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 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.

Full Text

Preamble

Species-Resolved Diagnosis of Laser-Accelerated Heavy Ions Using a Thomson Parabola Spectrometer Coupled with a CR-39 Detector∗ Yi-Yang Zhao,1, 2

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Species-resolved diagnosis of laser-accelerated heavy ions is crucial for understanding the underlying ac- celeration 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, lim- iting 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 C5+ and O7+ ions enable reliable distinction between C6+, N7+, and O8+ 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 Zr30+ 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 es- sential 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 ac- celeration has emerged as a promising alternative to con- ventional accelerators, owing to its compact setup, ultra- short pulse duration, and capability to produce extremely high peak currents [16–22]. As laser technology advances toward higher intensities, resulting in the acceleration of heavy ions with both higher energy and higher charge states [23, 24], the demand for accurate, species-resolved ion diagnostics be- comes increasingly critical. Recently, substantial progress has been achieved in laser-driven heavy-ion acceleration [25, 26], 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) [25], corresponding to charge states as high as Au61+ (q/m 0.31).

In another work, ∗ Yi-Yang Zhao and Di-Rui Xu are co-first authors of this article; This work is supported by the National Key R&D Program of China (Grant No. 2022YFA1603300) and National Natural Science Foundation of China (Grant No. U2241281) † Corresponding author, bosqw7@163.com ‡ Corresponding author, yqgu@caep.cn 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 [26], with charge states ranging from Au34+ to Au55+ (q/m 0.17–0.28).

Both studies employed Thomson parabola spectrometers (TPS) [27, 28] coupled with image plates (IPs) or scintillators for ion diagnostics. Although these measurements demon- strate remarkable heavy-ion acceleration, the diagnostic sys- tems cannot fully exclude contributions from lighter contam- inant ions—such as C4+ (q/m 0.33) and C3+ (q/m = 0.25), leaving species identification ambiguous.

To overcome these diagnostic limitations and achieve reli- able 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 [29]. One approach to mitigate this issue is the use of filters to block short-range ions [30], but this method is indirect and not universally applicable, since the rawdata of the blocked ions are discarded. To en- able direct and unambiguous identification, CR-39 which is a kind of solid-state nuclear track detectors (SSNTDs) has been adopted [31–33]. CR-39 detectors record individual ion impacts as latent tracks, which become visible after chemi- cal etching. The track diameter depends on the ion species and energy. [34–36]. Previous studies have demonstrated the identification of high-Z ions such as gold based on their large track diameters [37]. However, since this approach relies solely on absolute track size, it becomes ineffective when dif- values follow the same parabolic trajectory within the TPS image.

In our analysis, the ion energy is expressed in terms of en- ergy per nucleon (E/A), defined as E/A = $(\gamma - 1)$mi0c2 = $(\gamma - 1)$muc2 the total kinetic energy of where Ek the ion, $\gamma = (1 - v2/c2)-1/2$ is the Lorentz factor, v is the ion velocity, mi0 is the ion rest mass, A is the mass number, mu is the atomic mass unit, and c is the speed of light.

Ions with the same energy per nucleon have identical velocities, if they also share the same charge-to-mass ratio, they experience identical deflections in the TPS fields and are therefore mapped to the same position on the detector

plane. Conversely, from the measured spatial deflection in the TPS and the corresponding charge-to-mass ratio, the ion velocity is inferred using the full TPS deflection relations. The Lorentz factor γ is then evaluated, from which the energy per nucleon E/A is obtained through the above relation.

Despite the q/m and E/A information provided by the TPS deflection, ions with similar or identical charge-to- mass ratios—such as C6+ and O8+—overlap along the same parabola and therefore cannot be distinguished by their spa- tial positions alone. To overcome this limitation, CR-39 de- tectors are employed to record individual ion impacts, pro- viding an additional species-sensitive observ- able through track analysis. The correlation between track diame- ter (D) and energy per nucleon enables the extraction of species-specific information beyond the TPS spatial map- ping. ferent ion species produce tracks of comparable size, as in the case of fully stripped carbon (C6+) and oxygen (O8+) ions.

An alternative approach was proposed to distinguish C6+ from O8+ ions by employing multiple SSNTDs with different ion sensitivities [29]. In that work, polyethylene terephthalate (PET), which is insensitive to carbon ions within the rele- vant energy range, was combined with other track detectors to isolate the oxygen ion signal. While this method demon- strated 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 dif- ferent detectors due to beam spatial variations.

