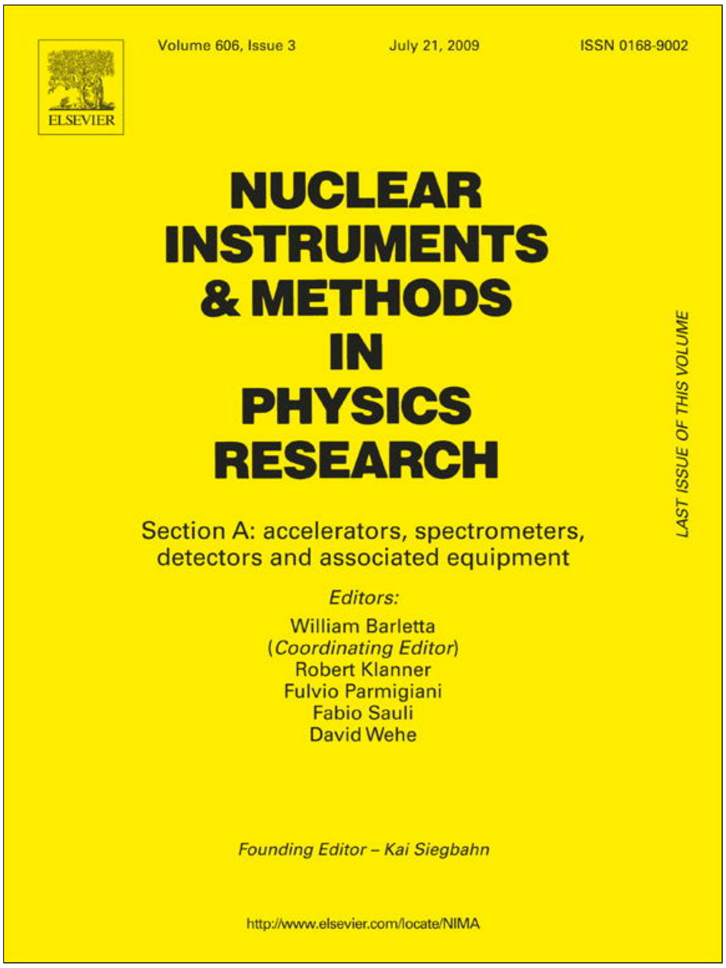
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Multi-coincidence ion detection system for EUV–FEL fragmentation experiments at SPring-8

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ABSTRACT

We have developed a dead-time free ion momentum spectroscopy technique that allows us to extract 3D momentum for each of up to 100 ions produced by a single free-electron-laser (FEL) shot, by reading signals from the three-layer delay-line detector by the multichannel digitizer and employing the software constant-fraction discrimination method.

1. Introduction

Ion time-of-flight (TOF) spectrometry is a standard tool because of its simplicity. Using position sensitive detectors the hit position on the detector allows to determine the momentum particle by particle. In particular the use of delay line detectors has become a widespread method for multi-particle momentum spectroscopy both for synchrotron radiation experiments [1] and laboratory laser experiments with high repetition rates (1 kHz or higher) [2,3]. This well-established approach is, however, limited to detect a few particles from a single event, or from a single light pulse. Self-amplified spontaneous-emission (SASE) free-electron-laser (FEL) light sources in the extreme ultraviolet (EUV) region, currently available at FLASH in Germany [4] and SCSS test accelerator in Japan [5], require redesigning the detection systems compared to those used at synchrotron sources or laboratory laser sources.

When the FEL beam is focused on clusters, for example, individual atoms in the particle may be ionized by a single photon of the FEL and as a result multiple ionization takes place for each cluster particle within a single FEL pulse [6–9]. The degree of ionization can be several hundreds for each particle, producing about the same number of ions via Coulomb explosion. Thus, the appropriate data acquisition system must be capable to record several tens ions shot by shot, assuming the ion detection of efficiency to be 10%. In the present letter, we describe how we have improved the above described multi-particle momentum spectroscopy method to detect up to 100 ions produced by a single shot of the FEL pulse.

2. Data acquisition system

The design of our ion spectrometer is described elsewhere [10]. Briefly, the spectrometer uses two acceleration regions

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with homogenous electric fields and a 268 mm long drift tube. The determination of the ion momentum is based on the measurements of the time-of-flight and the detector hit position for each ion. Here, a three-layer type detector (Roentdek HEX80) is used to minimize the dead-time [11]. The ions pass three grids with a transmission of ~70% before hitting the microchannel plate (MCP) in front of the delay line detector. Singly charged ions have a detection efficiency on an MCP of ~30%. Therefore we expect a total detection efficiency of ~10%.

