nature portfolio

Peer Review File

Ion acceleration from micrometric targets immersed in an intense laser field

Corresponding Author: Professor Ishay Pomerantz

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
please see the attached document

Reviewer #2

(Remarks to the Author)
GENERAL ASSESSMENT
Moderate revision.
CONCLUSION
The manuscript titled "Ion acceleration from micrometric targets immersed in an intense laser field" by Elkind et al. presents original experimental measurements of laser irradiation on micrometric bar targets. Despite the moderate laser pulse energy of 120 mJ, the study demonstrates proton acceleration to energies of 6–8 MeV. Furthermore, the authors propose an extended scheme involving a series of micrometric bar targets and a split laser pulse, potentially enhancing proton energies to 12 MeV via a cascading acceleration mechanism. The experimental findings are well-supported by PIC simulations, strengthening the interpretation of the observed phenomena.
However, I have a major concern regarding the Introduction section, which, in my opinion, lacks direct relevance to the presented results and requires significant revision. The impact of the findings should be articulated more clearly to help assess their significance within our subfield of physics.
MAIN COMMENTS
1. Relevance of acceleration mechanisms and applications: The introduction broadly discusses various laser-driven ion acceleration mechanisms and their applications, including fast ignition for inertial confinement fusion, neutron beam generation, and ion-based cancer therapy. However, the proton energies reported in this study (6–12 MeV) are significantly lower than what these applications typically require (e.g., ~250 MeV for proton therapy). The authors should focus on applications where their results are practically relevant and discuss them in greater detail. For instance, citing cancer therapy as motivation is not appropriate in the context of the presented results.
2. Relevance of advanced acceleration schemes: The manuscript mentions advanced acceleration schemes such as radiation pressure acceleration, breakout afterburner, and collisional shock acceleration. While these mechanisms are promising, they are not realistically achievable with the laser and plasma conditions used in this study. Their inclusion should be reconsidered or more clearly justified in relation to the presented work.
3. Mass-limited target acceleration: A more detailed comparison between the results obtained in this study and alternative laser-driven ion acceleration mechanisms using mass-limited targets (referencing works such as [24–29, 47], and probably also others) would strengthen the discussion. This comparison should highlight the advantages and limitations of the micro-bar target approach relative to existing methods.
4. TNSA at similar conditions: The study claims that micro-bar targets provide significantly higher proton energies than conventional target normal sheath acceleration (TNSA) under comparable laser conditions. However, the manuscript does not sufficiently address key performance metrics such as the number of accelerated protons and laser-to-proton energy conversion efficiency. Could the enhancement in proton cutoff energy outweigh the challenges associated with target fabrication and installation, especially when considering high-repetition-rate applications?
5. Proton spectra in simulations and experiments: The proton energy spectra presented in Figures 2a and 2c show good agreement in cutoff energy but significant discrepancies in total proton count and spectral shape, particularly in the low-energy region. In my assessment, this discrepancy might come from the initially large number of protons initialized in the

simulation.
6. Cascaded acceleration regime: More details should be provided on how to optimize the inter-bar distance and the delay between laser pulses in the proposed cascaded acceleration scheme. Ideally, these parameters should be linked to a simple model based on plasma expansion dynamics.
7. Simulation parameters and ionization effects
• Was the ionization module enabled in the PIC simulations?
• If not, how is the choice of initial ion charge state (Z_0 = 4 or 8) justified?
• Reference [52] suggests that an intensity of 4.3 × 10^{19} W/cm^2 could lead to ionization up to Z ≈ 40, not assessing the influence of the collisional ionisation. Would this significantly alter the plasma conditions?
• If ionization effects were not considered, the chosen simulation grid (32 nm × 20 nm × 160 nm or 10.7 nm × 6.7 nm × 80 nm) might struggle to resolve the reduced plasma skin depth at higher electron densities.
• While the experimental results remain the core contribution of the study, these simulation limitations should be acknowledged in the manuscript.
MINOR COMMENTS
1. Figure 2e: The unit of the electric field is missing—please specify.
2. Figure 3b, c and last paragraph on page 5: The text discusses electron temperature (T_e), whereas the plots show average electron energy (E_e). The relationship between these quties should be clarified.
3. Splitting the Discussion into several subsections would improve readability and help guide the reader through key findings.

