Studies of ultrafast dynamics in substrate-free nanoparticles at ELI using Timepix3 optical camera

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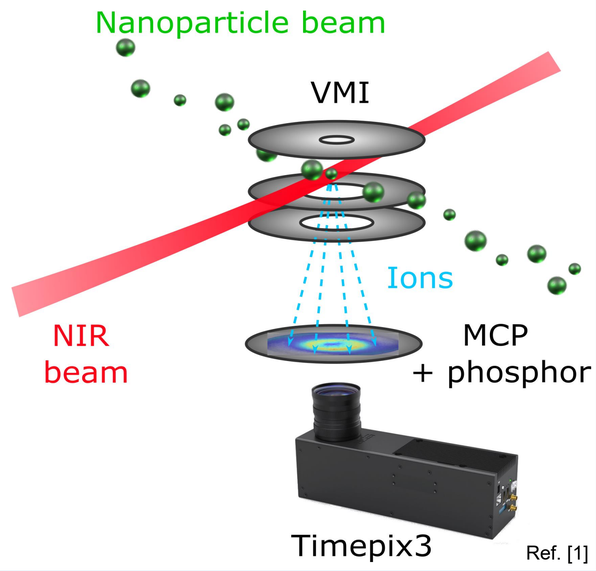
I. ELI ERIC

- The Extreme Light Infrastructure (ELI) European Research Infrastructure Consortium (ERIC) is the world's largest and most advanced high-power laser infrastructure
- ELI Beamlines provide access to some of the world's most powerful laser systems
- Focusing on plasma physics, material science, medical applications and advanced radiation sources
- Located in Czechia, Dolní Břežany near Prague

II. Interest of Study

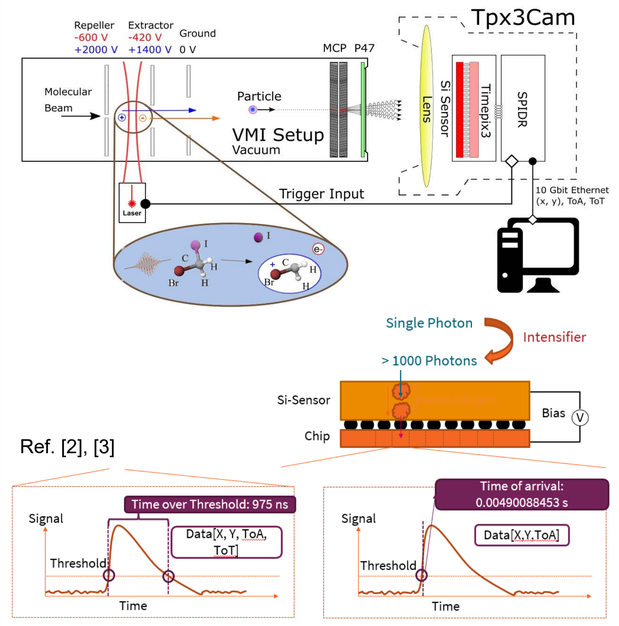
- Ultrafast optical imaging of ion dynamics
- Ions originating from free nanoparticles disintegrated by intense laser pulses
- Reconstructing hits distributions and behavior
- Need for a detector capable of individual time-stamping with nanosecond precision under extreme event occupancies (> 10 Mhits/s)



Ref. [1]

III. Timepix3

- Optical pixel detector with single-event time-stamping
- Captures X, Y, Time-of-Arrival (ToA), and Time-over-Threshold (ToT)
- ToA resolution 1.56 ns, ToT resolution 25 ns
- Operates in single-shot, event-based mode
- Supports >~10 MHz readout rate, ideal for high-repetition laser experiments
- Enables 3D ion imaging via combination with velocity map imaging (VMI)



Ref. [2], [3]

