

Shot-resolved transmission gating reveals relativistic transparency onset in laser-driven proton acceleration

Marvin E. P. Umlandt^{1,2}, Milenko Vescovi^{1,2}, Nicholas P. Dover³, Ginevra Casati³, Hiromitsu Kiriya⁴, Thomas Kluge¹, Akira Kon⁴, Kotaro Kondo⁴, Chang Liu⁴, Josefine Metzkes-Ng¹, Zufikar Najmudin³, Franziska Paschke-Bruehl^{1,2}, Richard Pausch¹, Thomas Püschel¹, Vidisha Rana^{1,2}, Hironao Sakaki⁴, Ulrich Schramm^{1,2}, Pengjie Wang^{1,*}, Nuo Xu³, Tim Ziegler¹, Mamiko Nishiuchi^{4,†} and Karl Zeil^{1,‡}

¹*Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany*

²*TUD Dresden University of Technology, Faculty of Physics, Dresden, Germany*

³*The John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London, London, United Kingdom*

⁴*Kansai Institute for Photon Science, National Institutes for Quantum Science and Technology, Kyoto, Japan*



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We investigate proton acceleration in the relativistic transparency regime using ultrathin foils irradiated by petawatt-class laser pulses, achieving proton energies exceeding 80 MeV. Shot-resolved analysis of transmitted spectra reveals that temporal gating at the onset of relativistically induced transparency shapes the pulse, producing either smooth or modulated spectra. A spectral smoothness metric, benchmarked against particle-in-cell simulations and a semianalytical gating model, demonstrates that different transmission levels correspond to distinct transparency onset times. We find that maximum proton energies are consistent with transparency occurring near the laser pulse peak, while later or absent onset can also drive efficient acceleration. These spectral diagnostics establish a powerful probe of acceleration cascades and a route to understanding and controlling shot-to-shot fluctuations in laser-ion interactions.

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I. INTRODUCTION

The pursuit of compact, high-performance laser-ion sources for applications such as radiotherapy and fast ignition [1,2] relies on advanced acceleration schemes that surpass the limits of conventional target normal sheath acceleration (TNSA), particularly regarding maximum ion energy and the broad energy spread. One of the most promising schemes is based on relativistically induced transparency (RIT) [3], in which an ultraintense laser pulse renders an initially opaque plasma transparent once the expanding electron density n_e drops below the relativistically corrected critical density $n_{cr} = \gamma n_c$, where γ is the Lorentz factor and n_c is the classical critical density. This transition enables volumetric energy deposition and efficient coupling into fast electrons [4–12], driving proton energies that have recently surpassed 100 MeV with petawatt-class lasers [13]. The onset of transparency

marks a particularly dynamic moment within the interaction, characterized by rapidly evolving electron density and electromagnetic fields. Rather than replacing existing mechanisms, RIT modifies and connects the two robust acceleration modes that also operate in opaque targets: front-side hole-boring radiation pressure acceleration (HB-RPA) and rear-side TNSA [12,14–17]. On a microscopic level, laser-driven proton acceleration from near-critical density foils can thus be viewed as a cascade of coupled stages: HB-RPA launches protons forward, RIT opens the plasma for volumetric coupling and enhanced accelerating fields, and TNSA continues the acceleration in the rear-side sheath. For petawatt-class ultrashort pulses, long-ranging Coulomb repulsion forces induced by residual plasma bulk ions can further accelerate the fastest protons even after the laser-plasma interaction [13,18]. It is therefore evident that the degree and timing of transparency critically govern the interplay and relative contribution of these mechanisms within the overall acceleration cascade and are responsible for the final proton energy gain. Optimal acceleration has been established to occur when the onset of transparency coincides with the arrival of the laser pulse peak at the target—the pulse-peak-transparency criterion—which maximizes laser absorption and energy transfer into fast electrons [19]. Simulations show that this condition is robust across a wide parameter range up to the 10 PW regime, making it a central benchmark for optimization and scaling [20]. Experimentally, however, pinpointing the onset of RIT is challenging: While it can in principle be identified through spectral phase information of transmitted light [21] or interference of transmitted with self-generated light [22], and while

*Present address: Shenzhen Key Laboratory of Ultraintense Laser and Advanced Material Technology, Center for Intense Laser Application Technology, and College of Engineering Physics, Shenzhen Technology University, Shenzhen, China.

†Contact author: nishiuchi.mamiko@qst.go.jp

‡Contact author: k.zeil@hzdr.de

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shot-to-shot correlations between integrated optical observables and proton performance have been reported [23], direct single-shot access to the temporal timing of the transparency onset relative to ion performance has remained elusive. Previous studies often relied on averaged monotonic transmission curves [13,16], which obscure the single-shot ultrafast pulse dynamics. Transmission alone thus proves too simplistic to explain the strong energy performance fluctuations observed even under nominally identical laser and target conditions. This instability, which indicates switching between distinct acceleration cascades or varying contributions of their underlying mechanisms, currently limits the viability of the RIT regime for applications and necessitates a more nuanced, shot-resolved diagnostic.