Reviewer #3

(Remarks to the Author)
The manuscript entitled “Ion acceleration from micrometric targets immersed in an intense laser field” reports on an experimental study of proton acceleration by intense laser irradiation of micrometric bar targets. To optimize ion acceleration, the transverse and longitudinal dimensions of the target are specially designed. It is found that the cutoff energies of protons are about 3 times improved compared to the flat-foil irradiation with the same laser energy. The paper is rather well written and comprehensible and it is suitable for publication. But there are a few questions that need to be explained.
1.In fact, many target design schemes have been proposed to improve the effect of femtosecond laser-driven TNSA acceleration, such as foam target, sub-micron grating target and micron-scale channels or wire-array target. It is recommended that the authors add references in the Introduction, and discuss their advantages and disadvantages compared with the targets used in this study.
2.The insets in Fig. 2(c) show that the electrons appear to be experiencing Coulomb expansion, so is the improvement in cutoff energy of ions related to Coulomb expansion? The author needs to provide further details to confirm their irrelevance.
3.As can be seen from Fig. 2(a), the energy conversion efficiency from the laser to the protons with energies higher than 1 MeV should be greatly improved compared with the flat-foil, and relevant simulation and experimental data should be supplemented.
4.Although the pulse contrast is better than 10^11 before t=-60 ps, the radiation hydrodynamics simulation or other evidence is still necessary to reveal the density distribution of the preplasma produced after the prepulse ablation micrometric bar target, and to support the selection of the pre-plasma scale length in the simulation.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
Thank you to the authors for the revision of the manuscript. Many things have been clarified since the last revision. The quality has been greatly improved and enabled greater understanding for the reader. I have noted a few minor points which I believe should still be extended for clarity and then I believe it can be ready for publication.

Now that we have the emittances separated by dimension, I would just like to ask for a few more details on this point. While we expect that the source size in ‘y’ is small, the divergence is expected to be larger due to the curved sheath. ‘z’ has a larger spatial extent but flatter sheath, and narrower divergence? A short explanation on why the emittances are different orders of magnitude should complement this new data.

Can the authors extend the sentences explaining the origin of the denser sheath at the rear - I think this could have been more explicit in their previous response. It is implied that in the case of the thinnest targets, the diffracted laser field at the target rear is what is pulling the rear surface electrons out? This could be visualised with the laser field superimposed, like in fig 2c, over the electrons in fig 3d? This is only a suggestion. I find this quite interesting, and particularly so if the sheath has the chance to be shaped by the diffracted laser pulse with this unique target geometry. Can the authors comment on this?

Reviewer #2

(Remarks to the Author)
GENERAL ASSESSMENT
Accept.

CONCLUSION
Let me appreciate that the authors sufficiently addressed my questions and comments; hence, the paper can be recommended for publication.

Reviewer #3

(Remarks to the Author)
The revised manuscript has adequately addressed and responded to the questions I was concerned about previously, and is now suitable for acceptance by the Communs Phys Journal.

May 31st, 2025

Dear Editor,

Thank you for handling the submission of our manuscript titled “Ion acceleration from micrometric targets immersed in an intense laser field” to Communications Physics. I am pleased to submit a revised version for further consideration. We are grateful for the constructive reports provided by all three reviewers. Their comments have led us to rerun key simulations, broaden the discussion, and clarify several aspects of the work.

Major improvements include:

1. **Introduction refocused on MeV-scale applications.** We now emphasize radiopharmaceutical production, fast neutron activation, and PIXE, and have removed or relocated material on ultra-high-energy acceleration mechanisms.
2. **Comprehensive PIC reruns with realistic gold ionization (Au^{+20}).** All figures based on simulations (Figs. 2–4) have been updated, yielding closer agreement with experiment.
3. **Performance benchmarking added.** New **Table 1** compares proton flux, total yield, and laser-to-proton conversion efficiency for μ-bar targets versus flat foils.
4. **Discussion re-organized into three subsections** (“Source Properties”, “Cascaded Acceleration”, “Practical Aspects”) and extended to address Coulomb-expansion versus TNSA, inter-bar spacing in multi-stage schemes, and emittance evolution in both transverse planes.

All changes are detailed point-by-point below. We look forward to the reviewers’ and your verdict.

Sincerely,
Ishay Pomerantz

Reviewer #1 (Remarks to the Author):

Review of ‘Ion acceleration from micrometric targets immersed in an intense laser field’ This paper discusses ion acceleration from interesting variable mico-targets with transverse sizes that can be smaller than the focal spot and with thicknesses in the 100’s nm range. The authors discuss how the ion energies surpass those when using conventional flat foils by up to a factor of 3. They also present extensive simulations which recreate the experimental results and extend this to investigate multiple pulses and staged proton acceleration and also discuss the emittance. The emittance presented is astonishingly low, orders of magnitude lower than previous work.
The work is interesting and the authors put it into good context and also discuss the limitations. I have a number of comments which I believe should be discussed before considering publication in Communications Physics.

1. The enhanced proton acceleration is attributed to a higher electron sheath density for thinner targets than thicker targets. The authors attribute it to laser diffraction from the edge, which forms attosecond electron bunches, but I mostly see a cloud which has no resemblance to the diffracted laser. The bunches are most likely directed away from the target and have less of an effect on the proton acceleration. So I find this confusing. Is it that the diffracted laser has sufficient field at the rear of the target that it is pulling electrons out of the target? I think the authors should show in the simulations how these electron bunches are affecting the sheath and flesh out the underlying physics here.

