Species-Resolved Diagnosis of Laser-Accelerated Heavy Ions Using a Thomson Parabola Spectrometer Coupled with a CR-39 Detector

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Abstract

Species-resolved diagnosis of laser-accelerated heavy ions is crucial for understanding the underlying acceleration mechanisms and optimizing beam quality. However, conventional Thomson parabola spectrometers (TPS) coupled with image plates or scintillators cannot distinguish ions with similar charge-to-mass ratios, limiting the accuracy of heavy-ion characterization. In this work, a diagnostic method combining a TPS with a CR-39 detector is presented for species-resolved identification of ions in laser-driven heavy-ion acceleration experiments. By correlating track diameter with ion energy per nucleon, reference curves derived from C^{5+} and O^{7+} ions enable reliable distinction between C^{6+}, N^{7+}, and O^{8+} ions and reconstruction of their respective spectra. The method further allows identification of heavy ions such as Zr^{30+} and the determination of their energy distributions. Moreover, it mitigates signal overlap at the high-energy end of TPS measurements, preventing ambiguity arising from overlapping ion traces. This simple and self-consistent approach substantially extends the diagnostic capability of TPS–CR-39 systems, providing accurate and intuitive species-resolved spectroscopy for laser-driven heavy-ion acceleration studies.

Full Text

Preamble

Species-Resolved Diagnosis of Laser-Accelerated Heavy Ions Using a Thomson Parabola Spectrometer Coupled with a CR-39 Detector

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Species-resolved diagnosis of laser-accelerated heavy ions is crucial for understanding the underlying acceleration mechanisms and optimizing beam quality. However, conventional Thomson parabola spectrometers (TPS) coupled with image plates or scintillators cannot distinguish ions with similar charge-to-mass ratios, limiting the accuracy of heavy-ion characterization. In this work, we present a diagnostic method combining a TPS with a CR-39 detector for species-resolved identification of ions in laser-driven heavy-ion acceleration experiments. By correlating track diameter with ion energy per nucleon, reference curves derived from C^{5+} and O^{7+} ions enable reliable distinction between C^{6+}, N^{7+}, and O^{8+} ions and reconstruction of their respective spectra. The method is experimentally validated at the Shanghai Superintense Ultrafast Laser Facility (SULF), where it further enables the identification of heavy ions such as Zr^{30+} and the determination of their energy distributions. Moreover, it mitigates signal overlap at the high-energy end of TPS measurements, preventing ambiguity arising from overlapping ion traces. This simple and self-consistent approach substantially extends the diagnostic capability of TPS–CR-39 systems, providing accurate and intuitive species-resolved spectroscopy for laser-driven heavy-ion acceleration studies.

Keywords: Laser-driven ion acceleration, Thomson parabola spectrometer, CR-39, Heavy ions, Species identification

Introduction

Heavy-ion beams from conventional accelerators are essential tools in nuclear science and technology, enabling nuclear-reaction studies [1–7], radiation-damage studies in materials [8–10], and applications such as heavy-ion radiotherapy [11–15]. In recent years, laser-driven heavy-ion acceleration has emerged as a promising alternative to conventional accelerators, owing to its compact setup, ultrashort pulse duration, and capability to produce extremely high peak currents [16–21]. As laser technology advances toward higher intensities, resulting in the acceleration of heavy ions with both higher energy and higher charge states [22, 23], the demand for accurate, species-resolved ion diagnostics becomes increasingly critical. Recently, substantial progress has been achieved in laser-driven heavy-ion acceleration [24, 25], while diagnostic techniques remain limited in achieving species-resolved ion identification. For instance, gold ions with cutoff energies up to 1.2 GeV have been obtained using carbon nanotube structured targets to enhance target normal sheath acceleration (TNSA) [24], corresponding to charge states as high as Au^{61+} (q/m 0.31). In another work, quasi-monoenergetic gold ion beams with energies up to 1.6 GeV were produced from 15 nm-thick self-supporting gold foils via a hybrid acceleration mechanism [25], with charge states ranging from Au^{34+} to Au^{55+} (q/m 0.17-0.28).