In this work, we present an innovative diagnostic method that enables the di- rect and unambiguous identification of ion species such as C6+, N7+, and O8+, whose identification has long been difficult in multi-component laser-accelerated ion beams. The proposed approach integrates CR-39 detectors with a TPS, com- bining the charge-to-mass and energy res- olution of the TPS with the diameter- energy correlations of ion tracks on CR-39 to achieve species-resolved ion identifi- cation. This method is further applied in a recent heavy-ion acceleration exper- iment conducted at the SULF, where zirco- nium ions with cutoff energies up to 850 MeV are success- fully identified. The results demonstrate that this approach substantially enhances the diagnostic capability of TPS–CR- 39 sys- tems, providing a robust, scalable, and precise frame- work for species-resolved spectroscopy in laser-driven heavy- ion acceleration research.

II. METHOD AND EXPERIMENTAL SETUP The proposed diagnostic method combines a TPS with a CR-39 to achieve species-resolved identification of ions in laser-driven heavy-ion acceleration experiments.

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 approxi- mation (which is valid in the high-energy region of interest where the cutoff energies are determined, with deflection angles remaining on the order of 10−2 rad in this experi- ment), the ion deflections along the horizontal (x) and

vertical (y) directions can be expressed as [27] B0LB(+ DB) miv2 E0LE(+ DE) where E0 and B0 denote the strength of the electric and mag- netic fields, LE and LB denote the lengths of the electric and magnetic field regions, DE and DB are drift distances, v is the ion velocity, and q/mi represents the ion charge-to-mass ratio. These relations indicate that ions with identical q/m Fig. 1 [Figure 1: see original paper]. Experimental setup at SULF. The microscope images of the etched CR-39 were assembled, as shown in the figure. The inset presents an image of etched tracks from a selected field of view for a laser shot on a zirconium target.

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, C5+ (q/m = 5/12) and O7+ (q/m = 7/16). Because these refer- ence tracks are obtained from the same CR-39 sheet with all other tracks, the resulting curves provide consistent and re- liable calibration data since they are under identical etching conditions. Furthermore, since the dependence of track di- ameter on energy is independent of ion charge state [39, 40], these reference curves serve as robust baselines for subse- quent 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 devia- tions indicate the presence of other ion species, such as heavy target ions. This combined TPS–CR-39 analysis enables re- liable discrimination of ions even when their charge-to-mass ratios are identical.

To demonstrate this method, experiments were conducted at the SULF, utilizing the SULF-10PW system. The experi- mental setup is illustrated in Fig. 1. Linearly polarized laser pulses with a duration of 30 fs and a central wavelength of λ = 800nm, carrying energies of 80 $\pm$ 5J on target, were focused onto the targets at an incidence angle of 10$\circ$ using an f/4 off-axis parabolic mirror, following reflection from a plasma mirror. The focal spot at the target plane had a measured full width at half maximum (FWHM) diameter of approximately 6 µm, enclosing about 24% of the total laser energy. The corresponding peak intensity was esti- mated to be on the order of 2×1021 W/cm2. A 10 nm thick zirconium layer deposited on a 10 nm diamond-like car- bon (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 mag- netic field of approximately 1 T and a pair of 15 cm-long elec- tric plates biased to 15–20 kV. The spectrometer was posi- tioned 93 cm from the target, with a 200 µm-diameter pin- hole defining an acceptance solid angle of approximately $3.6 \times 10-8$sr. The resulting energy uncertainty due to non-normal ion incidence is estimated to be about 1.5% at 900 MeV for Zr30+ ions. Ions deflected by the electric and magnetic fields were incident on the CR-39 detector.

The magnetic field strength was characterized using a Hall probe, and the quoted value represents the spatially averaged field over the effective ion trajectory. An

in- dependent cross-check using aluminum-filtered ion cut- offs yielded a consistent field strength within a 3% de- viation. Since the ion energy scales quadratically with the magnetic field, this corresponds to an estimated sys- tematic uncertainty of approximately 6% in the absolute energy scale. This uncertainty results in a uniform scal- ing of the energy axis and does not affect the relative diameter–energy-per-nucleon correlations or the species discrimination procedure, which relies on the shape and separation of the D–E/A trends rather than on the abso- lute energy values.