This comment made us realize that the text description is confusing. The formation of attosecond electron bunches is one consequence of the interaction. It persists for a duration shorter than the laser pulse, and it is not related to the formation of the enhanced sheath. We refer to the emission of these bunches as a context to one additional phenomenon which happens simultaneously in the same irradiation conditions and was reported on in our previous publication (Elkind 2023).

In the revised manuscript we removed the confusing statement in the PIC results in figure 2b, and only refer to these electron bunches in the introduction. Also, we expanded the text to state explicitly that the fact that for targets thinner than half the wavelength the electron sheath becomes populated also by electrons from the rear of the target (as shown in Fig. 3d) is an indication that the local field there is sufficient to pull electrons from both sides. We altered the description of Fig. 3(d):

“For a target thinner than half the laser wavelength (top, d = 0.2 μm), the laser field is sufficient to pull electrons from the rear of the target and the sheath is observed to be a mixture of front and back electrons.”

2. The staging concept seems like a distraction from the nice results, and I do not believe it adds much to the paper. It is not immediately clear to me how one would have such a small distance between the targets with multiple pulses. Can the authors expand on this further?

Considering this comment and the next one, we switched the order of the points of discussion to better reflect their relative importance. In the revised manuscript we first discuss the emittance and proton source size and then the proton numbers and conversion efficiency, leaving the cascaded acceleration scheme to be last.

To clarify about the target positioning, we added the following text:

“Target assemblies consisting of multiple μ-bars having set separation distances on the μm scale, can be realized using photolithography-based micromachining [Gershuni2019]. Realization of two foci that are a few μm apart, with a controllable relative delay, can be achieved by spatially dividing the beam into two parts before the final focusing optics,

with one part having an adjustable relative angle and front-facing position [aurand2016]. Such an optical manipulator is simple and compact, but it comes at the cost of reduced intensity due to the inherent astigmatic focusing of one of the beams. Alternatively, an astigmatic system can be realized by expanding the beam to a sufficiently large diameter such that different spatial parts of the focusing beam can be steered with the desired relative delay, while keeping the fluence below the optical damage threshold of the optics."

3. The normalized emittance is astonishingly low - we can see the source size in the plot, but can the authors provide the numbers?

In the revised manuscript we quote the source size for the high energy portion of the proton beam:

"These are shown in Fig. 2g for the case of a d = 0.2 μm, w = 2 μm μ-bar, color-coded by the final proton energy, and features a source size smaller than 4 μm^2 for E > 4 MeV protons."

a. We assume that because the cloud is quasi neutral, that the emittance doesn't blow up in TNSA - can you confirm the emittance further from the target at the end of the simulation? This would be using the RMS values for each weighted macroparticle later in time I believe.

We agree that the relevant figures of merit are the source-size and emittance calculated far from the target, after the end of the acceleration phase. This comment made us realize that we should clarify to the reader that by "virtual" source size, we refer to those measures. We expanded the text to read:

"Strong sheath fields close to the target may modify the proton trajectories following their emission. This affects the ability of a distant observer to determine the spread of their point of origin (their "source size"). To account for this effect, we obtained energy resolved "virtual" source distributions of the proton beam [Borghesi2004] by projecting the proton angle at the end of the acceleration phase back to the target plane."

b. Since the target is 2D, but you have 3D simulations, it would be interesting to see the difference in the emittance in both transverse directions.

We found this idea insightful and implemented it in Fig. 2. The separation of the emittance into its two transverse components further support the observation that the ultra-low emittance originates from the small source size of the protons. The extent of the proton source in the y direction is bound by the target lateral extent, and therefore the emittance remains rather constant with the proton energy. It drops only for the very high energy protons, which originates from a very small area. On the other hand, in the z direction protons can originate from the full extent of the target's long dimension, and as observed in Fig. 2g, it has strong correlation with the proton energy.

4. The authors discuss other papers, such as [44] which achieve 2MeV with 5mJ of laser (more than 20 times less energy), which if you project with TNSA scaling, would result in higher ion energies which may reduce the impact of this work e.g. the statements that 6 MeV was produced with *only* 120 mJ of energy. I believe it may be worthwhile to focus more on the small source size / low emittance of these targets which may be much more unique and exciting compared to others to increase the overall impact of the work.

Following this comment we revised the summary paragraph to reflect the relative importance of our findings: First the small source size and emittance, then the enhancement of the proton energies, and finally the prospects of cascaded acceleration.

Minor
1. Repeated sentence in the PIC methods section.

We removed the repeating sentence.