Both studies employed Thomson parabola spectrometers (TPS) [26, 27] coupled with image plates (IPs) or scintillators for ion diagnostics. Although these measurements demonstrate remarkable heavy-ion acceleration, the diagnostic systems cannot fully exclude contributions from lighter contaminant ions—such as C^{4+} (q/m 0.33) and C^{3+} (q/m = 0.25), leaving species identification ambiguous.

To overcome these diagnostic limitations and achieve reliable species-resolved ion measurements, various approaches have been explored. The main challenge originates from the fact that ions with the same charge-to-mass (q/m) ratio trace the same parabola on the TPS detector plane. Consequently, ions with similar q/m ratios are difficult to distinguish based on spatial separation alone [28]. One approach to mitigate this issue is the use of filters to block short-range ions [29], but this method is indirect and not universally applicable, since the raw data of the blocked ions are discarded. To enable direct and unambiguous identification, CR-39—which is a kind of solid-state nuclear track detector (SSNTD)—has been adopted [30–32]. CR-39 detectors record individual ion impacts as latent tracks, which become visible after chemical etching. The track diameter depends on the ion species and energy [33–35]. Previous studies have demonstrated the identification of high-Z ions such as gold based on their large track diameters [36]. However, since this approach relies solely on absolute track size, it becomes ineffective when different ion species produce tracks of comparable size, as in the case of fully stripped carbon (C^{6+}) and oxygen (O^{8+}) ions.

An alternative approach was proposed to distinguish C^{6+} from O^{8+} ions by employing multiple SSNTDs with different ion sensitivities [28]. In that work, polyethylene terephthalate (PET), which is insensitive to carbon ions within the relevant energy range, was combined with other track detectors to isolate the oxygen ion signal. While this method demonstrated the feasibility of separating carbon and oxygen ions, it requires multiple detectors positioned at different locations, introducing experimental complexity and raising concerns about the strict comparability of ion signals recorded on different detectors due to beam spatial variations.

In this work, we present an innovative diagnostic method that enables the direct and unambiguous identification of ion species such as C^{6+}, N^{7+}, and O^{8+}, whose identification has long been difficult in multi-component laser-accelerated ion beams. The proposed approach integrates CR-39 detectors with a TPS, combining the charge-to-mass and energy resolution of the TPS with the diameter-energy correlations of ion tracks on CR-39 to achieve species-resolved ion identification. This method is further applied in a recent heavy-ion acceleration experiment conducted at the SULF, where zirconium ions with cutoff energies up to 850 MeV are successfully identified. The results demonstrate that this approach substantially enhances the diagnostic capability of TPS–CR-39 systems, providing a robust, scalable, and precise framework for species-resolved spectroscopy in laser-driven heavy-ion acceleration research.

Method and Experimental Setup

The proposed diagnostic method combines a TPS with a CR-39 detector to achieve species-resolved identification of ions in laser-driven heavy-ion acceleration experiments. In a TPS, ions with different charge-to-mass ratios are spatially separated according to their deflections in mutually parallel electric and magnetic fields, forming characteristic parabolic traces on the detector plane. Under the small-angle approximation, the ion deflections along the horizontal (x) and vertical (y) directions can be expressed as [26]:

$$B_{0L}B(+D_B)m_{iv}^2E_{0L}E(+D_E)$$

where E_0 and B_0 denote the strength of the electric and magnetic fields, L_E and L_B denote the lengths of the electric and magnetic field regions, D_E and D_B are drift distances, v is the ion velocity, and q/m_i represents the ion charge-to-mass ratio. These relations indicate that ions with identical q/m values follow parabolic trajectories within the TPS image and undergo exactly the same deflection in the TPS fields. Consequently, ions with identical q/m and E/A values are deflected to the same position on the detector. This allows the energy per nucleon of ions to be directly determined from their spatial positions even before their species are identified, which differs from most previous TPS analyses [36, 37] where ion species identification is performed first and ion energy is then inferred for each specific species.

Despite this advantage, ions with similar or identical charge-to-mass ratios—such as C^{6+} and O^{8+}—overlap along the same parabola and therefore cannot be distinguished by their spatial positions alone. To overcome this limitation, CR-39 detectors are employed to record individual ion impacts, providing the basis for species discrimination through track analysis. The correlation between track diameter (D) and energy per nucleon allows extraction of additional species-specific information.