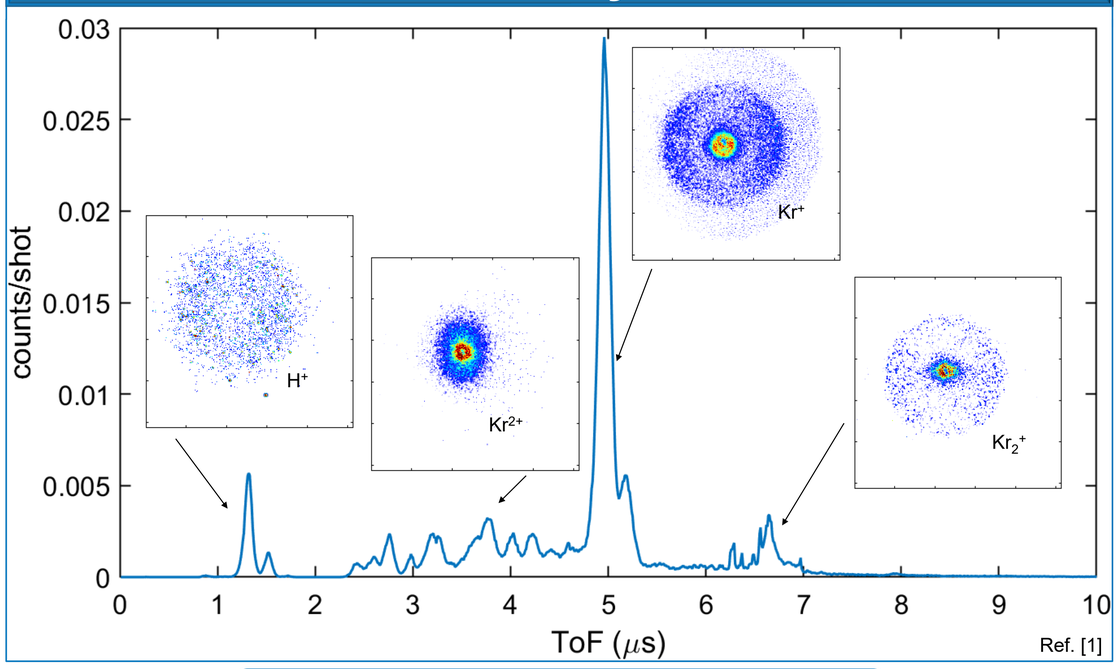
IV. Data Acquisition

- Integration of Timepix3 into the beamline
- Recording the ion hits with VMI
- Data acquired using the SPIDR readout system with 10Gbit Ethernet connection
- Handled real-time streaming of hit data (ToA, ToT, X, Y) to the acquisition computer for offline analysis

V. Post-processing

- Clustering algorithm for ~14 million hits
- Hits described by 15 parameters: Timestamp, X, Y, ToA, ToT, ToF, # of pixels in cluster etc. ToF is defined as time delay between Tpx3 pixel hit and laser signal
- Python analysis:
  - Overview information
  - Filtered data by ToF and # of pixels per cluster
  - Studying clusters behavior and correlations, reconstructing ion peaks and distributions, for filtered and unfiltered data

VI. Analysis



Ref. [1]

Fig. 1. Histogram of ToF (μs) distribution of generated H and Kr ions.

VII. Results

- Beam structure (Figure 2)
  - Laser running at 1 kHz
  - Timepix3 synch signal sent at 500 Hz
  - Alternating large and small nanoparticles lead to large and small occupancy sequences
- Data structure: large occupancy results in 409.6 μs (=2^{14} *25 ns) shift of measured ToA, which can occur consecutively for up to 4 times
- This readout misbehavior can be fully corrected for without loss of TOF information, see Figure 3