Reviewer #2 (Remarks to the Author):
GENERAL ASSESSMENT
Moderate revision.

CONCLUSION
The manuscript titled "Ion acceleration from micrometric targets immersed in an intense laser field" by Elkind et al. presents original experimental measurements of laser irradiation on micrometric bar targets. Despite the moderate laser pulse energy of 120 mJ, the study demonstrates proton acceleration to energies of 6–8 MeV. Furthermore, the authors propose an extended scheme involving a series of micrometric bar targets and a split laser pulse, potentially enhancing proton energies to 12 MeV via a cascading acceleration mechanism. The experimental findings are well-supported by PIC simulations, strengthening the interpretation of the observed phenomena. However, I have a major concern regarding the Introduction section, which, in my opinion, lacks direct relevance to the presented results and requires significant revision. The impact of the findings should be articulated more clearly to help assess their significance within our subfield of physics.
MAIN COMMENTS

1. Relevance of acceleration mechanisms and applications: The introduction broadly discusses various laser-driven ion acceleration mechanisms and their applications, including fast ignition for inertial confinement fusion, neutron beam generation, and ion-based cancer therapy. However, the proton energies reported in this study (6–12 MeV) are significantly lower than what these applications typically require (e.g., ~250 MeV for proton therapy). The authors should focus on applications where their results are practically relevant and discuss them in greater detail. For instance, citing cancer therapy as motivation is not appropriate in the context of the presented results.

Following this comment, we separated the context of the prospective applications of laser accelerated ions to those suitable to lasers at the intensity frontier, and those that are suitable to MeV-level energies:

"Prospective applications suitable for these lower energies include radiopharmaceuticals generation either directly [Maffini2023] or through the products of secondary nuclear reactions [Molloy2025, batani2025], and materials analysis techniques such as fast neutron activation [Mirani2023] and laser-driven particle-induced x-ray emission [Mirani2021]."

2. Relevance of advanced acceleration schemes: The manuscript mentions advanced acceleration schemes such as radiation pressure acceleration, breakout afterburner, and collisional shock acceleration. While these mechanisms are promising, they are not realistically achievable with the laser and plasma conditions used in this study. Their inclusion should be reconsidered or more clearly justified in relation to the presented work.

We omitted this overview sentence about RPA, BOA and CSA from the revised manuscript.

3. Mass-limited target acceleration: A more detailed comparison between the results obtained in this study and alternative laser-driven ion acceleration mechanisms using mass-limited targets (referencing works such as [24–29, 47], and probably also others) would strengthen the discussion.

This comparison should highlight the advantages and limitations of the micro-bar target approach relative to existing methods.

We added the following clause to the discussion, comparing the key advantages and disadvantages of using single formation micrometric targets like our μ-bars, and surfaces covered by random micrometric formations:

"Targets having a large surface covered with micrometric formations [Zigler2013, Floquet2013,curtis2018] are naturally more resilient to the laser's miss-pointing making them simpler and faster to align. This advantage is shared also with many other target designs which manipulate laser absorption to enhance TNSA [Sgattoni2012,prencipe2021,Jiang2018]. However, the stochastic nature of the overlap between their micrometric features and the laser field results in an inherent shot-to-shot variability of the accelerated ions. Beyond the increase in the proton energies and the reduced source-size reported here, single-formation targets like μ-bars and levitated spheres [Ostermayr2016]unveil the interaction dynamics in a straightforward manner by allowing parametric scans over their geometrical features."

4. TNSA at similar conditions: The study claims that micro-bar targets provide significantly higher proton energies than conventional target normal sheath acceleration (TNSA) under comparable laser conditions. However, the manuscript does not sufficiently address key performance metrics such as the number of accelerated protons and laser-to-proton energy conversion efficiency. Could the enhancement in proton cutoff energy outweigh the challenges associated with target fabrication and installation, especially when considering high-repetition-rate applications?

Following this comment and a comment from reviewer #3, we added Table 1, presenting a summary of the key properties of the proton beams: flux, number, and energy conversion efficiency for foils vs. μ-bar targets. The following discussion clause was added to the text:

"Key properties of the resulting proton beams for the cases of foil targets and $w = 2$ μm μ-bars (the narrowest we irradiated) are given in Table 1. For μ-bars, the 32% lower proton flux (at the laser direction) is nearly balanced by the increased emission cone-angle (Fig. 2f), yielding similar total proton numbers in both cases. However, the higher proton energies in the μ-bar case corresponds to a ~4 times higher coupling efficiency of laser energy to the proton beam, compared to that of conventional foil targets."