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. After etching, the CR-39 detectors were scanned using an optical microscope at 500× mag- nification, corresponding to a pixel size of 0.1838 µm in the acquired images. Automated image processing was ap- Fig. 2 [Figure 2: see original paper]. Reconstructed scatter plot of ion-track positions from auto- mated image analysis, corresponding to the assembled microscope images of the etched CR-39, with calculated q/m parabolas overlaid for reference. plied to extract the position, diameter, roundness, and aver- age grayscale value of each track. After preliminary filter- ing 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.

Fig. 3 [Figure 3: see original paper]. (a)Raw image of the IP showing the X-ray spot (resulting from X-rays passing through the pinhole, indicating the zero- deflection point of the TPS) and the corresponding parabolic trajectories of the ions. The parabolas are theoretically calcu- lated based on this reference point. The proton trajectory is marked in white, while other ion parabolas visible on the CR-39 detector are marked in black. The edge of the CR-39 detector is indicated by a white dashed outline, and the CR-39 scanning region is highlighted by a boxed area.(b) Stitched raw micro- scope image of the CR-39 scanning region, corresponding to the boxed area in panel (a).(c–e) Optical micrographs acquired at 500× magnification from the three regions marked in panel (b), showing representative ion track patterns.

The zero-deflection point of the TPS for constructing the theoretical parabolic trajectories in Fig. 2 was deter- mined in an experimentally anchored manner by placing an IP directly behind the CR-39 detector. During each laser shot, prompt X-rays generated at the target prop- agated through the TPS pinhole and produced a well- defined exposure spot on the IP. The center of this X-ray spot defines the zero-deflection point of the TPS, corre- sponding to the position of ions experiencing zero net de- flection by the electric and magnetic fields.

Because the CR-39 detector partially shields the IP, the outline of the CR-39 is simultaneously imprinted on the IP surface. By measuring the relative position between the CR-39 boundary and the X-ray spot center, the abso- lute location

of the TPS zero-deflection point on the CR-39 detector can be reconstructed.

Using this experimentally determined origin and the measured TPS field parameters, theoretical parabolic tra- jectories for different charge-to-mass ratios are calculated and overlaid onto the IP image, as shown in Fig. 3(a).

The corresponding CR-39 scanning region is shown in the stitched microscope image in Fig. 3(b), from which repre- sentative images of etched tracks are selected[Fig. 3(c-e).] III. 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 vis- ibility of protons [38], so protons were excluded from further 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. 4 Figure 4: see original paper, can be attributed with high confidence to C5+ and O7+ 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 hori- zontal position. This selection minimized contributions from adjacent parabolas, thereby reducing species mixing and ensuring accurate determination of D–E/A relationships.

Fig. 4(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 re- spective parabolas are formed exclusively by C5+ and O7+ ions. In contrast, as shown later, parabolas containing multi- ple species give rise to multiple distinct curves in the D–E/A 2-D phase space. The C5+ and O7+ 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 C5+ and O7+ tracks, we next analyzed the parabola cor- responding to a charge-to-mass ratio of 1/2. To ensure reliable Fig. 4. (a)Tracks around the q/m = 5/12 and 7/16 parabolas, at- tributed to C5+(brown dots) and O7+(orange dots) ions, respectively. (b) Extracted D-E/A correlations showing single, smooth curves for each species, confirming their purity and establishing ref- erence calibration data.The absolute energy scale carries a sys- tematic uncertainty of approximately 6% (see Section II for de- tails).

Fig. 5 [Figure 5: see original paper]. Identification of multiple ion species on the q/m = 1/2 parabola. (a) CR-39 image with the selection band indicated. The inset displays an expanded view where the selection band widens to 800 µm (b) Extracted D-E/A correlations from the parabola corre- sponding to q/m = 1/2. (c) The extracted E/A data revealing three distinct curves corresponding to C6+, N7+, and O8+. (d) Extracted D-E/A correlations when extending the

selected area. 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 ensure capture of all relevant tracks while minimizing contributions from neighboring parabolas [Fig. 5(a)].

The resulting D–E/A relationships [Fig. 5(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. 5(c)] enabled as- signment of the largest tracks to O8+, the smallest to C6+, and the intermediate tracks to N7+, likely originating from surface contamination or ambient nitrogen. The observation that the cut-off energy of C6+ and O8+ extend to higher than that of C5+ and O7+ is consistent with expectations, since ions with higher charge states are accelerated in stronger fields [41].