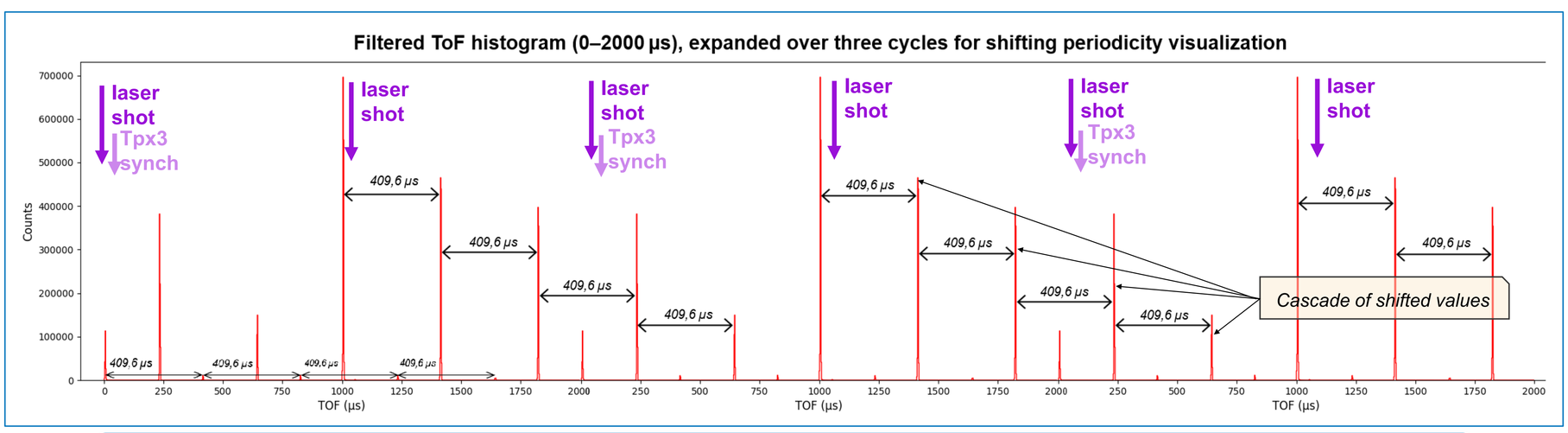


Fig. 2. ToF spectrum shown over 3 periods of 2000 μs. A clear shifting effect of 409.6 μs appears, likely due to the Timepix3 detector operating near its max readout rate (~80 Mpx/s). This causes overflows and pushes some hits into the next period. By subtracting the constant shift, spread-out data can be collected into a single peak. The dataset was taken using one 1 kHz laser beam.

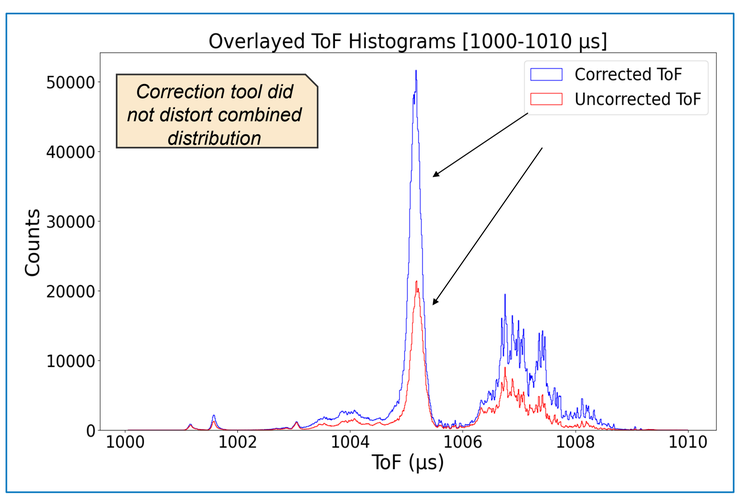


Fig. 3. Original and corrected distributions of Kr^+ peak at 1000-1010 μs. Combining shifted values by a 409,6 μs offset