Also in this context, we added the following sentence to the discussion about high-repetition-rate applications:

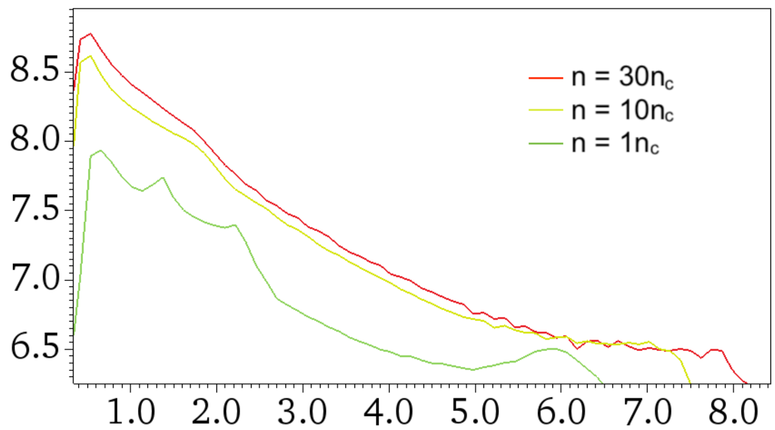
"The results presented here should motivate the development of liquid jets producing replenishing targets that are bound and stable in the transverse direction within the μm scale."

5. Proton spectra in simulations and experiments: The proton energy spectra presented in Figures 2a and 2c show good agreement in cutoff energy but significant discrepancies in total proton count and spectral shape, particularly in the low-energy region. In my assessment, this discrepancy might come from the initially large number of protons initialized in the simulation.

Following this comment, we investigated the origin of the low-energy flattening of the spectrum observed for narrow μ-bars in the experiment but not resolved in the simulation. We tested both the reviewer's hypothesis and other possible origins of this phenomenon described in

Macchi, A, et al., PPCF 55(12), 124020 (2013), DuBois, T.C., et. al, PoP 24(12) (2017), and Robinson, A.L., et al., PRL 96(3), 035005 (2006), related to a realistic representation of the contamination layer under computational load restrictions.

Lowering the initial proton density for simulations of w = 2 μm μ-bars resulted in following spectra:



The spectrum somewhat flattens, but modulations emerge for low energies. These modulations are very similar to those discussed in DuBois (2017) and Robinson (2006) and could originate from either unresolved electron refluxing or specific details on the initial ion species composition. Scanning over different proportions of H, C, and O did not reproduce a plateau either.

Our conclusion is that the mismatch in low energies may be a result of the large number of initialized protons which are required to accurately represent a realistic plasma scale-length, under the limitation on spatial resolution posed by our computational allocation. These were discussed in L´ecz, Z., et.al, NIM-A 727, 51–58 (2013). We added the following discussion to the revised text:

"For narrow μ-bars, the measured proton energy spectra feature flattening in the low-energy region that is not captured by simulations. Simulating the low-energy tail of laser-accelerated ions remains a challenge [macchi2013], as it often requires extremely high numbers of computational particles to accurately represent a realistic plasma scale-length, when the spatial resolution is limited by computational constraints [lecz2013]. This spectral flattening may stem from several numerically unresolved physical mechanisms, including fast electrons refluxing through the target that induces oscillating charge separation at the rear surface [dubois2017]; the emergence of ion acceleration mechanisms other than TNSA [fang2016]; and high sensitivity to the detailed density profiles of surface contaminants [robinson2006]."

6. Cascaded acceleration regime: More details should be provided on how to optimize the inter-bar distance and the delay between laser pulses in the proposed cascaded acceleration scheme. Ideally, these parameters should be linked to a simple model based on plasma expansion dynamics.

This comment drove us to start a new extension project about a comprehensive analytical analysis of the spectral dependence of a multi-target laser accelerator on the laser, target, and plasma parameters. For the current manuscript, we added the following simplistic analysis, based on Mora's model under a simplified assumption of a quasi-static field:

"For a given μ-bars separation distance and Δt chosen under the considerations above, the energy gain of protons injected at time t_{in} with respect to Δt to the rear sheath field of the second μ-bar, can be evaluated in the isothermal plasma expansion approximation [mora2003]: $m_p v dv/dx = eE(x, t_{in}) \approx 2\, k_B T_e / (x + c_s t_{in} + \sqrt{2}\, \lambda_D)$. Here, m_p is the proton's mass, v and x are its velocity and position with respect to the rear surface, λ_D is the Debye length, and c_s is the ion sound speed. For simplicity, we assumed above that the sheath field is quasi-static during the proton's interaction (i.e., "frozen" at time t_{in}). Separation of variables (x and v) and integration of both sides of the above expression yields: $\Delta\mathcal{E} = (1/2)\, m_p (v_\infty^2 - v_{in}^2) = 2\, k_B T_e \ln[(2\, c_s t_{in} + \sqrt{2}\, \lambda_D)/(c_s t_{in} + \sqrt{2}\, \lambda_D)]$ where we assumed that the sheath field extends only up to the ion front at $x \approx c_s t_{in}$. This implies an energy gain linear in t_in at early times ($c_s t_{in} \ll \lambda_D$), $\Delta\mathcal{E} \approx \sqrt{2}\, k_B T_e c_s t_{in} / \lambda_D$ and asymptotic at late times ($c_s t_{in} \gg \lambda_D$), $\Delta\mathcal{E} \approx 2 \ln(2)\, k_B T_e$."