The finite size of the TPS pinhole introduces a geomet- ric broadening of each parabolic trace on the detector plane, which can lead to partial overlap between neigh- boring parabolas at high energies. For the present spec- trometer geometry, this broadening is on the order of 300 µm. A key advantage of the present analysis method is that it exploits the established D–E/A relationships to identify and reject most misassigned tracks through their systematic deviations in the D–E/A plane. When the se- lection band is expanded to $\Delta y = 800$ µm, tracks from the neighboring O7+ parabola are included [inset of Fig. 5(a)].

According to Eq. (1), since the charge-to-mass ratio of O7+ is lower than 1/2, its E/A is overestimated, producing spuri- ous points above the O8+ curve, as shown in Fig. 5(d). How- ever, such misassigned tracks can be identified and excluded by reference to the established D–E/A relationships, leaving the reconstructed spectrum unaffected.

An additional continuous trace with a characteristic di- ameter of approximately 9 µm becomes visible when the selection band is expanded to $\Delta y = 800$ µm. This trace does not follow the established reference D–E/A correla- tions obtained from ions with unique charge-to-mass ra- tios and therefore cannot be consistently classified within the calibrated species framework. Based on compara- tive analysis of other experimental shots and control mea- surements, it is attributed to background or environmen- tal materials rather than to the zirconium target. Fur- thermore, estimates based on over-the-barrier ionization thresholds [42] indicate that zirconium charge states in this q/m range would require laser intensities well be- yond those achieved in the present experiment, and are therefore not expected to contribute to the observed dis- tributions. Consequently, this trace is excluded from the species-resolved analysis.

Fig. 6 [Figure 6: see original paper]. Analysis of heavy-ion signals and validation using stopping- power comparison. (a) D-E/A data from the q/m = 1/3 parabola. (b) Normalized electronic stopping power of C and Zr ions calculated using SRIM, consistent with the observed diameter-energy behavior In practice, adjusting the Δy window provides a bal- ance 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 us- ing 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 cor- relations, the approach effectively suppresses artifacts arising from overlapping parabolas. This capability is particularly important in scenarios such as proton cutoff-energy diagnos- tics, 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. 6(a), the 1/3 parabola contains tracks that align with the C5+ refer- ence curve, confirming the presence of C4+ 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.

Fig. 7 [Figure 7: see original paper]. Combined dataset illustrating charge-state-independent D- E/A trends. Four kinds of ions were observed in the experiment.

Previous studies have indicated that, for certain ions, the track diameter in CR-39 increases with the electronic stop- ping power at the detector surface [31, 43]. For heavy ions, because of the broad Bragg peak, the stopping power varies weakly with energy, leading to a relatively flat D–E/A depen- dence. Fig. 6(b) shows the normalized electronic stopping power of C and Zr ions as a function of E/A, calculated using SRIM [44], which reproduces the trends observed in Fig. 6(a).

On this basis, we attribute the tracks with large diameters primarily to Zr30+ ions. This charge state is Ne-like and is separated from the next ionization stage by a compar- atively large ionization energy, making further ionization less probable under the present experimental conditions.

A slight broadening observed at the low-energy end sug- gests that minor contributions from neighboring charge states cannot be excluded. These contributions, however, are confined to the low-energy region and do not affect the species identification or the spectral reconstruction in the energy range of interest. The single ion species observed in the 3/8 parabola is assigned to O6+. Fig. 7 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 follow- ing ions were identified: C4+, C5+, C6+, O6+, O7+, O8+, 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 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 in- formation can then

be applied to identify heavier target ions according to their characteristic track diameters.

Using this method, we successfully distinguished C6+, N7+ and O8+ 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 AVALIABILITY The data that support the fndings of this study are openly available in Science Data Bank at https:// cstr.cn/31253.11.sciencedb.j00186.00793 j00186.00793. https://doi.org/10.57760/sciencedb.

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N7+, and Zr30+.The corresponding energy spectra for differ- ent charge states of carbon, oxygen, nitrogen, and zirconium are presented in Fig. 8.

IV. SUMMARY In summary, we have developed a straightforward and ef- fective method for ion identification in laser-driven heavy-ion acceleration experiments by combining a TPS with CR-39 detectors. The approach

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