For typical experimental conditions, many singly charged ions are released in a single FEL shot from a single cluster. Many of them (10% in our case, due to the detection efficiency) need to be recorded including their TOF and detector hit positions within a short time window of some 100 ns. Depending on the hit position the time that a pulse needs to leave the delay line anode is 0–100 ns, therefore a substantial amount of temporal overlap of the signals from different ions occurs. A combination of the redundant information from a three layer delay line detector and a sophisticated logic is necessary to reconstruct all hit positions and momenta. Instead of conventional constant-fraction discriminators and time-to-digital converters an 8-channel digitizer (Acqiris DC282 $\times$ 2) is used [12,13]. The trigger signal is derived from the master oscillator of FEL. The complete waveforms of six signals from the three-layer delay-line anode and one from the MCP are recorded by seven channels of the 8-channel digitizer and stored in the computer. The timing signals are extracted offline from the each waveform by software resembling a constant-fraction discriminator [14]. We restrict the analysis to ions whose signal pulses do not overlap on at least two layers. The detected positions and TOF of each ion are obtained from the seven different timing signals and then the 3D momentum was calculated using the position and TOF information for the individual ions. The redundancy of the data set (only 4 out of 7 readouts are essential) allows us to perform a virtually dead-time free measurement for the 3D momenta of up to 100 ions produced by a single shot.

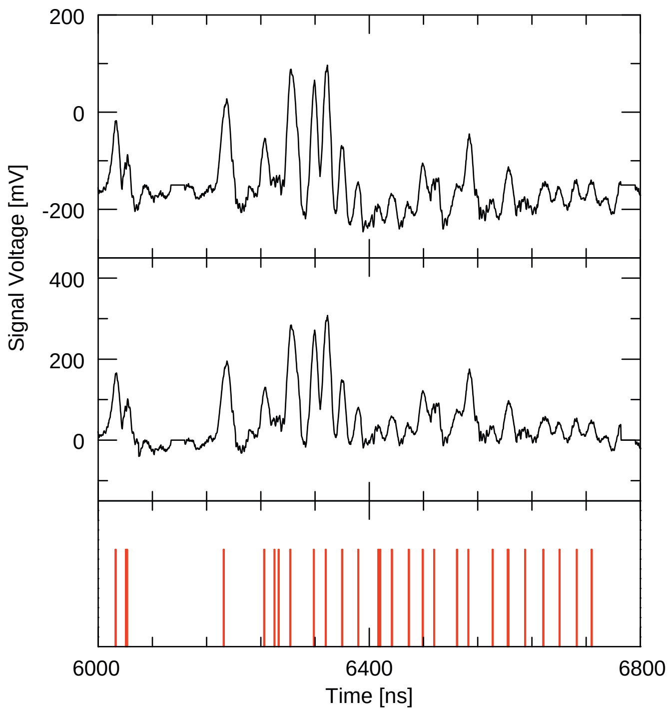

Fig. 1. Software constant-fraction discrimination. Top, raw data. Middle, after baseline correction. Bottom, timing signals as a result of the discrimination.

3. Experimental

The test experiment was carried out using EUV–FEL pulses at SCSS test facility in Japan [5]. The Kr clusters were produced by expanding Kr gas at a stagnation pressures of 1.5 and 3 atm at temperature 170 K, through a nozzle with a pinhole of 30 μm diameter and 0.25 mm thickness. The corresponding average cluster size was estimated to be $\langle n \rangle$~10 and 60 by the scaling law published in Refs. [15,16]. To focus the FEL beam onto the cluster beam of 1 mm in diameter, we used a concave mirror at normal incidence. This mirror was fabricated at Tohoku University, using a tungsten/vanadium coating on a super-polished quartz substrate with a focal length of 250 mm.