Here, using a petawatt-class laser to investigate high-performance ion acceleration from ultrathin foils, we introduce a spectral diagnostic approach based on the transmitted laser pulse spectrum that exploits the transparency onset. This mechanism, recognized for its utility in pulse cleaning [24], acts as an opening plasma shutter [21] that imposes an ultrafast temporal gate on the pulse. By quantifying spectral broadening and a Fourier-based smoothness parameter, we establish a single-shot metric that correlates with target transmission and enables the evaluation of individual shots in terms of their acceleration performance relative to the pulse-peak-transparency criterion. This approach establishes the link between transmission and transparency timing and indicates that the highest performance is consistent with this criterion, while also revealing that comparable energies can emerge from later-onset transparency scenarios.

II. EXPERIMENTAL SETUP AND SIMULATIONS

The experiment was conducted at the J-KAREN-P laser facility, which delivered p -polarized, 47 fs pulses with 11 J of energy on target at a central wavelength of 800 nm. The pulses were focused by an $f/1.4$ off-axis parabolic mirror to a peak intensity of $3.6 \times 10^{21} \text{ W cm}^{-2}$ corresponding to a normalized vector potential $a_0 \approx 41$. High-contrast conditions were ensured by a single recollimating plasma mirror setup [25]. Freestanding ultrathin formvar foils with thicknesses ranging from 20 to 500 nm were irradiated at an angle of 45° . Proton spectra were measured with three Thomson parabola spectrometers at 0° , 10° , and 45° with respect to the laser propagation axis, using calibrated imaging plates as detectors [26]. The laser light transmitted through the target was characterized by recording its energy on a calibrated screen and its spectral profile with a high-resolution spectrometer, which sampled a portion of the transmitted light guided outside the chamber by a recollimating beamline. The incident laser electric field was fully characterized on a shot-to-shot basis using a spectral phase interferometry for direct electric-field reconstruction (SPIDER) diagnostic applied to a small pickoff from the beam center. An additional Fourier-transform spectral interferometry (FTSI) setup [27] analyzed the interference pattern between this sampled transmitted light and the unperturbed reference pickoff to retrieve the temporal profile and relative delay of the pulse. A schematic of the complete experimental layout is provided in Fig. 1(a).

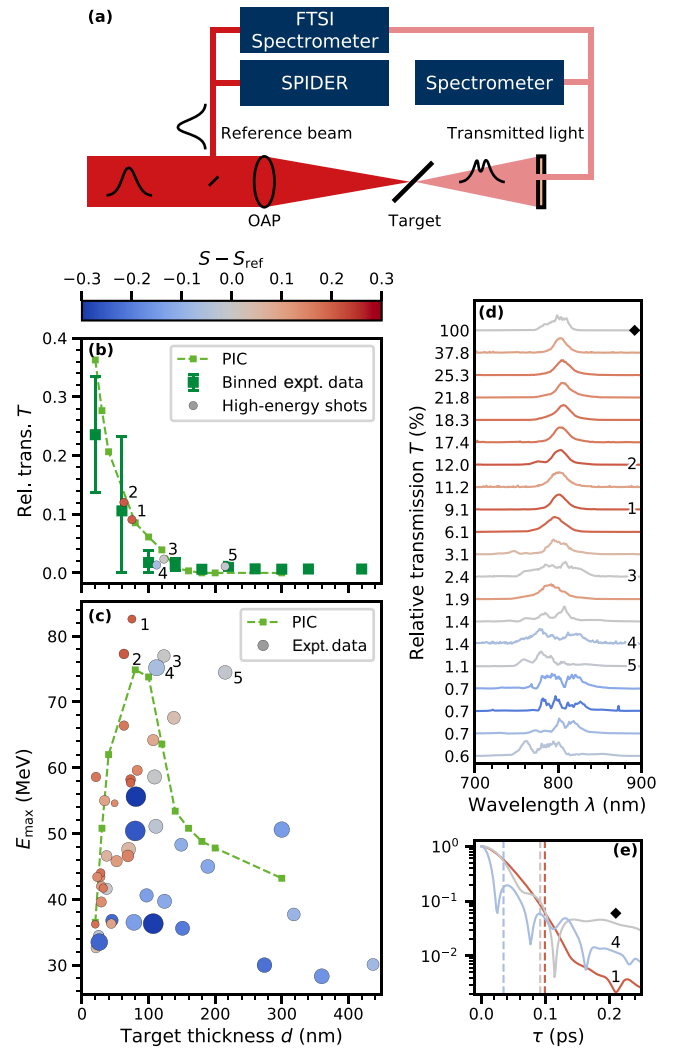


FIG. 1. (a) Schematic of the experimental setup used to retrieve transmission and time-domain pulse information. Thickness scans of (b) binned relative laser transmission T , showing the transition from transparent to opaque regime, and (c) maximum proton energy E_{max} with optimal thickness around 100 nm. In panel (c), experimental data are encoded by spectral width (marker size) and spectral smoothness deviation $S - S_{\text{ref}}$ (color). Three-dimensional (3D) PIC simulations (dashed lines) reproduce the trends, and the five highest-energy shots (>70 MeV) are marked 1–5 in all panels. (d) Representative transmitted spectra sorted by transmission, with reference spectrum of no-target shot marked by a diamond. (e) Fourier-domain magnitudes for representative smooth (1), modulated (4), and reference shots, illustrating the basis of the smoothness metric; vertical dashed lines indicate the integration threshold τ_{th} used for the calculation of S .