In our approach, reference diameter-energy per nucleon (D–E/A) relationships are established as baselines using ions with unique charge-to-mass ratios that do not overlap with other species within the TPS field of view—for instance, C^{5+} (q/m = 5/12) and O^{7+} (q/m = 7/16). Because these reference tracks are obtained from the same CR-39 sheet with all other tracks, the resulting curves provide consistent and reliable calibration data since they are under identical etching conditions. Furthermore, since the dependence of track diameter on energy is independent of ion charge state [38, 39], these reference curves serve as robust baselines for subsequent ion identification. Once these reference relationships are established, tracks along other parabolas can be analyzed: ions whose D-E/A data coincide with the reference curves are identified as the same species (e.g., C or O), while deviations indicate the presence of other ion species, such as heavy target ions. This combined TPS-CR-39 analysis enables reliable discrimination of ions even when their charge-to-mass ratios are identical.

In our analysis, the ion energy is expressed in terms of energy per nucleon (E/A) rather than total kinetic energy. Ions with the same energy per nucleon possess identical velocities; when they also share the same charge-to-mass ratio, they undergo exactly the same deflection in the TPS fields.

To demonstrate this method, experiments were conducted at the SULF, utilizing the SULF-10PW system. The experimental setup is illustrated in Fig. 1. Linearly polarized laser pulses with a duration of 30 fs and a central wavelength of $\lambda = 800$ nm, carrying energies of 80 ± 5 J on-target, were focused onto the targets at an incidence angle of 10° using an f/4 off-axis parabolic mirror, following reflection from a plasma mirror. This configuration yielded a laser intensity of approximately 2×10^{21} W/cm^2. A 10 nm thick zirconium layer deposited on a 10 nm diamond-like carbon (DLC) substrate was used as the target in the experiment.

The TPS was aligned along the laser axis at an angle of 12° relative to the target normal. It comprised a 6 cm-long magnetic field of approximately 1 T and a pair of 15 cm-long electric plates biased to 15–20 kV. The spectrometer was positioned about 1 m from the target, with a 200 µm-diameter pinhole defining its acceptance. Ions deflected by the electric and magnetic fields were incident on the CR-39 detector.

After irradiation, the CR-39 sheets were etched in a 6 mol/L NaOH solution at 80°C for 1.5 h. This relatively short etching time was chosen to prevent over-etching and saturation of tracks. An image of etched tracks from a selected field of view for a laser shot on a zirconium target is shown in the inset of Fig. 1. After etching, the CR-39 detectors were scanned using an optical microscope. Automated image processing was applied to extract the position, diameter, roundness, and average grayscale value of each track. After preliminary filtering to remove artifacts such as scratches and dust, the cleaned dataset provided the spatial and morphological information of all valid ion tracks. Fig. 2 presents the reconstructed spatial distribution of valid tracks obtained through automated image analysis for a laser shot on a zirconium target, serving as the basis for the subsequent E/A and D-E/A correlation analysis.

For the laser shot on a zirconium target, the TPS-CR-39 detector recorded several distinct parabolas corresponding to ions with charge-to-mass ratios of 1/2, 5/12, 7/16, 3/8 and 1/3, as shown in Fig. 2. Among these, those with charge-to-mass ratios of 5/12 and 7/16, shown in Fig. 3(a), can be attributed with high confidence to C^{5+} and O^{7+} ions, respectively. Ion tracks were selected within a narrow band centered on each parabola (5/12 and 7/16), defined by a limited vertical range (about 100 µm) around the calculated trajectory at each horizontal position. This selection minimized contributions from adjacent parabolas, thereby reducing species mixing and ensuring accurate determination of D–E/A relationships.

Results and Discussion

The parabolic distributions of ion tracks provide an initial indication of the ion species generated in the experiment. In laser-driven ion acceleration, surface contaminants such as carbon, hydrogen, and oxygen are typically observed. In our case, the short etching time of the CR-39 suppressed the visibility of protons [37], so protons were excluded from further analysis.