4. Results and discussion

Top panel of Fig. 1 depicts a portion of raw data from a single wire of the delay line. The software can find out the wavy baseline, subtract it as shown in the second panel, and then carry out constant-fraction discrimination [14] setting the discrimination level properly. The bottom panel depicts the timing signal as a result of the software constant-fraction discrimination. We have in total seven such timing signals from a single-shot measurement. Examining all possible combinations of such

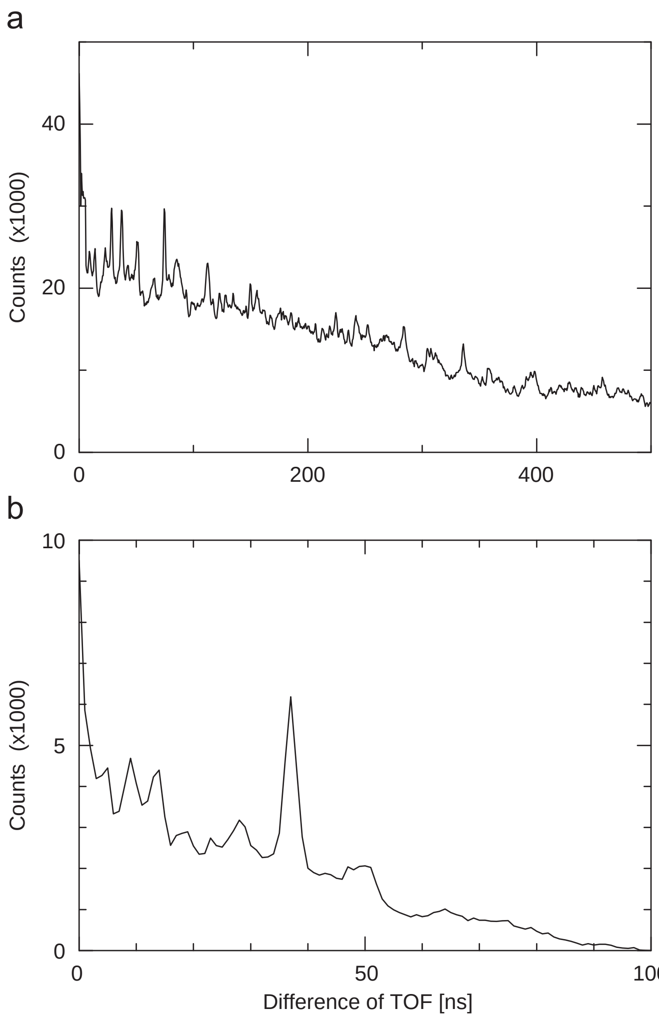

Fig. 2. Dead-time effects: upper panel, for ion pairs detected in the entire time interval of 30 μs; lower panel, for ion pairs detected within 100 ns time window.

seven timing signals, we find "hits" that are valid and thus can be used for retrieving 3D momentum.

The dead-time effects can be analyzed from the measured data by plotting a histogram of the distribution of the time differences of any detected ion pairs. Such plots are shown in Fig. 2, where the upper panel (a) includes any ion pairs detected in the observed time interval of 30 μs, whereas the lower panel (b) includes only ion pairs detected within the 100 ns time window when the ions arrive at the detector most densely. The time window of 100 ns corresponds to the maximum time that the pulse needs to leave the delay line anode. In both cases, we can clearly see that the events in which the two ions arrive at the detector at the same time can still be detected without suffering from the dead-time effects. In this way we can confirm that our detection system is practically dead-time free. Further careful inspections of the data reveal that substantial dead-time remains only for the case that two non-energetic parent ions hit the center of the detector. For the energetic fragments from clusters undergoing Coulomb explosion, the dead-time effects were practically negligible and more than 20 ions of the same mass were detected.