To support the measurements, three-dimensional particle-in-cell (PIC) simulations with SMILEI [28] were performed using experimental parameters. A Gaussian pulse with an FWHM pulse duration of 45 fs, a focal spot size of $1.5 \mu\text{m}$ (FWHM), and a peak intensity of $4 \times 10^{21} \text{ W cm}^{-2}$ was injected into a $30 \mu\text{m} \times 25.6 \mu\text{m} \times 19.2 \mu\text{m}$ box discretized into $1500 \times 640 \times 480$ cells. Targets were modeled as fully ionized formvar with electrons at $235n_c$, carbon at $(200/6)n_c$, and protons at $35n_c$, placed $10 \mu\text{m}$ inside the boundary. Each cell

contained 64 macroparticles per species, with higher counts for thinner foils to ensure accuracy.

III. RESULTS

A. Transmission and proton energy

The dependence of laser transmission and maximum proton energy on target thickness is summarized in Fig. 1. Transmission decreases monotonically with increasing thickness, shifting from a transparent to an opaque regime between 20 and >150 nm. In contrast, the maximum proton energy E_{max} follows the well-known nonmonotonic trend [16,29], peaking at around 100 nm. This window coincides with partial transmission (1%–10%), identifying an intermediate regime where RIT is most favorable. The overall behavior, including the optimal thickness, is reproduced by the PIC simulations by normalizing to the total experimental laser energy, accounting for the idealized Gaussian spatial profile. Energies of forward-directed protons exceed 80 MeV, consistent with the empirical high-energy scaling and the angular separation of acceleration mechanisms reported in Ref. [13], while lower-energy emission is dominated by the target-normal direction. As in previous work, this intermediate regime shows significant shot-to-shot variability, reflecting the strong sensitivity of the underlying plasma dynamics to laser and target conditions.

B. Spectral signatures

The spectra of transmitted light provide direct insight into plasma dynamics across regimes [Fig. 1(d)]. High-transmission cases exhibit narrow, smooth spectra, often smoother than the incident pulse itself (diamond marker at 100% transmission). Reduced transmission correlates with broader, more strongly modulated spectra. This systematic trend demonstrates that spectral shape serves as a robust indicator of the interaction regime, motivating the introduction of two complementary quantitative metrics: a 90% integrated spectral width and a Fourier-based spectral smoothness S . The width measure, based on cumulative intensity fractions rather than FWHM or Gaussian fits, is robust against strong modulations, isolated sidebands, or noise artifacts. It was obtained by calculating the spectral centroid and determining the wavelengths $\lambda_{\text{left},0.9}$ and $\lambda_{\text{right},0.9}$ at which 90% of the integrated intensity was reached on either side, with the width defined as $\Delta\lambda_{0.9} = \lambda_{\text{right},0.9} - \lambda_{\text{left},0.9}$. Reference shots without a target yielded a mean width of $\Delta\lambda_{\text{ref}} = 35 \pm 3$ nm. Our spectral smoothness metric, designed to quantify the degree of modulation independently of spectral width, exploits the properties of the Fourier transform: High-frequency modulations in the spectral domain correspond to features at larger values of the conjugate variable τ . A smooth, Gaussian-like spectrum produces a dominant central peak (DC term) near $\tau = 0$, while spectral fragmentation or sidebands redistribute power to larger τ [Fig. 1(e)]. The resulting dimensionless metric S is defined as the fraction of signal power contained within this central peak. The threshold τ_{th} defining this window is set to $2.5 \times \text{FWHM}$ of the DC term, capturing the main envelope, corresponding to $\approx 99.7\%$ of the energy for an ideal Gaussian profile. This metric ranges from 0 (strong modulation) to 1

(Gaussian-like smoothness). Reference spectra from no-target shots yielded $S_{\text{ref}} = 0.70 \pm 0.03$.

The transmitted spectra provide a direct link to proton energy performance. In Fig. 1(c), marker size encodes spectral width and color indicates spectral smoothness. Overall, in the thickness range leading up to the optimum at ~ 100 nm, the highest-performing shots in each thickness bin are consistently those with smoother ($S > S_{\text{ref}}$) and moderately broadened ($\Delta\lambda \gtrsim \Delta\lambda_{\text{ref}}$) spectra. Importantly, not all high-energy shots (>70 MeV, marked 1–5) share the same spectral signature: Some exhibit very smooth spectra (1 and 2), while others reach comparable energies despite stronger modulation (3, 4, and 5). These cases, typically located in the intermediate transmission regime [Fig. 1(d)], exhibit notable differences in their degree of broadening and modulation. Such spectral diversity, even among the highest-performing shots, points to shot-to-shot variations in the microscopic interaction dynamics, each leaving a characteristic spectral fingerprint on the transmitted light.