Fig. 3(b) presents the D–E/A relationships extracted from ions with charge-to-mass ratios of 5/12 and 7/16. Each yields a single, well-defined curve, confirming that the respective parabolas are formed exclusively by C^{5+} and O^{7+} ions. In contrast, as shown later, parabolas containing multiple species give rise to multiple distinct curves in the D–E/A 2-D phase space. The C^{5+} and O^{7+} reference curves thus provide a robust basis for distinguishing C and O ions on other parabolas.

Building on the reference D–E/A relationships obtained from C^{5+} and O^{7+} tracks, we next analyzed the parabola corresponding to a charge-to-mass ratio of 1/2. To ensure reliable track selection for the charge-to-mass ratio of 1/2 parabola, a $\Delta y = 300$ µm band was applied, centered on the calculated trajectory at each horizontal position. This range was chosen to slightly exceed the 200 µm TPS pinhole, ensuring capture of all relevant tracks while minimizing contributions from neighboring parabolas [Fig. 4(a)].

The resulting D–E/A relationships [Fig. 4(b)] exhibit three distinct, non-overlapping curves, indicating the presence of three different ion species with a charge-to-mass ratio of 1/2. Comparison with the reference data [Fig. 4(c)] enabled assignment of the largest tracks to O^{8+}, the smallest to C^{6+}, and the intermediate tracks to N^{7+}, likely originating from surface contamination or ambient nitrogen. The observation that the cut-off energy of C^{6+} and O^{8+} extend to higher than that of C^{5+} and O^{7+} is consistent with expectations, since ions with higher charge states are accelerated in stronger fields [40].

This procedure also illustrates how the method suppresses artifacts from overlapping parabolas at high energies. When the selection band is expanded to $\Delta y = 800$ µm, tracks from the neighboring O^{7+} parabola are included [inset of Fig. 4(a)]. According to Eq. (1), since the charge-to-mass ratio of O^{7+} is lower than 1/2, its E/A is overestimated, producing spurious points above the O^{8+} curve, as shown in Fig. 4(d). However, such misassigned tracks can be identified and excluded by reference to the established D–E/A relationships, leaving the reconstructed spectrum unaffected. In practice, adjusting the Δy window provides a balance between completeness and purity: narrower bands yield cleaner D-E/A relationships, while wider bands avoid loss of genuine tracks, which can still be correctly classified using the calibration curves. The analysis also highlights the robustness of this method in mitigating signal overlap at the high-energy end of the TPS image. By identifying and excluding tracks that deviate from the established D-E/A correlations, the approach effectively suppresses artifacts arising from overlapping parabolas. This capability is particularly important in scenarios such as proton cutoff-energy diagnostics, where signals from high-energy heavy ions (e.g., C or O) could otherwise be misinterpreted as high-energy protons.

Having completed the analysis of the 5/12, 7/16, and 1/2 parabolas, we next examined those corresponding to charge-to-mass ratios of 1/3 and 3/8. As shown in Fig. 5(a), the 1/3 parabola contains tracks that align with the C^{5+} reference curve, confirming the presence of C^{4+} ions. In addition, another group of tracks on this parabola cannot be attributed to C, N, or O; their diameters vary slowly with energy and remain larger than those of carbon above 3 MeV/nucleon. Previous studies have indicated that, for certain ions, the track diameter in CR-39 increases with the electronic stopping power at the detector surface [30, 41]. For heavy ions, because of the broad Bragg peak, the stopping power varies weakly with energy, leading to a relatively flat D-E/A dependence. Fig. 5(b) shows the normalized electronic stopping power of C and Zr ions as a function of E/A, calculated using SRIM [42], which reproduces the trends observed in Fig. 5(a). On this basis, we attribute these tracks with large diameters to Zr^{30+} ions. This charge state is Ne-like and fully stripped, with a large ionization gap to the next state. This large gap favors its population.

The single ion species observed in the 3/8 parabola is assigned to O^{6+}. Fig. 6 compiles all extracted D-E/A data; as expected, the D-E/A dependence is independent of charge state, causing curves of the same ion with different charge states to overlap. In this shot, the following ions were identified: C^{4+}, C^{5+}, C^{6+}, O^{6+}, O^{7+}, O^{8+}, N^{7+}, and Zr^{30+}. The corresponding energy spectra for different charge states of carbon, oxygen, nitrogen, and zirconium are presented in Fig. 7.