7. Simulation parameters and ionization effects

• Was the ionization module enabled in the PIC simulations?

• If not, how is the choice of initial ion charge state (Z_0 = 4 or 8) justified?

• Reference [52] suggests that an intensity of 4.3×10^{19} W/cm² could lead to ionization up to Z ≈ 40, not assessing the influence of the collisional ionisation. Would this significantly alter the plasma conditions?

• If ionization effects were not considered, the chosen simulation grid (32 nm × 20 nm × 160 nm or 10.7 nm × 6.7 nm × 80 nm) might struggle to resolve the reduced plasma skin depth at higher electron densities.

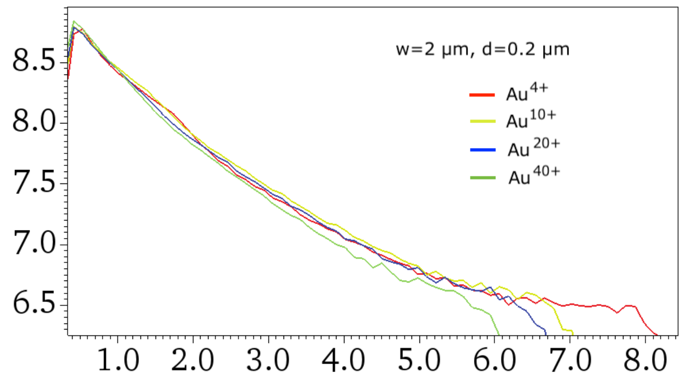
• While the experimental results remain the core contribution of the study, these simulation limitations should be acknowledged in the manuscript.

As the reviewer pointed out, the assumed initial charge state in the simulation does not affect the core conclusions of this study. Nevertheless, the treatment of this comment took the lion share of work towards this revised version. It resulted in re-running of all the simulations and reproduction of most of the paper's figures. The reason is that the presentation of the simulations in the original submission with a charge state of Au^{4+} can not be justified. We are grateful to the reviewer for noticing this oversight. This had the following implications on the revised manuscript:

1) The ionization module was not turned on in the simulations. We added the following statement to the Methods section to clarify:

   "Following the results of this sensitivity test, dynamical treatment of the ionization was not simulated to reduce computational load."

2) From Kawahito et al. (2020), an intensity of 4.3×10^{19} W/cm² can lead to ionization up to Z ≈ 40. In the revised manuscript we:
   a. Extended the sensitivity test of all simulations to the range of up to Au^{40+}. For example the resulting proton spectrum for the narrowest microbar are:



We updated the statement about this sensitivity test to read:

> *"Rerunning the simulations with initial ion charge states in the range of Au^{4+}--Au^{40+} and with a pre-plasma scale length in the range of $\lambda/80$ -- $\lambda/40$, resulted in an overall shift of the proton energies by a factor of 0.88--1.24, but the dependence on w remained unchanged."*

b. We re-ran all of the simulations supporting the results of this paper, now with the bulk of the target assumed ionization state of Au^{20+}. This resulted in updates to Fig. 2(c,d,e,f,g,h), Fig. 3, and Fig. 4. None of the paper's conclusions were altered due to these changes, however the agreement of the simulation with the experiment is now far closer in the absolute proton cut-off energies.

3) To ensure that the simulation resolves the reduced plasma skin depth at higher electron densities, we ran one computationally intensive simulation with a division of 8000 cells in the laser propagation direction (4 nm per cell), i.e. ¼ of the pre-plasma scale length. We amended the text to read:

"We conducted one computationally heavy simulation with a high resolution of $(8000)_x X (3000)_y X (300)_z$ cells to verify the consistency of the results."

MINOR COMMENTS

1. Figure 2e: The unit of the electric field is missing—please specify.

We replotted the figure with the electric field now in absolute rather than normalized units.

2. Figure 3b, c and last paragraph on page 5: The text discusses electron temperature (T_e), whereas the plots show average electron energy (E_e). The relationship between these quantities should be clarified.

We revised the text on that paragraph to indicate specifically that $\langle E_e \rangle \sim T_e$.

3. Splitting the Discussion into several subsections would improve readability and help guide the reader through key findings.

We revised the discussion section to have these three subsections: "Source properties", "Cascaded acceleration", and "Practical aspects".