C. Temporal gating dynamics

It is well established that the onset of RIT acts as a plasma shutter, temporally gating and shaping the laser pulse by suppressing its leading edge and transmitting the trailing part [21,30]. In the time domain, this gate shortens the pulse, directly linked to spectral broadening [31], while the extreme plasma conditions can enable additional complex modulations from relativistic self-phase modulation [32] or interference with plasma-generated coherent light, such as transition radiation [22]. These effects become significant at low transmission, where the directly transmitted laser field is weaker and thus comparable in amplitude to a persistent low-level floor of plasma-generated light, corresponding to later RIT onset in thicker targets. In contrast, our data reveal the absence of modulation—spectra smoother than the incident pulse itself—as a clear characteristic feature of high transmission, pointing to the dominant action of the temporal gate in the early-onset regime. To empirically validate the temporal gating dynamics predicted to govern RIT, we analyzed the FTSI measurements. While nonlinear pulse characterization techniques like frequency-resolved optical gating (FROG) lack an absolute timing reference, FTSI successfully extracts both the temporal profile and the positive delay relative to an unperturbed reference. Because plasma dispersion in these ultrathin targets is negligible compared to interactions with thicker foils [33], the measured delay directly reflects the opening of the plasma shutter at RIT onset. As shown in Fig. 2 for the high-transmission regime, the ensemble-averaged reconstructed envelopes exhibit a delayed onset and temporal truncation as transmission decreases. Moreover, an exemplary time-resolved transmittance curve extracted from the experimental data explicitly exhibits this ultrafast gating behavior. However, extracting absolute transmittance curves across regimes from single-shot FTSI data requires the transmitted spectrum to remain within the finite bandwidth of the reference pulse. This condition fails in the low-transmission regime, where the spectra broaden significantly beyond this bandwidth or become highly fragmented [Fig. 1(d)].

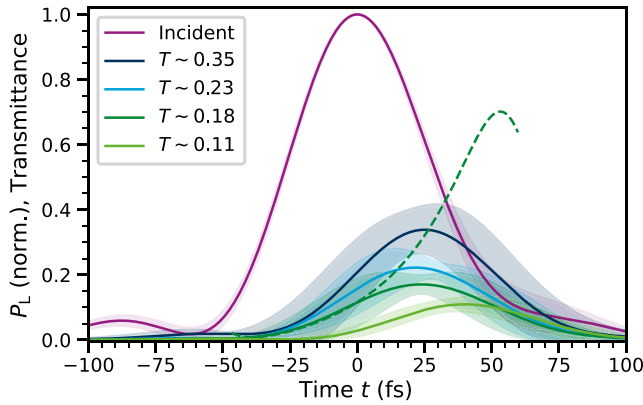


FIG. 2. Empirical observation of transmission gating via FTSL. Reconstructed temporal envelopes of the transmitted laser pulses in the high-transmission regime, ensemble averaged and grouped by relative transmission T . Shaded bands indicate the corresponding standard deviations, including for the incident pulse. As transmission decreases, the pulses exhibit a delayed onset relative to the incident pulse. An exemplary time-resolved transmittance curve (dashed line) is shown for one transmission bin ($T \sim 0.18$), illustrating the ultrafast gating dynamics; this curve is restricted to the main pulse envelope to avoid division artifacts in the low-intensity pulse wings.

To isolate the spectral consequences of this temporal gating without these experimental constraints, we employ a semianalytical model to systematically investigate the effect of transparency timing on the transmitted spectrum. In this model, the experimentally measured incident electric field—including both spectral amplitude and phase—is masked in the temporal domain by transmittance gates, which are derived from PIC simulations as the ratio of transmitted to incident power for different target thicknesses [Fig. 3(a)].

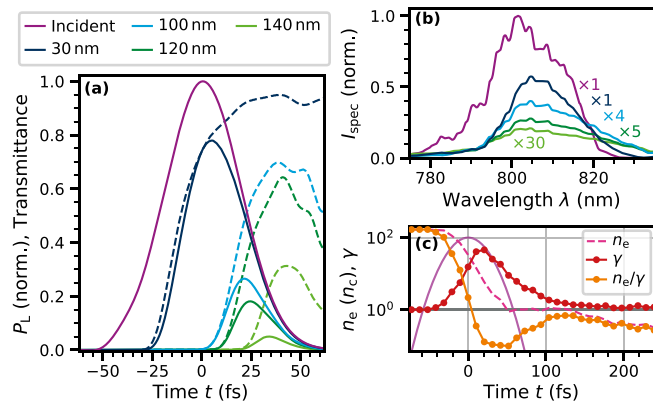


FIG. 3. (a) Transmitted laser power P_L (solid lines) and corresponding temporal transmittance (dashed) from the PIC simulations for different target thicknesses. (b) Synthesized transmitted spectra obtained by applying the transmittance curves from panel (a) as temporal gates to the experimentally measured incident pulse; spectra are scaled by the given factors. (c) Plasma parameter evolution for the 100 nm target, chosen for its match with the pulse-peak-transparency criterion, with transparency onset ($n_e/\gamma < n_c$) occurring near the laser peak. The incident laser pulse is shown in purple across all panels.