Summary

In summary, we have developed a straightforward and effective method for ion identification in laser-driven heavy-ion acceleration experiments by combining a TPS with CR-39 detectors. The approach exploits the spatial separation of ions by the TPS electromagnetic fields together with track-diameter measurements obtained from CR-39 after etching. Reference D-E/A relationships were first established from the commonly produced C and O ions and subsequently used to identify ions of the same charge-to-mass ratio in the D-E/A phase space. By comparing diameter-energy trends, carbon and oxygen ions can be reliably distinguished, and this information can then be applied to identify heavier target ions according to their characteristic track diameters.

Using this method, we successfully distinguished C^{6+}, N^{7+} and O^{8+} ions and reconstructed their energy spectra. We further applied it to identify zirconium ions generated in the experiments, determine their charge states, and obtain their corresponding spectra. Overall, this method provides a simple, practical, and robust tool for laser-driven heavy-ion identification. With deeper understanding of the dependence of track diameter on etching conditions and particle energy, and with more precise measurements, its applicability can be further extended to a wide range of laser-driven ion acceleration diagnostics.

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Data Availability

The data that support the findings of this study are openly available in Science Data Bank at https://cstr.cn/31253.11.sciencedb.j00186.00793 and https://doi.org/10.57760/sciencedb.j00186.00793.

References

[1] V.I. Zagrebaev, W. Greiner, Cross sections for the production of superheavy nuclei. Nucl. Phys. A 944, 257-304 (2015). doi: 10.1016/j.nuclphysa.2015.02.010
[2] Th. Stöhlker, T. Beier, H.F. Beyer et al., Atomic physics with highly-charged heavy ions at future facility: The scientific program of the SPARC collaboration. Nucl. Instrum. Meth. B. 233, 494-497 (2005). doi: 10.1016/j.nimb.2005.03.231
[3] J.J. Cowan, C. Sneden, J.E. Lawler et al., Origin of the heaviest elements: The rapid neutron-capture process. Rev. Mod. Phys. 93, 015002 (2021). doi: 10.1103/RevModPhys.93.015002
[4] H.R. Wang, C.J. Lin, N.R. Ma et al., The heavy-ion time-of-flight spectrometer HiToF. Nucl. Sci. Tech. 36, 232 (2025). doi: 10.1007/s41365-025-01819-9
[5] X.B. Wei, Y.H. Qin, S. Xiao et al., Data analysis framework for silicon strip detector in compact spectrometer for heavy-ion experiments. Nucl. Sci. Tech. 36, 132 (2025). doi: 10.1007/s41365-025-01743-y
[6] J.T. Zhang, K. Yue, H.X. Li et al., The development of the HIRFL-in-ring reaction measurements at CSR. Nucl. Instrum. Meth. A 948, 162848 (2019). doi: 10.1016/j.nima.2019.162848
[7] Y.H. Zhang, Y.A. Litvinov, T. Uesaka et al., Storage ring mass spectrometry for nuclear structure and astrophysics research. Phys. Scr. 91, 073002 (2016). doi: 10.1088/0031-8949/91/7/073002
[8] J. Chen, P. Jung, W. Hoffelner, Irradiation creep of candidate materials for advanced nuclear plants. Journal of Nuclear Materials 441, 688-694 (2013). doi: 10.1016/j.jnucmat.2013.04.024

[9] P.P. Hu, L.J. Xu, S.X. Zhang et al., Failure mechanisms of AlGaN/GaN HEMTs irradiated by high-energy heavy ions with and without bias. Nucl. Sci. Tech. 36, 13 (2025). doi: 10.1007/s41365-024-01567-2

[10] G.S. Was, Challenges to the use of ion irradiation for emulating reactor irradiation. Journal of Materials Research 30, 1158-1182 (2015). doi: 10.1557/jmr.2015.73

[11] F. Ballarini, D. Alloni, A. Facoetti et al., Heavy-ion effects: from track structure to DNA and chromosome damage. New J. Phys. 10, 075008 (2008). doi: 10.1088/1367-2630/10/7/075008