Reviewer #3 (Remarks to the Author):
The manuscript entitled "Ion acceleration from micrometric targets immersed in an intense laser field" reports on an experimental study of proton acceleration by intense laser irradiation of micrometric bar targets. To optimize ion acceleration, the transverse and longitudinal dimensions of the target are specially designed. It is found that the cutoff energies of protons are about 3 times improved compared to the flat-foil irradiation with the same laser energy. The paper is rather well written and comprehensible and it is suitable for publication. But there are a few questions that need to be explained.

1. In fact, many target design schemes have been proposed to improve the effect of femtosecond laser-driven TNSA acceleration, such as foam target, sub-micron grating target and micron-scale channels or wire-array target. It is recommended that the authors add references in the Introduction, and discuss their advantages and disadvantages compared with the targets used in this study.

We have added the suggested context to the Introduction, which now includes references to several examples of advanced target designs aimed at enhancing TNSA:

"Advanced target designs aimed to enhance TNSA via controlled pre-expansion, localized field enhancement, or increased heating of target electrons include foam layers [Sgattoni2012, prencipe2021,Jiang2018], sub-micron gratings [ceccotti2013,sgattoni2015,blanco2017], micron-scale channels [Lezhnin2022,Zou2019,Yang2018], and micro- or nano-structured wire arrays [Khaghani2017,Frontiers2023]."

We also added reference to these types of targets in the discussion about relative advantages:

"Targets having a large surface covered with micrometric formations [Zigler2013,Floquet2013, curtis2018,ceccotti2013,sgattoni201,blanco2017,Khaghani2017,Zhao2023] are naturally more resilient to the laser's miss-pointing and are potentially faster to align. This advantage is shared also with many other target designs which manipulate laser absorption to enhance TNSA [Sgattoni2012, prencipe2021,Jiang2018]."

2. The insets in Fig. 2(c) show that the electrons appear to be experiencing Coulomb expansion, so is the improvement in cutoff energy of ions related to Coulomb expansion? The author needs to provide further details to confirm their irrelevance.

This is an important point that we clarified in the revised submission. Indeed, Coulomb expansion drives electrons to expand from the target. So, in a sense the proton energy improvement is indirectly related to Coulomb expansion – but it's the expansion of the electrons, not an explosive separation of ions, that's important.

We explicitly confirm that Coulomb explosion of the target is not the cause of the higher proton energy, by observing that that for thicker targets, where a Coulomb explosion would if anything be similar or even stronger (due to more stored charge), we *do not* see increased proton energies. This indicates that the sheath physics (which differs between thin and thick cases) is what matters. We added the following paragraph to the revised manuscript:

"The inset in Fig.2(c) features Coulomb expansion of the electron sheath for a $w = 2$ μm, $d = 0.2$ μm μ-bar. The drop in proton energies for thicker targets in Fig. 3(a) indicates that the higher proton energies are indeed due to enhanced TNSA rather than to Coulomb explosion (i.e., not from the target

ions accelerating themselves by mutual repulsion), since in the latter case, proton energies would rise due to the increased stored charge."

3. As can be seen from Fig. 2(a), the energy conversion efficiency from the laser to the protons with energies higher than 1 MeV should be greatly improved compared with the flat-foil, and relevant simulation and experimental data should be supplemented.

We followed the reviewer's recommendation, and added Table 1, presenting a summary of the key properties of the proton beams: flux, number, and energy conversion efficiency for foils vs. μ-bar targets. The following clause was added to the discussion text:

"Key properties of the resulting proton beams for the cases of foil targets and w = 2 μm μ-bars (the narrowest we irradiated) are given in Table 1. For μ-bars, the 32% lower proton flux (at the laser direction) is nearly balanced by the increased emission cone-angle (Fig. 2f), yielding similar total proton numbers in both cases. However, the higher proton energies in the μ-bar case corresponds to a 4 times higher coupling efficiency of laser energy to the proton beam, compared to that of conventional foil targets."

4. Although the pulse contrast is better than 10^11 before t=-60 ps, the radiation hydrodynamics simulation or other evidence is still necessary to reveal the density distribution of the preplasma produced after the prepulse ablation micrometric bar target, and to support the selection of the pre-plasma scale length in the simulation.

The reviewer identified that we failed to mention the origin of the assumed scale-length. It is based on an evaluation in [Cantono, Giada, et al. *Sci. Rep.* 11.1 (2021): 5006] which used a very similar laser intensity profile (following contrast enhancement with a double plasma-mirror system) and similar targets (their reference flat Au foils). Using a simple sonic expansion model, they projected a scale length in the range of 20–70 nm. Similarly to our findings, the resulting TNSA spectrum (in PIC) had very small dependence on different values within this range. We added the following text to the PIC description in the Methods section:

"This evaluation relies on findings of Ref. [Cantono2021] which studied proton emission from ultrathin Au foils irradiated with similar laser intensity and temporal contrast. Using a simple sonic-expansion model they estimated a scale length in the range of 20--70~nm, which yielded minimal modifications to the resulting proton spectrum."