Fourier backtransformation then yields the synthesized transmitted spectra displayed in Fig. 3(b). The model reproduces the key experimental observations: Intrapulse gating broadens the spectrum through temporal truncation and produces a transmitted spectrum even cleaner than the incident by selectively passing the main pulse and clipping prepulse structures, an effect analogous to a temporal Fourier filter. The strong qualitative agreement between this simple gating model and the data, particularly in the high-transmission regime where its predictions for both width and smoothness are most accurate, provides compelling evidence that temporal gating is a dominant mechanism shaping the transmitted spectrum in the high- and intermediate-transmission regimes, and that variations in transmission are a proxy for the timing of the transparency onset.

IV. DISCUSSION

The analysis gains significance when compared to the pulse-peak-transparency criterion. PIC simulations show that for 80–100 nm targets the relativistically corrected ratio n_e/γ falls below n_c at the pulse peak [Fig. 3(c)], matching the condition for optimal acceleration and highest proton energies. In this regime, spectra are expected to be smoother than the input ($S > S_{\text{ref}}$) with moderate broadening. This expectation is reinforced by the dynamics on the pulse's trailing edge: As the laser intensity falls, the corresponding drop in γ leads to suppressed transmittance visible as the downturn in Fig. 3(a). This can further truncate the pulse and enhance spectral smoothness. In contrast, spectra with stronger modulation ($S < S_{\text{ref}}$) as observed experimentally indicate late RIT or delayed classical transparency onset. Postpulse contributions or coherent plasma emission components [22] reach intensities comparable to the transmitted light and interfere, dynamics that are beyond the scope of this work and are considerably harder to disentangle experimentally or reproduce in simulations.

The spectral properties of the transmitted light now enable the temporal gating effect to be directly linked to proton acceleration performance. In Fig. 4, the dataset from Fig. 1(c) is reorganized and plotted versus target transmission to emphasize the correlation between spectral broadening and smoothness across all shots and to compare with PIC simulations. While the simulations capture the spectral broadening trend [dotted line in Fig. 4(a)], predicting spectral smoothness would require future modeling that incorporates the measured incident spatiotemporal field structure. Nevertheless, our semianalytical model, which does use the incident field, correctly captures the qualitative trend, as shown in Fig. 4(b). As established in previous studies [13,16], high-energy proton shots cluster in the intermediate 1%–10% transmission range, but within this window, variations in broadening and smoothness can now be interpreted with respect to the pulse-peak-transparency criterion, enabling shot classification based on gating behavior rather than transmission alone. For low-performing shots within the nominally optimal thickness range [compare Figs. 1(c) and 4], the underlying dynamics are often ambiguous: Many shots exhibit strong spectral broadening and modulation, indicative of very late or absent RIT onset, while low performers with narrow, smooth spectra

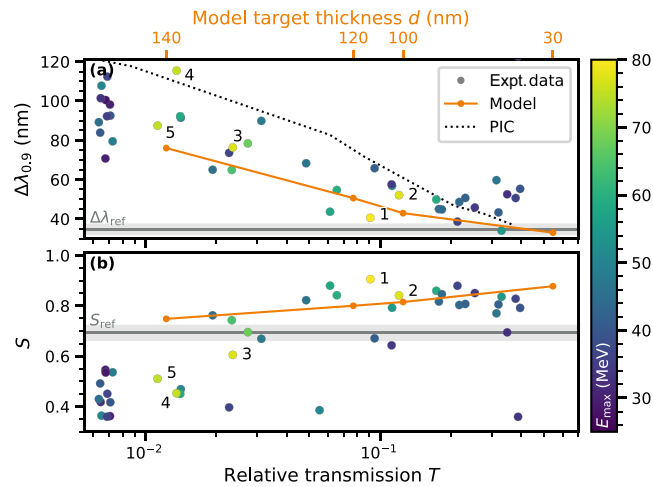


FIG. 4. Spectral properties of the transmitted light vs relative transmission for individual shots: (a) spectral width $\Delta\lambda_{0.9}$ and (b) spectral smoothness S . Experimental data are colored by maximum proton energy $E_{\max}$. Predictions from 3D PIC simulation for an ideal pulse (dotted line) and the semianalytical model (orange lines) are shown for comparison, with the top axis indicating the model's corresponding target thickness. Horizontal lines and shaded gray bands denote the means and the 1σ intervals from reference shots without targets.

suggest too-early onset and correspondingly reduced absorption. In contrast, the five highest-performing shots can be distinguished according to their spectral transmission features (Fig. 4). Shots 1 and 2 display smooth spectra consistent with an early-onset gating scenario near the pulse-peak criterion; here, the spectral smoothness induced by the temporal gate dominates the transmitted signature, and maximum acceleration coincides with high absorption (lowest transmission under RIT conditions). By matching the experimental signatures to the model predictions for the pulse-peak case, this provides strong indications that conditions consistent with the pulse-peak-transparency criterion coincide with highest acceleration performance. While these metrics isolate the longitudinal gating dynamics, overall acceleration efficiency remains sensitive to transverse spatial effects. Shot-to-shot variations in focal spot quality or wave-front aberrations, not captured by this longitudinal measurement, can account for additional energy discrepancies observed among shots exhibiting similar spectral signatures. Shots 3–5, however, reach comparable energies despite strongly structured transmitted spectra. While intrapulse RIT onset cannot be strictly excluded, the low transmission and large spectral broadening indicate very late onset and spectral modulation imprinted from other sources and confirm that cascades with a reduced RIT contribution can still yield similarly high proton energies, a seemingly intuitive yet previously experimentally unverified result.