[12] X. Li, S. Sun, S. Wang et al., Three dimensional approach to investigating biological effects along energetic ion beam pathways. Sci. Rep. 7, 44732 (2017). doi: 10.1038/srep44732

[13] W. Wang, X.X. Yuan, X.H. Cai et al., A beam range monitor based on scintillator and multi-pixel photon counter arrays for heavy ions therapy. Nucl. Sci. Tech. 33, 123 (2022). doi: 10.1007/s41365-022-01113-y

[14] J. Bin, L. Obst-Huebl, J.H. Mao et al., A new platform for ultra-high dose rate radiobiological research using the BELLA PW laser proton beamline. Sci. Rep. 12, 1484 (2022). doi: 10.1038/s41598-022-05181-3

[15] J. Han, Z. Mei, C. Lu et al., Ultra-High Dose Rate FLASH Irradiation Induced Radio-Resistance of Normal Fibroblast Cells Can Be Enhanced by Hypoxia and Mitochondrial Dysfunction Resulting From Loss of Cytochrome C. Front. Cell Dev. Biol. 9, 672929 (2021). doi: 10.3389/fcell.2021.672929

[16] A. Macchi, M. Borghesi, M. Passoni, Ion acceleration by superintense laser plasma interaction. Rev. Mod. Phys. 85, 751–793 (2013). doi: 10.1103/RevModPhys.85.751

[17] H. Daido, M. Nishiuchi, A.S. Pirozhkov, Review of laser-driven ion sources and their applications. Rep. Prog. Phys. 75, 056401 (2012). doi: 10.1088/0034-4885/75/5/056401

[18] B. Qiao, X.F. Shen, H. He et al., Revisit on ion acceleration mechanisms in solid targets driven by intense laser pulses. Plasma Phys. Control. Fusion 61, 014039 (2019). doi: 10.1088/1361-6587/aaf18e

[19] X.F. Shen, B. Qiao, A. Pukhov et al., Scaling laws for laser-driven ion acceleration from nanometer-scale ultrathin foils. Phys. Rev. E 104, 025210 (2021). doi: 10.1103/PhysRevE.104.025210

[20] H. Zhang, B.F. Shen, W.P. Wang et al., Collisionless shocks driven by 800nm laser pulses generate high-energy carbon ions. Phys. Plasmas 22, 013113 (2015). doi: 10.1063/1.4907194

[21] Y.R. Shou, X.Z. Wu, G.E. Ahn et al., Spatial and spectral measurement of laser-driven protons through radioactivation. Nucl. Sci. Tech. 34, 183 (2023). doi: 10.1007/s41365-023-01324-x

[22] J. Badziak, J. Domański, Acceleration of Heavy Ions by Ultrafast High-Peak-Power Lasers: Advances, Challenges, and Perspectives. Photonics 12, 184 (2025). doi: 10.3390/photonics12030184

[23] X.F. Shen, B. Qiao, A. Pukhov et al., Scaling laws for laser-driven ion acceleration from nanometer-scale ultrathin foils. Phys. Rev. E 104, 025210 (2021). doi: 10.1103/PhysRevE.104.025210

[24] P. Wang, Z. Gong, S.G. Lee et al., Super-heavy ions acceleration driven by ultrashort laser pulses at ultrahigh intensity. Phys. Rev. X 11, 21049 (2021). doi: 10.1103/PhysRevX.11.021049

[25] P. Martin, H. Ahmed, D. Doria et al., Narrow-band acceleration of gold ions to GeV energies from ultra-thin foils. Commun. Phys. 7, 3 (2024). doi: 10.1038/s42005-023-01425-4

[26] P. Martin, H. Ahmed, D. Doria et al., Absolute calibration of Fujifilm BAS-TR image plate response to laser driven protons up to 40 MeV. Rev. Sci. Instrum. 93, 053303 (2022). doi: 10.1063/5.0089402

[27] Y. Zhang, Z. Zhang, B. Zhu et al., An angular-resolved multi-channel Thomson parabola spectrometer for laser-driven ion measurement. Rev. Sci. Instrum. 89, 093302 (2018). doi: 10.1063/1.5042424