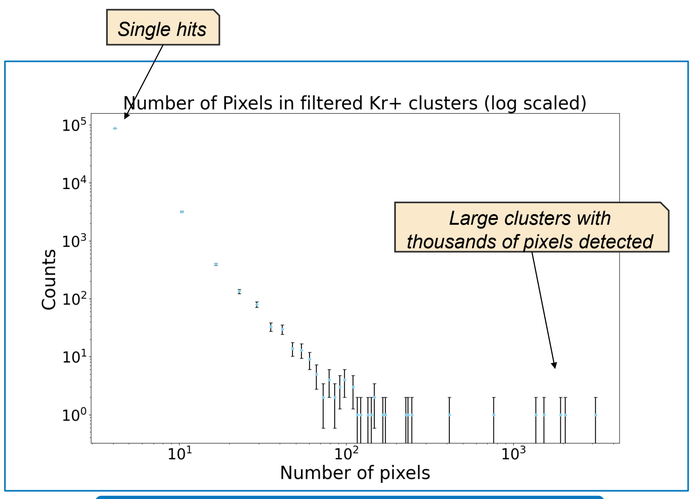


Fig. 4. Histogram of clusters population by pixels.

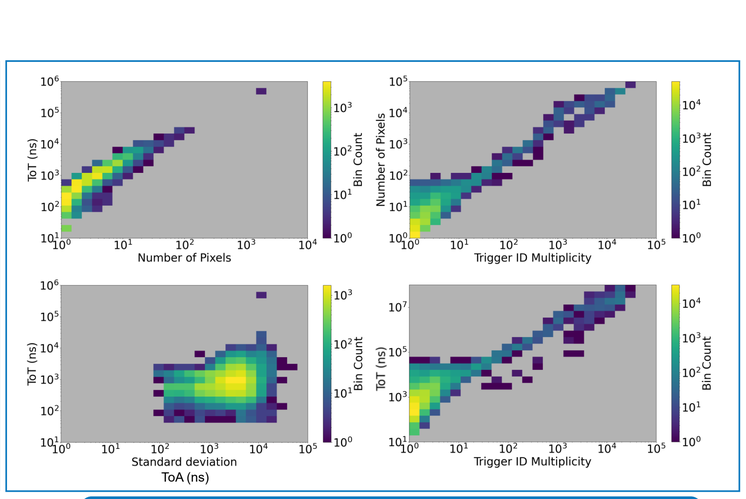


Fig. 5. Showing possible correlations of measured parameters and further capabilities of post-processed data analysis.

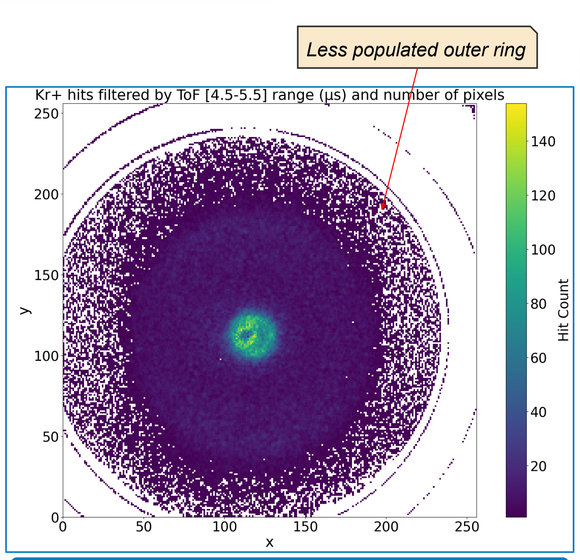


Fig. 6. 2D reconstruction of Kr^+ hits across the camera

VIII. Conclusions

- ✓ Timepix3 robustly captured ultrafast laser-induced ion bursts at ELI ERIC
- ✓ Enabled detailed reconstruction and analysis under high-intensity conditions
- ✓ Showed versatile analysis potential and stable performance in extreme occupancies
- ✓ Indications of reaching detector readout limits
- ✓ Simple 409.6 μs time-offset tool corrected event shifts and merged overflowed data

[1] Klimešová, E. (2025, 9th April). *Ultrafast dynamics in nanoscale matter using compact high-harmonic source at ELI Beamlines facility*. [PowerPoint slides] SPIE Conference.

[2] A. Zhao *et. al*., Review of Scientific Instruments **88**, 113104 (2017)

[3] Klimešová, E. (2024, 18th March). *TPX3CAM at MAC end-station*. [PowerPoint slides] ELI Beamlines facility, ELI ERIC Czech Republic

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