While the precise role and relative contribution of the individual acceleration stages within each cascade remains an

open question, the new single-shot-resolved insights help to reveal the dominant physical regimes and establish a direct experimental context for comparison with state-of-the-art simulations. Achieving a fully quantitative correspondence will require more accurate knowledge of the exact laser-plasma interaction parameters and reduced numerical simplifications to reliably assign or predict the conditions of a specific experimental shot.

V. CONCLUSION

In conclusion, a key implication of this work is the ability to diagnose the underlying acceleration dynamics on a shot-by-shot basis. The observation that high-performing shots can exhibit different spectral signatures suggests that optimal energy gain can be achieved through different relative contributions of acceleration mechanisms within the cascade. These spectral diagnostics provide a tool to distinguish between these configurations, offering deeper insight into the origins of shot-to-shot fluctuations than is possible from target thickness or total transmission alone. These results suggest that small variations in input parameters—such as the temporal pulse shape (spectral amplitude, phase, prepulses, or pulse rising edge), focusability (spatial phase), or spatiotemporal couplings—can trigger different acceleration cascades, as reported in RIT-assisted high-performance experiments [13,34]. Establishing direct shot-to-shot correlations between these laser parameters at the target and the resulting acceleration dynamics remains challenging, but future experiments could greatly benefit from the latest single-shot laser diagnostic developments for high-contrast temporal profiles [35] and complete spatiotemporal vector-field characterization [36]. The present results mark an important advance in understanding and controlling the complex interaction dynamics through advanced temporal pulse shaping or development of active feedback schemes. The interpretation is most robust in the transmission-dominated regimes; in the low-transmission limit, additional emission contributions and geometric effects such as laser beam steering out of the diagnostic's acceptance angle complicate the interpretation of observed signatures and therefore present a valuable direction for future studies.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