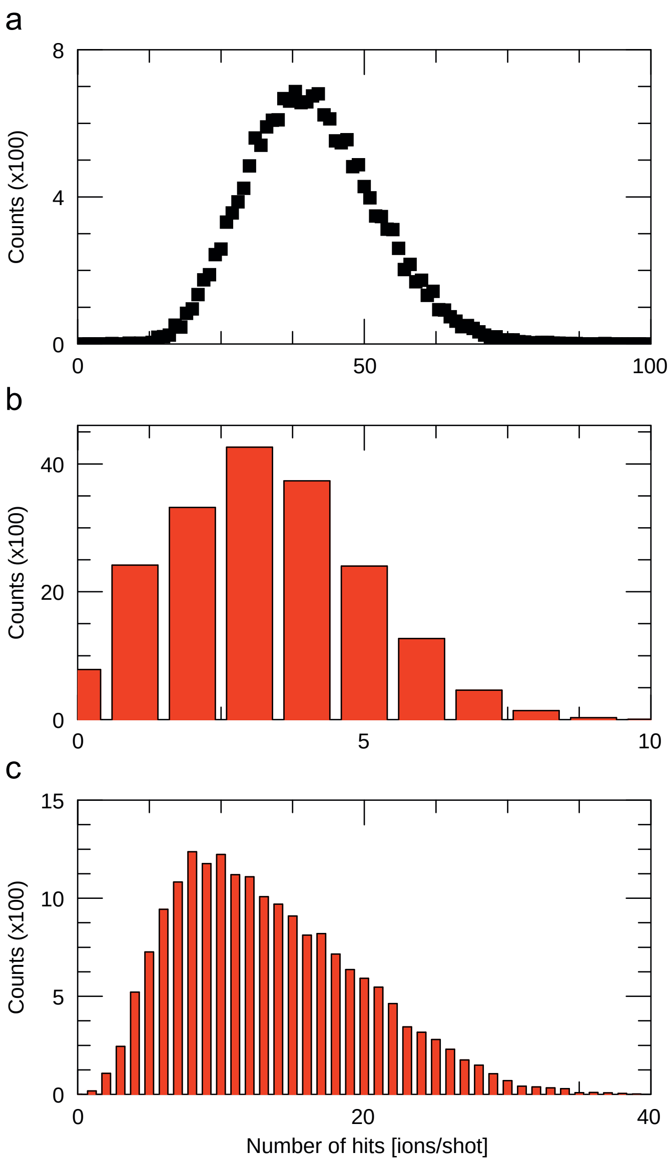

Fig. 3. Distribution for the number of hits: upper panel, retrieved from a single shot; middle panel, retrieved within a 100 ns time window; bottom panel, retrieved selecting only Kr^+ ions.

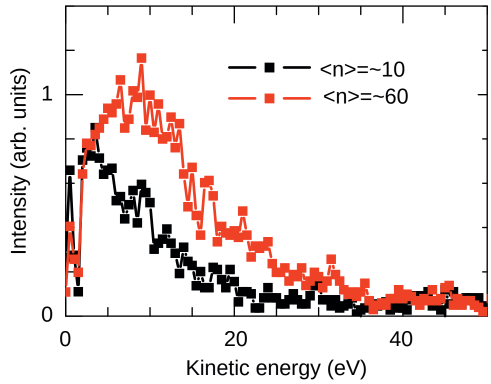

Fig. 4. Kinetic energy distributions obtained for the Kr^+ ions.

The upper panel (a) in Fig. 3 depicts a histogram of the distribution for the number of ions retrieved from a single-shot measurement. As can be seen in the figure, our detection system detected up to about 80 ions without suffering from dead-time effects. The middle panel (b) in Fig. 3 depicts a histogram of the ions detected in 100 ns time window when the ions arrived the detector most densely. This plot can be a measure of the real multi-hit capability of our detection system. As can be seen in the figure, our detector could detect up to eight ions "simultaneously". The bottom panel in Fig. 3 depicts a histogram of only the Kr^+ ions. We can clearly see that we can detect more than 20 ions of the same kinds.

The necessity of using the three-layer detector instead of the two-layer detector can be confirmed by artificially killing signals from one layer. The number of detected ions (i.e., the number of hits that are valid) immediately drops to by more than factor of three because of severe unresolved overlap of the pulses in the remaining two layers. As a result the number of the detected ion pairs given in Fig. 2 drops by more than one order of magnitude and the number of ions detected in 100 ns time window becomes less than three.

Our dead-time free 3D momentum-resolved measurement allows to obtain kinetic energies and angular distributions of fragment ions. As an example of the results, we present in Fig. 4 kinetic energy distributions of the energetic Kr^+ ions recorded at two different averaged cluster sizes $\langle n\rangle \sim 12$ and 60. For the present spectrometer setting, we could collect all Kr^+ ions emitted into 4π sr with kinetic energies up to $\sim$18 eV and their angular distributions were found to be isotropic. Therefore, we restricted the analysis to a 0.84 sr detection cone towards the ion detector so that we could extract the kinetic energies of the Kr^+ ions up to 50 eV. Fig. 4 clearly shows that the Kr^+ ions get more energy as the cluster size increases. Similar trends for the Xe and Ar cluster results was fully discussed in our previous papers [8,9] and were attributed to the increase in the number of photons absorbed by the cluster and thus the increase in the number of atomic ions with the increase of the clusters.

In conclusion, we have developed a novel dead-time free ion momentum spectroscopy technique that allow us to extract 3D momentum for each of up to 100 ions produced by a single FEL shot.

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