectors placed back-to-back and operated in the coincidence mode. The results obtained with strip detectors will be published elsewhere.

4. Experimental results

4.1. Rise time of the current response

The ^{197}Au ions passed through a stack of detectors and in each of them deposited approximately 800 MeV. To minimize the influence of the Landau fluctuations of the energy deposited by

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