- [1] M. Roth, T. E. Cowan, M. H. Key, S. P. Hatchett, C. Brown, W. Fountain, J. Johnson, D. M. Pennington, R. A. Snavely, S. C. Wilks, K. Yasuike, H. Ruhl, F. Pegoraro, S. V. Bulanov, E. M. Campbell, M. D. Perry, and H. Powell, Fast ignition by intense laser-accelerated proton beams, *Phys. Rev. Lett.* **86**, 436 (2001).
- [2] S. V. Bulanov, J. J. Wilkens, T. Z. Esirkepov, G. Korn, G. Kraft, S. D. Kraft, M. Molls, and V. S. Khoroshkov, Laser ion acceleration for hadron therapy, *Phys. Usp.* **57**, 1149 (2014).
- [3] P. Kaw and J. Dawson, Relativistic nonlinear propagation of laser beams in cold overdense plasmas, *Phys. Fluids* **13**, 472 (1970).
- [4] S. V. Bulanov, D. V. Dylov, T. Zh. Esirkepov, F. F. Kamenets, and D. V. Sokolov, Ion acceleration in a dipole vortex in a laser plasma corona, *Plasma Phys. Rep.* **31**, 369 (2005).
- [5] E. d'Humières, E. Lefebvre, L. Gremillet, and V. Malka, Proton acceleration mechanisms in high-intensity laser interaction with thin foils, *Phys. Plasmas* **12**, 062704 (2005).
- [6] L. Yin, B. J. Albright, B. M. Hegelich, K. J. Bowers, K. A. Flippo, T. J. T. Kwan, and J. C. Fernández, Monoenergetic and GeV ion acceleration from the laser breakout afterburner using ultrathin targets, *Phys. Plasmas* **14**, 056706 (2007).
- [7] A. Henig, D. Kiefer, K. Markey, D. C. Gautier, K. A. Flippo, S. Letzring, R. P. Johnson, T. Shimada, L. Yin, B. J. Albright, K. J. Bowers, J. C. Fernández, S. G. Rykovanov, H.-C. Wu, M. Zepf, D. Jung, V. Kh. Liechtenstein, J. Schreiber, D. Habs, and B. M. Hegelich, Enhanced laser-driven ion acceleration in the relativistic transparency regime, *Phys. Rev. Lett.* **103**, 045002 (2009).
- [8] B. M. Hegelich, I. Pomerantz, L. Yin, H. C. Wu, D. Jung, B. J. Albright, D. C. Gautier, S. Letzring, S. Palaniyappan, R. Shah, *et al.*, Laser-driven ion acceleration from relativistically transparent nanotargets, *New J. Phys.* **15**, 085015 (2013).
- [9] D. Jung, L. Yin, D. C. Gautier, H.-C. Wu, S. Letzring, B. Dromey, R. Shah, S. Palaniyappan, T. Shimada, R. P. Johnson, J. Schreiber, D. Habs, J. C. Fernández, B. M. Hegelich, and B. J. Albright, Laser-driven 1 GeV carbon ions from preheated diamond targets in the break-out afterburner regime, *Phys. Plasmas* **20**, 083103 (2013).
- [10] H. W. Powell, M. King, R. J. Gray, D. A. MacLellan, B. Gonzalez-Izquierdo, L. C. Stockhausen, G. Hicks, N. P. Dover, D. R. Rusby, D. C. Carroll, H. Padda, R. Torres, S. Kar, R. J. Clarke, I. O. Musgrave, Z. Najmudin, M. Borghesi, D. Neely, and P. McKenna, Proton acceleration enhanced by a plasma jet in expanding foils undergoing relativistic transparency, *New J. Phys.* **17**, 103033 (2015).
- [11] A. V. Brantov, E. A. Govras, V. F. Kovalev, and V. Yu. Bychenkov, Synchronized ion acceleration by ultraintense slow light, *Phys. Rev. Lett.* **116**, 085004 (2016).
- [12] A. Higginson, R. J. Gray, M. King, R. J. Dance, S. D. R. Williamson, N. M. H. Butler, R. Wilson, R. Capdessus, C. Armstrong, J. S. Green, S. J. Hawkes, P. Martin, W. Q. Wei, S. R. Mirfayzi, X. H. Yuan, S. Kar, M. Borghesi, R. J. Clarke, D. Neely, and P. McKenna, Near-100 MeV protons via a laser-driven transparency-enhanced hybrid acceleration scheme, *Nat. Commun.* **9**, 724 (2018).
- [13] T. Ziegler, I. Göthel, S. Assenbaum, C. Bernert, F.-E. Brack, T. E. Cowan, N. P. Dover, L. Gaus, T. Kluge, S. Kraft, *et al.*, Laser-driven high-energy proton beams from cascaded acceleration regimes, *Nat. Phys.* **20**, 1211 (2024).
- [14] B. Qiao, S. Kar, M. Geissler, P. Gibbon, M. Zepf, and M. Borghesi, Dominance of radiation pressure in ion acceleration with linearly polarized pulses at intensities of 10^{21} W cm⁻², *Phys. Rev. Lett.* **108**, 115002 (2012).
- [15] J. Psikal and M. Matys, Dominance of hole-boring radiation pressure acceleration regime with thin ribbon of ionized solid hydrogen, *Plasma Phys. Control. Fusion* **60**, 044003 (2018).
- [16] N. P. Dover, T. Ziegler, S. Assenbaum, C. Bernert, S. Bock, F.-E. Brack, T. E. Cowan, E. J. Ditter, M. Garten, L. Gaus, *et al.*, Enhanced ion acceleration from transparency-driven foils demonstrated at two ultraintense laser facilities, *Light Sci. Appl.* **12**, 71 (2023).
- [17] Y. Shou, Z. Gong, K. H. Pae, J. W. Yoon, J. H. Sung, S. K. Lee, S. Y. Kim, S. H. Kim, X. Wu, X. Yan, I. W. Choi, and C. H. Nam, Proton acceleration associated with sheet crossing in petawatt-laser-irradiated nanometer foils, *Phys. Rev. Lett.* **135**, 215002 (2025).
- [18] Y. Shou, X. Wu, K. H. Pae, G.-E. Ahn, S. Y. Kim, S. H. Kim, J. W. Yoon, J. H. Sung, S. K. Lee, Z. Gong, X. Yan, I. W. Choi, and C. H. Nam, Laser-driven proton acceleration beyond 100 MeV by radiation pressure and Coulomb repulsion in a conduction-restricted plasma, *Nat. Commun.* **16**, 1487 (2025).
- [19] S. D. R. Williamson, R. J. Gray, M. King, R. Wilson, R. J. Dance, C. Armstrong, D. R. Rusby, C. Brabetz, F. Wagner, B. Zielbauer, V. Bagnoud, D. Neely, and P. McKenna, Energy absorption and coupling to electrons in the transition from surface-to volume-dominant intense laser-plasma interaction regimes, *New J. Phys.* **22**, 053044 (2020).
- [20] J. Goodman, M. King, R. Wilson, R. J. Gray, and P. McKenna, Optimisation of multi-petawatt laser-driven proton acceleration in the relativistic transparency regime, *New J. Phys.* **24**, 053016 (2022).
- [21] S. Palaniyappan, B. M. Hegelich, H.-C. Wu, D. Jung, D. C. Gautier, L. Yin, B. J. Albright, R. P. Johnson, T. Shimada, S. Letzring, D. T. Offermann, J. Ren, C. Huang, R. Hörlein, B. Dromey, J. C. Fernandez, and R. C. Shah, Dynamics of relativistic transparency and optical shuttering in expanding overdense plasmas, *Nat. Phys.* **8**, 763 (2012).
- [22] S. D. R. Williamson, R. Wilson, M. King, M. Duff, B. Gonzalez-Izquierdo, Z. E. Davidson, A. Higginson, N. Booth, S. Hawkes, D. Neely, R. J. Gray, and P. McKenna, Self-referencing spectral interferometric probing of the onset time of relativistic transparency in intense laser-foil interactions, *Phys. Rev. Appl.* **14**, 034018 (2020).
- [23] J. H. Bin, K. Allinger, K. Khrennikov, S. Karsch, P. R. Bolton, and J. Schreiber, Dynamics of laser-driven proton acceleration exhibited by measured laser absorptivity and reflectivity, *Sci. Rep.* **7**, 43548 (2017).
- [24] M. Jirka, O. Klimo, and M. Matys, Relativistic plasma aperture for laser intensity enhancement, *Phys. Rev. Res.* **3**, 033175 (2021).
- [25] A. Kon, M. Nishiuchi, Y. Fukuda, K. Kondo, K. Ogura, A. Sagisaka, Y. Miyasaka, N. P. Dover, M. Kando, A. S. Pirozhkov, I. Daito, L. Chang, I. W. Choi, C. H. Nam, T. Ziegler, H.-P. Schlenvoigt, K. Zeil, U. Schramm, and H. Kiriya, Characterization of the plasma mirror system at the J-KAREN-P facility, *High Power Laser Sci. Eng.* **10**, e25 (2022).
- [26] M. Nishiuchi, H. Sakaki, N. P. Dover, T. Miyahara, K. Shiokawa, S. Manabe, T. Miyatake, Ko. Kondo, Ke. Kondo,