[28] Takamasa Hihara, Masato Kanasaki, Takafumi Asai et al., Discriminative detection of laser-accelerated multi-MeV carbon ions utilizing solid state nuclear track detectors. Sci. Rep. 11, 16283 (2021). doi: 10.1038/s41598-021-92300-1

[29] C. Baccou, V. Yahia, S. Depierreux et al., CR-39 track detector calibration for H, He, and C ions from 0.1-0.5 MeV up to 5 MeV for laser-induced nuclear fusion product identification. Rev. Sci. Instrum. 86, 083307 (2015). doi: 10.1063/1.4927684

[30] M.S. Schollmeier, J.J. Bekx, J. Hartmann et al., Differentiating multi-MeV, multi-ion spectra with CR-39 solid-state nuclear track detectors. Sci. Rep. 13, 18155 (2023). doi: 10.1038/s41598-023-45208-x

[31] M. Kanasaki, S. Jinno, H. Sakaki et al., The precise energy spectra measurement of laser-accelerated MeV/n-class high-Z ions and protons using CR-39 detectors. Plasma Phys. Control. Fusion 58, 034013 (2016). doi: 10.1088/0741-3335/58/3/034013

[32] B. Wu, K.G. Dong, Y.C. Wu et al., Identification of ion products produced from laser acceleration experiments using tracks on CR39. High Power Laser and Particle Beams 25, 0381 (2013). doi: 10.3788/HPLPB20132502.0381

[33] T.W. Jeong, P.K. Singh, C. Scullion et al., CR-39 track detector for multi-MeV ion spectroscopy. Sci. Rep. 7, 2152 (2017). doi: 10.1038/s41598-017-02331-w

[34] Y. Zhang, H.W. Wang, Y.G. Ma et al., Energy calibration of a CR-39 nuclear-track detector irradiated by charged particles. Nucl. Sci. Tech. 30, 87 (2019). doi: 10.1007/s41365-019-0619-

[35] Y.F. He, X.F. Xi, S.L. Guo et al., Calibration of CR-39 solid-state track detectors for study of laser-driven nuclear reactions. Nucl. Sci. Tech. 31, 42 (2020). doi: 10.1007/s41365-020-0749-

[36] F.H. Lindner, E.G. Fitzpatrick, D. Hafa et al., Charge-state resolved laser acceleration of gold ions to beyond 7 MeV/u. Sci. Rep. 12, 4784 (2022). doi: 10.1038/s41598-022-08556-8

[37] Vasiliki Kantarelou, Andriy Velyhan, Przemysław Tchórz et al., A Methodology for the Discrimination of Alpha Particles from Other Ions in Laser-Driven Proton-Boron Reactions Using CR-39 Detectors Coupled in a Thomson Parabola Spectrometer. Laser and Particle Beams 2023, 3125787 (2023). doi: 10.1155/2023/3125787

[38] A. Malinowska, M. Jaskóła, A. Korman et al., Characterization of solid state nuclear track detectors of the polyallyl-diglycol-carbonate (CR-39/PM-355) type for light charged particle spectroscopy. Rev. Sci. Instrum. 85, 123505 (2014). doi: 10.1063/1.4903755

[39] B. Dörshel, D. Fülle, H. Hartmann et al., Dependence of the etch rate ratio on the energy loss in proton irradiated CR-39 detectors and recalculation of etch pit parameters. Radiation Protection Dosimetry 71, 99-106 (1997). doi: 10.1093/oxford-journals.rpd.a032046

[40] J.Q. Yu, W.J. Ma, C. Lin et al., Shaping of ion energy spectrum due to ionization in ion acceleration driven by an ultra-short pulse laser. Plasma Phys. Control. Fusion 60, 115007 (2018). doi: 10.1088/1361-6587/aae0ac

[41] W. Qi, S.K. He, Y.Q. Gu et al., Intelligent algorithm based simulation of track etching process on CR39 detector. High Power Laser and Particle Beams 31, 056006 (2019). doi: 10.11884/HPLPB201931.190088

[42] J.F. Ziegler, M.D. Ziegler, J.P. Biersack, SRIM—The stopping and range of ions in matter. Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 268, 1818-1823 (2010). doi: 10.1016/j.nimb.2010.02.091

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