Jul 14st, 2025

Dear Editor,

Thank you for handling the submission of our manuscript titled “Ion acceleration from micrometric targets immersed in an intense laser field” to Communications Physics. We are grateful for the pertinent review process and pleased to submit a revised version.

Sincerely,
Ishay Pomerantz

Reviewer #1 (Remarks to the Author):
Thank you to the authors for the revision of the manuscript. Many things have been clarified since the last revision. The quality has been greatly improved and enabled greater understanding for the reader. I have noted a few minor points which I believe should still be extended for clarity and then I believe it can be ready for publication.

Now that we have the emittances separated by dimension, I would just like to ask for a few more details on this point. While we expect that the source size in ‘y’ is small, the divergence is expected to be larger due to the curved sheath. ‘z’ has a larger spatial extent but flatter sheath, and narrower divergence? A short explanation on why the emittances are different orders of magnitude should complement this new data.
We added the following explanation about the difference between the transverse components of the emittance:

“The large difference between ε_y and ε_z results from the increased horizontal divergence angle of the proton beam, observed both in the experiment and the simulation. This is another consequence of when the sheath no longer maintains the target’s aspect ratio for narrow targets.”

Can the authors extend the sentences explaining the origin of the denser sheath at the rear - I think this could have been more explicit in their previous response. It is implied that in the case of the thinnest targets, the diffracted laser field at the target rear is what is pulling the rear surface electrons out? This could be visualised with the laser field superimposed, like in fig 2c, over the electrons in fig 3d? This is only a suggestion. I find this quite interesting, and particularly so if the sheath has the chance to be shaped by the diffracted laser pulse with this unique target geometry. Can the authors comment on this?
This comment made us realize that the explanation for the simultaneous pull of electrons from the front and back surfaces should be put in the text in clearer terms. Since the diffraction does not take a direct role in this part of the underlying physics, superimposing the fields on the figure will not aid in relaying the explanation. We added the following description:

“For a target thinner than half the laser wavelength (top, d = 0.2 μm), the laser field may simultaneously pull electrons from both the front surface (to the -x direction) and the rear surface (to the +x direction) and the sheath is observed to be a mixture of front and back electrons.”

Review of ‘Ion acceleration from micrometric targets immersed in an intense laser field’

This paper discusses ion acceleration from interesting variable mico-targets with transverse sizes that can be smaller than the focal spot and with thicknesses in the 100’s nm range. The authors discuss how the ion energies surpass those when using conventional flat foils by up to a factor of 3. They also present extensive simulations which recreate the experimental results and extend this to investigate multiple pulses and staged proton acceleration and also discuss the emittance. The emittance presented is astonishingly low, orders of magnitude lower than previous work.

The work is interesting and the authors put it into good context and also discuss the limitations. I have a number of comments which I believe should be discussed before considering publication in Communications Physics.

1. The enhanced proton acceleration is attributed to a higher electron sheath density for thinner targets than thicker targets. The authors attribute it to laser diffraction from the edge, which forms attosecond electron bunches, but I mostly see a cloud which has no resemblance to the diffracted laser. The bunches are most likely directed away from the target and have less of an effect on the proton acceleration. So I find this confusing. Is it that the diffracted laser has sufficient field at the rear of the target that it is pulling electrons out of the target? I think the authors should show in the simulations how these electron bunches are affecting the sheath and flesh out the underlying physics here.
2. The staging concept seems like a distraction from the nice results, and I do not believe it adds much to the paper. It is not immediately clear to me how one would have such a small distance between the targets in reality with multiple pulses. Can the authors expand on this further?
3. The normalized emittance is astonishingly low - we can see the source size in the plot, but can the authors provide the numbers?
    a. We assume that because the cloud is quasi neutral, that the emittance doesn’t blow up in TNSA - can you confirm the emittance further from the target at the end of the simulation? This would be using the RMS values for each weighted macroparticle later in time I believe.
    b. Since the target is 2D, but you have 3D simulations, it would be interesting to see the difference in the emittance in both transverse directions.
4. The authors discuss other papers, such as [44] which achieve 2MeV with 5mJ of laser (more than 20 times less energy), which if you project with TNSA scaling, would result in higher ion energies which may reduce the impact of this work e.g. the statements that 6MeV was produced with *only* 120mJ of energy. I believe it may be worthwhile to focus more on the small source size / low emittance of

these targets which may be much more unique and exciting compared to others to increase the overall impact of the work.

Minor

1. Repeated sentence in the PIC methods section.