- Y. Iwata, Y. Watanabe, and Ki. Kondo, Ion species discrimination method by linear energy transfer measurement in Fujifilm BAS-SR imaging plate, *Rev. Sci. Instrum.* **91**, 093305 (2020).
- [27] L. Lepetit, G. Chériaux, and M. Joffre, Linear techniques of phase measurement by femtosecond spectral interferometry for applications in spectroscopy, *J. Opt. Soc. Am. B* **12**, 2467 (1995).
- [28] J. Derouillat, A. Beck, F. Pérez, T. Vinci, M. Chiaramello, A. Grassi, M. Flé, G. Bouchard, I. Plotnikov, N. Aunai, J. Dargent, C. Riconda, and M. Grech, Smilei: A collaborative, open-source, multi-purpose particle-in-cell code for plasma simulation, *Comput. Phys. Commun.* **222**, 351 (2018).
- [29] P. L. Poole, L. Obst, G. E. Cochran, J. Metzkes, H.-P. Schlenvoigt, I. Prencipe, T. Kluge, T. Cowan, U. Schramm, D. W. Schumacher, and K. Zeil, Laser-driven ion acceleration via target normal sheath acceleration in the relativistic transparency regime, *New J. Phys.* **20**, 013019 (2018).
- [30] W.-Q. Wei, Y. Wang, X.-L. Ge, Y.-Q. Deng, S.-Z. Zhang, F. Wan, J.-X. Li, Y.-T. Zhao, and X.-H. Yuan, Dynamics and manipulation of ultrashort laser pulses via plasma shutter, *Phys. Plasmas* **32**, 013109 (2025).
- [31] H. Y. Wang, C. Lin, Z. M. Sheng, B. Liu, S. Zhao, Z. Y. Guo, Y. R. Lu, X. T. He, J. E. Chen, and X. Q. Yan, Laser shaping of a relativistic intense, short Gaussian pulse by a plasma lens, *Phys. Rev. Lett.* **107**, 265002 (2011).
- [32] I. Watts, M. Zepf, E. L. Clark, M. Tatarakis, K. Krushelnick, A. E. Dangor, R. Allott, R. J. Clarke, D. Neely, and P. A. Norreys, Measurements of relativistic self-phase-modulation in plasma, *Phys. Rev. E* **66**, 036409 (2002).
- [33] V. Bagnoud, J. Hornung, T. Schlegel, B. Zielbauer, C. Brabetz, M. Roth, P. Hilz, M. Haug, J. Schreiber, and F. Wagner, Studying the dynamics of relativistic laser-plasma interaction on thin foils by means of Fourier-transform spectral interferometry, *Phys. Rev. Lett.* **118**, 255003 (2017).
- [34] M. Rehwald, S. Assenbaum, C. Bernert, F.-E. Brack, M. Bussmann, T. E. Cowan, C. B. Curry, F. Fiuza, M. Garten, L. Gaus, *et al.*, Ultra-short pulse laser acceleration of protons to 80 MeV from cryogenic hydrogen jets tailored to near-critical density, *Nat. Commun.* **14**, 4009 (2023).
- [35] T. Oksenhendler, S. Bock, J. Dreyer, R. Gebhardt, U. Helbig, T. Toncian, and U. Schramm, Advanced laser pulse metrology through 2D self-referenced spectral interferometry, *Sci. Rep.* **15**, 17729 (2025).
- [36] S. Howard, J. Esslinger, N. Weiße, J. Schröder, C. Eberle, R. H. W. Wang, S. Karsch, P. Norreys, and A. Döpp, Single-shot spatiotemporal vector field measurements of petawatt laser pulses, *Nat. Photon.* **19**, 898 (2025).